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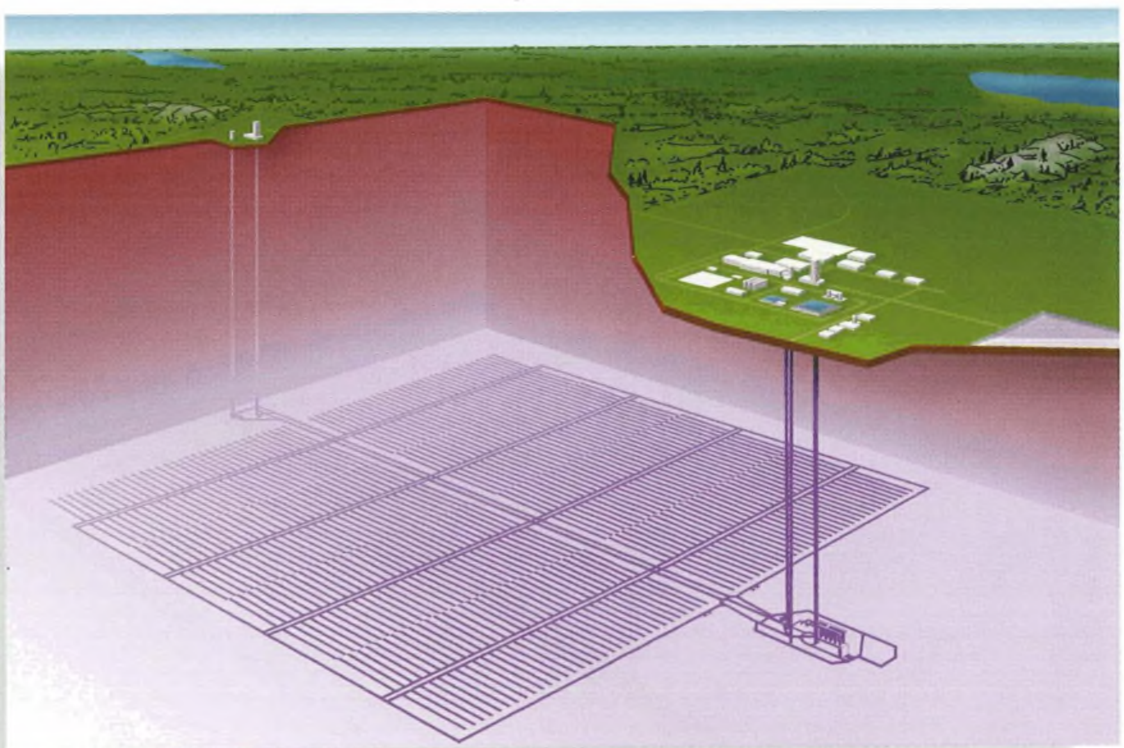
The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility

Le stockage permanent des déchets de combustible nucléaire du Canada : Ingénierie d'une installation de stockage permanent

G.R. Simmons, P. Baumgartner



AECL RESEARCH

THE DISPOSAL OF CANADA'S NUCLEAR FUEL WASTE: ENGINEERING FOR A DISPOSAL FACILITY

by

G.R. Simmons and P. Baumgartner

The Canadian Nuclear Fuel Waste Management Program is funded jointly by AECL and Ontario Hydro under the auspices of the CANDU Owners Group.

Whiteshell Laboratories
Pinawa, Manitoba ROE 1LO
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LE STOCKAGE PERMANENT DES DÉCHETS DE COMBUSTIBLE NUCLÉAIRE DU CANADA : INGÉNIERIE D'UNE INSTALLATION DE STOCKAGE PERMANENT

par

G.R. Simmons et P. Baumgartner

RÉSUMÉ

Dans ce rapport, on présente certains facteurs généraux à prendre en considération au stade de l'ingénierie d'une installation de stockage permanent de déchets de combustible nucléaire, des concepts et dispositions possibles d'installation souterraine ainsi qu'un plan conceptuel d'un centre de stockage permanent de combustible usé dont on s'est servi pour évaluer la faisabilité technique, les coûts et les effets possibles du stockage permanent. On présente les facteurs généraux à prendre en considération ainsi que les dispositions possibles d'installation souterraine pour démontrer qu'il y a des possibilités permettant d'adapter le plan aux conditions qui existent réellement dans le site. Le plan conceptuel d'un centre de stockage permanent de combustible usé comporte la description des deux éléments principaux de l'installation de stockage permanent, Bâtiment de mise en paniers du combustible usé et installation souterraine de stockage permanent; en outre, on identifie les bâtiments auxiliaires et les services nécessaires pour exécuter les travaux. On examine la construction, l'exploitation et le déclassement de l'installation de stockage permanent ainsi que la remise en état du site. On estime les coûts, les besoins de main d'oeuvre et les calendriers servant à évaluer les effets socio-économiques et pouvant servir à évaluer la charge financière du stockage permanent des déchets pour le consommateur d'électricité d'origine nucléaire.

Le Programme canadien de gestion des déchets de combustible nucléaire est financé en commun par EACL et Ontario Hydro sous les auspices du Groupe des propriétaires de réacteurs CANDU.

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ABSTRACT

This report presents some general considerations for engineering a nuclear fuel waste disposal facility, alternative disposal-vault concepts and arrangements, and a conceptual design of a used-fuel disposal centre that was used to assess the technical feasibility, costs and potential effects of disposal. The general considerations and alternative disposal-vault arrangements are presented to show that options are available to allow the design to be adapted to actual site conditions. The conceptual design for a used-fuel disposal centre includes descriptions of the two major components of the disposal facility, the Used-Fuel Packaging Plant and the disposal vault; the ancillary facilities and services needed to carry out the operations are also identified. The development of the disposal facility, its operation, its decommissioning, and the reclamation of the site are discussed. The costs, labour requirements and schedules used to assess socioeconomic effects and that may be used to assess the cost burden of waste disposal to the consumer of nuclear energy are estimated.

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PREFACE

In 1992, 15% of the electricity generated in Canada was produced using CANDU nuclear reactors. A by-product of the nuclear power is used CANDU fuel, which consists of ceramic uranium dioxide pellets and metal structural components. Used fuel is highly radioactive. The used fuel from Canada's power reactors is currently stored in water-filled pools or dry storage concrete containers. Humans and other living organisms are protected by isolating the used fuel from the natural environment and by surrounding it with shielding material. Current storage practices have an excellent safety record.

At present, used CANDU fuel is not reprocessed. It could, however, be reprocessed to extract useful material for recycling, and the highly radioactive material that remained could be incorporated into a solid. The term "nuclear fuel waste," as used by AECL, refers to either

- the used fuel, if it is not reprocessed, or
- a solid incorporating the highly radioactive waste from reprocessing.

Current storage practices, while safe, require continuing institutional controls such as security measures, monitoring, and maintenance. Thus storage is an effective interim measure for protection of human health and the natural environment but not a permanent solution. A permanent solution is disposal, a method "in which there is no intention of retrieval and which, ideally, uses techniques and designs that do not rely for their success on long-term institutional control beyond a reasonable period of time" (AECB 1987a).

In 1978, the governments of Canada and Ontario established the Nuclear Fuel Waste Management Program ". . . to assure the safe and permanent disposal" of nuclear fuel waste. AECL was made responsible for research and development on ". . . disposal in a deep underground repository in intrusive igneous rock" (Joint Statement 1978). Ontario Hydro was made responsible for studies on interim storage and transportation of used fuel and has contributed to the research and development on disposal. Over the years a number of other organizations have also contributed to the Program, including Energy, Mines and Resources Canada; Environment Canada; universities; and companies in the private sector.

The disposal concept is to place the waste in long-lived containers; emplace the containers, enveloped by sealing materials, in a disposal vault excavated at a nominal depth of 500 to 1000 m in intrusive igneous (plutonic) rock of the Canadian Shield; and (eventually) seal all excavated openings and exploration boreholes to form a passively safe system. Thus there would be multiple barriers to protect humans and the natural environment from contaminants in the waste: the container, the very low-solubility waste form, the vault seals, and the geosphere. The disposal technology includes options for the design of the engineered components, including the disposal container, disposal vault, and vault seals, so that it is adaptable to a wide range of regulatory standards, physical conditions, and social requirements. Potentially suitable bodies of plutonic rock occur in a large number of locations across the Canadian Shield.

In developing and assessing this disposal concept, AECL has consulted broadly with members of Canadian society to help ensure that the concept and the way in which it would be implemented are technically sound and represent a generally acceptable disposal strategy. Many groups in Canada have had opportunities to comment on the disposal concept and on the waste management program. These include government departments and agencies, scientists, engineers, sociologists, ethicists, and other members of the public. The Technical Advisory Committee to AECL on the Nuclear Fuel Waste Management Program, whose members are nominated by Canadian scientific and engineering societies, has been a major source of technical advice.

In 1981, the governments of Canada and Ontario announced that ". . . no disposal site selection will be undertaken until after the concept has been accepted. This decision also means that the responsibility for disposal site selection and subsequent operation need not be allocated until after concept acceptance" (Joint Statement 1981).

The acceptability of the disposal concept is now being reviewed by a federal Environmental Assessment Panel, which is also responsible for examining a broad range of issues related to nuclear fuel waste management (Minister of the Environment, Canada 1989). After consulting the public, the Panel issued guidelines to identify the information that should be provided by AECL, the proponent of the disposal concept (Federal Environmental Assessment Review Panel 1992).

AECL is preparing an Environmental Impact Statement to provide information requested by the Panel and to present AECL's case for the acceptability of the disposal concept. A Summary will be issued separately. This report is one of nine primary references that summarize major aspects of the disposal concept and supplement the information in the Environmental Impact Statement. A guide to the contents of the EIS, the Summary, and the primary references follows this Preface.

In accordance with the 1981 Joint Statement of the governments of Canada and Ontario, no site for disposal of nuclear fuel waste is proposed at this time. Thus in developing and assessing the disposal concept, AECL could not design a facility for a proposed site and assess the environmental effects to determine the suitability of the design and the site, as would normally be done for an Environmental Impact Statement. Instead, AECL and Ontario Hydro have specified illustrative "reference" disposal systems and assessed those.

A "reference" disposal system illustrates what a disposal system, including the geosphere and biosphere, might be like. Although it is hypothetical, it is based on information derived from extensive laboratory and field research. Many of the assumptions made are conservative, that is, they would tend to overestimate adverse effects. The technology specified is either available or judged to be readily achievable. A reference disposal system includes one possible choice among the options for such things as the waste form, the disposal container, the vault layout, the vault seals, and the system for transporting nuclear fuel waste to a disposal facility.

The components and designs chosen are not presented as ones that are being recommended but rather as ones that illustrate a technically feasible way of implementing the disposal concept.

After the Panel has received the requested information, it will hold public hearings. It will also consider the findings of the Scientific Review Group, which it established to provide a scientific evaluation of the disposal concept. According to the Panel's terms of reference "As a result of this review the Panel will make recommendations to assist the governments of Canada and Ontario in reaching decisions on the acceptability of the disposal concept and on the steps that must be taken to ensure the safe long-term management of nuclear fuel wastes in Canada" (Minister of the Environment, Canada 1989).

Acceptance of the disposal concept at this time would not imply approval of any particular site or facility. If the disposal concept is accepted and implemented, a disposal site would be sought, a disposal facility would be designed specifically for the site that was proposed, and the potential environmental effects of the facility at the proposed site would be assessed. Approvals would be sought in incremental stages, so concept implementation would entail a series of decisions to proceed. Decision-making would be shared by a variety of participants, including the public. In all such decisions, however, safety would be the paramount consideration.

The EIS, Summary, and Primary References

Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste (AECL 1994a)
Summary of the Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste (AECL 1994b)
The Disposal of Canada's Nuclear Fuel Waste: Public Involvement and Social Aspects (Greber et al. 1994)
The Disposal of Canada's Nuclear Fuel Waste: Site Screening and Site Evaluation Technology (Davison et al. 1994a)
The Disposal of Canada's Nuclear Fuel Waste: Engineered Barriers Alternatives (Johnson L.H. et al. 1994a)
The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility (Simmons and Baumgartner, this volume)
The Disposal of Canada's Nuclear Fuel Waste: Preclosure Assessment of a Conceptual System (Grondin et al. 1994)
The Disposal of Canada's Nuclear Fuel Waste: Postclosure Assessment of a Reference System (Goodwin et al. 1994)
The Disposal of Canada's Nuclear Fuel Waste: The Vault Model for Postclosure Assessment (Johnson L.H. et al. 1994b)
The Disposal of Canada's Nuclear Fuel Waste: The Geosphere Model for Postclosure Assessment (Davison et al. 1994b)
The Disposal of Canada's Nuclear Fuel Waste: The Biosphere Model, BIOTRAC, for Postclosure Assessment (Davis et al. 1993)

GUIDE TO THE CONTENTS OF THE ENVIRONMENTAL IMPACT STATEMENT, THE SUMMARY, AND THE PRIMARY REFERENCES

ENVIRONMENTAL IMPACT STATEMENT AND SUMMARY

Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste (AECL 1994a)

- provides an overview of AECL's case for the acceptability of the disposal concept
- provides information about the following topics:
  - the characteristics of nuclear fuel waste
  - storage and the rationale for disposal
  - major issues in nuclear fuel waste management
  - the disposal concept and implementation activities
  - alternatives to the disposal concept
  - methods and results of the environmental assessments
  - principles and potential measures for managing environmental effects
  - AECL's overall evaluation of the disposal concept

Summary of the Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste (AECL 1994b)

- summarizes the contents of the Environmental Impact Statement

PRIMARY REFERENCES

The Disposal of Canada's Nuclear Fuel Waste: Public Involvement and Social Aspects (Greber et al. 1994)

- describes the activities undertaken to provide information to the public about the Nuclear Fuel Waste Management Program and to obtain public input into the development of the disposal concept
- presents the issues raised by the public and how the issues have been addressed during the development of the disposal concept or how they could be addressed during the implementation of the disposal concept
- discusses social aspects of public perspectives on risk, ethical issues associated with nuclear fuel waste management, and principles for the development of a publicly acceptable site selection process

The Disposal of Canada's Nuclear Fuel Waste: Site Screening and Site Evaluation Technology (Davison et al. 1994a)

- discusses geoscience, environmental, and engineering factors that would need to be considered during siting

- describes the methodology for characterization, that is, for obtaining the data about regions, areas, and sites that would be needed for facility design, monitoring, and environmental assessment

The Disposal of Canada's Nuclear Fuel Waste: Engineered Barriers Alternatives (Johnson et al. 1994a)

- describes the characteristics of nuclear fuel waste
- describes the materials that were evaluated for use in engineered barriers, such as containers and vault seals
- describes potential designs for containers and vault seals
- describes procedures and processes that could be used in the production of containers and the emplacement of vault-sealing materials

The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility (this volume)

- discusses alternative vault designs and general considerations for engineering a nuclear fuel waste disposal facility
- describes a disposal facility design that was used to assess the technical feasibility, costs, and potential effects of disposal (Different disposal facility designs are possible and might be favoured during concept implementation.)
- presents cost and labour estimates for implementing the design

The Disposal of Canada's Nuclear Fuel Waste: Preclosure Assessment of a Conceptual System (Grondin et al. 1994)

- describes a methodology for estimating effects on human health, the natural environment, and the socio-economic environment that could be associated with siting, constructing, operating (includes transporting used fuel), decommissioning, and closing a disposal facility
- describes an application of this assessment methodology to a reference disposal system (We use the term "reference" to designate the disposal systems, including the facility designs, specified for the assessment studies. Different disposal facility designs are possible and might be favoured during concept implementation.)
- discusses technical and social factors that would need to be considered during siting
- discusses possible measures and approaches for managing environmental effects

The Disposal of Canada's Nuclear Fuel Waste: Postclosure Assessment of a Reference System (Goodwin et al. 1994)

- describes a methodology for
  - estimating the long-term effects of a disposal facility on human health and the natural environment,
  - determining how sensitive the estimated effects are to variations in site characteristics, design parameters, and other factors, and
  - evaluating design constraints

- describes an application of this assessment methodology to a reference disposal system (We use the term "reference" to designate the disposal systems, including the facility designs, specified for the assessment studies. Different disposal facility designs are possible and might be favoured during concept implementation.)

The Disposal of Canada's Nuclear Fuel Waste: The Vault Model for Postclosure Assessment (Johnson et al. 1994b)

- describes the assumptions, data, and model used in the postclosure assessment to analyze processes within and near the buried containers of waste

- discusses the reliability of the data and model

The Disposal of Canada's Nuclear Fuel Waste: The Geosphere Model for Postclosure Assessment (Davison et al. 1994b)

- describes the assumptions, data, and models used in the postclosure assessment to analyze processes within the rock in which a disposal vault is excavated

- discusses the reliability of the data and model

The Disposal of Canada's Nuclear Fuel Waste: The Biosphere Model, BIOTRAC, for Postclosure Assessment (Davis et al. 1993)

- describes the assumptions, data, and model used in the postclosure assessment to analyze processes in the near-surface and surface environment

- discusses the reliability of the data and model

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EXECUTIVE SUMMARY

ES.1 INTRODUCTION

In 1978, the governments of Canada and Ontario established the Nuclear Fuel Waste Management Program ". . . to assure the safe permanent disposal" of nuclear fuel waste. AECL was made responsible for research and development on ". . . disposal in a deep underground repository in intrusive igneous rock" (Joint Statement 1978). Ontario Hydro was made responsible for studies on the interim storage and transportation of used fuel and has contributed to research and development on disposal. In 1981, a further joint Canada-Ontario statement (Joint Statement 1981) confirmed support for the Nuclear Fuel Waste Management Program, announced "the process by which acceptance of the disposal concept will be undertaken . . .," and deferred the decision on allocation of "the responsibility for disposal site selection and subsequent operation . . . until after concept acceptance."

The disposal concept is a proposed method for the geological disposal of nuclear fuel waste in which

- the waste form would be either used CANDU* fuel or solidified highly radioactive reprocessing waste;
- the waste form would be sealed in a container designed to last at least 500 years and possibly much longer;
- the containers of waste would be emplaced in rooms in a disposal vault or in boreholes drilled from the rooms;
- the vault would be nominally 500 to 1000 m deep;
- the geological medium would be the plutonic rock of the Canadian Shield;
- each waste container would be surrounded by a buffer;
- each room would be sealed with backfill and other vault seals; and
- all tunnels, shafts, and exploration boreholes would ultimately be sealed so that the disposal facility would be passively safe, that is, long-term safety would not depend on institutional controls.

The disposal vault would be a network of horizontal tunnels and disposal rooms excavated deep in the rock, with vertical shafts extending from the surface to the tunnels. Rooms and tunnels could be excavated on more than one level. The vault would be designed to accommodate the rock structure

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* CANDU (CANada Deuterium Uranium) is a registered trademark of AECL.

and other subsurface conditions at the chosen site. The disposal container and vault seals would also be designed to accommodate the subsurface conditions at the chosen site. The disposal concept and its implementation constitute the proposed disposal strategy.

After the disposal facility was closed, there would be multiple barriers to protect humans and the environment from both radioactive and chemically toxic contaminants in the waste: the container; the waste form; the buffer, backfill, and other vault seals; and the geosphere.

The objectives of this report are to present general considerations regarding the engineering of nuclear fuel waste disposal facilities; to describe the conceptual design, operation and sealing of a reference disposal facility; and to present estimates of the personnel and funding required to implement this disposal facility. Our objective is to show that a disposal project can be organized and implemented in a manner consistent with legislation using available technology and methods, and to provide the information necessary for the preclosure and postclosure environmental and safety assessments (Grondin et al. 1994, Goodwin et al. 1994).

In developing the conceptual design of a used-fuel disposal centre discussed in this report, several assumptions were made regarding the characteristics of the disposal system components and the properties of the natural system or site. The assumed characteristics of the disposal system components include the selection of used fuel as the waste form, a titanium packed-particulate used-fuel container design, a room-and-pillar disposal vault arrangement, and borehole emplacement of individual disposal containers. The thermal and mechanical properties and structural characteristics were assumed for the natural system surrounding the disposal vault. The basis for these assumptions is discussed.

One assumption that warrants specific mention is the quantity of used fuel, which affects the size of the reference disposal vault. We assumed that 10.1 million used-fuel bundles would be accumulated for disposal by 2035. This was based on a 3% annual growth in nuclear electric generation and a replacement of all operating reactors in kind at the end of their operating life. More recently, projections of used-fuel arisings are of the order of 5 million used-fuel bundles. A reduction in the amount of used fuel has no effect on either the fundamental aspects of the facility design and operation or on the technical feasibility of nuclear fuel waste disposal. It does affect the overall size of the disposal vault, the inventory of radionuclides for the postclosure safety assessment, and the total and unit costs of disposal. The effect on cost is discussed.

ES.2 IMPLEMENTING NUCLEAR FUEL WASTE DISPOSAL

ES.2.1 GENERAL

Successful major projects such as the construction and operation of mines, industrial plants and power generating stations have been well organized and carefully controlled. For a nuclear fuel waste disposal facility to be successful, careful consideration must be given to project organization and responsibilities, to project management, to the safety and health of workers, the public and the environment, and to the development of implementation plans.

An implementing organization would establish the project structure and management, and the safety programs. This would include defining responsibilities and standards for managing the project, and for public, worker and environmental safety. These must comply with the applicable legislation, guidelines, and standards that define safe practices. The report discusses the means by which project structure and safety measures could be implemented.

The plans for project implementation would include an approach to identifying, rationalizing and reducing the design options prior to setting specific design specifications; integrating the specifications and regulatory requirements into a functional design; and accommodating the variability and uncertainty of the natural environment into the design and construction process.

An early objective of the implementing organization would be to define the project requirements, for example, the total amount of used fuel for disposal, the number of sites to be developed and the schedules to be met.

ES.2.2 ADMINISTRATIVE REQUIREMENTS

A formal quality assurance program would be developed, approved by the appropriate regulatory agencies, such as the Atomic Energy Control Board, and implemented prior to beginning the work that evolves into the siting, design and licensing of a disposal centre. For the geotechnical aspects of the project, this program would recognize and embody the observational method (Peck 1969), which is a key element for successful geotechnical projects.

A monitoring plan would be developed for the project to outline the conditions and parameters to be measured, and the spatial and temporal boundaries for each type of measurement. These would vary for each system or parameter, depending on the physical extent of the system and the magnitude and duration of the effect. It would cover the project from beginning to end and would include specifics on the methods and applications of monitoring and component testing. The plan would establish the acceptable range of values for each condition or parameter being measured, and the action to be taken if the condition or parameter exceeded this range. An approach to monitoring is presented by Simmons et al. (1994), and many of the methods are discussed by Davison et al. (1994a) and by Grondin et al. (1994). Monitoring data are used to establish baseline conditions and determine temporal changes in these conditions. This information can be used to assess the performance of a component or system, or the effects that a perturbation has on the environment. In the context of nuclear fuel waste disposal, monitoring would focus on the region of the environment influenced, or potentially influenced, by the disposal centre and the associated transportation systems.

Performance assessment would be carried out through the analysis of data collected from the monitoring activities and systems and conversion of the data into a form that can be compared with baseline conditions, regulatory criteria, derived criteria, design limits, and standards and assumptions made during the system design process. These comparisons would provide a measure of the environmental changes and effects that would occur over time, and would assist in determining their cause. The comparison would also provide a measure of the performance of various disposal system components against their specifications, and an assessment of the effects on the environments relative to those allowed by the permits and licences issued for the facility. Performance assessments would also be used to estimate future effects of the disposal facilities and transportation system as a component of the design process and of the licensing and approvals processes.

Implementing an occupational and public safety and health program, with the strong support of management, would promote safety and health in all aspects of work, and would communicate this commitment continuously to the workers and to the public. This commitment would be reinforced by management participation in the application of the safety philosophy in all areas of the project, and by a proactive policy of conducting activities in such a manner as to provide a safe and healthy working environment for workers and a safe environment for the public.

ES.2.3 <u>REGULATORY REQUIREMENTS</u>

In Canada, regulations specifically applicable to the operation of nuclear facilities and the control of radioactive materials are promulgated under the Atomic Energy Control Act (Government of Canada 1985). Besides meeting the requirements of all applicable regulations under the Atomic Energy Control Act, a nuclear fuel waste disposal facility would comply with all applicable legislation and regulations of the Canadian government and of the province and municipality in which the facility would be built. As well, it would comply with the transportation regulations of any municipality, province, or country through which the waste would be shipped (e.g., barge transportation of used fuel through waters controlled by the United States in the Great Lakes).

It is recognized that the legislation will evolve over time. An example is an amendment to the Atomic Energy Control Regulations being proposed that would reduce the cumulative effective dose limits for atomic radiation workers and for the public (AECB 1991a).

The discussion in this report is based on the legislation in effect as of 1991. The actual implementation of nuclear fuel waste disposal will be done in the context of specific regulations and guidelines in effect at the time of implementation.

ES.2.4 <u>DESIGN REQUIREMENTS</u>

The Used-Fuel Disposal Centre conceptual design study completed by AECL CANDU et al. (1992) was defined by a specification (Baumgartner et al. 1993) prepared in 1984-1985. It is based on receiving, packaging and disposing of CANDU fuel bundles (Figure ES-1) irradiated to an average burnup

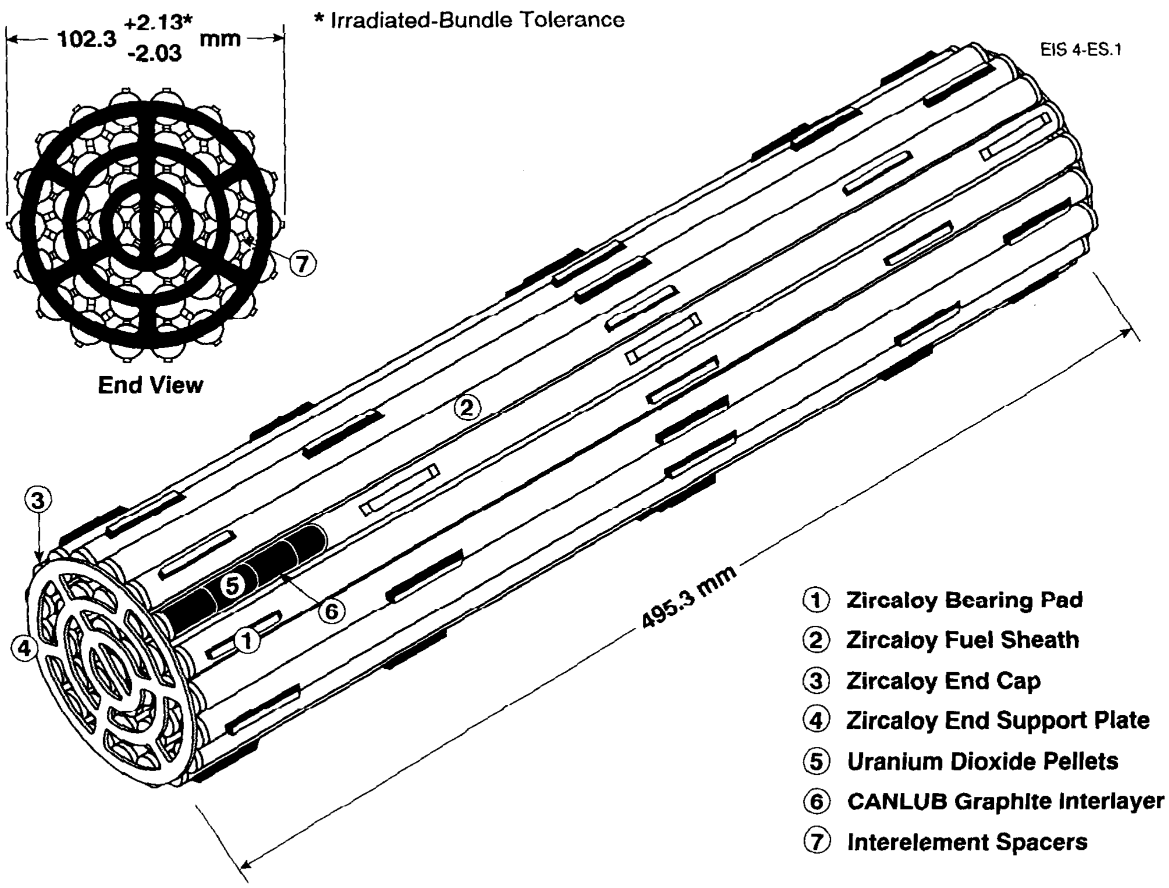


FIGURE ES-1: Typical CANDU Fuel Bundle for Bruce Nuclear Generating Station (after AECL CANDU et al. 1992)

of 685 GJ/kg U and cooled for 10 a after their discharge from a nuclear power reactor. The capacity of the disposal vault is about 191 000 Mg U, or about 10.1 million fuel bundles.

The disposal container is a packed-particulate used-fuel disposal container (Figure ES-2), fabricated from ASME Grade-2 titanium, which holds 72 used-fuel bundles. Therefore, the vault capacity is about 140 000 containers. The annual throughput in the conceptual design is about 250 000 used-fuel bundles, the assumed capacity of the used-fuel transportation system. This capacity is 3471 disposal containers per year, giving a disposal vault operating duration of about 40 a.

The following additional design requirements for this study would accommodate any restrictions on the components of the disposal system and limit the number of alternative cases addressed:

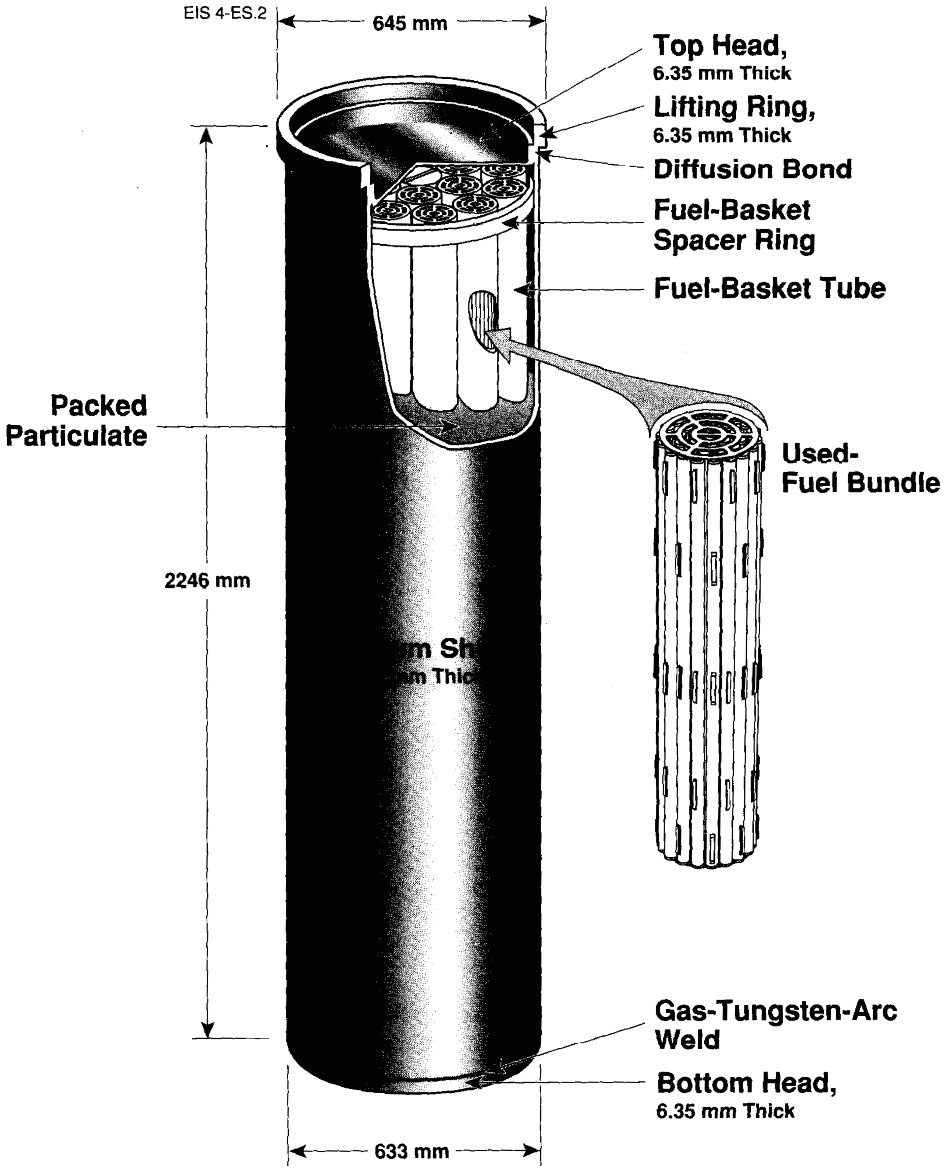


FIGURE ES-2: Titanium Shell, Packed-Particulate Used-Fuel Disposal Container

1. The disposal vault is located at a depth of 1000 m, although this depth was changed during design analyses to satisfy the mechanical and thermal-mechanical constraints listed below.

2. The maximum temperature at the container outer surface and throughout the buffer material must not exceed 100°C.

3. For thermal calculations, the reference used fuel has the average burnup of used fuel from the Bruce Nuclear Generating Station and a cooling period of 10 a after discharge from the reactor.

4. The near-surface extension zone, the layer of rock at the ground surface overlaying the disposal vault that could experience a loss of horizontal confining stresses, and the potential opening of vertical fractures must not extend more than 100 m below the ground surface.

5. The average strength-to-stress ratio is two or greater for the interroom pillars and, where applicable, the rock webs around the waste emplacement boreholes. As well, where applicable, the extraction ratio on the emplacement horizon is about 0.25.

6. The disposal vault will use shafts for access and will be arranged in a room-and-pillar configuration.

7. The emplacement configuration will be in-floor borehole emplacement with a single disposal container in each borehole.

ES.2.5 PROJECT SCHEDULE

A nuclear fuel waste disposal project would be subdivided into smaller elements for planning and control. One approach would be to establish stages and activities where the project stages are sequential, and to incorporate the major blocks of effort necessary to achieve nuclear fuel waste disposal. The activities may occur concurrently, and generally span more than one stage.

The project stages currently considered in the Nuclear Fuel Waste Management Program are shown in Figure ES-3.

The Siting Stage would involve developing the siting process, and site screening and site evaluation substages to identify suitable site(s) for waste disposal. Data would be gathered during site evaluation to develop an understanding of the surface and underground physical and chemical conditions in and around the site(s) to confirm their potential for safe disposal. During the siting stage, preliminary disposal facility designs would be prepared for each site being evaluated. A specific design for the preferred site would be completed and approved prior to deciding to proceed with underground evaluation. The end point of the siting stage would be a design based on the results obtained from the surface and underground evaluation studies, and approved for construction at the site selected for a disposal facility (see Chapter 3).

The Construction Stage would involve constructing the infrastructure and surface facilities needed to transport and dispose of nuclear fuel waste, the underground accesses and service areas, and a portion of the underground disposal rooms (see Chapter 4).

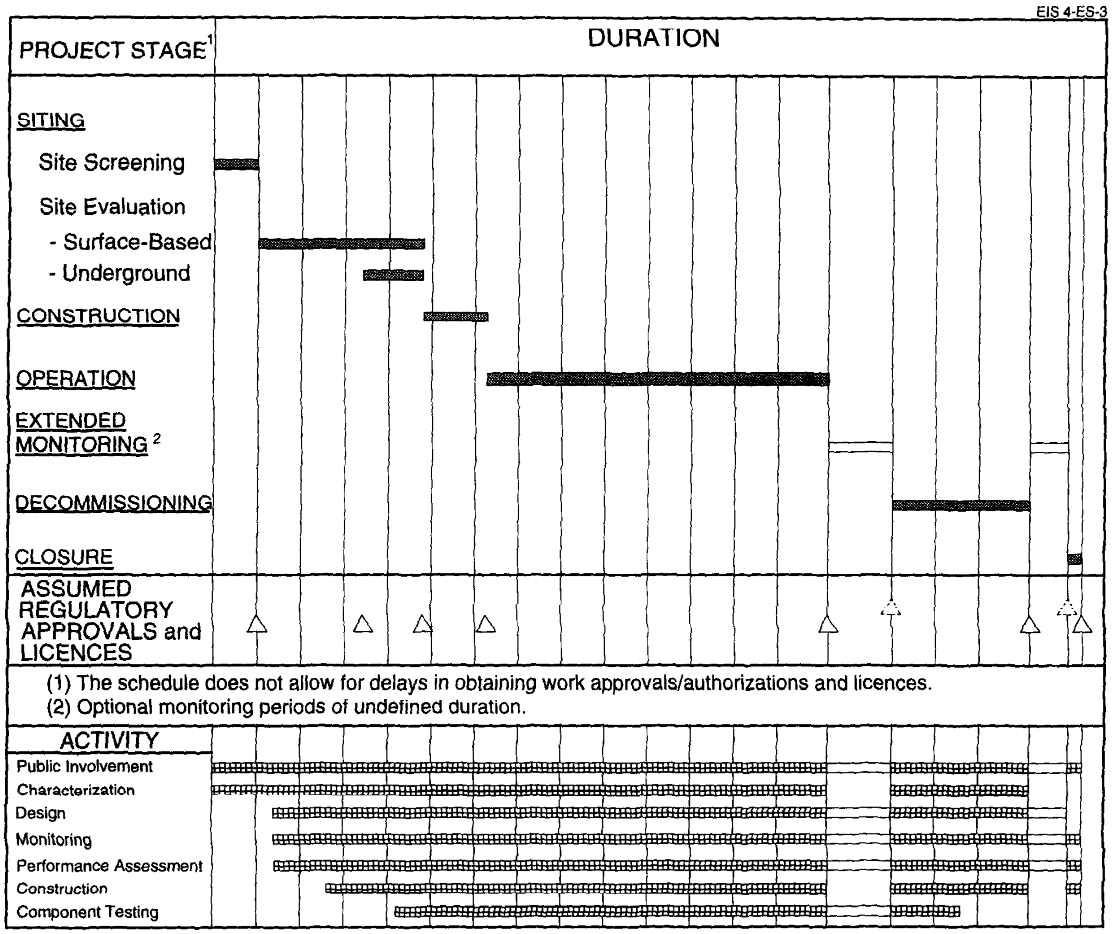


FIGURE ES-3: Used-Fuel Disposal Centre Schedule

The Operation Stage would involve receiving nuclear fuel waste transported to the disposal facility, sealing it in corrosion-resistant containers, sealing the containers in disposal rooms, and constructing additional disposal rooms, as necessary (see Chapter 5).

The Extended Monitoring Stages, if required, would involve monitoring conditions in the vault, geosphere, and biosphere between the operation and decommissioning stages and/or between the decommissioning and closure stages.

The Decommissioning Stage would involve the decontamination and removal of the surface and subsurface facilities; the sealing of the tunnels, underground service areas, shafts, and underground exploration boreholes; and the return of the site to a state suitable for public use (see Chapter 6).

The <u>Closure Stage</u> would involve the removal of monitoring instruments from any boreholes that could compromise the safety of the disposal vault, the sealing of those boreholes, and the return of the site to a state where safety would not depend on institutional controls (i.e., to a passively safe state). Monitoring could continue beyond closure if desired by the regulatory authorities or the public (see Chapter 6), provided that such monitoring did not compromise the long-term passive safety of the sealed disposal vault.

The major activities associated with the implementation of nuclear fuel waste disposal - public involvement, characterization, design, monitoring, component testing, performance assessment and construction (see Figure ES-3) - span two or more stages.

ES.2.6 DESIGN ANALYSES FOR THE USED-FUEL DISPOSAL CENTRE

During the preparation of the conceptual design for the Used-Fuel Disposal Centre described in Section ES.3, analyses were completed for airborne and waterborne radiological source terms, the radiation fields in work areas, the mechanical and thermal-mechanical stability of underground openings, and other parameters and conditions relevant to developing a design that would satisfy the design requirements.

The airborne and waterborne radiological source terms were calculated for various areas of the Used-Fuel Disposal Centre assuming initially that there was no filtration or collection of the contaminants. The radionuclide release without any decontamination of the contaminated air or water discharge streams was assessed and decontamination equipment was applied. High-efficiency particulate air (HEPA) filters were applied to the contaminated air streams, and ion exchange and filtration equipment was applied to the discharge water streams. The resulting radionuclide release after decontamination is projected to be many orders of magnitude lower than releases resulting from the operation of nuclear generating stations (Villagran 1991).

The radiation fields were calculated for work areas within the Used-Fuel Disposal Centre based on assumed inventories of used-fuel bundles and applying conservative assumptions for the effectiveness of the shielding. The calculated fields were used in conjunction with estimates of the duration of worker occupancy in the various areas to determine the radiation doses received by the workers. The calculated worker doses were compared with the regulatory requirements, and a few areas, such as the full transportation cask laydown area, where additional shielding would be added were identified in the process of design optimization to reduce the ambient radiation fields in work areas and, therefore, the dose to workers.

Thermal, mechanical and coupled thermal-mechanical analyses were done for the disposal rooms and emplacement boreholes. An analytical code was used initially to analyze the temperature distribution for a vault at a depth of 1000 m to select the borehole-to-borehole spacing that satisfied the 100°C maximum temperature limit. This spacing was 2.1 m between borehole centres, with three boreholes across a room and 94 boreholes along the length of the room. Making allowance for the space required for the operation of equipment and for the sealing of the disposal room resulted in a disposal room that was 230 m long with a cross section that was 8 m wide and 5.5 m high.

The stability of this room was analyzed under excavation (ambient temperature) conditions and under sealed (heated) conditions. Two cases were analyzed for the in situ stress conditions assumed at a depth of 1000 m with rooms excavated perpendicular to the maximum horizontal stress direction:

1. a disposal room with a reference flat floor and with boreholes spaced at 2.1 m across and along the room, and

2. a disposal room with a curved floor similar to the crown of the room and with boreholes spaced at 2.1 m across and 3.0 m along the room.

For both cases, the analyses of the excavation conditions indicated zones of yielding in the floor of the disposal room and along the emplacement borehole walls. We judged these zones to be larger than would be desired based on the Underground Research Laboratory studies of rock response to excavation. A similar analysis was done for the in situ stress conditions assumed at a depth of 500 m and a borehole spacing of 2.1 m across and along the room. The results indicated that the stability of the excavation boundaries would be acceptable and the disposal vault could be designed to meet the near-field thermal-mechanical specifications.

The specific borehole-emplacement configuration for the assumed in situ stress, room orientation and rock strength (or failure) criteria is suitable only for depths shallower than 1000 m. The in-room emplacement configuration may be preferable under higher in situ stress conditions.

Analyses were also done to assess the potential for shear displacement on a subhorizontal and a subvertical fault zone near a disposal vault at a depth of 1000 m under the influence of heat from the nuclear fuel waste. No shear displacements along a subhorizontal fault are expected below a depth of 100 m from the ground surface.

These analyses and others are discussed in the report. The discussion shows that methods exist to analyze the disposal facilities for compliance with regulatory and design requirements and to adjust the design to improve the safety and/or performance of various components of the disposal system.

ES.3 DISPOSAL FACILITY DESCRIPTION

A specification was developed in 1984 as the basis for a conceptual design study of a Used-Fuel Disposal Centre (Baumgartner et al. 1993). The disposal vault and waste emplacement alternatives selected were a single-level, room-and-pillar disposal vault with in-floor emplacement of individual disposal containers. It was assumed that the disposal centre is self-contained and located on a suitable plutonic rock body of the Canadian

Shield. The disposal centre includes a disposal vault (Figure ES-4) excavated into the rock body at a depth of 1000 m, and surface facilities for the receipt and packaging of used fuel in disposal containers (Figures ES-5 and ES-6). This conceptual design at depth of 1000 m provides for the longest construction times, the longest operation-cycle times, and the largest excavation and sealing-material volumes relative to a design for a disposal vault at a depth of 500 m.

The Used-Fuel Disposal Centre discussed in this report is based on a conceptual design prepared by AECL CANDU et al. (1992), with modifications and additions by the authors. The disposal centre is designed to receive, package and dispose of about 191 000 Mg of uranium in the form of 10.1 million used-fuel bundles. The disposal vault is essentially square in plan with an area of about 4 km^2. The used-fuel bundles are assumed to have been out-of-reactor for 10 a. Conceptual designs are presented for the primary facilities and equipment and for the operations for receiving, packaging and disposing of the used fuel. The necessary material supply, handling and preparation facilities and the utilities and services required to support siting, construction, operation, decommissioning and closure of the disposal centre are described. A simplified operating sequence is shown in Figure ES-7.

Used fuel is received at the packaging plant of the disposal centre in either a road or rail transportation cask that contains the used-fuel bundles in storage/shipping modules. The modules are unloaded from the casks in a module-handling cell. The modules may be held temporarily in a receiving surge-storage pool or they may be transferred directly to the used-fuel packaging cell. In the packaging cell, the fuel bundles are transferred from the shipping modules to the disposal container fuel baskets, 72 bundles to a basket, and each fuel basket is installed within a disposal container. Each bundle and container is monitored for nuclear material safeguards purposes during the transfer operations.

The reference disposal container shell and end closures assumed in this conceptual design are fabricated of 6.35-mm-thick ASME Grade-2 titanium. The loaded container is filled with a particulate, such as glass beads, which is compacted vibrationally to fill all the void space, allowing the container to withstand the expected external loads. A top head is pressed into the container, and the top head and container shell flanges are diffusion-bonded. The assumed quantity of used fuel requires about 140 000 disposal containers, each having a mass of about 2800 kg. When initially sealed in the disposal container, the 72 used-fuel bundles produce about 300 W of heat.

Following nondestructive testing (i.e., ultrasonic bond inspection and a helium leak test) to establish the integrity of the sealed container, each disposal container is loaded into a shielding container cask. Each full cask is transferred to the disposal vault using the cage in a dedicated waste shaft. When removed from the cage, the cask is moved by crane to an underground storage area or by truck directly to a disposal room.

In this conceptual design, each disposal room is about 8 m wide, 5 to 5.5 m high and 230 m long. Up to 282 vertical emplacement boreholes are drilled

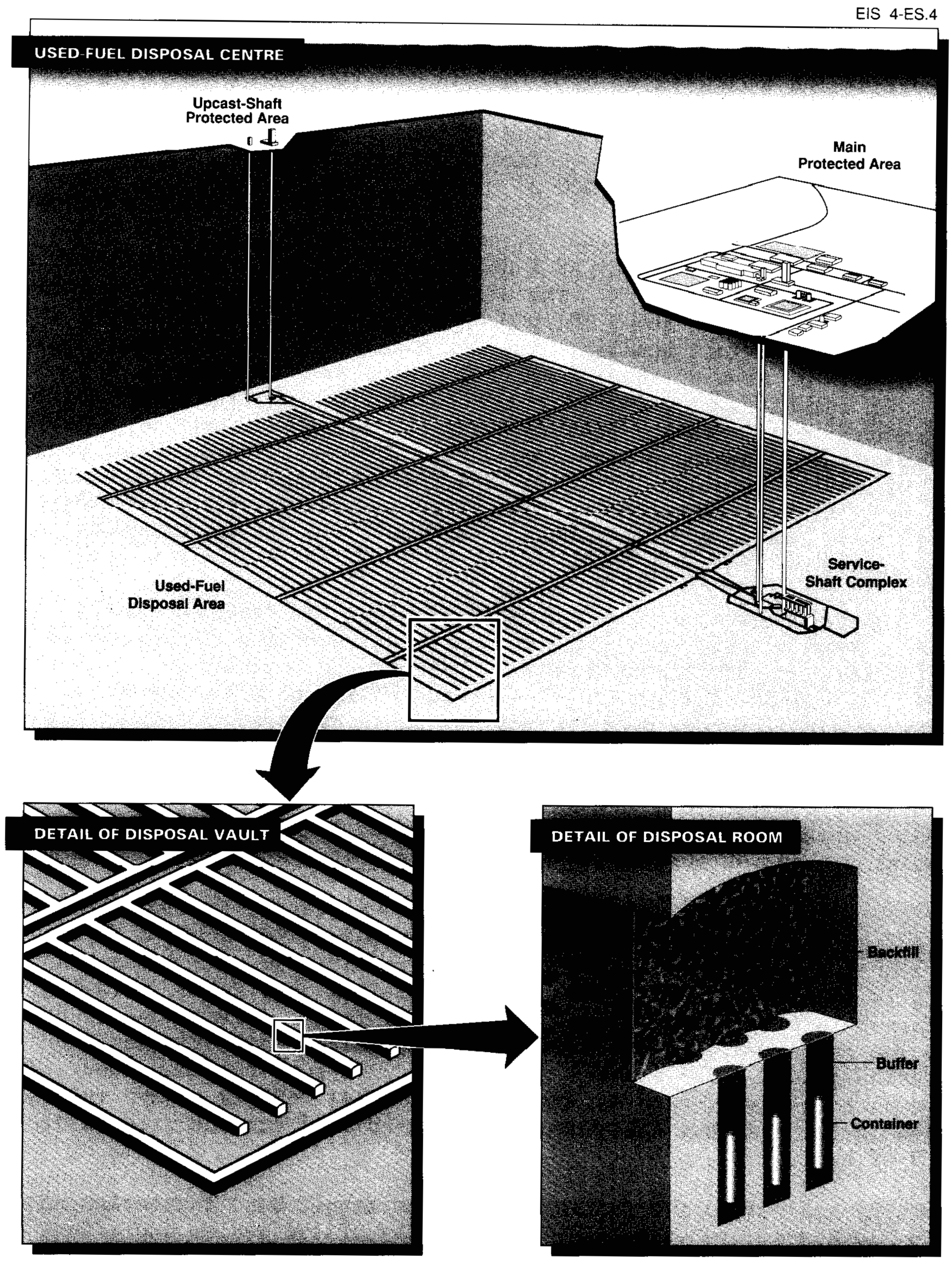


FIGURE ES-4: Used-Fuel Disposal Centre Perspective

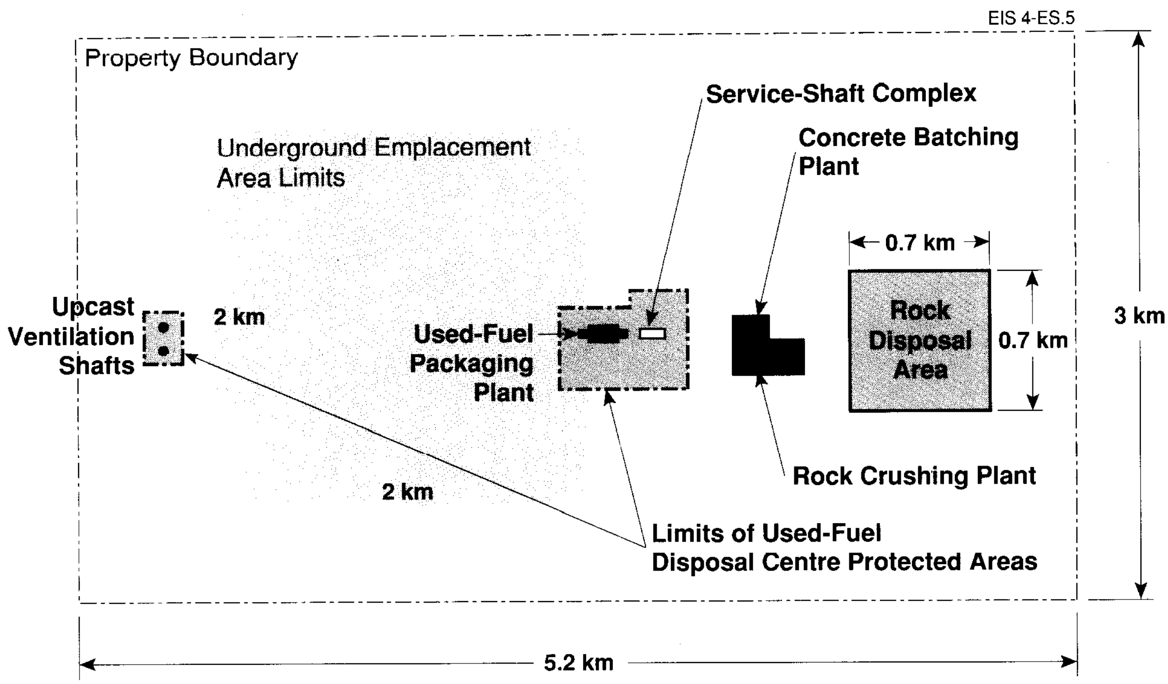
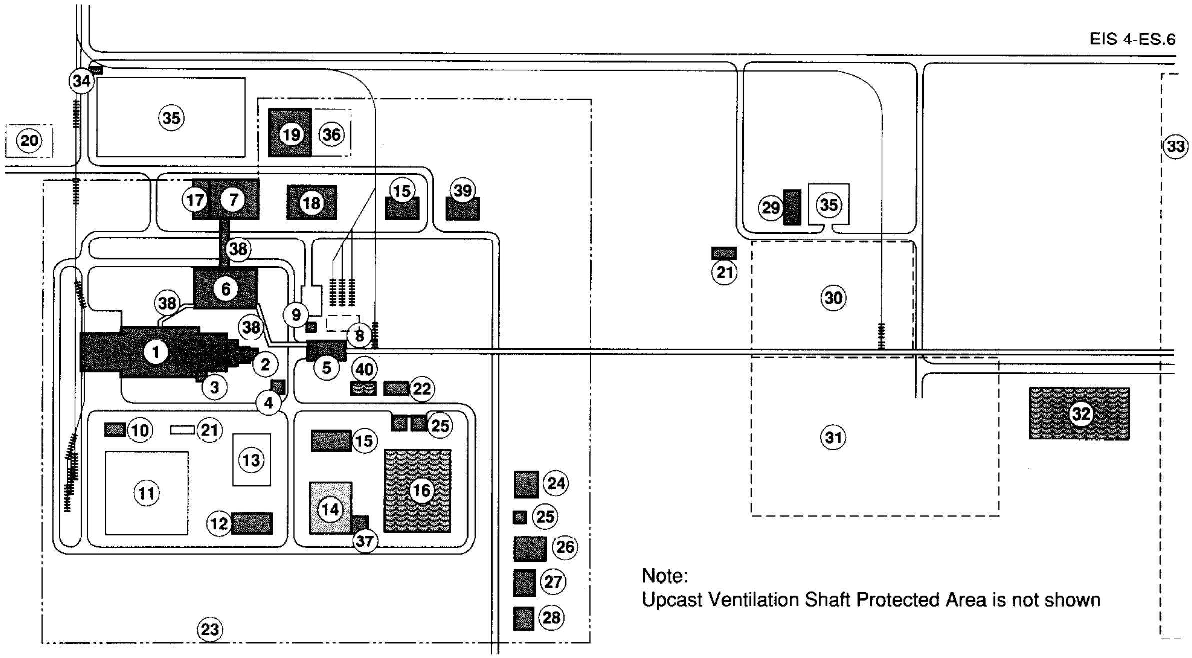


FIGURE ES-5: Used-Fuel Disposal Centre Land Requirements (after AECL CANDU et al. 1992)

in the floor of each disposal room, and each borehole is prepared to receive the disposal container. The emplacement boreholes are 1.24 m in diameter, and 5 m deep, and are spaced about 2.1 m apart, three across the room and 94 along the room, as required to keep the maximum temperature of the container shell below 100°C. The container placement sequence is shown in Figure ES-8. Before a container cask is received in the disposal room, a clay-based buffer material (i.e., 50% sodium-bentonite clay and 50% silica sand by mass) is compacted into the emplacement borehole and a hole is centrally augered into the buffer to receive the container. When the container has been emplaced, the radial gap between the container and the buffer is filled with dry silica sand to improve heat transfer, and additional buffer material is then placed and compacted over the container to the floor level of the disposal room.

When all the emplacement boreholes in a room have been filled, the room is backfilled by placing and compacting a mixture of 25% glacial-lake clay and 75% crushed granite, by mass, to fill the lower 3.5 m of the room. The upper portion of the room is filled by spray-compacting into place an upper backfill material similar in composition to the buffer material. A concrete bulkhead is constructed at, and grouted into, the room entrance to seal the room and to withstand the buffer and backfill swelling and the groundwater pressures. A safeguards seal may be incorporated into the bulkhead to detect unauthorized entry.



1. Used-Fuel Packaging Plant
2. Waste-Shaft Headframe
3. Stack
4. Downcast Ventilation Shaft
5. Service-Shaft Complex
6. Auxiliary Building
7. Admin. Bldg. Including Firehall
8. Sealing Material Storage Bins
9. Dust Collection Bag House
10. Active-Solid-Waste Handling Building
11. Waste Management Area
12. Active-Liquid-Waste Treatment Building
13. Low-Level Liquid Waste Storage Area
14. Sewage Holding Pond
15. Garage
16. Storm Runoff Holding Pond
17. Cafeteria
18. Basket and Container Fabrication Plant
19. Warehouse
20. Switchyard
21. Transformer Area
22. Air Compressors
23. Security Fence (Main Protected Area)
24. Powerhouse
25. Fuel Tanks
26. Water Storage Tanks
27. Water Treatment Plant
28. Pumphouse and Intake
29. Quality Control Offices and Laboratory
30. Concrete Batching Plant Area
31. Rock Crushing Plant Area
32. Process-Water Settling Pond
33. Rock Disposal Area
34. Guard House
35. Parking Area
36. Storage Yard
37. Sewage Treatment Plant
38. Overhead Corridor
39. Hazardous Materials Storage Building
40. Service-Shaft Complex Water Settling Pond

FIGURE ES-6: Used-Fuel Disposal Centre Site Layout (after AECL CANDU et al. 1992)

The operational sequence in the conceptual design, consisting of disposal-room excavation by the drill-and-blast method, emplacement-borehole drilling and preparation, waste emplacement, borehole sealing and room backfilling and sealing, continues throughout the operating period of the disposal vault. The disposal rooms are developed and filled in sequence, moving from the upcast shaft complex toward the service shaft complex (Figure ES-4) to control access, potential contamination, and potential radiation doses to personnel.

When the vault has been filled with waste, the monitoring data have been assessed to show compliance with the regulatory and design criteria, and the regulators have approved the decommissioning and closure plan for the centre, the access tunnels and shafts will be backfilled and sealed, the surface facilities will be decommissioned and disassembled, and the site will permanently marked and returned to a state suitable to allow public use of the surface.

ES.4 SCHEDULES

The assumptions used in estimating work schedules and costs for the various stages in the life cycle of the Used-Fuel Disposal Centre (Figure ES-3) are as follows:

1. The siting, construction, decommissioning and closure stages are estimated based on operation 24 h/d, 7 d/week.

2. The operation stage is estimated based on a 5-d week with two 8-h shifts per day, except for security/firefighting and essential site services, which are staffed 24 h/d, 7 d/week.

The work schedule for the operation stage was selected based on an assumed used-fuel transportation rate and packaging plant throughput, and provides significant reserve capability for adjusting the disposal centre annual capacity.

ES.5 RESOURCE REQUIREMENTS

The resource estimates for the Used-Fuel Disposal Centre were developed on the basis of conceptual design information and on assumptions on siting and on the extent of equipment engineering necessary to do certain operations. It is judged that the nominal cost estimates may be as much as 15% high or 40% low for the engineered barriers assumed in this report. These cost estimates could change significantly if different engineered barriers are selected and/or the disposal vault arrangement becomes more complicated to account for local site conditions. The costs are given in constant 1991 Canadian dollars excluding any financing costs.

The cost for the specific disposal centre to dispose of 10.1 million used-fuel bundles at a depth of 1000 m is estimated to be about $13.32 billion

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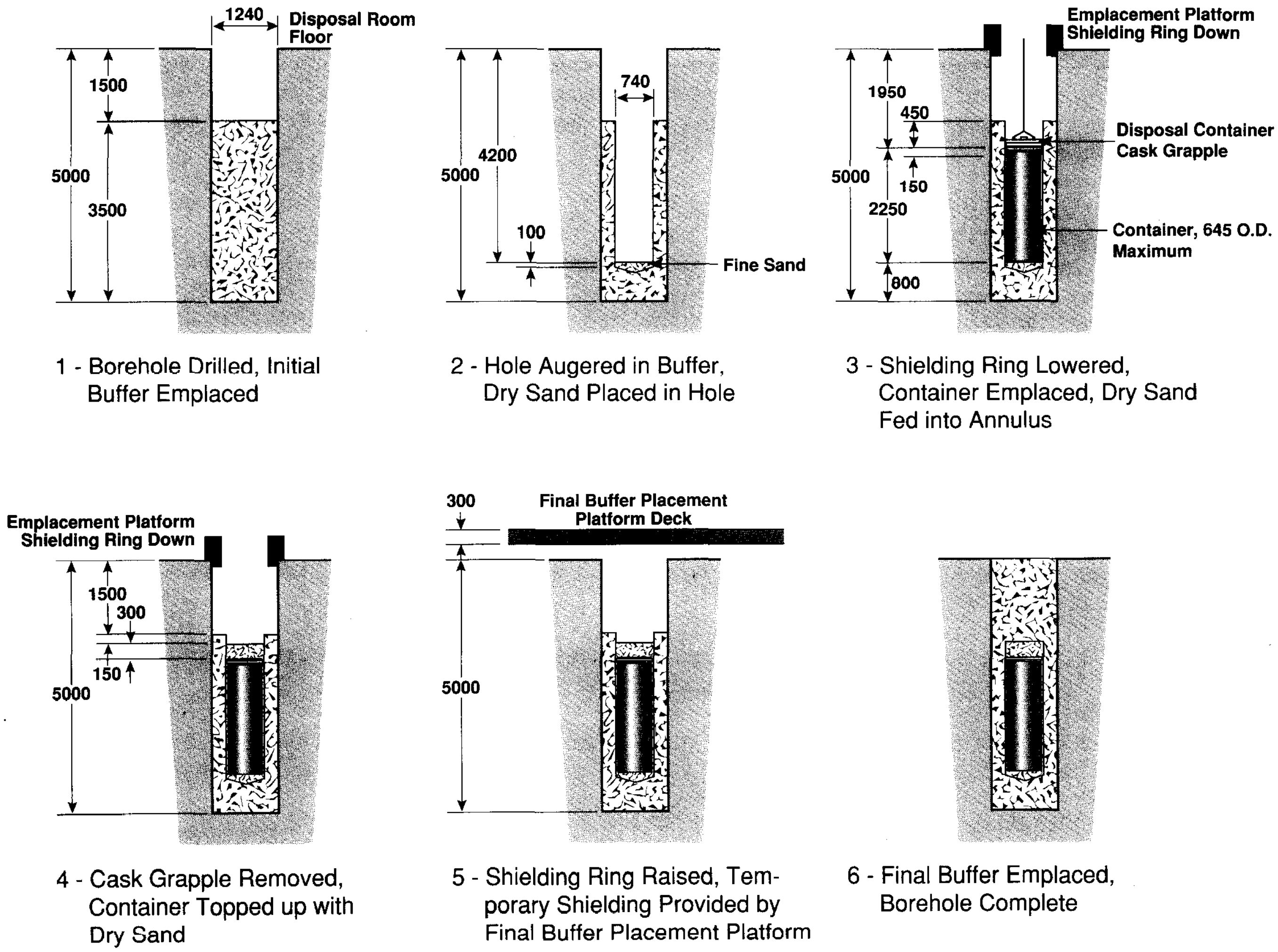

FIGURE ES-8: Borehole-Emplacement Sequence (after AECL CANDU et al. 1992). All dimensions are in millimetres.

from the beginning of the siting stage through to the end of the decommissioning and closure stage, a period of 89 a. It would provide about 62 200 person-years of direct on-site employment. The total cost might range from $11.32 billion to $18.65 billion for the assumptions noted above (Table ES-1). The corresponding lifetime labour requirement might range from 52 800 to 87 000 person-years (Table ES-2).

The cost of a disposal facility will be sensitive to changes in a wide range of parameters. Examples of the sensitivity of the disposal facility schedule and nominal costs to the quantity of used fuel for disposal and to the depth of disposal are shown in Tables ES-3 and ES-4 respectively.

TABLE ES-1

USED-FUEL DISPOSAL CENTRE LIFE-CYCLE COST SUMMARY

(Capacity = 10.1 million used-fuel bundles, Depth = 1000 m)
(in 1991 Canadian $ million)

Stage	Low Estimate	Nominal Estimate	High Estimate
Siting (23 a)	1 850	2 180	3 050
Construction (7 a)	1 540	1 810	2 530
Operation (41 a)	6 850	8 060	11 280
Decommissioning (16 a)	1 060	1 250	1 750
Closure (2 a)	30	30	40
Total	11 320	13 320	18 650

Note: The values in the columns do not necessarily add up to the total shown because of rounding.

TABLE ES-2

USED-FUEL DISPOSAL CENTRE LIFE-CYCLE LABOUR REQUIREMENT SUMMARY

(Capacity = 10.1 million used-fuel bundles, Depth = 1000 m)
(in person-years)

Stage	Low Estimate	Nominal Estimate	High Estimate
Siting (23 a)	6 880	8 100	11 330
Construction (7 a)	6 240	7 340	10 280
Operation (41 a)	33 880	39 850	55 800
Decommissioning (16 a)	5 720	6 730	9 430
Closure (2 a)	120	150	200
Total	52 840	62 170	87 040

Note: The values in the columns do not necessarily add up to the total shown because of rounding.

TABLE ES-3

SCALED NOMINAL COST ESTIMATES FOR DISPOSAL VAULT CAPACITIES OF 5, 7.5 AND 10.1 MILLION USED-FUEL BUNDLES

(Depth = 1000 m)

	5 million bundles		7.5 million bundles		10.1 million bundles	
Disposal Centre Stage	Duration (a)	Cost (1991 Canadian $ million)	Duration (a)	Cost (1991 Canadian $ million)	Duration (a)	Cost (1991 Canadian $ million)
Siting	23	2 140	23	2 160	23	2 180
Construction	5	1 520	6	1 630	7	1 810
Operation	20	4 060	30	6 040	41	8 060
Decommissioning	13	940	15	1 090	16	1 250
Closure	2	30	2	30	2	30
Total	63	8 680	76	10 950	89	13 320

Note: The values in the columns do not necessarily add up to the total shown because of rounding.

TABLE ES-4

COMPARISON OF NOMINAL COST AND SCHEDULE DURATIONS FOR A DISPOSAL CENTRE WITH A VAULT AT DEPTHS OF 500 AND 1000 m

(Capacity = 10.1 million used-fuel bundles)

	Depth = 500 m		Depth = 1000 m	
Disposal Centre Stage	Duration (a)	Cost (1991 Canadian $ million)	Duration (a)	Cost (1991 Canadian $ million)
Siting	22	2 110	23	2 180
Construction	7	1 780	7	1 810
Operation	41	8 060	41	8 060
Decommissioning	14	1 130	16	1 250
Closure	2	30	2	30
Total	86	13 110	89	13 320

Note: The values in the columns do not necessarily add up to the total shown because of rounding.

ES.6 DISCUSSION

It is feasible to design, build, operate and seal a nuclear fuel waste disposal facility with existing technologies, or with reasonable extensions of these technologies. The work presented in this report is based on over 15 a of study by AECL, Ontario Hydro, government departments, universities and private-sector consulting groups.

Although a nuclear fuel waste disposal vault will be a unique underground facility, its design, construction, operation and management are similar to many other major underground civil engineering projects. These include the Churchill Falls hydroelectric power house in Labrador, the NORAD defence facility in North Bay, Ontario, and the La Grande hydroelectric generating station near James Bay, Quebec, which have been engineered and constructed in the Canadian Shield (Acres 1993a). These facilities have been designed for, and constructed in, remote places, and have operated safely and within design specifications for many decades.

The approach to facility design and implementation presented in this report can be applied to adapt to the natural site conditions, and to satisfy the legislative and the design requirements that are relevant to the disposal of nuclear fuel waste. The specific conceptual design presented in this report represents a feasible and economical approach to the disposal of Canada's nuclear fuel waste.

Based on the presented cost estimates, the cost of disposing Canada's nuclear fuel waste is a small fraction of the cost of electricity derived from nuclear power (i.e., less than \$0.001/(kW·h)).

1. INTRODUCTION

1.1 GENERAL

About 15% of the electricity in Canada is generated from nuclear energy. As of 1992 January, Ontario Hydro, Hydro-Québec and the New Brunswick Power Corporation had installed nuclear-generating capacities of 11.2 GW, 0.6 GW and 0.6 GW respectively. Development work on Canada's nuclear power program began in 1954. The management of radioactive waste from nuclear power generation has always been an important component of the nuclear power program.

On 1992 January 01 there were about 828 000 bundles of used fuel in Canada, and their number is increasing at a rate of about 94 000 bundles per year. This used fuel is currently stored in concrete canisters or in water-filled pools at the nuclear generating stations. These storage facilities provide shielding from the radiation and cooling to remove the heat emitted by the used fuel. Such storage methods have been in use in Canada and elsewhere for almost four decades and have been proven to be safe and cost-effective. Experience has shown that used fuel could continue to be safely stored in this way for at least several decades (Wasywich and Frost 1991, Frost and Wasywich 1987).

Storage, while an effective interim measure for waste management, is not a permanent solution since the storage facilities require an organizational structure to operate, control, maintain and monitor their operation. This cannot be guaranteed forever. Rather than store the wastes, a method is needed to dispose of them permanently, eliminating the requirement for continuing human intervention to operate and maintain safe storage facilities. The intention would not be to stop institutional control, but to provide a management method that is passively safe, so that public health and the natural environment would be protected if institutional controls are lost.

In 1978, the governments of Canada and Ontario established the Nuclear Fuel Waste Management Program ". . . to assure the safe and permanent disposal" of nuclear fuel waste. AECL was made responsible for research and development on ". . . disposal in a deep underground repository in intrusive igneous rock" (Joint Statement 1978). Ontario Hydro was made responsible for studies on interim storage and transportation of used fuel and has contributed to the research and development on disposal. In 1981, a further joint Canada-Ontario statement (Joint Statement 1981) confirmed support for the Nuclear Fuel Waste Management Program, announced "the process by which acceptance of the disposal concept will be undertaken . . .," and deferred the decision on allocation of "the responsibility for disposal site selection and subsequent operation . . . until after concept acceptance."

Used CANDU* fuel consists of ceramic uranium dioxide pellets in metal tubes. It could be processed to extract useful material for recycling, but at

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* CANDU (CANadian Deuterium Uranium) is a registered trademark of AECL.

present it is not. If it were, the highly radioactive material that remained would be incorporated into a solid. The term "nuclear fuel waste," as used in this document, refers to either

- the used natural UO_2 fuel, or
- a solid incorporating the highly radioactive waste (called fuel reprocessing waste in this report) resulting from processing used fuel to extract useful material for recycling.

Both forms of nuclear fuel waste are highly radioactive. Living organisms are protected from such waste by both containment and shielding systems, which isolate the waste from the natural environment.

The development of a concept for the disposal of nuclear fuel waste is an objective of the Nuclear Fuel Waste Management Program. The disposal concept being investigated is a proposed method for the geological disposal of nuclear fuel waste in which

1. the waste form would be either used CANDU fuel or solidified highly radioactive reprocessing waste;
2. the waste form would be sealed in a container designed to last at least 500 a and possibly much longer;
3. the containers of waste would be emplaced in rooms in a disposal vault or in boreholes drilled from the rooms;
4. the vault would be nominally 500 to 1000 m deep;
5. the geological medium would be the plutonic rock of the Canadian Shield;
6. each waste container would be surrounded by a buffer;
7. each room would be sealed with backfill and other vault seals; and
8. all tunnels, shafts, and exploration boreholes would ultimately be sealed so that the disposal facility would be passively safe, that is, long-term safety would not depend on institutional controls.

The disposal vault would be a network of horizontal tunnels and disposal rooms excavated deep in the rock, with vertical shafts extending from the surface to the tunnels. Rooms and tunnels might be excavated on more than one level. The vault would be designed to accommodate the rock structure and other subsurface conditions at the chosen site. The disposal container and vault seals would also be designed to accommodate the subsurface conditions at the chosen site. The disposal concept and its implementation constitute the proposed disposal strategy.

After the disposal facility was closed, there would be multiple barriers to protect humans and the natural environment from both radioactive and chemically toxic contaminants in the waste: the container; the waste form; the buffer, backfill, and other vault seals; and the geosphere. The following criteria for the multiple barriers will determine how effectively they perform:

1. The container should isolate the waste form by maintaining structural stability and resisting corrosion.

2. The waste form should be a solid that retains the contaminants by resisting dissolution and leaching under expected vault conditions.

3. The vault seals, which include the buffer and backfill, should limit container corrosion, waste-form dissolution, and contaminant movement by inhibiting the flow of groundwater in the vault and controlling the chemical environment in the vault.

4. The geosphere should protect the waste form, container, and vault seals from disruptions from natural events and human intrusion; should maintain conditions in the vault favourable for long-term waste isolation; and should limit the rate at which contaminants from the waste could move from the vault to the biosphere.

The role of the barriers on the disposal system safety is discussed by Goodwin et al. (1994). The legislation that defines the requirements for environmental, public and occupational safety are discussed in Chapter 2 of this report.

The objectives of this report are to:

1. Discuss the methods and general considerations for engineering nuclear fuel waste disposal facilities.

2. Describe the conceptual design and operation of a reference disposal facility that is practicable with available technology, or reasonable extensions of available technology, and that has been used as a basis for preclosure and postclosure environmental and safety assessments (Grondin et al. 1994, Goodwin et al. 1994).

3. Present estimates of the personnel and funding required to implement the conceptual design.

A conceptual-level design for a Used-Fuel Disposal Centre was completed to provide background information for this report and other primary references. The conceptual design was developed by AECL CANDU et al. (1992) from a specification prepared in 1984-1985 (Baumgartner et al. 1993). The design was based on the best information available on the many alternatives for disposal system components at the time, or logical extensions of available technology judged practicable, but was not optimized for function or cost.

This report describes the processes and the used-fuel packaging and disposal facilities that could be successfully sited, designed, constructed, operated, decommissioned and closed following a suitable siting and engineering program. It is based largely on the work of AECL CANDU et al. (1992), with new information added to describe siting activities, supporting research and development and the preferred sequence of disposal-vault operations. The potential effect of the facilities on man and the environment are discussed by Grondin et al. (1994) and by Goodwin et al. (1994).

The objectives in these studies were to develop and demonstrate a design methodology; to describe, in a general way, the siting, construction, operation, extended monitoring, decommissioning and closure of a disposal centre; and to provide data for a demonstration of the pre- and postclosure environmental and safety assessment methodology. The quality of the work in these studies has been controlled by peer review of the specifications, methods and results of the studies, as is AECL's practice for publication of technical reports.

Other research is continuing to enhance our design capabilities, to develop alternative nuclear fuel waste packaging and emplacement concepts, to enhance our understanding of materials and processes relevant to disposal facility design, operation and safety, and to establish the base from which we may proceed with facility, component and process optimization.

1.2 DISPOSAL FACILITY ALTERNATIVES

1.2.1 General

A disposal facility for nuclear fuel waste would be designed and operated to receive nuclear fuel waste in shielded transportation casks, to repackage the waste in disposal containers (if necessary), to transfer them to the disposal vault, and to emplace them within appropriate sealing systems. The facility would be designed with appropriate consideration of the specific site conditions, and the requirements for performance monitoring, occupational and public safety, and environmental protection.

There are many factors that would affect the scope of each of these activities and therefore influence the decisions made regarding the design and operation of individual systems, components and equipment required for a disposal facility. Some of these are discussed in Section 1.2.2.

A variety of design concepts for facilities to dispose of nuclear fuel waste have been or are being considered internationally. The organizations considering disposal in hard, crystalline rock have tended to concentrate most of their resources on alternatives based on the room-and-pillar arrangement of underground excavations. This arrangement, which is commonly used in mining and civil engineering, consists of a series of regularly spaced rooms and interconnecting tunnels excavated on one or more levels, with the pillars of rock remaining between adjacent rooms providing structural support for the vertical loads. The arrangement alternatives are discussed in Section 1.2.3, and the room-and-pillar alternatives for the Nuclear Fuel Waste Management Program are discussed in Section 1.2.4.

1.2.2 Factors Affecting Disposal Facility Design and Operation

1.2.2.1 Site

The Canadian concept for nuclear fuel waste disposal is to site a disposal facility on the Canadian Shield and to excavate the disposal vault at an appropriate depth within a plutonic rock body. The site would be selected after consideration of a full range of social, economic and technical factors and with input from the public. From a functional perspective, the site would be suitable in size and topography for construction of the surface facilities necessary for disposal; would be reasonably accessible from existing roads, rail lines and electrical power systems; and would be adjacent to a suitable source of fresh water.

The technical suitability of any selected site would be confirmed prior to the construction stage by exploration drilling from the surface and by excavating one or more exploration shafts and some horizontal tunnels at the preferred disposal depth. These excavations would provide access to the volume of rock expected to contain the nuclear fuel waste and would allow additional exploration drilling and characterization testing to contribute to the understanding of the site conditions. Whenever possible, these excavations would be incorporated into the construction of the disposal vault. Where this is not practical, the excavations would be sealed.

1.2.2.2 Transportation System

The transportation system and disposal facility designs and operations are closely linked. Proximity to transportation routes (i.e., road, rail and/or navigable waters) would be a factor that would be considered in site screening and selection. The disposal facility would be designed to receive nuclear fuel waste carried by the appropriate transportation mode(s).

The receiving installations and handling equipment at the disposal facility would be compatible with the transportation casks used to handle the waste. These casks may be either an integral part of a disposal container, which would be disposed of with the waste, or it could be a reusable shielding vessel (i.e., cask), which would contain and protect the waste during transportation.

1.2.2.3 Nuclear Fuel Waste Receipt, Packaging and Inspection

The requirements for packaging nuclear fuel waste at the disposal facility would depend on the way the waste was packaged for transport to the site. The waste may be sealed in a suitable disposal container before being shipped to the disposal site. In this case, each container arriving at the disposal facility would be inspected and either accepted for disposal, or rejected and sent for repair. An alternative approach would involve receiving the waste in reusable transportation casks, repackaging and sealing it in disposal containers, and inspecting the sealed containers at the disposal facility.

In either case, systems and equipment would be required to inspect the disposal container for defects. Facilities would also be required in which defects on disposal containers could be repaired; if the defects cannot be repaired, the disposal containers would be disassembled so that the nuclear fuel waste could be sealed in new containers.

1.2.2.4 Disposal Vault Facilities

The disposal vault would comprise access openings (i.e., shafts and tunnels), underground service areas, and waste disposal areas. The arrangement and areal density of the waste containers within the disposal areas of the vault would depend on several factors, such as the heat generated by the radioactive decay in each waste container and its change over time, the geometry of the disposal container and the disposal rooms, the mechanical and thermal properties of the sealing systems and the rock, the required thickness of the sealing-system components, the in situ stress conditions, the rock-mass strength, and the degree of fracturing. The rock stress, strength and degree of fracturing may affect the stability of underground openings. The geometry and spacing of disposal rooms would be controlled by the fracture density and pattern, by the in situ excavation- and thermal-induced stresses, by the rock-mass strength and by the space requirements of equipment for emplacing and sealing the waste containers in the rooms.

Service areas would be provided for vehicle maintenance, for preparing and/or handling sealing material, for ventilation system control, for handling drainage water and waste rock, and for transferring and handling disposal containers.

1.2.2.5 Transfer of Disposal Containers to the Disposal Vault

Disposal containers that have passed inspection and are accepted for disposal would be either transferred "as is" to the disposal vault, if the container provides adequate radiation shielding, or they would be placed in a shielding container cask and transferred to the disposal vault. In the disposal vault, the containers would be moved to, placed and sealed within the disposal areas. The location and spacing of containers in the disposal areas would be determined based on temperature and stability factors established for the various engineered components and the rock mass. The sealing systems would comprise low-permeability materials, probably clay- or cement-based, to achieve an environment where the movement of groundwater is very slow and where the chemistry can be buffered by the sealing materials.

The sealing systems may include several elements, each installed separately, such as the clay-based buffer/backfill and/or cement-based grout/concrete plug systems proposed by Sweden, Canada and others, or single-element systems such as the crushed rock backfills proposed by the United States. The specific choice of sealing systems would be made based on the requirements placed on those systems to satisfy the safety goals of the disposal facility.

The individual disposal rooms would be either sealed as they are filled, or they would be left open until all waste containers had been emplaced, then sealed as part of decommissioning and closing the disposal vault. The approach chosen would depend, in part, on the characteristics of the sealing system. If components of the sealing system are intended to be active, such as the swelling clays used in some concepts, the desired performance characteristics of the materials must be maintained. Therefore, if the swelling clays are placed at the same time as the waste containers, it would likely be necessary to emplace the rest of the disposal-room sealing materials at that time to maintain the seal integrity. If the sealing system is passive and the disposal rooms are expected to be stable and easily maintained over the operating period of the disposal vault, the rooms could be left open until a decision is made to seal the entire vault.

1.2.2.6 Decommissioning and Closure

When the decision is made that no additional nuclear fuel waste would be disposed of in the vault, and approval is obtained to seal the vault, the underground excavations remaining open (i.e., possibly the disposal rooms, access tunnels, service areas, shafts and/or ramps) would be sealed. Prior to sealing, the equipment, services and installations, and possibly some material from the excavation surfaces would be removed to provide a sound surface to be in contact with the seals. All monitoring installations in the vault would also be removed and the boreholes would be sealed at this time. The surface facilities would be decontaminated and removed during this period since they would no longer be required to support ongoing operations.

The disposal facility would be closed when approval is obtained to remove all systems at the site that require institutional controls to maintain them in a safe condition. At that time, monitoring systems in surface-based boreholes would be removed and the boreholes would be sealed. Some surface-based monitoring systems that have no potential influence on the safety of the disposal system could be left in place at the discretion of the regulatory authorities or the public.

1.2.3 Some International Disposal Vault Concepts

There are three basic repository design concepts considered internationally that may be suited to disposal in plutonic rock: the WP-Cave concept, the very deep borehole emplacement concept, and the room-and-pillar concept (which we have adopted).

The Swedish WP-Cave concept (SKB 1989a) consists of a combined storage and disposal facility named after and based on the features of a design originally proposed by the Swedish consulting and construction company WP-System AB. It would be constructed at a depth of several hundred metres and would consist of a multilevel storage/disposal channel and shaft array entirely surrounded by a 5-m-thick clay-based engineered barrier, which in turn would be surrounded by a connected array of tunnels and boreholes to create a hydraulic cage (Figure 1-1). The design is intended to equalize the hydraulic pressures around the engineered barrier and thereby reduce the hydraulic gradients that otherwise could cause water movement through the waste emplacement volume. In other words, the system is designed to channel or deflect groundwater flow around the vault rather than through it.

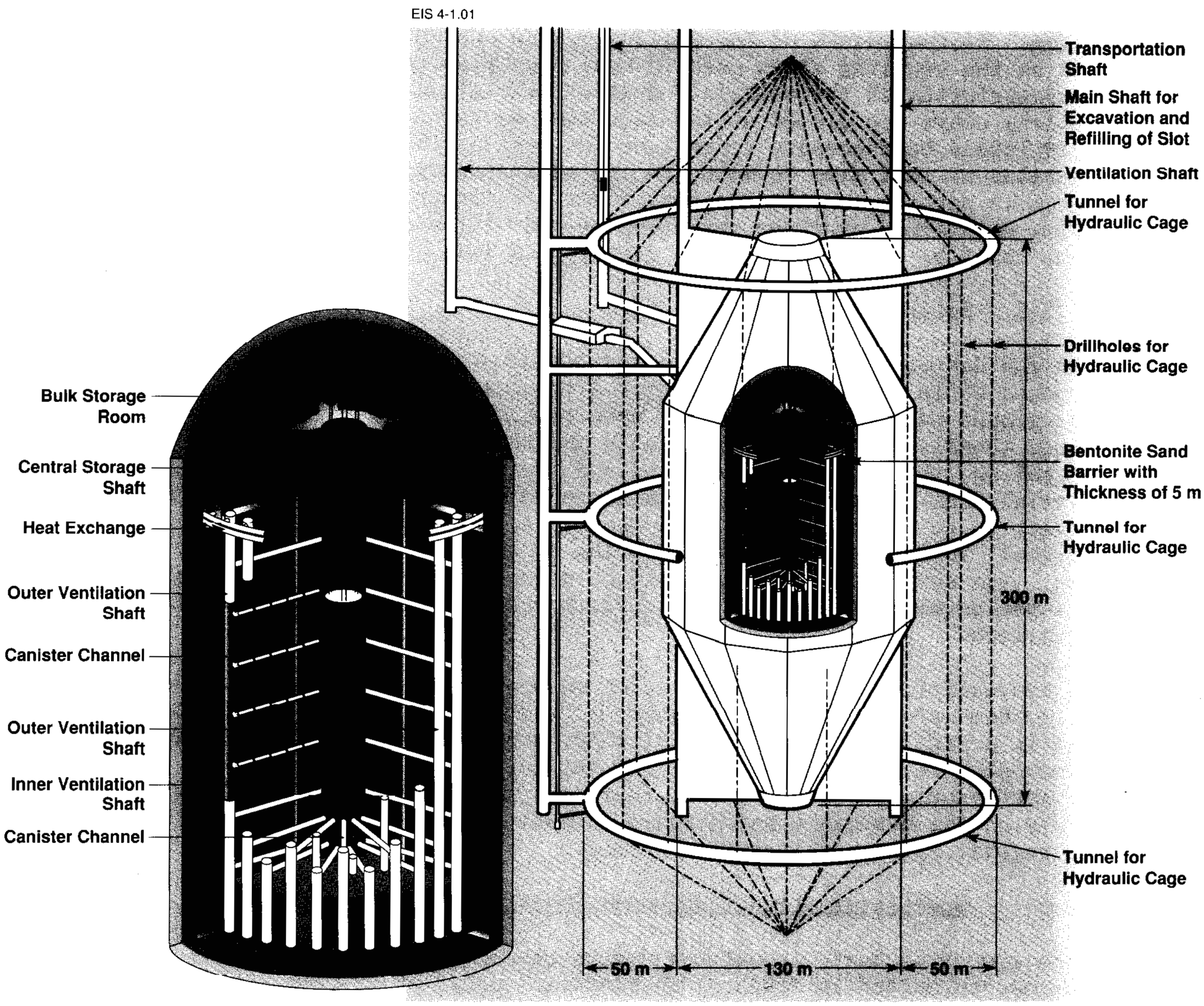


FIGURE 1-1: The Swedish WP-Cave Disposal Vault Configuration (after SKB 1989a)

The channel and shaft array would consist of a central shaft with several levels of waste storage and disposal channels (ramps) radiating outward at a 30° decline, an outer ventilation shaft array that supplies cooling air to each channel, an inner ventilation shaft array to remove cooling air from each channel, and the facilities and services to operate the facility for storage and disposal of waste.

The capacity of a WP-Cave is limited by the heat removal capacity of the ventilation system during the ventilation cooling period and by the thermal characteristics of the system when it has been completely backfilled with sand. In the design shown in Figure 1-1, which has a capacity of 1100 Mg U, two SKB-designed waste canisters would be placed in each channel, the diameter of which is based on materials-handling and air-cooling requirements. In this design, each waste canister contains 1.5 Mg U, there are 14 channels per level and there are 26 levels.

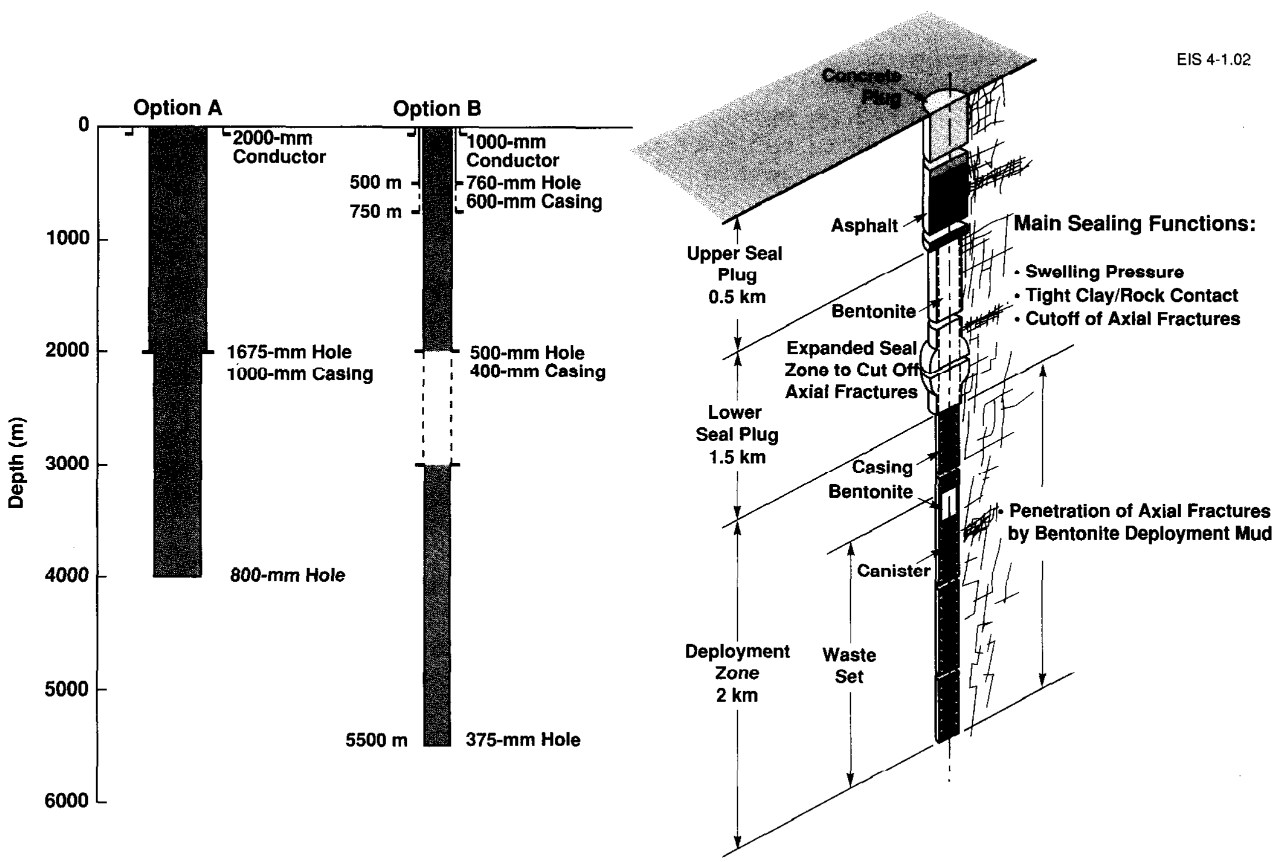
When the WP-Cave is sealed, the mechanical services are removed and all excavations within the barrier are backfilled with crushed rock before they are flooded with water. This improves the heat transfer and provides more rock surface for chemical interaction when the containers fail.

The SKB analyses showed the concept to be technically feasible, to be limited in waste capacity to about 1100 Mg U per facility, to require a large volume of competent rock, and to offer no substantial safety advantages over the Swedish room-and-pillar repository design (SKB 1983). As well, SKB noted that many elements of this concept require development and demonstration before it could be implemented.

The very deep borehole emplacement concept is intended to isolate the waste at a greater depth than would be practical in a mined vault. Three scenarios for emplacement of waste were considered by SKB in their conceptual design (SKB 1989b). These involved placing waste canisters in boreholes that would be drilled from the ground surface to depths of 4000 to 5500 m (Figure 1-2). The borehole diameters in the study scenarios varied from 800 mm to 375 mm. In this disposal concept, the waste canisters are lowered from the ground surface to fill the boreholes from the bottom, and the upper 2000 m of each borehole is sealed.

The waste canisters are first assembled on the surface in packages up to four canisters long. The canisters are separated and surrounded by blocks of highly compacted sodium-bentonite clay. Before any packages are emplaced, the lower portion of the borehole is filled with a bentonite/water slurry that will provide some buffer material in the voids between the package and the borehole wall. In each scenario, the waste packages are placed into the borehole so that the upper 2000 m of each borehole can be the seal zone. The lower 1.5 km of the seal zone is filled with highly compacted bentonite clay. This zone includes expanded-diameter zones to intersect and seal axial fractures that may parallel the borehole. The upper 0.5 km is an asphalt plug capped with concrete. The assessment concluded that the concept is substantially more expensive than the Swedish room-and-pillar disposal vault concept (SKB 1983), and requires a much larger research and development program to prove its feasibility.

The room-and-pillar disposal vault concept in hard, crystalline rock has been studied in the United States (U.S. DOE 1988), Japan (Araya et al. 1986), Sweden (SKB 1983), Switzerland (NAGRA 1985a) and the Commission of the European Communities (CEC) (CEC 1982), and is preferred in many other countries. A room-and-pillar disposal vault consists of a series of regularly spaced disposal rooms and interconnecting tunnels excavated on one or more levels within the geological medium selected for disposal. Figure 1-3 shows one possible single-level room-and-pillar disposal vault configuration. Access to the disposal levels could be by shafts, adits and/or ramps.



(a) Proposed General Arrangement of Two Options for Disposal Boreholes

(b) General View of a Completed Option A Borehole

FIGURE 1-2: The Swedish Very Deep Borehole Disposal Configuration (after SKB 1989b)

Table 1-1 compares the information from these various studies and highlights factors that are of interest for presenting the feasibility of nuclear fuel waste disposal. The room-and-pillar concept offers advantages in cost, safety, feasibility with current technology, flexibility and the extent of international study. The very deep borehole disposal concept was included in a comparative study of 12 disposal concepts issued by the CEC in 1982 (CEC 1982). The CEC assessment was done to select a repository design for more detailed consideration, and 11 room-and-pillar designs were rated more highly than the deep borehole design.

1.2.4 Room-and-Pillar Disposal Vault Configurations Studied in the Nuclear Fuel Waste Management Program

The room-and-pillar disposal vault configuration has been studied in Canada since the mid-1970s (Acres et al. 1978). A series of studies on alternative arrangements was conducted (Acres et al. 1980a, 1980b; Acres and RE/SPEC

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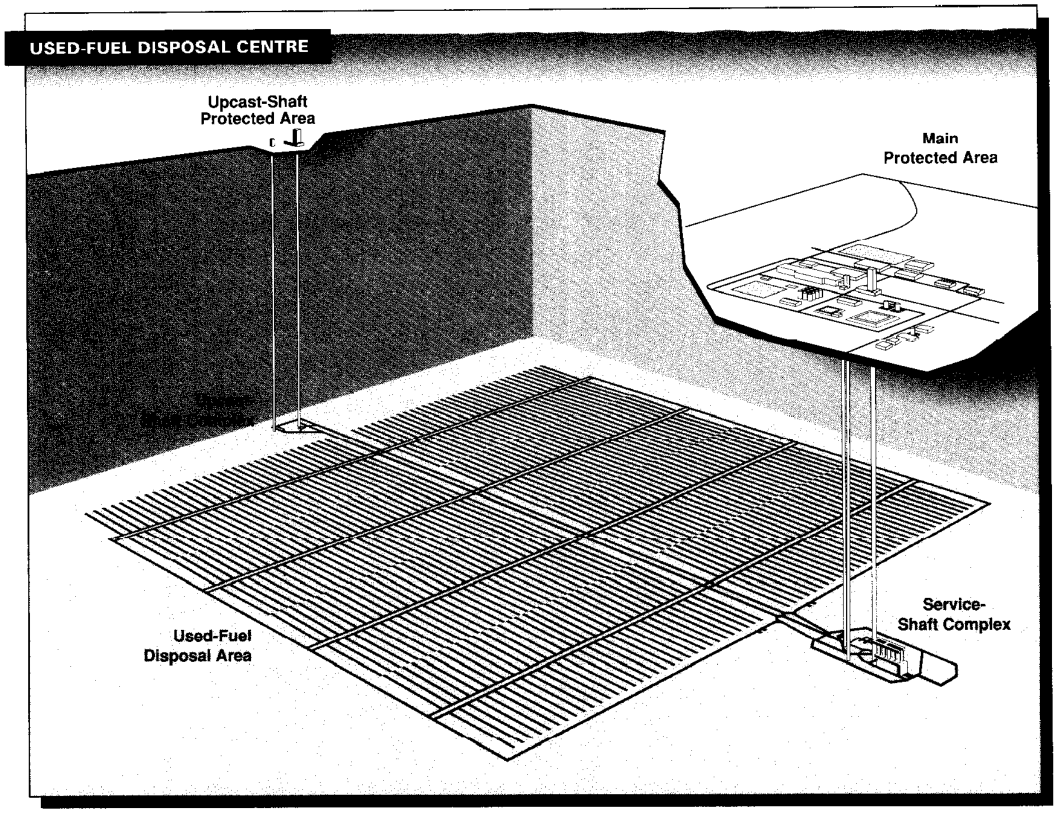

FIGURE 1-3: Used-Fuel Disposal Centre Perspective

1985; Acres 1993b). These alternatives included single- and multiple-level vault arrangements, the emplacement of waste containers in horizontal or vertical emplacement boreholes drilled from disposal rooms, the emplacement of waste containers in the disposal rooms and the emplacement of multiple containers in long vertical boreholes. Some of these container-emplacement alternatives are illustrated in Figure 1-4.

In a single-level configuration, all the waste would be emplaced at one elevation in the rock body (Figure 1-3, AECL CANDU et al. 1992). In a multiple-level configuration, the waste would be emplaced on two or more levels located at different elevations in the rock body (Figure 1-5, Acres and RE/SPEC 1985); or in a multiple-level long-hole configuration where the waste would be emplaced throughout the rock-mass volume between two or more levels (Figure 1-6, Acres 1993b).

Table 1-2 compares these three alternatives for room-and-pillar vault configurations. The characteristics of the single-level configuration are used as the base reference for each factor and the alternative configurations are ranked relative to the single-level configuration. This comparison shows that the single-level vault ranks well for used-fuel disposal in all technical categories and would be the least expensive to implement.

TABLE 1-1

COMPARISON OF DISPOSAL CONFIGURATIONS NORMALIZED TO THE ROOM-AND-PILLAR CONFIGURATION[1]

Configuration	Factors: International Interest in Configuration	Flexibility in Adapting to: Site Conditions	Flexibility in Adapting to: Waste Volumes	Short-Term Safety	Long-Term Safety	Retrievability	Relative Cost	Need for Technology Development
WP-Cave	lower	lower	lower	uncertain	less redundancy[2]	equal or easier	more[4]	greater
Very Deep Borehole	lower	uncertain	equal	lower	uncertain	harder[3]	more[4]	greater
Room and Pillar	base	base	base	base	base	base	base	base

Notes:

1. Information extracted from conceptual design reports.
2. SKB (1989a) note that there is less redundancy in the engineered barriers.
3. CEC (1982) notes this in Chapter 2, Section 1.3.
4. From comments in SKB (1989a) and SKB (1989b). The Very Deep Borehole configuration may have a higher total cost, but the expenditures would be distributed more uniformly over the disposal period. The impact on the electrical consumer may be less than the room-and-pillar configuration, depending on the financing scenario chosen.

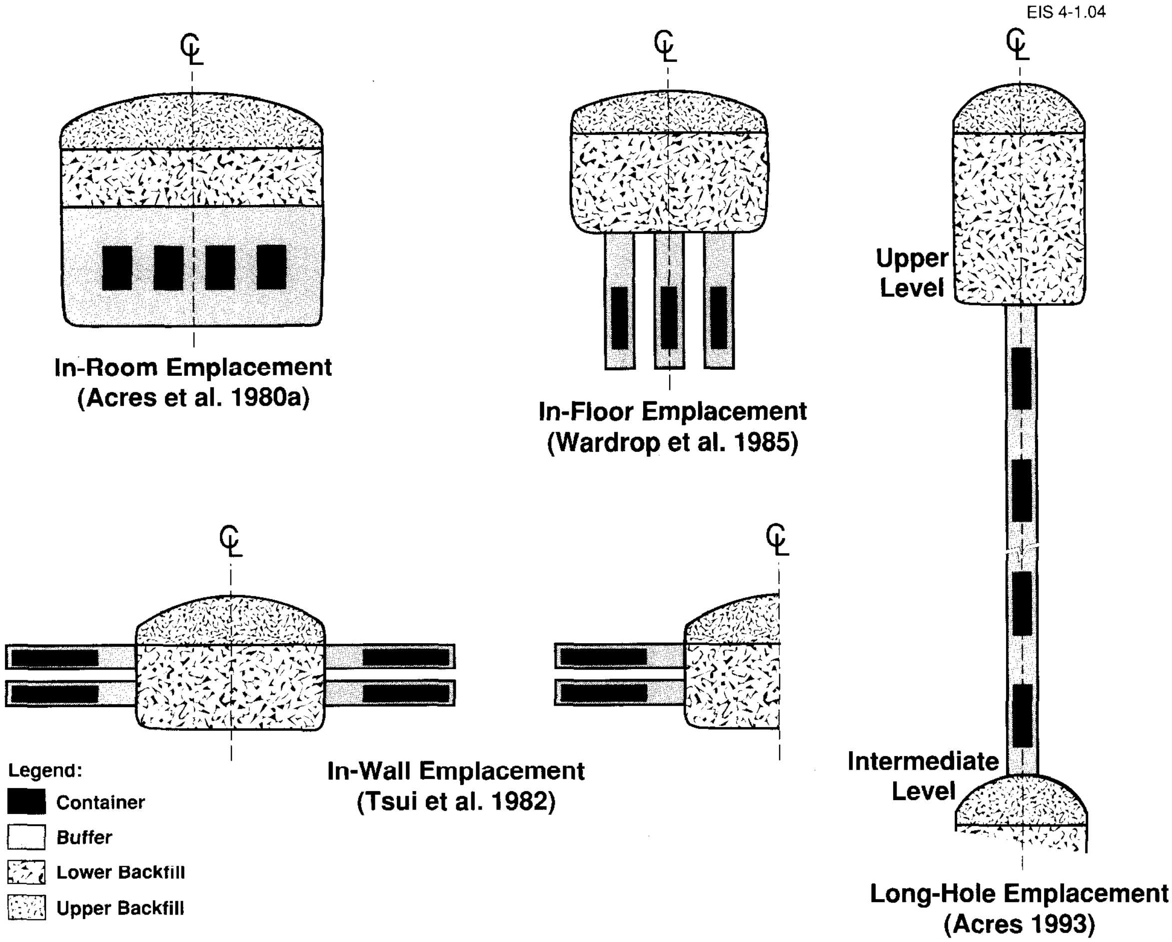

FIGURE 1-4: Container-Emplacement Alternatives Studied in the Canadian Nuclear Fuel Waste Management Program

The room-and-pillar configuration for underground excavations is a well-proven technology, widely used in mining and some civil engineering projects. It offers several advantages in its application to waste disposal, including

1. modularity in design, which allows the arrangement of disposal rooms to be adapted to variations in site conditions and total waste volumes;

2. flexibility in the spacing of disposal rooms and the spacing of disposal containers to limit the temperature increase on specific engineered and natural barriers; and

3. flexibility in the size, shape and orientation of excavations to enhance both the short- and long-term stability.

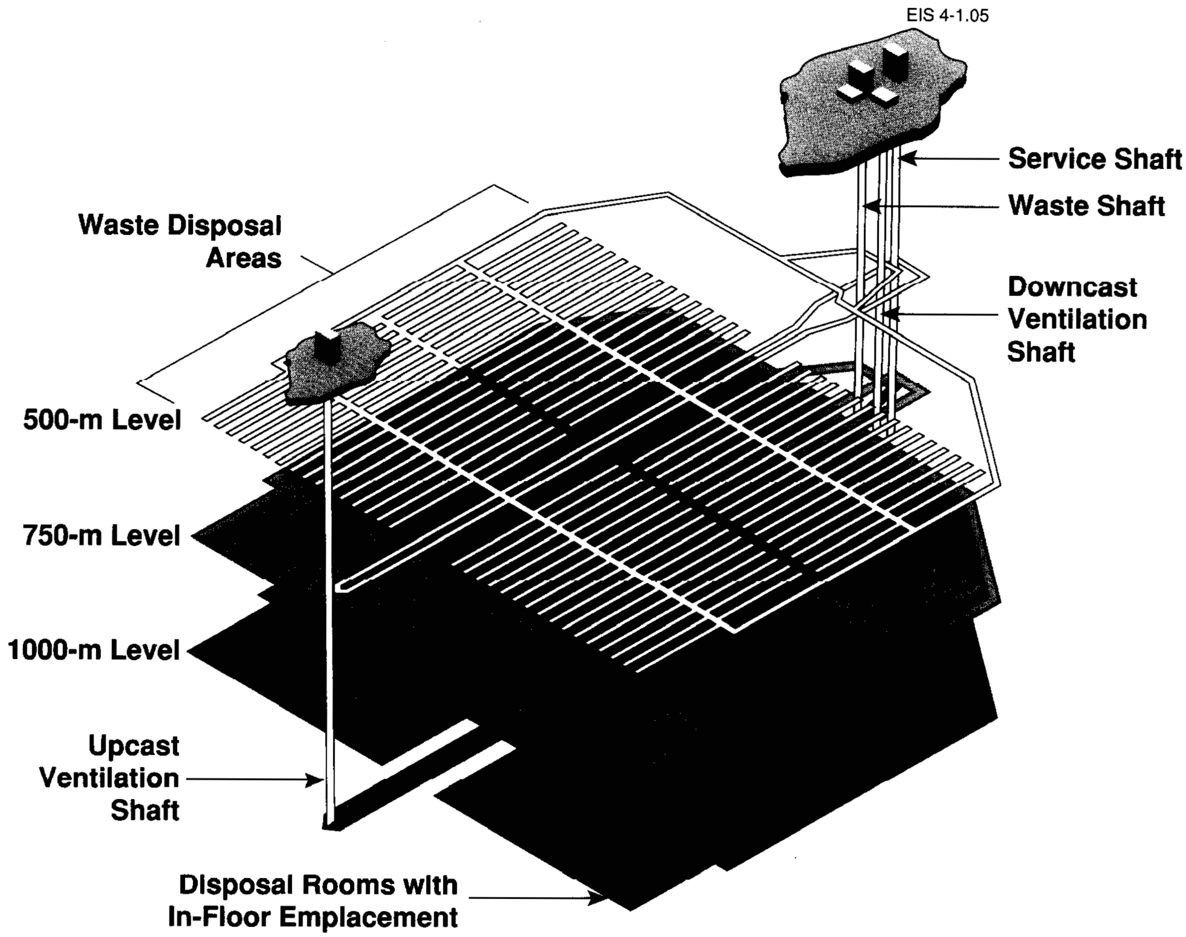

FIGURE 1-5: Multiple-Level Room-and-Pillar Disposal Vault Configuration (fuel reprocessing waste disposal) (after Acres and RE/SPEC 1985). The arrangements are similar at the 500-, 750- and 1000-m levels.

1.2.5 Some Disposal Container Alternatives Considered in Conceptual Design Studies

A range of packaging facilities for both used fuel and fuel reprocessing waste has been considered and has accommodated some of the disposal container alternatives discussed by Johnson et al. (1994a), as shown in Table 1-3.

These facility studies do not cover the full range of container design alternatives studied in the Nuclear Fuel Waste Management Program. However, the studies provided design experience to address the issues, processes and facilities for various container designs.

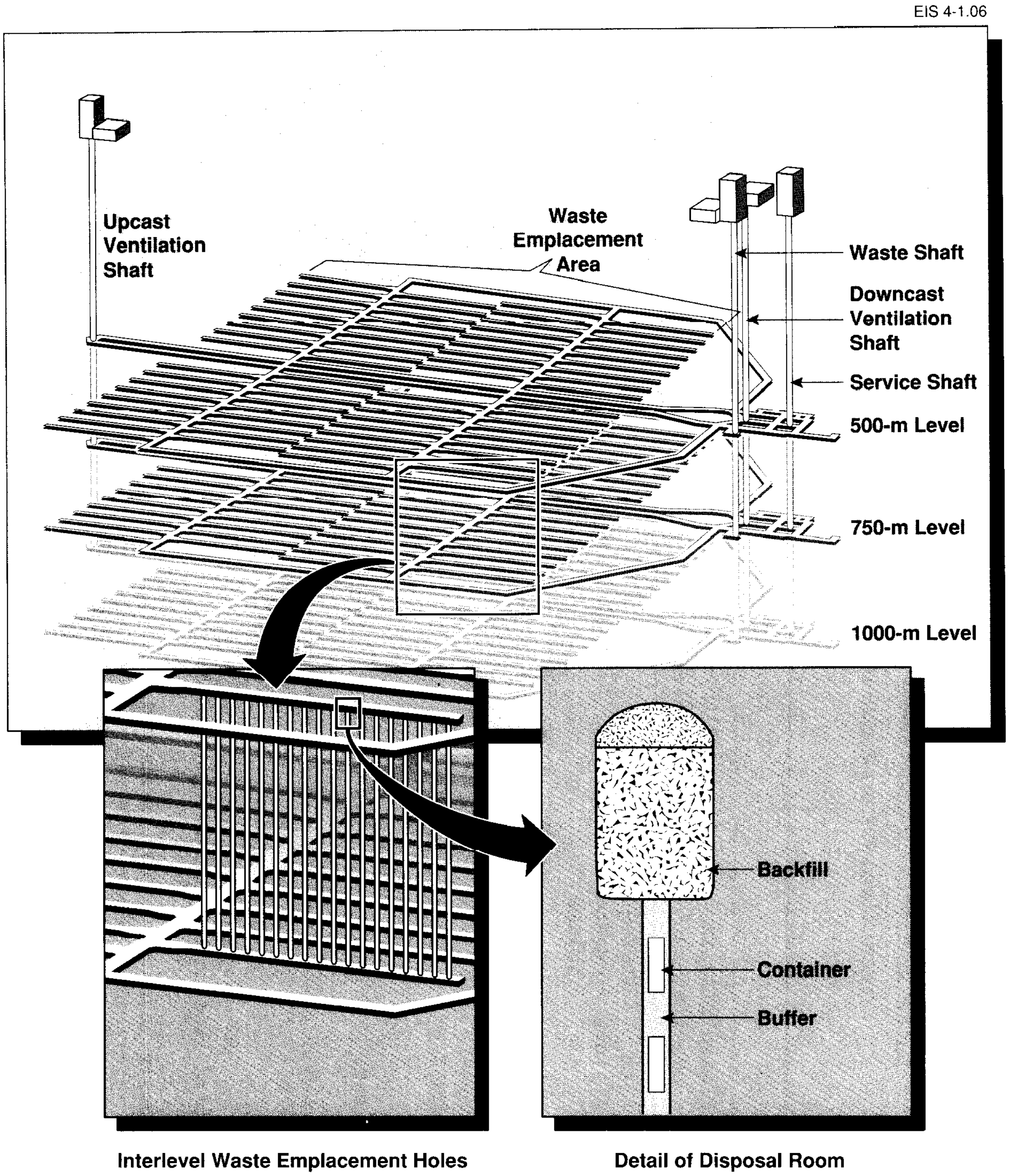

FIGURE 1-6: Long-Hole Room-and-Pillar Disposal Vault Configuration (fuel reprocessing waste disposal) (after Acres 1993)

TABLE 1-2

COMPARISON OF ROOM-AND-PILLAR VAULT CONFIGURATIONS[1]

(normalized to a single-level configuration)

Configuration	Factors						
	Flexibility in Adapting to		Pluton Plan Area Required for Disposal of		Ease of Retrieva-bility	Relative Cost for Used-Fuel Disposal	Need for Technology Development
	Site Conditions	Increased Waste Volume	Used Fuel	Fuel Reprocessing Waste			
Single-Level Vault	base	base	base	base	base	base	base
Multilevel Vault	equal	less	equal to less[2]	less	equal	higher	equal
Multilevel, Long-Hole Vault	less	less	equal to less[2]	less	less	much higher	greater

Notes:

1. Information extracted from conceptual design reports.

2. Depends on total waste inventory. For large quantities of used fuel (e.g., 10 million bundles), the long-term thermal interaction between the distributed wastes would require greater waste spacings at the vault level so that the multilevel plan area would be similar to that of a single-level vault. The amount of thermal interaction would be reduced for smaller quantities of used fuel, and so the plan area would be further reduced.

TABLE 1-3

CONTAINER ALTERNATIVES INCLUDED IN DISPOSAL FACILITY STUDIES

Container Dimensions O.D. x h (mm)	Container Material	Wall Thickness (mm)	Capacity (U-Used Fuel, R-Fuel Reprocessing Waste)	Filler Material	Reference
910 x 1275	304 L stainless steel	25	U-72 bundles	Cast lead	Acres et al. (1980a)
457 x 3275	304 L stainless steel	15	R-equiv. 72 bundles	Cast glass	Acres et al. (1980b)
630 x 2246	Grade-2 titanium	4.76	U-72 bundles	Glass bead	AECL CANDU et al. (1992)

These surface facility and disposal vault studies were not done to optimize designs, but rather to identify and study issues at a conceptual level. They are generally developmental and have been done at a relatively low level of detail.

1.3 THE USED-FUEL DISPOSAL CENTRE REFERENCE DESIGN

A specification was developed in 1984 as the basis for a conceptual design study of a Used-Fuel Disposal Centre (Baumgartner et al. 1993). The disposal vault and waste emplacement alternatives selected were a single-level, room-and-pillar disposal vault with in-floor emplacement of individual disposal containers. It was assumed that the disposal centre is self-contained and located on a suitable plutonic rock body of the Canadian Shield. The disposal centre includes a disposal vault (Figure 1-3) excavated into the rock body at a depth of 1000 m, and surface facilities for the receipt and packaging of used fuel in disposal containers.

The Used-Fuel Disposal Centre (AECL CANDU et al. 1992) is a conceptual design for a facility that would receive, package and dispose of about 191 000 Mg of uranium in the form of 10.1 million used-fuel bundles. The disposal vault is essentially square in plan with an area of about 4 km^2. The used-fuel bundles are assumed to be 10 a out-of-reactor. Conceptual designs are presented for the primary facilities, equipment and operations for receiving, packaging and disposing of used fuel. The necessary material supply, handling and preparation facilities and the utilities and services required to support siting, construction, operation, decommissioning and closure of the disposal centre are described.

Used fuel is received at the packaging plant of the disposal centre in either a road or rail transportation cask that contains the used-fuel bundles in storage/shipping modules. The modules are unloaded from the casks in a module-handling cell. The modules may be temporarily held in a receiving surge-storage pool or transferred directly to the used-fuel packaging cell. In the packaging cell, the fuel bundles are transferred from the shipping modules to the disposal container fuel baskets, 72 bundles to a basket, and each fuel basket is installed within a disposal container. Each bundle and container is identified for safeguards purposes in the transfer operations.

The reference disposal container shell and end closures assumed in this conceptual design are fabricated of 6.35-mm-thick ASME Grade-2 titanium. The loaded container is filled with a particulate, such as glass beads, which is vibrationally compacted to fill all the void space, allowing the container to withstand the expected external loads. A top head is pressed into the container and the top head and container-shell flanges are bonded by diffusion. The assumed quantity of used fuel requires about 140 000 disposal containers, each having a mass of about 2800 kg. When initially sealed in the disposal container, the 72 used-fuel bundles produce about 300 W of heat.

Following nondestructive testing (i.e., ultrasonic bond inspection and a helium leak test) to establish the integrity of the sealed container, each disposal container is loaded into a shielding container cask. Each full cask is transferred to the disposal vault, using the cage in a dedicated waste shaft. When removed from the cage, the cask is moved by crane to an underground storage area or by truck directly to a disposal room.

In this conceptual design, each disposal room is about 8 m wide, 5 to 5.5 m high and 230 m long. Up to 282 vertical emplacement boreholes are drilled in the floor of each disposal room, and each borehole is prepared to receive the disposal container. The emplacement boreholes are 1.24 m in diameter, and 5 m deep, and are spaced about 2.1 m apart, three across the room and 94 along the room, as required to keep the maximum temperature of the container wall below 100°C. Before a container cask is received in the disposal room, a clay-based buffer material (i.e., 50% sodium-bentonite clay and 50% silica sand by mass) is compacted into the emplacement borehole and a hole is centrally augered into the buffer to receive the container. When the container has been emplaced, the radial gap between the container and the buffer is filled with dry silica sand to provide heat conduction, and additional buffer material is then placed and compacted over the container to the floor level of the disposal room.

When all the emplacement boreholes in a room have been filled, the room is backfilled by placing and compacting a mixture of 25% glacial-lake clay and 75% crushed granite, by mass, to fill the lower 3.5 m of the room. The upper portion of the room is filled by spray-compacting an upper backfill material, similar in composition to the buffer material, into place. A concrete bulkhead is constructed at and grouted into the room entrance to seal the room and to withstand the buffer and backfill swelling and the hydraulic pressures. It might also be used as a safeguards seal for the room, since an attempt to gain entry to the sealed room from the panel tunnel could be detected from the indication of tampering on the bulkhead.

The operational sequence in the conceptual design, consisting of disposal-room excavation by the drill-and-blast method, emplacement-borehole drilling and preparation, waste emplacement, borehole sealing and room backfilling and sealing, continues throughout the operating period of the disposal vault. The disposal rooms are developed and filled in sequence, advancing from the upcast-shaft complex toward the service-shaft complex to control access, potential radioactive contamination, and potential radiation dose to personnel.

When the vault has been filled with waste, the monitoring data have been assessed to show compliance with the regulatory and design criteria, and the regulators have approved the decommissioning and closure plan for the centre, the access tunnels and shafts will be backfilled and sealed, the surface facilities will be decommissioned and disassembled, and the site will be permanently marked and returned to a state suitable to allow public use of the surface.

1.4 ORGANIZATION OF THIS REPORT

The first objective of this report, to discuss the engineering aspects of nuclear fuel waste disposal, is general and does not require a specific conceptual design. Chapter 2 deals with general considerations relating to the project's organization, design methodology and design process. It identifies major issues and factors that must be considered and activities that should be included during project implementation.

A specific conceptual design is used to address the second objective, describing a design for and the operation of a disposal facility. The issues are discussed in the context of a specific used-fuel disposal centre conceptual design. The discussion has been divided into stages and one section of the report presents an approach to implementing each stage. A specific aspect of the disposal facilities is discussed for each stage using the Used-Fuel Disposal Centre conceptual design as the example. Chapter 3 (siting stage) provides specific examples of the design approach and issues associated with implementing used-fuel disposal. Chapter 4 (construction stage) describes the facilities and systems necessary to implement used-fuel disposal. Chapter 5 (operation stage) describes the processes and operations necessary to receive used fuel, package it in corrosion-resistant containers, emplace it in a disposal vault and seal the disposal rooms. Chapter 6 (decommissioning and closure stages) describes the operations necessary to seal a used-fuel disposal vault, to dismantle and to remove the surface facilities. Together, Chapters 3 to 6 provide a complete presentation of the conceptual design.

The third objective, to reasonably estimate the personnel and funding required to implement disposal, also requires a specific conceptual design. Chapter 7 presents the cost estimates and labour requirements for the Used-Fuel Disposal Centre. The sensitivity of costs to the quantity of used fuel disposed of is also discussed.

Finally, Chapter 8 reviews the objectives of the report and discusses the feasibility of engineering disposal facilities.

The balance of this report should be read in the order that it is presented if the reader wants to review the information from the perspective of engineering a nuclear fuel waste disposal facility following the sequence in which the activities would be done. However, if the reader only requires further information on the actual handling of the used fuel, Chapter 5 provides a more detailed discussion of used-fuel disposal. Similarly, the reader may refer to any other chapter for specific detailed information on any other aspect of engineering the disposal facilities.

2. GENERAL CONSIDERATIONS FOR IMPLEMENTING A NUCLEAR FUEL WASTE DISPOSAL FACILITY

2.1 INTRODUCTION

Successful major projects such as the construction and operation of mines, industrial plants and power generating stations are well organized and carefully controlled. For a nuclear fuel waste disposal facility to be successful, careful consideration must be given to project organization and responsibilities; to project management; to the safety and health of workers, the public and the environment; and to the development of implementation plans.

Chapter 2 introduces the general issues relevant to each of these topics that would have to be considered in implementing nuclear fuel waste disposal. Important issues concerning project organization, management and safety include ownership and responsibilities, management of the project, and public, worker and environmental safety consistent with the legislation that defines safe practices and limits, and the means by which protection measures could be implemented.

The important issues related to planning project implementation include an approach to identify, rationalize and reduce the design options prior to setting specific design specifications; to integrate the specifications and regulatory requirements into a functional design; and to accommodate the variability and uncertainty in the natural environment into the design and construction process.

This section provides a sense of the range of issues that must be considered in implementing a project of this magnitude. It is not complete in that there are factors and issues other than those presented that must also be taken into account. However, the successful completion of several large geotechnical projects in the Canadian Shield (Acres 1993a) demonstrates that these factors can be completely identified, and that projects can be designed, constructed and operated to satisfy the defined requirements.

2.2 PROJECT RESPONSIBILITIES AND ORGANIZATION

2.2.1 Project Ownership and Definition

We indicate how AECL would propose to implement the disposal concept in our description of concept implementation. A composite organization called the implementing organization would be responsible for siting, constructing, operating, decommissioning and closing a disposal facility. Such an organization was selected to be able to describe the responsibilities and activities more clearly.

The implementation of the concept would involve a series of decisions about whether and how to proceed. Decision making would be shared among many participants, including potential host communities and the implementing organization. It would also be shared by governments and the owners of the waste to the extent they would not be represented by the implementing organization. In our description of concept implementation, "governments" include government agencies, such as regulatory agencies.

An early objective of the implementing organization would be to define the project requirements, for example, the total amount of used fuel that is to be disposed, the number of sites to be developed, the schedules to be met, and the mandate and identity of the project management team.

As a prerequisite, the project management team should have extensive nuclear and geotechnical project experience to coordinate and carry out all aspects of the project, and the skills and experience needed to interact with the public. The type of waste, the capacity of the disposal facility, the container (e.g., geometry, materials, fabrication), the sealing materials and systems, the form and characteristics of the waste to be received at the disposal site and the manner in which wastes generated from site operation would be handled are examples of the specific elements the implementing organization will have to determine in the course of optimization within the design process.

The implementing organization would interact with the federal and provincial governments, the utilities who own the waste, the federal and provincial regulatory authorities, and potential host communities to identify the issues important to each. They would develop an approach and a project plan that satisfies the requirements of all groups who would have responsibilities for or would be affected by the project. Some aspects of this plan are discussed in Sections 2.3, 2.4 and 2.5.

2.2.2 Legislation, Regulatory Documents, Guidelines, and Plans Relevant to Nuclear Fuel Waste Disposal

All activities undertaken in connection with the implementation of the disposal concept, including the transportation of nuclear fuel waste to a disposal facility, would have to comply with applicable legislative requirements. Such requirements are based on federal or provincial acts and regulations. Since municipalities receive their authority under provincial legislation, they may also have requirements that may be relevant.

In addition, directives, policies, or procedures of governments or government agencies might have to be considered. These could be found, for example, in regulatory documents issued by the Atomic Energy Control Board (AECB), in the Guidelines for the Decommissioning and Cleanup of Sites in Ontario issued by the Ontario Ministry of the Environment, or in the Federal Nuclear Emergency Response Plan prepared by Health Canada.

The Atomic Energy Control Act (Government of Canada 1985) establishes the AECB as the regulator of nuclear activities in Canada. During concept implementation, the implementing organization would obtain all the approvals required. These would include approvals from the AECB, which makes and enforces regulations that cover all aspects of the development, production, and application of nuclear energy. The AECB would regulate a nuclear fuel waste disposal facility, as it does all nuclear facilities in Canada. The major method by which the AECB regulates nuclear facilities and the use of radioactive materials is through its licensing process.

According to proposed amendments to the Atomic Energy Control Regulations (AECB 1986), a licence for a nuclear facility or for the use of a radioactive material would be issued only if the AECB was satisfied that the applicant would "provide adequately (a) for the protection of health and safety of persons; (b) for the protection of the environment; (c) for security in respect of all activities conducted under the licence; and (d) for the implementation of any applicable safeguards."

When licensing a nuclear facility, the AECB issues licences in stages, and may require that a licence be renewed periodically within the stage for which it was issued. The proposed amendments (AECB 1986) describe the sequence of licences that would have to be obtained from the AECB for a nuclear facility:

1. a licence to clear or excavate land or otherwise prepare the site,
2. a licence to construct the facility,
3. a licence to operate the facility, and
4. a licence to decommission the facility.

The proposed amendments also require that written approval be obtained from the AECB to abandon the site of a nuclear facility after decommissioning. To obtain such approval, the licensee must take adequate measures to limit the environmental effect caused by any preparation, construction, or development on the site; the licensee must remove all buildings, machinery, and equipment from the site; and the condition of the site must not be inferior to the condition it was in before being prepared for construction of the facility.

The AECB conducts inspections of the facilities to ensure compliance with the terms and conditions of their licence.

The implementation of nuclear fuel waste disposal would also be subject to many other legislative requirements, such as those for environmental assessment, environmental protection, occupational protection, and transportation of nuclear fuel waste. Approvals, including licences, in addition to those from the AECB could be required at several times throughout implementation.

Appendix D of the EIS (AECL 1994a) summarizes the more significant legislation, regulatory documents, guidelines, and plans, both federal and provincial, that could apply to the implementation of the disposal concept. Those summarized are not meant to constitute an exhaustive list, but are illustrative only. Additional information is provided by Grondin et al. (1994).

2.2.3 Quality Assurance

A quality assurance program provides a framework for planning, executing, and verifying work. The systematic methodology of quality assurance helps to achieve requirements, but more importantly, it provides the traceability that is needed to demonstrate that requirements have been met throughout the work process. This is essential to the assurance of quality in complex products and services, which cannot be evaluated simply by inspecting the end result.

Quality assurance programs would be developed for each of the five stages of concept implementation: siting, construction, operation, decommissioning, and finally closure of a disposal facility. This approach corresponds closely to regulatory guidelines for applying quality assurance to nuclear facilities (AECB 1991b). The quality assurance programs would be reviewed and accepted by regulators before the work for any stage is initiated.

Each quality assurance program would subscribe to a common set of principles and elements already developed for nuclear power plants (CSA 1992). Individual programs would differ in their emphasis and application, and in the unique standards or requirements they might invoke. To provide the flexibility needed to apply quality assurance to the range of work covered by each stage, quality assurance plans would be developed for specific aspects of the project. The plans would translate general quality assurance program requirements into the specific procedures that would be followed in the project.

Quality assurance program standards that have been applied to nuclear power plants (CSA 1983, 1984, 1986a, 1986b, 1987) would not be entirely appropriate for a nuclear fuel waste disposal vault because the properties and behaviour of the host environment are naturally variable and are never known entirely prior to construction. To accommodate changes in strength, structure, and groundwater conditions in the host environment, the design and construction of the vault would follow the observational method (Peck 1969), and would provide the latitude needed to accommodate the range of rock or soil characteristics that may be encountered.

The quality assurance programs applied to the design and construction activities for the disposal vault would be adapted to accommodate the observational method and the methods used to characterize the geological, geotechnical and hydrogeological conditions and behaviour of the host environment. Performance monitoring of the conditions and behaviour of the host environment would be an essential component of the quality assurance program, especially in the later stages. Quality assurance plans and control procedures for these types of activities have been developed by AECL and are being applied to some Nuclear Fuel Waste Management Program activities (Cooper et al. 1990, AECL 1990).

Quality assurance programs applied to all stages of developing, operating and sealing the disposal vault would be graded, that is, a level of effort would be given to assuring that the quality of work is commensurate with its importance to the result. Grading refers to the level of assurance of quality rather than to the level of quality itself. Quality assurance grades would be assigned based primarily on the importance of the work in ensuring the safe design, construction, and performance of the vault, and may also be based on other criteria such as the ability to repeat the work in the event of failure and economic considerations.

The requirements of the quality assurance program for implementing a disposal facility and the content for a quality assurance manual have been proposed by AECL CANDU et al. (1992).

2.3 PROJECT MANAGEMENT

The implementing organization would plan, organize and control all aspects of the work. It would provide efficient management within the economic, political, social, and regulatory framework in place at the time. Management functions would include the following:

1. establishing policies and procedures to ensure that the work is done effectively and efficiently and that public health and the environment are protected;
2. establishing occupational safety and health programs to ensure work safety;
3. interacting with the public and with regulatory authorities;
4. obtaining permits, licences, and approvals;
5. training workers;
6. implementing the quality assurance program;
7. establishing the infrastructure for and organizations to manage project effects, including emergency response planning; and
8. managing the characterization, engineering, procurement, and construction activities, the operation of the disposal facility, and the safety and administrative functions.

The implementing organization would integrate and coordinate the efforts and activities of the multidisciplined engineering, construction, procurement and operations teams, the efforts and activities of the various suppliers and contractors selected to provide their products and services, and of the permanent operational labour force. Project management would require experienced personnel and appropriate control, monitoring and documentation systems to provide accurate and timely data on the status of all project activities.

It would also identify or derive other project requirements such as

1. the regulatory requirements and criteria that govern the implementation of the project;

2. the project plan, which itemizes, organizes and schedules all project work;

3. the project management structure to plan, organize and control all activities to execute the project successfully;

4. the capability to design and evaluate the suitability of the components of the disposal facility;

5. the disposal facility systems and operational methods as derived from research programs; and

6. the monitoring and performance assessment plan for all site environments and components.

The project organization, management philosophy and design process must be sufficiently open and receptive to accommodate changes in the project in response to new information and changes in technology. The focus of the work would change accordingly as the project progresses through the various project stages. As well, new information might come from the characterization activities at the site, from studies in laboratories, or from changes in legislation. New information might also come from the community involvement process, where the interests, concerns and priorities of the host communities may change or new groups may emerge who should be involved in the process.

2.3.1 Approach to Project Management

At the start of the project, the implementing organization would determine the scope of the project and the distribution of responsibilities. The project team would be assembled and would produce a project plan, including the quality assurance program, a schedule and an estimate of costs. Areas of responsibility within the project might include characterization, design, construction, operation, procurement, monitoring, performance assessment, public interaction, legislative compliance (including licensing), administration and quality assurance. Each of these areas would be directed and supported by qualified professional, technical and administrative staff. The detailed organizational structure would depend on many factors, and cannot be defined at this time.

In order to develop a detailed project plan for executing the project, the necessary work would be divided into component activities and logically ordered to create a Work Breakdown Structure to be used in scheduling, estimating, reporting and document control. The plan would factor in the availability of resources and funding, key milestones, site conditions, and the processes for gaining approvals and licences. Also, contingencies, escalation, financing, and project management would be included in the work breakdown structure. The project plan and cost estimate would form the basis for the monitoring and control of the project. As work progressed, the work status, expenditures, scope and cost changes, and other pertinent items would be reported against this plan. The project plan and cost estimate would be reviewed periodically and, if necessary, amended to provide a realistic representation of the project requirements, progress and projections.

The involvement of those communities who may be host the project would be required to develop informed collective consent from the local and regional populace to the siting, construction, operation, decommissioning and closure of the disposal facility and to the transportation system. One objective would be to ensure that the views of all affected parties are heard and appropriately accommodated. The joint problem-solving/decision-making process should be demonstrated to be reasonable and it should be shown that any negative effects can either be mitigated, fairly compensated or handled by some combination of both (Greber et al. 1994).

The availability of and a process for distributing intervenor funding would also be established. Intervenor funding refers to funds made available to eligible individuals or groups to enable them to prepare for and take part in public reviews or hearings such as those contemplated under the Environmental Assessment and Review Process Guidelines Order (Government of Canada 1984, 1992) or under the Environmental Assessment Act (Government of Ontario 1990a). Funds might also be applied on an ongoing basis to support independent review activities by community advisory groups.

2.3.2 Adaptation in Project Management

The entire life cycle of the disposal facility would be defined as a project and could be divided into a number of sequential stages (see Section 2.5.1). Within each stage, the work would be further divided into groups of activities with common or complementary objectives. The project management structure and style chosen by the implementing organization must be flexible to accommodate the evolving nature of the work and of the regulatory environment as the project progresses within each stage and between the stages.

The project would have a simpler structure and simpler relationships with contractors, suppliers and permanent employees during the operations stage than during the siting and construction stages. During the operation stage, the project would be dealing with cyclical and repetitive operations in an environment that would be well-defined, whereas the site conditions would be progressively investigated and analyzed in the siting and construction stages, and the designs and construction would be adapted to this evolving understanding of site conditions. Achieving this adaptability would require visionary thinking, issues management and problem solving in a performance- and safety-driven working environment.

During the decommissioning and closure stages, the project would again be dealing with a construction-oriented environment. There would be greater uncertainty in the type of work undertaken in the decontamination, disassembly and removal or sealing of facilities. The number and type of contractors participating would likely be greater than during the operation stage.

The project schedules and costs are more vulnerable to change during the siting, construction and decommissioning stages than in the other stages. The project management group must recognize and adapt to these changes, which might be caused by changes in the understanding of the site conditions as determined from observations and measurements of responses to ongoing construction, from design and construction changes needed to accommodate equipment, material and labour availability, or from changes in legislation affecting the project.

Initial designs and design refinements based on "as-found" conditions would be produced during most stages of the disposal-facility life cycle. These would include conceptual-level designs for each of the potential disposal locations, a preliminary design for the surface-characterized sites, an initial detailed design for disposal facility construction, and a final design for closure.

As each stage progresses, increasingly more information on the site and its local variability would become available, and more observations of geological media responses would be made. These field observations would be "fed back" into the design process, possibly resulting in design, construction and quality-control modifications to suit local site conditions. The design should reflect expected conditions, with sufficient robustness and flexibility in design choices to accommodate the most unfavourable local conditions consistent with the available data.

2.3.3 Design Approach

The prediction of the performance of the disposal vault in the postclosure phase would be based on the results of models describing the behaviour of the individual vault components and the interactions among these components. The geometry of disposal containers, the materials from which they would be constructed, and the parameters that determine their performance would be described and modelled. Site-specific information would be required to model the performance of the natural barriers and the conditions that would prevail at the interfaces between the engineered and the natural barriers.

Vault design would minimize uncertainties in the vault performance and accommodate the variabilities of the natural barrier and, where possible, provide control of the conditions at the outer boundary of the engineered barriers. Details of the variabilities within a rock mass would remain largely unknown until exploration excavations are developed at a site.

The lack of details on the variability within a selected rock mass would not be unique to a disposal vault - such a lack is common in underground construction. Many major projects such as rail and highway tunnels, dams, pressure tunnels and underground powerhouses and storage chambers requiring a detailed knowledge of the engineering properties of the rock mass at a particular site have been completed successfully. These successes have been largely attributed to a design approach that accommodates observations made as construction advances (Acres 1993a).

The "observational method" is a geotechnical project design, construction and management method (Peck 1969) that allows a project to be modified as it progresses, using information on the geological conditions encountered and the excavation responses measured during construction. The method consists of a series of necessary and interrelated steps that embody good scientific and engineering practice. The embodiment of these steps in a project structure limits the inevitable uncertainties in predicting the performance of the underground works. The complete application of the observational method involves the following steps:

1. Exploration sufficient to establish at least the general nature, pattern and properties of the geological media, but not necessarily in detail.

2. Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions.

3. Establishment of a design based on a working hypothesis of behaviour anticipated under the most probable conditions.

4. Definition of items to be observed as construction proceeds, and estimation and, where possible, calculation of their anticipated values using the working hypothesis.

5. Estimation of the items noted in (4) under the most unfavourable conditions compatible with available data on the subsurface conditions.

6. Selection, in advance, of a course of action or design modification for all foreseeable significant deviations of the observational findings from those predicted by the working hypothesis.

7. Measurement of items to be observed as defined by (4) and evaluation of actual conditions.

8. Modifications to design/construction to suit actual conditions.

Peck notes that the observational design method seems somewhat contrived and rigid when formalized this way. When applied professionally with subtlety and creativity, the observational method leads to successful, satisfactory design.

The observational method necessitates a formal iterative engineering process (Figure 2-1). New information on the geotechnical environment gathered during the characterization, monitoring and performance assessment activities would be fed back continuously into the design process to ensure the appropriateness of the designs. This flexible approach would also accommodate changes in the legislative and/or the social-political environment that could affect the implementation of the project. As well, changes in other factors, such as the amount or form of nuclear fuel waste, that influence the design and arrangement of the facility could be accommodated without invalidating the basic design concept. New technology developments could also be accommodated.

2.4 SAFETY AND HEALTH

Ensuring safety and health would be one of the highest level objectives of the implementing organization. All applicable legislative requirements would be complied with.

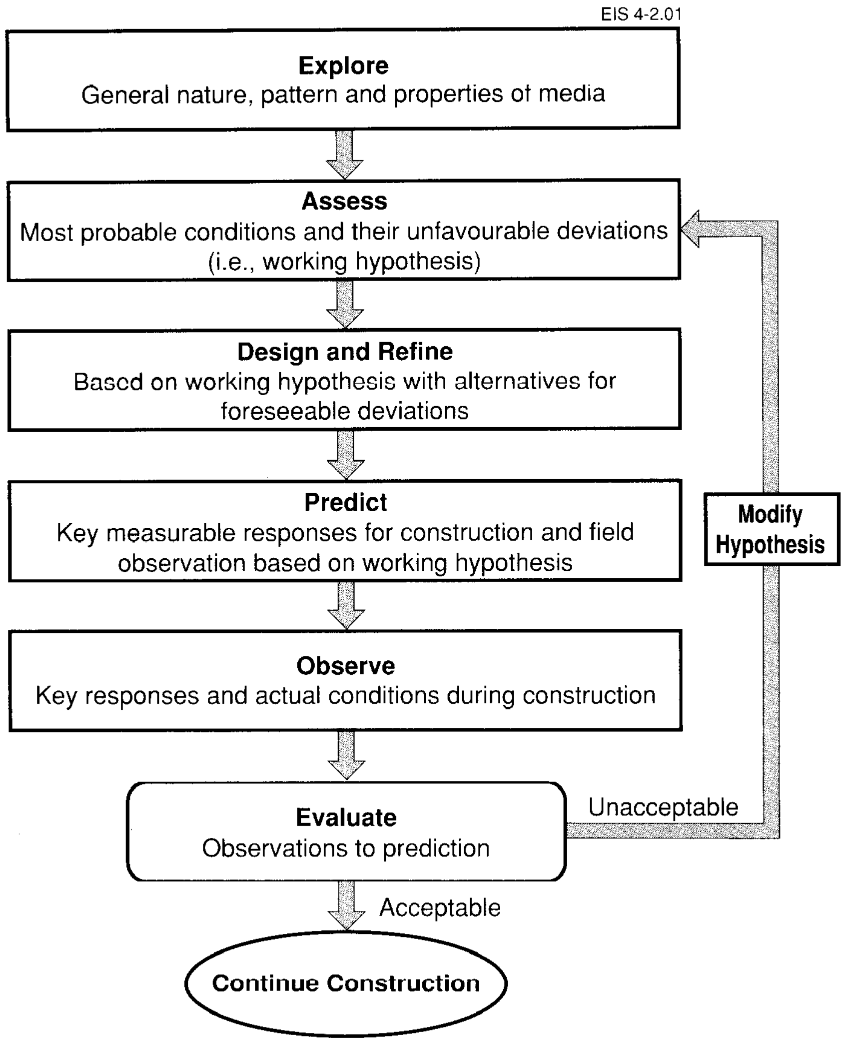

FIGURE 2-1: An Overview of the Observational Method in Geotechnical Engineering (after Peck 1969)

To satisfy the safety and health objective and the requirements of this legislation, the implementing organization would establish design and operational approaches to safety and health, would implement a safety and health committee structure and audit procedure, and would implement monitoring programs to establish baseline conditions and identify any changes in these conditions resulting from implementing the project.

Human factors engineering would provide one suitable approach to incorporating safety and health considerations into a disposal facility. The human factors engineering approach would formalize and incorporate other safety and health concepts such as the ALARA principle (As Low As Reasonably Achievable, the nuclear safety philosophy to ensure all exposures are kept as low as is practicable, with economic and social factors being taken into account). As such, it would provide a framework within which the designs of the structures, processes, systems and equipment related to individual activities and work areas would be refined. For example, methods could be applied to ensure that the designs and procedures facilitate safe and efficient operations as follows:

1. Task analysis to identify operator information requirements, required actions, feedback, communications and performance shaping factors, such as noise, confined space and stress, for use in specifying the most appropriate equipment for the tasks to be performed, and defining the procedures, communications and training needs.

2. Human error reliability analyses to evaluate alternative designs by predicting the probabilities of human error in operations conducted with particular design alternatives, and estimating the extent to which they degrade the safety of the system.

3. Human performance evaluation in alternative work environment configurations under specified conditions, such as the response to alarms, to highlight areas where further performance enhancements could be achieved through changes in design.

4. Communications analysis to systematically identify and assess tasks that require a worker to communicate with other people within and external to the facility, to identify the necessary communication links and facilities, and to contribute to the preparation of procedures.

5. Training needs analysis to identify the skills, knowledge and abilities required to perform the tasks and to categorize them into recruitment, training and upgrading requirements.

6. Workload assessment to estimate the workload associated with each task or activity and to identify required staffing levels.

Some of the legislation relevant to a nuclear fuel waste disposal project is discussed in Appendix D of the Environmental Impact Statement (AECL 1994a). One objective of this legislation is to establish the requirements for worker and public safety, and for health and environmental protection. Some of the safety and health measures are discussed below.

The implementing organization would develop and put in place programs, processes and agreements with objectives as follows:

1. Set a high standard in safety performance and raise the safety and health consciousness of the workers and the host communities.

2. Establish training, working procedures and attitude that would minimize the adverse effects potentially originating with the activities.

3. Establish mutual aid and support plans and agreements with local and regional governments and organizations to minimize the effects of unusual occurrences such as accidents and fires.

The following subsections discuss some of the programs and agreements that would be put in place to achieve the safety and health objectives.

2.4.1 Safety and Health Program

The objectives of a safety and health program would be to minimize any negative health effects of the disposal facility on the workers, to protect the safety, health and property of the public, and to protect the property of the implementing organization. Prior to the start of any work at the proposed disposal site(s), a safety and health program would be prepared and all project staff and contractors would be trained in its application. The program would include the following topics:

1. A statement of safety and health policy that places employee safety and health among its highest priorities, factors them into management and employee activities at all levels, and defines the responsibilities of executives, managers, supervisors and employees.

2. An overview of the work environment and planned activities (e.g., siting activities and work at a disposal facility). The overview would identify hazardous and potentially hazardous activities and areas.

3. References to the current editions of relevant safety and health legislation, the in-house safety and health procedures and manuals, and the locations where these documents and the equipment and services described in them are available.

4. An outline of workers' rights (e.g., right to knowledge about hazardous materials and how to handle them, to participate in safety meetings and joint employee/management safety and health committees and to refuse work that they consider unsafe).

5. A safety incident and accident reporting, investigation and response procedure.

6. A proactive safety and health program as described below.

7. Ongoing health monitoring and regular safety and health reviews and audits.

8. An emergency response plan (Section 2.4.3) describing the actions to be taken following an accident in the order of priority in which they are to be taken.

The implementing organization would participate proactively in the safety and health program, and would encourage the participation of all its employees and all contractors' staff. Contractors would be required to demonstrate good safety records, be members of a Workers Compensation system, submit safety and health plans as part of the tender process, and implement the plans while working on the project.

2.4.1.1 Occupational Safety and Health

An effective occupational safety program is a combination of individual behaviour and well-designed and maintained workplaces and work procedures. The behaviour is established through a strong and visible management commitment, the functional, effective and participatory safety programs, and visible reminders, such as the five-points safety system. This system, used by the Mine Accident Prevention Association of Ontario as an underground safety philosophy, is based on five key practices for accident prevention and workplace control:

1. Check for possible hazards on the way to and from your job site.

2. Ensure the workplace and equipment are in good working order.

3. Ensure workers are following proper job procedures.

4. Do something (extra) to improve the workplace, equipment, attitude.

5. Ensure that work can and will continue properly and efficiently (in accordance with set standards and procedures).

Safety also requires that the workplace be well managed and maintained and that all hazardous and potentially hazardous materials, conditions and operations be corrected, controlled or labelled. Warnings and procedures for control and application of the materials and operations are posted prominently in the workplace to continually remind management, supervisors and workers that hazards do exist and that methods have been developed and demonstrated to minimize or eliminate the associated risk.

Management must take positive actions that provide a high profile for safety by appropriate facility design, safe work practices and procedures, and a safety program to enforce the philosophy that worker and public safety is a key objective of the operation and a good way of doing business.

The safety philosophy and safety programs would be maintained and reinforced as important operational elements and as a necessary element of employee job performance. This would be achieved, or aided by, a continuous program of employee training in safety-related topics, including a review and revision of existing legislation, processes and operating procedures. These activities would be done in a formal way and would involve effective two-way communication.

The disposal facility would have employee groups who have specific skills or require special training. These groups would include security, fire protection, medical or first-aid, ambulance, underground rescue and emergency response personnel. They would have special responsibilities with respect to safety issues, particularly hazardous materials, radiation and radioactive contamination, related to their activities. These groups would have regular training sessions in aspects that relate specifically to their work. They should be members of, and participate in, local and national organizations that are specific to their expertise, such as mine rescue, firefighting or mines accident prevention associations.

As well, a radiation and industrial safety group would be developed as an advisory group to management, supervisors, workers and the safety committees on workplace risks. They would participate in the safety orientations for new staff, regular refresher programs for experienced staff, and they would stage mock incidents for testing emergency response procedures and capabilities. The mock incidents would make use of the actual site facilities for dealing with medical emergencies, accidents causing injury, hostile actions, fire on the surface or underground, and contamination accidents.

2.4.1.2 Protection from Radiological Hazards

The workers at a disposal facility would be classed as atomic radiation workers under the Atomic Energy Control Regulations (AECB 1992). At this time, the annual effective whole-body dose equivalent from ionizing radiation received by an atomic radiation worker must not be greater than 50 mSv. Since the doses from nonroutine operations (such as decommissioning, system repair and refurbishing) may be higher than those from routine operations, the implementing organization would limit the annual effective dose to atomic radiation workers to a design target that is a small percentage of the regulatory limit. As well, the As Low As Reasonably Achievable (ALARA) principle would be a dominant consideration in optimizing the facility design, and its processes and operations. This would ensure a reasonable margin of conservatism in budgeting dose commitment so that the regulatory limit would not be approached.

Currently, the AECB is in the process of revising the radiological dose limits for atomic radiation workers and for the public (AECB 1991a) to address the recommendations of the ICRP (1991). The annual dose limits, as proposed, are 20 mSv for atomic radiation workers and 1 mSv for the general public, to be achieved for all AECB licensed facilities by 1995 January 01. These represent a reduction to 40% and 20% respectively of the current regulatory limits. The design target suggested above would also satisfy the requirements of the proposed regulations. Under the proposed regulatory amendments, the ALARA principle for reducing occupational doses will remain a significant factor in the design and operation of facilities to handle radioactive materials. An example of the application of ALARA principle to the operation of facilities is the experience at Ontario Hydro, where the average annual effective whole-body dose was 1.9 mSv/a in 1991 and 2.6 mSv/a in 1992 (Ontario Hydro 1992, 1993a), well below the regulatory limit of 50 mSv/a.

The external and internal radiation doses to facility personnel would be limited by the design of the facility and processes, and by adherence to a set of approved operating procedures. Exposure to radiation fields might be controlled by one or more of the following: shielding, ventilation, contamination control, access control, occupancy and work control, and plant layout. In addition, protective clothing, breathing-air supply, respirators and decontamination procedures would be used when required.

All staff would wear radiation dosimeters to determine the dose received from external sources of radiation, and participate in a bioassay dosimetry program to determine the dose received from internal contamination. The disposal facility would be designed to minimize the exposure of workers and the environment to radiation fields and contamination. In some situations where the received dose cannot be determined with external dosimeters or bioassay techniques, such as the determination of exposure to radon progeny, the dose would be determined indirectly using the results from personnel air samples or area monitors. Measures such as ventilation dilution would be used to reduce the radon progeny hazard to meet regulatory requirements (AECB 1992).

A formal occupational radiation protection program would be implemented to emphasize radiation safety and to justify the radiation dose targets for all workers consistent with the ALARA principle. The radiation protection program would require the annual assignments of dose constraints, based on ALARA reviews, and a monitoring program to measure the effectiveness of the program in meeting the constraints. The lessons learned would be used to continually improve the program. In addition, an effective radiation protection program would keep abreast with the developments of the principles, practices and standards in the international nuclear community (e.g., the ICRP and the International Atomic Energy Agency) to be aware of progress and to anticipate possible changes in Canadian legislation.

2.4.1.3 Protection from Nonradiological Hazards

The facility designs and the operating procedures would be developed to protect workers from nonradioactive hazards. In the workplace, this would involve containing hazardous materials or limiting their concentrations in the workplace to limit the exposures received by individual workers to an acceptable level for such exposures.

The disposal facility would also be designed and operated to address other potential occupational risks, including the operation and maintenance of heavy equipment, the soot and dust associated with diesel equipment operation, materials and explosives handling and use, and the general characteristics of the underground working environment. The latter issue refers specifically to rock quality, excavation methods, excavation stability and maintenance requirements within the disposal vault. All of these potential risks must be minimized by design and by operating procedures.

With these designs and operating procedures, and with proactive participation from all levels of the organization, including the contractor's employees, effective occupational safety performance can be achieved.

2.4.1.4 Public and Environmental Safety and Health

The radiation protection program would also establish the public and environmental radiation protection targets that would be factors to be considered in establishing the allowable levels of radioactivity emissions including Derived Release Limits (DRLs) for the disposal facilities. As with radiation protection, public and environmental protection from non-radiological hazards would be achieved by establishing allowable levels of nonradioactive emissions from a disposal facility within the bounds of legislation. Once established, the allowable emissions from a facility would provide the basis for choosing target emission levels to be used to design and monitor the performance of emissions control systems.

The exposure of members of the general public to radiation from the operation of the disposal facility would be controlled by a combination of administrative and engineered features incorporated into the disposal facility design. These would include a set of approved operating procedures and regulations. Public exposure to radioactive and hazardous materials and operations would be limited by keeping the public away from the source and by limiting releases of these materials to be environment. All unauthorized persons would be excluded from the disposal facility supervised area and permanent habitation would be prevented within some buffer zone around the surface facilities. The width of this zone would be determined based on an environmental and safety assessment using site-specific atmospheric and surface conditions.

The safety of the public and the environment would be further protected by limiting the levels of radioactive and hazardous material contaminants in all the gaseous and water effluent streams so as not to exceed legislated limits. All effluent streams from the siting work areas and disposal facility would be regularly monitored to confirm performance. Hazardous liquid wastes and solid wastes would be collected and packaged for disposal at facilities approved for those materials. These facilities may be located on or away from the disposal facility site.

2.4.2 Monitoring and Performance Assessment

Two objectives of nuclear fuel waste disposal are to protect humans and the environment and to minimize the burden on future generations for any continuing management of this waste (AECB 1987a, 1987b). Monitoring and performance assessment activities will be essential to ensure that these objectives are met. Four interrelated environments should be considered:

1. The vault - comprises all materials, systems and installations within the boundary defined by the perimeter of the excavated openings. (The monitoring of the vault environment is discussed in this report.)

2. The geosphere - comprises the rock/groundwater system surrounding the vault, but excludes the vault, and has an overlap with the biosphere near the ground surface (Davison et al. 1994a).

3. The biosphere - comprises the portion of the Earth that includes the mixed sediments, surface water, soils and the lower parts of the atmosphere (Davison et al. 1994a, Grondin et al. 1994).

4. The human communities - comprise the social and economic system in the host communities (Grondin et al. 1994, Greber et al. 1994).

The effects of both the transportation and disposal systems would be monitored and assessed.

Monitoring is the continuous or intermittent observation and recording of condition(s). Monitoring data would be used to establish baseline conditions and to determine temporal changes in these conditions. This information can be used to assess the performance of a system within the environment or the effects that a perturbation has on the environment. Monitoring would be focussed on the region of the environment influenced, or potentially influenced, by the disposal facility or transportation system. A monitoring program would have spatial and temporal boundaries that vary for each system or parameter, depending on the physical extent of the system and the magnitude and duration of the effect. An approach to monitoring is presented by Simmons et al. (1994) and monitoring methods are discussed by Davison et al. (1994a), Grondin et al. (1994) and Greber et al. (1994).

A monitoring plan would be developed and implemented early in the siting stage for each site to be evaluated. Conceptual disposal facility designs and performance assessments would be prepared for each site to identify the limiting criteria within which transportation of waste to the site and disposal of waste on the site could be done with an acceptable margin of safety. The plan would explicitly state the conditions and parameters that would be measured to provide relevant data for comparison with the limiting criteria.

The plan would provide the following information for each condition or parameter to be monitored:

1. The physical location where the measurements will be taken or where data will be collected.

2. The expected range of values of the parameter or condition, and the applicable limiting criterion.

3. The method, equipment, instrumentation or test to be used to take the measurement or gather the data.

4. The frequency and overall duration of measurement.

5. The method(s) for analyzing the data.

6. The action to be taken if the parameter or condition reaches or exceeds the limiting criterion (i.e., mitigation).

As well, the monitoring plan would identify the agencies that would be responsible for collecting and analyzing the data. The plan would describe the form and frequency of reporting the results, and would define the role of governments, technical experts and the public in developing the plan and in reviewing the results. The plan would be reassessed and updated periodically, consistent with the needs and findings of each project stage, and regulatory changes and public concerns.

In the design of systems and components that are within the control of the disposal facility, design limits would be established to allow for the known natural variability and uncertainty in the understanding of the materials and systems. The design limits would be established below the limiting criteria to provide an expected operating range for each condition or parameter below the limiting criterion. If a monitored condition or parameter were to exceed a specified design limit, the significance of this would be assessed and an appropriate course of action would be determined.

Performance assessment is the evaluation of the functioning of a disposal system or system component in terms of one or more standards and criteria. For a disposal facility or transportation system, performance assessment would involve the analyses of data collected from the monitoring of activities and systems and the conversion of these data into a form that can be compared with baseline conditions, derived and regulatory criteria, standards, and assumptions made during the system design process. These comparisons would provide a measure of any environmental changes that may occur over time and would assist in determining their cause. They would also provide a measure of the actual and projected performance of various disposal facility systems and components against specifications and limits, and an assessment of the effects on the environments relative to those allowed by the permits and licences issued for the facility.

In the siting, construction, operation, and decommissioning stages these assessments would be used to refine designs for systems and components and to predict effects for permit and licence applications. The assessments would be done frequently during the siting stage when only limited information is available on the site conditions and system performance. In subsequent stages, as additional data are gathered, assessments would be done, although less frequently, to assess the quality of early data and to identify where design refinements and system modifications may be necessary to achieve specific or overall performance goals.

The implementing organization would review the monitoring and assessment results as they become available to identify any negative effects of the facility on the environment and to take appropriate action to minimize them. They would also use the results to identify potential causes and initiate actions to correct the design and/or operation of relevant components of the disposal system.

The disposal vault environment would be monitored during the period in which underground access is possible. Starting with the underground evaluation, the parameters and conditions relevant to the design and performance of the engineered barriers associated with the disposal of waste would be monitored. Information on the boundary conditions around the vault would be derived from data collected in the geosphere monitoring program. As discussed for a specific Used-Fuel Disposal Centre in Section 3.2.2.2, component testing would be developed as part of a monitoring plan for a disposal vault to assess the performance of those components of the disposal system that cannot be tested/monitored effectively in completed disposal rooms without compromising the integrity of the room seals. In the event that monitoring detects an anomalous condition requiring the retrieval of waste containers, the method of retrieval is presented in Section 5.4.7.

For the geosphere environment, baseline data would establish the physical and chemical characteristics of the rock and groundwater systems that could affect, or be affected by, the disposal facility. These data would be gathered both in boreholes drilled from the surface and from the subsurface after excavation of underground openings had begun. Additional equipment, instruments and tests would be applied to gather information on temporal changes in relevant parameters and conditions during the underground evaluation and the subsequent construction, operation and decommissioning of a disposal vault. The geotechnical perturbations caused by the surface-based and underground site evaluation activities, and the construction, operation and decommissioning of the disposal vault would be monitored and used to assess the validity of the assumptions made in the design of the disposal system and in preparing and validating the performance models for the site.

In the biosphere environment, relevant physical, chemical and biological characteristics of the air, surface water, groundwaters, soil and sediments, and characteristics of species of aquatic and terrestrial biota would be sampled and analyzed. Such data would first be collected during site evaluation to define baseline conditions. The continuation of biosphere monitoring throughout the later stages of the project would provide data on any changes that occur relative to the baseline conditions, indicate the likely causes of the changes, and may help to derive appropriate mitigation measures, if needed.

An important element of the biosphere monitoring plan would be the monitoring of human health. The development and maintenance of a program to monitor the baseline and long-term health of workers at the disposal facility and in the transportation system would be a priority. Although there are many uncontrollable factors that affect the interpretation of the results of worker health monitoring, such as population mobility, life-style and diet, worker health data would be available for public and regulatory review. Public health monitoring could be undertaken, if deemed appropriate, although it is unlikely to be an effective indicator of the disposal system performance because of the following factors:

1. The voluntary nature of public health monitoring and the mobility of the general population may preclude the gathering of data from a representative sample of the host communities.

2. Numerous other health and lifestyle factors must be quantified and, if possible, screened from the data to isolate the effect of the disposal systems.

3. The anticipated lack of sensitivity and timeliness of human health effects would preclude a measurable response indicative of disposal or transportation system performance.

However, public health monitoring may serve to reassure the host communities.

Biosphere monitoring could continue after the closure of the disposal facility if the regulators or the public so desire.

The social and economic effects of the disposal system would be monitored in the communities hosting the disposal facility. The monitoring data would provide quantitative information that could be used to assess the extent of the effect on each community. They could also be used to reach agreement on mitigation and compensation actions for any unacceptable effects of the project on a community. This is discussed further by Grondin et al. (1994) and by Greber et al. (1994).

2.4.3 Emergency Response Plan

An Emergency Response Plan would be established for both the radiological and nonradiological emergencies that may arise during all activities of disposal system siting, construction, operation, decommissioning and closure.

"Although the primary emphasis should be on prevention rather than on reactive or emergency response measures, the very nature of human activity dictates that emergencies [both natural and man-caused] can and will occur. Through appropriate preparation or emergency planning the risk, loss and damage resulting from such emergencies can be minimized" (CSA 1991). "An appropriate emergency plan will:

(a) ensure the safety of workers, responders, and the public,

(b) reduce the potential for the destruction of property or for losses of products,

(c) reduce the magnitude of environmental and other effects,

(d) assist response personnel to determine and perform proper remedial actions quickly,

(e) reduce recovery times and costs, and

(f) inspire confidence in response personnel, industry and the public" (CSA 1991).

This plan would outline the emergency planning, preparations and implementation. The planning and management strategies would deal with issues such as cost and risk assessment, protective measures against radiation exposures and radioactive and nonradioactive contaminant exposures, public education, effective planning and preparation, possible accidents and degrees of severity, off-site emergency operations, and provision of information to the public and the media. The plan would be developed with the surrounding municipalities and provincial and federal emergency response infrastructures and authorities to outline the principles, concepts, organization, responsibility, interrelationship and functions in dealing with likely emergencies within the disposal system (i.e., transportation and disposal).

Labour, occupational and public safety and health, environmental, dangerous goods handling and transportation, and emergency planning requirements under federal and provincial legislation outlined in Appendix D of the Environmental Impact Statement (AECL 1994a) have specific provisions for dealing with emergencies. The type and severity of emergencies can cover a wide range, including worker injury in a normal work environment, nuclear fuel waste transportation accidents, explosives or toxic material transportation accidents, forest fires surrounding or fires within the disposal facilities, loss of airborne or waterborne emissions control devices, and loss of radioactive materials containment structure regardless of cause (e.g., human error or sabotage, equipment failures, natural events). In each case there is a risk to the health of the workers, the general public, or the natural environment.

The implementing organization would ensure that the siting, construction and operation, decommissioning and closure are done in a manner that would minimize the potential for and effects from accidents. The implementing organization must also comply with the requirements of applicable emergency response legislation (e.g., Emergency Plans Act - Government of Ontario 1990b). For example, the Province of Ontario Nuclear Emergency Plan - Part I (Government of Ontario 1986) specifies the following responsibilities for the owner of the facility:

1. Infrastructure - provide dedicated communication links, radiological monitoring, on-site meteorological measurements, and emission assessment.

2. Study and Research - the off-site effects of nuclear emergencies and the techniques, procedures and measures required to deal with them.

3. Planning and Preparation - of an internal organization and procedures to meet the regulatory requirements, to assist the province and municipalities in their planning and preparation, to maintain their technical and operating procedures for dealing with emergencies, and to implement a public education program for the surrounding communities.

4. Provision of Personnel - recommend suitable staff for the province's emergency management organization, to serve on specific groups and committees, to carry out specific functions and responsibilities defined by the plan, to provide primarily host municipalities with technical liaison officers, and to provide a radiation monitoring service.

5. Operations - notify and assist the province and municipalities, to restore the situation to normal, to recommend and assist in appropriate protective measures, to conduct on- and off-site field monitoring, and to provide information and data.

6. Training - of implementing organization's staff required for emergency response, to participate in nuclear emergency exercises, and to assist the province in the planning and conduct of these exercises.

A comprehensive emergency response plan would be developed to cover coordinated responses for the disposal facility and other groups to incidents that represent a radioactive or hazardous material risk, a health and asset risk such as a fire on or off the disposal site, or an underground construction accident. If this plan is properly developed it should satisfy the requirements of applicable legislation and guidelines, it would increase the confidence of the local communities in the management and staff of the disposal facility, and it would contribute to the maintenance of a safe environment for workers and the public.

2.5 PLANNING FOR IMPLEMENTATION OF NUCLEAR FUEL WASTE DISPOSAL

The siting, construction, operation, decommissioning and closure of a disposal facility would be a complex and large-scale engineering project extending over many decades. The project would progress by discrete stages, each stage having a specific objective. Many concurrent and overlapping activities would be associated with these stages to support and assist the validation and confirmation of the site-specific geotechnical conditions, the designs and the performance models. One possible set of stages and activities is illustrated in Figure 2-2.

The project stages would be sequential and would incorporate the activities necessary to implement nuclear fuel waste disposal. Although the requirements for permits and licences have not been specified at this time, it is anticipated that the requirements may coincide with the completion of the stages of the project as discussed in Section 2.2.2. The time necessary to obtain these licences and permits depends on the regulatory approvals processes that would be applied to this type of project. The project sequence shown in Figure 2-2 assumes that these approvals processes would be concurrent with the project stages and would not create any delays.

2.5.1 Project Stages

The objective of the first stage, the Siting Stage, would be to obtain permission to commence the construction of a specifically designed disposal facility at a specific site on the Canadian Shield. The siting stage would initially involve site screening and site evaluation.

No decisions have yet been made about the type of siting process that will be applied to select a site to dispose of Canada's nuclear fuel waste. The siting process would likely be developed at the beginning of the implementation of the project in consultation with the public, governments, and regulators. The objective would be to develop an agreed set of principles and procedures for effective and equitable siting of a disposal facility, and to use these to guide the site screening and site evaluation activities (Greber et al. 1994).

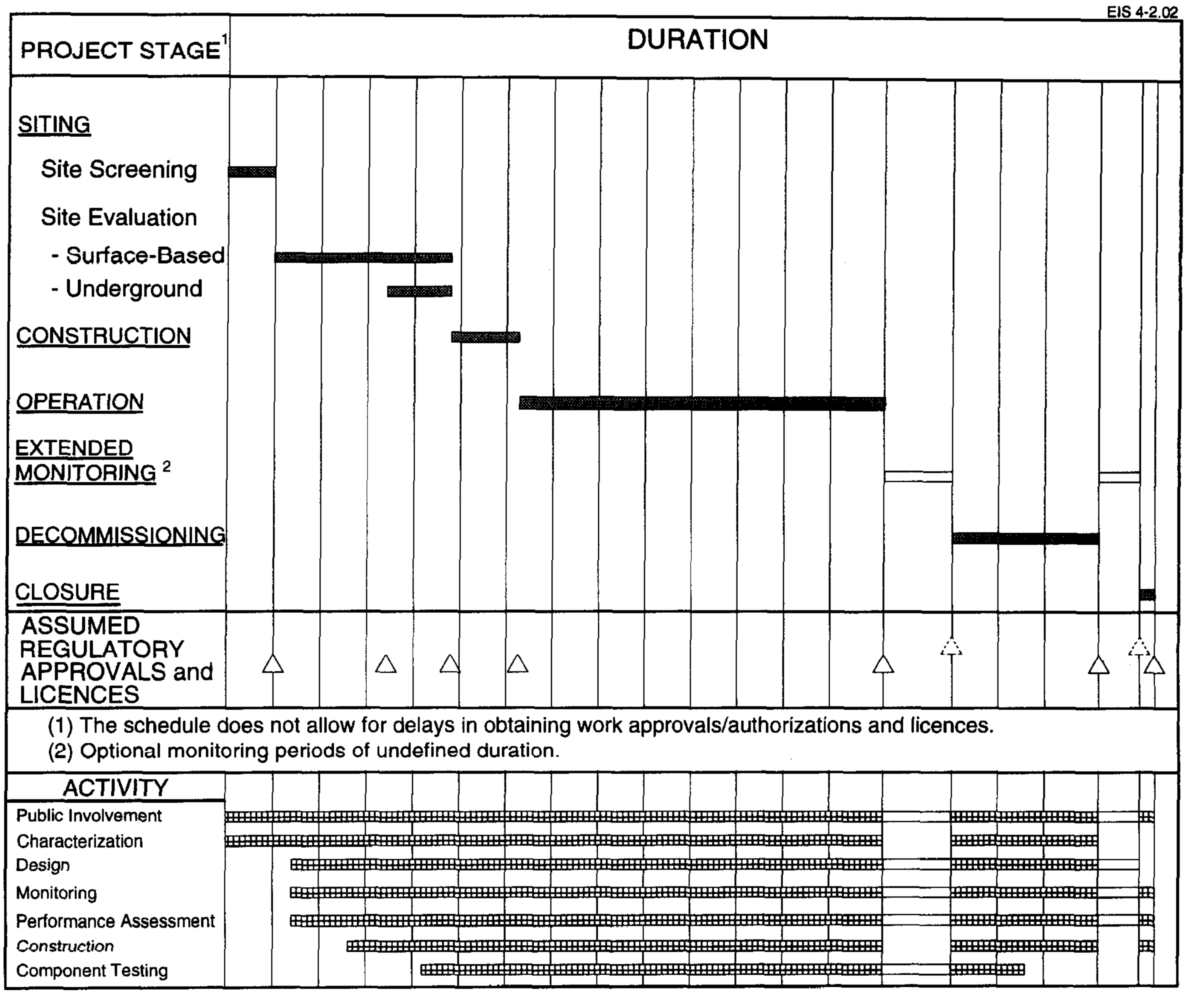

FIGURE 2-2: Schedule for Concept Implementation

The objective of the site screening would be to identify a small number of areas that have the characteristics desired for a disposal site, and warrant detailed investigation, within siting regions on the Canadian Shield (Davison et al. 1994a). The activities would include analyzing existing regional-scale data, performing some reconnaissance surveys to gather additional data, developing and applying criteria for accepting or rejecting locations and ranking them for further investigation. The selection of the siting regions to be screened could involve a great deal of government and public input.

Preliminary conceptual design work on surface and underground facilities would likely begin during site screening, primarily to establish the access, utility and infrastructure requirements. These requirements would be considered during site screening to ensure that they could be met at potentially suitable site locations in the areas selected for detailed evaluation. Details of the environmental and vault monitoring program would also be developed, and the plan to incorporate this program into subsequent site evaluation activities would be prepared during site screening.

Site evaluation follows from site screening. The objective of site evaluation would be to identify a preferred location for a disposal site and to obtain approval to construct a disposal facility at that site (Davison et al. 1994a). The activities would include thorough site characterization, disposal facility design, and performance assessment. Work would first begin at a relatively larger regional scale to identify preferred disposal locations in the broader context of the geological setting, and then in more detail in the area surrounding the location of the preferred site(s). Site characterization would involve airborne and surface investigations and borehole studies first of the regional areas, then at those smaller areas where potentially suitable sites might exist. Finally, site evaluation would involve thorough underground characterization activities in exploration shaft(s) and tunnel(s) at the preferred sites(s).

The Construction Stage would involve constructing the permanent facilities needed to begin disposing of nuclear fuel waste: transportation facilities and equipment, access routes, utilities, surface facilities, shafts, tunnels, underground facilities, and some of the disposal rooms. It also would involve establishing and applying the administration and control systems required to operate the disposal facility safely. All systems and facilities would undergo testing in preparation for full operation in accordance with regulatory requirements.

While all the surface facilities, surface infrastructure, shafts and underground infrastructure would be constructed and commissioned, the extent to which the disposal vault rooms would be excavated, serviced and commissioned during this stage would depend on the design capacity of the vault and the method proposed for its operation. Disposal vault designs for small volumes of waste might require that all disposal rooms be constructed during this stage where it is economical to do so. In other cases, for reasons of economics or because of the time required to construct all the necessary disposal rooms, enough rooms may be constructed to begin operations, and the remaining rooms would be constructed during the operations stage, concurrent with disposal operations.

During the period of underground construction and servicing, detailed site characterization information would continue to be collected from observations of the natural environment surrounding the excavation and from tests conducted to monitor the responses to excavation. These data would be used to refine the construction designs, to determine whether the design must be revised to account for any changes in conditions, and to conduct additional performance assessments of the disposal system and its components.

The Operation Stage would involve transporting nuclear fuel waste to the disposal facility in transport packages or sealed in disposal containers, putting the waste into and sealing corrosion-resistant disposal containers, if necessary, and emplacing the containers and sealing materials in the disposal vault. At the same time, if necessary, excavation of more disposal rooms would continue.

Characterization and testing activities would continue during the excavation of additional disposal rooms to gather data with which to select the design alternative that best suited the local conditions. In addition, these data would be used if changes in technology required changes in the design methods and processes. Any design revisions, if required, would likely be minor compared with those implemented earlier in the project life cycle.

The Extended Monitoring Stage would involve a continuation of the monitoring of conditions in the vault, geosphere, and biosphere between the operation and decommissioning stages and/or between the decommissioning and closure stages. Such monitoring would be performed if the regulators and/or the public required additional data on the performance of the partially sealed and/or sealed disposal vault.

Extended monitoring between the operation and decommissioning stages would provide additional data on the performance of the disposal vault with the disposal rooms backfilled and sealed and the access tunnels and shafts open. Extended monitoring between the decommissioning and closure stages would provide additional data on the performance of the sealed disposal vault. In the extended monitoring stage, the installed instrumentation and monitoring systems might compromise the long-term safety of the vault if the installations are not adequately maintained and eventually removed and sealed. Extended monitoring at either time would delay the following stages until sufficient information was collected.

The Decommissioning Stage would involve the decontamination, dismantling and removal of the surface and subsurface facilities, and the sealing of the tunnels, service areas, and shafts and the exploration and monitoring boreholes drilled from them. The site would be returned to a state suitable for public use and permanent markers would be installed. Access to any measurement instruments retained for extended monitoring would be strictly controlled.

The Closure Stage would involve the removal of measurement instruments from any boreholes that could compromise the safety of the disposal vault and the sealing of those boreholes. If there were no extended monitoring after decommissioning, this stage would be combined with decommissioning. During the closure stage, the objective would be to return the site to a state such that safety would not depend on institutional controls. Thereafter, although institutional control of the site would not be required for safety, control might be required for any continuing international safeguards measures or for any desired postclosure monitoring. Authorities at the time might choose to register land-use restrictions in records and on maps.

2.5.2 Project Activities

The following project activities have been defined to assist in the organization of the project. Unlike project stages that occupy discrete periods of time and do not overlap, project activities can occur concurrently and generally can continue through more than one project stage. The detailed specifications of any activity would vary with the surface and subsurface characteristics of the site, with the details of the designs of the various facilities and with appropriate legislation. The general objectives of the various activities are discussed below. The relationship between the stages and activities is shown in Figure 2-2.

The Public Involvement activity would involve providing information to the public, particularly those communities hosting the disposal facility and transportation system, and then obtaining input from them throughout all stages of nuclear fuel waste disposal. This input would be a major factor in initiating the siting process, establishing the criteria for siting, assessing socio-economic effects, deciding how these effects should be dealt with, and identifying and resolving public issues and concerns. As well, public input would be considered in planning and conducting other activities, such as characterization, design, monitoring and performance assessment.

The Characterization activity would involve the surface and subsurface investigation of regions, areas and sites to determine the conditions in the geosphere, biosphere and human communities. The data obtained would be used for site selection, facility design and performance assessment. Many of the measurement instruments installed for characterization would also be used for ongoing monitoring. Characterization would be a major activity during the siting stage, and would continue at the selected site during the construction, operation, decommissioning and any extended-monitoring stages.

The Design activity would involve the development of designs for the surface facilities and transportation system, and the development of vault designs of increasing detail for each of the sites under investigation throughout the preclosure phase, on the basis of data collected from characterization, monitoring, performance assessment, construction experience, regulatory requirements and public input. Information on specific site geology, hydrogeology and hydrogeochemistry would be used to recommend container geometry, container material and sealing system requirements and alternatives, as well as vault location and layout. Environmental assessments conducted at each of the sites would help develop any constraints on the design needed to provide acceptable performance for the disposal system.

The Monitoring activity would consist of the continuous or intermittent measurement of conditions in the region influenced, or potentially influenced, by the presence of the disposal facility and associated transportation system. Monitoring would be done to determine the baseline conditions and to identify any changes from the baseline conditions. Parameters indicating conditions in the vault, geosphere, biosphere, and human communities would be measured. Monitoring would be initiated early in the siting stage and would be continued until closure. It could also be continued after closure if required by regulators and/or the public.

The Component Testing activity would consist of the conducting and analyzing of tests to measure the performance of elements of the disposal facility and the associated transportation system. These tests would be initiated during the underground site evaluation substage and could continue through the construction and operation stages. For example, the performance of the container, the sealing materials, and the rock surrounding the excavations could be studied in underground test areas. Prior to the operation stage, heaters could be used to simulate the heat that would be produced by nuclear fuel waste.

The Performance Assessment activity would consist of the evaluation of the functioning of a disposal system or system component in terms of one or more standards and criteria. This would involve evaluating the current and future behaviour of the disposal system or a subsystem on the basis of data obtained by site characterization, monitoring and component testing, improved knowledge and understanding, and the standards and criteria in use at that time.

Performance assessment is equivalent to a safety assessment when the future effects on humans and non-human biota are evaluated in terms of safety standards. For a safety assessment, the system of interest depends on the disposal phase being assessed - for the preclosure phase, it is the disposal facility and associated transportation system; for the postclosure phase, it is the closed disposal vault.

Construction, as an activity, would consist of the development, fabrication and assembly of surface and underground installations for the disposal facility and associated transportation system. Construction activities would begin during the siting stage with the development of a support infrastructure for surface and underground evaluation. It would continue in the construction stage with construction of the disposal facilities and site installations, and in the operation stage with development and sealing of the disposal rooms. It would continue with disassembly of the facilities and sealing of tunnels, shafts and boreholes during the decommissioning and closure stages.

The methods that have been developed, or are proposed, in the Nuclear Fuel Waste Management Program for performing these activities are discussed by Davison et al. (1994a), Grondin et al. (1994), Goodwin et al. (1994) and later in this report.

2.6 DESIGN ISSUES AND FACTORS

In the process of defining the disposal facility project, there would be characteristics and requirements of the disposal system that would be fixed because they would be controlled by prior activities or because they were required by the legislation and the codes and standards in force in the jurisdictions hosting the project. Some of these could include the security and nuclear material safeguards requirements, acceptable environmental effects, transportation system requirements, and material properties and characteristics.

There would also be many characteristics and requirements that are flexible and would be either fixed as part of the project definition for design purposes or would remain flexible as long as possible in the design process. Some items that would be fixed early in the project as a basis for design might include the materials to be used for container, buffer and backfill, the characteristics of the waste, and the quantity of waste and rate of its movement in the disposal system. Fixing these early would provide a basis for the initial disposal system design but would not preclude later changes in the siting, construction or operation stages of the project. However, any significant changes might require redesign and modification of the disposal system if they occur after the construction stage begins, and might require changes in future waste emplacement operations if the need for change is identified after the operation stage begins. These changes could be applied also to waste already emplaced if there was a need.

Other characteristics, such as the depth of the disposal vault, would remain flexible until well into the siting stage because they are dependent on specific conditions at each particular site under consideration. The design process proposed in this report can accommodate changes in characteristics and requirements in a very flexible manner with the recognition that all significant changes would have a cost effect that may be a secondary consideration but would have to be assessed.

Some specific design issues and their relevance in the design process are discussed in the following sections. Approaches that may be taken to deal with the issues are presented in these discussions. This section presents design issues that are not totally dependent on the site characteristics. The design issues relevant to a site are discussed in Section 2.7.

2.6.1 Waste-Form Characteristics and Quantities

The characteristics and quantities of the nuclear fuel waste would influence many aspects of disposal facility design.

2.6.1.1 Waste-Form Geometry and Composition

The geometry and composition of the nuclear fuel waste would influence the geometry and design of the transportation casks, handling facilities and the disposal container. The nuclear fuel waste defined in the Nuclear Fuel Waste Management Program is either used CANDU reactor fuel or fuel reprocessing waste derived from the reprocessing of used CANDU reactor fuel (Johnson et al. 1994a). The CANDU reactor uses natural uranium oxide (UO_2) fuel in the form of stacks of ceramic pellets contained within Zircaloy-4 cladding. The fuel elements (either 37, 28 or 19 elements, depending on the design) are assembled into bundles as shown in Figure 2-3, each bundle containing approximately 20 kg of UO_2 and 2 kg of Zircaloy-4. Approximately 60% of the bundles in storage are of the 37-element design, with most of the remainder being of the 28-element design. The small dimensional and weight differences of the various designs have no significant effect on container design and dimensions or radionuclide content per unit mass of fuel (Johnson et al. 1994a). As reprocessing is not currently considered to be an economically viable alternative for Canada, it will not be the primary focus of the discussion in this report. However, the design for the disposal of fuel reprocessing waste would be similar to that for used fuel, with corrections for waste composition and geometry differences.

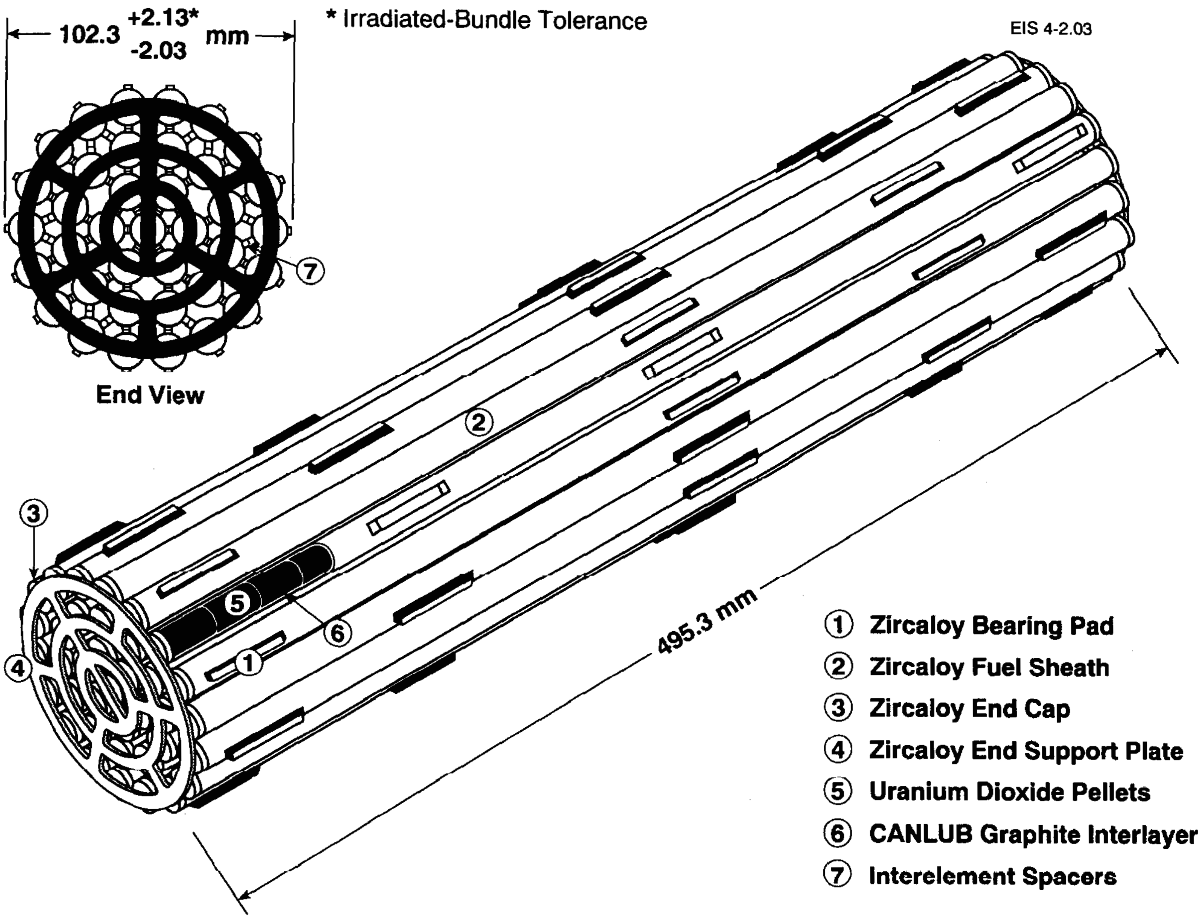

FIGURE 2-3: Typical CANDU Fuel Bundle for Bruce Nuclear Generating Station (after AECL CANDU et al. 1992)

2.6.1.2 Waste-Form Irradiation History

The irradiation history of a used-fuel bundle in a reactor would establish the composition of the used fuel when it is discharged. The irradiation history is generally expressed as the burnup or thermal energy produced in a reactor per unit mass of elemental uranium in the fuel (e.g., GJ/kg U). Based on this composition, the heat output and radiation emitted from the used fuel is calculated. The heat and radiation will decrease with time after discharge from a reactor, or cooling time, at a rate that depends on the isotopic composition of the used fuel. Therefore, the cooling time is a major factor in designing the shielding and the thermal aspects of storage areas, handling facilities, and the disposal vault. For example, a CANDU fuel bundle irradiated to 685 GJ/kg U and stored for 10 a after discharge from a reactor produces about 4 W of heat and provides an absorbed dose rate of about 35 Gy/h at a distance of 50 mm.

2.6.1.3 Waste-Form Quantity

The total quantity of nuclear fuel waste destined for disposal and the rate at which it could be shipped from storage locations, currently the nuclear generating stations, would be important design factors. The total quantity of waste would be one factor in determining the size of the disposal vault. The maximum rate at which waste could be shipped to a disposal facility from all sources would establish the maximum annual rate at which waste would arrive at a disposal facility and, therefore, the rate at which it must be handled, packaged and disposed of in order to maintain a continuous operation.

2.6.1.4 Waste-Form Packaging

The nuclear fuel waste would arrive at a disposal facility in some form of package. The nuclear fuel waste might be placed in the disposal container, one of the engineered barriers in the disposal concept, before or after shipment to the disposal facility. If the waste is placed in the disposal container before it arrives at the disposal facility, the design of the disposal facility would include provision for acceptance testing and repair, but would not provide for production-scale waste packaging. If the waste is shipped either partially packaged or with no preparation for disposal, the disposal facility design would have provision for production-scale packaging and inspection.

2.6.2 Nuclear Material Safeguards and Physical Security

As noted in Section 2.4.1.3, the AECB establishes the requirements for nuclear materials safeguards and physical security at licensed nuclear facilities. These requirements would influence the design and operation of the disposal facilities.

2.6.2.1 Nuclear Materials Safeguards

Nuclear material requiring safeguards is defined by the IAEA as any source material or special fissionable material (IAEA 1987). Source material is defined as uranium containing the mixture of isotopes occurring in nature, uranium depleted in the isotope 235, thorium, any of the foregoing in the form of metal, alloy, chemical compound, or concentrate, any other material containing one or more of the foregoing in such concentration as the Board of Governors shall from time to time determine, and such other material as the Board of Governors shall from time to time determine. The term source material is interpreted as not applying to ore or ore residue, in particular to yellow cake, a concentrate consisting essentially of U_3O_8. Special fissionable material is defined as plutonium-239, uranium-233, uranium enriched in the isotopes 235 or 233, any material containing one or more of the foregoing, and such other fissionable material as the Board of Governors shall from time to time determine.

Thus, used CANDU fuel contains nuclear material, and fuel reprocessing waste may or may not contain nuclear material depending on its final composition.

Although the IAEA has not established the requirements for safeguards of nuclear fuel waste disposal facilities, it has begun to consider the specific needs. In 1988, an advisory group (IAEA 1988) concluded in their report that solidified high-level radioactive waste from reprocessing used fuel could be released from safeguards when declared a waste for disposal, and that used fuel should not be released from safeguards requirements. In 1991, a consultants group (IAEA 1991) met to discuss the application of safeguards to used-fuel disposal facilities and to make recommendations for further research and development.

Despite the lack of specific IAEA requirements, the major elements required for safeguarding nuclear materials at a disposal facility could be based on current safeguards practices at nuclear facilities. These include the following elements that have been demonstrated as effective in safeguards applications at Canadian nuclear utilities:

1. Information about the purpose, location, design, and operation of the facility. This information would be assembled by the facility operator and agreed with the AECB who would transmit it to the IAEA through the Department of External Affairs. The IAEA would determine how to apply effective safeguards at that facility, and would request changes in the design and operation of the facility that they would consider necessary for the effective application of safeguards. The IAEA has the right to inspect the facility to ensure that it is constructed as shown in the design plans. The IAEA must examine any changes in the design and operation of the facility and has the right to verify them by inspection.

2. Safeguards Records System. The facility operator would set up a records control system, acceptable to the IAEA, that would include records accounting for the nuclear material at the facility, and operating records for the facility. By examining these records, the IAEA would be made aware of the quantity of nuclear material at the facility, in each designated area of the facility, and how the nuclear material was being stored and processed.

3. Safeguards Reports System. The facility operator would submit periodic and special reports to the AECB, as agreed between the Government of Canada and the IAEA, describing changes in inventory within each designated area of the facility, or providing details about unusual incidents affecting nuclear materials.

4. Inspection. The IAEA could send its inspectors to the facility to, among other things, verify information supplied in reports (i.e., submitted by the operator), verify the location, quantity and composition of nuclear material at the facility, investigate any indicated losses of nuclear material, if any are suspected, and investigate unexpected changes in the way nuclear material is contained. These inspections would provide the IAEA with the means to physically verify stocks, and changes of stock at the facility, and thereby detect possible diversion of nuclear material from its use for peaceful purposes.

The extent of IAEA inspector presence at a disposal facility would depend on the facility design, the capabilities of available safeguards containment/surveillance measures and equipment, and the preferences of the IAEA. The IAEA inspectors would have right of access to all areas of the disposal facility, with due consideration to personnel and process safety.

A disposal vault would represent a unique inspection and verification challenge because the nuclear material contained in used fuel would be sealed within the clay-based sealing materials and could not be readily inspected to verify its identity or quantity. The continuity of safeguards would depend on the ability of containment/surveillance systems to detect activities that could lead to diversion of the nuclear material. In this report, we indicate where the opportunities for applying safeguard measures can be provided in the Used-Fuel Disposal Centre during operation (Chapter 5), and during decommissioning and closure (Chapter 6).

2.6.2.2 Physical Security

As a condition of licensing disposal facilities that would contain nuclear materials, the AECB requires that the nuclear facilities include the installations, systems and personnel to protect persons and property, and to protect the nuclear materials from theft and sabotage (Government of Canada 1983).

The security systems proposed for a disposal facility would be determined as part of the licensing of the facility and might include the following requirements:

1. Provision of a security guard service.
2. Detection of unauthorized entry using a perimeter fence and alarm system.
3. Restriction of entry to authorized persons by controlled access at recognized entry points.
4. Identification of authorized persons by an identity badge system.
5. Security-related review of authorized persons, and continuing supervisory review.
6. Arrangements for response and support by civil police forces.

The physical security measures for the disposal facility should be similar to the measures that the AECB now requires at facilities that process and store used fuel with similar radiation emission levels (e.g., nuclear generating stations and the used fuel stored in concrete canisters). These measures would apply to the areas of a disposal facility containing nuclear fuel waste.

2.6.3 Occupational Safety and Health

A major factor in the design of a disposal facility would be workplace safety. As discussed in Section 2.4.2.1, the implementing organization would establish and encourage a safety and health program at the facility. The effectiveness of such a program could be enhanced by careful design of the installations and systems that would comprise the workplace. These installations and systems should reduce to a reasonable minimum the exposure of workers to hazardous materials, radioactive materials, and dangerous work environments.

This section presents some of the approaches that should be considered during the design of the facilities and processes to reduce the exposure of workers to radioactive and hazardous material, and to hazards in the workplace consistent with the ALARA principle.

2.6.3.1 Protection from Sources of Radiation

The common external radiation sources within a nuclear fuel waste disposal facility would be the nuclear fuel waste, and any wastes from operations that would be used to concentrate radioactive contamination, such as filter elements and ion-exchange resins. These sources would contain sufficient radionuclides to emit radiation that would require shielding to protect the workers. The quantity of operational wastes would be minimized through careful design and operation.

People, other living organisms and sensitive equipment must be protected from radiation through the use of shielding placed between the source and the subject to attenuate the radiation to acceptable levels. The requirement for shielding and the thickness and type of shielding for any application would depend on the type and energy of the radiation emitted by the source. The main types of external radiation sources that require shielding are beta, neutron and gamma emissions. Although all materials provide some shielding to radiation, some are preferred because they are better suited for different applications. The preferred shielding materials (e.g., polyethylene, paraffin wax, oil) to attenuate neutron radiation would contain a large proportion of light atoms. The preferred shielding materials (e.g., lead, depleted uranium, steel, concrete, soils, rock) to attenuate gamma radiation would contain a large proportion of heavy atoms. Shielding designs for gamma and neutron radiation would be more than adequate to provide protection from lower energy beta emissions.

The shielding design selected for any particular application would depend on the nature of the operations. The shielding may be fixed in place in the form of building structures or rock surrounding the disposal vault excavations and sealing materials. In this case, the material emitting the radiation would be handled, processed or placed within the structure using remote and robotic equipment. The shielding structure would attenuate the radiation emitted by the source(s) to a level that is a small percentage of that corresponding to the regulatory limits on worker exposure.

Alternately, portable shielding would be used if the objective is to move the source of radiation from one shielded facility to another. This portable shielding could be part of a package containing the radiation source and remain with it through all handling steps including its permanent disposal. Or it could be reusable, that is, it might contain the radiation source through one particular handling activity, then be returned empty to repeat the activity with another radiation source. For example, the used fuel would be contained in a specially designed transportation cask that would attenuate the radiation emitted by the fuel during its transportation from a nuclear generating station to a disposal facility. The used fuel would be removed from the cask at the disposal facility, and the empty cask would be returned to the nuclear generating station for reuse.

Each activity involving radiation sources that requires shielding would be considered both individually and within the context of the entire operation to select the appropriate type of shielding (i.e., fixed or portable), the shielding materials and the particular design that provides the required occupational safety in the most cost-effective manner.

2.6.3.2 Protection from Radioactive Contamination

The nuclear fuel waste would be the major source of radioactive contamination at a disposal facility. The rock surrounding the disposal-vault excavations may contain naturally occurring radioactive isotopes, which could be an additional source of contamination. The nuclear fuel waste would be packaged at a nuclear generating station or at a reprocessing waste vitrification plant for shipment to the disposal facility. Used fuel might carry contamination with it in the form of residues from the reactor primary heat transport system and storage pools, and material released from fuel elements with cladding failures. Fuel reprocessing waste would be sealed in the robust canister used in its solidification and would likely bring little contamination to the disposal facility.

The rock surrounding the underground excavations might contain natural uranium and thorium isotopes, which yield radon when they decay. Radon is a radioactive gas that might migrate into the excavations. When it decays, radon yields daughter products that are in the form of particulate contamination. The exposure of workers to radon in underground excavations would be minimized by designing the ventilation system(s) to move enough air through the excavations to dilute the radon to an acceptable concentration.

Radioactive contamination would be controlled by containment, ventilation, zoning of work areas, access restrictions, the control of movement of both persons and material, and the routine monitoring for contamination. Contamination found in "clean" zones would be removed immediately.

The containment of contamination by a structure would involve sealing the contamination in a controlled work area or a container. All operations required within the contaminated area would be done using remote handling equipment, or by workers in protective clothing to prevent their contact with the contamination (provided the radiation fields are sufficiently low).

Airborne and waterborne radioactive contamination might become hazardous to workers or the environment (see Section 2.6.3.3 to 2.6.3.7 below) and the contamination would need to be removed. The contaminated air or water would be passed through a process, such as filtration or ion exchange, that would remove a large portion of the contamination either suspended or dissolved in the stream. The contaminants would be trapped in a filter media or a resin material, or would be concentrated in a much smaller volume of air or water. These contaminated materials would be collected and treated to fix the contaminants in a solid form, which would be handled as a waste.

The spread of radioactive contamination would also be controlled through ventilation system design. The entire disposal facility or groups of work areas, such as buildings, would be divided into zones where the expected concentration of radioactive contaminants in each zone would be similar. Three or four contamination zones are common in nuclear facilities today.

The ventilation system would be designed to provide the lowest building air pressure in the zone with the highest potential radioactive contamination, a slightly higher air pressure in the zone with the next highest contamination potential, etc. The zone with the lowest potential for contamination would have the highest air pressure in the facility or building, and this would be slightly less than the outside air pressure. Access between the contamination control zones would be limited and blocked with doors. The air pressures would be such that air would move from a zone of lower potential contamination to a zone of higher potential contamination. The negative pressures in the zones would be maintained with an exhaust system to filter the air through high-efficiency particulate air (HEPA) filters before releasing it to the environment.

Contamination monitoring equipment that would detect radioactive contamination being carried on workers or equipment would be provided at the access doors that separate contamination zones. The contamination would then be removed (or possibly fixed in place on equipment) before the workers or equipment move to zones with less potential for contamination. The doors may also be locked to control worker access to zones where the expected level of radioactive contamination, the intensity of radiation fields or some other factor would represent an unacceptable risk to workers.

Housekeeping is a very important element of contamination control. Except for the most highly contaminated areas, where workers would not normally be allowed because of the high radiation fields and/or high contamination levels, work areas would be routinely monitored for radioactive contamination and any contamination found would be cleaned up.

An approach to contamination control would be established very early in the design of a disposal facility, and it would influence many structural, equipment and processing system decisions that would be made during the design of the facilities.

2.6.3.3 Reduction of Worker Exposure to Potential Radiation and Contamination Hazards

The occupational safety and health philosophy would be to minimize the exposure of workers to potential radiation and radioactive contamination hazards. This would be accomplished by minimizing the radiation fields and radioactivity of contamination that workers might encounter, and by minimizing the time that they would be exposed to (i.e., work in) either radiation fields or contamination.

The radiation fields in areas accessible to workers would be minimized through use of shielding, as discussed in Section 2.6.3.1. The level of radioactive contamination in areas accessible to workers would be minimized by containment and cleanup, as discussed in Section 2.6.3.2. These actions would provide an acceptable level of radiation and contamination in the work areas.

The time that individual workers spend performing the various operations in each work area and the protective measures taken are two other factors in determining the dose they would receive. The dose that a worker absorbs in an ionizing radiation field is a function of the intensity of the radiation field, the type of radiation (e.g., beta, gamma or neutron) and the time of exposure. The dose would be minimized by minimizing the duration of exposure through careful design and work planning and by minimizing the intensity through shielding design. As noted in Section 2.4.1.1, the AECB establishes the maximum annual permissible doses to which the designs and procedures must be controlled. In designing a facility, the objective would be to keep the doses to as low as reasonably achievable (i.e., the ALARA principle) and to a small percentage of the AECB regulatory limits.

There are many alternatives for minimizing the time during which workers are exposed to potential radiation fields and contamination. Occupancy controls might be used to restrict worker access to the areas (zones) with high radiation fields and levels of contamination during the workers' normal activities. Occupancy and work control could be implemented through the use of work permits. If access should be required, actions would be taken to remove radioactive sources or to provide temporary shielding for the material emitting the radiation and to clean up as much loose contamination as possible. Access might then be allowed for workers dressed in protective clothing, breathing clean air and under constant supervision. Working times would be limited and workers would be rotated to limit the dose to each worker.

The work areas normally occupied would be designed to provide a maximum degree of separation between activities that involve radioactive materials and activities that do not. For example, if requirements for the disposal facility necessitated simultaneous disposal of nuclear fuel waste and excavation of additional disposal rooms, the facility design could provide for the maximum practical degree of separation between these two general work areas. Similarly, the vault design could separate the disposal-room preparation and subsequent sealing activities from the intermediate waste handling and emplacement activities.

Careful design analyses and operations planning early in the design process would consider hazard reduction and accommodate it wherever possible in the design, consistent with the ALARA principle.

2.6.3.4 Control of Hazardous Materials

During all the stages of implementing a disposal facility, various materials would be used that could present a health risk to workers if mishandled or misused. Some of these materials anticipated in a specific Used-Fuel Disposal Centre conceptual design are listed in Section 3.3.5.2. Legislation and recommended practices exist for containing, sorting, handling and transferring these materials. Appendix D of the Environment Impact Statement (1994a) lists some of the regulations governing occupational safety. The design of the disposal facility and the operating procedures would be developed to ensure adequate protection of workers involved in the various activities, and would specify the type and quantity of each hazardous material. An important element in the control of hazardous materials is the Workplace Hazardous Materials Information System (Government of Ontario 1990c) that establishes a worker's right to know about hazardous materials and to training and information on the safe handling and use of hazardous materials.

Storage facilities, such as specifically designed and ventilated chemical storage cabinets and tanks, drip trays and containment curbs to control leakage and spills, fume hoods and ventilation systems to limit the concentration of fumes and particulates, and collection systems for waste materials such as used hydraulic fluid, oils and cleaners, appropriate for each hazardous material or group of similar hazardous materials would be incorporated in the work areas.

The detonators and explosives required for any drill-and-blast excavation work at the disposal facility would be stored separately on the surface in approved buildings or magazines. The quantity in storage at any time would depend on the rate of use, the distance to the suppliers and the size of shipment that would be cost-effective. The explosives and detonators would be moved to the work location in smaller quantities, such as needed for one day of excavation work, and would again be stored separately in approved magazines. The requirements for the safe storage and handling of explosives and detonators, and many other hazardous materials used in mining operations, are set out in legislation such as the Regulations for Mines and Mining Plants (Government of Ontario 1990d).

2.6.3.5 Control of Wastes

(i) Recycling of wastes

The siting, construction, operation, decommissioning and closure of a disposal facility would generate wastes. Although classified as wastes, these materials may be appropriate for recycling. The design of the facilities and processes and the subsequent construction and operation would consider recycling as a desired objective of waste handling. Examples of wastes that might be recycled are used motor oil and hydraulic fluid, water discharged from the facility process-water system and the disposal vault drainage system, metal scrap from machine shop activities, and waste paper from office activities.

The design of the disposal facility and the layout of work areas would be done in a way that encouraged separation at the source of all wastes that might be recycled as an environmental and/or economic benefit. If sufficient care were taken in work area layout and in planning and material flows, the recycling of materials would require very little extra effort on the part of each worker.

Three waste streams, air, water and rock, would be taken from the environment, used in the disposal facility in various ways, and returned to the environment. These materials would be sampled and treated, if necessary, before they are returned to the environment to ensure that the incremental effect on the environment from their use would not exceed legislated limits. In the case of air and water systems, this might involve a range of treatments varying from no treatment to settling and filtration to remove and concentrate undesirable contaminants prior to reuse or release. The settlement sludges and the filtration system media would be the waste to be managed. In the case of waste rock, this material would be used as an aggregate in concretes and backfills for construction and for sealing of the underground excavations. It might also be used on and off the site as a construction material for roads and buildings and for landscaping. If there was any waste rock remaining after decommissioning, it would be treated as a waste and rehabilitated appropriately.

(ii) Waste management and disposal

Recycling would be the preferred method of managing wastes because recycling would reduce the effects of a disposal facility on the environment. However, there would be wastes that cannot be recycled because of the nature of the waste (e.g., domestic sewage, radioactively contaminated material, hazardous material waste), the amount of waste (e.g., groundwater and excavated rock) or the lack of recycling opportunities. Such wastes would be managed safely and disposed of using processes and facilities that are licensed or approved for the particular waste. These processes and facilities may be developed as part of a disposal facility, or may be commercial facilities owned and operated by others.

Wastes that cannot be recycled might be divided into three general categories: domestic and office wastes, industrial or hazardous wastes, and radioactively contaminated wastes. The wastes would be collected and handled separately because they are quite different in their effect on the environment. The facilities, processes and operations would be designed to minimize the burden on the environment caused by the waste disposal facility. The following methods would achieve these goals:

1. Minimizing the creation of waste (e.g., minimize the air exhaust from building areas containing radioactive contamination).

2. Separating and containing contaminated waste streams to avoid contaminating "clean" wastes (e.g., design facilities and waste collection/handling systems to minimize the volume of waste that require treatment, design treatment systems that concentrate the contaminants into readily manageable form).

3. Providing adequate waste handling system capacities to accommodate abnormal conditions (e.g., design overcapacity into specific waste-handling systems such as the disposal-vault drainage system and the radioactive-liquid-waste systems to accommodate abnormal events such as fire suppression or excavation into a hydraulically conductive fracture zone).

4. Effective monitoring of waste streams to focus treatment efforts on only those streams that require clean up.

The alternatives available for disposing of each general category of waste would depend on the location of the disposal facility, the infrastructure that would be developed in the local area and the distance to licensed hazardous and radioactive waste disposal facilities. If facilities were available in the region, or if transportation to facilities outside the region were possible, the implementing organization might choose to store and package its wastes in each category (or in subcategories if necessary) in a manner acceptable to these various facilities and pay for their waste management services.

If licensed hazardous and radioactive waste management facilities were not available for some or all of these wastes from operations, such facilities could be developed as part of the nuclear fuel waste disposal facility. The design, licensing, operation and closure of these facilities would be done according to the appropriate legislation.

The range of facilities that would be required for wastes might include

1. domestic sewage treatment,

2. vault drainage water (i.e., groundwater and underground process water) collection and treatment,

3. domestic solid waste disposal (e.g., incineration, compaction and landfill),

4. hazardous waste treatment and disposal, and

5. low-level and intermediate-level radioactive solid waste disposal.

For any combination of on-site and off-site disposal facilities, the design of the disposal facility would include the storage and treatment facilities necessary for the separation, storage and preparation of the wastes for disposal.

2.6.3.6 Materials Handling Methods

Large quantities of several types of materials would be moved through various parts of the facility during the underground evaluation, construction, operation and decommissioning of a disposal facility. These materials might include

1. nuclear fuel waste (as received and as packaged for disposal),
2. disposal container materials and/or completed containers,
3. excavated rock from development of the disposal vault,
4. sealing material components (e.g., clay, sand and crushed rock),
5. sealing material (e.g., buffer, backfills and concrete), and
6. construction and operation materials.

The designers would choose a handling system for each of these materials that would be proven and reliable, would be suited to the material characteristics and quality requirements and would provide a safe working environment. In the selection of particular systems for each application, the requirements of radiological/industrial safety, standard civil/mining engineering practice, and the requirements of applicable legislation.

(i) Radioactive material handling

The choices are limited when handling nuclear fuel waste. It would arrive at a disposal facility in a shielded cask that would be either an integral part of the disposal container or a reusable transportation device. In the latter case, the nuclear fuel waste unloaded from this cask would likely be transferred into a shielded structure in which the waste packaging and/or package inspection would be done remotely. When a package containing a quantity of nuclear fuel waste in a container accepted for disposal is to be transferred into the vault there are three possibilities: it might be transferred without shielding by remote handling methods, it might be self-shielding, or it might be transferred in a shielded cask by contact handling methods. The choice would depend on the expected reliability associated with each method, the concurrent activities that would take place near the waste handling route, an analysis of the occupational risks associated with each alternative, and a cost analysis.

(ii) Nonradioactive material handling

Contact handling would be the handling method selected for the container material and the finished containers ready for filling. Depending on the material selected for the disposal container, there might be specific requirements for the design of the handling, storage and fabrication equipment. An example of this is the detrimental effect that iron contamination could have on the resistance of titanium to pitting by galvanic corrosion. To avoid this effect, no metallic iron-base materials should come in contact with the titanium material, from acquisition and fabrication through to container filling and disposal. This would require either the selection of compatible materials for all components of the fabrication and handling processes or the sheathing of iron-based components included in the design with a compatible material.

The method of handling nonradioactive bulk materials, including excavated rock, the components of sealing materials and the prepared sealing materials, would be selected to reduce the associated occupational risks. For dusty materials such as clays, sand and crushed rock, the methods chosen would provide sufficient containment and auxiliary dust removal to maintain a safe level of airborne particulates.

The alternatives for handling these bulk materials include enclosed conveyor systems, air-fluidized transfer in pipes, transport in covered trucks, and handling in sealed units such as containers, barrels or bags. In shafts, materials could be raised to the surface in batches using the skip or cage type of shaft conveyance, or they could be raised continuously using specially designed conveyor systems. Materials could be lowered down shafts in batches using skips or in containers or bags within a shaft cage, or they could be lowered continuously as an air-fluidized material or wet mix in pipes.

The choice of method would depend on many factors, including the characteristics of the material, its projected reliability and the ease of maintenance of the various alternatives chosen for each material. For example, the air-fluidized piping alternative would be a viable alternative for handling dry sand but not for excavated rock. The integration of the various materials-handling operations and the desire to minimize the number of different systems installed in a facility would also be factors in making the final choice.

2.6.3.7 Working Environment

A major aspect of occupational safety and health would be the design of a safe working environment. The major factors that would be considered in selecting and designing process, service and protection systems would be established from legislation that pertains to the project. The factors would include dust, heat and air quality, noise, stability of excavated openings, and workplace arrangement. These factors would be considered in the workplace designs beginning at the conceptual level of detail.

The control of air quality, including concentrations of dust and hazardous fumes, would require that the ventilation systems change the air in various areas frequently enough to carry away airborne contaminants and to replenish the oxygen. Where practical, these contaminants would be removed from the air so that some portion or all of the air could be recycled. This would be emphasized in the facility design for the disposal site locations where the cost of heating and/or cooling workplaces is a significant portion of the operating cost. Heat recovery would be considered as an alternative if recycling the airflow was not practical. For example, in a disposal vault, the naturally occurring radon gas, the airborne dust from excavation, sealing and material handling operations, the soot from diesel-powered equipment, the smoke from blasting, and the cost of heating the air in winter would be factors considered in determining the required airflows in various areas of the vault. The airflow requirements might be reduced through use of local filtration/dust separation equipment in areas where there is a high rate of dust generation (perhaps during backfilling and sealing). Water sprays may also be applied in excavation areas to prevent dust from becoming airborne.

Noise hazards to workers would be minimized in all work areas through careful selection of equipment to minimize the noise generated and through required use of approved hearing protection devices where necessary. Noise reduction at the source would likely be most effective in the surface facilities, although hearing protection equipment would be standard issue outside office and control room areas. In the disposal vault, the nature of the equipment and the work would limit the potential for noise reduction, and hearing protection equipment would be mandatory in many work areas.

Ground control methods would be used to minimize or eliminate the hazard to workers in excavations where there is a potential for roof and wall instability and rock falls. Ground control is the maintenance of excavations for safe worker access. The simplest form of ground control would be routine inspection and the scaling (i.e., the removal of pieces of rock that loosen on the excavation surface) of all exposed rock surfaces. In locations where the excavation dimensions and the natural joint spacing lead to loosening of rock blocks, rock bolts would be used to clamp these blocks in place. In locations where there is a continual spalling, or loosening of surface rock, rock bolts could also be used to support a wire screen on overhead surfaces, including shaft walls, to prevent the loose material from falling on workers. In zones such as faults where more substantial ground support may be necessary, cement-based grout, shotcrete, timber and/or concrete could be used to construct a liner around the excavation to support and stabilize the rock at the excavation perimeter. These ground control methods are widely used, and the specific choices for the ground support in a disposal facility would be developed during the design and applied during the construction of the excavations.

The other major aspect of excavation that would affect worker safety are the procedures and controls necessary to conduct the work. In drill-and-blast excavation, workers would be working with or handling hydraulic or pneumatic drilling equipment, vehicles in close quarters and explosives. Handling and operational procedures, and control of access to areas where blasts would be initiated, would be essential to safe operation. The continuous excavation by tunnel-boring machines or mobile mining equipment involves massive equipment with many complex moving parts. There are hazards associated with working in close proximity to these types of equipment.

The work areas would be arranged and constructed to provide ample space for workers around the equipment and operations being conducted. This approach to workplace design would allow workers to maintain a safe separation between themselves and any equipment, and between their activity and other activities being conducted in the same work space. As an example, during tunnel backfilling, the selection of the sizes and numbers of each type of equipment (potentially including supply trucks, spreaders, compactors and quality samplers) required to conduct the operation would be made with due regard for the space that would be available in which to do the work.

2.6.3.8 Decontamination and Decommissioning

The disposal facility designers would consider the actions that would be required to decontaminate and decommission the buildings, equipment and systems. These factors should be incorporated in the initial designs:

1. Minimize the extent of the facility that would likely contain radioactive or hazardous contamination during facility operation.

2. Provide sufficient access space to allow removal of equipment and the necessary lifting connection points.

3. Facilitate housekeeping during the facility operation to avoid difficult to access or difficult to remove buildups of radioactive and hazardous material contamination.

4. Minimize the amount of equipment and structural surfaces (e.g., porous concrete) that may become contaminated with difficult to remove radioactive material and design the contaminated surface material and equipment so that it would be relatively easy to disassemble and remove for disposal.

5. Design for easy decontamination by using finishes and fixtures on floors, walls and working surfaces that are impervious, washable, chemically resistant or easy to remove (e.g., strippable paint).

6. Minimize the use of monolithic and welded structures to ease decontamination and dismantling.

7. Minimize the size and simplify the installation of active-waste handling systems and equipment.

8. Where possible, make the equipment and structures that may become contaminated smaller and lighter to minimize the volume and weight of contaminated waste.

9. Facilitate volume reduction of contaminated material and components prior to their packaging for disposal.

10. Establish and maintain records of all contamination incidents.

If adequate attention is paid to these factors during design, construction and operation, the occupation hazards during decontamination and decommissioning and subsequent waste packaging, storage and disposal would be minimized.

2.6.4 Environmental and Public Safety

Many of the factors and design considerations related to worker safety discussed in Section 2.6.3 would contribute also to the safety of the environment and the public. As well, there are others that would be considered in the design and operation of a disposal facility.

2.6.4.1 Control of Public Access to the Disposal Facility

It is likely that the public would have access to the disposal facility on request as part of the public interaction activity. However, public access to the disposal facility would be supervised to minimize the potential for the public to be inadvertently exposed to hazards that could affect public health. The disposal facility and its site would likely be classified as a supervised area, with a few specific portions of the facility classified as a protected areas (Government of Canada 1983). The requirements for access control vary with the area classification.

Unsupervised public access would be discouraged on the site and would not be allowed within the protected area. Although public visits and inspections would be encouraged, the regulations and the need for public safety require that these visits be supervised by trained workers who would be responsible for the safety of the visitors.

The design of the disposal facility would include the space and facilities to receive and handle visitors, to make presentations and hold discussions (e.g., public affairs display area and theatre), to provide safe visitor access to the surface facilities (e.g., transportation cask receiving area and nuclear fuel waste packaging and inspection areas), and to provide visitor access to observe the operations in the disposal vault (e.g., excavation, waste emplacement, sealing preparation and application). The visits would also be planned and arranged to provide the necessary time and personnel to accommodate these public visits without disrupting operations.

2.6.4.2 Control of Emissions from a Disposal Facility

The safety and health of the public would be protected by minimizing their exposure to radioactive and hazardous materials during all stages of the implementation of a disposal facility. Control of the emissions of these materials from the disposal facility would involve the approaches to systems design discussed in Sections 2.6.3.1 to 2.6.3.5. Systems designed to protect workers, to control hazardous and radioactive materials, and to decontaminate or collect and store waste streams would also protect the environment and the public from exposure to unacceptable amounts of these materials resulting from disposal facility emissions.

The monitoring plan for the biosphere (Section 2.4.2.2) would include collection of data that would be used to monitor the performance of waste collection, waste storage and emissions control systems.

Section 3.3.5 discusses the radioactive and nonradioactive hazardous materials associated with a specific Used-Fuel Disposal Centre conceptual design.

2.6.5 Waste Emplacement Methods

Having focussed on the room-and-pillar configuration for the disposal vault (Section 1.2), two general waste emplacement arrangements would be available – in-room emplacement and borehole emplacement (Figure 1-4). In-room emplacement is the placement of waste within the confines of an excavated room or tunnel. Borehole emplacement is the placement of waste within a borehole of any length or orientation drilled from the confines of a room or tunnel. For either emplacement method, important factors for the design are the container heat output and its change with time, the temperature limits on the container and sealing materials, and the composition and properties of the sealing material. The spacial distribution of emplaced containers must allow for adequate heat transfer to control the component temperatures, and the borehole must be sufficiently larger than the container to provide the necessary thickness of buffer material.

The physical conditions, particularly fracturing, rock-mass strength and in situ stress, that exist at a given site could affect the selection of the emplacement method. The geometry of the excavated openings in a stressed medium concentrates stress at the perimeter of the opening. The extent of this concentration depends on the orientation of the excavations relative to the orientation of the principal stresses and the geometry of the opening(s) (see discussion in Section 2.7.2.2 (ii)). The magnitude of the concentrated stresses depends on the magnitude of the in situ stresses. In general, the increased complexity of excavation geometry associated with the borehole emplacement alternatives (Figure 1-4) would lead to higher stress concentrations in the rock around the intersections of the boreholes and the disposal rooms. The rock strength is more likely to be exceeded locally for a borehole emplacement alternative than for an in-room emplacement alternative. An overstress situation would result in local yielding, an associated increase in microcrack density, and freeing of pieces of rock from the excavation surface. There may be a depth for any site below which disposal would not necessarily be practical because of high in situ stresses and the potential for rock instability. This limiting depth would likely be greater for in-room emplacement than for borehole emplacement.

There are some potential operational and economic factors that favour borehole emplacement. For example, the volume of excavated rock per container may be lower for borehole emplacement than for in-room emplacement. Similarly, the volume of buffer and backfill required to seal the excavations would be less for the borehole emplacement configuration. In case the disposal containers must be retrieved, the disposal rooms would be more easily reexcavated when the nuclear fuel waste is located in boreholes drilled from the excavations. The borehole wall would also be available to use as a guide during waste retrieval operations. For in-room emplacement configurations, it would be necessary to locate and retrieve the nuclear fuel waste while the room is being reexcavated. These advantages are sufficient to make continued consideration of the borehole emplacement method attractive.

At each site being evaluated for disposal, an emplacement arrangement and a specific emplacement design would be developed to account for the site conditions. In the Nuclear Fuel Waste Management Program, some emplacement designs have been studied to assess their practicability. This section compares some of the emplacement design alternatives.

The manner and sequence of buffer and container placement are two main variables for in-room emplacement. Two methods studied as part of the Nuclear Fuel Waste Management Program are the compaction of backfill around disposal containers set on a precompacted backfill base (Acres et al. 1980a) and the preplacement of buffer within the room followed by the emplacement of containers into holes augered within the buffer (Wardrop et al. 1985). The Swiss (NAGRA 1985a) and Swedish (SKB 1992) programs have also examined the alternative of assembling the buffer mass from precompacted blocks of buffer material and emplacing containers of waste into the mass at the desired location during the assembly (Figure 2-4). The method proposed by Wardrop provides for the in situ compaction of the buffer mass followed by the emplacement of disposal containers within holes augered in the buffer mass. This alternative allows direct operator access during the emplacement of the buffer, except when emplacing containers, to aid in quality control of the buffer and container emplacement. It also reduces the possible exposures of

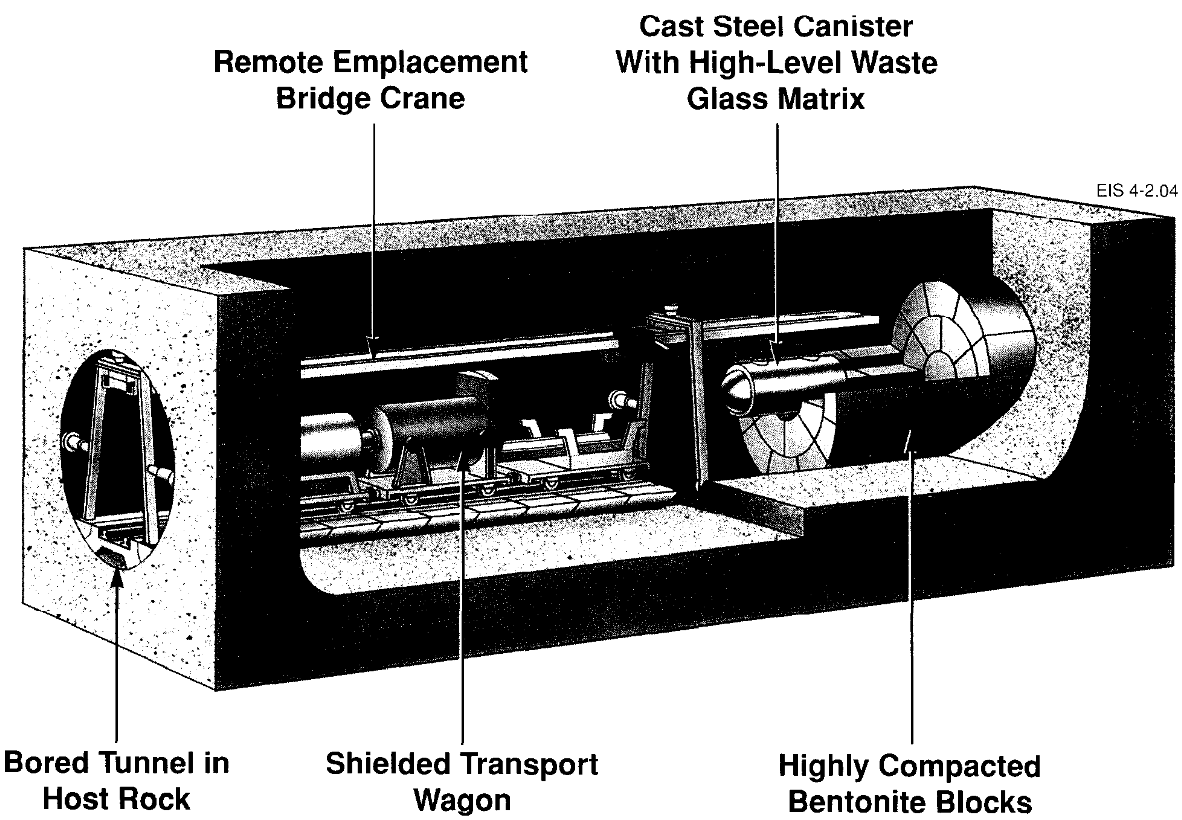

FIGURE 2-4: A Swiss In-Room Emplacement Concept (after NAGRA 1985)

operators to radiation by reducing the number of remote or shielded operations during waste emplacement, and the need for remediation or retrieval for operational upset or accident conditions.

The main variables for borehole emplacement are borehole orientation, length and diameter. The possible orientations would likely be into the floor or into the walls of the tunnels or disposal rooms. The lengths of the emplacement boreholes could vary from 5 to 6 m for a single container per hole to much longer for long-hole alternatives, where several containers are distributed along the length of each borehole. The diameter of the borehole would be a function of container diameter and the thickness of buffer required between the container and the rock.

The minimum buffer thickness has been 0.25 m for the borehole emplacement studies. The rock stress was taken as the average of the data from published information on the Canadian Shield, and the depth has been taken to be 1000 m for single-level vaults and 500 to 1000 m for multilevel vaults. In-floor borehole-emplacement alternatives in these studies (Acres et al. 1980b, Acres and RE/SPEC 1985, Wardrop et al. 1985 and AECL CANDU et al. 1992) involved the drilling of single-container emplacement boreholes in the disposal-room floors followed either by the compaction of sealing material around the container during emplacement or by preplacing buffer in the emplacement borehole and augering an opening for the container. SKB (1983) studied the alternative of placing highly compacted blocks of buffer into a borehole, lowering the container to a central opening in the buffer blocks and filling the balance of the emplacement borehole with precompacted bentonite blocks (Figure 2-5).

Tsui et al. (1982) assessed the thermal-mechanical implications of placing single containers in horizontal boreholes drilled into the pillars between the rooms, the in-wall borehole emplacement alternative, as compared with those of the in-floor borehole emplacement alternative with similar fuel wastes. For this analysis, two fuel reprocessing waste containers were placed horizontally, one above the other, into the pillar on either side of a disposal room, providing the equivalent to the four-container-abreast, in-floor emplacement arrangement (Acres et al. 1980b). In-wall emplacement reduced the local peak temperatures compared with the in-floor concept, but the differences in the calculated local thermal-mechanical stress values were small (see Figure 2-6). No significant reduction in stress and stress concentrations was observed for in-wall emplacement. However, considerable operational difficulties could be anticipated in horizontal emplacement of the containers and sealing system.

A long-hole emplacement alternative was analyzed by Acres (1993b) in which boreholes would be excavated between three levels in a multilevel disposal vault. The levels were assumed to be at depths of 500, 750 and 1000 m. In this study (Figure 1-6), the emplacement boreholes were developed by raise boring between levels, the bottom of each emplacement borehole was plugged, and buffer would be placed into the hole from the level immediately above. The containers were lowered to the top of the buffer and additional buffer material was placed around the container up to the next container emplacement location. Major issues that required further study and demonstration

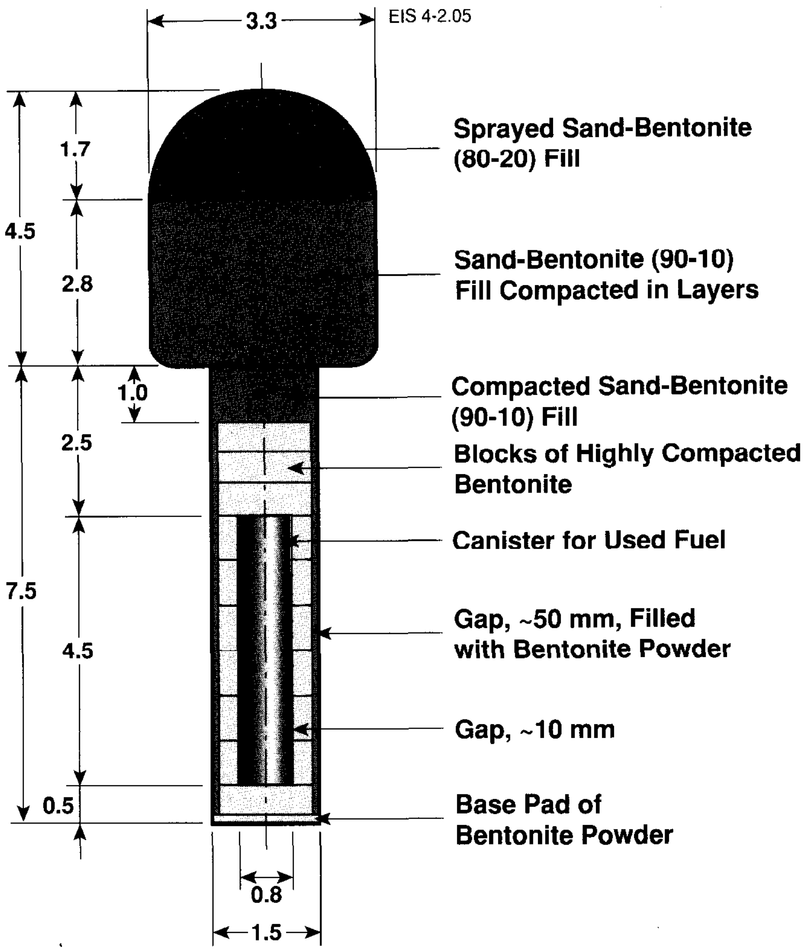

FIGURE 2-5: A Swedish Borehole Emplacement Concept (after SKB 1983). All dimensions are in metres.

included buffer placement and quality control, container emplacement, buffer column stability, recovery from operating errors, upsets or accidents, and disposal-container retrieval. While the vault design could be developed to meet the thermal and thermal-mechanical constraints, this alternative has not been pursued because of the need for extensive study and demonstration to show its operational practicability.

The borehole emplacement alternative currently preferred is in-floor emplacement of single containers in a borehole partially filled with a preplaced, in-hole-compacted buffer mass. The shallow-depth borehole (5 to 6 m) and preplacement of a large part of the buffer mass would allow inspection and quality control. The vertical borehole orientation would simplify the disposal container handling and placement of the annular sand layer. The vertical orientation would also aid in the placement and

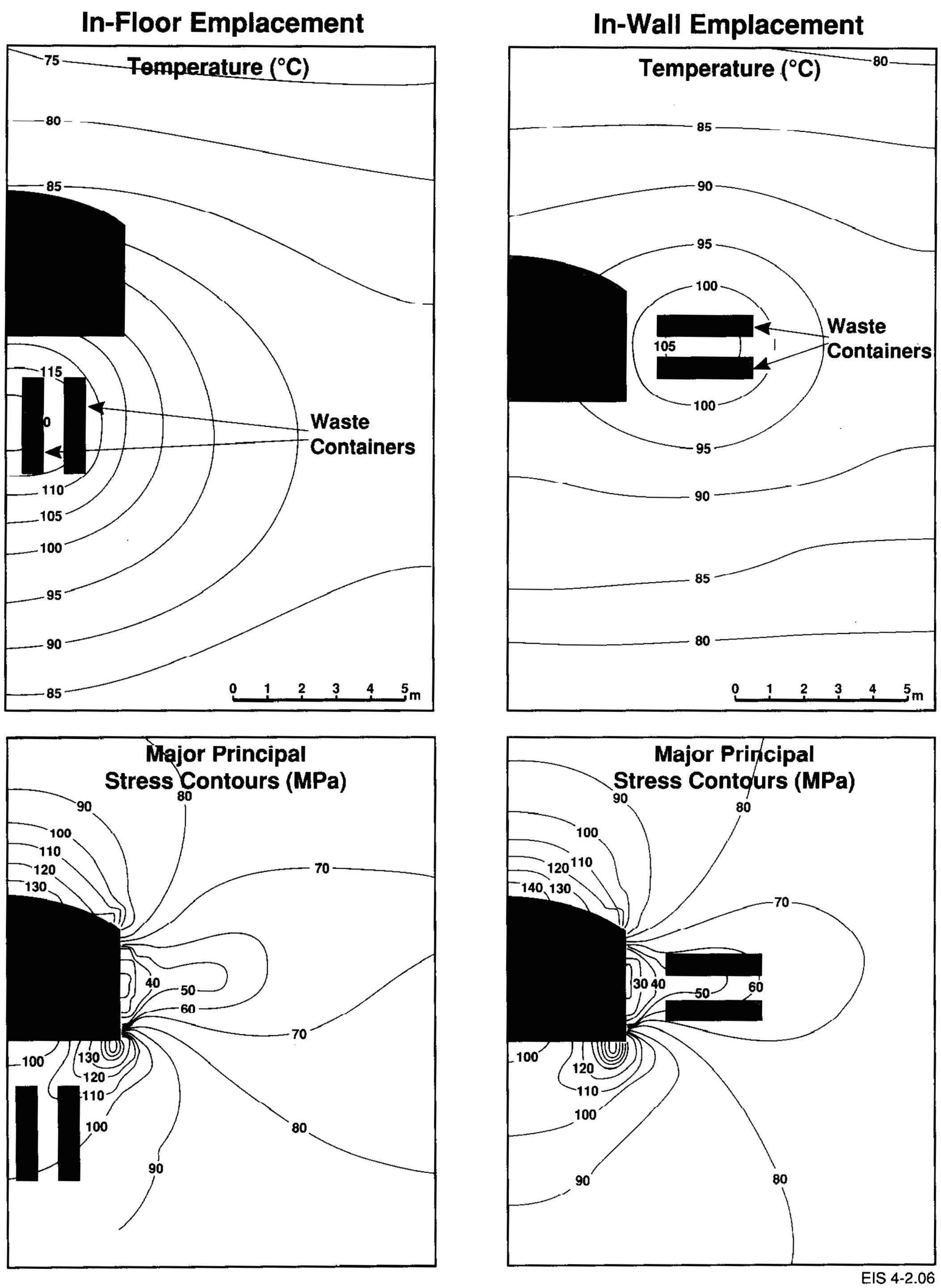

FIGURE 2-6: Temperature and Stress Distributions for Borehole Emplacement Alternatives (after Tsui et al. 1982)

compaction of final portion of the buffer mass. The shallow, vertical holes should also simplify the retrieval of containers should this be required. When an emplacement borehole has been filled with compacted buffer, the thickness of the overlying buffer would provide the radiation shielding necessary for a safe working environment in the disposal room.

The choice between in-room and in-floor borehole emplacement will depend on a number of factors. From a thermal perspective, the container spacings required for single-container-per-borehole in-floor emplacement (Tsui and Tsai 1994a) would be less than that required for in-room emplacement (Tsui and Tsai 1994b) because of the increased mass of buffer surrounding each container. The buffer has a lower thermal conductivity than rock. The in-room emplacement alternative would require a larger disposal vault area for a given number of containers than the in-floor emplacement alternative.

The selection of an emplacement method for any particular disposal site is dependent on several site-specific conditions. It is also dependent on the waste form characteristics and the waste isolation requirements placed on the container and sealing systems. No particular emplacement method is recommended because one can only be selected after site-specific evaluation studies have been completed.

2.7 SITE CONDITIONS

There are many design issues related directly to the conditions that would be found at a disposal site. These include rock-mass quality, the potential for ground disturbance by the excavation method, in situ stress redistribution around excavations, glacial loading and seismic loading. These are discussed briefly in the following sections as examples of addressing site-dependent issues.

2.7.1 Surface Conditions

The surface environment (i.e., biosphere and human communities) that exists in regions and locations selected for disposal site evaluation would influence several aspects of the facility design. Appropriate regional and local data would be gathered to define the surficial and near-surface conditions, the demographics and proximity of transportation corridors, electrical power, communications, water supply and population centres. These would be important elements in the design and cost of surface facilities and ancillary services.

The surface characteristics would affect the type and amount of excavation and fill needed to prepare the site for laying the foundations for structures and buildings, water collection and treatment ponds, rock disposal area, access roads, rail line, laydown and holding yards and utility networks. They would also define the local availability of suitable fill. The facility would be located away from areas susceptible to flooding, and protective measures would be incorporated to divert storm-water runoff. The demographics of the region would influence the selection of temporary or permanent accommodations for the labour force. Alternatives could range from a temporary construction stage camp, a permanent "fly-in" camp that would be used throughout the disposal project, expansion of an existing town(s), or the creation of a new town. The remoteness of the site from transportation and utility corridors would affect the length and construction cost of road, rail and utility links. Operation costs would be affected by the availability of cost-effective energy sources (e.g., natural gas heating vs. electric heating).

2.7.2 Underground Conditions

The geological and hydrogeological conditions of the disposal site would dominate the disposal vault design. The key design requirements of a disposal vault would be to limit the rate of water access to the waste form, the rate of radionuclide transport to the biosphere, and the peak and long-term temperatures imposed on the natural and engineered barrier materials to reduce thermally enhanced degradation processes such as container corrosion.

The site conditions that influence the design of a disposal vault would be the in situ stresses throughout the geological domains of a given site, the geothermal temperature gradient, the expected natural transient events (e.g., glaciation and seismicity) that would alter the stress conditions, the degree of fracturing within the rock mass, and the physical behavioural properties of the rock types, fractures and fracture zones (i.e., faults). The material behavioural properties such as the strength, deformational properties and heat transfer properties influence the vault design in terms of the thermal distribution of the waste within the vault, the depth of the vault and the size, geometry and orientation of the excavations.

The issues of rock quality, excavation disturbance, in situ stress and its concentration by excavations and heating, rock strength, and seismic loading are discussed in this section as specific examples of the effect of underground conditions on the design of the disposal vault.

2.7.2.1 Rock Quality

In general terms, rock masses in the Canadian Shield can be subdivided into three main fracture domains:

1. Fracture zones (faults) - volumes of intensely fractured rock.
2. Moderately fractured rock - volumes of rock containing a small number of sets of relatively widely spaced discrete fractures (joints).
3. Sparsely fractured rock - volumes of rock containing microcracks and very sparsely distributed discrete fractures not generally interconnected.

These domains are readily recognizable in boreholes and excavations, and their three-dimensional distribution controls groundwater flow and contaminant transport.

The rocks of the Canadian Shield are saturated with water and the water table is generally very near the ground surface, so any pore spaces or cracks in the rock would be filled with groundwater. The rate of groundwater movement through the rock depends on the hydraulic gradient and hydraulic permeability. The hydraulic gradient depends on the differences in groundwater head between different locations in the groundwater regime. The hydraulic permeability is affected by the sizes of the pores or fractures and the degree to which these are connected.

The spatial distribution of sparsely fractured rock within a disposal site volume would be a major factor in delineating the potential locations for waste disposal. Sparsely fractured rock tends to have lower hydraulic permeability than moderately fractured rock (Davison et al. 1988, Lee et al. 1983, Raven et al. 1986). The highly fractured rocks tend to be faults and/or major discontinuities that bound blocks of rock with lower fracturing intensity. The moderately fractured rocks, having intermediate hydraulic permeabilities, are often found near the surface of the rock body and adjacent to the highly fractured rock zones. This rock domain provides a zone of higher hydraulic permeability that must be considered in the selection and performance assessment of waste disposal locations at a site.

The locations, orientations and other characteristics of these rock domains must be well known for each site because they comprise the groundwater flow paths through the rock (Davison et al. 1994a). Volumes of sparsely fractured rock with low hydraulic permeability would be identified for waste disposal based on the mapping of the distribution and intensity of fracturing, and the distribution of hydraulic permeability.

The number and size of these sparsely fractured rock volumes required for a disposal vault would depend on the total disposal area or volume required, on the distribution and geometry of highly fractured rock domains, and on the waste exclusion distances required at each site between a waste disposal area and nearby highly fractured rock domains (Figure 2-7). These waste exclusion distances would be determined from the results of disposal system performance assessments and, if required for adequate safety at a site, would be a site design constraint. Any excavation and construction requirements that might affect the hydraulic conditions in the rock mass adjacent to the waste emplacement areas would be considered in these analyses.

Faults and fracture zones would likely need to be crossed by the disposal-vault shafts and/or tunnels to gain access to the sparsely fractured rock volume(s). The locations selected for the shafts and the arrangement of tunnels to and around waste disposal areas would minimize the number of penetrations as they would each require special attention during operation and decommissioning. The issues during operation would be structural integrity and control of groundwater inflow. During decommissioning, the major issue would be to minimize the pathways with potentially higher hydraulic permeability from the emplaced waste to the various points of penetration.

2.7.2.2 Rock-Mass Disturbance

The extent of disturbance or damage that could be created by excavation of openings in a rock mass under stress and by the added stress from the heat

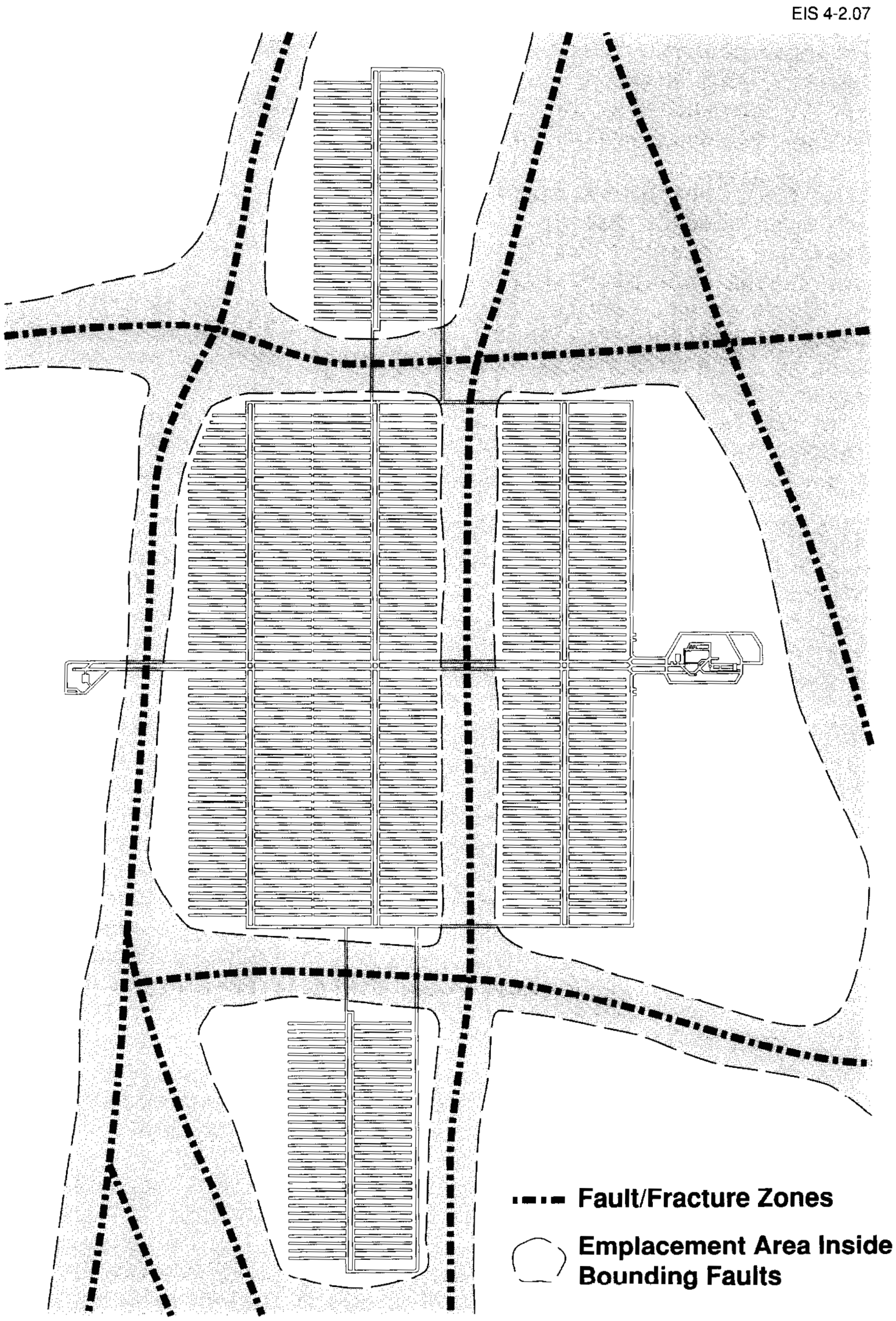

FIGURE 2-7: Disposal Vault Plan Partitioned to Suit Geological Conditions

generated by the waste form would be a factor in the design of the disposal vault. This could affect the stability of the excavation boundary and could create or enhance hydraulically permeable pathways for groundwater flow and radionuclide transport.

(i) Disturbance by excavation methods

The method of excavation could cause damage and could change the properties of the surrounding rock because of the excavation energy imparted to the rock mass. The extent and nature of this damage would depend on the total amount of excavation energy transferred to the rock at the excavation perimeter and the degree to which the energy would be focussed or dispersed.

Methods of excavation in plutonic rock could include the following:

1. Drill-and-blast or mechanical excavation methods (e.g., boring) for large excavations such as shafts, tunnels and rooms.

2. Coring, boring or percussion methods for large-diameter boreholes such as waste emplacement boreholes.

3. Coring, boring or percussion methods for small-diameter boreholes such as characterization and monitoring boreholes.

Continuous excavation methods such as coring, boring and percussion drilling, and mechanical excavation involve the removal of rock in a continuous process. These methods break the rock by applying high and very localized compressive force with sets of point or disc cutters to the rock, causing localized crushing and shear failure. The local nature of the loading is believed to have minimal effect on the rock mass remaining around the excavation. However, the equipment (such as tunnel-boring machines) used to move and apply load to the cutters must be massive to provide the forces and torque necessary to break the rock, and may cause damage to the excavation wall through loads applied by the hydraulically operated pads used to stabilize and propel the equipment.

On the other hand, drill-and-blast excavation rapidly releases large quantities of energy into the rock mass, and in the process reduces a large volume of competent rock (i.e., the blast round) into fragments. In drill-and-blast excavation, explosives are placed in one or more blast holes. The length, number and pattern of the blast holes and the quantity and type of explosive in each define the resulting opening. The objective in drill-and-blast excavation is to limit the energy released by the explosive in each blast hole to provide adequate fragmentation of the blasted rock, and to minimize the disturbance to the rock mass outside the excavation perimeter.

The damage caused by drill-and-blast excavation is attributed to the energy transmitted to the rock by the detonation of the explosive and the gas pressure developed in the blast holes. The extent of damage caused by drill-and-blast excavation might be controlled by the spacing and size of the blast holes, the type and amount of explosive placed in each blast hole, the degree of contact between the explosive and the blast-hole wall (i.e., the degree of coupling) and the sequence in which the explosive is initiated in the blast holes. As well, the creation of a final opening may be done in several steps (benching or pilot-and-slash) to minimize the damage to the surrounding rock through more effective control of the final step(s).

There are several techniques for designing blast rounds to achieve this objective, including the Swedish blast design method (Langefors and Kihlstrom 1978) and the cratering theory (Sperry et al. 1984). Specific examples of the application of controlled blasting methods are the work done in the Edgar Mine in Colorado for the United States Department of Energy (Sperry et al. 1984, Holmberg 1983) and work done by AECL Research in its Underground Research Laboratory (Kuzyk et al. 1987a, Favreau et al. 1987).

Drill-and-blast excavation experience shows that although the effects of blasting occur relatively instantaneously, they cannot be practically separated from damage caused by stress redistribution. Both effects cause changes in the fracture population and characteristics in the near-field rock. There have been no tests that compare the excavation-induced damage zones caused by the continuous and drill-and-blast excavation methods in the same body of hard crystalline rock. Such data might allow blast-related effects to be identified. In the Underground Research Laboratory, most drill-and-blast excavation was done by using blast rounds designed to control the effect of the excavation method on the excavation perimeter. Geological assessments around excavations (Everitt et al. 1989) indicated excavation damage limited to several tens of centimetres. Hydraulic assessments in an excavation-disturbed zone indicated that the zone of increased hydraulic permeability might extend 200 mm into the excavation wall and be discontinuous between adjacent blast rounds (Martin et al. 1992).

Thus, the degree of potential perimeter damage depends on the excavation method selected (Pusch 1989) and the controls placed on the design and execution of the method.

(ii) Disturbance by stress effects

The creation of a hole in a stressed elastic solid would cause a realignment of the surrounding stresses, resulting in localized stress concentrations around the hole (Jaeger and Cook 1979). The maximum stress concentrations would form at the hole boundary. The geometry of the hole (e.g., an excavated tunnel) and the orientation of the acting in situ stress field would affect the magnitude and location of the stress concentrations. If the concentrated stresses exceed the strength of the intact material, localized breakouts in the form of cracking and spalling could occur. Any stress redistribution could also cause a local change in the normal and shear stresses acting on pre-existing fractures. In either case, an increase in hydraulic permeability could be produced in a zone around the perimeter of an excavation, which would have to be considered in the decommissioning plans and the performance assessments.

On a larger scale there is also a natural variability in the in situ stresses conditions at any location in the Canadian Shield. This is caused by local geological conditions and by factors such as depth, and is apparent in the in situ stress data collected from the Canadian Shield (Herget 1980, 1986; Arjang 1991; Herget and Arjang 1991). Generally, the vertical stress depends on the density and depth of the overlying rock and the horizontal stresses are dependent on the regional tectonic conditions. The major horizontal stress tends to be significantly greater than the vertical stress at depths of 500 to 1000 m. The minor horizontal stress is more variable and can be either greater or less than the vertical stress. High values of horizontal stresses have been noted in the Canadian Shield (Herget 1980, 1986), and structural geological features such as faults can act as in situ stress domain boundaries, affecting both the stress magnitudes and orientations (Martin 1990).

Theory and practice have shown that the best method for minimizing stress effects in sparsely fractured rock and maintaining the stability of a single, long excavation (e.g., a tunnel or room) is to orient the excavation axis parallel to the major principal stress (σ_1), thereby reducing the deviatoric stress acting on the excavation cross section.

The ideal geometry for an excavation cross section is an ellipse with the major and minor axes identical in ratio and orientation to those of the major and minor stresses acting on the excavation cross section. For example, if the major stress is horizontal with a value of 40 MPa and the minor stress is vertical with a value of 20 MPa, the major-to-minor stress ratio is 2:1. Therefore, the ideal excavation shape would be an ellipse with a horizontal-to-vertical-dimension ratio of 2:1, such as an opening that is 6 m wide by 3 m high.

However, other factors may prevent the use of such simple approaches to excavation design. The principal stresses might not be in horizontal and vertical planes. Geological structures such as dikes and mesoscopic fractures (e.g., joints) may disturb the local uniformity of the stress field and may create the potential for wedge-shaped breakouts that affect the excavation stability, shape, or both. Vault operational and equipment clearance requirements may make the use of purely ellipse-shaped excavations impractical. Excavations with approximate oval shapes (i.e., concave walls, floors and roof with well-rounded corners) may be less suited to the stress conditions, but may have the offsetting advantages of flatter floors and walls.

In addition, experience in moderately and highly fractured rock has shown that long excavations are best oriented, where possible, perpendicular to major fracturing. Alignment along fractures tends to increase the potential for movement on fractures and for blocks to come loose, and is therefore the least favourable orientation for excavation stability (Barton et al. 1974; Bieniawski 1974, 1976).

Since multiple excavations would be required for a room-and-pillar disposal vault, the spacing between disposal rooms would be a design factor because the excavation stress concentrations could overlap in the pillars between the rooms. The average vertical stress acting on the pillar between the disposal rooms can be expressed as

$$\sigma_{pav} = \frac{\sigma_v}{1 - ER} \tag{2.1}$$

where σ_{pav} = average pillar stress (MPa), and
ER = extraction ratio;

and

$$\sigma_v = \gamma g d \tag{2.2}$$

where σ_v = vertical stress (MPa),
γ = density of rock (kg/m^3),
g = acceleration due to gravity (9.81 m/s^2), and
d = depth of vault (m).

The extraction ratio ER is defined as

$$ER = \frac{W_r}{W_p + W_r} \tag{2.3}$$

where W_r = width of disposal room, and
W_p = width of interroom pillar.

If the strength of the rock mass in the pillar is not exceeded by the stress, the mechanical responses would remain essentially elastic and the pillar would remain stable. Large excavation ratios in high-strength rock could lead to rock-burst conditions, which have been experienced in a number of mines in the Canadian Shield. A low extraction ratio of about 25% for a disposal vault design would avoid the potential for a rock burst (Ortlepp 1992) and would also accommodate up to 5 km of ice load from any future continental glaciation with some minor excavation-induced damage in the pillar boundary (Ates et al. 1993a).

Subsequent heating of the rock mass by the heat-generating waste would increase the stresses in the rock mass because of thermal expansion. The large-scale increase in stress ($\Delta\sigma$) over the expanse of the disposal vault, assuming plane stress boundary conditions (i.e., where $\Delta\sigma_v = 0$), is related to the coefficient of thermal expansion (α), the increase in temperature (ΔT), the Young's modulus (E) and Poisson's ratio (υ) of the rock as follows:

$$\Delta\sigma \approx \frac{\alpha \Delta T E}{1 - \upsilon} \quad . \tag{2.4}$$

The increase in local temperatures would be determined at each site being considered, taking into account the geothermal temperature gradient, the waste emplacement depth, the temperature design limits for the various materials (e.g., the disposal container outer shell, the buffer and the backfill), the thermal characteristics and quantity of used fuel (see Section 2.6.1), the thermal properties of the sealing materials and rock, the geometry of the disposal room, the distribution of disposal containers within a disposal room, the spacing between disposal rooms and the extraction ratio. Many of these factors are interrelated or closely dependent on other factors in the disposal system design. The temperature increase would be one element of an iterative design analyses.

Because rock masses are rarely purely elastic, isotropic and homogeneous materials, their response to excavation is likely to extend beyond the anticipated elastic response, particularly at the excavation boundary. The spatial extent of the disturbance resulting from stress redistribution around an opening is controlled by several additional factors, including the frequency and spacing of fractures and the physical properties of the rock and the fractures. The bulk of the rock mass responds elastically in the moderately to highly stressed rock that would be expected at depths between 500 and 1000 m in the Canadian Shield, but a zone immediately around the excavation could respond inelastically (Chandler and Martin 1990).

Typical physical properties of three Canadian Shield plutonic-rock masses are given in Table 2-1. The rock properties are not strongly affected by heating to temperatures below 100°C, and are not affected by the expected gamma-radiation (Durham et al. 1986) and neutron-radiation exposures (Van Konynenburg 1984).

Generally, the mechanical strength of intact rock in Canadian Shield plutons is high. The rock-mass strength (the rock mass includes the filled and unfilled fractures) also tends to be high. Based on core logs from AECL's research area characterization, both the core recovery and the derived Rock Quality Designation (RQD) (Deere 1964) approached 100%, except in fault zones.

A large percentage of the fractures have high-strength infillings that maintain their integrity during core drilling and handling. With the general reduction of fracture intensity with depth, the strength of the rock mass at disposal-vault depths would be controlled by the intact strength of the rock. With the indication that the quality and strength of sparsely fractured rock masses would tend to be high, moderately large underground structures with wall heights and roof spans of up to 8 or 10 m could be constructed with a requirement for no, or relatively light, ground support measures (e.g., rock bolts and/or screening).

The strength of a rock mass is usually based on the intact rock strength, but is reduced significantly to account for large-scale discontinuities. One of the most frequently cited failure criterion for rock masses is that proposed by Hoek and Brown (1980):

$$\sigma_{1f} = \sigma_3 + \sqrt{m\sigma_3\sigma_c + s\sigma_c^2} \qquad (2.5)$$

where σ_{1f} = stress at failure,
σ_3 = confining stress,
σ_c = uniaxial compressive strength of intact rock, and
m,s = empirical constants.

TABLE 2-1

PHYSICAL PROPERTIES OF RESEARCH AREA INTACT ROCK

Property	Research Area: Whiteshell	Research Area: Atikokan	Research Area: East Bull Lake
	Lac du Bonnet Granite (Katsube and Hume 1987, Jackson et al. 1989)	Eye-Dashwa Lake Granite	East Bull Lake Gabbro (Latham 1987)
Compressive Strength			
- Uniaxial (MPa)	187 ± 26*	212 ± 26	202 ± 50
- Triaxial Constants (m,s)			
- intact rock m_i@20-25°C, s	29.8, 1	33.5, 1	-
m_i@100°C, s	30.0, 1	36.5, 1	-
Young's Modulus (GPa)	67.1 ± 7.8	73.9 ± 5.2	86.9 ± 14.9
Poisson's Ratio	0.26 ± 0.05	0.26 ± 0.05	0.27 ± 0.05
Bulk Density (kg/m³)	2640 ± 60	2650 ± 20	2910 ± 80
Thermal Conductivity (W/(m·K))			
- 20-25°C	3.49 ± 0.35	3.17 ± 0.22	2.55 ± 0.72
- 100°C	3.18	2.76	-
Thermal Diffusivity (mm²/s)			
- 20-25°C	1.32 ± 0.23	1.22 ± 0.23	0.95 ± 0.23
- 100°C	1.15	-	-
Specific Heat (J/(kg·K))	1060 ± 200	1014 ± 200	1080 ± 194
Confined Coefficient of Linear Thermal Expansion (K^{-1})			
- 25-90°C	2.5×10^{-6}	2.8×10^{-6}	-

* ± denotes one standard deviation.

The empirical parameters m and s are in a general sense equivalent to the angle of internal friction and the cohesion of the rock mass. This empirical failure criterion requires an estimate of the rock-mass quality to establish the m and s parameters. If we assume that the rock mass would be sparsely fractured, then $s \simeq 1$ and m can be determined with the help of laboratory data.

Recent work at the Underground Research Laboratory (Martin 1993) has shown that the uniaxial compressive strength, σ_c, of Lac du Bonnet granite is not an intrinsic material property. Rather, it is an artifact of the testing procedure, which uses a relatively rapid rate of load application and does not allow time for microcracks to grow in the specimen. The uniaxial compressive strength is the short-term peak strength under rapid loading conditions and is not an appropriate basis for a failure criterion for designs requiring long-term performance.

Martin (1993) identified two intrinsic material properties, σ_{ci} and σ_{usc} (Figure 2-8), that provide a more appropriate basis for deriving a failure criterion for Lac du Bonnet granite. This confirmed work by Bieniawski (1967) in quartzite and by Rusch (1959) in concrete, which identified σ_{usc} as the long-term strength of these materials. σ_{ci} is the stress value at which stable microcracking will initiate in a brittle rock, and σ_{usc} is the stress value at which unstable crack growth will begin and represents the long-term strength for a brittle rock mass. A more appropriate failure criterion for design in rock where long-term strength is a factor may be derived by substituting σ_{ci} or σ_{usc} for σ_c in Equation (2.5).

The failure criterion based on σ_{ci} should be used for the design of underground openings if surface spalling conditions are to be avoided during excavation. The failure criterion based on σ_{usc} should be used for more general, uniform loading conditions in a rock mass, such as the thermal loading after disposal-room sealing and glacial loading.

All excavations within plutonic rock would display time-dependent microcracking as a stress-relief mechanism at material temperatures below 150°C (Wilkins and Rigby 1989). The rate of microcrack initiation and propagation would depend on the stress level and the material properties of the rock. The effect is nonelastic and irrecoverable since the cracking changes the physical properties of the rock. The modulus of elasticity and peak strength would be reduced and the microcrack population and the hydraulic permeability would be increased (Wilkins et al. 1985). Depending on the stress conditions, the microcracks might propagate to the extent of coalescing and form macroscale fractures in the excavation perimeters. This is often observed as slabbing and spalling (Martin 1989).

The stress relaxation associated with microcrack propagation and material property changes reduces the local stress concentration levels. Also, the stress gradients associated with the stress concentrations around the excavations diminish as a function of radial distance outward from the excavation perimeter. Thus, the rate of microcrack propagation decays rapidly with time and distance from the excavation perimeter (Wilkins and Rigby 1990, 1992). This has been observed by acoustic emission/microseismic monitoring in the high stress conditions surrounding the shaft of the

Underground Research Laboratory below 324 m (Talebi and Young 1989). Wilkins and Rigby's analyses and the Underground Research Laboratory experience show that time-dependent deformations, microcracking and excavation surface spalling decrease with time, and a stable excavation is achieved in a short period of time (i.e., in terms of days to weeks).

In addition to the thermal expansion stress, intragranular differential thermal expansion will occur between adjacent dissimilar mineral crystals, resulting in microcracking (Wilkins et al. 1987). The amount of microcracking will depend not only on the temperature increase but also on the degree of confinement on the rock. Short-term triaxial tests on intact rock show a decrease of peak strength as the temperature increases to 100°C. However, increasing the sample confining pressure tends to lessen this effect (Jackson et al. 1989). The effect of differential expansion would be very small for the conditions expected around a disposal vault (Wilkins et al. 1987).

While σ_{usc} would provide a good estimate for the long-term strength of the intact rock, rock loads slightly below this value can produce subcritical crack growth. This form of microcrack growth is frequently referred to as creep. For example, Schmidtke and Lajtai (1985) noted some failures in water-saturated specimens of Lac du Bonnet granite after 45 d with loads 15% lower than σ_{usc}. It is not clear whether laboratory test results can be applied directly to excavation design.

Field tests of excavations with stress concentrations that exceed σ_{usc} have been and are being performed in the Underground Research Laboratory to confirm the large-scale material response in situ (Read and Martin 1991). Experience in the unfractured rock of the Underground Research Laboratory has shown that localized rock failure occurs at stress levels above σ_{usc}, resulting in time-dependent formation of breakouts or notches in the excavation perimeters (Martin and Read 1992). The notches grew by rock spalling in the direction of the minimum principal stress acting on the opening, and reduced the zone of stress concentration to a smaller and smaller area at the tip of the notch until the process stopped. In this case of a 3.5-m-diameter tunnel, the total depth of each of the two diametrically opposite notches extended to a depth 40% greater than the original tunnel radius. The rationalization and selection of the strength criterion for a particular vault design would also consider factors relevant to the issue of radionuclide transport. In unfractured or sparsely fractured rock, these notches would not contribute to either a shortened or a higher velocity flow path for radionuclide transport, provided that the notches from each disposal room would be "cut off" by sealing methods in the disposal room and at the interconnecting tunnels.

In moderately fractured rock, which has a greater degree of hydraulic interconnection than sparsely fractured rock, the rock strength might not be a limiting performance criterion. The stress changes caused by excavation would change the normal and shear loads of pre-existing fractures. Coupled with the disturbance caused by excavation methods and with stress-induced microcracking, an excavation-disturbed zone could be created with the potential for increasing the local hydraulic permeability (Martin et al. 1990). The excavation disturbance and its effect on local hydraulic permeability has been examined theoretically (Pusch 1989, Kelsall et al. 1984).

The hydrogeological implications of an excavation-disturbed zone are difficult to measure because the zone is very close to the excavation boundary, which interferes with tests for connected permeability. One test has been completed in the sparsely fractured rock of the Underground Research Laboratory (Martin et al. 1992). The depth of the hydraulic pathway was limited to about 0.2 m from the excavation and was not well connected between the disturbed zones created by adjacent controlled blast rounds. The limited continuity would contribute to the effectiveness of a tunnel seal installed at this location. This type of test is qualitative and very location- and design-specific, depending on the rock properties, excavation blast design, tunnel geometry and in situ stresses.

Our purpose in presenting this discussion of in situ stress and strength is to familiarize the reader with the range of factors that may influence the extent of a temperature- and stress-induced disturbance of a rock mass as it affects excavation stability and local groundwater flow conditions. The number of factors and the extent of interrelationships are so extensive that the design process could include several iterations, each including a complete assessment of the performance of the disposal system. The significance of specific vault and site design elements on the overall performance of the system must be "fed back" from the disposal system assessment during each iteration. As an example of the type of feedback that might occur, the results of a sensitivity analysis (Chan and Stanchell 1990) on the overall hydraulic behaviour of a hypothetical disposal vault situated in the Whiteshell Research Area will be used. This study assumed porous-media equivalent materials, was limited to particle tracking of groundwater movement, and did not consider diffusion and dispersion processes. The results inferred that excavation disturbance might slow the rate of transport of vault contaminants through the geosphere by increasing the local porosity and by reducing the local groundwater velocity. The analyses also showed that an increase in the waste exclusion distance between the waste emplacement area and a nearby fault zone could be effective in reducing transport from the vault. The excavation-disturbed zone should not have significant effects on groundwater pathways from the vault, provided the shafts and tunnels are reasonably sealed and local hydraulic gradients are not parallel to the direction of these excavations. The major design decisions to accommodate site conditions can be made relatively quickly as long as there is effective interaction among the site characterization, performance assessment and design activities.

(iii) Seismic loading

The main design factors to deal with seismic loads would be the characterization of the long-term seismic hazard at each potential disposal site, the regional pattern of faults (Davison et al. 1994a), a vault design to minimize the number of fault intersections with the disposal vault shafts and tunnels, and the selection of an appropriate waste exclusion distance between the waste disposal rooms and adjacent faults (Figure 2-8).

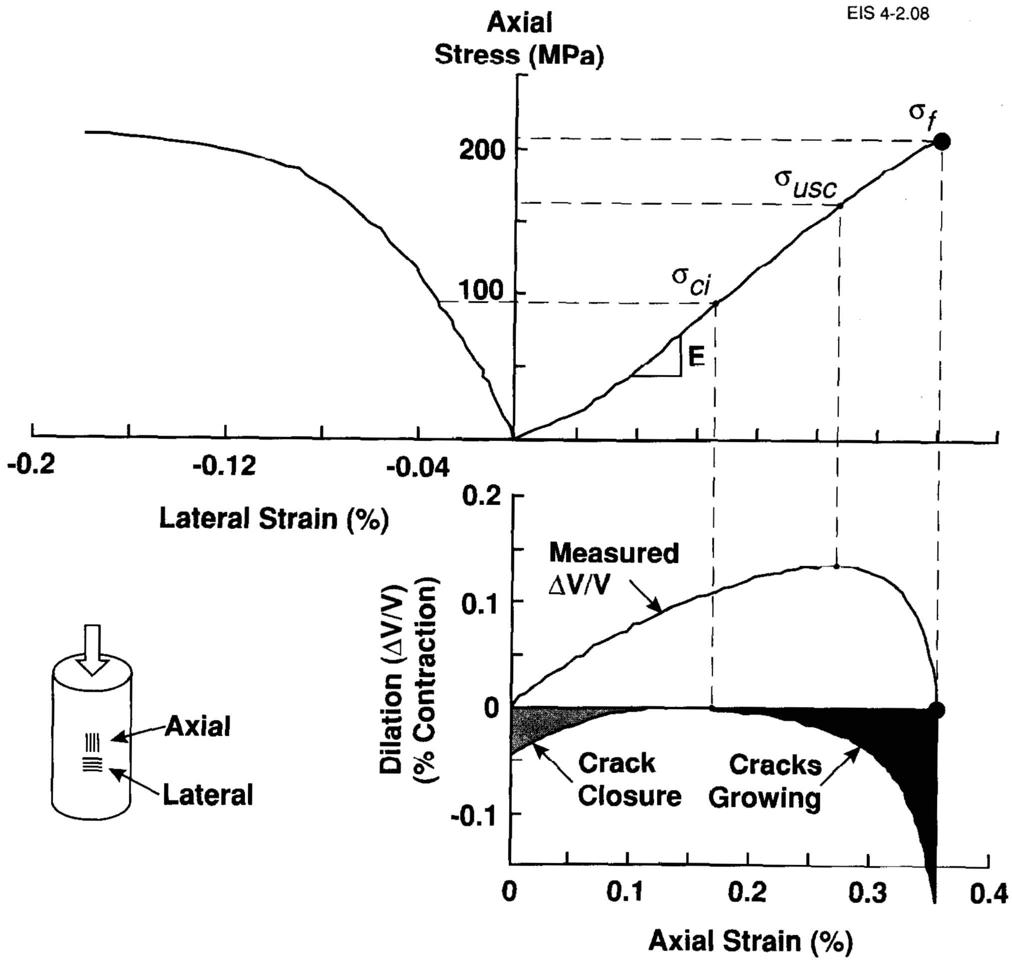

FIGURE 2-8: Typical Stress/Strain Characteristics of Lac du Bonnet Granite from Stress Domain I

Experience in California, Japan and Alaska has shown that tunnels suffered no damage below a peak ground acceleration of about 0.2 g (1.9 m/s^2) (Dowding 1978). Between 0.2 and 0.5 g, either no damage or only minor damage was experienced. The minor damage was in the form of tunnel liner cracking, surface spalling and minor rock falls. Although the amount and intensity of damage increased with increased acceleration in general, some excavations experienced no damage at accelerations up to 0.7 g.

Atkinson (1992) estimates that an earthquake in northwestern Ontario with a moment magnitude of 6.5 would produce a peak ground acceleration at the surface of 0.37 g at a surface distance of 20 km from the epicentre of an event that occurred at a depth of 10 km. The probability of this occurrence is discussed by Davison et al. (1994a). Ates et al. (1994a) suggest that backfilled and sealed tunnels and disposal rooms in sparsely and moderately fractured rock of the Canadian Shield should experience either no damage or only minor damage from earthquakes with a moment magnitude of 6.5 at surface distances of 20 km or more.

The intensity or degree of damage would be related to the local ground conditions. For example, in 1976 the magnitude 7.8 Tangshan earthquake (Lee 1987) produced variable damage throughout an underground coal mine located about 12-16 km directly above the hypocentre. The damage intensity increased with increasing fracture frequency in the rock mass, and there was major damage at the fault zones, where the shear strength of the rock mass is the lowest. In effect, each of the sparsely to moderately fractured rock masses delineated by the faults oscillated somewhat differently from the others, resulting in shear motion in the faults. These seismic ground motions may alter the hydraulic permeability distribution in the fracture network, and increased or new inflows of groundwater into excavations can be expected (Ates et al. 1994b). The increased or new inflows of groundwater should not affect the sealed disposal areas(s) of a disposal vault because they would be located in the intrablock areas of sparsely to moderately fractured rock away from hydraulically active fracture zones.

2.8 SUMMARY

This chapter presented many of the organizational, administration and design issues relevant to implementing nuclear fuel waste disposal. We have included this information to emphasize the need for

1. effective organization and assignment of responsibilities;

2. comprehensive and interactive project management;

3. an effective safety and health program, with due regard for legislation in a participatory environment;

4. an effective monitoring program in which the parameters and conditions monitored are sensitive to the performance of the disposal systems and its components; and

5. application of the observational method to accommodate the natural system variability and uncertainty.

We have also presented some of the important issues and factors that should be considered when implementing a disposal system, and some important site conditions that would affect the choices made in disposal vault design.

Having presented this general information, we now discuss the engineering and operational aspects of implementing disposal. This discussion is based on a reference disposal facility conceptual design (see Section 1.3 for a brief introduction) and is presented by project stage (defined in Section 2.5.1).

3. THE SITING STAGE OF THE USED-FUEL DISPOSAL CENTRE

3.1 INTRODUCTION

To better illustrate the engineering and operations of the systems and processes necessary to implement nuclear fuel waste disposal, the balance of this report is based on the Used-Fuel Disposal Centre introduced in Section 1.3.

The main facilities, processes and operations are described, beginning with the siting stage (Chapter 3) and progressing through the construction (Chapter 4), operation (Chapter 5), and decommissioning and closure (Chapter 6) stages.

This chapter focuses on the facilities needed in the siting stage for surface and underground evaluation, and on the specific design assumptions used and analyses performed in developing the Used-Fuel Disposal Centre conceptual design.

The Used-Fuel Disposal Centre conceptual design (AECL CANDU et al. 1992) is based on a specification derived from AECL's knowledge base as of 1985 (Baumgartner et al. 1993). The specific selection of the various system components (i.e., disposal container, borehole emplacement and sealing systems) was largely based on the systems that we know the most about and/or individual judgements on their suitability. No system or component optimization was attempted because this would have been premature, especially since the disposal site has not been selected.

Work on the Siting Program (Davison et al. 1994a), the Used-Fuel Disposal Centre conceptual design (AECL CANDU et al. 1992) and changes made in the conceptual design during the preparation of this report allowed us to define the durations of the project stages (see Section 2.5.1) as follows:

1. Siting Stage - 23 a.

2. Construction Stage - 7 a.

3. Operation Stage - 41 a.

4. Decommissioning Stage - 16 a.

5. Closure Stage - 2 a.

These are shown in Figure 3-1 along with the specific durations of the activities defined in Section 2.5.2 and the assumed licensing requirements as discussed in Section 2.2.2.

3.2 ENGINEERING DURING SITING

3.2.1 Site Screening and Evaluation

The major engineering activities during the siting stage of the Used-Fuel Disposal Centre (Figure 3-1) as defined in Section 2.5.1 include: interpreting the engineering data collected for each site and developing a conceptual design for disposal facilities at each site; designing and constructing access infrastructure and support facilities for surface-based evaluation at the potentially suitable site locations; contributing to the selection process to focus on fewer areas, eventually selecting one preferred site for underground evaluation; designing, constructing and operating the infrastructure, facilities and exploration excavations required for underground characterization and component testing; designing, conducting and analyzing the underground characterization and component tests; and completing construction designs for the disposal facilities using information collected from the surface and underground evaluation activities. The methods and techniques for siting are discussed by Davison et al. (1994a) and by Greber et al. (1994). The preclosure and postclosure environmental and safety assessment methodologies are discussed by Grondin et al. (1994) and by Goodwin et al. (1994) respectively.

The engineering effort increases through the screening, surface-based evaluation and underground evaluation substages. A relatively sparse amount of data would be gathered and assessed for many locations or areas within the Canadian Shield during site screening. Conceptual disposal facility and transportation system designs would be produced based on these data to identify any design and construction issues that may contribute to discriminating among the potential locations. These would also be useful in discussions with the public on potentially acceptable locations.

During surface-based evaluation, characterization activities would provide more information on a smaller number of areas that may contain suitable sites. The conceptual designs would become more specific for each area to reflect the specific conditions within the area. As the surface-based evaluation activities focus on a preferred site(s) within the area(s) being studied, a preliminary design for a disposal facility at that site(s) would be prepared using all available information on the conditions in and surrounding the preferred site(s). When a site is chosen for underground evaluation, the design of the selected surface facilities and the disposal vault elements would advance and detailed designs would be prepared for the surface infrastructure, headframes, hoisting systems and services necessary for the underground exploration shafts and tunnels. The permanency of these installations would depend on site-specific conditions. In some cases, they would be temporary and would be replaced during the construction stage, while in other cases they would be constructed to eventually become part of the disposal centre installations.

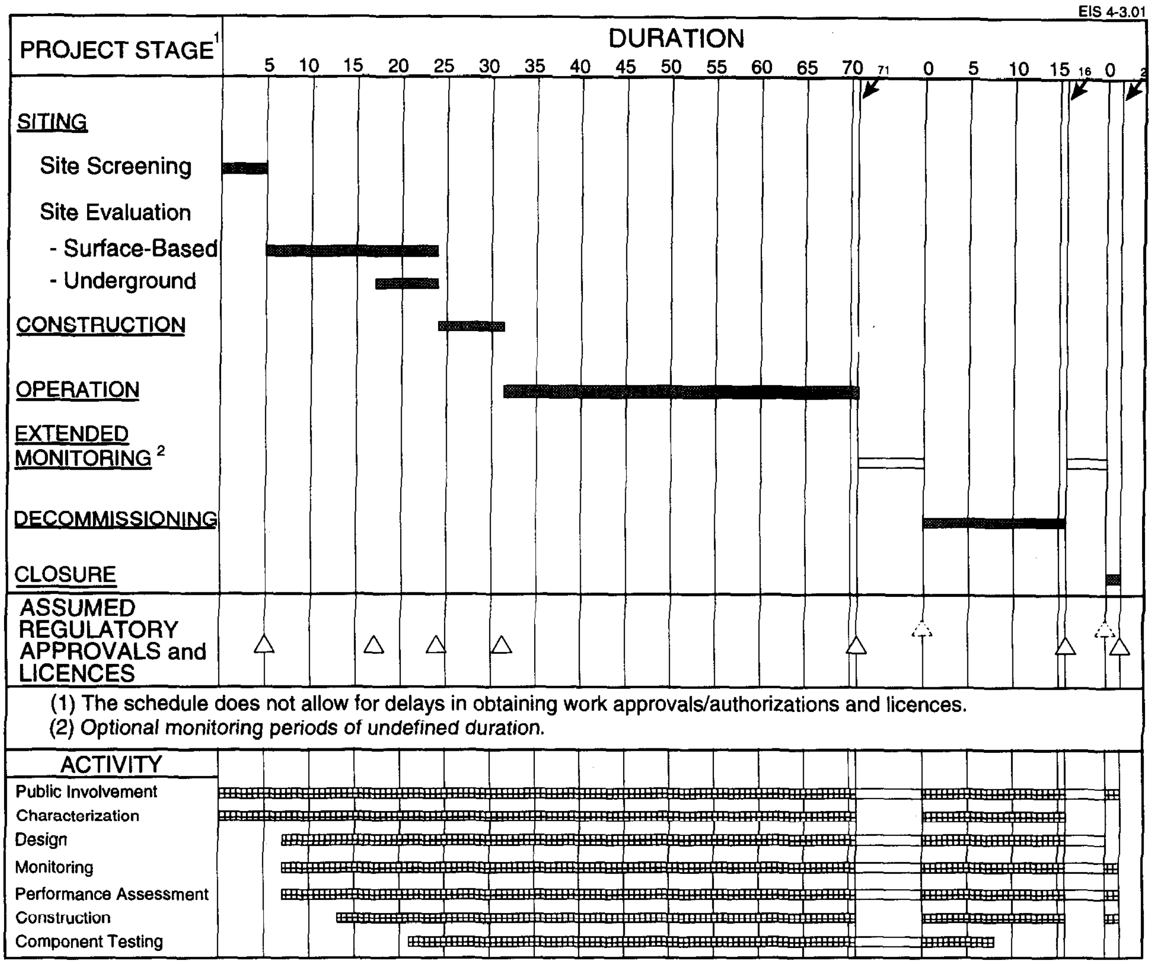

FIGURE 3-1: Schedule for the Used-Fuel Disposal Centre Project

3.2.2 Engineering During Underground Evaluation

3.2.2.1 Underground Exploration Facilities Construction

The decision to proceed with the construction of exploration shafts and tunnels for thorough underground evaluation at a preferred site represents a major commitment towards developing a disposal facility at that site because of the magnitude and cost of the work required. Underground evaluation involves several concurrent activities. The shafts, tunnels and rooms necessary to conduct the planned underground evaluation activities have to be constructed and serviced. The surface-based evaluation studies and monitoring programs already established would continue so that the effects of constructing the exploration excavations can be monitored.

These data are used to verify and refine the understanding of the site and its surroundings. The underground evaluation data would be collected and analyzed, and the disposal centre designs and performance assessment would be revised on the basis of the more detailed underground information.

The detailed design for the construction and the installations necessary for underground evaluation are used to initiate work. The number of exploration shafts to be constructed during site evaluation depends on the preliminary design for the disposal vault. If all the shafts for the disposal vault are planned to be located in one general area, only one exploration shaft is likely to be required. If the disposal vault design required shafts to be located in two or more widely separated groups, one exploration shaft in each group may be excavated. These shafts would likely be constructed at the location of the planned disposal vault shafts. Two shaft groups are used in the Used-Fuel Disposal Centre conceptual design (Section 4.3). Therefore, it is assumed that two shafts, the downcast ventilation shaft and the excavation panel upcast ventilation shaft, are excavated initially as exploration shafts (Figure 3-2).

The installations for this stage are an upgraded site access infrastructure, electrical power supply, water supply, and the headframes, hoists, service systems and buildings required to create and support the access to the underground.

After the exploration shaft(s) are excavated to the disposal vault horizon, an underground drilling and exploration tunnelling program would be undertaken to obtain data on the actual volumes of rock intended to contain the disposal rooms, service areas and the component test area. The suitability of the disposal horizon would be reassessed based on data collected from the shaft and the shaft station excavation, and from underground drilling and tunnelling at the vault horizon. The disposal vault design and performance assessment would be reviewed and revised to take account of the site-specific information from the characterization in and around these exploration excavations. The underground characterization methods and the data to be collected are discussed by Davison et al. (1994a) and by Everitt et al. (1994).

The underground exploration would be extended by excavating small exploration tunnels within the planned route of the disposal vault perimeter tunnels. This provides detailed data along the disposal vault perimeter and allows access at various locations for further drilling and testing to determine the important parameters to design the access tunnels, disposal rooms, service areas and the component test area of the disposal vault. The extent to which these exploration tunnels are excavated and exploration boreholes are drilled is a function of the complexity and variability of the characteristics of the site.

As the additional data from the characterization activities in the exploration excavations become available, they would be used continuously to confirm and refine the understanding of the site. The detailed design for the disposal vault excavations and installations would be refined and extended on the basis of this improved understanding. Some important elements of design such as the geometry of service areas, access tunnels and disposal

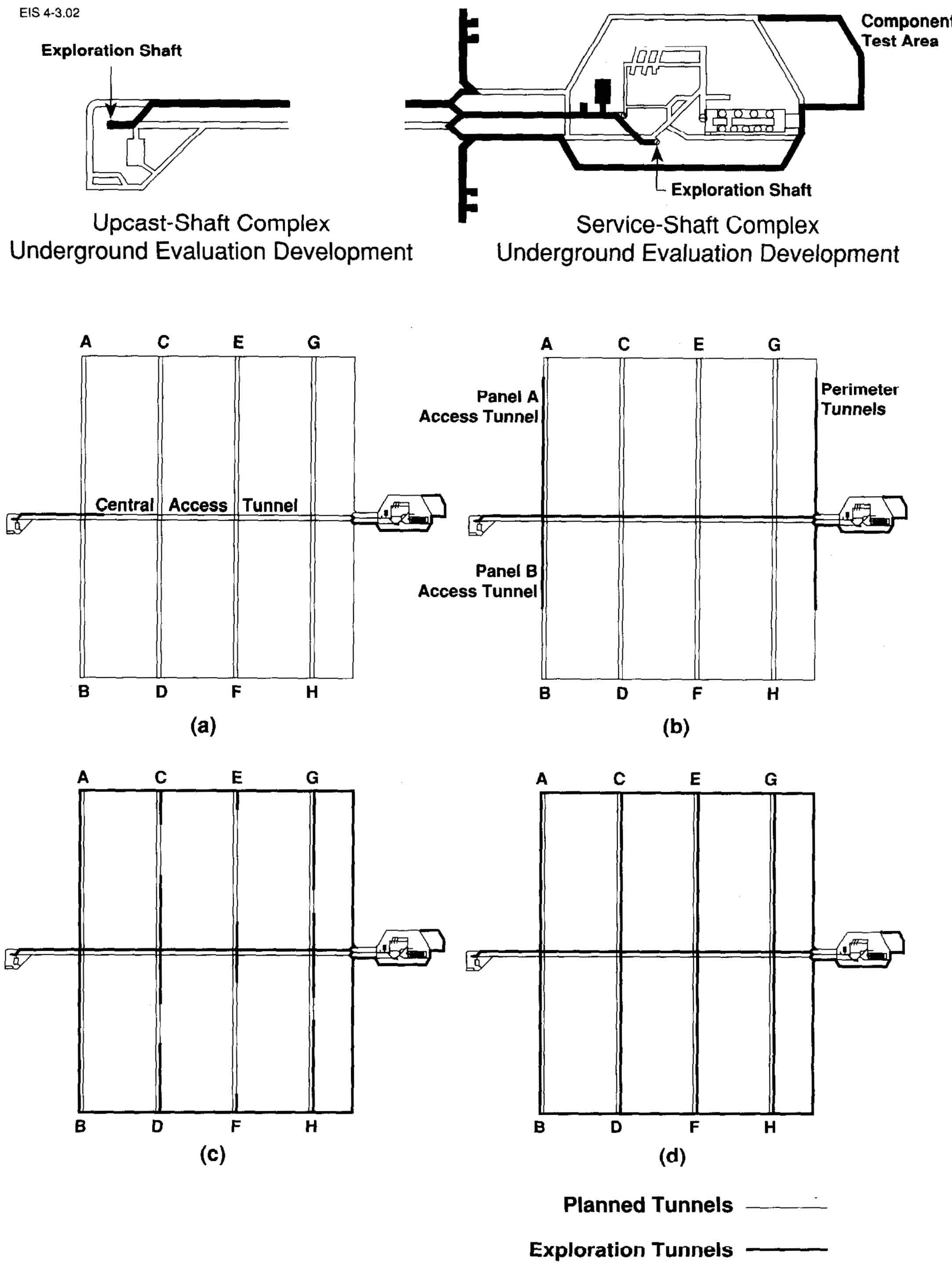

FIGURE 3-2: Underground Evaluation Construction Sequence

rooms, the design of permanent shaft installations, the geometric arrangement of the tunnels and rooms to provide the required operating logistics for occupational safety and nuclear materials safeguards, the provision of an adequate waste exclusion distance in the rock between any nearby major pathways of groundwater movement and emplaced waste containers, and the method of emplacing waste containers in the disposal rooms might be altered by this information.

The improved knowledge of the site conditions and the revised disposal vault designs developed using characterization data gathered from the exploration excavations would be used to update the performance assessment of the disposal system. The purpose is to confirm that all environmental and human safety criteria would be satisfied or to initiate design changes that would lead to them being satisfied. The monitoring program would be reviewed and expanded to incorporate some of the instrumentation installed during the underground evaluation, and to specify those additional monitoring systems that must be implemented to prepare for construction of the disposal facility.

3.2.2.2 Component Test Area

There would be an extensive monitoring program to gather data on the effect of the disposal system in the four environments, as discussed in Section 2.4.2.2. If carefully planned, this monitoring in the biosphere, the vault, human communities and most of the geosphere could be done directly, with no effect on the performance of the disposal system. It might not be possible to install monitoring systems in the disposal vault and in the geosphere very near to the waste-disposal rooms without locally threatening the long-term performance of the disposal system. Monitoring systems would have to be invasive to gather data from the container, the sealing systems, and the volumes of a rock immediately surrounding the waste-disposal rooms and emplaced container. Data on the performance of these systems would be obtained with little effect on the long-term disposal system by establishing controlled tests in locations where the containers could later be removed and emplaced in a final disposal environment. These component test locations may be separate from the disposal rooms (e.g., in a single-component test area), strategically located in representative conditions within the disposal vault in specially excavated rooms, or some combination of the two. For this Used-Fuel Disposal Centre conceptual design, it has been assumed that all such tests are located in the component test area near the planned service-shaft complex (Figure 3-2).

A series of physical materials property tests, technology demonstration tests and performance assessment tests would be conducted in the component test area(s) to provide information on the short-term in situ performance of the specific site. The physical and chemical properties of the rock mass, the procedures and equipment to be used in construction, and some of the systems required for operation would be developed and demonstrated in the component test area during the siting stage. This testing provides the initial data for design and process optimization, and reduces the amount of refinement that would be necessary during the construction stage.

Studies will proceed during the construction stage to develop and demonstrate the systems, procedures and equipment required in the operation stage. Tests will be installed to assess the performance of individual disposal-system components and of combined disposal-system components, and may extend over the operating life of the vault. In particular, the large-scale properties and characteristics of the rock mass and groundwater system, and the independent and coupled performance of various system seals will be tested. These tests will be designed to evaluate the performance of individual system components and interactive effects between components. They could include

1. tests to evaluate the response of the rock mass, groundwater systems, buffer and backfill systems to changes caused by excavation and heating;

2. solute transport studies;

3. emplacement of recoverable used-fuel containers to do detailed monitoring of their performance over the operating life of the vault;

4. emplacement and testing of borehole seals;

5. emplacement and testing of shaft and tunnel seals to demonstrate their performance;

6. material corrosion tests in the natural environment; and

7. demonstration of construction methods and of the suitability of quality-control procedures.

The tests would begin during the construction stage and would be performed, monitored and analyzed over the entire period during which the vault would be open (i.e., the tests would be dismantled during the Decommissioning Stage). The primary purpose of these tests is to confirm the longer term performance of these elements of the disposal systems over several decades, and to support the application for approval to decommission and close the vault. The component test program will evolve as the vault operations progress and may continue through an extended monitoring stage if extended monitoring activities are carried out before the disposal vault is decommissioned. The component test area(s) will be disassembled and sealed during decommissioning.

The types of tests will be planned when the site-specific properties and vault design are established. The experience from AECL's Underground Research Laboratory (Peters et al. 1994; Simmons 1988, 1990) and from other underground laboratories in Sweden (OECD 1983, 1985, 1990) and Switzerland (NAGRA 1985b) provides a basis for designing and conducting component tests.

3.2.2.3 Schedule for Underground Evaluation Activities

The underground evaluation substage in this Used-Fuel Disposal Centre conceptual design takes about six years to complete (Figure 3-3). It will

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DESCRIPTION	SIZE (m)	QTY (m)	TIME (months)
A) SHAFT SINKING			
MOBILIZATION & SET-UP			3
#1 Exploration Shaft [1]	4.6 I.D.	1075	27
#2 Exploration Shaft [1]	4.6 I.D.	1075	27
#1 Headframe			6
#2 Headframe			6
B) LEVEL EXCAVATION			
#1 Shaft Complex			1.7
#2 Shaft Complex			2.7
Central Access Tunnel [2]	4 x 3.5	2140	4.25
Perimeter Access Tunnel	4 x 3.5	2815	12.5
Panel Access Tunnel - A	4 x 3.5	1030	5
Perimeter Access Tunnel	4 x 3.5	2815	12.5
Panel Access Tunnel - B	4 x 3.5	1030	5
Panel Access Tunnel - G	4 x 3.5	1030	5
Panel Access Tunnel - H	4 x 3.5	1030	5
Panel Access Tunnel - E	4 x 3.5	1030	5
Panel Access Tunnel - F	4 x 3.5	1030	5
Panel Access Tunnel - C	4 x 3.5	1030	5
Panel Access Tunnel - D	4 x 3.5	1030	5
C) CHARACTERIZATION			
Mapping			57
Exploratory Drilling			27.5
D) COMPONENT TEST AREA			
Access Tunnel		300	1.5
Test Excavations (equiv. m)	8 x 5.5	1500	7
Component Testing			27

(1) Including instrument arrays
(2) Two crews

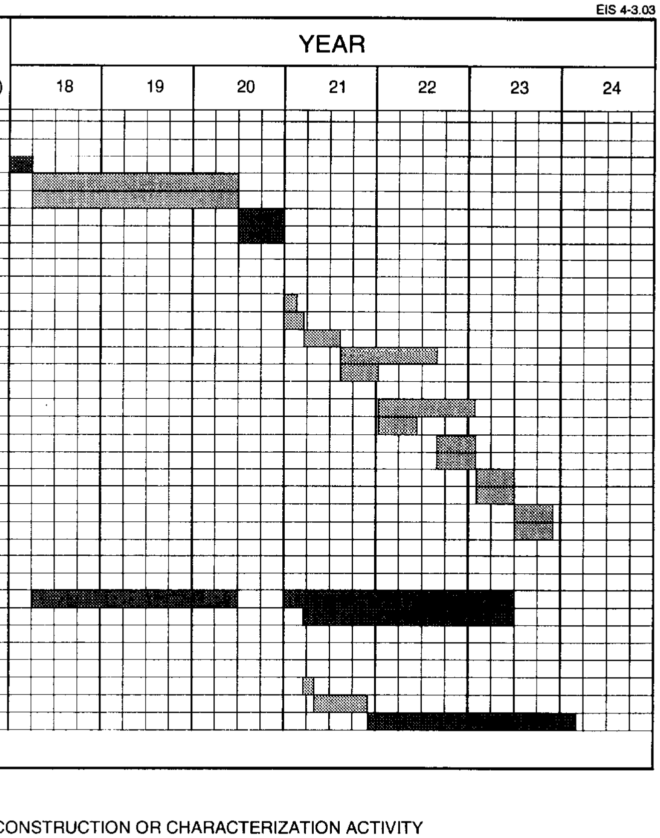


FIGURE 3-3: Underground Evaluation Schedule

take about three years to sink and equip two exploration shafts to an assumed depth of 1000 m, with excavation work taking place two shifts per day, seven days a week, and geotechnical characterization taking place during the third shift of each day. The duration of the shaft excavation includes a total of 40 weeks in each shaft to allow for the installation of rock mass and groundwater response monitoring instrument arrays (assumed to be 10 arrays at 4 weeks/array).

The exploration tunnels on the vault horizon along the route of the planned access tunnels (central, perimeter and panel access tunnels) shown in Figure 3-2 will require about three years for excavation. Initially, the central access tunnel is excavated between the bases of the two exploration shafts (Figure 3-2a). The excavation of the two perimeter tunnels and the panel A and B access tunnels to delineate the outer vault boundaries follows the breakthrough of the central access tunnel (Figures 3-2b and 3-2c). Underground mapping and characterization proceeds concurrently with tunnel advancement. It is assumed there will be three excavation crews per shift, and the characterization crews will work on a three shifts per day, seven days per week schedule. Because excavation occurs at several locations concurrently, the ongoing characterization activities will be scheduled at free locations to minimize disruptions to the overall excavation productivity, as demonstrated on the 240 Level at the Underground Research Laboratory (Kuzyk et al. 1987b). Exploration diamond drilling also proceeds concurrently with excavation.

The excavation of a component test area also occurs simultaneously with the excavation of the central access tunnel, and is considered a priority because of the need for testing. The excavation of the test area will require about a year. The testing and demonstration program in the component test area begins during the latter part of the siting stage and continues until the decommissioning stage.

Excavation of the remaining panel access tunnels will be completed (Figures 3-2c and 3-2d) following completion of the component test area and the vault perimeter excavations.

It is anticipated that the vault configuration at an actual site would be designed to account for local site-specific information, and could be significantly different from the simple vault configuration shown in Figure 1-3. An example of a more complex vault design is shown in Figure 2-8, where the vault has been arranged as several segments in the blocks of rock between the faults and the fracture zones. This complexity might extend the time necessary to develop exploration tunnels on the vault level, particularly if exploration drilling is required to establish local conditions before tunnel excavation proceeds.

On the other hand the duration of and activities in underground evaluation could be reduced if the knowledge gained in early work either confirmed the geotechnical models developed in surface-based evaluation or led quickly to validated models that provided a basis for design. This would be governed by the complexity and variability of the site.

3.3 USED-FUEL DISPOSAL CENTRE CONCEPTUAL DESIGN ASSUMPTIONS AND ANALYSES

3.3.1 Introduction

The Used-Fuel Disposal Centre conceptual design is a generic study not fully related to conditions at any particular site. Therefore, the data that would normally evolve from site-specific field activities have been assumed so that the design analyses necessary for the conceptual design could be completed. This section discusses the assumptions made and the design analyses undertaken in the conceptual design process. The management, administration and design factors and issues discussed in Chapter 2 were considered in completing the conceptual design.

Although the discussion that follows involves only one set of analyses, the design process during the siting stage of an actual disposal facility would involve several iterations. Each iteration would use improved data from the siting activities and feedback from the performance assessment of the disposal system.

3.3.2 Used Fuel and Packaging Assumptions

3.3.2.1 Quantities, Source and Disposal Rate

The total mass of used fuel assumed for disposal in the conceptual design is 191 133 Mg of elemental uranium in the form of used fuel from CANDU reactors (Baumgartner et al. 1993). This represents about 10.1 million used-fuel bundles. This estimate was based on the assumption that all nuclear-electrical generating capacity existing or under construction in Canada after 1986 would be maintained, one additional CANDU reactor would be built in Canada outside of Ontario, and the annual growth rate of nuclear-generated electricity in Ontario after 1995 would be 3%. The vault capacity was determined by the number of used-fuel bundles accumulated by the year 2035.

During the development of the study specification, this estimate of used-fuel arisings was considered to be a reasonable basis for conceptual design. However, there is considerable uncertainty in the projection of used-fuel arisings because of the wide range of economic, social and political factors that may influence the expansion of nuclear-electric generation. The current projection by Ontario Hydro (1991), the major nuclear utility in Canada, is for 75 000 Mg of used fuel to be accumulated during the 40-a operating life of the Pickering A and B, Bruce A and B, and Darlington nuclear generating stations, with no replacement of stations beyond their life cycle. This is equivalent to about 4 million used-fuel bundles, significantly less than the amount assumed in the Used-Fuel Disposal Centre conceptual design.

The conceptual design developed is flexible and modular, allowing the capacity to be changed with no fundamental change in the proposed processes and operations. The capacity of the used-fuel transportation system has been assumed to be about 250 000 used-fuel bundles per year for this conceptual design. This quantity is enough to fill 3471 disposal containers per year. About 41 a will be required to dispose of 10.1 million used-fuel bundles at this disposal rate.

3.3.2.2 Used-Fuel Characteristics

The reference fuel bundle specified by Baumgartner et al. (1993) is the CANDU fuel bundle designed for the Bruce Nuclear Generating Station. This bundle consists of 37 fuel elements and is about 495 mm long and 102 mm in overall diameter (Figure 2-3). The mass of the bundle is 23.74 kg and it contains 18.93 kg U. The average fuel burnup chosen for the thermal and thermal-mechanical calculations was 685 GJ/kg U, the mean burnup from the Bruce Nuclear Generating Station. This yields a heat output of about 4.13 W/bundle for a cooling period of 10 a out-of-reactor. A conservative assumption of 1008 GJ/kg U was selected for the radiation shielding calculations, taking into account the wide range of fuel burnup in the Bruce reactors. About 90 to 95% of the burnups determined for the reference used-fuel bundle would be less than this value. Details on shielding requirements are provided by Baumgartner et al. (1993) and by AECL CANDU et al. (1992). Fuel bundles for other CANDU nuclear generating stations are similar in composition and geometry, and are amendable to the same packaging and disposal methods.

In this conceptual design, the cooling time for all used fuel received at the disposal centre is assumed to be 10 a out-of-reactor. In practice, much of the used fuel in Canada would be considerably older than this, with a correspondingly reduced heat and radiation output, by the time disposal is implemented. This introduces a degree of conservatism to the design in terms of both radiological safety for workers and heat output from each container.

The heat output is shown in Figure 3-4 as a function of time for a container with 72 fuel bundles. Further details on used fuel are given by Johnson et al. (1994a).

3.3.2.3 Used-Fuel Disposal Container Specifications

The reference used-fuel disposal container design is a titanium-shell, packed-particulate container (Teper 1985, Johnson et al. 1994a). It consists of a thin-walled container holding a basket of 18 bundle-retaining

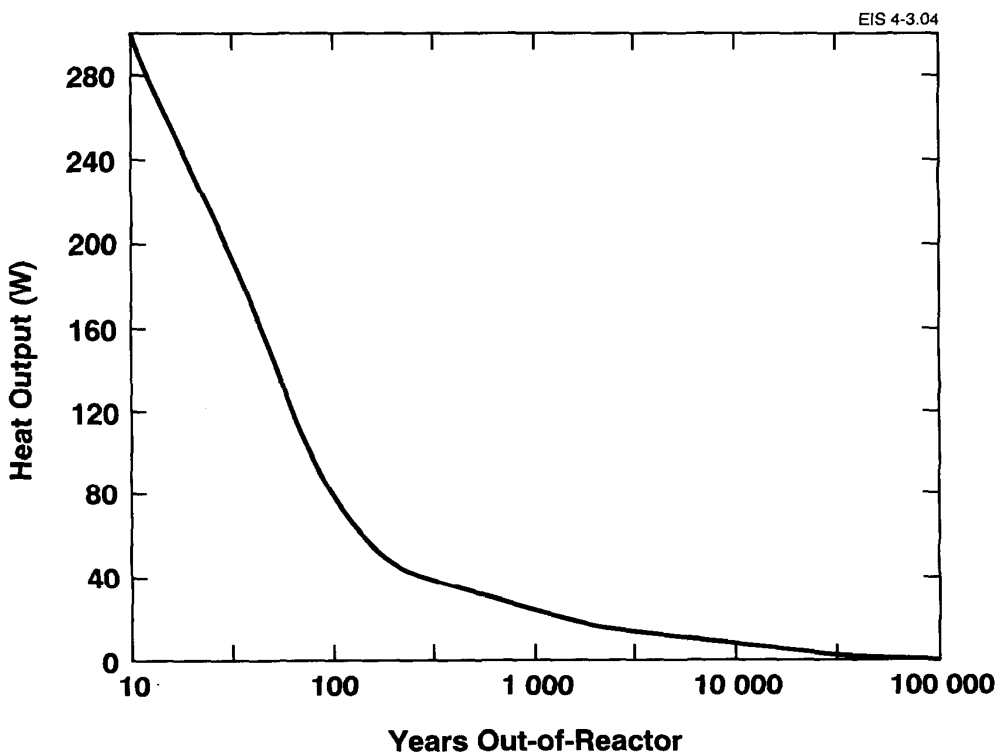


FIGURE 3-4: Used-Fuel Disposal Container Heat Output as a Function of Time

tubes (Figure 3-5). These thin-walled, mild-steel tubes, 114 mm in diameter and 2000 mm long, are placed around a central thick-walled pipe. Each of the 18 tubes will hold four used-fuel bundles, for a total of 72 bundles in the basket. The basket is contained in a 6.35-mm-thick ASTM SB-265 Grade-2 titanium container shell and top and bottom heads. All the void space around the basket and fuel bundles within the container is filled with a vibrationally compacted glass-bead particulate ranging in size from 0.7 to 1.0 mm in diameter. The container-shell and bottom-head seams are joined by gas-tungsten-arc butt welding. The top head is attached by diffusion bonding.

The maximum temperature that the outer surface of the container is allowed to experience at any time within the vault environment is set at 100°C (Johnson et al. 1994a). The container properties assumed for heat transfer analysis are shown in Table 3-1.

3.3.2.4 Schedules and Capacities

Assumptions have been made regarding the schedules, annual used-fuel quantities to be handled, and the surge-storage requirements necessary to accommodate disruptions in the used-fuel handling systems as a basis for developing the Used-Fuel Disposal Centre conceptual design. These are not specific recommendations or requirements for the implementation of disposal at a specific site. However, they are factors that would have to be specified for any project undertaken.

(i) Schedules

It is assumed that activity is continuous 24 h/d, 7 d/week during the siting, construction, decommissioning and closure stages. There would be noncritical-path activities within this schedule that could be done on a less continuous basis if it were cost-effective to do so.

During the operation stage, the used-fuel receipt, packaging, and disposal activities and disposal-room excavation activities are assumed to require 16 h/d, 5 d/week. The site security, fire protection, and utility operation continues 24 h/d, 7 d/week. The used-fuel handling activities are scheduled on a calendar that comprises thirteen 28-d cycles per year. Each cycle includes twenty 16-h working days. The Container and Basket Fabrication Plant and the Used-Fuel Packaging Plant are assumed to operate for 12 of the 13 cycles less 10 statutory holidays and to use the thirteenth cycle for vacations and shutdown maintenance, giving two hundred thirty 16-h working days per year. The disposal vault activities are assumed to take place during all 13 cycles, giving two hundred sixty 16-h working days per year.

Ample time is allowed in this working schedule to accommodate any underestimates in the duration of individual operations and activities. Any additional time required for these activities could be taken from the "non-working" shifts in the schedule through use of overtime or the introduction of an additional scheduled work shift(s).

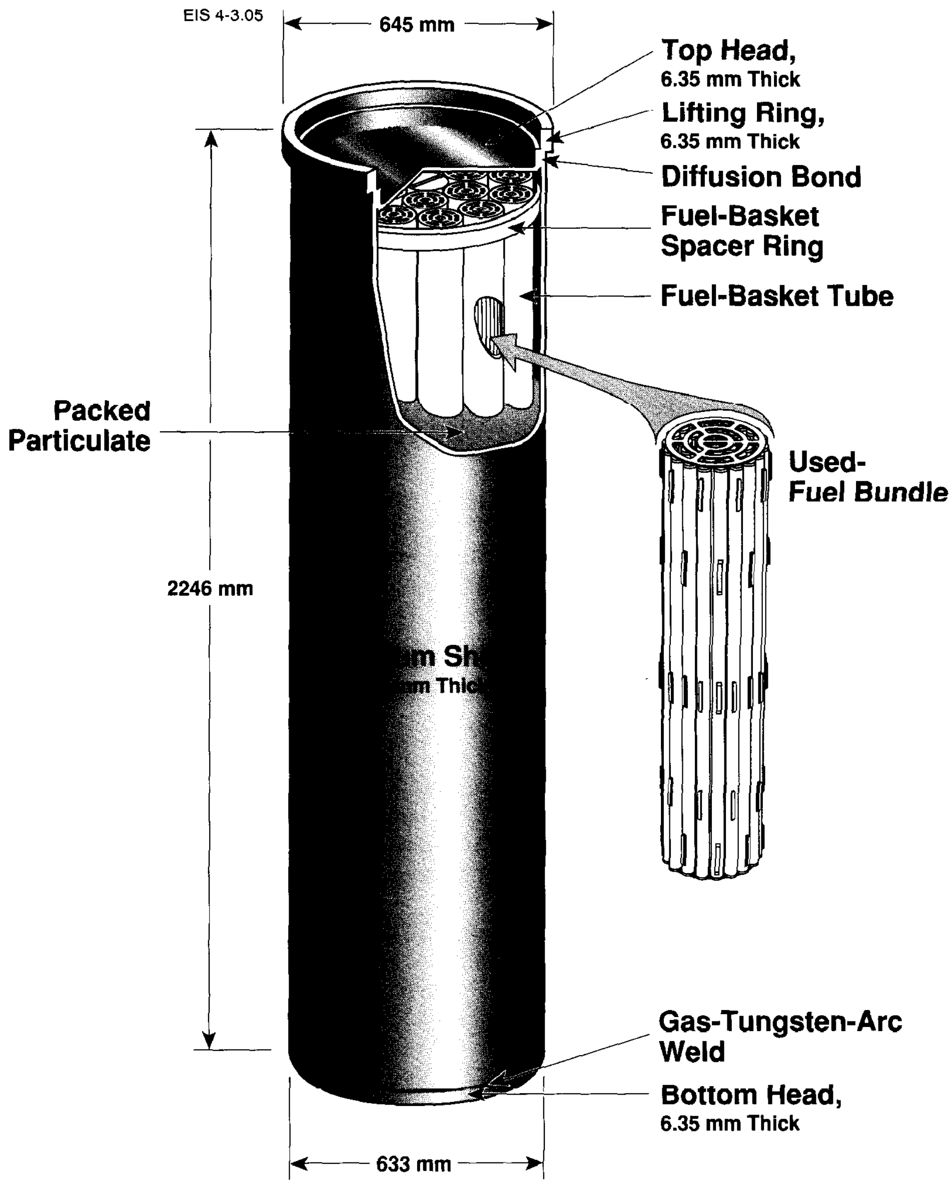


FIGURE 3-5: Titanium-Shell, Packed-Particulate Used-Fuel Disposal Container

TABLE 3-1

THERMAL AND THERMAL-MECHANICAL MATERIAL PROPERTIES

(after Baumgartner et al. 1993)

Property	Granite Rock Mass	Buffer and Backfill	Container
Thermal Conductivity (W/(m·°C))	3.0	1.5	1.4
Specific Heat (J/(kg·°C))	845	750	500
Dry Mass Density (kg/m³)	2650	1670/2100	3980
Young's Modulus (GPa)	35	0.2	0.2
Poisson's Ratio	0.25	0.4	0.4
Coefficient of Thermal Expansion (10^{-6}/°C)	8	0	0
Blast Fracture Zone (BFZ) (m)	0.5*	NA**	NA
Young's Modulus in Blast Fracture Zone (E_{BFZ}) (GPa)	0 to 35* (from 0.0 to 0.5 m into the rock wall)	NA	NA

* Values specified by Baumgartner et al. (1993) but not used in the subsequent analyses as they could not be justified from experience.

** Not applicable.

(ii) Used-fuel capacities

The sequence of activities in the disposal vault operation is based on emplacing and sealing a disposal container in each usable emplacement borehole in a disposal room in one 28-d cycle. Each disposal room could have up to 282 emplacement boreholes, although the actual number drilled and the actual number used for disposal in a room will depend on the local geological and hydrogeological conditions. Therefore, there is a peak potential requirement for 282 containers per cycle or 3666 containers per year.

The Used-Fuel Disposal Centre conceptual design has a maximum potential for 512 rooms, which could have up to 144 384 emplacement boreholes. The assumed quantity of used fuel to be disposed of in the lifetime of the vault is about 10.1 million used-fuel bundles, which would fill 140 256 disposal containers. Therefore there is a surplus of 4128 emplacement boreholes within the conceptual design to allow for avoiding some areas of the local geology or rejecting some drilled emplacement boreholes. This allows for a "rejection rate" of about 3%.

If we assume that this borehole rejection rate occurs uniformly over the operation stage, it amounts to emplacing an average of about 3558 containers per year. As the basic annual production of containers is 3471, there may be a need to produce between 196 (upper bounding case) and 88 containers (average case) additional containers in some years. It would require between 6 and 12 days additional operation of the Used-Fuel Packaging Plant to prepare the additional containers. The used-fuel bundles for this additional production would be available in surge storage as discussed below.

(iii) Surge-storage requirements

A surge-storage capacity is provided in the Used-Fuel Disposal Centre conceptual design to minimize the effect of disruptions in the transportation, packaging or disposal operations, and to provide a reserve of used-fuel bundles and disposal containers to meet the potential variation in the rates of disposal container emplacement. Table 3-2 outlines the specified surge-storage capacity at various locations in the disposal facility.

The surge storage would contain about 305 full used-fuel disposal containers, which is equivalent to 20.5 d of normal production. These may be used to supply the extra requirements of the disposal vault. The used fuel necessary to fill another 509 disposal containers, which is equivalent to 34 d of normal packaging-plant operation, would also be in surge storage.

These disposal containers and other fuel bundles in surge storage provide the flexibility to accommodate minor disruptions in the shipping of used-fuel bundles to the disposal site, short periods when the disposal-container emplacement rate exceeds the production rate, and disruptions in the surface and underground operations.

The reserve (unused) capacity in the surge-storage areas provides the flexibility to continue receiving and/or packaging during disruptions in operations in the packaging plant and/or disposal vault. It also provides the flexibility to accelerate the rate of used-fuel transportation during periods convenient for the nuclear generating stations with a minimum of disruptions to the operations of the Used-Fuel Disposal Centre.

3.3.3 Vault Sealing Components

Clay-based sealing materials specified for the conceptual design are based on the results of the vault sealing research program (Johnson et al. 1994a). Cement-based materials are restricted from use in close proximity to the emplaced waste because the effect of the cement on the local groundwater chemistry, the waste form and the other engineered barrier materials is at the present time uncertain. Concretes may be used for bulkhead construction at the disposal-room entrance and in access tunnels and shafts, and cement-based grouts may be used to control groundwater movement into the excavation and around seals.

The two clay-based sealing materials specified are the reference buffer material and the reference backfill material. The buffer (Dixon and Gray 1985) is a mixture of sodium-bentonite clay (a montmorillonite-rich clay found in commercial quantities in the central plains of North America) and

TABLE 3-2

SURGE-STORAGE CAPACITY

Surge-Storage Area (see Section 4.4 for local arrangement and description)	Specified Capacity		
	Storage/Shipping Modules	Disposal Containers	Equivalent Days of Disposal Vault Operation* (rounded off)
Full Transportation Cask Laydown Area (when ½ full)	57	NA**	5
Receiving Surge-Storage Pool (when ½ full)	325	NA	29
Headframe Surge-Storage Pool (when ½ full)	NA	290	19.5
Headframe Container-Cask Laydown Area (when ½ full)	NA	4-5	0.5
Disposal Vault Cask Storage Area (when ½ full)	NA	8	0.5

* Number of days the disposal vault could operate on the used fuel or disposal containers in surge storage.

** Not applicable.

well-graded silica sand mixed in a 1:1 dry mass ratio. The buffer material properties are presented in Tables 3-1 and 3-3. The buffer is compacted in place in layers to achieve a near-homogeneous mass with a minimum dry density of 1.67 Mg/m^3 at an optimum moisture content of 17 to 19%. The minimum dry density is 95% of the dry density attainable in ASTM test D-1557-78 (ASTM 1982).

The buffer serves as the sealing material surrounding the used-fuel container. The option of compacting the buffer in layers in the borehole before preparing for container emplacement (Wardrop et al. 1985) was chosen to provide occupational radiological protection, to meet buffer compaction quality-control specifications and to prevent container damage by compacting buffer immediately around the container.

TABLE 3-3

SPECIFICATION FOR REFERENCE BUFFER MATERIAL

(after AECL CANDU et al. 1992)

Parameter	Silica Sand	Bentonite	Reference Buffe
Moisture Content (mass %)			
Liquid limit	NA*	210	135
Plastic limit	NA	45	18
Air dry	0.5	6 to 7	3 to 5
Minimum Specific Surface (m^2/g)	NA	590	290
Predominant Clay Mineral	NA	Sodium montmorillonite	Sodium montmorillonite
Cation Exchange Capacity, (meq/100 g)** (approximate)	NA	40	80
Particle Size Distribution (mm)	(% Passing)	(% Passing)	(% Passing)
2	92-100	100	96-100
1.5	86-98	100	92-100
1	76-88	100	88-94
0.5	52-64	100	76-82
0.25	24-35	100	62-68
0.1	1-11	100	51-56
0.06	0-6	100	50-53
0.002	0-2	70	35-36
Minimum Dry Density (Mg/m^3)	NA	NA	1.67
Compaction Water Content (%)	NA	NA	17-19

* Not applicable.

** meq = milliequivalents.

The reference backfill material (Yong et al. 1985) is a mixture of glacial-lake clay (an illite-rich lake clay deposited in glaciated regions of North America) and crushed granite mixed in a 1:3 dry mass ratio. The reference backfill properties are presented in Tables 3-1 and 3-4. The backfill is compacted into place in layers to achieve a near-homogeneous mass with a minimum dry density of 2.1 Mg/m^3 at a moisture content of 6 to 8%. The minimum dry density is 95% of the dry density attainable in ASTM test D-1557-78 (ASTM 1982).

The need for two backfill materials for sealing tunnels and rooms was identified in the course of the conceptual design study (AECL CANDU et al. 1992). The reference backfill was specified for the lower portion of the

TABLE 3-4

SPECIFICATION FOR REFERENCE BACKFILL MATERIAL

(after AECL CANDU et al. 1992)

Parameter	Crushed Granite	Glacial-Lake Clay	Reference Backfill
Moisture Content (mass %)			
Liquid limit	NA*	112	28
Plastic limit	NA	31	not plastic
Particle Size Distribution (mm)	(% Passing)	(% Passing)	(% Passing)
19.1	100	100	100
12.7	85-100	100	89-100
10.0	79-95	100	84-96
6.0	63-83	100	72-87
2.0	36-60	100	52-70
1.5	27-53	100	45-65
1	20-47	100	40-60
0.5	12-37	100	34-53
0.25	0-27	100	25-45
0.10	0-16	100	25-37
0.064	0-13	99	25-35
0.01	0-10	95	24-31
0.004	0-10	82	21-28
0.002	0-5	67	17-21
Minimum dry density (Mg/m^3)	NA	NA	2.1
Compaction water content (%)	NA	NA	6-8

* Not applicable.

disposal rooms, which overlies the emplacement boreholes in the floor. It also was specified as the sealing material for the lower portion of all other horizontal excavations (tunnels and ancillary service rooms) and for the shafts. The placement and compaction methods for the lower backfill are discussed further by AECL CANDU et al. (1992) and in Section 5.4.6.

The thickness of this lower backfill material is limited by the headroom required to operate the placement and vertical compaction equipment. An upper backfill identical in composition to the buffer material was chosen to fill the void remaining above the lower backfill for this conceptual design study. The material selection and placement method for upper backfill are discussed further in Section 5.4.6.

Concrete bulkheads are installed immediately following backfilling in the entrance to each disposal room, and later at strategic locations in the access tunnels and shafts when they are backfilled. One purpose of the bulkheads is to provide a means of closing the rooms to protect the integrity of the sealing materials. It also provides an opportunity for applying a nuclear materials safeguards seal that will allow detection of tampering with the filled room. AECL CANDU et al. (1992) present a method for constructing these bulkheads.

In the conceptual design study, it is assumed that each disposal room will be backfilled and sealed with a concrete bulkhead as soon as all the emplacement boreholes have been either filled with a disposal container surrounded by buffer or filled with buffer if no container is to be placed in the borehole. This is done to maintain the integrity of the buffer material, to allow vault operations to continue without having to routinely maintain the disposal rooms that have been filled with containers but are not backfilled, and to avoid the use of restraint structures to prevent the extrusion of the swelling buffer from emplacement boreholes. Without either room backfilling or the use of an extrusion restraint, any volumetric expansion of the bentonite clay in the buffer would reduce the dry density of the clay and so would reduce its effectiveness as a sealing material.

3.3.4 Materials Handling Systems

3.3.4.1 Used-Fuel Handling and Transfer

A shielded, contact-handling system for used-fuel transfers was specified for the Used-Fuel Disposal Centre conceptual design study. Shielding casks are required to transfer used fuel from a nuclear generating station to the Used-Fuel Packaging Plant, and to transfer disposal containers from the packaging plant to the emplacement boreholes in the disposal vault. Ontario Hydro (1989a) has developed and licensed a road transportation cask for used fuel (Figure 3-6), and has developed a conceptual design for a rail transportation cask (Figure 3-7). In the conceptual design study, these are assumed to be the casks in which used fuel would arrive at the Used-Fuel Disposal Centre.

Cask-loading/unloading operations at the disposal centre are normally performed at four locations:

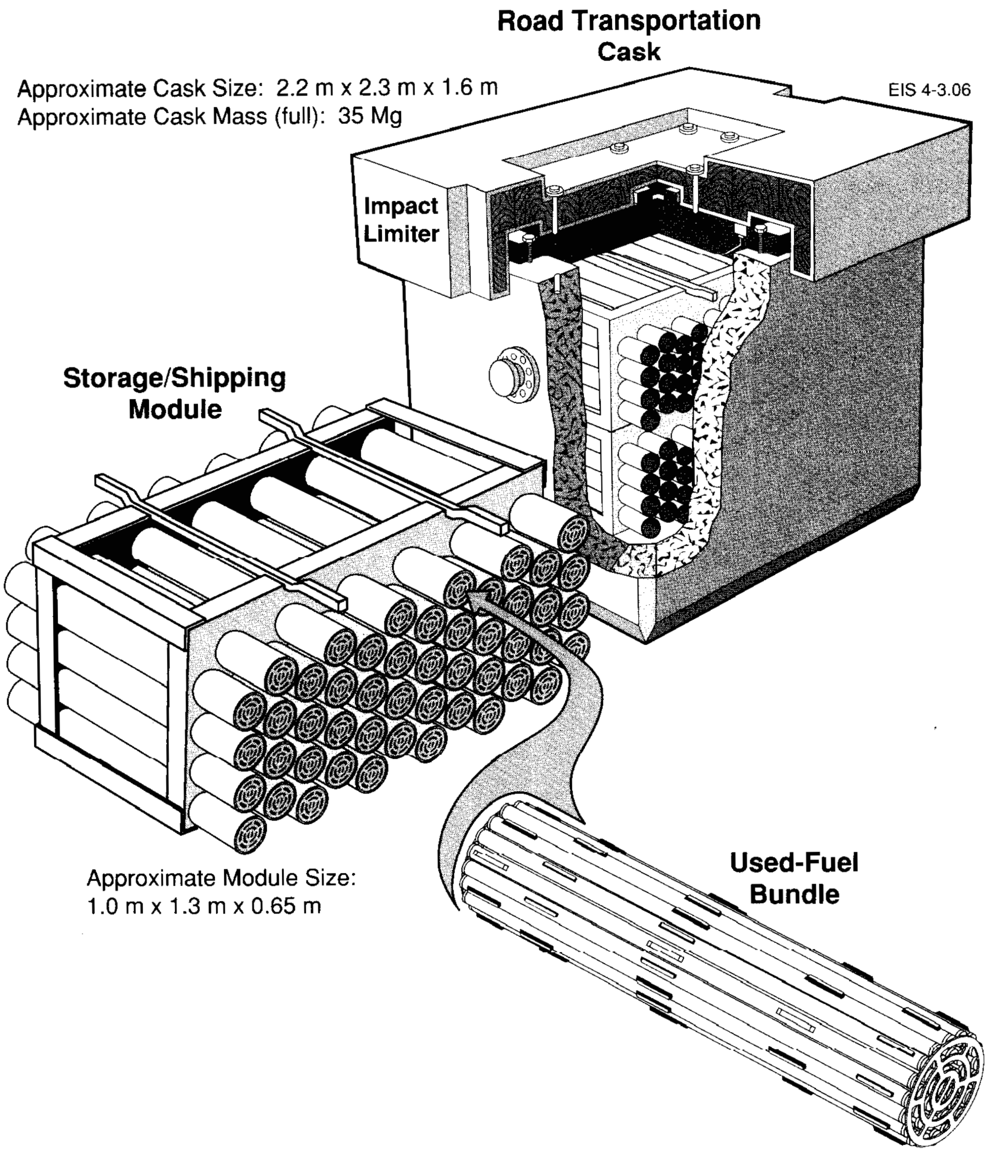


FIGURE 3-6: Ontario Hydro Road Transportation Cask with Two Shipping/ Storage Modules and Used-Fuel Bundles (96 bundles/module)

1. The packaging-plant module-handling-cell port under dry conditions for storage/shipping module unloading.

2. The packaging-plant cask-support platform (outside the used-fuel packaging cell) under dry conditions for container loading.

3. The packaging-plant headframe surge-storage pool under wet conditions for container loading.

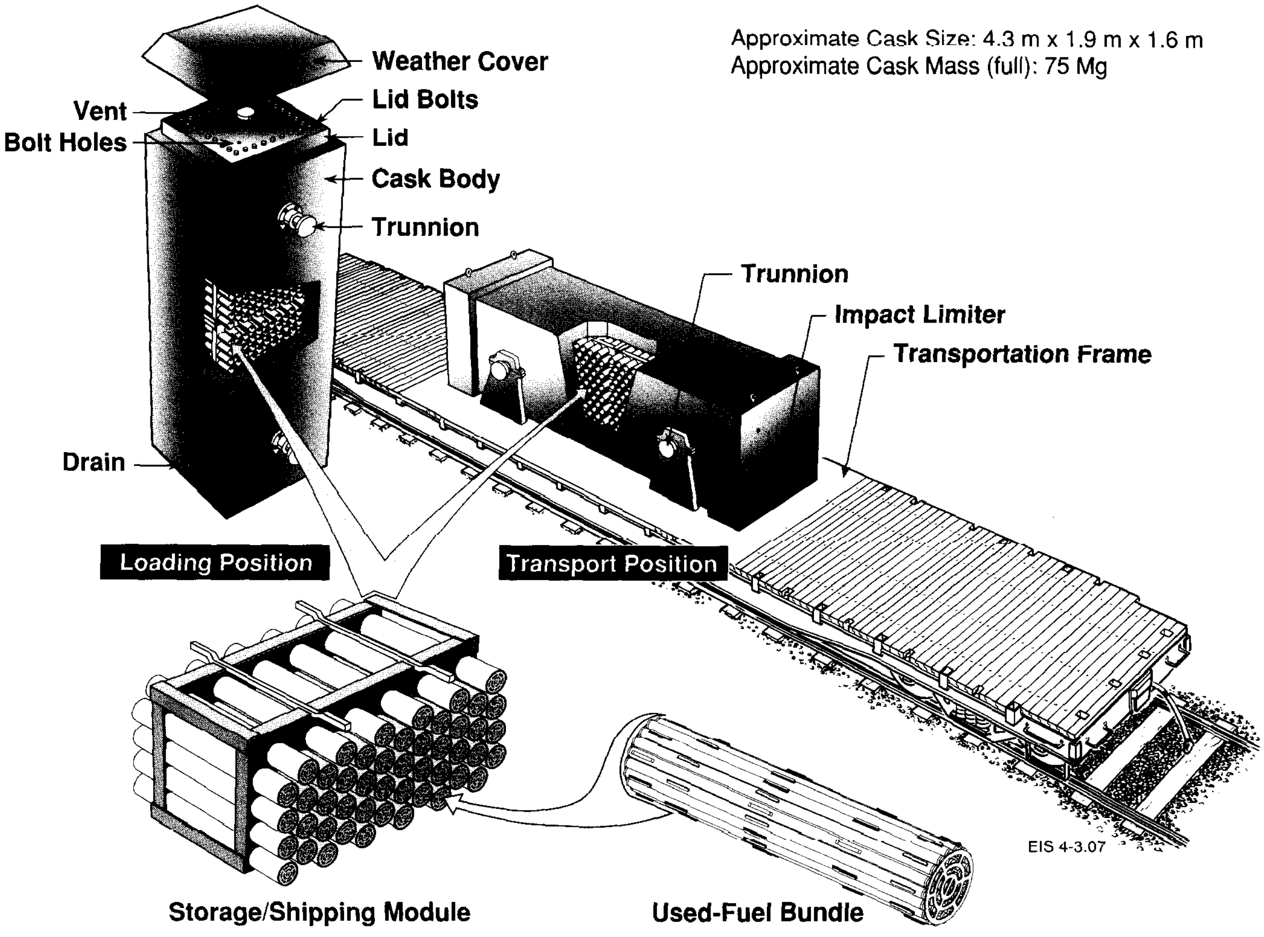


FIGURE 3-7: Ontario Hydro Rail Transportation Cask with Six Shipping/ Storage Modules and Used-Fuel Bundles (96 bundles/module)

4. The disposal vault emplacement borehole under dry conditions for container installation in an emplacement borehole.

The Used-Fuel Disposal Centre surface facilities accommodate the receiving and the unloading of the road and rail casks, and handling and storage of the storage/shipping modules. A container cask conceptual design was developed to interface with several loading points and to accommodate the reference disposal container.

The technology for this integrated cask handling and operation is available in the Canadian nuclear industry. For example, dry loading and unloading of cobalt-60 assemblies from nuclear generating stations into dry transfer casks and from casks to storage bays is a standard operating practice. Dry loading of used-fuel storage containers into transportation casks and from transportation casks to dry storage concrete canisters (at the Whiteshell Laboratories, Gentilly, Douglas Point and Point Lepreau nuclear generating stations) has been performed, but the quantities of used fuel are far smaller than those anticipated for a disposal centre. The road and rail-cask unloading operation in the packaging-plant module-handling cell was derived from the facilities being built at the Darlington nuclear generating station.

3.3.4.2 Excavation Method and Materials Handling

The drill-and-blast excavation method was selected for the Used-Fuel Disposal Centre conceptual design study. It is used routinely in mining and civil engineering in rock types similar to those proposed for the disposal vault. Full-face boring machines, commonly used to tunnel through plutonic and similar rocks, excavate circular openings, which are not compatible with the flat disposal-room floor favourable to borehole emplacement of disposal containers that was adopted in this conceptual design. Another alternative, continuous hard-rock excavation machines, is currently under development and may prove to be more suitable for excavating a favourable disposal-room geometry and for excavating the tunnel and room vault arrangement. However, they are not yet proven production tools. These machine-excavation methods may yield a lesser degree of induced damage in the rock mass around the openings than drill-and-blast excavation, but this has not been demonstrated. Experience in AECL's Underground Research Laboratory indicates that the damage induced by drill-and-blast excavation can be minimized by careful blast-round design and application (Kuzyk et al. 1987a, Favreau et al. 1987).

In the Used-Fuel Disposal Centre conceptual design study, ground control (see Section 2.6.3.7) is achieved by standard rock-bolting methods from scissors-lift trucks. The actual bolting requirements would be dictated by the observed ground conditions, and could vary from no bolts in regions of sparsely fractured rock to heavy bolting with screening and/or shotcrete in fractured zones. Screen and bolts may be a cost-effective substitute for continual maintenance in openings such as access tunnels and ancillary facilities that will be open for many years.

The handling of excavated materials from an underground excavation is also a well-developed practice in worldwide civil and mining activities. The excavated-rock removal rate required for the operations assumed in this Used-Fuel Disposal Centre conceptual design is about 1200 Mg/shift during the construction stage of the conceptual disposal vault. The excavated-rock removal rate drops to about 770 Mg/shift during the operation stage, comprising 650 Mg from excavation of additional disposal rooms and 120 Mg from drilling emplacement boreholes. All excavated-rock handling equipment is selected and sized based on these rates.

These materials-handling rates are determined by balancing the requirements of the construction and operation sequence and schedule, the disposal-vault size, the arrangement and emplacement concept, and the overall economics of the disposal centre. The Used-Fuel Disposal Centre conceptual design presented here has not optimized these factors. The design for an actual disposal facility would include the necessary iterations to achieve this optimization.

The materials-handling rates are the main factors influencing the design of the shafts and materials-handling systems, and the selection of the number and types of materials-handling equipment. The number of trucks required to transport the excavated rock also depends on the haulage distance between the excavation location and the service shaft, which is at a maximum during the excavation of the first panels. The rock excavation and handling equipment estimated in the Used-Fuel Disposal Centre conceptual design are shown in Table 3-5.

TABLE 3-5

DISPOSAL-VAULT EXCAVATION EQUIPMENT (WITHOUT ALLOWANCE FOR SPARES)

(after AECL CANDU et al. 1992)

	Construction Stage	Operating Stage
Three-Boom Hydraulic Drill Jumbo	6	4
Load-Haul-Dump Vehicle (LHD) 6-Mg Capacity	4	3
Truck 24-Mg Capacity (for maximum haulage distance)	11	7
Explosive Truck	3	2
Scissors-Lift Truck (for roof bolting)	3	2
Emplacement Hole Core Drill	0	3

The service-shaft equipment necessary to move this excavated rock from the disposal vault to the surface is specified based on the maximum excavation rate. Two skips (shaft conveyances designed to carry bulk materials) are provided in the service shaft in the conceptual design, giving a peak available skipping capacity of 2100 Mg/shift during the construction stage. This is reduced to about 800 Mg/shift during the operating stage because one skip is then dedicated to the transfer of vault-sealing materials from the surface to the vault level.

3.3.4.3 Sealing-Materials Handling

The sealing materials to be handled and the methods of transfer from surface to underground in the Used-Fuel Disposal Centre conceptual design are summarized in Table 3-6.

TABLE 3-6

VAULT SEALING MATERIALS-HANDLING METHODS

Material	Handling Method in Service Shaft	Average Handling Capacity per Shift (Mg)
Crushed Granite	Skip	287
Crushed Granite Fines[1]	Skip	53
Bentonite Clay	Pneumatic Transfer Pipe	112
Glacial-Lake Clay[2]	Pneumatic Transfer Pipe	115
Silica Sand	Skip	120
Concrete[3]	Transfer Pipe	117

Notes: 1. Ratio of crushed granite to crushed granite fines is assumed to be 5.4:1 by mass.

2. Transport of glacial-lake clay is done over 15 d per 28-d cycle.

3. Concrete is used at this rate for two 24-h days per 28-d cycle.

The skip and pipe capacities in the service shaft are sized to satisfy the average demands. In an optimized design, the various operations would be planned in detail and the effect of peak demands would be considered. In such an optimization, details of dust suppression and collection systems would also be determined.

In the Used-Fuel Disposal Centre conceptual design, the transfer of sealing materials within the disposal vault is by modified mine trucks with a capacity of 24 Mg. The modifications include the installation of rotating drum mixers (similar to conventional batch concrete trucks) to prevent buffer, backfill and concrete component segregation during transit and to control moisture content. AECL CANDU et al. (1992) determined that five vehicles are necessary to transport the required masses of finished clay-based materials. The mixing drums on these trucks are cleaned and used for concrete remix and transport during the construction of a concrete bulkhead.

3.3.4.4 Personnel and Equipment Handling

Table 3-7 summarizes the methods adopted in the Used-Fuel Disposal Centre conceptual design to handle personnel and equipment. These methods were

TABLE 3-7

PERSONNEL AND EQUIPMENT HANDLING SYSTEMS

Location	Type	Routine (R) Maintenance (M) Emergency (E)	System	Capacity Persons	Capacity Mg
Surface	Personnel	R, M, E	Foot	NA*	NA
			Vehicle	NA	NA
	Equipment	R, M	Vehicle	NA	NA
Waste Shaft	Container-Cask	R	Waste Cask Cage	0	38
	Personnel**	M, E	Waste Cask Cage	NA	38
Service Shaft	Personnel	R, M	Service Cage	50	10
		E	Auxiliary Cage	10	1
	Equipment	R, M, E	Service Cage	NA	10
Downcast Ventilation Shaft		N.A.	None		
Upcast Ventilation Shaft - Inactive	Personnel	M, E	Emergency Cage	25	3
	Equipment	M, E	Emergency Cage	NA	3
Upcast Ventilation Shaft - Active	Personnel	M, E	Maintenance Cage	Low	Low
	Equipment	M, E	Maintenance Cage	Low	Low
Disposal Vault	Personnel	R, M, E	Foot/Vehicle	As Required	
	Equipment	R, M, E	Vehicle	As Required	

* Not applicable.

** Personnel are not normally transported in the waste shaft. However, shaft maintenance would be done from the waste-cask cage and it could also be used for emergency transport of personnel.

developed as part of the design analyses and integration process, considering available capacities, radiological/industrial safety issues, standard mining/civil engineering practice, and the requirements of applicable legislation. Personnel on the surface or in the disposal vault either walk or use vehicles, depending on the distance to be travelled. Equipment is moved on the surface and underground using an appropriate vehicle or handling system.

Transfers between the surface and the disposal vault use the hoists and conveyances in four of the five shafts, depending on the purpose of the transport. Routine transfers of personnel and material take place in the service cage or the auxiliary cage in the service shaft. The hoisting systems in the upcast ventilation shafts are available for shaft maintenance and emergency transport of personnel and equipment.

The container casks are routinely transported in the waste shaft. The only time people are in this shaft is when personnel conduct periodic shaft and equipment inspections and maintenance, and the cage will not contain radioactive materials during these activities. Personnel could be transported in the waste shaft cage under emergency conditions.

3.3.5 Radioactive and Hazardous Material Emissions

3.3.5.1 Radioactive Emissions

Radioactive emissions from a Used-Fuel Disposal Centre are important factors in analyzing the occupational, environmental and public safety during the preclosure phase. Radiological source terms were derived to help assess the significance of the potential airborne and waterborne emissions from the Used-Fuel Disposal Centre. These were used to assess the need for treatment systems, to estimate decontamination factors required for the treatment systems and to provide post-treatment emissions that are below current regulatory limits. Potential postclosure phase emissions are discussed by Goodwin et al. (1994).

The routine airborne and waterborne source terms were first derived by AECL CANDU et al. (1992) as part of their conceptual design for the Used-Fuel Disposal Centre. This work focussed on the packaging plant, where the fuel bundles are removed from the transportation cask and loaded into the disposal containers. Coarse estimates based on preliminary design information, literature review, and approximate contaminant removal efficiencies for HEPA filters and ion-exchange resins were used as guides in the conceptual design of the emissions control systems.

An independent and more rigorous assessment of the source terms, decontamination factors and emissions was subsequently carried out by Villagran (1991) in support of the preclosure environmental and safety assessment done by Grondin et al. (1994). Villagran used the completed draft design of the conceptual disposal centre (AECL CANDU et al. 1992) and additional research and operational experience, where applicable. Villagran notes that the anticipated emission rates (Table 3-8) are many orders of magnitude lower than those of operating nuclear generating stations. Both AECL CANDU et al. (1992) and Villagran (1991) made conservative assumptions in their analyses, particularly where no direct operating experience or information was available.

3.3.5.2 Hazardous Materials

A wide range of materials would be used and wastes would be produced during the construction, operation and decommissioning of a Used-Fuel Disposal Centre. Many of these would be potentially hazardous to man and the environment, and their presence must be recognized in the development of operating procedures, the layout of building structures and the design of

TABLE 3-8

AIRBORNE AND WATERBORNE RADIONUCLIDE SOURCE AND EMISSIONS TERMS

(after Villagran 1991)

Radionuclide	Airborne Source (Bq/week)	Decontamination Factor	Airborne Emissions (Bq/week)	Waterborne Source (Bq/week)	Decontamination Factor	Waterborne Emissions (Bq/week)
H-3	2.11E+07	1	2.11E+07	1.11E+05	1	1.11E+05
Kr-85	3.27E+08	1	3.27E+08	0.00E+00	1	0.00E+00
Sr-90	5.22E+06	3333	1.57E+03	4.75E+07	1000	4.75E+04
Ru-106	8.84E+03	3333	2.65E+00	2.46E+04	1000	2.46E+01
Te-125m	4.07E+06	3333	1.22E+03	7.27E+06	1000	7.27E+03
I-129	4.98E+02	1	4.98E+02	8.89E+02	1	8.89E-01
Cs-134	5.08E+07	3333	1.53E+04	1.33E+07	1000	1.33E+04
Cs-137	6.30E+07	3333	1.89E+04	2.44E+07	1000	2.44E+04
Ce-144	7.63E+02	3333	2.29E-01	4.36E+03	1000	4.36E+00
Pm-147	5.38E+04	3333	1.61E+01	3.08E+05	1000	3.08E+02
Eu-154	4.97E+03	3333	1.49E+00	2.84E+04	1000	2.84E+01
Eu-155	2.11E+03	3333	6.32E-01	1.20E+04	1000	1.20E+01
U-234	2.66E+00	3333	7.98E-04	1.52E+01	1000	1.52E-02
U-238	3.26E+00	3333	9.78E-04	1.86E+01	1000	1.86E-02
Pu-238	8.15E+02	3333	2.45E-01	4.66E+03	1000	4.66E+00
Pu-239	1.70E+03	3333	5.09E-01	9.71E+03	1000	9.71E+00
Pu-240	2.33E+03	3333	6.98E-01	1.33E+04	1000	1.33E+01
Pu-241	1.44E+05	3333	4.31E+01	8.21E+05	1000	8.21E+02
Am-241	2.97E+03	3333	8.90E-01	1.70E+04	1000	1.70E+01
Am-242m	2.16E+00	3333	6.47E-04	1.23E+01	1000	1.23E-02
Cm-244	1.20E+02	3333	3.59E-02	6.84E+02	1000	6.84E-01
C-14	2.43E+04	1	2.43E+04	4.35E+04	1	4.35E+01
Fe-55	1.72E+06	3333	5.16E+02	3.07E+06	1000	3.08E+03
Ni-59	4.99E+02	3333	1.50E-01	8.91E+02	1000	8.91E-01
Co-60	7.49E+06	3333	2.25E+03	1.36E+07	1000	1.36E+04
Ni-63	6.56E+04	3333	1.97E+01	1.17E+05	1000	1.17E+02
Nb-94	1.14E+03	3333	3.42E-01	2.04E+03	1000	2.04E+00
Sb-125	1.47E+06	3333	4.41E+02	2.63E+06	1000	2.63E+03

service systems. A listing of some of the nonradioactive hazardous materials considered likely to be present at the Used-Fuel Disposal Centre conceptual design is given in Table 3-9.

The purpose of the listing is to highlight processes and materials that would have to be considered in the preclosure environmental and safety assessments, and in a future detailed design of a facility.

The Used-Fuel Disposal Centre conceptual design (AECL CANDU et al. 1992) provides only brief descriptions or assumptions of standard control and abatement methods rather than detailed design descriptions for systems to control worker and public exposures. State-of-the-art industrial practices would be applied in the construction, operation, decommissioning and closure stages, and these are assumed in the development of design descriptions, schedules and cost estimates.

3.3.6 Site Conditions

3.3.6.1 Surface Conditions

The specific assumptions for the surface conditions used in the Used-Fuel Disposal Centre conceptual design are presented in Section 4.2.1.

3.3.6.2 Underground Conditions

The geosphere properties assumed in the analyses of the Used-Fuel Disposal Centre conceptual design are essentially based on information derived from our studies of the Whiteshell Research Area (WRA) (Table 2-1) in terms of rock type (granite), rock-mass properties and rock quality (Baumgartner et al. 1993). The constraints initially placed on the conceptual vault design and its components are as follows:

1. The maximum container outer surface temperature is 100°C.

2. The maximum buffer/backfill temperature is 100°C.

3. The maximum depth of the near-surface extension zone is 100 m. This near-surface extension zone (previously called the perturbed fracture or perturbed fissure zone) is the volume of rock at the ground surface overlying the disposal vault that could experience loss of horizontal confining stresses and potential opening of vertical fractures because of the uplift of the rock mass caused by thermal expansion displacements around the heated vault.

4. The minimum average strength-to-stress ratio (safety factor) for the rock in the pillar and interborehole rock web is 2.0.

5. The maximum room extraction ratio is about 0.25. The extraction ratio is defined in Equation (2.3) in Section 2.7.2.2. This was subsequently increased in AECL CANDU et al. (1992) to 0.267.

6. No artificial support for the container-emplacement borehole is allowed prior to buffer emplacement.

TABLE 3-9

MAJOR NONRADIOACTIVE HAZARDOUS MATERIALS

(after AECL CANDU et al. 1992)

Classification	Main Use or Generation	Main Hazard	
		Type*	Location
1. Gases, Dust and Fumes			
Argon	Used in basket and container fabrication	A	Basket and Container Fabrication Plant
	Used during bonding of container lid	A	Used-fuel packaging cell, compressed-gas storage building
Chlorine	Used for domestic water treatment	H, Co	Water treatment plant chemical storage building
Diesel engine exhaust	Produced by transporters and other diesel equipment	A, H	Surface and underground
Dust and smoke	Produced during rock crushing, blasting and excavation	H, Vi	Crushing plant, buffer prep. plant, underground
Helium	Used for container leak test	A	Used-Fuel Packaging Plant, compressed-gas storage building
Hydrogen	Generated by radiolysis of water	E, Fi	Surge-storage pools, container emplacement room
Natural gas or propane	Used for heating	A, E, Fi	Piping, downcast ventilation shaft, compressed-gas storage building
Ozone	Produced in the vicinity of high-voltage electrical equipment	H	Transformers on surface and underground

continued...

TABLE 3-9 (continued)

Classification	Main Use or Generation	Main Hazard	
		Type*	Location
Acetylene	Used in maintenance welding	E, Fi	Surface and underground
Oxygen	Used in maintenance welding	E, Fi	Surface and underground
Welding fumes	Produced from welding during basket and container fabrication Produced from welding during during maintenance work	H	Basket and Container Fabrication Plant, surface and underground
2. Liquids			
Acids	Used to passivate the titanium containers Used in batteries for underground vehicles and uninterruptible power system Used in maintenance, cleaning, etc.	H, Co	Basket and Container Fabrication Plant Auxiliary building, chemical storage building Surface and underground
Bases	Used to control the pH around 10 in the water pools	H, Co	Surge-storage pools, chemical storage building
Other solvents	Used in the process of basket and container fabrication Used to swab the area to be welded in containers, used in maintenance work	H, Fi	Basket and Container Fabrication Plant Used-Fuel Packaging Plant, auxiliary building, surface and underground
Diesel and fuel	Used to refuel vehicles and machinery	Fi	Fuel tanks (surface and underground)

continued...

TABLE 3-9 (concluded)

Classification	Main Use or Generation	Main Hazard	
		Type*	Location
Hydrazine	Used in chemistry control (of water)	H, Fi	Surge-storage pools, chemical storage building
Oil, grease and antifreeze	Used in engines, hydraulic systems and machinery	Fi, H	Surface and underground, chemical storage building
Sewage	Washrooms, showers, kitchen facilities	H, Po	Surface and underground
Wastewater	Washing of rock, vehicles and physical plant, coolant, groundwater drainage	H, Po	Rock Crushing Plant, surge-storage pools, surface and underground
3. Solids			
Explosives	Used in excavation	E	Underground facility, explosives magazines
Office, kitchen and shop waste	Scrap paper, materials and food	Po, H	Primarily on surface at landfill site
Scrap metal	Produced during container fabrication and maintenance of facilities and equipment	Po, H	Surface and underground

* Type of Hazard Codes:

A - Asphyxiant
Co - Corrosive
E - Explosive
Fi - Fire
H - Health (skin irritation, inhalation or ingestion)
Po - Air or water pollutant
Vi - Vision limitation (mechanical or chemical)

7. The geothermal gradient is assumed to be 12°C/1000 m of depth, with the Earth's average surface temperature being 5°C (after Drury and Lewis 1983, Jessop and Lewis 1978).

8. The assumed in situ stresses are based on Herget (1980) for the average stress conditions of the Canadian Shield, and were modified to increase the lithologic load to that generated by the granite density (in this case, 2700 kg/m³) as follows:

$$\sigma_v = 0.0265Z \quad (3.1)$$

and $$\sigma_{Ha}/\sigma_v = \frac{251.68}{Z} + 1.14 \quad . \quad (3.2)$$

By substituting Equation (3.1) into (3.2),

$$\sigma_{Ha} = 0.0302Z + 6.7 \quad (3.3)$$

and $$\sigma_{Ha} = \frac{\sigma_{Hmax} + \sigma_{Hmin}}{2} \quad (3.4)$$

where σ_v = vertical stress (MPa),
σ_{Ha} = average horizontal stress (MPa),
Z = depth (m),
σ_{Hmax} = maximum horizontal stress (MPa), and
σ_{Hmin} = minimum horizontal stress (MPa).

Note: The vertical stress calculated from this formula is about 9% higher than the average vertical stress predicted by Herget (1980).

9. The vault horizon is initially assumed to be at a depth of 1000 m. Although the reference depth for a disposal vault is nominally 500 to 1000 m, the 1000-m depth was initially selected for study and analysis as being conservative for the assumed stress conditions. At this depth, the ambient stresses and geothermal temperature are higher than at 500 m, and the heat transfer and material handling distances and sealing lengths are longer. Subsequent analyses (see Section 3.3.7.2) indicated that there would be yielding in the disposal-room floor and the emplacement-borehole walls at 1000 m, but this could be avoided by moving the vault horizon to 500 m. (Note: The actual depth selected for a disposal vault would not be limited to this nominal range. At any site the depth chosen would be an optimization among the many factors affecting the overall performance of the disposal system.)

10. The rock-mass properties and strengths assumed for the thermal and thermal-mechanical analyses are shown in Tables 3-1 and 3-10, and were derived by Baumgartner et al. (1993) from the results of rock property testing by the Canada Centre for Mineral and Energy Technology (CANMET) (Katsube and Hume 1987); the rock-mass classification systems (Barton et al. 1974; Bieniawski 1974, 1976)

TABLE 3-10

FAILURE CRITERION AND CLASSIFICATIONS FOR GRANITE

	Intact Rock (laboratory)	Intact Rock (rock web between boreholes)	Rock Mass (peak strength)	Rock Mass (residual strength)
Failure Criterion				
Uniaxial Compressive Strength (σ_c)	190 MPa	110 MPa*	190 MPa	190 MPa
Value of Parameter m	30	30	17.5	3
Value of Parameter s	1	1	0.19	0
CSIR (Council for Scientific and Industrial Research) Classification				
Intact Strength Rating			12	12
Rock Quality Designation (RQD) Rating			20	10
Joint Space Rating			30	15
Joint Condition Rating			20	20
Groundwater Rating			7	7
Joint Orientation Rating			-5	-5
CSIR Rock Mass Rating (RMR)			84	59
NGI (Norwegian Geotechnical Institute) Rating				
Rock Quality Designation (RQD)			100	50
Joint Set Number (Jn)			0.5	9
Joint Roughness Number (Jr)			5	3
Joint Alteration Number (Ja)			1	1
Joint Water Reduction (Jw)			1	1
Stress Reduction Factor (SRF)			10	2.5
NGI Quality Index (Q)			100	6.7

* Scaled value of uniaxial compressive strength calculated to account for the dimensions of the rock web between emplacement boreholes (~0.9 m) (Hoek and Brown 1980).

and an empirical failure criterion for rock masses discussed in Section 2.7.2.2 (Hoek and Brown 1980). The values were selected to be representative of the material, with a tendency toward conservatism. The uniaxial compressive strength of the inter-borehole rock web was derated in Table 3-10, assuming that the rock was intact (i.e., Hoek and Brown failure criterion parameters m = 30 and s = 1, Equation (2.5) in Section 2.7.2.2) and flawed, but unfractured. This was based on the assumption that fracture spacings would be greater than 3 m in the areas where emplacement boreholes would be drilled. This derated strength was based on a rock core specimen size strength correction relating the strength of the 45-mm-diameter core to the strength of ~900-mm-diameter core (i.e., the approximate minimum thickness of the intact rock web) with the following equation (after Hoek and Brown 1980):

$$\sigma_c = \sigma_{c45}(45/d)^{0.18} \quad (3.5)$$

where σ_c = uniaxial compressive strength of 900-mm core,
σ_{c45} = uniaxial compressive strength of 45-mm core, and
d = approximate minimum thickness of rock web (i.e., 900 mm).

The confined strength of the rock web was further decreased (from m = 30 to m = 18.3) to allow the tensile strength to be increased from a derived value of less than 4 MPa to the 6 MPa observed at the Underground Research Laboratory (Martin 1993).

A residual rock-mass strength was provided in Table 3-10 for use if a significant volume of rock around the room excavation had a strength-to-stress ratio of less than 1.0. (Note that the m and s parameters are reduced.) The residual strength value would be applied to this rock if progressive yielding were analyzed.

3.3.7 Geosphere and Disposal Vault Thermal and Structural Analyses

The thermal and structural analyses necessary to develop a disposal vault and waste emplacement configuration that would meet the established specifications and constraints are essential components of the design process. The thermal and mechanical constraints on individual components of the disposal system and the overall structural stability must be considered in such analyses.

Scoping calculations were completed in the Used-Fuel Disposal Centre conceptual design study to identify and resolve rock-mass behavioural issues to illustrate the approach to thermal and structural design of a disposal vault. They were performed using the assumptions described in Sections 3.3.2, 3.3.3 and 3.3.6, and resulted in some restrictions on the applicability of the reference design.

3.3.7.1 Thermal Scoping Calculations and Analyses Approach

Thermal analyses were initially done (Baumgartner et al. 1994) for the Used-Fuel Disposal Centre conceptual design study using the HOTROK analytical code (Mathers 1985) to develop an initial container spacing that satisfied the thermal criteria on the container and buffer material. An approximately square waste emplacement area was selected for this study since it would provide long heat transport path lengths for disposal containers emplaced in the centre of the vault. This square geometry provides a conservative analysis by maximizing the duration of elevated temperatures compared with rectangular or irregular geometries.

The centreline borehole spacings in the room were set at 2.1 m along and 2.1 m across the disposal room in this conceptual design on the basis of the initial thermal scoping analyses and the limiting temperature criterion of 100°C at the outer surface of the container. This allowed an initial arrangement of three containers spaced across a 7.5-m-wide room and a room-to-room centreline spacing of 30 m, for a disposal vault room extraction ratio of 0.25.

Although these initial thermal scoping analyses with the HOTROK code gave the minimum allowable container spacing in the waste emplacement area for this conceptual design, the other features of the vault design had not yet been incorporated. These features included partitioning of the vault into panels, providing space for access tunnels, and defining the room sizes to suit operations and equipment as discussed in Sections 3.3.8.2 and 3.3.8.3. (Note that the analysis of space requirements for borehole preparation and waste emplacement equipment and for ventilation ducting yielded a revised room width of 8 m and an extraction ratio of 0.267.)

A three-dimensional thermal finite-element method analysis of the immediate room area by Tsui and Tsai (1994a), using the ABAQUS computer code (available from Hibbitt, Karlsson and Sorensen, Inc., 1080 Main Street, Pawtucket, RI 02860, U.S.A.), confirmed the HOTROK thermal scoping calculations. The finite-element method (e.g., the ABAQUS code) can provide a better representation of the composition of the various components and materials than the HOTROK code, which uses an analytical method for one material. The ABAQUS code is described by Hibbit, Karlsson and Sorensen, Inc. (1989) in a user's manual.

The average geothermal gradient assumed for the Canadian Shield is 12°C/km and the mean surface temperature is assumed to be 5°C. Therefore the ambient rock temperature in these analyses is 11°C at a depth of 500 m and 17°C at a depth of 1000 m. Figure 3-8 shows the near-field temperature rise in the central plane of the disposal containers at various times in a disposal vault. The peak temperature rise of 84°C at the outer surface of the container is reached at about 30 a, after which the container temperature begins to decrease. In the analysis, the maximum temperature at the outer surface of the container caused by waste heating is 95°C at a vault depth of 500 m. A vault situated at a depth of 1000 m with the same waste emplacement geometry would undergo a similar temperature rise (i.e., 84°C) in 30 a, but the maximum temperature at the outer surface of the container would reach 101°C since the ambient temperature at this depth is 17°C.

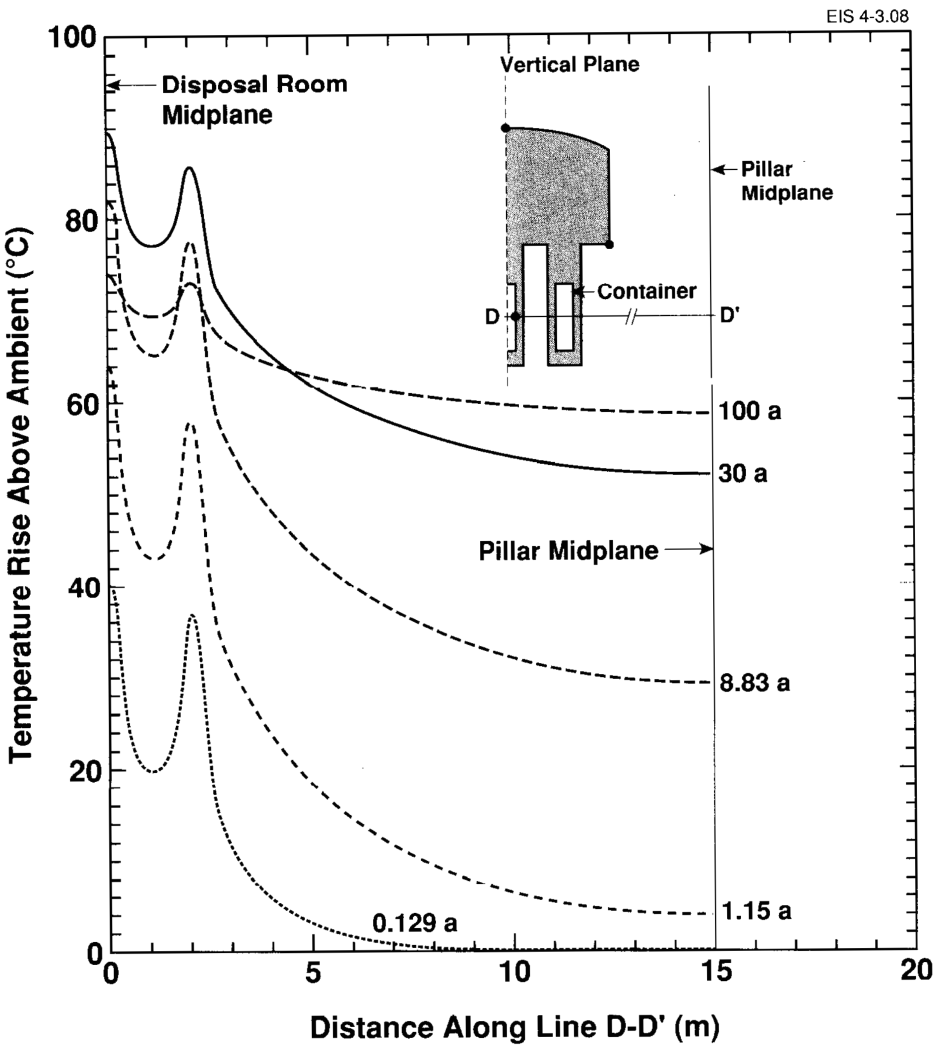


FIGURE 3-8: Temperature Profiles Along Line D-D' in the Container Midplane for Selected Post-Emplacement Times

A far-field or geosphere-scale thermal finite-element analysis was performed by Golder Associates (1993) for the volume around, above and below the entire disposal vault using the ANSYS finite-element computer code (available from Swanson Analysis Systems, Inc., Johnson Road, Houston, PA 15342, U.S.A.). The analysis took into account the added non-heat-generating space of the access corridors (Figure 1-3). Instead of performing a complete three-dimensional analysis, the far-field model was simplified by performing a two-dimensional axisymmetric finite-element analysis. Since the waste emplacement area of the vault is nearly square in plan, the emplacement area was represented as a circular disk of equivalent area (Figure 3-9).

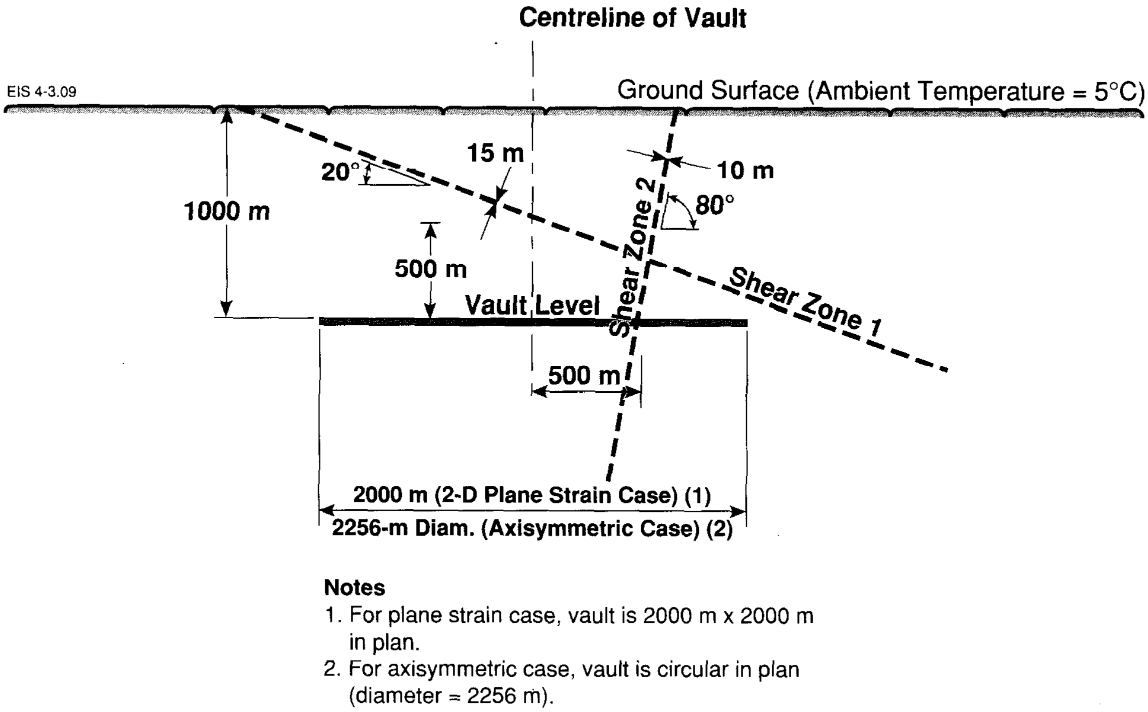


FIGURE 3-9: Far-Field Vault Model for Thermal-Mechanical Analyses (after Golder 1993)

The heat source was "smeared" or uniformly distributed over the disk area in the far-field analysis, resulting in an initial thermal load of about 10.4 W/m^2. The analysis (results are shown in Figures 3-10, 3-11 and 3-12) confirmed the scoping calculations by Baumgartner et al. (1994) performed with the HOTROK code. These figures show that the thermal pulse from the decay of radionuclides in the used fuel would heat a significant volume of rock for a period of over 50 000 a, and it would take over 100 000 a to approach the initial ambient temperature.

Based on the thermal results of Baumgartner et al. (1994), Golder Associates (1993), Tsui and Tsai (1994a) and AECL CANDU et al. (1992) completed a design for a disposal vault with an emplacement-borehole spacing of 2.1 m x 2.1 m in disposal rooms at a depth of 1000 m in anticipation that the local stress conditions around the disposal rooms would satisfy the specifications.

Stress analyses were then performed to assess local and large-scale structural stability issues. The local-scale issues are related to the potential for rock-mass yielding and breakouts in the disposal rooms and in the rock webs between the emplacement boreholes. The large-scale issues are related to the ground surface uplift, the potential movement along existing fault planes, and the opening of fractures in the near-surface extension zone.

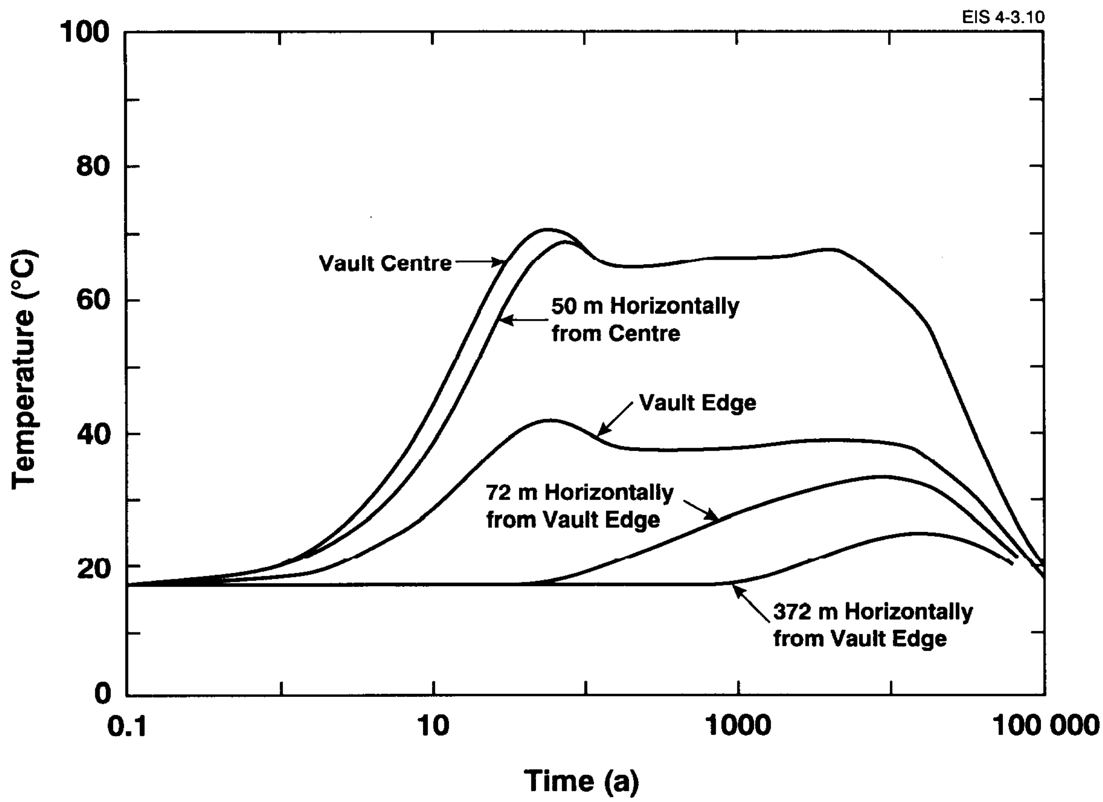


FIGURE 3-10: Variation of Temperature with Time of Emplacement (axisymmetric case) (after Golder 1993)

3.3.7.2 Local-Scale Thermal-Mechanical Analyses

(i) Initial finite-element method analyses

The local-scale analyses of a disposal room for the Used-Fuel Disposal Centre conceptual design (Tsui and Tsai 1994a) used a three-dimensional thermal-mechanical finite-element model also developed with the ABAQUS computer code, and it assumed instantaneous excavation of rooms and emplacement boreholes. In preparing for this analysis, Tsui and Tsai used a minimum in situ horizontal stress of 37.1 MPa and a maximum horizontal stress of 45 MPa at a depth of 1000 m. These stresses are within the range of published data (Herget 1987). This increased the average horizontal stress stated in our specification (Baumgartner et al. 1993) by about 10% to 41.1 MPa. The vertical stress of 26.5 MPa was retained. For a disposal room oriented perpendicular to the maximum horizontal stress direction, this increases the ratio of the in situ horizontal to vertical stresses acting on the room cross section, resulting in a stress ratio of 1.7. The resulting horizontal in situ stress ratio for the boreholes in the floor of the room is about 1.2.

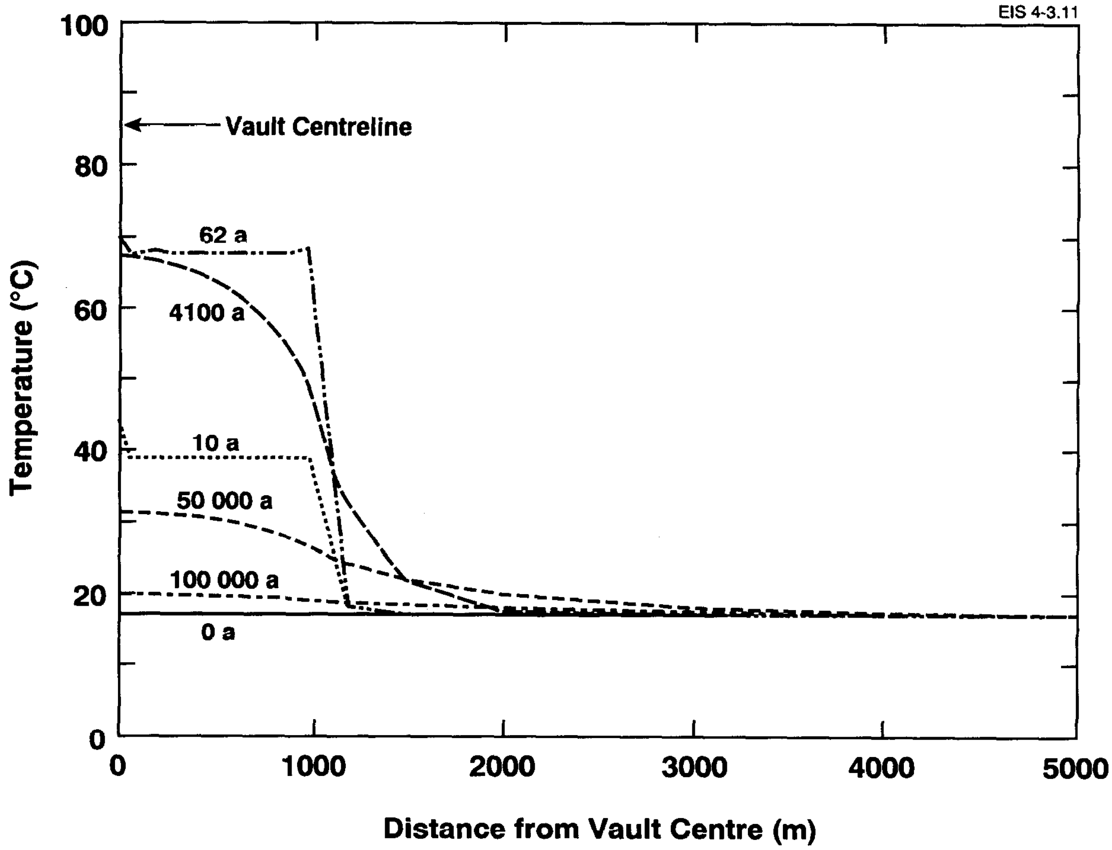


FIGURE 3-11: Distribution of Temperature at Vault Level (axisymmetric case) (after Golder 1993)

Tsui and Tsai (1994a) assumed the axis of the disposal room to be aligned perpendicular to the maximum horizontal stress direction. It was recognized that the preferred disposal-room orientation is parallel to the maximum horizontal stress direction because this provides the lowest ratio of horizontal to vertical stress acting on the room cross section (e.g., the ratio would be about 1.4 in this orientation). However, the more conservative case was used for the initial analyses because stress conditions alone do not necessarily dictate room or tunnel orientations in practice. The existence, frequencies, orientations, and mechanical properties of single fractures or fracture sets may strongly influence the excavation orientation and geometry. For example, the possibility of rock block or wedge breakouts may be higher for particular orientations between the excavations and the fracture sets. Where these conditions are prominent, they would be significant factors in determining the orientation of the excavations. As single fractures and fracture sets vary greatly among potential sites, they were not specifically considered in the Used-Fuel Disposal Centre conceptual design or in Tsui and Tsai's (1994a) analysis.

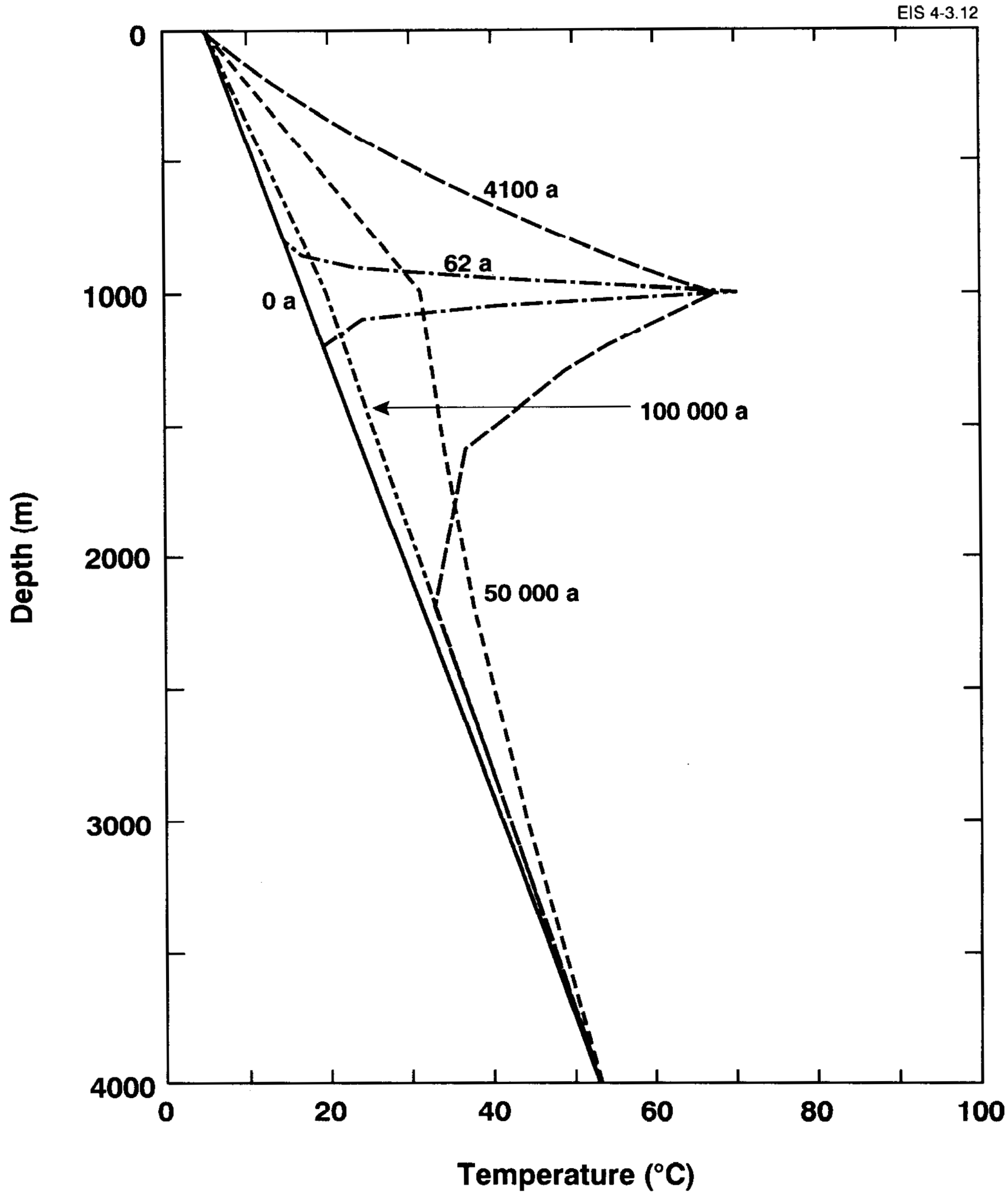


FIGURE 3-12: Distribution of Temperature with Depth Along Centreline of Vault (axisymmetric case) (after Golder et al. 1993)

Tsui and Tsai's (1994a) initial analysis indicated no serious overstress conditions, although local areas at the room perimeter and the collar and walls of the boreholes showed some shallow zones of potential tensile and shear failure (i.e., the local strength-to-stress ratio was less than 1). These small zones were expected to represent very minor surface spalling and were not considered to be a stability issue.

However, recent studies in the Underground Research Laboratory (Martin and Read 1992) have shown that localized areas of overstress manifest themselves as zones of progressive yielding and spalling. This spalling generally results in the formation of a notch in the wall of the excavation, as discussed in Section 2.7.2.2, unless the excavation wall is constrained by support measures. Extensive notching or breakout of this type in the disposal-room boundaries or the emplacement borehole walls would not satisfy the intent of the conceptual design specification. The results of Tsui and Tsai's (1994a) analyses were reconsidered based on this experience. Several alternative arrangements for container spacing and a change in the depth of the disposal vault to 500 m were considered.

(ii) Finite-element analyses of alternative disposal arrangements

Tsui and Tsai (1994a) analyzed a disposal vault at a depth of 1000 m in which the disposal rooms had a curved floor and the emplacement borehole spacing along the axis of the room was increased from 2.1 m to 3 m. This increase in borehole spacing would reduce the capacity of the disposal vault to about 7.1 million used-fuel bundles. The potential for yielding or breakouts along the walls of the boreholes was reduced but not eliminated under the ambient temperature condition. This effect and the potential for more extensive breakouts from thermally induced stresses was considered unacceptable unless the spacing of the boreholes along the room axis was increased further.

Consequently, a disposal vault at a depth of 500 m was analyzed. This depth is within the nominal range established in the Nuclear Fuel Waste Management Program. Tsui and Tsai (1994a) retained the flat disposal-room floor and the centre-to-centre emplacement-borehole spacing of 2.1 m both across and along the disposal room and the disposal room oriented perpendicular to the maximum horizontal stress direction for this analysis. This alternative retains the inventory of 10.1 million fuel bundles within a 4-km^2 emplacement area, and limits the amount of changes in disposal vault costs (see discussion in Chapter 7).

Tsui and Tsai (1994a) again reassessed the in situ stress assumptions used in earlier analyses using a more recent compilation and interpretation of data by Herget (1987) for the analyses of the disposal vault at a depth of 500 m. They separated Herget's average horizontal stress data into a maximum and minimum horizontal stress by applying the ratios of maximum/minimum horizontal stresses given by Herget (1987). The resulting maximum (σ_1) and minimum(σ_2) horizontal stresses are as follows:

$$\sigma_1 = 0.0419Z + 13.44 \text{ (depth 0 to 900 m)} \quad (3.6a)$$

$$\sigma_1 = 0.0123Z + 40.25 \text{ (depth below 900 m)} \quad (3.6b)$$

$$\sigma_2 = 0.0323Z + 6.28 \text{ (depth 0 to 900 m)} \quad (3.7a)$$

$$\sigma_2 = 0.0099Z + 26.57 \text{ (depth below 900 m).} \quad (3.7b)$$

The vertical stress (σ_3) is:

$$\sigma_3 = 0.0265Z \quad (3.8)$$

where $\sigma_3 = \sigma_v$, the minor principal stress, is assumed to be vertical (MPa),

$\sigma_1 = \sigma_{Hmax}$, the maximum principal stress, is assumed to be horizontal (MPa),

$\sigma_2 = \sigma_{Hmin}$, the intermediate principal stress, is assumed to be horizontal (MPa), and

Z = depth (m).

Thus, Tsui and Tsai's calculated in situ stresses at a depth of 500 m are

σ_1 = 34.4 MPa,

σ_2 = 22.4 MPa, and

σ_3 = 13.3 MPa.

The empirical rock failure criterion (Hoek and Brown 1980) derives a tensile strength value of 3.7 MPa for the strength parameters used. However, the observed tensile strength of intact medium-grained granite at the Underground Research Laboratory is about 6 to 8 MPa. Thus, the m parameter of the failure criterion (Equation (2.5)) was reduced in the analyses from 30 to 18.3 to allow a tensile strength of 6 MPa.

Tsui and Tsai (1994a) analyzed the disposal vault at a depth of 500 m under excavation (i.e., at ambient temperature) and sealed (i.e., at elevated temperature) conditions with the disposal-room axes oriented perpendicular to the maximum horizontal stress direction. For the sealed-condition case, the support pressures provided by bentonite swelling were applied to the borehole walls – 1 MPa for the upper 2 m of the hole and 0.5 MPa for the lower 3 m of the borehole. These swelling pressures were based on early unpublished results (i.e., about 1.5 a of heating) from the Underground Research Laboratory Buffer/Container Experiment (Thompson et al. 1992). The support pressures applied to the disposal-room boundaries were the weight of the materials for the backfill and a swelling pressure of 0.5 MPa for the upper backfill. No allowance was included in the magnitude of these support pressures for residual stresses from the compaction of the materials and stresses resulting from thermal expansion.

The results of the analyses for the excavation conditions indicate that the walls of the disposal room and the emplacement boreholes are stable, although there may be a possibility for subhorizontal crack formation about

1 m below the floor of the room. As well, the average strength-to-stress ratios calculated over the thinnest portion of the rock webs range from 2.5 to 4.

The analysis of the sealed condition indicates that there may be spalling along the length of the emplacement boreholes, that subhorizontal cracking could progress to a depth of 2 m below the floor, and that the average strength-to-stress ratio decreases over the rock webs to values of 1.7 to 2.1. The spalling and cracking is localized around the boreholes in the sparsely fractured granite under the floor of the disposal rooms. The high strength-to-stress ratios (i.e., greater than 4) in the pillars between disposal rooms show that spalling and cracking are unlikely to propagate between rooms. The rooms remain relatively isolated from each other hydraulically and remain isolated from the hydraulically permeable pathways for groundwater movement. This should not be detrimental to the isolation of the waste.

Tsui and Tsai (1994a) analyzed a second case for the disposal vault at a depth of 500 m in which the disposal rooms were oriented parallel to the maximum horizontal stress direction.

The results of the excavation analysis for this case (Figure 3-13) show that the room and boreholes are stable, with no overstress condition around the boreholes. The average strength-to-stress ratio in the rock webs exceeds 3.3 when calculated over a vertical section through the thinnest part of the webs. The strength-to-stress ratio within the pillar between adjacent disposal rooms exceeds 4 at points beyond 2 m from the room wall.

The analysis of the sealed condition after 30 a of heating included the support pressures from the sealing materials, as discussed above. Figure 3-14 shows that the strength-to-stress ratios around the disposal room and the emplacement boreholes for the sealed case are lower than those in Figure 3-13 because of the addition of the thermal expansion stresses. These results indicate that there should be little to no spalling in the boreholes, and the potential for horizontal fracturing in the top 1 m of the borehole should be limited. In general, the rock mass surrounding the disposal room and the boreholes has an average strength-to-stress ratio of 2 or greater, with local areas around the upper 1 m of the boreholes between 1 and 2. The average strength-to-stress ratio in the rock webs is 2. The pillar between disposal rooms retains a strength-to-stress ratio greater than 4.

(iii) Progressive yielding and rock burst analyses

Tsui and Tsai (1994a) did not analyze for progressive yielding in zones that indicated a strength-to-stress ratio less than 1 for shear conditions. In this type of analysis, material having a strength-to-stress ratio below 1 would be given residual material properties (e.g., the residual strength properties in Table 3-10), and the stress analysis would be redone. These steps would be repeated until the analysis results in a strength-to-stress ratio of 1 or greater at all locations.

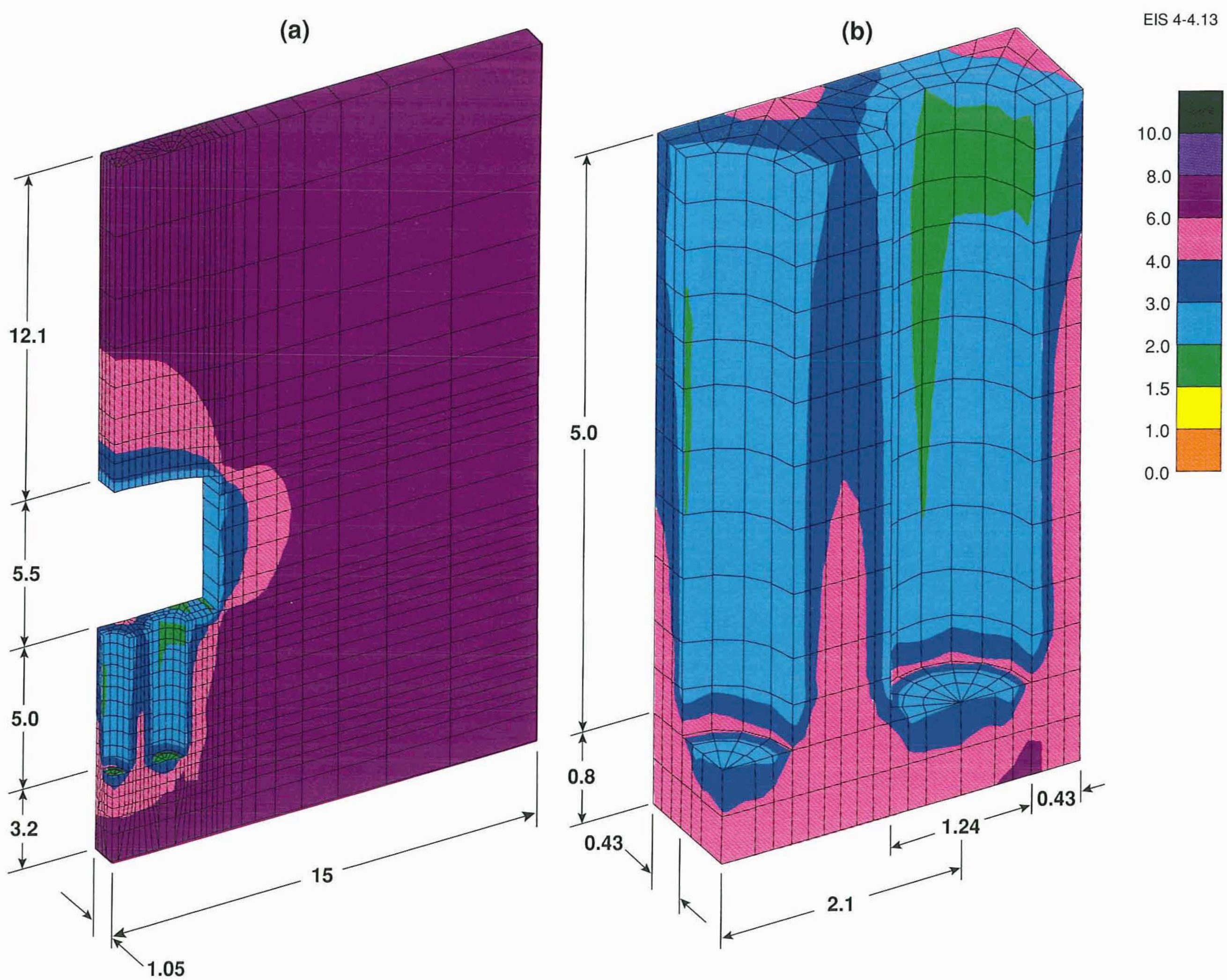


FIGURE 3-13: Strength/Stress Ratios Based on Hoek and Brown Failure Criterion Around a Disposal Room at a Depth of 500 m Immediately After Excavation (Tsui and Tsai 1994a)

(a) Disposal Room and Rock-Web Region
(b) Rock-Web Region

No progressive yielding analyses were performed in the analyses of excavation conditions for disposal vaults situated at depths of 500 and 1000 m. There were overstress conditions in shear (i.e., strength-to-stress ratios less than 1) along major portions of the emplacement-borehole walls for the analyses of disposal vaults at a depth of 1000 m, with emplacement borehole spacings of 2.1 m x 2.1 m (flat floor) and 2.1 m x 3.0 m (curved floor).

We considered this situation to be unacceptable before waste emplacement operations even begin, and so the analyses of progressive failure were not done. There were no zones of shear overstress for the analyses of the disposal vaults at a depth of 500 m, with emplacement borehole spacings of

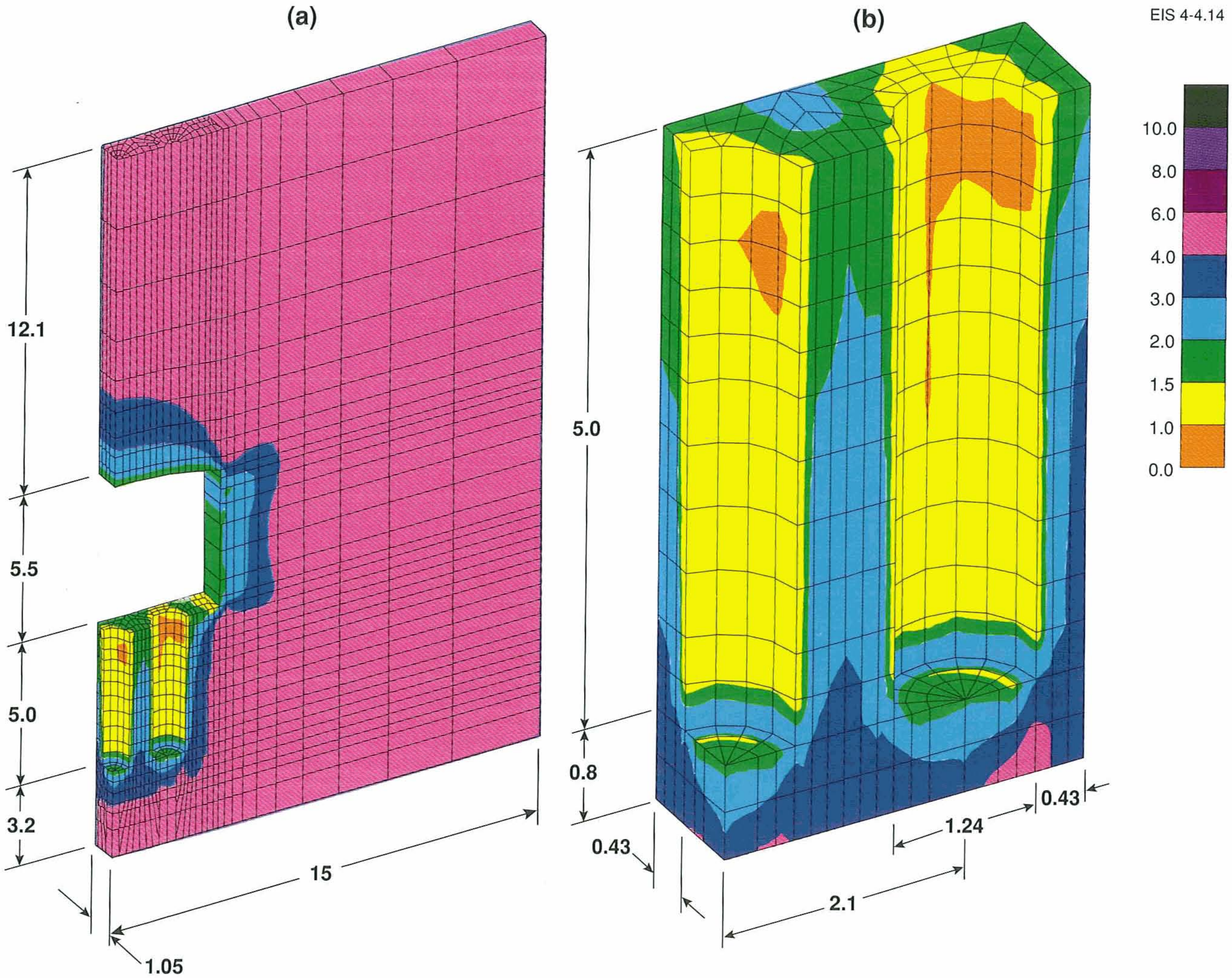


FIGURE 3-14: Strength/Stress Ratios Based on Hoek and Brown Failure Criterion Around a Disposal Room at a Depth of 500 m 30 a After Container Emplacement (Tsui and Tsai 1994a)

(a) Disposal Room and Rock-Web Region
(b) Rock-Web Region

2.1 m x 2.1 m (flat floor) and disposal rooms oriented parallel with and perpendicular to the maximum horizontal stress direction. Progressive failure analyses were not relevant for these cases.

There was no shear overstress and so no progressive yielding analysis was needed for the analysis of the sealed condition of the disposal vaults at a depth of 500 m, with the disposal rooms oriented parallel to the maximum horizontal stress directions. The analysis of the case with the disposal rooms oriented perpendicular to the maximum horizontal stress direction indicated a zone of shear overstress along the emplacement borehole wall.

The breakout formations in the boreholes are very near the excavation surface. Since the rock must dilate for the yielding process to continue, and sealing materials and the breakout debris would limit the amount of dilation that could occur, it was judged that the process would soon stop. Similarly, the backfill material in the disposal room would constrain any dilation that could occur because of horizontal cracking in the floor of the disposal room. There is insufficient knowledge to quantify and model the complex behaviour of the constrained-breakout debris, the yielding rock and the sealing materials, and so no progressive yielding analysis was attempted.

Progressive yielding in the rock mass adjacent to underground excavations, including microcracking of the rock matrix, and the role that backfilling and sealing materials play in controlling dilation are being investigated by field experiments at the Underground Research Laboratory and by analyses. The response of rock to excavation and the mechanisms controlling rock breakouts are being studied at the Underground Research Laboratory in the Mine-By Experiment (Read and Martin 1991). The results of this type of research at the Underground Research Laboratory and future characterization and component testing at the preferred disposal site proposed in Section 3.3.2 would provide the appropriate material properties and performance criteria (e.g., limiting design values for strength-to-stress ratio at various critical locations in the disposal room) for use in the construction design analyses of a disposal vault at an actual site.

As well, an analysis by Wilkins and Rigby (1993) considered the increase in microcrack population (i.e., creep by progressive microcracking) in a volume of rock located between an outer disposal vault room and a subhorizontal fault, as shown in Figure 3-9. Wilkins and Rigby assumed high in situ stress, high thermally induced stresses, relatively low rock strength, a distance of 45 m between the fault and the nearest point of the closest excavation, and an excavation with a diameter of 8 m, typical of the disposal rooms in this conceptual design. The analysis showed that the envelope of rock surrounding the disposal room with a strain of 0.001 or more extends a maximum distance from the room boundary of 2.75 m at 1000 a and 3 m at 100 000 a after container emplacement. In this very pessimistic analyses, extensive microcracking around an excavation only occurs to a distance of about one excavation radius from the excavation boundary. Based on their analysis, Wilkins and Rigby estimate that there will be no effect on massive rock beyond one excavation diameter (8 m) from the excavation boundary.

In a separate review, Ortlepp (1992) considered the risk for rock bursting rather than progressive yielding as a failure mechanism in highly stressed, medium-grained granite. The Ontario Mines and Mining Plants Regulations (Government of Ontario 1990d) define a rock burst as ". . . an instantaneous failure of rock causing an expulsion of material at the surface of an opening or a seismic disturbance to a surface or underground mine." From this perspective, no distinction is made about the magnitude of the rockburst event, although these Ontario government regulations require a notice in writing of a rock-burst occurrence in an applicable jurisdiction when the mass of displaced rock exceeds 5 Mg.

Ortlepp (1992) reviewed the rock and stress conditions at the Underground Research Laboratory and this disposal vault conceptual design. He states that the most probable rock-burst source and damage mechanism is strain bursting, where the energy that causes damage is derived from the internal strain energy within the volume of rock that is disrupted, and that the events occur very close to the excavation surface, where stress concentrations are the highest. Bursting is very sensitive to excavation shape and excavation technique. Ortlepp concluded from his extensive experience of rock-burst conditions and events that ". . . there is no realistic probability of significant rock-burst risk associated . . . with the creation and utilisation of a functional repository in the same type of environment . . . (as the Underground Research Laboratory)." The stress magnitudes at the 420 Level of the Underground Research Laboratory are relatively high and the stress ratio around the openings is also very high so that the risk of sudden events such as rock bursting in a disposal vault constructed in a similar medium-grained granite rock body should be low. However, localized, small-scale strain bursts of rock slabs, as occasionally experienced in the Underground Research Laboratory, could occur.

(iv) Sequential borehole drilling analyses

In another analysis using the disposal room and stress orientation for the vault located at a depth of 1000 m, Tsui and Tsai (1994c) showed that the sequence in which emplacement boreholes are drilled in a disposal-room floor can influence the peak stresses in the rock web between the boreholes. The sequence of drilling row after row of three boreholes across the width of the room chosen in the Used-Fuel Disposal Centre conceptual design (Section 5.4.3.3) was confirmed as one of the better ways to control the transient stresses in the rock webs and borehole walls. For this case, transient stresses developed in the most highly stressed web while the borehole array is being drilled are about 5% greater than the final stresses in the web after completion of all the boreholes. The most highly stressed part of the web is the narrow portion of rock between two of the boreholes along the centreline of the room floor. The analysis also showed that if the line of boreholes along the centreline of the room was drilled first, followed by the boreholes on each side of the room, the transient stresses in the same web could be about 25% greater than the final stresses. As this was an elastic stress analysis, not a strength analysis, the results are also applicable to a vault situated at any depth, including one situated at 500 m.

(v) Conclusion of local-scale analyses

The minimum allowable borehole-to-borehole spacing at a depth of 500 m is 2.1 by 2.1 m for the in situ stress state, room orientation and material properties assumed by Tsui and Tsai (1994a). The analyses of several alternatives for disposal vault depth and orientation shows the process by which the design can be adapted to the conditions. If the magnitude and/or the deviatoric stress conditions are greater (e.g., as experienced in the Underground Research Laboratory) or the strength of the materials is less than the values assumed, either the borehole spacing or the age of the waste would need to be increased, which would reduce the peak temperatures and the thermal expansion stresses. Alternatively, other waste emplacement methods that eliminate the rock web, such as in-room emplacement, could be used.

3.3.7.3 Large-Scale Thermal-Mechanical Analyses

Golder Associates (1993) used the two-dimensional axisymmetric finite-element model created for the thermal analysis (Section 3.3.7.1) in the geosphere or large-scale thermal-mechanical analyses. The horizontal principal stresses were taken to be equal (at 1000 m, $\sigma_1 = \sigma_2 = \sigma_{Ha} = 37.1$ MPa). The average horizontal stress was taken to be 6.7 MPa, as given by Equation (3.3), at the surface, where the vertical stress (σ_v) is zero.

The analysis by Golder Associates (1993) using a "smeared" heat source indicated that the thermal expansion forces did not create an extension zone at or near the ground surface in the rock mass above the vault where the compressive normal load across any near-vertical fracture could drop to zero. However, the compressive normal load across vertical or near-vertical fractures could be reduced from the initial load in the top 300 to 350 m of the rock mass above the vault (Figure 3-15) as a result of the heating. At depths below about 350 m the compressive normal loads across any vertical or near-vertical fracture would be expected to increase from the initial load because of this heating effect.

There was no significant increase in vertical stress created by thermal expansion since the ground surface is free to move upwards (Figure 3-16). The vertical displacements would be about 15 mm after about 60 a following instantaneous waste loading in the vault. Such vertical displacements would be measurable with precision land surveys and could be monitored. Vertical displacements are anticipated to be less than 300 mm after 4000 a. These displacement values are dependent on the in situ coefficient of thermal expansion of the rock mass overlying and surrounding the disposal vault.

Golder Associates (1993) also performed a limit equilibrium stability analysis for two shear (i.e., fault) zones at subvertical and subhorizontal orientations in the surrounding geosphere (Figure 3-9) near the vault at a depth of 1000 m. The approach was to determine the normal and shear stresses acting along the segments of the faults zones from a two-dimensional finite-element analysis under the specified thermal conditions. These stresses were used to evaluate the potential for shear displacement along the length of the faults. The limit equilibrium approach was used because material-property values for representative fault zones are not available. A range of potential friction angles and cohesions was used in this sensitivity analysis. It was also assumed that hydraulically drained conditions applied (i.e., there were no excessive pore pressures), since the shear zone loading rate caused by thermal expansion should be sufficiently low that any excessive pore pressures would be able to dissipate.

The shear strength was calculated using the relationship

$$\tau_r = c' + \sigma_n \tan \phi' \qquad (3.9)$$

where c' = 0 to 240 kPa, effective,

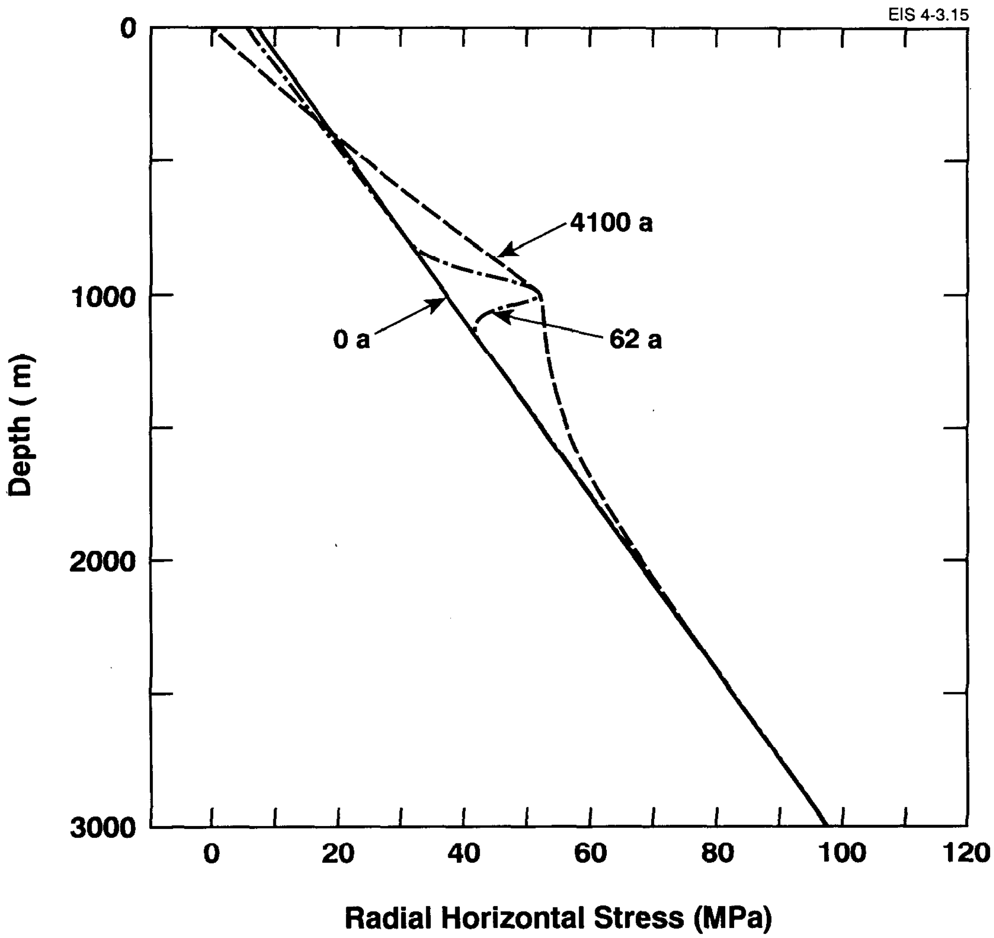


FIGURE 3-15: Variation of Horizontal Stresses with Depth at 62 and 4100 a After Emplacement (axisymmetric case) (after Golder 1993). This analysis assumes that $\sigma_i = \sigma_2$.

ϕ' = 25° to 40°, effective, and

σ_n = normal stress calculated in the finite-element model.

The results for the subhorizontal fault (Table 3-11) show that the shear strength to shear stress ratio is generally high, except within 100 m of the ground surface. This indicates a high resistance to movement on the fault. The results for the subvertical fault (Table 3-12) show that the high horizontal stress has a larger component of stress normal to the fault, which effectively precludes any possibility of instability or movement. In all cases, the analyses showed that there is no potential for instability to develop in nearby shear zones because of the heating and expansion of the rock mass surrounding the disposal vault.

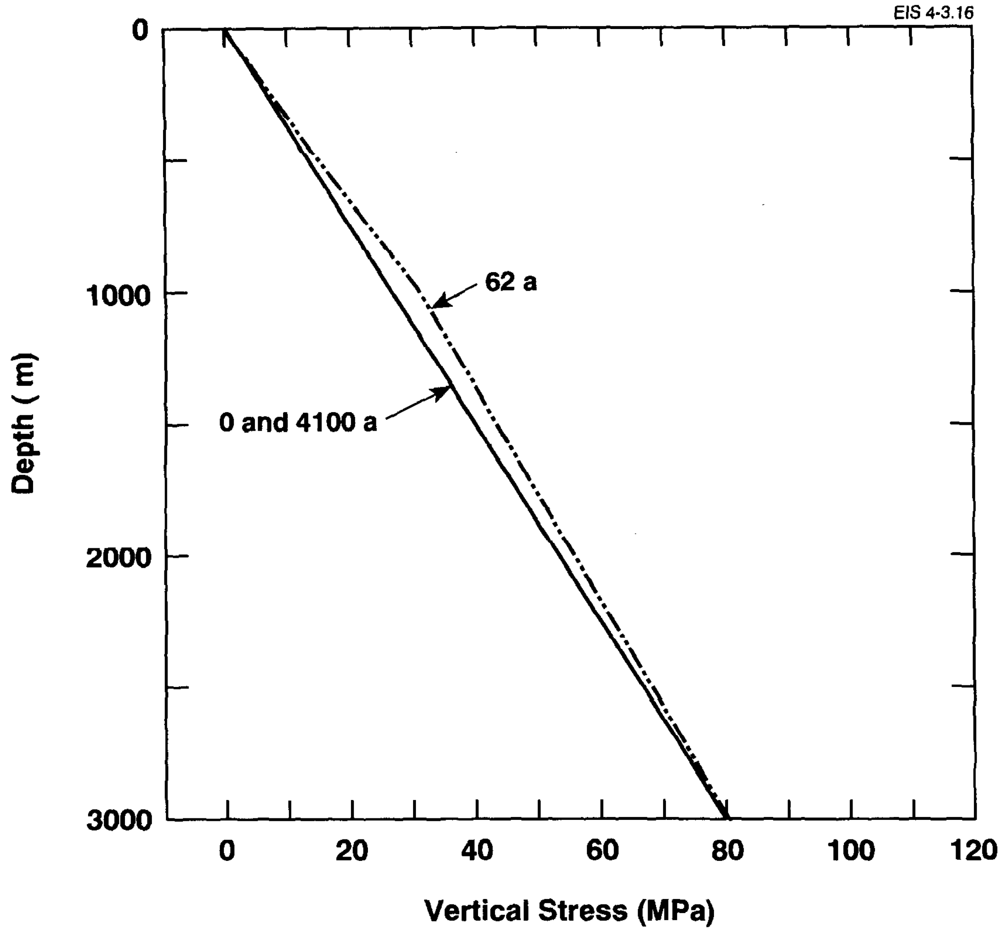


FIGURE 3-16: Variation of Vertical Stresses with Depth at 62 and 4100 a After Emplacement (axisymmetric case) (after Golder 1993)

The implications of setting the disposal vault at a depth of 500 m (see Section 3.3.7.2 (ii)) have not been analyzed explicitly. The thermal gradient from the vault to the surface would be greater for a vault at a depth of 500 m than for a vault at a depth of 1000 m (Figure 3-12). This would result in lower long-term temperatures in the rock mass, smaller volumes of rock heated to a given temperature, and lower thermal expansion forces. While the analysis indicated that a near-surface extension zone would not form for a vault at a depth of 1000 m, a near-surface extension zone could be expected to form for the case of the vault at a depth of 500 m. The horizontal compression zone around the vault is likely to limit the depth of this zone to about 100 m. No increase in fault instability is anticipated.

TABLE 3-11

SHEAR STRENGTH/SHEAR STRESS RATIOS ALONG SHEAR ZONE 1 (SUBHORIZONTAL)

(see Figure 3-9) (after Golder 1993)

Depth Below Surface (m)	Shear Strength/Shear Stress Ratio							
	Case 1 c' = 0 ϕ' = 25°		Case 2 c' = 0 ϕ' = 40°		Case 3 c' = 240 kPa ϕ' = 25°		Case 4 c' = 240 kPa ϕ' = 40°	
	80 a	4200 a	80 a	4200 a	80 a	4200 a	80 a	4200 a
25	0.3	0.4	0.6	0.6	0.4	0.5	0.7	0.7
75	0.6	1.2	1.1	2.2	0.8	1.4	1.3	2.4
125	1.0	5.5	1.8	5.9	1.1	6.1	1.9	6.2
175	1.3	>10.0	2.4	>10.0	1.5	>10.0	2.5	>10.0
250	1.8	>10.0	3.3	>10.0	2.0	>10.0	3.4	>10.0
350	2.3	>10.0	4.3	>10.0	2.5	>10.0	4.4	>10.0
450	2.7	4.5	4.9	8.1	2.9	4.7	5.0	8.3
550	3.2	3.7	5.7	6.7	3.3	3.8	5.8	6.8
650	4.0	4.7	7.3	8.5	4.2	4.9	7.4	8.6
750	5.5	4.6	9.8	8.2	5.6	4.7	9.9	8.3
825	7.2	4.0	>10.0	7.3	7.3	4.1	>10.0	7.4
875	5.7	3.3	>10.0	6.0	5.8	3.4	>10.0	6.1
925	3.4	2.7	6.0	5.0	3.5	2.8	6.1	5.1
975	3.2	2.6	5.8	4.6	3.3	2.7	5.8	4.7
1075	3.8	2.8	6.8	5.1	3.9	2.9	6.9	5.2
1150	3.9	2.9	7.1	5.2	4.0	3.0	7.2	5.2
1250	4.3	3.8	7.8	6.8	4.4	3.9	7.9	6.9

3.3.7.4 Discussion

This chapter presented a process for the design of a disposal vault so that the design would meet thermal-mechanical specifications. The results of the above relatively simple, linear analyses provide insight into the thermal and mechanical processes that affect the structural response of a rock mass to excavation and to heating. The methods of analysis, such as the finite-element method in solid body mechanics, are commonly used engineering tools for both soil and rock. The specific computer codes that were used, ABAQUS and ANSYS, have been tested against established closed-form analytical solutions during their development and use. In an actual application, the excavation designs derived from thermal, mechanical and thermal-mechanical modelling would be field-tested as they are constructed to ensure that the more complex and nonlinear material behaviour models incorporated into such analyses are reasonable representations of the response of the rock and the sealing materials to perturbations. The experiments being performed in the Underground Research Laboratory (Simmons 1990) provide the field testing for

TABLE 3-12

SHEAR STRENGTH/SHEAR STRESS RATIOS ALONG SHEAR ZONE 2 (SUBVERTICAL)

(see Figure 3-9) (after Golder 1993)

Depth Below Surface (m)	Shear Strength/Shear Stress Ratio							
	Case 1 $c' = 0$ $\phi' = 25°$		Case 2 $c' = 0$ $\phi' = 40°$		Case 3 $c' = 240$ kPa $\phi' = 25°$		Case 4 $c' = 240$ kPa $\phi' = 40°$	
	80 a	4200 a	80 a	4200 a	80 a	4200 a	80 a	4200 a
25	2.8	1.6	5.1	2.9	3.1	3.0	5.4	4.2
75	3.2	1.9	5.9	3.5	3.5	2.3	6.1	3.9
125	3.6	2.1	6.5	3.8	3.8	2.3	6.7	4.0
175	3.9	3.9	7.1	7.1	4.1	4.1	7.3	7.3
250	4.4	2.4	7.9	4.3	4.5	2.5	8.1	4.4
350	4.9	2.6	8.9	4.7	5.1	2.7	9.1	4.7
450	5.7	3.1	>10.0	5.6	5.8	3.2	>10.0	5.7
550	6.2	3.4	>10.0	6.2	6.4	3.5	>10.0	6.3
650	6.9	3.8	>10.0	6.9	7.0	3.9	>10.0	7.0
750	7.6	4.2	>10.0	7.6	7.7	4.3	>10.0	7.7
825	8.1	4.6	>10.0	8.3	8.3	4.7	>10.0	8.4
875	7.8	4.9	>10.0	9.3	7.9	4.9	>10.0	8.9
925	6.8	5.1	>10.0	>10.0	6.9	5.2	>10.0	9.3
975	5.6	5.5	>10.0	9.9	5.7	5.6	>10.0	>10.0
1025	5.8	5.9	>10.0	>10.0	5.9	5.9	>10.0	>10.0
1075	7.9	6.6	>10.0	>10.0	8.0	6.7	>10.0	>10.0
1150	>10.0	7.9	>10.0	>10.0	>10.0	8.0	>10.0	>10.0
1250	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0

the material behaviour models for the Lac du Bonnet batholith (Martin 1993), and also for the engineered sealing materials developed. Field testing would have to be done at a future disposal site, when it is selected, to validate the models and material properties for the specific site conditions.

3.3.8 Vault Arrangement, Component Sizing and Operational Logistics

3.3.8.1 General

The balance of this report discusses the design issues, construction, operation, decommissioning and closure of a disposal facility with the disposal vault at a depth of 1000 m. As noted in Section 3.3.7, there might be disposal vault designs for which the combination of rock strength, in situ stress conditions, disposal-room shapes and waste emplacement configurations would limit the disposal vault to depths shallower than 1000 m.

However, these conditions and design options may vary considerably with the site(s) being considered, and it is not appropriate to place general restrictions on the depths for which the conceptual design can be applied. The balance of this report deals with subjects that are not particularly sensitive to the depth of the disposal vault, and so a conceptual design at the maximum nominal depth (i.e., 1000 m) has been chosen.

The disposal vault arrangement chosen in the conceptual design is a system of access tunnels and disposal rooms arranged into eight distinct panels (Figure 1-3). The overall dimensions of the container emplacement area are about 2 km by 2 km. These dimensions are based on an ideal site and do not account for any adaptations that might be required at an actual site to account for local conditions. For example, adjustments to the vault geometry and layout would be required to accommodate site-specific rock structure and stress conditions. One possible arrangement for a vault where faults and fracture zones are encountered on the disposal level is shown in Figure 2-7.

The following requirements and factors were considered in determining the vault layout for the Used-Fuel Disposal Centre conceptual design:

1. A room extraction ratio of about 0.25.

2. Spacing the used-fuel containers to limit the maximum temperature of the container outer surface, or the peak buffer temperature, to 100°C.

3. Keeping the number of openings to the surface to a minimum.

4. Flexibility of operations.

5. Separating radioactive and nonradioactive material handling operations.

6. Providing appropriate ventilation.

7. Ensuring reasonable traffic flow patterns.

8. Moving the excavation and emplacement operations move from the upcast-shaft complex to the service-shaft complex as boreholes are filled.

9. Providing underground ancillary facilities outside the container emplacement area.

10. Keeping the shaft complexes at least 200 m away from the container emplacement area to reduce the temperature increase around the shafts.

11. Forcing the underground drainage-water flow towards the upcast-shaft complex, where it is collected and pumped.

12. Meeting safeguards requirements for used fuel.

These were established to provide guidance in areas of occupational and radiological safety, vault and container structural stability, and operational logistics. The requirements, which individually deal with single components or elements of systems, were also considered collectively in developing the conceptual layout for the disposal vault. As the conceptual design progressed, there were several iterations to ensure that all factors had been dealt with adequately in the final arrangement.

3.3.8.2 Sizing of Disposal-Vault Elements

The centreline emplacement borehole spacing in a Used-Fuel Disposal Centre disposal room was set at 2.1 m along and 2.1 m across the room. This results in an arrangement with three containers spaced across the room, a room-to-room centreline spacing of 30 m, and an initially assumed room width of 7.5 m. These dimensions provide a room extraction ratio of 0.25.

However, when operational factors are considered, a final disposal-room minimum height of 5 m and a width of 8 m were selected to provide sufficient clearance space for the disposal equipment needed to drill boreholes 5 m deep by 1.24 m in diameter on the 2.1 m x 2.1 m spacings, to place, compact and auger the buffer material, and to accommodate the disposal-container cask. The increase in room width from 7.5 to 8 m resulted in an increase in the room extraction ratio to 0.267. This increase was considered acceptable, and the interroom spacing was not revised. The roof was arched to a maximum height of 5.5 m (Figure 3-17) for stability purposes.

A rail-mounted platform system for disposal-room operations was chosen to provide

1. simplified and rapid equipment mobilization and alignment,
2. simplified repeated registration of the equipment over boreholes,
3. a stable foundation for equipment, and
4. support for radiation shielding to allow for container and final buffer emplacement.

The room is 230 m long, 195.3 m of which is used for emplacement boreholes. This provides for a maximum of 282 emplacement boreholes per room. With this room length, the assumed operations sequence limits the time during which the emplaced buffer remains unconstrained in an emplacement borehole, free to absorb water. On the assumed schedule, the time from initial emplacement of buffer in an empty borehole in a disposal room until final emplacement of buffer over a container in the same borehole varies from 15 to 28 calendar days. An additional time of 56 calendar days is required to backfill the lower room, making a total duration of 71 to 84 d from initial buffer placement until full constraint is provided by the lower backfill. Free-swelling tests performed on buffer material in the laboratory indicate that the swelling of the buffer material will be negligible during this period of time.

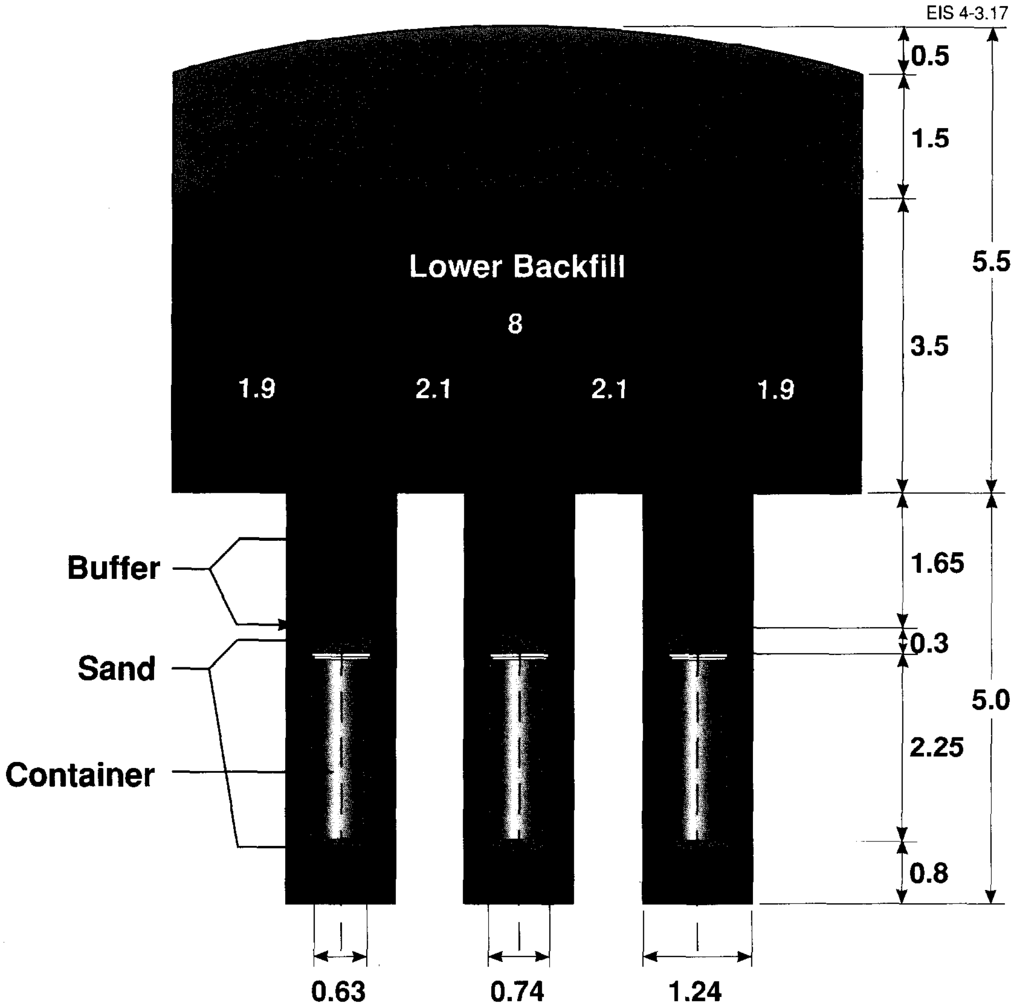


FIGURE 3-17: Disposal-Room and Emplacement-Borehole Configuration. All dimensions are in metres.

A length of 13.5 m is provided at the end of a disposal room for equipment storage during the container-emplacement operations. The borehole auger and final buffer-placement platforms occupy this space when the container emplacement platform is set over the boreholes that are nearest the end of the room. As the emplacement operations retreat towards the room entrance, this space is no longer required because the equipment would be stored over boreholes already filled.

The 21.2 m of length at the entrance provides space for the concrete bulkhead, with a minimum separation of 16.6 m between the bulkhead at the room floor to the centreline of the nearest emplacement boreholes. This distance is included to reduce the possibility of chemical contamination of the local groundwater at the emplacement boreholes by the constituents in the cement used in the bulkhead. The effect of these chemicals on the rate of dissolution of used fuel is being studied.

The diameters of the emplacement borehole and the container hole augered in the buffer were fixed in the course of the Used-Fuel Disposal Centre conceptual study at 1240 and 740 mm respectively to provide adequate annular clearance between the container and the buffer. This clearance is required for the container grapple and hoisting mechanism, and to allow free flow of the dry silica sand as it is placed into the annulus.

The panel tunnels are sized to accommodate the underground cask transporter, the transfer of the equipment platforms from room to room, and the transfer of the container cask from the cask transporter onto the container-emplacement platform using a 40-Mg bridge crane mounted on the roof of the panel tunnel. Thus, the panel tunnels are 6 m wide and 6.5 m high.

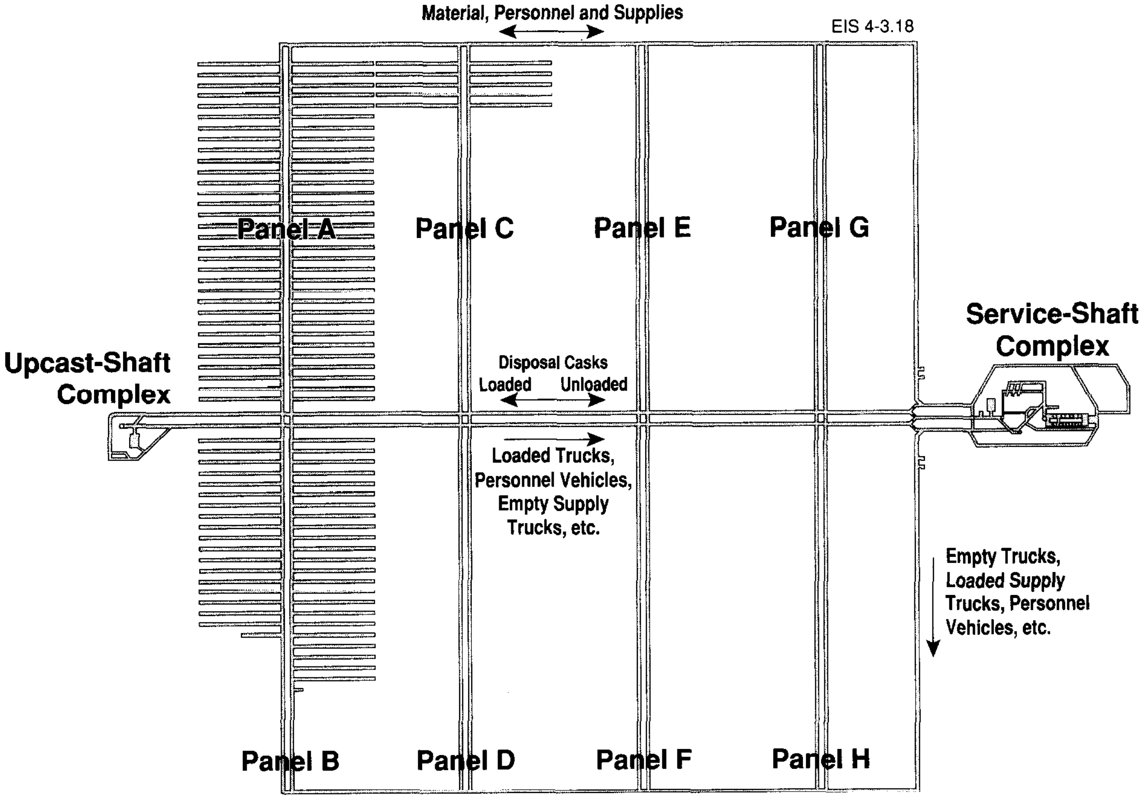
The central access and perimeter tunnels are sized to accommodate passing traffic and the container cask on a transporter, and are 6 m wide and 5 m high, with arched roofs.

3.3.8.3 Vault Layout

The disposal vault layout would be influenced by the local and regional geological structure and hydrogeological flow system, and by the in situ stress and physical properties of the rock mass. These factors may dominate the vault layout and help focus the choice of excavation methods.

No major geological features were specified as design factors for this conceptual design study. Therefore, a 2 km x 2 km single-level vault was assumed in the conceptual design (Figure 1-3). This square geometry was selected because it provides a thermal environment for the central containers in the disposal vault that reasonably ensures that the most significant path for conductive heat transfer is vertically upward and downward. In this case, the temperature peak caused by thermal interaction among the containers is the highest peak and the duration of the thermal transient is the longest. Eight rooms can be aligned end to end in a 2-km-long emplacement area for the selected room length of 230 m.

A system of access tunnels was developed to satisfy the requirements for separation of construction and container-emplacement operations, flexibility of operation, and controlled traffic flow paths. The approach selected uses central access and perimeter tunnels that join at the shaft groups and that separate the vault into two halves (Figure 3-18). The groups of disposal rooms in each half of the vault are divided into four segments or panels by the crosscutting panel tunnels so that each panel can either be operated as an isolated excavation or an isolated emplacement area. With the central access tunnel twinned, this arrangement provides eight independent panels. With the panel tunnels twinned, each panel has two essentially independent work areas. This allows the container-emplacement operations to be separated from borehole preparation, placing of lower room backfill and room sealing operations.



Note (1) This figure shows the situation at about Year 2 of the operation stage.
(2) ——→ Vehicle movement direction.
(3) For excavation of panels G and H the crew size would be reduced and work would extend over five years.

Operating Years	Panel Operations: Container Emplacement	Room Excavation Years 1 to 4	Room Excavation Year 5
1 - 5	Panel A	Panel B	Panel D
6 - 10	Panel B	Panel C	Panel E
11 - 15	Panel C	Panel D	Panel F
16 - 20	Panel D	Panel E	Panel G
21 - 25	Panel E	Panel F	Panel H
26 - 30	Panel F	Panel G	Note (3)
31 - 35	Panel G	Panel H	Note (3)
36 - 40	Panel H		

FIGURE 3-18: Panel Excavation and Emplacement Sequence (after AECL CANDU et al. 1992)

Given that faults and fracture zones may be encountered on a disposal vault horizon, the square vault geometry designed to maximize thermal effects may not be used at an actual site during the implementation of disposal. Rather, the disposal vault might be partitioned into two or more separate emplacement zones to avoid these features. The observational method (Section 2.3.3) applied to the construction design and to subsequent design modifications would provide the framework within which the field data could be used in developing a vault design to suit specific site conditions. The panel arrangement in the Used-Fuel Disposal Centre conceptual design provides the functional independence necessary to allow vault partitioning.

An example of a partitioned vault arrangement is shown in Figure 2-7. Each panel or grouping of panels in this arrangement can function independently and is located within the rock blocks between the faults and fracture zones. Similarly, room lengths and spacings can be adjusted to suit the geometry of the available rock blocks, and sufficiently thick barriers of sound rock are provided to separate the container emplacement areas from the faults and fracture zones.

3.3.8.4 Vault and Panel Operational Logistics

(i) Vault logistics

In developing the general layout of the vault (Figure 3-18), logistical considerations were taken into account. The twinned central access tunnels allow excavation operations on one side of the vault and emplacement operations on the other side to occur without conflict. Work progresses in a retreat fashion, that is, emplacement and excavation begin in panels nearest the upcast-shaft complex (Panels A and B respectively) and progress toward the service-shaft complex. This is shown in more detail in Figure 3-19.

A perimeter access tunnel is provided around each side of the disposal vault. Waste containers are moved in the central access tunnel during emplacement operations, and all other personnel, equipment, supplies and materials are moved in the perimeter access tunnel. The tunnel arrangement in the excavation panel allows one-way traffic flows in the excavation panel. There are no equipment installations in the excavation-panel tunnels that would interfere with vehicle movement.

Ventilation airflows can also be readily distributed, controlled and segregated using the tunnel network selected. Two independent ventilation circuits are provided, one for each of the emplacement and excavation sides of the vault. Fresh air is supplied by the downcast ventilation shaft in the service-shaft complex. Exhaust air is removed by the two upcast ventilation shafts at the other end of the vault: one shaft is reserved for potentially contaminated air (i.e., the emplacement side) and one is used for normal exhaust air (i.e., the excavation side). Ventilation control doors are provided to route the ventilation to the appropriate shaft as the mode of operation of the panels is changed between excavation and emplacement. These doors are equipped with interlock alarms and position monitors to ensure that proper ventilation flows and access controls are maintained. Since operations retreat to the service-shaft complex, fresh airflows to the operation areas before exhausting through the completed excavation or

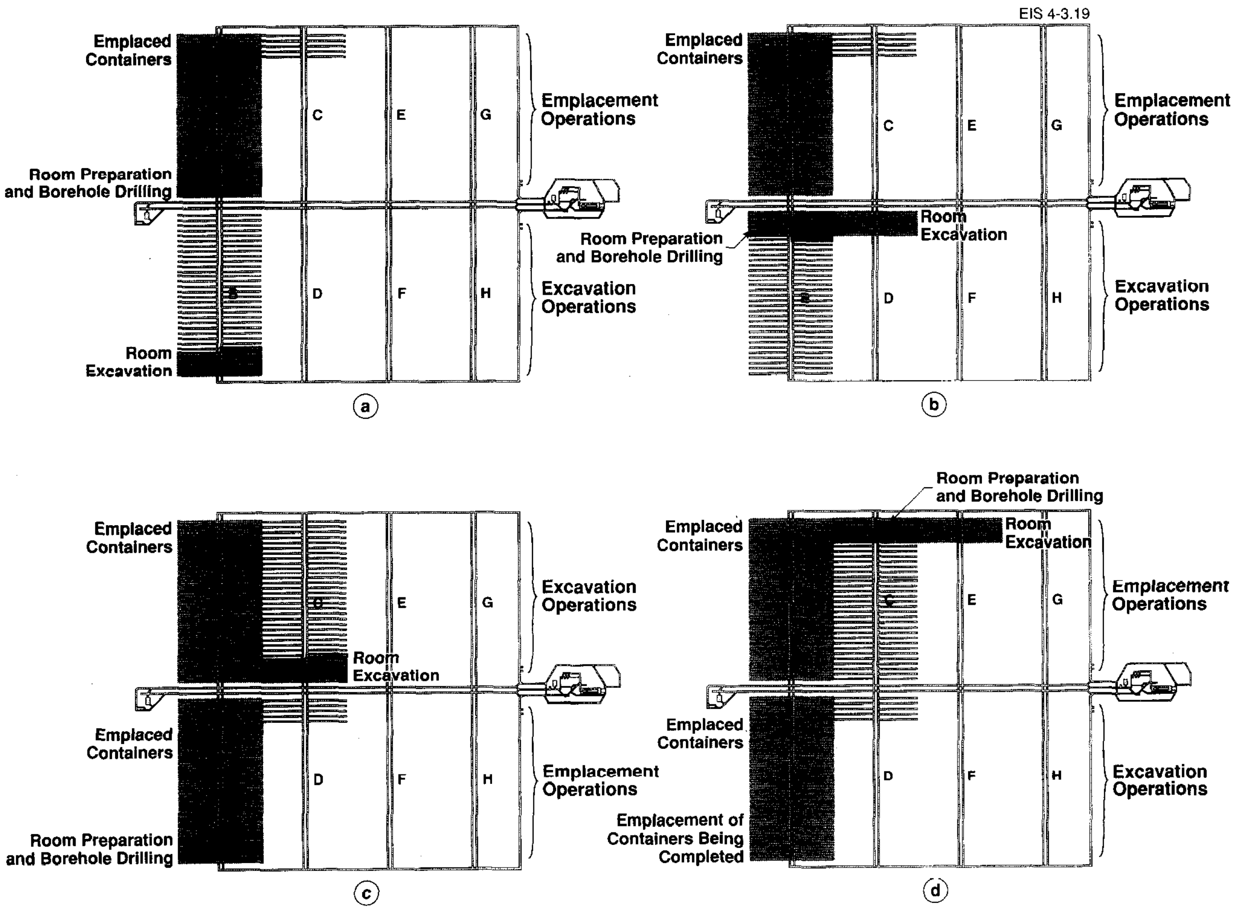
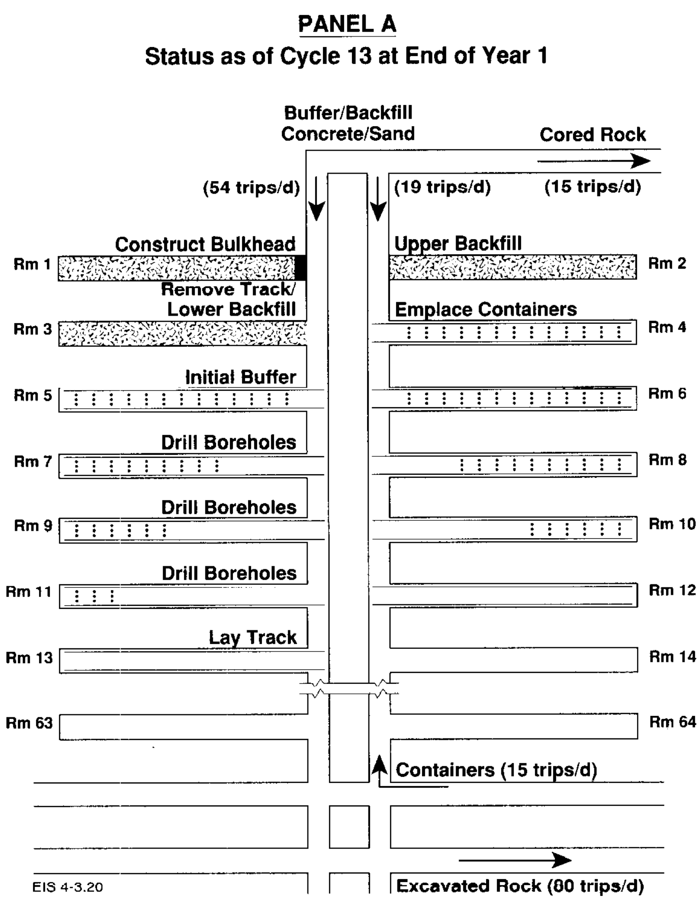


FIGURE 3-19: Room Excavation and Disposal Operations Sequence. The activity sequence within the panel is shown in Figure 3-20.

emplacement areas, thus reducing the potential for smoke, dust or radioactive contamination in the operating areas. Within a given panel, fresh air is supplied from the perimeter access tunnel and is exhausted through the central access tunnel.

An operational changeover occurs as the emplacement operations in a panel are completed. For example, assume that waste emplacement is occurring in Panel A and excavation in Panel B (Figure 3-18). When the emplacement operations in Panel A are completed, waste emplacement activities begin in Panel B and excavation begins in Panel C, the next panel retreating back from Panel A. At that time, the materials handled in the central, perimeter and panel access tunnels and the ventilation system upcast shafts are changed over.

In practice, as the end of a 5-a panel excavation and emplacement cycle approaches, there is a period of up to 1 a where some of the emplacement



Disposal Room Sequencing

28-d Cycle	Track and Services	Drill Boreholes	Initial Buffer	Emplace Containers	Lower Backfill	Upper Backfill	Construct Bulkhead
			Panel A				
1	RM 1						
2	2						
3	3	RM 1					
4	4	2					
5	5	1, 3					
6	6	2, 4					
7	7	1, 3, 5					
8	8	2, 4, 6	RM 1				
9	9	3, 5, 7	1				
10	10	4, 6, 8	2	RM 1			
11	11	5, 7, 9	3	2	RM 1		
12	12	6, 8, 10	4	3	2	RM 1	
13	13	7, 9, 11	5	4	3	2	RM 1
			Panel B (not shown)				
65	1	59, 61, 63	57	56	55	54	53
66	2	60, 62, 64	58	57	56	55	54
67	3	61, 63, 1	59	58	57	56	55
68	4	62, 64, 2	60	59	58	57	56
69	5	63, 1, 3	61	60	59	58	57
70	6	64. 2. 4	62	61	60	59	58
71	7	1, 3, 5	63	62	61	60	59
72	8	2, 4, 6	64	63	62	61	60
73	9	3, 5, 7	1	64	63	62	61
74	10	4, 6, 8	2	1	64	63	62

NOTE: 1. Activities in period 13 shown in diagram.
2. Container emplacement includes augering or buffer and final buffer emplacement.
3. Equipment in rooms 6, 8, 10, 12 not operating in period 13.

FIGURE 3-20: Disposal-Room Operating Sequence and Material-Flow Diagram (after AECL CANDU et al. 1992)

operations, particularly disposal-room preparation, move to the construction side of the vault. This is illustrated in Figure 3-19 for the emplacement of containers in Panels A and B (i.e., two 5-a cycles). Room preparation, emplacement-borehole drilling and buffer emplacement are done ahead of the actual container emplacement (Figure 3-19a). These operations are transferred to the recently excavated Panel B on the excavation side of the vault at the end of Year 4 as the preparation of rooms in the panel on the emplacement side of the vault is completed (Figure 3-19b). Room excavation begins in Panel D on the excavation side of the vault during this period of overlap (i.e., excavation activities are completed in Panel B in Year 4 and move to Panel D where 10 to 12 rooms are excavated in Year 5). However, when waste emplacement activities are completed in Panel A and are about to begin in Panel B, ventilation airflows, services and access tunnel uses are switched to have Panel B the emplacement side of the vault (Figures 3-19c and 3-19d). Excavation activities move to Panel C to continue room excavation and servicing.

Individual disposal rooms must be ventilated when staff and equipment are working in them. Portable ventilation equipment is provided to exhaust air from the end of each room and discharge it into the panel tunnel. This draws air from the panel tunnel through the room and into the exhaust ducts. As activities in a room are completed, the ventilation equipment is removed and reassembled in the next room in which work is scheduled.

To implement this segregation of operations, all the disposal rooms in Panel A and 10 to 12 rooms in each of Panels B and C must be excavated during the construction stage of the disposal vault (see Section 4.3.3).

(ii) Panel logistics

The panel tunnel connects the disposal rooms to the central and perimeter access tunnels. Again, as with the central access tunnels, two parallel panel tunnels are provided to separate the container-emplacement operations from the other operations.

The activities and their sequence for container emplacement in and sealing of each room are as follows.

1. Room preparation and track laying.

2. Borehole drilling.

3. Initial buffer emplacement.

4. Container and final buffer emplacement.

5. Track removal and lower room backfill emplacement.

6. Upper room backfill emplacement.

7. Bulkhead construction.

Nonradioactive operations (1), (2), (3), (5) and (7) are conducted on one side of the panel, and radioactive operation (4) and nonradioactive operation (6) are carried out on the opposite side (Figure 3-20). The operations switch from one side to the other side of the panel and advance by one room every 28 calendar days as a cycle for container emplacement is completed. Thirteen cycles are required to complete the emplacement operations in each disposal room.

During emplacement operations, the underground container cask transporter has dedicated and unhindered access to move through the central access tunnel and the panel tunnel to a location near the entrance to the appropriate disposal room. The tracks and curbs, which extend across each panel tunnel from rooms in which activities are under way, allow no crossover of vehicles between the central access and the perimeter access tunnels. The vehicles return along the route by which they came after being monitored for contamination.

The entire disposal vault, including the disposal rooms, is classed as a Zone 2 radiological hazard area in the Used-Fuel Disposal Centre conceptual design. In Zone 2 there is a potential for radioactive contamination, which would be removed immediately upon discovery. No contamination is expected from a sealed container and decontaminated cask. There is also a limit of 2.5–25 μSv/h for the radiation field in Zone 2. This is consistent with the contact radiation emission rate on the container cask of less than 19 μSv/h. Section 4.4.9 provides a more extensive discussion of radiological zoning requirements. The vault and panel layout and associated logistical controls are developed to minimize exposure to and spread of radioactive contamination and exposure to radiation fields (the ALARA principle). In the case of handling loaded disposal container casks, this involves procedures for handling and storage that limit the time during which workers are in close proximity to the casks.

3.4 SUMMARY

The major design activities for a nuclear fuel waste disposal facility would take place during the siting stage and would become more detailed as the number of sites being considered is reduced and as more characterization data become available on the relevant conditions for the sites still being considered. Many of the factors and issues that require consideration in the organization, administration and design of a disposal facility are discussed in Chapter 2.

This section described the engineering activities that would take place during the siting stage of disposal facility implementation. By using the Used-Fuel Disposal Centre conceptual design as the example, we have presented the design assumptions and some of the approaches to address specific design issues. The design options selected to resolve these issues have been presented for this conceptual design to show that the design and analysis approaches are practicable and could be applied to the design and construction of a disposal facility.

As discussed in Section 3.3.8.1, the remaining chapters of this report describe a Used-Fuel Disposal Centre with a disposal vault located at a depth of 1000 m. Although the specific disposal-room and emplacement-borehole arrangements are better suited to the rock conditions assumed at a depth of 500 m, the vault at a depth of 1000 m provides the longest construction periods, longest cycle times for operations and the largest volumes for excavation and sealing. The descriptions of the facilities, processes and procedures for the construction (Chapter 4), operation (Chapter 5), decommissioning and closure (Chapter 6) of a vault are independent of depth, and the effect of depth on cost, schedule and resource requirements (Chapter 7) is small.

4. THE CONSTRUCTION STAGE OF THE USED-FUEL DISPOSAL CENTRE

4.1 INTRODUCTION

A series of activities would be completed during the construction stage to create the Used-Fuel Disposal Centre, including construction of the Used-Fuel Packaging Plant, the disposal vault, the buffer and backfill preparation plant, the surface and underground ancillary service facilities, and the provision of the utilities and the infrastructure needed to operate the disposal centre. Although all the surface facilities, surface infrastructure, shafts and underground infrastructure would be constructed and commissioned in advance of the operation stage, only part of the vault, consisting of the access tunnels and those disposal rooms needed for the first five years of operation, would be constructed during this stage. The construction stage would begin at the end of the siting stage when approval for construction was issued, and it would end when the surface and underground facilities are installed and commissioned, with the first panel of underground disposal rooms excavated and serviced, and 10 to 12 rooms in each of the two succeeding panels excavated. The disposal centre design and plans approved during the siting stage would be used in the construction. They would be revised as necessary to accommodate the conditions of the specific site through application of the observational method.

In preparation for applying for an operating licence, the implementing organization would demonstrate during the construction stage that the facility performance satisfies the design and regulatory specifications, and that abnormal conditions can be dealt with safely. Prototype containers and baskets would be produced to show that they can meet tolerance and quality specifications, and that defects can be detected and repaired or reworked. Once the appropriate approvals have been received, the packaging plant would be commissioned with used-fuel bundles to demonstrate that all operations and processes meet specifications, and that abnormal processes and operations could be accommodated. The buffer and backfill preparation plant would be operated to demonstrate that the end products meet specifications and that the quality-control measures are effective. The materials handling systems for fuel transport and disposal container casks, for sealing materials, and for personnel, materials and equipment would be operated to demonstrate that all operations and systems function properly, and that abnormal events or conditions can be handled safely. In the vault, all container cask handling, container emplacement, buffer placement and backfill placement equipment would be commissioned to demonstrate that their performance meets specifications and that quality-control measures can detect abnormal conditions or defective workmanship. Waste-container retrieval equipment and operations would be demonstrated.

The construction of the Used-Fuel Disposal Centre would follow the standard sequence for the construction of any large project, and would be influenced by the location, means of access, and services available at the site. One likely sequence for the development of the main facilities follows.

1. Construct or upgrade the means of site access, the utilities and site service systems necessary for development of the major surface and underground facilities. Some of the installations used during the siting stage may be retained or upgraded.

2. Construct the administrative facilities and security systems for the disposal centre.

3. Sink remaining shafts and upgrade the existing exploration shafts.

4. Upgrade existing exploration tunnels and excavate additional tunnels to complete the access tunnel array (Figure 3-2d).

5. Construct the Used-Fuel Packaging Plant and the container fabrication buildings, and complete the shaft headframes and complexes.

6. Construct the waste storage facilities and handling systems, material storage facilities and preparation systems, the service areas at the shaft bottoms, and the initial disposal rooms.

7. Construct all equipment and systems necessary to operate the disposal centre and emplace waste, and commission them to demonstrate the required level of performance.

The auxiliary facilities would be constructed at the appropriate time.

Construction of the Used-Fuel Disposal Centre would commence when the following conditions are met.

1. The project management team has been established to manage the construction stage.

2. Detailed design drawings, specification and construction plans have been produced, checked and approved, and an engineering group has been established to direct the implementation of the design, as well as make design corrections, modifications and take remedial actions, should this be necessary.

3. Approvals for construction have been received from all appropriate federal, provincial and municipal regulators and authorities, following a public and community consultation program.

4. The quality assurance program has been upgraded for construction purposes, quality-control procedures have been established and qualified inspectors are available.

5. A qualified underground characterization team has been established and their activity plans have been integrated into the underground construction plan.

6. Qualified contractors and subcontractors have been awarded contracts.

The systems and activities relating to construction and preparation for operation are discussed in the following sections. The site and support services are presented first to set the stage for subsequent discussions of the construction of the disposal vault and the primary surface facility. The design descriptions are limited to the facilities and systems that are unique to waste disposal and safety. More conventional facilities and systems such as the administration building, dust-collection equipment, sewage and storm-runoff holding ponds, warehouse, switch and transformer yards, powerhouse, fuel and water storage tanks, quality-control laboratories and parking areas are only noted briefly for completeness. In all cases, the facilities created, rather than the construction process, are the focus of the presentation. We believe that discussion of the function of the facilities will better acquaint the reader with the type of installations and the thought processes that would be required to complete the construction stage successfully.

4.2 SITE AND SUPPORT SERVICES IN THE USED-FUEL DISPOSAL CENTRE CONCEPTUAL DESIGN

The Used-Fuel Disposal Centre requires support services to operate effectively. The provision of these services is generally routine for nuclear facilities. It is not necessary to demonstrate the technology and capability for performing the various tasks to prove the feasibility of implementing a waste disposal system. These services are discussed because they must be provided as part of the disposal centre.

The site and support services would be developed when required from the beginning of the siting stage to the completion of the construction stage. A detailed schedule has not been developed because these elements of the disposal centre are not expected to be on the critical path for construction.

4.2.1 Site Characteristics, Layout and Access

Since the Used-Fuel Disposal Centre conceptual design presented here is not focussed on a specific site, certain assumptions were made about the nature and location of the site for design purposes. These assumptions are consistent with conditions that could exist at a disposal site located on the Canadian Shield.

The site is assumed to be

1. relatively flat and undeveloped,
2. within 300 km of a populated centre (~15 000 inhabitants),
3. within 25 km of suitable railway lines, highways and electrical power grid,
4. adjacent to a suitable source of fresh water (at least 250 L/s),
5. in a plutonic rock body of the Canadian Shield,

6. unpopulated within the required surface property area boundary, and

7. in a zone of low seismic hazard.

Since the disposal centre is assumed to be up to 300 km from a populated centre, a townsite has been included in the conceptual design. However, other alternatives, such as flying workers into a site camp, would also be possible. The disposal centre and the townsite are conceived as self-contained units that will require only rail and road transportation, a suitable water source and electrical power to function for normal operations and conditions. For abnormal conditions, emergency response agreements with federal, provincial and surrounding municipal governments and mutual aid agreements with other appropriate organizations will be created to supply emergency aid and resources as needed (see general discussion in Section 2.4.2).

The disposal centre site has overall dimensions of 5.2 km x 3 km (Figure 4-1). The site is divided into a nonradioactive, unfenced supervised area to which public access is discouraged by signs posted on the perimeter, and two potentially radioactive, protected areas that are fenced to inhibit and aid in the detection of any unauthorized entry. The Used-Fuel Packaging Plant, service-shaft complex and some ancillary services

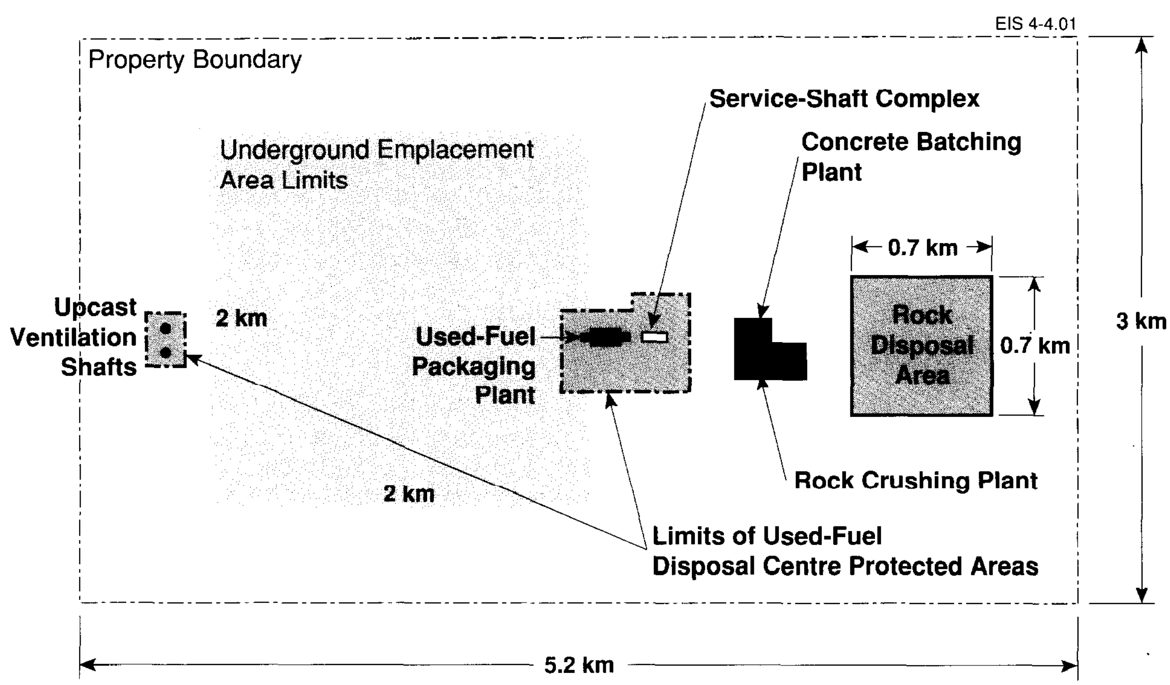


FIGURE 4-1: Used-Fuel Disposal Centre Land Requirements (after AECL CANDU et al. 1992)

comprise the main protected area. The upcast ventilation shafts, headframes and some services are fenced as a second protected area with separate access control.

The disposal centre is accessed by constructing connections to major highway and rail systems (Figure 4-2). The road and rail access onto the site are controlled by security personnel. Vehicles entering the disposal centre have access to all buildings and service areas outside the protected areas. Trains entering the disposal centre have access to the concrete batching plant and to the main protected area.

Access to the main protected area is controlled at the security-fence boundary as discussed in Section 4.2.9.1. One personnel gate, four road gates and two rail gates are provided. Road access within the protected area is provided to all buildings and operating areas, and rail access is provided to the Used-Fuel Packaging Plant for shipping-cask handling, and to the sand, bentonite and lake clay receiving bins.

4.2.2 Site Support Services

The disposal centre requires the installation of structures and equipment, and the development of administrative control systems and service systems for its operating success. Many of these are standard financial control and administration systems, health care, cafeteria and maintenance services that are not unique to this type of project. In the conceptual design, it is assumed that the disposal centre is remote from the nearest community. Therefore, the disposal centre is designed to be self-sufficient for utilities and services.

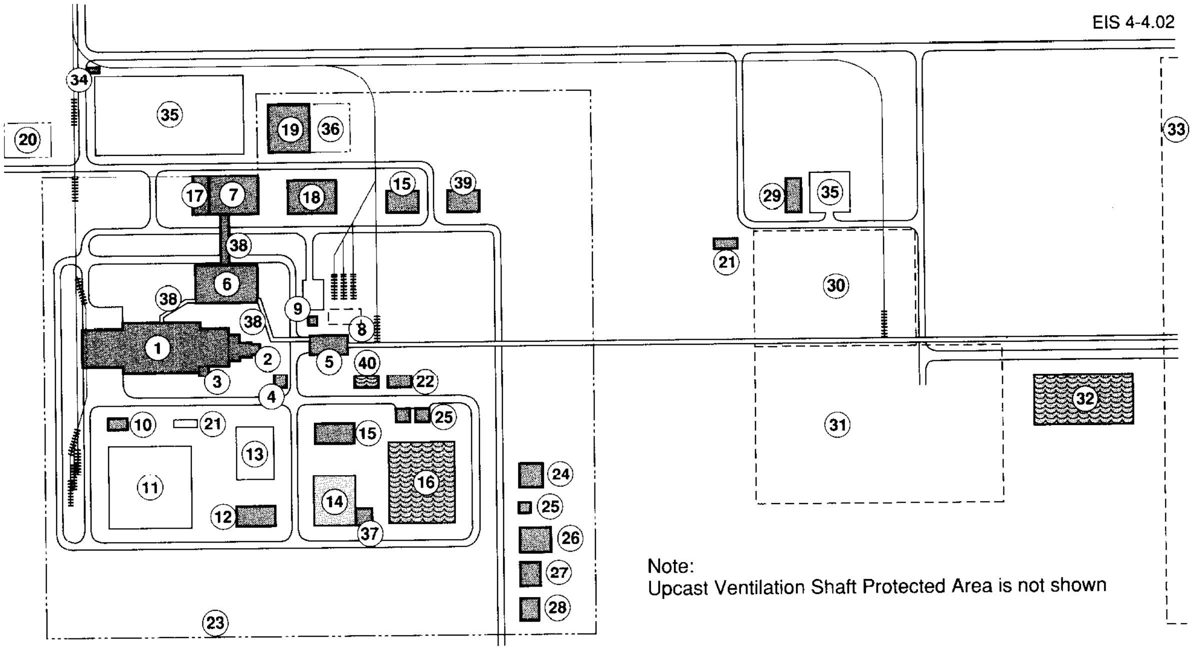
4.2.3 Utilities

In the Used-Fuel Disposal Centre conceptual design, the disposal centre obtains electrical power from a transmission line built to connect to a regional power grid, has a suitable water source available, and has propane and other fuels delivered by truck or rail as required. Other utilities are generated on site.

4.2.3.1 Electrical Systems

The electrical power distribution system provides electrical power to process, control and instrumentation, to heating, ventilation and air-conditioning, and to lighting and service loads. It includes connections with the off-site grid, on-site standby generating units, distribution equipment, and the necessary protection and controls. The total estimated load for this conceptual design is 22 MW, with 7 MW required by underground operations and 15 MW required by the surface facilities. Approximately 4 MW of standby power is provided to maintain the safety of personnel and to protect the facilities, as dictated by personnel and equipment safety criteria, during any outage of the off-site electrical grid.

All electrical equipment would be designed, built, tested and installed in accordance with all applicable codes, regulations and standards in force at the time of construction.



1. Used-Fuel Packaging Plant
2. Waste-Shaft Headframe
3. Stack
4. Downcast Ventilation Shaft
5. Service-Shaft Complex
6. Auxiliary Building
7. Admin. Bldg. Including Firehall
8. Sealing Material Storage Bins
9. Dust Collection Bag House
10. Active-Solid-Waste Handling Building
11. Waste Management Area
12. Active-Liquid-Waste Treatment Building
13. Low-Level Liquid Waste Storage Area
14. Sewage Holding Pond
15. Garage
16. Storm Runoff Holding Pond
17. Cafeteria
18. Basket and Container Fabrication Plant
19. Warehouse
20. Switchyard
21. Transformer Area
22. Air Compressors
23. Security Fence (Main Protected Area)
24. Powerhouse
25. Fuel Tanks
26. Water Storage Tanks
27. Water Treatment Plant
28. Pumphouse and Intake
29. Quality Control Offices and Laboratory
30. Concrete Batching Plant Area
31. Rock Crushing Plant Area
32. Process-Water Settling Pond
33. Rock Disposal Area
34. Guard House
35. Parking Area
36. Storage Yard
37. Sewage Treatment Plant
38. Overhead Corridor
39. Hazardous Materials Storage Building
40. Service-Shaft Complex Water Settling Pond

FIGURE 4-2: Used-Fuel Disposal Centre Site Layout (after AECL CANDU et al. 1992)

The electrical loads are arranged on busses through the use of electrical distribution equipment and switch gear powered from the regional electrical grid (4160 V AC), on-site standby diesel generators (600 V AC) and an uninterruptible power system (250-V DC/inverter system). The specific power sources depend on how critical a specific load is to environmental, occupational and radiological safety, and the size of the load. Large power loads are supplied from the grid and possibly the standby diesel generators, whereas smaller loads whose continuous operation is critical are supplied from the uninterruptible power system.

4.2.3.2 Water Supply Systems

The water supply in the Used-Fuel Disposal Centre conceptual design is assumed to be a nearby lake or river of sufficient size to supply the water demands of the disposal centre. The pumphouse is located adjacent to the water source. Three levels of water purity are provided: process water/fire water, domestic water and demineralized water (Table 4-1 and Figure 4-3). There is a good potential to recycle a large fraction of the discharged process and some domestic wastewaters for reuse as process water/fire water.

(i) Process water/fire water

Process water/fire water is fresh water from which the fish, weeds, algae, and large particulates are removed by screening and straining. The process-water requirement for heat exchangers, such as the Used-Fuel Packaging Plant surge-storage pool heat exchangers, is based on a process-water temperature rise of 10°C. A closed circuit with chemistry control may be required if the actual process-water chemistry is such that chemistry adjustments are required to achieve the desired service life from components.

The demands in this conceptual design study are based on an open system, on the planned operating schedule for the facilities, and include a generous allowance. The process water is drawn at a peak rate of 8200 m^3/d from the water source through screens, and it is distributed through piping systems to the surge-storage pool heat exchangers, the crushing plant, underground drilling and washing, other general surface requirements and to the domestic-water treatment facility.

The fire-water system has a maximum capacity of 200 L/s (17 280 m^3/d). The fire-water system demand is in addition to the process-water system demand, and this demand is required only on an emergency, not a continuous, basis. Two pumps, rated at 100 L/s, are provided: one pump is driven by a diesel engine and the other by an electric motor. The pumps discharge into an underground looped fire-water main 0.2 m in diameter. Normally, a small electric jockey pump maintains the system pressure. The high-capacity pumps engage automatically when the jockey pump cannot maintain the system pressure, that is, when water is being used from the fire-water system.

(ii) Domestic water

Domestic water is process water that is filtered and treated to make it safe for drinking. The peak domestic-water demand of 489 m^3L/d is estimated using the following daily requirements:

1. A total estimated work force of 900 people, at an assumed general requirement of 200 L/d per person, requires about 180 m^3/d, distributed both on the surface (162 m^3/d) and underground (18 m^3/d).

TABLE 4-1

WATER REQUIREMENTS
(after AECL CANDU et al. 1992)

	Domestic		Demineralized		Process		Fire	
	m^3/d(max)*	L/s(max)*	m^3/d(max)*	L/s(max)*	m^3/d(max)*	L/s(max)*	m^3/d(max)*	L/s(max)*
A. Surface								
Used-Fuel Packaging Plant	8	0.1	6	-	900	11		
Concrete Plant (intermittent, 24 h/d, 1 or 2 d/month)	34	0.4	-	-	-	-		
Crushing Plant (8 h/d)	-	-	-	-	3600	125		
General Surface	162	44	-	-	2000	23	17 280	200
Supply to Domestic and Demin. Water Systems (rounded off)	-	-	-	-	500	15		
Total Surface	204	44.5	6	-	7000	174	17 280	200
B. Underground								
Buffer/Backfill Plant	267	5	-	-	-	-		
Drilling, Washing	-	-	-	-	1200	21		
General Underground	18	0.2	-	-	-	-		
Total Underground	285	5.2	0	-	1200	21		
Overall Total	489	49.7	6	-	8200	195	17 280	200

* Note: The daily water requirements (m^3/d) are the total estimated daily usage. The instantaneous water requirements (L/s) are the peak demands needed during the day.

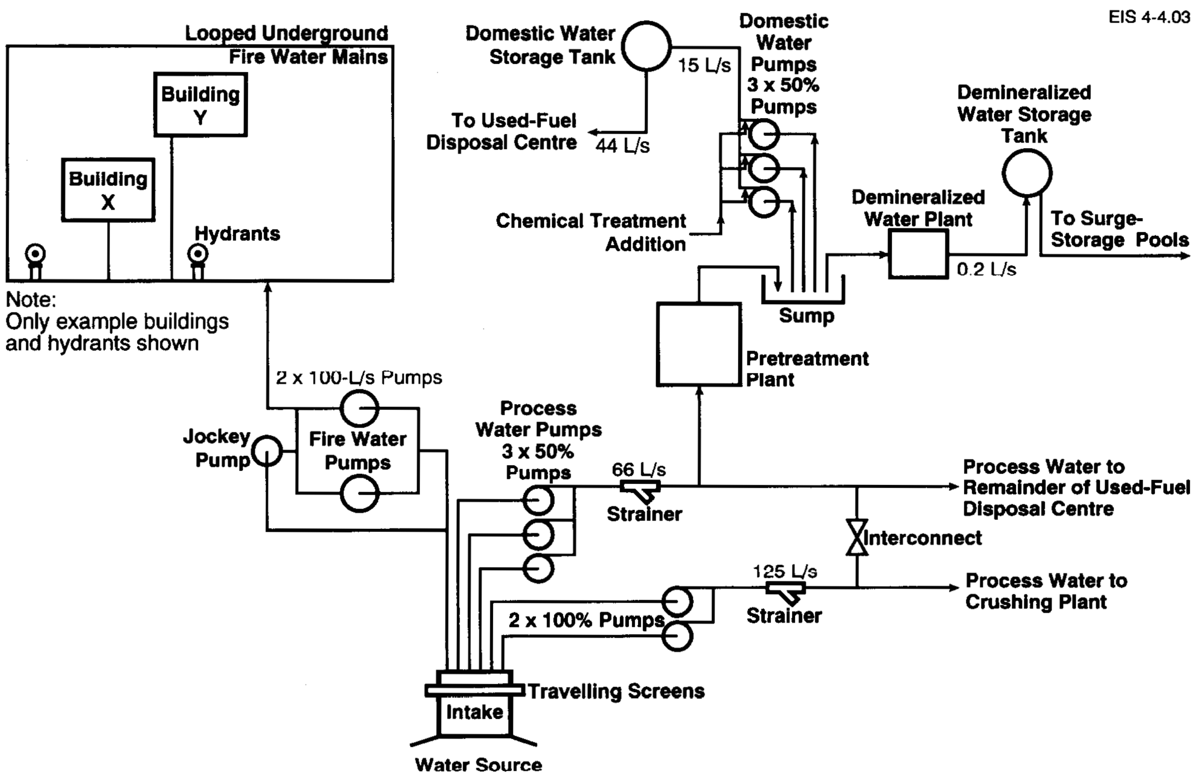


FIGURE 4-3: Water Supply Systems Flow Diagram (after AECL CANDU et al. 1992). Flow rates are maximum values.

2. Decontamination of 15 containers and 6 road casks per day requires about 8 m^3/d.

3. The concrete batch plant, which operates 24 h/d for 1 to 2 d/month, requires about 34 m^3/d of water for concrete preparation to better control the chemistry of the prepared concrete.

4. Preparation of buffer/backfill material requires about 267 m^3/d for operation 16-h/d.

Process water is pretreated at the water treatment plant by chemical dosing, flocculation and filtering by sand filters to remove suspended solids. The clarified water is then pumped and treated at a rate of about 15 L/s to a domestic-water storage tank. The hydro-pneumatic tank supplies peak loads of up to 50 L/s.

(iii) Demineralized water

Demineralized water is process water from which suspended matter and dissolved ions have been removed by ion exchange and activated carbon filtration. It is used in the packaging plant surge-storage pools, both for the initial charge and to make up for evaporation losses. This latter demand is estimated at 6 m^3/d for the pools, based on an evaporation rate of 10^{-4} kg/($m^2 \cdot s$) for 28°C water. Additional chemistry control is provided in the pool water purification circuits (see Sections 4.4.3 and 4.4.7).

4.2.3.3 Compressed-Air System

Two levels of compressed-air purity are required for disposal centre operation: service air and breathing air. There is no requirement for instrument air since the use of pneumatic instruments is not planned. The total requirement for service air is about 3 m^3/s at 900 kPa above atmospheric pressure, including the supply of breathing air. There is very little use of pneumatic drilling equipment in the conceptual design, but service air is required to clean the disposal-room floors with compressed-air blow pipes. The breathing air is primarily needed during intermittent maintenance work in the Zone 3 and Zone 4 contamination areas during the operating stage, and for decontamination and disassembly during the decommissioning stage. (The concept of zoning for radioactive contamination and radiation dose control is discussed in Section 4.4.9.1.) For breathing air, all compressed air contaminants such as oil mist, dust and moisture are removed from the service air by refrigerated dryers and filters. The air is humidified on location at the time of use. An airflow rate of 0.15 m^3/s is assumed, which is sufficient to supply a maximum of 10 maintenance workers in plastic suits.

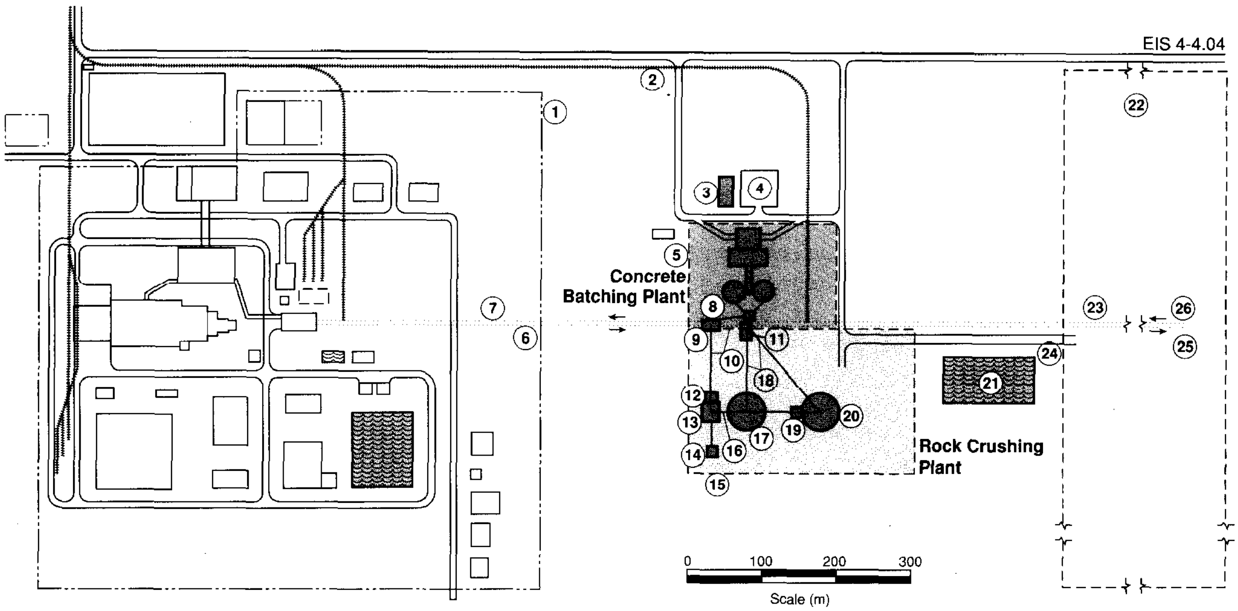
4.2.4 Rock Crushing Plant

The rock crushing plant is constructed to produce crushed rock with a size distribution suitable for preparing backfill material and concrete. The crushing plant is located at least 500 m from the service-shaft headframe to separate the main operating areas from the crushing plant noise and dust (Figure 4-4). The excavated-rock disposal area is located about 1000 m away and in the same direction as the crushing plant for the same reasons. Figure 4-4 also shows the location of the material transfer conveyors and crushing plant components.

The crushing plant (Figure 4-5) comprises the following facilities:

1. Transfer and wash facility.
2. Coarse-rock crushing.
3. Medium-rock crushing and screening.
4. Fine-rock crushing and screening.
5. Fines removal circuit.
6. Crushed-rock storage bins.

The crushing plant in the Used-Fuel Disposal Centre conceptual design has a design capacity of 150 Mg/h. Excavated rock is received by conveyor from either an 800-Mg-capacity excavated-rock bin in the service-shaft headframe (Section 4.3.1.1) or from the rock disposal area.



1. Security Fence
2. Railway Spur
3. Quality-Control Office and Laboratory
4. Parking
5. Concrete Batching Plant Area
6. Mine-Rock Conveyor
7. Crushed-Rock Backfill Conveyor
8. Concrete Aggregate Conveyor
9. Crushed-Rock Storage Bins
10. Inclined Conveyor
11. Conveyor Transfer and Wash Facility
12. Drying Plant
13. Secondary and Tertiary Crushing and Screening Plant
14. Dust Collection Baghouse
15. Rock Crushing Plant Area
16. Inclined Conveyor
17. Enclosed Medium-Rock Stockpile
18. Inclined Conveyors
19. Primary Crusher Station
20. Enclosed Coarse-Rock Stockpile
21. Process-Water Settling Pond
22. Rock Disposal Area
23. Return Conveyor
24. Access to Disposal Area
25. Mobile Stacking Conveyor
26. Return Hopper

FIGURE 4-4: Layout of Surface Facilities to Support Underground Operations (after AECL CANDU et al. 1992)

The transfer and wash facility routes the excavated rock from the service-shaft rock bin to the rock disposal area during primary development or when the amount of excavated rock exceeds the immediate requirements of the crushing plant, from the service-shaft rock bin to the crushing plant when excavated rock is available in the bin, or from the rock disposal area reclaim system to the crushing plant when excavated rock is not available from the service-shaft rock bin.

High-pressure water jets on a multideck vibrating screen are used to remove nitrates and fines, and the rock feedstock is classified as to size for the coarse- and medium-rock and rock-fines circuits. Conventional crushing (jaw and cone crushers), classification (screen and spiral classifiers) and drying processes produce three products: concrete aggregate, crushed rock and crushed rock fines. All materials are transferred by covered belt conveyors and are stored within enclosed stockpiles or mass-flow bins. All process equipment is housed in heated buildings with adequate space for maintenance, electrical and dust control equipment, and spare parts.

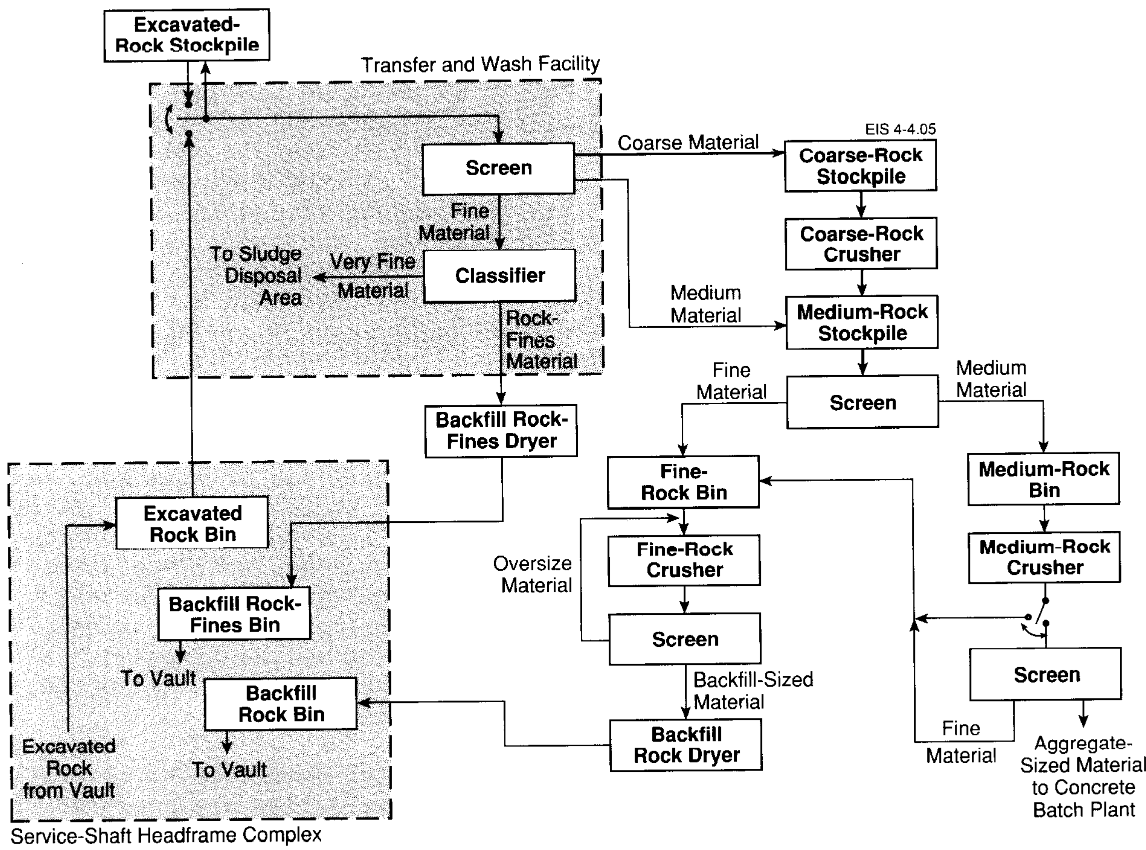


FIGURE 4-5: Rock Crushing Plant Flow Diagram (after AECL CANDU et al. 1992)

4.2.5 Concrete Batching Plant

The concrete batching plant, designed to meet the guidelines of CSA/A23.1 (CSA 1990), is located adjacent to the rock crushing plant (Figure 4-4). Medium-sized aggregate from the crushing plant is received by conveyor. The batching plant is fully automated and comprises two 4-m^3 mixers, three storage silos for cement, aggregate and dry additives, conveyors, and auxiliary systems such as metered additive dispensing systems.

4.2.6 Waste Management Systems

Systems are designed and constructed to control and manage the airborne, waterborne, liquid and solid wastes that are generated during the construction, operation and decommissioning stages of the disposal centre. The philosophy for air and water is to reduce the amount of any hazardous contaminants in air and water discharge streams to below legislated limits prior to returning them to the natural environment. This would require the decontamination of large volumes of air and water (e.g., by use of filters and/or ion-exchange resins). The contaminants would be contained in a small and manageable volume (the filter media or ion-exchange resin), which would be treated as a waste. The volumes of solid wastes and other hazardous wastes would be minimized, and the wastes would be packaged and stored for transfer to approved disposal facilities. Table 3-8 lists significant radionuclide contaminants expected to be present in the air and water systems from the receipt, handling and disposal of used-fuel bundles. Table 3-9 catalogues major nonradioactive hazardous materials used in construction, operation and decommissioning that may contribute to the contamination of the waste stream. All emissions would be monitored, documented and reported to the appropriate public, government and regulatory authorities in order to demonstrate that the discharges are well within the limits set for the Used-Fuel Disposal Centre.

4.2.6.1 Air Discharge

In facilities that do not contain significant quantities of hazardous materials, or where the materials present do not have the potential to contaminate the building air, the ventilation systems discharge directly to the environment. Facilities or portions of facilities containing operations in which significant dust or fumes are generated, such as the rock crushing plant, excavated rock or buffer/backfill materials handling and transfer areas, and basket and container welding facilities, are equipped with air filtration systems to collect particulates. The particulates collected, and any disposable filters, are handled as a solid waste.

Facilities housing operations involving radioactive materials, such as the packaging plant module-handling and fuel-packaging cells, are equipped with air filtration systems comprising roughing and HEPA (high-efficiency particulate air) filters to collect particulate contaminants. The quantities of gaseous contaminants are quite small (Table 3-8), and no special provision is made to collect these materials. The spent filter assemblies are handled as a radioactively contaminated solid waste.

In facilities where there is the potential for the release of airborne radioactive contamination following an accident, such as during the handling of disposal containers in the waste shaft and the disposal rooms, airborne-contaminant filtration systems are installed for use when necessary as discussed in Sections 4.3.1.2 and 4.3.6. Spent filter assemblies are managed as radioactively contaminated solid wastes.

4.2.6.2 Wastewater Management

Systems are constructed to manage wastewaters. These waters are classified either as nonradioactive or potentially radioactive, depending on the source (Table 4-2). The sources of potentially radioactive wastewaters, which are primarily associated with the operation and decommissioning stages, include contaminated domestic water from the decontamination of casks and containers in the Used-Fuel Packaging Plant (8 m^3/d) and from laundries, washrooms and showers used for workers, and clothing from potentially contaminated work areas (30 m^3/d). These wastes are filtered, collected in storage tanks and sampled for levels of contamination (Figure 4-6). In many cases, the level of contamination would be so low that the water could be released directly

TABLE 4-2

WASTEWATER TREATMENT REQUIREMENTS

(after AECL CANDU et al. 1992)

Approximate Quantity (m^3/d, max)					Source
	Normally Nonradioactive				
		Settling Required			
Low-Level Radioactive Wastes (During Operation Stage)	Clear	From Surface	From Underground	Surface Sewage	
8					Packaging Plant - Decontaminate containers and casks
30					Laundry, Washrooms, etc., for radiation workers
	2900				Return process water from heat exchangers, etc., general usage
		3600			Crushing Plant
			1200		Drilling, Rock Washing
			18		Treated Sewage
			1000		Groundwater
				132	Laundry, Washrooms, etc., for non-radiation workers
38	2900	3600	2218	132	Totals

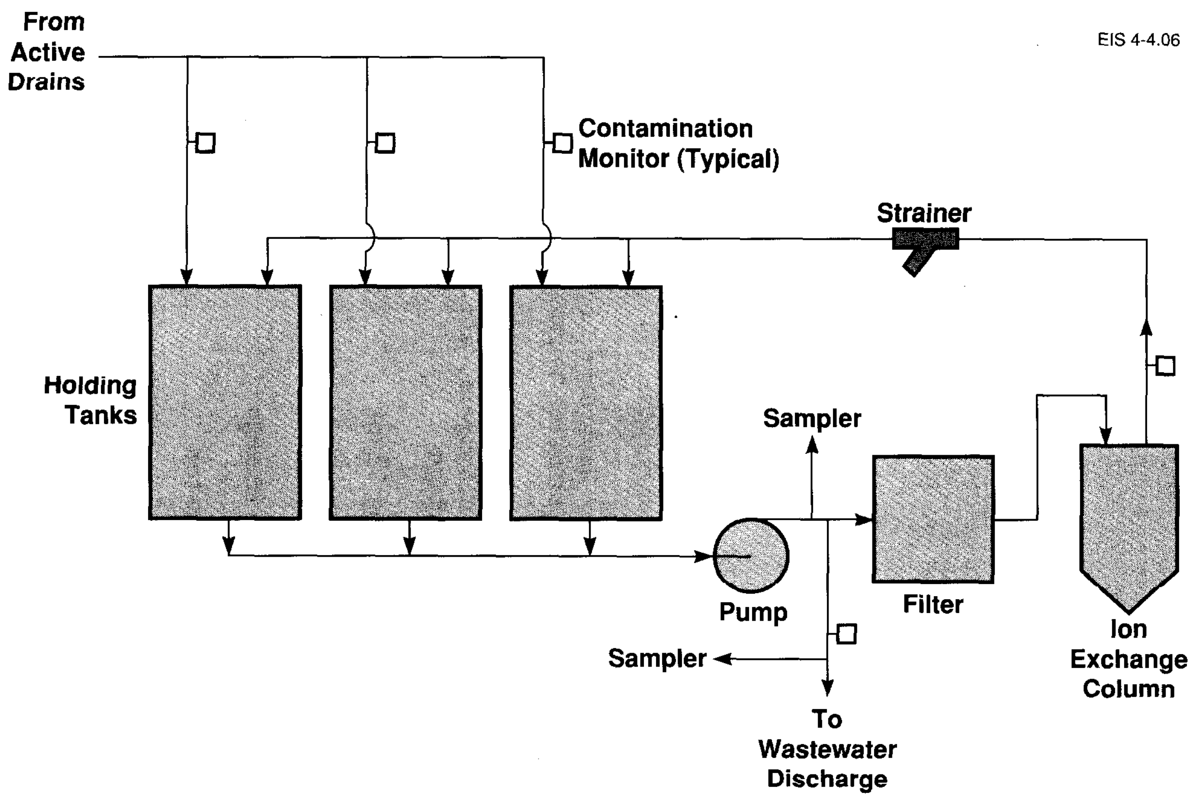


FIGURE 4-6: Low-Level Radioactive Contaminated Water Cleanup System - Flow Diagram (after AECL CANDU et al. 1992)

to the environment. If further cleanup is required, the water is circulated through a filtration/ion-exchange or filtration/reverse osmosis system to reduce the contaminant levels and ensure compliance with effluent limits established for release to the environment (see Figure 4-6). The filters, ion-exchange resins and reverse osmosis media are handled as a radioactively contaminated solid waste.

The nonradioactive wastewater comes from several sources during the construction, operation and decommissioning, and is managed as discussed below.

1. Clear water from process heat exchangers, general plant usage and rain (2900 m^3/d) is not expected to contain significant quantities of contaminants, and can be recycled or released directly to the environment. This water is monitored regularly to ensure compliance with legislation governing its reuse or discharge. The emphasis of contaminant control is placed on prevention (i.e., detection and correction at source), rather than subsequent treatment. Water reuse would be maximized in an optimized design.

2. Water containing solids from the rock disposal area drainage, from the rock crushing plant (3600 m^3/d) and from the underground (2200 m^3/d) is pumped to separate holding ponds designed to reduce the solids content to acceptable levels for both recycling within the plant and discharge to the environment. The sediments from the ponds are managed as solid waste.

   The rock disposal area drainage and the crushing-plant waters are treated at the settling ponds near the crushing plant (Figure 4-4). These waters may be contaminated chemically from excavation residues and leaching of chemicals from the rock by precipitation and process waters. Prior to reuse or discharge to the environment, these waters are sampled for the level of chemical contaminants to ensure that the total quantities of contaminants released in these waters do not exceed applicable legislated limits. A water treatment facility (e.g., ion exchange) would be provided for use if the concentrations of specific chemical contaminants are higher than allowed for discharge or reuse because of site-specific conditions. The Used-Fuel Disposal Centre conceptual design does not include a treatment system for these waters.

   The bulk of the underground water is pumped from a sump system located underground in the upcast-shaft complex (Section 4.3.7.3) and is treated in settling ponds located near to the upcast ventilation shaft headframes. In the event that there is unacceptable radioactive or chemical contamination in the underground water, the water will be treated using a filtration/ion-exchange system prior to being discharged to the environment or being reused.

   The underground drainage water collected in the underground part of the service-shaft complex (Section 4.3.7.1) is pumped to a settling pond on the surface near the service-shaft headframe. The drainage water is settled, sampled and treated, if necessary, in the same manner as the other underground drainage waters.

3. Sewage water (132 m^3/d) is collected and treated in a manner that depends on the site location. A sewage treatment plant, shown on Figure 4-2, or a nearby municipal sewage system, if available, would handle this waste. An on-site sewage treatment plant is assumed for the Used-Fuel Disposal Centre conceptual design.

In all cases, these waste streams are sampled and treated to meet local, provincial and federal standards before being released to the environment.

4.2.6.3 Liquid and Solid Waste Management

Hazardous liquid wastes used at the disposal centre are collected in approved containers and stored in suitable structures on site until sufficient volumes are available for shipment to licensed disposal facilities.

Solid wastes with no radioactive contamination and of no economic recycle value, such as kitchen wastes, office wastes, machine shop and maintenance wastes, could be transported to a suitable municipal landfill or could be disposed of in an approved landfill at the Used-Fuel Disposal Centre. The choice depends on location, topography, legislation, economics and public preferences.

In the Used-Fuel Disposal Centre conceptual design, 19.5 Tg of rock is excavated from the disposal vault. Of this amount, about 12.6 Tg is transferred to a rock disposal area and about 6.9 Tg is reused in the vault as aggregate in backfill and concrete. The surplus rock in the disposal area can be used on the disposal centre site or in the local area for civil construction and site refurbishment. The particulate from dust separators and bag-house filters, and sludges from the settling ponds and from the underground sumps are also disposed of in suitably designed collection pits in the rock disposal area. Any runoff from the waste-rock disposal area is collected, sampled and treated to meet local, provincial and federal standards before release to the environment (see Section 4.2.6.2(b)).

The solid wastes that are radioactively contaminated are collected separately from other wastes. They are categorized by the IAEA (after IAEA 1987) as the following wastes:

1. Low-level waste, which does not require shielding during normal handling and transportation because of its low radionuclide content, and does not contain alpha-emitting radionuclides in quantities over the regulatory limits for uncontrolled release.

2. Intermediate-level waste, which has a lower level of radioactivity and heat output than high-level waste, but generally requires shielding during handling and transportation. An exception to the shielding requirement may be intermediate-level waste that only contains one or more alpha-emitting radionuclides, usually actinides, in quantities above the regulatory limits for uncontrolled release.

3. High-level waste, any waste with a radioactivity level comparable to nuclear fuel waste.

An alternative approach to characterizing low- and intermediate-level wastes is being used at AECL's Chalk River Laboratories (Buckley and Charlesworth 1988). There, the waste is classified by the type of disposal facility into which it will be placed based on the projected containment time that it requires to protect man and the environment and to satisfy legislation. Making this projection of containment time requires sound knowledge of the quantity of each radionuclide contained in each container of waste. The limits on quantities of individual or groups of radionuclides per container allowed in each facility are determined by a safety assessment for each a particular facility. The facilities and "normal hazardous lifetime" for wastes compositions that can be placed in them are as follows.

Disposal Facility Concept	Nominal Radiological Hazardous Lifetime
Improved Sand Trenches	150 a
Intrusion-Resistant Underground Structure Facilities	500 a
Shallow Rock Cavity (Geological Disposal)	>500 a

The classification of low- and intermediate-level solid wastes and the facilities used for their disposal would be based on the requirements of facilities licensed to handle these types of wastes when the Used-Fuel Disposal Centre begins operation.

The used-fuel bundles, their components and contents are high-level waste, and the packaging and disposal of this material is the objective of the disposal centre. Waste management, as discussed in this section, pertains to the low- and intermediate-level wastes during disposal centre operation and decommissioning.

The low-level waste includes used operating supplies, clothing, rubber gloves, and rubber boots, and the intermediate-level waste includes filter units, ion-exchange resin, reverse osmosis media and hot-cell equipment. Each is reduced in volume by compaction or cutting, packaged in approved containers and stored in suitably shielded and controlled facilities. Radioactively contaminated drainage sump sludges are collected in approved containers and are treated as radioactively contaminated solids. When a sufficient volume of a category of waste has accumulated, these wastes are shipped to the appropriate licensed disposal facility assumed to be in existence prior to the operation of the disposal centre. The volume of compacted radioactive solid waste from the operation stage is estimated to be a total of 2000 m^3, with another 2000 m^3 estimated from decommissioning. An alternative, which has not been investigated, is to place and seal these wastes in an area of the disposal vault outside the used-fuel emplacement area prior to sealing the vault.

4.2.7 Warehousing and Stores

A disposal facility requires warehouse and stores facilities to receive, store and dispense the materials, supplies and equipment that are necessary for effective operation. In the Used-Fuel Disposal Centre conceptual design, receiving/storage facilities are provided in warehouse facilities as well as at the Used-Fuel Packaging Plant (e.g., baskets, containers and top heads, operating supplies), the Container and Basket Fabrication Plant (raw materials), the workshops (raw materials, equipment, consumables), the auxiliary building (general stores) and the vehicle shops.

Warehousing is provided for materials, equipment and supplies in the form of a vehicle garage (1250 m^2), a general warehouse building (3000 m^2), a hazardous materials storage building (e.g., for chemicals) and an outdoor storage yard (3000 m^2) (Figure 4-2). A radioactive solid-waste storage building (3720 m^2) provides controlled storage for packaged low- and intermediate-level solid wastes prior to their disposal.

There are also material receiving and storage areas that are outdoors. These include bins and tanks for dry storage of bentonite clay, glacial-lake clay, silica sand, cement, gasoline, diesel fuel, and liquid propane.

4.2.8 Manufacturing and Maintenance

Maintenance and manufacturing support is required for the effective operation of a disposal facility. The Used-Fuel Disposal Centre conceptual design assumes that a maintenance group is part of the organization and that it is supplied with the appropriate mix of trades and labour personnel (e.g., civil, electrical, mechanical and instrument) and the facilities necessary to plan and implement a comprehensive maintenance program for all surface and underground facilities and equipment.

The normal evolution of an operating plant requires the manufacture of new or modified facilities, systems and equipment. The maintenance group has facilities incorporated into the various buildings, mainly in the auxiliary building, and staff to handle small manufacturing and construction projects. This group and its facilities are included in the estimated cost as either a cost factor (e.g., as $/ha for the site or as buildings, shops and equipment) and in the trades, staff, materials and supervision required for the project.

Larger projects will likely be done infrequently, and are assumed to be contracted out to avoid large fluctuations in staff.

4.2.9 Physical Security and Fire Protection

The facilities at the disposal centre represent a substantial investment to the implementing organization, and the used fuel in the disposal centre represents a significant potential hazard to humans and the environment. Therefore, facilities need to be designed and operating procedures put in place to protect the assets and to mitigate this hazard under normal and unusual circumstances. Continuous physical security and fire protection is implemented during site evaluation and will continue until the vault is sealed and the facilities removed.

The security and fire protection staff are trained to protect the assets and operations at the disposal centre by using facility resources and by calling on local/regional law enforcement or fire departments in the event of incidents. The external mutual aid and emergency response agreements would be completed early in the project and would be maintained through to closure. The level of security and fire protection staffing at a disposal centre is determined by legislation in force when a facility is developed, the distance to and capabilities of local/regional forces, and the size, layout, asset value and hazards associated with the operation.

AECL CANDU et al. (1992) estimated that a full-time staff of 54 working in shifts is necessary during disposal centre operation to provide access control, security, site and building inspection, and fire protection 7 d/week, 24 h/d. This staff is trained in the hazards of, and special procedures for dealing with, radioactive materials. It has also been assumed that an underground rescue response group, comprising several teams of experienced workers (i.e., six persons per team), is formed from the underground staff to provide fire fighting and rescue support for incidents in the disposal vault. These teams and their supervisors are also specifically trained to handle the additional hazards associated with the presence of radioactive materials.

4.2.9.1 Physical Security

Physical security for the Used-Fuel Disposal Centre is provided by a combination of facility design and layout, personnel identification and authorization, and trained security staff. The disposal centre is divided into an unfenced supervised area and two protected areas as discussed in Section 4.2.1 (Figure 4-1). The supervised area, comprising most of the site, is posted with signs warning against unauthorized entry, and is regularly patrolled by security staff. The protected areas (the packaging plant and service-shaft complex, and the upcast-shaft complex) are securely fenced, have guarded or locked access points, and are monitored continuously by security staff.

The supervised area is readily accessible only from the main disposal centre access road or the rail line. All other roads that may cross the site boundary are equipped with locked gates and cutoff fences at the site boundary. The cutoff fences extend a sufficient distance on each side of the gate to prevent vehicle passage around the gate. Access to the main surface facilities in the supervised area is controlled by building receptionists during work days and by keeping buildings locked at other times. The supervised area and buildings are patrolled regularly by security staff.

The security offices are in the administration building, which is located on the boundary of the main protected area (Figure 4-7). Security administration, change rooms and the security monitoring room are located in a wing of the administration building shared with the fire-fighting facilities. The security monitoring room is constructed to resist forced entry with hand-held tools and light firearms.

The protected areas are surrounded by a 2.5-m-high security fence topped by three strands of barbed wire leaning outward (Government of Canada 1983). At least 5 m of ground on each side of the fence is kept clear for security monitoring and to form a fire break. An intrusion detection system monitors the integrity and motion of the fence. The boundaries of the protected areas along the fence and the entrance to each building are lighted to an average intensity of 100 lx or higher. Closed-circuit television cameras are installed to survey all access control gates along the security fence and all buildings accessing the protected areas. The cameras have overlapping fields of view.

Access to the main protected area surrounding the packaging plant and service-shaft complex is via one of seven gates (Figure 4-7). Gate 1, through the administration building, is used for worker access and has a

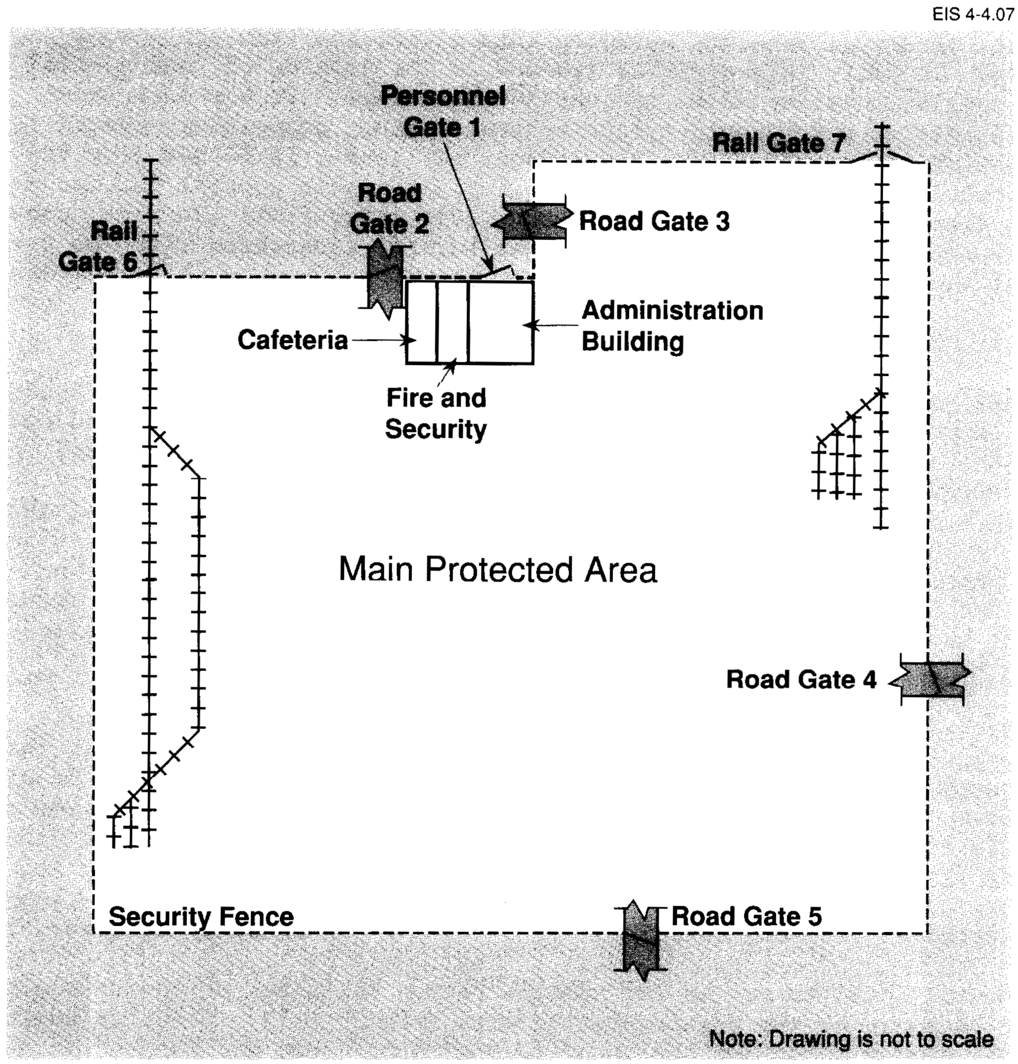


FIGURE 4-7: Conceptual Arrangement of Packaging Plant and Service Shaft Protected Area Access Control

continuously manned security station. All workers are checked when entering or leaving Gate 1. Gates 2, 3, 4 and 5 are used for road access and are normally locked. Gates 6 and 7 are used for rail access and are also normally locked. Security staff attend these normally locked gates and inspect shipments when the gates are in use.

Access to the protected area surrounding the installations at the upcast ventilation shafts is also through normally locked road and personnel gates. Security staff attend these gates and inspect all shipments passing through these gates. Because the upcast ventilation shafts provide an emergency exit route from the disposal vault, one-way exits and sufficient building space are provided for evacuated personnel to safely exit the shaft conveyance and to remain in a safe and heated area until clothing and transportation are arranged.

Access to all buildings in the protected areas and all facilities and buildings outside the protected area are controlled by self-locking doors that require magnetic cards or a security code to gain access. The entry and exit from these buildings are recorded electronically and the information is available in the security monitoring room. All persons entering the protected area must wear a visible badge displaying their photograph.

Security staff are equipped with independent communication systems, such as two-way radios for on-site communication, and radio base stations in the security monitoring room for off-site communications (e.g., with external law enforcement and emergency response forces), in addition to the regular communication systems at the disposal centre.

As part of the physical security program, all employees undergo a security screening and clearance procedure that is repeated periodically during their employment.

4.2.9.2 Fire Protection

The Used-Fuel Disposal Centre conceptual design conforms to the National Building Code of Canada (NRCC 1985), the National Fire Code of Canada (NRCC 1986), and the appropriate National Fire Protection Association standards to minimize the occurrence of fires and to detect, suppress and mitigate their occurrence. The principal objectives for fire protection are the protection of the public from fire and from the by-products of fire, including radiological releases that might result from a fire, the protection of facility workers in conformance to Canadian legislation, and the prevention of economic loss.

The fire protection systems included in the Used-Fuel Disposal Centre conceptual design include the fire-water system, fire detection and alarm systems, automatic fire extinguisher systems and manual fire extinguishing equipment.

The fire-water distribution system is described in Section 4.2.3.2, and is shown schematically in Figure 4-3. This system loops the site in a way that provides a water supply from two directions to all outdoor hydrants and all buildings requiring hose stations and sprinklers.

A variety of fire detection and alarm systems (Figure 4-8) is provided consistent with the use of each installation or building. All indoor areas are equipped with manual alarm switches near fire exits. Automatic fire detectors are installed in all indoor areas that may contain enough combustible material to sustain a fire if they are not protected by automatic sprinklers. Electric fire alarm bells are located throughout normally occupied areas. The fire detection, alarm and automatic extinguishing systems are equipped with sensors to monitor the status of all important components. The entire system is monitored and controlled by a fire alarm

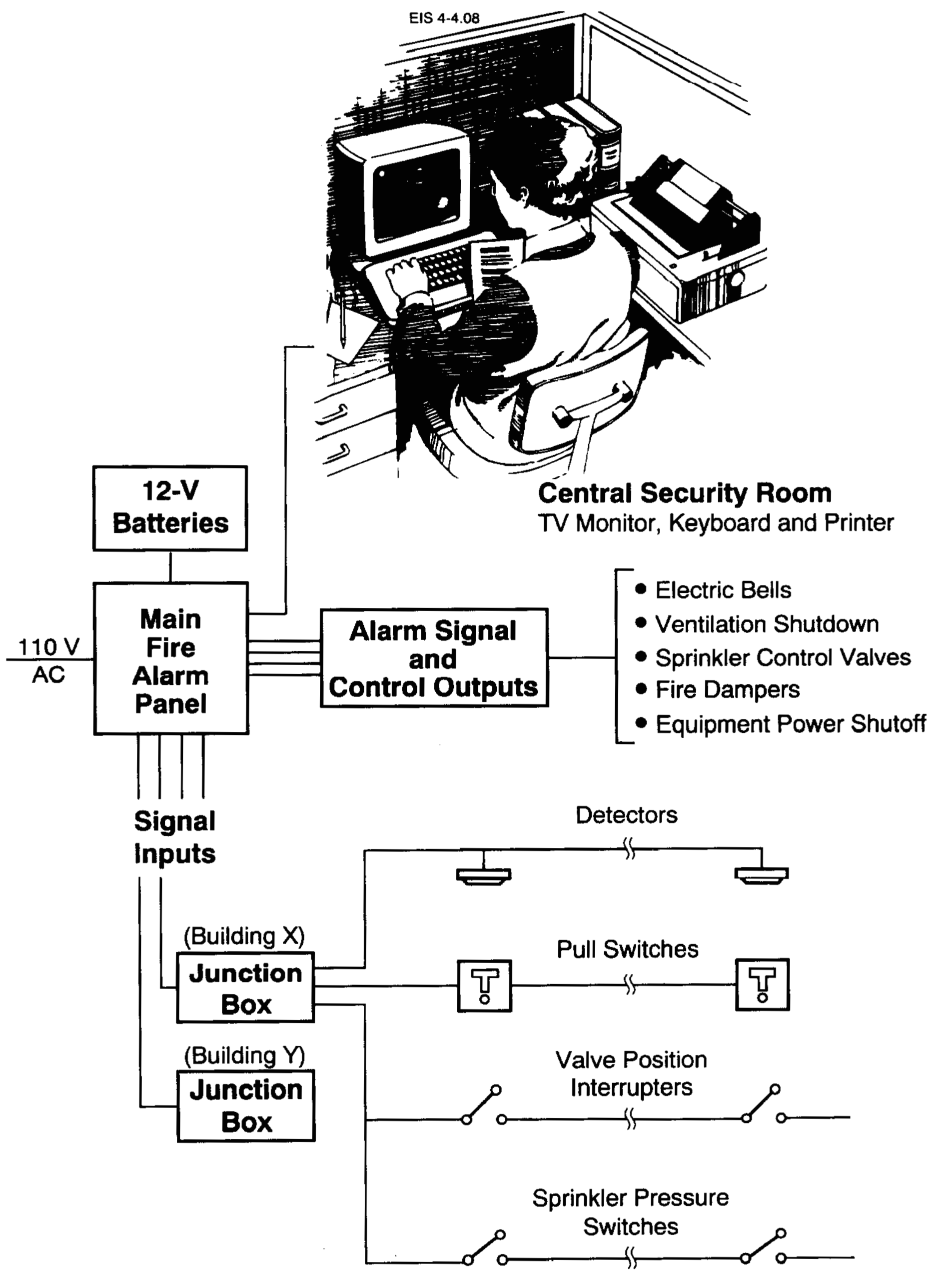


FIGURE 4-8: Schematic of Fire Alarm System (after AECL CANDU et al. 1992)

system control panel capable of initiating alarm, monitoring and control functions. The control panel is located in the security monitoring room.

Automatic fire extinguisher systems are included in the disposal centre to protect against all fire hazards of potentially significant consequences. Depending on the area being protected, one of three systems is installed.

1. Automatic sprinkler systems are installed in service buildings, active and inactive workshops, the warehouse, powerhouse (diesel generator) and indoor garages. They are also installed in the transportation receiving and laydown areas, the Container and Basket Fabrication Building, the pump house and its intake area, the ventilation-unit buildings, air-compressor building and solid active-waste handling building. Equipment susceptible to water damage in areas with sprinklers is shielded or encapsulated as necessary. Floor drains and curbs are installed as necessary in buildings equipped with sprinklers. The floor drains are connected to the active-waste drainage system in those areas where there may be radioactive materials.

2. Automatic total flooding systems (e.g., approved nonreactive gases or dry chemicals) are used where water could cause serious damage or unsafe conditions. They are installed in the module-handling and fuel-packaging cells, the computer rooms and associated record storage rooms, control equipment room, and motor control centres.

3. Dry chemical or carbon dioxide extinguishing systems are installed in the cooking areas of the cafeteria and other designated cooking areas provided for workers without convenient access to the cafeteria.

Manual fire-extinguishing systems and equipment are the fourth main element of the fire protection system. Fire hydrants are located at a spacing of about 100 m around the plant such that all buildings can be serviced. Standpipe systems and fire hoses are provided for most building interiors and the vault. Metal-fire extinguishing materials are located in the hot cells in case of zirconium fires, and are dispensed with remote or robotic manipulators. Portable extinguishers are provided throughout the plant.

One fully equipped fire truck is provided for the site. The number of fire trucks and fire fighters for an actual disposal facility would depend on the proximity and experience of local community fire-fighting forces that could provide backup support under an emergency response mutual-aid agreement.

4.2.10 Communication Systems

A disposal centre is equipped with communication systems that provide efficient and cost-effective operation and can be used to announce abnormal conditions when necessary.

The following communications systems are included in the Used-Fuel Disposal Centre conceptual design:

1. a telephone system,

2. a maintenance communication system,

3. a public address system,

4. a radio system,

5. an emergency alarm system, and

6. a clock system.

The telephone system includes a private automatic branch exchange (PABX) to connect the disposal centre to the regional telephone utility. The PABX telephone lines serve the entire disposal centre. A portable paging system is included for workers who are working within the site boundaries but are remote from direct telephone or radio system access.

An independent maintenance communication system, comprising locally mounted plug stations and a patch panel for interconnections, is provided in operating and service areas. This allows work areas to be interconnected with a dedicated communication link as required during specific operation and maintenance activities.

In potentially radioactive areas, the two systems described above allow communications by workers in plastic suits to workers in other plastic suits, to the telephone system and to the maintenance communication system.

The public address (PA) system is available to all areas of the disposal centre to provide paging and one-way communication services. This system is also equipped with tone generators, horns and flashing lights (e.g., for noisy underground workplaces) to provide distinct fire alarm and radiation hazard warnings as part of the alarm system.

The radio system permits both on-site and off-site communications, and consists of portable two-way radios, radio receivers and transmitters. These are routinely assigned to the physical security and fire protection staff for dealing with normal patrols and for emergency response. They are also issued to operations and maintenance staff as necessary to improve operational efficiency.

The alarm system provides workers with warning of hazardous occurrences such as fire, hazardous material releases, abnormal levels of radioactivity and contamination. Specific detectors (smoke, heat, radiation monitors) are strategically located in all work areas to monitor the workplace conditions. Audible and/or visible alarms are provided to alert control room operators, physical security and fire protection staff, and radiation and industrial safety staff. These alarms and odour alarms also advise local surface and underground workers of hazardous conditions in their area(s).

An example of an odour alarm is the stench gas emergency warning system that would be installed in the disposal vault ventilation system. When a hazardous condition is detected, this system introduces a very detectable odour to the incoming fresh air at the downcast ventilation shaft to warn the workers. This is similar in concept to the addition of components, such as mercaptans, to natural gas or propane for leak detection purposes. Workers would then follow the appropriate emergency response procedure of either reporting to the first-aid and safety refuge station (Section 4.3.5), or barricading and sealing themselves within an excavation if egress is unsafe.

A master and slave clock system is provided to give standardized time throughout the disposal centre.

4.2.11 Summary

Installation of these site support facilities early in the construction stage makes them available to support the ongoing underground and surface facility construction activities. This reduces the costs associated with use of temporary equipment and installations, and provides an excellent test of the permanent installations under service conditions prior to beginning the operation stage. The operating staff takes responsibility for systems as they are declared serviceable by the construction contractor. This approach spreads the development of operation and maintenance procedures and system commissioning over more of the construction stage, thus more evenly distributing the work load of the disposal centre operating staff.

4.3 USED-FUEL DISPOSAL CENTRE DISPOSAL VAULT CONSTRUCTION

Exploration shafts and tunnels would be excavated during the siting stage, as discussed in Section 3.2.2. The initial locations and shapes of these excavations will have been selected on the basis of an anticipated design and layout of the disposal vault. The data gathered during the underground evaluation will have been applied to confirm or adapt these excavation designs and layouts to the observed conditions. Those exploration excavations that are still consistent with the current disposal vault design are used in the construction stage, and those that are not consistent are incorporated into service areas or are sealed, depending on the reason for the design change.

Five shafts in two groupings are necessary for effective operation in the Used-Fuel Disposal Centre conceptual design. One grouping at the service-shaft complex (Figure 4-9) comprises a service shaft, a waste shaft and a downcast ventilation shaft. The other grouping at the upcast-shaft complex (Figure 4-10) comprises an emplacement-panel upcast ventilation shaft, which is potentially radioactive, and an excavation-panel upcast ventilation shaft. It was assumed that two shafts, the downcast ventilation and the excavation-panel upcast ventilation shaft, would be developed as exploration shafts during the siting stage (Section 3.2.2.1).

In the construction stage, we assumed that the construction of the disposal vault begins with the sinking of three additional shafts and the full development of the underground tunnels and service areas. The service shaft, the waste shaft, and the emplacement panel upcast ventilation shaft are excavated by full-face drill-and-blast sinking methods. At the present time, options such as drill-and-blast raising, raise boring, and shaft boring are not considered appropriate because they do not provide sufficient accuracy

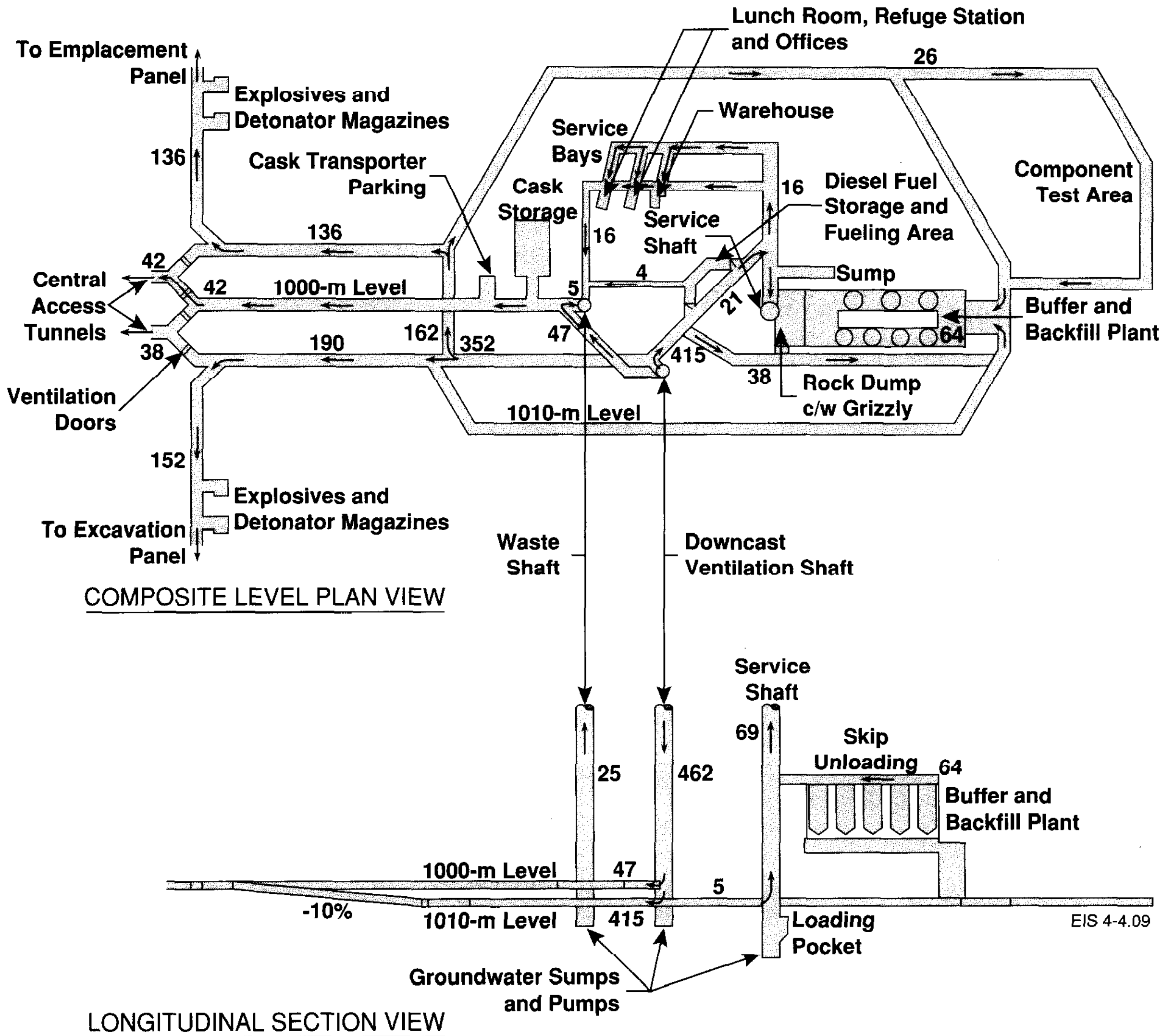


FIGURE 4-9: Shaft Bottom Arrangement - Service-Shaft Complex (after AECL CANDU et al. 1992). Ventilation flows are in m^3/s.

on verticality and they will not readily accommodate the size and length required.

The two existing exploration shafts created during the siting stage provide the access, ventilation and excavated-rock handling services for the concurrent excavation of additional vault access tunnels, and the enlargement of the existing exploration tunnels to access tunnel sizes. The underground ancillary facilities, including the service-shaft complex, the upcast-shaft complex, and the buffer and backfill plant, are then excavated and constructed. When the new shafts are capable of handling the underground development activities, the exploration shafts will be refurbished and

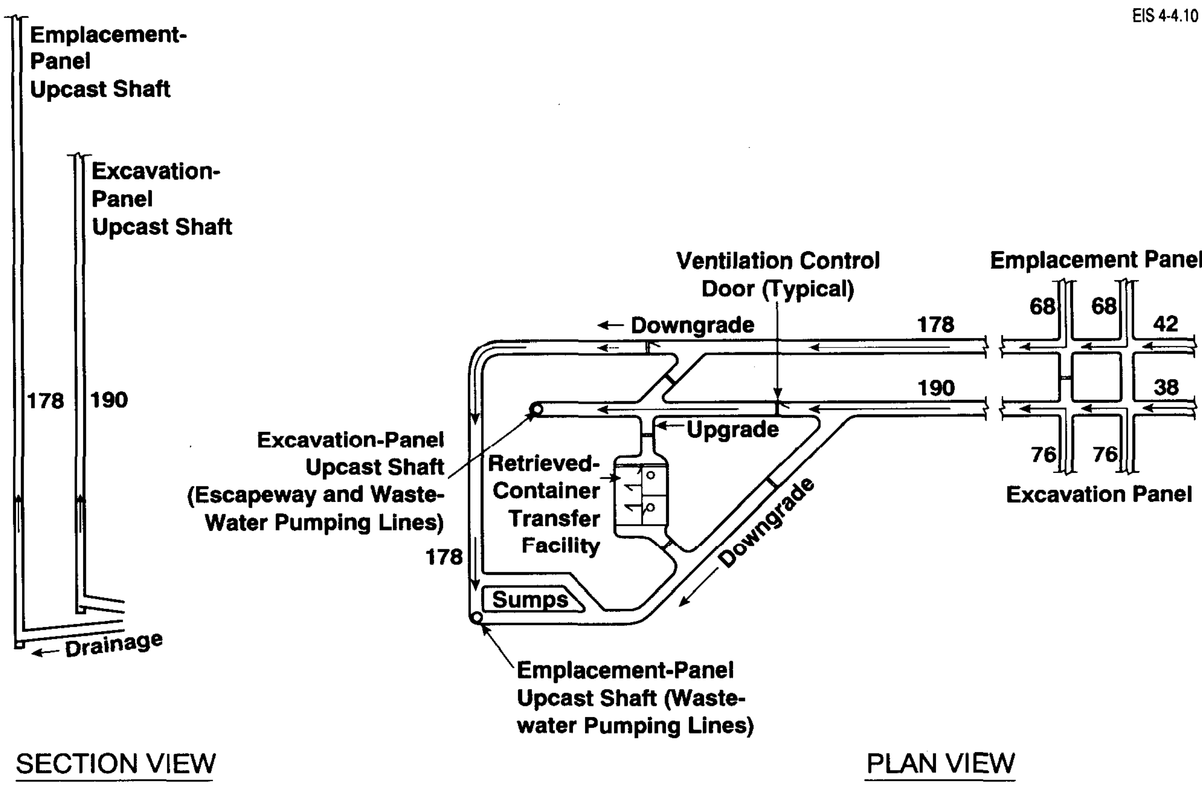


FIGURE 4-10: Shaft Bottom Arrangement - Upcast-Shaft Complex (after AECL CANDU et al. 1992). Ventilation flows are in m^3/s.

converted for use as the downcast ventilation shaft and the excavation-panel upcast ventilation shaft.

Because the new shafts and tunnels are excavated in close proximity to excavations developed during the siting stage, the ground conditions and locations of any fracture zones in the rock mass would have to be well known and well characterized. Grouting may be necessary to control groundwater seepage from such fracture zones if the shafts or tunnels must be constructed through them. An allowance is included in the disposal centre cost estimate for these activities.

When the shafts and vault access tunnels are complete, the first panel of disposal rooms and 10 to 12 disposal rooms in each of the second and third panels will be excavated. Emplacement boreholes will be drilled into the first 10 to 12 disposal rooms in the first panel prior to the onset of the operation stage. The disposal vault at the end of the construction stage is shown in Figure 4-11.

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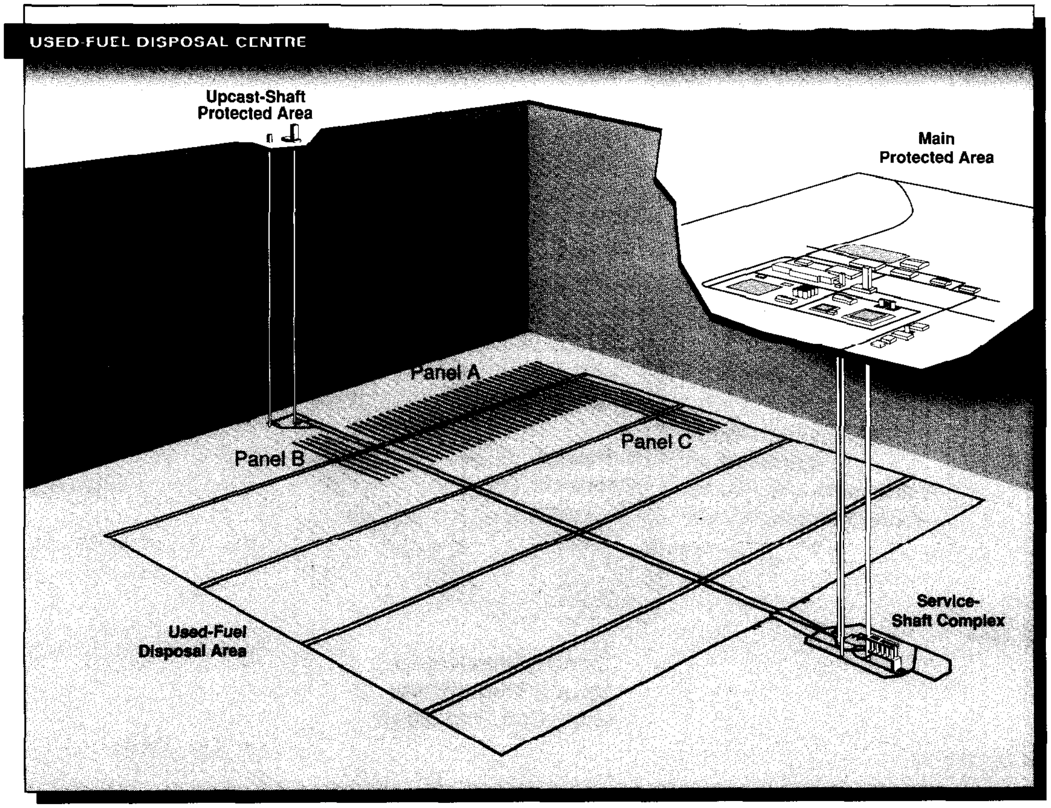


FIGURE 4-11: Used-Fuel Disposal Centre at the End of the Construction Stage

4.3.1 Shafts

Five shafts are included in the Used-Fuel Disposal Centre conceptual design. They are divided areally into two groups, the service-shaft complex and the upcast-shaft complex (Figure 4-1). Both complexes also include other underground installations. The service-shaft complex includes the surface and underground systems of the service shaft, the waste shaft and the downcast ventilation shaft, the underground service and maintenance areas, the buffer and backfill preparation plant, the component test area and associated ancillary systems (Figure 4-9). The upcast-shaft complex includes the emplacement and the excavation panel upcast ventilation shafts, the associated ancillary systems, and the retrieved-container transfer facility (Figure 4-10).

4.3.1.1 Service Shaft

The service shaft (Figures 4-9 and 4-12) provides the main services and underground access for workers, materials and equipment for the balance of the construction stage, and for the operation, the optional extended monitoring and the decommissioning stages.

The permanent 60-m-high concrete headframe will be erected on completion of sinking operations in the service shaft and the service-shaft conveyances will be commissioned.

The service shaft (Figure 4-13) is 7.9 m in diameter and, if necessary for ground control, may be lined with 0.3 m of concrete during excavation. It is equipped with these conveyances:

1. Two 9-Mg skips for in-balance hoisting of excavated rock and/or lowering of buffer and backfill component materials.

2. One 10-Mg service cage in balance with a counterweight for hoisting workers, equipment and supplies.

3. One 1-Mg auxiliary cage without a counterweight for hoisting workers.

The service shaft is also equipped with power and communications cables and service pipes, including a concrete supply pipeline, clay and bentonite supply lines, and compressed air, water and diesel-fuel supply lines.

The service shaft is ventilated with an upward flow of air (69 m^3/s) supplied from the downcast ventilation shaft.

The cages, counterweight and skips travel on guides mounted on steel shaft sets (i.e., a structural steel framework). The service-shaft surface installations (Figure 4-12) consist of a headframe, binhouse, collar house and shop, and warehouse buildings. The headframe is a rectangular concrete structure and is designed to house

1. the hoists, motors and sheave wheels for the cages and skips;

2. the collar house for the loading of workers, materials and equipment into the service cage;

3. the skip dumping-and-loading facilities for excavated rock and sealing materials respectively;

4. the surge bins for excavated rock and sealing materials, such as glacial-lake clay, bentonite and silica sand, and associated materials handling equipment, such as feeders, belt conveyors and pneumatic conveyors;

5. the dust suppression and collection systems, including bag-house filters; and

6. the overhead crane facilities for the handling of materials and equipment in the collar house, and for the servicing and maintenance of the major hoisting components in the headframe.

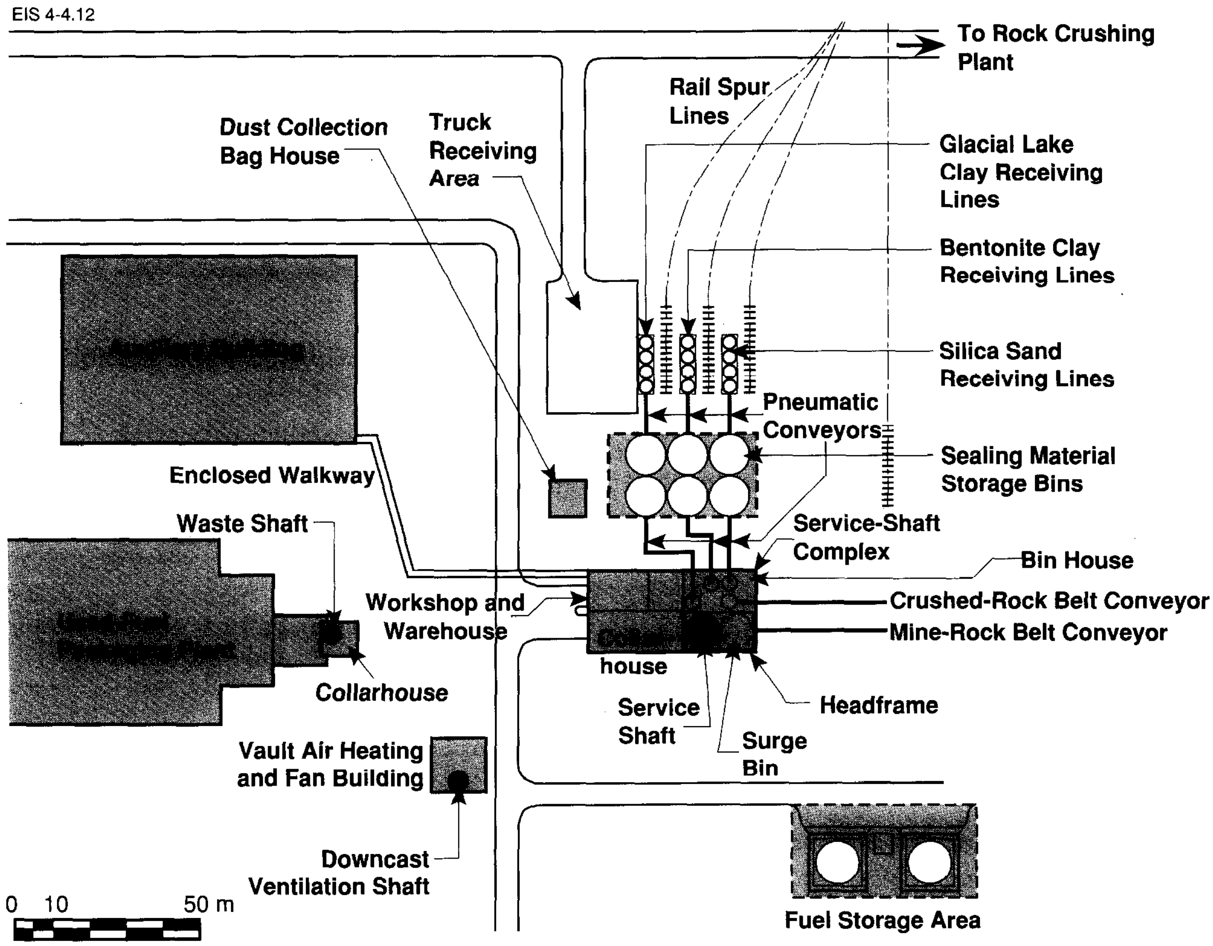


FIGURE 4-12: Service-Shaft Complex Surface Facilities Layout (after AECL CANDU et al. 1992)

A 4-rope, 1000-kW friction hoist with a 3.66-m-diameter drum provides either a total skip hoisting capacity of 260 Mg/h, or a simultaneous hoisting and lowering capacity of 100 Mg/h in each direction for excavated rock and for buffer or backfill material at a maximum speed of 13 m/s. A 4-rope, 500-kW friction hoist with a 3.66-m-diameter drum hoists payloads of either 10 Mg or 50 workers in the service cage at a speed of 7 m/s. Normally, the hoist slows down under electrical control, and the brakes are only used at final stop. In the case of an emergency, the hoist emergency brakes will bring the system to rest from full speed so that the deceleration rate is less than the rate that produces rope slippage on the friction hoist drum. The number of hoist ropes on friction hoists provides a safety factor of 6 to 8 against dropping the cage or skips.

A 150-kW single-drum hoist provides a hoisting capacity of 10 persons per trip in the auxiliary cage at a speed of 7 m/s. Mechanical braking systems

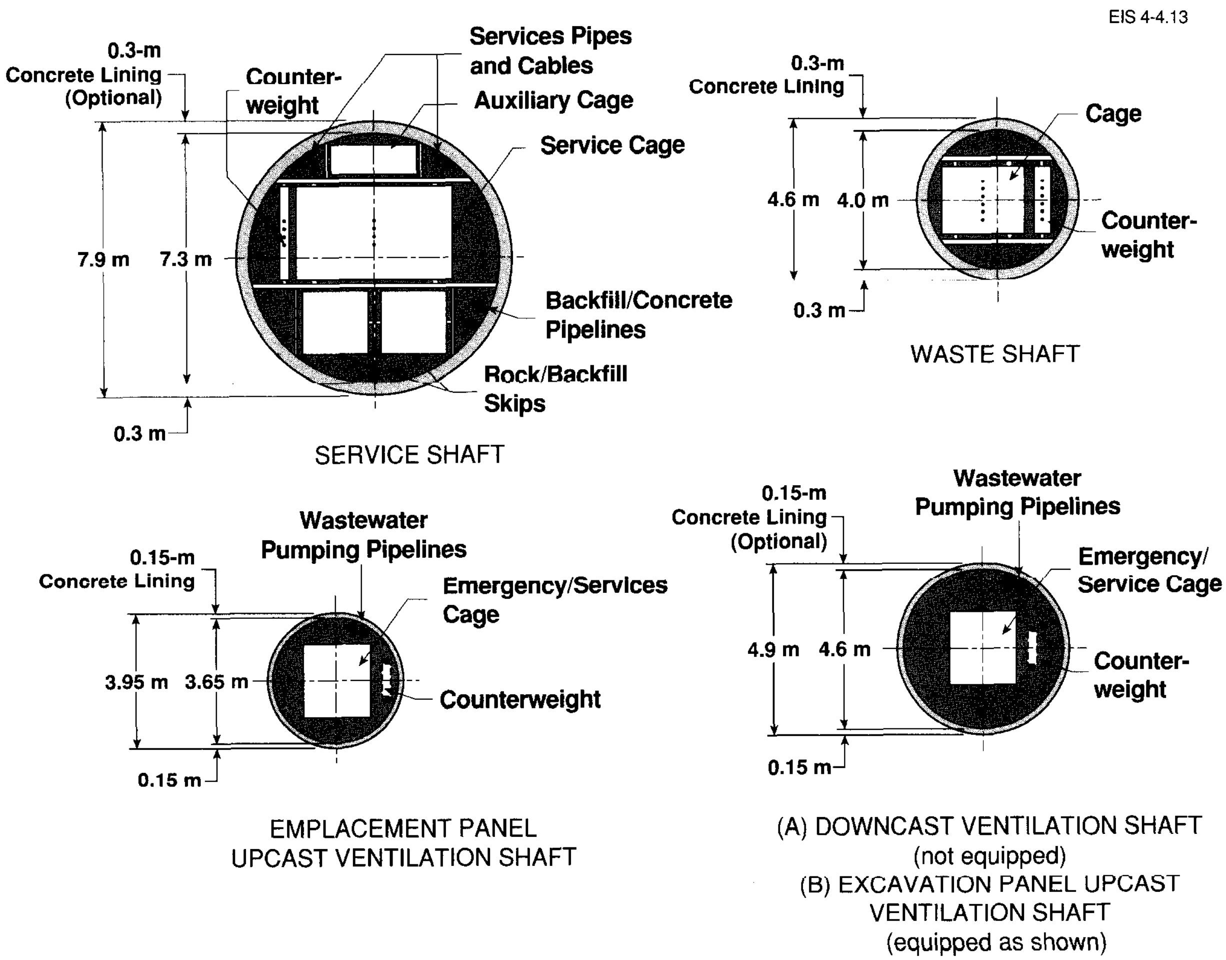


FIGURE 4-13: Typical Shaft Cross Sections (after AECL CANDU et al. 1992)

on the cage will interact with the guides to bring it to rest should a rope or hoist failure result in free fall of the auxiliary cage.

Safety features of all the hoisting systems are consistent with technology currently used in underground mining. This is described more fully by AECL CANDU et al. (1992).

4.3.1.2 Waste Shaft

The waste shaft (Figures 4-12 and 4-13) is dedicated to the transportation of container casks. No personnel or other materials or equipment will be hoisted in this shaft other than for inspection and maintenance. The shaft is 4.6 m in diameter, lined with 0.3 m of concrete, and equipped with a 38-Mg-capacity cage in balance with a counterweight. Steel guides are mounted on steel sets. A 700-kW friction hoist with a 3.8-m-diameter drum has six 38-mm-diameter head ropes and four tail ropes, and operates at a maximum hoisting speed of 3.3 m/s. The hoist and the waste-shaft cage are equipped with the braking systems discussed in Section 4.3.1.1.

The waste-shaft concrete lining is installed to facilitate decontamination if the shaft becomes radioactively contaminated and to eliminate any possibility of loose rock falling into the shaft and interfering with container cask transfers. The shaft has two drainage systems: one directs water from the rock/liner interface to the normal service-shaft complex drainage system and the other handles the water in the shaft sump.

The waste-shaft sump, located at the bottom of the shaft, is constructed of concrete with a welded stainless-steel liner. It is designed to accommodate a damaged container cask if one is accidentally dropped down the shaft, and contains sufficient water to partially decelerate the cask (i.e., cushion its landing) and to provide radiation shielding during subsequent retrieval operations. The water cover over the potentially damaged cask and disposal container also minimizes the potential for airborne radioactive contamination. The stainless-steel sump liner provides containment and simplifies decontamination if it is required. The waste shaft sump is provided with a drainage and filtration system to deal with this situation (Section 4.3.7.2).

The waste-shaft headframe is a rectangular concrete structure with a reinforced concrete foundation, which forms part of the shaft collar. The collarhouse is connected directly to the container-cask laydown area of the Used-Fuel Packaging Plant (Figure 4-12). The waste shaft is ventilated by an upward flow of air (25 m^3/s) supplied from the downcast ventilation shaft airflow. An air exhaust fan and a HEPA filter system are installed in the headframe (Section 4.3.6) to filter radioactive particulate from the ventilation air before it is discharged to the environment.

4.3.1.3 Downcast Ventilation Shaft

The downcast ventilation shaft provides the fresh ventilation air supply for all operations and activities in the disposal vault. It is located in the service-shaft complex (Figures 4-9 and 4-12) and therefore establishes this complex as the fresh-air end of the disposal vault. It is not equipped with a shaft hoist and conveyance.

The downcast ventilation shaft (Figure 4-13) is 4.9 m in diameter. Because it is assumed to be one of the refurbished exploration shafts, all the shaft services, buntons and guides are removed, and a 0.15-m-thick concrete lining is installed if needed for ground control or to reduce resistance to airflow. An 1800-kW fan supplies 462 m^3/s of air to the vault. The fan is installed in a vault-air-heating and fan building built directly over the shaft collar. Ventilation-air heating is discussed in Section 4.3.6.

4.3.1.4 Upcast Ventilation Shafts

There are two upcast ventilation shafts located in the upcast-shaft complex at the end of the vault opposite to the service-shaft complex (Figures 4-1 and 4-11). One shaft, the emplacement panel upcast ventilation shaft (Figure 4-13), is 3.95 m in diameter and is lined with 0.15 m of concrete to facilitate decontamination if the shaft becomes radioactively contaminated and to prevent the movement of radionuclides into the geosphere. It provides exhaust ventilation at a rate of 178 m^3/s for the panels where container emplacement and associated activities are occurring, and the exhaust air is classified as potentially radioactive. A HEPA filter system is installed as part of the surface installations adjacent to the shaft headframe (Section 4.3.6).

This shaft is equipped with a service cage in balance with a counterweight, both of which run on rope guides. Rope guides are used to reduce friction losses in the ventilation airflow. Two drainage-water discharge pipes are located in the shaft. Drainage water is pumped to a surface water-treatment plant from an underground sump located in the upcast-shaft complex. One pipe is normally in use, with the other providing standby capacity. The service cage, operated by a 150-kW double-drum hoist, provides access for shaft and pipe inspection and maintenance only. The drum hoist system is equipped with braking systems as discussed in Section 4.3.1.1. The cage is normally left in the headframe to minimize its effect on shaft ventilation airflow.

The other upcast shaft (Figure 4-10), the excavation panel upcast ventilation shaft (one of the refurbished exploration shafts), is excavated to have a diameter of 4.9 m and, if necessary for ground control or to reduce the resistance to airflow, may be lined with 0.15 m of concrete. It provides exhaust ventilation at a rate of 190 m^3/s for the panel where excavation is occurring. This shaft is equipped with a 25-person-capacity emergency cage. A 2000-kW double-drum hoist operates the cage in balance with a counterweight, both on rope guides. The drum hoist system is equipped with braking systems as discussed in Section 4.3.1.1. The cage is normally left in the headframe to minimize its effect on ventilation airflow.

4.3.2 Vault Access Tunnel Excavation

The vault access tunnels (Figure 4-14) are excavated concurrently with new shaft sinking, using the established exploration shaft(s) until the service shaft and its facilities are commissioned. All the exploration tunnels are enlarged to the specified final dimensions. The central access and panel access tunnels are each twinned by adding a second, parallel tunnel.

The central access tunnels are excavated to be 6 m wide and 5 m high. During the construction stage, 2.5 km of new central access tunnels are excavated and 2.5 km of exploration tunnels are enlarged. The 6 km of perimeter access tunnels, extending from the service-shaft complex to the last panel tunnels nearest the upcast-shaft complex, are also enlarged to be 6 m wide and 5 m high. The panel tunnels are excavated to be 6 m wide and 6.5 m high. There are 8 km of new panel tunnel excavation and 8 km of exploration tunnel enlargement. Drainage grades of -1% are maintained toward the upcast-shaft complex.

The tunnels are excavated using drill-and-blast methods. Either "pilot-and-slash" or "full-face" techniques could be used for new tunnels, depending on site-specific conditions. The full-face technique is preferred, if the rock quality is appropriate and acceptable excavation wall rock quality

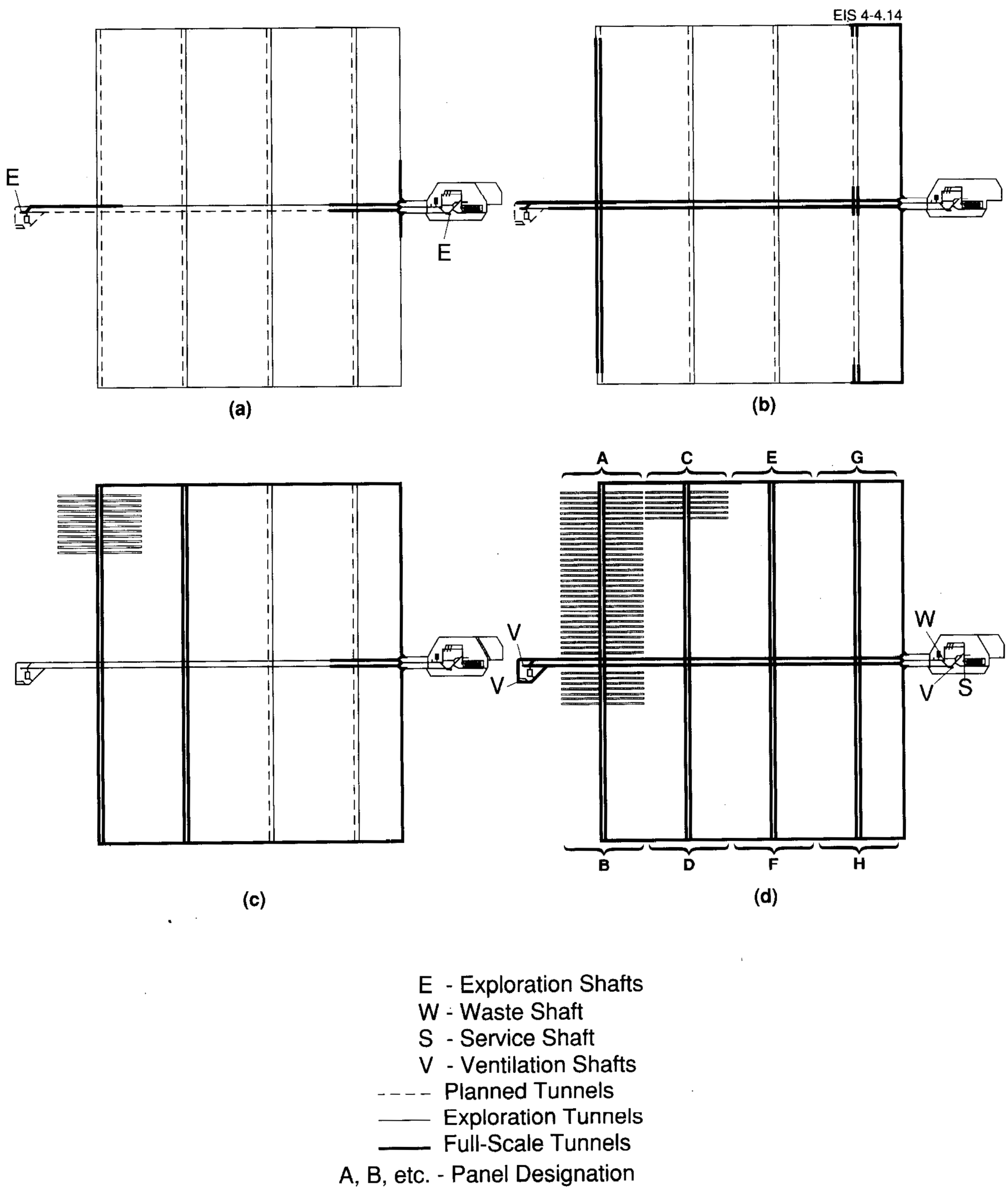


FIGURE 4-14: Disposal Vault Construction Sequence

can be achieved, because it is more productive than the pilot-and-slash method. The tunnels in the Used-Fuel Disposal Centre conceptual design are assumed to be excavated by the pilot-and-slash method. The exploration tunnels require only slash blasting to final dimensions, which is similar to the slashing in the pilot-and-slash technique.

The excavated rock is removed from the excavation face using 6-Mg diesel load-haul-dump (LHD) vehicles, and loaded into 24-Mg-capacity, rubber-tired diesel trucks. The trucks are end-loaded and haul the excavated rock to a rock bin at one of the exploration shafts while the service shaft is being constructed, or the service shaft when it is completed, for hoisting to surface. Rubber-tired diesel equipment is assumed to be used to excavate the access tunnels and other underground excavations because it is well proven in the civil and mining industries, and provides good mobility and flexibility.

The Used-Fuel Disposal Centre conceptual design assumes that excavation work proceeds with three excavation crews per shift working simultaneously. There are three sets of excavation equipment, one set for each crew. A crew may concentrate their effort on only one excavation location, or may excavate at two or more locations if the schedule, distances and equipment availability allow.

Mobile diesel-powered equipment requirements assumed in the cost estimate are listed in Table 4-3.

When the service shaft is completed, it replaces the service and rock handling functions provided by the exploration shafts. The exploration shafts are then refurbished and equipped to serve as ventilation shafts.

Since the exploration tunnels provide a ventilation network for the vault level, the only auxiliary forced-air ventilation needed is during the excavation of the twinning tunnels. Fresh-air volumes are supplied to these tunnel faces through 1.22-m-diameter flexible ducts using underground auxiliary fans. The volumes of airflow were calculated on the basis of the mining regulations of the Government of Ontario (1990d), but these requirements might not be applicable to an actual disposal vault.

4.3.3 Disposal-Room Excavation

Disposal rooms in the Used-Fuel Disposal Centre are excavated during two stages. Room development during the construction stage includes Panel A, consisting of 64 rooms, each 8 m wide by 5.5 m high, and 10 to 12 rooms in each of Panels B and C (Figure 4-14d), which represents a total excavation length of about 20 km.

Room excavation during the operation stage consists of the excavation of about 425 disposal rooms (i.e., those not excavated in the construction stage) having a combined length of about 98 km. This excavation is discussed further in Section 5.4.

Disposal rooms are developed using either the pilot-and-slash or the full-face drill-and-blast excavation method, depending on ground conditions and

TABLE 4-3

DIESEL-POWERED EQUIPMENT REQUIREMENTS FOR DISPOSAL VAULT CONSTRUCTION
(after AECL CANDU et al. 1992)

Description	Total No. of Units	Total Power (kW)
Excavation		
Three-Boom Hydraulic Drill Jumbo	6	360
LHD 6-Mg Capacity	4	540
Truck 24-Mg Capacity	11*	2200
Scissors-Lift Truck	3	180
Explosive Truck	3	180
Subtotal	27	3460
Ancillary		
Grader	1	60
Utility Truck	1	60
Diesel Fuel and Lubrication Truck	1	60
Service Vehicle	2	120
Supervisor Vehicle	2	80
Personnel Carrier	2	80
Subtotal	9	460
TOTAL	36	3920

* The maximum number required for the greatest haulage distance to the service shaft.

resulting excavation wall quality, with full-face being the preferred method for economic reasons. The Used-Fuel Disposal Centre conceptual design assumes that the rooms are excavated by the pilot-and-slash method. Rooms are driven at a 1% longitudinal upgrade with a 2% slope across the room to ensure adequate drainage of process water and groundwater.

During excavation of the rooms, the auxiliary 112-kW fans mounted in the panel access tunnels provide 34 m^3/s of ventilation air into the rooms through 1.22-m-diameter flexible ducting (see Section 4.3.6).

On completion of the excavation of a disposal room, the excavation services are removed from the room and the rock surfaces are mapped geologically. Any features of particular interest are photographed. In particular, details of exposed geological discontinuities are recorded and added to the geotechnical database. This database is used to project the likely geological conditions in the immediate vicinity of the emplacement boreholes. By applying the observational method to vault engineering, alternate designs appropriate for the observed geological conditions would be available to accommodate any changed conditions. For example, if a zone of significant fracturing is encountered, the emplacement borehole arrangement may be changed to leave a clear zone without any emplacement boreholes within and immediately around the fractured zone.

Fractures may be further characterized using geophysical surveys such as ground-probing radar, cross-hole acoustic techniques and hydrogeological testing from boreholes drilled to intersect the fracturing away from the disposal room. Data obtained from these characterization activities are used to select between several alternative treatment methods to seal the fractures. The need for sealing and the selection of the method of sealing are based on performance criteria developed for each waste disposal area of the vault based on the results of a performance assessment of the disposal system.

It is likely that no treatment of fractures will be required in many of the disposal rooms. In the others, grouting of fracture zones intersecting the room will be needed, possibly as an operational expediency and possibly as part of room sealing. The emplacement borehole spacings may be increased to reflect possible reductions in the strength of the local rock mass.

For logistical purposes, room preparation and emplacement-borehole drilling are performed during the construction stage in the first 10 to 12 rooms (i.e., 2800 to 3400 boreholes) of Panel A. This provides the necessary allotment of completed boreholes to keep borehole drilling sufficiently ahead of container-emplacement operations at the beginning of the operation stage. Details of disposal-room preparation for waste emplacement are discussed in Section 5.4.3.

4.3.4 Buffer and Backfill Preparation Plant

The buffer and backfill preparation plant in the Used-Fuel Disposal Centre conceptual design is situated underground adjacent to the service shaft (Figure 4-9). It is designed to receive and store buffer and backfill component materials transferred from the surface and to prepare the final sealing products (Figures 4-15 and 4-16). Silica sand, crushed rock fines, and crushed rock are lowered to the vault level in a dedicated service-shaft skip at a rate of 100 Mg/h. They are discharged into a skip dump and diverter chute arrangement. The diverter chute directs crushed rock onto a shuttle conveyor that moves the material to one of three 2600-Mg bins. Crushed rock fines are conveyed to and stored in one 2600-Mg bin. Silica sand is directed into a hopper feeding a screw conveyor system that transfers the sand to one 3000-Mg bin.

Sodium-bentonite and glacial-lake clays are conveyed pneumatically from the surface and discharged directly into their respective bins. Two 1500-Mg bins are required for each clay type.

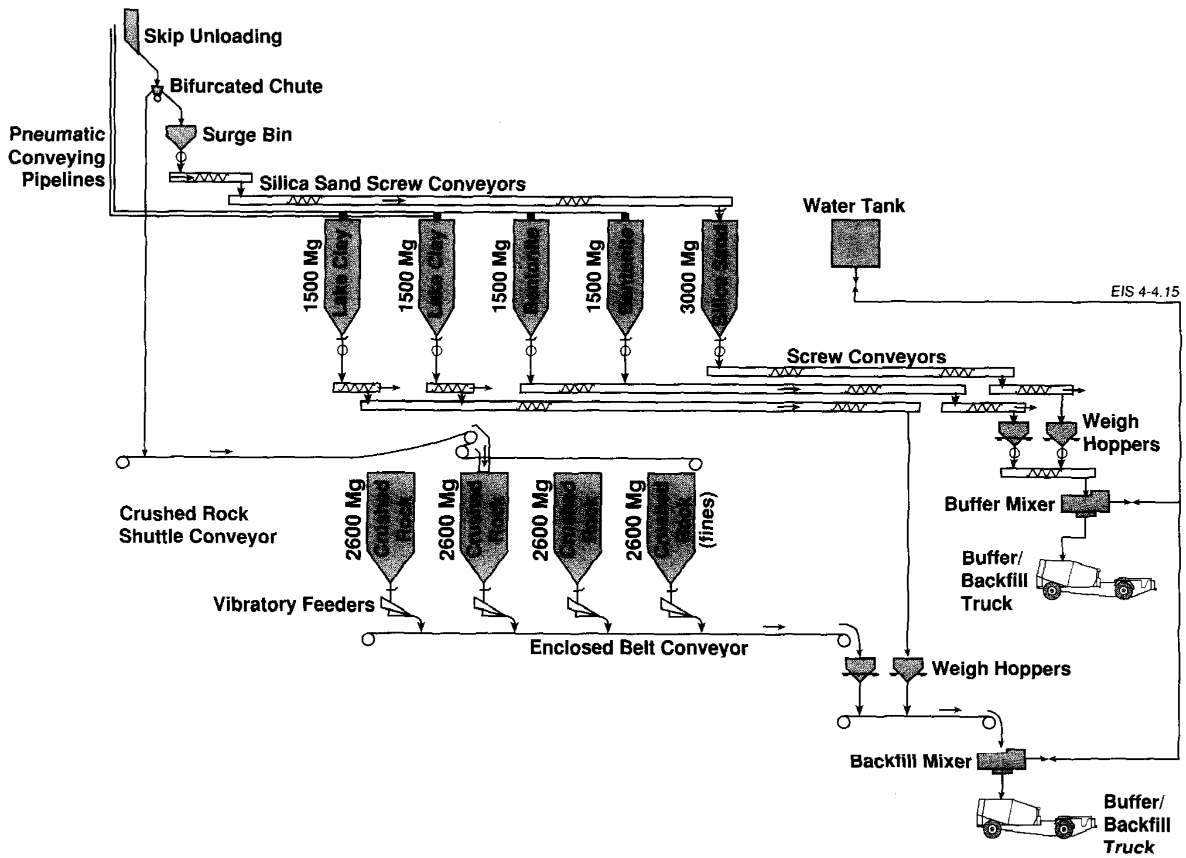


FIGURE 4-15: Buffer/Backfill Plant - Flow Diagram (after AECL CANDU et al. 1992)

The storage bin capacities are equivalent to half a month's buffer and backfill requirements, and include additional capacity for tunnel sealing during the vault decommissioning stage. Bins are excavated in rock, constructed of concrete and sealed with epoxy to prevent infiltration of moisture from the rock (Figure 4-16). All bins are designed to minimize material holdup and material segregation, and to maximize the full-flow or live capacity of the bin.

The bin top area and skip-dump area are provided with a monorail crane system for maintenance purposes.

Three sealing system components are prepared in batches in two independent mixing circuits: one for producing the lower backfill product and the other for producing the buffer and upper backfill product. For simplicity, the buffer and upper backfill are assumed to have the same composition, but compositional changes can be made if their suitability is demonstrated.

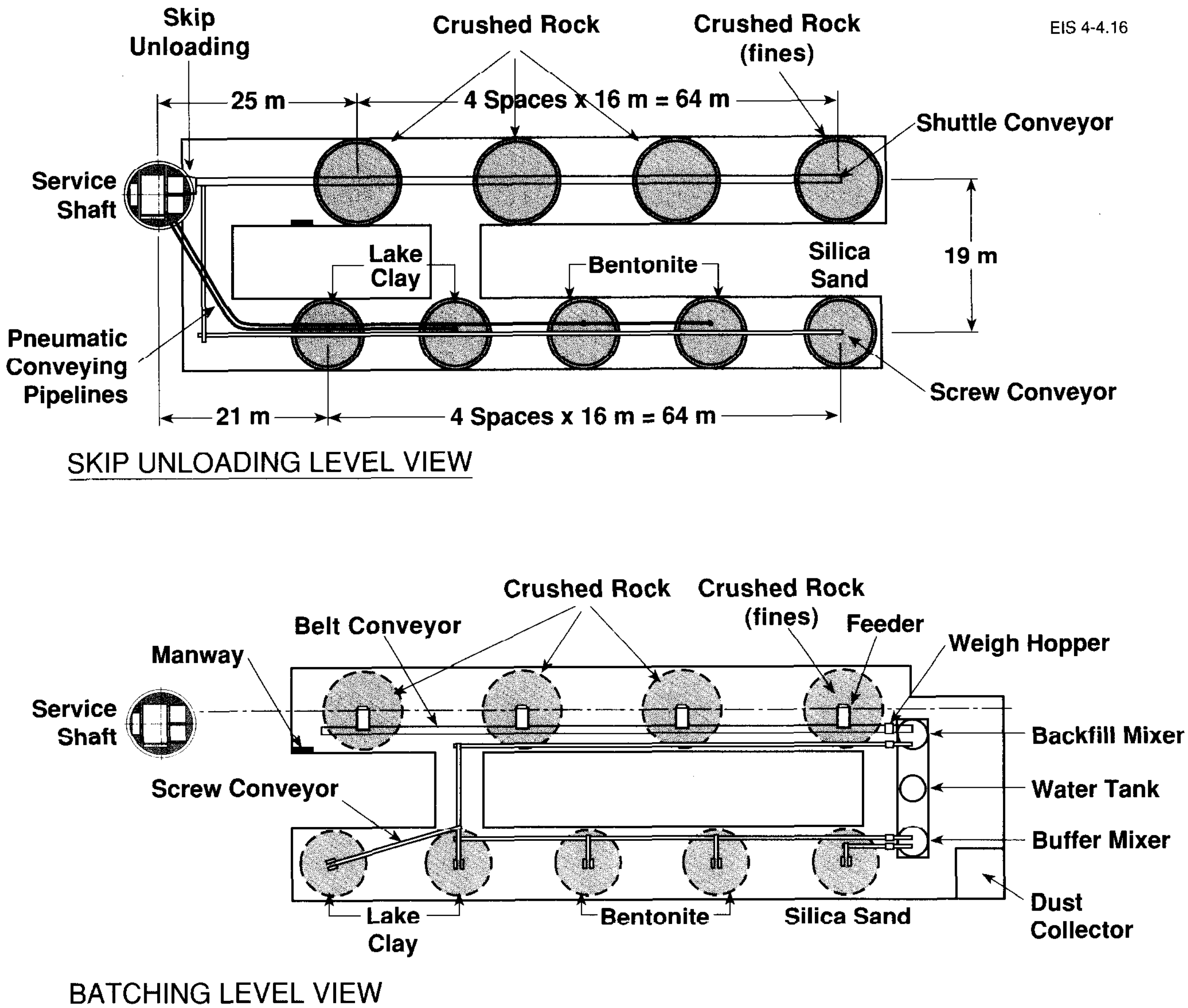


FIGURE 4-16: Buffer/Backfill Plant - General Arrangement Plans (after AECL CANDU et al. 1992)

The crushed rock and crushed rock fines are withdrawn by vibrating feeders onto an enclosed belt conveyor. Clay is carried by a screw conveyor system. All materials are transferred to individual weigh hoppers that use load-cell measurement equipment to provide a high degree of weighing accuracy. When loaded, the weigh hoppers automatically discharge through feeders into a rotating pan mixer with a capacity of 100 Mg/h for lower backfill and 50 Mg/h for buffer and upper backfill product. The moisture content of the mix is adjusted by the metered addition of water into the mixer from a 135 000-L domestic-water storage tank.

The entire batch plant is humidity-controlled to minimize the absorption of moisture by the various buffer and backfill components. Provisions for dust control are incorporated at every point where materials are handled in the open. The dust collection system includes dust hoods, ducts, filters and fans.

The buffer and backfill batch-mixing operations are fully automated and computer-controlled. A system-flow operation panel is provided in a central location to continuously display the status of equipment and materials. The bin levels for all materials are monitored continuously with level-detection systems and are displayed on the panel. The moisture content of additives is monitored using probe-type resistivity measurement techniques. Alarm systems are provided to detect and indicate abnormal conditions. Automatic shutdown sequences are incorporated and priorities are assigned to respond to various emergency conditions. Quality-control facilities to measure grain size, moisture content, and compaction and swelling properties of the finished products are provided to ensure that the products meet the required technical specifications.

4.3.5 Underground Ancillary Facilities

The major underground ancillary facilities in the Used-Fuel Disposal Centre are located at the bottoms of the service-shaft and the upcast-shaft complexes. Portions of these facilities are developed during the siting stage. The excavation of new facilities and the enlargement of existing facilities are conducted with full-face, benching, pilot-and-slash or slashing methods most appropriate for the size and shape of the final excavations.

These are the main facilities and service areas in the service-shaft complex (Figure 4-9).

1. A cask storage area for the surge storage of one day's throughput of 15 casks with used-fuel containers, equipped with a transporter loading/unloading area and an overhead crane for cask handling (e.g., the storage area is normally half full to allow for supply or disposal disruptions).

2. Maintenance service facilities consisting of several service bays for all aspects of vehicle and equipment maintenance and repair, a washdown bay with water collection and treatment systems, lubricant storage, paint shop, machine and welding shop, and parts and tire storage.

3. A diesel fuel storage for one day's vehicle fuel requirements (14 000 L) complete with fire alarms, heat-activated air-lock doors, and water sprinklers and spill catch pits (fuel is supplied daily from the surface through a transfer line in the service shaft).

4. A service-shaft rock dump and a skip loading pocket complete with a coarse-rock grizzly screen and hydraulic rock breaker.

5. Two sets of separate explosive and detonator storage magazines with a capacity of 1400 kg of explosives and associated detonators (one set is located in each half of the vault, and only the set on the side of the vault where disposal rooms are being excavated is in use at any time).

6. A first-aid and safety refuge station, complete with seals, utilities, oxygen supply and communications, for emergency containment of workers in the event of a fire or radiological incident where egress from the vault is not immediately possible.

7. The service-shaft complex drainage-water sumps and pumps.

8. Offices, washroom and lunchroom facilities.

9. Access and ventilation tunnels complete with ventilation control structures and doors.

10. A component test area with access and services for testing disposal system equipment and components.

The service-shaft complex is ventilated with air from the downcast ventilation shaft (Figure 4-9). Ventilation exhaust air from operations where noxious fumes may be present, such as the vehicle and equipment maintenance areas, fuel storage and lubricant storage areas, is directed up the nearby waste shaft. The waste shaft is normally not occupied by workers and the fumes do not represent an occupational health risk. Inspections and maintenance of the waste shaft would be scheduled for times when there is no activity in these service areas. Air from other operations, such as the buffer and backfill preparation plant, is filtered as required to remove particulate materials, and is exhausted up the service shaft.

The main facilities in the upcast-shaft complex (Figure 4-10) are the vault drainage-water sump and pumping systems (Section 4.3.7), the ventilation airflow control system (Section 4.3.6) and the retrieved-container transfer facility (Section 5.4.7). There would also be a refuge station set up and equipped in this area. The upcast-shaft complex is ventilated with the air discharging from the disposal vault using the ventilation control doors to balance flows.

4.3.6 Vault Ventilation System

The vault ventilation system is installed during the construction stage and is designed to satisfy appropriate mining, radiological and occupational safety and health legislation, with emphasis on these specifications:

1. Providing adequate airflows for the operation of diesel-powered equipment, thereby ensuring that concentrations of oxygen and harmful gases are kept within acceptable limits.

2. Providing dilution of radon gas and its daughters to below acceptable limits and flushing them from the vault. (In this

conceptual design, it is assumed that the diesel equipment airflow requirements are sufficient to meet this need.)

3. Removing dust produced during normal operations and maintaining dust concentrations within acceptable limits.

4. Maintaining a safe and comfortable working environment for all underground personnel.

5. Ensuring the separation of ventilation in the emplacement panel from the excavation panel, and the continuous airflow from inlet to discharge through each half of the vault.

6. Providing filtration to collect any airborne radioactive contamination that may be released from used-fuel disposal containers during underground operations.

A system of fans and air-control bulkheads installed at strategic locations provide the airflow and direction control in the Used-Fuel Disposal Centre conceptual design. The ventilation systems and controls, including the portable systems to be used during waste emplacement and sealing operations, are described in this section.

Primary ventilation is provided by a push-pull arrangement of fans. A forcing fan on the surface introduces fresh air into the downcast ventilation shaft. The majority of this air is exhausted through the two upcast ventilation shafts after passing through the vault. One fan on each upcast shaft pulls the air up these shafts. A small quantity of air is exhausted up the waste shaft and service shaft. A fan is located at the top of the waste shaft to keep the waste-shaft headframe under negative pressure.

The waste-shaft exhaust ventilation system is equipped with a HEPA filter system on the surface. Air normally bypasses the filters. If a radioactive contaminant release is detected in the waste-shaft headframe, e.g., because of accidental damage to the container and used fuel during transfer of container casks in the shaft or in the shaft-bottom area, an automatic damper system diverts air through the HEPA filter installation to remove any potential radioactive particulate contamination before the air is released to the environment. As well, the alarm system is actuated to notify surface and underground workers of an unusual situation. The HEPA filter system has a surface area of 10 m^2 and is rated for a flow of 12 m^3/s. The waste-shaft headframe air pressure is maintained at a slightly less than atmospheric pressure at all times so that fresh air enters the building.

The concentration of radon and its daughters in the vault air is an important factor in designing the ventilation system. Radon comes from the rock surfaces and fractures exposed by excavation, and from the groundwater moving in the fractures. The rate of radon release in a disposal vault would be dependent on site-specific conditions, and the concentration in the air would generally be controlled by moving sufficient air to keep the concentrations below the levels that may represent a risk to workers. Radon concentrations in non-uranium mines are generally maintained at acceptable levels by the ventilation airflows necessary for the operation of diesel equipment underground. We have used the airflow requirements for diesel equipment as the basis for determining the airflows for the Used-Fuel Disposal Centre conceptual design.

The ventilation airflow rate required in any area of the vault will depend primarily on the number and power rating of the diesel-powered equipment operating in that area. The major underground airways are the perimeter access tunnels, the central access tunnels, and the appropriate panel tunnels being operated at the time. Auxiliary ventilation fans and ducting are provided for each disposal room in which work is in progress. The arrangement of these tunnels in this conceptual design permits the creation of separate ventilation circuits for excavation and emplacement panel operations. These circuits are referred to as the excavation panel and the emplacement panel circuits. The primary ventilation flows for the underground vault are shown in Figure 4-17, and the distribution of major airflows in the vault is summarized in Table 4-4.

The downcast ventilation-shaft supply fan in the conceptual design is housed in a building situated over the shaft, which also accommodates the heaters for the underground air. The intake-air heating system is designed to raise the air temperature from an assumed lowest temperature of -43°C to a temperature of 2°C to prevent freezing in the shaft. It is assumed that the heating system is fueled by propane and that it has a capacity of 24 600 kW. The average annual fuel consumption is approximately 2.7×10^6 m^3 of propane. Adiabatic compression due to the pressure increase between ground surface and 1000-m depth further heats the air by about 8°C, and heat transfer between the air and rock walls also heats (in winter) or cools (in summer) the air, giving relatively comfortable working conditions in the vault.

The exhaust fan for each upcast ventilation shaft is housed in a fan room adjacent to the headframe, and is connected to the shaft by a sloping tunnel intersecting the shaft near the shaft collar. This arrangement leaves the headframe free for operation of the inspection and emergency hoists. One upcast shaft is dedicated to handling the exhaust air from the emplacement panel operations and the other is dedicated to handling the exhaust air from the excavation panel operations. The ventilation control system consists of two sets of connection tunnels complete with ventilation control structures and doors (Figure 4-10) to route the potentially radioactive airflow from the designated waste emplacement panel to the emplacement panel upcast shaft, and the exhaust airflow from the designated excavation panel to the excavation panel upcast shaft. This arrangement is maintained for the duration of the operation stage by redirecting airflows every five years as the emplacement and excavation panels switch sides of the vault.

The emplacement panel upcast ventilation shaft is provided with a HEPA filter system that is normally bypassed. If radioactive contamination is detected in the airflow, automatic control dampers divert exhaust air through the HEPA filter installation and alarms annunciate. In addition, the main fans are throttled back to approximately 50% of the normal airflow to reduce the volume of air passing through the HEPA filters and extend their filtration capacity. The HEPA filter system has a surface area of 75 m^2 and is rated for a flow of 90 m^3/s. The reduction in airflow through

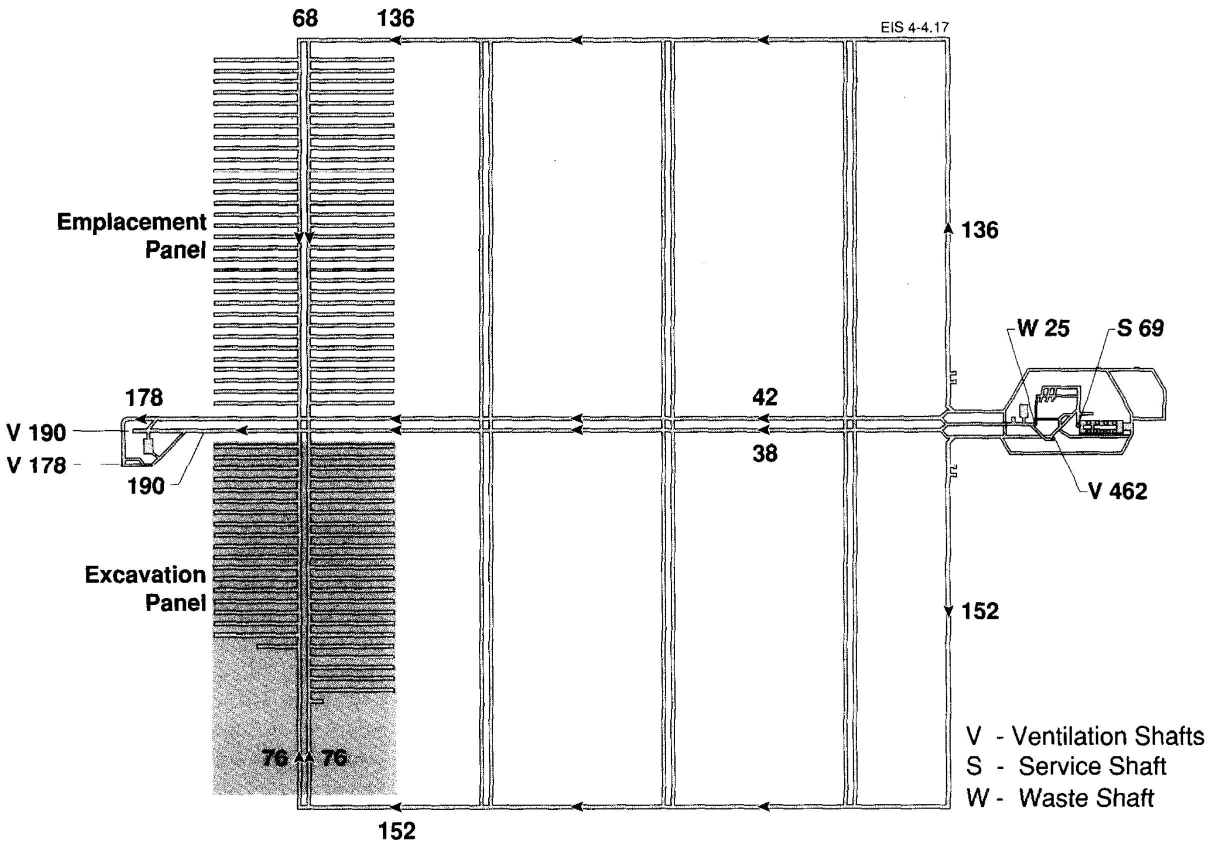


FIGURE 4-17: Primary Ventilation Airflows (after AECL CANDU et al. 1992). Ventilation flows are in m^3/s.

the vault does not increase the hazard to underground workers since an underground alarm system (e.g., stench gas, claxtons and flashing lights) advises them to shut off most diesel equipment and follow emergency response procedures (e.g., use transport vehicles to move toward the first-aid and safety refuge station at the service-shaft complex along the clean-air pathway).

The distribution of ventilation air from the downcast ventilation shaft throughout the vault is controlled by adjustable ventilation control doors (Figure 4-9) located at all splits in the airflow paths. The required distribution of air is achieved by adjusting ventilation openings in these doors.

The four ventilation doors at the entrance to the central access tunnels are operated in pairs to separate the air supplies to the two central access tunnels (Figure 4-9). These separate air supplies contribute to the effective isolation of the operations in the excavation and emplacement

TABLE 4-4

DISTRIBUTION OF PRIMARY VENTILATION AIRFLOW IN THE DISPOSAL VAULT

(after AECL CANDU et al. 1992)

Shafts	Airflow (m^3/s)
Total volume of air into vault:	
Downcast shaft (1800-kW fan @ 2.1-kPa static pressure)	462
Volumes of air out of vault:	
Excavation panel upcast shaft	190
Emplacement panel upcast shaft	178
Service shaft	69
Waste shaft (55-kW fan @ 1.4-kPa static pressure)	25
	462
Excavation Panel Circuit	
Central access tunnel	38
Perimeter access tunnel (split to two panel tunnels)	152
Total to excavation panel upcast shaft (750-kW fan @ 2.2-kPa static pressure)	190
Emplacement Panel Circuit	
Central access tunnel	42
Perimeter access tunnel (split to two panel tunnels)	136
Total to emplacement panel upcast shaft (670-kW fan @ 1.9-kPa static pressure)	178
Service-Shaft Ancillary Circuit	
Service-shaft bottom	5
Buffer/backfill plant	64
Total to service shaft	69
Waste-Shaft Ancillary Circuit	
Maintenance area	16
Cask handling area at shaft bottom	5
Diesel fuel storage	4
Total to waste shaft	25

sides of the vault. After approximately five years, when emplacement operations move a panel on the other side of the vault, the door positions are reversed to adjust the airflows to those required by the activities on each side of the vault.

Table 4-5 provides the ventilation demand required by the diesel-powered units during vault operation. The regulatory requirement of 0.06 m^3/s minimum airflow per kilowatt of maximum-rated engine output is exceeded in

TABLE 4-5

OPERATION STAGE DIESEL-POWERED EQUIPMENT REQUIREMENTS
(after AECL CANDU et al. 1992)

Description	No. of Units in*		Total Power (kW)		Ventilation Demand (Supply) (m^3/s)	
	Panel or Perimeter Tunnels	Central Access Tunnels	Panel or Perimeter Tunnels	Central Access Tunnels	Panel or Perimeter Tunnels	Central Access Tunnels
Excavation Panel Circuit						
Excavation						
Three-Boom Hydraulic Drill Jumbo	4	-	240	-		
LHD 6-Mg Capacity	3	-	405	-		
Truck 24-Mg Capacity	5	2	1000	400		
Explosive Truck	2	-	120	-		
Scissors-Lift Truck	2	-	120	-		
Subtotal	16	2	1885	400	113	24
Ancillary						
Grader	1	-	60	-		
Utility Truck	1	-	60	-		
Diesel Fuel and Lubrication Truck	1	-	60	-		
Service Vehicle	2	-	120	-		
Supervisor Vehicle	2	-	80	-		
Personnel Carrier	2	-	80	-		
Subtotal	9	0	460	0	28	0
Total	25	2	2345	400	141 (152)	24 (38)
Emplacement Panel Circuit						
Emplacement						
Cask Transporter	1	2	335	670		
Borehole Drilling						
LHD 6-Mg Capacity	1	-	135	-		
Truck 24-Mg Capacity	1	-	200	-		
Buffer/Backfill Materials						
Mixer Truck	5	-	1000	-		
Room Backfilling						
LHD 4-Mg Capacity	2	-	200	-		
Dozer	1	-	75	-		
Compactor	1	-	75	-		
Total	12	2	2020	670	121 (136)	40 (42)

* The vehicle traffic is controlled to avoid an accumulation of vehicles in any area in excess of the capacity that can be accommodated safely by the ventilation airflow.

all locations. Airflows within the vault level are controlled by adjustable ventilation control doors along the central access tunnels, at the entrance to every panel, and at cross connections between central access tunnels. All these doors will normally be closed, except for the doors of the panel tunnels in use at a particular time.

Auxiliary ventilation is provided during activities within individual disposal rooms, either during excavation or emplacement. During excavation, 34 m^3/s of air is provided by a 112-kW fan supplying air through a temporary, 1.22-m-diameter flexible duct suspended from the crown of the room along one side wall. During waste emplacement, all disposal rooms in which activity is proceeding are equipped with two rigid ventilation ducts (Figure 4-18). Auxiliary ventilation is provided by a 50-kW exhaust fan fitted to each duct. The greatest ventilation demand arises during backfilling of the lower part of the room, for which 14 m^3/s of ventilation air is provided by each fan. Filters are provided to remove dust from the air before discharge into the panel tunnel.

A HEPA filter system is provided on the exhaust from the disposal room in which containers are being emplaced. This filter system is portable since these units must be moved every two months to the next room in which containers are to be emplaced. During container emplacement, each duct ventilating the room is equipped with a bypass damper arrangement. In the event of airborne radioactive contamination the monitoring system actuates, an automatic damper to direct air into a single duct actuates an alarm and shuts down the auxiliary fans. A third fan starts up and draws the exhaust air through the portable HEPA filter installation. The HEPA filter system has a surface area of 3 m^2 and is rated for a flow of 4 m^3/s. This airflow is more than adequate for the needs of the workers since there is no diesel equipment ventilation demand in the room. Also, the workers will vacate the disposal room toward the perimeter tunnel (i.e., clean air source) when the alarm sounds.

4.3.7 Vault Water Drainage System

Water that is supplied for use underground and any groundwater seeping into the excavations will be directed to and collected in sumps for pumping to surface. The vault water drainage system consists of tunnel drainage channels, collection sumps, and pumps and pipes to collect and transfer water to the surface treatment facilities. There are three independent drainage systems: one to collect and pump water from the service-shaft complex, one to deal with water in the waste-shaft sump, and one to service the balance of the vault and the upcast-shaft complex. As well, a portable system is used for disposal-room drainage during container-emplacement activities.

Drainage channels will be made at convenient locations in the floors of the excavations, normally near one or both walls, during the excavation of access tunnels and work areas.

4.3.7.1 Service-Shaft Complex Water Drainage System

The service areas and rooms in the underground portion of the service-shaft complex (Figure 4-9) are excavated with a grade of -1% toward their access

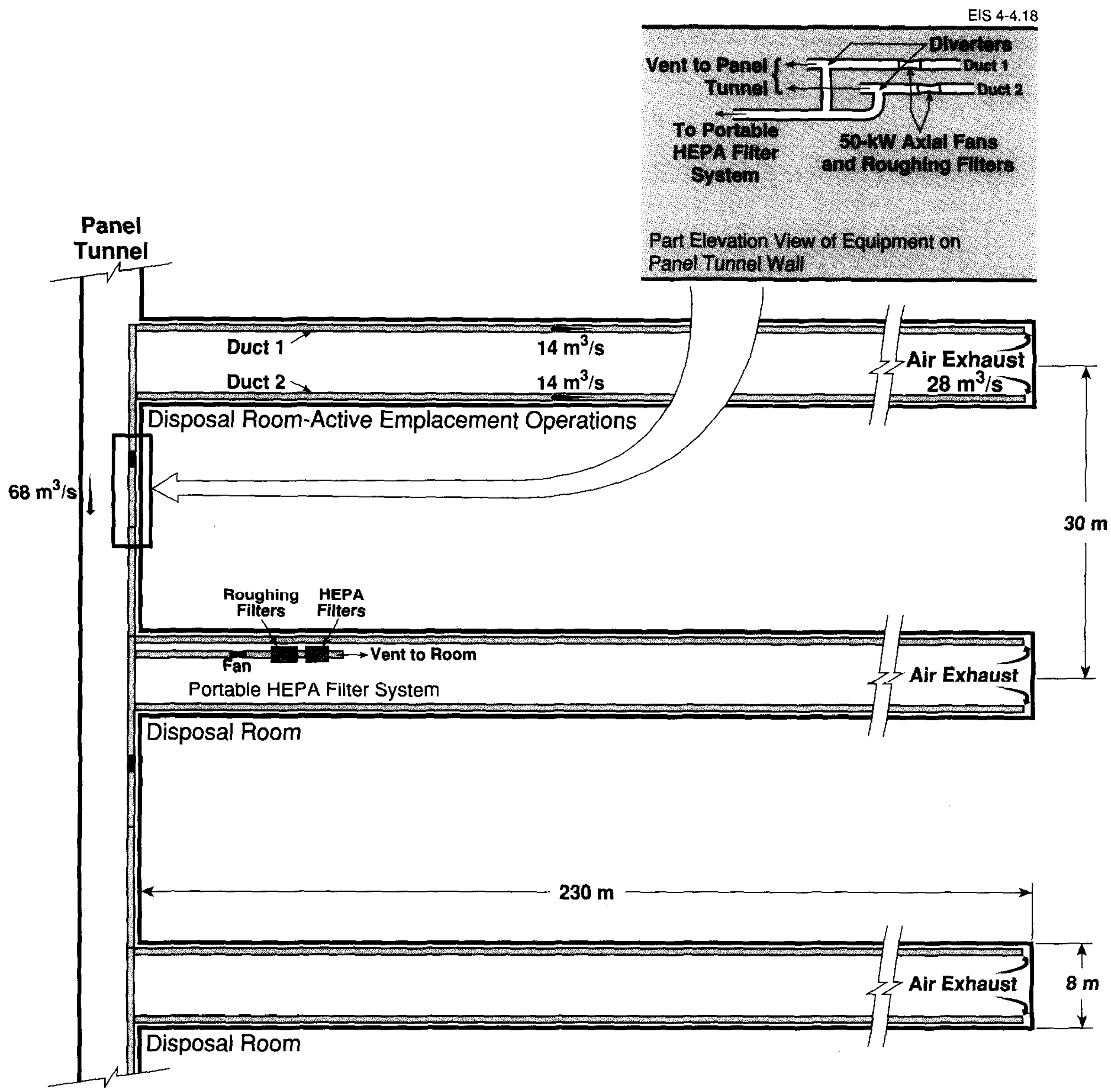


FIGURE 4-18: Disposal-Room Ventilation During Container Emplacement - Partial Plan

tunnel. The tunnels are excavated with a -1% grade towards a sump. Where the tunnel arrangement makes it impractical to maintain a -1% grade towards the service-shaft complex sump, local sumps are constructed and the water is pumped through pipes to the service-shaft complex sump. As well, each of the three shafts is constructed with a sump below the level of the lowest access to the shaft to collect water that seeps into the shaft. The water collected in the shaft bottom sumps of the service and downcast ventilation shafts is pumped to the main sump. As well, the water seepage collected and drained from behind the waste shaft liner is directed to the main sump.

Water is introduced into the "settling" compartment of the service-shaft complex sump (Figure 4-9) by gravity drainage or by pumping from the shaft sumps and local sumps. The water then flows over a weir structure that controls the carryover of particulate and organic matter into the "clear water" compartment. The clear water is pumped to the surface through piping installed in the service shaft and is transferred to the service-shaft complex water settling pond (Figure 4-2, Section 4.2.6.2).

The settling compartments are inspected at regular intervals and, when necessary, the organic matter is absorbed from the surface and the settled particulate sludge is removed. These materials are handled as solid wastes.

4.3.7.2 Waste-Shaft Sump Installations

A separate drainage system is provided for the water in the waste shaft sump. As this shaft is used routinely to handle container casks, there is a low probability that radioactive contamination could be released into the shaft. One very low probability event that would result in a release of contamination in the waste shaft would be the dropping of a loaded container cask down the shaft with subsequent breaching of the container and possible damage to the contained fuel. The waste shaft is provided with an extra deep sump and a more extensive sump pumping system. The waste-shaft-liner drain system diverts most of the groundwater collected between the rock and the shaft liner to the service-shaft-complex sump, bypassing the waste-shaft sump. This minimizes the amount of debris and sediments collected in this sump. If a loaded cask is dropped down the shaft, the sump water will decelerate the cask and cushion its impact, control the dispersion of any radioactive contamination, and provide radiation shielding during retrieval of the damaged cask and its contents.

The water collected in the waste shaft sump may be pumped directly to the service-shaft complex sump, it may be pumped through a local recirculating filtration system, or it may be pumped to the active-liquid-waste treatment building on the surface. The transfer to the surface is through either a pipe installed in the waste shaft, if it is not damaged by the incident leading to the contamination, or through an alternate pipe installed in the service shaft.

The local recirculating filtration system, comprising cartridge filters and ion-exchange columns in shielded housings, is used to remove radioactive contaminants from the sump water and to reduce the turbidity of sump water so that the activities necessary to remove the damaged cask and its contents can proceed under direct observation. Excess sump water is transferred to the service-shaft complex sump or to the active-liquid-waste treatment plant, depending on its residual level of radioactive contamination. The filter cartridges and ion-exchange resin are handled as potentially contaminated solid waste.

4.3.7.3 Upcast-Shaft Complex Water Drainage System

The central access and perimeter access tunnels from the service-shaft complex are sloped downwards at a grade of 1% towards the upcast-shaft complex. The panel tunnels and the parallel perimeter tunnels are sloped downward at a 1% grade toward the central access tunnels. Within a panel each disposal room is also sloped downward at a 1% grade toward the panel tunnel. This construction results in a water drainage path on each side of the vault to direct all the water that seeps into the excavations, and is used in the operations, to one of the central access tunnels at a location near the upcast-shaft complex.

The drainage water from each central access tunnel is combined in the upcast-shaft complex and directed into the drainage-water sump. The drainage-water sump consists of a series of "settling and clear-water" compartments, and a pump station for clear water that includes standby pumping capacity. The capacity for this system is 2200 m^3/d, which assumes a groundwater seepage rate of 1000 m^3/d (Table 4-2). The water from the clear-water compartment is pumped to a settling pond located in the protected area surrounding the upcast-shaft complex headframes. This settling pond is discussed in Section 4.2.6.2. The sludge from the settling compartments is removed, when necessary, and handled as a solid waste.

4.3.7.4 Disposal-Room Water Drainage System

There is a low probability of accidentally releasing radioactive contamination into the disposal room during the disposal-container emplacement operations. Each disposal room is constructed with a local sump to minimize the potential of this contamination entering the general water drainage system. A portable pump with contamination monitoring and filtration equipment draws water from this sump and normally directs it to the panel tunnel drainage channel. If unexpected radioactive contamination is detected, the contaminated water is passed through the filtration system prior to discharge into the panel tunnel drainage channel. Routine monitoring of drainage water within a panel tunnel would be conducted to ensure adequate performance of the room drainage system.

4.3.8 Abnormal Conditions

Systems, equipment and services safety and reliability are important factors in the design of the disposal vault. The work environment must provide occupationally and radiologically safe conditions during both normal and abnormal conditions. As many equipment failures and accidents are difficult to foresee in a conceptual-level design, a comprehensive program would be put into place during detailed-level design to define all possible utility failures, equipment failures and accidents, and to devise preventative measures. These would be incorporated into the detailed design in such a way that the system will remain in or be put into a safe condition when a failure or accident occurs. Examples of features that are assumed in this conceptual design to deal with abnormal conditions are given in the following paragraphs.

The cranes and hoisting systems are designed to a "single-mode" fail-safe specification. In this case, any single failure of a crane component would cause the crane to lock in its current position. No crane movement would be permitted, except following repair of the system component or by overriding the automatic circuit by the maintenance crew and operations staff. The override would be done under careful supervision. One example of the use of the manual override could be loss of the power to the container cask hoist during container placement. If the hoist was mechanically sound, the manual drive would likely be used to complete the lowering of the container into the emplacement borehole. The shaft hoists are a special case and have multiple breaking safety systems (Section 4.3.1.1).

The electrical power distribution system includes on-site diesel generators that will activate if the grid power is lost, and will supply power to services, equipment and systems that are important to environmental, occupational and radiological safety or that are critical to the security of assets such as buildings, equipment and information. The standby power will provide sufficient ventilation to maintain the radiological zoning and contamination control safe conditions and breathing air quality standards. It will also provide the power to maintain the safety, security and computer systems so that data are not lost (Section 4.2.3.1).

The ventilation systems are designed so that noncritical equipment failures are announced and so that actions can be taken to avoid significant safety and health consequences from a failure. For example, if the exhaust fans in the underground vehicle maintenance area fail, the conditions would be announced in the systems control room and locally so that any operating motors could be shut down to maintain air quality. Local instruments are provided to monitor air quality, and workers would move to a properly ventilated area if the air quality was a concern. Critical equipment functions are protected through installation of multiple units so that one unit could be out of service without affecting the system performance.

Diesel fuel delivery to the underground vehicle refueling area is through a pipeline from surface storage tanks. The transfer of the daily fuel requirements from the surface to the underground fuel storage is done in one delivery, and otherwise the pipe is empty. There is a single storage tank in the fueling area holding one day's supply of 14 000 L. The fueling area is located near the waste shaft and ventilation air is exhausted through the waste shaft, which is normally unoccupied. The area is equipped with heat-activated ventilation doors to isolate it in the event of a fire and heat-activated water sprinklers to cool down a fire. There are catch pits both inside the fuel storage area and outside it to catch fuel leakage and fuel-water mixes from fire suppression. Vehicles refuel at the fuel storage area or are refueled in the work areas by a lubrication and diesel fuel truck.

Explosives and detonators are transported underground separately in batches that meet one day's requirements, and are stored in approved storage magazines located away from critical shaft installations. The transfers are done on the third shift when no underground work is scheduled. Two sets of magazines are provided so that the explosives and detonators are stored on the excavation panel side of the vault.

The vault ventilation systems are designed to assist in providing safe underground conditions in the event of an underground fire. The fans on the system are reversible so that the direction of underground airflows can be changed as required for underground fire suppression and personnel rescue operations. Each major work area is provided with a fully equipped refuge station where workers can seal themselves in and await for a mine rescue team to prepare a safe means of egress.

The excavation design, ground control and routine maintenance activities will result in structurally safe underground excavations. In the unlikely event of a major fall of rock from the excavation crown or walls, there might be service and equipment damage and injury to personnel. The underground systems are designed to provide the opportunity to isolate the damaged sections and maintain the rest of the system serviceable. The mine rescue teams will be trained to respond to rock falls by removing injured personnel and by returning the area to a sufficiently safe state that repair operations can proceed.

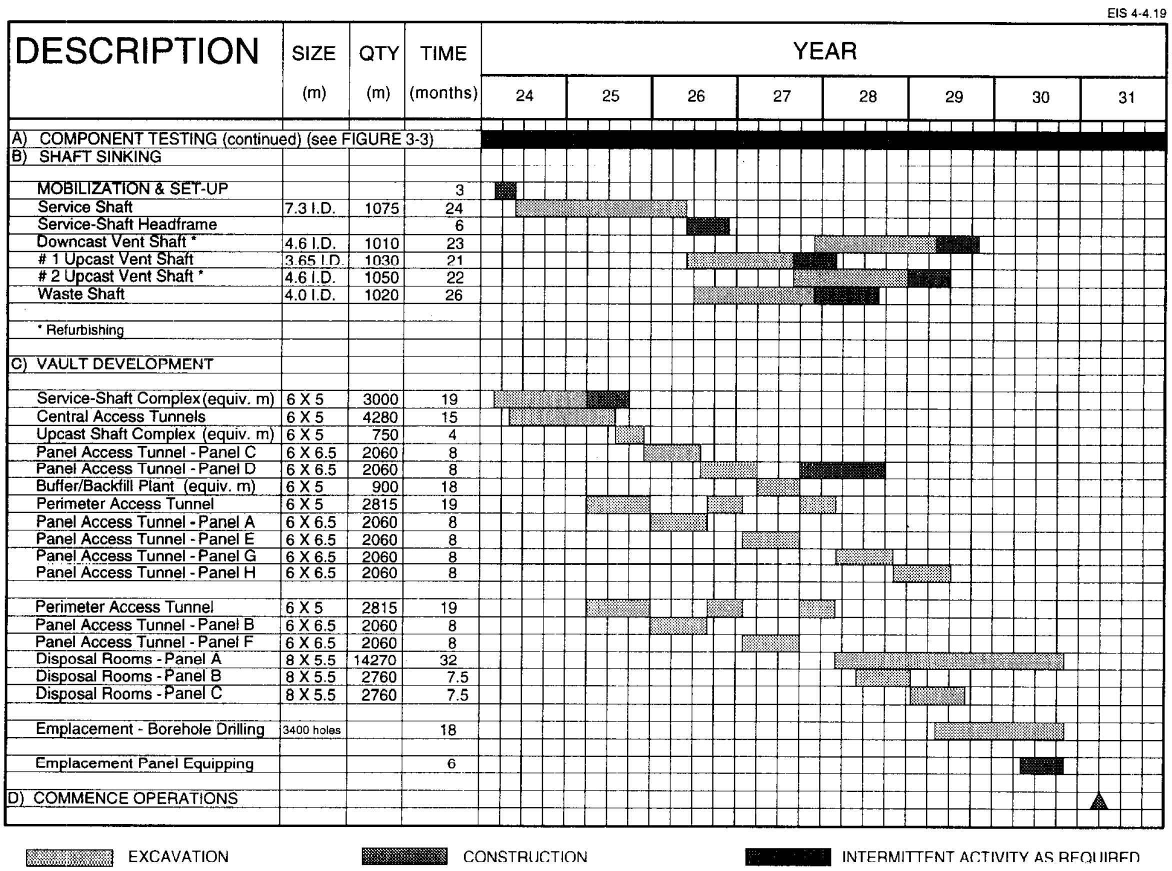
The equipment, installation and procedures are available for container retrieval from an emplacement borehole. The reasons for retrieval may include damage to the container on emplacement, emplacement of a container in a borehole or by a method that is later classified as unsuitable, a requirement to reverify the nuclear material or container serial number, and recovery of containers used in component test areas for examination.

Communications systems are provided that allow communication of abnormal conditions by telephone, visual light signal, alarm bell or smell (stench gas in the ventilation system). Personnel are trained to respond to these signals in a way that enhances their safety.

4.3.9 Construction Stage Schedule for Vault Development

The excavation of the disposal vault in the Used-Fuel Disposal Centre conceptual design spans three stages of the project schedule. The shaft and tunnel excavation associated with underground exploration and characterization takes place during the last 6 a of the siting stage. Additional tunnelling and room excavation will occur during the 7 a of the construction stage. The excavation and servicing of the disposal rooms will be completed during the first 35 a of the operation stage.

The construction stage allows 7 a to complete the construction of the underground accesses and services, the first panel of disposal rooms, including the first set of emplacement boreholes, and 10 to 12 rooms in each of two other panels (Figure 4-19). The exploration shafts and tunnels constructed during the siting stage provide access underground and systems for personnel and material handling. This reduces the construction time of 10 a estimated by AECL CANDU et al. (1992) (where there is no preceding underground evaluation in the siting stage) to 7 a. This 3-a reduction is possible in this conceptual design because vault-level construction activities proceed concurrently with development and refurbishing of shafts using the exploration shafts and tunnels already completed.



EIS 4-4.19

DESCRIPTION	SIZE (m)	QTY (m)	TIME (months)
A) COMPONENT TESTING (continued) (see FIGURE 3-3)			
B) SHAFT SINKING			
MOBILIZATION & SET-UP			3
Service Shaft	7.3 I.D.	1075	24
Service-Shaft Headframe			6
Downcast Vent Shaft *	4.6 I.D.	1010	23
# 1 Upcast Vent Shaft	3.65 I.D.	1030	21
# 2 Upcast Vent Shaft *	4.6 I.D.	1050	22
Waste Shaft	4.0 I.D.	1020	26
* Refurbishing			
C) VAULT DEVELOPMENT			
Service-Shaft Complex (equiv. m)	6 X 5	3000	19
Central Access Tunnels	6 X 5	4280	15
Upcast Shaft Complex (equiv. m)	6 X 5	750	4
Panel Access Tunnel - Panel C	6 X 6.5	2060	8
Panel Access Tunnel - Panel D	6 X 6.5	2060	8
Buffer/Backfill Plant (equiv. m)	6 X 5	900	18
Perimeter Access Tunnel	6 X 5	2815	19
Panel Access Tunnel - Panel A	6 X 6.5	2060	8
Panel Access Tunnel - Panel E	6 X 6.5	2060	8
Panel Access Tunnel - Panel G	6 X 6.5	2060	8
Panel Access Tunnel - Panel H	6 X 6.5	2060	8
Perimeter Access Tunnel	6 X 5	2815	19
Panel Access Tunnel - Panel B	6 X 6.5	2060	8
Panel Access Tunnel - Panel F	6 X 6.5	2060	8
Disposal Rooms - Panel A	8 X 5.5	14270	32
Disposal Rooms - Panel B	8 X 5.5	2760	7.5
Disposal Rooms - Panel C	8 X 5.5	2760	7.5
Emplacement - Borehole Drilling	3400 holes		18
Emplacement Panel Equipping			6
D) COMMENCE OPERATIONS			

FIGURE 4-19: Disposal-Vault Construction Schedule

4.4 USED-FUEL DISPOSAL CENTRE PACKAGING PLANT CONSTRUCTION

A facility is required in the Used-Fuel Disposal Centre in which cask transporters carrying transportation casks are received, bundles are placed and sealed into corrosion-resistant disposal containers, and the containers are inspected and transferred for disposal. The Used-Fuel Packaging Plant is designed to perform these and other functions relevant to preparing used fuel for disposal.

This section describes the facilities and equipment necessary to perform these functions. Road and rail transporters carrying transportation casks based on Ontario Hydro design concepts (Figures 3-6 and 3-7 respectively) are received in these facilities (Figure 4-20). The casks are removed from the transporter and are placed for temporary storage in a full-cask laydown area. Fuel within these casks is contained within Ontario Hydro storage/shipping modules, each holding 96 used-fuel bundles. Damaged transportation casks may be safely opened and emptied in the damaged-transportation-cask hot cell.

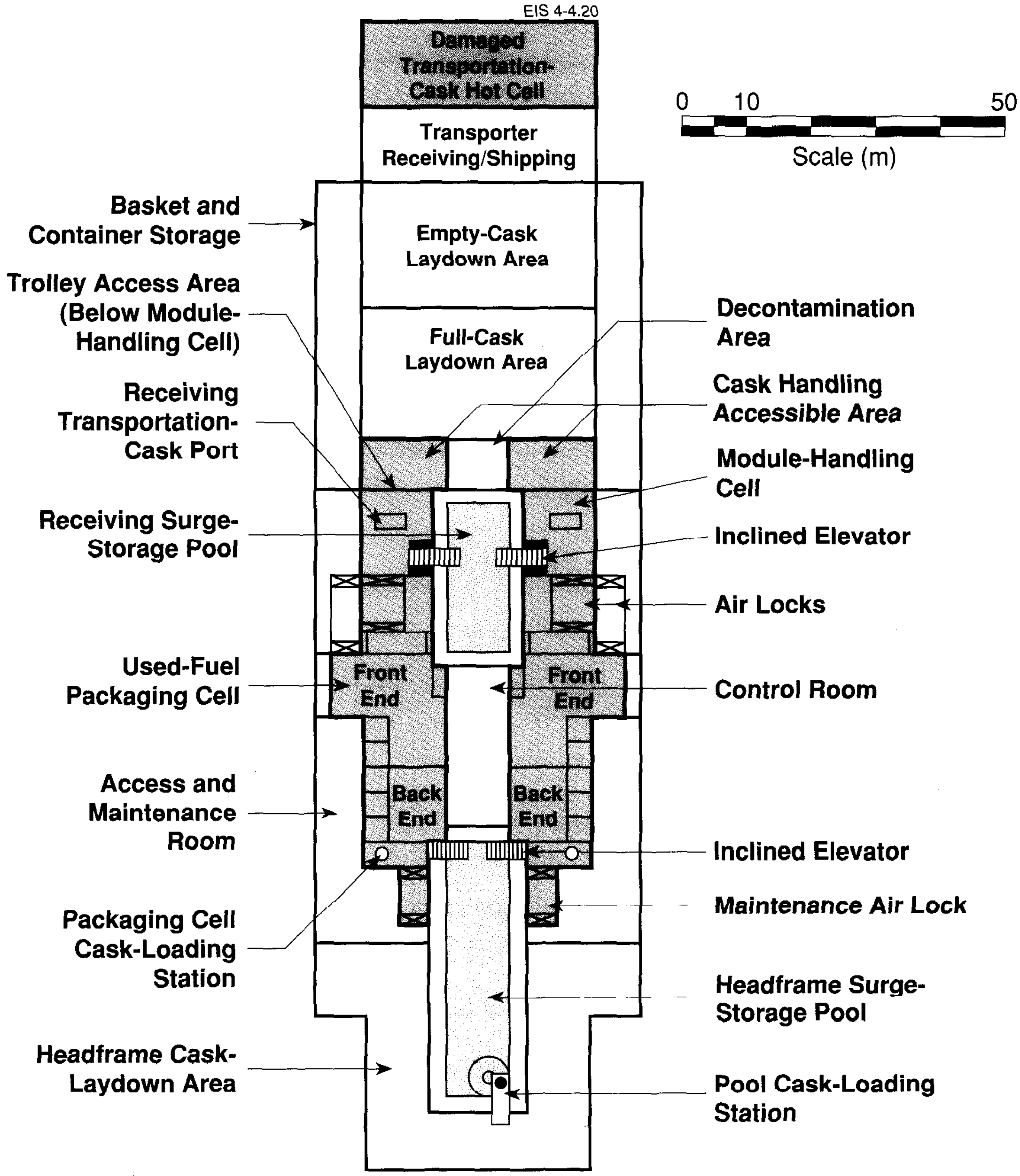


FIGURE 4-20: Simplified Plan of the Used-Fuel Packaging Plant (after AECL CANDU et al. 1992). This figure shows two independent, identically equipped fuel-packaging lines separated by the shared surge-storage pools and control room.

The processing lines in which the casks are unloaded and the fuel bundles are packaged are designed as two parallel and independent packaging lines sharing common shielded storage and control areas. The common storage areas, two water-filled pools, are provided to smooth irregularities in the packaging and disposal operations that would be caused by disruptions in the transportation system, the used-fuel packaging process or the operation of the disposal vault. They are normally filled to half capacity. The receiving surge-storage pool is provided at the receiving end to store full storage/shipping modules unloaded from transportation casks in either packaging line that are not currently required to supply used fuel to the packaging operation. A headframe surge-storage pool is provided at the waste-shaft headframe end of the packaging process to store filled, sealed and inspected disposal containers that are not currently required in the disposal vault operation. A waste-shaft headframe cask laydown area is also provided as a place to temporarily store loaded disposal container casks prior to placing them in the waste shaft cage for transfer to the vault.

In the conceptual design, it has been assumed that the disposal containers and baskets are fabricated at the Used-Fuel Disposal Centre in a separate building (Section 4.5).

A full transportation cask is moved into one of the two used-fuel packaging lines, the lid fasteners are removed, and the cask is raised and sealed to the receiving port of the storage/shipping module-handling cell (Figure 4-21). Equipment in this cell is provided to remove the receiving-port cover and the cask lid, and to lift the storage/shipping modules individually from the cask into the cell. Once in the cell, the modules are either dried and transferred to the used-fuel packaging cell or they are transferred to the receiving surge-storage pool for temporary storage. Storage/shipping modules are retrieved from the surge-storage pool to provide used fuel when there are no full transportation casks to provide used-fuel bundles for the packaging line.

When a transportation cask has been emptied of storage/shipping modules containing used-fuel bundles, it is filled with empty storage/shipping modules and the cask lid is reinstalled. The module-handling cell port lid is reinstalled and the cask is moved to the decontamination area. Following decontamination, the transportation cask lid fasteners are reinstalled and the cask is moved to the empty-cask laydown area (Figure 4-20) for return to a nuclear generating station on a transporter (e.g., truck trailer or rail car).

A disposal-container basket-loading carousel is provided at the beginning of the used-fuel packaging cell (Figure 4-22) in each packaging line to move the used-fuel bundles from the storage/shipping module to the cylindrical basket that will be placed into the corrosion-resistant disposal container (Figure 4-23). While each fuel bundle is in the carousel, there is an opportunity to visually inspect and examine it for damage, for inventory control and for safeguards purposes. The carousel and hydraulic rams provide a means of moving used-fuel bundles from the storage/shipping module configuration to the basket configuration. They also provide a means of moving damaged bundles, or bundles requiring further examination, to a special handling area.

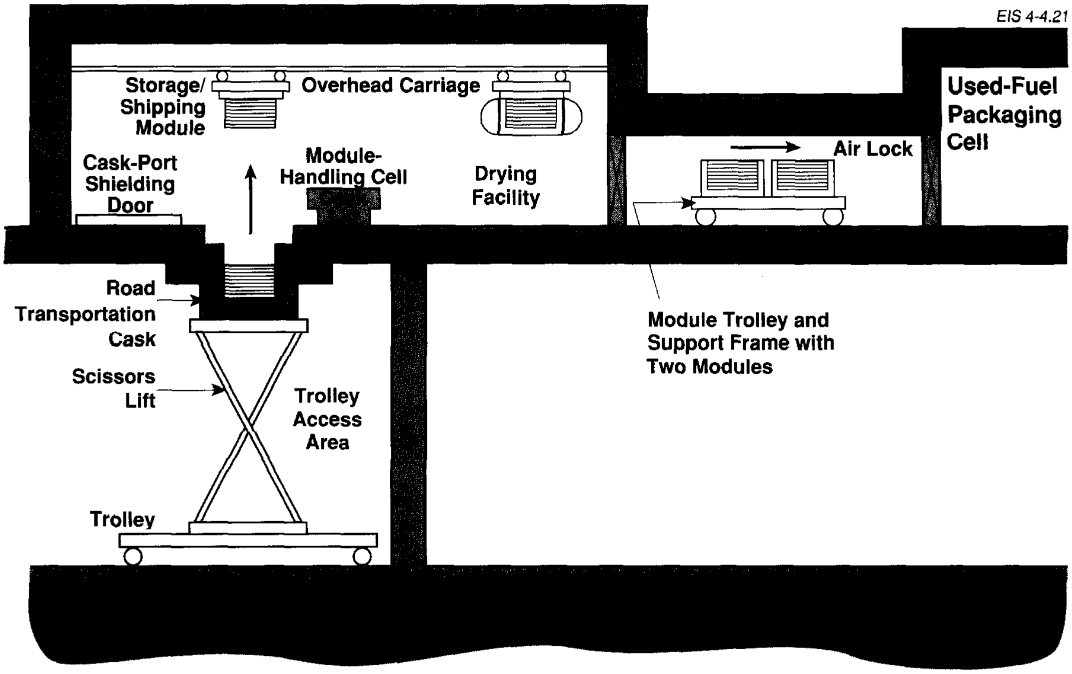


FIGURE 4-21: Module Handling Cell (after AECL CANDU et al. 1992)

When the disposal-container basket has been filled, it is moved to a vertical orientation, and is lifted and placed into an empty disposal container shell. All remaining space in the disposal container is filled with a particulate material (Figure 4-24), and the container lid is installed and sealed in place with a diffusion bond (Figure 4-25). The sealed container is moved to the ultrasonic inspection station where the diffusion bond is inspected for defects. If a container passes this inspection, it is given a helium leak test. If the leak test is successful, the container is decontaminated and either placed in temporary storage in the headframe surge-storage pool or loaded into a disposal container cask (Figure 4-26). The loaded disposal container cask is placed in the waste-shaft headframe cask laydown area (Figure 4-22) for transfer underground.

The Used-Fuel Packaging Plant (Figure 4-20) also provides access areas and a basket and container-shell storage room. The two-storey building is a reinforced concrete structure. As there are currently no precedents for constructing used-fuel packaging facilities, the packaging plant is assumed to be designed according to the Canadian design practice for concrete containment structures of CANDU nuclear generating stations (CSA 1982), which also accommodates seismic loading (CSA 1980). These construction standards are not being recommended as necessary – they are used only as a basis to estimate costs for this conceptual design.

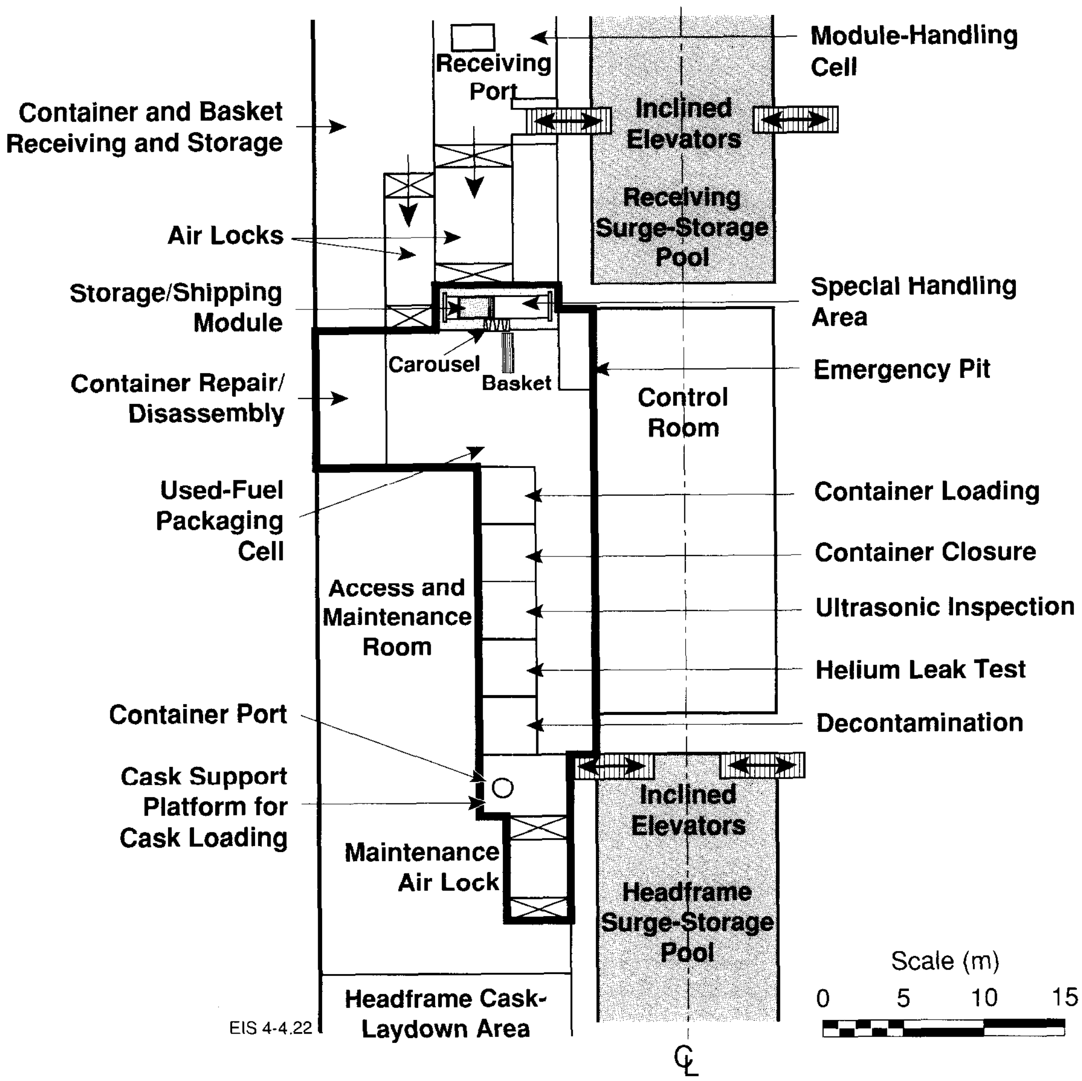


FIGURE 4-22: Arrangement of Used-Fuel Packaging Cell (after AECL CANDU et al. 1992)

This section describes the facilities, equipment and services to perform these operations. The installations for handling damage fuel bundles and containers with defects are also discussed. The operation of these facilities is discussed in Section 5.2.

4.4.1 Used-Fuel Transporter and Transportation Cask Receiving and Shipping Area

The used-fuel transporter and transportation cask receiving and shipping area (Figure 4-20) is equipped with four transporter receiving/shipping positions with suitable loading docks for the incoming and outgoing road

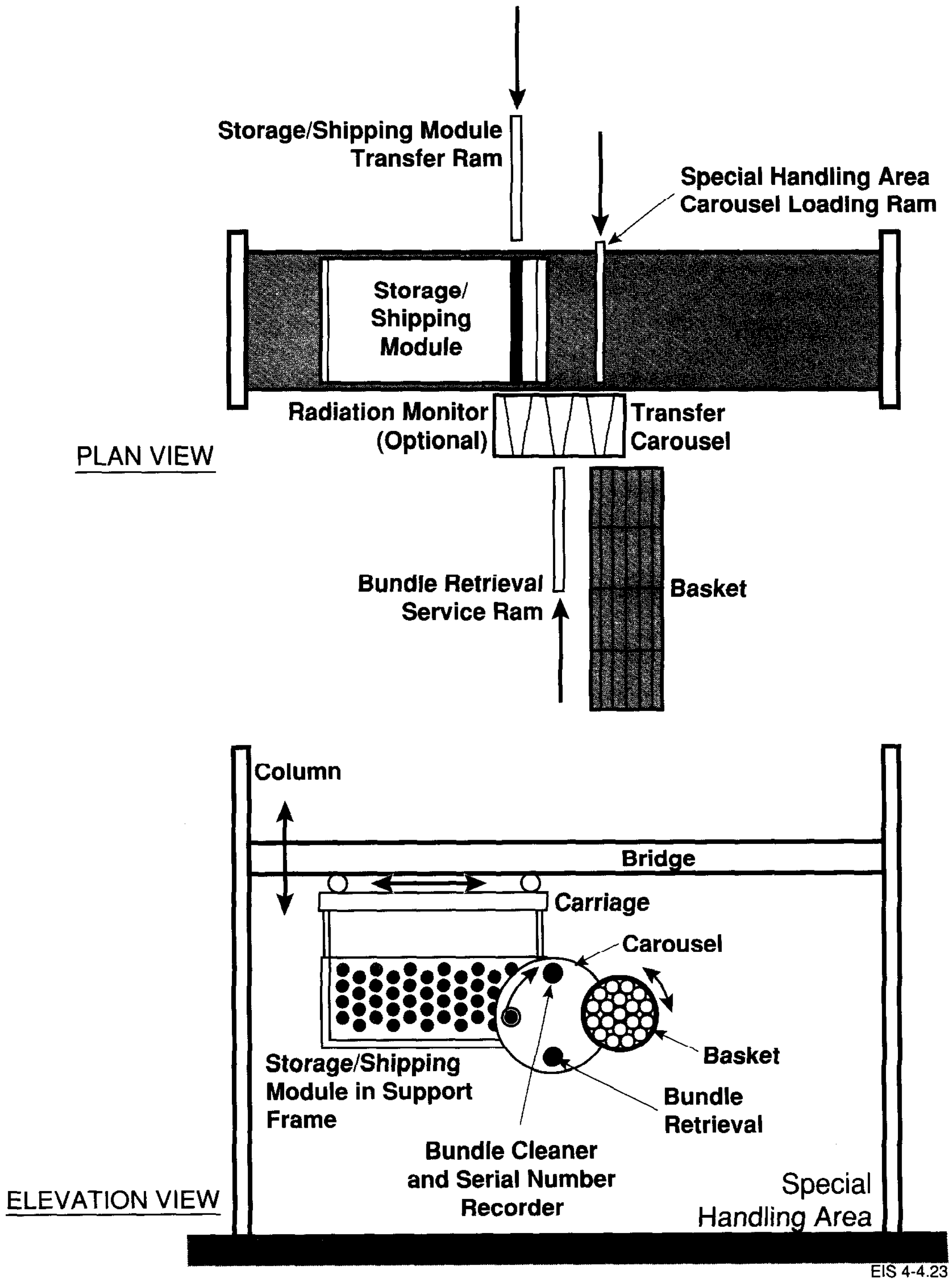


FIGURE 4-23: Bridge/Carriage and Used-Fuel Transfer Assemblies (after AECL CANDU et al. 1992)

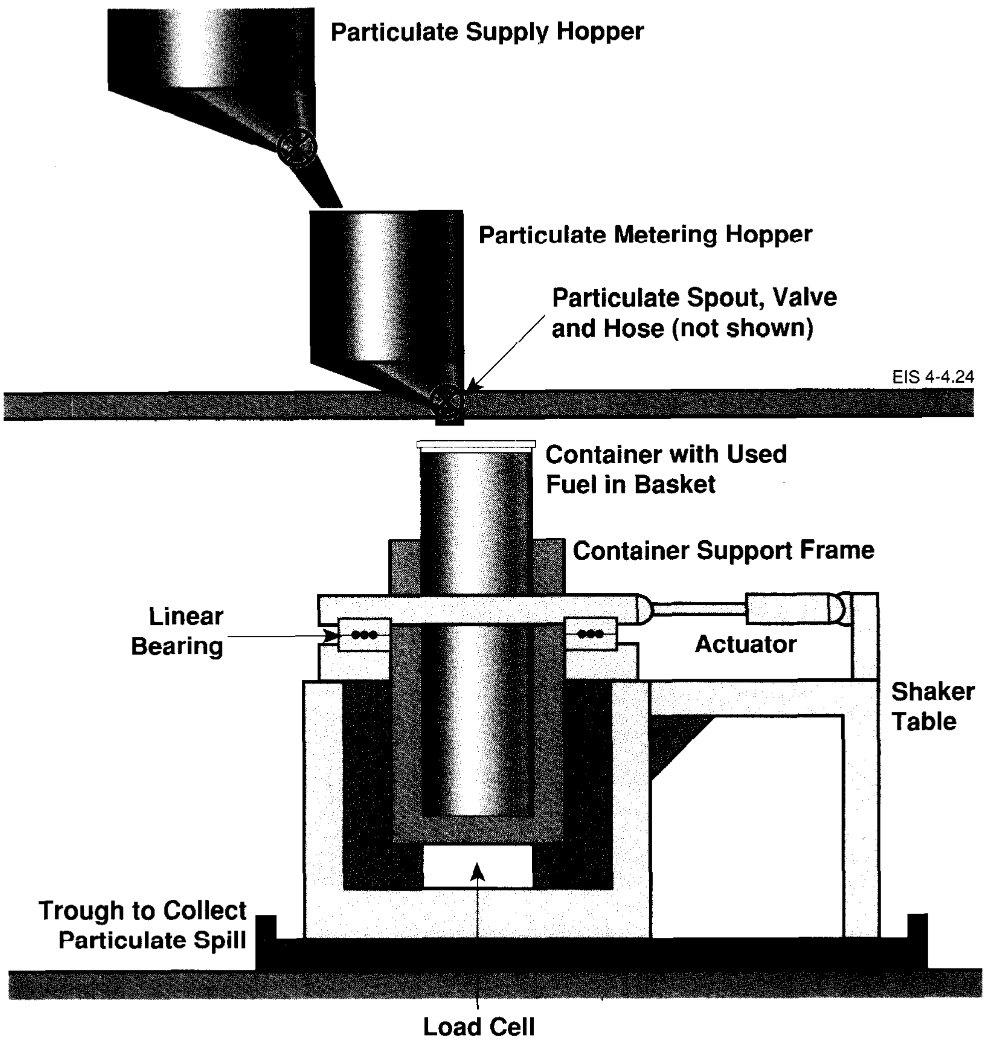


FIGURE 4-24: Container Loading Station (after AECL CANDU et al. 1992)

and rail transporters that carry the used-fuel transportation casks. The road (Figure 3-6) and rail (Figure 3-7) transportation casks for shipping used fuel within storage/shipping modules from the nuclear generating stations to the packaging plant have been described by Ontario Hydro (Carter 1985, Shetler 1986). The empty-cask laydown area, the full-cask laydown area, the cask decontamination area and the damaged-transportation cask hot cell are adjacent to the receiving/shipping positions. The empty-cask laydown area is used to store the empty and decontaminated casks before they are loaded onto a transporter when a full cask has been removed.

It has space to store empty casks equivalent to a 10-d supply of used fuel, with the number of casks depending on the mix of road and rail shipments.

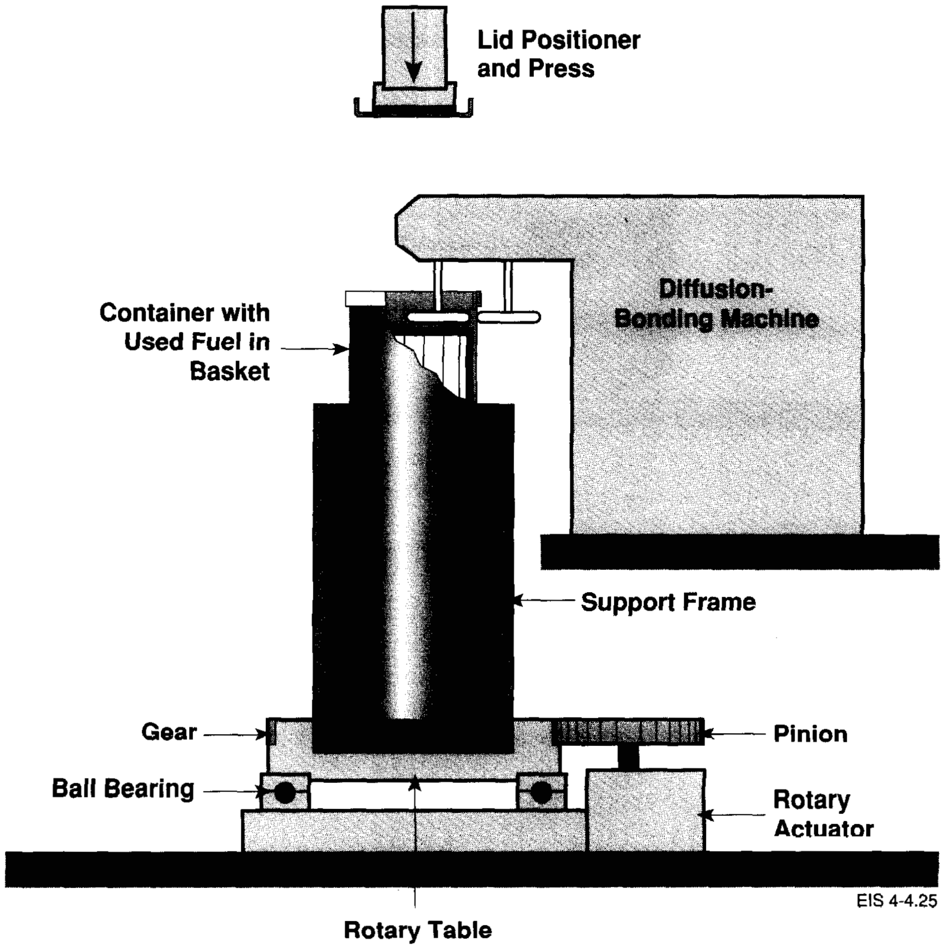


FIGURE 4-25: Container Closure Station (after AECL CANDU et al. 1992)

For example, 19 rail transportation casks, 57 road transportation casks, or some mix of the two types could be stored in the empty-cask laydown area.

The full-cask laydown area also provides space to store loaded shipping casks equivalent to a 10-d supply of used fuel. This area will have shielding walls to protect staff from the radiation fields emitted by the loaded transportation casks while they are in storage.

The cask decontamination area is located adjacent to the cask laydown areas. Water jets are provided to clean a loaded cask prior to unloading and to decontaminate casks after unloading. Air blowers are provided to dry the casks. An overhead bridge and trolley crane with a capacity of 100 Mg is provided to transfer loaded and empty casks within this area, and to and from the cask trolley.

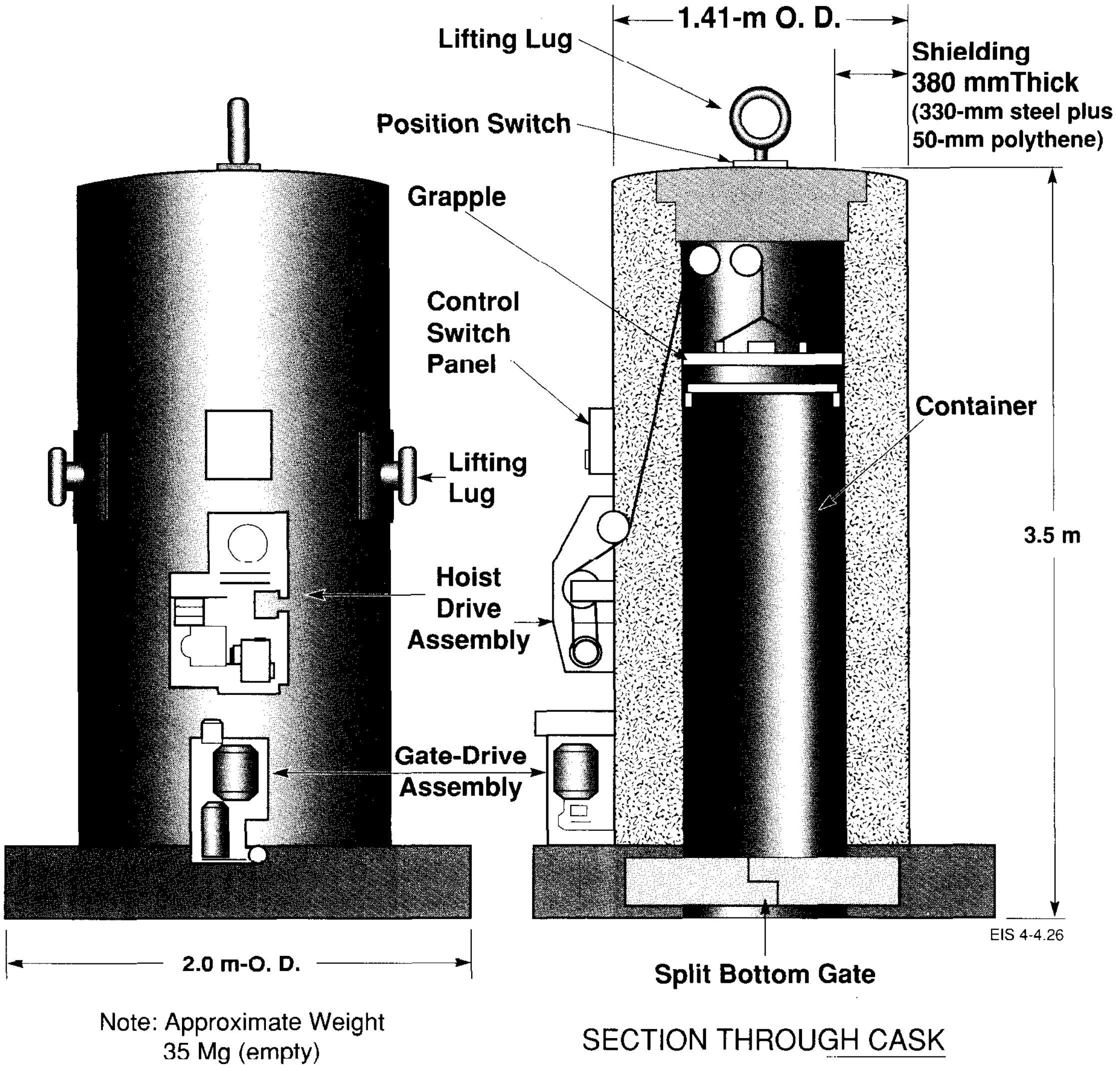


FIGURE 4-26: Disposal Container Cask (after AECL CANDU et al. 1992)

A cask trolley equipped with a scissors-lift is provided for each module-handling cell (Figure 4-21). These trollies are used to move the full casks under and up to the cask port of each module-handling cell, and to withdraw the empty casks for return to the empty-cask laydown area.

A hot cell is provided for handling a damaged transportation cask (Figure 4-20) (an operating description of the hot cell is provided in Section 5.2.1). The transportation cask would be considered damaged if it has actually been physically damaged, as might be the case in a transportation accident or if the safeguards seals have been damaged and the nuclear material content required reverification. Remote manipulators, tools, safeguards, decontamination and ancillary equipment are provided in this hot cell to inspect, open and remove the contents of a damaged cask, and to prepare the damaged contents appropriately for processing in the packaging plant. Intact fuel bundles are transferred to the storage/shipping modules and the components of damaged fuel bundles are transferred to damaged-fuel cans. Each of these is loaded into special handling casks and transferred to the module-handling cell.

4.4.2 Module-Handling Cell

The Used-Fuel Packaging Plant has a module-handling cell (Figures 4-21 and 4-27) for each of the two packaging lines shown in Figure 4-20. Each module-handling cell consists of a shielded hot cell facility designed to remove used-fuel storage/shipping modules remotely from the transportation casks. The cell has 1.26-m-thick concrete boundaries with viewing windows that are 1.1-m-thick oil-filled glass units. This construction limits the maximum radiation field to 2.5 μGy/h at the outer boundary of a cell containing full modules.

A cask port is provided in the floor of each module-handling cell (Figure 4-21). The port is equipped with a shielding lid and is notched to allow either a road or rail transportation cask to nest into the bottom of the port to minimize radiation fields in the cask trolley-access area below.

A lid-handling tool, supported on a carriage that runs on overhead rails, is provided to remove the lid of the cask within the module-handling cell.

A second carriage supported by the same overhead rails is equipped with a module-handling tool. The design of this tool is based on an existing tool used in the storage bay at the Pickering Nuclear Generating Station, but modified to operate in a dry environment. There are two module routing options. The carriage controls allow the module to be moved either through a forced-air drier to a module trolley or to the inclined elevator that goes into the receiving surge-storage pool. The storage/shipping module is transferred on the module trolley directly to a used-fuel packaging cell. The module is transferred on the inclined elevator to the receiving surge-storage pool for storage. The module is returned from the pool through a drier at a later time when an alternate source of used fuel is required for the packaging cell.

The module drier is an enclosure fitted with inlet and outlet air ducts that seal against the open ends of a module. The drier inlet duct has a series of warm-air manifolds with air outlets positioned opposite each fuel bundle location in the storage/shipping module. The outlet air duct is equipped with an air filtration system to collect any contamination that is loosened from the bundles during drying (Figure 4-27).

A module trolley (shown in Figure 4-27) has a capacity of two modules and is provided for moving dried modules. Each module is located in a separate support frame on the trolley. Floor-mounted rails are provided in the module-transfer tunnel and in the air lock to the used-fuel packaging cell for trolley movements. Empty modules returning from the used-fuel packaging cell are handled in the same manner on a separate but identical trolley and

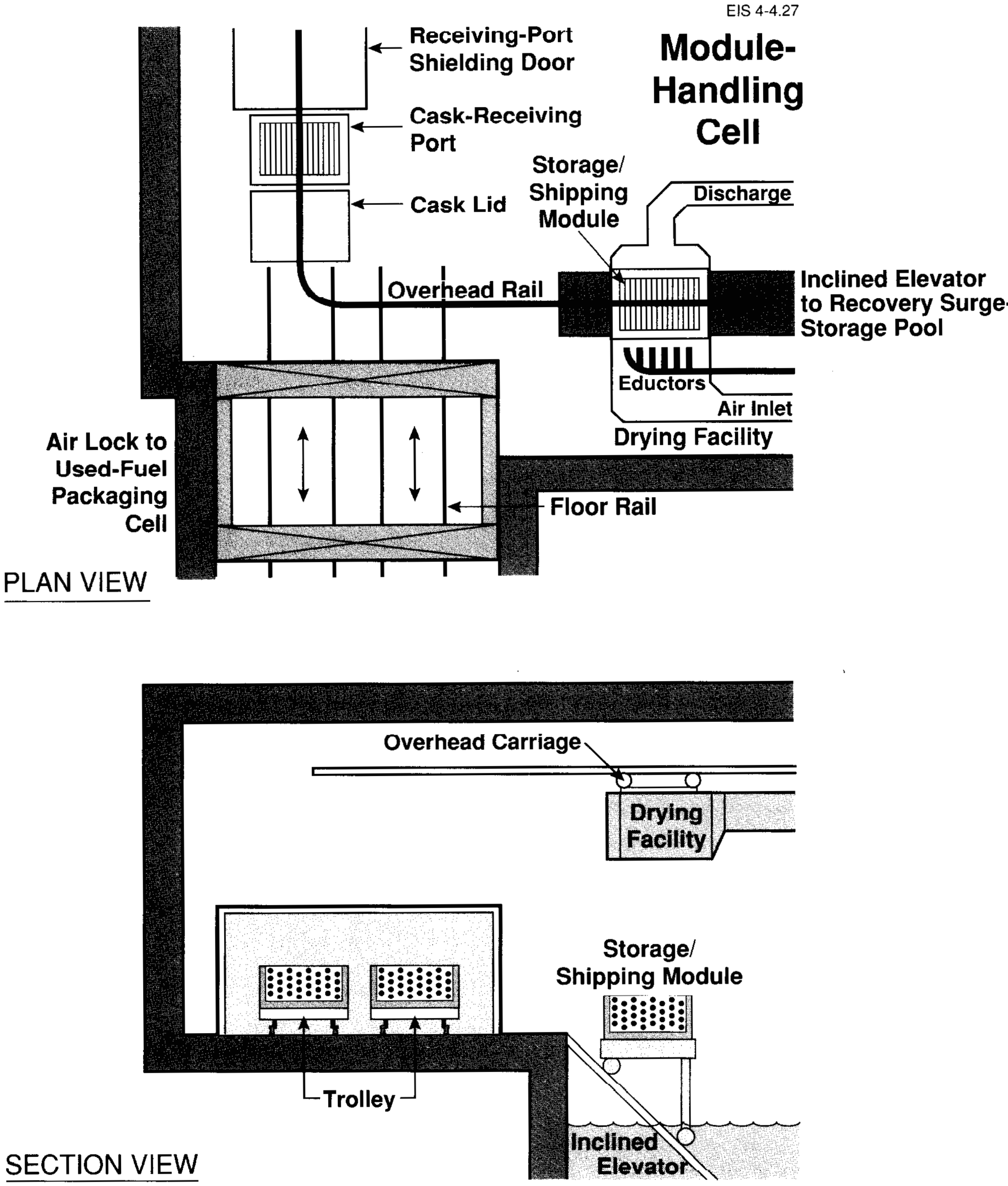


FIGURE 4-27: Used-Fuel Drying Facility (after AECL CANDU et al. 1992)

rail system. The air lock has two sets of rails to allow simultaneous operations.

4.4.3 Receiving Surge-Storage Pool

The receiving surge-storage pool is a stainless-steel-lined concrete structure used to temporarily store storage/shipping modules containing used-fuel bundles. These fuel bundles are retrieved to maintain process continuity if operations preceding the packaging operations are stopped. The pool is at least 10 m wide and 25 m long, and is filled with demineralized water to a depth of 7.37 m. Its construction is similar to that of storage pools at nuclear generating stations. A single pool provides surge storage for both fuel packaging lines.

The receiving pool has a capacity for 650 storage/shipping modules, corresponding to a three-month packaging plant throughput. The normal operating load of the pool is half this capacity, or 325 modules. The decay heat from the used fuel is about 260 kW at full capacity.

A cooling and purification circuit is provided to remove the radiogenic heat from the used fuel, to control the water chemistry and to remove radioactive contamination released from any defective fuel bundles. The pool water is pumped continuously through a process-water-cooled heat-exchanger circuit, a filter and an ion-exchange column. Provision is made to safely remove and handle the filters and ion-exchange resin as radioactive solid waste when required.

Two inclined elevators, one from each module-handling cell, are provided to move the storage/shipping modules into and out of the pool (Figure 4-28). The modules are handled with a tool suspended from a manbridge spanning the pool. The design of the module-handling tool in the pool (Figure 4-29) is based on that of a unit presently in use at the Pickering Nuclear Generating Station.

Modules are supported in stacking frames (Figure 4-30). Three stacking frames are arranged across the pool and ten along the pool length, for a total of 30 stacking frames. Each stacking frame consists of a stainless-steel structure of angle, pipe and expanded metal mesh. Each stacking frame supports four columns of six modules, for a total of 24 modules containing 2304 fuel bundles.

The structure is supported on, and free to tilt within limits relative to, a base that supports both the frame and the 24 modules. The base is held loosely to the frame by pins that allow the base to flex in accordance with floor variations of up to 9.6 mm without causing distortion of the frame structure. This also provides shear strength against seismic conditions that may tend to shift the upper frame relative to the base. The frame also provides smooth passage to guide each module into position via the guide blocks at the top of the frame and the vertical guide angles.

In structure and function, the module stacking frames are similar to those that are in service at the Pickering Nuclear Generating Station.

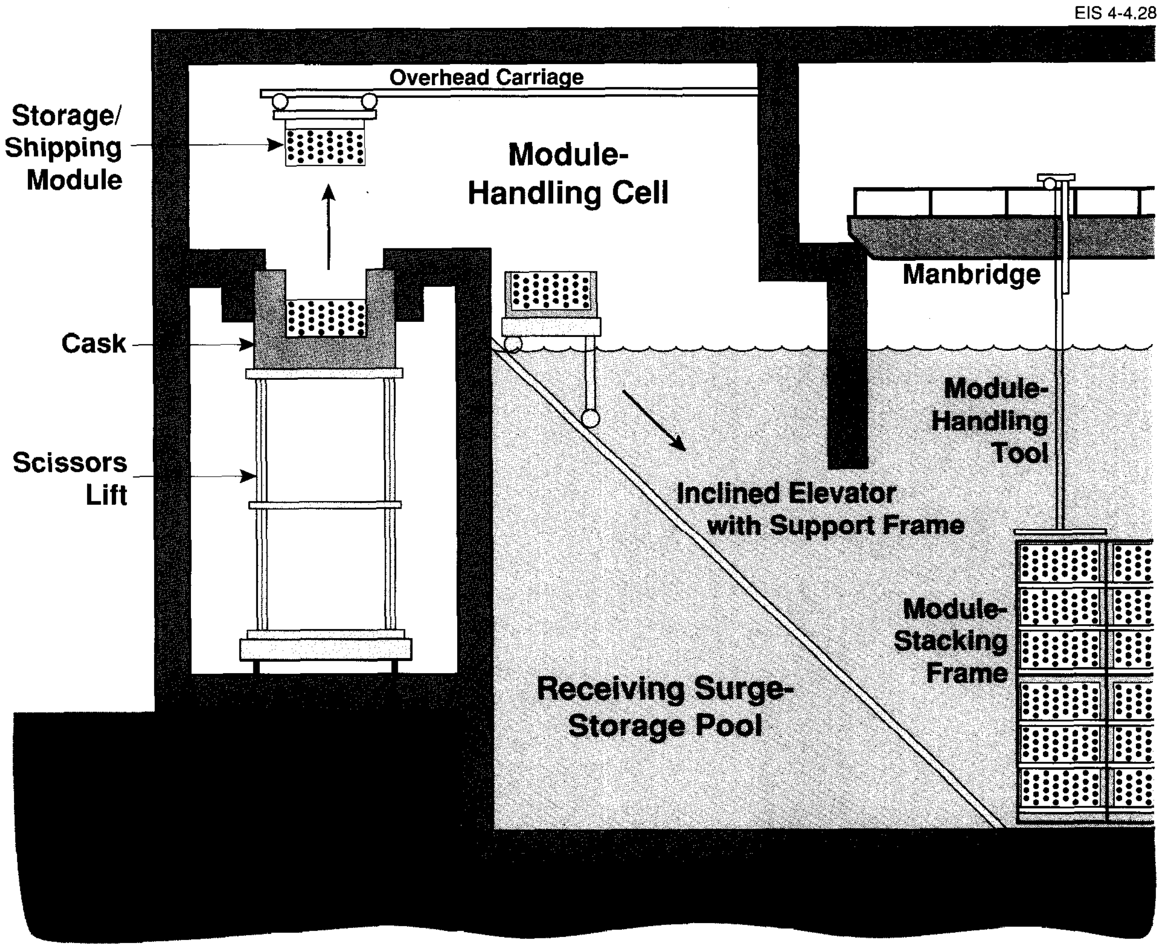


FIGURE 4-28: Receiving Surge-Storage Pool Module Handling (after AECL CANDU et al. 1992)

The required depth of water over the full array of modules in the stacking frames is 3.25 m, yielding a maximum radiation field of less than 0.1 μGy/h at the water surface. This water depth provides sufficient space to transfer a module 0.3 m above the module array while maintaining 2.3 m of water cover, limiting the maximum radiation field to 2.5 μGy/h at the water surface (Figure 4-31).

4.4.4 Used-Fuel Packaging Cell

A used-fuel packaging cell (Figures 4-20 and 4-22) is provided in each of the two process lines to transfer used-fuel bundles from the storage/shipping modules to the baskets for the disposal containers. It also includes the facilities needed to transfer the baskets into disposal containers, and

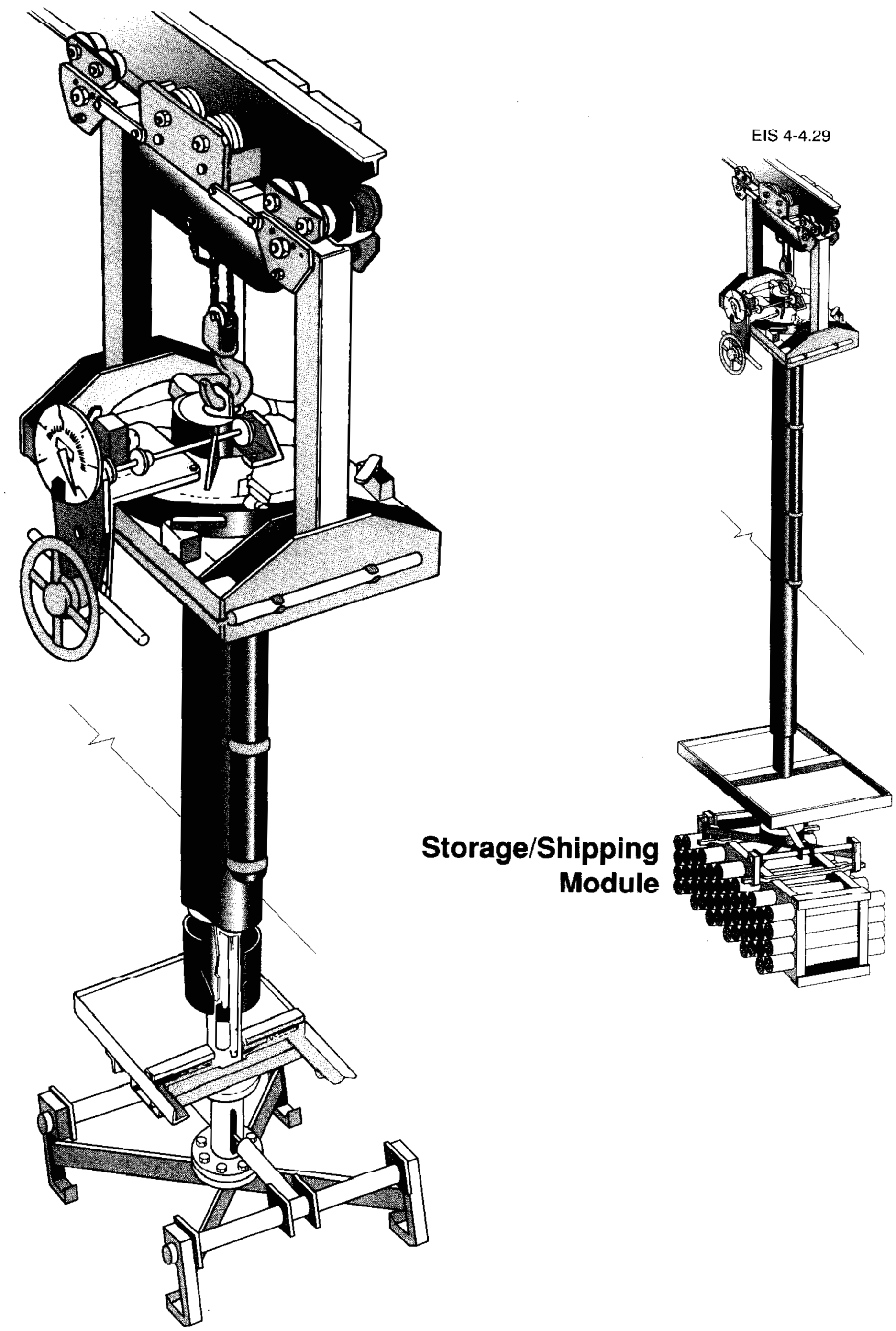


FIGURE 4-29: Module-Handling Tool Used in Receiving Surge-Storage Pool
(after AECL CANDU et al. 1992)

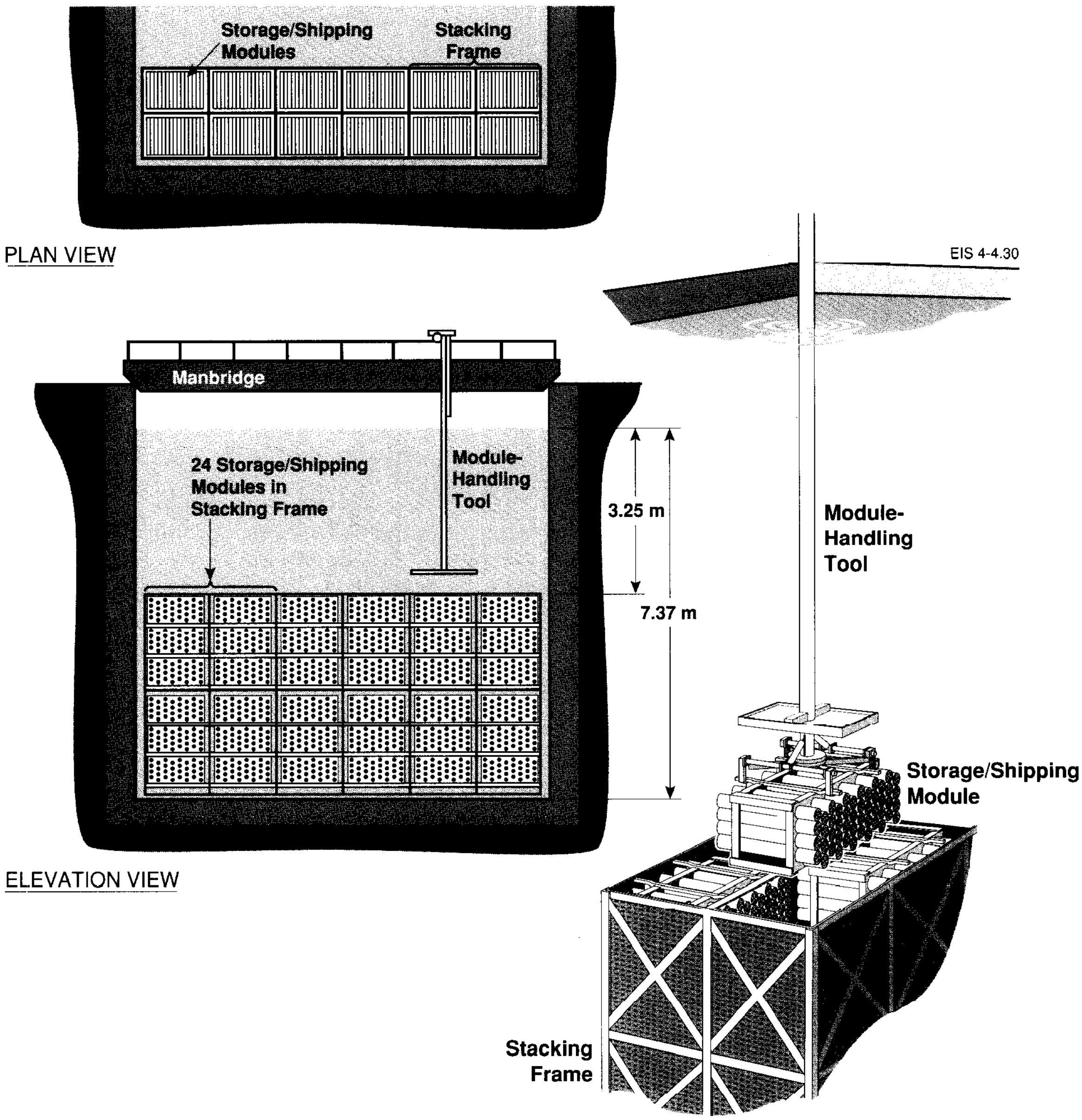


FIGURE 4-30: Module-Stacking Frame in Receiving Surge-Storage Pool (after AECL CANDU et al. 1992)

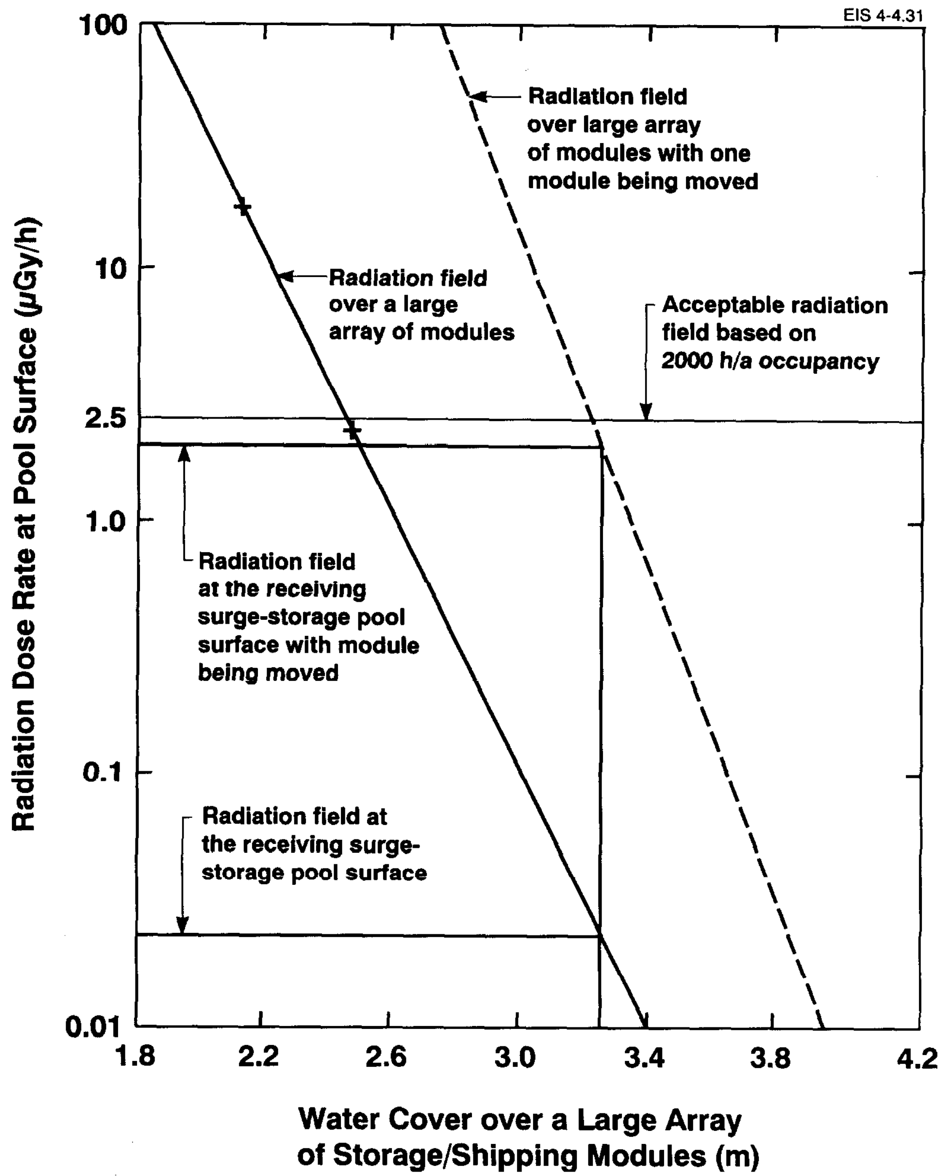


FIGURE 4-31: Radiation Dose Rate Above the Receiving Surge-Storage Pool (derived from AECL CANDU et al. 1992)

to seal, inspect, decontaminate and rework the containers. Each cell is a shielded enclosure provided with appropriately located viewing windows. The packaging cell boundaries are constructed from 1.26-m-thick concrete and the viewing windows are constructed from 0.47-m-thick shielding glass to limit the external contact radiation field to 2.5 μGy/h. Air locks with appropriate safety interlocks are provided to allow workers, equipment and material access into the cell, to ensure that any airborne contamination is confined within the cell, and to provide shielding when used fuel is present in the cell. Provisions similar to those used at nuclear generating stations to control access to areas with high-radiation fields are installed to ensure that worker access is not possible when used fuel is present in the cell.

Baskets and containers are handled within the cell by a travelling bridge crane. The crane is operator-controlled from outside the cell. Crane maintenance access is provided at one end of the cell, with shielding for workers provided by the cell structure.

The cell is provided with services, including electrical power, compressed air, water, helium, ventilation designed for dealing with high levels of radioactive contamination, and active drainage.

An emergency pit is provided to receive bundles, modules, baskets or containers in the event of an accident. The pit is normally dry, but it can be flooded with domestic water to immerse objects for shielding purposes.

Storage/shipping modules are moved into the cell through an air lock from the module-handling cell. Disposal containers and baskets are moved into the cell from the basket and container receiving areas. Access to and from the headframe surge-storage pool is provided by an inclined elevator. Hatches and ports with contamination control are provided for equipment maintenance.

All operations involving used-fuel transfer can be observed by a safeguards camera surveillance system if desired.

4.4.4.1 Module Handling

The end of the packaging cell nearest the module-handling cell is equipped with a column-supported bridge and carriage (Figure 4-23) for picking up a module from the transfer trolley and positioning it at the used-fuel transfer assembly. The carriage has a latch assembly capable of picking up one module by its frame. The vertical motion of the bridge and the horizontal motion of the carriage provide the accurate positioning of the module during fuel transfer. The bridge vertical motion is provided by electric-motor-driven ball screws mounted on the support columns. The key drive elements are located so that they are accessible from the outside of the cell for maintenance.

The carriage is propelled horizontally on the bridge. The carriage is provided with limited vertical motion capability to be used for fine positioning, whereas the column vertical motion drive is used for coarse positioning. The basic design is similar to the Pickering Nuclear Generating Station fuelling machine carriage.

4.4.4.2 Used-Fuel Transfer Assembly

The used-fuel transfer assembly comprises three main components: a tilt table with a basket-support saddle, a carousel, and transfer rams for fuel-bundle transfers from a shipping module to a container basket (Figures 4-23 and 4-32). The types of operations required to complete this transfer are similar to the remote handling or robotics operations in other areas of the nuclear industry. Since Canada is a leader in robotics technology (e.g., the Canadarm used on the U.S. space shuttles), the development of reliable equipment can be based on existing technologies.

The tilt table is equipped with a support saddle for the container basket. The saddle is made in two halves with a hinged joint so that it can be opened lengthwise to receive the basket (Figure 4-32). After the basket has been positioned horizontally in the cradle, the saddle clamps around the basket to retain it in position. The tilt table has horizontal and rotary motion capabilities for accurate positioning during the transfer operation. Horizontal motion is achieved with a rack and pinion drive to provide a positive drive similar to that installed on the module-handling cell carriage.

The carousel, a rotary device with four axial holes at a fixed radius from the centre of rotation, is used to receive fuel bundles from a storage/shipping module and to move the bundles into position for loading into a disposal container basket. Three transfer rams push fuel bundles into and out of the carousel holes at various stop locations in its rotation. One ram pushes a single used-fuel bundle from the module to the carousel. Two separate operations are required to empty a module tube because the module contains two used-fuel bundles in each tube. A second ram pushes a fuel bundle from the carousel to the basket. A third ram pushes a bundle from the carousel into a special handling area (Figure 4-23). The carousel rotates in 90° steps, with a pause for operations at each step. The equipment for these operations operates in the following sequence.

1. At the first position on the carousel, a ram is provided to transfer a fuel bundle from the storage/shipping module to a carousel hole. As noted above, two operations are required to empty a module tube.

2. At the second position, mechanical cleaning and optical viewing equipment could be installed to allow cleaning and reading of the bundle end plates to obtain the manufacturer and serial number, if desired for accounting purposes.

3. At the third position, a ram is provided to transfer a structurally sound and properly identified bundle into a basket pipe. A gamma-radiation monitor could be installed at this location to measure the magnitude and energy spectrum of the radiation field emitted by the bundle. This may be a safeguards requirement if continuity of safeguards on received material is broken, perhaps because of equipment failure or damage.

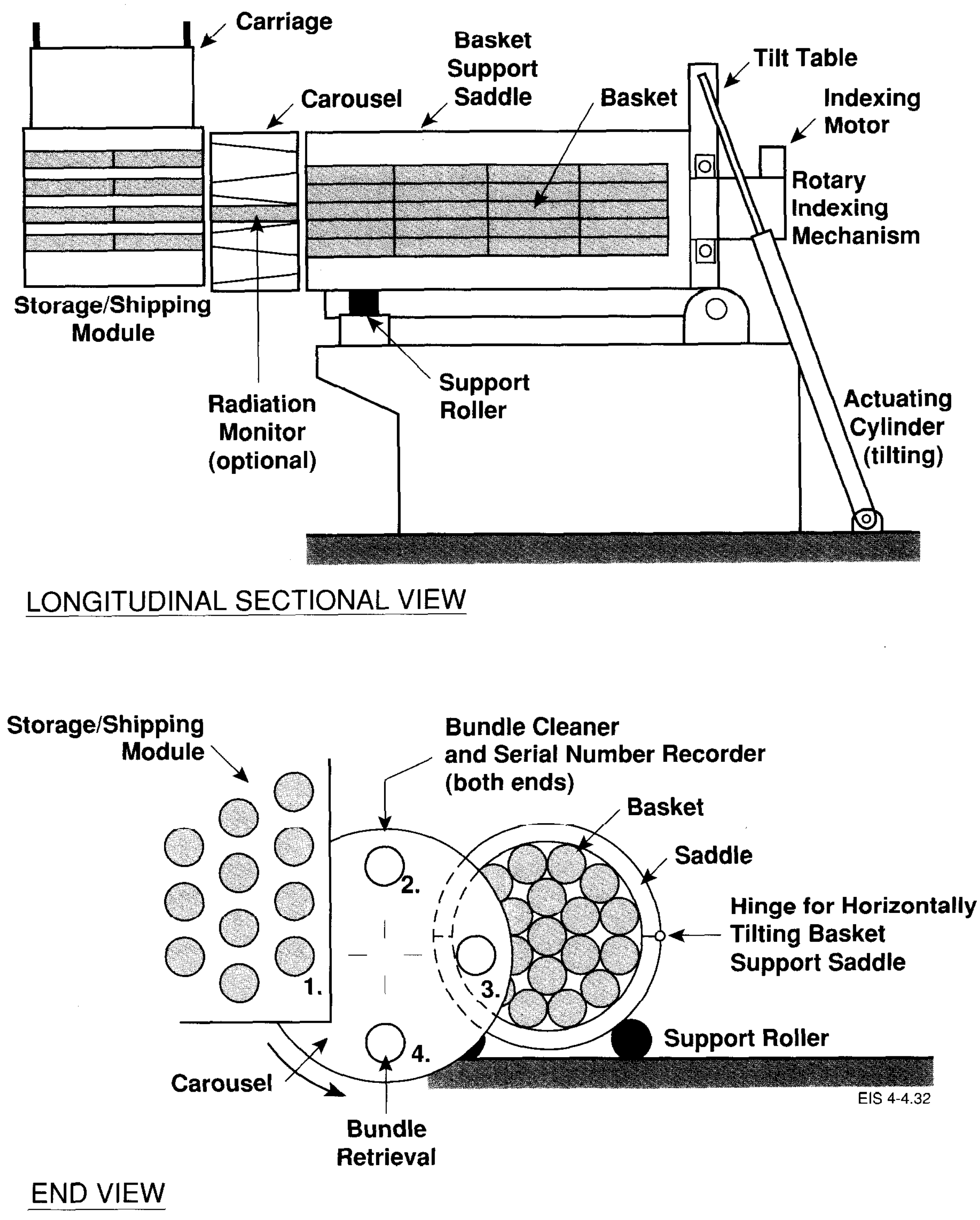


FIGURE 4-32: Used-Fuel Transfer Assembly (after AECL CANDU et al. 1992)

4. At the fourth position, a facility is provided to move a damaged fuel bundle or a fuel bundle that is specified for closer examination into a special handling area, or to insert a bundle from elsewhere back into the system for transfer into a basket (e.g., a bundle that has been previously removed for examination). A remote handling device with an appropriate tray and manipulator is used to manoeuvre the fuel bundle. A bundle rotator adjacent to a viewing window in the cell allows detailed examination and inspection of any bundle.

The tilt table pivots from the horizontal to the vertical position for removal of the full container basket from the support saddle. The tilt table is provided with adjustable mechanical stops for both the horizontal and vertical positions of the saddle. The packaging-cell bridge crane has a lifting device compatible with the lifting fixture on the basket's central structural pipe. This is connected to the vertical basket for transfer to the container loading station.

The rotary indexing motion for the carousel and basket support saddle is achieved using commercially available indexing mechanisms, as are generally used on CANDU fuelling machines for precise magazine indexing. Sensors are provided to ensure that the positions are lined up properly prior to each transfer operation.

The rams are operated by an electrically driven ball-screw drive. This choice is based on ease of positional control and monitoring. Ram forces are limited to prevent damage to the fuel bundles. A mechanism is provided to sense the position of the fuel bundle as it is pushed by the ram from the module into the carousel. When the fuel bundle has almost completely entered one of the axial holes in the carousel, the mechanism stops the advance of the trailing bundle and pushes the first bundle completely into the carousel, thus separating the two bundles before the carousel rotates.

The axial holes for fuel bundles in the carousel are tapered, with the larger opening adjacent to the module. This permits a larger tolerance on the positional error between the module and carousel fuel-bundle positions during transfer. The fuel-transfer assembly can handle damaged fuel bundles safely because the confinement of the used fuel in the axial holes in the carousel and the large ram-head diameter will ensure that the complete bundle is transferred into the basket. The tapered contour of the carousel holes and the close proximity of the module carousel and basket also help to ensure the complete transfer of the bundle. More severely damaged fuel bundles are transferred to the special handling area for separate processing (see Section 5.2.2).

4.4.4.3 Container Loading Station

The purpose of the container loading station is to load the container basket into the container shell and to fill all the void space with a particulate material to support the shell against external hydrostatic and buffer swelling loads. The station consists of a shaker table and a particulate supply bin and metering hopper.

The shaker table supports the container shell while the loaded basket is inserted, and it supports the basket/container assembly while particulate is loaded and compacted. The table is supported on linear ball bearings and has an actuator attached near the centre of gravity of the structure to impart horizontal vibratory motion to compact the particulate (Figure 4-24).

The packaging cell is provided with a bridge crane. It is equipped with one lifting device to pick up the basket by the central pipe and another to pick up the container shell by its circumferential flange. The crane is used to place the container shell on the shaker table, to insert the loaded basket into the container shell and to remove the loaded disposal container.

A particulate metering hopper and valve are located outside the cell as is the particulate bin supplying the hopper (Figure 4-24). A particulate filler hose complete with a valve is provided immediately below the particulate metering hopper. The particulate filler hose passes through the shielding wall to connect to the end nozzle located above the container. A load cell is included on the shaker table as a quality-control device to ensure that the mass of particulate corresponds with the metered particulate volume and is within the range required to completely fill the voids in a container.

4.4.4.4 Container Closure and Inspection Station

The purpose of the container closure and inspection station is to seal loaded disposal containers by placing a top lid on the container, joining the lid to the container with a diffusion bond, and checking the integrity of the completed containers. The following equipment is installed in the container closure station (Figure 4-25):

1. A rotary table to hold and rotate the container while the diffusion-bond closure seal is made.

2. A rotating titanium wire brush (not shown in Figure 4-25) to remove all deposits from the diffusion bond surface of the container, and a swab tool to clean it with a noncorrosive cleaning liquid.

3. A remotely operated lifting device to pick up the container top head and place it over the container.

4. A hydraulic press on the lifting device actuator to press-fit the top head into the container shell.

5. Diffusion-bonding equipment comprising two wheels that contact the inner and outer surfaces of the head container-seal area and pass a high-amperage, low-voltage pulsed D.C. current between the wheels through the bond area.

6. Closed-circuit television equipment for visual inspection of the closure bond.

Equipment is provided at the inspection stations (Figure 4-22) to inspect the integrity of the final closure bond between the lid and the container using ultrasonic methods (all other joints are inspected in the Container and Basket Fabrication Plant discussed in Section 4.5). Also, the integrity of the entire container will be inspected using a helium leak test. Development studies carried out on ultrasonic inspection (Moles and Dolbey 1985) and examination by helium leak-testing methods have indicated the viability of both for determining the integrity of the diffusion bond. Container inspection methods are discussed more fully by Johnson et al. (1994a).

Ultrasonic coupling is achieved at the ultrasonic inspection station by using a water jet. A rotary table is provided to support the container vertically, and skirting is provided to keep the bonded joint dry during ultrasonic inspection (i.e., to prevent ingress of water into the container should the joint have a defect). (Water-jet coupling for ultrasonic transducers has now advanced to the point of practicality (Dowker and Moles 1987, Piercy et al. 1989). A test assembly used in laboratory tests is shown in Figure 4-33.)

The ultrasonic inspection technique uses the propagation of sound waves through solids to identify any anomalies that may be present. Sound waves between 1 and ~25 MHz with wavelengths of 5 to 0.1 mm are introduced into the container material in the area of the diffusion bond, and the reflected or the attenuated sound is picked up by a receiver. In the reflection method, the probe that introduces the sound waves into the material also receives the reflected sound waves. In the attenuation method, a separate probe on the other side of the diffusion bond receives the sound waves passed through the bond area. In either case, the signal received is analyzed and a variety of flaws within the bond can be identified. As noted by Johnson et al. (1994a), flaws as small as 0.13 mm in diameter were detected, although this may be a lower limit for ultrasonic inspection.

The helium leak-testing station consists of two vacuum vessels with vacuum pumps, a helium gas supply and a helium mass-spectrometer leak detector. In this procedure, a completed container is placed under vacuum in one of the vessels. After the air is evacuated from the vessel, the evacuated space is repressurized with helium. Thus, a defective container is provided with an internal helium inventory. The container is then transferred to the second vacuum vessel connected to the helium mass-spectrometer leak detector. Another vacuum is drawn, and if a leak is present, helium escapes from the container into the vessel and subsequently into the leak detector. Johnson et al. (1994a) note that the helium leak test will detect defects that pass completely through the container and allow helium to enter the container.

If a defective container is identified, it will be transferred to the container repair/disassembly station discussed in Section 4.4.4.5. Any container with a repaired defect will be reinspected prior to acceptance for disposal. There is a very low probability that the nature, size, orientation, location or some other characteristic of a defect on a container may cause it to be undetected during these inspections. Since production-scale inspection and performance statistics are not available for container

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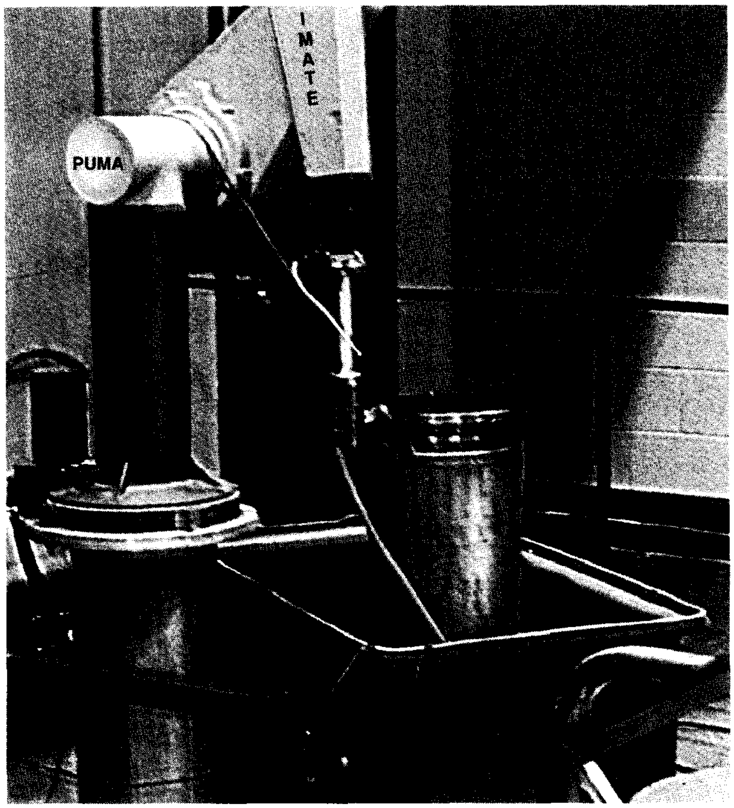


FIGURE 4-33: Inspection of Diffusion-Bonded Titanium Ring by a Water-Jet-Coupled Ultrasonic Transducer Mounted on an Industrial Robot

fabrication, Johnson et al. (1994a) estimated that between 0.01% and 0.1% of the containers sealed in a disposal room would have a defect that will lead to premature failure. The container is considered to fail when the full material thickness is penetrated at any point, eliminating absolute containment of the contents.

This suggests that between 14 and 140 containers with defects will pass inspection during the operation stage. While these defects may affect the isolation of the fuel bundles, they are not expected to alter the structural strength of the container; this structural strength is a factor in the retrieval of the container from the disposal vault should this be required.

4.4.4.5 Used-Fuel Container Repair/Disassembly Station

In the event that a container was not sealed successfully, a container repair/disassembly station is provided to either attempt weld repairs or, failing that, to disassemble the container for removal of the loaded basket.

The defective container is repaired or disassembled at the front end of the packaging cell in a special fixture (Figure 4-34) comprising the following elements:

1. a rotary table that holds the defective container in a vertical position,

2. clamps to hold the container at the top and bottom,

3. a remotely operated welder to attempt a final closure bond repair (not shown in Figure 4-34),

4. abrasive disc cutters to remove the top and bottom ends,

5. an abrasive disc cutter to cut the container shell axially in two places 180° apart,

6. a grapple to grip and remove the shell components (not shown in Figure 4-34),

7. a vacuum system to remove the particulate covering the basket-lifting attachment and a surrounding trough to collect spilled particulate, and

8. a jib crane to move the basket of used fuel onto a trolley for transport to the container loading station.

Viewing ports for visual inspection and possibly safeguards surveillance equipment are provided for this process.

4.4.4.6 Disposal Container Decontamination Station

The decontamination station consists of an enclosed chamber equipped with strategically located water jets to remove loose external contaminants from the container surface, a wet vacuum system to remove residual water sitting on the top head of the container, and an air blower for subsequent drying. A swipe-test station is provided to monitor containers for surface contamination before they are moved from the packaging cell.

4.4.5 Disposal Container Cask

The disposal container cask is exempt from design, testing and qualification requirements of the Transportation Packaging of Radioactive Materials Regulations (AECB 1990) since it will not leave the site. A conceptual design of a disposal container cask for transferring full disposal containers from the packaging plant to the disposal vault emplacement borehole was developed by AECL CANDU et al. (1992).

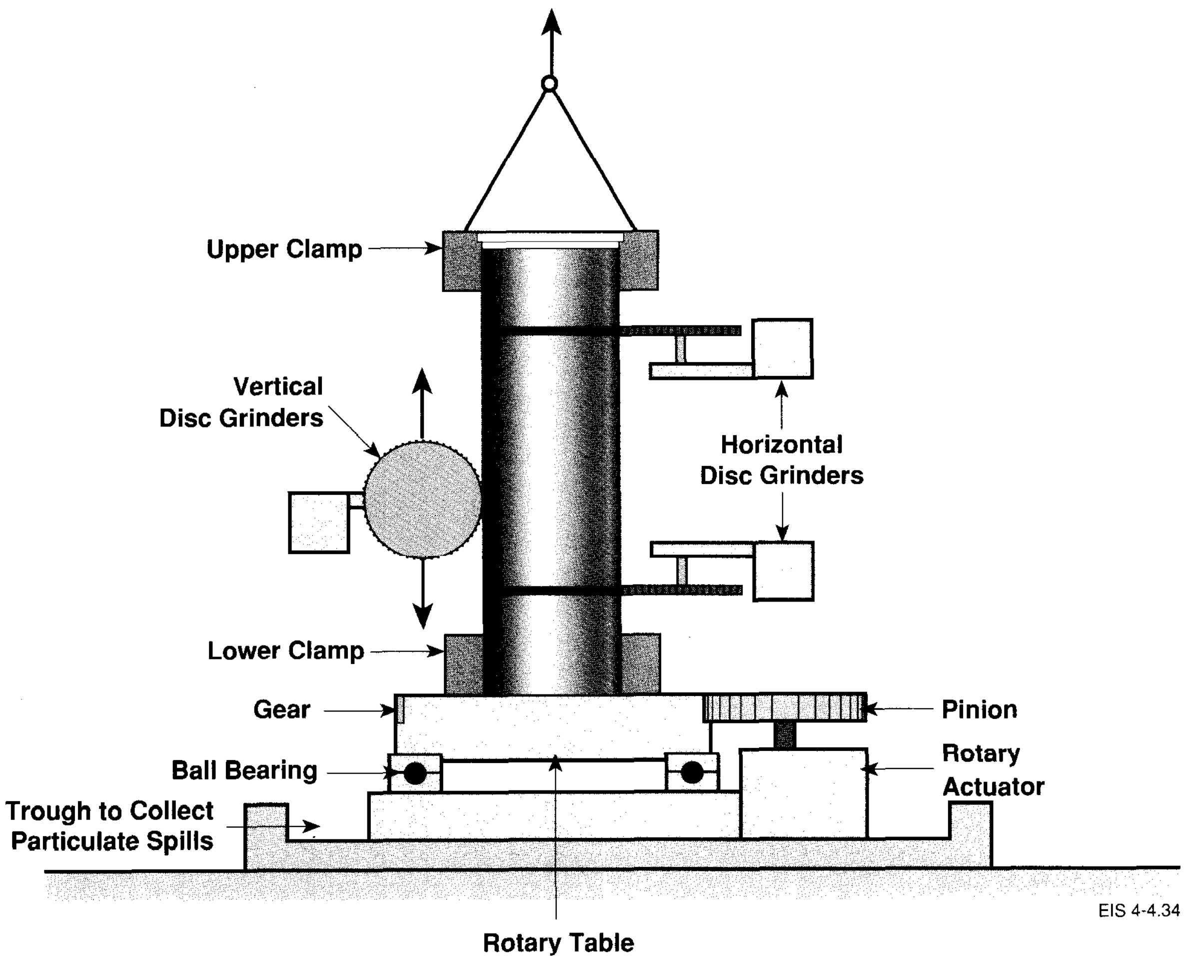


FIGURE 4-34: Defective Container Removal Fixture (after AECL CANDU et al. 1992)

This container cask (Figure 4-26) is designed to attenuate the radiation field from a full disposal container of high-burnup used fuel (Section 3.3.2.2), which yields an absorbed radiation dose rate of ~52 Gy/h on contact with the container surface to an on-contact absorbed dose rate on the outer surface of the cask of 19 μGy/h. This attenuation is achieved with a 330-mm-thick steel shell for gamma shielding and 50 mm of polythene for neutron shielding. The disposal container configuration and dimensions establish the cask geometry. The overall height of the cask, excluding the top lifting lug, is 3.5 m, the overall width is 2 m, the shell outside diameter is 1.41 m and the mass, less container, is about 35 Mg. All cask components that could come into contact with the container are fabricated from, or lined with, Grade-2 titanium to minimize the potential of contamination of the container surfaces with foreign materials that may enhance container corrosion.

Dual hoisting systems are provided to remotely load and unload the container cask. They use single-failure-proof safety features that include a mechanical fail-safe cask latching system (Figure 4-35). The lower opening of the cask is equipped with a split gate located in the enlarged lower section of the cask assembly (Figure 4-26). This gate is opened and closed by either a motorized chain drive or an electric screw drive, which will move only when being driven and will allow manual operation if the drive power is lost. The top cap of the cask is bolted in place and can be removed to allow emergency access. Two large trunnions, one per side, provide lifting lugs at 90° to the gate actuator to permit the hoists and handling vehicles to lift and transport the casks.

Various interlocks similar to those used on casks for handling radioactive cobalt are provided to prevent inadvertent operations, such as closing the gate while the container is not completely in the cask or opening the gate at an improper location. A system to indicate whether the cask is full or empty is provided.

The container grapple mechanism (Figure 4-35) in the container cask is an electromechanical device consisting of three lifting jaws that can be actuated to move radially inward to grapple the container-lifting ring on the upper outer surface of the reference container (Figure 3-5). The device is self-aligning and incorporates a mechanical sensor that permits the lifting jaws to grasp only when the correct radial and vertical position of the grapple on the container is reached.

The container cask is moved either by lifting on the one lifting lug installed into the top head, by lifting on the two lifting trunnions located on opposite sides of the cask, or by securing it on the underground transport vehicle.

Provision is made to install safeguards seals on the container cask gates or gate drives after the cask has been loaded with a disposal container, and on the top cap bolts. The requirement for seals would be set by the AECB in consultation with the implementing organization.

The massive steel construction required for radiation shielding results in a very robust cask that will resist damage from handling impacts. If a loaded cask is subjected to a severe impact in handling, its interior would be monitored for airborne radioactive contamination. If present, the contamination would indicate possible container damage, and the cask would be wrapped in plastic to prevent the spread of contamination and returned to the used-fuel packaging cell so the container could be removed for examination.

4.4.6 Used-Fuel Container Transfer to Headframe Storage

Containers leaving the decontamination station are transferred to either the packaging-cell cask-loading station or to the headframe surge-storage pool (Figure 4-22). Inclined elevators are provided for transfers to the headframe pool.

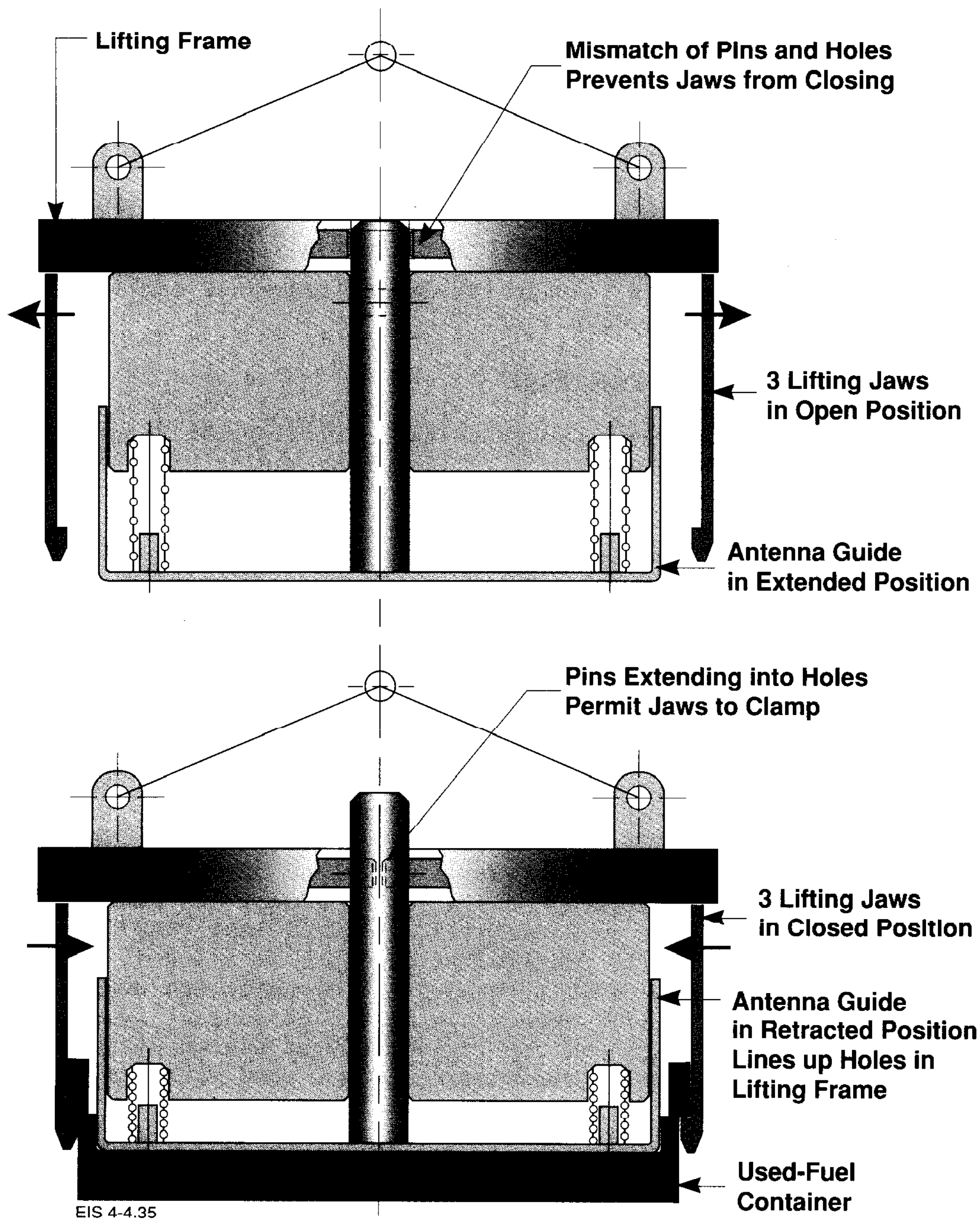


FIGURE 4-35: Container Cask Grapple Mechanism (after AECL CANDU et al. 1992)

The packaging-cell cask-loading station (Figure 4-36) consists of a cask support platform on top of the containment of the packaging cell adjacent to the decontamination area and a sliding table that moves a container from the decontamination area to a position under the loading port of the cask support platform. The empty container cask (described in Section 4.4.5 and shown in Figure 4-26) positioned on top of the platform (Figure 4-36) is equipped with a hoist and grapple (Figure 4-35), and a hoisting mechanism. These provide the means of grasping and raising the container into the cask.

A rail-mounted trolley is used to transfer loaded container casks to the waste-shaft headframe cask laydown area.

4.4.7 Headframe Surge-Storage Pool

The headframe surge-storage pool provides temporary disposal container storage to maintain process continuity if either packaging or disposal operations are stopped.

There is one common headframe surge-storage pool (Figures 4-22 and 4-37) servicing both packaging-cell process lines. Up to a two-month output of loaded containers (i.e., 580 containers) can be stored prior to transfer underground. At maximum capacity, the heat output from the stored containers is about 175 kW. The pool is normally maintained about half full.

The pool is 10 m wide, 45 m long and 7.15 m deep. The containers are arranged in 12 rows across the width of the pool, with 50 per row along the length. A manbridge spans the pool and supports the used-fuel container-handling tool.

The minimum depth of water required above a container being transferred with its base 0.3 m above the array of stored containers has been estimated to be 2.1 m; this will result in a radiation field of less than 2.5 μGy/h at the pool-water surface. The required water depth in the pool is 7.15 m to accommodate the container height, the 0.3-m clearance, the single level of stored containers and the 0.2 m from the container support frame to the pool floor. The water depth above the large array of stored containers is 4.65 m. The radiation fields at the surface of the pool water as a function of the depth of the water cover are given in Figure 4-38.

As in the receiving surge-storage pool, a cooling and purification circuit is provided to remove radiogenic heat from the pool water, to control the pool-water chemistry and to remove radioactive contamination from the pool water. Similarly, an inclined elevator from each used-fuel packaging cell moves containers into the pool, and a container-handling tool suspended from the manbridge grasps and moves the containers within the pool (Figure 4-37).

A storage framework is anchored to the pool floor and provides a single-level array of seismic-restraining storage supports for the containers.

Containers are moved from the pool to the used-fuel packaging cell on the inclined elevator or to a disposal container cask at the pool cask-loading

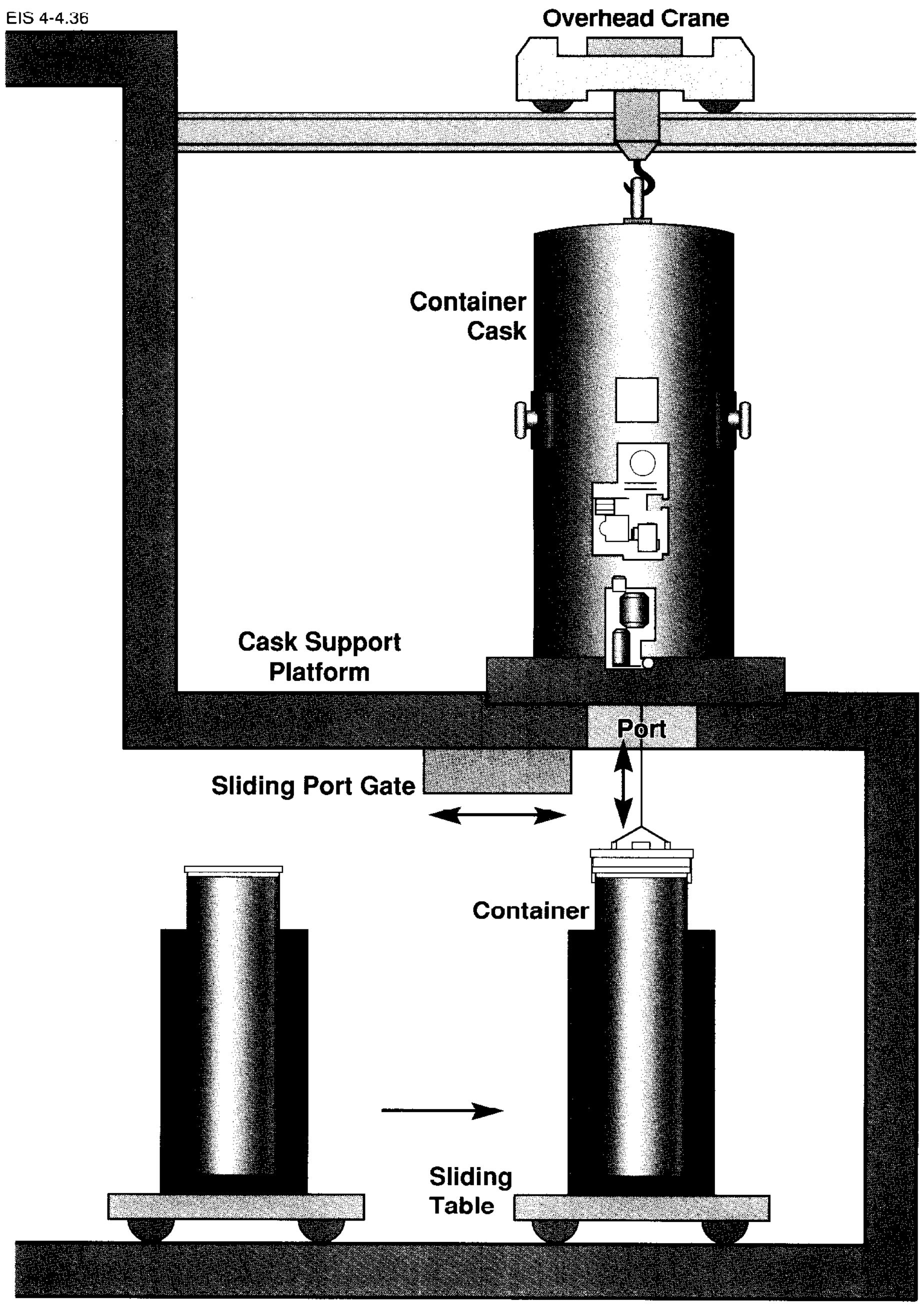


FIGURE 4-36: Packaging Cell Cask-Loading Station (after AECL CANDU et al. 1992)

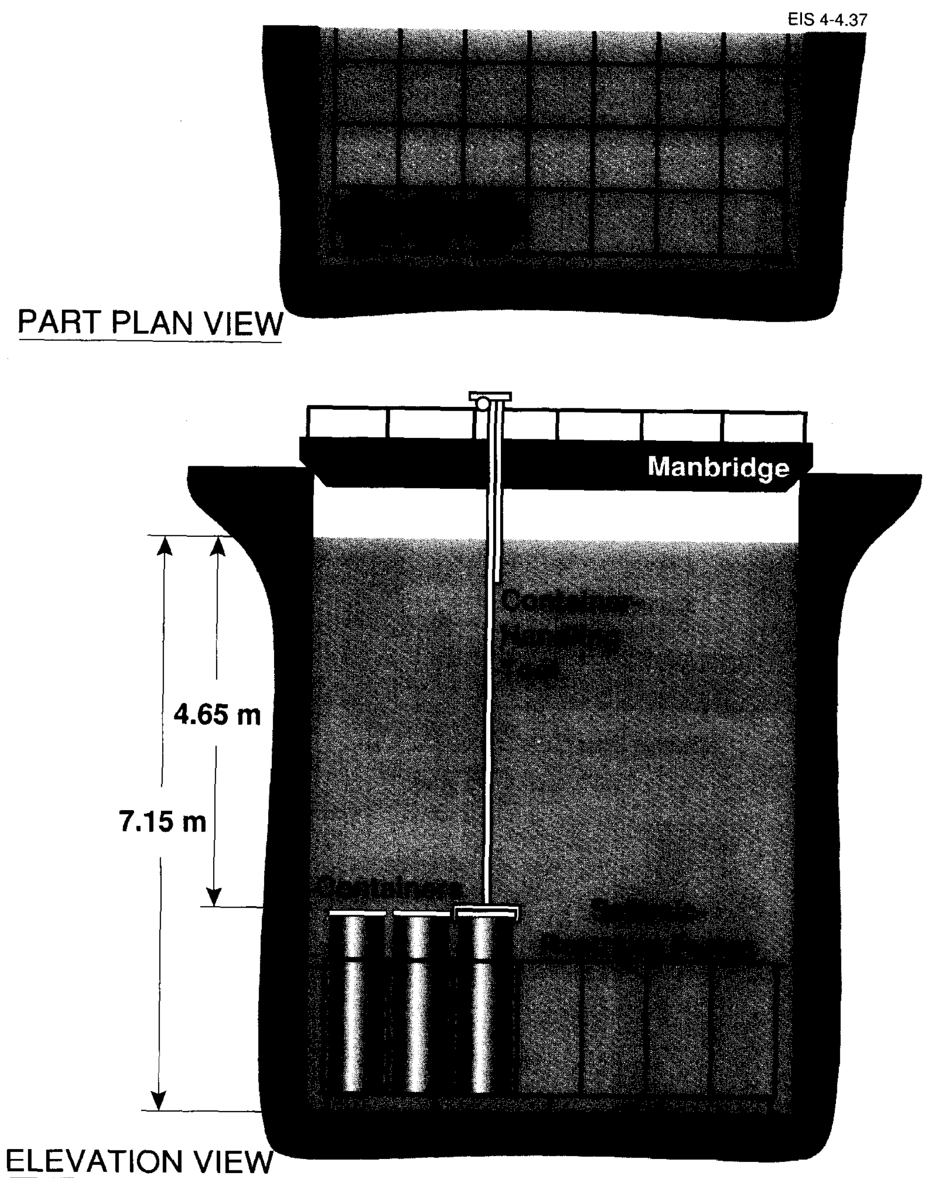


FIGURE 4-37: Headframe Surge-Storage Pool (after AECL CANDU et al. 1992)

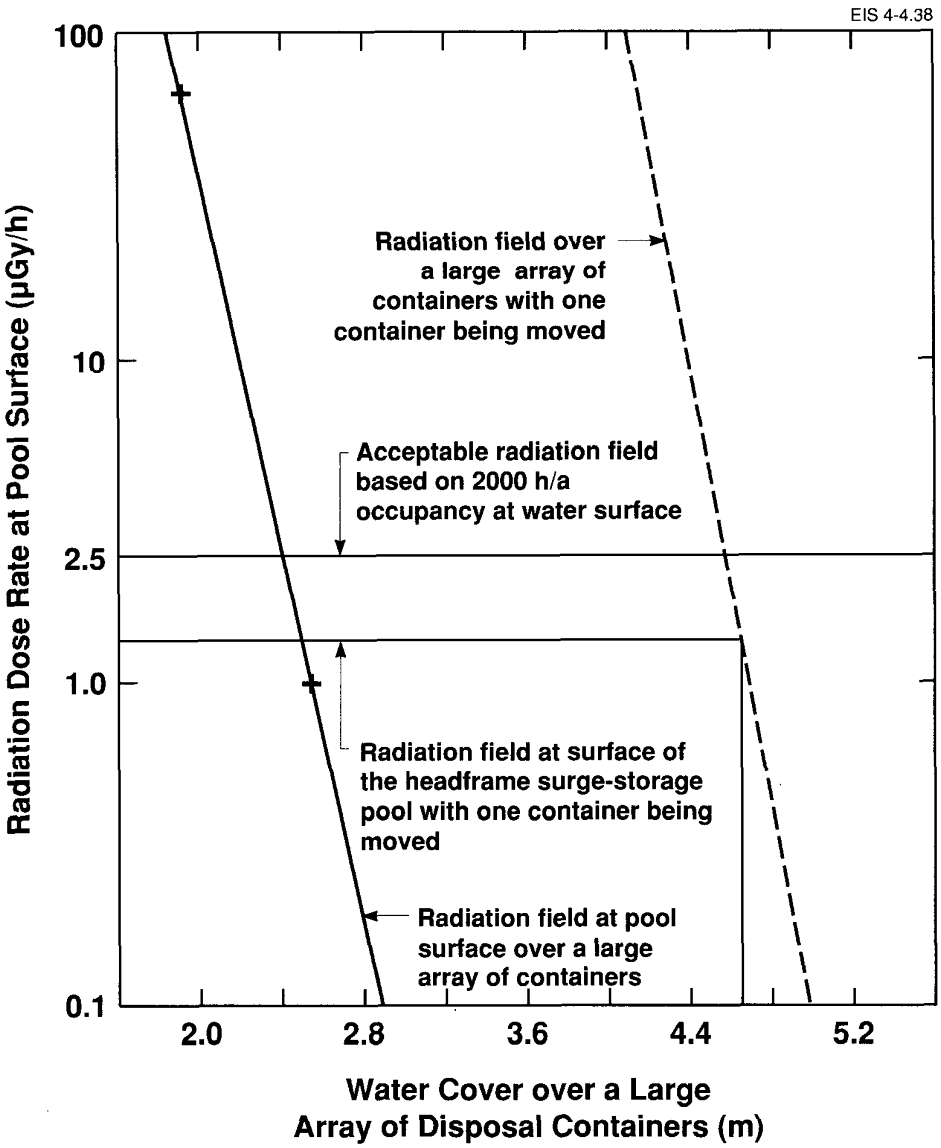


FIGURE 4-38: Radiation Dose Rate Above the Headframe Surge-Storage Pool (derived from AECL CANDU et al. 1992)

station. The pool cask-loading station (Figure 4-39) consists of a cask support platform and shielding guide, and a rotating carousel. The carousel is located on the pool floor and can be rotated to allow a container to be loaded in the pool handling area and then to position it below the port of the cask support platform. The shielding guide extends from the cask support platform sufficiently deep into the pool to provide shielding for the radiation field emitted from the container as it is lifted into the cask from the carousel position. It also guides the container as it is

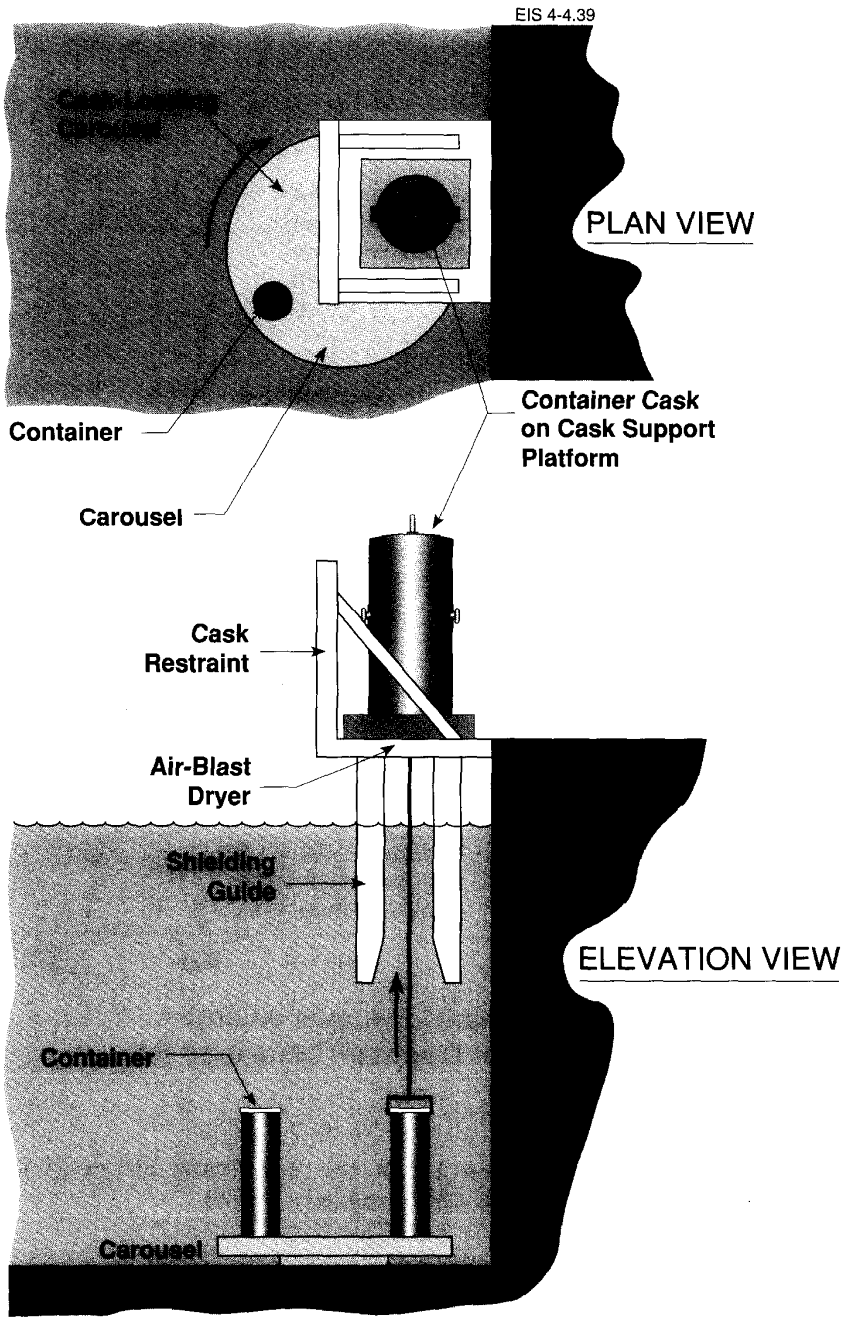


FIGURE 4-39: Headframe Surge-Storage Pool Cask-Loading Station (after AECL CANDU et al. 1992)

lifted from the bottom of the headframe pool. The shielding limits the maximum radiation field at its outer surface to 2.5 μGy/h.

An air blower on the shielding guide removes excess water from the side and bottom of the container as it is lifted into the cask. A wet vacuum system removes the water from the top head of the container. A trolley is used to transfer the container casks to and from the station. The casks are lifted on and off the support platform with an overhead crane and are loaded on trolleys for handling in the waste-shaft headframe cask laydown area.

4.4.8 Waste-Shaft Headframe Cask Laydown Area

The waste-shaft headframe cask laydown area is the transfer location where the disposal containers within the container casks are taken underground for disposal. This area is the last section of the Used-Fuel Packaging Plant. This area is located in the waste-shaft collar house (Figures 4-12 and 4-20), adjacent to the packaging-cell cask-loading station, the headframe pool cask-loading station and the waste-shaft headframe. The storage capacity for casks in this area is 8 to 10 casks to allow continuous operation. The laydown area is equipped with a short-span overhead travelling bridge crane for lifting full and empty casks from and onto the cask trolleys that are used for loading full casks onto and unloading empty casks from the waste-shaft cage.

4.4.9 Used-Fuel Packaging Plant Radiation Zoning, Ventilation, Heating and Air Conditioning

The heating, ventilation and air-conditioning (HVAC) system for the packaging plant is designed to maintain the air quality in accessible areas to acceptable levels. It also provides comfortable working conditions for the operators, maintains suitable temperatures for the equipment, and limits airborne releases of hazardous materials to acceptable amounts.

4.4.9.1 Radiation Zoning

The Used-Fuel Disposal Centre is divided into four radiation zones that take into account the radiation hazards in each area. The four zones defined in Table 4-6 are based on current nuclear facility operating practice (AECL CANDU et al. 1992). A similar approach is used at AECL's Whiteshell Laboratories (Barnard et al. 1985). The classification of areas is based on the potential risk involved with the entry of staff to each area, considering both the internal and external radiation hazards. The effective zoning used in the conceptual design is the higher of either the internal or the external radiation zoning for each area, and is shown in Figure 4-40.

The most hazardous areas in the disposal centre (Zones 3 and 4) are recognized as areas requiring special emphasis to prevent inadvertent exposures of personnel. The control and movement of personnel in these areas will be subject to stringent operational procedures and physical barriers. Atomic radiation workers, who are allowed to enter the Zone 3 and 4 areas, are subject to special health supervision and individual monitoring for both external and internal radiation exposures. The Zone 1 and 2 areas are also

TABLE 4-6

DEFINITION OF RADIATION ZONES

(after AECL CANDU et al. 1992)

Zone	Radiation Hazard: Potential for Internal Contamination	Radiation Hazard: External Radiation Dose Rate (μSv/h)	Access Status	Maximum Annual Effective Dose+ (mSv)
1	No potential for contamination.	<2.5	Entry is allowed to all staff and to members of the public.	5
2	Potential for contamination. Contamination is not tolerated, and it is eliminated immediately once discovered.	2.5-25	Work zone for Atomic Radiation Workers only.	5-50
3	Contaminated area. Contamination levels are less than the derived air or surface concentration limits.	25-250	Controlled access. Protective clothing is required.	*
4	High levels of contamination. Levels are higher than the derived air or surface concentration limits.	>250	Normally inaccessible area. Special protective clothing and equipment are required. Special equipment should also be provided for fuel-bundle handling or for decontamination purposes in the packaging plant.	*

\+ Maximum annual effective dose is based on 2000 h in zone per year.

* Controlled-access area. Entry permitted only after special authorization. Total individual effective annual dose shall not exceed 50 mSv (currently under review by AECB (1991a)), achieved by managing individuals' exposure time.

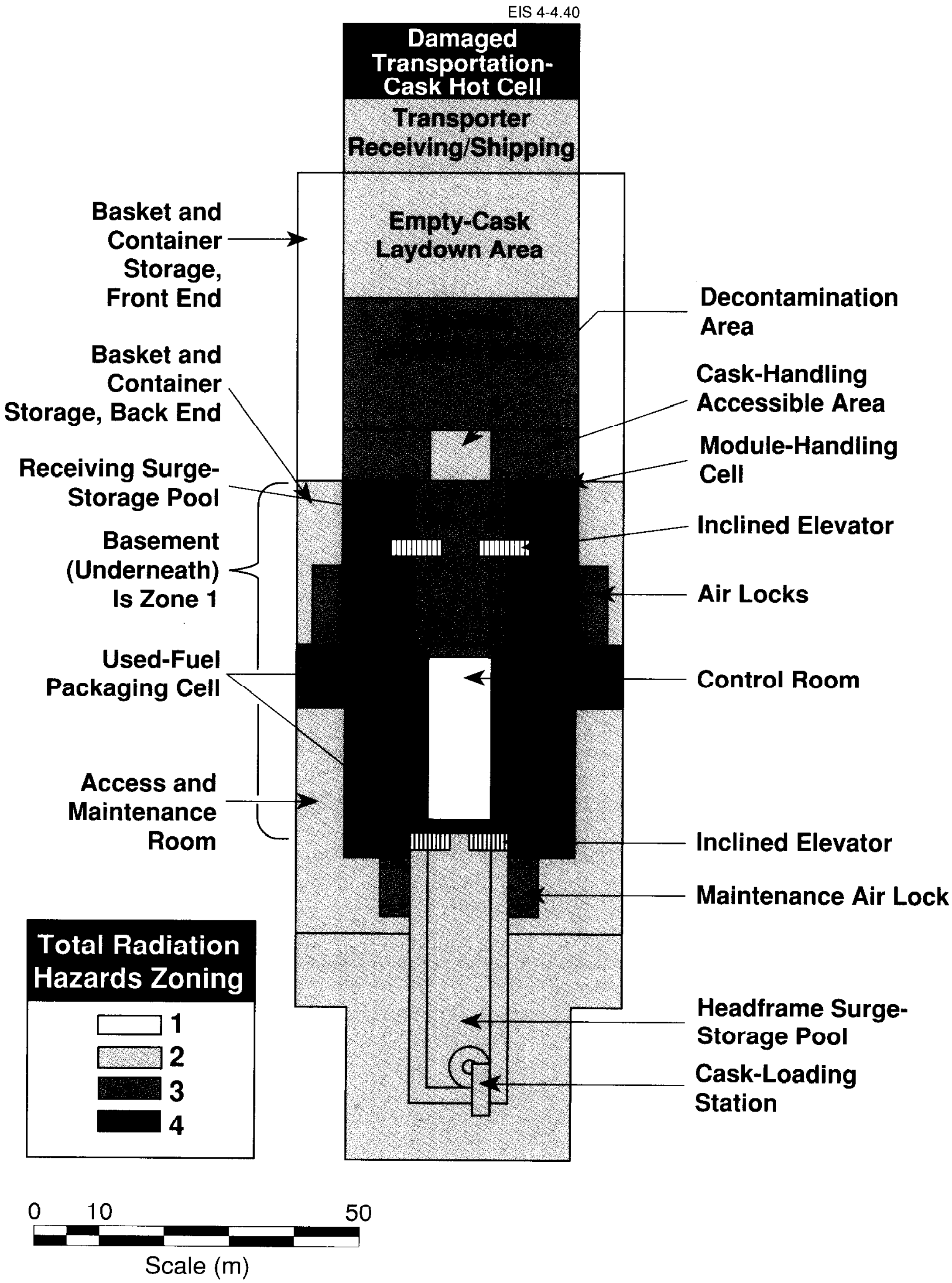


FIGURE 4-40: Packaging Plant Zoning Based on Total Radiation Hazards (after AECL CANDU et al. 1992)

subject to procedural control, but workers in these areas would not normally require individual monitoring or special health supervision. The public is allowed access to Zone 1 areas and supervised access to areas of Zone 2 (note that supervision may be required in Zone 1 areas for security reasons). The control function is usually achieved to a satisfactory degree by monitoring the working environment via routine contamination and radiation surveys.

The level of "internal radiation hazard" is assigned based on the projected calculated air and surface contamination concentrations in each area and on the definition of zoning (Table 4-6). Most of the areas in the disposal centre are not normally expected to contain radioactive contamination, and they are therefore classified as Zone 1 or 2. The areas that have potential for contamination are classified as Zone 3 or 4. The classification is done by comparing the concentration ratio (CR) to 1. CR is defined as

$$CR = \sum_i \left(\frac{AC}{DAC} + \frac{SC}{DSC}\right)_i \quad , \tag{4.1}$$

where AC and SC are the expected air and surface radionuclide concentrations respectively. DAC and DSC (Table 4-7) are the derived allowable air and surface concentration to satisfy limits on inhalation of radionuclides by atomic radiation workers (ICRP 1979, Johnson and Dunford 1983). The summation i is over all the radionuclides.

An area is classified as Zone 1 if there is no potential for contamination, and as Zone 2 if there is potential for contamination but CR = 0. The area is classified as Zone 3 if CR $\leq$ 1 and as Zone 4 if CR $\geq$ 1. The zoning based on the internal radiation hazards is presented in Table 4-8.

The level of "external radiation hazard" is assigned based on the average radiation dose rates in the areas (Table 4-8) (AECL CANDU et al. 1992) and on the definition of zoning (Table 4-6).

4.4.9.2 Ventilation, Heating and Air Conditioning in the Packaging Plant

Airborne radioactive contamination in accessible areas is controlled by ventilation zoning (Figure 4-41), which is based on the internal radiation hazard zoning.

The ventilation system layout and differential pressures in the Used-Fuel Disposal Centre conceptual design are used to create airflows from zones of no or low contamination (e.g., Zone 1 or 2) to areas of higher contamination (e.g., Zone 3 or 4). Airborne radioactive releases to the environment are controlled by using low air throughputs (i.e., six air changes per hour) in the normally inaccessible Zone 3 and 4 areas, and by filtering exhaust airflows as necessary to remove airborne particulates. Fifteen air changes per hour are provided in the Zone 1 and 2 areas.

Table 4-9 shows the approximate room volumes for the packaging plant and the required ventilation flow rates. Figure 4-42 shows a simplified ventilation flow diagram for the Used-Fuel Packaging Plant. The total fresh-air supply

TABLE 4-7

DERIVED AIR AND SURFACE CONCENTRATIONS

(after AECL CANDU et al. 1992)

Radionuclide	Half-Life (a)	Concentration	
		Air (Bq/m^3)	Surface (Bq/m^2)
H-3	12.3	8×10^5	NA
C-14	5760	9×10^2	9×10^5
Fe-55	2.7	3×10^4	3×10^7
Ni-59	7.5×10^4	1×10^5	1×10^8
Co-60	5.3	5×10^2	5×10^5
Ni-63	100	4×10^4	4×10^7
Kr-85	10.7	5×10^6	NA
Sr-90	29.1	6×10^1	6×10^4
Nb-94	2×10^4	2×10^2	2×10^5
Ru-106	1	2×10^2	2×10^5
Sb-125	2.8	4×10^3	4×10^6
I-129	1.6×10^7	1×10^2	NA
Cs-137	30	2×10^3	2×10^6
Ce-144	0.8	2×10^2	2×10^5
Pm-147	2.6	2×10^3	2×10^6
Eu-154	8.8	2×10^2	2×10^5
Pu-238	87.7	0.1	100
Pu-239	2.4×10^4	0.1	100
Pu-240	6537	0.1	100
Pu-241	14.4	4	4×10^3
Am-241	432	0.1	100
Cm-244	18.1	0.2	200

NA - Not applicable (i.e., a gas)

rate under normal conditions is about 200 m^3/s. This fresh air is supplied by the following sources:

1. Four heating and ventilating units, each with a capacity of 30 m^3/s, at the shipping/receiving end of the building (Zone 2).

2. Two HV units, each with a capacity of 40 m^3/s, one at each side of the building, adding air at the basement level (Zone 1).

3. Fresh-air makeup of 1 m^3/s to the control room area through the air-conditioning unit.

4. Two HV units, each with a capacity of 7.5 m^3/s, at the damaged transportation-cask hot cell (Zone 4), when required.

TABLE 4-8

USED-FUEL DISPOSAL CENTRE RADIATION ZONING

(after AECL CANDU et al. 1992)

Area	Identification	Internal Radiation Hazard		External Radiation Hazard		Effective Radiation Hazard Zoning
		CR Value	Zoning	Dose Rate (μSv/h)	Zoning	
A	Receiving/Shipping	~0	2	20	2	2
B	Full-Cask Laydown Area	~0	2	100	3	3
C1/C2	Cask-Handling Accessible Area	~0	2	50	3	3
D1/D2	Module-Handling Cell	1200	4	≥250	4	4
E	Decontamination Area	~0	2	≤2.5	1	1
F	Empty-Cask Laydown Area	~0	2	≤2.5	1	2
G	Receiving Surge-Storage Pool	0.4	3	5	2	3
H1/H2	Air Lock	300	4	≥250	4	4
J1/J2	Used-Fuel Packaging Cell, Front End	300	4	≥250	4	4
JJ1/JJ2	Used-Fuel Packaging Cell, Back End	0.02	3	≥250	4	4
K1/K2	Air Lock	<0.02	3	100	3	3
L	Headframe Surge-Storage Pool	~0	2	12	2	2
M	Headframe Cask Laydown Area	~0	2	20	2	2
N	Waste-Shaft Conveyance	~0	2	25	2	2
P	Underground Cask Storage	~0	2	25	2	2
Q	Disposal Room	~0	2	25	2	2
R1/R2	Basket and Container Storage, Front End	~0	1	≤2.5	1	1
S1/S2	Basket and Container Storage, Back End	~0	2	25	2	2
T1/T2	Air Lock	~0	3	100	3	3
U1/U2	Access and Maintenance Room	~0	2	12	2	2
V	Control Room	~0	1	≤2.5	1	1
W	Damaged Transportation-Cask Hot Cell (when required)	1200	4	≥250	4	4

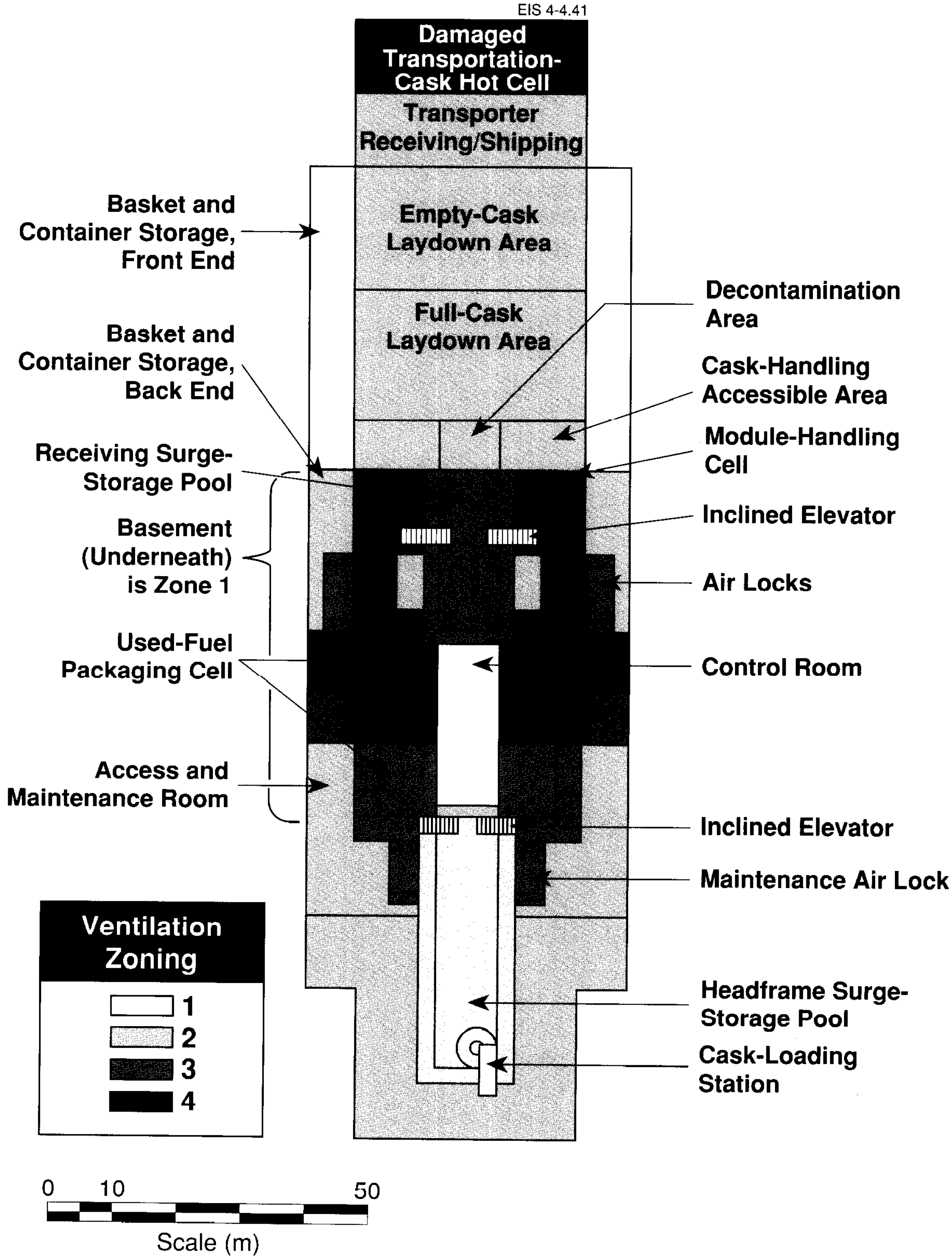


FIGURE 4-41: Used-Fuel Packaging Plant Ventilation Zoning (after AECL CANDU et al. 1992)

TABLE 4-9

VENTILATION REQUIREMENTS FOR USED-FUEL PACKAGING PLANT
(after AECL CANDU et al. 1992)

Area	Area Description	Approx. Volume (m^3)	Ventilation Zone	Air Changes per Hour	Airflow (m^3/s)			
					Zone 1	Zone 2	Zone 3	Zone 4
A	Shipping/Receiving	5 400	2	15		22.5		
B	Full-Cask Laydown Area	9 000	2	15		37.5		
C1	Cask-Handling Access	1 500	2	15		6		
C2	Cask-Handling Access	1 500	2	15		6		
D1	Module-Handling Cell	720	4	6				1.2
D2	Module-Handling Cell	720	4	6				1.2
E	Decontamination	750	2	15		3		
F	Empty-Cask Laydown Area	9 000	2	15		37.5		
G	Receiving Surge-Storage Pool	2 800	3	15*			12	
H1	Air Lock	60	4	6				0.1
H2	Air Lock	60	4	6				0.1
J1	Packaging Cell Front End	2 070	4	6				3.5
J2	Packaging Cell Front End	2 070	4	6				3.5
JJ1	Packaging Cell Back End	1 150	3	6			2	
JJ2	Packaging Cell Back End	1 150	3	6			2	
K1	Container Air Lock	75	3	15			0.3	
K2	Container Air Lock	75	3	15			0.3	
L	Headframe Surge-Storage Pool	4 800	2	15		20		
M	Headframe Storage	3 000	2	15		12.5		
R1	Basket and Container Storage	1 680	1	15	7			
R2	Basket and Container Storage	1 680	1	15	7			
S1	Basket and Container Storage	1 680	2	15		7		
S2	Basket and Container Storage	1 680	2	15		7		
T1	Air Lock	60	3	15			0.2	
T2	Air Lock	60	3	15			0.2	
U1	Access and Maintenance Room	1 000	2	15		4.2		
U2	Access and Maintenance Room	1 000	2	15		4.2		
V	Control Room	1 800	1	15	10**			
W	Damaged Transportation-Cask Hot Cell (when required)	9 000	4	6				15
	Basement***	14 400	1	15	60			
Total Air Movement****					84	167.4	17	24.6

* 15 air changes per hour because pool is normally accessible despite being Zone 3.

** Recirculating so that only 1 m^3/s of fresh air is required.

*** Basement includes areas under Control Room, under Module-Handling Cell, etc.

**** The total airflow requirements are generally satisfied by recirculating air from lower zones to higher zones. The total fresh-air supply is 201 m^3/s.

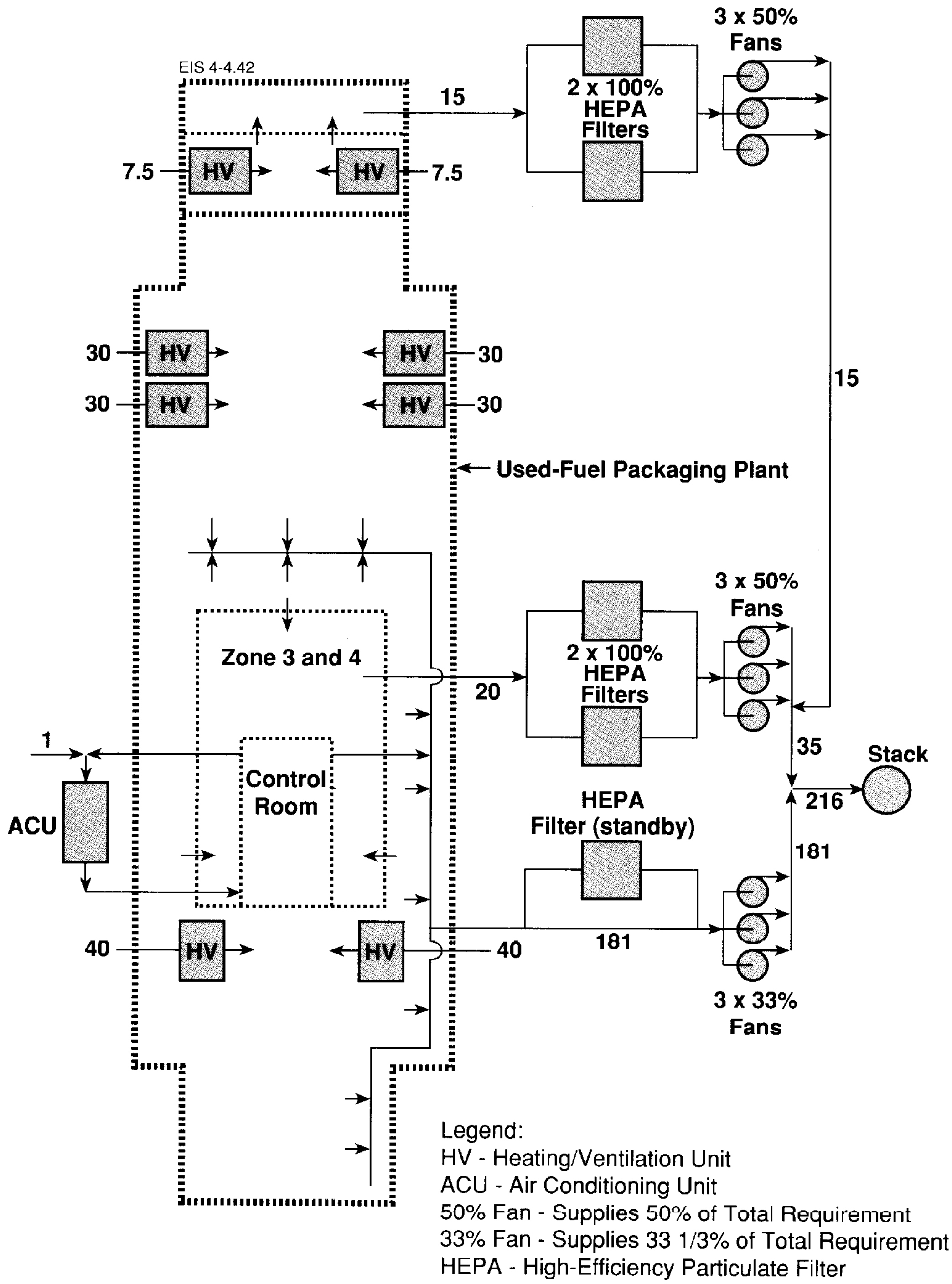


FIGURE 4-42: Simplified Used-Fuel Packaging Plant Ventilation Flow Diagram (after AECL CANDU et al. 1992). Ventilation flows are in m³/s.

The above supply rates may be reduced by up to 50% during extreme winter weather conditions to maintain acceptable temperatures with the heating capacity provided. This will reduce the number of air changes per hour in accessible areas proportionately. This reduction is expected to be of short duration and does not represent a risk to workers.

The incoming fresh air in the heating and ventilation units is heated by electrical heating coils, propane or natural gas heaters, depending on economics and availability. The Used-Fuel Disposal Centre cost estimate (Chapter 7) includes a general allowance for local heating systems. Space heaters are provided throughout the Used-Fuel Packaging Plant to compensate for building heat losses. The maximum total Used-Fuel Packaging Plant heat load without a heat recovery system is approximately 8 MW. Heat recovery systems would be examined as part of the detailed design. Alternately, a central heating plant could be employed for the entire Used-Fuel Disposal Centre to supply hot water to the heating and ventilation units. This option was not assessed in the Used-Fuel Disposal Centre conceptual design.

The control room and adjacent support areas are air conditioned to maintain relatively constant, comfortable conditions throughout the year. Heating is provided by electric heating coils, and cooling is provided by cooling coils cooled with process water. The total airflow rate is approximately 10 m^3/s, with 10% (1 m^3/s) fresh-air makeup and air exhaust. This system can be placed on 100% recirculation to permit occupancy of the control room in the event that the outside air is contaminated.

The exhaust air from Zones 3 and 4 (approximately 20 m^3/s) is filtered continuously to remove particulates, and is discharged through the packaging plant stack. Two HEPA (high-efficiency particulate air) filters and three fans, each sized for 50% of the required system capacity, and on standby power, ensure continuous reliable exhausting of Zone 3 and 4 areas. Figure 4-43 shows the airflows to and from Zones 3 and 4. These flows are achieved by suitable sizing and/or adjustment of fans, filters, ducting and dampers to maintain Zone 4 at a lower pressure than Zone 3, which in turn is at a lower pressure than Zone 2.

Air from Zone 2 that does not flow to Zone 3 flows directly to the stack via three fans with a capacity of 60 m^3/s each (1/3 of the total system capacity). Standby HEPA filters are provided to remove airborne particulates should the Zone 2 air become contaminated.

The exhaust air in the ventilation discharge stack is monitored continuously for conformance with emission limits.

4.4.10 Used-Fuel Packaging Plant Control and Instrumentation

Many operations are carried out in the Used-Fuel Disposal Centre between the receipt of the transportation casks and the loading of the container casks. These are done either manually or automatically, depending on the degree of hazard to workers, the convenience of operation, and the need for, and difficulty of, quality control. Fuel-handling equipment, instrumentation and control concepts that have been, or are being, successfully used in CANDU nuclear generating stations are used wherever appropriate.

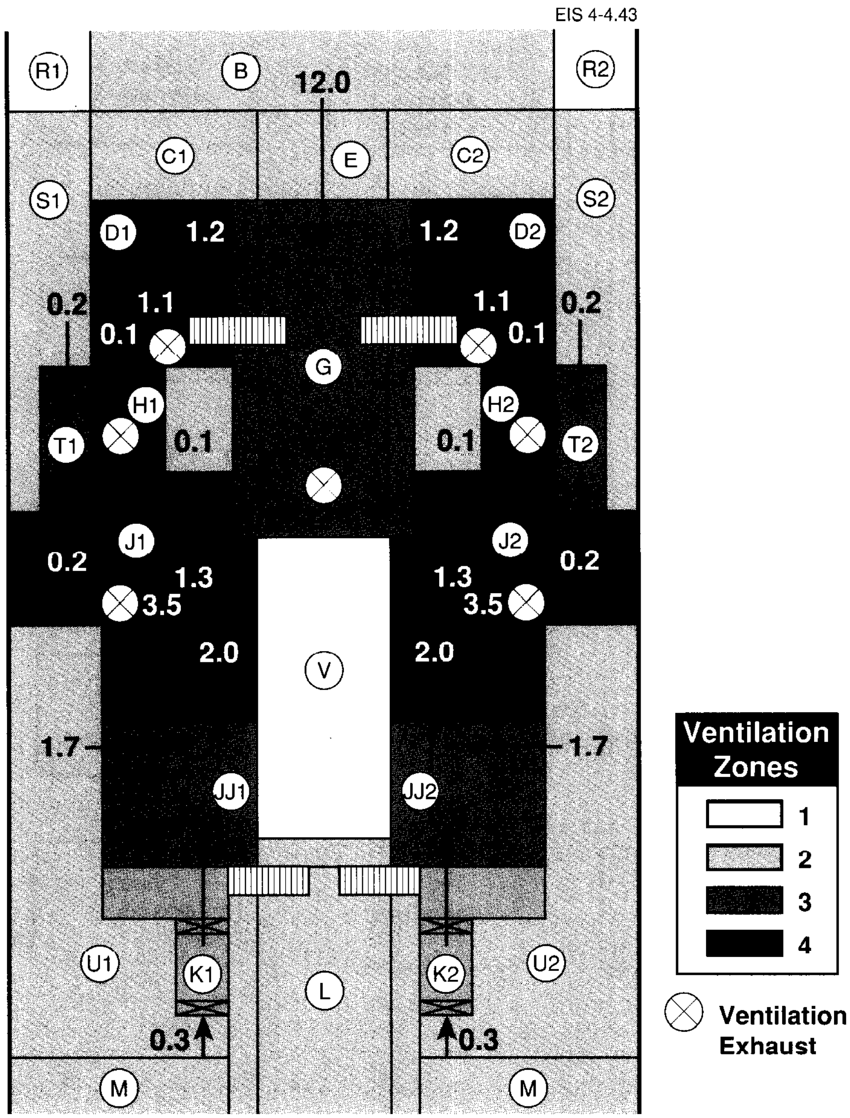


FIGURE 4-43: Used-Fuel Packaging Plant Zones 3 and 4 Ventilation (after AECL CANDU et al. 1992). Ventilation flows are in m^3/s.

Most of the packaging plant operations are carried out automatically using computer control systems that function under the supervision of operators located in the packaging-plant control room. The control systems, shown in simplified form in Figure 4-44, are based on the use of a central processor that communicates with and controls through a distributed network of special-purpose control processors. In addition to supervising the operation of special-purpose processors, the central processor sends and receives signals to and from the packaging plant, including local control

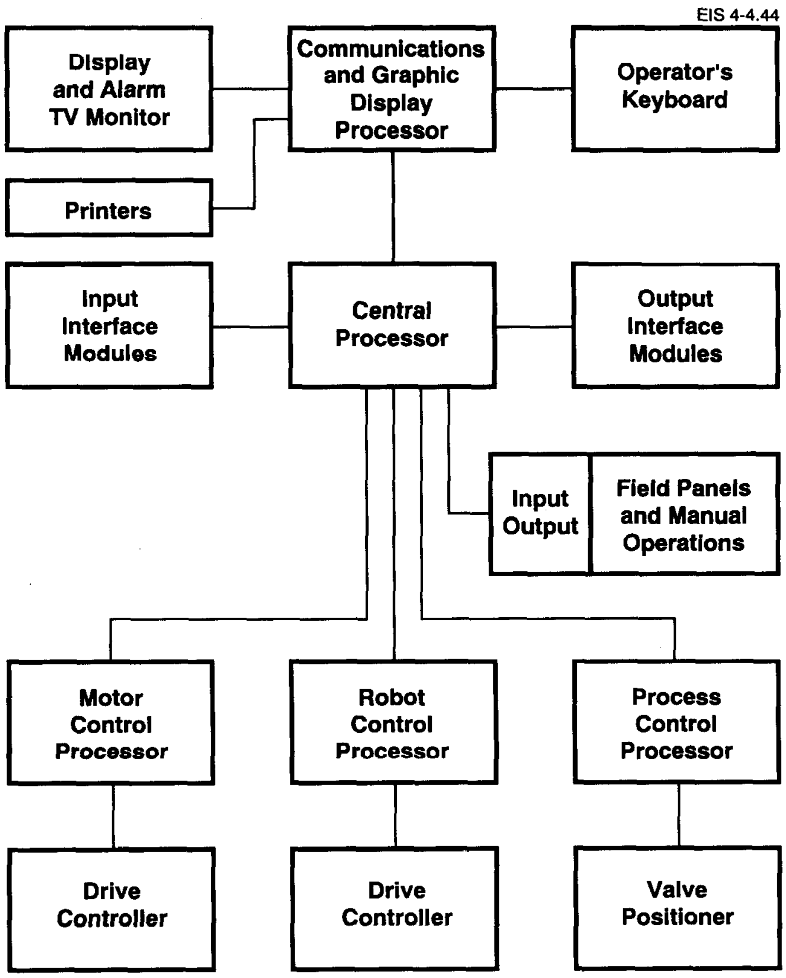


FIGURE 4-44: Simplified Overall Control System Block Diagram Showing Typical Interfaces (after AECL CANDU et al. 1992)

consoles located close to equipment requiring an operator. Since some local consoles contain processors that control plant equipment, the control system is said to be "distributed." A local console is installed at each area in the plant where a local communications cable or bus joins the intraplant bus.

The operators are provided with a control console equipped with keyboards and several CRT monitors for displays and alarms. The operators are able to assume control over any piece of equipment by keyboard entry from the control console, and are able to monitor any variable on one of the monitors from the same location. This gives the operators the ability to intervene in cases of abnormal operation, and then to return the plant to automatic operation from the control console.

A communications system is provided throughout the packaging plant where control or monitoring instrumentation are required. It is used to exchange control or monitoring signals between different parts of the plant and, in particular, to link these areas with the control room. Figure 4-44 is a simplified block diagram of the plant control system with typical processors, controllers and interfaces.

The communications and graphics display processor provides the operators in the control room with a means of controlling and monitoring all functions and processes in the plant. The operators enter plant control instructions from a keyboard to the communications and graphics display processor that then communicates with the central processor. Display instructions are processed directly and the information requested is displayed on a monitor. This communications and graphics display processor also displays alarm messages coming from the central processor. These may appear on a monitor and/or a printer.

A variety of instrumentation is installed to effectively and reliably measure process and environmental conditions such as flows, levels, temperatures, vibration, pressure and pressure drops, radiation levels, and equipment positions. The instrumentation provides data to the control processor for operational control and sequencing, and provides process and environmental status data, including alarms, to the operators.

Redundancy in instrumentation, communications buses and controllers is provided to ensure that a failure of any single component does not lead to a shutdown of the overall process. As much as practicable, the design employs instrumentation and logic processors that are of modular construction, allowing ease of replacement or reprogramming.

The control system for the Used-Fuel Disposal Centre is located in the packaging plant near the control room shown on Figure 4-20. The control system monitors and controls other site activities, including the following in addition to the monitoring and control of the packaging plant operations:

1. the fire protection systems,
2. the plant electrical supply,
3. the plant compressed air supply,
4. the plant water supply,
5. the active drainage system,
6. the plant heating, ventilation and air conditioning systems,
7. the disposal vault services,
8. the biosphere, geosphere and vault monitoring systems, and
9. the inventory control system.

An alarm analysis capability is provided for the control operator to analyze alarm information during normal and abnormal operational occurrences. The data accumulation, analysis, alarming and storage functions operate automatically and require no operator intervention. A main control-room annunciator system provides a constantly updated indication of alarm and clearance messages, a lighted message panel for a number of important alarm conditions, and a permanent record of the times of all alarms and clearances that have occurred.

4.4.11 Equipment Maintainability and Reliability

Equipment for handling used fuel will become contaminated during normal operation and will require periodic maintenance, repair and replacement. The sources of contamination are radioactive corrosion products on used-fuel bundles, and any gases or fuel particles released from bundles containing fuel elements with damaged cladding. The level of contamination is expected to be low enough to permit a considerable amount of contact maintenance of equipment after the used fuel is removed or shielded and a primary decontamination has been performed. Radiation fields encountered during maintenance activities will be measured and worker radiation doses will be controlled to ensure effective radiation protection.

All equipment and components are designed for easy replacement, and components that require routine servicing are made readily accessible. Simplicity in the system design to minimize the requirements for maintenance, servicing and repair contributes toward a reliable system. Where possible, the drives and actuators for the equipment are located outside the hot cells so they will be readily accessible for servicing, and power transmission is achieved by means of through-wall penetrations. A similar design philosophy is applied to the module- and container-handling equipment in the surge-storage pool facilities. Drives and actuators for the handling tools are located above the water surface for easy access.

Regular maintenance schedules will be established and updated based on a reliability analyses of individual systems and components to achieve high reliability, and adequate spares will be maintained to prevent a prolonged outage. If the failure of a particular component could result in prolonged equipment outage, a spare piece of equipment or a manual means of operation is provided, where practicable, for that component.

4.4.12 Abnormal Conditions

Every effort is made to provide safe and reliable material handling and radiological protection systems for normal operating conditions. In addition, consideration must be given in the design to the possibility of accidents or abnormal conditions. Since many equipment failures and accidents are difficult to foresee in a conceptual-level design, a comprehensive program would be put into place during detailed-level design to define all possible utility failures, equipment failures and accidents, and to devise preventive measures. This will include "fail-safe" systems design whereby equipment that can fail will be designed in such a way that the system will remain in, or be put into, a safe condition when a failure occurs.

For example, lifting cranes will be designed to meet a "single-mode" fail-safe specification. In this case, any single failure of a crane component would cause the crane to lock in its current position. No crane movement would be permitted, except following repair of the system component or by the override of the automatic circuit by the maintenance crew and operations staff. The override would be done under careful supervision.

Similarly, fail-safe zone control ventilation systems will be designed to maintain the appropriate airflow conditions to maintain worker and public safety when a component or electrical power supply to the site fails.

The following additional examples of features were considered in the Used-Fuel Disposal Centre conceptual design to deal with abnormal conditions:

1. A mechanical interlock is provided on the scissors lift to prevent inadvertent separation of the used-fuel transportation cask from the receiving port at the module-handling cell. This is in a controlled access area, so there will be no personnel in the immediate vicinity in case of an accident.

2. Possible accidents during handling of the modules and containers in their respective pool storage facilities will be of relatively low severity since the water shielding offers the necessary protection, and corrective measures can be implemented with manually operated tools and with the aid of a crane when required.

3. Possible accidents within the module-handling cell and the packaging cell could result in damage to the fuel bundles. Personnel are protected by the walls of the facilities, which provide the necessary shielding and contain any airborne contaminants. Accidents in this category would consist of accidental dropping of either the module or the basket containing used fuel, which may fail and spill their contents onto the floor of the cell.

4. Gantry robots and robots that can be manoeuvred along the floor are provided in the packaging plant to handle the larger components, such as the fuel bundles, modules, baskets and containers. Other robotic devices such as manual or powered manipulators are installed to collect any spilled contents from the floor and for general housekeeping. If appropriate for the circumstance, the damaged fuel would be moved into an emergency pit where it cold be handled dry or covered with water by filling the pit (Section 4.4.4).

5. Pits are provided within the module-handling cells and the packaging cells to handle modules, baskets and containers in the event of an accident. The pits are built adjacent to the surge-storage pools and have a gate that allows water to flow from the pool. Once the pit is flooded, the damaged module, basket or container, complete with radioactive contents, can be handled with manually operated hand tools. Hand-operated manipulators are also provided through penetrations in the shielding walls and/or ceiling.

Grondin et al. (1994) include an assessment of the occupational effects of the facilities under normal and abnormal conditions in their preclosure assessment.

4.5 BASKET AND CONTAINER FABRICATION PLANT

Disposal containers and fuel-bundle baskets could be fabricated either at the disposal centre or by an off-site fabricator. On-site fabrication of 15 containers and baskets per day is assumed in the Used-Fuel Disposal Centre conceptual design. On-site fabrication in a dedicated shop was selected, largely to minimize damage of these bulky items in transport and to reduce the potential for metallic (e.g., iron) contamination of the disposal container surfaces from fabrication tools and handling equipment.

The basket and container fabrication plant is a structure about 60 m long and 40 m wide complete with heating, ventilation and services. The basket and container fabrication lines are completely separated to avoid cross-contamination of materials (Figure 4-45).

The fabrication plant is designed to produce the 3471 baskets and containers required annually, and has suitable raw material, consumables and product-inventory storage areas. The plant also includes chemical and metallurgical testing laboratories to confirm that the raw materials satisfy the material specifications.

An area is provided for the receipt, inspection and storage of materials. Docking facilities with an adjustable platform are provided for unloading

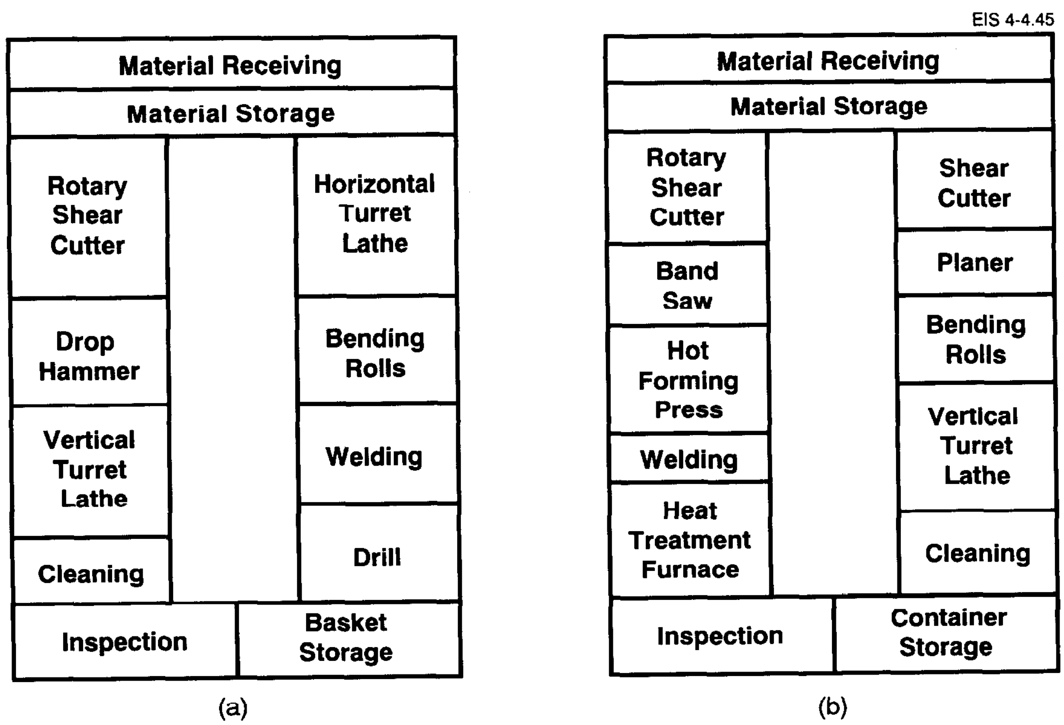


FIGURE 4-45: Schematic of Basket (a) and Container (b) Fabrication Facility (after AECL CANDU et al. 1992)

transport vehicles. Overhead crane facilities and forklift trucks are provided for unloading and handling the various materials.

Much of the materials handling and fabrication equipment is automated. Extensive use is made of numerical control machinery and robotic welding equipment.

The basket fabrication area includes (Figure 4-45a)

1. a horizontal turret lathe to cut piping and bar stock into required lengths;

2. bending rolls to form rings from bar stock;

3. a power-driven drop hammer to form miscellaneous small attachments;

4. a vertical turret lathe to carry out the finish machining of components with specified tolerances;

5. a drill for miscellaneous parts;

6. a mechanical rotary shear cutter to cut the blank plates for the circular end caps;

7. a welding fixture to maintain the basket components in alignment while the tubes are tack-welded;

8. a shop for welding;

9. an area for cleaning finished products;

10. lift trucks, overhead cranes and jib cranes; and

11. inspection and storage areas.

All titanium forming, machining and handling operations are performed in the container fabrication area in accordance with good industrial practice to ensure no contamination of the material with embedded iron-containing particles. The container fabrication area includes (Figure 4-45b)

1. a shear cutter to cut plate to size for container shells;

2. a planer to prepare shell plate edges for welding;

3. a rotary shear cutter to cut top and bottom head closure plates;

4. a band saw to cut bar or strip material for lifting rings;

5. bending rolls to bend shell plates into cylinders and to form lifting rings;

6. a press with forming mandrels to hot form the top- and bottom-head closures;

7. a vertical turret lathe to prepare the head-closure edges for welding;

8. a vacuum heat-treatment furnace to heat treat the top- and bottom-head closures and, if necessary, the welded shell;

9. a cleaning facility to remove grease and oil from the components with chemical solvents;

10. fixtures to hold the components during welding;

11. automatic linear welding equipment for seam welding of container shells; and

12. automated circumferential welding equipment to weld bottom-head closures and lifting rings to shells.

Inspection facilities are provided for complete dimensional and fabrication quality inspection of the finished container baskets. Radiography and/or ultrasonic and dye-penetrant inspection methods are provided for all container welds. Segregated storage facilities are provided for the finished containers and top-head closures. Provision is also made to store inspection records in a centralized area.

4.6 AUXILIARY BUILDING

The auxiliary building is located adjacent to the Used-Fuel Packaging Plant (Figure 4-2), and houses the facilities that are closely associated with its operation. It is a two-storey building with a basement, and provides the main access for workers into the potentially radioactive and protected area of the site via an overhead corridor from the administration building. The building dimensions are about 75 m by 50 m.

The first floor contains the mechanical and electrical workshops, stores and various storage areas. The second floor contains the change rooms, lockers, showers and health physics area. It also contains the environmental and counting laboratories, change room and shower area, and radiation protection equipment area. A proposed layout for the first and second floors is shown in Figure 4-46. The basement contains various building equipment and sample archives.

The employees whose jobs are in zones where there is the potential for radioactive contamination will change from regular clothes to working clothes in the auxiliary building, and have access routes from there to the Used-Fuel Packaging Plant and the service-shaft headframe.

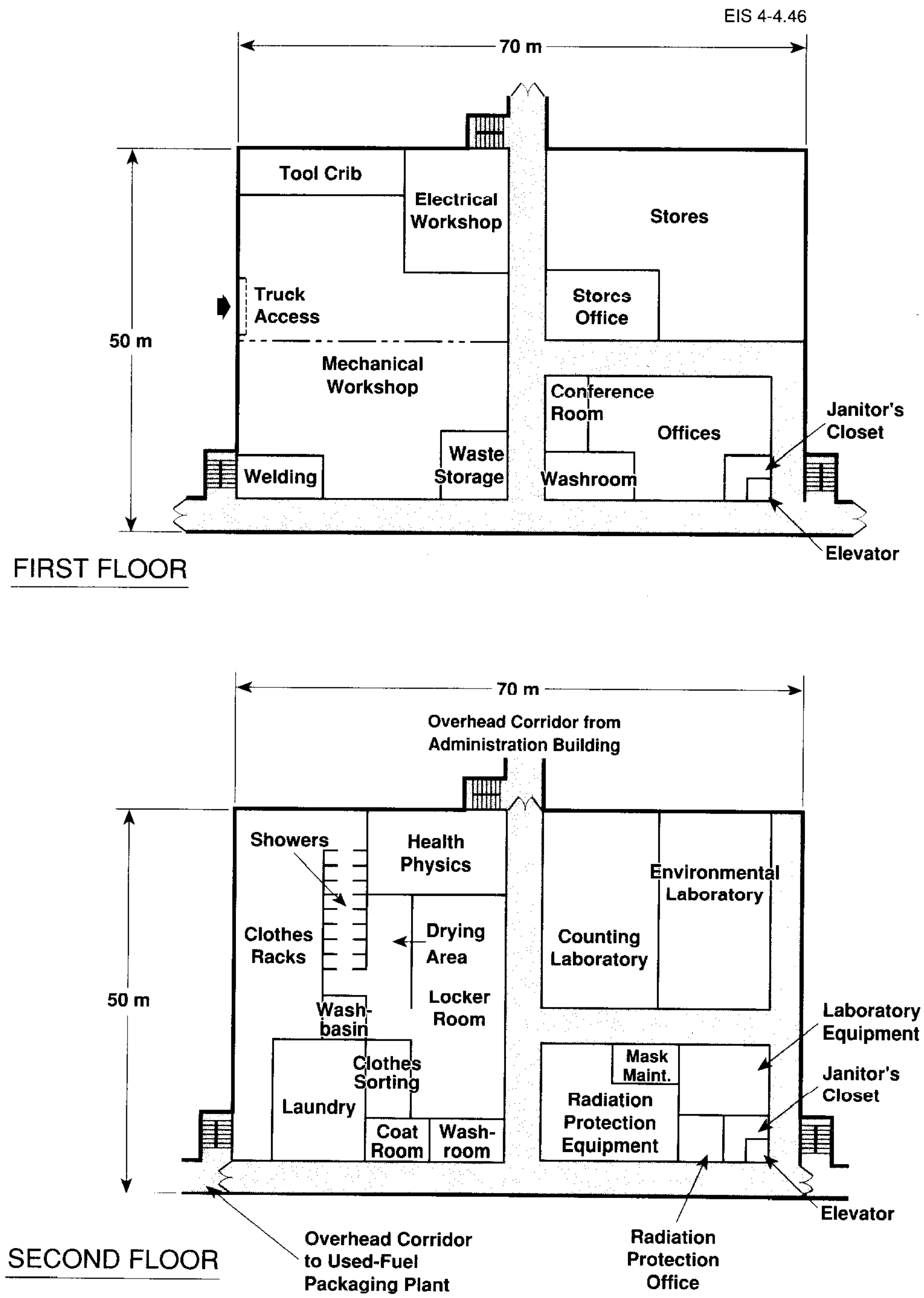


FIGURE 4-46: Auxiliary Building Floor Plans (after AECL CANDU et al. 1992)

5. THE OPERATION STAGE OF THE USED-FUEL DISPOSAL CENTRE

5.1 INTRODUCTION

5.1.1 General

The operation stage involves the receipt, packaging and disposal of used fuel. The Used-Fuel Disposal Centre conceptual design assumes that 10.1 million used-fuel bundles will be disposed of over a period of about 41 a. This involves receiving used-fuel bundles in transportation casks, transferring them from storage/shipping modules to disposal container baskets, placing and sealing the baskets into corrosion-resistant containers, transferring the containers in casks into the disposal vault, and sealing each container in a buffer-lined emplacement borehole. When all the emplacement boreholes in a disposal room are filled, the room is filled with compacted backfill materials and sealed with a concrete bulkhead. Excavation and preparation of additional disposal rooms will continue concurrently with disposal operations.

The operation stage begins when the construction of appropriate surface and underground facilities is complete (Figure 4-11), the systems and equipment are commissioned, an operating licence is granted and sufficient used fuel has been received to half fill the various surge-storage bays and cask storage areas. One panel (i.e., Panel A) with 64 disposal rooms will have been excavated, 10 to 12 rooms will be ready for initial buffer emplacement operations, and 10 to 12 rooms in each of two subsequent panels (i.e., Panels B and C) will have been excavated, as shown in Figure 4-14d. This excavation in Panels B and C is necessary to ensure a smooth transition from emplacement to excavation as disposal operations move from Panel A to Panel B.

Prior to operation, the staff will be trained, and the management, the administration and the operational procedures necessary to conduct operations will be established. Operating and quality-control procedures, end-product specifications, and method specifications based on experience during commissioning and start-up will be available; the work force will be trained and qualified for their activities, and will have been indoctrinated into a safety and health program. The quality assurance program will be revised to reflect the activities and quality-control procedures needed for the operation, and all staff will be trained in its application. The safeguards containment/surveillance equipment, procedures and systems will have been demonstrated to the satisfaction of the AECB and the IAEA staff before used fuel is brought to the site. The waste management and occupational/public safety programs, systems and procedures will have been reviewed and accepted by the appropriate regulatory and public review groups.

The design description of the conceptual disposal centre facilities and systems was presented in Chapter 4, and is discussed in more detail by AECL CANDU et al. (1992).

The following sections describe the operations in the important facilities of the disposal centre in sufficient detail to show their integration and practicability. The Used-Fuel Disposal Centre operations flowchart is shown in Figure 5-1. This figure shows the sequence of operations that must be followed from the receipt of fuel to sealing of a disposal room.

The technology necessary to perform the various container fabrication and packaging operations has been demonstrated in many cases, but in others it is assumed on the basis of extrapolation from available technology. A thorough discussion of many technology issues is given by Johnson et al. (1994a) and in Chapter 2. Some of the specific technologies selected for this reference engineering concept are also identified by Johnson et al. (1994a) and in Chapter 3.

5.1.2 Monitoring Disposal System Performance

The various operating systems will be put into normal operation once the disposal centre receives an operating licence. At this time, quality-control and performance-monitoring systems will be in place, and baseline data should be available for the undisturbed site and for conditions at the end of the construction stage so that the performance of the systems can continue to be monitored and controlled.

The quality of all incoming materials, fabricated products and final emplacements is controlled through the formal quality assurance program. Regular assessment or testing of product quality will be done to confirm the suitability of method specifications (i.e., the procedure for completing an operation to the requirements of a specification), fabrication procedures and installation standards established for each operation. The quality assurance program provides for formal review of existing procedures and approval of revised or new procedures consistent with the adaptive approach being taken in the design of the facility.

In the vault, room excavation will continue until the last five years of the fuel emplacement period, and room sealing will continue until the end of the fuel emplacement period. Therefore, characterization, monitoring, and design activities will continue to identify and respond to the in situ conditions. The newly exposed ground conditions would be assessed in the context of the known site conditions to determine the suitability of each new room for waste disposal, and to adapt the excavation and sealing designs, if necessary. In accordance with the observational method, these activities will terminate only with the completion of disposal vault sealing (Chapter 6).

The rock/groundwater system will respond to new hydraulic and thermal perturbations once heat-generating waste is emplaced in the vault and the emplacement boreholes and disposal rooms are sealed. The sealing materials, groundwater and rock begin to heat and expand thermally, the groundwater pore pressures may begin to rise, moisture begins to migrate in the buffer and backfill materials, and the chemistries of the various components of the vault environment begin to interact. The various monitoring systems installed as part of the characterization and monitoring activities during the siting and construction stages and any additional systems deemed necessary in the operation stage will measure the changes in displacement,

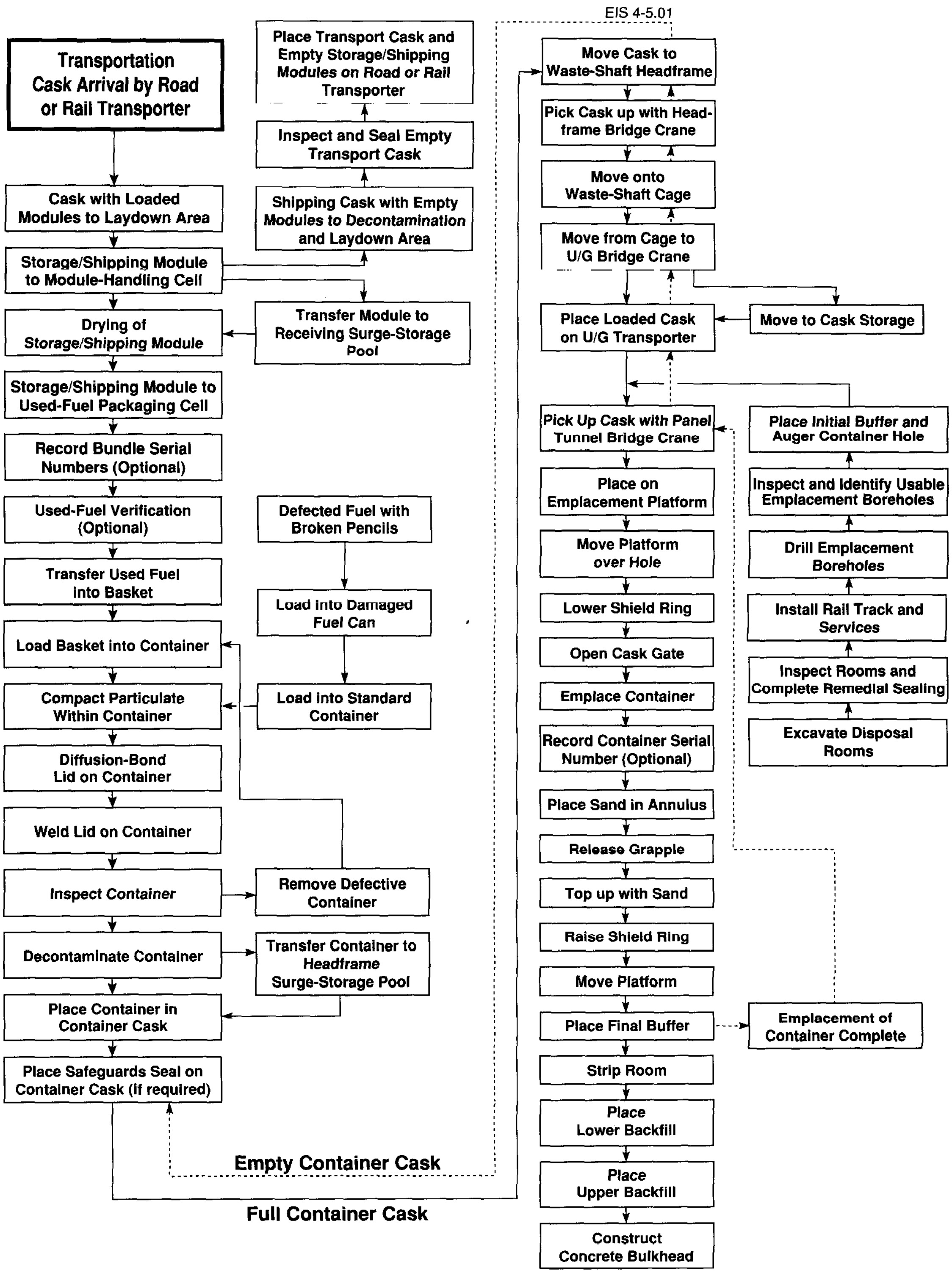


FIGURE 5-1: Used-Fuel Disposal Centre Operations Flowchart (after AECL CANDU et al. 1992)

stress, pressure, temperature and chemistry over time. (Performance monitoring and component testing were discussed in Sections 2.4.2.2 and 3.2.2.2.)

5.1.3 Schedule for Used-Fuel Disposal Centre Operation

The work schedule assumed for most operations in the Used-Fuel Disposal Centre is 260 working days per year. This is divided into 13 twenty-eight-calendar-day cycles. In each cycle, work will generally be done on a 5-d week, two 8-h shifts per day basis. Therefore, each 28-calendar-day cycle normally contains 20 working days with 40 working shifts. However, some specific operations, such as concrete placement, shaft inspection and maintenance, and explosives receipt, will be scheduled 24 h/d, as required. As well, certain operations, such as security, fire protection and site services, are assumed to operate 7 d/week, 24 h/d.

The Container and Basket Fabrication Plant and the Used-Fuel Packaging Plant will normally operate for 12 twenty-eight-day cycles per year with time off for 10 statutory holidays. This schedule provides 230 working days with one 28-day cycle available for vacations and maintenance activities. The underground operations in the disposal vault are assumed to be scheduled for 13 twenty-eight-day cycles or 260 working days per year.

The operations are planned so that critical activities are completed within a 16-h period or with overtime by working into the third shift in the day.

These 230-working-day and 260-working-day per year schedules use 460 and 520 respectively of the 1095 available shifts in a year. This provides a margin of at least 575 shifts for maintenance, repairs or modifications, and to make up any slippage in the rate of used-fuel packaging and disposal. Ample time has been allowed in this schedule to accommodate any underestimates in the durations of individual operations and activities. However, any increases in operating times required for aspects of waste packaging and emplacement would involve increased costs. It is anticipated that these costs can be accommodated in the uncertainty range in the cost estimate described in Chapter 7.

5.2 USED-FUEL PACKAGING PLANT

5.2.1 Used-Fuel Receipt and Storage

At full operating capacity, about 50 storage/shipping modules, each containing 96 fuel bundles, are received at the disposal centre each week. This requires receiving either 25 road casks or 9 rail casks or some combination of the two cask types.

The road or rail transporter is received at one of the four stations in the transportation cask receiving and shipping area (Figure 4-20). In the normal situation where the transportation cask has not been damaged in transit and at least one of the safeguards seals is intact, the cask will be handled following normal procedures. If the cask has been damaged, or both safeguards seals are broken, the cask will be moved to the damaged transportation-cask hot cell. Normally, a filled transportation cask

(Figure 3-6 and 3-7) is removed from the transporter, the impact limiter is removed, and the cask is placed in the full-cask laydown area. An empty, decontaminated cask, loaded with empty storage/shipping modules, and an impact limiter are placed on the transporter for return to the nuclear generating stations. Metal tags and safeguards seals are used to identify loaded casks, and metal tags are used to identify empty, decontaminated casks. The metal tags would have appropriate wording and could be colour-coded to improve recognition.

A cask is moved from the full-cask laydown area to one of two scissors-lift trolley stations for unloading into a module-handling cell. As the cask is unloaded from its top, the closure devices (i.e., bolts or nuts) sealing the top lid are removed before the cask is loaded on the scissors-lift trolley.

The scissors lift is used to raise the cask to form a seal with a port in the module-handling cell floor (Figure 4-21). When the cask has been sealed into the floor port, the port-shielding lid is removed from the inside of the cell. The cask lid is then removed and placed on the floor of the module-handling cell. The storage/shipping modules of used fuel are removed from the cask using a module-handling tool.

Depending on the state of the packaging plant operations, the module is either transferred directly to the used-fuel packaging cell (Section 5.2.2) or to the receiving surge-storage pool. In the latter case, the modules are lowered into the pool on an inclined elevator, and they are transferred using the pool manbridge and module-handling tool into secure stacking frames within the pool (Figure 4-28). The modules are retrieved and put into the packaging cell by reversing this storage sequence.

The modules are dried in a forced-air drier and placed on a trolley at the air lock to the packaging cell before they are transferred to the packaging cell (Figure 4-27). There are two trolleys at the air lock, each holding two modules. The dried, full modules are transferred to the packaging cell on one trolley, and the empty modules are returned to the module-handling cell on the other. The empty modules are placed into the empty casks, which are sealed and stored in the empty-cask laydown area to await shipment off-site.

Although there is a low probability that a transportation cask may be damaged on receipt or that the safeguards seals may be broken, it could happen. To deal with this eventuality, the cask would be transferred to the damaged transportation-cask hot cell, which is accessible from the transporter receiving and shipping area (Figure 4-20). This operation will be essential for any damaged casks. This may be the preferred method for reestablishing the continuity of knowledge for the used-fuel inventory in casks whose safeguards seals have been broken. The operations in this hot cell would likely be manually controlled because of the wide variability in the possible physical condition of the transportation casks.

The defected transportation cask would be inspected visually in this hot cell, the lid bolts would be removed, and the lid would be set aside. Depending on the physical condition of the cask, the storage/shipping modules would be lifted out and set in a storage area within the cell. Any pieces of damaged fuel bundles that remain in the cask would be removed and the cask would be moved to a decontamination compartment within the cell for cleanup. The empty, damaged cask would be prepared for shipment to its owner for repair or disposition.

Individually, the contents of each storage/shipping module would be unloaded onto an inspection table where intact bundles would be identified and placed in other storage/shipping modules. Damaged fuel-bundle components and pieces would be gathered and weighed for nuclear material inventory purposes and would be placed in a damaged-fuel can. In this way the entire inventory of the damaged cask would be reconfirmed and allocated to a storage/shipping module or a damaged-fuel can.

This procedure might also be followed for transportation casks received at the disposal centre with no intact safeguards seal. By transferring these casks to the hot cell, the potential for disruptions to the routine operations of the package plant is eliminated since the nuclear material inventory is verified and safeguards are reestablished for the contents of these casks before the material is entered into the packaging process lines.

When a storage/shipping module has been filled with properly identified, structurally intact fuel bundles recovered from casks that were damaged or for which continuity of safeguards containment was lost, it would be placed in a specially designed transfer cask. This special transfer cask would be decontaminated and moved to the cask port in the module-handling cell. The storage/shipping would be transferred for normal packaging through a module handling cell as discussed above. When a damaged-fuel can has been loaded with the desired amount of damaged fuel-bundle parts and components, it would be closed and placed in a specially designed transfer cask. This special transfer cask would be decontaminated and moved to a transfer port into a module-handling cell. The damaged-fuel can would be inserted into the packaging process through the special handling area (Figure 4-23). The packaging of these cans is discussed in Section 5.2.2.

5.2.2 Used-Fuel Packaging

An empty storage/shipping module is placed on the empty module trolley in the used-fuel packaging cell (Figure 4-20), and a full module is picked up from the full module trolley. The bridge and carriage positions the module relative to the used-fuel transfer assembly.

The used-fuel transfer assembly is loaded with a used-fuel container basket in a horizontal position. The basket is positioned using rotary and lateral motion so that fuel bundles can be transferred to all positions of the basket (Figure 4-32).

The individual used-fuel bundles are transferred sequentially from the storage/shipping module via the transfer carousel into one of the 18 pipes of the disposal container basket. The end plates on the bundle can be cleaned during this operation so that the manufacturer and serial numbers can be read and recorded for accounting purposes. If desired, the optional gamma-radiation monitor can read the magnitude and energy spectrum of the radiation being emitted from the bundle to confirm the presence of used fuel. In the event that a bundle is damaged from shipping or handling and is unable to be transferred to the basket, or cannot be adequately identified and needs further examination, it is transferred into a special handling area (Figure 4-23) using the bundle retrieval service ram.

Facilities are provided in the special handling area to manually clean and examine intact used-fuel bundles to identify them adequately for inventory and, if necessary, safeguards purposes. The used-fuel bundles are returned to the basket loading process by placing them into empty slots in a storage/shipping module for transfer into a basket. Damaged fuel bundles and fuel-bundle components are placed into a 500-mm-high damaged-fuel can. Each can will be identified with a serial number and its contents will be recorded. The diameter of the damaged-fuel can will depend on the method chosen to place them into the disposal container. If the damaged-fuel cans are individually placed directly into the container, the outside diameter could be about 600 mm and four cans could be placed in one container. If the cans are first placed in a special handling basket, the outside diameter of the damaged-fuel can would be controlled by the design of the basket. In this case it is likely only three damaged-fuel cans could be fit in a disposal container. We have not prepared a conceptual design for the damaged-fuel can.

When a storage/shipping module is empty, the operation stops, the empty module is returned to the appropriate transfer trolley, and a full module is picked up by the bridge/carriage assembly. When a container basket is filled, the operation also stops, the basket is indexed to the vertical orientation on the tilting table, and is removed from the saddle and replaced with an empty basket. The loaded basket is moved to the container loading station in a vertical orientation.

An empty container shell is placed on the container shaker table (Figure 4-24) at the container loading station, and the loaded basket is lowered into the container. The container surface that forms part of the closure bond is covered with a removable sleeve to protect it from abrasion and metal contamination by the basket during this operation. The void space in the container is then filled with a fixed volume of glass-bead particulate from the particulate-metering hopper, and the particulate is compacted by the vibration of the table. Similarly, when three damaged-fuel cans have been filled at the special handling area or the damaged transportation-cask hot cell, they are moved individually to the shaker table and are filled with vibrationally compacted particulate. They are then placed into a container shell and the balance of the container void space is filled with vibrationally compacted particulate.

If necessary from a safeguards perspective, the serial numbers of all fuel bundles and damaged-fuel cans can be recorded against the serial number of the disposal container into which they are loaded and sealed.

The container of used fuel and compacted particulate is transferred to the rotary table of the container closure station (Figure 4-25). The inner surface of the container shell at the location to be sealed by the diffusion bond is cleaned with a titanium brush and swabbed with a noncorrosive cleaner. The top-head closure for the container is preselected to provide the interference fit necessary for a successful diffusion bond and is press-fit to the correct location in the top end of the container.

The head closure is diffusion-bonded using a method that has been demonstrated in the Nuclear Fuel Waste Management Program (Johnson et al. 1994a). The bond is made by rotating the container around its axis on the rotary table while a drive wheel and a free wheel put a substantial force across the surfaces to be bonded. A high-amperage, low-voltage direct current is pulsed through the joint by the electrode wheels as the container is rotated. The polarity of the current is reversed with each pulse.

After visual examination, the sealed container is moved to the rotary table of the ultrasonic inspection station. As discussed in Section 4.4.4.4, the ultrasonic coupling is achieved using a water jet. Following a successful ultrasonic inspection, the container is moved by the bridge crane to the helium leak-testing station, where it is tested as described in Section 4.4.4.4. Figure 4-33 shows a developmental robotic assembly for ultrasonic testing of diffusion bonds.

Containers that fail to pass either of these nondestructive tests are moved to either the container closure station or the container repair station for repair or disassembly. If the ultrasonic inspection identifies an unacceptable defect in the diffusion-bonded top closure joint, an attempt is first made at the container closure station to repair it by passing a second diffusion bond elsewhere on the sealing flange. Failing that, a gas-tungsten-arc weld may be attempted at the container repair station. If a container passes the ultrasonic test but fails the helium leak test, or fails either test following closure repair, the container is disassembled (Figure 4-34) and the loaded basket is retrieved for reloading into another container at the container loading station.

Disassembly involves setting and clamping the container vertically on a rotary table, cutting the top and bottom of the container with an abrasive disc cutter and cutting the shell axially on each side. The container shell sections are removed, checked for radioactive contamination, decontaminated, if necessary, and may either be recycled if suitably decontaminated or treated as low-level radioactive waste. A vacuum and catchment system contains and recycles the spilled glass particulate.

A container that passes inspection is decontaminated at a decontamination station using water jets to wash the container exterior. A wet-vacuum system is used to remove water sitting on the top-head closure, and air driers complete the process. Swipe tests are performed to check for surface contamination. The container is then ready to be loaded into a container cask or placed in the headframe surge-storage pool. As noted in Section 4.4.4.4., perhaps 14 to 140 of the containers that pass inspection during the operation stage will have very small manufacturing defects or will fail prematurely.

The inspection stations are the only facilities at the disposal centre where the integrity of a disposal container can be assessed. When a container has successfully passed inspection, it is assumed that subsequent wet or dry storage and dry handling will not be detrimental to the container integrity. This assumption would be confirmed during facility commissioning and startup, and periodically during the operation stage. This confirmation would involve retesting the integrity of disposal containers following long periods in wet and dry storage and extensive handling in container casks. Procedures would also be developed to verify the performance of the inspection equipment at regular intervals.

5.2.3 Disposal Container Transfer to the Waste Transport Shaft

The decontaminated containers are handled in one of two streams when they leave the packaging cell. They are either put into temporary storage in the headframe surge-storage pool via an inclined elevator, as described in Section 4.4.6, or are loaded directly into container casks for underground disposal.

The decontaminated containers to be moved directly underground are loaded onto a sliding table in the decontamination area and moved to a location under the loading port in the cask support platform (Figures 4-22 and 4-36) of the packaging-cell cask-loading station. The container cask described in Section 4.4.5 is positioned over the port by an overhead crane. The cask-bottom gate and packaging-cell loading-port gate are opened. The container positioned below the cask support platform is raised into the cask using the container grapple (Figure 4-35) and hoist drive on the cask. When the container is in the cask, the cask-bottom and loading-port gates are closed. The loaded and sealed cask (Figure 4-26) is placed on a trolley by an overhead crane and is towed to the waste-shaft headframe cask laydown area.

Containers in the headframe pool are retrieved either via the cask-loading carousel of the pool cask-loading station for normal conditions (Figure 4-39) or via the inclined elevator to the packaging cell decontamination station, and are loaded into the container casks using the packaging-cell cask-loading station (Figure 4-22) if the pool cask-loading station is not in operation (see Section 4.4.6). The full container cask is transferred to a trolley and is towed to the waste-shaft headframe cask laydown area to await transfer underground.

The loading of container casks at any of the stations can be observed by an IAEA safeguards inspector and by safeguards containment/surveillance cameras, if required. Each container cask, serial number and its contents may be recorded, and the cask may be sealed with two safeguard seals by an IAEA inspector or by an operator, if required, according to the agreed safeguards measures.

5.3 BASKET AND CONTAINER FABRICATION

The materials for the disposal container basket consist of carbon steel tube, pipe, plate and bar stock. The basket (Figure 5-2) has 19 vertical tubes and pipes. Eighteen tubes are designed to hold four used-fuel bundles each and the nineteenth, the central pipe, is a structural member used to handle the basket. The basket and container fabrication equipment is discussed in Section 4.5.

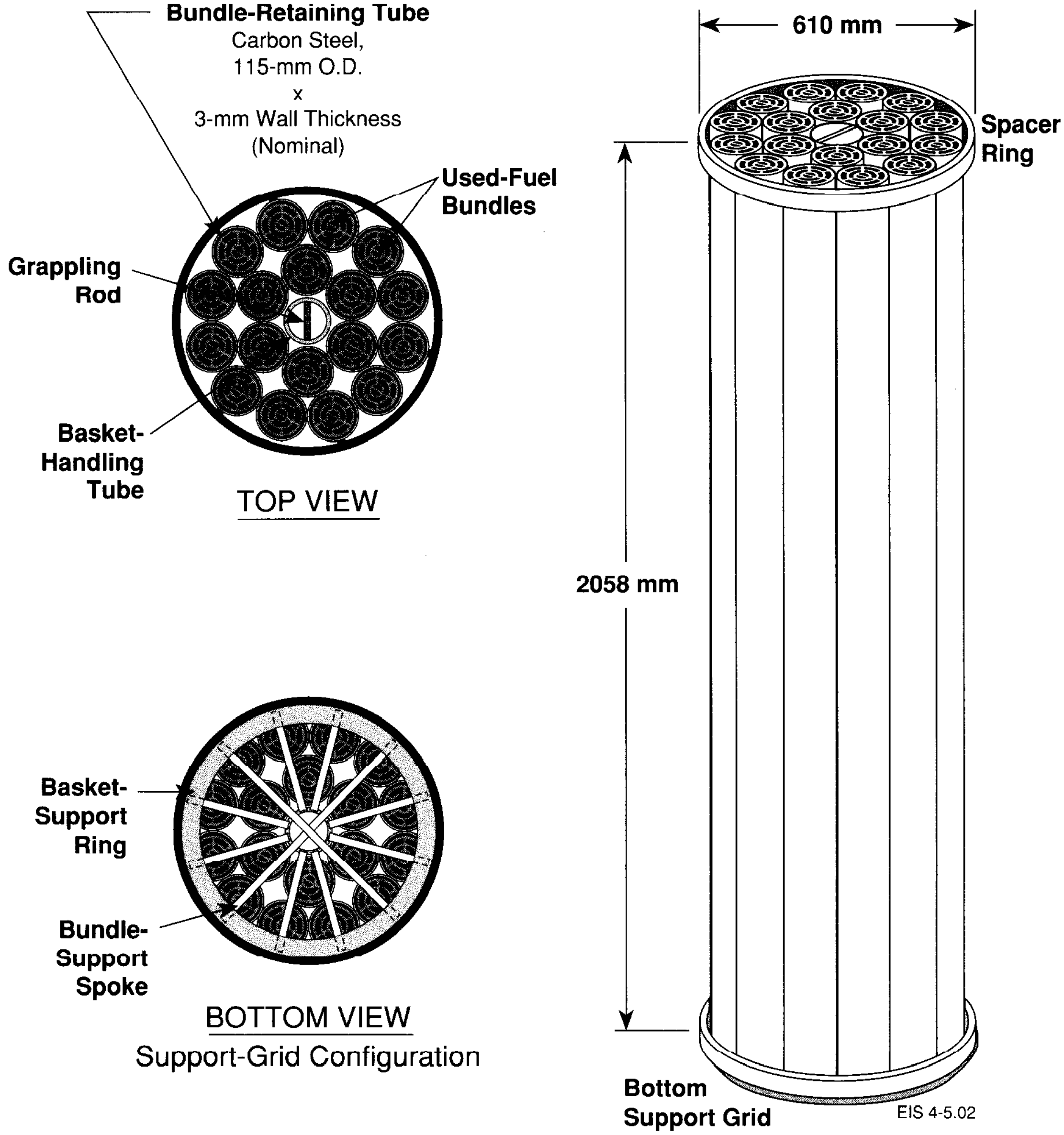


FIGURE 5-2: Used-Fuel Disposal Container Basket (after AECL CANDU et al. 1992)

The 18 tubes for the fuel bundles and the central structural pipe are cut to length with the horizontal turret lathe, the spacer ring and the spoked wheel ring are cut from pipe, the spokes for the bottom ring are cut from bar stock, and the small attachments needed to complete the assembly are forged from bar stock using the drop hammer. The basket components are cut to the final size on a turret lathe. The components are assembled in a welding fixture that maintains alignment during final welding. The basket components are welded together, and the final assembly is inspected for compliance with specifications prior to being placed in inventory.

The material for the disposal container is 6.35-mm-thick titanium plate. The container (Figure 3-5) is a vessel comprising formed bottom and top heads, and a rolled shell. A reinforcing ring is added at the top of the head to serve as the lifting fixture.

The blanks for the heads are cut by the rotary shear cutter from the appropriate plate, and the heads are formed to shape in a hot-forming press. These heads are vacuum heat-treated at temperatures from 540 to 590°C for 30 min in a heat-treating furnace to reduce the material stresses caused by forming. After heat treating, final preparation of the weld or bonding surfaces is done in a vertical turret lathe. The shell material is cut from plate with the shear cutter, the weld surfaces are prepared using the planer, and the plate is formed into a cylinder in bending rolls. All components except the top head are assembled in a series of welding fixtures, and are joined by gas-tungsten-arc welding. The lifting ring is cut from plate with the band saw, formed on the bending roll and welded to the shell. A unique container serial number is stamped into the outer surface of the lifting ring. If deemed necessary to relieve the residual stresses caused by welding, the welded container shell can also be heat-treated at 540 to 590°C for an appropriate period in a vacuum furnace. This heat-treating step has not been included in this conceptual design.

The finished assembly is inspected visually, and all welds are radiographed. The top heads are also given a dimensional inspection. The dimensions of the top opening in each shell and of each top head, along with an identification number, are stamped on the components in noncritical areas to ease the matching of heads and shells in the Used-Fuel Packaging Plant, where the shell/head interference fit is an important factor in achieving good diffusion bonds. The completed container assemblies and heads are placed in storage until they are required in the packaging plant.

5.4 DISPOSAL VAULT OPERATIONS

5.4.1 Separation of Air and Material Flows

Activities in the disposal vault during the operation stage take place concurrently in three areas: in the excavation panel, in the emplacement panel and in the underground ancillary service areas. The general sequence of operations and the location of these areas is shown on Figure 3-19. The underground ancillary service areas are discussed in Sections 4.3.4, 4.3.5 and 4.3.7. The others are discussed in this section.

In the Used-Fuel Disposal Centre conceptual design, the disposal vault is arranged to minimize the worker activity in areas that are exposed to potentially radioactive contaminated air and/or vault drainage water or to the handling of disposal containers (Sections 4.3.6 and 4.3.7). The excavation panel operations are physically separate from the emplacement panel operations. Both panels are supplied with fresh ventilation air from the service-shaft complex by a network of tunnels and ventilation/access control doors. However, each panel has a separate ventilation exhaust.

The panel operations also have separate vault drainage-water circuits. The drainage-water circuits from the emplacement and excavation panels are separate systems until they reach the upcast-shaft complex water-drainage system. Operations within the emplacement panel are scheduled so that container emplacement is segregated from most other operations.

These arrangements minimize the potential for workers to be exposed to radioactivity, and are the basis for the physical arrangement and sequence of operations discussed here.

5.4.2 Panel Construction and Servicing

The panel excavation and emplacement sequence during the early part of the operation stage is shown in Figure 3-19. The emplacement of used-fuel disposal containers begins in Panel A, excavated as part of the construction stage, while the excavation crews are excavating and servicing the last 48 to 50 disposal rooms of Panel B and the first 10 to 12 rooms of Panel D. These two operations, excavation and emplacement, are always done on opposite sides of the central access tunnels to allow separation of ventilation airflows and material flows. Each operation is estimated to take about five years per panel.

The work in each disposal room within the emplacement panel follows the sequence shown in Figure 5-3, which takes advantage of the parallel panel tunnels to separate waste emplacement operations from other operations in the preparation and sealing of disposal rooms. The operating duration from preparation to sealing an individual disposal room corresponds to 13 twenty-eight-day operating cycles. Most activities in the room take place during the cycles when actual container emplacement is being done from the other of the parallel panel tunnels. The exceptions are the container-emplacement operations and the upper backfill installation in that room. During the emplacement of upper backfill, done concurrently with container emplacement in the next room, the workers are upstream of the emplacement operations in terms of the ventilation air supply and of the water-drainage system to minimize the potential for exposure.

By scheduling concurrent container emplacement and disposal-room excavation, the duration of the construction stage and, therefore, the costs incurred prior to beginning disposal, are reduced. As well, the time between excavation and sealing of a disposal room is minimized, which will minimize the amount of effort required to provide a continuing safe working environment in disposal rooms.

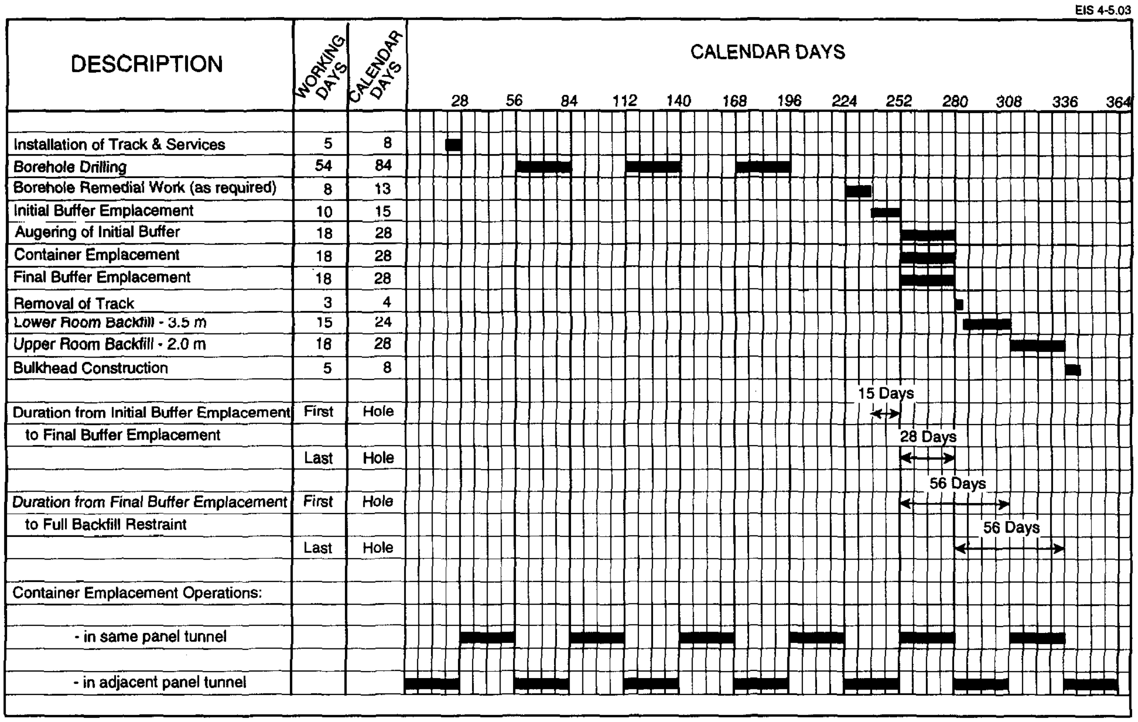


FIGURE 5-3: Disposal-Room Schedule for a Given Room (after AECL CANDU et al. 1992)

When waste containers have been emplaced in all the rooms of Panel A, the emplacement operation moves to Panel B. The excavation and servicing operations move to the rooms of Panel C and the first 10 to 12 rooms of Panel E. In this manner, Panels B through H are excavated, serviced and filled during the operating life of the vault.

As the emplacement rate of containers is the controlling activity in the disposal vault schedule, the excavation time for a room in the excavation panel is tailored to the 28-calendar-day cycle (i.e., 20 working days) necessary to fill the maximum of 282 emplacement boreholes in a disposal room. The room-excavation operations are based on underground construction methods using careful drill-and-blast excavation because it is well proven. Five years are needed to develop 64 disposal rooms, 32 rooms from each of the twinned panel tunnels. Each disposal room is 5.5 m high with an arched crown 8.0 m wide and 230 m long. This requires an excavation rate of 26 200 Mg of rock every 20 working days, or 1310 Mg/d. To achieve this, excavation occurs simultaneously in two rooms, one crew working in each room and excavating one complete 3.2-m blast round per shift. This is a practical excavation rate, and the many excavation faces available allow flexibility in assigning work areas. The panel-tunnel and disposal-room services, including electrical power, water, compressed air and ventilation, are installed as part of the excavation operations. Room excavation and characterization details are discussed in Section 4.3.3.

The excavated rock is loaded into 24-Mg mine trucks and is dumped through a grizzly screen with a rock breaker into the service-shaft loading pocket. The skip, dedicated to transporting excavated rock, has a capacity of 9 Mg and the skipping rate is 800 Mg/shift. The rock is transferred to a storage bin in the service-shaft headframe, and then to a conveyor that transports it either to the excavated-rock disposal area or directly to the rock crushing plant.

5.4.3 Disposal-Room Preparation

The layout and operating concept for each panel is designed to separate the work areas for activities involving radioactive materials from most other activities. Each panel is divided into distinct halves, each comprising one panel tunnel and 32 disposal rooms (Figure 3-20). In any 28-d cycle, one of the panel tunnels is the drilling panel tunnel and the other is the emplacement panel tunnel.

The following activities take place in disposal rooms accessed from the drilling-panel tunnel.*

1. Installation of rail track and ventilation ducts.
2. Simultaneous emplacement-borehole drilling in three rooms.
3. Initial buffer placement in emplacement boreholes.
4. Lower backfill placement.
5. Bulkhead construction.

The following activities take place in disposal rooms accessed from the emplacement-panel tunnel.

1. Augering container openings in the initially placed buffer.
2. Emplacing the container, sand and final buffer.
3. Upper-room backfilling.

5.4.3.1 Schedule

As discussed in Section 5.4.2, the operations within a panel are planned on a 28-calendar-day cycle, and alternate from one side of the twinned panel tunnels to the other between cycles. That is, when a disposal room is filled with containers, an activity requiring 28 calendar days to complete, the emplacement operation moves to a room on the other side of the panel tunnels. For this new cycle, emplacement operations begin in a disposal room that was prepared previously to accept containers, and is accessed from what was the drilling panel tunnel. The drilling panel operations move to disposal rooms accessed from what was previously the emplacement

* Those activities enclosed by "*" are discussed in this section. The others are discussed in Sections 5.4.5 and 5.4.6.

panel tunnel. The schedule for operations in a disposal room is shown in Figure 5-3. When container-emplacement operations are taking place in one disposal room on one side of a panel (e.g., augering initial buffer, container emplacement and final buffer placement), all other room preparation and sealing activities except upper backfill placement cease in rooms on that side for a full 28-calendar-day cycle.

5.4.3.2 Ventilation and Rail-Track Installation

The first operation in preparing a room for emplacement is the installation of the ventilation ducts and the rail track. The ventilation system comprises two rigid, steel ducts that are installed to the end of the disposal room and are anchored to the rock at the corners of the arched crown of the room (Figures 5-4 and 4-18). Details are discussed in Section 4.3.6.

The potential for and the significance of groundwater seepages is assessed during the preparation of each disposal room. The seepage areas are sealed using grout if the seepage rate is significant and could degrade the quality of the buffer during emplacement operations. If the rate of seepage is lower but might still interfere with buffer or backfill quality, or the potential for condensation dripping from the crown of the room is significant during these operations, a fabric "umbrella" would be installed, as shown in Figure 5-4, to deflect this moisture to the drainage channels outside the rail track.

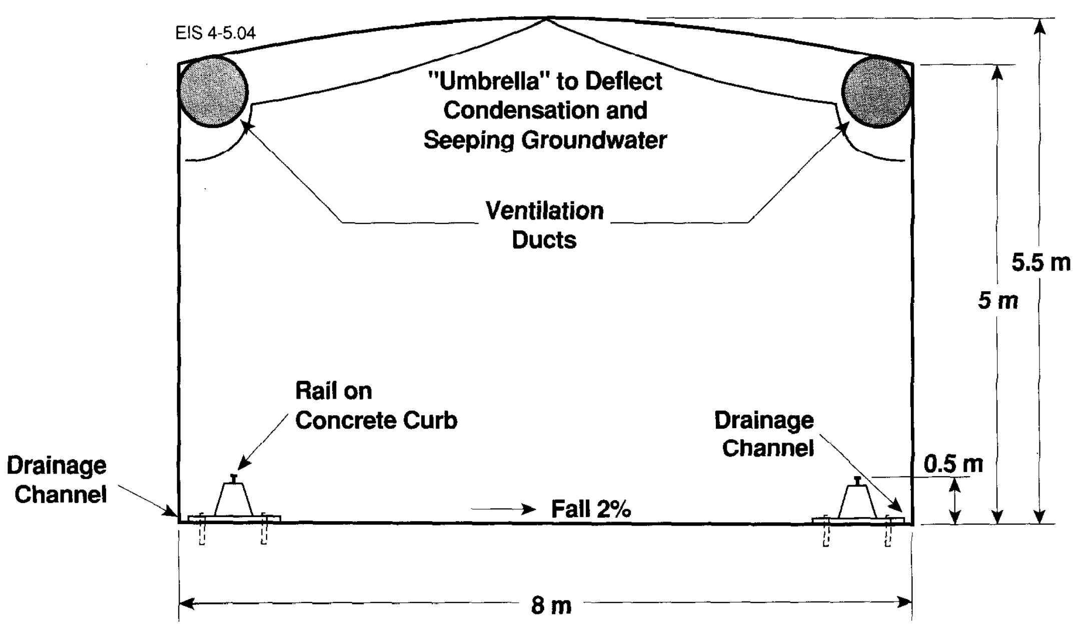


FIGURE 5-4: Disposal-Room Preparation (after AECL CANDU et al. 1992)

The rail track is installed in segments to simplify removal for room backfilling. Concrete curbs are formed and poured on each side of the room (Figure 5-4), and are anchored into the floor of the disposal room with short dowels at regular intervals. The track gauge is 6.8 m. The curb on both sides of the room also acts as a channel for directing drainage water to the panel tunnel. Pipes are put through the curbs at regular intervals to allow water from the centre of the room to reach the drainage channel. These are plugged before the initial buffer emplacement begins. The curbs and track extend from the room entrance across the panel tunnel so that the rail-mounted equipment can be reached by an overhead crane in the panel tunnel.

The overhead crane is installed in the panel tunnel to move the rail-mounted equipment from room to room, the loaded container casks from the transporters to the emplacement platform, and the empty casks from the emplacement platform to the transporters. At any time, there is rail track extending across the panel tunnels from several rooms. This necessitates temporary ramps and rail-track crossovers so vehicles can move into and out of the rooms to handle emplacement borehole core, buffer material and routine maintenance operations.

Installation of the room ventilation system, the curb, and the rail track takes about five days of a cycle. The balance of this cycle and the next 28-calendar-day cycle are reserved for the concrete to set before rail-mounted platforms are placed on the rails and moved into the room.

5.4.3.3 Emplacement-Borehole Drilling

The emplacement-borehole drilling begins in the operating cycle after the rail-curb concrete has set. The total time to drill 282 boreholes in a room is assumed to span five 28-day cycles. Drilling takes place during three of the five cycles when disposal containers are being emplaced in the rooms off the other panel tunnel (Figure 5-3). Drilling is conducted in three or more disposal rooms off a drilling panel tunnel at the same time, depending on the drilling rate. The drilling activity occurs only in the rooms attached to the designated drilling panel tunnel. This sequence of operations is only practical if there is a complete set of the necessary drilling equipment available in each of the three rooms off each panel tunnel (i.e., at least six sets) to avoid having to relocate the equipment from one panel tunnel to the other every 28 d.

Each drilling rig is mounted on an electrically powered rail-mounted platform approximately 7.5 m wide and 5 m long. The rig can be moved as a single unit from one disposal room to the next using the panel-tunnel overhead crane. The drilling unit is currently conceived to be a diamond core drill comprising a rotary table, a derrick, a winch, a rock breaker and a vacuum unit. The equipment is similar to that used for surface foundation work, modified for low headroom and electrical power. The diamond-drill core barrel is double-walled, with cooling air and/or water fed through the annulus to remove drill cuttings and to improve penetration and reduce wear. However, other methods such as blind boring or water-jet drilling might be used.

The core drill is mounted on a transverse slide assembly to enable it to be set over any of the three borehole positions across the width of the room (Figure 5-5). Index location indents on the slide indicate the 2.1-m hole centres for the emplacement boreholes. It is assumed for this discussion that the hole spacing is uniform throughout the vault, though the spacing can be adjusted as required, particularly along the axis of a room.

The boreholes are drilled in a retreat manner, starting at the end of the room farthest from the entrance. The first set of holes is drilled 13.5 m from the end of the room to allow space to park equipment used during the subsequent emplacement operations. Reference points are fixed to the track to identify the centrelines of the emplacement boreholes along the room. These are surveyed to ensure their accuracy and to serve as the location markers for future activities. The platform is located over the desired axial location, and the wheels are locked for drilling. The wheel locks and the mass of the platform and drill provide stability during drilling.

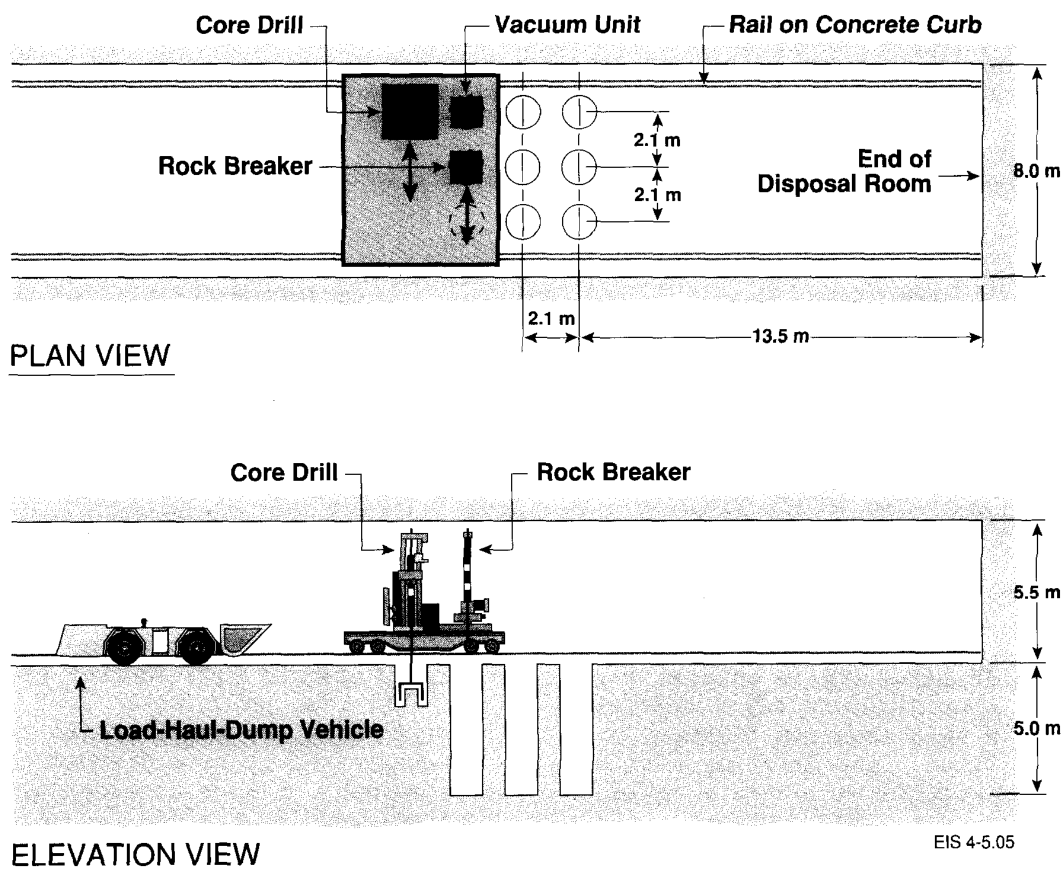


FIGURE 5-5: Emplacement-Borehole Drilling (after AECL CANDU et al. 1992)

Additional stability may be provided by thrust supports jacked against the walls and crown of the room.

For this conceptual design, it is assumed that a single emplacement borehole requires six coring runs to reach the design depth of 5 m. Each section of core is broken off by wedging, and the core is lifted from the hole and placed in the bucket of a load-haul-dump vehicle. The drill is positioned over the next borehole location and restarted on completion of one borehole.

Water is used to cool and lubricate the drill bits and to flush the cuttings from the boreholes during the drilling operations. This water first fills other drilled boreholes and then flows through the rail-track curbs into the drainage channels or flows downgrade to the panel tunnel. An alternate arrangement would be to use nearby boreholes as drill cutting and water collection sumps and to recycle the clarified water.

When a hole is accessible from the end of the platform away from the room entrance, the rock breaker mounted on the platform is used to chip the bottom of the hole to a clean surface if required. The rock chips and standing water are vacuumed from the borehole and the floor of the room. A telescoping vacuum tube ensures sufficient reach to clean all the working areas. The rock chips and water from the vacuum unit are transferred to a load-haul-dump vehicle.

One load-haul-dump vehicle services the drilling platforms in all three rooms being drilled, and transfers the rock cores and the vacuumed waste to a truck in the panel tunnel for transfer to the loading pocket at the service shaft. The cores are broken at the loading pocket grizzly screen to manageable sizes for skip transfer to the surface.

As a room of boreholes is completed, each borehole is pumped dry of water and cleaned of rock residue from the drilling operations. Each borehole is surveyed to record actual locations and verticality. It is assumed that the drilling accuracy is within 0.5% of vertical or 25 mm off line at the bottom of the hole. Temporary safety covers are placed over the open boreholes.

The typical cycle time assumed for a 1.24-m-diameter, 5-m-deep borehole is 145 min. For the assumed rate of production, a drill platform is able to drill about 5.3 emplacement boreholes per day. No drilling method of this scale has yet been shown to provide the desired drill rates of 35 to 40 mm/h. However, the desired rate of emplacement-borehole production is considered to be a reasonable extrapolation of current boring or drilling technology. The issue is one of production-scale equipment design and engineering rather than of technology development. The requirement for over 140 000 boreholes should provide the incentive for the necessary equipment development program when construction of a disposal vault is committed. If the individual machine production rates required cannot be achieved, the plan can readily be adjusted to use more machines and operators in more disposal rooms to attain the required borehole production rate.

5.4.3.4 Borehole Characterization, Remedial Treatment and Acceptance

When the borehole drilling and cleanup operations are completed in the disposal room, the drain pipes through the rail-track curb from the centre of the room are plugged to prevent any seepage water or condensation that is directed into the drainage channels from interfering with the buffer placement operations.

Each emplacement borehole is characterized to confirm its suitability for container emplacement. This includes physical examination, mapping and photography to identify any natural or induced fractures, and measurement of water inflows. By comparing the actual conditions with site-specific acceptance criteria developed from the disposal system performance assessment model, a decision is made on acceptance, the need for remedial treatment such as grouting, or the rejection of each emplacement borehole. If a borehole is rejected, it will be completely filled with buffer material during initial buffer emplacement.

5.4.3.5 Initial Buffer Emplacement

The reference buffer (Section 3.3.3) is emplaced in the borehole once a borehole is accepted for the emplacement of containers. The first operation is to vacuum all the boreholes to remove any standing water and debris using the drilling platform equipment. The drilling platform is then moved to the next room scheduled for borehole drilling. The initial buffer emplacement platform is installed in the room. This platform is about 7.5 m wide and 5 m long (Figure 5-6), and carries three dynamic compactors, three buffer-storage hoppers and a vacuum system. It is used to fill and compact the lower 3.5 m of each emplacement borehole accepted for disposal with the reference buffer material. It is also used to completely fill any emplacement boreholes that are not accepted for disposal with compacted reference buffer material.

The three dynamic compactors are fixed to align over the emplacement borehole centres. Each compactor applies a dynamic load similar to that applied during the modified Proctor compaction test (ASTM 1982). The compaction plate is dimpled or textured to knead the reference buffer during compaction, and it rotates to distribute the contact pressures over the entire surface within the borehole. A hopper with a capacity of 7 Mg is adjacent to each compactor to store the loose buffer material required for each borehole. A retractable feed pipe is used to feed the buffer material from the hopper into the borehole for each compaction lift. Sufficient buffer material is fed into each borehole to form a compacted lift thickness of no more than 0.15 m. The buffer is compacted in about 24 layers to a depth of 3.5 m. It is estimated that a single layer is emplaced and compacted to the specified density in 1.5 min. This operation is conducted simultaneously in the three boreholes. All units on the platform are operated from a single control console on the platform.

The initial buffer is placed in the boreholes in a retreat manner, beginning at the end of the room. The platform is moved beyond the first two sets of three boreholes, and the vacuum unit is used to clean and dry the

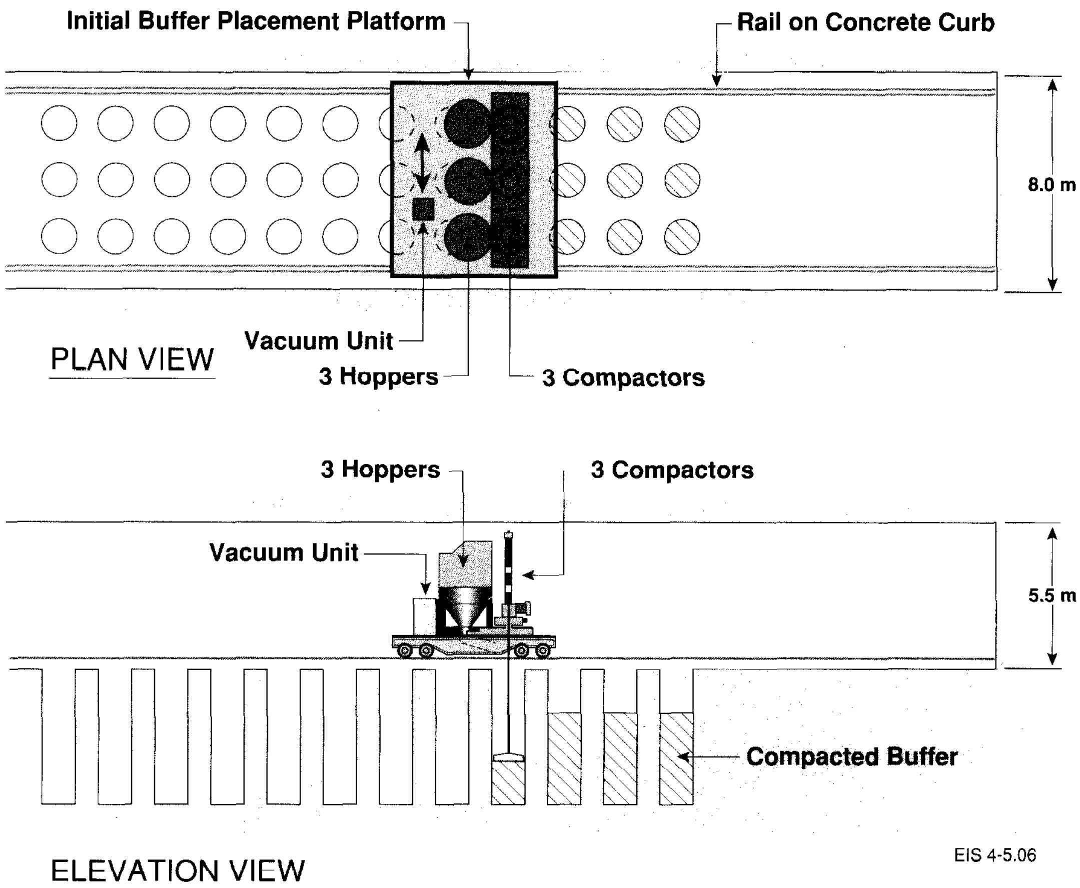


FIGURE 5-6: Initial Buffer Emplacement (after AECL CANDU et al. 1992)

boreholes. The platform is then aligned over the first set of boreholes using the reference points previously installed on the track.

The platform is moved to the panel tunnel between setups to refill the buffer hoppers from the buffer material transport trucks. These 24-Mg trucks have a capacity of about 12 m^3, or 18 Mg of buffer, and two trucks are used to provide the 21 Mg of buffer required to fill the hoppers. If this type of operation is optimized, the use of larger buffer hoppers on the initial buffer emplacement platform or a separate buffer transport platform should be considered to minimize platform movement.

The cycle time assumed for the placement of the initial 3.5 m of buffer in a row of three boreholes is about 67 min, including time to refill the buffer hoppers at the panel tunnel. At this rate, the initial buffer is placed in 33 boreholes per working day, so that a complete room of 282 boreholes is done in about 9 working days. Fifteen calendar days or 10 working days are allowed in the disposal-room schedule (Figure 5-3) for this operation.

The in-hole dynamic compaction of buffer material has been demonstrated in the Underground Research Laboratory with hand-held hydraulic compactors, and has shown that the desired density can be achieved (Kjartanson et al. 1991). However, production-scale equipment to meet the assumed compaction time has not been demonstrated. If smaller lifts or longer compaction times are required, additional equipment and staff can be provided to maintain the initial buffer emplacement rate. The primary form of quality control is a method specification by which the buffer material (see Section 5.5.4) is placed and compacted by a prescribed procedure that has been shown to produce reliable results. The end product would be sampled and tested regularly at a frequency based on operating experience to confirm its quality.

The method of placing and compacting buffer followed by the augering of a central hole for the disposal container was chosen over a method of placing and compacting buffer around a removable liner. The principal reason for this selection was the relative ease of placing and compacting buffer over a large area compared with the limited equipment working space between the liner and borehole walls, particularly near the bottom of the buffer hole (i.e., 5 m below the room floor), and to reduce the potential of incomplete compaction immediately adjacent to the walls (i.e., as a result of friction along the borehole and liner walls). Other factors considered were the potential for disposal container damage and difficulties associated with the radiation field.

5.4.4 Container Transfer into the Vault

A full container cask is moved from the waste-shaft headframe cask laydown area by a short-span bridge crane (Figure 5-7) to the waste shaft. The bridge crane has an extendable beam and rail that line up with a similar beam and rail constructed into the top of the waste-shaft cage.

The cycle time to load a full cask onto the cage at the surface, lower it to the emplacement level, unload it, load an empty cask onto the cage, return to the surface and unload the empty cask is estimated to be 44 min. Thus, when time is allowed for shift changes and meal periods, a maximum of 17 loaded casks can be moved underground in a 16-h work day. This capacity exceeds the 15 loaded casks per day that must be moved to maintain the disposal schedule.

To prepare for cask loading in the waste-shaft headframe, the cage is aligned in the loading position and the cage portion of the beam and rail is locked firmly at the correct elevation for loading (Figure 5-7). The extendable segment of the beam and rail on the crane is swung into alignment with the beam and rail in the cage. The empty cask is transferred out of the cage and placed on a floor-mounted cask handling trolley. The loaded cask is transferred into the cage and the power cable to the monorail-crane trolley is disconnected. The cask remains suspended from the crane trolley during cage movement, and is stabilized against swinging.

The hoist is actuated to raise the cage slightly in order to pick up the load that is being carried by the locking device that fixes the cage beam and rail in place. The locking device is then released and the cage is

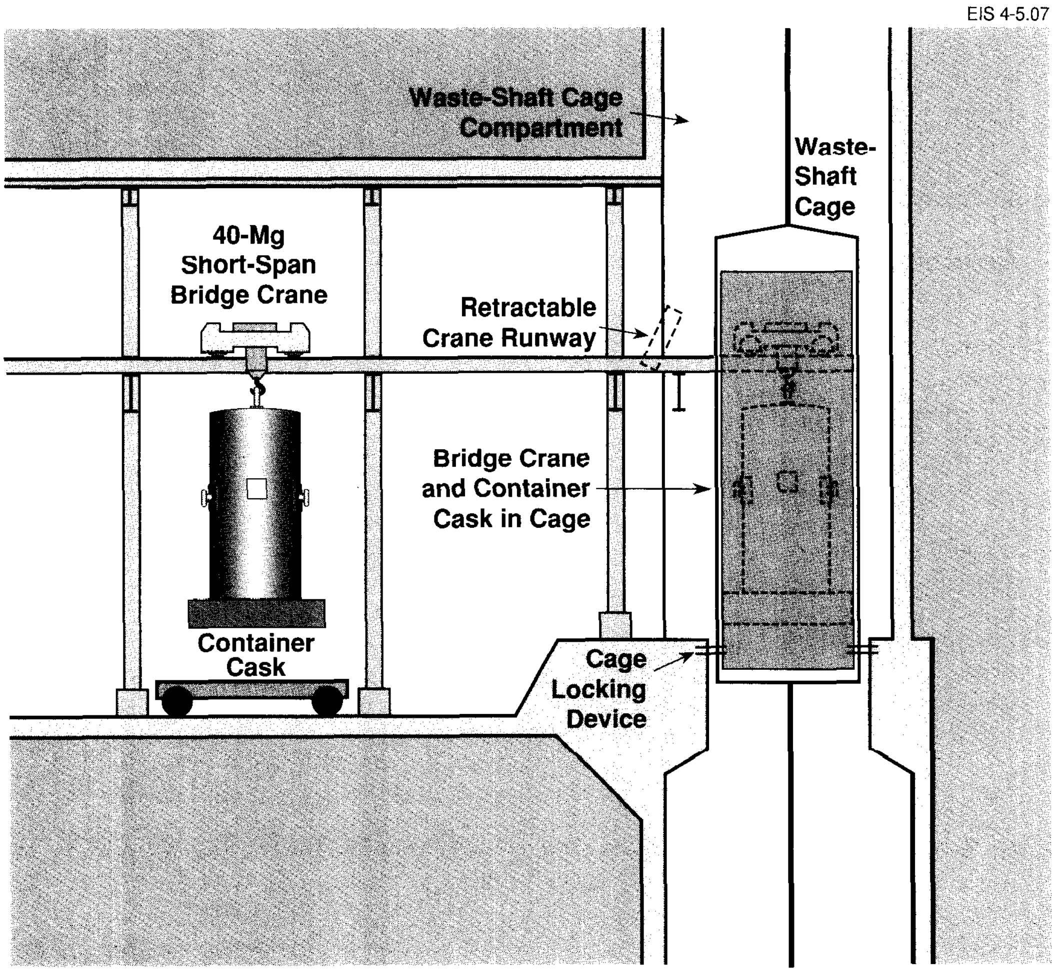


FIGURE 5-7: Container-Cask Handling at the Waste-Shaft Headframe (after AECL CANDU et al. 1992)

lowered to the vault level at 3.5 m/s. This type of operation is necessary during loading and unloading at the surface and at the disposal vault level to ensure that the proper range of tension is always maintained on the ropes of the friction hoist.

At the vault level, the cage beam and rail are mechanically locked at the correct elevation, an extendable segment of the beam and rail on the vault-level crane is swung into place, the power for the crane is connected, and the crane trolley and cask are moved from the cage onto an underground container cask transporter (Figure 5-8) or to the cask storage area. The transporter roadway is at a lower level than the waste-shaft cage floor in the transporter loading area to allow the cask to be positioned on the

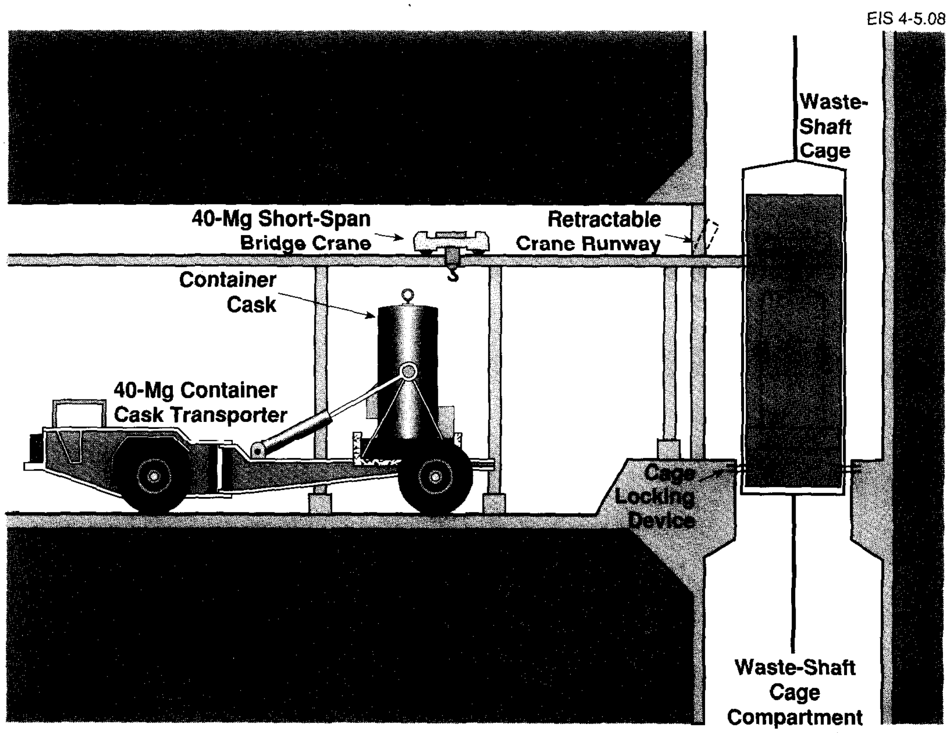


FIGURE 5-8: Container-Cask Handling at the Waste-Shaft Bottom (after AECL CANDU et al. 1992)

transporter. The crane trolley is then moved to the empty-cask laydown area, and an empty cask is picked up and moved into the waste-shaft cage for transfer to the surface.

The method selected for the waste-shaft cage operations involves transporting the crane trolley with each cask. Another practicable alternative is to construct a "cask-carrying" floor in the cage, which can be locked at the correct elevation for loading and unloading, set the cask onto this floor with an extendable crane and stabilize the cask from tipping, remove the extendable crane, and raise the cage to pick up the load being supported by the "cask-carrying" floor before releasing the positional lock. Additional equipment, either the beam, rail and crane trolley or the "cask-carrying" floor, must be carried as extra mass in both alternatives.

The underground cask storage area has a capacity of 15 casks (i.e., one day's throughput) and it normally contains seven or eight casks to meet surge requirements.

The transporter is a modified 40-Mg mine truck chassis fitted with a specially designed frame to accommodate the disposal container cask. Once loaded, the cask is tilted (Figure 5-9) to minimize the headroom required

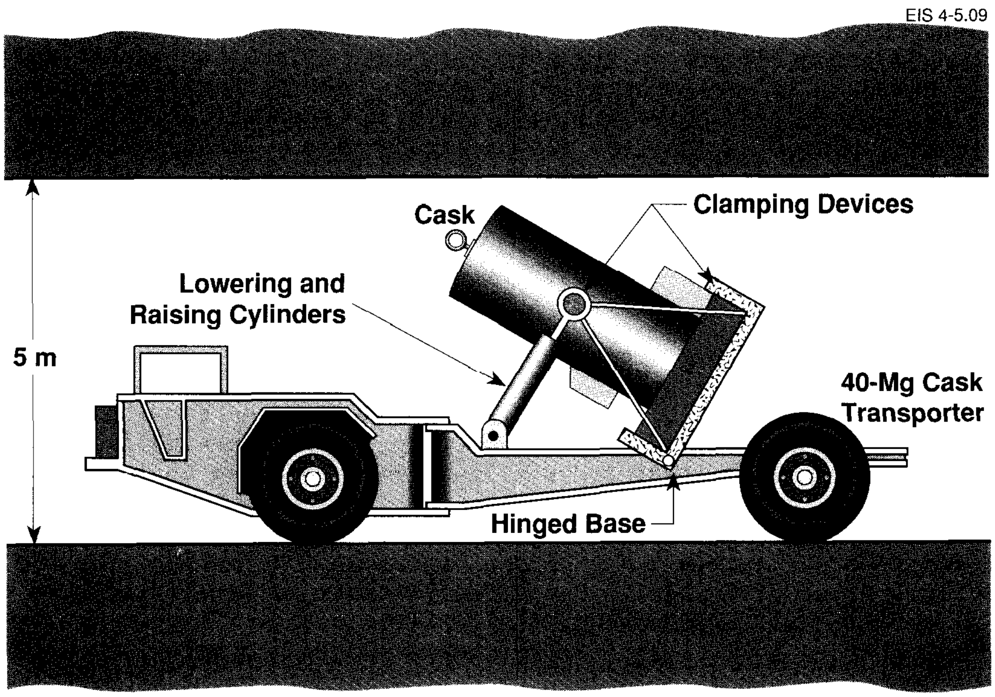


FIGURE 5-9: Underground Container-Cask Transporter (after AECL CANDU et al. 1992)

to move the cask in the underground haulageways, and to improve the stability of the loaded transporter. The transporter has interlocks that prevent the cask from being tilted until it has been securely clamped into the transporter frame. The loaded cask is moved along the central access tunnel on the side of the vault in which containers are being emplaced, and through the emplacement panel tunnel to the disposal room where containers are being emplaced. The central access tunnel leading to the emplacement panel is used exclusively for container cask transportation. The only other use is periodic supervisory inspection and any maintenance inspections and work.

The estimated time for a cycle of moving a loaded container cask to a disposal room and returning an empty cask to the waste-shaft station is 72 min. Two transporters are required to transfer the required 15 containers per day.

5.4.5 Disposal-Container Emplacement

Safeguards surveillance equipment may be installed to record activities before any disposal containers are emplaced in a disposal room. The drainage channels for the room where emplacement is taking place are diverted to a local sump at the panel tunnel. Groundwater draining from the room is monitored for radioactivity during the emplacement operations, and would be diverted through a local filtration system if radioactive contamination is detected. Otherwise the water flows directly into the panel tunnel drainage channel. The filters on the portable local filtration system are handled as potentially contaminated solid waste. The probability of elevated levels of radioactive contamination is very low because the only sources are residual contamination from the packaging plant, failure of a container so that its internal contamination enters the groundwater, or an accident that damages a container and the contained used fuel. These are all unlikely events. However, if such an event did occur, the spread of airborne (Section 4.3.6) and waterborne (Section 4.3.7) radioactive contamination would be limited.

The first step in the emplacement sequence is to inspect each borehole into which a container may be placed. If the state of the upper borehole walls (i.e., above the initial buffer mass) appears unchanged from the initial characterization following borehole drilling, it is approved for augering. If the borehole is rejected, it is filled with compacted buffer material to totally seal the opening. The borehole is prepared for disposal-container emplacement by augering an axial opening into the initial buffer which was compacted into the bottom 3.5 m of the emplacement borehole. This is done using the rail-mounted auger. The auger platform is located between the end of the disposal room and the final buffer and container-emplacement platforms (Figure 5-10). It is positioned and used to auger the container opening in the buffer while a full container cask is being transferred to the emplacement platform at the room entrance.

5.4.5.1 Buffer Augering and Cask Transfer to the Emplacement Platform

The auger platform comprises the auger drill, vacuum unit, lifting crane, buffer reprocessing hopper, screw conveyer and a small sand hopper (Figure 5-11). The platform is aligned over an emplacement hole using the reference points on the rails, and an augering template is inserted into the borehole to rest on the buffer material. The template has an outside diameter of about 1.22 m, an inside diameter of 0.75 m, and is used to locate the auger on the borehole axis.

The container hole is augered into the buffer in four steps of 0.7 m each. The auger is withdrawn after each step, and the loose buffer material is vacuum-transferred to the reprocessing hopper, where the material is prepared for reuse in the final filling of the emplacement borehole. Fine sand is placed in the bottom of the emplacement borehole to smooth the depression left by the end of the auger and to accommodate any remaining buffer material cuttings. The auger platform then retreats to the end of the disposal room, where it is stored during the emplacement operations.

The time necessary to auger a container hole in the buffer and place the sand base is estimated to be 16 min. This productivity has not been demonstrated and, if a longer time proved necessary, additional auger(s) could be provided on the auger platform for simultaneous operation.

The container cask transporter is moved into position in the panel tunnel outside the disposal room during the augering operation. The cask is transferred from the transporter to the emplacement platform using the 40-Mg crane mounted on the crown of the panel tunnel (Figure 5-12).

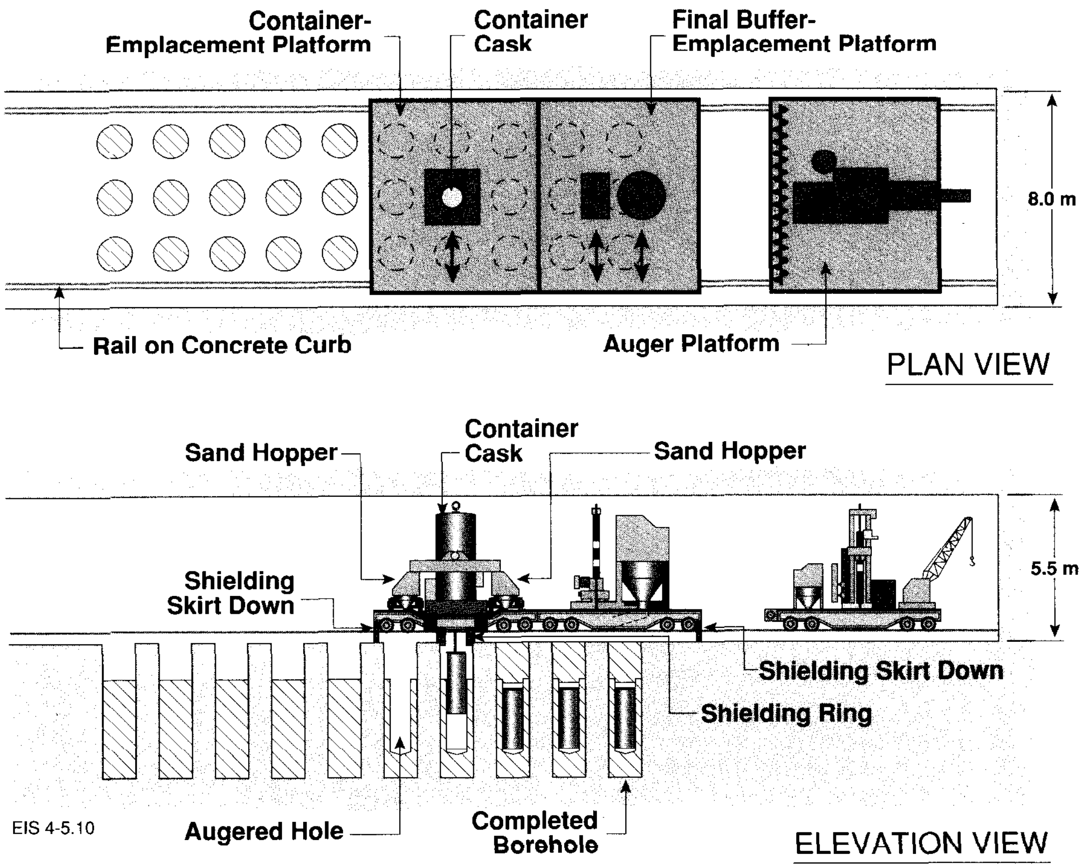


FIGURE 5-10: Container Emplacement (after AECL CANDU et al. 1992)

The emplacement platform is 7.5 m wide and 5 m long, and during the emplacement operations it is normally connected to a final buffer emplacement platform (Figure 5-10). These platforms are connected to provide continuous radiation shielding during the two-part operation of container and final buffer placement. The two platforms can be separated so that they can be readily moved between disposal rooms.

5.4.5.2 Container Emplacement

The cask is placed in the cask support frame on the emplacement platform. This frame can move across the platform, and the platform can move along the length of the room to align with any emplacement borehole. The cask is supported by horizontal beams that clamp to the lifting lugs on the sides of the cask, and it sits in a recess in the shielding floor of the platform.

The emplacement platform is moved to the correct row of boreholes and the cask support frame is set to the correct transverse position of the selected

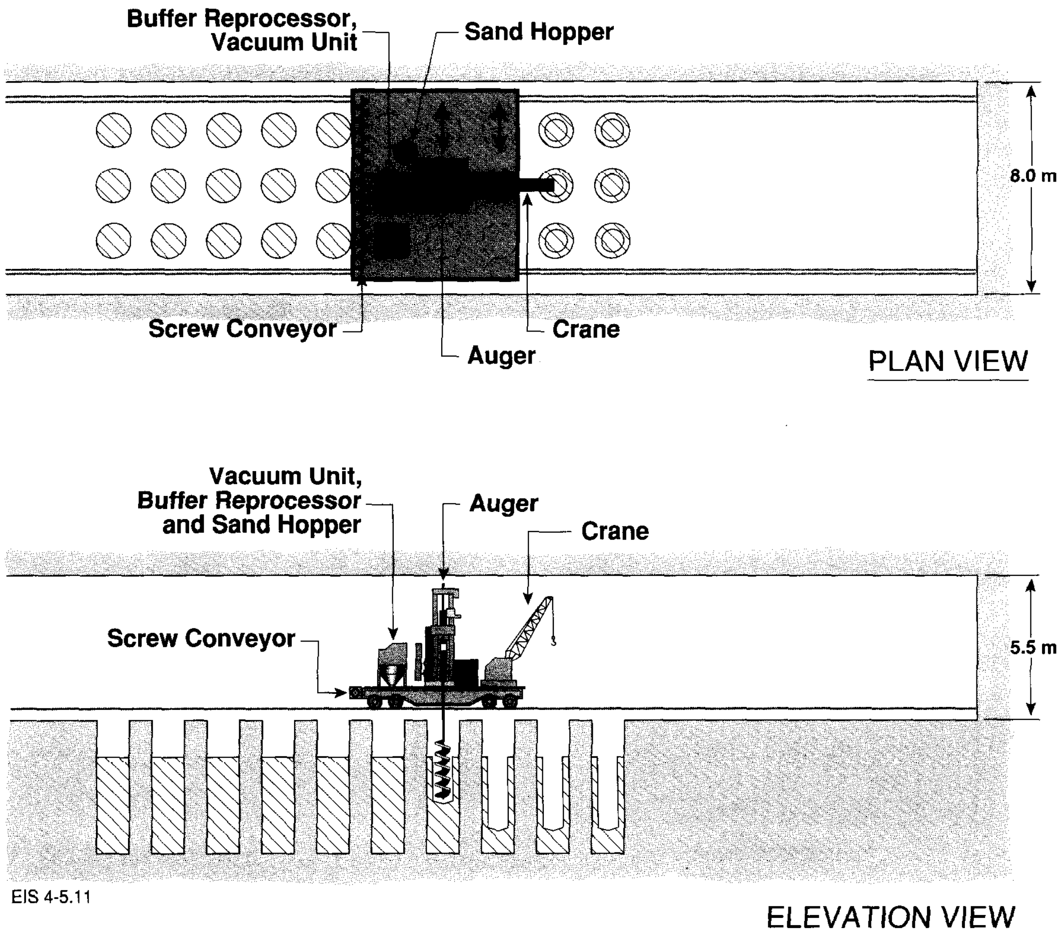


FIGURE 5-11: Augering of Buffer Material (after AECL CANDU et al. 1992)

emplacement hole (Figure 5-10). The initial alignment is done with the aid of reference points on the rails, and the platform brakes are locked. The final alignment of the cask support frame is done by the operator using information from TV cameras, viewing the emplacement borehole via optical fibres that run through the shielding. These optical fibres are linked to a viewer and a computer that provide information to the operator for the alignment of the platform so that the telescoping shielding ring can be positioned correctly with respect to the borehole. The emplacement platform, the final buffer platform and the cask support frame are locked in place once the final position adjustments are made.

The telescoping shielding ring, designed to protect the operators from the radiation emitted by a container, is lowered from the platform to the collar of the borehole (Figure 5-13). The shielding ring comprises two concentric rings, the outer fixed ring and the inner ring, which is free to slide vertically within the outer ring and fit into the borehole collar.

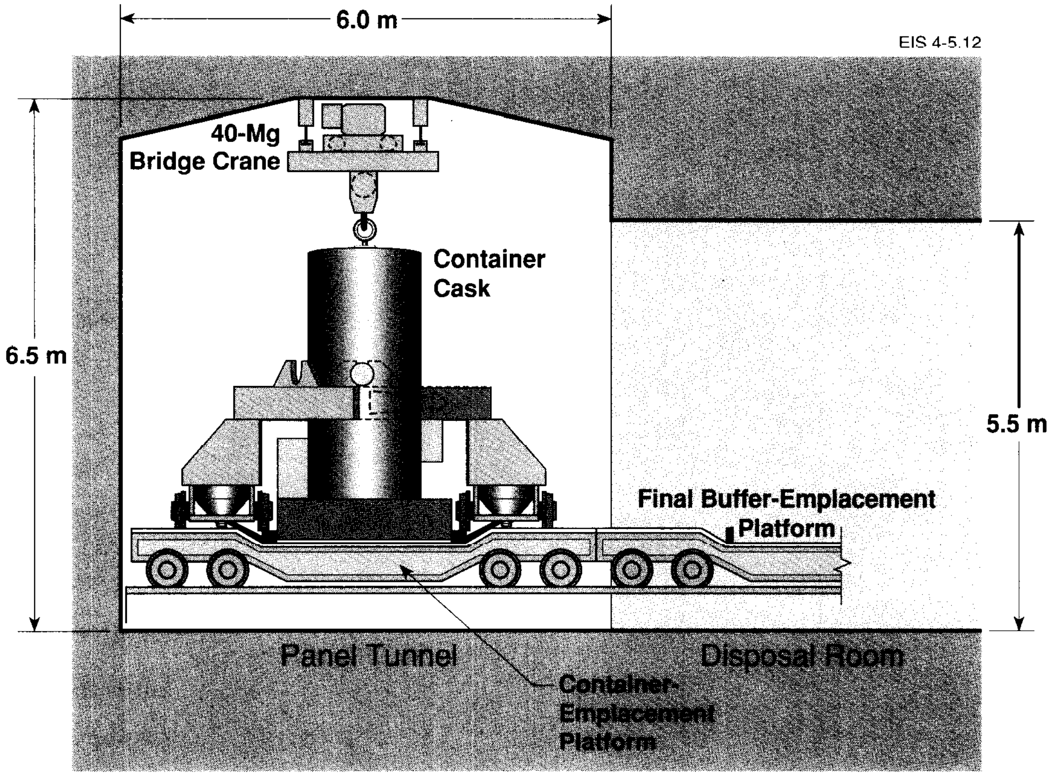


FIGURE 5-12: Cask Transfer to Emplacement Platform (after AECL CANDU et al. 1992). Temporary ventilation duct arrangement is shown in Figure 4-18.

The inner ring overlaps the outer ring to provide a continuous shield of 300-mm-thick steel around the container as it is being lowered. This shielding and the shielding provided by the platforms and skirts provide radiation attenuation similar to that provided by the disposal container cask.

When the inner shielding ring is in place, the shielding skirts that cover all sides of the connected emplacement and final buffer platforms are lowered to the floor of the room. Completion of these shielding operations releases the safety interlocks and allows the cask gate and hoist to be operated. The cask safeguards seals are removed if these seals were installed as a safeguards measure before the bottom gate is opened. If desired, the magnitude and energy spectrum of the radiation emitted from the container can also be monitored. This provides the safeguards verification of the container identity and, if necessary, its contents. The cask bottom gate is opened and the cask hoisting system is used to lower the disposal container through the shielding ring into the augered hole in the buffer, setting it on the sand base. The container lowering operations are

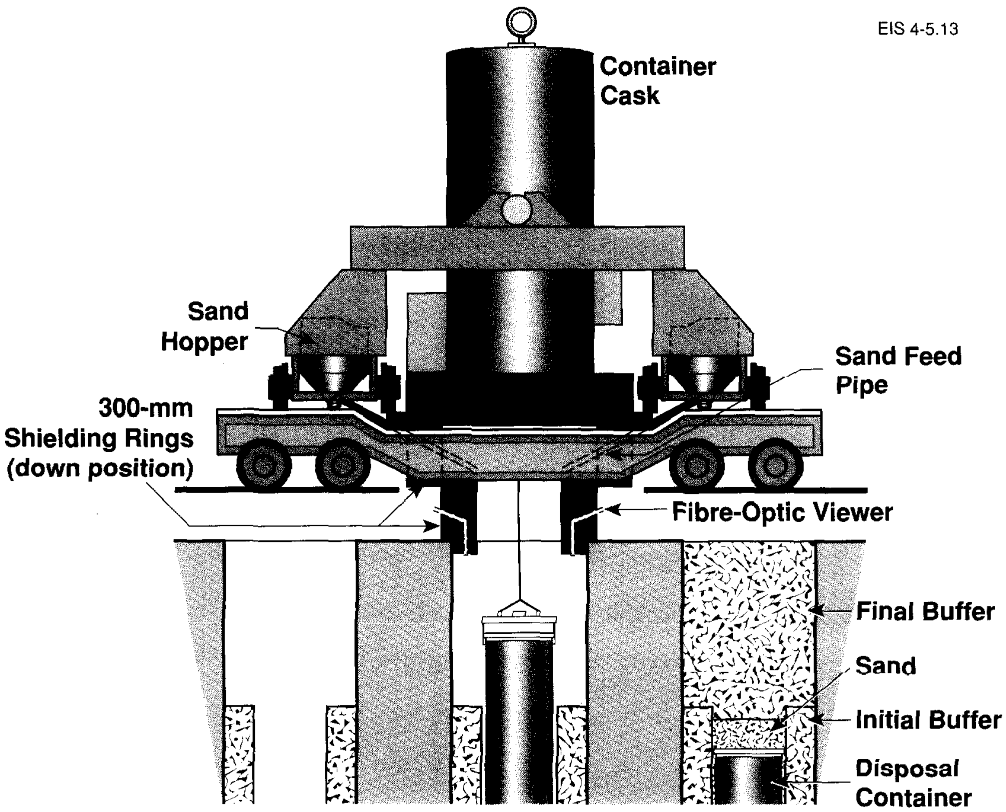


FIGURE 5-13: Container-Emplacement Platform (after AECL CANDU et al. 1992)

viewed with the optical system in the shielding rings to detect any abnormalities. No personnel are permitted in the disposal room during this operation unless they are on the emplacement/final buffer platform.

The operators and safeguards inspectors involved in container-emplacement operations are located on the shielded decking of the container and final buffer emplacement platforms. The platform decking provides sufficient shielding to prevent an unacceptable radiation dose to personnel during the container handling and buffer placement. The operation of the container-emplacement platform is from a console mounted on the platform handrail. The container cask is controlled from and the operations are viewed on a panel mounted on the cask. The final buffer emplacement operations are directed from a control panel mounted on the final buffer emplacement platform.

The space between the container and the buffer wall varies from ~25 mm to 75 mm. This space is filled with dry silica sand to provide conductive heat transfer from the container. Sand feed pipes are spiralled through the fixed portion of the shielding ring to maintain shielding integrity, and telescope past the inner shielding ring, as shown on Figure 5-13. A premeasured amount of silica sand (e.g., approximately 600 kg), fluidized with air, is fed into the space between the buffer and the container, and placement is observed by the optical system.

At this point, the grapple is released from the container and is withdrawn into the cask. The cask bottom gate is closed. Another premeasured amount of sand (e.g., ~300 kg) is poured onto the top of the container to a depth of ~0.3 m above the container top. This sand layer protects the container from the dynamic forces applied during the compaction of the final buffer into the borehole. At this point in the operation, the shielding ring and skirts are raised so that the platforms can be moved for final buffer emplacement. There remains a significant radiation field from the emplacement borehole to the bottom of the platform decks; however, the 0.3 m of shielding on the decks of the platforms protects the operating personnel.

The optical system conceived for the cask has not been demonstrated, but there is significant industrial experience with fibre-optic viewers, and a system based on this technology is considered to be practicable. The fibre-optic viewers would be placed at sufficient locations around the cask to provide complete circumferential viewing for observing the operations, and if required, for reading container serial numbers.

The operation for placing dry sand in the annulus between the container and the buffer has also not been demonstrated on a production scale inside shielding. A test was successfully conducted at the Underground Research Laboratory where dry sand was poured manually into the annulus between an electrical heater simulating a used-fuel disposal container and precompacted buffer in a similar geometric configuration. This test showed the operation to be practicable.

5.4.5.3 Final Buffer Emplacement

The platforms are moved ~5 m towards the room entrance to align the final buffer emplacement platform with the emplacement borehole (Figure 5-14), and the shielding skirts are relowered. The final buffer emplacement platform has a hopper to supply the reference buffer material (Section 3.3.3) and a single computer-controlled compactor. As noted in Section 5.4.5.2, the platforms are designed with sufficient shielding to protect operating personnel. Physical barriers are designed into the platforms to limit the exposure of personnel to radiation fields, and a radiation detector and alarm are provided to warn of unexpected conditions.

The hopper is filled with the augered buffer material, obtained from the auger platform reprocessing hopper, as well as fresh material. The loose buffer material is fed into the emplacement borehole through a retractable screw conveyor in quantities that yield compacted lifts of 0.15 to 0.2 m. Each lift is compacted separately before the next layer is added. A computer is used to control the frequency, force and duration of the compaction of each lift, and the addition of loose buffer for the next lift. This control ensures the quality of the emplaced buffer in a situation where the operator cannot physically inspect the operation. The compacting procedure

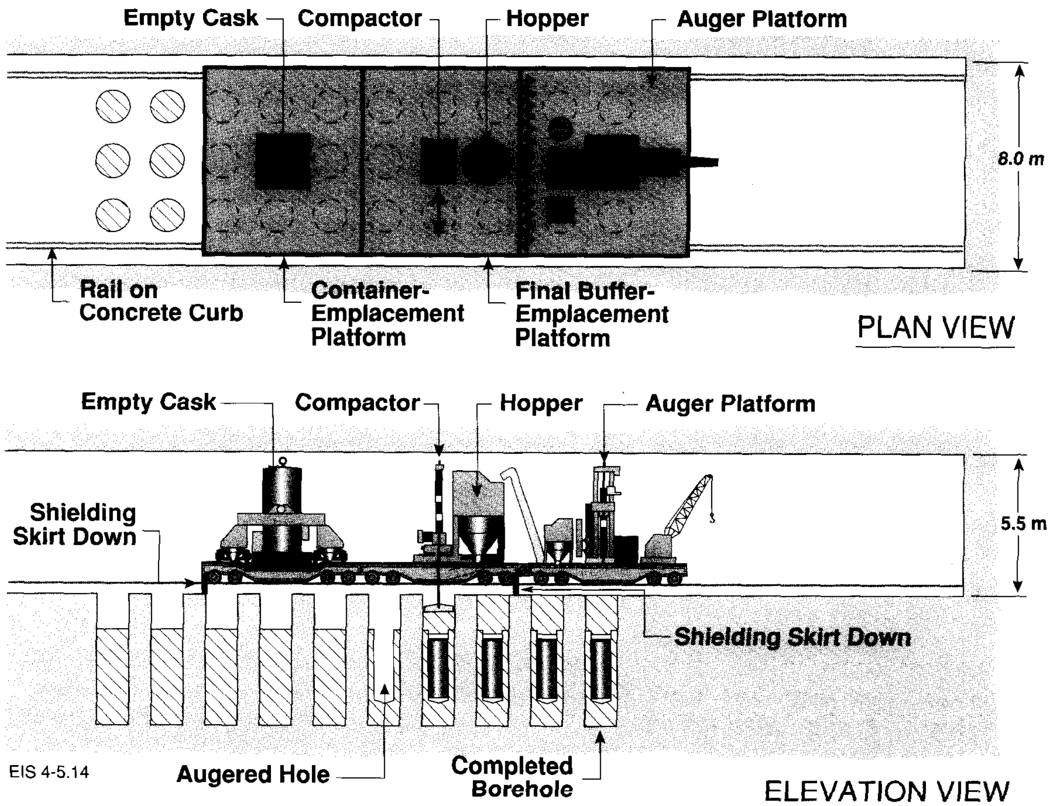


FIGURE 5-14: Final Buffer Emplacement (after AECL CANDU et al. 1992)

and the computer controller would be designed to the specified buffer density without overstressing the container. The compaction equipment would be developed during the component testing activity in the construction stage. A method specification would be developed to provide the necessary compaction density over the entire borehole area for the specifically developed compaction equipment.

Each lift of buffer requires ~300 kg of material for a total of ~3300 kg in 11 lifts. The buffer material for this operation comes from the auger platform (~2000 kg) and from fresh material supplies (~1300 kg). The sand hopper on the emplacement platform is also recharged when the fresh buffer material is added to the hopper on the final buffer platform.

When the buffer has been emplaced up to the floor of the room, there is sufficient sand, buffer material and rock surrounding the container to reduce the radiation field in the working areas of a disposal room to 0.7 μGy/h, yielding a worker dose equivalent below the regulatory and design limits.

Quality-control tests are performed on samples taken periodically from the emplaced final buffer material to ensure that the final product meets the specification. The methods specifications and operating procedures would be modified if necessary to maintain the characteristics of the final buffer at the specified values.

A safeguards seal could be placed across the buffer-filled borehole as each borehole containing a disposal container is completed.

5.4.6 Disposal-Room Sealing

Although there are advantages to keeping the disposal rooms open for some time period (e.g., to allow for ventilation cooling of the emplaced waste, to provide access for performance monitoring, and to provide easy access for disposal-container retrieval, if this were necessary), the benefits of prompt sealing override these advantages. The integrity of the clay-based buffer material is enhanced by placing the lower backfill soon after buffer placement and before the buffer begins to swell. Also, the backfill will provide a small support pressure on the surfaces of the disposal room that will contribute to the stability of these surfaces as thermal-expansion displacements occur, caused by the heat from radionuclide decay in the used fuel. The backfilling of disposal rooms soon after the completion of container emplacement also eliminates the requirement for continued inspection and maintenance of these openings, and therefore reduces operating costs. In addition, the sealed room provides an easier arrangement for applying safeguards containment/surveillance measures if they are required underground.

On the other hand, if the disposal rooms are kept open, the swelling of the buffer would need to be constrained by borehole caps bolted into the stressed borehole rock webs or braced against the crown of the disposal room, and the caps could not be removed for later backfilling without some potential loss of buffer performance. The caps and bolts would need to be compatible with the sealed vault environment. No support would be available from the backfill to contribute to excavation stability as thermal-expansion displacements occur and it is probable that some localized deterioration of the excavations would occur, requiring continuing maintenance of the ground and supports.

If safeguards containment/surveillance measures are required underground, they would be complicated by repeated entry into rooms for maintenance with the risk of damaging the seals and surveillance equipment, possibly increasing the risk of having to retrieve containers for safeguards verification.

Thus, based on the above factors, it has been decided for this conceptual design that the disposal rooms would be backfilled and sealed when container emplacement within a room is complete. However, if it was desirable to leave one or more rooms open, this could be done at an increased cost and with increased operations and maintenance effort.

The first operation in room sealing is the removal of the rail track and concrete curbs, and the verification of the safeguards seals, if installed, on each of the boreholes containing waste containers. Following this, the safeguards surveillance equipment, if any, is moved to monitor the room from a location near the entrance, and the seals over the boreholes with containers are removed. The room is backfilled in two stages using different materials and techniques for each stage. The groundwater seepage into the room is reviewed prior to beginning backfill placement. Any localized areas where the seepage rate could interfere with the backfill placement or where the potential for radionuclide migration is a concern will be grouted to achieve acceptable seepage rates.

In the first backfilling cycle, which is done in the first 28-d cycle after the container-emplacement cycle, the lower 3.5 m of the room is backfilled with the reference backfill material (Section 3.3.3), termed the lower backfill material, a mixture of crushed granite and glacial-lake clay. It is compacted using conventional vertical compaction equipment. In the second cycle, the upper portion of the room is backfilled with upper backfill material, a mixture of bentonite clay and silica sand. For simplicity, this conceptual design assumes that the upper backfill material has the same composition as the reference buffer material (Section 3.3.3), although other compositions would likely be as effective. It is pneumatically emplaced, a procedure that was demonstrated as part of the International Stripa Project (Pusch and Nilsson 1982).

Buffer/backfill mixer trucks are used to move 22-Mg batches of lower backfill material from the underground buffer and backfill preparation plant to the entrance of the room being backfilled. The 3-m^3 load-haul-dump vehicles are used to transfer the backfill material from the buffer/backfill mixer trucks to the work area in the disposal room. The lower backfill is placed in lifts of ~0.2-m uncompacted thickness and compacted. Load-haul-dump vehicles equipped with dozer blades are used to spread the backfill evenly in the desired lift thickness. A load-haul-dump vehicle modified with a 3-Mg padded drum roller compacts the backfill to the desired density using a method specification for the number of roller passes. The actual moisture content and density achieved in compacted lower backfill material are checked periodically by removing samples of emplaced material to ensure adherence to specifications. The backfilling operations are illustrated in Figure 5-15. A complete lower backfill installation as shown in Figure 5-15 requires about 6600 m^3 of compacted lower backfill.

The upper backfill is placed pneumatically (Figure 5-16) because of the limited headroom remaining in the disposal room. The in situ effective dry-clay density that can be achieved by pneumatic placement within such a confined space is estimated to average about 0.9 Mg/m^3. At this density, the hydraulic permeability is less than 1×10^{-10} m/s, similar to that of the compacted lower backfill. Although upper backfill can be expected to vary in placement density associated with the pneumatic emplacement method, the high-performance reference buffer material composition was selected to compensate for local density and hydraulic permeability variations. Large-scale upper backfill placement tests are required to optimize the upper backfill composition so that the bentonite clay content is minimized, and a hydraulic permeability equal to or lower than that expected of the reference lower backfill material is achieved. Placement specifications would be developed from these trials to result in an acceptable emplaced density of the upper backfill material.

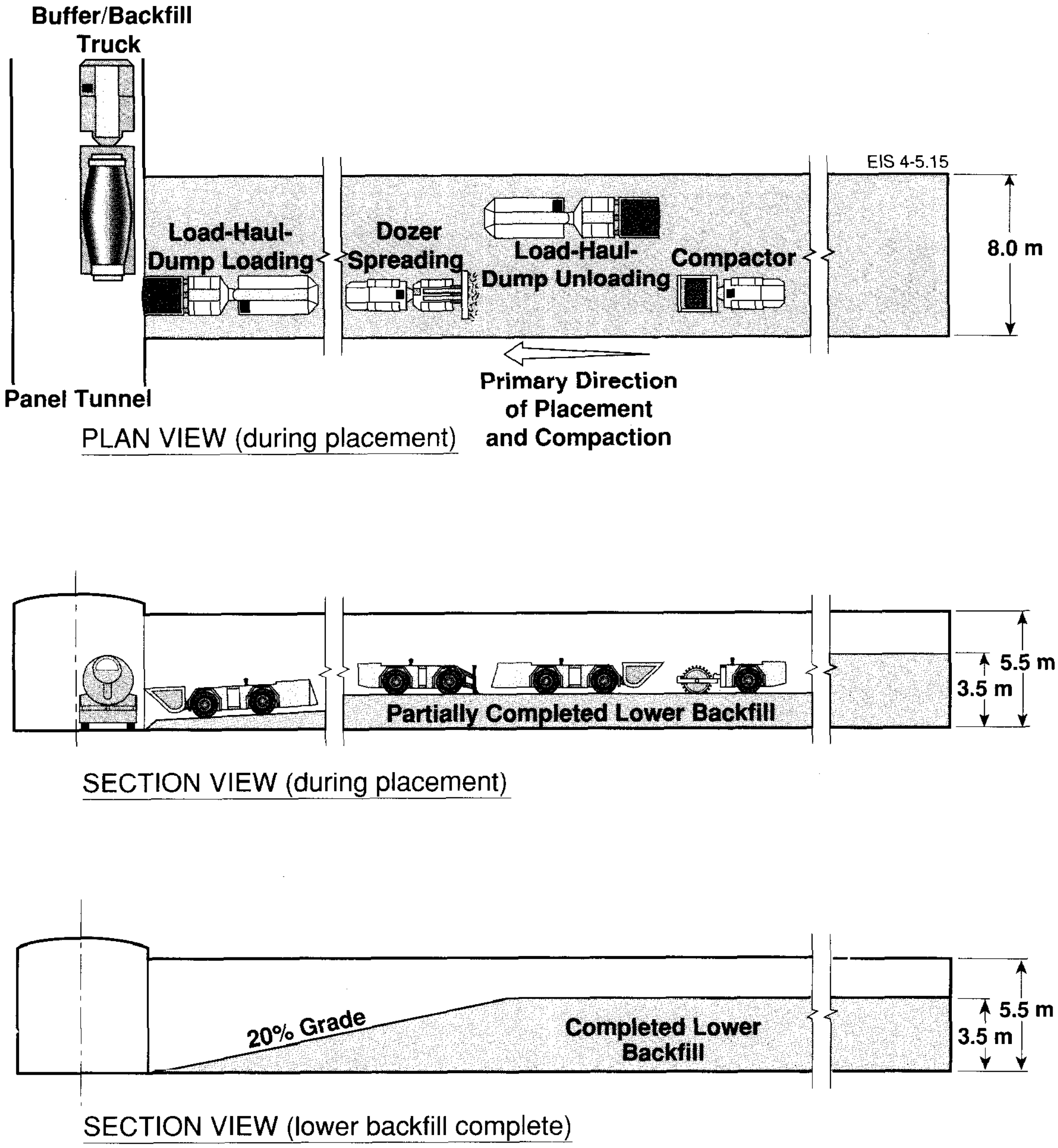


FIGURE 5-15: Lower Backfill Placement (after AECL CANDU et al. 1992)

The upper backfill is transported to the disposal room in 24-Mg trucks, each carrying 18 Mg of backfill (Figure 5-16). The materials-receiving and air-conveyance units, which move the backfill to the point of emplacement, are located at the entrance to the room. An air pipeline moves the backfill to the nozzle on a mobile trailer located at the face.

The upper backfill is applied uniformly with a nozzle having an exit velocity of ~30 m/s. The nozzle is held normal to the face and ~2 m away to maximize the compaction and minimize the rebound. Special ventilation is

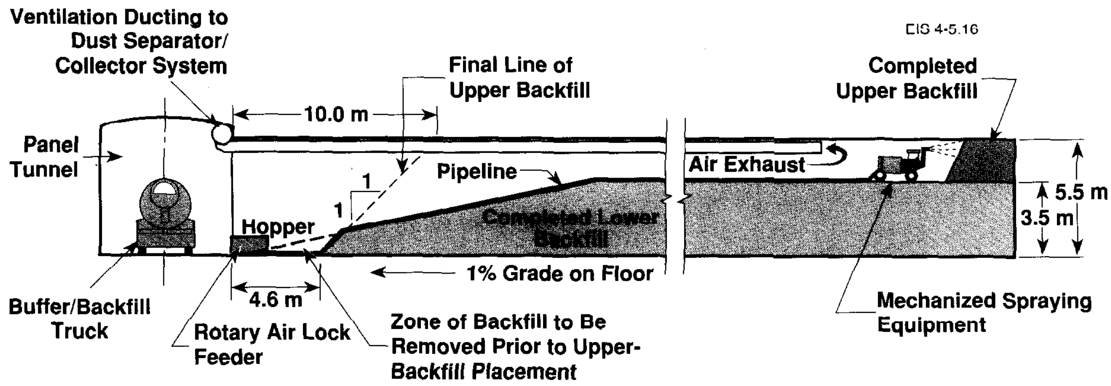


FIGURE 5-16: Upper Backfill Placement (after AECL CANDU et al. 1992)

installed to control dust in the working environment because of the fine particle size and low moisture content of these materials. The total volume of compacted upper backfill in final form is about 3400 m^3 per room.

The final step in sealing the disposal room is the construction of a concrete bulkhead seal at the entrance to the room. The bulkhead restrains the buffer and backfill as they swell, isolates the room hydraulically from the panel tunnel, and could also become part of a safeguards seal for the nuclear material in the disposal room. The location and approximate dimensions of the concrete bulkhead seals are shown in Figure 5-17. The bulkhead requires ~310 m^3 of concrete.

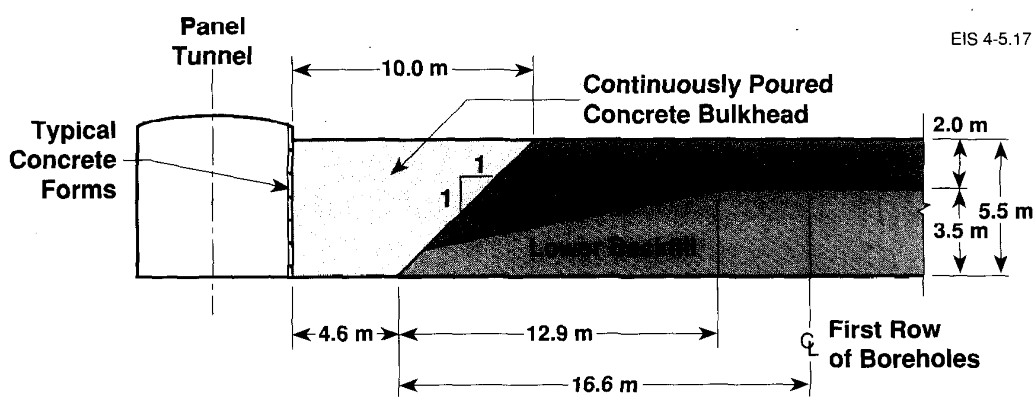


FIGURE 5-17: Installation of Concrete Bulkhead at Room Entrance (after AECL CANDU et al. 1992)

A section of the backfill at the entrances to the room, varying from 4.6 m long at the floor to 10 m long at the crown, is removed (~21 m^3 of material) in preparation for bulkhead construction. The floor, walls and roof of the room are thoroughly cleaned to provide a good concrete/rock contact. Standard formwork is erected at the room entrance to contain the concrete while it is placed and while it sets. The lower and upper backfill material provides containment for the other side of the bulkhead. The concrete is delivered from the batching plant to the entrance of the room in trucks and is pumped continuously into the formwork through the ports provided. Manually operated vibrators are used throughout the pour to eliminate voids.

The excavation-disturbed zone around the room entrance is grouted in a two-stage operation. As discussed by Johnson et al. (1994a), both cement- and clay-based grouts could be used in a disposal vault. This conceptual design assumes the use of cement-based grouts because of their strength and resistance to hydraulic erosion. The first grouting may be done at the time the room is developed. Cement-based grout is injected into holes drilled around the room entrance to seal any fractures that are seeping groundwater. The second stage of grouting occurs after the bulkhead is in place, in angled boreholes drilled through the bulkhead into the surrounding rock, to seal the interface between the bulkhead and the rock in the event that concrete shrinkage occurs.

The complete backfill and sealing of a disposal room requires 41 working days, or about 64 calendar days. The lower backfill is placed during the drilling panel operations (28 calendar days). The upper backfill is placed during the emplacement-panel operations (28 calendar days), and the bulkhead is constructed during the next cycle of drilling-panel operations (8 calendar days). Therefore, the disposal-room sealing covers three consecutive 28-calendar-day operating cycles (Figure 5-3).

5.4.7 Container Retrieval

The AECB (1985) requires that containers be retrievable during the operating life of the disposal vault. This capability is a planned requirement at the end of the operation stage or the beginning of the decommissioning stage to retrieve containers of used fuel placed in the component test areas for performance tests. The effort required to retrieve a container(s) depends on how much work has been done since the disposal container was emplaced. For illustrative purposes, we will look at the retrieval of containers from a sealed disposal room. The operations are somewhat simpler if the room or borehole has not been sealed.

The retrieved container might be emplaced in another borehole if it was removed for safeguards inspection, it might be transferred to the packaging plant for refurbishment or replacement if defects caused by manufacturing or handling were suspected, or it might be placed in storage if all the containers are being retrieved. The retrieval of all containers would require the construction of disposal container storage facilities with the capacity to hold the inventory of containers being retrieved.

Although AECL CANDU et al. (1992) recommended that the panel tunnels and portions of the perimeter tunnels be backfilled and sealed as part of the sealing of each completed panel in the operations stage, in this conceptual design we have assumed that they are left open until the decommissioning stage. The continued access to the panel and perimeter tunnels requires a commitment to ongoing maintenance, but it provides improved access for monitoring and, if necessary, waste retrieval. Some increased ground support measures and maintenance might be needed in these tunnels to offset the increase in stresses arising from the thermal expansion of the rock mass as it is heated by the used fuel (Section 3.3.7.2). Thus, container retrieval would require removal of the disposal-room sealing bulkhead and the backfill materials to gain access to the sealed emplacement boreholes, followed by removal of the container(s) from the borehole(s).

These operations are achievable with available technology. However, to optimize the efficiency and safety of retrieval operations, equipment and procedures would have to be specifically developed for each step in this process, especially for retrieving the container from the emplacement borehole. In this section, generalized conceptual descriptions of the retrieval process are given to identify the steps and facilities required and to identify other systems at the disposal centre that may be affected. In addition, adequate safeguards inspection and continuous containment/surveillance monitoring might be required during retrieval.

5.4.7.1 Gaining Access to the Emplacement Borehole

The concrete bulkhead and the compacted backfills would be removed to gain access to the emplacement boreholes. Equipment would be developed for this purpose. Bulkheads could be removed by careful drill-and-blast excavation. Alternatively, hydraulic rock breakers could be used instead of explosives. An extension of the road-header type of continuous excavation equipment used in soft rocks could be used to remove the upper and lower backfills. The broken concrete and loosened backfill material would be handled by load-haul-dump vehicles and trucks. As the backfill near the container boreholes could be contaminated by radioactive materials, monitoring procedures would be instituted to detect these materials. Special procedures and equipment would be developed to segregate and handle any contaminated material.

Ventilation and other services would be reestablished as necessary. On completion of backfill excavation, concrete curbs would be poured and rail track installed, similar to the arrangement for container-emplacement operations.

5.4.7.2 Container-Retrieval Operations

The proposed container-retrieval equipment would be rail-mounted and supplied with the shielding rings, skirts, decks and housings necessary to minimize the radiation exposure to equipment operators and any safeguards inspectors. A remotely operated core drill, enclosed within a shielded housing and mounted on a rail platform, would be set up in the room. The unit would be positioned over the selected borehole. The surveying records from the container-emplacement operations would be used to ensure that retrieval equipment was located precisely.

The first operation would be to drill an annular recess in the floor around the emplacement borehole ~0.4 m wide and at least 0.5 m deep to receive the lower shielding ring on the retrieval platforms. The shielding rings would be designed to allow access to the entire cross section of the borehole for the retrieval operations. The buffer-augering retrieval platform (Figure 5-18) would be positioned over the emplacement borehole and its inner shielding ring would be lowered to fit into the recess drilled around the borehole collar.

A temporary ventilation system would be set up to filter any contaminants drawn from the borehole during the retrieval operation. The filter system would remove particulates that might be present in quantities large enough to be a risk to the operators. The room air would be monitored for radioactive contamination and would be diverted through a filter system if any unexpected quantity was detected. The operators would have contamination suits and breathing apparatus available for use if the room air became contaminated.

The upper 1.65 m of buffer material would be removed in several passes of an auger. At the end of each pass, when the auger is filled with buffer cuttings, it would be raised into the shielded containment housing and rotated into the cleaning compartment. In this compartment, cuttings from the auger would be moved into a waste-buffer hopper. The cuttings would be treated as a potentially contaminated material until radioactive contamination monitoring proved otherwise.

The shielding ring would be raised, a cover would be placed over the hole, and the retrieval platform supporting a buffer trepanning auger would be moved into place and located over the borehole (Figure 5-19). The cover would be set aside, and the shielding ring would be lowered from this platform into the drilled recess to reestablish local ventilation and shielding over the borehole. The trepanning auger would be lowered into the borehole and would cut an annular slot about 100 mm thick to a depth of about 4.7 m from the room floor in the buffer material adjacent to the emplacement borehole wall. The buffer cuttings would be cleaned frequently from the trepanning auger by raising the auger into the shielded containment housing and rotating it into the cleaning compartment where the cuttings would be removed. These cuttings would also be handled as potentially contaminated solids until proven otherwise.

When the trepanning operation is complete, the shielding rings would be lifted, and the retrieval platform supporting the container-retrieval cask would be located over the borehole (Figure 5-20). Its shielding ring would be lowered into place and a specially designed grapple would be lowered into the trepanned slot. The grapple might be a metal cylinder lined with an inner rough-textured rubber air-inflatable bladder, similar to an industrial lifting bag, which can be inflated with air to a pressure between 500 and 1000 kPa. The bladder would be constructed in many segments so that failure of one segment would not disable the grapple. A system would be required to free the container and surrounding buffer from the buffer that

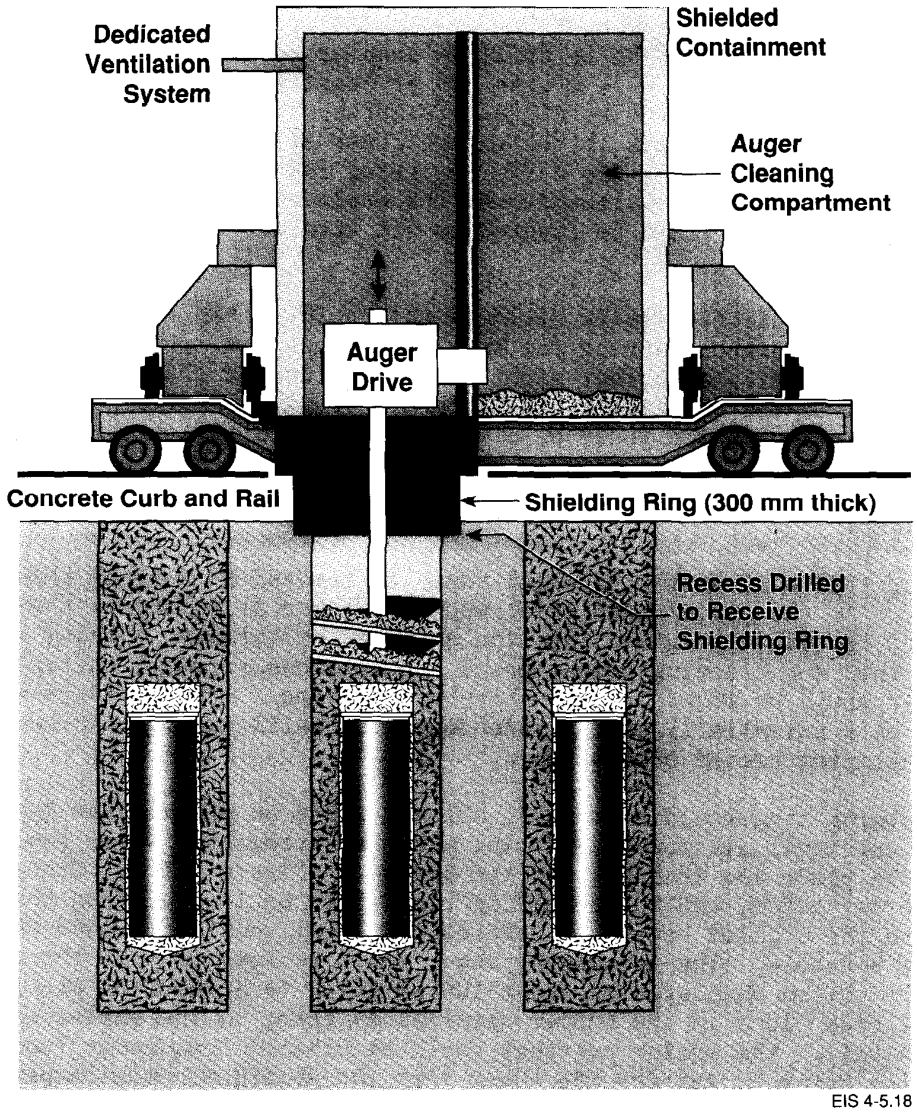


FIGURE 5-18: Container Retrieval - Buffer Augering

would remain in the borehole. One approach would be to equip the lower edge of the grapple with high-pressure water-jet nozzles to cut horizontally through the buffer material to free the container from the lower mass of buffer. A preferable approach would be to use a dry method of freeing the container/ buffer from the borehole. A dry technique, such as wedging to break the buffer below the container, would significantly reduce the potentially contaminated liquid waste that would be created during retrieval operations.

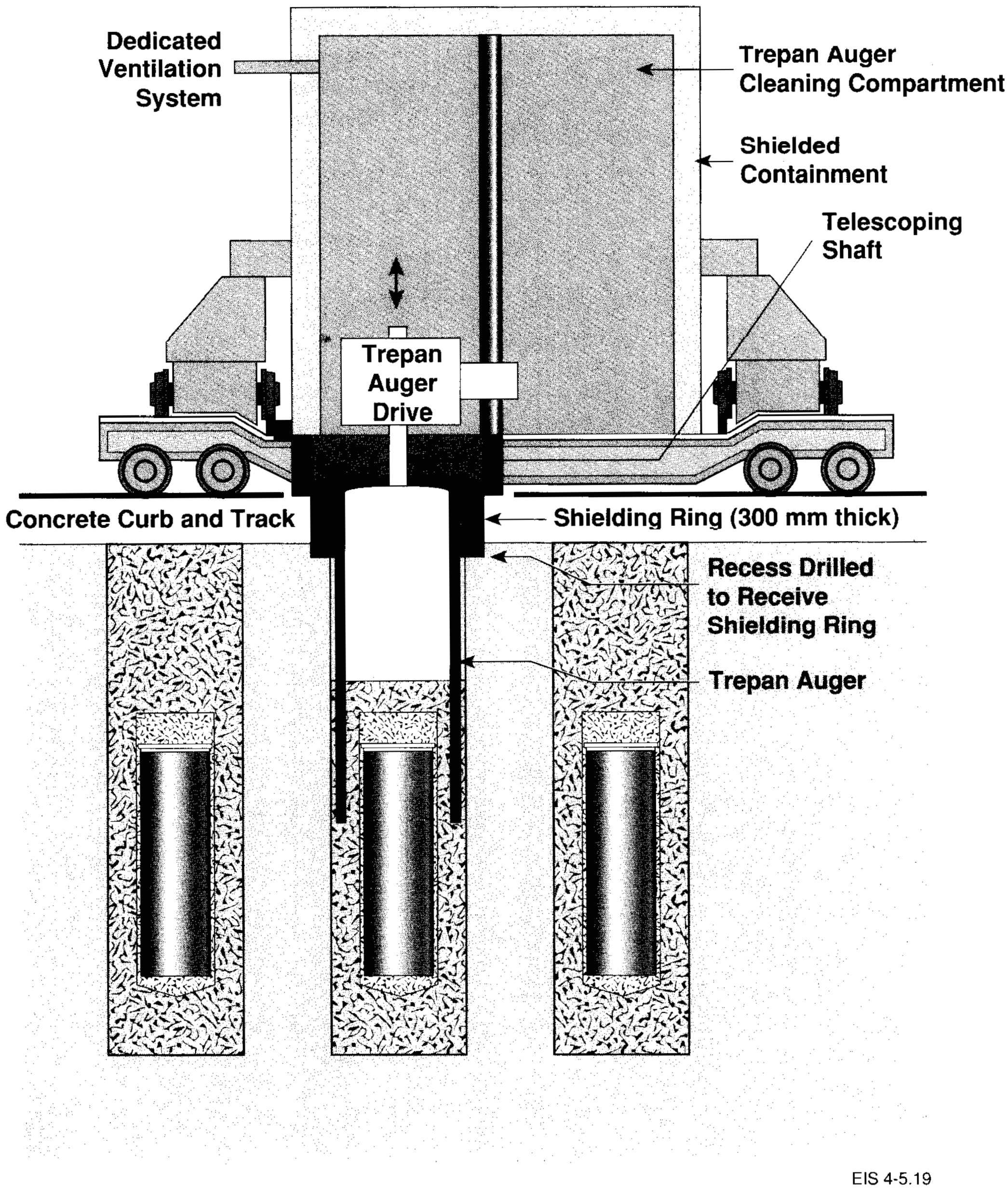


FIGURE 5-19: Container Retrieval - Buffer Trepanning

If the water-jet cutting technique is employed, water and clay slurry would be discharged through pipes built into the segments of the grapple and collected in a shielded portable holding tank. The tank and contents would be treated as contaminated material until it could be checked. If not contaminated, the coarse contents would be allowed to settle. The decant liquid would be filtered to remove the remaining suspended solids before being

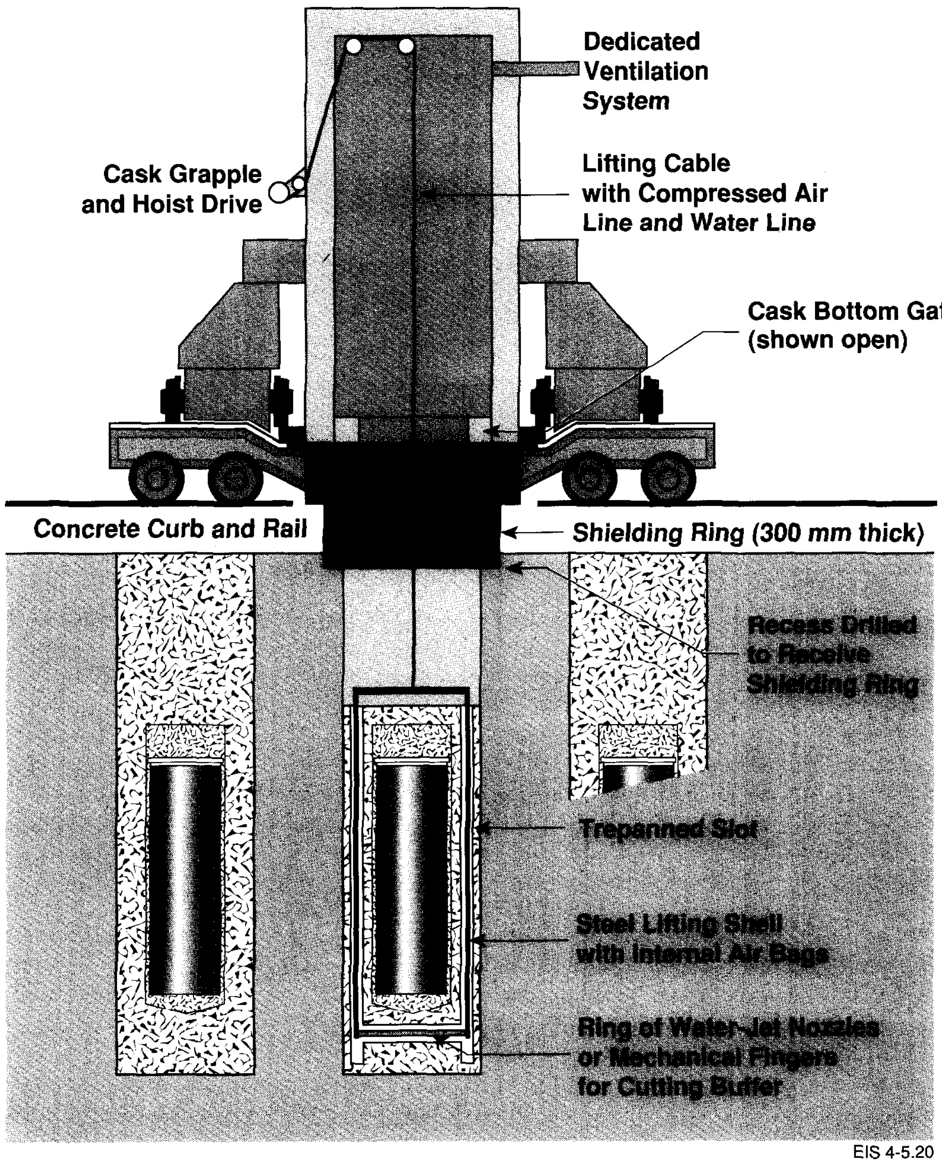


FIGURE 5-20: Container Retrieval - Grappling and Removal

released to the underground drainage system. The collected sludge and filters would be carried to the surface either for reuse or for proper disposal. If contaminated, the tank would be moved to the surface active-waste treatment building for treatment.

At this point in the retrieval process, one of two possible approaches could be taken, depending on the condition of the buffer material, the sand

and the container as a unit. If the unit is structurally intact and the container can be lifted by clamping the buffer material with the inflatable bladder of the grapple, it would be raised into the container-retrieval cask and the bottom gates would be closed. The container-retrieval cask would be moved to the retrieved-container transfer facility for cleanup and packaging.

If the buffer, sand and container assemblage is not structurally intact, the buffer and sand might loosen from the container and jam in the annulus between the container and the rock. In this circumstance, the retrieval process would have an additional step of cleaning out the annular space, and would use a smaller-diameter grapple assembly to grip on and lift the container alone. In both cases, it is assumed that the container itself is structurally sound for the recovery operations (i.e., the container structure will support the basket and fuel bundles during lifting).

The container is expected to be structurally sound and capable of providing support for the basket and fuel bundles for many centuries after closure. However, this might not always be the case. If retrieval is undertaken in boreholes where the container is damaged, a recovery grapple that provides adequate support below the container would be required.

One approach that could be used to free the container from the buffer mass in the borehole and to provide support for a damaged container is to use a grapple with curved fingers that nest into the lower end of the grapple assembly and are pivoted on one end to extend inward into the buffer mass below the container as the grapple assembly is rotated slowly. The fingers would be nested when the grapple is being lowered into the annular slot in the buffer mass.

Hydraulic actuators would rotate each finger on its pivot, causing the free end to move inward from the grapple assembly. This motion and a slow rotation of the grapple would cause the fingers to penetrate the buffer material below the container. The fingers would weaken the buffer material and would provide a lower support of the container, basket, fuel bundles and attached buffer material to aid in handling. The shape, length and number of the fingers and the force required to embed them in the buffer would be determined for the container design and buffer material chosen.

The complex grapple with extending fingers could have two advantages over the simpler grapple. First, it might provide a more effective way than the high-pressure water jets for breaking the buffer material below the container. The fingers might either create a slot in the buffer as they seat or by their presence provide a plane of weakness in the buffer that could be mechanically broken. The inflatable bladder of the grapple could be used to apply uneven side-to-side loads to the buffer to break it and free the segment containing the container, basket and fuel bundles. Second, the grapple could contain and lift a structurally damaged container and its contents in situations where the container is not stiff enough to allow a sufficient load to be placed on the buffer and sand to allow the container to be lifted into the cask.

Site- and design-specific information would be available when the retrieval procedures and equipment are being developed. The retrieval process would be optimized to provide an efficient and safe operation.

5.4.7.3 Retrieved-Container Transfer Facility

The retrieved-container transfer facility at the upcast-shaft complex (Figure 4-10) would receive the retrieved container from the container-retrieval cask. The retrieved container would be lowered through a port at a transfer station into a hot cell. Any residual buffer and sand within the cask and on the container grapple would be removed before the grapple is raised into the container-retrieval cask. All remaining buffer material and sand would be removed from the container in the hot cell using dry methods. The cleaned container would be either decontaminated or sealed in a plastic or metal overpack, and would be transferred into a container cask for transport to the surface.

The solid wastes (e.g., used buffer and sand) collected in the transfer facility would be potentially contaminated and would be handled as active solid waste. This material and the cuttings from the augering operations would be sealed in transport containers for transfer to the waste management facilities on the surface. On the surface they would be checked for contamination and might be reused, if uncontaminated, or they would be stored for disposal in approved facilities, if contaminated. The ventilation system filters would be packaged and transferred to the surface waste management facilities for disposal.

5.5 VAULT SEALING MATERIALS PREPARATION

The Used-Fuel Disposal Centre conceptual design includes facilities for the receipt, transportation, storage, preparation and batching of the materials to prepare buffer, backfills and high-performance concrete.

In total, 13.6 Tg of material is required to seal the vault (Table 5-1). The materials required to prepare buffer and backfills are sodium-bentonite clay, glacial-lake clay, silica sand, crushed granite, crushed granite fines and water (Table 5-2). The materials required to prepare concrete for vault seals are special cements, pozzolana, aggregate, water and additives. They are procured and transported to the disposal site or prepared on site.

5.5.1 Glacial-Lake Clay, Sodium-Bentonite Clay and Silica Sand Receiving and Storage Facility

Glacial-lake clay is used for the lower backfill, and bentonite clay is used for the buffer and upper backfill. All clay materials are procured from existing commercial suppliers. Suitable quantities of bentonite deposits deposits are located primarily in Saskatchewan and Alberta. Glacial-lake clays are found extensively in southern Manitoba and northwestern Ontario.

All glacial-lake clay and bentonite is processed at the source to meet material specifications and is only shipped to the disposal centre following quality-control inspection and testing to ensure compliance with specifications.

TABLE 5-1

QUANTITIES OF VAULT SEALING END PRODUCTS

Sealing Products	Disposal Room Quantities (Tg)	Balance of Vault (Tg)	Vault Total (Tg)	% of Total
Silica Sand (alone)	0.18	0.00	0.18	1.3
Buffer	1.20	0.00	1.20	8.9
Lower Backfill	6.73	1.55	8.28	61.1
Upper Backfill	2.40	0.46	2.86	21.1
Vault Seals	0.44	0.19	0.63	4.6
Shaft Backfill	0.00	0.41	0.41	3.0
Total	10.95	2.61	13.56	100.0

Silica sand is obtained from existing suppliers following quality-control programs to ensure that all the silica sand meets the sealing material specifications.

Glacial-lake clay and sodium-bentonite clay are transported to the site by rail in bulk carriers. An optional truck-receiving area is incorporated into the layout of the facility to accommodate truck haulage during interruptions in rail service. Each carload and/or truckload of acceptable material is conveyed pneumatically to delivery bins (Figure 4-12). Rail cars and trucks are equipped to load and unload contents pneumatically.

Random samples are taken during transfer of each carload to the delivery bin for quality analysis in an on-site laboratory. The clay materials are tested for grain size, moisture content, organic content, liquid limit, plastic limit, mineral composition and swelling characteristics. A minimum of 24 h is required to complete the testing (AECL CANDU et al. 1992). Based on a comparison of the test results and the material specifications, a decision is made to either transfer the clay material to delivery bins or return it to the supplier. In some cases, additional processing by the supplier may bring the clay up to the required material specifications.

The clay material meeting specification is then conveyed pneumatically from the delivery bins to permanent storage bins (Figure 4-12). The capacity of the bins is about equivalent to two weeks of buffer and backfill requirements. The pneumatic conveying system from the delivery bins to the storage bins is an air-lift system similar to those used in the cement industry.

TABLE 5-2

QUANTITIES OF VAULT SEALING MATERIALS

Sealing Material Components	Disposal Room Quantities (Tg)	Balance of Vault (Tg)	Vault Total (Tg)	% of Total
Bentonite Clay				
Buffer	0.60	0.00	0.60	
Upper Backfill	1.20	0.23	1.43	
Vault Seals	0.00	0.07	0.07	
Subtotal	1.80	0.30	2.10	15.5
Glacial-Lake Clay				
Lower Backfill	1.68	0.39	2.07	
Shaft Backfill	0.00	0.10	0.10	
Subtotal	1.68	0.49	2.17	16.0
Silica Sand				
Buffer	0.60	0.00	0.60	
Annulus	0.18	0.00	0.18	
Upper Backfill	1.20	0.23	1.43	
Vault Seals	0.00	0.02	0.02	
Subtotal	1.98	0.25	2.23	16.5
Crushed Granite				
Lower Backfill	5.05	1.16	6.21	
Shaft Backfill	0.00	0.31	0.31	
Vault Seals	0.33	0.07	0.40	
Subtotal	5.38	1.54	6.92	51.0
Cement				
Vault Seals	0.10	0.02	0.12	
Grout and Other	0.01	0.01	0.02	
Subtotal	0.11	0.03	0.14	1.0
Total	10.95	2.61	13.56	100.0

The clay and bentonite are withdrawn from the storage bins on demand from the buffer and backfill preparation plant, and are conveyed by a pneumatic conveyor system to the surface surge bins in the service-shaft complex (Figure 4-12). The air stream is cleaned by using cyclone separators and filters before the air is discharged into the atmosphere.

Glacial-lake clay and sodium-bentonite clay are discharged from the surge bins and carried by a pneumatic conveyor system down the service shaft (Figures 4-13 and 4-15) to the buffer and backfill preparation plant.

The silica sand is transported to the site either by rail or truck, depending on the source. As with the clay materials, silica sand is conveyed pneumatically to delivery bins, and quality-control samples are taken for testing. The silica sand is tested to determine its grain size distribution and moisture content. Acceptable material is conveyed pneumatically to storage bins. Material that does not meet specifications is returned to the supplier.

Silica sand is then conveyed pneumatically to a surge bin in the binhouse of the service-shaft complex as required by the buffer and backfill preparation plant and container-emplacement operations. Silica sand is discharged from the surge bin into a screw conveyor for transfer to a hopper in the service-shaft headframe. The capacity of the hopper is equivalent to the skip capacity, and the hopper is refilled automatically during the hoisting cycle of the previous load. This hopper is also used for crushed rock and crushed rock fines. The skip is loaded by a retractable feeder from the hopper and is then lowered to the skip dump at the batch plant level (Figure 4-15). The skip is equipped with a removable dust hood to control dust during handling operations. All equipment used for more than one material is thoroughly cleaned when changing over from one material to another.

Special cement (e.g., reground Type 50) is obtained from existing suppliers whose product quality is acceptable. The material is transported in bulk rail carriers to the disposal centre. The cement in each bulk carrier is sampled for quality-control testing. Standard ASTM tests and any special tests related to waste disposal are conducted over about six weeks. The bulk carriers remain sealed during this time. Cements that successfully pass the quality inspection are transferred to an environmentally controlled storage bin at the concrete batch plant.

5.5.2 Rock Crushing Plant

The crushing plant (Figures 4-4 and 4-5) produces crushed rock with a size distribution suitable for use in lower-room backfill material and in concrete aggregate. The crushing plant uses the excavated rock being brought to the surface from the disposal-room excavation or rock reclaimed from the excavated-rock disposal area as feed material. Of the total 19.5 Tg of granite excavated from the disposal vault, about 35% (i.e., 6.9 Tg) will be crushed and returned to the disposal vault as aggregate for lower backfill and concrete.

The rock being fed to the crushing plant is washed, crushed and classified by size to size distributions suitable for lower backfill and for concrete aggregate. Each product is stored in mass-flow bins and is transferred to the headframe on enclosed conveyor systems.

The crushed rock products are tested regularly to ensure that they meet the requirements for backfill and concrete component materials (CSA 1990). The samples are tested for grain size, moisture content, nitrate content and organic content. The potential effect of organic content and other impurities on the performance of the engineered barriers are discussed by Johnson et al. (1994b). Samples are taken at intermediate points in the crushing plant to monitor the performance of individual parts of the plant.

The crushing plant produces wastes, dust, dust-laden water and a water slurry. Wherever practical, the dust is collected in cyclone separators and bag filters, and is disposed of in approved facilities on site or nearby in the region. The dust-laden water is treated at the process-water treatment plant and is recycled or discharged to the environment. The residue is buried on site. The water slurry is concentrated and buried on site. The recovered water is either recycled or discharged. The Used-Fuel Disposal Centre conceptual design did not fully address water recycling since the effect of retained contaminants on sealing materials performance has not been studied, but recycling would be considered in the detailed design.

Workers involved in the operation of the crushing plant are required to wear suitable eye, hearing and breathing protection.

5.5.3 Concrete Batch Plant

The concrete component materials are special cements (e.g., reground sulphate-resistant cement), pozzolana (e.g., silica fume), aggregate (e.g., crushed granite), additives (e.g., superplasticizer) and water. All cements, pozzolana, and additives are procured from existing commercial suppliers who meet the required specifications. Bulk carriers supply the cement and pozzolana, which are unloaded pneumatically to delivery bins following quality-control testing. The mixers are fed crushed granite aggregate from a measurement hopper by a single, pivoted swing conveyor, and cement from a measurement hopper by a pneumatic conveyor. Pozzolana and other additives are added automatically, dry additives by conveyors, and liquid additives by metered dispensing systems. The quality of the batching-plant concrete is controlled by full-time qualified operators and inspectors who routinely test the batching-plant feed materials and concrete product quality to ensure it meets standards (CSA 1990).

Concrete is moved from the batching plant to the service-shaft collar in 24-Mg rotating-drum trucks. The concrete pumping system in the service-shaft collar-house delivers the concrete to a remixing and truck-filling station underground via piping in the service shaft (Figure 4-13). The concrete is discharged into trucks equipped with 22-Mg rotating drums to prevent concrete segregation during transit. These trucks may be backfill trucks used for transporting concrete on an intermittent basis (e.g., for disposal-room concrete-bulkhead seals).

5.5.4 Buffer and Backfill Preparation Plant

The buffer material assumed in the Used-Fuel Disposal Centre conceptual design is a mixture of 50% sodium-bentonite clay and 50% well-graded silica sand (see Section 3.3.3). The lower backfill material is a mixture of 25% glacial-lake clay and 75% crushed granite. An upper backfill is also required, but a program reference has not been established. A mixture of 50% sodium-bentonite clay and 50% silica sand was assumed because the buffer material has the characteristics appropriate for the upper backfill (see Section 5.4.6).

The batching process comprises two independent circuits, one for producing the lower backfill product, and one for producing the buffer and upper backfill products (see Section 4.3.4). The production rate of buffer and backfill vary, depending on the operations being carried out in the disposal rooms (Table 5-3).

The crushed rock and fines, and the glacial-lake clay are carried by their respective conveyors in the lower-backfill batching circuit (Figure 4-15) to individual weigh hoppers. When the weigh hoppers are loaded with the required quantity of material, they automatically discharge through feeders into a rotating-pan mixer. The moisture content of the mix is adjusted by the metered addition of water into the mixer from the domestic-water storage tank. The backfill is mixed until it reaches the specified degree of homogeneity by applying a method specification that will be confirmed by regular sampling.

The mixed backfill is discharged into trucks equipped with 22-Mg rotating drums and water tanks, and is transported to the disposal rooms. The rotating drums prevent segregation of the backfill during transit.

The mixing process in the buffer and upper backfill circuit (Figure 4-15) is similar to the lower backfill process. Sodium-bentonite clay and silica sand are withdrawn simultaneously from their respective bins and are transferred to individual weigh hoppers by a screw conveyor. The material is then discharged into a rotary-pan mixer. The moisture content is adjusted by the metered addition of domestic water. When the product reaches the specified degree of homogeneity, it is discharged into trucks identical to the lower backfill trucks, but with a reduced capacity of 18 Mg of material. The homogeneity will be achieved by following a method specification that will be confirmed regularly by material sampling and testing.

TABLE 5-3

BUFFER AND BACKFILL PRODUCTION RATES

(after AECL CANDU et al. 1992)

	Total Per 28-d Period (Mg)	Maximum Per Day (Mg)	Maximum Hourly Rate* (Mg)
Lower Disposal-Room Backfill	13 768	918	66
Upper Disposal-Room Backfill	5 730	318	23
Buffer	2 307	239	17

* Based on operation 14 h/d.

The buffer and backfill final products are sampled as the buffer and backfill trucks are filled. Each sample is tested for grain size, moisture content, compaction and swelling characteristics. Any collected dust is trucked to the waste-rock loading pocket at the service shaft for transfer to the surface, and is disposed of in the rock disposal area.

5.6 APPLICATION OF SAFEGUARDS MEASURES

Safeguards measures are incorporated into the design of individual facilities, systems and operations of this conceptual design to maintain accountability of all nuclear materials and to detect any diversion. The following section describes opportunities to apply safeguards measures that we believe should satisfy current IAEA practices for nuclear facilities in Canada.

With current containment/surveillance methods, it is estimated that up to 12 safeguards staff could be needed for the disposal centre: two disposal-centre staff and ten full-time IAEA inspectors.

5.6.1 Safeguards Measures at the Surface Facility

The IAEA inspectors may verify the seals (and/or other containment and identification devices) on the transportation casks when they are received at the disposal centre to ensure that the numbered seals and casks received correspond with those reported as being shipped to the disposal centre. They may also visually check that the cask has not been opened by some means without violating the safeguards seals (e.g., by cutting through the cask side wall and repairing the opening).

The IAEA inspectors may periodically check the sealing devices on transportation casks that are temporarily stored in the cask laydown area. The case laydown area could be monitored using camera surveillance.

Transportation casks containing empty modules are normally shipped back to the reactor site. The act of placing empty modules into the casks may be observed by camera surveillance. The IAEA inspectors may verify that the casks shipped from the disposal centre do not contain used fuel. The surveillance information could be independently confirmed by measuring the gross weight and radiation field at the surface of each cask.

It is assumed that the IAEA inspectors are present when the sealing device on the cask is opened. The used fuel in the cask is contained in storage/shipping modules, with each module holding 96 bundles. The operators count and record the number of modules and the number of used-fuel bundles in each module that each cask contains. The removal of each module from the cask and its transfer to the module-handling cell or to the receiving surge-storage pool may be observed by either the IAEA inspectors and/or the IAEA surveillance cameras.

The modules containing bundles that require temporary storage in the surge-storage pool are placed in frames that rest on the bottom of the pool. The design of the frames and the module structure prevent the removal of bundles through the sides or bottom of the frame (Figure 4-30). When the frame is filled with modules, a top is placed over it to totally contain all the fuel bundles. The top is provided with a lock and an IAEA inspector may seal it remotely with safeguards seals. The pool is under continuous surveillance by IAEA cameras to record any irregular activity. The inspectors may periodically reverify the seals on the frames by remote means and inspect the frame to ensure that no opening has been made that would permit the removal of bundles.

The transfer of modules from the surge-storage pool to the module-handling cell may be observed by IAEA inspectors and/or surveillance cameras. The inspectors may verify the seals when the frame is opened and may reseal the frame if any modules remain in it.

The inspectors and surveillance camera may observe all activities in the module-handling cell and in the used-fuel packaging cell remotely. Surveillance may continue with cameras when no operations are taking place in these cells.

If required, the IAEA inspectors at the packaging cell used-fuel transfer assembly may verify that each used-fuel bundle contains irradiated uranium (i.e., that a "dummy" bundle has not been substituted for used fuel) by remote radiation measurements. However, this would not be necessary if there was continuity of containment/surveillance measures on the nuclear material at the disposal centre from the receipt of the transportation cask to the packaging operation.

If there is a need for more than simple item counting (e.g., bundle counters at nuclear generating stations), the IAEA inspectors may remotely read the serial number and manufacturer of each used-fuel bundle removed from the modules and placed in a disposal container. The operators can record this data and ensure that it conforms with the information received for the bundles shipped to the disposal centre.

The IAEA inspectors may remotely verify the loading of used fuel into each disposal container and the permanent sealing of the top. The operators record the serial number of the disposal container. Each disposal container may be under IAEA camera surveillance from the time used-fuel bundles are placed in that container until the disposal container is placed in a container cask and that cask is sealed.

A disposal container is normally placed in a container cask at the back end of the packaging cell and the cask is transferred to the vault. The cask may be sealed by an IAEA inspector using two safeguards seals after it is loaded with a container from the cell. Two seals provide redundancy in the event that one seal is damaged during handling and storage.

If the disposal containers are not transferred immediately to the vault, they are not placed in casks. Instead, they are placed temporarily in the headframe surge-storage pool. The IAEA inspectors can observe the transfer of the disposal containers to this pool. The containers may be under IAEA camera surveillance when they are stored in this pool. When the disposal containers are to be transferred from the headframe surge-storage pool to the vault, they are placed in a container cask and the cask may be sealed by an IAEA inspector with two safeguards seals.

Casks placed on the waste-shaft hoist can be weighed on entering or leaving the vault. These weight measurements may be verified by the IAEA inspectors to ensure that casks containing used fuel are not removed from the vault unless the operator has notified the IAEA of this removal, and approved safeguard measures for this eventuality are agreed to. The transfer of casks into and out of the vault may be under constant camera surveillance.

The IAEA has the right to inspect the above-ground facilities and the vault periodically and verify the sealed casks, the containers in the headframe surge-storage pool and any design changes. The inspectors may use the operators' records to determine the quantity and possibly the serial numbers of used-fuel bundles that have been placed in disposal containers and that are in storage or transit prior to being placed in the emplacement boreholes.

The special handling area of the used-fuel packaging cell could be designed so that the only readily available routes to transfer nuclear material would be those used for normal operation. These are the storage/shipping module and the damaged-fuel cans. The other accesses to this area are for maintenance and these could be monitored by containment/surveillance systems. In order to enter information on broken fuel bundles into the nuclear material inventory, care would be taken to keep all material from individual bundles together and to possibly identify the bundles from serial numbers on the hardware. An appropriate method of material accounting would be agreed with the AECB and the IAEA. The following approach might be used.

1. The mass of hardware and nuclear material would be measured and recorded against the bundle serial number and the serial number of the damaged-fuel can into which it is placed for all damaged fuel-bundle parts that can be attributed to an identified bundle.

2. The mass of all damaged fuel-bundle parts that cannot be attributed to an identifiable fuel bundle would be measured and recorded in a special inventory account that attributes the material to a particular storage/shipping module or transportation cask shipment. The material is also recorded against the serial number of the damaged-fuel can into which it is placed.

5.6.2 Safeguards Measures in the Disposal Vault

The safeguards measures required in a disposal vault have not been established by the AECB or the IAEA, and so the Used-Fuel Disposal Centre conceptual design assumes that IAEA inspectors are continuously present in the vault during operations. This assumption was made in lieu of specific national and international guidelines or legislation, and may be considerably more complex than the measures that would eventually be set. In making this assumption, AECL is not recommending safeguards measures for a disposal vault. We are providing a basis for estimating the costs associated with applying this set of safeguards measures and showing that application of safeguards measures is practicable.

The inspectors would monitor the serial numbers of loaded container casks in the vault; verify the disposal containers in the emplacement holes in disposal rooms; and install, check and remove safeguards seals on the backfilled holes, as required.

It is assumed that an IAEA inspector would be present whenever a sealed container cask is opened. Immediately prior to the removal of a disposal container from a container cask for emplacement in its borehole, the IAEA inspector would verify the seals on the cask and also that the cask has not been opened by other than normal means of access (e.g., by cutting through the cask walls).

The IAEA inspector would monitor the disposal container being transferred into its borehole and being covered with dry silica sand and buffer. If required by the IAEA, the inspector could place a safeguards seal across the top of each filled borehole containing a disposal container. This seal might be two perpendicular wires or bars across the top of the filled borehole between sets of pins that are mounted in the rock.

Although it would not likely be required because of the continuity of containment/surveillance measures through the facility, the IAEA inspector could also monitor the radiation energy spectrum emitted from each container as it is transferred into an emplacement borehole to ensure that it contains used fuel.

Each container cask being handled in a disposal room would be under IAEA camera or closed-circuit television surveillance. The floor area above these boreholes would also be under surveillance when the containers are placed and sealed in the emplacement boreholes. If there is any loss of this surveillance, the safeguards seals across the top of each filled emplacement borehole in this room could be verified by the IAEA inspector and then surveillance could be reinstituted.

An IAEA inspector could verify the seals across the top of a filled borehole before the area above the borehole is backfilled. When each room is being backfilled, the surveillance cameras from the room would be transferred to the panel tunnel to observe the entrance to the disposal room, and the safeguards seals would be removed from each borehole. The inspectors could periodically observe the construction of the concrete bulkhead at the entrance to each room. In addition, a safeguards seal such as multistrand fibre-optic cable could be incorporated into the bulkhead structure, and could be verified periodically to detect any tampering.

In the event of loss of surveillance or if the inspectors are unable to confirm that disposal containers have not been removed from sealed boreholes, the inspectors may require some containers to be removed from the boreholes for verification. This action is likely to be very infrequent because of the redundancy of the possible safeguards measures described and because it is highly undesirable from operations, radiological and cost considerations.

The IAEA could install seismic monitoring instruments at strategic locations in each panel, in adjacent panels and on the surface to detect and determine the location of any noise within the rock surrounding the disposal vault that might indicate attempts to excavate a diversion path into a disposal room(s). The purpose of the activities generating the noise would be investigated. These seismic instruments would be removed as the vault undergoes backfilling and sealing during the decommissioning stage.

5.6.3 Equipment and Equipment Attributes Associated with the Application of Safeguards

Specialized equipment would be required for the safeguards system for a used-fuel disposal facility. Several examples are discussed in this section.

The road and rail transportation casks must be designed to permit the application of safeguards seals to the cask lid. They must be fabricated so that the IAEA inspectors can be assured by visual observation of the surface that the cask has not been opened at any place on its surface. Each cask must have a unique mark (e.g., serial number) that is fireproof, cannot be easily falsified and permits identification.

The used-fuel bundles contained in storage/shipping modules may be placed in the receiving surge-storage pool prior to processing in the used-fuel packaging cell. The storage frames in the pool can be designed to permit the remote safeguards sealing of these frames. Similar frames are now in use in many Canadian CANDU reactor facilities.

The safeguards measures would likely require the use of surveillance cameras. The IAEA employs film cameras and closed-circuit television cameras and videotape for safeguarding many types of nuclear facilities. These cameras have operated satisfactorily for many years and they or updated models could meet surveillance requirements at a disposal facility.

Each disposal container must have a unique mark (e.g., serial number) that cannot be easily falsified and can be read and recorded remotely when the container is being loaded, transferred and placed in the disposal room.

Radiation detection equipment would likely be required to monitor the unloaded transportation casks after they are resealed prior to shipment from a disposal facility. The portable hand-held radiation detection meters now used are adequate to perform this monitoring. A radiation monitor could also be used to measure the gamma energy spectrum and intensity of radiation from each used-fuel bundle during container-basket loading, and from containers being placed in emplacement boreholes. This monitoring device is likely to be similar to the equipment used to check used-fuel bundles at some CANDU reactors to ensure that each fuel bundle contains used fuel. This monitor could be incorporated in the used-fuel transfer assembly carousel used to load fuel into the disposal container basket, and a portable unit could be used in the vault.

Each container cask must have a unique identification mark (e.g., serial number), a surface that indicates if the cask has been opened at places other than through its bottom and top openings, and must be designed so that it can accept safeguards seals. In these respects, the design is similar to the transportation casks.

The IAEA inspectors could apply safeguards seals on transportation casks, module storage frames, container casks, emplacement boreholes, safeguards equipment, and the disposal-room bulkheads. The IAEA has expended considerable effort in research and development of seals for use in safeguards applications. They use many types of seals in their current inspection operations (e.g., Type X seals, ultrasonic seals and fibre optic seals (IAEA 1984)). These seals could be used, as applicable, at a disposal facility. In addition, work is well advanced, through international support programs of technical assistance to the IAEA, to eliminate the requirement for IAEA inspectors to apply seals is person (Martinez et al. 1991) and to eliminate nuclear material remeasurement (Taylor and Walford 1991). In the first case, trials are ongoing for the VACOSS electronic seal, which could allow facility operators to apply and remove cask seals under camera surveillance without the personal presence of an IAEA inspector. This could simplify many sealing procedures and reduce IAEA staff needs. In the second case, the development of dual containment/surveillance devices based on independent and physically different principles integrated into an appropriate system could provide sufficient safeguards redundancy to preclude any further reverification measurements. This is critical to used-fuel disposal since any reverification (i.e., retrieval of the disposed fuel simply to reverify its presence) would be enormously expensive and counterproductive.

Container casks could be weighed on entering or leaving the waste-shaft cage, and the weight and the cask destination could be recorded automatically. This weighing and recording could be done by the installation of equipment now commercially available, or it could be integrated with the shaft hoisting system.

Seismic monitoring instruments could be used to monitor the sealed, backfilled disposal rooms and the backfilled vault to detect and locate unreported activities that might be associated with the excavation of a diversion path to the used fuel. Seismic monitors are now used commercially for underground geophysical surveys. It is anticipated that these monitors could be adapted to meet IAEA requirements.

The implementation of nuclear material inventory and safeguards would require dedicated staff, facilities and equipment. These could include redundant computer hardware and software systems for inventory control; information backup and storage; facilities for viewing, maintaining and storing records from video surveillance cameras; secure record storage and inventories for inspection reports and other inventory control data; dedicated office space for any IAEA inspectors and other staff; and other infrastructure support staff and facilities.

6. THE DECOMMISSIONING AND CLOSURE STAGES OF THE USED-FUEL DISPOSAL CENTRE

6.1 INTRODUCTION

The decommissioning stage includes the decontamination, dismantling and removal of the surface and subsurface facilities; the sealing of all subsurface boreholes; the backfilling and sealing of the tunnels, shafts and service areas; and the sealing of surface boreholes not needed for ongoing monitoring. Access to any installations retained for extended monitoring is strictly controlled. Otherwise, the site is returned to a state suitable for public use. Permanent markers are placed to indicate the surface overlaying the sealed disposal vault. Land-use restrictions could be archived in federal, provincial and municipal records and maps.

The closure stage involves the removal of measurement instruments from the surface boreholes used to monitor and seal these boreholes. This stage is separated from decommissioning only if extended monitoring is required after decommissioning; otherwise, this stage immediately follows decommissioning. The objective of closure is to return the site to a state so that the safety of the disposal vault does not depend on institutional controls.

The decommissioning stage of the Used-Fuel Disposal Centre begins when the waste emplacement operations have been completed, sufficient performance monitoring data have been collected to support approval to decommission and seal, as appropriate, and the decommissioning and sealing system designs and plans have been approved by the appropriate regulatory process and authorities.

Work in the decommissioning stage might be planned in an integrated manner to most effectively use resources and to minimize the duration and cost of the decommissioning stage. Alternatively, work could be planned on a less integrated basis over a longer period of time if this approach was more consistent with the regulatory and public positions at the time. This alternative would be appropriate if the decision is made to dispose of the low- and intermediate-level wastes from the Used-Fuel Disposal Centre operation and decommissioning in the disposal vault. This would necessitate the excavation of disposal areas for these wastes that are separate from the used-fuel disposal rooms, perhaps from the access tunnels to the component test area, into which these wastes would be placed and sealed prior to disposal vault decommissioning. This alternative would also be consistent with a regulatory and public desire to decommission surface facilities while deferring a decision on decommissioning the disposal vault. The integrated approach without low- and intermediate-level waste disposal in the vault is assumed in this discussion and in the Used-Fuel Disposal Centre resource requirements presented in Chapter 7.

The recommendation to decommission and close a disposal facility would be made by the implementing organization and approved by the regulatory agencies, with appropriate public interaction. Before recommending these actions, the implementing organization would have analyzed available information from laboratory and in situ tests, and from monitoring activities, to develop predictions of the postclosure effects on human health and the environment. An approach to postclosure assessment is described by Goodwin et al. (1994).

These analyses would have been sufficient to confirm that, as a minimum, the following requirements of the AECB have been met.

1. "The burden on future generations shall be minimized by . . . ensuring that there are no predicted future risks to human health and the environment that would not be currently accepted" (AECB 1987a).

2. "The predicted radiological risk to individuals from a waste disposal facility shall not exceed 10^{-6} fatal cancers and serious genetic effects in a year, calculated without taking advantage of long-term institutional controls as a safety feature. . . . The period for demonstrating compliance with the individual risk requirements using predictive mathematical models need not exceed 10 000 years. Where predicted risks do not peak before 10 000 years, there must be reasoned arguments that beyond 10 000 years the rate of radionuclide release to the environment will not suddenly and dramatically increase, and acute radiological risks will not be encountered by individuals" (AECB 1987a).

3. "A disposal system must be able to accommodate natural disturbances likely to occur, such that any increase in risk to members of the public as a result of these disturbances will be insignificant" (AECB 1985).

4. "The effectiveness of the disposal system must not be compromised by any provision that may be made for . . . postclosure retrieval or postclosure measurements" (AECB 1985).

Additional requirements to be satisfied as a prerequisite to decommissioning may be established by other regulatory groups and through consultation with local governments and community groups. The data necessary to show compliance with these requirements would also be gathered by the monitoring programs.

From a technical perspective, the decisions to decommission, and later to close, the disposal centre would be based on an assessment of the past, current and projected performance of the disposal system and its components. The performance of the individual components and subsystems would be assessed against the regulatory and derived criteria established for them in the system design and in the monitoring plan. The overall performance of the disposal system would be assessed against system requirements such as those described above. However, the actual criteria and requirements to be satisfied would be those in force at the time the decisions are required.

The regulators and the public may wish a period of extended monitoring of the vault and its environment after decommissioning. This would involve the use of surface-based monitoring systems. If these systems are installed in boreholes that pass near the disposal vault, they may represent a groundwater pathway that would have unacceptable consequences if they were not properly maintained and eventually sealed.

All decommissioning and closure activities in this conceptual design are assumed to take place three shifts a day, seven days a week, as in the construction stage. This schedule is selected because the work does not depend on the rate of container receipt, which sets the operations shift requirements, and because it is expected to minimize the duration and cost of the work. The schedules and cost estimates produced for this conceptual design are also based on the assumption that the surface and vault activities are integrated to ensure that the surface facilities required to support the underground activities are available as long as required.

The conceptual plan for decommissioning and closure of the disposal vault and surface facilities is discussed in the following sections. A schedule for vault sealing activities is given in Figure 6-1.

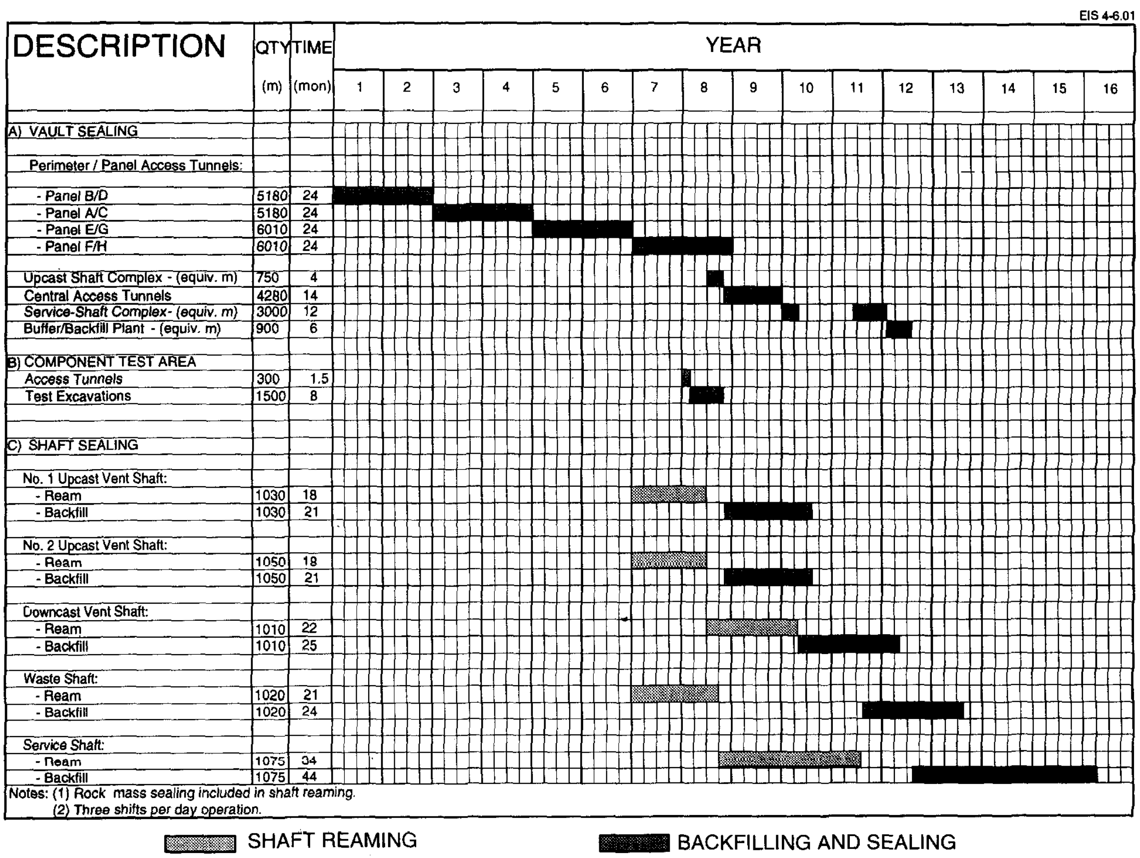


FIGURE 6-1: Vault Sealing Schedule (after AECL CANDU et al. 1992)

6.2 DISPOSAL VAULT DECOMMISSIONING

Decommissioning of the disposal vault involves the removal of permanent operating systems and furnishings, the installation of temporary services and the furnishings, and the refurbishment or preparation of the exposed rock surfaces for installation of seals. The details of operations required to prepare for sealing and the sealing systems to be used depend on site-specific and disposal-system-specific factors that are not now available. Current concepts are presented for the vault sealing systems and operations in the following description to indicate the type of work required. Details on the development of sealing materials and systems are provided by Johnson et al. (1994a), and the materials are discussed in Section 3.3.3.

6.2.1 Underground Exploration Borehole Sealing

Exploration boreholes would have been drilled from underground access excavations for a variety of reasons, mainly characterization and monitoring, during the siting, construction and operation stages. If any boreholes were drilled from disposal rooms, they would have been sealed during the operation stage. Any equipment installed in exploration boreholes drilled from the access tunnels, service areas and shafts, is removed during the decommissioning stage, and the boreholes are sealed as the sealing of the excavations progresses.

The boreholes may be sealed with a composite borehole seal similar to that shown in Figure 6-2. The components of the seal are cement-based and clay-based materials. The cement-based seal materials, which have a low hydraulic permeability and will resist erosion by moving groundwater, are installed at selected locations to isolate fracture zones and other hydraulic flow paths from the vault. The clay-based seal materials, which have a low hydraulic permeability and will swell as they absorb groundwater, are placed in adjacent sections of sparsely fractured rock, where they are not susceptible to erosion from water flow. The entire borehole is filled in this manner.

Prior to sealing the borehole, a thorough review is conducted of all available core logs, borehole logs and downhole test results to ascertain the regions that must be sealed with clay-based materials, and to identify the distribution of hydraulic permeability, the fracture frequency and the possible chemical deposits along the borehole. Preparation of the borehole includes removing any equipment or instruments installed in the boreholes, cleaning and flushing the boreholes, and pressure-grouting the water-bearing zones, if necessary.

The cement seal could be placed using the balance method often used in the petroleum industry to seal the vertical and inclined boreholes that have been drilled downward. In this method, grout is injected into a borehole that is filled with a material that is similar density to and chemically compatible with the grout. The weight of the compatible material over the grout forces the grout into relatively open fractures.

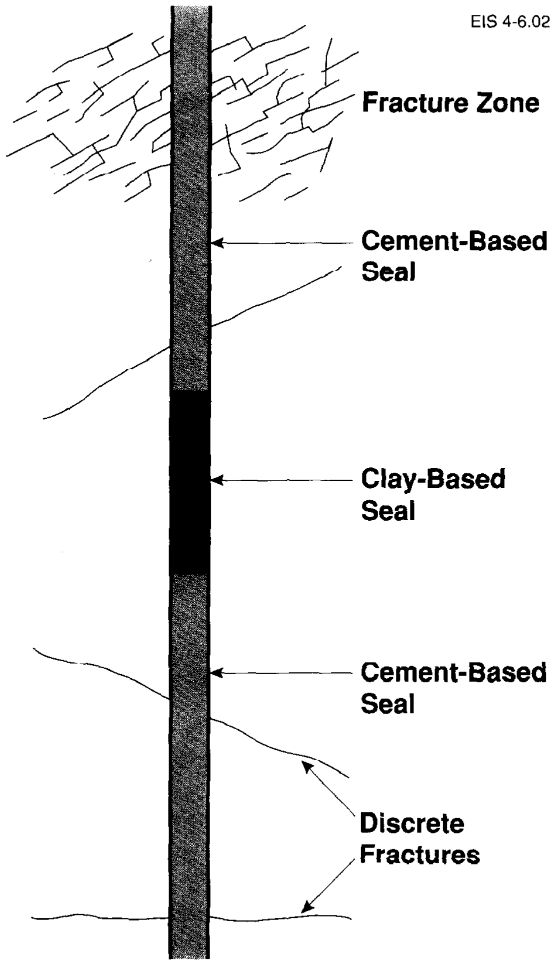


FIGURE 6-2: Typical Borehole Seal System (after AECL CANDU et al. 1992)

The clay-based seals may be sections of highly compacted bentonite clay inside a perforated copper pipe, as have been tested in Sweden (Pusch and Bergström 1980). The bentonite seals are installed after the underlying concrete has set. The bentonite swells as it saturates with groundwater, filling the complete section of the borehole. A cap is placed over the bentonite insert before additional cement is placed into the borehole. The entire borehole is sealed in this manner.

A similar method would be developed for sealing horizontal and near-horizontal boreholes and for boreholes that have been drilled upward.

6.2.2 Sealing of Access Tunnels and Ancillary Facilities

The sealing operations are carried out in a retreat manner towards the service-shaft complex to maximize the use of the buffer and backfill preparation plant. Any intersecting fault and fracture zones are grouted (as discussed below) before the tunnels and ancillary surface areas are backfilled, some rock bolts and all equipment anchor bolts are removed if and when it is safe to do so, the holes are sealed, and all rock surfaces are cleaned. Any instrumentation and equipment installed in boreholes drilled from these areas is removed and the boreholes are sealed with cement- and clay-based materials, as discussed in Section 6.2.1.

Fracture zones may have been grouted during the construction and operation of the vault as an operational expediency to control water inflows. In some cases, the grouts used may not have been designed or placed in a manner consistent with the requirements of a long-term seal system. These locations may be regrouted as part of the sealing operation to enhance the long-term integrity. This may be the case if the grouts and grout application methods specified for the long-term sealing system were developed after the original grout application. However, some grout applications to seal fracture zones during the construction and operation stages could be used as a demonstration of the grout materials and application methods proposed for long-term sealing systems. These would be monitored over the operating life of the vault to obtain data on their performance in an unconfined environment around a tunnel. These data would contribute to the final design of the grout component of the long-term seal system.

One approach to grouting these fracture zones during the disposal vault decommissioning and sealing involves drilling multiple grout holes at a relatively close spacing from the excavation to intersect the fracture zone near the excavation boundary. The holes may be washed with high-pressure water and air to improve the grout/rock contact. The grout, likely a cement-based material, is injected into each grout hole. Leakage-test holes are interspersed among the grout holes to assess the quality of the grout seal and, if necessary, additional grout holes are drilled and grouted between the primary grout holes to ensure that an adequate seal is achieved.

The exposed rock surfaces become coated to some degree by debris, engine and hydraulic oil, diesel soot, blasting smoke, paint contamination and microorganisms during the vault construction and operation. Similarly, the floors are covered with gravel road beds or concrete work pads, and have water drainage ditches. All such materials are removed from the rock surfaces, loose rock is scaled off and the surfaces are cleaned to concrete-placement quality prior to backfilling and sealing. The access tunnels are sealed in a manner similar to that used for disposal rooms (Section 5.4.6).

The sequence of access tunnel sealing would be to seal the perimeter and panel tunnels in a retreat fashion from the upcast-shaft complex to the service-shaft complex while the central access tunnels are kept open for ventilation and access purposes (Figure 3-2). Local ventilation systems using portable exhaust fans and duct tubing are installed and are exhausted into the flow-through ventilation system. The central access tunnels are sealed concurrently from the upcast-shaft complex toward the service-shaft complex when the perimeter and panel tunnels have been sealed. The periodic crossovers between the tunnels are used to provide flow-through ventilation, and portable fans and ducting are used to draw air from the work area and to exhaust it into the return-air tunnel. The service areas in the upcast- and service-shaft complexes are sealed immediately prior to the start of shaft sealing in each complex.

The ancillary service areas and the tunnels are sealed in a manner similar to that used for the disposal rooms (Section 5.4.6). The procedures are modified to suit the geometry for some of the ancillary service areas where the configurations of the openings are not the same as the disposal rooms and tunnels. This may include the use of hand-operated equipment in areas where the large diesel-powered mobile equipment cannot operate.

When all other ancillary service areas have been decommissioned and sealed, the backfill and buffer preparation plant is disassembled and rebuilt on the surface. This plant is needed since sealing materials are required for the underground areas formerly occupied by the buffer and backfill plant, and for the shafts.

Concrete bulkhead seals are installed at strategic locations in the tunnels. These bulkheads are similar to the disposal-room bulkheads (Section 5.4.6), and may also include sections of highly compacted bentonite blocks to provide a seal element that will exert a radial load on the walls of the excavation being sealed. Blocks of highly compacted bentonite are specified for this purpose because the fabrication and use of highly compacted bentonite in block form was studied extensively in the Organisation for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) International Stripa Project, as discussed by Gray (1993). In situ compaction may also be practicable, but has not been demonstrated. Possible locations for bulkhead installations are in sound rock near tunnel intersections and near the intersections with significant fracture zones (Figure 6-3).

6.2.3 Shaft Sealing

Shaft sealing is the last step in the sealing of the disposal vault. The backfilling of the tunnels and ancillary areas is complete at the shaft bottoms, and there is access only between the bottom of the shafts within the service-shaft complex and within the upcast-shaft complex. These tunnels, which connect the shaft bottoms within each complex, allow for the removal of muck from shaft reaming, if it is done to remove shaft liners, and any water that collects at the shaft bottoms.

The following preparation is done before the shafts are backfilled:

1. Instrumentation is removed from boreholes drilled into the shaft walls and these holes are sealed as described in Section 6.2.1.

2. Shaft services and shaft furnishings are removed, and anchor boreholes are sealed.

3. The concrete liner is removed from the waste and emplacement panel upcast ventilation shaft (and from other shafts if installed).

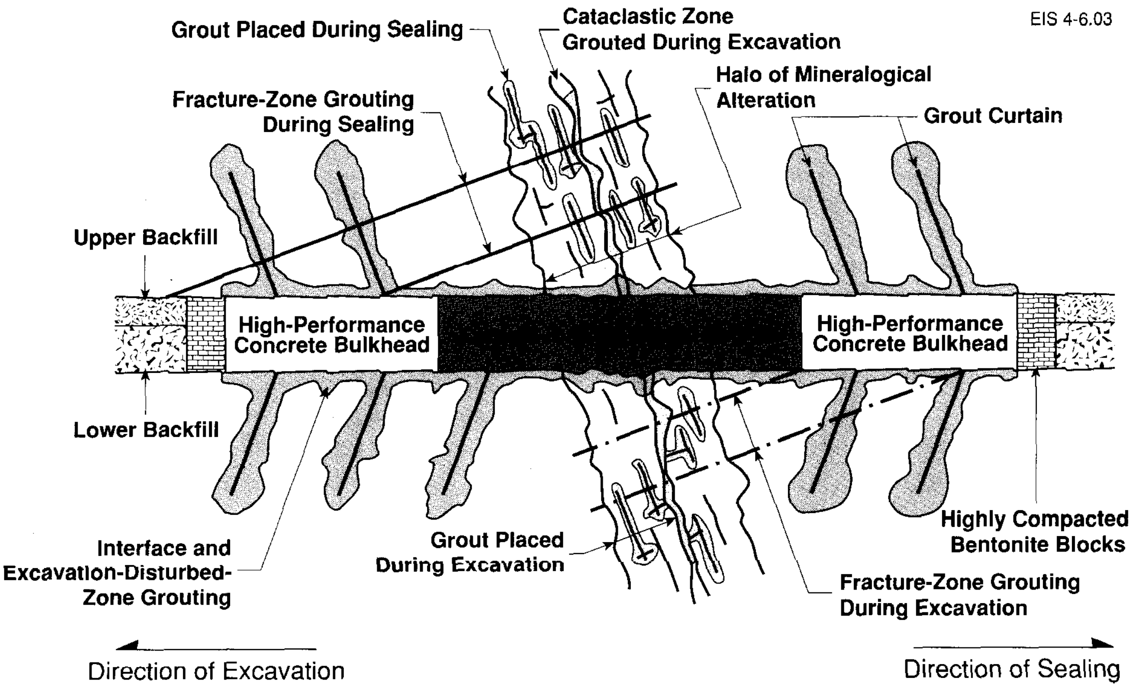


FIGURE 6-3: Isolation of a Major Fracture Zone in an Access Tunnel

4. The shaft is re-equipped to provide temporary access and services for sealing.

5. The shaft rock walls are cleaned and scaled to concrete-placement quality.

6. Fracture zones are grouted to limit water inflow to the shafts.

7. The excavation-disturbed zone is grouted at seal locations.

These operations are carried out in the shafts from working platforms suspended from hoist ropes. A concept for a three-deck working platform is shown in Figure 6-4. Zones in the rock are selected for grouting based on borehole data and characterization studies. The objective of this grouting is to have a structurally stable rock surface with water seepage rates that are compatible with shaft seal placement. The grouting may be carried out by drilling fan arrays of grout holes angled into the target area. The orientation, size and spacing of these grout holes are determined from an assessment of the observed conditions at each location selected for grouting. During grouting, hydrogeological and geophysical monitoring systems are used to gather data to aid in assessing the effectiveness of the grout coverage and, if necessary, additional grout holes may be drilled and grouted. Any monitoring boreholes installed to assess the performance of the grout are sealed.

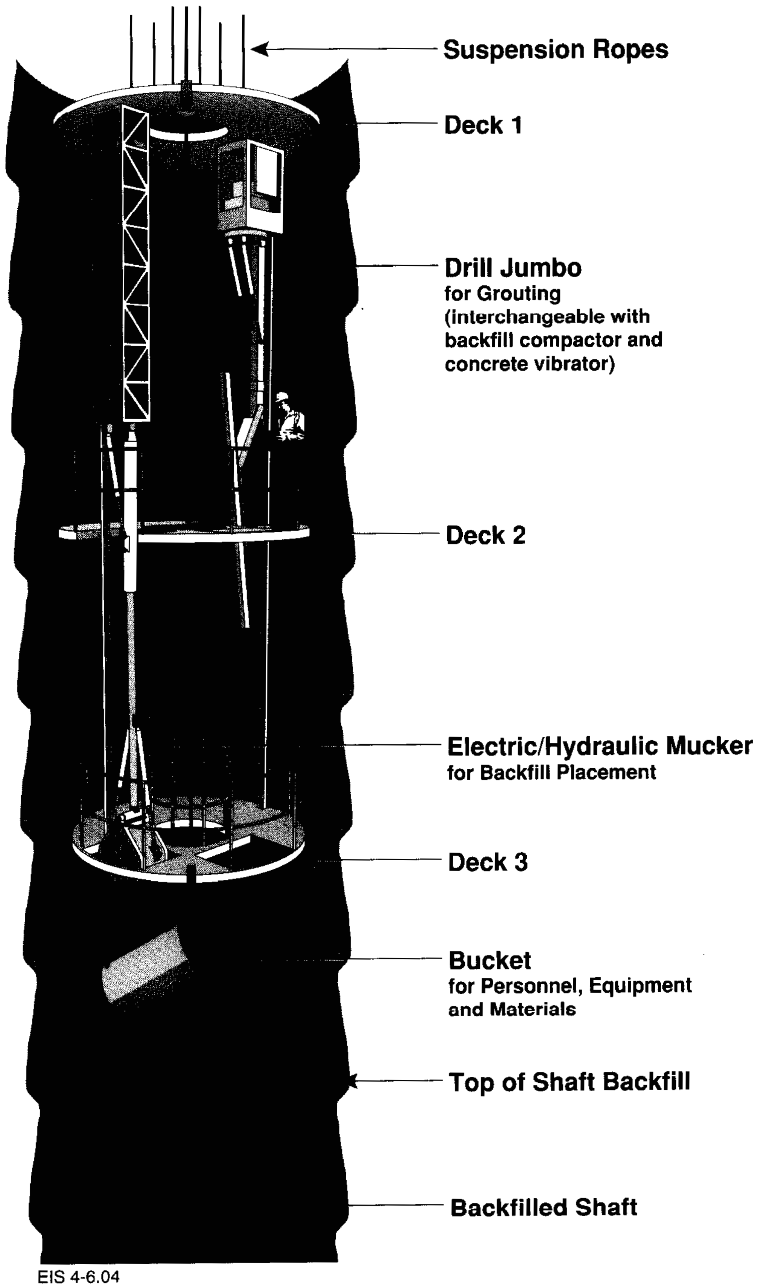


FIGURE 6-4: Conceptual Arrangement for a Three-Deck Shaft Working Platform for Shaft Sealing

Shaft services to be removed include the compressed-air lines, clay and concrete transfer lines, water supply pipes and fittings, drainage lines, power supply and lighting cables, diesel fuel lines, and telephone and signal cables. Furnishings to be removed include all of the shaft guides and sets, steel support brackets, brattice and lower crash beam assemblies. The shaft designs will have provided separation of those services and installations that are potentially contaminated with traces of radioactive or hazardous materials to facilitate separation of those materials that require special handling from those that are normal industrial waste and could be recycled if appropriate.

AECL CANDU et al. (1992) proposed the removal of the shaft lining and a 1.0-m annulus of wall rock to expose a sound, clean rock surface for sealing. In their proposed operation, the liner and rock would be removed by raise-bore reaming. The need to remove a continuous 1-m annulus of rock from the wall of each shaft is uncertain. This conceptual design assumes that the concrete shaft liners, where installed (Section 4.3.1), are removed by reaming, with only a minimal amount of the rock being removed. However, the removal of liners and 1 m of rock annulus for five shafts is assumed for scheduling and cost estimating purposes. Whereas the reaming would tax present technology (i.e., a modified raise bore machine might be used), the advances in shaft boring and drilling techniques in the future are expected to result in adequate reaming capability. The muck from the reaming operation falls to the shaft bottom and is loaded into skips in the other shaft(s) at that shaft complex for transport to the surface. When the last shaft at each shaft complex is to be backfilled, the remaining tunnels are sealed, backfilled, and the final bulkheads are installed. The muck from reaming the last shaft at each shaft complex is allowed to accumulate on the shaft bottom and is removed using a mucking machine and buckets similar to the methods used in shaft excavation.

Reaming has been proposed because at least the waste shaft and the emplacement panel upcast ventilation shaft are assumed to have concrete liners. The liners are assumed to be installed in these shafts because there is a greater potential for radioactive contamination in these shafts, and the liner would separate this contamination from the natural environment and simplify decontamination operations. Concrete liners would be considered as an alternative for each shaft during a detailed design to control radioactive contamination, to control the rock at the excavation boundary or to minimize resistance to ventilation airflow.

Following the shaft reaming, the shaft is re-equipped for the wall cleaning and sealing. The shaft walls are resupported with rock bolts and mesh, if necessary, to provide a safe working environment. This requires the installation of a drum hoist and a conveyance for material and personnel transport, and the additional hoists necessary to operate a working platform and backfill emplacement equipment. The number of decks on the working platform is governed by the number of concurrent operations that are to be done. Figure 6-4 shows a three-deck shaft working platform supporting the backfill distribution and compaction equipment and providing a workplace for progressive removal of the temporary furnishings in the shaft. Openings in the decks permit the lowering of the backfill, concrete and other sealing materials necessary to seal the shaft.

The shaft is surveyed for local instabilities and high water-seepage rates, and these are controlled by further grout injection.

When the preparations are complete, the shaft sealing begins with the placement of backfill and composite concrete/bentonite block seal elements. The current concept for a shaft seal system is shown in Figure 6-5 and the choice of precompacted blocks over in situ compaction of bentonite is discussed in Section 6.2.2. The backfill material may be the lower backfill used in sealing the disposal rooms. The shaft sealing system is largely backfill with strategically placed concrete and highly compacted bentonite block seal elements to isolate the major fracture zones from the vault. The concrete plugs are formed and placed using a construction practice appropriate for the concrete composition and properties selected. The thickness of the concrete plugs would be designed for the characteristics of the place in which they are constructed. The concrete material is prepared and placed using the same procedures used for the disposal-room and tunnel bulkheads. The highly compacted bentonite blocks are placed either on backfill (below a fracture zone) or concrete (above a fracture zone), and are sandwiched by the other material as shown in Figure 6-5. The thickness of the highly compacted bentonite block seal would be designed for the characteristics of the locale. The material is prepared at the surface, transported down to the work site and is placed mechanically or manually.

The backfill is placed using the same general methods and quality-control procedures applied in the disposal rooms (Section 5.4.6). However, the placement equipment is specially designed to provide the proper compaction in the circular, vertical shaft configuration. The backfill material is prepared at the surface and is conveyed down the shaft in buckets. It is spread in lifts appropriate for a 150-mm compacted thickness. Padded-drum rollers or vibrating compactors may be used to compact the backfill material to the required density.

The collar of each shaft is sealed with a reinforced concrete plug anchored to the surrounding rock. The length of the plug depends on the geological structure and topography of the site and the expected erosional effects of future glaciation. The plug serves to discourage inadvertent human intrusion.

6.3 DECONTAMINATING AND DECOMMISSIONING SURFACE FACILITIES

6.3.1 Introduction

The surface facilities will be decommissioned by removing the facilities and all possibility of radiation exposure to the public that might arise from their existence. This means removing all radioactive and nonradioactive systems, installations and structures, and rendering the site "clean" within regulatory limits. The site is returned to a state suitable for unrestricted public access and restricted subsurface use, and is marked with permanent markers to signify the presence of the underground disposal vault.

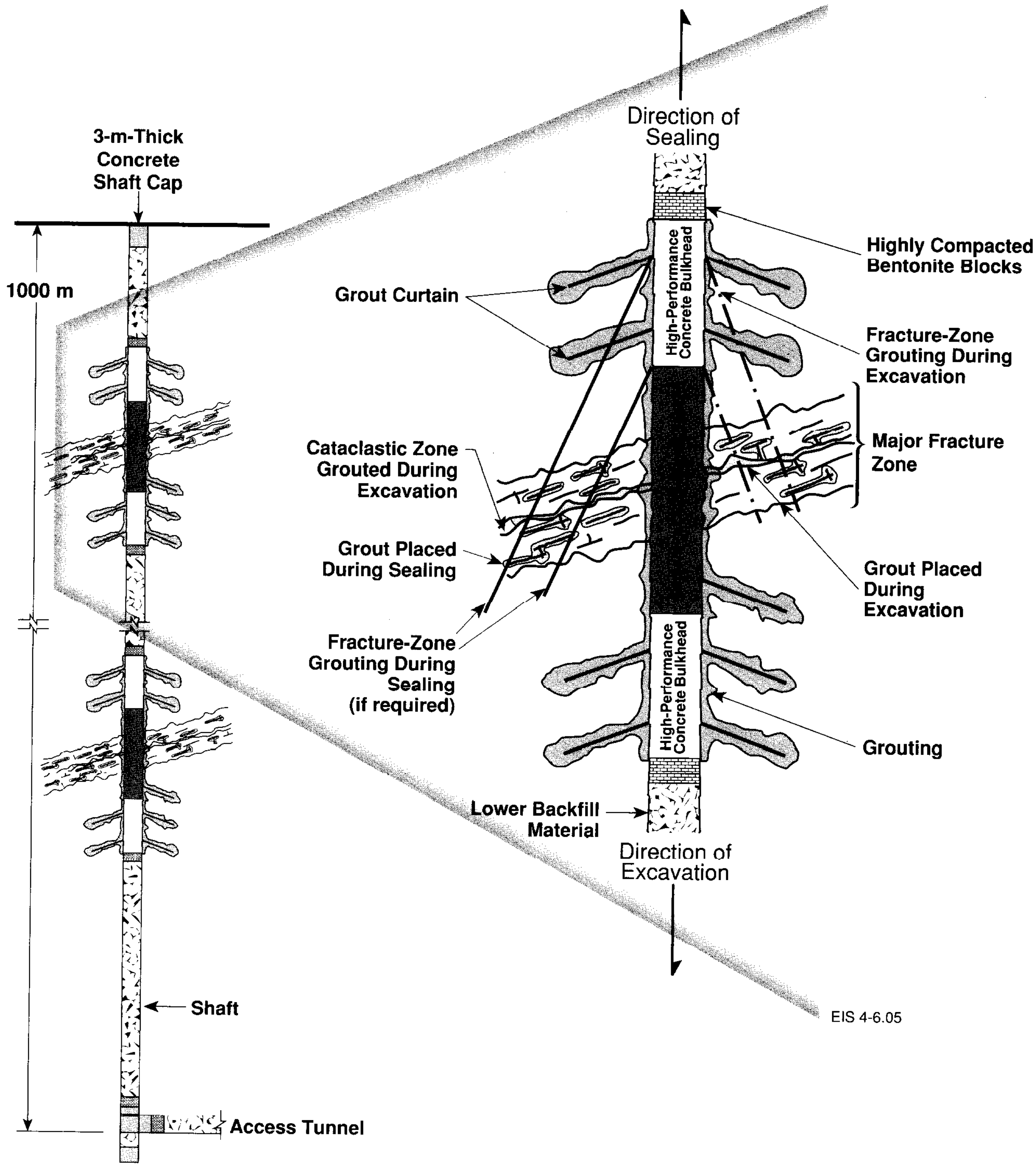


FIGURE 6-5: Typical Shaft Seal System

The decontamination activities would be planned to remove and concentrate as much of the hazardous and radioactive material residues as practical. These are the objectives for these activities:

1. The decontamination of hazardous and radioactive residues from equipment, installations and structures to as low as practical to maximize the quantities that can be handled as "uncontaminated" waste, and minimize the quantities that fall into the low- and intermediate-level categories.

2. The minimization of the volume and the maximization of the concentration of the hazardous and radioactive material residues removed in the decontamination processes.

The technology for decontamination is widely used, and large facilities such as the Gentilly-1 Nuclear Generating Station have been decontaminated successfully (Le and Denault 1985).

The complexity of the decontamination program required for any facility depends primarily on the extent of the radioactive and other hazardous material contamination built up during the operating lifetime of the facility. The required decontamination program is determined by three main factors: the total radioactive and hazardous materials inventory, the characteristics of this inventory, and the physical state of the contaminants.

The total inventory of radioactive contaminants in the surface facilities after disposal of all the used fuel depends on the amount of radioactive contaminants released during the operating lifetime of the facility, and the degree to which decontamination has been part of normal operations.

The source of contamination is mainly the activated corrosion products of the primary heat transport systems from which the fuel is taken, the actinides and fission products released from fuel bundles with cladding defects, and fuel bundles damaged in transport or in process. Much of the contamination would have been collected by the pool and ventilation filtration systems, and by routine cleaning of work areas.

The physical state of the contamination is characterized according to whether it is in a loose or fixed state, and by how easily it can be removed. This usually determines the need for and extent of decontamination or removal of the contaminated item by disassembly or demolition. Loose contamination is generally easy to remove, whereas fixed contamination is more difficult to remove, often requiring partial demolition and removal of structures. Generally, small areas of high contamination require less effort to remove than the same amount of contamination dispersed over large areas.

6.3.2 Preparations for Decontamination

The initial preparation for decontamination and decommissioning occurs during the design of the facilities. Individual installations and systems should be designed and constructed to provide for effective contamination control and decontamination in the operation stage and for efficient decontamination during the decommissioning stage. The objective is to create installations and systems that are relatively easy to clear of radioactive contamination using methods that minimize the amount of radioactively contaminated waste produced by the cleaning. As well, the interiors of structures that might become contaminated with fixed (not easily removed) contamination during their operating life should be constructed so that the contaminated surface can be removed relatively easily and with a minimum volume of waste. An example of this would be to cover the interior surfaces of the module-handling cell, the packaging cell and the storage pools with a material such as stainless steel or epoxy paint to protect the concrete structure from becoming radioactively contaminated.

When the approach to decontamination of the surface facilities is being planned, the first step is to conduct a detailed survey to confirm the location and amounts of hazardous material and radioactive contamination in the facilities that are indicated by the records kept during the operation stage. The highest levels of contamination are likely to be in the used-fuel packaging cells, the module-handling cells, the receiving surge-storage pool and their associated support systems, such as the pool purification, ventilation and solid/liquid radioactive waste management systems and facilities.

Methods for decontaminating each contaminated area of the disposal centre are specified on the basis of the level of contamination and the characteristics of the contaminated area. Loose contamination is usually removed and contained using a fluid wash, such as air flushing of ventilation systems for collection on filters, vacuuming with special machines, scabbing contaminated structural surfaces to remove the contamination, or flushing with water or a solvent into an active drainage system. Materials with fixed contamination are disassembled or demolished and placed in containers for disposal in approved facilities. In some cases, it may be simpler, more cost-effective and safer to convert loose contamination on an item to fixed contamination (e.g., by painting), and to remove the entire item as contaminated waste. However, this practice should be discouraged because of its effect on the amount of radioactively contaminated waste that would result.

The contaminated material is generally removed mechanically or chemically by physically separating the contaminated material from the balance of the system, installation or structure. Contaminated pieces are broken down into small enough sizes to be efficiently packed in low- and intermediate-level waste containers. Chemical cleaners containing contaminants are collected, neutralized and solidified for disposal.

The type of equipment required for decontamination is similar to the equipment used during routine housekeeping and maintenance of the disposal centre. The processes and equipment for decontamination is a developing area of technology. Those selected for application at the decommissioning stage would be state-of-the-art technology for that time. Based on current technology, the equipment would include the following items:

Hydrolaser: an electrically driven, high-pressure (up to 70 MPa) water jet with a water flow rate up to 35 L/min.

Scarifier: a manually operated pneumatic hammer with special heads for removing concrete surface layers.

Demolition hammer: a manually operated electric or pneumatic hammer/chisel.

Underwater vacuum cleaner: a cleaner designed not only to clean underwater surfaces but to pick up loose debris such as bolts and nuts.

Chipping hammer: manually operated electric or pneumatic chisels in various sizes.

Portable ventilator: a large extraction fan with HEPA filter and flexible ducts.

Wet/Dry vacuum cleaner: industrial models with HEPA filters, used to vacuum up debris and water.

Cleaning cabinet: an enclosed cabinet with windows, having connections to an external hydrolaser system, for decontaminating small items.

Since the technology for demolition is well established, the disassembly and disposal of systems, installations, and structures that are not contaminated, or have been decontaminated, is not described here.

6.3.3 Decontamination and Decommissioning Activities

Decommissioning begins with the contaminated areas that are to be decontaminated and disassembled down to the basic building structures while all other support systems are in place. The following decommissioning sequence could be used for the Used-Fuel Disposal Centre:

1. Module-handling cells and used-fuel packaging cells.
2. Surge-storage pools and pool service systems.
3. Air locks, decontamination areas, laundry and washrooms.
4. Ventilation systems.
5. Liquid- and solid-waste treatment facilities.

These operations were described by AECL CANDU et al. (1992).

The contaminated material collected during the decommissioning stage is estimated to be similar in volume to the intermediate- and low-level waste accumulated during the operation stage of the disposal centre. This volume is estimated to be ~2000 m^3 for the decommissioning stage, assuming extensive use of the compaction methods for volume reduction proposed by AECL CANDU et al. (1992). The wastes are temporarily stored on site during each stage until sufficient quantities are accumulated to be shipped off site to a licensed low- or intermediate-level waste disposal facility (see discussion in Section 4.2.6.3).

The small volumes of solid waste with higher levels of contamination, such as spent resin and filters from the pool water purification circuits and the liquid-waste treatment systems, are also packaged in boxes or in drums. These boxes may require storage in shielding cells and transportation in casks.

The radioactive liquid wastes collected during operation and decommissioning are treated in ion-exchange and/or reverse osmosis columns and filters to reduce or remove the contamination. The cleaned water is released to the environment in the plant water discharge flow, and the ion-exchange resins, the reverse osmosis and the filter media are handled as a solid radioactive waste. The Waste Treatment Centre at AECL's Chalk River Laboratories has demonstrated the effectiveness of these systems (Sen Gupta 1994).

When the major areas have been decontaminated, the service systems, such as active filter and drainage systems, are decontaminated, disassembled, and packaged for disposal. Where these systems are embedded in structures, a portion of the structure may be disassembled to remove the contamination (e.g., duct or pipe). Finally, following treatment of all collected wastes, the storage tanks and treatment systems are decontaminated and the contents are packaged using temporary systems and installations that can be readily packaged for disposal.

After decontamination, the facilities are disassembled and demolished by conventional means. The waste from demolition comprises metal and nonmetal (e.g., timber, concrete) materials. Disposal of these wastes depends on the location of the site. Many system components and metallic wastes could have scrap or resale value once they are confirmed to be free of contamination, if the disposal centre is close enough to suitable markets. Otherwise, the materials are placed in a properly designed disposal area on the site or moved off site to an approved disposal area in the region.

Once the vault has been sealed, all facilities and buildings have been removed, and any areas with unacceptable residual contamination have been cleaned to meet regulatory requirements, the site will be landscaped to promote natural growth and, if appropriate, will be reforested. The waste-rock disposal area would be stabilized to minimize any potential effects on the environment.

Depending on the policies and requirements developed at the time by regulatory authorities, certain structures and access routes may remain for monitoring and safeguards purposes. Such facilities may include instrumented boreholes and surface installations for geosphere and biosphere monitoring, and an acoustic emission/microseismic network for safeguards monitoring. Access to any such facilities would be strictly controlled.

Permanent markers would be installed at the site to provide an indication to future generations of the presence of the sealed disposal vault. These markers could have markings that are internationally recognized as representing a potential risk to humans and the environment. Alternatively, a series of symbols such as those currently used for poisons and radiation could be used. The markers should also include a map of the surface area under which the disposal vault is situated. International standards have not been established, but the IAEA has begun work to develop a position on the requirements for safeguards of used-fuel disposal vaults (IAEA 1988, 1991).

A second means of identifying the disposal vault location that does not depend on physical site markers is also required in case the markers are removed or defaced, such as by glaciation. A possible approach to maintaining a record of the vault location would be to have the disposal vault shown on geological survey and other standard maps to be archived internationally. These records may survive in some form and would provide future societies with an alternative source of information on the location of the land surfaces where drilling and excavation could be hazardous to humans and the environment.

6.4 DISPOSAL CENTRE CLOSURE

Closure of the Used-Fuel Disposal Centre consists of the removal of instruments from surface-based monitoring boreholes and the sealing of these boreholes. The process of sealing these boreholes is similar to that discussed in Section 6.2.1. Closure is limited to those boreholes that could compromise the long-term safety of the site. Shallow boreholes (*e.g.*, less than 50 m deep) and deep boreholes distant from the disposal vault and not intersecting potential radionuclide transport pathways may not need to be sealed and may remain available for extended monitoring, if desired. Also, safeguards containment/surveillance monitoring (e.g., an acoustic emissions/microseismic network) could be maintained as long as the IAEA and Canada consider them to be necessary.

6.5 CLOSURE AND POSTCLOSURE SAFEGUARDS

The ground area above the backfilled disposal vault could be under IAEA containment/surveillance measures. After the vault has been backfilled and sealed, inspectors may visit the site periodically to detect any attempts to reopen the vault either by removing the backfill or by excavating new passages to the vault disposal rooms.

Seismic monitoring instruments could be located on the surface in the rock above and around the vault so that the inspectors could detect and locate the source of any noise that might be associated with an attempt to excavate a new shaft or to reopen the backfilled shaft.

Inspections and containment/surveillance measures would continue as long as the IAEA and Canada consider them necessary for safeguarding the sealed vault.

6.6 POSTCLOSURE RETRIEVAL OF USED FUEL

The sealing of a disposal vault during the decommissioning stage does not irrevocably remove the used fuel from society's control. If the retrieval of used fuel would be required, significant time, effort and resources would be necessary to gain access to the disposal rooms and retrieve the disposal containers. Two of the possible reasons for considering the retrieval of used fuel sealed in a disposal vault might be

1. to use the used fuel as a resource (i.e., to recover the fissile material for other uses), and

2. to investigate the reason for disposal system performance that is quite different from the expected performance.

The retrieval of used fuel from the sealed disposal rooms is discussed in Section 5.4.7. The additional requirements to gain access to the sealed disposal rooms are described here.

Two alternatives are possible to gain access to the disposal rooms given that the shafts and tunnels are backfilled and sealed: either the pre-existing shafts and tunnels could be re-excavated by removing the sealing materials, or new shafts and tunnels could be created in the rock. The choice would likely be influenced by the ease of excavation (i.e., through sealing materials versus rock), the estimated cost, and the plans for reusing the disposal vault. In the latter case, for example, the disposal of highly radioactive fuel reprocessing wastes might be contemplated within the existing disposal vault.

To accomplish postclosure retrieval, a site infrastructure and facilities similar to those required for the original disposal would be needed to carry out the tasks. These would include shaft headframes, retrieval casks, container casks, materials handling equipment, used-fuel storage and handling facilities, utilities, roads and rail access, waste handling, treatment and storage facilities, and transportation vehicle loading and inspection areas. The used-fuel safeguards procedures and measures would have to be re-established to accommodate the recovery and handling of used fuel.

The resources needed to carry out postclosure retrieval operations are anticipated to be similar in magnitude to the resources required to complete the original disposal.

7. RESOURCE REQUIREMENTS FOR IMPLEMENTING THE USED-FUEL DISPOSAL CENTRE CONCEPTUAL DESIGN

7.1 INTRODUCTION

This report has presented information on the organization, administration, and implementation of a particular facility design to dispose of used fuel. This section provides overall estimates for the resources required to implement the Used-Fuel Disposal Centre presented in Chapters 3 to 6.

The estimated schedule and the resources required for implementing disposal within a fixed-capacity facility provide the nuclear electric utilities with a data set that may be used to determine the appropriate disposal charge to be included in their electrical power rates. In their analyses, each utility adjusts the basic information, such as that provided in this chapter, to a specific schedule and capacity suited to their nuclear capacity projections and disposal planning schedules. For example, Ontario Hydro charged its customers less than $0.001/(kW·h) for used-fuel disposal (Ontario Hydro 1993b). This amount was determined by applying appropriate scaling factors to the capacity-dependent (i.e., capital) and duration-dependent (i.e., operating) costs developed in a cost study. The scaled costs for disposing of 4 million to 5 million used-fuel bundles were estimated to be $3489 million in capital and $1646/bundle, in 1993 Canadian dollars (Ontario Hydro 1993b).

The Used-Fuel Disposal Centre cost and labour estimate presented in this section has been based on information developed to a conceptual level. The accuracy of the cost estimate given in this section depends on the available design information. The design data developed by AECL CANDU et al. (1992) and subsequent modifications discussed in this report are limited in detail for conventional structures, processes and equipment; however, they are more detailed for the more specialized processes, equipment and structures. The estimates presented here are based on this information:

1. An assumed program of continuing research activities.

2. A proposed program of site screening and surface-based site evaluation activities (Davison et al. 1994a, Greber et al. 1994).

3. Conceptual design data.

4. Type, quantity and sizing of equipment.

5. Approximate utility and service requirements.

6. Type and quality of construction methods.

7. Assumed facility size, location and conditions.

We estimate the range of uncertainty in the overall cost estimate of this particular conceptual design to be -15% to +40%. That is, the estimate may be too low by 40% or it may be too high by 15%. The cost estimate would change, perhaps significantly, if different engineered barriers were selected and/or the disposal vault arrangement became more complicated to account for local site conditions.

The disposal centre costs are presented by project stage in the following sections. The costs related to the settlement of workers are discussed, and the costs of used-fuel transportation are presented. The cost estimates include an allowance for monitoring, performance assessment and continuing supportive research anticipated during siting, construction, operation, decommissioning, and closure. Limited container retrieval as required to deal with containers used in component tests is also included.

The costs of other nonroutine activities have not been included. For example, one nonroutine activity for which costs have not been estimated is container retrieval, except as noted above, since many specific cases would have to be analyzed to develop a representative cost. Important variable factors affecting the cost of retrieval include the number of containers to be retrieved (e.g., one container, one room of containers, one panel of containers or the entire vault contents), the state of the containers (e.g., intact, breached with contaminated buffer, or failed with contaminated buffer and backfill), and the time of retrieval (e.g., on emplacement in the borehole prior to borehole sealing, after a borehole is sealed, after a room is sealed or after the vault level is sealed). Also, the costs of the review and approvals process, including compensation and mitigation, have not been included because the process is not likely to be defined until just before the project is implemented.

The estimated cost of a Used-Fuel Disposal Centre will vary with the total quantity of used fuel emplaced for disposal. It will also vary with the depth of the disposal rooms, the annual rate of disposal (as this sets the duration of the operation stage) and the magnitude of the facilities and process systems that must be designed and installed. Two examples are provided in Section 7.4 to provide a sense of the significance of these factors on the total cost for disposal. The sensitivity of cost and schedule to disposal centre capacity is shown by comparing disposal centres of this conceptual design with capacities of 10.1 million, 7.5 million and 5 million bundles of used fuel. The sensitivity of cost and schedule to disposal vault depth is shown by comparing the reference 10.1-million-fuel-bundle vault at a depth of 1000 m to the same vault located at a depth of 500 m.

7.2 DISPOSAL CENTRE COSTING BASIS

The scope of the Used-Fuel Disposal Centre cost estimate for the construction, operation, decommissioning and closure stages was defined by AECL CANDU et al. (1992) on the following basis:

1. Financing, escalation charges, and profit for the implementing organization are not included.

2. The labour rates are derived from the Statistics Canada Socio-Economic Information Management System (CANSIM) database developed for cost estimating for midsized Ontario communities, and represent the cost of hiring the workers from an outside contractor(s), overhead and profit included.

3. Field-purchased costs are the direct cost of minor materials and supplies purchased locally, and include a contractor's overhead and profit related to these purchases.

4. Engineering, management and other costs represent the cost of obtaining these services through service contracts with private consultants and contractors and include overhead and profit for the supplying companies.

5. Goods and services, provincial, municipal and property taxes are not included.

These provide the base rates for costing, and should not be taken as a recommendation on the way in which the implementing organization should organize and operate the project.

The cost estimate for the siting stage and the optional extended monitoring stages are generalized estimates based on AECL siting research program experience, extrapolated to the anticipated scale of a disposal centre siting program. In addition, an allowance has been included for the research that would be required to support the implementation of disposal from the start of the siting stage to the end of the decommissioning stage.

The used-fuel transportation cost estimates are derived from Ontario Hydro studies (Ontario Hydro 1989a).

The cost estimate, presented in constant 1991 dollars, is distributed according to project stages as defined in Section 2.5.1 (Figure 3-1). The cost estimates for each stage are summarized in Section 7.2.1.

7.2.1 Used-Fuel Disposal Centre Cost Estimates

The Siting Stage consists of site screening, surface-based site evaluation, underground site evaluation, development and operation of the component test area, and engineering design. Extensive surface and subsurface facilities and component testing and monitoring systems would be designed and installed, and performance assessments would be conducted over the 5-a duration for site screening and 18 a for site evaluation. This requires about 8100 person-years of activity at an estimated cost of about $2180 million.

The Construction Stage consists of continued component testing and design and design refinement; the construction of the disposal vault facilities, including all the tunnels, 80 to 90 disposal rooms and about 3000 waste emplacement boreholes; the construction of all the surface facilities and the packaging plant, the upgrade of access routes and utilities, the establishment of a new town for a population of about 3000 persons (see Section 7.2.2); the establishment of a construction camp and temporary construction-work-force accommodations; and the provision of engineering and management services. It is estimated that about 7300 person-years of activity are required over a period of 7 a, with a peak work force of about 1300 persons, for an estimated cost of $1810 million.

The Operation Stage spans 41 a during which the used-fuel bundles are transported from the nuclear generating stations, received, packaged and disposed of. Operations consist of waste container manufacturing, waste packaging, disposal-room and borehole excavation, waste-container emplacement, and borehole and room sealing. The work force is about 1000 persons and the average annual cash flow is about $200 million for labour, supplies and equipment. The estimated total cost for this stage is $8060 million, with about 39 900 person-years of activity, not including the cost of used-fuel transportation discussed in Section 7.3.

Following the cessation of operations, an Extended Monitoring Stage may be required before the regulators and the public approve disposal centre decommissioning. For this option, a work force of 90 to 150 persons is required to maintain access, equipment, facilities, physical security, safety and monitoring systems, and to analyze and interpret data. Although much of the operations equipment are temporarily "mothballed," much of the ancillary service facilities operate at a reduced capacity to support the staff activities. Thus, an estimated $23 million and 110 persons per annum were assumed for this period. Although the length of this activity is undefined, a duration range of 0 to 50 a can be envisioned.

The Decommissioning Stage consists of the decontamination of the radiological facilities, that is mainly the packaging plant, followed by the radioactive waste management facilities as the need for them diminishes. When appropriate, these facilities are dismantled and demolished, and the radioactively contaminated materials are packaged and moved to approved off-site disposal facilities. The exploration and monitoring boreholes and the access tunnels in the disposal vault are sealed, followed by reaming, if necessary, and sealing of the shafts. The site is returned to a state suitable for public access, and site markers are erected to identify the underlying disposal vault. It is estimated that about 6700 person-years of activity are required over a period of 16 a, with a peak work force of about 490 persons, for an estimated cost of $1250 million.

Following completion of decommissioning, another Extended Monitoring Stage may be required before the regulators and the public approve the closure of the site. For this option, a work force of 20 to 40 persons is required to maintain monitoring systems, control the site, and analyze and interpret data. Very limited facilities such as temporary offices, shops and accommodations are necessary to support the on-site staff activities. Thus, an estimated $9 million and 25 persons per annum has been assumed for this period. Although the length of this activity is undefined, a duration of 0 to 50 a can be envisioned.

The Closure Stage consists of removing monitoring instruments from surface-based boreholes and sealing the boreholes. It is estimated that about 150 person-years of activity are required over a period of 2 a for an estimated cost of $30 million.

The life-cycle cost for this conceptual Used-Fuel Disposal Centre from the beginning of the siting stage through to the end of the closure stage, a minimum period of 89 a, is estimated to be about $13 320 million, providing a total of 62 200 person-years of direct on-site employment (assuming no extended monitoring). Incorporating a range of accuracy of -15 to +40% for all components, the total cost can range from $11 320 million to $18 650 million (Table 7-1). The corresponding lifetime labour requirement can range from 52 800 to 87 000 person-years (Table 7-2). The cost estimate for the Used-Fuel Disposal Centre is presented in Table 7-3 in terms of cost by project stage for various facility and activity groupings. The average labour rates are derived from the cost estimate by stage and reflect the varying skills mix required for management administration, technology and trades, and are shown in Table 7-4. The details of the estimated cash flows and labour requirements are shown in Figure 7-1 and Table 7-5, and in Figure 7-2 and Table 7-6 respectively.

TABLE 7-1

USED-FUEL DISPOSAL CENTRE LIFE-CYCLE COST SUMMARY

(Capacity = 10.1 million used fuel bundles, Depth = 1000 m)
(1991 Canadian $ million)

Stage	Low Estimate	Nominal Estimate	High Estimate
Siting (23 a)	1 850	2 180	3 050
Construction (7 a)	1 540	1 810	2 530
Operation (41 a)	6 850	8 060	11 280
Decommissioning (16 a)	1 060	1 250	1 750
Closure (2 a)	30	30	40
Total	11 320	13 320	18 650

Note: The values in the columns do not necessarily add up to the total shown because of rounding.

TABLE 7-2

USED-FUEL DISPOSAL CENTRE LIFE-CYCLE LABOUR REQUIREMENT SUMMARY

(Capacity = 10.1 million used fuel bundles, Depth = 1000 m)
(person-years)

Stage	Low Estimate	Nominal Estimate	High Estimate
Siting (23 a)	6 800	8 100	11 330
Construction (7 a)	6 240	7 340	10 280
Operation (41 a)	33 880	39 850	55 800
Decommissioning (16 a)	5 720	6 730	9 430
Closure (2 a)	120	150	200
Total	52 840	62 170	87 040

Note: The values in the columns do not necessarily add up to the total shown because of rounding.

TABLE 7-3

DISTRIBUTION OF NOMINAL PROJECT COSTS IN EACH STAGE BY MAJOR FACILITY OR ACTIVITY

(Capacity = 10.1 million used-fuel bundles, Depth = 1000 m, Costs in 1991 Canadian $ million)

Major Facility or Activity	Siting			Construction	Operation	Decom-missioning	Closure	Total
	Screening	Surface Evaluation	Underground Evaluation					
Management and Administration	47	158	40	125	247	102	5	725
Characterization	30	455	8	*	*	*	—	493
Engineering Design and Licensing	46	195	38	110	20	112	1	521
Performance Assessment	34	119	38	30	84	35	3	344
Research	132	232	180	168	580	53	—	1 345
Site Monitoring	—	51	28	44	149	60	7	340
Project Support	—	—	72	25	186	33	7	322
Component Testing	—	—	70	133	115	70	—	388
Buildings	—	—	13	72	26	16	—	127
Electrical Power Systems	—	—	6	65	27	**	—	98
Basket and Container Plant	—	—	—	43	2 028	2	—	2 073
Used-Fuel Packaging Plant	—	—	—	47	1 026	15	—	1 088
Surface Infrastructure	—	—	10	178	1 104	233	7	1 532
Shafts	—	—	65	102	114	127	—	408
Tunnels	—	—	88	156	—	337	—	581
Vault Equipment	—	—	8	60	81	1	—	150
Buffer/Backfill Plant	—	—	—	13	15	10	—	38
Room Excavation	—	—	—	112	510	—	—	623
Room Preparation and Container Placement	—	—	—	9	619	—	—	629
Room Sealing	—	—	—	—	991	—	—	991
Underground Infrastructure	—	—	5	81	15	2	—	103
Training	—	—	2	20	88	28	—	138
Townsite	—	—	—	171	—	—	—	171
Others (Insurance, Warranty, etc.)	—	—	8	44	30	12	—	94
Total	289	1 210	679	1 808	8 055	1 248	30	13 321

Note: The values in the rows or columns do not necessarily add up to the total shown because of rounding.

* Characterization cost included in related excavation activities cost.

** Cost included in appropriate building cost.

TABLE 7-4

AVERAGE LABOUR RATES DERIVED FROM COST ESTIMATE

(1991 Canadian $ thousand/person-year)
(see Tables 7-5 and 7-6)

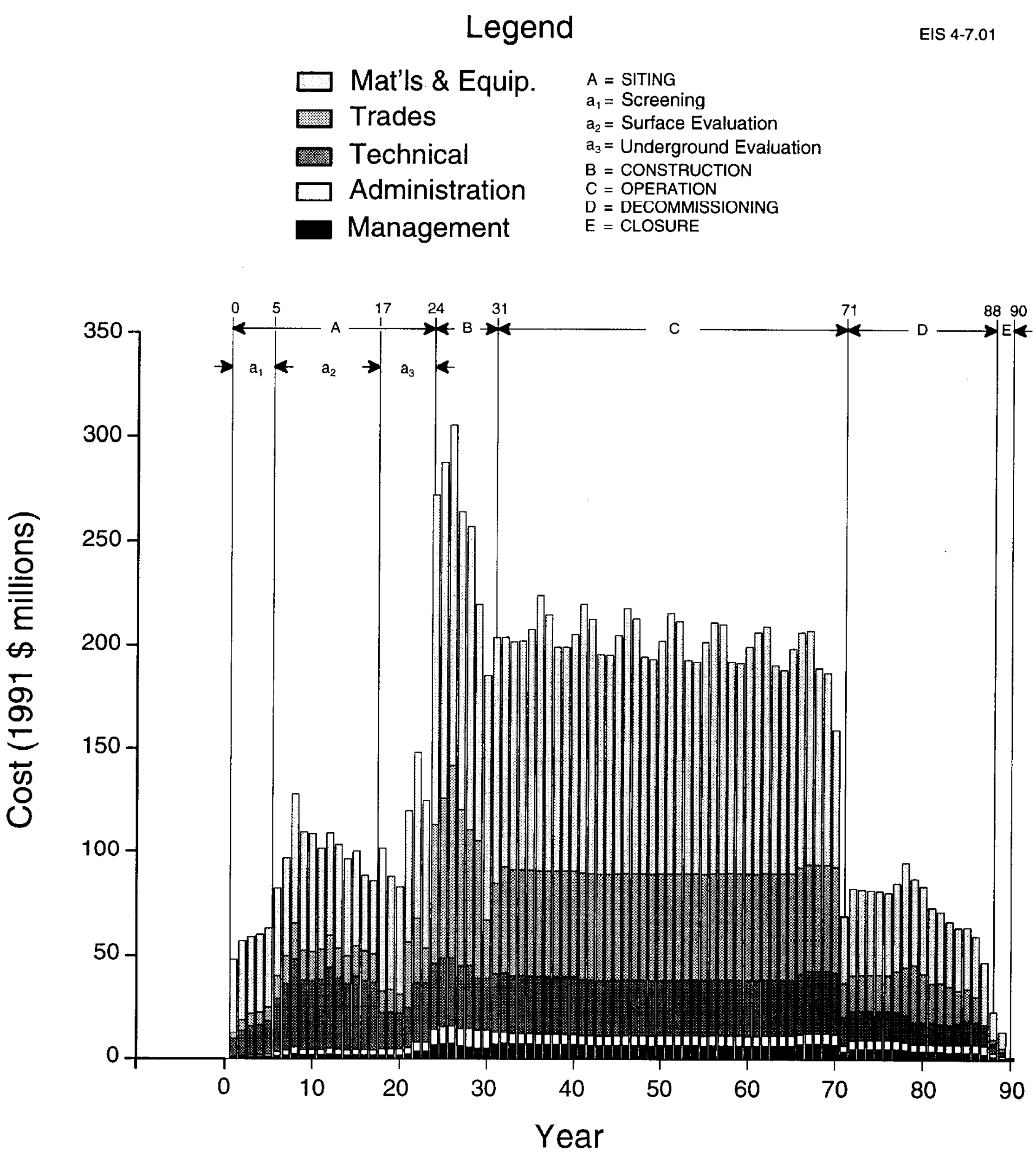
	Management Staff	Administration Staff	Technical Staff	Trades Staff
Siting-Screening	198	76	162	112
Siting-Surface Evaluation	198	76	165	112
Siting-Underground Evaluation	152	76	87	124
Construction	152	83	103	111
Operation	132	75	96	86
Decommissioning	142	78	96	87
Closure	117	77	82	91

The average annual cost, distributed over the project life cycle, is about $150 million, ranging from a low of about $20 million to a high of about $300 million.

The cost estimate for nuclear fuel waste disposal is strongly influenced by major elements in the disposal system design. As an example of the significance of these, the costs of the thin-walled, packed-particulate titanium disposal containers (Figure 3-5) and the sealing materials and systems associated with clay-based seals are given in Table 7-7. In this conceptual design, the disposal containers represent about 16% and the sealing materials/systems represent about 10% of the total "nominal estimate" cost of disposal.

In a future design optimization, it will be important to understand the sensitivity of disposal system costs to the selection of disposal system component designs. We have not performed a sensitivity analysis in this study because it was not our objective to optimize the design. Sensitivity analyses and optimization offer the most benefit when applied in the context of a specific site and, in general, are left for the future implementation of disposal.

Financial calculations related to borrowing, discounting and escalating costs are not included. Taxes and compensation costs are not included because these will likely be determined by consultation and negotiation among governments, utilities, regulators and the public. The decisions on these issues will be made when disposal is implemented.



Notes: 1. The cost fluctuation every five years during operations stage reflects capital equipment replacements.
2. Research costs are included as contracts under materials and equipment.

FIGURE 7-1: Used-Fuel Disposal Centre Annual Cash-Flow Requirements

TABLE 7-5

USED-FUEL DISPOSAL CENTRE ANNUAL NOMINAL CASH FLOW REQUIREMENTS

(Capacity = 10.1 million used-fuel bundles, Depth = 1000 m)
(1991 Canadian $ million)

Year	Management	Administration	Technical	Trades	Materials, Contracts and Equipment	Yearly Sums
SITING						
Site Screening						
1	0.5	0.6	8.3	3.4	35.3	48.0
2	0.7	0.9	12.3	5.1	38.1	57.1
3	0.8	1.1	14.3	5.9	37.4	59.5
4	0.8	1.1	14.7	6.1	38.0	60.8
5	0.9	1.3	16.3	6.8	38.4	63.7
Subtotal	3.8	5.1	65.9	27.3	187.2	289.1
Site Evaluation (Surface)						
6	1.5	2.0	25.8	10.8	42.5	82.5
7	1.8	2.5	32.2	13.4	46.8	96.7
8	2.4	3.3	42.5	17.8	61.5	127.5
9	1.9	2.6	33.8	14.1	57.3	109.8
10	1.9	2.6	33.4	13.9	57.1	108.9
11	1.9	2.6	34.1	14.2	48.5	101.3
12	2.2	3.0	38.9	16.2	48.9	109.2
13	2.0	2.7	34.5	14.3	50.1	103.5
14	1.8	2.5	32.2	13.3	46.4	96.2
15	2.0	2.7	35.3	14.6	45.5	100.2
16	1.9	2.6	33.7	14.0	36.1	88.2
17	1.9	2.5	32.8	13.6	35.3	86.1
Subtotal	23.4	31.5	409.1	170.1	575.9	1 210.1
Site Evaluation (Underground)						
18	1.8	3.0	17.6	10.7	68.4	101.5
19	1.8	3.0	17.9	11.2	54.1	88.1
20	1.8	3.0	17.6	9.1	51.7	83.3
21	2.3	3.3	19.5	31.3	63.2	119.5
22	3.8	4.1	29.5	31.0	79.7	148.1
23	3.8	4.1	29.1	16.5	71.0	124.5
24	0.5	0.6	4.2	0.3	9.3	15.0
Subtotal	15.8	21.2	135.5	110.1	397.3	680.0
TOTAL SITING	43.0	57.8	610.4	307.6	1 160.4	2 179.2

continued...

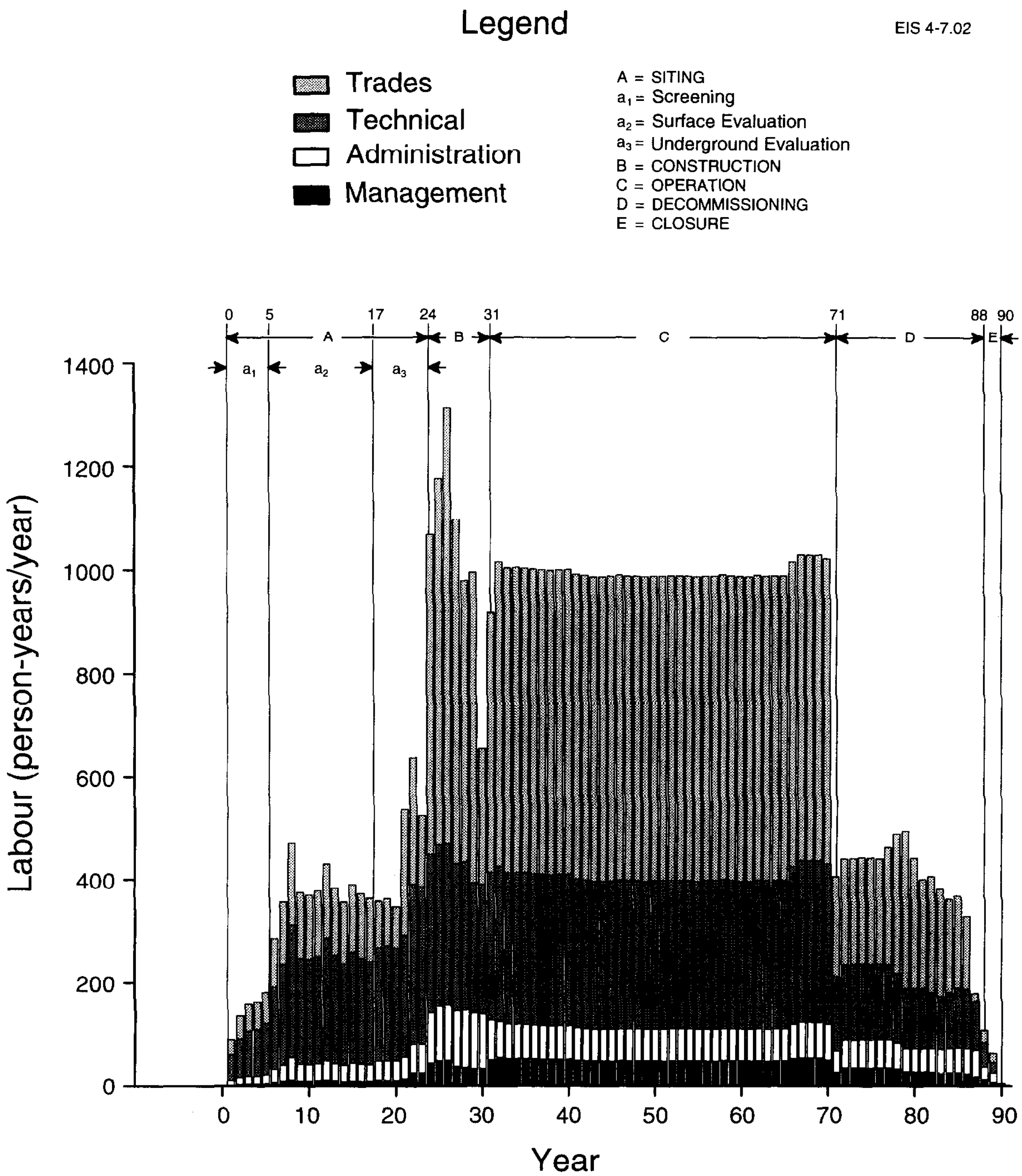
TABLE 7-5 (continued)

Year	Management	Administration	Technical	Trades	Materials, Contracts and Equipment	Yearly Sums
CONSTRUCTION						
24	6.1	7.4	27.4	66.6	149.1	256.7
25	7.2	8.8	32.6	76.9	162.4	288.0
26	7.4	8.8	32.6	92.4	164.2	305.5
27	6.2	8.8	29.8	75.3	143.6	263.7
28	5.9	9.2	30.2	65.5	146.1	256.8
29	5.4	9.0	24.8	66.3	113.9	219.5
30	5.4	9.0	24.7	28.4	117.3	184.8
31	1.2	1.9	5.4	3.4	21.4	33.3
TOTAL CONSTRUCTION	44.8	63.1	207.7	474.8	1 018.0	1 808.3
OPERATION						
31	5.9	4.0	22.5	40.5	97.3	170.2
32	7.6	5.2	28.9	50.7	111.3	206.2
33	7.2	5.0	28.1	50.7	110.4	203.2
34	7.2	5.0	28.2	50.7	110.8	203.2
35	7.2	5.0	28.0	50.7	116.6	197.0
36	7.0	4.9	28.0	50.7	133.1	223.1
37	6.9	4.9	28.0	50.7	123.9	219.2
38	6.9	4.9	27.9	50.7	108.4	202.6
39	6.9	4.9	28.0	50.7	108.4	202.4
40	6.9	4.9	28.0	50.7	114.6	196.5
41	6.6	4.7	27.5	50.7	130.2	218.2
42	6.5	4.6	27.4	50.7	123.3	217.5
43	6.4	4.6	27.2	50.7	106.4	199.1
44	6.4	4.6	27.2	50.7	106.1	198.1
45	6.5	4.6	27.3	50.7	115.5	202.8
46	6.5	4.7	27.4	50.7	128.2	214.5
47	6.5	4.7	27.3	50.7	123.4	217.3
48	6.5	4.7	27.3	50.7	104.8	197.9
49	6.4	4.6	27.2	50.7	104.0	196.1
50	6.5	4.7	27.3	50.7	112.6	201.5
51	6.5	4.7	27.3	50.7	126.1	211.5
52	6.5	4.7	27.3	50.7	122.1	216.0
53	6.5	4.7	27.3	50.7	103.2	196.3
54	6.5	4.7	27.3	50.7	102.4	194.9
55	6.4	4.6	27.2	50.7	112.2	201.3
56	6.5	4.7	27.3	50.7	121.4	205.5
57	6.5	4.7	27.3	50.7	120.6	214.0
58	6.5	4.7	27.4	50.7	102.2	195.0
59	6.5	4.7	27.3	50.7	101.6	193.5
60	6.4	4.6	27.2	50.7	110.0	199.0
61	6.4	4.6	27.2	50.7	116.9	199.9
62	6.5	4.7	27.4	50.7	119.5	213.2

continued...

TABLE 7-5 (concluded)

Year	Management	Administration	Technical	Trades	Materials, Contracts and Equipment	Yearly Sums
OPERATION (concluded)						
63	6.5	4.7	27.3	50.7	100.3	192.8
64	6.5	4.7	27.3	50.7	98.5	190.4
65	6.5	4.7	27.3	50.7	108.9	198.8
66	7.0	5.0	29.3	50.7	114.0	195.7
67	7.3	5.1	30.3	50.7	113.4	202.5
68	7.3	5.1	30.3	50.7	94.8	183.1
69	7.3	5.1	30.3	50.7	92.6	180.4
70	6.7	5.1	30.0	50.7	66.2	150.5
71	1.7	1.4	8.1	8.9	14.4	34.5
TOTAL OPERATION	268.6	192.2	1 115.8	2 028.5	4 450.6	8 055.6
DECOMMISSIONING						
71	2.1	1.7	6.0	7.2	18.0	35.0
72	5.1	4.0	14.4	17.2	41.8	82.5
73	5.1	4.1	14.5	17.2	41.0	81.8
74	5.1	4.1	14.5	17.3	40.7	81.7
75	5.1	4.1	14.5	17.3	40.3	81.2
76	5.1	4.1	14.5	17.1	39.7	80.4
77	5.1	4.0	14.4	19.3	42.2	85.0
78	4.7	3.8	13.1	23.0	49.9	94.5
79	4.1	3.5	10.7	27.3	41.5	87.1
80	4.1	3.5	10.7	23.1	42.1	83.4
81	4.1	3.5	10.7	18.8	36.4	73.5
82	4.0	3.5	10.0	19.9	34.0	71.5
83	3.6	3.7	9.6	18.8	31.3	66.9
84	3.6	3.9	10.3	15.8	30.4	64.0
85	3.6	4.0	11.2	15.6	29.8	64.2
86	3.5	4.0	11.1	12.2	29.3	60.0
87	2.8	4.1	9.0	1.1	30.1	47.1
88	0.6	0.7	1.5	0.2	5.2	8.2
TOTAL DECOMMISSIONING	71.0	64.1	200.6	288.4	623.7	1 247.8
CLOSURE						
88	0.9	1.2	2.5	1.9	8.7	15.2
89	0.9	1.3	1.8	1.6	7.7	13.3
90	0.1	0.2	0.1	0.1	0.8	1.3
TOTAL CLOSURE	1.9	2.7	4.4	3.6	17.2	29.9
GRAND TOTAL	429.2	379.9	2 138.9	3 102.8	7 269.8	13 320.7



Notes: 1. Research labour is not included since it is an off-site contract.
2. 1 person-year = 261 days.

FIGURE 7-2: Used-Fuel Disposal Centre Annual Labour Requirements

TABLE 7-6

USED-FUEL DISPOSAL CENTRE ANNUAL NOMINAL LABOUR REQUIREMENTS

(Capacity = 10.1 million used-fuel bundles, Depth = 1000 m)
(person-years)

Year	Management	Administration	Technical	Trades	Yearly Sums
SITING					
Site Screening					
1	2.4	8.3	50.1	30.1	90.8
2	3.5	12.5	76.3	45.3	137.5
3	4.1	14.5	88.3	52.8	159.7
4	4.2	15.0	90.8	54.4	164.5
5	4.7	16.6	100.5	60.5	182.2
Subtotal	18.9	67.0	405.9	243.0	734.8
Site Evaluation (Surface)					
6	7.4	26.3	157.3	95.8	286.8
7	9.3	32.8	195.6	119.8	357.5
8	12.3	43.5	257.2	158.6	471.6
9	9.8	34.4	205.1	125.8	375.1
10	9.6	34.0	202.8	123.9	370.3
11	9.8	34.7	207.2	126.1	377.9
12	11.2	39.5	236.3	144.0	431.1
13	9.9	35.0	209.8	127.6	382.3
14	9.2	32.9	195.9	118.9	356.8
15	10.2	36.0	214.6	130.4	391.1
16	9.7	34.3	204.9	124.3	373.2
17	9.4	33.3	199.4	120.9	363.0
Subtotal	118.0	416.8	2 485.9	1 516.0	4 536.7
Site Evaluation (Underground)					
18	11.3	38.6	219.4	88.8	358.1
19	11.3	38.6	223.3	89.1	362.3
20	11.3	38.6	218.1	79.8	347.8
21	14.6	42.4	235.5	243.1	535.6
22	26.0	55.9	309.5	244.8	636.2
23	26.0	55.9	303.6	137.9	523.4
24	3.7	7.8	43.7	5.0	60.2
Subtotal	104.2	277.7	1 553.2	888.5	2 823.6
TOTAL SITING	241.0	761.5	4 445.1	2 647.5	8 095.2

continued...

TABLE 7-6 (continued)

Year	Management	Administration	Technical	Trades	Yearly Sums
CONSTRUCTION					
24	41.8	89.7	262.2	613.1	1 006.9
25	49.6	106.6	311.7	708.0	1 175.8
26	50.5	107.5	311.9	844.8	1 314.7
27	40.1	107.3	284.2	666.2	1 097.9
28	37.9	111.4	285.4	544.3	979.0
29	34.5	108.4	250.0	602.4	995.3
30	33.9	108.0	249.2	262.6	653.8
31	7.4	23.3	54.7	33.6	119.0
TOTAL CONSTRUCTION	295.6	762.2	2 009.5	4 275.0	7 342.3
OPERATION					
31	43.9	54.5	230.6	468.9	798.0
32	56.4	69.9	299.4	590.1	1 015.8
33	54.0	67.2	292.4	590.1	1 003.8
34	53.9	67.1	293.4	590.1	1 004.4
35	53.7	66.8	292.2	590.1	1 002.8
36	52.8	66.0	292.2	590.1	1 001.1
37	52.5	65.7	292.2	590.1	1 000.5
38	52.3	65.4	291.1	590.1	998.9
39	52.5	65.7	292.2	590.1	1 000.5
40	52.5	65.7	292.2	590.1	1 000.5
41	49.9	63.1	287.9	590.1	990.9
42	49.2	62.4	287.5	590.1	989.1
43	48.8	61.9	285.3	590.1	986.1
44	48.8	61.9	285.3	590.1	986.1
45	49.0	62.2	286.4	590.1	987.6
46	49.2	62.4	287.5	590.1	989.1
47	49.0	62.1	286.4	590.1	987.6
48	49.0	62.1	286.4	590.1	987.6
49	48.8	61.9	285.3	590.1	986.0
50	49.0	62.1	286.4	590.1	987.6
51	49.0	62.1	286.4	590.1	987.6
52	49.0	62.1	286.4	590.1	987.6
53	49.0	62.1	286.4	590.1	987.6
54	49.0	62.1	286.4	590.1	987.6
55	48.8	61.9	285.3	590.1	986.0
56	49.0	62.1	286.4	590.1	987.6
57	49.0	62.1	286.4	590.1	987.6
58	49.2	62.3	287.5	590.1	989.1
59	49.0	62.1	286.4	590.1	987.6
60	48.8	61.9	285.3	590.1	986.0
61	48.8	61.9	285.3	590.1	986.0
62	49.2	62.3	287.5	590.1	989.1

continued...

TABLE 7-6 (concluded)

Year	Management	Administration	Technical	Trades	Yearly Sums
OPERATION (concluded)					
63	49.0	62.1	286.4	590.1	987.6
64	49.0	62.1	286.4	590.1	987.6
65	49.0	62.1	286.4	590.1	987.6
66	53.1	67.0	304.4	590.1	1 014.6
67	55.0	69.2	312.9	590.1	1 027.2
68	55.0	69.2	312.9	590.1	1 027.2
69	55.0	69.2	312.9	590.1	1 027.2
70	50.1	69.5	310.7	590.1	1 020.3
71	12.9	18.4	83.8	106.9	222.0
TOTAL OPERATION	2 030.6	2 569.9	11 664.7	23 589.0	39 854.2
DECOMMISSIONING					
71	15.1	21.9	60.8	85.7	183.4
72	36.5	52.9	147.1	203.6	440.1
73	36.6	53.1	147.7	203.7	441.1
74	36.8	53.3	148.3	204.4	442.7
75	36.6	53.1	147.7	204.4	441.9
76	36.6	53.1	147.7	203.1	440.5
77	36.5	52.9	147.1	226.2	462.7
78	33.7	49.7	135.4	269.4	488.2
79	29.0	44.1	115.2	305.7	494.0
80	29.0	44.1	115.2	254.1	442.4
81	29.0	44.1	115.2	211.3	399.6
82	27.6	45.1	108.5	224.2	405.3
83	24.2	47.0	102.2	207.5	381.0
84	24.3	49.5	107.3	180.0	361.1
85	24.3	50.0	115.4	178.0	367.8
86	23.2	49.8	114.1	142.2	329.3
87	17.5	51.7	94.5	16.1	179.8
88	3.8	9.0	16.1	2.8	31.8
TOTAL DECOMMISSIONING	500.5	824.5	2 085.3	3 322.2	6 732.5
CLOSURE					
88	8.5	16.2	30.6	21.0	76.3
89	7.3	17.0	22.2	17.5	63.9
90	0.6	2.6	0.8	1.2	5.1
TOTAL CLOSURE	16.3	35.8	53.6	39.6	145.3
GRAND TOTAL	3 084.1	4 953.9	20 258.2	33 873.4	62 169.6

TABLE 7-7

ESTIMATED NOMINAL COST OF TWO ELEMENTS OF THE USED-FUEL DISPOSAL SYSTEM

(Capacity = 10.1 million used-fuel bundles, Depth = 1000 m)
(1991 Canadian $ million)

Component	Estimated Cost		
	Surface Facilities	Disposal Vault	Total
Reference Basket and Container Fabrication Cost (materials, labour and facilities)	2073		2073
Clay-Based Sealing Material Costs			
- Bentonite Clay		1059	1059
- Silica Sand		28	28
- Lake Clay		107	107
- Buffer and Backfill Preparation Plant		37	37
- Crushed Rock	70		70
Total Sealing Materials	70	1231	1301

7.2.2 Work-Force Settlement Options and Cost Estimate

Four work-force settlement options are identified:

1. Develop a new town for a remotely located disposal centre.
2. Upgrade a nearby existing small town(s).
3. Settle within a nearby major centre.
4. "Fly-in" from a distant major centre.

For an operating work force of about 1000 and their families, the direct settlement requirements could range between 2500 and 3500 persons, depending on the settlement option selected. The larger estimate includes the number of service-sector workers needed in a new or upgraded small town(s).

A new town accommodating about 3000 people is included in the project cost estimate at a cost of about $171 million. This cost was derived by AECL CANDU et al. (1992) from information collected from towns, including Tumbler Ridge, British Columbia, one of the most recent new towns in Canada.

It is possible that the disposal centre may be established near an existing small community or major centre, and the influx of about 1000 employees and their families could create significant pressures on the existing community infrastructure and services. This could be mitigated through upgrading by providing additional services and facilities. Such pressures would be smaller for a major centre. Significant upgrades to a small community may have to be funded by the disposal centre as mitigation of this effect (e.g., schools, hospital, clinics, recreation facilities, municipal hall, public works). No costs are derived for this or the following options because the base community and infrastructure are not defined. The costs are judged to be less than the new town option discussed above.

The concept of flying the work force in from a major centre is an alternative to creating a new town or expanding an existing small town. This should not have a significant effect on the major centre. However, air transportation, an all-weather airfield, and subsidized site accommodations and recreational facilities would be required at the disposal centre for the work force, which may rotate on a weekly or bi-monthly basis as is currently the practice with some uranium mines in northern Saskatchewan. Also, this alternative may have a very significant social effect because it is disruptive to the family life and relationships of the work force. This choice might also require a change in the operational basis of the disposal centre during the operation stage to a 24-h/d, 7-d/week operation, although the flexibility to do this may be limited by the capacity of the used-fuel transportation system. A change in annual throughput would change the duration of the operation stage.

The settlement cost estimate is derived for the new town option since it forms the simplest basis. The operations of any town are assumed to be directed by the municipality based on taxes collected within the community. No municipal taxes or grants-in-lieu of taxes are included in the estimate for the disposal centre. These would be negotiated between the implementing organization and the local community(ies) when a disposal centre is being implemented.

7.3 TRANSPORTATION COSTS

The cost of the used-fuel transportation system is not included in the disposal centre cost estimate given in Table 7-1. The various modes and distances of used-fuel transport are discussed by Ontario Hydro (1989a). A summary of the costs and labour requirements, adjusted for 250 000 used-fuel bundles/a and a total inventory of 10.1 million bundles to be shipped from three utilities to the disposal centre, is shown in Table 7-8.

For this total inventory, 9.4 million bundles are assumed to be shipped 400 km (i.e., to the south centroid of Ontario) and 1900 km (i.e., to the north centroid of Ontario) by road and 400 km and 1400 km by rail from Ontario nuclear generating stations, 250 000 bundles shipped 700 and 2200 km by road and 700 and 1700 km by rail from Quebec, and 440 000 bundles shipped 1500 and 3000 km by road and 1500 and 2500 km by rail from New Brunswick.

The transport modes considered include rail, road and combinations of rail-water and road-water and the distances considered range from a minimum distance of 400 km to a maximum of 1900 km for Ontario Hydro shipments. The rail-water and road-water mode combination costs and labour requirements are intermediate in value compared with the short-distance road and long-distance rail cases, and are not evaluated further or shown.

TABLE 7-8

USED-FUEL TRANSPORTATION LIFE-CYCLE COST AND LABOUR REQUIREMENTS
(Capacity = 10.1 million used-fuel bundles)

Transport Mode-Location	Cost (1991 Canadian $ million)	Labour (person-years)
Rail - North Centroid	2140	1300
Rail - South Centroid	1410	1200
Road - North Centroid	770	4700
Road - South Centroid	400	2600

Note: Data derived from Ontario Hydro (1989a) transportation cost and labour information. Costs escalated by an average of 18% from 1988$ to 1991$.

7.4 SENSITIVITY OF DISPOSAL COST TO VARIATIONS IN DISPOSAL CENTRE CAPACITY AND DISPOSAL VAULT DEPTH

7.4.1 Sensitivity of Disposal Cost to Disposal Vault Capacity

As discussed in Section 3.3.2.1, different estimates of used-fuel arisings can be made, and, in turn, this affects the required disposal system capacity. The used-fuel arisings in this conceptual design are based on an assumption for the production of 10.1 million used-fuel bundles (Section 3.3.2). Other assumptions have been made by the electrical utilities. For example, Ontario Hydro (1989b) assumed that 4 to 5 million used-fuel bundles will be produced from nuclear-generated electricity in their province. If some contribution of used-fuel is considered from other utilities with nuclear electric generation, a 5-million-fuel-bundle disposal-vault capacity would be more representative of arisings from stations currently operating in Canada. The actual duration of operation for a used-fuel transportation system and a disposal centre, and the size of the disposal vault, would depend on the inventory of used-fuel destined for disposal and the rate of used-fuel transportation from all participating nuclear-electricity-generating utilities to the disposal centre.

The costs associated with the transportation of used fuel from nuclear generating stations to a disposal centre are discussed by Ontario Hydro (1989a) in their used-fuel transportation assessment. These costs would likely vary linearly with the total mass of used fuel shipped for disposal as long as the annual shipping rate is constant and the shipping period covers at least several years. However, the costs would be sensitive to distance and to the mode of transportation used, as shown in Table 7-8.

The costs associated with the siting and closure stages of a disposal centre would remain relatively constant for any reasonable mass of used-fuel disposed at a given site. They would be much more sensitive to the site-specific biosphere and geosphere conditions than to variations in the mass of used fuel disposed. The costs associated with the construction, operation and decommissioning stages of a disposal centre are more directly related to the quantity of used fuel packaged and disposed of.

This section presents the estimated cost of disposal for the total quantity of 10.1 million bundles of used fuel (i.e., this conceptual design), 7.5 million bundles and 5 million bundles of used fuel. These costs are estimated by scaling the 10.1-million-bundle conceptual design estimate and using the same 250 000 annual used-fuel-bundle throughput rate. Data are provided in Table 7-9 for total disposal vault capacities of 7.5 million and 5 million used-fuel bundles.

The derivation of the cost estimates for the lower capacities is done by developing revised schedules for each reduced capacity to adjust duration-dependent costs, by determining those cost elements that are a function of total capacity, and by scaling to adjust capacity-dependent costs.

7.4.2 Sensitivity of Disposal Cost to Depth of Disposal Vault

There may be some circumstances for which the practical depth of particular disposal vault designs may be limited to less than 1000 m, as discussed in Section 3.3.7. To show the sensitivity of cost and schedule for two different depths of the disposal vault, the conceptual design discussed in Chapters 3 to 6 was estimated and scheduled for depths of 1000 m and 500 m. The results are shown in Table 7-10.

The influence of depth on schedule and cost is small relative to the overall cost of the project. The disposal vault at a depth of 500 m has schedule savings of 1 a during the siting stage (i.e., the exploration shafts are shorter and are on the critical path) and savings of 2 a during decommissioning (i.e., the shafts are shorter and shaft sealing is on the critical path). The cost reductions for this vault are realized during the siting, construction and decommissioning stages. Where there is a cost reduction without a corresponding schedule reduction, the shaft-related activities are not on the critical path and do not affect the overall project schedule during that stage.

7.5 SUMMARY

This section presented nominal estimates of the cost ($13 320 million (1991)) and labour requirements (62 200 person-years) for disposing of 10.1 million used-fuel bundles in a 1000-m-deep geological disposal facility of a particular conceptual design. The level of uncertainty in these estimates is -15% to +40% with no changes in the assumptions. The sensitivity of the estimated cost to the quantity of waste disposed has also been shown through presentation of the scaled costs for disposing of 5 million and 7.5 million fuel bundles in a similarly designed facility (Table 7-9). The sensitivity of the estimated cost to the depth of the disposal vault has been shown through presentation of the costs and schedule for a similarly designed facility with disposal depths of 500 and 1000 m (Table 7-10). These scaled costs are subject to the range of uncertainty stated above.

TABLE 7-9

SCALED NOMINAL COST ESTIMATES FOR DISPOSAL VAULT CAPACITIES OF 5, 7.5 AND 10.1 MILLION USED-FUEL BUNDLES

(Depth = 1000 m)

Disposal Centre Stage	5 million bundles		7.5 million bundles		10.1 million bundles	
	Duration (a)	Cost (1991 Canadian $ million)	Duration (a)	Cost (1991 Canadian $ million)	Duration (a)	Cost (1991 Canadian $ million)
Siting	23	2 140	23	2 160	23	2 180
Construction	5	1 520	6	1 630	7	1 810
Operation	20	4 060	30	6 040	41	8 060
Decommissioning	13	940	15	1 090	16	1 250
Closure	2	30	2	30	2	30
Total	63	8 680	76	10 950	89	13 320

Note: The values in the columns do not necessarily add up to the total shown because of rounding.

The cost of transporting used fuel from nuclear generating stations in Ontario, Quebec and New Brunswick to a disposal facility at two locations in Ontario is shown in Table 7-8. This is based on a transportation study by Ontario Hydro (1989a), with extrapolation for the other provinces. The information shows the sensitivity of transportation cost to the mode of transportation (i.e., road or rail) and the location of the disposal facility.

The estimates given here are applicable to a specific design of facility and transportation system, are valid for a specific set of assumptions, and have an inherent uncertainty associated with them. They provide an indication of the level of resources that would likely be required to site, construct, operate, decommission and close a nuclear fuel waste disposal system.

8. SUMMARY AND DISCUSSION

8.1 INTRODUCTION

This report has presented general considerations and an approach to engineering nuclear fuel waste disposal, a conceptual design description of a reference Used-Fuel Disposal Centre sited in plutonic rock that uses current or adaptations to current technology, and estimates of personnel and funding requirements to implement the reference conceptual design as stated in the objectives.

TABLE 7-10

COMPARISON OF NOMINAL COST AND SCHEDULE FOR A DISPOSAL CENTRE WITH A VAULT AT DEPTHS OF 500 AND 1000 m

(Capacity = 10.1 million used-fuel bundles)

Disposal Centre Stage	Depth = 500 m Duration (a)	Depth = 500 m Cost (1991 Canadian $ million)	Depth = 1000 m Duration (a)	Depth = 1000 m Cost (1991 Canadian $ million)
Siting	22	2 110	23	2 180
Construction	7	1 780	7	1 810
Operation	41	8 060	41	8 060
Decommissioning	14	1 130	16	1 250
Closure	2	30	2	30
Total	86	13 110	89	13 320

Note: The values in the columns do not necessarily add up to the total shown because of rounding.

8.2 USED-FUEL DISPOSAL CENTRE OVERVIEW

The Used-Fuel Disposal Centre conceptual design is sized to accept and dispose of about 191 000 Mg of uranium in the form of about 10.1 million used-fuel bundles, which would represent the amount of used fuel that may arise in Canada during about 100 years of nuclear power generation at the current rate of production.

The disposal centre consists of two parts: the surface facilities and the disposal vault. The surface facilities receive used fuel from nuclear generating stations in road or rail casks. The used-fuel bundles are sealed into corrosion-resistant, titanium containers in a fuel packaging plant. Other ancillary services are provided.

The disposal vault is reached and serviced by five shafts grouped into a service-shaft complex (three shafts) and an upcast-shaft complex (two shafts) at opposite ends of the excavation. The disposal rooms are arranged in panels that are constructed on a single horizontal level at a depth of 1000 m in the plutonic rock of the Canadian Shield. The containers are transported into the underground facilities and are emplaced into short, vertical boreholes drilled into the floor of the disposal rooms. The container is surrounded by a clay-based buffer material within each borehole. Each disposal room is backfilled with clay-based backfill materials, and the room entrance is sealed when all its emplacement boreholes have been filled. The construction of additional disposal rooms occurs concurrently with emplacement of disposal containers in separate panels in a "retreat" fashion. That is, the disposal rooms are constructed sequentially, starting in panels nearest the upcast-shaft complex and then retreating toward the service-shaft complex. Perimeter and central access tunnels are arranged so that the movement of used-fuel containers is separated from the movement of personnel, excavation and sealing materials. When all disposal rooms in the vault are filled and sealed, and approvals are obtained, all remaining underground openings are also sealed with clay-based backfill.

The operation stage of the disposal centre is projected to last 41 a. The full life-cycle for this conceptual design, from the beginning of siting to the end of closure, is 89 a, and could be longer if extended monitoring stages are incorporated.

8.3 CONCEPTUAL-LEVEL DESIGN

The design put forth in this report has been done at a conceptual engineering level. That is, sufficient detail has been included to demonstrate the basic engineering feasibility of the concept. The optimization of system components, operating methods and the overall design was not an objective and was not performed. It is recognized that the design will have to be optimized to enhance the technical design and to improve the use of resources. The characteristics of the site that is ultimately selected will also have a major influence on the disposal facility design.

Many alternatives exist for the elements of the conceptual design presented here. For example, the disposal depth of the vault may be shallower than 1000 m, the vault could be partitioned into two or more segments in a fashion similar to that shown in Figure 2-7 rather than in a square plan configuration, the disposal rooms in the vault may be constructed on more than one horizontal level, the container may have different shapes and may be fabricated from copper or some other material instead of titanium, containers may not be emplaced in vertical boreholes but may be placed in horizontal boreholes or within the room, the vault may be smaller in size either because of a smaller projected growth in nuclear power generation or because more than one vault may be constructed to serve regional requirements. Furthermore, future technical advances may lead to improved ways of constructing and/or operating a disposal facility. The presentation of this conceptual design does not preclude future modifications or implementation of different alternatives. This report presents a conceptual design that demonstrates that a disposal facility is feasible, and establishes a benchmark against which other alternatives can be measured. It is recognized that changes and improvements would be made in future years.

8.4 DESIGN CONSERVATISM

The parameters specified for the development of the conceptual design have generally been selected to be most challenging for engineering design.

Consider the choice of a 1000-m depth for the disposal vault rooms. As discussed in Section 3.3.7, a disposal vault of this conceptual design could not be located satisfactorily in the assumed in situ stress field at the 1000-m depth initially specified. The analyses indicated that a disposal vault of this particular design at this depth could not satisfy the requirement that there should be no localized yielding as indicated by an overstress condition in a linear, elastic thermal-mechanical stress analyses in the boundaries of the disposal room or the emplacement boreholes under excavation conditions (i.e., before emplacement of the buffer, waste containers or backfill). However, the analyses with the disposal vault at 500 m did satisfy the no-yielding specification because of the lower in situ stresses at the shallower depth. The borehole emplacement conceptual design may be applicable below 500 m under either more favourable site conditions (e.g., very strong rock and/or lower in situ stresses than assumed in this study) or at higher cost (e.g., greater spacing between the emplacement boreholes for disposal containers).

The disposal centre costs presented in Chapter 7 are based generally on a disposal vault at a depth of 1000 m. This tends to be conservative because deeper shafts and longer transfer distances require longer construction and material handling times, and in some cases more staff and equipment are necessary to complete operations. However, the scaled cost estimated for a disposal centre with a disposal vault at a depth of 500 m indicates that the cost is relatively insensitive to depth.

The age of the used fuel was assumed to be 10 a out-of-reactor. Much of the used fuel will be considerably older by the time an actual disposal vault is in operation. This will result in lower radiation fields and heat generation. In general, lower temperatures and thermal stresses would result for the disposal geometry given in this conceptual design.

The total used-fuel arisings assumed for this study (10.1 million used-fuel bundles) was based on an optimistic estimate for nuclear electric generation projected 50 a into the future when the estimate was made in 1985. It is now reasonable to assume that the used-fuel arisings during that period would be less than 10.1 million bundles and would require a smaller disposal vault emplacement area than is presented in this report. The arrangement of the disposal-vault emplacement area as a number of discrete panels allows the capacity of the disposal vault to be adjusted to suit the future used-fuel inventory with due regard for site conditions.

The cost estimates and schedules for disposal centres with vault capacities of 5, 7.5 and 10.1 million used-fuel bundles, included in Chapter 7, show the variation in overall costs with capacity. The high, fixed costs associated with the siting stage and the proportion of the costs that are relatively constant over a wide range of capacities indicate that a single, large disposal centre would be more economical than two or more regional disposal centres with the same total capacity.

8.5 USED-FUEL DISPOSAL CENTRE FEASIBILITY

The key conclusion of this report is that it is feasible to construct, operate, decommission and close a Used-Fuel Disposal Centre assuming the use of existing, or reasonable extensions of existing, technology. The work presented in this report is based on over 15 a of study by AECL, Ontario Hydro, government departments, universities and private sector consulting groups.

Baumgartner and Simmons (1987) reviewed the earlier work from which the conceptual design presented in this report has evolved.

In addition, AECL has participated in and kept abreast of similar programs that are in progress in other countries. Sweden, Switzerland, Finland and the United States have all made significant progress in studying the feasibility of underground disposal of nuclear wastes in crystalline rocks, including the conceptual design of disposal centres and the development of underground in situ laboratories. For example, the handling of used fuel in an underground environment has been demonstrated in the Spent Fuel Test - Climax conducted by the United States Department of Energy (Patrick 1986). The information from these programs is available to AECL through bilateral agreements as well as through direct participation, and has been a contributing factor in our conceptual designs.

The Underground Research Laboratory situated near AECL's Whiteshell Laboratories has provided, and will continue to provide, a focal point for developing and testing the characterization, design, monitoring and construction technologies needed to assess the performance of and to implement a disposal facility. Many of the geotechnical technologies and excavation methods described in this report are based on actual practical experience and on technical development programs. The radioactive materials handling, processing and occupational safety and health technologies are based on decades of actual experience in nuclear facilities in Canada and elsewhere.

Although a nuclear fuel waste disposal vault is a unique underground facility, the design, construction, operation and management of the disposal centre is similar to that required for many other major underground civil engineering projects. These include the Churchill Falls hydroelectric power house in Labrador, the NORAD defence facility in North Bay, Ontario, and the La Grande hydroelectric generating station near James Bay, Quebec, which have been constructed in the Canadian Shield. These facilities have been designed for, and constructed in, remote places and have operated safely and within design specifications for many decades (Acres 1993a).

8.6 CONCLUSION

A nuclear fuel waste disposal facility with a disposal vault located at a depth of 500 to 1000 m in the plutonic rock of the Canadian Shield can be built to meet its objectives using current technology or reasonable extensions of current technology, and represents a practicable way of disposing of nuclear fuel waste. To date, disposal methods for nonradioactive wastes have used near-surface landfills, which rely primarily on liners and clay barriers, and may require perpetual monitoring and maintenance. In contrast, the conceptual design presented here places the waste within engineered barriers at a considerable depth below the ground surface in a disposal system that does not require continuing maintenance or monitoring after the disposal centre has closed.

Based on the cost estimates presented, the cost of disposing of Canada's nuclear fuel waste is large in terms of total dollars but represents only a small fraction of the price paid by consumers for the electricity derived from nuclear power (i.e., less than \$0.001/(kW·h)).

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REFERENCES

Acres Consulting Services Limited in association with RE/SPEC Ltd. 1985. A feasibility study of the multilevel vault concept. Atomic Energy of Canada Limited Technical Record, TR-297.*

Acres Consulting Services Limited in conjunction with RE/SPEC Inc., Dilworth, Secord, Meagher and Associates and Hagconsult AB. 1978. Radioactive waste repository study Atomic Energy of Canada Limited Report, AECL-6188.

Acres Consulting Services Limited in association with RE/SPEC Inc., Dilworth, Secord, Meagher and Associates, and Design and Project Engineering Branch, in association with W.L. Wardrop and Associates Ltd. 1980a. A disposal centre for irradiated nuclear fuel: Conceptual design study. Atomic Energy of Canada Limited Report, AECL-6415.

Acres Consulting Services Limited in association with RE/SPEC Inc., Dilworth, Secord, Meagher and Associates, and Design and Project Engineering Branch in association with W.L. Wardrop and Associates Ltd. 1980b. A disposal centre for immobilized nuclear waste: Conceptual design study. Atomic Energy of Canada Limited Report, AECL-6416.

Acres International Limited. 1993a. Case histories of underground civil engineering projects in the Canadian Shield. Atomic Energy of Canada Limited Report, TR-M-18.**

Acres Consulting Services Limited. 1993b. A preliminary study of long-hole emplacement alternatives. Atomic Energy of Canada Limited Technical Record, TR-346.*

AECB (Atomic Energy Control Board). 1985. Regulatory policy statement. Deep geological disposal of nuclear fuel waste: Background information and regulatory requirements regarding the concept assessment phase. Atomic Energy Control Board Regulatory Document R-71.

AECB (Atomic Energy Control Board). 1987a. Regulatory policy statement. Regulatory objectives, requirements and guidelines for the disposal of radioactive wastes - long-term aspects. Atomic Energy Control Board Regulatory Document R-104.

AECB (Atomic Energy Control Board). 1987b. Regulatory guide. Geological considerations in siting a repository for underground disposal of high-level radioactive waste. Atomic Energy Control Board Regulatory Document R-72.

AECB (Atomic Energy Control Board). 1991a. Proposed amendments to the Atomic Energy Control Regulations for reduced radiation dose limits based on the 1991 recommendations of the International Commission on Radiological Protection. A proposal amendment to the regulations. Atomic Energy Control Board Consultative Document C-122.

AECB (Atomic Energy Control Board). 1991b. Quality assurance programmes for nuclear facilities. A proposed regulatory policy statement. Atomic Energy Control Board Consultative Document C-22.

AECB (Atomic Energy Control Board). 1992. Office consolidation of atomic energy control regulations, with amendments to 1992 August 27. Atomic Energy Control Board, Ottawa.

AECL (Atomic Energy of Canada Limited). 1990. Geological and Environmental Science Division Quality Assurance Manual. Atomic Energy of Canada Limited Quality Assurance Document 000.001, Revision 0. (Available from Director, Disposal Technology Division, AECL Research, Whiteshell Laboratories, Pinawa, Manitoba R0E 1L0.)

AECL CANDU in association with J.S. Redpath Mining Consultants Limited, Golder Associates, and The Ralph M. Parsons Co. 1992. Used-fuel disposal centre - A reference concept. Atomic Energy of Canada Limited Report, TR-M-3.**

AECL (Atomic Energy of Canada Limited). 1994a. Environmental impact statement on the concept for disposal of Canada's nuclear fuel waste. Atomic Energy of Canada Limited Report, AECL-10711, COG-93-1.

AECL (Atomic Energy of Canada Limited). 1994b. Summary of the environmental impact statement on the concept for disposal of Canada's nuclear fuel waste. Atomic Energy of Canada Limited Report, AECL-10721, COG-93-11.

Araya, S., T. Ishii, K. Sekijima, Y. Utsugida, K. Watanabe and M. Imazu. 1986. Conceptual designs of geological repositories for high level wastes, IAEA-SM-289/36. In *Proceedings of an IAEA Symposium on the* Siting, Design and Construction of Underground Repositories for Radioactive Wastes, Hanover, 1986, 495-506.

Arjang, B. 1991. Pre-mining stresses at some hard rock mines in the Canadian Shield. Canadian Mining and Metallurgical Bulletin 84 (945), 80-86.

ASTM (American Society for Testing Materials). 1982. Standard test method for determining the moisture - Density relations of soils. American Society for Testing Materials Standard D-1557-78.

Ates, Y., D. Bruneau and W.R. Ridgway. 1994a. Continental glaciation and its potential impact on a used-fuel disposal vault in the Canadian Shield. Atomic Energy of Canada Limited Report, AECL-10140, COG-94-256.

Ates, Y, D. Bruneau and W.R. Ridgway. 1994b. An evaluation of potential effects of seismic events on a used-fuel disposal vault. Atomic Energy of Canada Limited Technical Record, TR-623,* COG-94-257.

Atkinson, G.M. 1992. Seismic hazard in northwestern Ontario. Atomic Energy of Canada Limited Report, TR-M-22.**

Barnard, J.W., E.J.K. Cowdrey, C. Brown and W.P. Brown. 1985. Radiation protection manual Whiteshell Nuclear Research Establishment. Atomic Energy of Canada Limited Report, WNRE-659.*

Barton, N., R. Lien and J. Lunde. 1974. Engineering classification of rock masses for the design of tunnel support. Rock Mechanics 6, 189-236.

Baumgartner, P., J.L. Crosthwaite, M.N. Gray, L.J. Hosaluk, P.H. Seymour, G.B. Wilkin, C.R. Frost, J.H. Gee and J.S. Nathwani. 1993. Technical specification for a concept assessment engineering study (CAES) of a used-fuel disposal centre (UFDC). Atomic Energy of Canada Limited Technical Record, TR-410,* COG-92-189.

Baumgartner, P., T.V. Tran and R. Burgher. 1994. Sensitivity analyses for the thermal response in a nuclear fuel waste disposal vault. Atomic Energy of Canada Limited Technical Record, TR-621,* COG-94-258.

Baumgartner, P. and G.R. Simmons. 1987. Disposal centre engineering for the Canadian Nuclear Fuel Waste Management Program. Radioactive Waste Management and the Nuclear Fuel Cycle 8, 219-239.

Bieniawski, Z.T. 1967. Mechanism of brittle fracture of rock, Parts I, II and III. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 4, 395-430.

Bieniawski, Z.T. 1974. Geomechanics classification of rock masses and its application in tunnelling. In Advances in Rock Mechanics, Proceedings of the Third Congress of the International Society for Rock Mechanics, Denver, Volume II, Part A, 27-32.

Bieniawski, Z.T. 1976. Rock mass classification in rock engineering. In Proceedings of the Symposium on Exploration for Rock Engineering, Johannesburg, 1976, Volume I, 97-106.

Buckley, L.P. and D.H. Charlesworth. 1988. AECL experience with low-level radioactive waste technologies. Atomic Energy of Canada Limited Report, AECL-9787.

Carter, T.J. 1985. Used-fuel storage and transportation. In Proceedings of the Eighteenth Information Meeting of the Nuclear Fuel Waste Management Program, 231-244. Atomic Energy of Canada Limited Technical Record, TR-320.*

CEC (Commission of the European Communities). 1982. General conceptual design study for a high-level waste repository in a granite formation. Commission of the European Communities Report, EUR 7620.

Chan, T. and F. Stanchell. 1990. A numerical study of some effects of nuclear fuel waste vault construction and closure on evolution of groundwater flow paths in the geosphere. In High-Level Radioactive Waste Management, Proceedings of the International Topical Meeting, Las Vegas, 1990, Volume 1, 525-536.

Chandler, N.A. and C.D. Martin. 1990. Implications of in situ stress on vault design in granite. In Proceedings of the International Symposium on Unique Underground Structures, Denver, 1990, Volume 2, 65.1-65.19.

Cooper, R.B., K.W. Dormuth, I.D. Garg, G.R. Sherman, K.J. Truss and W. Willborn. 1990. Applying quality assurance to R&D projects. Quality Progress, 27(3), 21-26. Also available as Atomic Energy of Canada Limited Report, AECL-10241.

CSA (Canadian Standards Association). 1980. Seismic qualification of CANDU nuclear power plants - CAN3-N289 series. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1982. Requirements for concrete containment structures for CANDU nuclear power plants - CAN3-N287 series. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1983. Construction and installation quality assurance for nuclear power plants - CSA/CAN-N286.3-83. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1984. Procurement quality assurance for nuclear power plants - CSA/CAN-N286.1-84. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1986a. Commissioning quality assurance for nuclear power plants - CSA/CAN-N286.4-M86. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1986b. Design quality assurance for nuclear power plants - CAN/CSA-N286.2-86. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1987. Operations quality assurance for nuclear power plants - CAN/CSA-N286.5-M87. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1990. Concrete materials and methods of concrete construction/methods of test for concrete - CAN/CSA-A23.1-M90/A23.2-M90. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1991. Emergency planning for industry - CAN/CSA-Z731-M91. Canadian Standards Association, Rexdale, Ontario.

CSA (Canadian Standards Association). 1992. Overall quality assurance program for nuclear power plants - CSA/CAN-N286.0-92. Canadian Standards Association, Rexdale, Ontario.

Davis, P.A., R. Zach, M.E. Stephens, B.D. Amiro, G.A. Bird, J.A.K. Reid, M.I. Sheppard and M. Stephenson. 1993. The disposal of Canada's nuclear fuel waste: The biosphere model, BIOTRAC, for postclosure assessment. Atomic Energy of Canada Limited Report, AECL-10720, COG-93-10.

Davison, C.C., A. Brown, R.A. Everitt, M. Gascoyne, E.T. Kozak, G.S. Lodha, C.D. Martin, N.M. Soonawala, D.R. Stevenson, G.A. Thorne and S.H. Whitaker. 1994a. The disposal of Canada's nuclear fuel waste: Site screening and site evaluation technology. Atomic Energy of Canada Limited Report, AECL-10713, COG-93-3.

Davison, C.C., T. Chan, A. Brown, M. Gascoyne, D.C. Kamineni, G.S. Lodha, T.W. Melnyk, B.W. Nakka, P.A. O'Connor, D.U. Ophori, N.W. Scheier, N.M. Soonawala, F.W. Stanchell, D.R. Stevenson, G.A. Thorne, S.H. Whitaker, T.T. Vandergraaf and P. Vilks. 1994b. The disposal of Canada's nuclear fuel waste: The geosphere model for postclosure assessment. Atomic Energy of Canada Limited Report, AECL-10719, COG-93-9.

Davison, C.C., T. Chan and N.W. Scheier. 1988. Experimental activities of the Canadian Nuclear Fuel Waste Management Program to validate geosphere models. In Geoval – 1987, Proceedings of a Symposium on Verification of Geosphere Performance Assessment Models, Stockholm, 1987, Volume 2, 401-422.

Deere, D.U. 1964. Technical description of rock cores for engineering purposes. Rock Mechanics and Engineering Geology 1, 17-22.

Dixon, D.A. and M.N. Gray. 1985. The engineering properties of buffer material - Research at Whiteshell Nuclear Research Establishment. In Proceedings of the Nineteenth Information Meeting of the Nuclear Fuel Waste Management Program. Volume 3, 513-530. Atomic Energy of Canada Limited Technical Record, TR-350.*

Dowker, D.J. and M.D.C. Moles. 1987. Robotic inspection of prototype titanium diffusion bond final closure weld interim demonstration. Ontario Hydro Research Division Report 87-26-K.***

Dowding, C.H. 1978. Seismic stability of underground openings. In ROCKSTORE '77, Proceedings of a Symposium on Storage in Excavated Rock Caverns, Stockholm, 1977, Volume 2, 231-238.

Drury, M.J. and T.J. Lewis. 1983. Water movement in Lac du Bonnet batholith as revealed by detailed thermal studies of three closely-spaced boreholes. Tectonophysics 95, 337-351.

Durham, W.B., J.M. Beiriger, M. Axelrod and S. Terrenero. 1986. The effect of gamma irradiation on the strength and elasticity of climax stock and westerly granites. Nuclear and Chemical Waste Management 6, 159-168.

Everitt, R.A., P.M. Thompson and C.D. Martin. 1994. An approach to underground characterization of a disposal vault in granite. Atomic Energy of Canada Limited Report, AECL-10560.

Everitt, R.A., P. Chernis, D. Good and A. Grogan. 1989. Mapping of the excavation damage zone around the circular access shaft at Atomic Energy of Canada Limited's Underground Research Laboratory. In Excavation Response in Geological Repositories for Radioactive Waste, Proceedings of an NEA Workshop, Winnipeg, 1988, 271-282.

Favreau, R.F., G.W. Kuzyk, P.J. Babulic, R.A. Morin and N.J. Tienkamp. 1987. The use of blast simulation to improve blast quality. In Proceedings of the First International Symposium on Rock Fragmentation, Keystone, CO, 1987, 424-435.

Federal Environmental Assessment Review Panel. 1992. Final guidelines for the preparation of an environmental impact statement on the nuclear fuel waste management and disposal concept. Federal Environmental Assessment Review Office, 13th floor, Fontaine Building, 200 Sacre-Coeur Blvd., Hull, Quebec K1A 0H3.

Frost, C.R. and K.M. Wasywich. 1987. UO_2 oxidation in air at 50°C to 400°C and the implications for CANDU irradiated fuel dry storage. In Proceedings of the Workshop on Chemical Reactivity of Oxide Fuel and Fission Product Release, Berkeley, U.K., 1987, 319-355.

Golder Associates. 1993. Used-fuel disposal vault: Far-field thermal and thermal-mechanical analysis. Atomic Energy of Canada Limited Report, TR-M-15.**

Goodwin, B.W., D.B. McConnell, T.H. Andres, W.C. Hajas, D.M. LeNeveu, T.W. Melnyk, G.R. Sherman, M.E. Stephens, J.G. Szekely, P.C. Bera, C.M. Cosgrove, K.D. Dougan, S.B. Keeling, C.I. Kitson, B.C. Kummen, S.E. Oliver, K. Witzke, L. Wojciechowski and A.G. Wikjord. 1994. The disposal of Canada's nuclear fuel waste: Postclosure assessment of a reference system. Atomic Energy of Canada Limited Report, AECL-10717, COG-93-7.

Government of Canada. 1983. Physical security regulations, SOR/83-77, and as amended by SOR/84-81; 85-1016 and SOR/91-585. Canadian Government Publishing Centre, Supply and Services Canada, Hull, Quebec K1A 0S9.

Government of Canada. 1984. Environmental assessment and review process guidelines order, SOR/84-467. Canadian Government Publishing Centre, Supply and Services Canada, Hull, Quebec K1A 0S9.

Government of Canada. 1985. The atomic energy control act, R.S.c.A-16. Canadian Government Publishing Centre, Supply and Services Canada, Hull, Quebec K1A 0S9.

Government of Canada. 1992. Canadian environmental assessment act. Canadian Government Publishing Centre, Supply and Services Canada, Hull, Quebec K1A 0S9.

Government of Ontario. 1986. Province of Ontario nuclear emergency plan – Part I – Provincial master plan. Queen's Printer for Ontario.

Government of Ontario. 1990a. Environmental assessment act, R.S.O. 1990, c.E.18. Queen's Printer for Ontario.

Government of Ontario. 1990d. Mines and mining plants regulations, R.R.O. 1990, Reg. 854. Queen's Printer for Ontario.

Government of Ontario. 1990c. Workplace hazardous materials information system (WHMIS), R.R.O. 1990, Reg. 860. Queen's Printer for Ontario.

Government of Ontario. 1990b. Emergency plans act. R.S.O. 1990, c.E.9. Queen's Printer for Ontario.

Gray, M.N. 1993. OECD/NEA International Stripa Project Overview, Volume III, Engineered Barriers. Svensk Kärnbränslehäntering AB, Stockholm.

Greber, M.A., E.R. Frech and J.A.R. Hillier. 1994. The disposal of Canada's nuclear fuel waste: Public involvement and social aspects. Atomic Energy of Canada Limited Report, AECL-10712, COG-93-2.

Grondin, L., K. Johansen, W.C. Cheng, M. Fearn-Duffy, C.R. Frost, T.F. Kempe, J. Lockhart-Grace, M. Paez-Victor, H.E. Reid, S.B. Russell, C.H. Ulster, J.E. Villagran and M. Zeya. 1994. The disposal of Canada's nuclear fuel waste: Preclosure assessment of a conceptual system. Ontario Hydro Report N-03784-940010 (UFMED), COG-93-6.***

Herget, G. 1980. Regional stresses in the Canadian Shield. In Underground Rock Engineering, Proceedings of the 13th Canadian Rock Mechanics Symposium (The H.R. Rice Memorial Symposium), Toronto, 1980, CIM Special Volume 22, 9-16.

Herget, G. 1986. Changes of ground stresses with depth in the Canadian Shield. In Rock Stress and Rock Stress Measurements, Proceedings of the International Symposium, Stockholm, 1986, 61-68.

Herget, G. 1987. Stress assumptions for underground excavations in the Canadian Shield. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 24, 95-97.

Herget, G. and B. Arjang. 1991. Update on ground stresses in the Canadian Shield. In Proceedings – Stresses of Underground Structures, Ottawa, 33-47.

Hibbitt, Karlsson and Sorensen, Inc. 1989. ABAQUS: Verification Manual, Version 4.8, Providence, RI.

Hoek, E. and E.T. Brown. 1980. Underground excavations in rock. The Institution of Mining and Metallurgy, London.

Holmberg, R. and P.A. Persson. 1980. Design of tunnel perimeter blasthole patterns to prevent rock damage. Transactions of the Institution of Mining and Metallurgy Section A 89, 37-40.

Holmberg, R. 1983. Hard rock excavation at the CSM/OCRD test site using the Swedish blast design techniques. Battelle Memorial Institute Report, BMI/OCRD-4(3).

IAEA (International Atomic Energy Agency). 1980. Guidelines for States' systems of accounting for and control of nuclear materials, International Atomic Energy Agency, IAEA/SG/INF/2, Vienna.

IAEA (International Atomic Energy Agency). 1984. IAEA safeguards: safeguards techniques and equipment. International Atomic Energy Agency, IAEA/SG/INF/5, Vienna.

IAEA (International Atomic Energy Agency). 1987. IAEA safeguards glossary – 1987 edition. International Atomic Energy Agency, IAEA/SG/INF/1 (Rev. 1), Vienna.

IAEA (International Atomic Energy Agency). 1988. Advisory group meeting on safeguards related to final disposal of nuclear material in waste and spent fuel, International Atomic Energy Agency, STR-243 (revised), Vienna.

IAEA (International Atomic Energy Agency). 1991. Consultants' report on safeguards for final disposal of spent fuel in geological repositories. International Atomic Energy Agency, STR-274, Vienna.

ICRP (International Commission on Radiological Protection). 1977. Radiation protection. International Commission on Radiological Protection Report, ICRP-26, Pergamon Press, New York.

ICRP (International Commission on Radiological Protection). 1979. Limits for intakes of radionuclides by workers, Part 1, ICRP Publication 30, Annals of the ICRP 2 (3/4), Pergamon Press, New York.

ICRP (International Commission on Radiological Protection). 1991. 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Annals of the ICRP 21(1-3), Pergamon Press, New York.

Jackson, R., J.S.O. Lau and A. Annor. 1989. Mechanical, thermomechanical and joint properties of rock samples from the site of AECL's Underground Research Laboratory, Lac du Bonnet, Manitoba. In Proceedings of the 42nd Canadian Geotechnical Conference on Materials, Winnipeg, 1989, 41-49.

Jaeger, J.C. and N.G.W. Cook. 1979. Fundamentals of Rock Mechanics, third edition. Chapman and Hall Limited, London.

Jessop, A.M. and T.J. Lewis. 1978. Heat flow and generation in the Superior Province of the Canadian Shield. Tectonophysics 50, 55-77.

Johnson, J.R. and D.W. Dunford. 1983. Dose conversion factors for intakes of selected radionuclides by infants and adults. Atomic Energy of Canada Limited Report, AECL-7919.

Johnson, L.H., J.C. Tait, D.W. Shoesmith, J.L. Crosthwaite and M.N. Gray. 1994a. The disposal of Canada's nuclear fuel waste: Engineered barriers alternatives. Atomic Energy of Canada Limited Report, AECL-10718, COG-93-8.

Johnson, L.H., D.M. LeNeveu, D.W. Shoesmith, D.W. Oscarson, M.N. Gray, R.J. Lemire and N. Garisto. 1994b. The disposal of Canada's nuclear fuel waste: The vault model for postclosure assessment. Atomic Energy of Canada Limited Report, AECL-10714, COG-93-4.

Joint Statement. 1978. Joint Statement by the Minister of Energy, Mines and Resources Canada and the Ontario Energy Minister, 1978 June 05. Printing and Publishing, Supply and Services Canada, Ottawa K1A 0S9.

Joint Statement. 1981. Joint Statement by the Minister of Energy, Mines and Resources Canada and the Ontario Energy Minister, 1981 August 04. Printing and Publishing, Supply and Services Canada, Ottawa K1A 0S9.

Katsube, T.J. and J.P. Hume (editors). 1987. Geotechnical studies at Whiteshell Research Area (RA-3). Canada Centre for Mineral and Energy Technology, Mining Research Laboratories Divisional Report, MRL 87-52 (INT).

Kelsall, P.C., J.B. Case and C.R. Chabannes. 1984. Evaluation of excavation-inducted changes in rock permeability. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 21, 123-135.

Kjartanson, B.H., M.N. Gray and B.C.M. Pulles. 1991. Developments for in-situ tests on compacted bentonite-based buffer material. Materials Research Society Symposium Proceedings 212 (Scientific Basis for Nuclear Waste Management XIV), 467-474.

Kuzyk, G.W., P.A. Lang and G. LeBel. 1987a. Blast design and quality control at the second level of Atomic Energy of Canada Limited's Underground Research Laboratory. In Proceedings of the International Symposium on Large Rock Caverns, Helsinki, 1986, 147-158.

Kuzyk, G.W., P.A. Lang and D.A. Peters. 1987b. Integration of experimental and construction activities at an underground laboratory. Tunnels and Tunnelling 19(7), 27-30.

Langefors, U. and B. Kihlstrom. 1978. The Modern Technique of Rock Blasting, third edition. John Wiley and Sons, Inc., New York.

Latham, A.G. (editor). 1987. Geotechnical studies at East Bull Lake Research Area (RA-7). Canada Centre of Mineral and Energy Technology, Mining Reserach Laboratories Divisional Report, MRL 87-94 (INT).

Le, H. and P. Denault. 1985. Gentilly-1: Decontamination program. American Nuclear Society Transactions 50, 107-108.

Lee, C.F. 1987. Performance of underground coal mines during the 1976 Tangshan earthquake. Tunnelling and Underground Space Technology 2, 199-202.

Lee, P.K., R. Pearson, R.E.J. Leech and R. Dickin. 1983. Hydraulic testing of deep fractures in the Canadian shield. Bulletin of the International Association of Engineering Geology, No. 26-27, 461-465.

Martin, C.D. 1989. Shaft excavation response in a highly stressed rock mass. In Excavation Response in Geological Repositories for Radioactive Waste, Proceedings of an NEA Workshop, Winnipeg, 1988, 331-340.

Martin, C.D. 1990. Characterizing in situ stress domain at the AECL underground research laboratory. Canadian Geotechnical Journal 27, 631-646.

Martin, C.D. 1993. The strength of massive Lac du Bonnet granite around underground openings. Ph.D. Thesis, Department of Civil and Geotechnical Engineering, University of Manitoba, Winnipeg, Manitoba.

Martin, C.D. and R.S. Read. 1992. Strength of massive granite around underground excavations. In 16th Canadian Rock Mechanics Symposium, 1992, Sudbury, Ontario, 1-11.

Martin, C.D., C.C. Davison and E.T. Kozak. 1990. Characterizing normal stiffness and hydraulic conductivity of a major shear zone in granite. In Proceedings of the International Symposium on Rock Joints, Loen, Norway, 1990, 549-556.

Martin, C.D., E.T. Kozak and N.A. Chandler. 1992. Hydraulic properties of the excavation-disturbed zone around underground openings. In 45th Canadian Geotechnical Conference, Toronto, 89-1—89-10.

Martinez, R.L., S.L. Scheider, B. Richter, R. Guenzel, K.J. Gaertner and A. Terrasi. 1991. The new design of the VACOSS-S/MIVS interface system. In Nuclear Materials Management, Proceedings of the 32nd Annual Meeting of the Institute of Nuclear Materials Management, New Orleans, 1991, Volume XX, 637-640.

Mathers, W. 1985. HOTROK, A program for calculating the transient temperature field from an underground nuclear waste disposal vault. Atomic Energy of Canada Limited Technical Record, TR-366.*

Minister of the Environment, Canada. 1989. Terms of reference for the nuclear fuel waste management and disposal concept environmental assessment panel. Printing and Publishing, Supply and Services Canada, Hull, Quebec K1A 0S9.

Moles, M.D.C. and M.P. Dolbey. 1985. Inspection development for closure welds. In Proceedings of the Nineteenth Information Meeting of the Nuclear Fuel Waste Management Program – Engineered Barriers and Waste Forms, Volume 1, 93-115. Atomic Energy of Canada Limited Technical Record, TR-350.*

NAGRA (Nationale Genossenshaft für die Lagerung Radioaktiver Abfälle). 1985a. Projekt Gewähr, nuclear waste management in Switzerland – Feasibility studies and safety analysis. Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle Report, NAGRA NGB 85-09.

NAGRA (Nationale Genossenshaft für die Lagerung Radioaktiver Abfälle). 1985b. Grimsel test site, overview and test programs. Nationale Genossenshaft für die Lagerung Radioaktiver Abfälle Technical Report 85-46.

NRCC (National Research Council of Canada). 1985. National Building Code of Canada NRCC 23174, Supply and Services Canada, Hull, Quebec K1A 0S9.

NRCC (National Research Council of Canada). 1986. National Fire Code of Canada NRCC 23175, Supply and Services Canada, Hull, Quebec K1A 0S9.

Ontario Hydro. 1989a. Used-fuel transportation assessment (UFTA). Ontario Hydro Report 89289.***

Ontario Hydro. 1989b. Used nuclear fuel management plan and future costs. Ontario Hydro Report 89105.***

Ontario Hydro. 1991. Radioactive materials management at Ontario Hydro - The plan for used fuel. Ontario Hydro Report.***

Ontario Hydro. 1992. Ontario Hydro health and safety performance 1991. Ontario Hydro Report HSD-92-3.***

Ontario Hydro. 1993a. Ontario Hydro health and safety performance 1992. Ontario Hydro Report HSD-93-1.***

Ontario Hydro. 1993b. Depreciation review committee recommendations. Ontario Hydro Report.***

OECD (Organisation for Economic Co-Operation and Development). 1983. Proceedings of the Workshop on Geological Disposal of Radioactive Waste – In Situ Experiments in Granite. Stockholm, 1982. Organisation for Economic Co-Operation and Development, Paris.

OECD (Organisation for Economic Co-Operation and Development). 1985. Proceedings of the Second NEA/Stripa Project Symposium, Radioactive Waste Disposal – In Situ Experiments in Granite. Stockholm, 1985. Organisation for Economic Co-Operation and Development, Paris.

OECD (Organisation for Economic Co-Operation and Development). 1990. Proceedings of the Third NEA/SKB Symposium on the International Stripa Project – In Situ Experiments Associated with the Disposal of Radioactive Waste. Stockholm, 1989. Organisation for Economic Co-Operation and Development, Paris.

Ortlepp, W.D. 1992. Assessment of rockburst risk in the underground research laboratory – Pinawa, Manitoba, Canada. Steffen, Robertson and Kirsten. Atomic Energy of Canada Limited Report, TR-M-12.**

Patrick, W.C. (compiler). 1986. Spent fuel test – Climax: An evaluation of the technical feasibility of geologic storage of spent nuclear fuel in granite – Final report. Lawrence Livermore National Laboratory Report, UCRL-53702.

Peck, R.B. 1969. Advantages and limitations of the observational method in applied soil mechanics. Ninth Rankine Lecture. Géotechnique 19, 171-187.

Peters, D.A., G.W. Kuzyk and D.P. Onagi. 1994. Design and construction management of Atomic Energy of Canada Limited's Underground Research Laboratory. In Unpublished Documents Cited in the EIS and Primary References. Atomic Energy of Canada Limited Technical Record, TR-567.

Piercy, R.J., J.R. Antonacci and M.D.C. Moles. 1989. Robotic inspection of prototype titanium diffusion bond final closure weld - Final report. Ontario Hydro Report 89-247-K.***

Pusch, R. and A. Bergström. 1980. Highly compacted bentonite for borehole and shaft plugging. In Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, 1980, 161-168.

Pusch, R. and J. Nilsson. 1982. Buffer mass test – Rock drilling and civil engineering. Svensk Kärnbränslehantering AB Stripa Project Internal Report, TR 82-07.

Pusch, R. 1989. Influence of various excavation techniques on the structure and physical properties of "near-field" rock around large boreholes. Svensk Kärnbränslehantering AB Technical Report, TR 89-32.

Raven, K.G., D.J. Bottomley, R.A. Sweezey, J.A. Smedley and T.J. Ruttan. 1986. Hydrogeological characterization of the East Bull Lake research area, Contaminant Hydrogeology Section, National Hydrology Research Institute, Inland Waters Directorate, Environment Canada.

Read, R.S. and C.D. Martin. 1991. Mine-by experiment final design report. Atomic Energy of Canada Limited Report, AECL-10430, COG-91-305.

Rusch, H. 1959. Physical problems in the testing of concrete. Zement-Kalk-Gips (Cement and Concrete Association Library Translation No. 86, 1960) 1-9.

Schmidtke, R.H. and E.Z. Lajtai. 1985. The long-term strength of Lac du Bonnet granite. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 22, 461-465.

Sen Gupta, S.K. 1994. Integrated plant for volume reduction, immobilization, and disposal of aqueous mixed radwaste. Atomic Energy of Canada Limited Report, AECL-10976.

Shetler, A. 1986. Description of road, rail and water transportation systems for the disposal of irradiated fuel. Ontario Hydro Report 86291.***

Simmons, G.R. 1988. Geotechnical research at Atomic Energy of Canada Limited's Underground Research Laboratory. In Proceedings of the International Symposium on Uranium and Electricity – The Complete Nuclear Fuel Cycle, Saskatoon, 1988, 4.7-4.20.

Simmons, G.R. 1990. Operating phase experiments planned for Atomic Energy of Canada Limited's Underground Research Laboratory. In Proceedings of the International Symposium on Unique Underground Structures, Denver, 1990, Volume 2, 67.1-67.19.

Simmons, G.R., P. Baumgartner, G.A. Bird, C.C. Davison, L.H. Johnson and J.A. Tamm. 1994. An approach to criteria, design limits and monitoring in nuclear fuel waste disposal. Atomic Energy of Canada Limited Report, AECL-10737, COG-94-30 (in preparation).

SKB (Svensk Kärnbränslehantering AB). 1983. Final storage of spent nuclear fuel, KBS-3, Volumes 1 to 4. Svensk Kärnbränslehantering AB, Stockholm.

SKB (Svensk Kärnbränslehantering AB). 1989a. WP-cave-assessment of feasibility, safety and development potential, Svensk Kärnbränslehantering AB Technical Report, TR 89-20.

SKB (Svensk Kärnbränslehantering AB). 1989b. Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential. Svensk Kärnbränslehantering AB Technical Report, TR 89-39.

SKB (Svensk Kärnbränslehantering AB). 1992. Project on alternative systems study (PASS) final report. Svensk Kärnbränslehantering AB Technical Report, TR 93-04.

Smith, R.M., D.W. Jung, P. Baumgartner. 1988. International safeguards at a potential Canadian nuclear disposal centre for wastes and/or used fuel, Atomic Energy of Canada Limited Report, AECL-9449.

Sperry, P.E., G.P. Chitombo and W.A. Hustrulid. 1984. Hard rock excavation at the CSM/OCRD test site using crater theory and current United States controlled smooth wall blasting practices. Battelle Memorial Institute Report, BMI/OCRD-4(4).

Talebi, S. and P. Young. 1989. Failure mechanisms of crack propagations induced by shaft excavation at the Underground Research Laboratory. In Proceedings of the International Symposium on Rock at Great Depth, Pau, France, 1989, 1455-1461.

Taylor, K. and F.J. Walford. 1991. The use of dual containment/surveillance systems. In Nuclear Materials Management, Proceedings of the 32nd Annual Meeting of the Institute of Nuclear Materials Management, New Orleans, 1991, Volume XX, 139-143.

Teper, B. 1985. Feasibility assessment of the particulate-packed, thin-wall container. In Proceedings of the Nineteenth Information Meeting of the Nuclear Fuel Waste Management Program - Engineered Barriers and Waste Forms, Volume 1, 21-32. Atomic Energy of Canada Technical Report TR-350.*

Thompson, P.M., B.H. Kjartanson and R.S. Read. 1992. Design and construction of two major experiments at the URL. In High Level Radioactive Waste Management, Proceedings of the Third International Conference, Las Vegas, 1992, Volume 1, 1082-1089.

Tsui, K.K., C.F. Lee, A. Tsai and N.L. Harris. 1982. Thermomechanical modelling of a nuclear waste vault in crystalline hard rock. In Proceedings of the Fourth International Conference on Numerical Methods in Geomechanics, Edmonton, 1982, Volume 2, 503-512.

Tsui, K.K. and A. Tsai. 1994a. Three-dimensional thermal and thermomechanical analyses for the near-field of a disposal vault with the borehole emplacement option. Ontario Hydro Report NWESD N-03788-940014 (UFMED).***

Tsui, K.K. and A. Tsai. 1994b. Three-dimensional thermal and thermo-mechanical analyses for the near-field of a disposal vault with an in-room emplacement option. Ontario Hydro Report NWESD N-03788-940015 (UFMED).***

Tsui, K.K. and A. Tsai. 1994c. The effects of sequential excavation during the construction of a disposal vault with borehole emplacement option. Ontario Hydro Report NWESD N-03788-940016 (UFMED)***.

U.S. DOE (United States Department of Energy). 1988. Site characterization plan overview, Yucca Mountain Site, Nevada Research and Development Area, Nevada. U.S. Department of Energy Report, DOE/RW-0198.

Van Konyenburg, R.A. 1984. Radiation doses in granite around emplacement holes in the spent fuel test – climax. Final Report. Lawrence Livermore National Laboratory Report, UCRL-53580.

Villagran, J.E. 1991. Derivation of the source term for chronic radioactive emissions from the used-fuel disposal centre during the preclosure phase. Ontario Hydro Report 89358-Rev. 2.***

Wardrop, W.L. and Associates in association with Canadian Mine Services Ltd. and Hardy Associates (1978), Ltd. 1985. Buffer and backfilling systems for a nuclear fuel waste disposal vault. Atomic Energy of Canada Technical Record, TR-341.*

Wasywich, K.M. and C.R. Frost. 1991. Examination of used CANDU fuel following 27 years of storage under water. In Proceedings of the Third International Conference on Nuclear Fuel Reprocessing and Waste Management, RECOD '91, Sendai, Japan, 1991, Volume 1, 371-376.

Wilkins, B.J.S., Y. Liner, G.L. Rigby. 1985. Estimations of changes in microcrack population, elastic modulus and permeability, due to differential – thermal expansion in plutonic rock surrounding a nuclear fuel waste disposal vault. Materials Research Society Symposium Proceedings 50 (Scientific Basis for Nuclear Waste Management IX), 99-105.

Wilkins, B.J.S., G.L. Rigby and W.F. Heinrich. 1987. MCROC – a model to estimate time-dependent microcracking in plutonic rock due to heat. Atomic Energy of Canada Limited Report, AECL-9083.

Wilkins, B.J.S. and G.L. Rigby. 1989. MCDIRC – a model to estimate the creep of intact rock around a shaft. In Proceedings of the International Symposium on Rock at Great Depth, Pau, France, 1989, 629-634.

Wilkins, B.J.S. and G.L. Rigby. 1990. Comparison of time-dependent strains measured at the Canadian Underground Research Laboratory (URL) with those calculated from the model MCDIRC. Atomic Energy of Canada Limited Report, AECL-10239.

Wilkins, B.J.S. and G.L. Rigby. 1992. Expected acoustic emission from around a shaft in intact rock. Journal of Acoustic Emission 10, 522-528.

Wilkins, B.J.S. and G.L. Rigby. 1993. Creep in the sparsely fractured rock between a disposal vault and a zone of highly fractured rock. Atomic Energy of Canada Limited Report, AECL-10879, COG-93-214.

Yong, R.N., P. Boonsinsuk and G. Wong. 1985. Development of backfill material for a nuclear fuel waste vault. In Proceedings of the Nineteenth Information Meeting of the Nuclear Fuel Waste Management Program - Engineered Barriers and Waste Forms, Volume 3, 561-594. Atomic Energy of Canada Limited Technical Record, TR-350.*

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** Unpublished contractor's report prepared for AECL Research, available from Library, Reports Services, AECL Research, Whiteshell Laboratories, Pinawa, Manitoba R0E 1L0.

*** Unrestricted report available from Ontario Hydro, 700 University Avenue, Toronto, Ontario M5G 1X6.

Wilkins, B.J.S. and G.L. Rigby. 1993. Creep in the sparsely fractured rock between a disposal vault and a zone of highly fractured rock. Atomic Energy of Canada Limited Report, AECL-10879, COG-93-214.

Yong, R.N., P. Boonsinsuk and G. Wong. 1985. Development of backfill material for a nuclear fuel waste vault. In Proceedings of the Nineteenth Information Meeting of the Nuclear Fuel Waste Management Program - Engineered Barriers and Waste Forms, Volume 3, 561-594. Atomic Energy of Canada Limited Technical Record, TR-350.*

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GLOSSARY

abnormal conditions: (1) Situations that are planned for in the operation of a system, but are not encountered on a day-to-day basis.

(2) Accidents.

absorbed dose: The amount of energy deposited in a unit mass of irradiated material; the unit of absorbed dose is the gray (Gy).

accident: A substantial deviation from the normal operating conditions of a nuclear facility or transportation system, when relevant engineered safety features do not function according to design. An accident could lead to the release of radioactive materials.

actinide: An element with an atomic number from 89 (actinium) to 103 inclusive. All actinides are radioactive. Examples are uranium and plutonium.

AECB: See "Atomic Energy Control Board."

AECL: See "Atomic Energy of Canada Limited."

aggregate: Granular material such as sand, gravel, crushed stone, crushed hydraulic-cement concrete, or iron blast-furnace slag, used with a hydraulic cementing medium to produce either concrete or mortar.

ALARA: As Low As Reasonably Achievable, the nuclear safety philosophy that the design and use of radioactive sources, and the practices associated with them, should be such as to ensure that exposures are kept as low as is practicable, economic and social factors being taken into account. A basic principle of dose limitation in radiation protection, taken from the Recommendations of the International Commission Radiological Protection (ICRP 1977).

annual dose: An abbreviation for "annual effective dose equivalent." It is the sum, over one year, of the effective dose equivalent resulting from external exposure and the committed effective dose equivalent from that year's intake of radionuclides for a member of the critical group. The SI unit of measurement of annual dose is sieverts per year (Sv/a).

Atomic Energy Control Board (AECB): The Canadian federal regulatory agency with jurisdiction over nuclear facilities and nuclear materials, that achieves regulatory control through a comprehensive licensing system. Established in 1946, the organization's mandate is "to ensure that the use of nuclear energy in Canada does not pose undue risk to health, safety, security and the environment." Through its licensing and inspection systems, the AECB provides control and supervision of the development, application and use of atomic energy in Canada and participates on behalf of Canada in international measures of control.

Atomic Energy of Canada Limited (AECL): A Canadian Crown corporation created 1952 April 1 to develop nuclear technology for peaceful uses.

atomic radiation worker: As provided by the Atomic Energy Control Regulations, any person who in the course of his/her work, business or occupation is likely to receive a dose of ionizing radiation or an exposure to radon daughters in excess of the maximum permissible limits for the general public.

audit: In IAEA usage, a documented activity undertaken to determine by investigation, examination and evaluation of objective evidence the adequacy of or the adherence to established procedures, instructions, specifications, regulatory codes, standards, administrative or operational programs and other applicable documents, and the effectiveness of their implementation.

axisymmetric: A form of symmetry obtained by rotating an object in a plane 360° around an axis that lies within the plane.

backfill: In a disposal vault, the material used to refill excavated portions in disposal rooms, shafts and tunnels after the waste packages and buffer have been emplaced. Two backfills are being considered in the Canadian Nuclear Fuel Waste Management Program:

(1) a mixture of glacial lake clay and crushed granite from the vault excavation, and

(2) a mixture of sodium bentonite clay and silica sand, also called a buffer.

barrier: A feature of a disposal system that delays or prevents radionuclides from escaping from the disposal vault and migrating into the biosphere. A <u>natural</u> <u>barrier</u> is a feature of the geosphere in which the disposal vault is located. An <u>engineered</u> <u>barrier</u> is a feature made or altered by man, and includes the waste form and its container, casks for transportation and disposal of the waste and any sealing materials used. See also "cask."

baseline conditions: An established reference against which impacts can be measured.

batholith: A large mass of intrusive igneous rock, most of which consolidated at a considerable depth below the surface of the Earth. Similar to a pluton except that it is much larger.

benching: A method of excavation by which floors of large tunnels or large underground rooms are extended downwards (i.e., the height of the tunnel is increased by excavation of the floor). Usually, this is achieved by drilling small-diameter blast holes downwards from the floor of "the bench" and removing the blasted rock on the new, lower floor. The step from the new to the previous floor is termed a "bench."

bentonite: Absorptive colloidal formed by the chemical alteration of volcanic ash. It is composed mainly of montmorillonite and related minerals in the smectite group. Sodium-rich bentonite has a particular attraction for water and swells when wet. It is being considered as a major component of the buffer material used in a disposal vault.

biosphere: Usually defined as the portion of the Earth inhabited by living organisms. In the context of the Nuclear Fuel Waste Management Program, it has a more specific meaning. In aquatic areas the biosphere/geosphere interface occurs between the deep compacted and the shallow mixed sediments, and in terrestrial areas the interface is formed by the water table. Thus, the biosphere includes mixed sediments, surface waters, soils, and the lower parts of the atmosphere. Even though the overburden and the geosphere may contain microorganisms, these regions are considered here to be parts of the geosphere. See also "geosphere."

blind boring: The process of making a large-diameter borehole in which the cutting tool removes the entire cross section of a borehole as rock chips. See also "raise boring."

borehole: Exploration boreholes are holes drilled into the Earth's surface to study and characterize the underground rock structure and/or to measure the subsurface environment. Emplacement boreholes are holes drilled into the floors or walls of a room in a disposal vault, into which containers of nuclear fuel waste would be placed and sealed.

buffer: A substance placed around the waste containers in a disposal vault, consisting of highly impermeable material. The primary purpose of this material is to serve as an additional barrier by retarding the movement of water. It would also affect the rates of container corrosion, fuel dissolution, and radionuclide migration. In the Nuclear Fuel Waste Management Program, the reference buffer material (RBM) is a compacted sand-bentonite mixture.

buffer zone: An area surrounding a nuclear installation, such as a disposal facility, to which access is limited. Its purpose is to ensure an adequate distance between the facility and places used by or accessible to the public.

burnup: In reactor physics, the energy released in a nuclear reactor per unit of mass of fuel. The units are gigajoules per kilogram of uranium (GJ/kg U).

cage: See "conveyance, shaft."

Canadian Shield: An extensive area of Precambrian rock exposed over large parts of central and eastern Canada. The Canadian Shield lies approximately to the east of a line passing through Great Bear Lake, Great Slave Lake, Lake Athabasca and Lake Winnipeg, and to the north of the continuation of this line through Lake Superior, Lake Huron and the St. Lawrence River. It is composed of metamorphic and igneous rocks. Orogenic events have occurred over different parts of the Shield at various times but some parts have been free of such activity for about 2.5 billion years. Almost the entire Canadian Shield has been stable for the last 900 million years.

CANDU Owners Group (COG): A group formed in 1984 by Canadian utilities operating CANDU reactors and AECL Research. Its purpose is to provide a framework that will promote closer cooperation among the utilities owning and operating CANDU stations in matters relating to plant operation and maintenance, and to foster cooperative development programs leading to improved plant performance.

CANDU: CANadian Deuterium Uranium, the name of the Canadian-designed reactor that uses natural uranium fuel and is moderated by heavy water. CANDU is a registered trademark of AECL.

cask: See "container cask" or "transportation cask."

cladding: An external, usually metallic, layer directly surrounding nuclear fuel or other substances that seals and protects it from the environment and protects the environment from radioactive materials produced during irradiation. Also known as "clad."

clay: Minerals that are essentially hydrous aluminum silicates or occasionally hydrous magnesium silicates, with sodium, calcium, potassium and magnesium cations. Also denotes a natural material with plastic properties that is essentially made up of fine to very fine particles. Because of good sorption characteristics, certain types of clay are being considered by some countries as a barrier around the waste emplaced in a disposal vault.

closure stage: In the Canadian Nuclear Fuel Waste Management Program, a period of time in the preclosure phase of nuclear fuel waste disposal that includes the removal of measurement instruments from any boreholes that could compromise the safety of the disposal vault and the sealing of those boreholes. If there were no extended monitoring after decommissioning, this stage would be combined with decommissioning. During the closure stage, the objective would be to return the site to a state such that safety would not depend on institutional controls.

code: In computing, one or more statements of a computer language, such as FORTRAN or PASCAL. Code is a general term that, depending on the context, could refer to computer programs, subroutines, functions or a part of any of these.

Commission of the European Communities: The organization responsible for managing the affairs of the European Coal, Steel and Atomic Energy Communities. The Secretariat is located in Brussels, Belgium.

commissioning: The process by which a nuclear facility and its components and systems, once constructed, are made operational and verified to be in accordance with design assumptions and predefined performance criteria; both non-nuclear and nuclear tests are included.

concrete canister: A receptacle used for above-ground dry storage of nuclear fuel waste.

conservative assumption: A cautious, or moderate, estimate of a parameter value that is at the limit of the range of expected values, and that, if wrong, will result in a prediction that overestimates the actual dose or impact.

construction stage: The period of time in the preclosure phase of nuclear fuel waste disposal that includes constructing the facilities needed to begin disposing of nuclear fuel waste: transportation facilities and equipment, access routes, utilities, surface facilities, shafts, tunnels, underground facilities, and some or all of the disposal rooms. It also involves establishing and applying the administration and control systems required to safely operate the disposal facility.

container: See "disposal container."

container cask: A heavy shielding vessel in which disposal containers would be transported within a used-fuel disposal facility. It would provide radiological protection during the transfer of the disposal containers from the surface packaging plant to the underground emplacement boreholes.

containment: (1) For a disposal system, the retention of radioactive material in such a way that it is effectively prevented from being dispersed into the environment, or is released only at a regulated and acceptable rate.

(2) The structure(s) used to effect such retention.

(3) In safeguards applications, the structural features of a nuclear facility or equipment that enable the IAEA to establish the physical integrity of an area or item by preventing undetected access to or movement of nuclear or other material, or interference with the item, IAEA safeguards equipment or data. Examples are the walls of a storage room or or a storage pool, transport casks and storage containers. See also "surveillance" and "containment/surveillance measures."

containment/surveillance measures: The application of containment and/or surveillance (C/S), an important safeguards measure complimenting nuclear material accounting. The application of C/S measures is aimed at verifying information on movement of nuclear or other materials, devices and samples or preservation of the integrity of safeguards relevant data. In many instances, C/S measures cover the periods when the inspection is absent and this contributes to cost-effectiveness. C/S measures are applied, for instance,

(1) to ensure during flow and inventory verification that each term is inventoried without duplication and that the integrity of samples is preserved;

(2) to ensure that IAEA instruments, devices, working paper and supplies are not tampered with;

(3) to check the validity of previous measure and thereby reduce the need for remeasuring previously verified items.

The indication of an anomaly by C/S measures does not necessarily by itself indicate that material has been removed. The ultimate resolution of C/S anomalies (e.g., broken seals) is provided by nuclear materials account.

If any C/S measures has been, or may have to be, compounded, the IAEA shall, if not agreed otherwise, be notified by the fastest means available. Examples might be seals that have been broken inadvertently or in an emergency, or seals of which the possibility of removal after advance notification to the IAEA has been agreed between the IAEA and the operation.

conveyance, shaft: An elevator-like vehicle used in shafts and similar excavations to move personnel and materials to various levels. If used to transport people and equipment, it is referred to as a "cage," but if used to move bulk materials, it is referred to as a "skip."

core: (1) In a nuclear reactor, the central arrangement of nuclear fuel elements, control rods and supporting structures that sustains a nuclear reaction and generates heat.

(2) In mining, geotechnical and civil engineering, a sample of material obtained by drilling. See also "core drilling."

core drilling: Drilling with a hollow bit and core barrel to obtain a core sample of the rock mass. See also "borehole."

core log: A record of the analysis of rock and overburden through which a borehole passes. The core log describes core samples from various depths as the hole is drilled. See also "core drilling."

corrosion: Gradual destruction of the surface of a metal or alloy by a chemical processes such as oxidation or the action of a chemical agent. General corrosion is uniform erosion over the whole surface of the material, whereas local corrosion is accelerated penetration at sensitive places such as crevices and stressed areas. The term is often applied to glasses and ceramic waste forms as well as metals.

criteria: Principles or standards on which a decision or judgement can be based. They may be qualitative or quantitative. Objective criteria are specified in terms of the environmental consequences of radioactive releases. Derived criteria are cast in terms of the physical characteristics of a specific facility and site, and of any releases of radioactivity from it.

daughter product: A nuclide that is directly produced by the radioactive decay of a radionuclide; the daughter product may itself be radioactive. Also known as "daughter" or "progeny."

decay: See "radioactive decay."

decay heat: The heat that continues to be generated by disintegrating radionuclides in used nuclear reactor fuel after it is removed from the reactor core.

decommissioning: The actions required, in the interests of health, safety, security and protection of the environment, to permanently retire a nuclear facility from active service, possibly including decontamination of the site.

decommissioning stage: A period of time during the preclosure phase of nuclear fuel waste disposal that includes the decontamination, dismantling and removal of the surface and subsurface facilities, and the sealing of the tunnels, service areas, and shafts and the exploration boreholes drilled from them. The site would be returned to a state suitable for public use and permanent markers would be installed.

decontaminate: To remove radioactive contaminants with the objective of reducing the residual radioactivity level in or on materials, persons or the environment.

decontamination factor: The initial amount of contaminating radioactive material divided by the final amount following a decontamination process. The term may refer to specified individual or groups of radionuclides or to gross radioactivity.

diffusion: The spontaneous migration of atoms or molecules in a gas, liquid, or solid from a region of high concentration of the diffusing species to regions of low concentration, or more accurately, from a region of high to low chemical potential.

disposal: A permanent method of long-term management of radioactive wastes in which there is no intent to retrieve the wastes. Ideally, disposal uses techniques and designs that do not rely on long-term institutional control beyond a reasonable period of time.

disposal container: A durable receptacle for enclosing, isolating and handling nuclear fuel wastes for disposal. In a disposal vault, the containers would serve as one barrier between the waste form and the human population. Sometimes called "waste container" or just "container."

disposal facility: A disposal vault and the supporting buildings and equipment to receive the waste and package it in durable containers, shafts and equipment to transfer the containers from the surface to the vault, equipment to handle the containers in the vault, and the materials and equipment to excavate the vault, emplace the disposal containers, and fill and seal the vault, tunnels and shafts.

disposal system: All structures, materials, processes, procedures or other aspects that, when taken together, constitute the means by which the safe disposal of the waste is achieved. Also called "waste disposal system."

disposal vault: An underground structure excavated in rock. In the preclosure phase, the disposal vault comprises the underground excavations in plutonic rock, including the access shafts, access tunnels, underground service areas and installations, and disposal rooms on one or more levels where containers of nuclear fuel waste would be emplaced and sealed for disposal. In the postclosure phase, the disposal vault comprises the disposal rooms and associated access tunnels, the nuclear fuel waste and the engineered barrier systems used to contain the waste and seal all openings.

dose: A general term denoting the quantity of radiation or radiation energy absorbed by a specified mass of a substance. "Dose" is often qualified to refer to specific quantities, and to an individual versus a group of people; examples are absorbed dose, dose equivalent, effective dose equivalent, committed effective dose equivalent, and collective dose. The SI unit of measurement of dose is the sievert (Sv). In the EIS preclosure and postclosure assessments, dose is frequently encountered in expressions such as "annual dose" and "dose per year." In these cases, it is an abbreviation of "annual effective dose equivalent commitment."

dose equivalent: The strict definition of radiological dose is the energy absorbed per unit mass of tissue exposed to ionizing radiation, measured in grays (Gy). The dose equivalent, measured in sieverts (Sv), is the product of the dose and a radiation weighting factor. This weighting factor is a function of how a certain type of radiation deposits its energy within the body. Radiation with high weighting factors deposits a lot of energy in a short distance, whereas radiation with lower factors deposits less energy over the same distance. For example, alpha radiation has a weighting factor of 20, whereas beta and gamma radiation have a value of 1. The dose equivalent accounts for the fact that different types of radiations react differently within the body.

drill-and-blast excavation: In construction, a method of excavating rock by using explosives placed in one or more drill holes. The size and shape of the rock broken by this method (i.e., of the excavated opening and the size of the pieces of broken rock) can be controlled by selecting the size of each drill hole, the number of drill holes in an array, the shape of the array of drill holes, the amount and type of explosive in each drill hole and the sequence in which the explosives in the boreholes are initiated.

dry storage: A method of keeping used nuclear reactor fuel in concrete canisters in air or in an inert atmosphere (as opposed to water).

effect: A change to the social and/or natural environment caused by the activities associated with the transportation or disposal of nuclear fuel waste. Socio-economic effect: any social or economic change(s) that can be perceived by those affected and which is determined to be of importance to them. Biophysical environment impact: any change(s) in the local wildlife, plants, soil, water, etc., resulting from a nuclear fuel waste disposal facility or from associated transportation activities.

emplacement: The placing of waste in a prepared storage or disposal location. In the disposal vault, the placing of waste containers within buffer mass located in either a disposal room or an emplacement borehole drilled from a disposal room.

engineered barrier: See "barrier."

environment: The objects, conditions and influences surrounding an organism, human or otherwise, that affect its life, survival and development. Often qualified by preceding words such as "vault," "natural," "biophysical," "socio-economic," and "surface."

environment, natural: All the conditions and influences, not human-derived, surrounding an organism, human or otherwise, that affect its life, survival, and development, except, in the case of humans, those factors covered under "socio-economic environment." It includes the biosphere and geosphere.

equilibrium: The state of a system with no external energy or material inputs for which there are no macroscopic changes taking place, e.g., a chemical system in which a certain reaction and the reverse reaction are taking place at equal rates.

exposure: Irradiation of persons or materials. Exposure of persons to ionizing radiation may be either external, from sources outside the body, or internal, from sources inside the body.

extended monitoring stage: A period of time in the preclosure phase of nuclear fuel waste disposal that includes monitoring conditions in the vault, geosphere, and biosphere, between the operation and decommissioning stages and/or between the decommissioning and closure stages. Such monitoring would be performed if regulators and/or the public required additional data on the performance of the partially sealed and/or sealed disposal vault.

extraction ratio: The ratio of the excavated area to the total area where excavations occur in a disposal vault. For a room-and-pillar vault configuration with regularly spaced disposal rooms, the figure is obtained by dividing the width of an excavated room by the distance between the centrelines of adjacent rooms.

far-field: A large-scale region containing a disposal vault and its surrounding strata, such that, for modelling purposes, the vault may be considered as a single entity. In the far-field the influence of individual waste packages cannot be distinguished. See also "near-field."

fault: In geology, a break in the continuity of a rock formation caused by shifting of the Earth's crust, where adjacent surfaces have been displaced parallel to the plane of the fracture.

finite-element method: A numerical technique for studying problems in heat conduction, fluid mechanics, electrical field theory, or structural mechanics. A system is represented by discrete elements interconnected at nodal points or nodes. The technique is usually employed for complex problems for which an analytical solution cannot be obtained exactly or approximately.

fission product: An atom produced either by nuclear fission or by the radioactive decay of an unstable atom produced by fission.

fracture: A breakage in a rock or mineral.

fracture zone: A zone in which faulting has taken place.

fuel element: The smallest structurally discrete part of a nuclear reactor fuel bundle that has fuel as its principal constituent; usually a thin sealed metallic tube containing a stack of uranium dioxide pellets.

fuel reprocessing waste: The highly radioactive materials left over after the valuable elements have been removed from used fuel.

fuel waste: See "nuclear fuel waste."

full-face excavation: A method of excavation in which the excavation (e.g., tunnel, shaft) is advanced by removing the material in the opening cross section in one step. See also "pilot-and-slash excavation."

geological disposal: All approaches to the long-term management of nuclear fuel wastes that depend on placing the wastes underground in a selected host medium to isolate the wastes from humans and the environment.

geological setting: The characteristics existing at a specific site including the different types of soil, rock and sediment, their form, distribution and age relationships and their physical and chemical properties.

geology: The study of the origin, history and structure of the Earth.

geosphere: The solid outer portion of the Earth's crust. In the Nuclear Fuel Waste Management Program concept for the geological disposal of nuclear fuel waste, the geosphere, consisting of the rock and groundwater system, is one of the major barriers surrounding the disposal vault. Also known as "lithosphere."

glaciation: The formation, movement, and recession of glaciers or ice sheets, and the geological processes, including erosion and deposition, and the resulting effects of such processes on the Earth's surface.

glass beads: Glass particles that are compacted around the tubes of used nuclear fuel and into the spaces between the fuel and the shell of the disposal container to provide internal support against underground pressures.

gradient: The magnitude and direction of the greatest rate of change of a scalar property, such as the gradient of temperature or the gradient of contaminant concentration in a disposal vault.

granite: A coarse-grained igneous rock consisting mostly of quartz (20 to 40%), alkali feldspar and mica. A number of accessory minerals may be present.

groundwater: Water beneath the Earth's surface in soils and geological formations. The water may rise from a deep magmatic source or come from rainfall soaking into the Earth.

grout: A fluid mixture of cement and water, or a mixture of cement, sand and water used to seal boreholes and fractures in a rock mass or to seal surfaces and structures.

hazardous: A potential for creating a harmful effect.

health: Complete physical, mental, emotional and social well-being.

high-efficiency particulate air (HEPA) filter: A filter used for removing submicrometre and larger particles from a gaseous stream.

hot cells: Shielded and individually ventilated enclosures, fitted with remote manipulation systems that allow an operator to perform tasks involving radioactive materials without being exposed to radiation beyond a specified allowable dose. The facility provides containment, shielding, remote handling and viewing.

HOTROK: A computer program for calculating the transient temperature field from an underground nuclear waste disposal vault.

human factors engineering: The study of the interaction between people and their working environment with the aim of reducing the potential for human error, and in so doing maximizing safety, efficiency and comfort of the work environment.

hydrogeochemistry: The study of the chemical composition of groundwater and the physical and chemical processes that produced the observed distributions of elements and nuclides.

hydrogeology: The study of the geological factors relating to the Earth's water.

IAEA: See "International Atomic Energy Agency."

ICRP: See "International Commission on Radiological Protection."

institutional controls: Continuing actions and precautions by society that ensure the implementation and achievement of a desired course of action. These controls could include monitoring, surveillance, maintenance, record keeping, and imposing land-use restrictions.

International Atomic Energy Agency (IAEA): The organization established in 1957 by the United Nations as the international body responsible for on-site inspections of nuclear reactors and safeguards measures that assist the member states of the Agency to demonstrate that no nuclear material is being diverted for non-peaceful purposes from safeguarded nuclear facilities. The Secretariat is located in Vienna, Austria.

International Commission on Radiological Protection (ICRP): An independent non-government expert body founded in 1928. This Commission establishes radiation protection standards that are followed by most countries.

ion exchange: Reversible exchange of ions between a liquid phase and a solid phase that is not accompanied by any radical change in the solid structure.

ionizing radiation: Electromagnetic energy (e.g., X-ray or gamma-ray photons) or rapidly moving atomic or subatomic particles having sufficient energy to displace electrons from atoms or molecules, thereby producing ions. Ionizing radiation may produce skin or tissue damage.

licence: In the nuclear industry, a formal document issued by a regulatory agency for major stages in the development of a nuclear facility that permits the implementing organization to perform specified activities.

load-haul-dump vehicle (LHD): A low-profile front-end loading vehicle designed for use in underground openings and mines that is used to remove rock, to move it to another location and to dump it (e.g., into trucks). It is also used to move equipment, materials and supplies.

mechanical excavation: A method of breaking and excavating rock or other hard, brittle material by using mechanical force, generally applied to a small area of the material, to cause local failure.

The machines include tunnel boring machines, raise borers, blind borers, and drills.

mitigation: Actions taken to reduce or offset negative socio-economic or biophysical environmental effects.

mitigation measures: Actions taken to alleviate the detrimental impacts of an event or continuing activity. They can include actions to avoid, minimize, correct, eliminate or compensate for negative impacts.

model: An analytical or mathematical representation, quantification or simulation of a real system and the ways that phenomena occur within the system. Individual or subsystem models can be combined to give system models. In SYVAC3-CC3, for example, the system model consists of the vault, geosphere and biosphere models.

monitoring: (1) The continuous or intermittent measuring of a condition that must be kept within prescribed limits. Activities carried out to facilitate the identification and management of socio-economic and biophysical environmental impacts.

(2) The measurement of radiation or radioactivity for reasons related to the assessment or control of exposure to radiation or radioactive material and the interpretation of such measurements.

montmorillonite: A soft hydrous aluminum silicate clay mineral, which has a considerable capacity for exchanging part of the aluminum for magnesium and bases.

natural barrier: See "barrier."

natural environment: See "environment, natural."

near-field: A small-scale region within the confines of a disposal vault such that, for modelling purposes, individual components (e.g., disposal containers, emplacement boreholes, disposal rooms) can be analyzed. See also "far-field."

NGS: See "Nuclear Generating Station."

nuclear facility: A facility and its associated land, buildings and equipment in which radioactive or fissionable substances are produced, processed or handled on such a scale that considerations of nuclear safety are required.

nuclear fuel waste: A solid, highly radioactive material that is either the used nuclear fuel that has been removed from a CANDU nuclear power reactor or a waste form incorporating the highly radioactive waste that would be removed from the fuel if the fuel were to be recycled. See also "high-level waste."

Nuclear Fuel Waste Management Program: A program of research and development on radioactive waste management established in a 1978 Joint Statement by the Government of Canada and the Government of Ontario. The aim is to develop and assess the concept of disposing of nuclear fuel waste in the plutonic rock of the Canadian Shield. AECL is responsible for verifying the safety of this disposal method. Ontario Hydro is responsible for developing and demonstrating nuclear fuel waste storage technology, and for transportation of these wastes from reactor sites. A second Joint statement in 1981 imposed the restriction that the concept must be assessed, reviewed and accepted before a site could be accepted.

nuclear generating station (NGS): One or more nuclear reactors, together with the structures, systems and components necessary for safety, and for the production of power in the form of heat or electricity. Also called "nuclear power plant."

operation stage: The period of time in the preclosure phase of nuclear fuel waste disposal that includes transporting nuclear fuel waste to the disposal facility, putting the waste into corrosion-resistant containers, and emplacing the containers and sealing materials in disposal rooms in the vault. Construction of disposal rooms would continue at the same time.

optimization: (1) The use of protective measures to reduce the expected harm to a population from exposure to radiation resulting from some activity involving radioactive materials, to a level as low as reasonably achievable, economic and social factors being taken into account.

(2) The evolutionary design of facilities, components and implementation procedures that improve operating efficiency and/or reduce costs for waste disposal. These steps are consistent with regulatory requirements and the ALARA principle for occupation and public health and safety. See also "ALARA."

Organisation for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA): An intergovernmental body that conducts research and serves as a forum for collaborative advancement of the economics of its 24 industrially developed member states. The Secretariat is located in Paris, France.

packaging: (1) The packing of nuclear fuel waste to conform to radioactive material shipping regulations established to prevent loss, release or dispersion of radioactive material.

(2) The packing of nuclear fuel waste into disposal containers at a disposal facility.

panel: (1) In a disposal vault, a group of disposal rooms excavated from a common single access tunnel or pair of access tunnels.

(2) In the Environmental Assessment and Review Process (EARP), the Environmental Assessment Panel is the group responsible for the environmental assessment of a proposed project.

performance assessment: Estimation of the current and future behaviour of the disposal system or a subsystem on the basis of new data (obtained by site characterization, monitoring, and component testing) and accumulated knowledge; and evaluation of the current and future behaviour on the basis of standards and criteria.

Performance assessment is the same as impact assessment when the future effects on humans and non-human biota are estimated. For impact assessment, the system of interest depends on the disposal phase being assessed: for the preclosure phase, it is the disposal facility and associated transportation system; for the postclosure phase, it is the closed disposal vault. Also see "safety assessment."

permeability: The capacity of a porous rock, sediment or soil to transmit a fluid. The SI unit of measurement is square metres (m^2).

person-year: A unit of work equal to one year of work done by one person. This is defined as 261 d/a, including statutory holidays and vacations.

pilot-and-slash excavation: A method of excavation in which the material necessary to achieve the final desired opening cross section is removed in two or more steps. Generally in tunnelling, a tunnel is driven by first excavating a small pilot tunnel and then enlarging the pilot tunnel to full dimension and shape by slash blasting. See also "slashing." This method is suggested for drill-and-blast excavation to minimize blast damage effects in excavation perimeters (e.g., tunnels, rooms).

plane stress analysis: A two-dimensional mathematical analysis technique used in solid mechanics in which the object in the plane being analyzed is unconfined in the out-of-plane direction so that the out-of-plane stress is zero.

plutonic rock: Intrusive igneous rock formed at considerable depth beneath the surface of the Earth by cooling of magma. Also called "intrusive igneous rock" and "crystalline rock."

pool: A water-filled pool, usually at the site of a nuclear generating station, in which used nuclear reactor fuel is stored. Sometimes called "water-pool facility," or "fuel bay."

postclosure assessment: Safety analysis of the waste disposal system, starting after the disposal vault has been closed. The objectives are to determine the long-term impacts of the disposal facility, and to provide estimates of risk that can be compared with regulatory criteria. See also "performance assessment."

postclosure phase: The project phase following the closure stage for a disposal facility, after the underground facilities have been decommissioned and sealed, the monitoring systems whose continued operation could affect long-term disposal vault safety have been sealed, and the surface facilities have been decontaminated and decommissioned.

preclosure: In nuclear fuel waste disposal, the project phase that includes the siting, construction, operation, decommissioning and closure stages of a disposal facility and associated transportation systems.

preclosure assessment: Safety analysis of the waste disposal system that deals with potential impacts during siting, construction, operation, decommissioning and closure of a disposal facility. It includes an assessment of the transportation of used nuclear reactor fuel from nuclear generating stations to the disposal facility.

progeny: See "daughter product."

protected area: A physical security, control zone around a nuclear facility that is circumscribed at the perimeter of the area by a fence that inhibits and aids in the detection of any unauthorized entry.

quality assurance: All planned or systematic actions needed to provide adequate confidence that a product or service will meet specified requirements.

quality control: Actions that provide a means to fix and measure the characteristics of an item, process, facility or person in accordance with quality assurance requirements.

radiation: The high-speed nuclear particles emitted by nuclei, taken to be synonymous with ionizing radiation. The four major forms of radiation are alpha and beta particles, neutrons and gamma rays.

radiation protection: Measures associated with limiting the harmful effects of ionizing radiation on people, such as limiting external exposure or bodily incorporation of radionuclides, as well as the prophylactic limitation of bodily injury resulting from either of these. Also, all measures designed to limit radiation-induced chemical and physical damage in materials. Also called "radiological protection."

radioactive: Emitting radiation. See "radiation."

radioactive contamination: The presence of a radioactive substance in or on a material or place where it is undesirable or could be harmful.

radioactive decay: The changing and progressive decrease in the number of unstable atoms in a substance because of their spontaneous nuclear disintegration or transformation during which particles and/or electromagnetic radiation are emitted.

radioactive material: A substance containing one or more constituents which exhibit radioactivity. For special purposes such as regulations, this term may be restricted to radioactive material with a radioactivity level or specific activity greater than a specified value.

radioactive waste: Any material that contains or is contaminated with radionuclides at concentrations or radioactivity levels greater than the "exempt quantities" established by the regulatory agencies and for which no use is foreseen.

radioactivity: The spontaneous emission of radiation, either directly from unstable atomic nuclei, or as a result of a nuclear reaction.

radionuclide: An unstable nuclide that undergoes radioactive decay.

raise: In mining, the excavation of a vertical or inclined passage between two levels in a mine or between a mine level and surface for the purpose of access and ventilation.

raise boring: A two-step machine method for raise excavation, whereby a hole is first drilled between two excavations, followed by back reaming to a larger diameter. Normally the hole is drilled from the top. After breakthrough at the lower excavation, the drill bit is replaced with a large reaming head and is retracted back to the top, allowing the rock cuttings to fall into and be removed from the lower excavation. Also see "raise."

regulatory limit: The maximum amount of a contaminant (e.g., toxic, radioactive, sonic, visual, etc.) that can be released to the environment. The limit is established by a national or international regulatory authority.

repository: See "disposal vault."

reprocessing, waste: See "fuel reprocessing waste."

research area: A region of up to several hundred square kilometres where geological and some biological field studies have been conducted for the Nuclear Fuel Waste Management Program. The principal research areas are the Whiteshell Research Area (near Lac du Bonnet, Manitoba), the Atikokan Research Area, the East Bull Lake Research Area (near Massey, Ontario) and the Chalk River Research Area.

retrieval: The removal of waste from the location where it has been emplaced.

safeguards: The verification measures taken to detect the diversion of used nuclear fuel or other nuclear materials for weapons manufacture or for unknown purposes. The system is designed to deter diversion by the risk and consequences of early detection by giving timely notification to the International Atomic Energy Agency. This falls within the framework of international non-proliferation policy entrusted to the IAEA in its statute and by the Treaty on the Non-Proliferation of Nuclear Weapons (see that term).

safety assessment: Evaluation of the behaviour of a disposal system, and comparison of the results with appropriate standards or acceptability criteria. The system under consideration is the entire disposal system, and one acceptability criterion is a limit on radiological risk to individuals of the critical group. Also see "performance assessment."

safety criteria: Standards or criteria used to judge the acceptability of the protection afforded people and the environment. In the Canadian disposal system, one safety criterion is a limit on radiological risk to individuals of the critical group.

seal:
(1) In disposal, such things as buffer material, backfill, bulkheads, grout and plugs that act as barriers in a disposal vault by helping to isolate the waste material and to retard the movement of water. Seals such as buffer materials would also affect the rates of container corrosion, fuel dissolution, and radionuclide migration.

(2) In safeguards, a tamper-indicating device used to join movable segments of a containment in a manner that would make access to its contents without opening of the seal or breaking of the containment difficult. Seals may be applied on safeguarded material or equipment, on operator's equipment and on IAEA property.

seismicity: Movement within the Earth caused by earthquakes or ground vibration.

shaft: A passage, usually vertical, excavated from surface to subsurface facilities, and used for moving personnel, equipment, disposal containers and materials, and for ventilation.

shaft conveyance: See "conveyance, shaft."

shaft set: A structure constructed of wood or metal elements that is installed along the full length of a shaft to support the conveyance system and its guides, the service and utility installations, ladder ways, and other installations in the shaft.

shear zone: See "fault" and "fracture zone."

shielding: A material interposed between a source of radiation and persons or equipment, to protect them from radiation. Common shielding materials are concrete, water, steel, earth and lead.

site evaluation: The process of identifying and characterizing a preferred site and obtaining approval to construct a disposal facility at that site.

site screening: The process of identifying a small number of areas that have characteristics desired for disposal and thus warrant detailed investigation. The activities would include analyzing existing regional scale data (characterization), and developing and applying criteria for accepting or rejecting area for further investigation.

siting stage: A period of time in the preclosure phase of nuclear fuel waste disposal that includes the development of the siting process, site screening and site evaluation.

skip: See "conveyance, shaft."

slash: A drill-and-blast excavation method by which excavations are enlarged. This usually involves drilling and blasting near-parallel holes outside of the opening perimeter.

socio-economic: Generally used to refer to partial economic analysis and partial social and cultural analysis.

sodium bentonite: A clay formed from volcanic ash decomposition and largely composed of montmorillonite and beidellite. See also "bentonite."

stage: A period of time in the preclosure phase of nuclear fuel waste disposal (see siting stage, construction stage, operations stage, decommissioning stage, closure stage).

storage: The emplacement of waste in a facility in such a way that isolation, monitoring, environmental protection and human control are provided, <u>and</u> subsequent action involving treatment, transport and disposal or reprocessing is expected. Compare with "disposal."

structure: (1) In geology, (a) the relationship between different parts of a rock (e.g., texture, fabric, flow, fracturing, cleavage), (b) the overall relationship of rock masses (e.g., folding, faulting nonconformities).

(2) In geotechnical/mining engineering, the created excavations (e.g., tunnels, rooms, shafts, pillars).

supervised area: An area is one in which working conditions, including the possible occurrences of minor mishaps, require the worker to follow well-established procedures and practices aimed specifically at controlling radiation exposures.

surface contamination: Radioactive material deposited on the surface of a structure or object, measured by the amount of radioactivity per unit area of surface. The surface contamination can be fixed (not removeable) or non-fixed (removeable).

surge storage: A holding area capable of accepting a temporary excess of nuclear materials for stockpiling during equipment outages or a period of restricted handling capacity.

surveillance: (1) Planned activities performed to ensure that the conditions at a nuclear facility remain within the prescribed limits, and to detect in a timely manner any unsafe condition or degradation of structures, systems and components that could later result in an unsafe condition arising.

(2) In safeguards applications, the collection of information through observation by IAEA safeguards inspectors and/or instruments, aimed at monitoring the movement of nuclear material and the detection of interference with containment and tampering with IAEA safeguards devices, samples and data. Surveillance may also be used for observing various operations or obtaining relevant operational data. IAEA safeguards inspectors may carry out surveillance assignments continuously or periodically at strategic points. See also "containment" and "containment/surveillance measures."

topography: The detailed and exact physical configuration of the surface of the Earth at a specific location or in a region.

transportation cask: A robust shielding vessel that dissipates heat, provides physical containment and radiological protection during the transportation and handling of nuclear fuel waste. Transportation casks are assumed to carry used nuclear fuel from nuclear generating stations to a disposal facility. Compare with "container cask."

tunnel: A horizontal or nearly horizontal underground passageway.

tunnel boring: A machine excavation method by which tunnels are created. In effect this uses a very large diameter, self-propelled drill.

Underground Research Laboratory (URL): An AECL experimental facility excavated in a granite batholith near the Whiteshell Laboratories, Manitoba. It is used to carry out studies, experiments and engineering demonstrations related to rock mechanics, hydrogeology and excavation and sealing. The URL is comprised of main access and ventilation shafts excavated to a depth of about 443 m. The main testing levels are at depths of 240 m and 420 m. Additional shaft stations are excavated at depths of 130 m and 300 m.

used fuel: Nuclear reactor fuel that has undergone fission in a nuclear reactor to the point where its further use is no longer efficient because of the buildup of atomic species that hinder the production of heat in the reactor. Sometimes called "irradiated fuel" or "spent fuel."

used-fuel bundle: A number of nuclear reactor fuel elements held together by end plates and separated by spacers attached to the fuel cladding near the middle of the bundle (see also used fuel).

Used-Fuel Disposal Centre: The reference conceptual design description of a used-fuel disposal facility developed for use in concept assessment. This includes the surface and underground site, workings, structures, processes and systems necessary to receive used nuclear fuel in transportation casks, package it in disposal containers, emplace and seal it in a geological medium and provide all the supporting services and systems to do so in a safe and acceptable manner. The design was used by AECL to assess the engineering feasibility, costs, safety and potential environmental impact of disposing of used nuclear fuel in the manner described in the EIS documents. The design is based on specifications for all disposal system components and activities.

validation: The process by which one provides evidence or increased confidence that the predictions created by a model correspond to the real system that the model is asserted to represent. It is carried out by comparing calculated results to field observations and experimental measurements. A conceptual model and the computer program derived from it are considered to be "validated" when the comparison with measurements on a real system shows that they provide a sufficiently good representation of the actual processes occurring in the real system, in keeping with the intended use of the model. Compare with "verification."

variability (of a parameter): The ability of a quantitative characteristic to have different values. Changes in the value of a quantity with time or space.

vault environment: The surrounding conditions and influences within the vault.

vault, disposal: See "disposal vault."

verification: (1) The process by which one provides evidence or increased confidence that a computer code correctly executes the calculations it is asserted to perform. A verified computer code is one that has correctly translated a specified algorithm into computer code. Verification can be carried out, for example, by comparing the results of a computer code with results produced by other computer codes or by analytical solutions. Compare with validation.

(2) In safeguards applications, verification of inventory is a basic IAEA safeguards inspection activity carried out to confirm the operator's recorded book inventory of nuclear material present at a given time within a material's balance area. Verification of inventory change is an inspection to confirm a recorded increase or decrease in a material's balance area.

waste container: See "disposal container."

waste disposal system: See "disposal system."

waste form: The physical and chemical state in which the waste material is prepared (e.g., liquid or solid, dispersed in concrete or glass) before it is put into containers and prepared for disposal.

waste management: The administrative and operational activities involved in handling, treating, conditioning, transporting, storing and disposing of unwanted hazardous materials.

waste stream: Any circulating liquid or gaseous refuse, or any continuously produced solid refuse.

Whiteshell Research Area (WRA): A tract of land located in the Whiteshell region of southeastern Manitoba, and near AECL's Whiteshell Laboratories. Much of the information used in the postclosure EIS derives from research studies at the WRA. In particular, the geosphere model is based on detailed hydrogeological studies of the WRA.