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CTECH

Radioactive Materials Management

Conceptual Design for a Deep Geologic Repository for Used Nuclear Fuel

Report of a Study carried out for Ontario Power Generation, New Brunswick Power, Hydro-Québec and Atomic Energy of Canada Limited

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NOTICE to the Reader

“This document has been prepared by CTECH Radioactive Materials Management, a joint venture of Canatom NPM Inc. and RWE Nukem Ltd. (“Consultant”), to update the conceptual design and cost estimate for a deep geologic repository (DGR) for long term disposal of used nuclear fuel. The scope is more fully described in the body of the document. The Consultant has used its professional judgment and exercised due care, pursuant to a purchase order dated October 2001. (the “Agreement”) with Ontario Power Generation Inc. acting on behalf of the Canadian nuclear fuel owners (“the Client”), and has followed generally accepted methodology and procedures in updating the design and estimate. It is therefore the Consultant’s professional opinion that the design and estimate represent a viable concept consistent with the intended level of accuracy appropriate to a conceptual design, and that, subject to the assumptions and qualifications set out in this document, there is a high probability that actual costs related to the implementation of the proposed design concept will fall within the specified error margin.

This document is meant to be read as a whole, and sections or parts thereof should not be read or relied upon out of context. In addition, the report contains assumptions, data, and information from a number of sources and, unless expressly stated otherwise in the document, the Consultant did not verify those items independently. Notwithstanding this qualification, the Consultant is satisfied that the updated conceptual design and cost estimate was carried out in accordance with generally accepted practices in a professional manner .

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Summary

Since 1996, Ontario Hydro and, subsequently, Ontario Power Generation (OPG) have continued the development of the geologic repository concept for used CANDU fuel. This work has resulted in modifications to the concept developed earlier by AECL. Since April 1, 2000, the four used nuclear fuel owners in Canada; Ontario Power Generation (OPG), Hydro-Québec (HQ), New Brunswick Power (NBP) and Atomic Energy of Canada Limited (AECL) have jointly agreed to examine various approaches for the safe management of used nuclear fuel, including isolation in a deep geologic repository (DGR). As part of the projects implemented under that agreement, a contract was awarded to CTECH to prepare an updated DGR conceptual design.

This report describes the conceptual design of a DGR for used CANDU fuel using the in-room emplacement method. The DGR design was developed for a generic site and it consists of shafts, access tunnels and a grid of emplacement rooms excavated at a depth of 1000 m in low-conductivity, sparsely fractured rock in the Canadian Shield. After encapsulation in copper/steel double shell containers, the fuel is placed inside the repository rooms that are elliptical in cross section. The containers are arranged in two parallel lines along the axis of the emplacement rooms and completely enclosed with clay-based sealing materials.

The description of the DGR design process starts with a description of the used fuel container (UFC) which is a double-shell copper/steel structure. The outer copper shell is designed to provide corrosion protection and the inner steel shell to provide the required structural strength. The report covers the studies conducted to ensure viability of the container design and describes also the repository layout along with the analyses performed to verify its thermal and mechanical performance. Construction methods and operation of the DGR are described, as well as the design and operation of ancillary and support facilities.

The report briefly discusses requirements and possible approaches to preclosure monitoring of the DGR and outlines a possible method for retrieval of UFCs from the repository if it became necessary. It should be noted that the DGR is designed for passive safety, i.e. the safety and performance of the repository is not dependent of long-term institutional controls.

The updated DGR conceptual design demonstrates that CANDU fuel bundles can be received, packaged in UFCs and placed in the DGR emplacement rooms in a safe manner. The radiological safety and environmental effect of the DGR both during project implementation and over the long term will be addressed in separate reports. The requirements and possible approaches to preclosure monitoring of repository performance are also discussed in further detail in a separate document.

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1 Introduction

A design concept for deep geologic disposal of used CANDU fuel was developed by Atomic Energy of Canada Limited (AECL) during the period 1978 – 1996, under the Canadian Nuclear Fuel Waste Management Programme. This programme was created in 1978 by a joint initiative of the federal and Ontario governments. The AECL-developed concept [1,2] underwent extensive review under the federal Environmental Assessment and Review Process. The results of that review are documented in the final report of the Environmental Assessment Panel, published in March of 1998 [3]. The Panel report summarised the concept review and recommended changes to address comments from a broad range of stakeholders, including the public.

Since 1996, Ontario Hydro and, subsequently, Ontario Power Generation (OPG) have continued the development of the geologic repository concept for used CANDU fuel. This work has resulted in modifications to the concept developed by AECL. Since April 1, 2000 the four used nuclear fuel owners in Canada; Ontario Power Generation (OPG), Hydro-Québec (HQ), New Brunswick Power (NBP) and Atomic Energy of Canada Limited (AECL) have jointly agreed to examine various approaches for the safe management of used nuclear fuel. This report documents the work done in one of the several projects carried out under that initiative and examines the long-term isolation of CANDU used fuel in a deep geologic repository (DGR).

1.1 STUDY OBJECTIVES

The objectives of this engineering study are to update the DGR Conceptual Design, including in the facility design all equipment and systems required to undertake the following:

- receive used nuclear fuel shipped from interim storage and/or from extended storage facilities
- encapsulate the used nuclear fuel in long-lived used fuel containers (UFCs)
- place the UFCs in the DGR
- retrieve the UFCs from the repository during the preclosure phase, if required.

The conceptual design will be in sufficient detail to confirm the engineering feasibility of the repository design and to allow the preparation of a conceptual cost estimate for the implementation of a DGR facility that includes its siting, construction, operation, decommissioning, closure and postclosure management.

1.2 CHANGES TO AECL CONCEPT

The used fuel repository concept developed by AECL [2] between 1978 and 1994 was based on encapsulating the used CANDU fuel in titanium containers with a capacity of 72 fuel bundles each. Those containers were then placed in boreholes drilled in the floor of the emplacement rooms in a repository excavated in granitic rock in the Canadian Shield. Subsequently, AECL considered a second configuration for emplacement of the used fuel containers within the repository rooms (in-room emplacement) which was outlined in a report by Baumgartner et al published in 1996 [4]. The DGR concept described in the present study is a further development of the in-room emplacement configuration. This design is based on encapsulation of the fuel in copper/steel double-shell containers with a capacity of 324 bundles, and emplacement of these containers inside the emplacement rooms, in a horizontal position. The containers are arranged in two rows parallel to the longitudinal axis of the emplacement rooms and are surrounded and supported by an assembly of pre-compacted blocks of buffer and dense backfill material. This arrangement is illustrated in Figure 1.

The major differences between the AECL design concept for in-floor container emplacement and the DGR conceptual design described in this report are listed in Table 1. The main assumptions used for the DGR design developed in this study are listed below:

- the assumed ambient in situ stress conditions, the Young's modulus, and the coefficient of thermal expansion of the rock have been increased to be representative of the conditions likely to exist in sparsely fractured granite
- updated rock mass strength design limits, based on an improved understanding of the performance of sparsely fractured rock have been adopted
- the average burn-up of used fuel has been increased to reflect current experience in reactor operations and the reference fuel age has been increased from 10 to 30 years
- the design limit for the temperature of the outer surface of the UFC has been set at 100^0C to provide an appropriate design margin
- the UFC design incorporates an outer copper shell that provides corrosion protection and an inner, steel, structural support vessel, designed to withstand the external forces generated by hydrostatic and buffer swelling pressures.
- the fuel capacity of the UFC has been substantially increased from the previous 72-bundle container proposed by AECL, to 324 bundles
- a in-room emplacement method has been selected to provide greater flexibility in excavation design for the high stress environment and to provide greater thickness in buffer and dense backfill materials around the UFCs
- a method to retrieve emplaced UFCs during the preclosure phase is outlined as part of the repository design.

The conceptual DGR design discussed in this report is generic and has not been based on conditions at any particular site. However, many of the site conditions assumed for design purposes have been drawn from results of studies carried out at the Whiteshell Research Area and surrounding region, including the Underground Research Laboratory. Therefore, data that would normally evolve from site-specific field activities have been taken from available sources to enable the design analyses necessary for the conceptual design to be completed. This report discusses the assumptions made and the analyses undertaken.

No formal system or component performance or cost optimisation has been undertaken during this study for the reason that many of the criteria for optimisation need to be established by the implementing organisation. However, the design process has examined optional repository arrangements and DGR layouts before arriving at the practicable conceptual designs presented.

The scope of the DGR design concept presented in this report has been formulated without considering any effects from possible faults, fractures or other geological structural features that could influence the proposed layout of the emplacement rooms and access tunnels. However, the design can be readily modified to accommodate any changes resulting from any geological structures encountered.

While it is appreciated, given the degree of confidence gained from previous work, that granite at the depth proposed is in most part only sparsely fractured, zones of significant thrust faulting and fracturing are typically seen in many plutonic rock masses. While the assumptions regarding uniform in-situ stresses across the DGR horizon and homogeneous sparsely fractured granite are consistent with the use of continuum models for the analyses, it must be appreciated that during the detailed design stage potential geological variability must be considered. This should be carried out from both a stress and geological structural viewpoint.

1.3 SUMMARY OF REPORT CONTENTS

Chapter 1, this chapter provides an introduction to and the objectives for the study and provides the relationship to other programme activities. It also provides an introductory, generic description of the DGR facility and its operation.

Chapter 2 describes the design process that resulted in an update of the in-room emplacement concept and the DGR underground layout design and the implementation description. The design process includes the setting of specifications in their initial and final form, the scoping analyses that were performed to arrive at the final emplacement room arrangement and the integration of components into a generic repository design.

Chapter 3 describes details of the generic DGR facility design. It begins with a description of the UFC copper outer shell, the steel inner vessel and the factors that influenced the UFC design. The chapter also describes the DGR underground layout and factors that influenced its design including numerical thermal and thermal-mechanical analyses, material handling and movement, general logistics and the separation of radiological and non-radiological operations. The chapter considers detailed emplacement room design parameters, the filling and sealing materials, and the operational processes. Finally, the chapter addresses the updated design of the used-fuel packaging plant, where UFCs will be loaded and sealed and the modifications to the common surface facilities, compared with those described in [2] needed to support the DGR operations.

Chapter 4 presents a description for the implementation of the DGR facility. It outlines the project stages and activities and itemises a specific plan for each of the project stages; siting, construction, operation, decommissioning and closure.

Finally, Chapter 5 reviews the report objectives and discusses the technical feasibility of the in-room emplacement method and its implications on structural and operational performance. This chapter also presents issues identified during development of the design that should be addressed during the next stage of the design phase.

1.4 GENERAL DESCRIPTION OF THE DGR

The DGR will include surface facilities for the receipt and packaging of used fuel in corrosion resistant containers, together with a series of underground emplacement rooms served by access shafts and tunnels all excavated in plutonic rock. The DGR facility will be self-contained, except for the supply of materials and UFCs and their components, and will be located on a suitable rock body in the Canadian Shield. The DGR facility has been designed to receive, package and dispose of CANDU used-fuel bundles at a rate of 120,000 per annum. The design assumes that these used-fuel bundles have been discharged from reactors and stored for 30 years prior to receipt at the DGR facility.

During operation, the used fuel will be received at the DGR used fuel packaging plant (UFPP) in road transportation casks that contain the used-fuel bundles held in storage modules or in storage baskets. Two UFPP process lines will be provided to unload modules from their casks in receipt cells and a third line will allow storage baskets to be processed. In the fuel handling cells, the used-fuel bundles will be transferred from the storage modules or storage baskets to carbon steel fuel baskets with a capacity of 108 bundles. Three of these baskets, which are described in Figure 2, will be loaded into the UFC. Each bundle and UFC is monitored and accounted for nuclear material safeguards purposes during all transfer and emplacement operations. The heat generated by the 324 used-fuel bundles in a UFC is approximately 1140 W.

The UFC outer shell will be fabricated from oxygen-free, phosphorous doped (OFP) copper and has a wall thickness of 25 mm. The composition of OFP copper is given in Section 3.1.2. The inner steel shell will be fabricated from carbon steel with a minimum shell thickness of 96 mm. Fuel baskets and complete UFC assemblies are assumed to be fabricated off-site and shipped to the DGR facility when required. The loaded UFC inner vessel will be fitted with a bolted lid, the air evacuated and replaced with inert gas, then sealed. Subsequently, the lid will be placed on the copper outer shell and electron-beam welded to the body. The electron-beam weld will constitute the permanent containment seal of the UFC. The main parameters of the UFC are shown in Table 2. The derived packaging rate will be approximately 370 UFCs per annum.

Following non-destructive testing of the UFC electron-beam seal weld using two independent techniques, the outer surface of each UFC will be monitored for contamination and decontaminated if required. Then, the UFC will be encased in a bentonite jacket and the entire assembly will be placed into a rail mounted, shielded UFC cask, as shown in Figure 3. Each loaded UFC cask will be transferred underground using a dedicated shaft (the waste shaft). This shaft will also be used to transfer pre-compacted blocks of sealing materials underground on route to the emplacement rooms. The loaded wagon will be removed from the shaft at the emplacement room level to allow an empty rail mounted cask to be returned to the surface. Underground the loaded wagons will be driven by locomotive to either a surge-storage area or directly to an emplacement room.

Emplacement rooms will be single-level, room-and-pillar type excavations designed for in-room emplacement of individual UFCs. The layout of the emplacement rooms together with their access tunnels will be essentially square with a plan area of approximately 2 km^2 as shown in Figure 4. The layout will consist of 104 emplacement rooms arranged within 4 sections, each containing two panels, each comprising 13 rooms, serviced by approximately 14 km of access tunnels. Each emplacement room will have an elliptical shaped cross-section, nominally 4.2 m high and 7.14 m wide, and a length of 315 m. Each room will contain 108 containers, placed horizontally, two abreast at 2.52 m centre-to-centre spacing and at a longitudinal centre-to-centre spacing of 5.13 m. The main parameters of the underground layout are described in Table 3.

The UFCs will be located within a mass of pre-compacted buffer and dense backfill blocks and associated sealing materials and structures (Figure 1). The centre-to-centre spacing between emplacement rooms is 45 m. The layout presented represents the minimum area that the DGR could be contained within, while satisfying the design parameters, and assumes that it will be located within a uniform sparsely fractured plutonic rock mass in the Canadian Shield. The actual configuration of the repository will be a function of the characteristics of the rock mass, and particularly, the presence of any structural discontinuities or other geological features that would require the relative location and geometry of the panels and access tunnels to be adjusted.

The layout of the DGR emplacement rooms limits the temperature at the surface of the UFCs to a maximum value of 97^0C, which will be reached at 16 years after emplacement. The maximum UFC surface temperatures are less than the design limit requirement of 100^0C throughout the life of the repository.

The emplacement rooms will be excavated by the drill and blast method. A low-heat, high performance concrete floor structure will be laid and rails installed for rail-mounted equipment. Ventilation and utilities will also be installed. The concrete floor will provide a uniform base for the accurate placement of pre-compacted blocks of dense backfill and buffer sealing materials that will form the UFC emplacement structure. The rails will provide a horizontal datum for alignment of the UFC cask with the emplacement room mobile shielding gamma gate. This shielded ‘port’ will provide access to the unshielded UFC emplacement equipment, comprising a central transfer/traversing table and two UFC insertion carts. Connection of the UFC cask to the gamma gate will allow a UFC to be passed through to the transfer/traversing table. From this location the UFC will be traversed to one of the two insertion carts designed to place the UFC in its final location. The insertion carts will be guided using slots located in the concrete floor to ensure accurate placement of the UFCs.

Before a UFC cask is received in an emplacement room, notionally 42 specially shaped precompacted blocks of dense backfill and 54 precompacted blocks of buffer will be placed along a 5.13 m long section of the room. The shape and arrangement of blocks provide two horizontal, octagonal key shaped slots, each capable of receiving a UFC and bentonite jacket assembly, followed by two shielding/sealing plugs of buffer material. The gap between the dense backfill blocks and the walls and roof of the room will be filled with a pneumatically placed light backfill, prior to placement of the UFCs.

With the blockwork emplacement structure in place, a UFC cask will be positioned in front of the emplacement area shield wall to allow the jacketed UFC to be withdrawn from the cask and onto a horizontal transfer/traversing table behind the shield wall. With the empty UFC cask removed from the emplacement room a loaded shielding/sealing plug cask will be positioned at the shield wall. Two shielding/sealing plugs will then be transferred from the cask and positioned behind the jacketed UFC on the transfer/traversing table. This table will allow the jacketed UFC and shielding/sealing plugs to be traversed across the room to the centreline of the emplacement location and onto an insertion cart. With the jacketed UFC and shielding/sealing plugs in place on the insertion cart the cart will be moved forward into the emplacement location within the emplacement structure. This procedure will be repeated for a second UFC that will be located in the other key shaped slot (emplacement location) within that emplacement room. With both jacketed UFC assemblies in position in the blockwork structure the insertion carts will be lowered simultaneously. The insertion carts will then be withdrawn and the remaining slot beneath the two jacketed UFCs will then be filled with pre-compacted dense backfill and buffer blocks, utilising lifting attachments mounted on the front of the insertion carts. Any void between the UFC jacket and the buffer mass to be filled using dry granular bentonite and rounded sand mixture. This material will be installed pneumatically through a hollow lance inserted into the top gap formed between the buffer plugs and pre-placed blocks. The temporary equipment, such as rails, ventilation ducting and mechanical and electrical services will be removed from the area to be utilised for placement of the next two UFCs.

The container emplacement operational sequence consists of: room preparation, placement of pre-compacted blocks, pneumatic injection of light-backfill, UFC emplacement and filling of the gap between the bentonite and buffer material with pellets made of a sand/bentonite mixture. Two containers are emplaced simultaneously, in symmetrical positions with respect to the vertical axial plane of the emplacement room. This sequence is repeated until the room is full, following which the room is sealed by a concrete bulkhead. Normally, four repository rooms will be worked on in parallel on a two-shift per day, five-day per week basis. The emplacement operations sequence is described in more detail in Appendix A.

As used fuel emplacement is carried out in one section, excavation of further emplacement rooms will be undertaken in the adjacent section on the opposite side of the DGR central access tunnels. In addition, sealing material blending and mixing and block compaction will be simultaneously performed in the buffer and dense backfill preparation and block compaction plant located on the surface adjacent to the waste shaft complex. All transportation will be provided by rail-mounted equipment and will utilise the waste shaft for transfers underground.

After each room has been filled, and the bulkhead sealed, it will be necessary to demonstrate that the engineered barriers are performing satisfactorily. This will be the primary function of a preclosure monitoring programme aimed at confirming repository performance. The specific criteria and requirements for monitoring will be developed as the detailed repository design becomes established, when the site-specific conditions are known and when the requirements from safety/performance assessments for the repository have been defined. The methods and instrumentation systems to be used will depend on key issues such as the timescale over which the monitoring will be required and the frequency and nature of the required measurements. Similarly, the sensitivities required of the instrumentation will depend on the criteria to be established by the operator and the regulators of the repository.

The requirements and possible approaches to repository performance monitoring will be discussed in further detail in a separate report.

2 Description of the DGR Design Process

The DGR design process that has lead to the facility description provided in this report has involved the application of design parameters and specifications set by previous development work by OPGI [5]. Using these parameters and specifications, which are summarised in Section 2.1 together with information from existing repository design experience drawn from the international sphere, a preliminary DGR design was produced and analysed. This procedure, described in Section 2.2 was an iterative process, resulting in the design presented being justified where possible by the adoption of current engineering practice as well as theoretical assessment.

2.1 DGR DESIGN PARAMETERS AND SPECIFICATIONS

The repository has been designed for in-room emplacement of CANDU used fuel bundles packaged within copper and steel containers as this configuration is considered to provide more flexibility for siting purposes compared with an in-floor configuration. The repository has been provided with shaft access and it has been assumed that the repository will be excavated in plutonic rock of the Canadian Shield at a depth of 1000 m.

Different excavation techniques have been considered, that include the drill and blast method and the use of tunnel boring machines. These have been assessed based on criteria including, cost, design flexibility, proven capability and the effect on long term performance with respect to blast damage.

An example of the in-room emplacement method is described in [4] but alternative methods of placement in a horizontal attitude have been considered. The emplacement system includes the placement of the required quantities and configuration of clay-based sealing materials as outlined in Section 2.1.5.

A concept for retrieving the UFCs from emplacement rooms that have been filled with clay-based sealing materials, but prior to sealing the access tunnels and shafts has been developed.

The repository design will include a system of monitoring the performance of the engineered barriers during the preclosure phase; that system will be described in a separate report.

A target rate of 120,000 fuel bundles/year has been used as the basis for the design of the facility leading to an assumed 30 year operational life.

Further details of the specifications are presented in the following subsections, with discussion of their derivations covered throughout the balance of the report.

2.1.1 Used-Fuel Characteristics

The reference CANDU fuel bundle designed for the Bruce Nuclear Generating Station has been used as a basis for the design of the UFC. This fuel bundle consists of 37 fuel elements and is approximately 495 mm long and 102 mm in overall diameter, as shown in Figure 5. Its total mass is 23.7 kg and it contains 19.25 kg of elemental uranium (kgU) when initially loaded into the reactor [6].

For the purposes of the DGR thermal analyses and the calculation of radionuclide inventories, the reference fuel has been assumed to have the following characteristics:

Burn-up	220 MWh/kgU
Bundle Power	455 kW/bundle
Cooling period	30 years

These are conservative values for used fuel from OPG reactors that represent approximately 90% of the total Canadian used fuel inventory. A more restrictive fuel burn-up of 280 MWh/kgU has been assumed for the purposes of radiation shielding calculations. This value takes into account the range of fuel burn-ups that may be encountered by the DGR facility. However, approximately 90 to 95% of used fuel bundles would have a burn-up less than this value. Fuel bundles for other CANDU nuclear generating stations will be similar in composition and geometry to the reference fuel and will be amenable to the same packaging and emplacement methods.

The 30 year cooling period is the time that all used fuel will have been discharged from reactors prior to being received at the DGR. It should be noted that the previous AECL disposal concepts [2, 4] were based on a 10 year out-of-reactor cooling period.

The properties of the reference CANDU used fuel used in the development of the DGR concept design presented in this report have been taken from Tait et al [6]. This report defines the physical characteristics for the reference fuel as well as its thermal and radioactive properties for differing values of fuel burn-up, power and out-of-reactor cooling periods. From information drawn from this reference, Table 4 has been compiled listing the UFC heat output as a function of the contained fuel bundles out-of reactor time.

2.1.2 Used-Fuel Quantities and Fuel Emplacement Rate

The total projected inventories of used CANDU nuclear fuel and fuel waste from Canadian power reactors and research facilities is equivalent to 3,557,451 standard CANDU fuel bundles [7]. Using this figure as a reference, the capacity of the DGR has been conservatively set at 3,600,000 bundles.

The capacity of the used-fuel transport system employed to deliver used fuel from nuclear generating stations to the DGR has been taken as 120,000 used fuel bundles per year [5]. This will translate into an average delivery rate to the DGR of 629 transportation casks per year, requiring 370 UFCs to be filled and placed in the DGR each year.

The DGR used fuel receipt and packaging plant presented in this conceptual design adopts a multiple process line approach. This plant and its process lines will accommodate both the average target delivery/emplacement rate of used fuel bundles, as well as potential peak delivery rates of used fuel within either modules or dry storage baskets, as suggested in the revised inventory shipping schedule shown in [7]. The potential peak delivery rates from this reference require the capability of processing 5.5 used fuel modules or 2.2 irradiated fuel dry storage baskets per day.

2.1.3 Used-Fuel Container (UFC)

The UFC will consist of a double shell vessel with a cylindrical geometry that will contain fuel baskets whose primary function is to maintain the geometry of the fuel array independently of the container position or orientation. The inner steel vessel will provide structural support, while the outer shell constructed of oxygen-free, phosphorus-doped (OFP) high purity copper will provide corrosion protection.

The UFC will accommodate fuel packaged in a cylindrical geometry array with a cross section of 54 fuel bundles of the sizes used in current CANDU reactors. The configuration of a fuel basket designed to maintain this fuel geometry inside the container will be based on a hexagonal bundle array of 61 bundle positions, with the six vertices excluded and the centre position left unoccupied. The container will accommodate six layers of fuel bundles for a total capacity of 324 fuel bundles.

A corrosion shell thickness of 25 mm has been adopted for the UFC assessed by this project. The external surface temperature of the copper outer shell of a UFC emplaced in the DGR shall not exceed 100°C at any time [5]. The design dose rate limit at the outer surface of the UFC is not to exceed 15 Gy/h [5].

The UFC inner vessel has been designed to withstand, under normal conditions, a maximum isostatic design pressure of 15 MPa. This includes a maximum buffer swelling pressure of 5 MPa plus a hydrostatic pressure of 10 MPa, equivalent to the water head at a depth of 1000 m. A maximum design temperature of 120^{o}C has been assumed for structural analysis of the inner load-bearing component.

The UFC has been assessed to withstand a maximum external hydrostatic pressure, due to glaciation, of 45 MPa at a temperature of 50^{o}C without exceeding the yield strength of the inner vessel material.

The averaged properties of a UFC assumed for heat transfer analysis are shown in Table 5, and the UFC heat output is shown in Table 4.

2.1.4 Radiation Protection Requirements

The requirements for radiation protection within the DGR facility have been based on CNSC Radiation Protection Regulations. These regulations specify that the maximum occupational whole body dose equivalent to a radiation worker shall not exceed 20 mSv/a, or 1 mSv/a to a member of the public. However, as larger doses tend to occur from non-routine operations (i.e. major maintenance, upgrades, accidents and decommissioning), the DGR radiation protection systems have been designed for much lower exposure levels for normal operations, in order to account for process upset or accident conditions. Therefore, the design of the DGR facility has been based on not exceeding a routine dose of 2 mSv/a to an individual worker during normal operations. This limit corresponds to an individual worker being exposed to an average dose rate of 1 μSv/h for 2000 hours i.e. nominally one year based on 50 weeks at 40 hours per week (a conservative limit as the DGR operations are based on a 46 week year).

Using this criteria all DGR facilities that require radiation protection have been designed so that the surface dose rate at their operational face is less than 1 μSv/h. This is conservative, since not all operations require 100% occupancy at the operational face.

2.1.5 Emplacement Room Sealing Materials and Components

Two groups of materials have been identified as having the necessary characteristics to meet the requirements for sealing for the in-room emplacement design; clay-based materials, and high-performance cements and concretes.

The use of high performance cements and concrete will be extended to the interior of the emplacement rooms. Low-heat, high performance concrete will be used for the construction of a uniform platform on the floor of the room supporting rails and equipment and for placing and aligning precompacted dense backfill and buffer blocks, as well as the construction of bulkheads at the emplacement-room entrances, in access tunnels and shafts. Although the specified concrete has been deemed suitable for use within the emplacement rooms by Johnson et al [8], the interfaces between the concrete and the rock and between the concrete and clay-based sealing materials, and the concrete itself, as it degrades over long time scales, could provide a potential groundwater flow path. Therefore, the emplacement room design incorporates the minimum quantity of concrete to provide a flat floor for the introduction of emplacement equipment. In addition, cross-sectional segments of the concrete floor within the emplacement rooms will be removed at certain intervals and replaced with clay-based sealing materials to interrupt potential flow paths along the concrete and concrete interfaces.

Four clay-based sealing materials are specified for the in-room emplacement design; a bentonite jacket around the UFC, buffer and dense backfill materials that form the emplacement room emplacement structure and a light backfill material used to fill the space between the emplacement structure and the emplacement room walls and roof. The specifications for the clay-based materials are presented in Section 3.3.2 and a minimum thickness of 0.5 m is required for the bentonite/buffer material and a further 0.5 m for the dense backfill material.

In addition to these groups of sealing materials, a thin layer of a dry granular bentonite and rounded sand mixture will be placed in the gap between the buffer and the jacketed UFC, to provide for conductive heat transfer and to maintain the density of the clay-based sealing system.

In addition to providing part of the emplacement room sealing system, the bentonite jacket around the UFC will provide a protective barrier for the UFC against mechanical damage to its outer surface during its transfer from the surface facilities and during the final emplacement.

Concrete bulkheads will be positioned at the entrance to each emplacement room immediately after the emplacement of the final UFC. Bulkheads will also be constructed at strategic locations in access tunnels and shafts as they are sealed during the decommissioning stage. One purpose of bulkheads will be to provide a means of closing emplacement rooms to protect the integrity of the sealing materials. Without a bulkhead as an extrusion restraint, any volumetric expansion of the bentonite clay in the jacket/buffer would reduce the dry density of the clay and may reduce its effectiveness as a sealing material. Bulkheads will also provide an opportunity for applying nuclear materials safeguards seal that will allow detection of human intrusion into a filled room.

2.1.6 Ambient In Situ Stress State

To evaluate the excavation phase of the DGR, assumed to be at a nominal depth of 1000 m within a suitable plutonic rock body within the Canadian Shield, the same ambient principal in situ stresses have been assumed as used by Baumgartner et al. (1996) [2]. These stresses were based on measurements from the Underground Research Laboratory (URL) at Whiteshell, assuming linearly increasing gradients as a function of depth.

Based on that data, at 1000 m depth, the rock stresses along the primary-horizontal, secondary-horizontal and vertical axes are:

$\sigma_1 = \sigma_{H\text{ far-field}} = 65$ MPa $\quad \sigma_2 = \sigma_{h\text{ far-field}} = 49.4$ MPa and $\sigma_3 = \sigma_{V\text{ far-field}} = 26$ MPa

Further information at various depths, is given in Annex 5.

2.1.7 Rock Mass Material Properties and Design Limits

In order to incorporate appropriate characteristics for the rock mass and basic rock material, rock mass material properties and derived strength limits were established using URL experience [2] and summarised in Table 1 of Annex 5.

For modelling appropriate rock mass strength envelopes, the Hoek-Brown failure criterion (Hoek & Brown, 1988) has been used with the following parameters:

a) Under Excavation Loading Conditions

Peak strength design limit, $m = 16.6$, $s = 1$ and $\sigma_{ex} = 100$ MPa.

b) Under Thermally-induced Loading Conditions

Peak strength design limit, $m = 25$, $s = 1$ and $\sigma_{ti} = 150$ MPa*,* if and only if, the peak strength under excavation load is not exceeded.

These Hoek-Brown limit values have respectively been defined for Annex 5 case (a) based on URL experience and for Annex 5 case (b) on Baumgartner et al. (1996) [2] thermal loading calculations for the equivalent "long-term" strength of the Lac du Bonnet granite.

For assessing the possible extent of damage around the rooms both the Hoek-Brown criterion and the deviatoric stress approach have been used. The latter being utilised to provide an additional check for estimating the extent and likelihood of possible breakout formation and also for estimating the probable extent for maximum potential breakout depth.

The criteria adopted for assessing these aspects of behaviour of the rock mass during the initial excavation phase (prior to thermal loading) are as follows:

$(\sigma_1 - \sigma_3) = 100$ MPa possible breakout formation likely initiated in that zone. (1a)

$(\sigma_1 - \sigma_3) = 75$ MPa contour defining the depth/extent of maximum breakout. (1b)

2.1.8 Emplacement Room and UFC Spacing Considerations

The following requirements were addressed when considering longitudinal and lateral spacing of UFCs within an emplacement room, and the lateral spacing of adjacent emplacement rooms:

To minimise stress concentrations at the surfaces of the emplacement rooms, the rooms will have an elliptical cross section with the major access in the horizontal plane and an aspect ratio of approximately 1.7.

The maximum extraction ratio (ER), determined in a direction perpendicular to the axis of the rooms at the repository mid-plane has been limited to 0.25 [5]. ER is defined as follows:

$$ER = W/(W+P) \qquad (2)$$

Where ER = extraction ratio

W = width of the emplacement room (m), and

P = width of the pillars between emplacement rooms (m).

The sealing materials surrounding the UFC, i.e. the bentonite/buffer and dense backfill will each have a minimum thickness of 0.5 m and will form a near symmetric structure around the UFC. In addition, the quantity of low-heat, high performance concrete used to construct the emplacement room floor platform has been kept to a minimum (see Section 2.1.5).

The emplacement room cross-section has been sized to provide the required clearances for excavation, placement of sealing materials and UFC emplacement. The cross-section has also been minimised, after taking into account the aforementioned parameters, to assist maintaining the outer surface of the UFC below the specified temperature limit of 100°C.

2.2 DESIGN PROCESS

Previous work has been carried out to develop stable emplacement room shapes and emplacement arrangements that meet the thermal and mechanical specifications at depths between 500 m and 1000 m [2]. Results from this work have been taken into account in establishing the parameters and specifications in Section 2.1 and were used as the starting point for developing the DGR concept design presented in this report.

The remainder of this section describes the design approach that was used to ensure that the various interacting design requirements were satisfied, with a minimum amount of iteration.

2.2.1 Establishment of Basic Design Configuration

The initial phase of the DGR design update was aimed at establishing an outline design for the underground works to enable a preliminary analysis to be undertaken to ensure that the UFC thermal constraints were not exceeded.

To satisfy this objective an outline design of the UFC was established to accommodate the specified number of fuel bundles in the configuration required. The resulting UFC design, based on information generated by Maak and Simmons [9], was then assessed to ensure that it met the necessary shielding and material compatibility design parameters.

The increased size and weight of the UFC from earlier designs, added to the complexity of its placement within the DGR emplacement rooms. It was therefore necessary to assess different methods of placement to ensure the UFC could be located safely, accurately and without damage to its outer surface during transfer and placement. The outcome of the assessment resulted in the incorporation of a bentonite jacket around the entire UFC to protect it from mechanical damage. To ensure the condition of the UFC and its bentonite jacket could be assured, it was proposed that the latter was fitted following the filled UFCs quality checks in the used fuel packaging plant and prior to its transfer to the underground emplacement rooms.

The development of a suitable method for emplacing a jacketed UFC within the DGR, while taking into consideration the specified underground design parameters, allowed a DGR emplacement room arrangement to be established. As part of this exercise and as a starting point, the initial gap between the surfaces of two adjacent horizontal UFCs within the emplacement rooms, was set to the same value as used in the previous in-room design [4].

Using this emplacement room arrangement, and applying the specification for the minimum allowable pillar width between adjacent emplacement rooms as described in Section 2.1.8, allowed an initial DGR underground layout to be developed. This layout was then subjected to thermal analysis to establish if it was likely to result in acceptable temperatures at the UFC surface. This initial DGR layout set adjacent emplacement rooms as close together as the constraints allowed which was considered to be the most pessimistic arrangement from a thermal viewpoint.

Once the method of handling and emplacing UFCs was agreed, an outline UFC cask design was established in order to determine the overall weight of a cask to accommodate the UFC within a bentonite jacket. Shielding calculations were carried out on the cask arrangement to determine the minimum thickness of radiological shielding material required to ensure that the cask's external surface radiation did not exceed design limits. The resulting outline cask design was then used as a basis to undertake an assessment of the possible methods for transferring the cask from the surface facilities to the underground DGR.

2.2.2 Design Development

Based on the initial underground layout, a 2D thermal analysis was conducted to establish the approximate temperature that may exist at the surface of UFCs over the long time periods being considered. The results from this analysis, based on closely arranged emplacement rooms, indicated that the UFCs surface temperatures exceeded the specified 100^0C limit.

Based on this information a number of the parameters were adjusted, and a number of further analyses undertaken. Those parameters adjusted included the centre-to-centre horizontal distance between two UFCs across the emplacement room, the centre-to-centre distance between emplacement rooms in the DGR layout and the longitudinal spacing of the UFCs within the emplacement rooms. Increasing the centre-to-centre distance between UFCs across the emplacement room did not provide any substantial reduction in peak UFC surface temperatures. However, increasing the spacing between adjacent emplacement rooms did result in a significant reduction. Using these findings allowed a revised DGR underground layout to be generated that was used as a basis for further thermo-mechanical analyses.

Methods of constructing the underground openings were reviewed, particularly the use of the drill and blast method and also the use of tunnel boring machines (Annex 4). It was concluded that the drill and blast method would be assumed as the basis for the construction of all the DGR underground openings. In parallel with this the underground ventilation system together with the order of initial and ongoing emplacement room construction was considered. This element of the work led to the conclusion that a single upcast ventilation shaft would be able to accommodate the necessary airflow, and that a segregated ventilation system between underground construction and emplacement operations could be accommodated.

Having established the outline cross-section of the emplacement rooms, a number of different methods of placing the clay-based sealing materials and emplacing the UFCs were considered. These included:

- Changing the orientation of the UFC so that their axes lay across the emplacement room rather than along it
- Placing only the lower clay-based sealing materials manually then placing the UFCs by

overhead devices and remotely placing the remaining clay-based sealing materials

- Placing the majority of the clay-based materials manually, leaving an upper slot to lower the UFCs into position using an overhead cantilevered lifting arrangement, and then remotely placing the remaining clay-based sealing materials
- Placing the majority of the clay-based materials manually, leaving lower slots to transport the UFCs into position using carts, and then semi-remotely placing the remaining clay-based sealing materials

It was concluded that there were significant benefits in placing as much of the clay-based sealing material as possible while personnel access was available, since it would be difficult to achieve the correct alignment and adjustment of the component parts by remote means. This resulted in the selection of the option with the lower slots that allows the weight of the UFC to be supported from the concrete floor, as the most robust solution.

Shielding calculations were carried out for the chosen lower slot option to determine the thickness of buffer material that had to be positioned at the end of each UFC to ensure that operator dose rates were maintained at an appropriate level. The calculations also determined the arrangement of the shield wall that was necessary to allow personnel access for transfer of the UFC from its transport cask into its emplacement location.

The design of the UFC cask was also refined based on the emplacement technique that had been established. This allowed the detail of underground roadways to be determined to allow the transfer of the cask to the emplacement rooms.

Initial layouts were established for the Used Fuel Packaging Plant (UFPP), to enable two cask types loaded with CANDU used fuel to be received and unloaded. The processes to be undertaken were assessed and a facility to allow the transfer of used fuel bundles from either cask type into UFCs was established. Earlier work also dictated that the UFPP was to include the ability to place a bentonite jacket around the UFC before loading it into a cask for transfer underground. Scoping shielding calculations were undertaken on the UFPP structures to ensure that sufficient shielding was provided so that dose rates to personnel were kept within specified limits. Ventilation and zoning of the building were also considered at this stage.

As part of the UFPP design process a throughput study was carried out to determine the number of processing lines that were required to satisfy the specified throughput of 120,000 fuel bundles per year [5]. The same throughput study also addressed the underground working patterns in the DGR, and in particular those to be adopted within the emplacement rooms.

2.2.3 Design Integration

The modified DGR underground layout was used as the basis for a near-field 3D thermo-mechanical analysis to give a more accurate prediction of the temperatures and stresses that may be reached in the vicinity of the emplacement rooms. These calculations were followed by a far-field thermo-mechanical analysis to predict the thermal and stress conditions in the granite rock formation surrounding the DGR. The results from this work are reported in Annex 2 and give confidence that the specified requirements can be achieved.

Having established that the proposed system was satisfactory from both the thermal and rock stress viewpoints the detail design of the UFC was checked. This included analysing the UFC under both internal and external pressure loading cases, and against potential loads imposed during its handling. The UFC was also assessed to ensure its constructability and compatible materials were employed.

With the concept surface facilities and underground layout established, possible options were examined for retrieving UFCs from the emplacement room sealing material structure, prior to sealing the DGR access drifts and shafts. This exercise was carried out with the aim of providing a UFC retrieval scheme that would be feasible to develop further.

A detailed description of the concept DGR design update, emanating from the design specifications and process outlined in the section, is set out in Section 3 of this report.

3. Design Description of the DGR Facility

This chapter describes the design of the DGR facility. It begins with a detailed description of the UFC and the engineered barriers surrounding the UFC. This is followed by a description of the repository layout and the factors that influenced the repository design followed by a description of the fuel emplacement rooms. Finally the design of surface facilities, including the used fuel packaging plant (UFPP) and Sealing Materials Compaction Plant along with other surface support facilities is described.

3.1 USED FUEL CONTAINER

The UFC is a key component of the DGR system since it provides primary containment for the used fuel during the DGR operating period and into the postclosure phase for a period expected to exceed one million years. The container design and material properties are described in this Section.

3.1.1 UFC Design

The UFC developed for the current DGR design concept is a high-integrity vessel designed to provide long-term containment for the used fuel and is based on the information developed by Maak and Simmons in [9]. The container has two major components: a 25 mm thick outer shell made of OFP copper that provides a corrosion barrier and a 96 mm thick inner shell made of carbon steel, which is the load-bearing component of the assembly, based on the work carried out by Poon et al [10]. The copper shell material is described in detail in Section 3.1.2.1. and is based on the work by Maak [11]. The 25 mm thickness proposed in the study specifications ensures corrosion protection under repository conditions for a period of time in excess of 1,000,000 years as reported by King et al [12]. Stress analyses were carried out to show that the copper outer shell of the UFC is also capable of sustaining the stresses it will be subjected during manufacture, loading, and sealing of the container, as well as the stresses it will be subjected to during emplacement and through its extended life in the repository. The steel inner vessel is designed to sustain the stresses from cumulative loads resulting from buffer swelling pressures and hydrostatic pressures in the repository, including the increased loads expected during glacial periods.

The third component of the UFC is a set of three baskets, made of carbon steel, designed to hold the fuel in a specific geometry inside the container. The baskets are essentially an assembly of 54 tubes, which each hold, two fuel bundles, yielding a basket capacity of 108 bundles. The tubes are assembled in a hexagonal array chosen to minimise the void space inside the UFC.

The assembled UFC is provided with a bentonite jacket to protect it from mechanical damage during transfer to the emplacement room and during final emplacement. The jacketed UFC assembly is shown in Figure 6 and the main parameters listed in Table 2.

Further details on the UFC design, including metallurgical considerations and the stress and thermal analyses are given in Annexes 1 and 2**.**

3.1.2 UFC Material Properties

The material properties of the copper and carbon steel components that make up the UFC are described in this section and are summarised in Table 6; the values given in that table are taken from Bond et al [13].

3.1.2.1 Copper Properties

The selected material for the outer corrosion barrier of the UFC is the reference material developed by the Swedish programme by Werme [14]. It is a high purity, oxygen-free copper with a low phosphorus content of 40 to 60 ppm, specifically chosen to give the copper matrix the required ductility to meet the DGR performance demands. This is termed OFP copper.

Post yield properties for the copper have been modelled using a stress-strain curve defined from the true stress/ strain data shown in Table 3b of Annex 2. Once the final plasticity data point on the stress strain curve is reached, subsequent loading assumes perfectly plastic behaviour. The visco-plastic nature of copper on the long time-scales being considered means that the stresses in the container are over estimated.

The creep behaviour of the copper container has been assessed using the following empirical creep function for copper established by Borgesson [15]:

$$\dot{\varepsilon} = 1.58 \cdot 10^{-17} \cdot \sigma_j^{3.4} \quad \text{for } \sigma_j < 130 \text{ MPa.} \qquad (3)$$

Where σ_j is the von Mises stress in MPa and

$\dot{\varepsilon}$ is the strain rate (1/s)

3.1.2.2 Carbon Steel Properties

The inner container is constructed from carbon steel to SA516-70, whilst the ends are constructed using steel to SA105. Properties for this grade of steel are shown in Table 6. In comparison to the copper, creep of the steel at the anticipated peak repository temperatures is negligible, and will not be taken into consideration.

3.1.3 UFC Pressure Analysis

One of the key requirements of the UFC container is to withstand the pressure loading applied through a combination of swelling of sealing materials and hydrostatic water pressure. Under normal conditions, the maximum isostatic pressure loading will be 15 MPa (5 MPa due to buffer swelling, and 10 MPa hydrostatic pressure – equivalent to the water head at 1000 m). During periods of glaciation, it is assumed that the container will be subjected to an increase in pressure loading of 30 MPa (i.e. 45 MPa total loading) due to the additional pressure created by a 3000 m thick ice layer. The container design specification requires the stresses in the container to remain within ASME III design limits for Level A loading under normal conditions, and below yield during periods of glaciation.

In order to demonstrate compliance with this design specification, an axisymmetric finite element model of the copper outer and carbon steel inner containers was created. The 1 mm fitting gap between the two components was explicitly modelled, with a contact surface, to allow collapse of the copper corrosion barrier to be accurately taken into account. In common with all of the finite element analyses carried out as a part of this programme, the models were constructed using PATRAN, whilst the analyses themselves were carried out using ABAQUS/Standard (version 6.2) developed by Hibbitt, Karlsson & Sorensen Inc [16].

The maximum (local) von Mises stress in the steel inner component under normal conditions is predicted to be 131 MPa, rising to 226 MPa as the pressure loading is increased from 15 MPa to 45 MPa (Figure 26 of Annex 2). The corresponding Tresca stress is 151 MPa, for a uniform pressure distribution of 15 MPa, rising to 258 MPa for a pressure distribution of 45 MPa. It should be noted that these are peak stresses. For carbon steel SA516-70 / SA105, the minimum specified tensile strength is 485 MPa, and the minimum specified yield strength is 260 MPa. This gives a design stress intensity of 161.7 MPa for Level A loading, in accordance with the criteria of ASME III Article III 2000, and 260 MPa for periods of glaciation (σ_{yield}).

The copper corrosion barrier is designed to collapse onto the steel inner container, and is thereafter supported by it. Following the collapse of the copper container onto the load bearing steel inner container, the maximum (localised) tensile stress in the copper, under normal operating conditions, is 68.4 MPa (Figure 27 of Annex 2). The creep rate at this stress level is typically less than 8×10^{-4} year^{-1}. The application of additional loading due to glaciation results in further collapse of the copper, and a reduced stress of 46.7 MPa. This can be compared with an ultimate tensile strength for the copper of 200 MPa. The maximum plastic strain in the copper outer barrier following its collapse against the steel liner is 6.6%, under normal conditions. This rises to a strain of 9.5% at a pressure loading of 45 MPa following a period of glaciation. This compares with a tensile strain to failure (from conventional tensile testing) of around 29% [13]. Although the strain to failure in creep is generally lower than the tensile strain to failure, the results indicate that pressure deformation effects will dominate. In any case, the support offered by the steel container will mean that although there is a possibility that some creep damage may occur, it would be limited to the inner surface of the copper container. It is therefore concluded that failure of the copper corrosion barrier is unlikely. It is however recommended that a detailed creep analysis of the container is carried out once information is available on the rate of swelling of the backfill materials.

In addition to the external pressure cases, due to formation pressure, the intact container is required to withstand an internal pressure rise that may occur from gas production due to the corrosion of the container internal components, release of fission gas products from the used fuel, helium build-up from alpha decay of radionuclides in the used fuel, and radiolysis of any water remaining in the container on sealing. The analysis has determined the maximum internal pressure that can be retained by an unsupported copper container (i.e. assuming no support from the clay-based sealing materials and ignoring external hydrostatic pressure). Initial yield would occur at the point when the inner pressure reaches 0.6 MPa, with local yielding occurring in the container lid (Figure 29 of Annex 2). Ultimate failure of the copper container would occur at a pressure of approximately 2.3 MPa (Figure 30 of Annex 2), when global yielding of the container lid occurs.

The above analysis is relevant only to a container retrieval scenario a long time after emplacement because, even neglecting buffer swelling pressures, the external hydrostatic pressure would be about 10 MPa. Unless the inner-shell mechanical seal has failed, the interstitial space between the two UFC shells will be at vacuum because electron-beam welding of the copper shell lid is carried out in an evacuated chamber. Therefore, to result in copper shell failure, the retrieval scenario would also need to assume failure of the inner-vessel seal as well as an abnormally high amount of residual water in the container.

The current stress analysis has not examined the effects of non-uniform swelling of sealing materials. Further analyses may be required to assess the effect of non-uniform pressure fields.

3.1.4 UFC Handling Load Analysis

It is required to demonstrate that the proposed design of UFC is sufficiently robust to withstand the anticipated handling loads. In order to achieve this, a three dimensional model of the UFC was developed, incorporating details of the lifting feature. The model was subjected to two loading configurations, deemed to be representative of the worst case scenarios of those likely to be encountered i.e. a two-point lift and vertical lift.

3.1.4.1 Two-Point Lift

It is assumed that the UFC copper shell and it’s steel inner vessel will be manufactured off-site and delivered to the DGR facility pre-assembled in the horizontal attitude. This empty UFC will be handled using slings with appropriate protection to ensure no damage to the copper outer surface.

This condition was replicated in the model by locally restraining the model from downward vertical movement over the lower half of the container, at a distance of 0.5 m from each end. To account for dynamic effects, the analysis considered a maximum vertical acceleration of 5g, this being the maximum credible value for normal operation on rail or road transport [17]. Further conservatism was introduced by assuming a fully loaded container (25 tonne), thus ensuring that the case analysed was bounding for all similar loading conditions.

The analysis predicts a maximum von Mises stress in the copper corrosion barrier of 47 MPa (c.f. yield at 60 MPa), and 21 MPa in the steel inner container (c.f. yield at 260 MPa), Figures 31 and 32 of Annex 2 respectively. The maximum predicted deflection will be 0.16mm. Because the model accurately represents the post yield properties of the copper shell, and the contact between the inner and outer containers, the results predict the actual contact stress distribution, resulting in the two geometrically separate stress peaks shown in the steel shell stress profile, Figure 32 of Annex 2.

3.1.4.2 Vertical Lift

When fully loaded, the UFC with its inventory of three baskets containing spent CANDU fuel, with the inner vessel lid bolted and the copper vessel lid welded to the body, will be lifted using a grapple connected to the UFC lid-lifting feature. The grapple engages with the UFC lid in three locations around the circumference, each “finger” being 150 mm wide.

The half model of the UFC was used with appropriate boundary conditions to emulate this loading configuration. To account for dynamic loading, a load factor of 1.5 was applied, based on typical values used in the design of lifting equipment [18].

The analysis predicts a maximum von Mises stress of 63.3 MPa in the copper, and a corresponding maximum deflection of 0.4 mm, Figures 34 and 35 of Annex 2. ASME III Fig NB-3221-1 places a limit of 1.5 x design allowable stress (60 MPa for this copper) for the sum of primary membrane plus bending stress (but excluding all secondary and peak stresses due to discontinuities). Although this peak stress is marginally above this limit, it is a self-equilibrating stress at the discontinuity and thus this limit does not strictly apply. The main issue with stress concentrations at a discontinuity is their propensity to initiate a fatigue crack. In this case, the anticipated number of loading cycles is only one or two. Fatigue data for oxygen free high purity copper, from Brandes et al [19] indicates a life in excess of 300×10^6 cycles for a stress range of 117 MPa. It is therefore considered that the proposed UFC container lid lifting feature design is satisfactory. Although the proposed grapple design is also adequate, the anticipated stresses in the container lid could be reduced following changes to the grapple design during the detailed design stage.

In addition to the normal operation condition considered above, the analysis was extended to determine the maximum load that could be applied to the lid lifting feature before failure of the copper shell would occur. This was achieved by determining the load required to develop a plastic strain of 29%, the failure strain for the copper. The maximum load that can safely be applied to the container lifting feature is 75 tonnes, at which point the whole of the container wall has begun to yield, Figure 36 of Annex 2. Changes in the design of the grapple will not result in an increase in the maximum load that can be applied to the container lid.

3.1.5 Fabrication, Sealing and Inspection

It is assumed that the UFC copper shell, base and lid will be fabricated off-site, with the shell and base being welded as an assembly following fabrication. To ensure a good match and intimate contact between the lid and shell, each lid will be matched to a specific pre-fabricated shell/base assembly. Matched lids and shells will be identified with matching serial numbers.

In the Swedish programme electron-beam welding is a well-established technique and, currently the reference method for seal-welding the copper lid, Rajainmaki et al [20]. However, friction stir welding has recently been investigated as an alternative sealing method and further development work is in progress, Andersson [21] and SKB [22]. Since it is a more established technology, electron-beam welding has been chosen as the reference method for sealing the copper vessel for the purpose of this study.

The UFC inner steel vessel will also be manufactured off-site. To prevent any distortion of the copper shell/base assembly during transport or storage, it is assumed that the steel vessel will be inserted into the shell assembly soon after its fabrication. Following suitable packaging the complete UFC assembly together with matched steel and copper lids will be shipped to the DGR facility.

Baskets will be constructed from an array of carbon steel tubes welded together with additional support provided by three restraining rings and a base plate. The length (height) of each basket will accommodate two layers of fuel bundles, as shown in Figure 2. The baskets will be manufactured off-site; be suitably packaged and shipped to the DGR facility.

At the DGR facility, 108 fuel bundles will be loaded into each basket, with a total of three loaded baskets being installed into the UFC assembly, as shown in Figure 7. With the used fuel loaded, the UFC inner vessel carbon steel lid will be bolted in position and connections made to evacuate the inner vessel prior to backfilling with an inert gas. Following this procedure, the inner vessel connections will be sealed and all the seals checked for integrity by monitoring for leakage.

The copper shell lid will be placed on the copper shell, welded and the weld inspected using radiography and ultrasonic techniques. The feasibility of using an ultrasonic array technique for the inspection of container welds has been demonstrated by Stepinski et al [23].

The main parameters of the UFC and its components are presented in Table 2.

3.1.6 Summary

A copper-shelled UFC design for in-room emplacement within a DGR has been developed. The design uses an inner steel vessel to resist the external pressures that occur at a repository depth of up to 1000 m. The suitability and compatibility of materials have been assessed, and the ability to manufacture the proposed UFC design has also been examined, leading to the conclusion that the design presented offers a viable solution which meets the specified requirements. For further details see Annex 1.

The UFC design has been shown to be able to satisfactorily withstand the design loading following saturation of the repository, as well as any build-up of pressure within the container. Under normal conditions, the UFC stresses remain below the ASME III service level A design stress limit for the material, whilst during a period of severe glaciation, the stresses in the steel container remain below the materials specified yield stress. Further work will be required to confirm the suitability of the UFC design when subjected to non-uniform loading.

It has been shown that the UFC can withstand all credible normal handling loads. Stresses remain within acceptable limits during lifting operations using the UFC lid lifting feature, although the actual stress level will be dependent on the detailed design of the grapple used. The feature can be used to apply a maximum pull of 75 tonnes (three times the weight of a loaded UFC), in the event of needing to retrieve a UFC at a later date. Based on IAEA acceleration profiles for road and rail transport, the UFC design will not sustain damage during transportation in a fully loaded condition. The UFC analyses conducted within the scope of this study included only loads and conditions derived from normal operations of the repository. Analyses to assess container responses to abnormal operating conditions or specific accident scenarios will be required at a later stage.

3.2 DESIGN OF UNDERGROUND LAYOUT

The underground area of the DGR will consist of the emplacement area and underground access ways and infrastructure required to safely conduct the emplacement operations. Essential components of the DGR will comprise; emplacement rooms, shafts for vertical access to the repository level, and tunnels that provide access to the emplacement rooms. The dimensions and shapes of all the repository tunnels and shafts are given in Table 7. In addition, ancillary underground facilities are required to remove excavated rock, store and distribute the sealing materials, transport personnel, materials and equipment, and provide maintenance.

3.2.1 General Requirements

The following requirements and factors were considered in determining the DGR layout for this study:

- Providing a DGR extraction ratio less than 0.25
- Spacing the UFCs to limit the maximum temperature of the UFC outer surface, or the peak buffer temperature, to 100^{0}C
- Providing four shafts for operations
- Providing for flexibility of operations
- Separating radioactive and non-radioactive working environments
- Providing separate ventilation circuits to both the excavation and emplacement operating areas
- Ensuring reasonable traffic flow patterns
- Ensuring that excavation and emplacement operations retreat from the upcast-shaft complex to the service-shaft complex as emplacement rooms are filled
- Providing underground ancillary support facilities outside the emplacement area
- Establishing the shaft complexes at least 100 m away from the emplacement area to reduce the temperature increase around the shafts
- Ventilation flows within the underground facilities will direct the exhaust ventilation air towards the Upcast Shaft Complex, where it is discharged to surface under controlled and monitored conditions, and
- Applying a nuclear-material safeguards method for used fuel emplacement although no requirements have yet been established by the International Atomic Energy Agency (IAEA).

3.2.2 Design Overview

The DGR arrangement for the in-room emplacement of used nuclear fuel will be a system of access tunnels and emplacement rooms arranged into four distinct sections (Figure 4) that have been designated sections A, B, C and D. The overall dimensions of the UFC emplacement area are approximately 1.4 km by 1.4 km. These dimensions are based on an ideal site and do not account for any adaptations that may be required at an actual site because of local geological or geotechnical conditions (e.g. specific rock structures, faults and stress anomalies).

The in-room emplacement DGR design will use central access and perimeter tunnels that join at the opposite end of the DGR where an exhaust shaft will be located. With the central access tunnels twinned, four independent sections of the DGR layout will be created, with each section containing two emplacement panels. A section will consist of 26 emplacement rooms contained between two adjacent tunnels (Figure 4). Each section will be divided into distinct halves to create two panels per section, with each panel containing 13 emplacement rooms. The main parameters of the underground layout are given in Table 3.

Equipment within the DGR is a combination of rubber tyred and rail-mounted equipment. Underground movement of materials and personnel is provided by a rail system that is installed throughout the DGR. The rail system consists of suitable ASCE (American Society of Civil Engineers) rail on steel ties with a gauge of approximately 1.26 m.

The rail system provides:

- Stable and rapid equipment movement and alignment
- Simplified repeated positioning of equipment for emplacement room block placement
- Simplified repeated positioning of equipment for UFC emplacement
- Reduced friction and low effort for movement of equipment
- Bulk handling of materials (i.e. multi-unit trains)
- Reduced materials handling and transfer operations
- Reduced requirement for heavy lift equipment underground.

Emplacement room excavation will be undertaken by mining contractors on a campaign basis. Entry to the emplacement panels will be made via the perimeter or central access tunnels. Excavation, and installation of emplacement-room services, take place in a sequential manner in one half of the DGR, while buffer and/or dense backfill material block placement and UFC emplacement take place in the other half of the DGR (Figures 8 to 11). This separation of activities is essential to smooth DGR operation and worker safety. The system of access tunnels proposed allows UFCs and clay based sealing materials to be delivered for emplacement via one half of the perimeter access tunnels, with empty UFC transporters and rail cars returned along the adjacent central access tunnel. This permits emplacement room excavation traffic to use the other half of the DGR perimeter and central access tunnels, thereby ensuring separation of nuclear and non-nuclear activities. To further separate the nuclear and non-nuclear emplacement activities, one panel tunnel will be used to gain access to one half of the section for placement of UFCs, while the other panel tunnel for the section will be used for block placement activities, as shown in Figure 12.

Physically separating excavation operations from UFC emplacement operations will minimise worker exposure to potentially radioactively contaminated air and/or drainage water, UFC transporters and complex traffic flows.

When campaign mining of emplacement rooms is not in progress, UFCs and associated emplacement personnel may use either of the central/perimeter tunnels depending upon facility logistics, providing all material movements are carried out in a unidirectional clockwise direction.

Ventilation airflows can be readily distributed, controlled and segregated using the tunnel network. Two independent ventilation circuits will be provided; one for the emplacement side and one for the excavation side of the DGR. Ventilation control doors will be used to direct and control the quantity of fresh air required for emplacement and excavation activities. Doors will be equipped with interlock alarms and position monitors to ensure proper flows are maintained.

From the general requirement, for operations to retreat from the upcast ventilation shaft complex to the service shaft complex, a fresh air supply will be directed from the service shaft complex, through the operation areas and completed excavation/emplacement areas, to the upcast ventilation shaft complex. This will reduce the potential for blasting gases, dust or radioactive contamination from entering occupied operating areas. Within a given panel, fresh air will be supplied via the central access tunnel and exhausted through the perimeter access tunnel (Figure 13).

During the development of the Service Shaft Complex all drifts, shops and test component areas will have a positive gradient of approximately 2% radiating out from the main sump located in the Service Shaft Complex (Figure 14). This will prevent accumulation of ground water and water produced during excavation at the development face. In a similar fashion, whilst developing the repository, all perimeter and central access drifts of the DGR will have a positive gradient of approximately 2% towards the Upcast Shaft Complex. This allows water to flow away from the excavation and emplacement panel operations and will be collected in local sumps. Transport of production and ground waters to the main sump will be via sealed pipelines for collection in a main sump located close to the bottom of the Service Shaft within the Service Shaft Complex. The drainage water will then be pumped to the surface settling pond and water-treatment plant where potentially contaminated water can be treated. The drainage-water will then be sent for reuse underground or released into the environment after meeting regulatory requirements.

3.2.3 Design Criteria and Parameters Used for Numerical Analysis

The design specifications and the reasons for their use, are discussed within the following Section.

3.2.3.1 Ambient In Situ Stress and Temperature Conditions

The ambient principal in-situ stresses assumed for the DGR can be defined by the following functions, originally presented in Appendix B of Baumgartner et al [24]. The finite element models have been formulated to accurately consider the in-situ rock stress at all depths.

$$\sigma_1 = 0.1345 MPa / m_{depth} + 18.5 MPa \qquad < 300\text{ m} \qquad (4a)$$

$$\sigma_1 = 0.00866 MPa / m_{depth} + 56.3 MPa \qquad \text{from 300 to 1400 m} \qquad (4b)$$

$$\sigma_1 = 0.0403 MPa / m_{depth} + 12.1 MPa \qquad > 1400\text{ m} \qquad (4c)$$

$$\sigma_2 = 0.1112 MPa / m_{depth} + 9.9 MPa \qquad < 300 \text{ m} \qquad (5a)$$

$$\sigma_2 = 0.00866 MPa / m_{depth} + 40.7 MPa \qquad \text{from 300 to 1660 m} \qquad (5b)$$

$$\sigma_2 = 0.0293 MPa / m_{depth} + 6.4 MPa \qquad > 1660 \text{ m} \qquad (5c)$$

$$\sigma_3 = \sigma_v = 0.0260 MPa / m_{depth} \qquad (6)$$

where σ_v = vertical stress; and σ_1 σ_2, σ_3 are the major, intermediate and minor principal stresses respectively.

The geothermal gradient is assumed to be 0.012°C/m of depth, with the average surface temperature of a site on the Canadian Shield being 5°C, Drury et al [25] and Jessop et al [26]. At the nominal repository depth of 1000 m, this gives an ambient temperature of 17°C.

3.2.3.2 Rock Mass Properties

A volume of sparsely fractured granite was selected as the host medium for the emplacement area of the DGR. The rock mass material properties and the derived strengths of the rock mass used in the design analyses are largely based on measurements taken on Lac du Bonnet granite [4]. The reference concept terms indicate that the DGR is to be assumed to be sited in a sparsely fractured rock mass assumed to be isotropic and homogeneous. In sparsely fractured rock the water flow is assumed to be negligible thus there is no convective heat transfer away from the container. In practice, the existence of water flow pathways at various depths may beneficially influence the actual temperature profile achieved.

Rock mass strength is discussed Section 2.1.7, while the assumed elastic constants and thermal properties for the rock mass are shown in Table 5.

3.2.3.3 Rock Strength Design Limits

Under uniaxial conditions, for the granite rock considered, the onset of stable crack initiation (σ_{ci}) is approximately 70 to 75 MPa. In comparison, the stress for the onset of unconfined unstable crack growth (σ_c) is approximately 150 MPa, and the peak unconfined compressive strength (σ_f) is approximately 210 MPa (i.e. the conventional value from laboratory testing).

For the purposes of the current work the assessment of thermo-mechanical stability is made by calculating a factor of safety based on the Hoek and Brown empirical failure criterion model, Hoek and Brown [27], defined as follows:

$$\sigma_{1f} = \sigma_{3f} + \left(m \cdot \sigma_c \cdot \sigma_{3f} + s \cdot \sigma_c^2\right)^{1/2} \qquad (7)$$

where σ_{1f} = major principal stress at failure
σ_{3f} = minor principal stress at failure
σ_c = uniaxial compressive strength
m, s = empirical strength parameters.

The peak strength and associated empirical strength parameters used in the failure model are σ_c = 100 MPa, m = 16.6, s = 1 following excavation, and σ_c = 150 MPa, m = 25, s = 1 following placement of the backfill materials. Note that these values equate to an intact rock tensile strength of 6 MPa, which is below the average observed value of 10.4 MPa for wet Lac du Bonnet granite at the URL, Martin [28].

In practice the mechanical strength of the rock at the excavated surface of the emplacement room is going to be dependent on the extent of the excavation damage zone. The mining procedures adopted for the excavation of the emplacement rooms will need to minimise the extent of any such damage zone.

A criterion is set for the structural performance of the geosphere near the ground surface. The uplift of the geosphere immediately surrounding the DGR, caused by thermal expansion from heat from the used fuel, may open or extend near-surface, subvertical fractures and, thus, enhance groundwater flow. This near-surface extension zone (also called the perturbed fracture or perturbed fissure zone) is defined as the volume of rock overlying the DGR that could experience loss of horizontal confining stresses. These are horizontal stresses greater than or equal to zero for a “no-tension” analysis, Zienkiewicz et al [29] and potential opening or extension of subvertical fractures. For the purposes of this assessment, the maximum depth of the near-surface extension zone, measured from ground surface, is set at 100 m, as in previous studies [24].

3.2.3.4 Sealing Material Properties and Specifications

The in-room emplacement method focuses on the emplacement of UFCs within the confines of an excavated room (Figure 1). The basic requirements of sealing components for the repository can be summarised as follows:

- Provide a low hydraulic conductivity barrier around the UFC which would limit the access of possible corrosion agents (including microbes) to the UFC surface and which would also provide a barrier to the transport of contaminants that may be released upon eventual failure of the UFC

- Swell sufficiently when water is absorbed from the surrounding rock to seal any opening between the UFC and the host rock. The strength of the swelled material will be sufficient to support the UFC without significant deformation

- Sorb and retain released radionuclides to significantly retard the rate and extent of radionuclide migration.

Two groups of materials were identified, Johnson et al [30] as having the necessary characteristics to meet the requirement for repository sealing for the in-room emplacement design; clay-based materials, and high-performance cements and concretes.

Bentonite clays that predominantly contain montmorillonite, a member of a group of clay minerals termed smectites, have a set of special properties that make them particularly attractive as sealing materials. Montmorillonite is a highly surface-active clay mineral that confers the special properties of swelling, plasticity and very low hydraulic conductivity, and it also provides the ability to sorb and retain cations.

Because of the effect of cement-based materials on local ground water chemistry, the waste form and the other engineered barrier materials, high-performance cements and concretes are considered to offer a potential alternative. Test information on these materials [8] suggest that they possess very low porosity, reduced pH and extremely low hydraulic conductivities. In addition, microcracks generated in these high-performance materials tend to self-seal, Onofrei et al [31].

Although high-performance cements and concretes offer potential advantages for use within the DGR, continued uncertainty on their long-term effects has resulted in a policy to minimise their use within the confines of the emplacement rooms. Applying this policy, minimum quantities high-performance cements and concretes will be used as a functional structure for the construction of smooth platforms on the floor of the emplacement rooms. These platforms will be used for supporting rails and equipment and for placing and aligning pre-compacted dense backfill and buffer blocks. High-performance cements and concretes will also be used for the construction of bulkheads used as a sealing function at emplacement room entrances, in access tunnels and in shafts. Cement-based grouts may be used to control groundwater movement into the excavation and around seals.

In addition to these sealing materials, a dry granular bentonite and rounded sand mixture will be pneumatically delivered into the gap between the bentonite jacket and the pre-placed blocks to provide for conductive heat transfer and to maintain the density of the clay-based sealing system.

The specifications for the basic physical properties of clay-based sealing materials are presented in Table 8. In practice, the thermal conductivity of the bentonite jacket material is dependent on the moisture content of the material, which in turn varies with distance from the surface of the container. Values for thermal conductivity of the jacket material have been derived, as a function of distance from the container, from Ageskog et al [32]. The sealing materials are all assumed to have uniform, linear elastic, isotropic properties.

3.2.4 Results of Underground Design Analysis

The following sections summarise the results of the various thermo-mechanical analyses carried out on the DGR as a part of this programme of work.

3.2.4.1 Near-field Thermo-Mechanical Model

The near-field analysis provides a detailed assessment of the thermal and stress conditions in the material surrounding the emplacement container. The use of a 3D model allows the UFC longitudinal spacing to be accurately taken into account.

The model used for this assessment considered a “unit cell” of the repository. The “cell” consisted of a hexahedral portion of the repository and geosphere, bounded on the upper side by the Earth’s surface and at the bottom by a plane 10,000 m below the repository horizon; on one set of opposing sides by the vertical mid-plane along the longitudinal axis of the emplacement room and by the vertical mid-plane along the longitudinal axis of the inter-room pillar; and on the second set of opposing sides by the vertical mid-plane between the two sets of UFCs and by the vertical mid-plane passing through the UFC. Details of the dimensions assumed for various clay-based sealing material components in the near-field analysis are given in Figure 2 of Annex 2. The longitudinal spacing between UFCs was assumed to be 1.25 m (0.78 m required for shielding purposes), and the room spacing 45 m between room centres. By considering the minimum spacing between UFCs in this way, the assessment will provide a conservative assessment of temperatures and stresses. Following an initial analysis, it was concluded that assuming the copper outer container is in intimate contact with the steel inner container provides a worst case for the predicted copper temperature. It is anticipated that this would, in any case, ultimately be the case, following creep of the copper due to the application of water pressure, and the effects of the swelling of the clay-based sealing materials. The computer model therefore ignored the small gap between the inner and outer container shells.

The heat flux due to the radioactive decay of the fuel was applied to the inner surface of the steel inner container. This assumes perfect heat transfer out of the fuel bundles and within the container, thus presenting a worst case, as far as the UFC temperature history is concerned. A further conservatism is that the model considers a situation where all of the fuel is placed in the DGR instantaneously and that the decay heat from all UFCs is the same. In practice, the fuel will have spent varying lengths of time out of the reactor before emplacement, in some cases much more than 30 years, and emplacement is scheduled to take place over approximately 30 years.

For the thermal portion of the analyses, the top boundary condition (representing ground surface) was modelled as a constant temperature (i.e. isothermal) boundary set at 5°C, to represent the average Canadian Shield surface temperature. After 10,000 years, the surface temperature is assumed to reduce to 0°C, in order to account for a period of glaciation. The bottom boundary condition was also modelled as an isothermal boundary set to the ambient temperature at the bottom of the model, assuming a geothermal vertical gradient of 0.012°C/m [5]. This gradient has been previously used for assessments to depths of 4000 m, this analysis assumes this thermal gradient remains valid to a depth of 11,000 m. All four vertical boundaries were modelled as adiabatic planes of mirror symmetry to reflect the heat generated within the cell (Figure 6 of Annex 2). This mirror symmetry mimics the thermal contribution from all the surrounding "unit" cells, in effect replicating an infinite tabular array of infinitely long parallel emplacement rooms. As such, it is a conservative representation of the conditions likely to be encountered in the middle of the repository. All voids were assumed to be filled with sealing materials and the repository was considered to remain dry during the initial stages. Conduction was therefore considered to be the dominant heat transfer mechanism, and the effects of radiative and convective heat transfer were not considered. In terms of assessing the peak temperature of the copper container, this is a conservative assumption.

For the structural analyses the boundary conditions are as follows. The top boundary will be free to displace vertically, and the perimeter will be rigidly constrained laterally. The bottom boundary will be rigidly fixed against displacement, both vertically and laterally. The four vertical boundaries will be fixed against out-of-plane lateral displacement and will be attached to the top and bottom boundaries to maintain the appropriate continuity (Figure 6 of Annex 2). This also constrains the "unit" cell to displace consistently with the surrounding "unit" cells and to allow the build-up of horizontal stress caused by thermal expansion.

The model has not claimed any potential benefit due to ground support from the swelling of the backfill materials, in view of the uncertainty and time dependence of this effect. Also, the stiffness of the backfill materials has been assumed to be very low (E=0.1 GPa) therefore the reactive ground support effect is minimised. This is considered to result in a conservative assessment.

3.2.4.2 Near-field Thermo-Mechanical Analysis Results

The temperature history plots (Figures 11a of Annex 2) show results at three locations (Figure 8 of Annex 2). The results indicate a rapid increase in the container temperature over the first decade, reaching a peak temperature of 97°C after 16 years for a container located at the centre of the DGR, and given an ambient temperature of 17°C at the repository depth of 1000 m. Thereafter, the temperature falls to around 75°C, until 1000 years after emplacement, when the model predicts a further rise in the UFC temperature to 95°C, 6000 years after emplacement. The rock temperature rises from 17°C, at the time of emplacement to 73°C after 50 years.

The model then predicts a reduction in rock temperature to 68°C, followed by a secondary rise to a temperature of 93°C 6000 years after fuel emplacement.

As a consequence of the thermal diffusivity ($\alpha = k/\rho\ Cp$) of the rock, combined with the rate of change of the waste radioactive decay heat, steady state thermal conditions are not achieved until late in the life of the DGR. Prior to the time at which the temperature begins to rise for the second time, the thermal energy from the used fuel is dissipated by heating up an expanding volume of rock (Figure 11b of Annex 2). Subsequent to this, however, the volume of rock being heated remains constant, because of the increasing ambient rock temperature with depth and steady state conditions being reached for heat flow in the repository to surface direction. Because the heat required to increase the volume of rock affected is greater than the heat lost to the atmosphere, this results in the secondary rise in temperature. Since the near field model does not allow heat to be lost at the sides of the model, it will tend to over estimate the magnitude of this effect.

The stress analysis results are shown as plots of Factor of Safety using the Hoek and Brown failure criterion described previously, for two orientations of the emplacement room, and at two times, immediately following excavation and the time of peak stress. Figures 13a and 13b of Annex 2 show results with the room principal axis perpendicular to the major horizontal in-situ stress component (worst case), whilst Figures 13 c and 13 d of Annex 2 show results when the room principal axis is parallel to the major horizontal in-situ stress component. The stress analysis results are shown for 100 years after waste emplacement, this corresponding to the time of peak stress at the DGR. The time of peak stress corresponds to the time of peak rock temperature (ignoring the secondary peak effect, which as discussed above is over estimated by the current analysis).

For the worst case orientation (major horizontal stress perpendicular to the room principal axis), the factor of safety values are generally well above 2.0 at all times, beyond a perimeter annulus of about 750 mm thick or less, depending on the location around the room perimeter, and approaching 1.0 at the periphery of the room. After excavation, the factor of safety remains in excess of 1.2 in all locations, whereas at the time of peak stress, the factor of safety drops below 1.0 at the crown and floor of the emplacement room over a length of around 1 m either side of the room principal axis, and at the junction between the concrete floor and the room wall. The minimum value is 0.78, located at the crown of the emplacement room. In all cases, the region in which the failure criterion is not satisfied extends to a depth of less than

300 mm. The maximum principal compressive stress is 204 MPa, Figure 14 of Annex 2. Therefore, some localised rock damage is anticipated at the crown and base of the emplacement room. However, because the damage will not initiate until after the sealing material has been placed, and the limited extent of the damage zone, this is not considered to adversely affect the long term safety of the DGR. It will however, need to be considered should waste retrieval ever become necessary.

When the room is oriented more favourably with respect to the rock in-situ stress profile (i.e. with the maximum horizontal stress parallel to the principal axis of the emplacement room), the minimum factor of safety increases to 1.70 after excavation and 0.91 after 100 years, Figures 13c and d of Annex 2 respectively. In this case, only a very small region in the vicinity of the junction between concrete floor and the emplacement room wall exceeds the failure criterion. The minimum principal stress (compression) is 180 MPa, Figure 15 of Annex 2, thus the compressive strength capacity of the granite is not exceeded at any time.

Excavation-induced displacements at the room perimeter are directed inward (i.e., convergence), and are of the order of 6 mm. Thermal loading causes a further convergence of about 4 mm in the walls of the room, and an expansion of about 5 mm in the roof and floor at 100 years.

Although the analysis predicts localised cracking at the crown and base of the emplacement room, in service the rock is constrained by the sealing materials and collapse of the room is not anticipated. Should a UFC need to be retrieved, however, additional precautions should be taken to ensure the safety of mining personnel against the fall of loose material.

High stresses may influence the detailed design of the emplacement room access roadways immediately prior to the bulkhead seals; an area of the DGR design not addressed by the current programme. In the event that these thermally induced stresses affect this area, a number of design solutions could be put in place to ameliorate the situation such as, increasing the spacing between the last emplaced UFCs and the emplacement room bulkhead, and/or increasing the separation between adjacent emplacement room entrances. Both these design alterations would have the effect of reducing the rock temperatures in the emplacement room access roadways thereby reducing the thermally induced stress levels. However, these design changes would increase the area of the repository, potentially resulting in an increase in its construction costs.

3.2.4.3 Far-field Thermo-mechanical Model

The far-field analysis provides an assessment of the thermal and stress conditions in the granite some distance away from the DGR. This assessment will confirm that the DGR depth is adequate to prevent cracking of the surrounding rock formation due to the thermal expansion of the formation local to the DGR. In addition, the assessment will enable a judgement to be made on the likely influence of the stresses on groundwater flow in the vicinity of the DGR.

The model used a simplified representation of a quarter section of the DGR, the extent of which was sufficient such that the temperature of the rock at the boundaries remained unaffected by the presence of the DGR. The model was bounded on the upper side by the Earth’s surface and at the bottom by a plane 10,000 m below the DGR horizon. The DGR was represented by a plane of material providing the required heat loading, although details of the emplacement rooms were not included. Details of the dimensions assumed for the analysis are given in Figure 17 of Annex 2. It has conservatively been assumed that the DGR will be configured as tightly as possible, thus maximising the temperatures and stresses at the centre of the DGR. In practice, the DGR is likely to be more spread out due to local features within the rock formation, and temperatures will be reduced. The heating from the radioactive decay of the fuel was averaged over the volume of the DGR, based on an assumption of a full DGR containing 3.6 million used fuel bundles. This approach tends to under estimate temperatures locally in the DGR during the early stages, however, it gives a better indication of temperatures and stresses in the rock formation away from the emplacement rooms than the near-field models as the DGR edge effects are explicitly considered. In order to provide a conservative assessment of the peak temperature reached in the surrounding rock formation heat transfer as a consequence of groundwater flow is not considered.

As with the previous models, the upper surface boundary condition was modelled as an isothermal boundary, with a temperature of +5°C, representing the average Canadian Shield surface temperature, reducing to 0°C after 10,000 years to account for a period of glaciation. The lower boundary was also modelled as an isothermal boundary, such that a geothermal gradient of +0.012°C/m of depth is achieved [5]. The vertical boundaries were modelled as adiabatic planes of symmetry. The vertical planes of the model were constrained not to move, as was the lower horizontal plane. The upper horizontal plane, the earth's surface, was free to move. A summary of the boundary conditions used is shown in Figure 18 of Annex 2. The model is thus representative of a DGR positioned in an infinite extent of granite.

Stress analyses were performed at key stages in the DGR life (namely 100; 1,000; 10,000 and 100,000 years), using temperature fields appropriate to the assessment time as calculated in the thermal analysis. It has conservatively been assumed that the emplacement rooms are oriented with the room's longitudinal axis perpendicular to the highest principal stress to accommodate possible variations in the far-field stresses. Between 10,000 and 100,000 years, an additional load due to 3,000 metres of ice spread uniformly on the surface was included. For the purposes of these assessments, it has been assumed that the effects of additional loads attributable to changes in the geologic stress field will be adequately buffered by the clay-based sealing materials, and therefore do not need to be explicitly considered at this stage of the DGR design process.

3.2.4.4 Far-field Thermo-Mechanical Analysis Results

Figure 19 of Annex 2 shows the thermal history for three locations within the DGR, the DGR centre (equivalent to the previous near-field case), at the mid-point along one edge of the DGR, and at a corner location. In addition Figure 20 of Annex 2 shows how the temperature distribution in the surrounding geosphere varies with time. The temperatures predicted by the analysis drop significantly with distance away from the centre of the DGR, with the peak rock temperature at a corner of the DGR being only 33°C, compared with a peak temperature at centre of the DGR of 70°C. The far-field analysis predicts that the peak temperature will be developed at around 4,000 years from emplacement, and it would take over 100,000 years to return to the initial ambient temperature,

Also shown in Figure 19 of Annex 2 is the temperature history at the crown of an emplacement room at the centre of the DGR, as predicted by the near-field analysis. As anticipated, the peak temperatures generated by the far-field model are less than those generated by the near-field model. For the initial period, approximately 100 years, this can be attributed to the heat generated by the individual UFCs in the plane of the DGR being averaged over the entire emplacement area, as defined by the initial gross thermal load. Between 100 years and 2,000 years after emplacement, there is a good correlation between the two models. Thereafter the models diverge again as the near-field model under estimates the cooling influence of the DGR periphery.

Generally, the far-field model is accurate for periods beyond 2,000 years in the immediate plane of the DGR and earlier in time as the distance from the plane of the DGR increases (i.e., the localised heating effects are "smeared" out). It is therefore considered that the DGR will initially reach a temperature of 70°C some 100 years after emplacement. The rock temperature will then remain more or less constant for some 4,000 years, after which the temperature will steadily decline, returning to the initial ambient conditions around 100,000 years from emplacement.

The stress analysis predicts a maximum tensile stress (at surface) of 1.3 MPa after 10,000 years, Figure 21 of Annex 2. This is significantly below the quoted tensile strength for the homogeneous isotropic rock considered of 6 Mpa and indicates that no new fracture zones would be initiated. The region over which the stress remains tensile, thus the region in which some limited opening or extension of subvertical fractures could occur is less than 9 m vertically, in the vicinity directly above the DGR. This is significantly less than the specified depth of 100 m, and negligible impact on groundwater flow is anticipated. The maximum uplift is approximately 25 cm on the ground surface above the centre of the repository at approximately 10,000 years after emplacement.

It is considered that the above results confirm that the proposed DGR design will meet the design specification. It should also be borne in mind that the above results are based on conservative assumptions, and actual figures are likely to be less onerous in practice.

In order to determine the ventilation requirements to enable operators to comfortably carry out their work within the DGR, it is important to determine the likely temperature in an emplacement room adjacent to an already filled room. In order to do this the temperature profile at the edge of the far-field model has been used. This can be considered a worst case, being analogous to the condition when filling the last emplacement room, with the adjacent room having been one of the first rooms to be filled. Figure 24 of Annex 2 shows how temperature varies with distance from the edge of the DGR, thirty years after emplacement. The temperature of the rock formation in the vicinity of an adjacent emplacement room is predicted to be no higher than 21°C.

3.2.4.5 Thermo-Mechanical Analysis Summary

Based on a conservative assessment, the outer surface of the UFC will reach a maximum temperature of 97°C, 16 years after emplacement. The surrounding granite formation will reach a maximum temperature of 73°C after 57 years, which will then remain nearly constant for around 10,000 years, after which the temperature will gradually decay, until after 100,000 years, the temperature in the vicinity of the repository will have returned to near undisturbed conditions. Although the analyses predict some localised damage to the rock formation at the periphery of the emplacement room at the crown and base locations due to thermal expansion, this is not considered to adversely affect the long term safety of the DGR. However, its presence should be taken into account during any subsequent retrieval operations.

The analyses carried out as a part of this programme of work have confirmed that the proposed DGR and associated UFC designs can meet the current design specification requirements. Clearly, more detailed analysis will be required during the detailed design stage, using more site-specific thermo-mechanical material properties and details of the in-situ rock formation stress state. Also, further work will be required to demonstrate the integrity of the DGR barriers under less favourable conditions, i.e. during periods of seismic activity.

3.2.4.6 NFOLD Numerical Analysis

Numerical analyses of the concept DGR layout design were undertaken using the displacement discontinuity program NFOLD. These analyses were carried out to assess three states during the development and operation of the DGR. The assessments were to check overall stability conditions:

- for the excavations prior to thermal loading
- after all the emplacement rooms are filled
- during excavation of clay-based sealing materials to retrieve one or more containers, at various times after emplacement.

Based on the assumptions for uniform in situ stresses and homogenous, sparsely fractured rock mass conditions incorporated into the NFOLD model, the proposed repository layout at a depth of 1000 m is generally satisfactory. This conclusion being applicable from a global rock stability viewpoint for the creation of the excavations prior to their thermal loading, and also from the overall stability perspective once the emplacement rooms have been filled.

The numerical results indicate that:

- The 45 m distance between centres of the emplacement rooms is adequate for maintaining stability of the sparsely fractured rock mass between these rooms
- An elliptical cross-section shape for the emplacement rooms, is endorsed as the most appropriate shape to achieve minimal stress concentrations at the excavation perimeter. However, a field based optimisation programme is required during the UCF phase which will include stress measurements to determine the magnitudes, orientations and variability of ambient in situ stresses so that appropriate robust excavation designs can be derived
- The emplacement rooms should be arranged so that the longitudinal axes of the waste emplacement rooms are oriented parallel to the major horizontal stress, as this reduces the potential for rock damage and failure around the

- In situ stress measurements must be undertaken in the initial stages of design investigation at the chosen site to confirm magnitudes and orientations. Knowledge of the rock mass stresses is paramount for selecting the best layout development

- Additional ground support will likely be required at the corners and entranceways to the emplacement rooms

- The intersections of proposed accessways located at the centre of the repository could be highly stressed. It is suggested therefore that the chain rib pillars in the vicinity of these accessways should be widened to at least 60 m to minimise superposition of stresses.

3.2.5 Excavation Method

The DGRs underground access tunnels and emplacement rooms will be excavated by drill and blast methods.

As part of the design update an investigation was carried out to compare the use of tunnel boring machines (TBMs) and drill and blast methods. This investigation is reported in Annex 4, however, the main conclusions are summarised below:

- Drill and blast techniques can provide the desired elliptical cross section of the emplacement rooms
- It has been demonstrated by the Canadian Nuclear Society [33] that with careful blast design and construction practices, drill and blast methods can provide an acceptable excavation damage zone (EDZ) using smooth wall blasting techniques
- TBMs would be an effective means of excavation for a circular opening
- TBM techniques minimise the depth of the EDZ
- The technical feasibility of boring an elliptically shaped tunnel has not been demonstrated with certitude, although a number of manufactures are developing prototype machines that require a multi-head TBM or a mobile miner/road header approach.

It was concluded that future advancements in technology may well result in TBMs becoming more viable for the application being considered. To help ensure efficient use of resources, it is recommended that future advancements in this area continue to be monitored.

Excavation will generally be by “full-face” advance, with the “pilot and slash” method being used on an as-needed basis. The initial excavation from the shaft carried out during the underground evaluation in the Underground Characterisation Facility will be excavated to 3.0 m by 3.0 m and later slashed out to full size.

The access drifts are anticipated to be excavated by full-face techniques, unless it is considered that pilot and slash provides greater flexibility than full-face advance for the wide excavation openings, which could occur when dealing with any problematical geotechnical structure.

Equipment used during the mucking of the emplacement rooms will have to cater to the “rounded” floor profile of the rooms. This profile could be difficult for the operation of conventional, rectangular-shaped LHD buckets, although the use of a small-capacity LHD for final clean-up would be a practical solution. Another approach would be to use a “temporary” flat floor to allow most of the emplacement room to be excavated utilising conventional LHD machines, with subsequent excavation of the floor to size. Final mucking after trim blasting or slashing could be achieved by a variety of methods including "gathering-arm" machines. However, this analysis assumes that excavation is by full-face blasting using conventional LHD mining equipment.

Where ground control is required, standard rock-bolting methods will be used. The equipment utilised and the method of ground control will be pre approved by OPG or its representative, prior to its application. On a basis of the anticipated ground conditions, there will be essentially no requirement for heavy bolting, use of screen and/or shotcreting, although a budget allowance has been provided for unexpected local conditions.

3.2.6 Emplacement Room Construction

Essential to the excavation process is the ability to safely excavate the emplacement rooms, whilst emplacement of the UFCs is in progress in other parts of the DGR. There are a number of factors to consider:

- Excavation must be done in such a manner that the structural integrity of the adjacent section is not compromised
- Emplacement, hence excavation, will retreat towards the Service Shaft Complex
- Separate ventilation airflows will be provided for emplacement and mining operations.

Initially the mining contractor will excavate 39 emplacement rooms. The location of these rooms will be in the upper and lower half of Section A and the lower half of Section B (see Figure 8). Task allotment in the excavation process includes:

- Pouring of concrete floors in all excavated emplacement rooms
- Establishing rail track access across the emplacement sections and a minimum of four (4) emplacement rooms.

The emplacement sequence will commence in the lower panel of Section B, and then proceed to Section A. At this particular juncture, emplacement will be isolated to the left of the central access corridor (Figure 9), allowing the campaign excavation to proceed on the right-hand side of the DGR.

During the second excavation campaign (Figure 9) an additional 26 emplacement rooms will be provided. The excavation activity will be isolated to the upper panel of Section B and the lower panel of Section D.

The excavation time to provide the 26 emplacement rooms has been estimated to take 935 days (Annex 4), or approximately 2.6 years based on operating 365 days per year. Initial studies indicate that it will take approximately 7.5 years to fill a 26 room section based on operating 230 days per year.

Details of the subsequent third and final excavation campaigns are provided in Annex 4.

By scheduling concurrent UFC emplacement and emplacement-room excavation operations, the duration of the construction stage and, therefore, the costs incurred prior to beginning emplacement, are reduced. As well, the time between excavation and sealing of an emplacement room is minimised, which minimises the amount of effort required to maintain a continuing safe working environment in emplacement rooms.

3.2.7 Shafts

The design of the repository incorporates four shafts, which is one fewer shaft than recommended in previous studies. The shafts are divided into two groups: the service shaft complex and the upcast shaft complex. The service shaft complex includes the service shaft (downcast), the waste shaft (upcast), maintenance complex exhaust shaft (upcast), UFC storage area, empty rail car storage area, loaded car storage area, UFC transport repair facility, central underground warehouse and stores, trackless excavation equipment maintenance complex, refuge station and other underground facilities (Figure 14). The upcast shaft complex is the location for the exhaust ventilation shaft (upcast) as shown on Figure 15.

A study was undertaken (Annex 7) to provide for a Waste Shaft hoisting system that would safely and effectively transfer the casks underground given that the total mass of the UFC, bentonite jacket and shielding cask was estimated to be 86.5 tonne. A total of five cases were investigated that considered the horizontal or vertical transport of the UFC and shielding provided either by containment in a shielding cask or transportation of the UFC and bentonite jacket in a shielded cage. A cost analysis of the five cases was completed and a description of each case given below:

Case #1 A cask containing a UFC with bentonite jacket is loaded on a railcar in the surface used fuel packaging plant, moved to the shaft and pushed in the horizontal position into the shaft cage. The railcar with cask is pulled out of the cage at the DGR level and moved to the emplacement location. Cage payload including railcar is a maximum at 95.2 tonne, with estimated cage mass of 38.1 tonne.

Case #2 A UFC with bentonite jacket is moved to the shaft in a transport cask then transferred to a lighter unshielded railcar for transit down the shaft. The cage is unshielded, but fixed shielding is installed around the shaft compartment at landings. At the DGR level a crane beside the shaft transfers the UFC with bentonite jacket to another transport cask for travel to the emplacement location. Payload weight is reduced to 40.4 tonne, with a cage mass of 16.1 tonne.

Case #3 Similar to Case #2, except that the shaft cage is shielded so that work around the loaded cage would be possible in case of operating problems. Transfers between a light railcar used in the cage and a cask and railcar used for transport outside the shaft area would still be necessary. Payload remains at 40.4 tonne, but cage mass is increased to 60.0 tonne.

Case #4 A cask with UFC with bentonite jacket is brought to the shaft in a horizontal orientation, then picked up by a large crane beside the shaft, rotated to vertical position, and set on a special railcar for movement in and out of the shaft. At the DGR level the procedure is reversed, using another large crane to return the cask to a horizontal orientation and load it on another railcar for transport to the emplacement area. Projecting trunnions are needed on the cask for pickup by the crane. Payload is 95.0 tonne, with cage mass of 38.0 tonne.

Case #5 Similar to Case #4, except that the cask and cage are designed so that the cask can be picked up and tilted using the main shaft hoist, eliminating the need for additional cranes beside the shaft. No railcar is carried in the cage. Payload is 86.5 tonne, with cage mass of 39.0 tonne.

- Case #1 is recommended as the base case for ongoing studies utilising a Koepe hoist. This is the most expensive option, but it offers the simplest cask handling procedures and therefore minimises the risk of damage to the UFC and associated bentonite jacket. This is expected to result in lowest maintenance requirements and accident frequency. The large shaft diameter offers greater flexibility should plans require handling of larger equipment. The marginal cost difference between this option and the least expensive is approximately C$4,600,000.
- Hoisting speed is not critical because of the low duty cycle. A speed of 2.5 m/s (7.7 rpm) was used for study purposes.
- The Koepe hoist will be tower mounted in a concrete headframe. Overall height will be approximately 38.0 m to the top of the roof parapet
- As the Waste Shaft will be sunk after DGR access is made available through the Service Shaft, excavation by raise-and-slash methods offers more economical sinking and potentially enhanced wall rock conditions through the use of pilot-and-slash blasting methods. However, this method would require sub-level development from other shafts.
- Conventional shaft lining would consist of a nominal 300 mm thickness of concrete. In this shaft intermittent curbs will be provided, located at 5.5 m spacing, to support the shaft sets. This will reduce initial cost slightly and greatly reduce decommissioning work.
- The projected duty of the waste shaft will require less than one hour per day of shaft time. Alternate uses of this very large payload hoisting system can be considered with no compromise to the primary requirement. These uses include, transport of heavy excavation equipment, transport of buffer and dense backfill blocks and bulk materials from a surface preparation plant.

3.2.8 Underground Ventilation

The ventilation requirement for the underground DGR is based on two factors:

- The air volume requirement to provide dilution of excavation contaminates
- Dissipation of heat to provide a comfortable working environment.

The use of a campaign approach to excavation, where a mining contractor will be mobilised/demobilised as required, will result in a variation of diesel powered mining and excavation equipment being used. Diesel powered equipment required by the mining contractor will total approximately 1125 kW. To satisfy Ontario Government legislation, a supply of 0.06 m^3/s/kW of air needs to be supplied. Therefore, 67.5 m^3/s of fresh air will be required to ventilate diesel powered equipment utilised in the excavation process. Since this equipment may not be centralised along one emplacement panel access drift and because of its highly mobile nature, the air volume will need to be increased by approximately 50% to 100 m^3/s. As the equipment is expected to work in more than one emplacement panel, equal amounts of air must be allocated to each panel.

The Ontario Occupational Health and Safety Act and Regulations for Mines and Mining Plants do not specifically address the human need for ventilation. However, the regulations do specify minimum acceptable oxygen levels, upper limits for toxic gas concentrations (i.e. CO, NO_2, etc.) and a dilution factor for the operation of diesel powered equipment (0.06 $m^3/s/kW$ operating diesel). In a similar fashion, Canada's Atomic Energy Control Board, specifies radiological exposure levels, but do not specify dilution or minimum air volume requirements. It has been CTECH's experience that if sufficient air volumes are provided to dilute the by-products of a diesel powered combustion engine; the human need for ventilation is also addressed.

During emplacement of UFCs, a minimum air velocity of 0.5 m/s in the access tunnels will maintain air temperatures to below 27^oC; a temperature considered to be a comfortable effective air temperature for the work being undertaken. Based on this air velocity and the cross sectional area of the access tunnels an air volume of 15 m^3/s will be required. Similarly, the air requirement in the emplacement rooms will be 12 m^3/s. However, an allowance of 14 m^3/s has been allowed to provide for the operation of 233 kW of diesel equipment in the emplacement room, permitting the use of a 6m^3 LHD machine or similarly sized equipment.

Allowing for room excavation and emplacement to take place simultaneously and considering the air requirements of the Service Shaft Complex, the air volume requirements are estimated to be as summarised below.

Location	**Emplacement Activities Only**	**Emplacement and Excavation Activities**
Service Shaft Complex:		
Waste Shaft (upcast)	20 m^3/s	20 m^3/s
Maintenance Complex Shaft (upcast)	50 m^3/s	50 m^3/s
Emplacement Room Excavation	--	100 m^3/s
Used Fuel Emplacement	70 m^3/s	70 m^3/s
Total Air Volume Requirement	**140 m^3/s**	**240 m^3/s**

With respect to the positioning of the main fans, exhaust fans will be required on the Maintenance Complex Exhaust Shaft and Upcast Ventilation Shaft.

During the winter months the Service Shaft must be heated to prevent freezing of the shaft and sheave wheels. A push-pull arrangement will be incorporated into the shaft design, with a blowing fan on surface and a suction fan located underground. The surface fan will deliver 260 m^3/s of heated air, with 240 m^3/s being drawn down the Service Shaft, and the excess 20 m^3/s upcasting through the headframe of the Service Shaft. A fan placed underground within the Service Shaft Complex will draw the required maximum of 240 m^3/s down the Service Shaft, placing the Service Shaft Complex under positive pressure. Since the exhaust shaft in the Upcast Shaft Complex will only draw a maximum of 170 m^3/s, the surplus air delivered via the Service Shaft will upcast the Maintenance Complex Shaft and the Waste Shaft.

During emplacement only activities, the air handling volumes of the Service Shaft fans and the Upcast Shaft Complex fan will be decreased to compensate for the reduced air volume required.

The Service Shaft will have similar internal dimensions (7.3 m) to the Service Shaft specified in [2].

The Maintenance facility raise dimension will be designed on a basis of air volumes to be handled during the pre-emplacement development phase, prior to establishing the Upcast Ventilation Shaft to the surface, with maximum airflows of 150 m^3/s. In this regard, CTECH recommends a concrete lined circular shaft of 3.96 m internal diameter. However, it would have to be driven an additional 0.6 m in diameter to allow for a nominal 0.30 m concrete liner thickness.

The Upcast Ventilation Shaft will be a concrete lined ventilation raise of 3.66 m internal diameter. As in the case of the Maintenance Facility Exhaust Raise, the concrete lined shaft will be mined 0.6 m greater in diameter to allow for the 0.3 m concrete liner.

3.2.9 Access Tunnels

The access tunnels to the emplacement rooms will be sized to accommodate the UFC transport cask, transport of material and room-to-room transport of equipment. In addition, consideration has been given to the size of underground mining equipment that will be used to develop the tunnels. The access tunnels will be sized to provide for waste + rock transport by means of a 30 tonne truck and the provision of two ventilation ducts of a maximum size of 1.38 m. This will result in an access tunnel that is 7.0 m wide and 4.2 m high. The access tunnel will be rectangular in cross-section with an arched back, as illustrated in Figure 16. The tunnel width will not be designed for the installation of twin track for passing purposes as proposed in previous studies. As an average of less than two casks will be transported in any 24-hour period, and because of the proposed approach to movement of casks and buffer blocks, only a single track will be required. Movement of the casks and blocks is described in Sections 3.3.5.2 and 3.3.5.3.

During excavation of the access tunnels, the primary ventilation circuit will comprise the Service Shaft and the Maintenance Facility exhaust raise. The ventilation corridor established between the Service Shaft and the Maintenance Facility's exhaust raise would be the only source of fresh air. The use of low resistance auxiliary ventilation systems will be required for development purposes.

Whilst developing the access tunnels, the entrance of each emplacement room (25 m access curve to the room) will be developed. Transition from a rectangular to elliptical tunnel cross section will occur along the emplacement room's access curve, so that the advancing face will be elliptical at least one round before the planned position of the 12 m thick concrete bulkhead and grout plug. (Figure 17).

3.2.10 Sealing Materials Handling

Component materials used to formulate the buffer, dense backfill and high-performance concrete must meet material specifications and inspections before they are approved for use in the DGR.

Low-heat, high-performance concrete will be transferred from the surface batching plant to the Service Shaft using rotating-drum trucks. The concrete pumping system in the Service Shaft will deliver the concrete to a remixing and truck filling station underground. Trucks will then deliver the concrete to the required destination via the appropriate access tunnels.

Buffer and dense backfill will be formed into compacted blocks within the Sealing Materials Compaction Plant situated on the surface (see section 3.4.5.1), and transferred underground via the Waste Shaft. The blocks will be transferred on rail cars directly to the required emplacement room. A storage area will be provided to allow rail cars to be assembled into a train, if necessary, or to allow temporary storage if the emplacement room is not ready to receive the materials.

3.2.11 Cask and Buffer Block Movement

The proposed design of the UFC transport cask requires the emplacement room entrance to be provided with a 25 m centreline turning radius. Therefore, ingress and egress to and from emplacement rooms within a panel will be in one direction only (Figure 17).

In transporting UFC casks and sealing materials to an emplacement panel, the rail cars will be towed by locomotive. Since each emplacement panel will have its own access drift (Figure 8), the combination of single emplacement room access and the uni-directional traffic flow, will allow the UFC cask and/or sealing material trains to be drawn past the entrance to the room before being reversed in.

Off-loaded trains will return to the Waste Shaft in the Service Shaft complex, either by the central or perimeter access tunnels, in a clockwise direction, according to the established uni-directional transport system.

The estimated time for moving a loaded UFC cask to an emplacement room and return with an empty cask to the Waste Shaft station will be 72 minutes. A maximum of two locomotive trips a day will be required to satisfy the specified UFCs emplacement rate on the basis that only one cask is transferred per trip.

Marshalling drifts will be established above the Waste Shaft’s perimeter access tunnel, to provide space for organising “unit trains” of buffer block and dense backfill material. The marshalling drift to the right of the Waste Shaft (Figure 14) will be for full rail cars, whilst the marshalling yard to the left of the Waste Shaft will be utilised as a temporary storage area for empty rail cars returning from the emplacement room. Within the Waste Shaft station there will be a UFC cask storage area, sized to provide sufficient storage for the UFC cask and buffer block cask cars required on a daily basis.

3.3 EMPLACEMENT ROOM DESIGN

This section provides an overview of the DGR emplacement-room design process and describes the main room components, discusses the source and rationale for selected design parameters, summarises the results of the design analyses and presents the operations associated with the UFC emplacement.

3.3.1 Design Overview

The emplacement room design is consistent with the implementation of a multi-barrier safety philosophy. Each of the room components provides an independent function aimed at physically and chemically containing the used fuel for an extended period of time. The engineered barriers in the emplacement room include the UFC, its bentonite jacket and surrounding buffer, the dense backfill, the light backfill and the concrete bulkheads and bulkhead seals. In addition to these materials providing structural and sealing functions, the emplacement rooms have a concrete floor that provides support for the precise operations required during the assembly of the engineered barriers and emplacement of the UFCs.

The emplacement rooms are designed to have an elliptical cross-section with a height of 4.2 m and a width of 7.14 m, and are to be excavated at a depth of 1000 m. The preferred orientation for the repository is such that the emplacement rooms longitudinal axis is parallel to the direction of maximum rock stress. The horizontal rock stresses are assumed to be higher than the vertical stresses and the ratio of the stresses in the cross-sectional plane determine the aspect ratio of the emplacement room. This ratio minimises the tangential stress concentrations at the emplacement room rock surfaces.

The size of the emplacement room cross section is based on the space required to surround each UFC with the specified minimum thickness of bentonite/buffer material (0.5 m) and dense backfill (0.5 m). Both these materials are placed in the room in the form of pre-compacted blocks. The dense backfill being placed directly on the emplacement room concrete floor, while the additional space between the dense backfill and the rock surface is filled with light backfill. The cross-section of the emplacement room is illustrated in Figure 1.

The drill-and-blast method used to excavate the emplacement rooms will enlarge the excavation by a further 150 mm in all directions at the end of a blasted section because of the necessity to drill blast holes slightly outward to maintain minimum excavation size. However, the finite-element model design analyses, discussed in Section 3.2.4, has used the emplacement room parameters given in Table 3.

Low-heat high-performance concrete will be used for the construction of the emplacement room floor and will support rails and equipment for placing and aligning the pre-compacted dense backfill and buffer blocks. Although the rail and other temporary furnishings will be removed as the room is filled, the concrete floor will remain a permanent part of the room structure. The properties and specifications of high-performance concrete are discussed in Section 3.2.3.4. Referring to Figure 1, the concrete floor section will be shaped to provide a 4.6 m wide platform from which to conduct emplacement operations. At the centre of the emplacement-room the concrete platform will be approximately 0.5 m thick.

Although the specified concrete has been deemed suitable for use within the emplacement rooms, Johnson et al [8], the interfaces between the concrete and the rock and between the concrete and clay-based sealing materials, and the concrete itself as it degrades over long time scales, could provide a potential groundwater flow path. Therefore, the emplacement room design incorporates the minimum quantity of concrete to provide a flat floor for emplacement operations to be undertaken. In addition, cross-sectional segments of the concrete floor within the emplacement rooms will be removed at approximate 50 m intervals along its length. These approximately 50 cm wide gaps will be and replaced with clay-based sealing materials to interrupt potential flow paths along the concrete and concrete interfaces as the emplacement procedure retreats along the emplacement room. During the emplacement procedure the structural function of the missing segments of concrete will be performed by supporting components such as steel plates that will be removed and re-used as the emplacement operation progresses. The exact placement of these seals will depend on the location of fractures within the individual emplacement room and as such their precise positioning will be site-specific.

3.3.2 Materials Specifications

The material properties for the low heat high performance concrete are given in Table 5. This material is used for the floor of the emplacement rooms and for the bulkheads at the emplacement room entrances as described in Section 3.2.3.4.

The composition of the clay-based sealing materials are given in Table 8 and the Thermo-Mechanical properties are given in Table 5. The materials involved are, bentonite (for the UFC jacket), buffer material, dense backfill, light backfill and a gap infill material as described in Section 3.2.3.4.

3.3.3 Design Criteria and Parameters

The emplacement room arrangement for the in-room emplacement method presented in this report was developed based on a number of design parameters. A description of these parameters with relevant boundaries and limits, based on the requirements in Section 2.1.8, are listed below:

- to minimise stress levels and the consequent excavation damage at the rock surface, the emplacement rooms will have an elliptical cross-section with an aspect ratio of 1.7, with the major axis of the ellipse in the horizontal plane [5]
- the minimum pillar width between adjacent emplacement rooms will be a minimum of three times the emplacement room width [5] - see Section 3.2.2 for the emplacement room separation distance adopted in the proposed DGR layout
- the sealing materials surrounding the UFC, i.e. the bentonite/buffer and dense backfill will each have a minimum thickness of 0.5 m and will form a nearly symmetric structure around the UFC
- the quantity of low-heat, high performance concrete used to construct the emplacement room floor platform will be minimised
- the emplacement room cross-section will be sized to provide the required clearances for excavation, placement of sealing materials and UFC emplacement
- the size of the emplacement room cross-section will be minimised, after taking into account

the aforementioned parameters, to assist maintaining the outer surface of the UFC below the specified temperature limit of 100°C.

Following systematic review of the above parameters, an emplacement room height of 4.2 m was established that satisfied all the above requirements. Consequently an emplacement room width of 7.14 m was derived using the aspect ratio described above. A cross-section of the emplacement room design is shown in Figure 1.

For the assessment of the structural integrity of the sealing material blocks prior to emplacement of the lower support blocks, but after positioning of the UFC, estimates of the mechanical strength of the sealing materials were required. These have been obtained from Reference [34]. For the purposes of this assessment, a tensile strength of 250 kPa, and an unconfined compressive strength of 0.9 MPa for the bentonite jacket has been assumed. The relationship between compressive and shear strength is derived from the von-Mises yield criterion, which states that plastic flow occurs when the shear strain energy reaches a critical value.

$$(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2=const \tag{8}$$

In uniaxial compression, yield occurs when $\sigma_1 = Y$, $\sigma_2 = 0$, $\sigma_3 = 0$,

$$(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2=2\cdot Y^2 \tag{9}$$

At yield in pure shear, $\sigma_1 = -\sigma_2 = \tau_{xy}$, = k and $\sigma_3 = 0$ thus the von-Mises criterion becomes:

$$(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2=k^2+k^2+4k^2 \tag{10}$$

The constant must have the same value under any stress condition, thus

$$6k^2=2\cdot Y^2 \quad \text{or} \quad k=\frac{1}{\sqrt{3}}Y \tag{11}$$

A maximum shear strength of 250 kPa for the bentonite jacket has therefore been assumed. The strength properties for the buffer material (a 50% silica sand and 50% bentonite mix) have been based on a “rule of mixtures” approach. It is assumed that the sand has no tensile strength and therefore the buffer material tensile strength is reduced by 50% compared to bentonite alone. A similar approach has been adopted in determining the shear strength. i.e. tensile strength = 125 kPa , and shear strength = 260 kPa.

In the absence of more detailed information at this stage, the tensile, compressive and shear strengths for the dense backfill have been assumed to be the same as for the buffer material. Clearly the backfill material structural behaviour is highly dependent on the shear softening and strain hardening properties of the clay based materials, for which suitable material properties are not currently available. Once these properties are established for the anticipated DGR conditions, the stability analysis should be reviewed.

3.3.4 Analytical Considerations

The emplacement room arrangement, including its size, shape and inventory of sealing materials and UFCs, comprised a number of the parameters used in the analysis to asses whether the DGR complied with the various constraints placed upon its design. This section describes the analytical approach adopted in satisfying these constraints, as well as presenting the analysis carried out to determine the stability of the sealing material emplacement structure.

A staged design process was used to establish the disposal room geometry. Material properties and design criteria were established. Initial scoping calculations combined with 2 D thermal finite element analysis were used to define the required UFC and emplacement room spacing (see section 2.2 for the room spacing used), thus determining the minimum footprint for the DGR.

After a specific geometry for the shape and size of emplacement room and DGR were determined, more precise numerical methods were used to confirm and refine the estimates from the preliminary analyses. Local temperatures and stresses within an emplacement room were considered in a three-dimensional finite element model of a section through the centre of the DGR (near-field assessment), replicating an infinite array of emplacement rooms. A development of the near-field model was used to confirm the stability of the clay-based sealing materials both prior to emplacement of the UFCs, and after emplacement, but before placement of the buffer and dense backfill blocks beneath the UFCs.

A broader analysis considering stresses on a DGR scale (far-field assessment) was used to obtain a more realistic assessment of the temperature profile within the DGR at longer timeframes, and to establish the magnitude of temperature variations within the DGR. The far-field assessment was also used to determine the magnitude of stresses at the surface above the DGR.

Details of all of the finite element analyses are contained in Annex 2 to this report, with a brief summary of both the near and far-field assessments and their associated results given in Section 3.2.4. However, a description of the analysis to confirm the stability of the clay based sealing materials, together with a summary of the results is given in the following sub-section.

3.3.4.1 Emplacement Structure Stability Analysis

To establish the integrity of the chosen emplacement room emplacement buffer/dense backfill structure during the placement of the bentonite sleeved UFCs, a 2-D mechanical analysis of the emplacement room, prior to the emplacement of the lower cavity infill blocks, was carried out using a two dimensional model.

The analysis was carried out in two stages, the first without the UFC and bentonite jacket being in place; and secondly, with the UFC and jacket in-situ. The interface between the jacket and the buffer blocks was modelled as a low friction contact surface. The purpose of the assessment was to demonstrate that the proposed emplacement procedure was feasible in principle. For simplicity, it was assumed that the various types of backfill act homogeneously. However, in practice, this will not necessarily be the case depending on the nature of the interfaces between the individual blocks of material. Once visco-plastic properties are available for the sealing materials, and details of individual blocks and any mechanical interlocking features are designed, a more detailed analysis will be required to confirm the safety of the final design.

Before emplacement of the UFC, the calculated maximum displacement of the emplacement structure is 1.46 mm, Figure 37 of Annex 2. It should be noted that these results do not take into account any time dependent visco-plastic deformation of the clay, and thus if there is a significant time delay between placing the emplacement room buffer and dense backfill blocks, and placing the UFC the deflections may be larger. Also clay based materials exhibit a significant stress hardening characteristic, which has not been considered in the current analysis. Figures 38 to 40 of Annex 2 show maximum and minimum principal stress and maximum shear stress respectively in the dense backfill and buffer material prior to positioning of the UFC and jacket. Maximum stress values are summarised, by material in Table 6 of Annex 2, which also shows the relevant design allowable stress for each material. In all cases, the predicted stress is below the design allowable, and therefore it is considered that the proposed emplacement methodology is practical.

With the UFC in place, and the clay-based sealing materials in position, the maximum deformation is 1.27 mm, Figure 41 of Annex 2. Figures 42 to 44 of Annex 2 show maximum and minimum principal stress and maximum shear stress respectively in the dense backfill, buffer and jacket materials after positioning of the UFC, but before placement of the gap infill blocks to support the UFC. As previously, maximum stress values are summarised, by material in Table 6 of Annex 2, and once again, in all cases the predicted stress is below the design allowable, and therefore it is considered that the proposed emplacement methodology is practical.

Clearly the backfill material structural behaviour is highly dependent on the shear softening and strain hardening properties of the clay based materials, for which suitable material properties are not currently available. Once these properties are established for the anticipated DGR conditions, the stability analysis should be reviewed.

3.3.4.2 Stability Analysis Summary

Analyses have been carried out to demonstrate the stability of the clay based sealing material blocks during the emplacement operation. Assessments were carried out both prior to UFC placement and following UFC placement, but prior to placement of the buffer and dense backfill blocks beneath the UFC. In both cases, deformation of the blocks was negligible, <1.5 mm. Stresses in the blocks were also low and remained within the assumed allowable limits for the various clay-based sealing materials. The calculated stress levels and allowable limits are given in Table 6 of Annex 2. It was therefore concluded that the proposed emplacement methodology would be feasible.

3.3.5 Emplacement Room Operations

This Section describes the overall emplacement room operations, from their excavation to final sealing. Within this process, operations include the initial preparation of the emplacement rooms, construction of buffer and dense backfill emplacement structures, emplacement of the

UFCs within the prepared slots in the assembled emplacement structure and plugging of the emplaced UFC and the area beneath it. After an emplacement room is filled, a low-heat high-performance concrete bulkhead will be constructed to seal the room entrance.

3.3.5.1 Emplacement Room Preparation

During the excavation of an emplacement room panel a number of primary activities are carried out to permit the UFC emplacement process to proceed in a planned manner. As each emplacement room is excavated a low-heat, high performance concrete floor will be laid. As the number of emplacement rooms within a panel will not be called into service for up to 10 years, rooms will be shuttered off, until required for UFC emplacement. However, to allow on-going regular inspections of the emplacement rooms to verify their condition, a portable ventilation system will be provided to ensure safe access.

A description of the overall DGR underground ventilation system is given in Annex 4. However, the emplacement room auxiliary ventilation system installed prior to UFC emplacement, will consist of two rigid ducts, each fitted with a 50 kW exhaust fan that handle approximately 14 m^3/s of air. During emplacement operations, a portable high-efficiency, particulate air (HEPA) filter will be provided on the exhaust from the emplacement room where UFC emplacement is being carried out. Each duct will be equipped with a radiation monitor and bypass damper. Under normal conditions, the HEPA filter will be bypassed. However, upon detection of radioactive contaminants, the damper will be activated, an alarm sounded for emplacement-room evacuation and the air exhaust routed through the HEPA filter. This concept of auxiliary ventilation will be similar to the system described for the in-floor emplacement method [2].

Emplacement operations will be carried out in four emplacement rooms at any one period. Based on a working pattern of two eight hour shifts per day (230 working days per year), this will allow six teams of operators to emplace up to two UFCs per day, or the average emplacement requirement of 1.61 UFCs per day. The listing of the activities undertaken by these teams and the times allocated to carry them out are described in Appendix A

The make up of the six teams will comprise four teams constructing the sealing materials emplacement structures, with the remaining two teams involved with the emplacement of UFCs. The emplacement sequence, shown in Figure A1 of Appendix A, outlines how the work will be organised. This will involve two teams (A1 & A2) installing blocks in rooms 1 and 2 on the first shift of day 1, followed by a further two teams (B1 & B2) carrying on with the installation of the blocks in rooms 1 and 2 during the second shift. On day two the same pattern will be used, resulting in the completion of the emplacement structures in rooms 1 and 2 by the end of day 2.

On days 3 and 4 the same teams will carry out and complete the installation of the emplacement structures in rooms 3 and 4. Over this period the first UFC emplacement team will install the first UFC in room 1 during the first shift of day 3, while the second UFC will be installed by the second emplacement team during the second shift of day 3. On the first shift of day 4 the first emplacement team will install the first UFC in room 2, while the second emplacement team will install the second UFC in room 2 during the second shift of Day 4.

On days 5 and 6 the teams will install emplacement structures in rooms 1 and 2 and UFCs in rooms 3 and 4. The teams will continue to alternate between these four rooms in the described manner until the rooms are filled. The same procedure will then be repeated in the next four rooms.

Prior to commencement of the above UFC emplacement operations in the four emplacement rooms to be worked on, the rooms will be prepared for the planned operations. The key activities that will be carried out include:

- the removal of the emplacement rooms shuttering to allow free access for operators and equipment
- the installation of the emplacement room central rail system
- the installation of mechanical and electrical utilities, including the auxiliary ventilation system, along the length of the rooms
- the installation of the emplacement room mobile shield wall and the ancillary equipment for the emplacement of UFCs and buffer/dense backfill blocks that includes the UFC transfer/traverse table and insertion carts

Following the installation of the above equipment, emplacement of dense backfill and buffer blocks to form the initial emplacement structures can begin.

Based on Figure 1 the cross section of the emplacement room will be made up using seven dense backfill blocks and nine buffer material blocks. The blocks will all be approximately 0.9 m long, requiring six layers of blocks to accommodate one emplacement pitch (5.13 m) within the emplacement room. This equates to 42 dense backfill blocks and 54 buffer material blocks, 96 in all. In addition, the lower areas beneath each emplaced UFC will be filled with a total of 12 dense backfill blocks and 12 buffer material blocks, giving a total of 120 blocks to be placed. The individual blockwork emplacement activities and the times allocated to carry them out are given in Appendix A.

The pre-compacted blocks are transported from the waste shaft to the emplacement room on rail cars. The railcars will allow the blocks to be transferred through the opening in the emplacement room mobile shield wall, via the UFC transfer/traversing table and on to a turntable/scissorlift device. This device will allow the blocks to be moved to the working face of the emplacement structure and raised to the correct position.

Specially designed block handling equipment will be provided to allow the final placement of the blocks in their allocated positions, utilising suction type grabs as proposed by SKB [35] and IHH [36]. In the case of both initial emplacement room blockwork placement, and subsequent emplacement structure construction, the operation of this equipment will be able to be carried out by local operators. This non-remote handling capability is possible in the first case because no UFCs have been emplaced, and in the latter case because the emplaced UFCs will be shielded by the closure buffer/dense backfill end plugs. To assist in the construction of the emplacement structure a temporary steelwork frame will be erected to support the upper blocks during installation. Once the blocks are installed and providing self support the steel frame will be disassembled and removed for reuse on later structures. To achieve the required block placement schedule each block emplacement team will utilise two block-handling grabs. A fuller description of the block placement activities and their timings are given in Appendix A.

Light backfill will then be pneumatically delivered using modified shotcrete placement equipment similar to that used in the Stripa Buffer Mass Test. Described by Pusch et al [37]. The light backfill will be placed into the void between the emplacement structure and the boundary of the emplacement room. A minimum space of 150 mm, at two pinch points, with an average of 300 mm, will be provided around the buffer material to allow access for the pneumatic nozzle. This method ensures that the light backfill completely fills all the remaining indentations and irregularities on the emplacement room surface. The fact that the proposed light backfill is relatively compressible and may allow the bentonite jacket, buffer and dense backfill to expand needs to be taken into consideration in determining the final constituents to ensure the expansion of these materials is kept to acceptable levels.

Following the construction of the emplacement structure operators will retire behind the mobile shield wall to allow the UFC emplacement procedure to be carried out, described in Section 3.3.5.2.

Following the emplacement of the two UFCs and their buffer material end plugs, operators are able to access the area beyond the mobile shield wall.

Radiation assessments have been carried out to determine the shielding requirements of the mobile shield wall, the UFC emplacement structure end plug and the dose attained from a UFC within the structure with no lower supporting blocks in place. These calculations described in full in Annex 3, set the shielding material and its thickness to attenuate the radiation dose at the working surfaces to less than 1 µSv/h. The calculation carried out to determine the dose attained without the lower blocks in place shows that at 1.25 m from the emplacement structure face the dose will be less than 1 µSv/h. In practice this will allow operators to place lower blocks on the insertion cart for transfer beneath the emplaced UFC. Physical barriers may be provided to prevent operators encroaching to within 1.25 m of the structure face during these operations.

The preparation of the next emplacement room emplacement structure will require the dismantling and removal of a 5.13 m length of ventilation ductwork, electrical and mechanical services adjacent to the mobile shield wall. This will allow the mobile shield wall together with the transfer/traversing table and insertion carts to be retracted by the same emplacement pitch length. This will then allow the rails to be removed to permit installation of the sealing materials for the next emplacement structure. Removed rails and services may be reused and installed in one of the next four emplacement rooms to be filled.

3.3.5.2 UFC Emplacement

The DGR underground layout, its shafts, tunnels and emplacement rooms together with the sequencing of its excavation are described in Section 3.2.6. Based on the method of DGR construction outlined, this Section describes the overall emplacement room operations from their excavation to final sealing. Within this process, operations include the initial preparation of the emplacement rooms, construction of buffer and dense backfill structures, emplacement of the UFCs within the prepared slots in the assembled emplacement structure and plugging of the emplaced UFC and the area beneath it. After an emplacement room is filled a low-heat, high-performance concrete bulkhead will be constructed to seal the entrance to the room.

The following activities take place during UFC emplacement:

- Emplacement of the UFC(s)
- Emplacement of the end buffer plugs

- Emplacement of the lower buffer and dense backfill plugs
- Infilling the annulus around the UFC sleeve and the buffer blocks.

The first step in the UFC emplacement sequence will be the measurement and visual inspection the UFC slot in the buffer block emplacement structure, into which the UFC will be placed to ensure that it meets its requirements. Should a slot be rejected due to quality control deviations, or the surrounding rock mass is deemed unsuitable for UFC emplacement in the particular locale, the UFC slot and the lower cavity will be filled with dense backfill and buffer blocks as required to fill and seal the slot. If the surrounding rock mass and the slot walls in the emplacement structure are acceptable, UFC emplacement will be approved and proceed.

A conceptual design has been developed for the UFC transport cask that will be used to transfer a UFC from the UFPP to the underground emplacement rooms. The horizontally orientated cylindrical cask, provided with an internal roller table to load/unload the bentonite jacketed UFC, will be mounted on a chassis supported on two-four wheeled carts. The chassis will pivot on the carts when traversing curves. The fully laden weight of the arrangement will be approximately 95 tonne. The cask design will also incorporate an on-board UFC retrieval system (to withdraw the UFC should the primary drive fail), as well as gamma/neutron gates to enable the cask to connect with the corresponding UFC dispatch and receipt facilities. The cask is exempt from many of the design, testing and qualification requirements of the Transportation Packaging of Radioactive Materials Regulations (AECB 1990) since it is intended only for internal transfer of UFCs within the DGR facility. A general arrangement of the UFC transport cask is shown in Figure 3.

The cask has been designed to attenuate the radiation field from a loaded UFC to an on-contact dose rate of less than 1 µSv/h. The gamma and neutron attenuation is achieved through the use of steel and polythene in the cask construction; Annex 3 contains the shielding analysis.

A loaded cask will be moved from the UFPP jacketing and dispatch cell to the waste shaft headframe, where it will be driven into the waste-shaft cage for transfer underground. On arrival underground the cask will be pulled, using a dedicated diesel locomotive, to an emplacement room for UFC emplacement, or to the component test area sidings where it will be held prior to transport to the emplacement room. These sidings will normally hold two casks to meet surge requirements (i.e. one-days operation). Following emplacement of the UFC, the empty casks will be returned to the surface. For normal operations within the DGR, four UFC casks will be required to satisfy both DGR throughput as well as surge storage and maintenance requirements.

The UFC emplacement process will begin with the positioning of the UFC cask in the emplacement room (Figure 18). The cask design will accommodate the necessary radiation shielding to allow for the presence of personnel within the emplacement room area, outside the mobile shield wall provided on the transfer/traversing table, during the emplacement operations. Shielding requirements have established that a laminate comprising of 50 mm of steel, 50 mm of polythene and a further 100 mm of steel, will be sufficient to meet the 1 µSv/h exposure design limit for workers involved during emplacement operations.

The jacketed UFC will be transferred from the cask by connecting its gamma/neutron gate assembly to the shield wall transfer port. Following the docking procedure, that includes the opening of both the cask gamma/neutron gate and the shield wall transfer port, the jacketed

UFC will be driven out of the cask onto the transfer/traversing table utilising a roller bed. The UFC will be supported on a support plate that will allow it to travel unhindered across the roller beds. With the UFC positioned on the transfer/traversing table the cask and shield wall gates and port will be closed to allow the removal of the empty UFC cask from the emplacement room.

A second dedicated cask carrying two bentonite shielding/sealing plugs will then be connected to the shield wall transfer port. Following the cask docking procedure, two shielding/sealing plugs will be transferred from the cask and positioned behind the jacketed UFC on the transfer/traversing table. This second cask has been designed to attenuate the radiation shine from the jacketed UFC positioned on the transfer/traversing table when the shield wall transfer port and cask gate are open. Calculations determined that a 20 mm thick steel cask provided sufficient shielding to reduce the surface dose rate on the cask to less than 1.0 µSv/h, during the end plug transfer operations.

The transfer/traversing table will allow the UFC and shielding/sealing plugs to be traversed across the room to the centreline of the emplacement location and onto an insertion cart. With the UFC and shielding/sealing plugs in place on the insertion cart, the cart will be moved forward into the emplacement location within the emplacement structure, guided by slots in the concrete floor.

This procedure will be repeated for a second UFC that will be located in the other key shaped slot (emplacement location) within that emplacement room. With both jacketed UFC assemblies in position in the blockwork structure the insertion carts will be lowered simultaneously, to minimise the possibility of deflections within the structure caused by uneven loading. The insertion carts will then be withdrawn, together with the UFC support plates, to allow the remaining slot beneath the two UFCs to be filled with pre-compacted dense backfill and buffer blocks. These are required to provide support to the UFCs and to radiologically shield personnel during the installation of the sealing materials for the next pair of UFCs. Radiation shielding calculations have established that, providing operations are carried out at least 1.25 m from the final UFC end plug positioned in the emplacement structure, these lower blocks may be located manually. These calculations, described in Annex 3, show that the dose rate reflected from the UFC within the emplacement structure will be less than 1 µSv/h at 1.25 m from the structure face with the lower blocks not in place. Any void between the UFC jacket and the buffer mass to be filled using dry granular bentonite and rounded sand mixture. This material will be installed pneumatically through a hollow lance inserted into the top gap formed between the buffer plugs and pre-placed blocks.

Various interlocks will be provided to prevent inadvertent operations, such as opening the cask gamma/neutron gate unless it is locked to the mobile shield wall. Interlocks will also prevent opening of the shield wall transfer port unless one of the two cask types were in position, or if there were confirmation there were no high levels of activity within the restricted area.

The massive construction required for radiation shielding will result in a robust cask that resists damage from handling impacts. If a loaded cask was subjected to a severe impact in handling, its interior could be monitored for any airborne contamination. If present, the cask would be wrapped in plastic to prevent the spread of contamination (i.e. containment) and returned to the UFPP for further examination.

3.3.5.3 Emplacement Room Sealing

The in-room emplacement design requires that emplacement rooms are sealed when all UFC emplacements within the room are complete. High-performance concrete bulkheads provide a means of closing the rooms to protect the integrity of the sealing materials. Without a bulkhead as an extrusion restraint, any volumetric expansion of the bentonite clay in the buffer would reduce the dry density of the clay and reduce its effectiveness as a sealing material. The bulkhead will also provide an opportunity for applying nuclear-materials safeguard containment/surveillance (C/S) measures that would allow detection of intrusion into the filled emplacement room.

Section 7.1 of Annex 5 discusses the issues regarding the positioning of the emplacement room bulkheads. Although specific analysis has not been undertaken, interpolation of results from emplacement room rock stress analyses carried out, suggests that the space between the last emplaced UFCs and the emplacement room sealing bulkhead should be of the order of one emplacement room diameter. However, because this precise distance does not have a significant effect on the DGR layout (and ultimate cost), a separation distance of I m, similar to that used in [4] has been used in the conceptual design presented. The actual separation distance required will need to be established during the detailed design stage of the DGR.

The emplacement room sealing bulkheads will normally be monolithic concrete plugs 12 m thick, formed and poured directly within the room perimeter. Once poured the final operation will be to cement grout the rock/concrete interface and the surrounding rock mass, as appropriate, for the excavation damage zone (EDZ) and natural fracturing conditions.

Under certain circumstances, such as significant excavation damage resulting in an increased permeability zone, the bulkhead performance may be enhanced by using a keyed bulkhead and a bentonite element i.e. gasket, to interrupt the groundwater flow pathway along the EDZ. For such purpose, the notch cut into the rock surface to accept the keyed bulkhead and bentonite should be of the appropriate dimensions to seal the high-permeability EDZ over a reasonable length.

The complete filling and sealing of an emplacement room will require an average of 67 working days for the placement of 6500 precompacted blocks and 108 UFCs in the 315 m long room.

It is estimated that the clay-based sealing materials and the emplacement room rock surfaces can be prepared in one day. This would include the placement of a water-tight barrier between the clay based sealing materials and the bulkhead’s back form wall. The water-tight barrier would be developed and tested during the UCF Design and Test phase. With respect to the emplacement room rock surfaces, they will be scaled of loose material then washed with water and blown dry with compressed air.

The concrete will be poured continuously, thereby requiring a 24-hour per day operation. Due to the massive size of the bulkhead, it is estimated that such a pour could require approximately 500 hours or 21 days for the placement of concrete. The time constraint is to provide for proper curing and cooling of concrete. Improper heat dissipation can lead to cracking of the concrete mass. Once properly cured a further week will be required for stripping the bulkheads exterior formwork and grouting the bulkhead’s perimeter.

3.3.5.4 Tunnel and Shaft Sealing

The sequence of access tunnel sealing would be to seal the perimeter and panel tunnels in a retreat fashion from the upcast shaft towards the service shaft complex while the central access tunnels are kept open for ventilation and access purposes. Local ventilation systems using portable exhaust fans and duct tubing will be installed and exhausted into the flow-through ventilation system. The central access tunnels will be 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 will be used to draw air from the work area to exhaust it into the return-air tunnel.

Two types of backfill material will be used for the tunnels, namely:

- Lower dense backfill, similar to that used in the emplacement rooms, consisting of 70% crushed granite, 25% glacial lake clay and 5% bentonite
- Upper light backfill, comprising 50% crushed granite and 50% bentonite.

The lower backfill materials will be transferred to the appropriate tunnel using mixer trucks and load haul dump vehicles will be used to place the backfill in the tunnels at the working location. A load haul dump vehicle modified with a suitable roller will compact the backfill to the desired density using a number of roller passes. The lower 2.2m of the 4.2m high tunnels will be filled by dense backfill placed and compacted by this method.

The upper light backfill will be placed pneumatically because of the limited headroom in the tunnels. The upper backfill will be transported to the tunnels in suitable trucks and transferred to material-receiving and air transfer units at an appropriate location in the tunnel. An air pipeline will move the backfill to the nozzle on a mobile trailer located at the working face. Special ventilation may be required to control dust in the working environment because of the fine particle size and low moisture content of the materials.

It is envisaged that an assemblage of sealing material blocks would be placed in conjunction with a concrete bulkhead to form a sealing bulkhead at strategic locations along the tunnels, for example on both sides of an intersected fault. This is described in more detail in Section 3.3.5.3.

Shaft sealing is the last step in sealing the underground facility. The backfilling of the tunnels and ancillary areas will be complete at the shaft bottoms. All shaft services and shaft furnishings will be removed together with all shaft concrete liners.

The shafts will be sealed using dense backfill comprising 70% crushed granite, 25% glacial lake clay and 5% bentonite. A multi-tier working platform will be used to deliver, place and compact the dense backfill to the required density. The backfill material will be prepared at the surface and transported down the shafts in buckets. It will be spread in layers of approximately 150 mm compacted thickness with the compaction being carried out using vibrating compactors to obtain the required density.

A number of sealing bulkheads will be placed at strategic locations, as required, in each of the shafts. These shaft seals will be of similar construction to those used for tunnel sealing.

3.4 DESIGN OF SURFACE FACILITIES

3.4.1 General Requirements

The DGR facility will be a self-contained complex. It will include the used fuel packaging plant (UFPP) and all the surface facilities associated with UFC emplacement operations, such as the waste shaft and service shaft headframes, the concrete batching plant, the backfill preparation plant and the rock crushing plant. In addition, it will include the auxiliary facilities that contain all the required operational and personnel services such as the auxiliary building, administration building, powerhouse, warehouse, fire hall and security building and waste management facilities.

This section describes the site layout and assesses the land requirements. A proposed layout and detailed description is presented for the major non-conventional buildings such as the UFPP and the sealing materials compaction plant.

3.4.2 Site Layout

The site layout of the DGR is shown in Figure 19. The facility is laid out such that all buildings that have or handle radioactive, or potentially radioactive material will be located in the inner active zone and are separated from other buildings by a security fence. The main facilities located in the inner zone are the UFPP, discharge stack, waste shaft headframe, service shaft headframe, downcast ventilation shaft fan house, solid and liquid waste management facilities, storm delay pond and the auxiliary building. The active area security fence will be provided with lighting and visual and automatic intruder detection systems. Personnel and vehicular access into the active area will be controlled through gates provided with radiation monitors and security check-points.

Located in the inactive zone are the administration building and cafeteria (buildings 7 and 17), concrete batching plant (area 30), the rock crushing plant (area 31), sewage treatment plant and pond (area 37). Other facilities included in the inactive zone are the water treatment plant (building 27) and water storage tanks (area 26), fuel tanks (area 25), hazardous material storage building (building 39), transformer area (area 21), powerhouse (area 24), warehouse and storage yard (building 19, area 36), service shaft complex water settling pond (area 40), process water settling pond (area 32) and the quality control offices and laboratory (building 29).

Straddling the active/inactive zone is the sealing materials compaction plant (building 18).

The layout of the buildings provides for the safe and efficient operation of the facility in terms of radiological zoning, material traffic patterns and interaction between the services provided by the different buildings.

3.4.3 Land Requirements

The land required to accommodate the proposed DGR covers an area encompassed within dimensions 3 km x 2 km, as shown in Figure 19. The DGR facility does not include provision for the disposal of low and intermediate level waste since it is assumed that this waste will be transported off site to a dedicated facility. The overall property boundaries provide for an exclusion zone of at least 1.0 km from the UFPP; similar to the exclusion zone provided for a CANDU-600 nuclear generating station. Since the UFPP stack is the only significant source of airborne emissions, there are no requirements for an additional exclusion perimeter.

3.4.4 Inner Zone Facility Descriptions

The following facilities will be incorporated within the inner secure zone of the surface facilities and will comprise facilities that may contain radioactive materials or those that give direct access to the underground workings.

3.4.4.1 Used Fuel Packaging Plant

The used fuel packaging plant (UFPP) is a two-storey reinforced concrete structure that incorporates the necessary plant and equipment to carry out the following tasks:

- Receive laden and dispatch empty used fuel off-site transport casks and also deal with transport casks requiring decontamination or maintenance
- Accept and discharge used fuel bundles from shipping/storage modules or dry storage baskets
- Provide buffer storage for fuel modules and dry storage baskets
- Repack used fuel bundles within UFCs
- Purge, seal, weld, inspect and decontaminate UFCs
- Repair or replace any unacceptable UFCs
- Place acceptable UFCs within a bentonite jacket
- Export the UFC/bentonite jacket assembly to the DGR waste shaft headframe
- Store new UFCs and new UFC baskets
- Manage radioactive waste arisings from the UFPP operations.

The UFPP will be designed to undertake all the above tasks in a safe manner and to maintain operator dose under normal conditions to less than 2 mSv/annum.

Section 3.4.6 gives further details of the operations carried out in the UFPP. Elevations and plans of the proposed UFPP are shown in Packaging Plant Figures 20 and 21.

3.4.4.2 Used Fuel Basket and UFC Storage

Dedicated space for new used-fuel baskets and UFC will be provided within the UFPP to receive, store and despatch baskets and UFCs to the UFPP process as required.

The baskets and UFCs will be located in appropriate frames and will be provided with packaging to prevent damage during transport and to ensure that the items are protected from deteriorating during the storage period.

The capacity of the store will provide six weeks supply of baskets and UFCs at any time. This is consistent with the spare capacity of the used fuel surge pool that will run half full, leaving six weeks spare capacity. This equates to 50 UFCs and 150 baskets, leading to an overall storage area of approximately 420 m² for UFCs stacked two high, and a further 420 m² for baskets also stacked two high.

The storage area will be provided with a 20 tonne Safe Working Load (SWL) electrically operated overhead travelling crane, capable of handling the packaged UFCs and baskets.

The storage area will be heated and ventilated as part of the UFPP, with temperature and humidity held at levels to prevent moisture condensing on the items being stored.

3.4.4.3 Active Solid Waste Handling Facility

Solid intermediate and low level waste (ILW and LLW) will primarily emanate from UFPP operations with small quantities of mainly LLW arising from the packaging plant auxiliary building and filter changing operations carried out at various locations within the active handling area. To minimise transport and handling operations associated with the majority of this waste, the solid waste handling facility will be located adjacent to the UFPP.

The solid waste handling facility will have a direct connection to the UFPP sealed storage basket cutting cell to permit the transfer of basket sections for processing, packaging and subsequent export.

ILW processing will be undertaken within a shielded contained cell fitted with the means to remotely handle and process the waste. The ILW cell will provide means to sort, decontaminate and monitor solid wastes to enable it to be exported from the cell as ILW or LLW as appropriate. The ILW facility will also include the provision to package damaged fuel elements for subsequent emplacement within a UFC, or export from the cell within a shielded off-site transport cask. The need for a hot cell, shielded and equipped to process damaged fuel is likely to present the most onerous requirement in designing this facility.

The LLW handling area will consist of a series of radiological containments to allow sorting, volume reduction and packaging of the waste to be carried out by semi-remote/remote means. Provision will be included to monitor completed waste packages to provide an alpha-beta-gamma inventory prior to their export.

3.4.4.4 Waste Shaft Headframe

The Waste Shaft headframe will be constructed of concrete. The height of the headframe has been estimated to be 38m with the Koepe hoist being installed above ground in the headframe tower. Sufficient clearance will be provided below the hoist floor to provide for cage changes and loading of the casks.

As described in Section 3.3.5.2, the cask will be transported in a horizontal attitude.

In the event of an upset condition in the headframe, collar house, or transport of the UFC to the repository level in the shaft, a HEPA ultra-filtration system will be incorporated into the headframe’s design. The unit will be sized to handle an airflow of 30 m^3/s to contain the 20 m^3/s upcasting the Waste Shaft, plus 50% more for building leakage.

3.4.4.5 Downcast Ventilation Fan House

During the winter months, the Service Shaft will be heated to prevent freezing of the shaft and sheave wheels. A push-pull arrangement will be incorporated into the shaft ventilation design, with a blowing fan on the surface and a suction fan located underground. The surface fan for this application will be a low pressure type, requiring only enough power to overcome the back-pressure of the associated duct work and air heating coils serving the Service Shaft's headframe.

Estimated duties are:

• Service Shaft Surface Fan	190 – 260 m^3/s
• Service Shaft Underground Fan	140 – 240 m^3/s

3.4.4.6 Auxiliary Building

This facility will include offices, radiation and industrial safety laboratories, change house and mine dry. The building will be a 2 storey steel framed structure with basement and will have a 3,500 square metre foot print providing a total gross floor area of 10,500 square metres.

Building Composition:

Roof
Insulated protected membrane roofing on metal deck.

Walls
Exterior Walls: Preformed insulated wall metal panels.
Insulated masonry cavity dado wall to 2.4 m above grade.
Internal Walls: Concrete block in high traffic areas.
Gypsum board on metal studs (demountable in office areas).

Floors
Non-dusting hardener treatment applied to areas with exposed concrete.
Quarry tile or similar ceramic tile for change rooms and lockers and health physics areas.
Vinyl composite tiles in areas requiring higher degree of finish than exposed concrete.
Carpet in office areas.

Ceilings
Exposed structure with fire protection as required in shops area.
Suspended gypsum board in areas requiring fire protection and a higher degree of finish other than exposed structure.
Suspended acoustic tile in all other areas.

3.4.4.7 Remaining Inner Zone Facilities

Other facilities will be provided within the inner zone of the surface facilities and these will include:
Discharge Stack

Service Shaft headframe
Waste Management Area
Active Liquid Waste Treatment and Storage

These facilities essentially remain as described in [4], and therefore are not described in detail in this document.

3.4.5 Outer Zone Facility Descriptions

The following facilities will be incorporated within the outer zone of the surface facilities and will comprise facilities that do not contain radioactive materials.

3.4.5.1 Sealing Materials Compaction Plant

A more detailed description of the facility is given in Section 3.4.8.

This facility will receive component materials for the manufacture of bentonite, buffer and dense backfill blocks. This will include crushed granite from the rock crushing plant that uses excavated rock from underground excavations. These materials will be transferred to a series of storage bins within the facility.

This facility will also receive component materials for the light backfill that will be transferred to storage bins. This will be pneumatically transferred to the service shaft for despatch underground.

The bentonite and buffer material and dense backfill are formed into compacted blocks within the sealing materials compaction plant.

Completed blocks are conveyed from the compaction machines to the block-loading bay where blocks are inspected, sorted and placed on rail flat cars. The blocks are grouped logically on the flat cars, with blocks for the bentonite jacket being despatched to the UFPP for placement around the UFC. The remainder, that have been arranged to provide the desired combination of blocks for emplacement in the emplacement rooms are despatched to the waste shaft where they are transferred underground on the rail cars.

3.4.5.2 Administration Building

Administration building will include offices, fire hall and cafeteria. The building will be a two storey steel frame structure with basement and will have a 8,000 square metre foot print providing a total gross floor area of 24,000 square metres.

Building Composition:

Roof
Insulated protected membrane roofing on metal deck.

Walls
Exterior Walls: Preformed insulated modular metal panels with an integrated curtain wall glazing system.

Internal Walls: Concrete block in high traffic areas. Gypsum board on metal studs (demountable type in office areas).

Floors
Non-dusting hardener treatment applied to areas with exposed concrete.
Quarry tile or similar ceramic tile for washrooms and kitchen area.
Vinyl composite tiles in areas requiring higher degree of finish than exposed concrete.
Carpet in administration office areas.

Ceilings
Exposed structure with fire protection as required in fire hall and service area.
Suspended gypsum board in areas requiring fire protection and a higher degree of finish other than exposed structure.
Suspended acoustic tile in all other areas.

3.4.5.3 Garage/Warehouse

This facility will include maintenance shops, repair bay warehouse and storage yard. The building will be single storey pre-engineered steel structure with a total gross floor area of 10,500 square metres.

Building Composition:

Roof
Pre-finished insulated metal.

Walls
Exterior Walls: Pre-finished insulated metal.
Internal Walls: Concrete block in high traffic areas.

Floors
Non-dusting hardener treatment applied to areas with exposed concrete.
Vinyl composite tiles in washrooms and office areas.

Ceilings
Exposed structure.
Suspended acoustic tile in washroom and office areas.

3.4.5.4 Quality Control Offices and Laboratories

This facility will include offices and laboratories. The building will be single storey with basement and will have a gross floor area of 6,000 square metres.

Building Composition:

Roof
Insulated protected membrane roofing on metal deck.

Walls

Exterior Walls: Preformed insulated modular metal panels with an integrated curtain wall glazing system.
Internal Walls: Concrete block in high traffic areas. Gypsum board on metal studs (demountable type in office areas).

Floors
Non-dusting hardener treatment applied to areas with exposed concrete.
Quarry tile or similar ceramic tile for washrooms and kitchen area.
Vinyl composite tiles in areas requiring higher degree of finish than exposed concrete.
Carpet in office areas.

Ceilings
Exposed structure with fire protection as required in fire hall and service area.
Suspended gypsum board in areas requiring fire protection and a higher degree of finish other than exposed structure.
Suspended acoustic tile in all other areas.

3.4.5.5 Powerhouse

The powerhouse will house the standby power generator and related equipment. The building will be a steel structure with pre-finished insulated metal wall panels.

3.4.5.6 Fuel Storage Tanks

Fuel storage tanks will be installed in a lined containment area. Fuel will be pumped to the standby generator and other users on site. A metered fuel dispensing station will be provided next to the storage tanks.

3.4.5.7 Compressor Building

Air compressors will be housed in a pre-engineered building with steel structure and insulated metal wall panels

3.4.5.8 Water Storage and Distribution

The source of fresh and fire-fighting water will be a local river or lake upstream from the surface facility’s watershed. Two water storage tanks will be provided, one to store fresh and fire water the second to store potable water. The potable water treatment plant, potable, fresh and fire-water distribution pumps will be will be housed in a pre-engineered building.

Potable, fresh and fire-water will be distributed around the site in buried pipelines. Hydrants will be strategically located to provide protection for all the facilities.

3.4.5.9 Sewage Treatment Plant

Sewage will be collected from all the serviced buildings and piped by gravity to the sewage treatment plant. The treatment plant will be designed to meet effluent discharge quality. The effluent will discharge to the local drainage course. The treatment plant will be house in a pre-engineered enclosure.

3.4.5.10 Mine Water Settling Pond

Mine water pumped from mine dewatering sumps will be piped to the service shaft complex settling pond (Figure 19, Area 40). The water from the pond will be monitored and treated for contaminants at the sewage treatment plant (Figure 19, building 37) to ensure it meets effluent discharge quality prior to either discharge to the local drainage course or sent for re-use underground.

3.4.5.11 Storm Water Run off Holding pond

Storm water run off from the site, including the waste rock disposal area (Figure 19, area 33), will be directed to the storm water holding pond (Figure 19, area 16). As in the case of Section 3.4.5.10, water from this pond will be monitored and treated for contaminants at the sewage treatment plant prior to discharge to the local drainage course.

3.4.5.12 Concrete Batch Plant and Rock Crushing Plant

Concrete batch plant with rock crushing and screening facilities will be provided.

3.4.5.13 Waste Rock Storage Area

The area outside the outer security fence will be used for storage of waste rock generated from the excavation of the repository. The storm water run-off from this area will be redirected to the storm water run-off holding pond, where it will be monitored prior to discharge.

3.4.5.14 Remaining Outer Zone Facilities

Other facilities will be provided within the outer zone of the surface facilities and these will include:
Hazardous materials storage,
Substation,
Bag House,
Primary Exhaust Shaft and standby HEPA filtration bag house
Bag House
These facilities essentially remain as described in [2], and therefore are not described in detail in this document.

3.4.6 Detailed Description of the UFPP

Used-fuel handling operations will be performed in the used-fuel packaging plant (UFPP). The associated hazards require remote operation, reliable process systems and special support facilities. All used fuel handling processes are assumed to be capable of meeting nuclear material safeguard measures that the International Atomic Energy Agency may formulate for spent nuclear fuel repository facilities.

The UFPP will be a two-storey reinforced concrete structure, designed and constructed according to Canadian practice for concrete containment structures of the CANDU nuclear generating stations (CSA 1982), that also accommodates seismic loading (CSA 1980). Plans and elevations indicating the various facilities within the proposed UFPP are shown in Figures 22 and 23.

Packaging plant operations include the receipt of used fuel bundles in two cask types; one containing modules and the other containing storage baskets (see Section 3.4.6.1). The modules provide a package to restrain the fuel bundles during (either wet or dry) storage and transport, allow direct access to the fuel bundles and do not provide containment. Following removal of the fuel bundles the modules may be re-used. The baskets are sealed and, while also providing restraint, require cutting open to access the fuel bundles within. After this procedure a basket can not be reused and will be sent to the Active Solid Waste Handling Facility.

Three process cells are included within the UFPP for receipt of used fuel transportation casks. Two of these cells are dedicated to the receipt and handling of used fuel bundles within modules, as these make up 90% of the throughput. A third cell is dedicated to the receipt and handling of used fuel within sealed storage baskets, which require a more complex handling procedure.

Once fuel bundles have been removed from the modules and baskets and placed into UFC baskets within the two handling cells, one dedicated to modules and the other to both modules and baskets, the UFC baskets will be placed into UFCs using one of the two UFC packaging process lines. Each UFC process line starts from a fuel handling cell and finishes with the completed UFC assembly within a UFC transport cask ready for delivery to the waste shaft headframe. Both UFC processing routes are identical.

The used-fuel bundles are transferred from the shipping modules or sealed baskets to used fuel container (UFC) baskets. Each of these baskets contain 108 fuel bundles in two layers of 54. Three baskets are installed within a UFC that comprises a carbon steel load bearing inner vessel within a corrosion-resistant copper shell.

A storage pool is provided to allow wet storage of up to three months delivery of fuel modules and a dry store is incorporated to allow the storage of six weeks deliveries of sealed baskets.

Other operations undertaken in the UFPP include UFC purging, sealing and welding, inspection of UFC welds, repair and/or rework of failed UFCs and decontamination of the completed UFC. The final process within the UFPP involves placing the completed UFC into a bentonite jacket and transferring the whole assembly into the UFC cask for onward movement underground.

The UFPP will process approximately 370 UFCs per annum by operating three parallel packaging lines; two capable of processing modules, and one processing sealed baskets. The plant will operate notionally 230 days per annum, five days per week, on a two, eight-hour shift/day basis

3.4.6.1 Used Fuel Receipt and Storage

Used fuel will be received at the repository by road, contained in one of two types of packages depending upon on the storage facility from where it originated. Used fuel stored at facilities in shipping/storage modules (Figure 24) will be transported to the DGR in the OPG Irradiated Fuel Transportation Cask (IFTC). This includes all fuel coming from OPG facilities.

Used fuel stored in sealed storage baskets (Figure 25) will be transported to the DGR in a cask designed to accommodate three such dry storage baskets. Fuel in dry storage or in trays in wet storage at AECL, Hydro-Québec and New Brunswick Power sites will be transported in this type of cask.

The rectangular shaped IFTC shown in (Figure 24) is designed to accommodate two shipping/storage modules one stacked on the other and each containing 96 fuel bundles. The IFTCs overall dimensions are 1881x1556x1824 mm (excluding protrusions and attachments). The lid is secured by 32 bolts and is sealed using two 'viton' elastomer O-rings. An impact limiter is bolted to the upper end of the IFTC that also serves as a heat shield in case of local fire. Two trunnions are fitted to the body of the IFTC to facilitate lifting the cask. The IFTC is also fitted with a drainage port near the bottom and a vent/test port on the lid. Both these ports can be used for leak testing as well as a further port at a point on the lid seal. The all up weight of the IFTC is 34.7 tonnes. A full description of the IFTC and its handling procedures is given in [38].

The irradiated fuel dry-storage basket cask design is only in the conceptual stage. However, for the purposes of this work the cask is assumed to be similar in design to the IFTC, but of cylindrical construction as shown on Figure 26. The cask lid will be secured and sealed in a similar fashion to the IFTC as well as being protected by a similar impact limiter. In all other respects the basket cask can be assumed to contain the same features and fittings as the IFTC and will adopt the same handling procedures.

The two types of cask are unloaded by lifting the loaded modules or baskets vertically out. Similarly both casks are capable of being loaded and unloaded within a pool (wet) or by connecting the cask to a specially designed dry cell. Dry unloading is the adopted procedure for the DGR Facility. This will be accomplished by coupling the fuel cask to the unloading port in the appropriate UFPP receiving cell.
On arrival of a transport trailer within the UFPP receipt bay, the IFTC will be placed on a cask transporter using the receipt bay's 40 tonne overhead travelling crane (OTC). Alternatively, the cask may be transferred to the shielded cask buffer storage area in the receipt bay for temporary storage, utilising the OTC.

Following removal of the casks impact limiter, the cask transporter will be driven to the relevant cask vent cell; two dedicated for IFTCs containing used fuel modules, and one dedicated to IFTCs carrying sealed used fuel baskets.

The cask vent cells permit man access to a cask to facilitate venting and lid bolt removal on cask import. During empty cask export, the cell is used to replace the lid bolts, pressure test the lid seals, check for surface contamination and possible decontamination of the cask and/or cart.

With lid bolts removed the transporter will position the cask beneath the appropriate receiving cell port and raise it until the cask top flange is sealed against the port containment door. The receipt cell gamma gate will then open to allow the containment door together with the cask lid to be remotely lifted in to the cell. This procedure will maintain the cleanliness of the cask lid outer surface and minimise the need for routine decontamination of the cask lid on its removal from the cell.

Depending on the state of the UFPP operations, modules will be either transferred directly to the fuel handling cell cart utilising the receipt cells OTC for onward movement to the fuel handling cell (Section 3.4.6.3), or to the surge-storage pool. In the latter case, the modules will be lowered into the pool on an inclined elevator, and transferred using the pool manbridge and module-handling tool into secure stacking frames within the pool (Figure 27). The modules will be retrieved to the receipt cell by reversing this storage sequence.

Following drying in the receiving cell booth, modules will be loaded onto the handling cell cart utilising the receipt cell OTC for transfer to the fuel handling cell.

Depending on the state of the UFPP operations, baskets are either transferred directly to the fuel handling cell transfer cart utilising the overhead crane for onward movement to the fuel handling cell (Section 3.4.6.3), or to the dry basket buffer store, see Figure 23. In the latter case, baskets will be transferred to the storage area within the receipt cell using the receipt cell OTC and placed in an appropriate position. Baskets are retrieved and transferred to the fuel handling cell cart utilising the OTC, allowing baskets to be transferred to the basket cutting and fuel bundle transfer cell.

The probability of a transportation cask being damaged on receipt, or of safeguards seals being broken, is low. In this event, the cask would be transferred to the cask vent cell that is accessible from the receiving and shipping area. This operation is essential for any damaged casks. The operations in this cell will likely be manually controlled because of the wide variability in the possible physical condition of the transport cask and will be limited to those activities that may be required to allow the damaged cask to be returned to the consignor for full repair.

3.4.6.2 UFC and UFC Basket Receipt and Storage

UFCs and used-fuel baskets will be fabricated at an off-site facility and transported to the DGR site. A segregated area is provided within the UFPP for receipt, inspection and storage of new UFCs, their top heads and the carbon steel baskets. The receipt and storage area is located at ground floor level at the end of the UFPP building, with the storage area served by a 20 tonne OTC. The storage area is sized to accommodate sufficient new UFCs and baskets to satisfy six weeks UFPP production requirements.

Inspection facilities are provided to ensure complete dimensional and fabrication quality control of the new UFCs and baskets.

New UFCs will be stored within their transport packaging to minimise potential damage. On demand a packaged UFC will be placed on a transport cart using the in–store 20 tonne OTC, prior to being transferred in to the new UFC loading cell. At this point the packaging will be removed and the UFC inspected before being lifted, using the in-cell 5 tonne OTC, into the UFC shielded cart, previously set in the horizontal orientation with its detachable lid removed.

The same new UFC transport cart will be utilised to transfer pre-prepared bentonite jackets into the jacketing cell through a second door within the new UFC loading cell. These pre-prepared jackets will be off loaded and handled using the in-cell 30 tonne OTC. Further details of the UFC bentonite jackets are given in Section 3.4.6.3.

New UFC baskets are posted into the fuel handling cells via a transfer tunnel beneath and connecting the two cells. The transfer tunnel will be served by a rail car capable of carrying three baskets. The baskets will be lifted from the rail car by the in-cell 8 tonne OTC, through a floor-mounted port protected by a gamma gate/containment hatch.

3.4.6.3 Used-Fuel Packaging

Two dedicated receipt lines are provided to transfer fuel bundles within modules to either of the two fuel handling cells. One further receipt line is dedicated to handling and transferring fuel bundles from sealed baskets to one of the two fuel handling cells.

Used-fuel modules can be received at one of the two fuel handling cells, either directly from the transport cask, or from the surge pool, in which case they are dried prior to being transferred to a fuel handling cell.

Within a fuel handling cell, modules will be placed in the fuel handling machine where an empty basket will also be loaded in a horizontal position. The basket will be positioned using lateral and rotary motion so that the fuel bundles can be transferred to all positions of the basket (Figure 28). Individual fuel-bundles will be transferred sequentially from the module using a transfer carousel, into one of the 54 carbon steel tubes that comprise the basket. The fuel bundle end plates can be cleaned during this operation so that the manufacturer and serial numbers can be read and recorded for accountancy purposes. If required, a gamma-radiation monitor may be employed to measure the magnitude and energy spectrum of the radiation being emitted from each bundle to confirm the presence of used fuel for nuclear safeguards purposes. In the event that a bundle is damaged during shipping or handling so it is unable to be transferred to a basket, or cannot be adequately identified and needs further examination, it will be transferred into a special handling area using a bundle-retrieval service ram (Figure 28).

When a module is empty the operation will stop and the empty module will be returned to the receipt cell for despatch in an empty transport cask. Another module will then be delivered to the fuel handling cell. When a basket is filled with 108 fuel bundles (two layers of 54), the used-fuel transfer operation will stop and the basket rotated to the vertical position. The filled basket will then be transferred in the vertical orientation to the UFC loading station.

Sealed dry storage baskets will be received either directly from the transport cask, or from the receipt cell dry storage area, and located in a sealed storage basket (SSB) rail car within the irradiated fuel dry storage basket receipt cell. The SSB rail car, will incorporate an on-board turntable, and will then be transferred to the basket cutting cell. Within this cell the SSB rail car will be positioned next to the basket cutting machine, and using the on-board turntable the basket top section will be cut from the fuel carrying lower portion. The basket top will then be removed and discharged to the active solid waste handling facility skip. With the fuel bundles within the storage basket now accessible, the SSB rail car will be advanced in to the fuel bundle transfer area. The storage basket cutting and fuel bundle transfer sequence is shown in Figure 29.

Prior to bundle transfer, a UFC basket rail car carrying an empty UFC basket will be parked in the fuel bundle transfer area. When positioned, an array of fuel bundle support rods mounted on the UFC basket rail car beneath the basket, will be raised. These rods take up the space in the UFC basket normally occupied by the lower layer of fuel bundles to allow the first layer of fuel bundles to be placed within the basket using the fuel bundle transfer machine.

The fuel bundle transfer machine will be a remotely operated grab, fitted to a carriage running on rails that in turn will be mounted on an overhead steel frame. The machine will allow for the grab to traverse in the x, y and z directions to permit any bundle to be withdrawn from the cut storage basket and placed in any location within the UFC basket. The grab will grip each bundle end plate and transfer the bundle in a vertical orientation. With all of the UFC basket tubes filled, the fuel bundle support rods will be lowered to allow further fuel bundles to be loaded in the upper layer of the UFC basket. Damaged fuel bundles withdrawn from the storage basket may be placed in storage cans for possible future loading into a purpose designed UFC for subsequent emplacement within the DGR.

When the UFC basket is fully loaded, the UFC basket rail car will be driven from the fuel bundle transfer machine and into the fuel basket handling cell. The handling cell 8.0 tonne OTC will then lift the full basket from the rail car and place it either within a waiting UFC, or in an appropriate laydown area to await the batch filling of UFCs.

When storage baskets are empty, the SSB rail car will be removed from the fuel bundle transfer machine to allow the empty basket to be lifted from the rail car and transferred to the active solid waste handling facility skip. The SSB rail car will then be returned to the basket receipt cell to await the next storage basket.

The top and bottom sections of the used-fuel basket will be despatched to the Active Solid Waste Handling Facility via a waste transfer port within the floor of the basket cutting cell. The port will allow access to a waste receipt skip capable of being connected to the underside of the port and protected using a gamma gate assembly within the cell. The Active Solid Waste Handling Facility will sort, package and monitor the waste received prior to its export off-site to dedicated low and intermediate level waste treatment and disposal facilities. A further description of the operations and contents of the Active Solid Waste Handling Facility is given in Section 3.4.6.4.

An empty new UFC, with the inner vessel steel lid in position, will be placed horizontally in a UFC shielded cart located within one of the two new UFC loading cells that serve the two UFC packaging lines. With the shielded cart detachable lid in place, the shielded UFC will be turned to the vertical. Once in this orientation the cart will be driven from the UFC loading cell and along its packaging line transfer tunnel to be connected to the UFC loading port beneath the fuel handling cell. Figure 30 shows the general arrangement of these operations.

Connecting the UFC to the fuel handling cell port will be carried out by raising the UFC within the shielded cart, using the cart onboard lifting table, to seal with the underside of the cell containment door beneath the ports gamma gate. With the gamma gate opened, the containment door will be lifted into the cell together with the UFC steel vessel inner lid. This procedure will expose the UFC inner steel vessel internals to the cell atmosphere while protecting the outside surfaces of the UFC assembly (and shielded cart) from cell borne contamination.

At this stage three filled used-fuel baskets will be loaded into the UFC using the in-cell 8 tonne OTC prior to the inner vessel steel lid being replaced. The steel lid outer surface will remain free from contamination courtesy of its seal with the containment door. Closure of the cell gamma gate and lowering of the loaded UFC allows the shielded cart to be transferred to the sealing cell.

Connections to all four subsequent UFC processing cells will utilise a similar docking arrangement to that adopted for the fuel handling cell, except that because these cells will notionally be free of air borne contamination, containment hatches/doors will not be required. However, to protect man entry within any of these cells from a passing loaded UFC each cell will be provided with a gamma gate assembly.

Following docking at the sealing cell, the inner vessel steel lid will be remotely bolted into position prior to connections being made to the lid apertures to allow the vessel contents to be evacuated before being replaced with an inert gas. After filling the UFC with inert gas, connections will be removed and the lid apertures plugged and sealed prior to withdrawing the UFC from the cell.

At the UFC lid welding station the copper lid will be placed on the UFC and electron beam welded into place. The copper lid circumferential weld will then be subjected to radiographic examination at the subsequent lid weld inspection cell, followed by independent ultrasonic testing of the weld within the same cell. For further description of the non-destructive UFC testing proposed, refer to Section 4 of Annex 1. Should the weld be satisfactory the UFC will be transferred to the UFC receipt cell by lifting it from the shielded cart through an open port, using the in-cell 25 tonne OTC. Within this cell the completed UFC will be remotely swabbed to establish levels of contamination. Should the UFC be found to be contaminated it will be remotely decontaminated before being re-checked for any residual contamination. The clean UFC will then either be transferred to a ‘passed’ UFC holding bay to await delivery to the UFC jacketing cell or delivered to the jacketing cell direct.

If weld defects are found, these will be rectified where practical and re-checked to allow the UFC to proceed to the UFC receipt cell. Should any major faults occur that can not be rectified, then the UFC will transferred to the failed UFC lid removal cell where the UFC lid is cut off and removed, leaving the inner steel lid in place. The UFC will then be transferred to the inerting cell where the inner steel lid bolts will be removed. The UFC will then be transferred to the fuel handling cell where the steel lid will be removed to allow the UFC fuel baskets to be unloaded for packaging in to another UFC. The now empty failed UFC will be transferred to the new UFC loading cell where the failed UFC will be checked for contamination and possible decontamination, prior to establishing whether to salvage or condemn it as secondary waste.

UFCs that satisfy all quality assurance requirements will be transferred from the UFC receipt cell using the in-cell 30 tonne OTC through a floor mounted port in to the UFC jacketing and dispatch cell. Within this cell a bentonite jacket will be fitted over the UFC to protect it from mechanical damage during the emplacement operation. This process is illustrated in Figure 31. Two pre-compacted bentonite blocks will be introduced into two half section tilting frames set in the horizontal attitude. The bentonite block that forms the bottom half of the jacket will be located on a support plate. A cylindrical tapered base plug will be positioned on the bentonite block that forms the top half of the jacket. The two tilting frames will be raised to the vertical orientation and moved into contact with the UFC that is being held by the in-cell 30 tonne OTC. Following the closure of the two halves of the tilting frame and the release of the UFC from the OTC, a bentonite plug will be positioned on top of the UFC to complete the jacket. The whole assembly will then be lowered to the horizontal and the jacket clamp removed from above the UFC. The jacketed UFC located on its support plate will then be transferred utilising roller beds into the UFC cask for transfer to the Waste Shaft via an enclosed corridor.

3.4.6.4 Active Solid Waste Handling Facility

The solid ILW/LLW active solid waste handling facility will be located within the UFPP complex, in an area adjacent to the basket cutting cell. The facility will comprise a suite of shielded remote handling cells, to manage potential gamma emitting wastes, linked to a series of LLW radiological containment areas to process LLW by remote means or by personnel subject to controlled access to specific areas. The shielded cells will allow the import of potential ILW, its sorting, segregation and possible decontamination by various means. The cells will permit either shielded or unshielded waste export, depending on the waste categorisation. The LLW handling area will allow sorting, volume reduction and packaging of waste prior to its monitoring and subsequent export from the facility.

The UFPP sealed fuel basket cutting cell will be connected to the waste management facilities shielded waste receipt cell via a floor mounted transfer port protected by an alpha sealed gamma gate. A skip within the receipt cell will be capable of being connected to the underside of this port to allow cut sections of fuel baskets and possibly damaged fuel elements, identified during basket cutting operations, to be loaded. The scissor lift mounted skip will transfer waste to the receipt cell working area. Here large items will be lifted from the skip via an in-cell 0.5 tonne OTC on to a handling trolley fitted with the requisite jigs and fixtures to hold and secure the items of waste to be processed. Examples of items to be handled in this manner will include:

Basket base plate	1 m diameter x 19 mm thick	133 kg
Basket top plate	1 m diameter x 9.5 mm thick	67 kg
Basket tube	1 m diameter x 0.5 m high x 9.5 mm thick	132 kg

The shielded cell suite will be provided with facilities to remotely swab trolley mounted items to monitor levels of contamination and to decontaminate if necessary using dry techniques. A further downstream area will be available within the confines of the shielded cell to decontaminate items using wet techniques should this be required.

The ILW cell facility will be provided with a transition zone to allow the safe export of decontaminated items of waste into a radiologically contained area. This transition will include an alpha seal gamma gate to allow the handling trolley to transfer decontaminated waste items from the cell and into the contained area. With the cell gamma gate closed this area will be accessible to operators equipped with suitable personnel protective equipment. Within this area waste will be re-monitored to verify it conforms to LLW categorisation. Should this be the case the waste will be packaged in to standard LLW boxes/containers for export to a dedicated off-site LLW disposal facility.

Damaged fuel elements or parts of elements delivered to the receipt cell will be handled using the cell master slave manipulators (MSMs). The damaged fuel/fuel elements will be sealed into cans to await loading into a UFC specifically designated for the disposal of damaged fuel.

3.4.7 UFPP Ventilation

The ventilation system will be designed to provide the minimum air change rate through the spaces commensurate with compliance to current standards and codes of practice.

The principles used as a basis for minimising the throughput of air will be:

1. To minimise the airborne effluent arising (high air change rates encourage the generation of airborne particulate under fault conditions).
2. To reduce the waste arisings associated with the ventilation treatment equipment (disposal of dirty HEPA filters).
3. To reduce the capital cost of the ventilation plant.
4. To reduce the operating cost of the ventilation plant.
5. To reduce the maintenance cost of the ventilation plant.
6. To reduce the heating load of the fresh air supply.

To achieve the minimum throughput of air the ventilation system will be designed on the basis of cascading air through the building spaces. Fresh air will be supplied to a number of spaces in the building commensurate with achieving the air change rate and to generate the necessary movement of air from areas of lower potential contamination to areas of higher potential contamination.

Where air is cascaded from working areas into a Cell a HEPA filter will be provided at the Cell air inlet to ensure protection against back flow of contamination in the event of fault conditions

The air supply volume and the operating areas air exhaust volumes will be maintained at a constant value year round in order to properly control the environment within the building and maintain the operating stability of the systems. All operating areas within the building will be maintained at a small but uncontrolled negative pressure with respect to atmospheric pressure. All Zone 4 classified Cells (see below) will be maintained at a specific and controlled negative pressure.

All spaces within the building perimeter will be classified in accordance with the potential contamination criteria, ranging from Zone1 to Zone 4, in accordance with the definitions laid down in Table 9. Figures 32 and 33 show the general arrangement of the Used Fuel Process Plant (UFPP) indicating the Zone classifications of the building areas and the room identification numbers.

The lowest classification for any internal space within the building will be Zone 2. All classifications must however be verified by the appropriate RPA (Radiological Protection Adviser) as part of detail design. The classifications shown on the drawings reflect the initial considerations only.

Air change rates will be in accordance with the following general parameters:

Zone 2 (Corridor spaces). 1 – 2 air changes per hour.
Zone 2 (Working areas, low risk). 1 – 2 air changes per hour.
Zone 2 (Working areas, high risk). 5 – 10 air changes per hour.
Zone 3 (Operating spaces). 1 – 5 air changes per hour.
Zone 4 (Cells). 1 – 30 air changes per hour (determined by the process and any heat generation within the Cell).

Ventilation air will be extracted by three separate systems:

Zone 2, Space Exhaust.
Zone 3, Space Exhaust.
Zone 4, Cell Active Exhaust.

Zone 2 Space Exhaust air will not usually be HEPA filtered, but will be monitored for entrained activity.

Zone 3 Space Exhaust will be single stage HEPA filtered, with monitoring equipment provided after the filters.

Zone 4 Cell Active Exhaust will be filtered by two stages of HEPA filters, with monitoring equipment provided at the filters.

To offset the potential contamination hazard at each of the Cask/UFC Docking stations and the associated Gamma gates, local HEPA filtered inlet and HEPA filtered exhaust will be provided through the Docking Station enclosure, extracted by the Zone 4 Cell Active Exhaust system.

All Zone 4 Cells and the Docking Stations will each be automatically maintained under a controlled depression by automatic regulating devices provided as part of the Zone 4 Cell Active Exhaust system.

The air extracted by the Zone 2 and Zone 3 Space Exhaust systems will generate the required movement of air through the building spaces, with the resultant air velocity through openings sufficient to prevent back flow of contamination.

Figure 34 shows a block flow diagram of the ventilation arrangements within the UFPP (excluding the Control Room), and the airflow routes through the UFPP.

The spaces served by the air supply system, the volume of the supply air, and the extent of the Zone 2 and Zone 3 Space Exhaust systems, will be determined and verified as part of the detail design. The requirement for the filtration of the Zone 2 Space Exhaust system and the extent of the Zone 3 Space Exhaust filtration can only be determined by Hazard Assessment using the principles of As Low As Reasonably Practicable (ALARP).

3.4.7.1 Fresh Air Supply

Air will be delivered to the building spaces by a number of modular air handling units which will be installed in a Supply Air Plant Room. These units will each comprise frost protection heater, pre filter and main filters, a main filter, and a centrifugal air supply fan, and will operate on a run and automatic standby basis. All supply air to the building spaces will be ducted from the plant room, with branch ducts and air supply grilles serving each space. The air supply volume will be maintained at a constant value.

The heating applied to the fresh air will be sufficient to temper the air to room conditions only. The ventilation supply air will not be used to compensate for losses from the building during periods of low temperature.

No re-circulation of any air through the building will be provided, except in the case of the control room. The Control Room will be served with a separate re-circulating system with fresh air make up. Cooling will be provided to the Control Room only, to maintain comfort conditions in summer. Cooling will not be provided to any other space within the building.

3.4.7.2 Heating

All ventilation supply air to the building and the Control Room will be heated to room condition only. Ventilation air will not be used to offset the building fabric losses as there will be an insufficient volume of air to absorb the heating load. A piped distribution of heating services to space heaters fitted within the building spaces will be provided. The heating medium will be determined during the detail design development, which will be affected by economics at the time and the availability of suitable fuels.

Heating equipment will not be fitted within any of the Zone 4 classified spaces.

3.4.7.3 Air Exhaust

Air flow within the building will be induced to flow from areas of lower potential contamination to areas of higher potential contamination be means of the air exhaust system.

Three separate air exhaust systems will be provided. These are:

Zone 2 Space Exhaust.
Zone 3 Space Exhaust.
Zone 4 Cell Active Exhaust.

Each exhaust system will be stand alone, air being ducted out of each space via exhaust grilles. The Zone 3 and Zone 4 exhaust air will be continuously filtered by safe change HEPA filter banks to ensure compliance with statutory atmospheric discharge limits. Standby filters will enable filter changes to be carried out with the exhaust system operating. Automatic standby fans will be provided to ensure continuous and reliable exhaust airflow.

The HEPA filter banks will be housed in a separate and dedicated Filter Room.

The provision of HEPA filtration to the Zone 2 Space Exhaust system will be determined by a Hazardous Operations Assessment (HAZOP) during the detail design.

The air volume of the Zone 2 and Zone 3 Space Exhaust systems will each be automatically maintained at a constant value year round in order to properly control the movement of air through the building. The extract fans will be housed in a separate and dedicated Fan Room.

An automatic depression control device will be provided at the exhaust duct from each Zone 4 Cell in order to maintain the correct operating condition within each of these spaces. The Zone 4 Cell Active Exhaust system will be automatically regulated to provide a constant depression at the main exhaust duct such that the depression control devices at each Zone 4 Cell operates correctly to maintain the Cell depression as the exhaust HEPA filters within the exhaust system become dirty. The Zone 4 Cell Active Exhaust fans will be located with the Zone 2 and Zone 3 exhaust fans in the dedicated Fan Room.

The provision of charcoal filters for the removal of iodine are not envisaged due to the low iodine inventories.

All air extracted from the building will be discharged to atmosphere via a stack located outside the building.

3.4.8 Detailed Description of Sealing Materials Compaction Plant

Component materials used to formulate the buffer, dense backfill and concrete, must meet material specifications and inspections before they are approved for use in the DGR. Bulk carriers supply most of the component material, other than the crushed granite, which will be stored on the surface in the sealing materials storage bins or at the concrete batching plant.

Crushed granite and concrete used within the DGR will be produced at surface facilities located within the DGR facility. Full-time qualified operators and inspectors will monitor the production process to ensure the end products meet the specified requirements.

The surface located rock crushing plant will produce crushed granite with a size distribution suitable for the dense and light backfill and the high-performance, low-heat concrete. The crushing plant uses excavated rock brought to the surface from underground excavations. In total, approximately $1.16\text{x}10^6$ m^3 of granite rock will be excavated from the DGR underground openings during their construction. Of this approximately 40% or 470,000 m^3 will be returned as constituents within the various sealing materials, based on the material compositions given in Table 7 of [2].

The low-heat, high-performance concrete will be moved from the batching plant to the service shaft using rotating-drum trucks. The concrete pumping system in the service shaft delivers the concrete to a remixing and truck filling station underground.

The low-heat, high-performance concrete will be piped in batch loads to a concrete unloading area in the immediate Service/Production Shaft area (see Figure 14) from where it will be transferred to rotating-drum trucks sized for underground use.

Crushed granite and bentonite that constitute the light backfill raw materials will be transferred by pneumatic conveyors from the sealing materials storage bins to the service shaft. Buffer material and dense backfill will be formed into compacted blocks within the sealing materials handling plant and transferred to the waste shaft for onward movement to an underground receipt facility.

The batch mixing and block compaction areas will be located within the sealing materials handling plant. The material components will be taken from the bins in metered loads and mixed to prescribed process requirements. The batch mixing process comprises two batching circuits, any one of which can produce the desired dense backfill or buffer products as required.

To produce the dense backfill, crushed granite, glacial-lake clay and bentonite clay are simultaneously withdrawn from their bins and transferred by belt and screw conveyors respectively in the batching circuit, 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 will be adjusted by the metered addition of water into the mixer from the domestic-water storage tank. The dense backfill will be mixed until it reaches the specified degree of homogeneity by applying a method specification that will be periodically confirmed by sampling.

The mixing process for the buffer product will be similar to the dense backfill process. Bentonite clay and silica sand will be withdrawn and transferred to weigh hoppers by a screw conveyor, discharged into a rotary-pan mixer and water added and mixed until the desired material specifications are met. The buffer will then be transferred to the block compaction area by conveyor. Product quality is achieved by following a method specification that is confirmed regularly by material sampling and testing of grain size, moisture content, compaction and swelling characteristics.

The mixing process for the bentonite jacket components will be similar to the dense backfill process. Bentonite clay will be withdrawn and transferred to weigh hoppers by a screw conveyor, discharged into a rotary-pan mixer and water added and mixed until the desired material specifications are met. The bentonite will then be transferred to the block compaction area by conveyor.

From the batch mixers, bentonite, buffer and dense backfill material will be belt-conveyed to hoppers in the block compaction area. A number of block compaction machines (Figure 35) are located in the compaction area and spare capacity equating to 40% of the nominal throughput will be provided. The spare machines would be used when other machines are being serviced for mould and compaction head changeouts and repair/maintenance, or if the block production falls behind schedule.

Each block compaction machine receives material from the metering hopper located above the block mould. Enough material to form a 50 mm thick compacted layer will be poured from the metering hoppers into the mould of the compaction machine. The mould will be vibrated to level the material. The compaction head will then be lowered onto the layer of material when the mould will be strongly vibrated again, creating the desired compaction density. This process of material placement, levelling and compaction will be repeated until the block is completed.

Completed blocks are conveyed from the compaction machines to the block-loading bay where blocks are inspected, sorted and placed on rail flat cars. Blocks are grouped logically on the cars to provide the desired combination for assembly when they transferred underground via the waste shaft.

3.4.9 Description of Waste Shaft Facility

The Waste Shaft facility will consist of a surface headframe and collar house, hoisting plant, shaft and shaft station for off-loading the used fuel at the DGR elevation approximately 1000 m below surface.

The Waste Shaft headframe will be constructed of concrete. The overall height is 38.0 m to the top of the roof parapet which will provide sufficient room for tower mounting of the Koepe hoist, deflection sheaves and clearances for operation of the cage and cage change-out. A basement below the surface collar elevation will be provided for the installation of banking beams and tail rope inspection, as illustrated in Figure 4, Annex 7.

The hoist and shaft will be designed for the horizontal transportation of a cask containing a UFC jacketed in bentonite in an unshielded cage. The cage payload including railcar is estimated to be 95.2 tonne, with estimated cage mass of 38.1 tonne. The diameter of the shaft is 6.15 m. A counterweight will function with the cage with six ropes of 54 mm diameter each. The hoist diameter is 6210 mm and the RMS power requirement is 1420 kW.

The cage will have a floor designed as a platform that can slide within the framework of the cage. This allows the payload to be landed on banking beams while the weight of the tail ropes and major part of the cage remains suspended from the head ropes. This will eliminate rope stretch during loading.

The bentonite-jacketed UFC will be loaded in to a rail mounted cask within the packaging plant and transported to the collar house of the Waste Shaft headframe. It will be loaded in to the cage with the cage in the chaired position. Transportation in the horizontal position avoids lifting and re-orientation of the cask during transport from surface to underground and reduces the likelihood of damage to the jacketed UFC during the re-orientation process. The advantage of transporting the cask in the vertical position is that the diameter of the shaft is less than for horizontal transportation, although the costs are not significant (See Annex 7).

3.5 RETRIEVAL OF EMPLACED UFC

Review of work carried out by Lkalbantner et al [39] revealed that low pressure hydrodynamic removal of bentonite within the DGR emplacement rooms provided the method with the highest potential for the retrieval of emplaced UFCs. On this basis an outline scheme for the removal of sealing materials to allow retrieval of UFCs was developed and is described in this Section.

It should be noted that the low pressure hydrodynamic technique provides one method for retrieval of UFCs. However, there are a number of other basic techniques that could be used as the basis for alternative schemes, and these may include:

- Mechanical techniques, including full face boring, milling and core drilling
- Coal mining and soft earth tunnelling techniques
- Higher pressure hydrodynamic techniques
- Thermal techniques, and
- Electrical techniques

3.5.1 Preparatory Work

It has been assumed that access roadways will not have been sealed and will therefore provide free access to the sealing bulkhead at the end of the emplacement room. It was also assumed that the roadways will have been adequately maintained with no risk of major rockfalls, and that the emplacement room concrete sealing bulkhead will have been removed using conventional mining techniques and any required rock support will have been introduced.

3.5.2 Overview

The proposed method of retrieving an emplaced UFC will involve removing the sealing materials from below the UFC while introducing physical support, followed by the release of the buffer/dense backfill materials around the UFC and withdrawing the UFC into a cask for transfer to the required location.

3.5.3 Initial Setting to Work

The initial tasks will be to prepare the vertical face of the clay-based sealing materials to accept a gamma gate to give protection to workers when the retrieval process is carried out.

The gamma gate will be installed utilising a purpose designed trolley with on-board lifting equipment to locate the gamma gate and seal it to the floor and the face of the clay-based sealing materials. The grooves in the emplacement-room floor will be cleared of any residual clay-based sealing materials. Rails will be installed in line with the UFC to be retrieved (off set from the centre line of the emplacement room) located by the grooves in the emplacement-room floor, to within approximately 5 m of the clay-based sealing material. These rails will allow the introduction of equipment to the required position along the emplacement-room. The engineered spaces along the emplacement room concrete floor that were filled with sealing materials will be provided with a bridging structure to give support to retrieval equipment.

3.5.4 Removal of Lower Sealing Materials

A UFC support carriage will be positioned in front of the gamma gate, with a containment housing placed over it and sealed to the gamma gate as well as to the floor. The lower section of the gamma gate will then be opened to allow the UFC support carriage to be driven forward.

The service vehicle will be driven to the correct location behind the containment housing, the height adjusted utilising outriggers to ensure correct alignment, and the ram and services connected. Physical stops will be bolted to the floor of the emplacement room to prevent the service vehicle from moving during retrieval operations.

The UFC support carriage will accommodate a series of jets that will apply water at low pressures to remove the clay-based sealing materials as the carriage is progressively pushed forward utilising the service vehicle ram.

The UFC support carriage is equipped with a series of rollers that will come into contact with the UFC and support it as the carriage moves forward. Height adjustment will be provided to ensure that the rollers remain in contact with the UFC. This may be confirmed by utilising load sensors within the system. The main jets for sealing material removal will be positioned at the front of the UFC support carriage, but additional jets will be provided as required along the length of the carriage to ensure that the sealing material does not reassert itself and restrict the movement of the carriage.

Figure 36 shows the UFC support carriage at various stages of insertion into the emplacement structure.

Water will be supplied from the service vehicle via the ram, with the resultant slurry being removed from the containment housing by a pumping system also mounted on the service vehicle. A separate bowser will be provided to enable slurry to be transferred to the surface for treatment and disposal.

With the UFC support carriage located beneath the UFC, the service carriage ram will be retracted, the containment housing will be fully drained, the gamma gate closed and the containment housing and service vehicle removed.

3.5.5 Releasing the UFC

Additional equipment will be used to remove the sealing material materials from around the UFC, as shown in Figure 37.

The shielded containment housing and water distribution system within it will be mounted on a rubber tyred vehicle that will be able to be pushed into the correct position using a separate truck. The housing will then be capable of being located onto the gamma gate and sealed to the floor.

The service vehicle will be driven to the correct location behind the containment housing, the height adjusted utilising outriggers to ensure correct alignment, and the ram and services connected. Physical stops would be bolted to the floor of the emplacement room to prevent the service vehicle from moving during retrieval operations.

The equipment within the shielded containment housing will comprise an outer support cylinder that will initially be supported from the shielded containment housing. A nozzle tube support frame will be located inside the outer support cylinder that will be fitted with a series of water pipes to provide low pressure washing of the bentonite. This action will create a path for the support cylinder and inner frame to be progressively inserted together over the full length of the UFC.

The gamma gates will be opened and the above assembly pushed forward by the ram of the service vehicle. As the outer support cylinder is progressively moved into the emplacement structure it will be supported on the previously installed UFC support carriage. Figure 37 shows this process at various stages of cylinder insertion.

It may be necessary to provide water to the exterior of the outer support cylinder, as it is being inserted in to the emplacement structure, to prevent the sealing material materials from swelling and trapping the outer support cylinder before it has reached its full extent of travel. A separate set of nozzles will be provided to remove any bentonite residues from the UFC top handling device when the equipment is fully inserted.

A draining facility will be provided in the end of the outer support cylinder and also in the lower area of the shielded containment housing to allow sludge formed by these activities to be removed. A separate bowser will be provided to enable the slurry to be transferred to the surface for treatment and disposal.

The inner frame and its attachments will be withdrawn back into the shielded containment housing, the sludge and water pumped out and the gamma gate closed. The service vehicle will be uncoupled and removed to allow the shielded containment housing to be released and removed. It is assumed that the outer support cylinder will become trapped within the sealing materials and will be removed during the dismantling of the remaining sealing materials.

3.5.6 Removing the UFC

Following the previously described operations the UFC will be supported on the UFC support carriage rollers, with a clearance around the UFC maintained by the outer support cylinder.

A shielded UFC cask, mounted on a suitable trailer, will be introduced and coupled to the gamma gate. With the gates opened the UFC will be pulled into the cask using a ram that can be coupled to the top ring of the UFC, see Figure 38. The cask will also be provided with roller supports that can be extended to connect with those on the UFC support carriage. Once the UFC has been withdrawn into the cask and the rollers retracted, the cask gate will be closed and the cask released for transfer to the surface for subsequent action. The gamma gate will then be removed from the emplacement structure face and the above procedure repeated for the adjacent UFC in the emplacement room.

3.5.7 Remaining Retrieval Operations

When the two adjacent UFCs within the emplacement room have been removed it will be possible to excavate the remaining sealing materials by conventional cutting, loading and transfer techniques, as man access will be permitted. It will be necessary to check the integrity of the rock progressively as sealing materials are removed and to provide additional rock support as required. When the top layers of sealing material have been removed it will be possible to recover the outer support cylinders and the UFC support carriages for further use, following cleaning. The remainder of the sealing materials will then be removed.

The above sequence will be repeated for subsequent UFCs, if necessary.

4 Engineering a DGR for a Depth of 1000 m in Sparsely Fractured Rock

A complete design description for a DGR facility has been presented in Chapter 3. The DGR is designed to be structurally stable at the 1000 m depth, in a sparsely fractured granite pluton. The DGR, shown in Figure 4, and the surface facilities including the UFPP, shown in Figure 19, meet the objective of producing a facility design with a DGR at a depth of 1000m in a relatively impermeable, sparsely fractured rock mass.

The siting, construction, operation, decommissioning and closure of a DGR facility will be a complex and large-scale engineering project extending over many decades. The project will progress by discrete phases, each phase having a specific objective. Many sequential, concurrent and overlapping activities will be associated with these phases to support and assist the validation and confirmation of the specific geotechnical conditions of the site, designs and performance assessment models. One possible set of implementation phases, summarised in the DGR schedule shown in Figure 39, is described in the following sections.

4.1 SITING PHASE PLAN

The Siting Phase will involve developing a siting process and site screening criteria, site screening and site evaluations, preparation of safety assessment and environmental impact documents, participation in public consultations and hearings, and the preparation of license applications.

Geological and other natural environment data will be gathered during site screening and evaluations to develop an understanding of the surface and underground physical, chemical and biological conditions in and around the potential sites to confirm their suitability for hosting a DGR. The site characterisation activities will include analysing existing regional-scale data, performing reconnaissance surveys to gather additional data, borehole investigations, developing and applying criteria for accepting or rejecting locations and ranking them for further investigation. These site characterisation activities will be coupled with extensive public and government consultation leading to the selection of a preferred site.

During the Siting Phase, preliminary conceptual repository facility designs will be prepared for each site being evaluated. Design work will be completed for the surface and underground facilities primarily to establish the access, utility and infrastructure requirements. These requirements will 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 repository monitoring programme will also be developed, and the plan to incorporate this programme into subsequent site evaluation activities will be prepared during site screening. Following the selection of a preferred site, a preliminary DGR design specific for the site will be completed and approved prior entering into the environmental assessment process.

The implementing agency will be required to demonstrate, during the environmental assessment process, that there will be no significant adverse environmental effects that cannot be justified, resulting from the construction, operation, decommissioning and closure of the DGR, and during the postclosure period. Whilst there will inevitably be much focus on the radiological components of environmental impact, the more conventional environmental concerns will also be addressed. A comprehensive environmental survey to measure and record the current background conditions at the proposed site will be conducted.

The end point of the Siting Phase will be the receipt of a Construction License giving approval to begin construction of the DGR facility on the preferred site.

4.2 CONSTRUCTION PHASE PLAN

The Construction Phase will involve constructing the infrastructure and surface facilities needed to dispose of nuclear fuel, the underground access ways and service areas, and a portion of the underground emplacement rooms. However prior to the start of full-scale construction there will be a period of underground evaluation in the Underground Characterisation Facility (UCF) that this report assumes will form part of the DGR. Data gathered in the UCF would be used to confirm suitability of the site and to gather additional information for the detailed design of the DGR. The Construction Phase will begin with the receipt of regulatory approval to start construction and would end when the first used fuel is received at the site.

4.2.1 Underground Evaluation

Underground investigations in the UCF will provide improved definition of the geotechnical parameters determined from surface investigations. As the underground evaluation proceeds, the design of the underground repository will evolve as the geologic structures and characteristics of the site become better defined. The purpose of the underground evaluation is:

- To gain direct access to the repository-level environment
- To verify and refine the surface-based evaluation interpretation of site conditions and behaviours
- To delineate in detail the acceptable areas for used fuel emplacement
- To perform geotechnical mapping, characterisation and component testing for deriving engineering design values and constraints
- To develop final construction and operation designs for the DGR and its components, that may differ from the symmetrical layout indicated in Figure 4, due to the presence of faults or other geological features.

The underground evaluation will be accomplished in three phases. Figure 40 demonstrates the initial phase to establish the infrastructure for test work to be undertaken to determine the characteristics of the rock mass in the UCF. From a logistics perspective approximately 3700m of drifting and raising will be required during this phase. Initially, mucking of excavated material into rail cars will be required, but as exploration development continues, proper provisions for rock handling must be in place and operational. During this phase of the construction, the following facilities will be established:

- Service/Production Shaft complete with loading and spill pocket
- Rock dump, grizzly and storage bin
- Concrete unloading drift
- Mine water sump

- Explosive and detonator magazines
- Main refuge station
- Mechanised drill and blast maintenance facility
- Component Test Area (CTA)
- Maintenance Facility Exhaust Raise
- Permanent fuel and lubricant storage area.

The function of the CTA is to carry out experiments to define DGR design parameters. This area provides the opportunity for the DGR operators to plan and layout the remainder of the facility and conduct tests for the most effective UFC emplacement and retrieval methods. The CTA will be located so that the DGR shafts, access tunnels and emplacement rooms will not interfere with the long-term tests and demonstrations.

In the initial phases all drifts around the exploration shaft will be initially driven 3.0 m x 3.0 m, then slashed to the required shape and dimension, dependent upon its function and experimental study being undertaken. In addition, the central access tunnels, perimeter tunnels and panel access tunnels, which pass through and around the underground facility, will be driven at this time.

During the initial driving of the central access tunnels, perimeter tunnels, and panel access tunnels geotechnical studies will continue, to further define and characterise the design components of the underground facility. These geotechnical studies will include:

- Approximately 6000 m of 76 mm and 96 mm diameter horizontal and sub-horizontal exploratory diamond drilling in and around the projected repository horizon
- An additional 37,000 m of 76 mm and 96 mm diameter exploratory diamond drilling in and around the repository horizon with all holes being grouted upon completion
- Characterisation of the geological environment by core and borehole logging and sampling, excavation mapping, borehole sampling and testing, excavation deformation measurements, and geophysical imaging
- Excavate the equivalent of about 2,000 m of exploration sized tunnels and begin rock mass behavioural testing in the CTA
- Conduct appropriate research and development as needed
- Produce the detailed engineering specifications and plans for the construction of the DGR facility.

After the completion of the characterisation studies of the underground facility, in which the central access, perimeter and panel access tunnels are developed (Figure 40) the following will have been completed:

- Approximately 2600 m of 4.2 m by 7 m rectangular perimeter tunnel
- Approximately 2600 m of 4.2 m by 7 m rectangular drift comprising the central access corridor
- Approximately 9300 m of 4.2 m by 7 m rectangular panel access tunnel complete with emplacement room entrances
- The Service Shaft Complex, except for the Waste Shaft, Waste Shaft access and rail car parking
- Approximately 150 m extension of the right-hand central access drift (4.2 m by 7 m) to the Primary Exhaust Raise
- Figure 14 demonstrates the support infrastructure that will be in place in the Service Shaft Area, whilst Figure 15 provides details of the infrastructure associated with the Exhaust Shaft Complex.

A number of the activities outlined are sequential in nature (infrastructure, shaft sinking, initial drilling, tunnelling, and component testing), whereas others are parallel activities associated with the sequential activities (characterisation and additional drilling during the excavation process). Approximately two years of component testing for deriving engineering design values and constraints will be required in order to develop final construction and operation designs of the DGR and its components after excavation of the CTA and prior to completion of this project phase.

The exploration shafts are located such that they will fit in with the plans for subsequent phases of the implementation. The exploration tunnels and other underground facilities are also located and constructed such that they could be easily adapted to be used as the actual underground repository elements.

All excavation, drilling and construction activities during underground evaluation are based on 3 shifts/day, 360 days per annum. Component testing is assumed to occur over 1 shift/day, 230 days per annum.

4.2.2 Facility Construction

After the underground evaluation studies have been carried out and the final designs completed the construction of the full-scale DGR facility can begin. The purpose of the construction is to build all the facilities necessary for the operation of the DGR and its components. Provision is made in the design for concurrent excavation during the Operational Phase. The Construction Phase plan consists of the following activities:

- Upgrade the site infrastructure to perform large scale shaft sinking and tunnelling
- Construct the UFPP and associated facilities

- Sink and equip the waste shaft to a depth of approximately 1,000 m and develop the empty and loaded rail car areas

- Excavate 39 emplacement rooms (i.e. 1.5 Sections), 4.2 m by 7.14 m in size, to give a total of 12,285 m of available room space for the Operation Phase

- Characterise the geotechnical environment by core and borehole logging and sampling, geological mapping, borehole sampling and testing, excavation deformation measurements, geophysical imaging and in situ stress testing

- Carry out additional rock mass behavioural tests in the CTA. The tests will continue into the Operations Phase.

- Prepare the access tunnels with services and ventilation ducting; pour concrete for floors, and install rails

- Prepare a minimum of four emplacement rooms with services, ventilation ducting and install rails

- Commission all the underground equipment and produce detailed operating procedures

- Conduct appropriate research and development as needed

- Prepare the detailed safety case for the operation of the DGR facility and apply for an operating licence.

A number of the activities outlined are sequential in nature (infrastructure, shaft sinking, initial drilling and tunnelling), whereas others are parallel activities associated with the sequential activities. Figure 40 shows the underground repository layout at the end of the Construction Phase.

4.3 OPERATION PHASE PLAN

The Operation Phase will involve receiving used nuclear fuel transported to the DGR facility, sealing it in corrosion resistant UFCs, placing and sealing the UFCs in emplacement rooms, and constructing and preparing additional emplacement rooms. After the last UFC has been placed in the DGR there will be a period of extended monitoring.

4.3.1 Emplacement of Used Fuel Containers

The purpose of the Operation Phase is to emplace and seal the UFCs in the DGR. There are three major concurrent groups of operational activities occurring during the Operation Phase:

- Room excavation, including drilling and blasting, muck removal and ground support installation

- Room preparation, including the installation of concrete floors, installation of rails and other support services (mechanical and electrical)

- UFC emplacement involving installation of dense backfill and buffer blocks, placement of the light backfill material, emplacement of jacketed UFCs, installation of remaining dense backfill and buffer blocks and injection of dry granular bentonite and sand mixture infill.

After all the UFCs are emplaced in a room, the room bulkhead is constructed.

The three major activities are scheduled to take place concurrently, such that when UFCs are being emplaced in one Section on one side of the central access tunnel, room preparation and room excavation takes place in another Section on the other side of the central access tunnel. It is envisaged that room preparation and excavation will be of shorter duration than UFC emplacement operations and therefore there will be periods where ongoing construction is suspended, with construction being carried out on a campaign basis. Two separate ventilation systems will be maintained: one for the radiological operations (UFC emplacement) and the other for non-radiological operations (i.e. room excavation and room preparation). A single upcast shaft will be utilised to accommodate extract from both systems.

Sufficient rooms will be excavated and prepared during the Construction Phase such that at the start of the Operation Phase, the crews for these activities are at staggered locations and operate in a non-interfering mode. Specifically, the rooms in the lower panel of Section B and all rooms in Section A will have been excavated and prepared at the commencement of the Operation Phase. Sealing material block placement and UFC emplacement will then start in the lower panel of Section B. When all rooms in the lower panel of Section B are filled, UFC emplacements will then take place in Section A. At an appropriate time during the filling of Section A, the next room excavation campaign will be initiated in the upper panel of Section A followed by the lower panel of Section D (see Figure 8).

The principle of segregating the radiological operations from the non-radiological operations will be maintained. Central access tunnels will be twinned to reduce the potential for traffic accidents, particularly with radioactive loads and to provide a secondary route for worker and material transport. The emplacement operations will retreat from the upcast shaft complex towards the waste and service shaft complex. Thus the work will progress from potentially contaminated areas towards clean areas with a source of fresh air, enhancing the environment for workers.

At the end of each cycle when the emplacement operations are completed in a room Section, each functional activity will be moved to the next sequence of rooms in the opposite Section across from the central access tunnels. See Figure 9 through to Figure 11.

4.3.2 Extended Monitoring

The extended monitoring activities will involve monitoring and assessing the conditions in the vicinity of the DGR prior to its decommissioning and closure. The extended monitoring programme will make use of the shafts and underground access tunnels while they are still available prior to sealing the underground facilities in the Decommissioning Phase. Extended monitoring activities will include environmental and repository performance monitoring, which will include rock mass behaviour and seismic monitoring. The monitoring data will be used to predict the long-term performance of the sealed repository.

A work force will be present at the facility to maintain full access, equipment, facilities, physical security, safety and monitoring systems, and to analyse and interpret data. Although much of the operations equipment will be "mothballed", most of the ancillary service facilities will operate at reduced capacity to support site staff activities both above and below ground in the DGR.

Extended monitoring activities will end when regulatory approval is received to decommission the DGR facility.

4.4 DECOMMISSIONING PHASE PLAN

The purpose of the Decommissioning Phase is to:

- Decontaminate and remove all the related underground support works
- Backfill and seal the balance of the underground facility that consists of all exploratory and instrumented boreholes drilled from underground, tunnels, service and upcast shaft complexes, CTA and shafts
- Decontaminate and dismantle the UFPP, sealing and compaction plant and associated facilities
- Dismantle all surface buildings and associated facilities
- Dismantle and remove the rock crushing plant, concrete batch plant, shaft headframes, fans and collarhouses
- Dismantle and remove all surface infrastructure including roads, drainage and services

The Decommissioning Phase plan consists of the following activities:

- Remove instruments from all underground boreholes and seal each borehole
- Backfill the upcast complex, installing sealing bulkheads at strategic locations
- Ream the waste and upcast shafts to remove the concrete linings and any wall rock degradation, re-equip each shaft with services and stagings, and backfill the shafts including the installation of shaft sealing bulkheads at strategic locations
- Backfill the central access tunnels, installing tunnel sealing bulkheads at strategic locations
- Dismantle and backfill the CTA, service shaft complex, maintenance/storage area, and install sealing bulkheads at strategic locations
- Ream the service shaft to remove the concrete lining and any wall rock degradation, re-equip the shaft and backfill, installing shaft sealing bulkheads at strategic locations

- Decontaminate and dismantle the UFPP and associated facilities
- Dismantle all other surface facilities, services and infrastructure
- Prepare safety assessments and apply for approval to release the site

All sealing and decommissioning activities are scheduled for 3 shifts/day, 360 days per annum.

4.5 CLOSURE PHASE PLAN

The purpose of the Closure Phase is to:

- Remove instruments from all surface boreholes and backfill and seal each borehole, except those that are needed for monitoring in the postclosure period
- Recondition the site surface to a state suitable for public use with the provision that subsurface use be restricted
- Prepare safety assessments and apply for approval to release the site.

The activities and related data for this phase will be the same for the facility described in [2]. Closure work is assumed to occur over 1 shift/day, 230 days per annum.

5 Conclusions

Work has been conducted to update the design concept of a DGR for isolation of used CANDU nuclear fuel in the crystalline rock of the Canadian Shield. The conceptual ‘in-room’ design described in this report constitutes a further development of an earlier disposal concept prepared by AECL. The updated design considers encapsulation of used fuel in copper containers (UFCs) that will be located within emplacement rooms excavated in granite at a depth of 1000 m. The design demonstrates that used CANDU fuel bundles shipped from interim storage facilities can be received, re-packaged in UFCs and located in emplacement rooms in a safe and efficient manner.

The overall conclusions drawn from the engineering studies undertaken during the concept DGR design update are outlined below:

- The design of a long-lived used fuel container is viable, which is able to accommodate 324, 30 year cooled CANDU used fuel bundles and, following its emplacement within the DGR maintain its integrity for a minimum period of 100,000 years
- It has been demonstrated that a UFC can be designed to:
    - provide sufficient mechanical strength to maintain its physical integrity during all credible loading and envisaged handling scenarios
    - attenuate the outer surface dose to less than 15 Gy/h
    - achieve and sustain a surface temperature to less than 100°C
- It has been established that the proposed design of UFC assembly can be manufactured, based on existing techniques being developed for similar applications

- It has been demonstrated that an emplacement room arrangement can be developed to satisfy all the following design constraints and requirements:
    - permit the controlled horizontal emplacement of two adjacent UFCs within the emplacement room cross section while maintaining the integrity of the UFC surface
    - ensure that the minimum thickness of sealing materials surrounds the emplaced UFCs
    - maintain the UFCs outer surface temperature to below 100°C (meeting this constraint is dependent on both the UFC design and the DGR layout)
- To prevent damage to the UFC outer surface, the UFC can be encased within a bentonite jacket at the used fuel packaging plant prior to its transfer underground to the DGR emplacement room
- A viable DGR layout to accommodate the inventory comprising 3.6 million CANDU used fuel bundles can be developed that satisfies the Hoek and Brown rock stability failure criterion following excavation as well as the UFC thermal constraints
- Analysis has shown that following emplacement of UFCs within the DGR, localised damage at the crown of the emplacement rooms may occur. However, this damage will not compromise the long term safety and performance of the DGR.
- The idealised DGR layout presented will need to be modified to accommodate site specific conditions that may lead to an increase in its overall footprint
- A shaft hoisting system to transfer a loaded UFC cask to the required depth of the DGR is viable using existing technology
- The conceptual DGR layout is capable of being operated using four access shafts; waste, service, upcast ventilation and maintenance area ventilation shafts
- Drill and blast is the preferred method of excavation of the underground openings, based on current technology
- A UFPP design can be developed to receive, handle, package and dispatch underground CANDU used fuel bundles at the specified rate of 120,000 bundles per year
- The conceptual design presented allows the DGR construction and emplacement processes to be carried out while meeting the specified used fuel emplacement rate
- Shielding calculations demonstrate that allowable operator dose rates will not be exceeded during normal operations, with the exception of handling road transportation casks that may be dealt with by incorporation of management procedures, local shielding or a modified cask design
- Retrieval of an emplaced UFC is feasible, and a viable outline scheme can be developed. Rock stability issues have been identified, particularly with early retrieval, and the implications of these will require further consideration

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TABLE 1

COMPARISON BETWEEN DISPOSAL FACILITY STUDIES

Item	Emplacement Method	
	In-Floor Borehole	In-Room
Depth	500 to 1000m	1000m
Quantity of Waste	10.1 million bundles	3.6 million bundles
Ambient *In situ* Stresses	Average for Canadian Shield	Upper Range for Canadian Shield
Used Fuel Container	Particulate-packed, Ti-shell 633mm diameter, 2246mm long 72 bundle capacity	Cu outer shell, steel inner shell 1168mm diameter, 3867mm long 324 bundle capacity
Used Fuel Cooling Period	10 Years	30 Years
Container Heat Output	297 W	1139 W
Maximum Container Surface Temperature	100^0C	100^0C
Rock Strength		
- Excavation	σ_c = 190 Mpa, m=17.5, s=0.19	$\boldsymbol{\sigma_c}$ = 100 Mpa, m=16, s=1
- Thermal	σ_c = 190 Mpa, m=17.5, s=0.19	σ_c = 150 Mpa, m=25, s=1
- Rock Web	σ_c = 110 Mpa, m=30, s=1	Not Applicable
- Factor of Safety	2 (avg. for rock web and pillars)	1 (at excavation)
Young's Modulus	35 GPa	60 GPa
Specified Minimum Buffer Thickness	25 cm	100 cm (50 cm bentonite/buffer, 50 cm dense backfill)
Low-heat, High-performance Concrete	Only at disposal room bulkhead	Central floor of disposal room and bulkhead
Maximum Worker Radiation Dose Rate	5 mSv/a	2 mSv/a

TABLE 2

MAIN PARAMETERS OF THE USED FUEL CONTAINER (UFC)

Component	Material	Dimensions (mm)	Volume of material	Mass (kg)
Jacket	Bentonite	1670 across flats octagon by 4380 long	6.055	9688
Outer Shell	OFP Copper	1168 outside diameter, 1118 inside diameter by 3867 long	0.428	3770
Inner Shell	Carbon Steel	1116 outside diameter, 924 inside diameter by 3708 long	1.468	11500
Basket	Carbon Steel	3 baskets each 920 outside diameter by 1035.4 long	0.191	1500
Used Fuel Bundles	CANDU Fuel	324 bundles each 102.3 diameter by 495.3 long	0.792	7690
		Total		34148

TABLE 3

MAIN PARAMETERS OF THE UNDERGROUND LAYOUT

Item	Dimensions (m)	Comment
Emplacement Room Cross Section	4.2 high by 7.14 wide	Elliptical
Emplacement Room Length	315	Includes 37m for sealing bulkhead and turning radius
UFC Lateral Spacing	2.52	Centre to centre
UFC Longitudinal Spacing	5.13	Centre to centre
UFCs per Emplacement Room	108	2 abreast by 54 along room
Number of Emplacement Rooms	104	In 4 sections, each with two panels of 13 emplacement rooms
Lateral Spacing of Emplacement Rooms	45	Centre to centre
Total Number of UFC Spaces Available	11232	3,639,168 Used Fuel Bundles

TABLE 4

USED FUEL HEAT OUTPUT.

Time out of reactor (years)	Container heat output (W) 324 bundles per container
30	1138.61
40	961.40
50	821.06
60	708.48
75	580.06
100	440.84
150	310.88
200	258.73
300	221.19
500	180.99
1,000	125.27
10,000	44.48
100,000	2.55
1,000,000	0.92
10,000,000	0.62

TABLE 5

GRANITE AND SEALING MATERIALS THERMO-MECHANICAL PROPERTIES

Property	**Lac du Bonnet Granite**	**Low heat high performance concrete**	**Fractionated silica sand**	**Buffer**	**Bentonite jacket**	**Dense backfill**	**Light backfill**
Thermal conductivity (W/m°C)	3.00	1.85	1.0	1.70	0.90 0 – 100 mm 1.05 100 – 200 mm 1.15 200 – 250 mm	2.00	0.70
Specific heat (kJ/kg°C)	0.845	0.9	0.82	1.38	1.38	1.19	1.30
Density (kg/m^3)	2650	2430	1450	1250	1600	2270	1380
Young's modulus (GPa)	50	50	0.10	0.10	0.10	0.20	0.10
Poisson's ratio	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Coefficient of thermal expansion (10^{-6}/°C)	10	10	N/A	N/A	N/A	N/A	N/A
Swelling pressure (kPa)	0	0	0	800 – 2000	800 - 2000	<50	100 - 200

NOTE: Values of Sealing materials in the Table assume a saturation of 85% immediately following placement.

TABLE 6

UFC MATERIAL PROPERTIES

Property	OFP Copper	Carbon Steel
Thermal conductivity (W/m°C)	380	59
Specific heat (kJ/kg°C)	0.39	0.46
Density (kg/m^3)	8930	7800
Young's modulus (GPa)	117	200
Poisson's ratio	0.3	0.3
Coefficient of thermal expansion (10^{-6}/°C)	16	12

TABLE 7

EXCAVATION DESIGN PARAMETERS

Item	**Dimensions (m)**	**Comment**
Waste Shaft	6.15	Circular, internal diameter
Service/Production Shaft	7.30	Circular, internal diameter
Maintenance Facility Exhaust Raise	3.96	Circular, internal diameter
Primary Exhaust Shaft	3.66	Circular, internal diameter
Perimeter Access Drift	4.2 x 7.0	Rectangular, arched back
Central Access Drift	4.2 x 7.0	Rectangular, arched back
Section Access Drift	4.2 x 7.0	Rectangular, arched back
Emplacement Room	4.2 x 7.14	Elliptical
UFC Transport Turning Radius	25	Centreline
Minimum Distance Emplacement Rooms to Perimeter Access Drift	45	Centreline to centreline
Minimum Distance Emplacement Rooms to Central Access Drift	45	Centreline to centreline
Distance between Emplacement Rooms	45	Centreline to centreline
Distance between Emplacement Room Ends	22.7	
Total Width of Emplacement Area	1358	Centre to centre perimeter drifts
Total Length of Emplacement Area	1343	Centre to centre uppermost section access to lowermost section access drift

TABLE 8

SPECIFICATION FOR CLAY-BASED MATERIALS COMPOSITION

Material	Composition	
	Clay Type Content (dry wt %)	Aggregate Type Content (dry wt %)
Bentonite Jacket	Bentonite 100	None
Buffer	Bentonite 50	Silica Sand 50
Dense Backfill	Lake Clay/Bentonite 25/5	Crushed Granite 70
Light Backfill	Bentonite 50	Crushed Granite 50
Sealing Material Infill	Bentonite 50	Rounded Silica Sand 50

TABLE 9

RADIOLOGICAL CLASSIFICATION OF AREAS

Zone	Potential for Internal Contamination	External Radiation Dose Rate	Access Status	Maximum Annual Effective Dose.
1	No potential for contamination	Less than 1.0 µSv/h	Entry is allowed to all staff. Access area to members of public	2.0 mSv
2	Potential for contamination. Contamination is not tolerated and is eliminated once discovered.	Between 1.0 and 10 µSv/h	Work zone for Nuclear Energy Workers (NEWs) only.	Between 2 mSv and 20 mSv.
3	Contaminated area. Contamination levels are less than the Derived Air or Surface Concentration.	Between 10 and 250 µSv/h	Controlled access. Protective clothing is required.	Controlled access area. Entry permitted after special authorisation. Total individual effective annual dose shall not exceed 20 mSv.
4	High levels of contamination. Levels are higher than the Derived Air or Surface Concentration.	Higher than 250 µSv/h	Normally inaccessible area. Special protective clothing and equipment is required. Special equipment should also be provided for handling fuel bundle separation accident or for decontamination purposes in the UFPP.	Controlled access area. Entry permitted after special authorisation. Total individual effective annual dose shall not exceed 20 mSv.