1106/MD18085/REP/01

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

December 2002

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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:

$\sigma_1 = \sigma_{H\ far\text{-}field} =$ 65 MPa $\sigma_2 = \sigma_{h\ far\text{-}field} =$ 49.4 MPa and $\sigma_3 = \sigma_{V\ far\text{-}field} =$ 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 σ_{ex} = 100 MPa.

b) Under Thermally-induced Loading Conditions

Peak strength design limit, m = 25, s = 1 and σ_{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:

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

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^{0}C 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 $300x10^6$ 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 100^0C
- 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.

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

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

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

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

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

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

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

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^{o}C; 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) Maintenance Complex Shaft (upcast)	 20 m^3/s 50 m^3/s	 20 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.

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = const \quad (8)$$

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

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2 \cdot Y^2 \quad (9)$$

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

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = k^2 + k^2 + 4k^2 \quad (10)$$

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

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

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 1.16×10^6 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 - Thermal - Rock Web - Factor of Safety	σ_c = 190 Mpa, m=17.5, s=0.19 σ_c = 190 Mpa, m=17.5, s=0.19 σ_c = 110 Mpa, m=30, s=1 2 (avg. for rock web and pillars)	$\boldsymbol{\sigma_c}$ = 100 Mpa, m=16, s=1 σ_c = 150 Mpa, m=25, s=1 Not Applicable 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

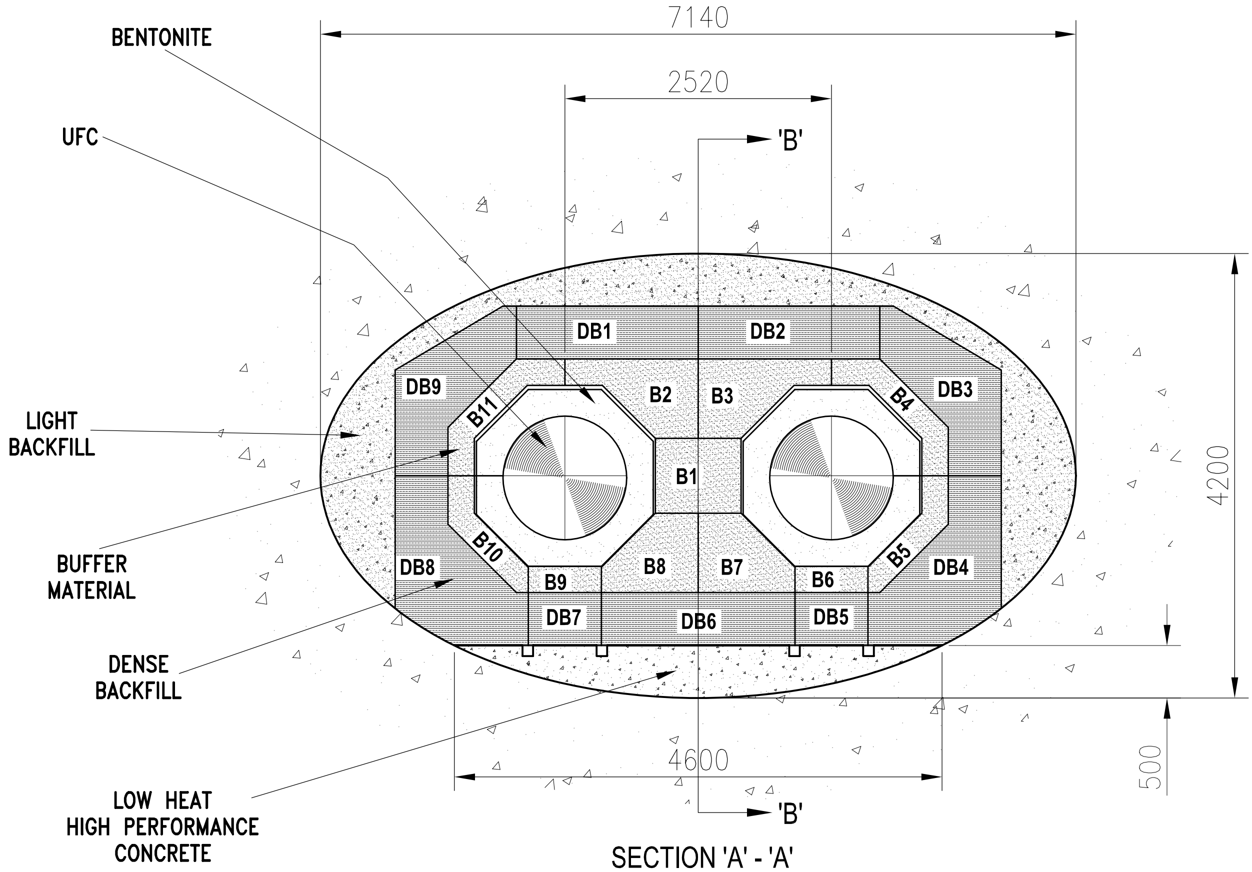
Material	Composition	
	Clay Type Content (dry wt %)	Aggregate Type Content (dry wt %)
Bentonite Jacket	Bentonite 100	None
Buffer	Bentonite 50	Silica Sand 50
Dense Backfill	Lake Clay/Bentonite 25/5	Crushed Granite 70
Light Backfill	Bentonite 50	Crushed Granite 50
Sealing Material Infill	Bentonite 50	Rounded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

Figures - Main Report



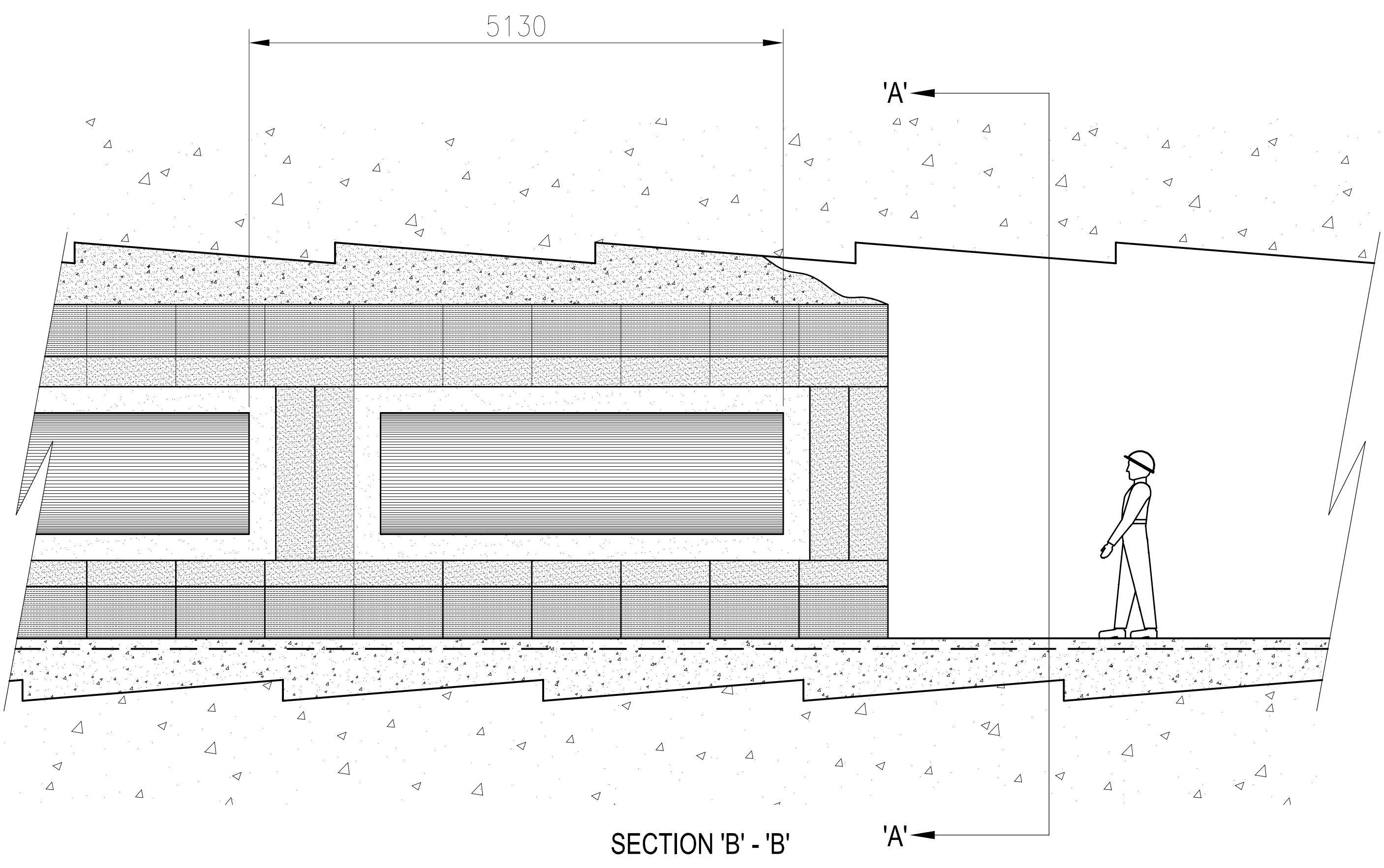


FIGURE 1 DGR EMPLACEMENT ROOM SHOWING GENERAL ARRANGEMENT OF EMPLACED BLOCKS AND UFCs

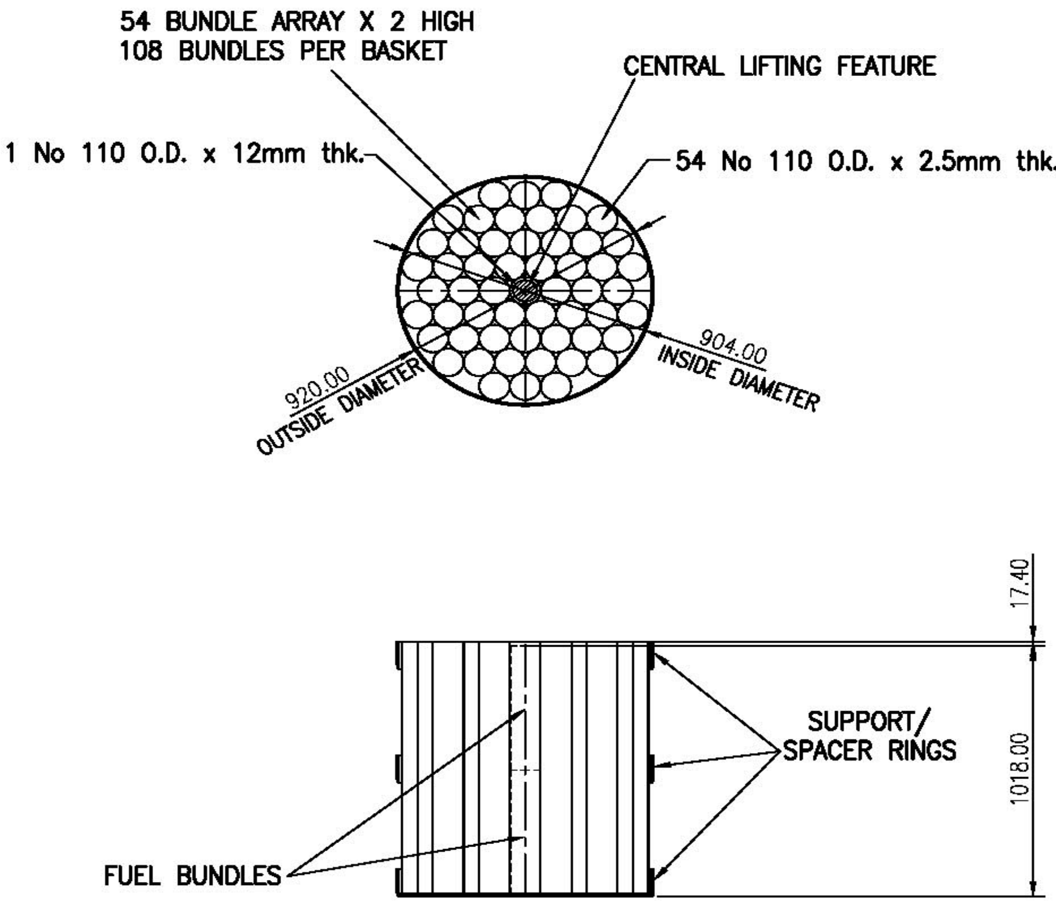


FIGURE 2 108 BUNDLE USED FUEL BASKET

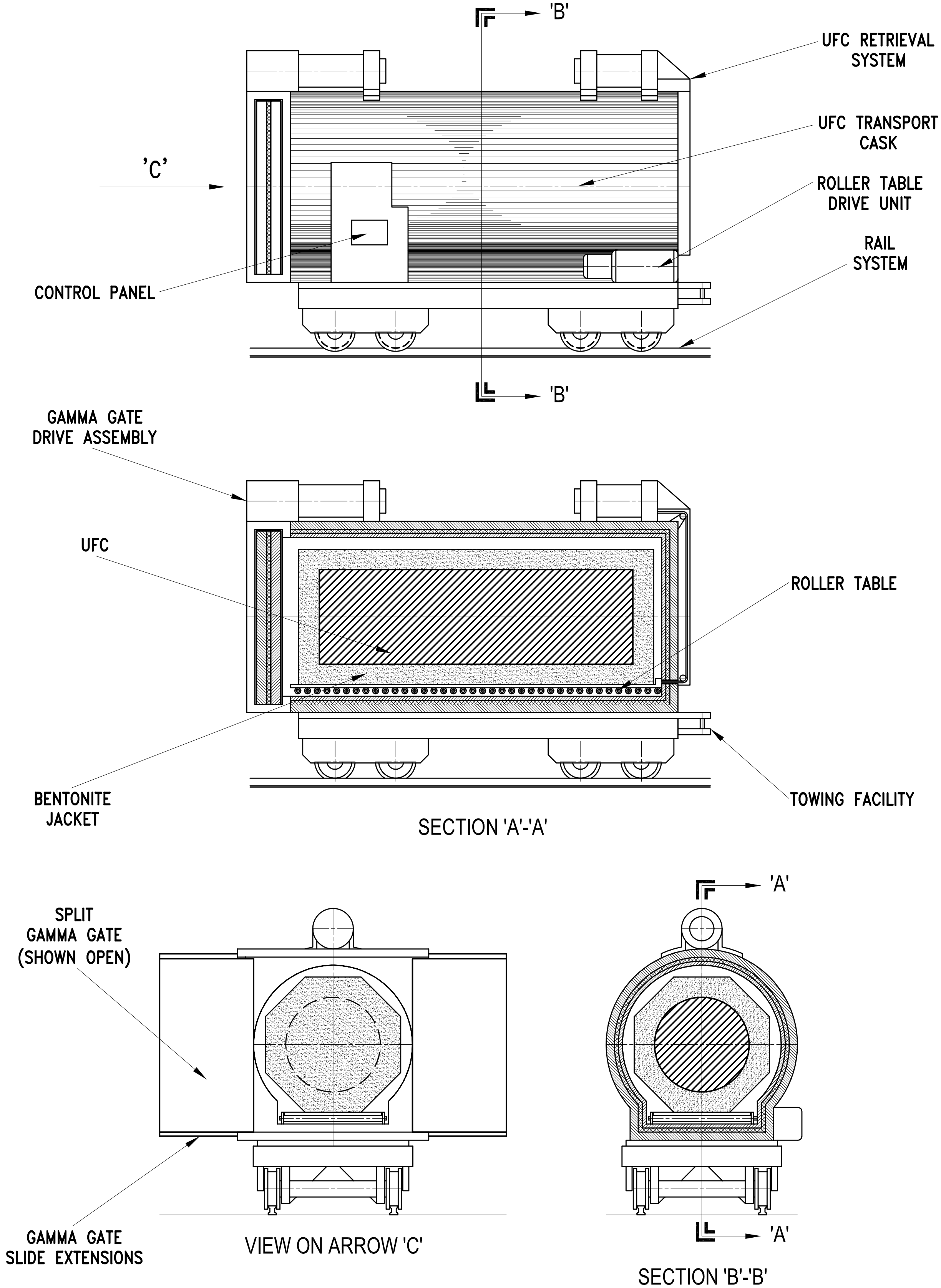


FIGURE 3 GENERAL ARRANGEMENT OF UFC TRANSPORT CASK

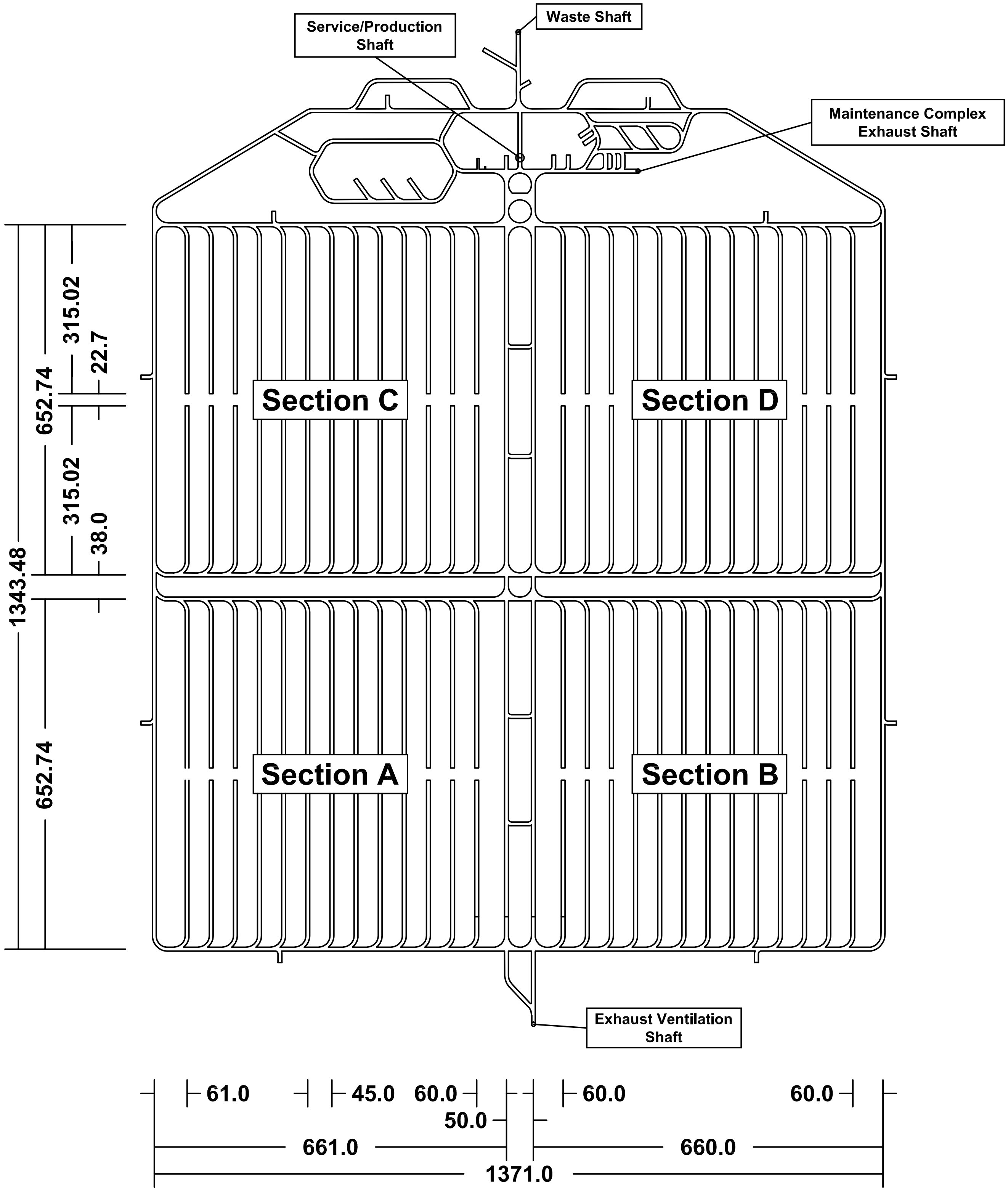


FIGURE 4 - GENERAL LAYOUT - PROPOSED PLAN OF DEEP GEOLOGIC REPOSITORY

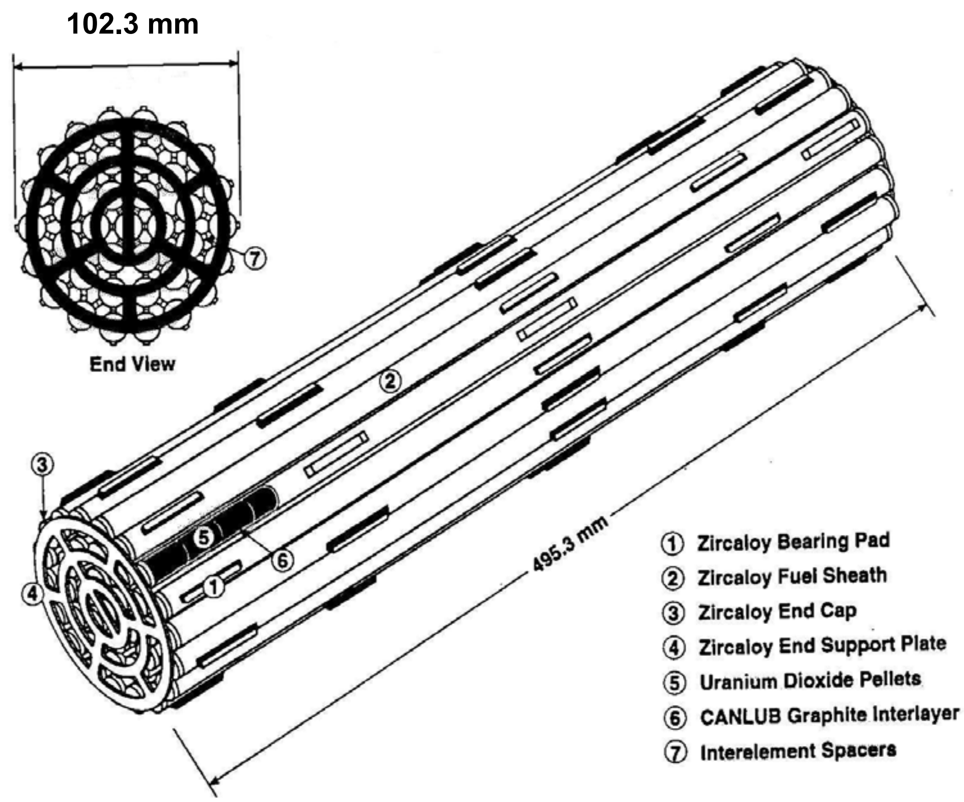


FIGURE 5 TYPICAL CANDU FUEL BUNDLE FOR BRUCE NUCLEAR GENERATING STATION

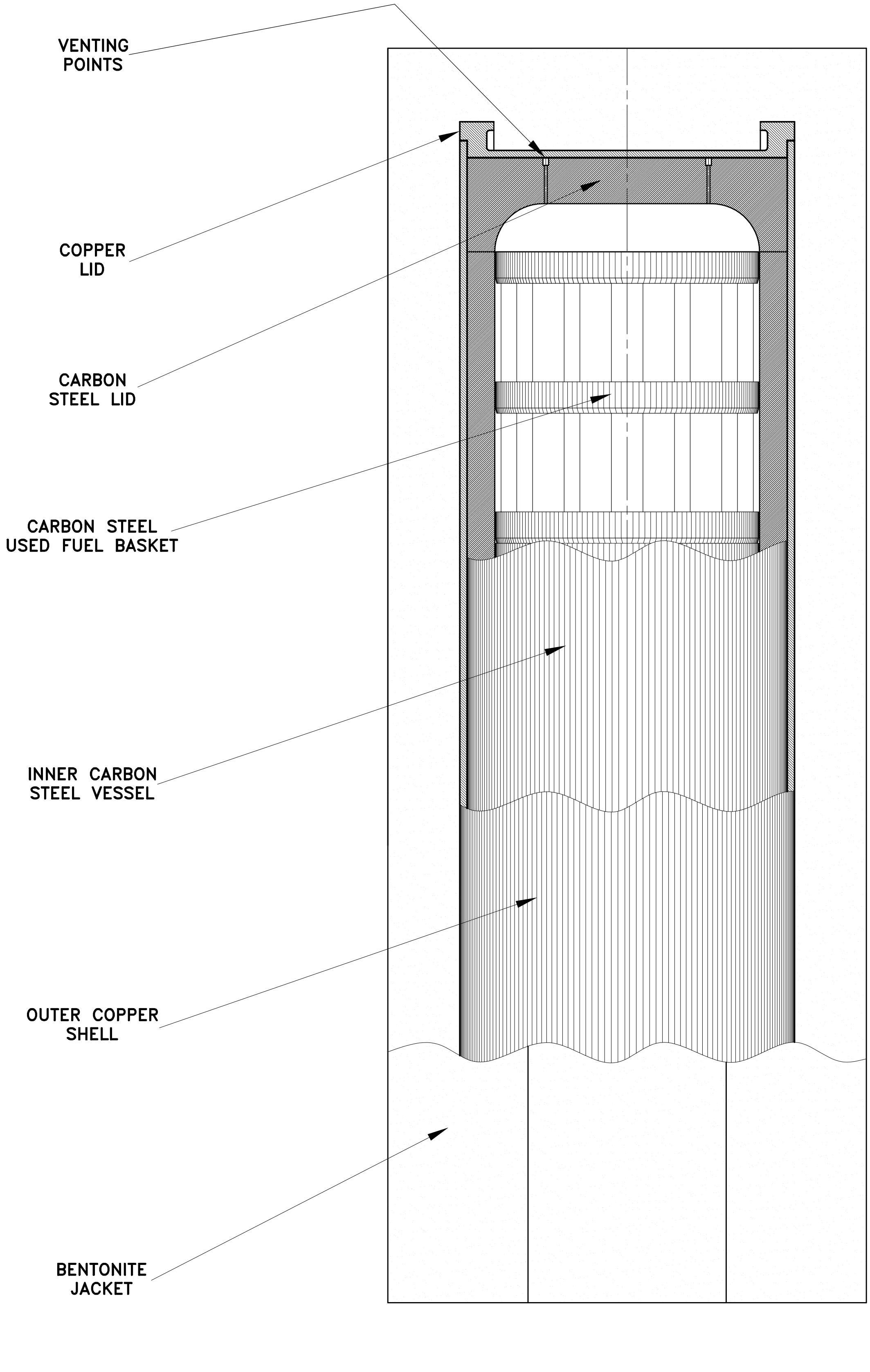


FIGURE 6 ASSEMBLY OF JACKETED USED FUEL CONTAINER (UFC)

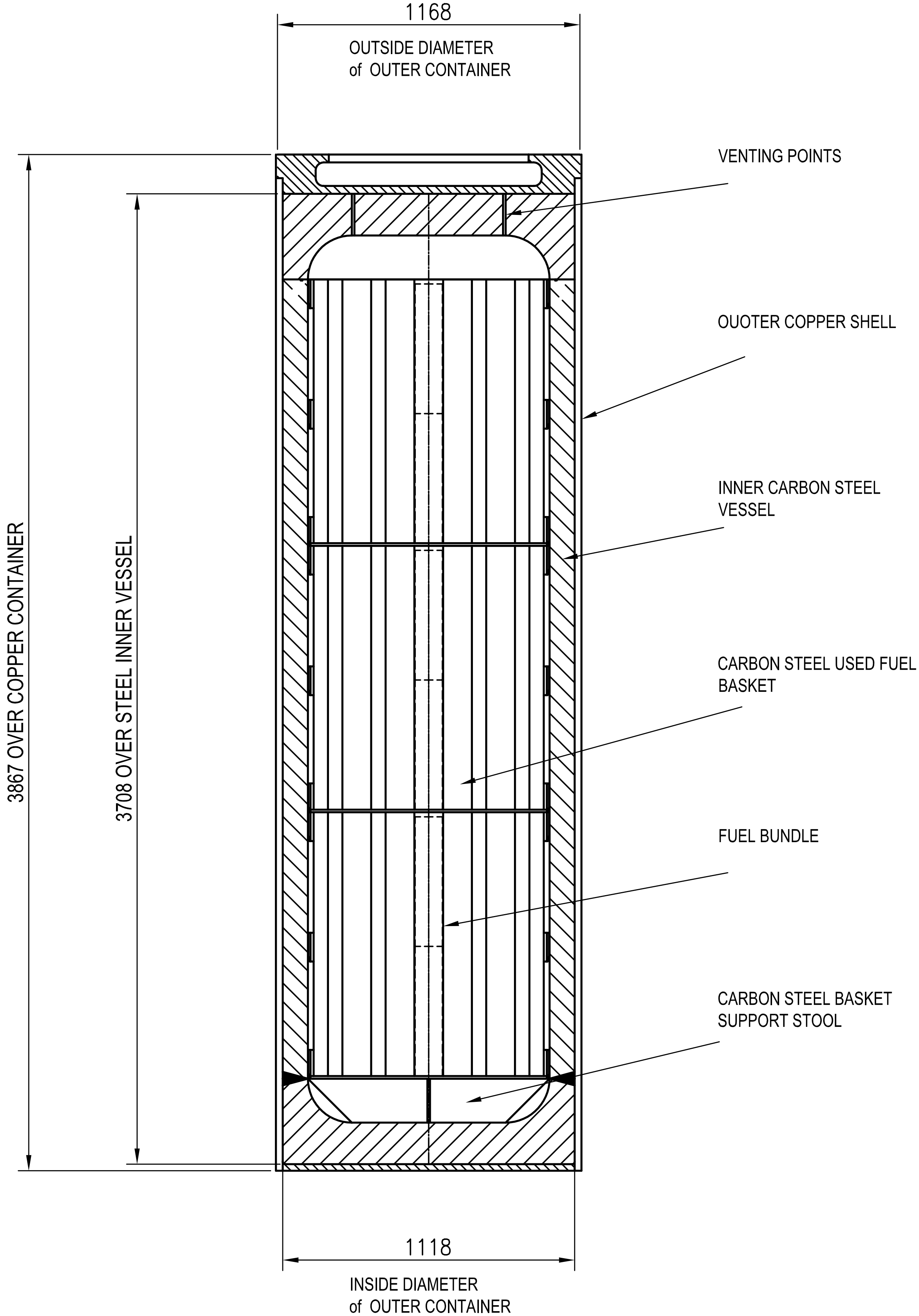


FIGURE 7 ASSEMBLY OF USED FUEL BASKETS AND CONTAINER

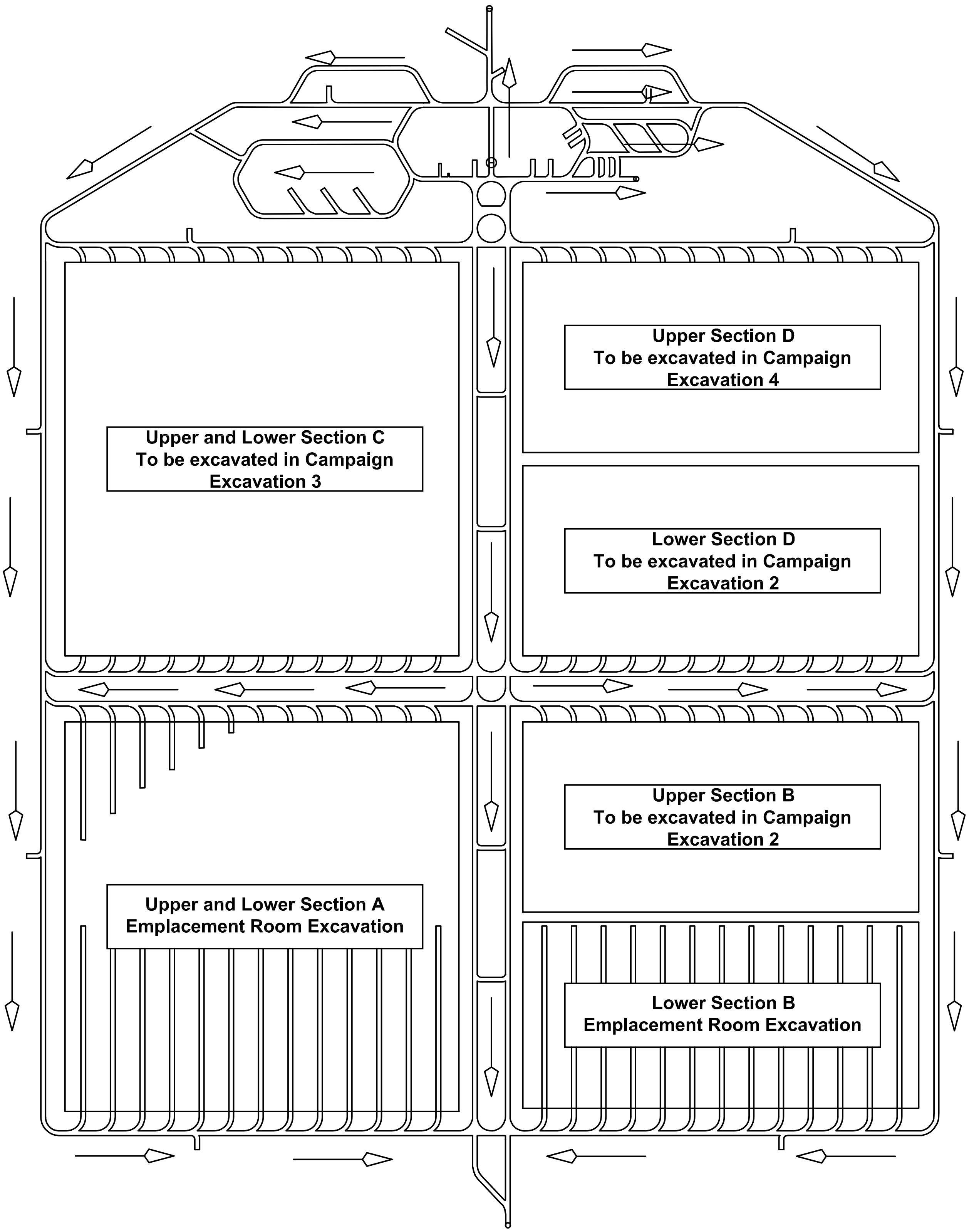
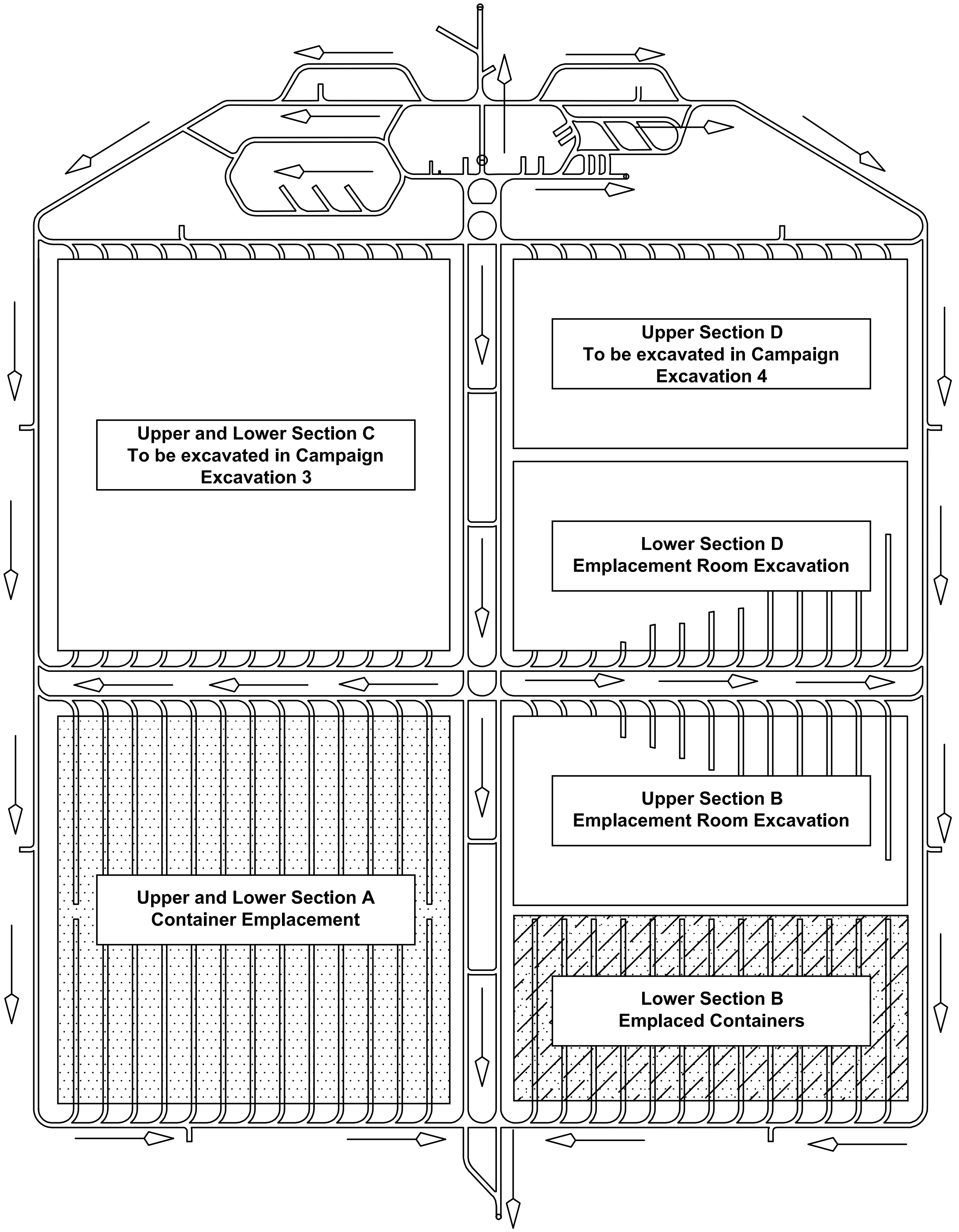
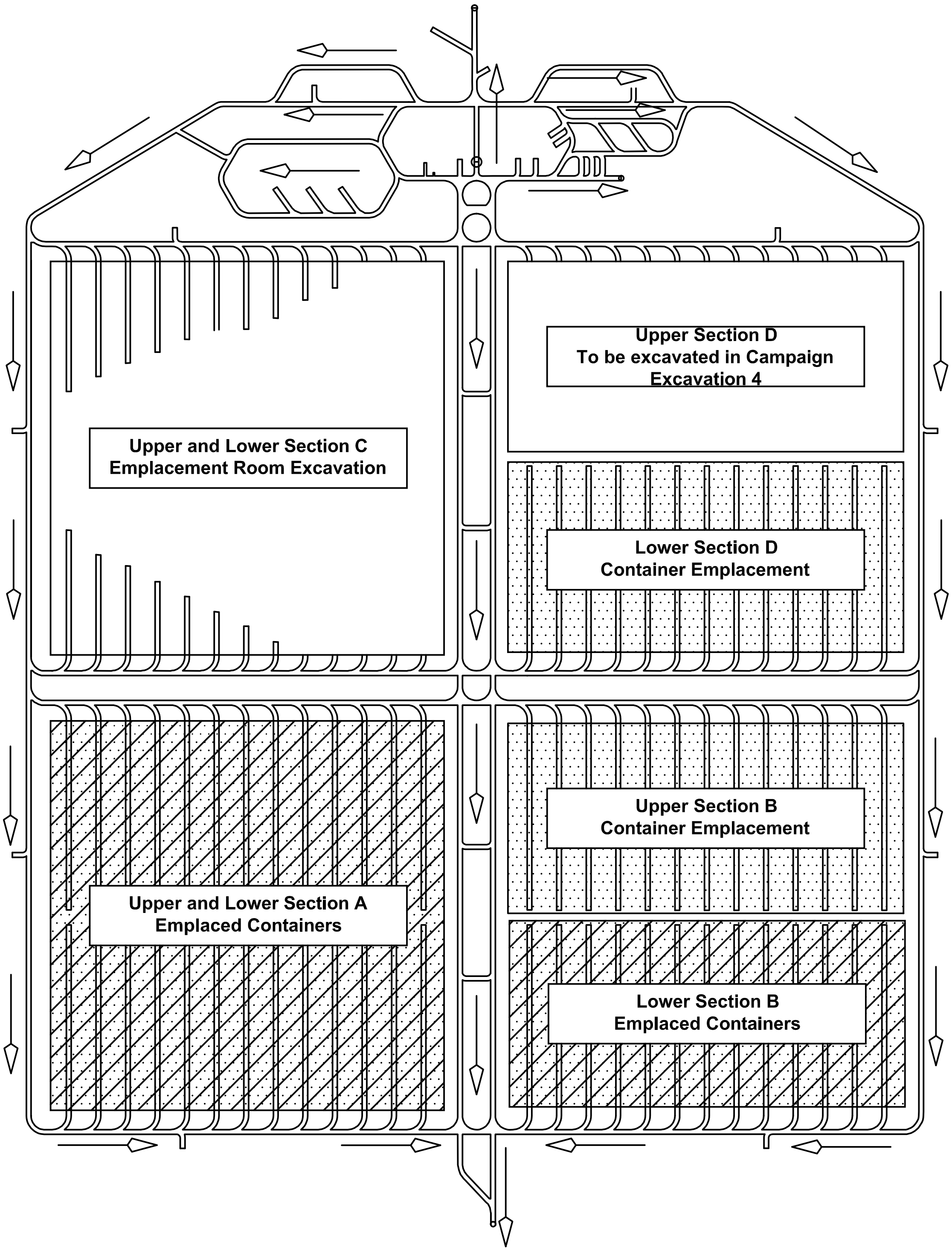


FIGURE 8 - PHASE 1 EXCAVATION AND UFC EMPLACEMENT SEQUENCE



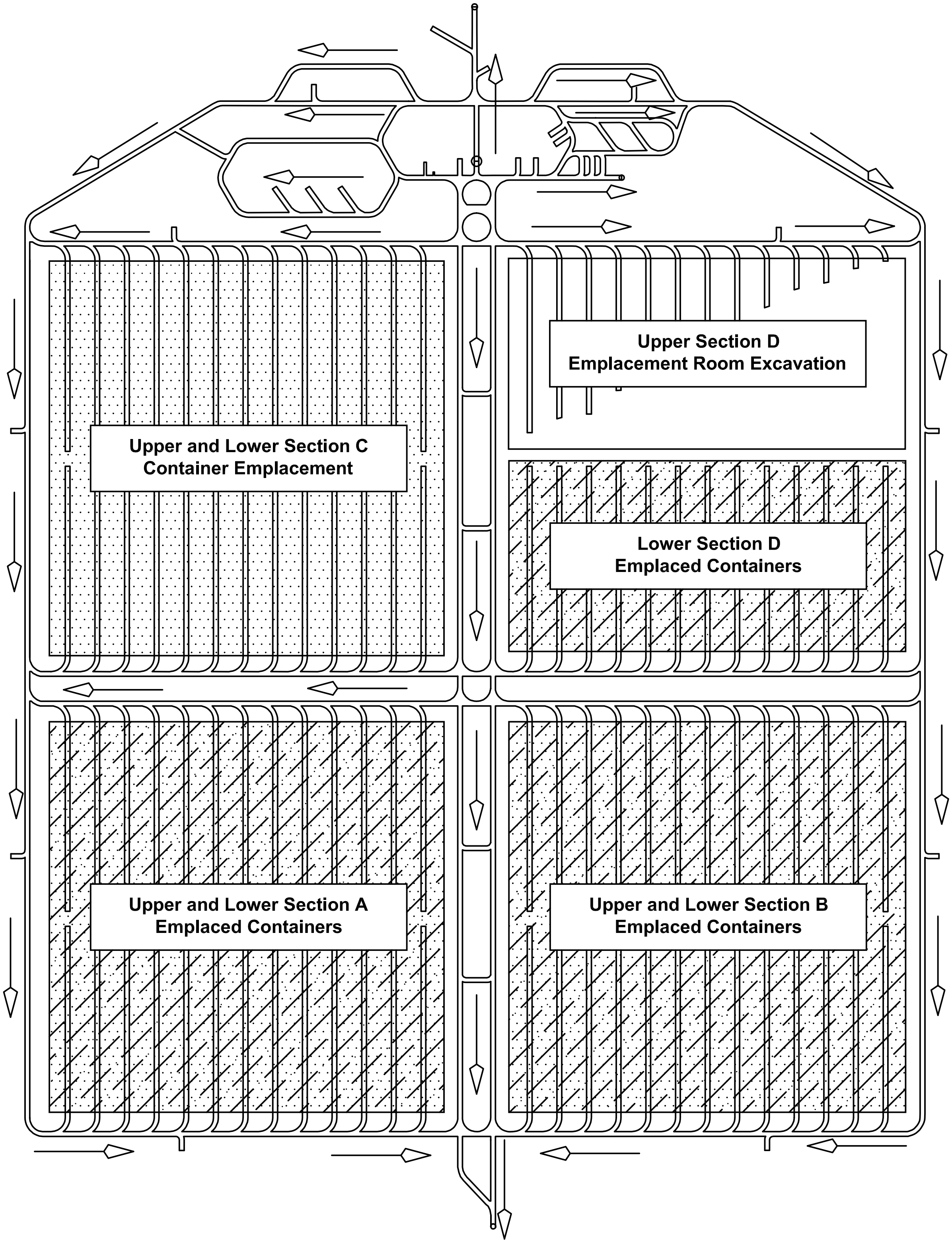
Note: Airflow direction demonstrates non-mixing of excavation and emplacement air.

FIGURE 9 - PHASE 2 EXCAVATION AND UFC EMPLACEMENT SEQUENCE



Note: Airflow direction demonstrates non-mixing of excavation and emplacement air.

FIGURE 10 - PHASE 3 EXCAVATION AND UFC EMPLACEMENT SEQUENCE



Note: Airflow direction demonstrates non-mixing of excavation and emplacement air.

FIGURE 11 - PHASE 4 EXCAVATION AND UFC EMPLACEMENT SEQUENCE

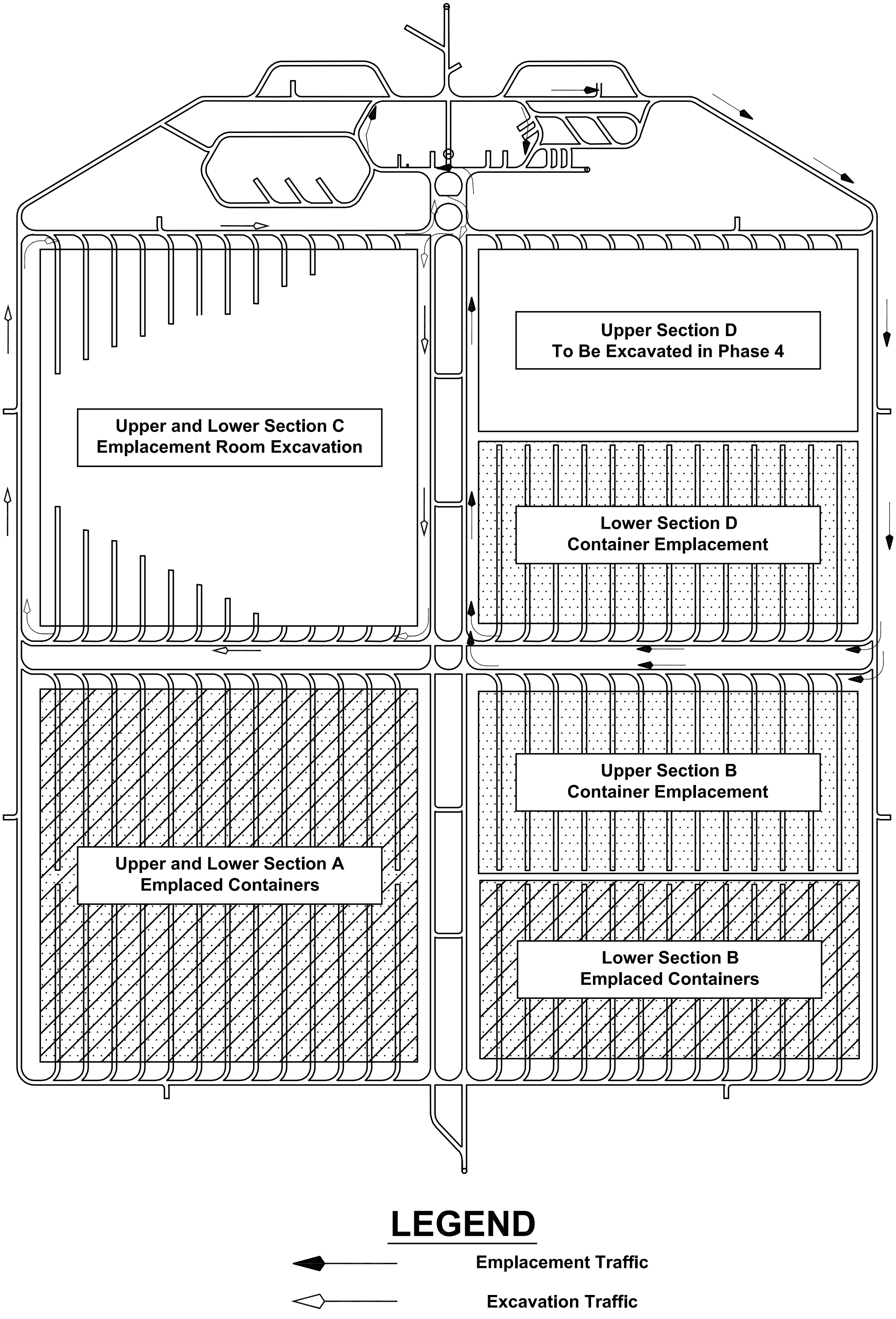


FIGURE 12 TYPICAL MOVEMENT OF TRAFFIC DURING EMPLACEMENT AND EXCAVATION OPERATIONS

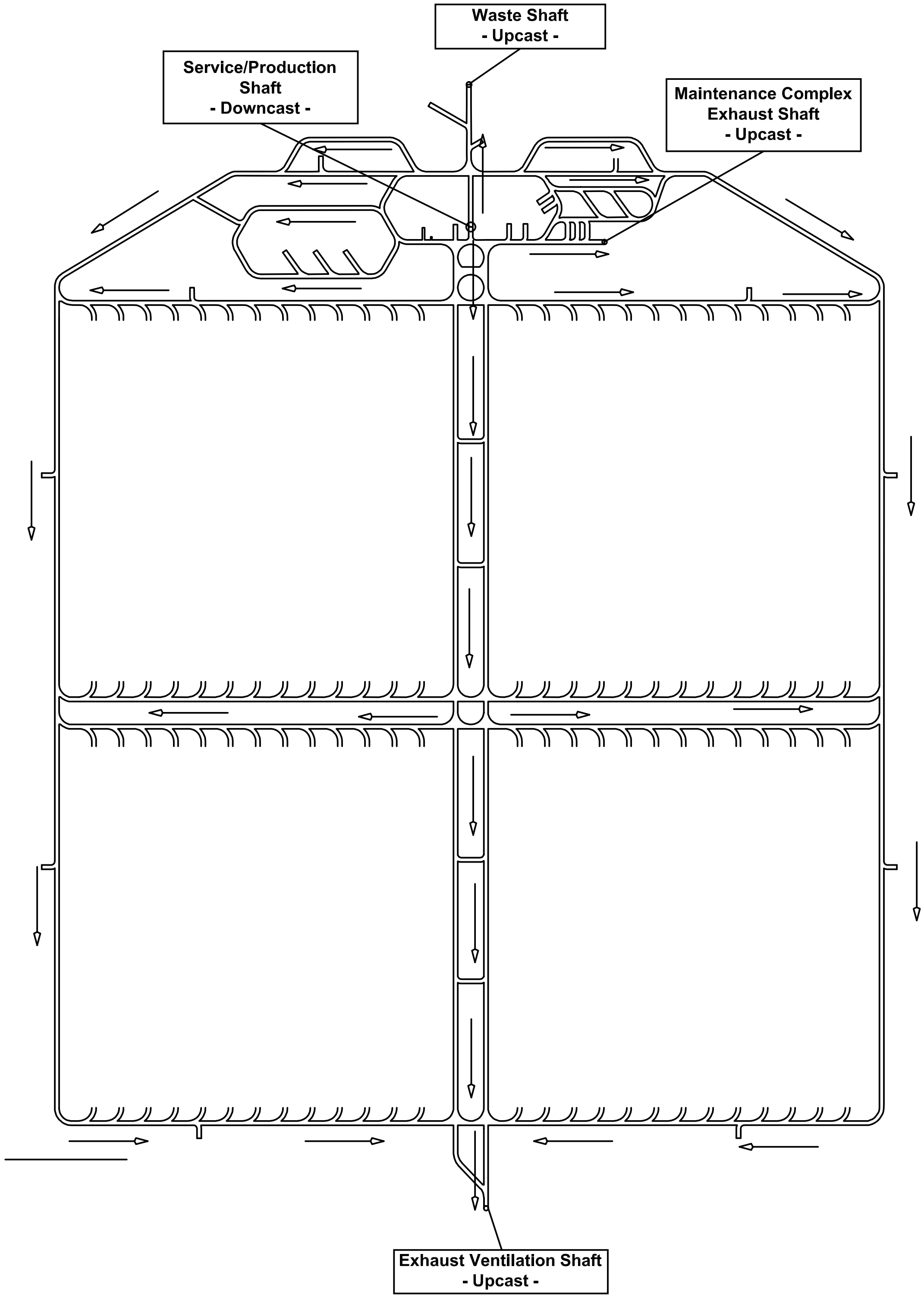


FIGURE 13 - VENTILATION SCHEMATIC FOR THE DEEP GEOLOGIC REPOSITORY

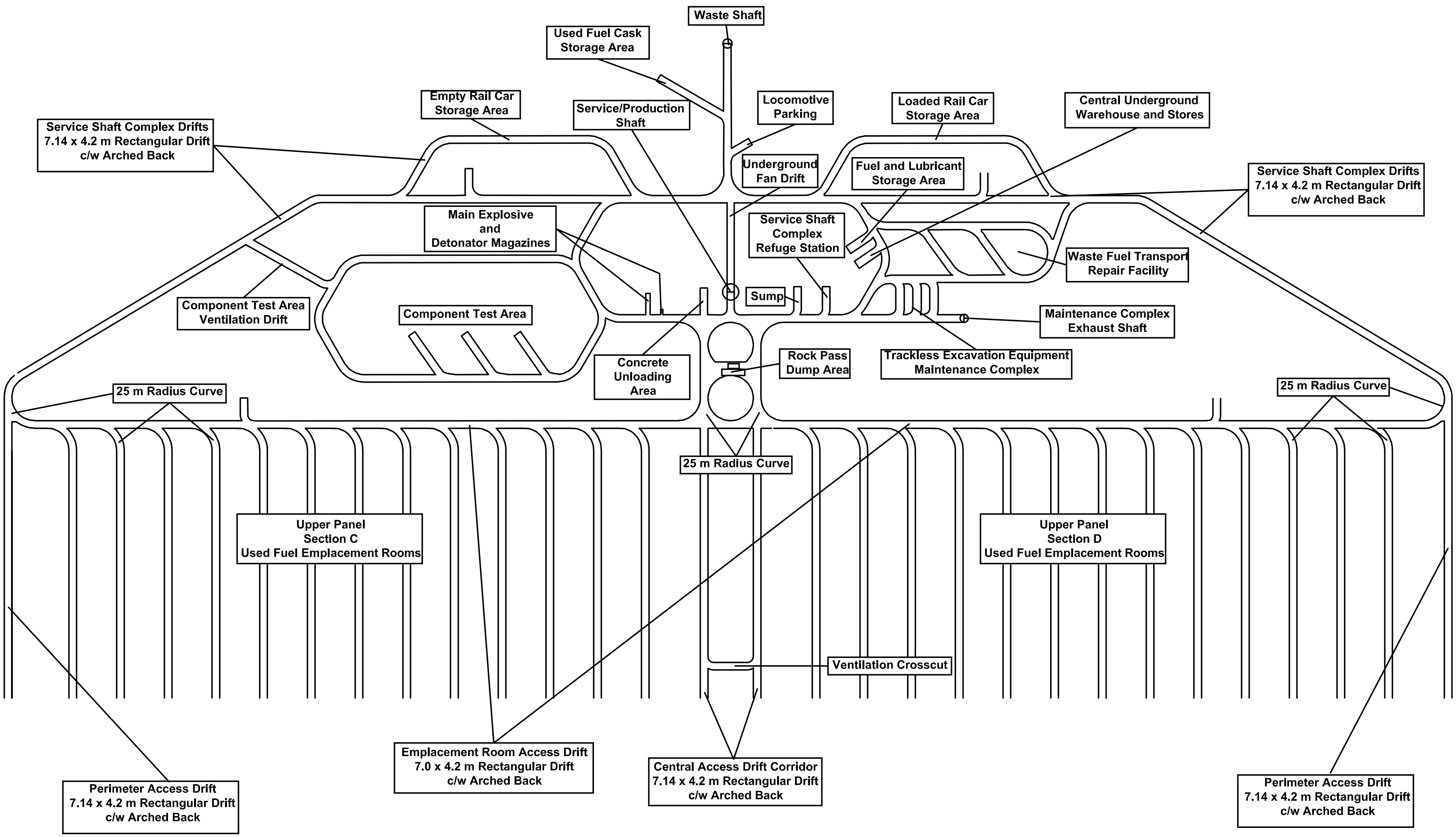


FIGURE 14 - DETAIL OF SERVICE SHAFT AREA

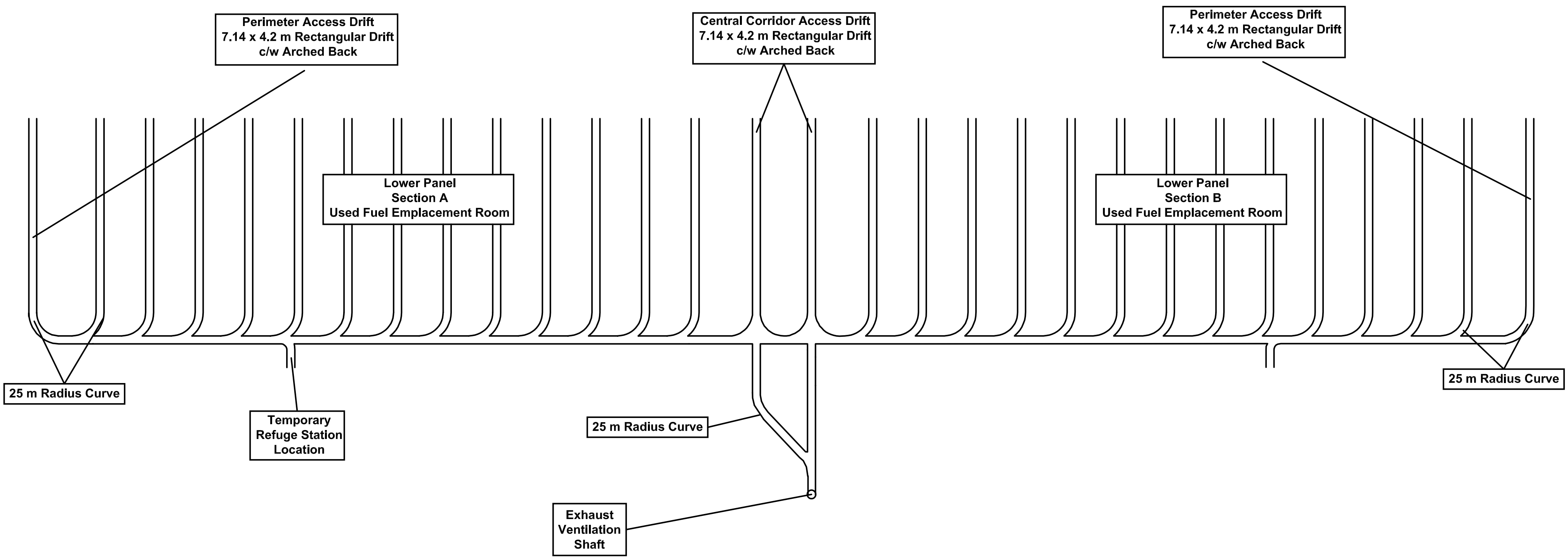
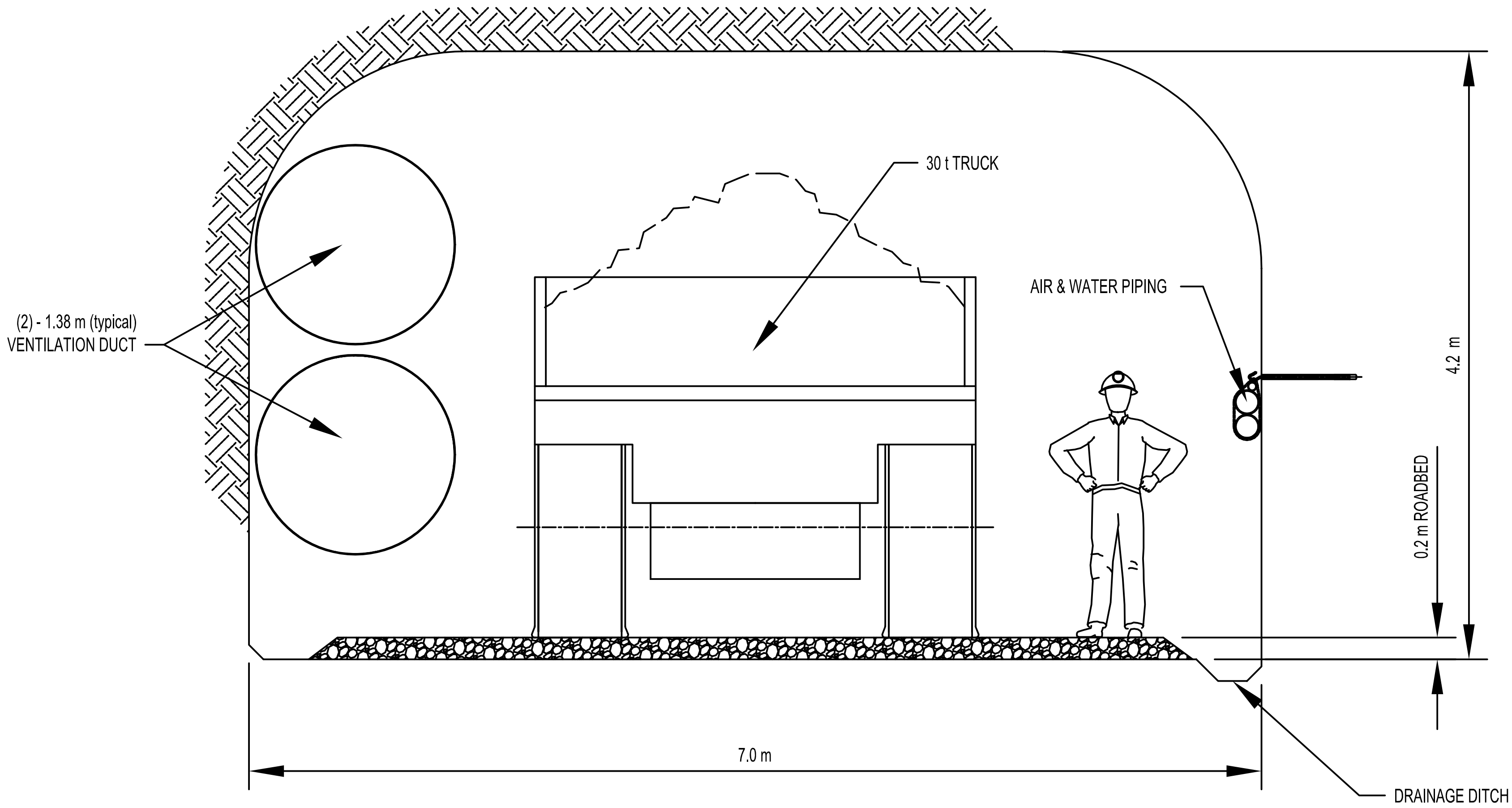


FIGURE 15 DETAIL OF THE UPCAST SHAFT COMPLEX



NOTE:
- LAYOUT MAY BE MIRRORED DEPENDING ON WHETHER AN UPPER OR LOWER EMPLACEMENT PANEL IS BEING DEVELOPED.

FIGURE 16 CROSS SECTION OF ACCESS TUNNELS

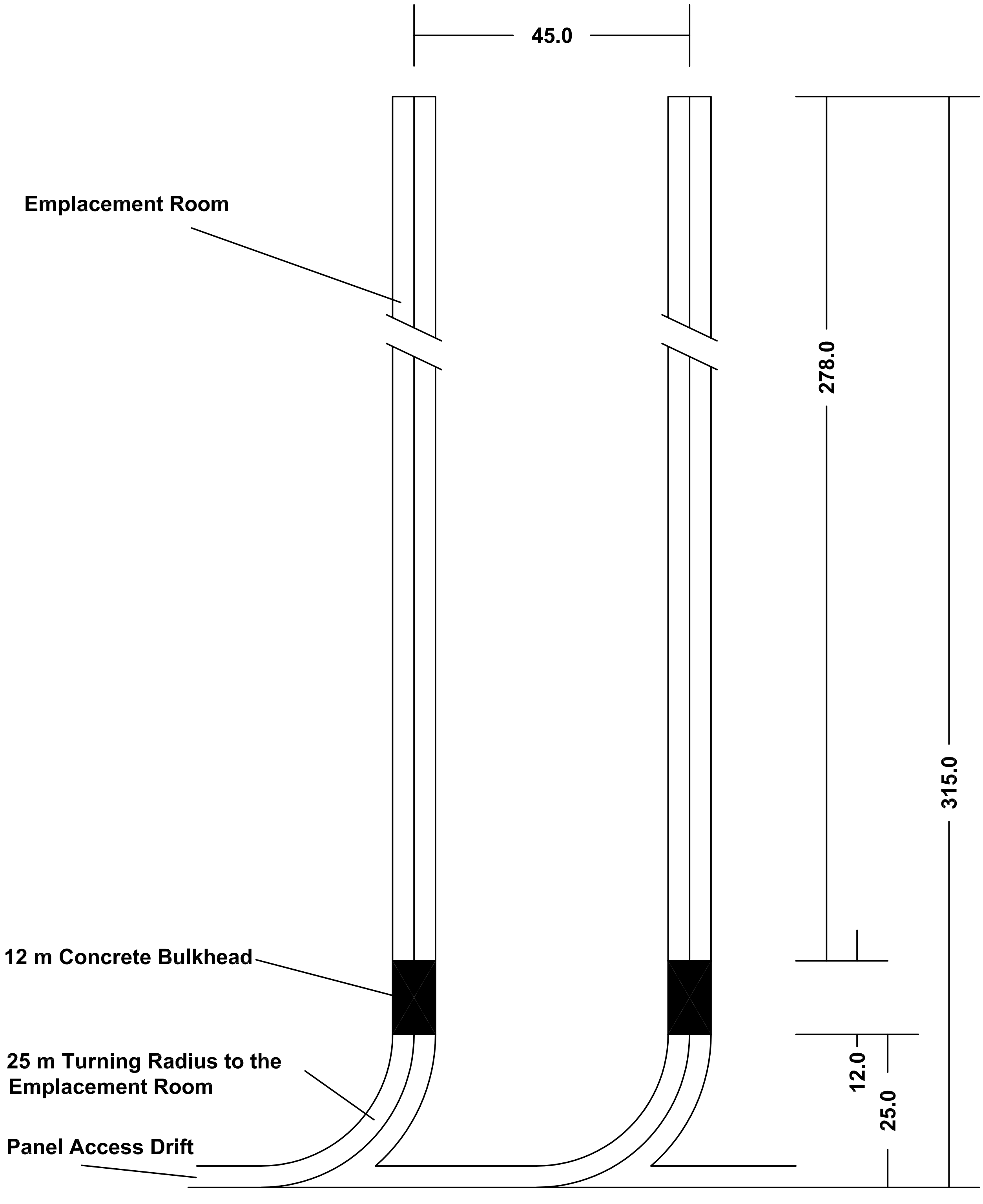


FIGURE 17 LOCATION OF 12m THICK EMPLACEMENT ROOM BULKHEADS

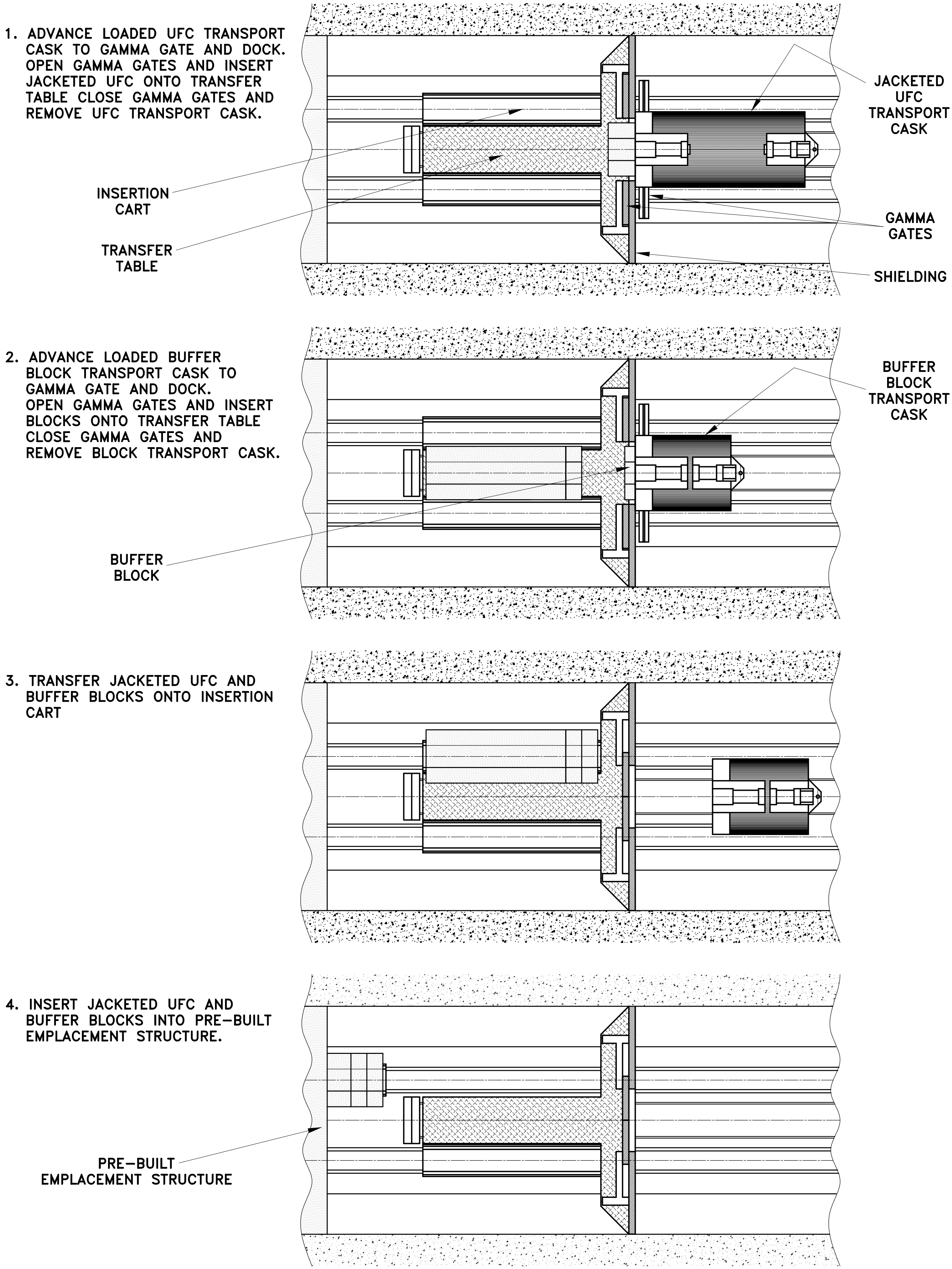
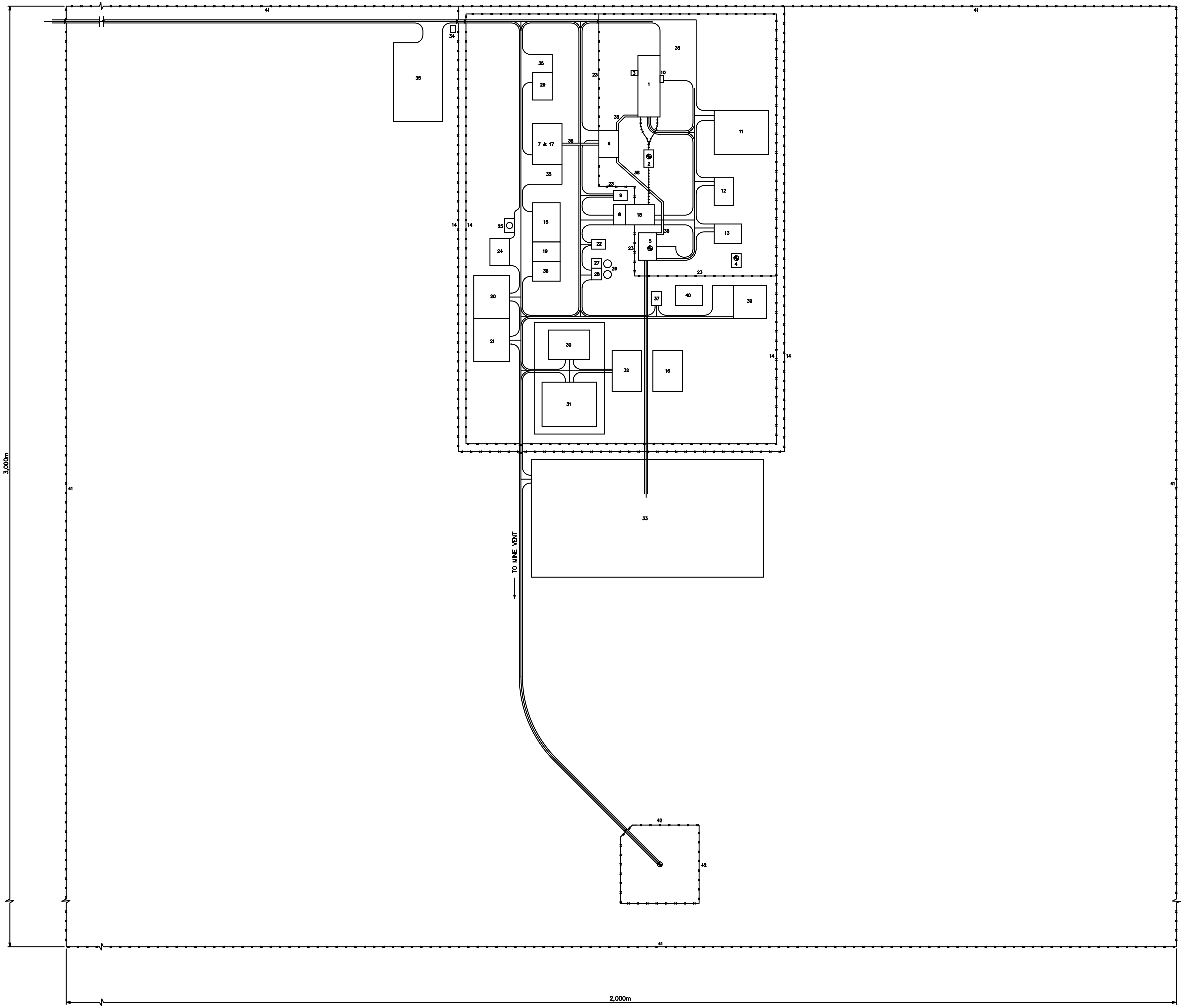


FIGURE 18 SEQUENCE OF EMPLACEMENT ROOM OPERATIONS



LEGEND:

1. USED-FUEL PACKAGING PLANT
2. WASTE-SHAFT HEADFRAME
3. STACK
4. UPCAST VENTILATION SHAFT
5. SERVICE-SHAFT COMPLEX
6. AUXILIARY BUILDING
7. ADMIN. BLDG. INCLUDING FIREHALL
8. SEALING MATERIAL STORAGE BINS
9. DUST COLLECTION BAG HOUSE
10. ACTIVE SOLID WASTE HANDLING FACILITY
11. WASTE MANAGEMENT AREA
12. ACTIVE LIQUID WASTE TREATMENT BLDG.
13. LOW-LEVEL LIQUID WASTE STORAGE AREA
14. MAIN SECURITY FENCE
15. GARAGE
16. STORM RUNOFF HOLDING POND
17. CAFETERIA
18. SEALING MATERIALS COMPACTION PLANT
19. WAREHOUSE
20. SWITCHYARD
21. TRANSFORMER AREA
22. AIR COMPRESSORS
23. SECURITY FENCE (ACTIVE SITE)
24. POWERHOUSE
25. FUEL TANKS
26. WATER STORAGE TANKS
27. WATER TREATMENT PLANT
28. PUMPHOUSE
29. QUALITY CONTROL OFFICES AND LABORATORY
30. CONCRETE BATCHING PLANT AREA
31. ROCK CRUSHING PLANT AREA
32. PROCESS-WATER SETTLING POND
33. WASTE ROCK DISPOSAL AREA
34. GUARD HOUSE
35. PARKING AREA
36. STORAGE YARD
37. SEWAGE TREATMENT PLANT
38. OVERHEAD CORRIDOR
39. HAZARDOUS MATERIALS STORAGE BUILDING
40. SERVICE-SHAFT COMPLEX WATER SETTLING POND
41. PERIMETER FENCE
42. SECURITY FENCE

FIGURE 19
SURFACE FACILITIES DEVELOPMENT OVERALL SITE PLAN

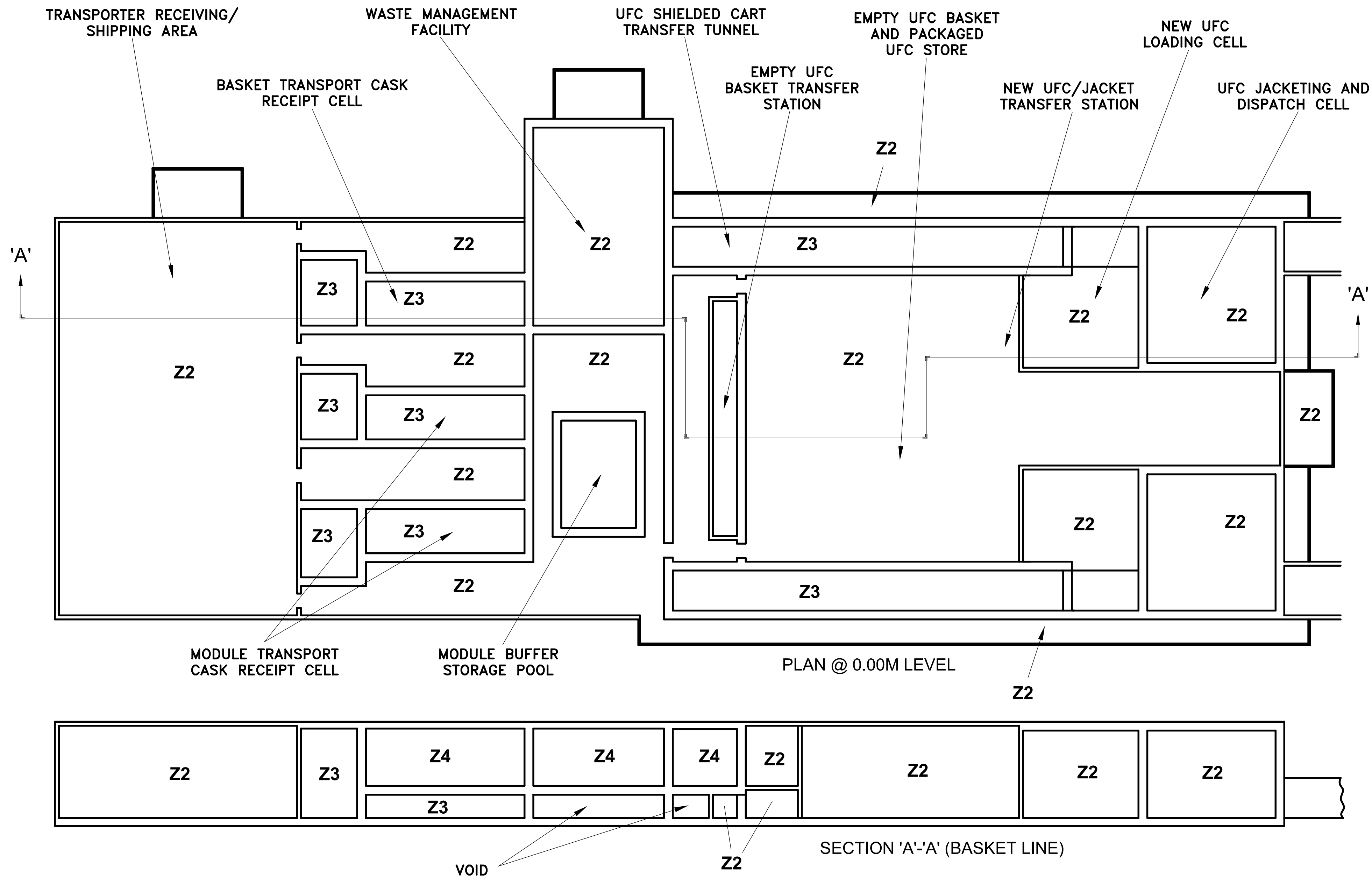


FIGURE 20 SIMPLIFIED PLAN AND ELEVATION OF THE USED FUEL PACKAGING PLANT

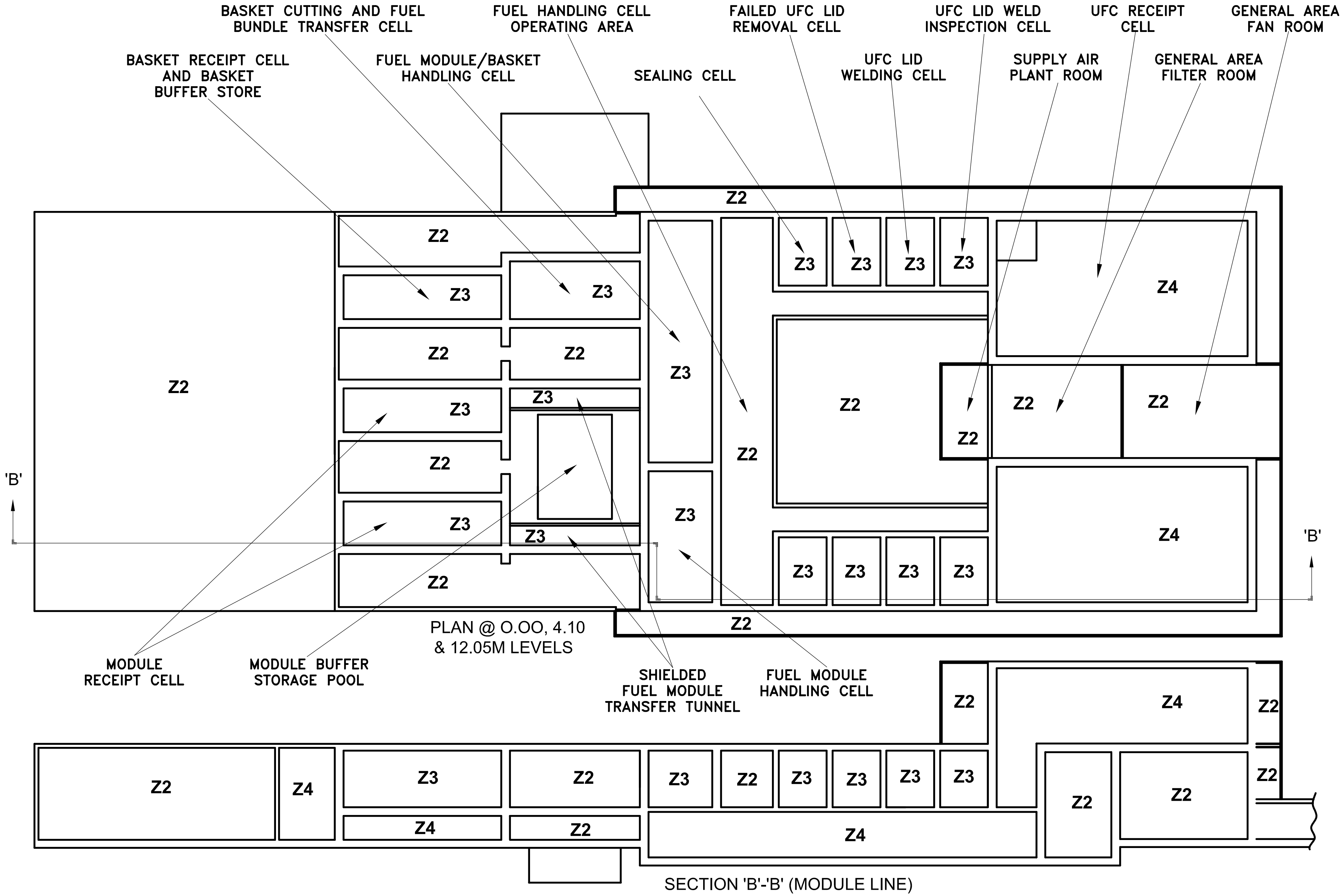


FIGURE 21 SIMPLIFIED PLAN AND ELEVATION OF THE USED FUEL PACKAGING PLANT

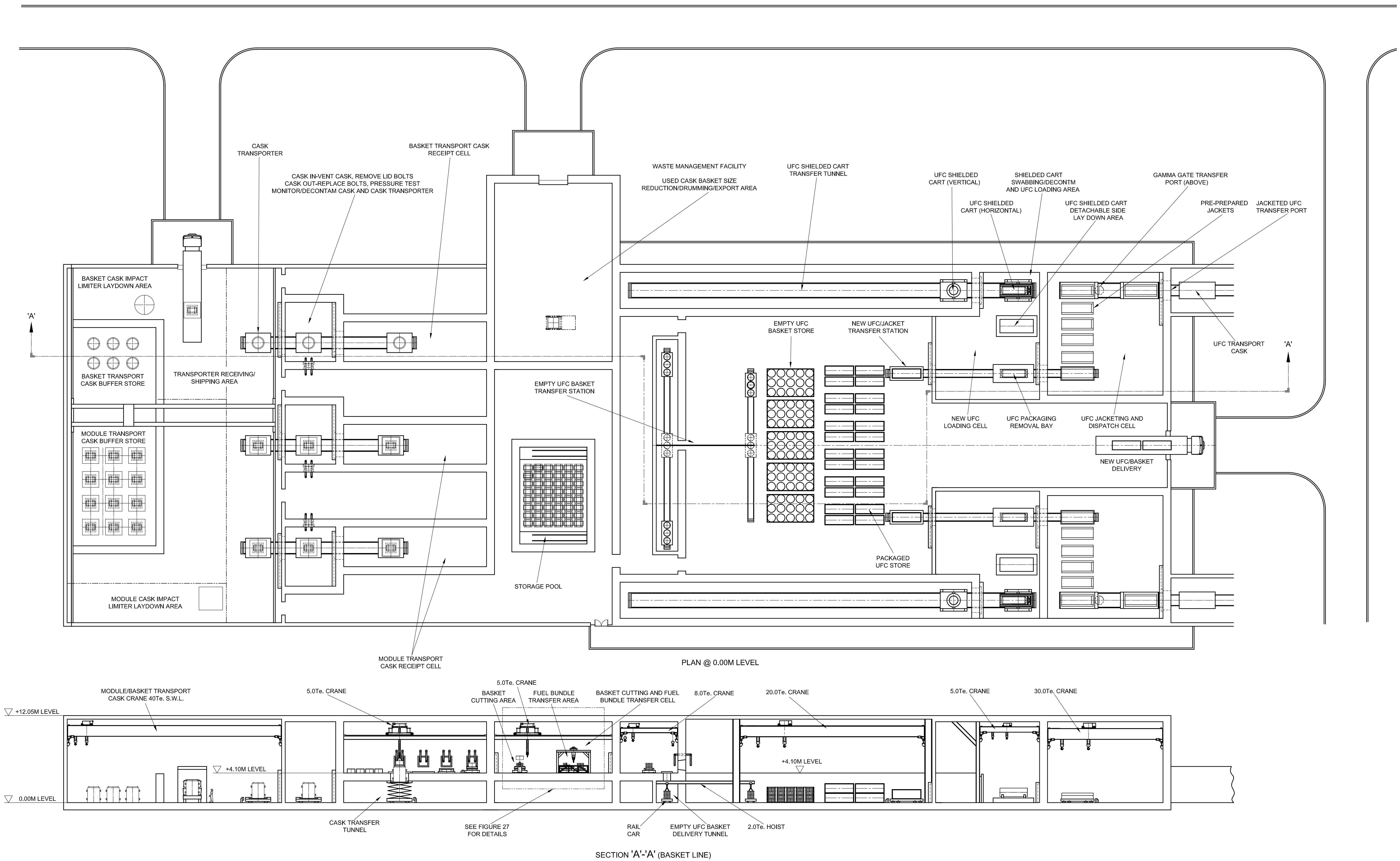


FIGURE 22 USED FUEL PACKAGING PLANT (UFPP) LAYOUT SHEET 1 OF 2

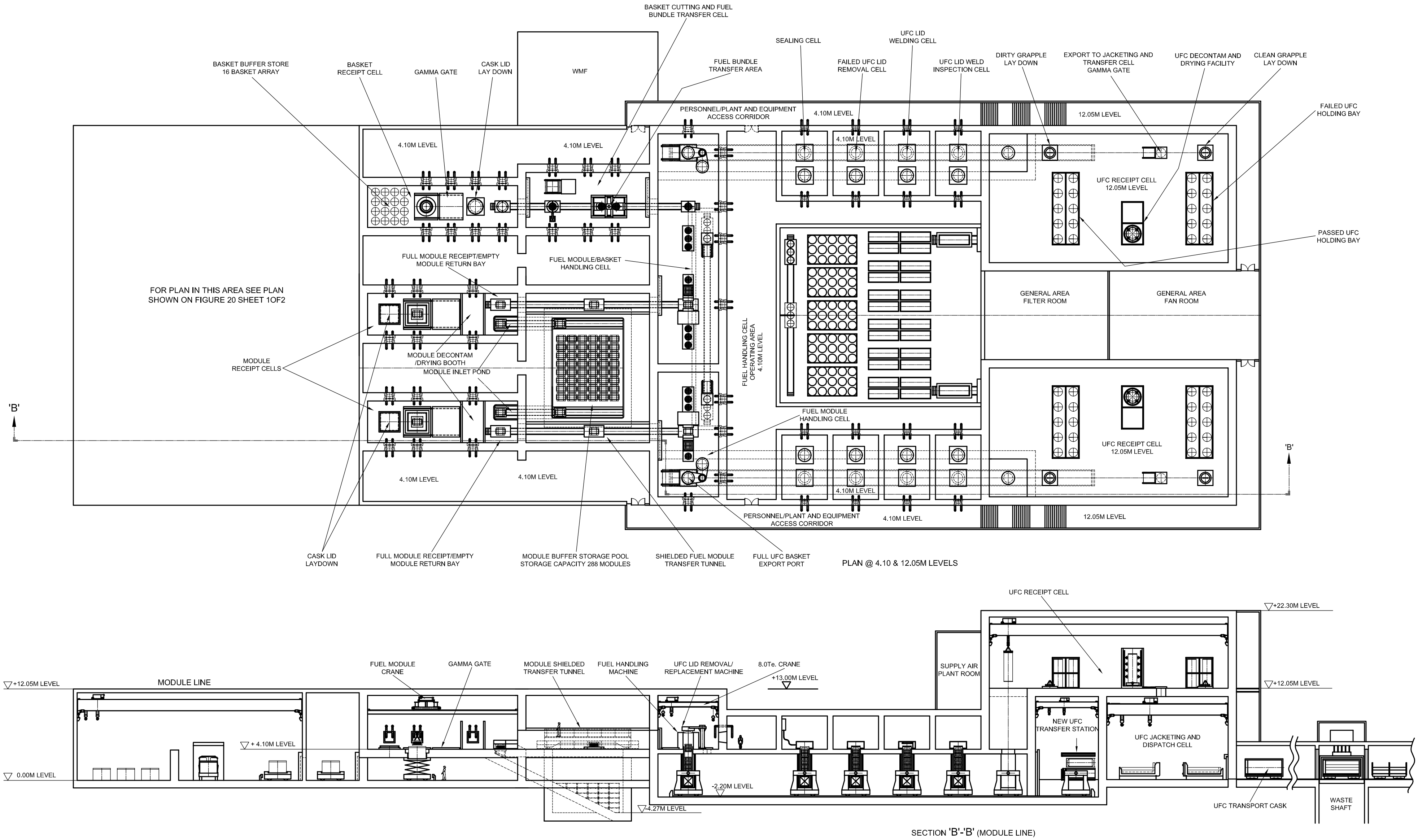


FIGURE 23 USED FUEL PACKAGING PLANT (UFPP) LAYOUT SHEET 2 OF 2

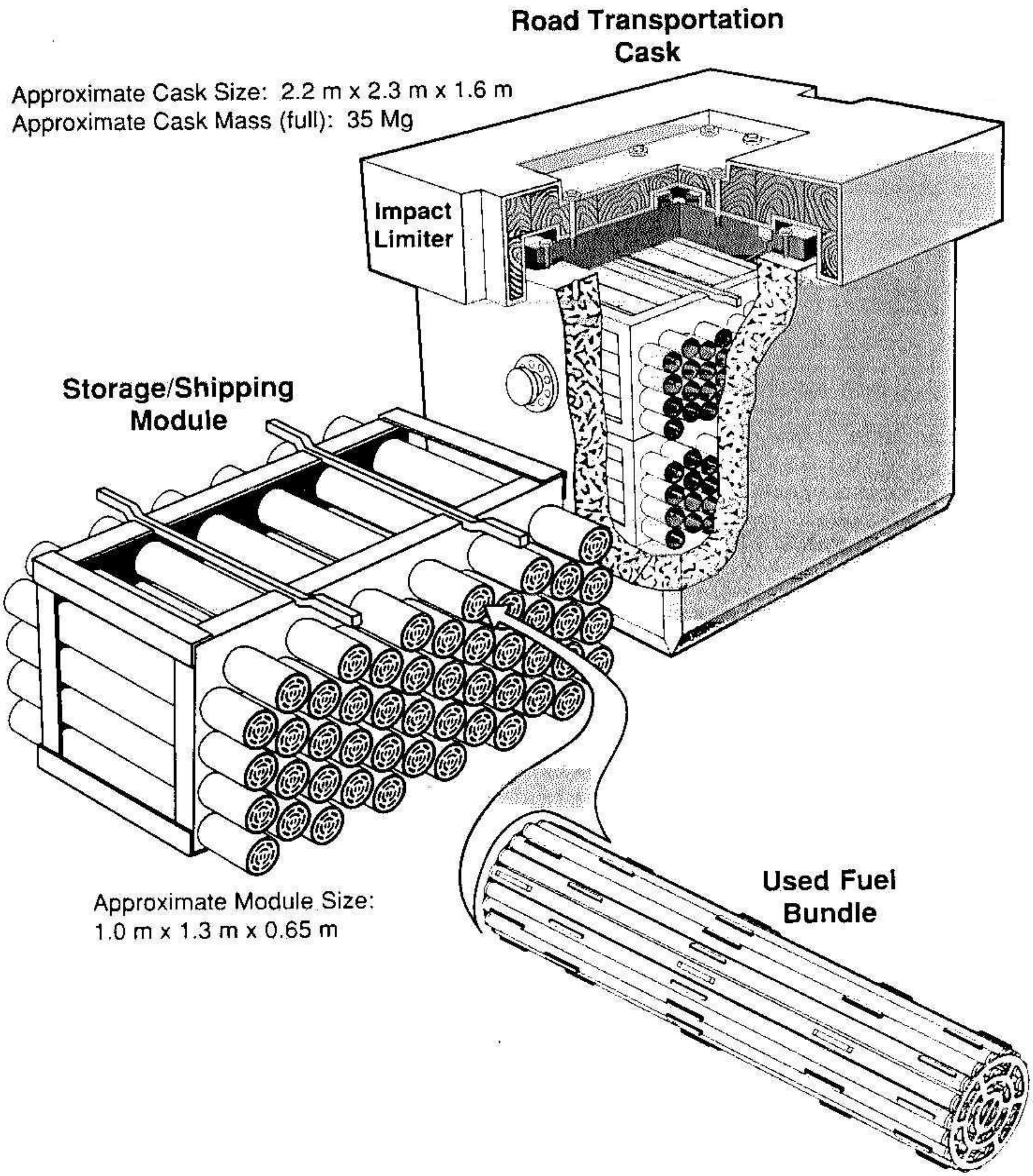
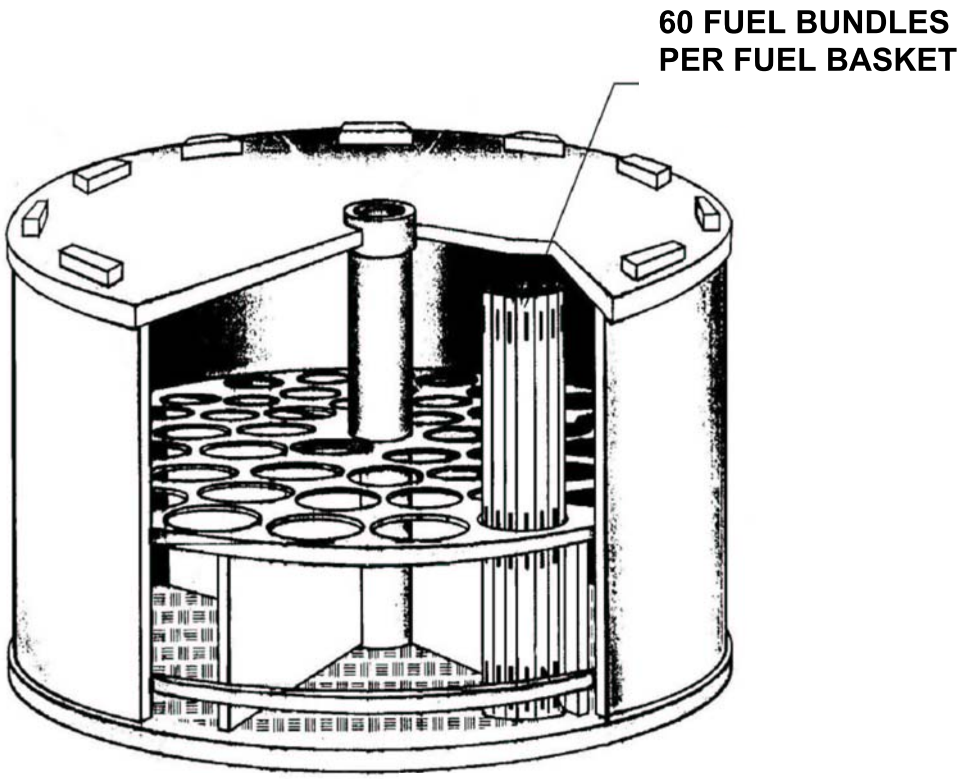


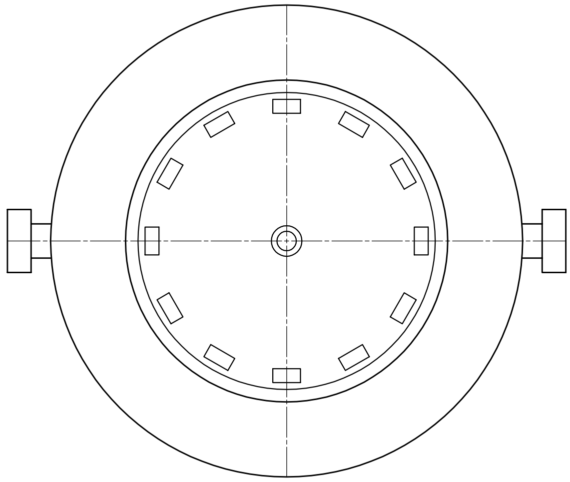
FIGURE 24 IRRADIATED FUEL TRANSPORT CASK (IFTC) SHOWING SHIPPING MODULE AND USED FUEL BUNDLE



FUEL BASKET DIMENSIONS:-
OUTSIDE DIAMETER = 1070mm
HEIGHT = 560mm

FUEL BASKET WEIGHTS:-
EMPTY = 450Kg
FULLY LOADED = 1942Kg
(60 FUEL BUNDLES)

FIGURE 25   USED FUEL BASKET



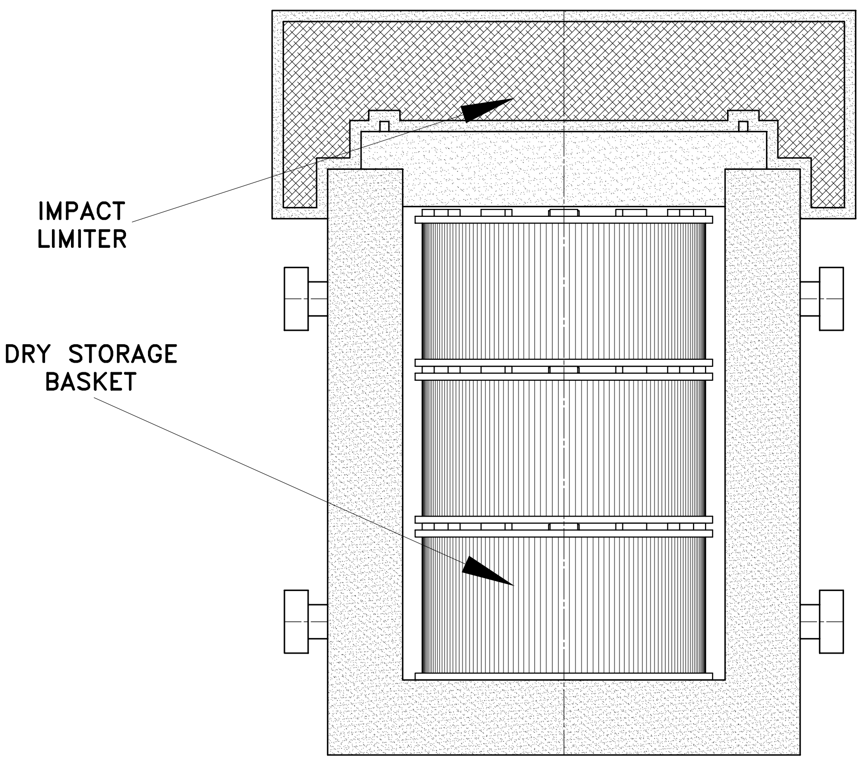


FIGURE 26 GENERAL ARRANGEMENT OF PROPOSED DRY STORAGE BASKET TRANSPORT CASK

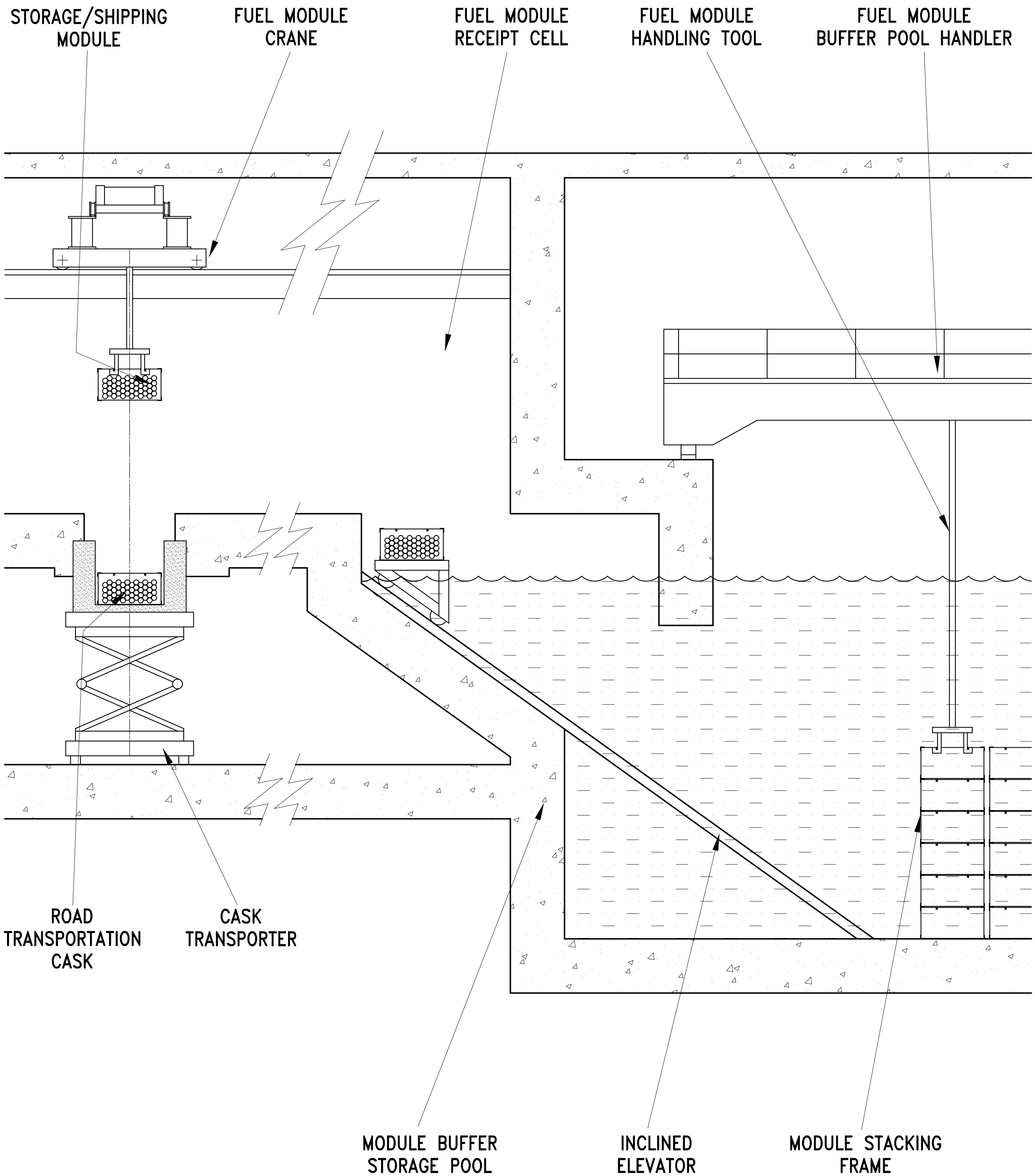
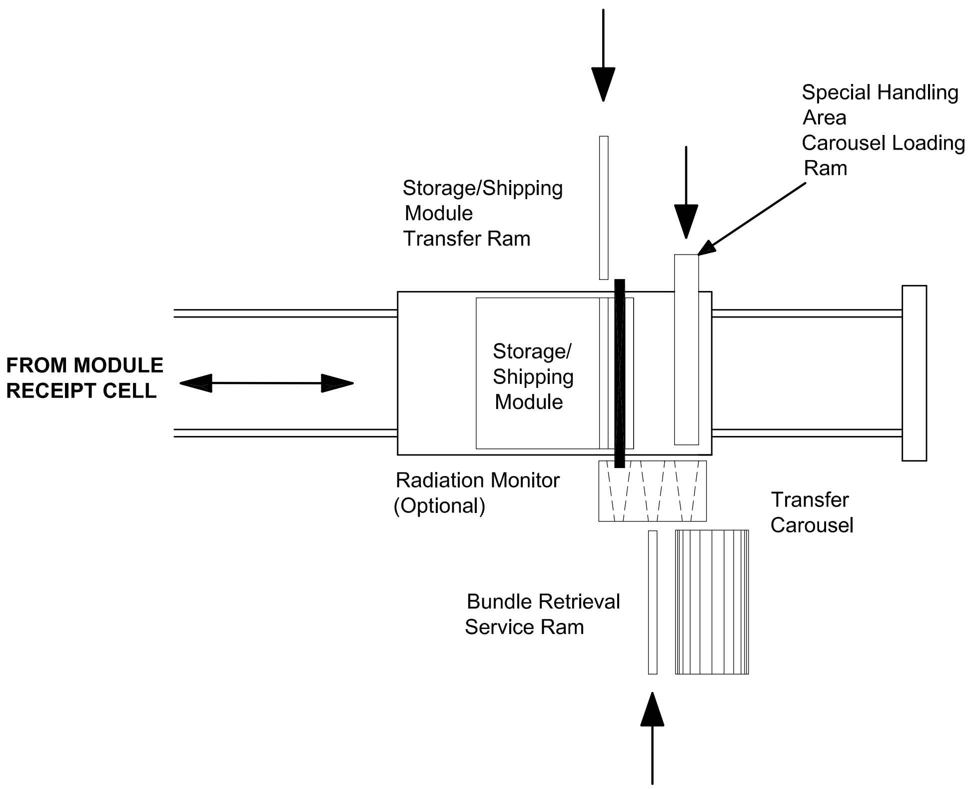
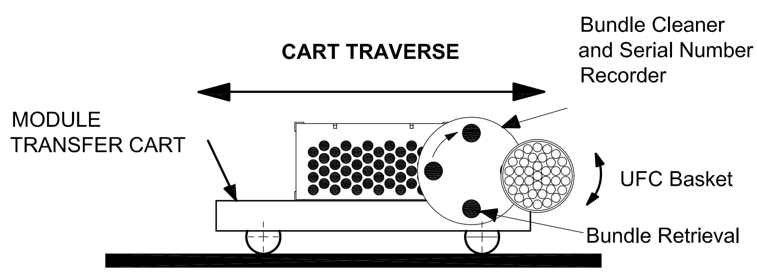


FIGURE 27 FUEL MODULE BUFFER STORAGE POOL

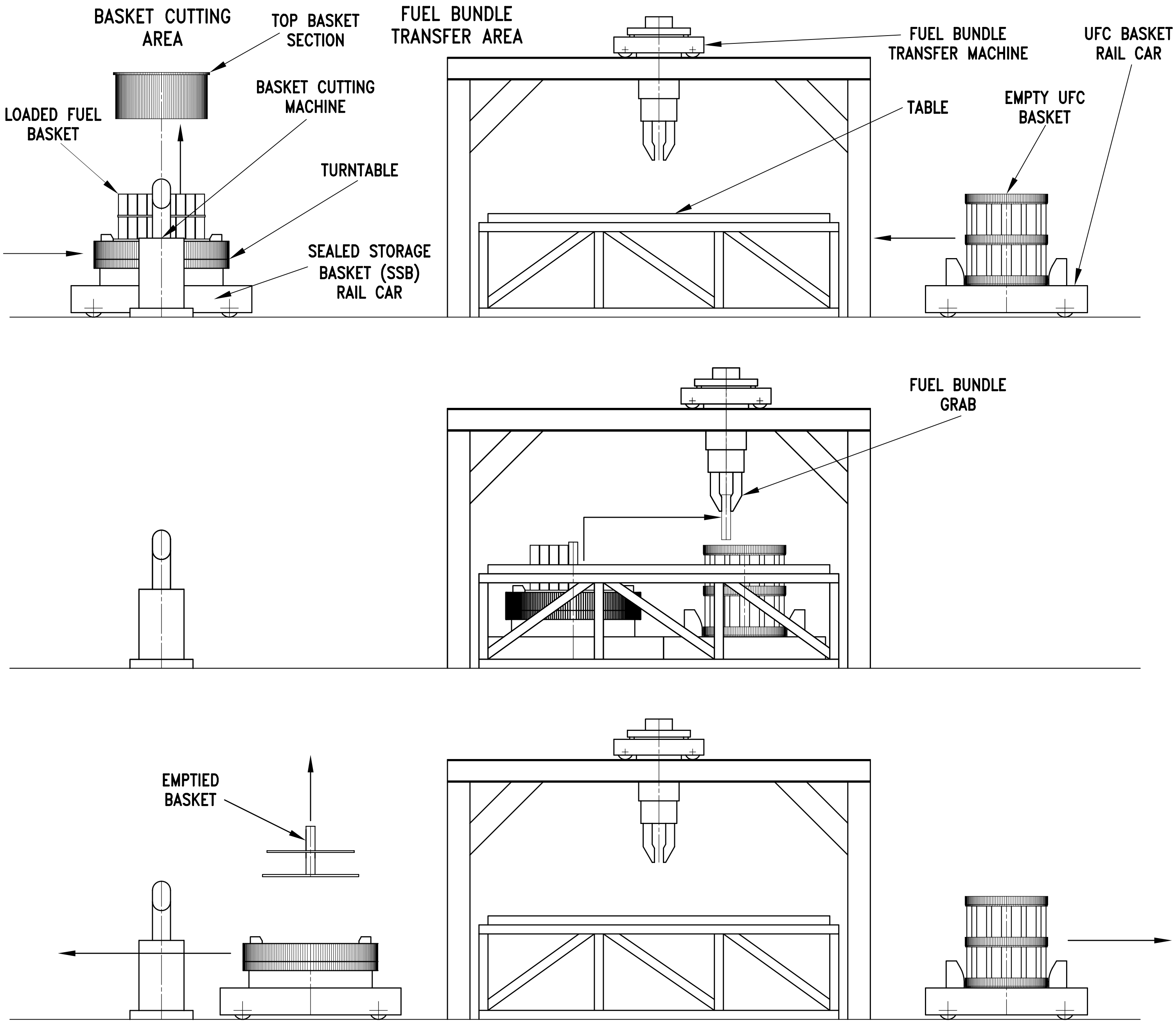


PLAN VIEW



ELEVATION VIEW

FIGURE 28 FUEL HANDLING CELL FUEL BUNDLE TRANSFER ARRANGEMENT



1. ADVANCE THE UFC BASKET RAIL CAR WITH EMPTY UFC BASKET INTO THE FUEL BUNDLE TRANSFER MACHINE. ADVANCE THE SEALED STORAGE BASKET (SSB) RAIL CAR WITH LOADED BASKET TO THE BASKET CUTTING AREA. CUT THE BASKET IN THE APPROPRIATE PLACES, REMOVE THE TOP BASKET SECTION AND DISCHARGE TO THE WASTE MANAGEMENT FACILITY. ADVANCE THE SSB RAIL CAR INTO THE FUEL BUNDLE TRANSFER MACHINE.

2. WITH THE UFC BASKET IN POSITION RAISE FUEL BUNDLE SUPPORT RODS. TRANSFER FUEL BUNDLES AND FILL UFC BASKET BOTTOM LAYER. LOWER SUPPORT RODS AND TRANSFER TOP LAYER OF FUEL BUNDLES INTO UFC BASKET.

3. REMOVE THE FILLED UFC BASKET RAIL CAR AND SSB RAIL CAR FROM THE FUEL BUNDLE TRANSFER MACHINE.
   ADVANCE THE UFC BASKET RAIL CAR TO THE FUEL BASKET HANDLING CELL.
   REMOVE THE EMPTIED SEALED STORAGE BASKET AND DISCHARGE TO THE WASTE MANAGEMENT FACILITY.
   RETURN THE SSB RAIL CAR TO THE BASKET RECEIPT CELL.

FIGURE 29 SEQUENCE DIAGRAM FOR STORAGE BASKET FUEL BUNDLE TRANSFER

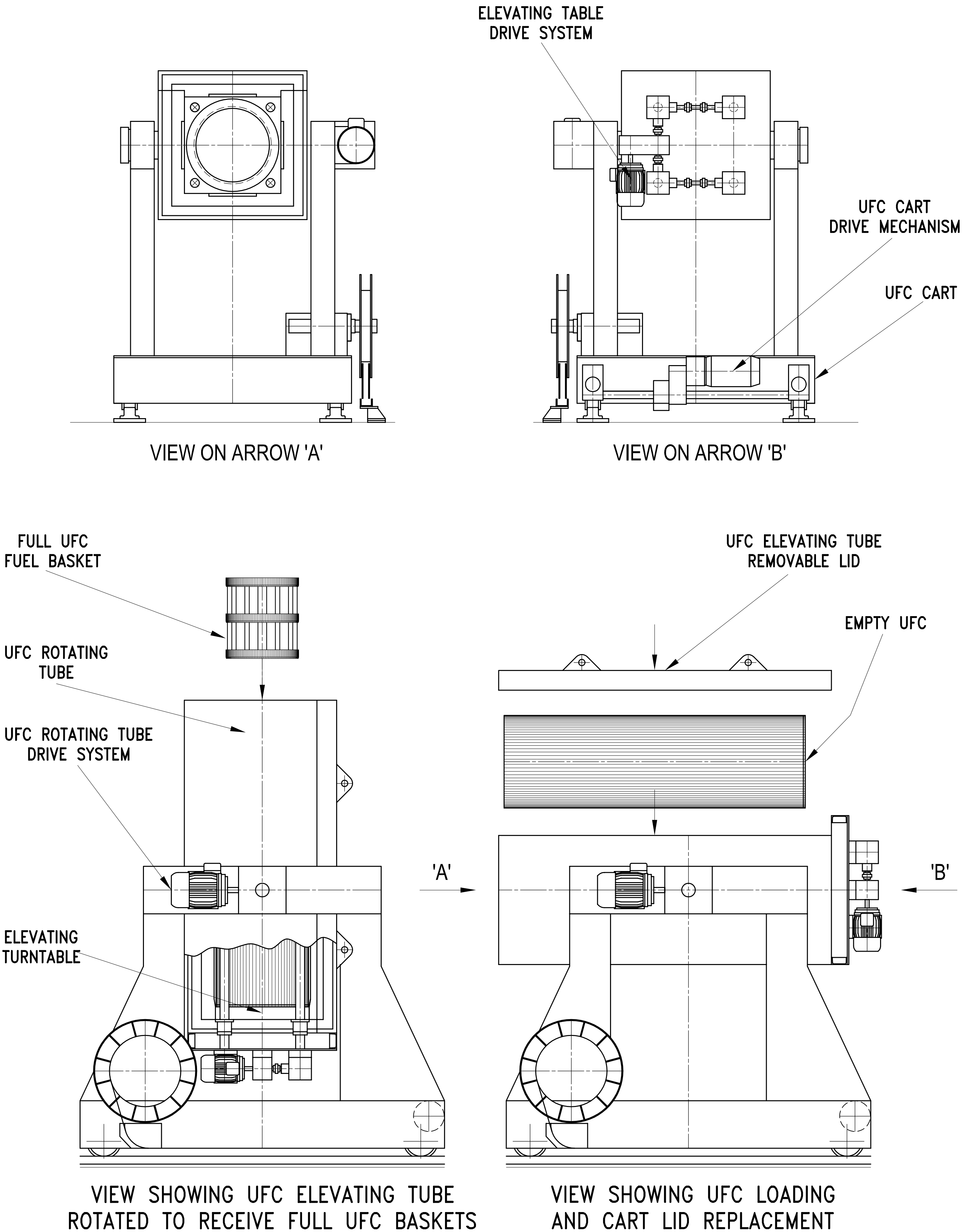


FIGURE 30 GENERAL ARRANGEMENT OF UFC ELEVATING CART

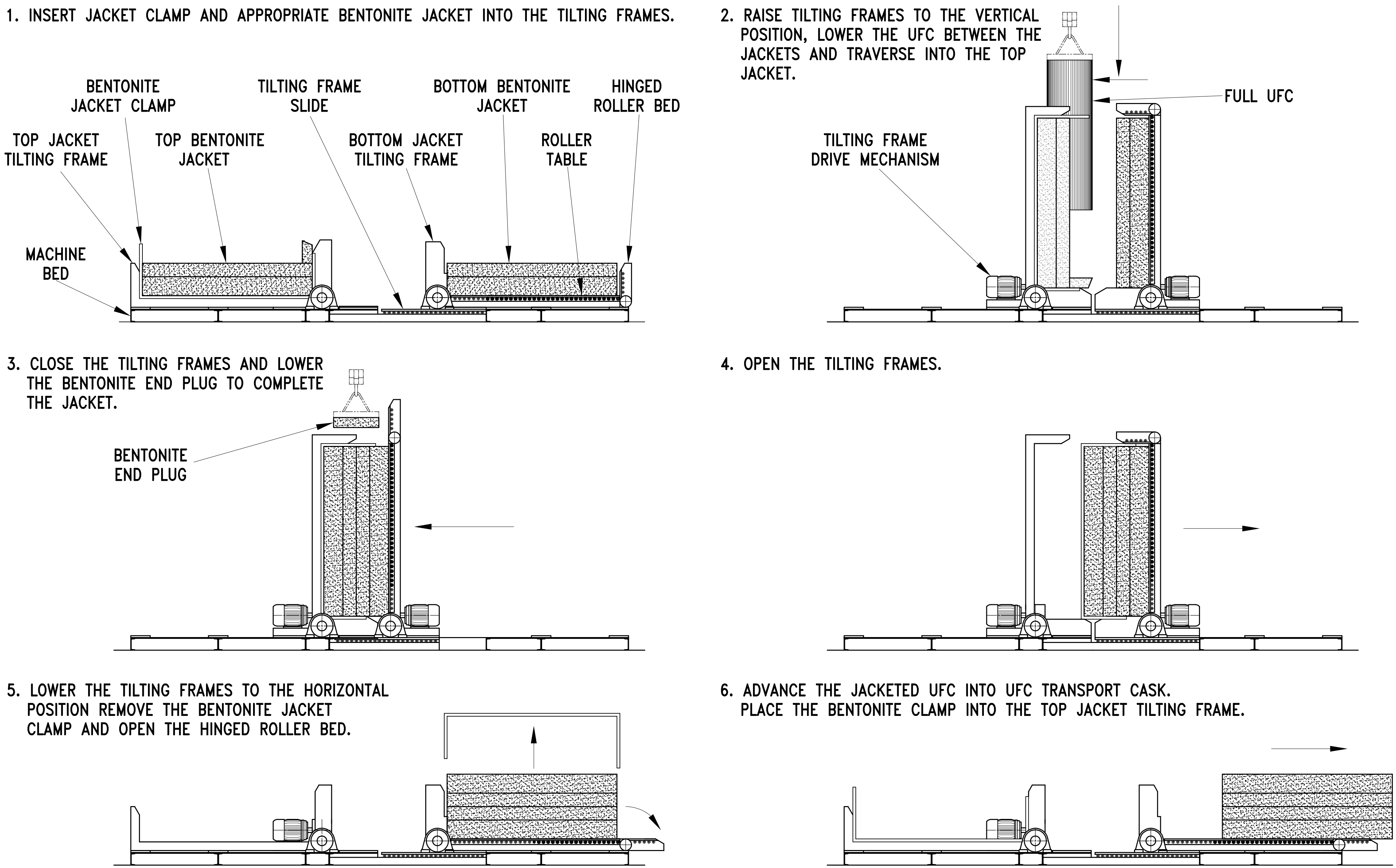


FIGURE 31 GENERAL ARRANGEMENT OF UFC JACKETING MACHINE

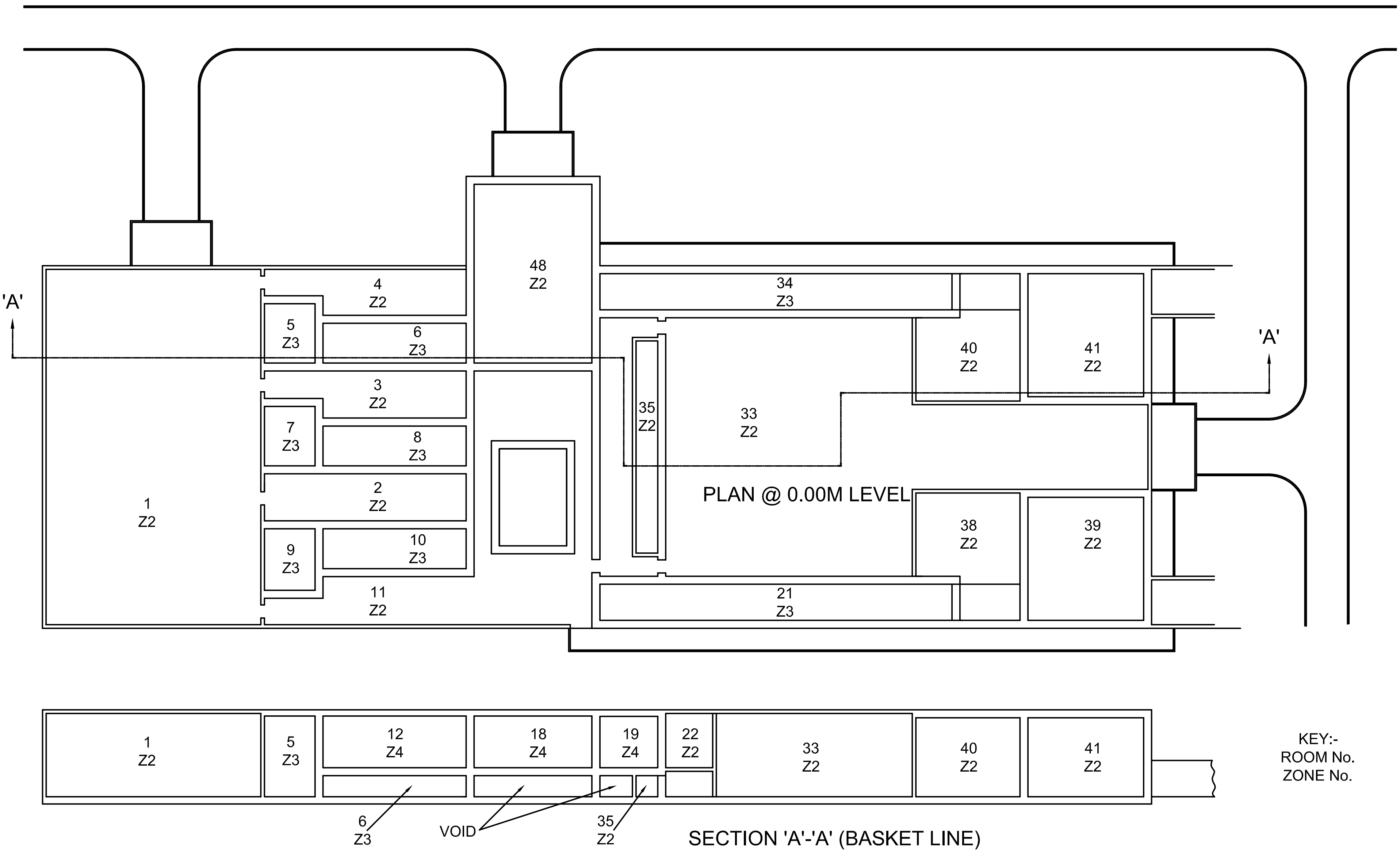


FIGURE 32 UFPP ZONING AND ROOM NUMBERS SHEET 1 OF 2

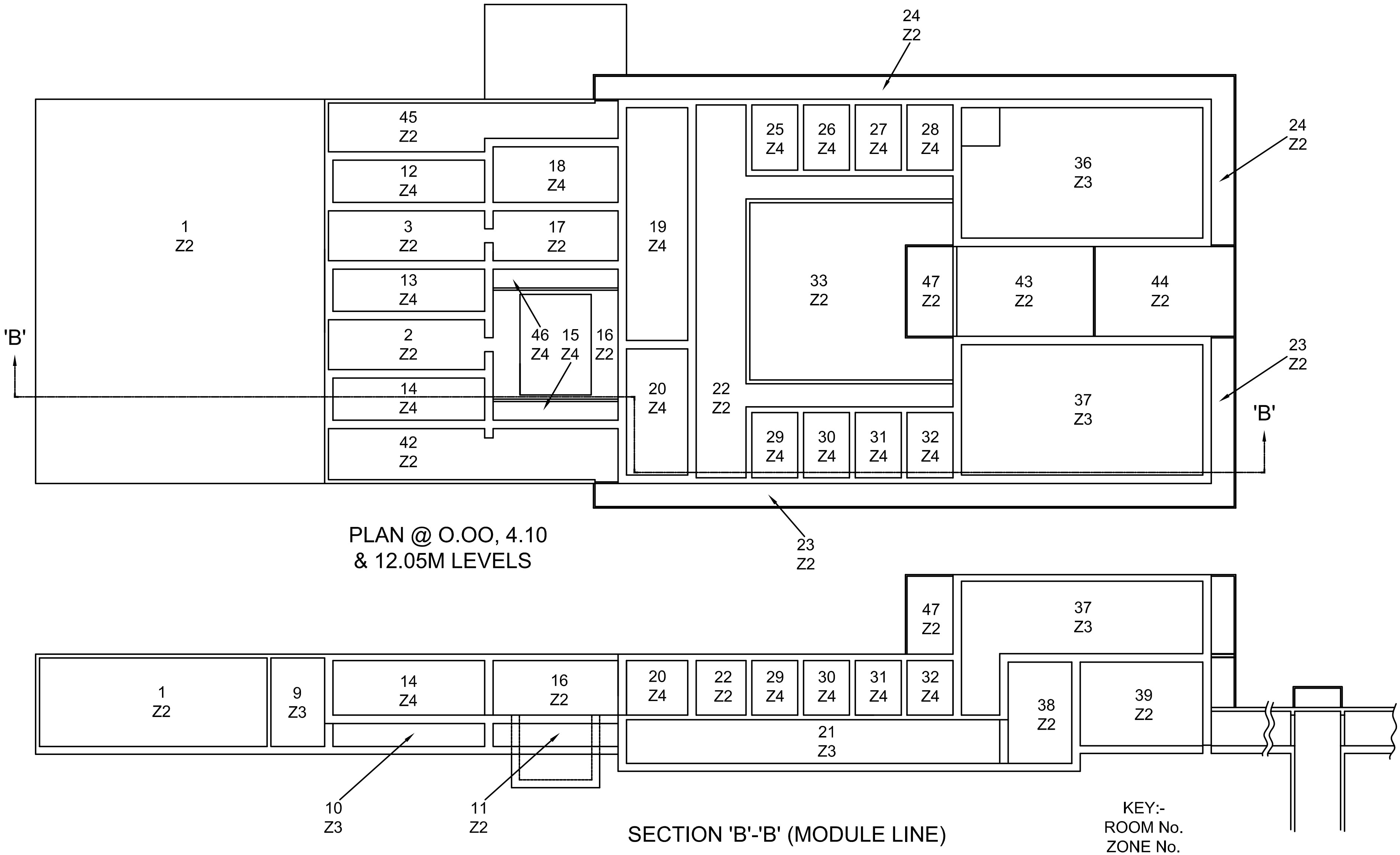
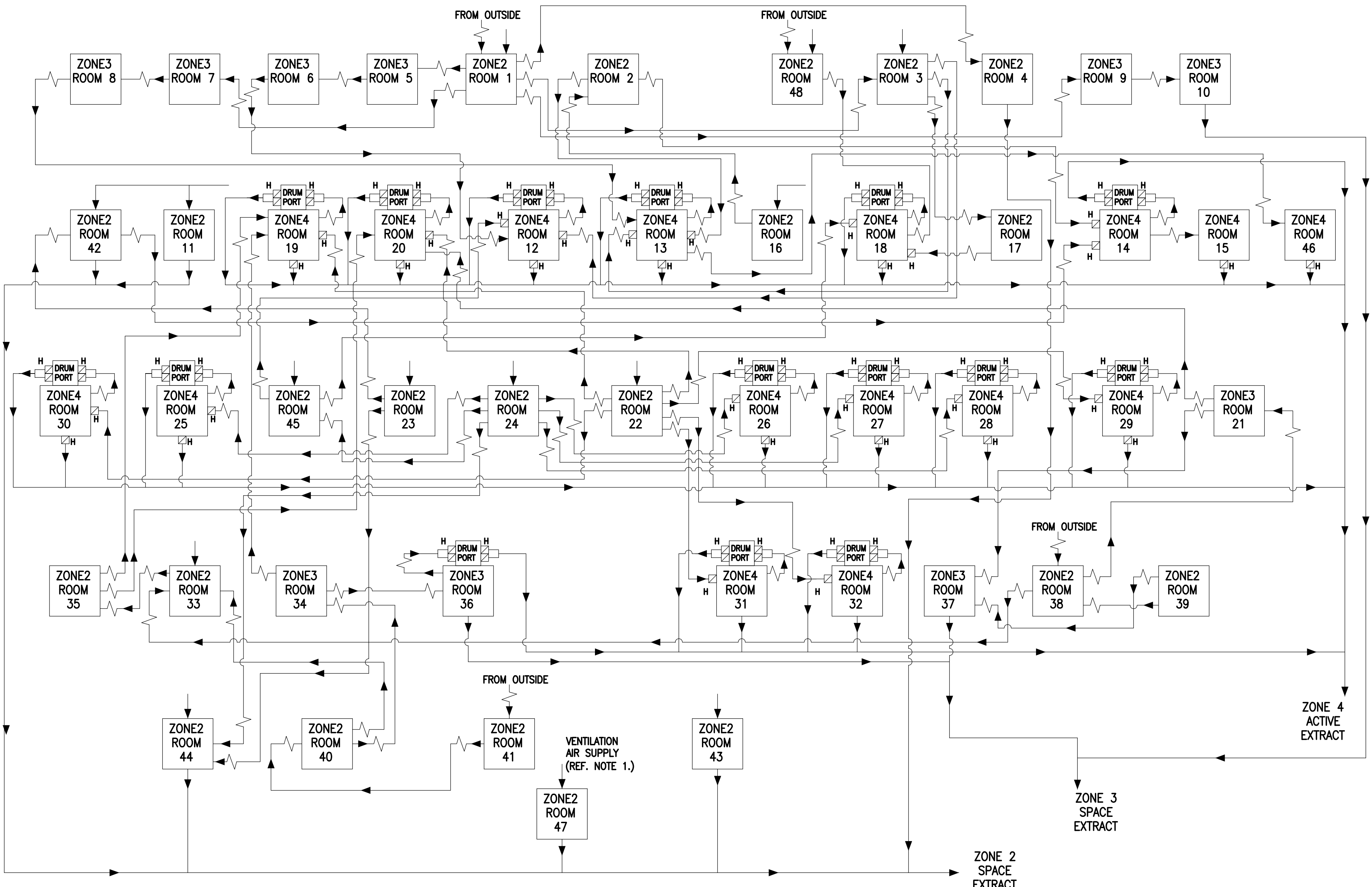


FIGURE 33 UFPP ZONING AND ROOM NUMBERS SHEET 2 OF 2



NOTE 1. FRESH AIR IS SUPPLIED TO ROOMS 1, 3, 11, 16, 22, 23, 24, 33, 42, 43, 44, 45

NOTE 2. H ⊠ HEPA FILTER

NOTE 3. PROVISION OF DRUM PORT INLET HEPA FILTERS TO BE DETERMINED BY HAZOP.

FIGURE 34 UFPP VENTILATION BLOCK FLOW DIAGRAM

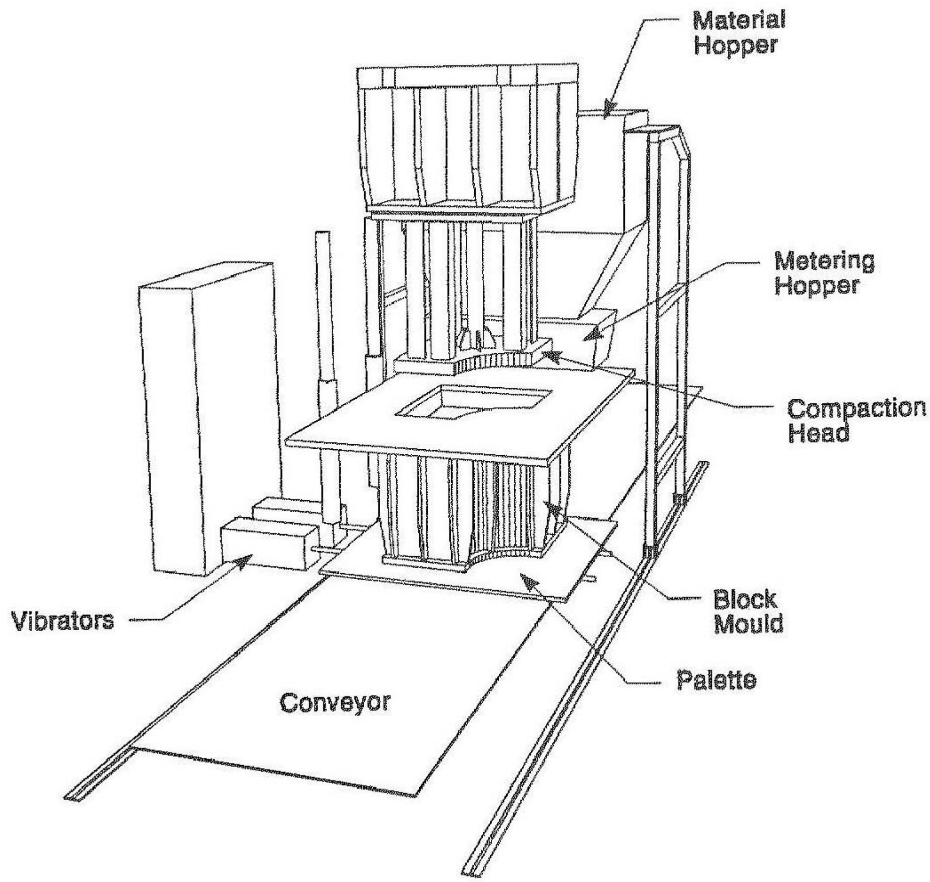


FIGURE 35 BLOCK COMPACTION MACHINE

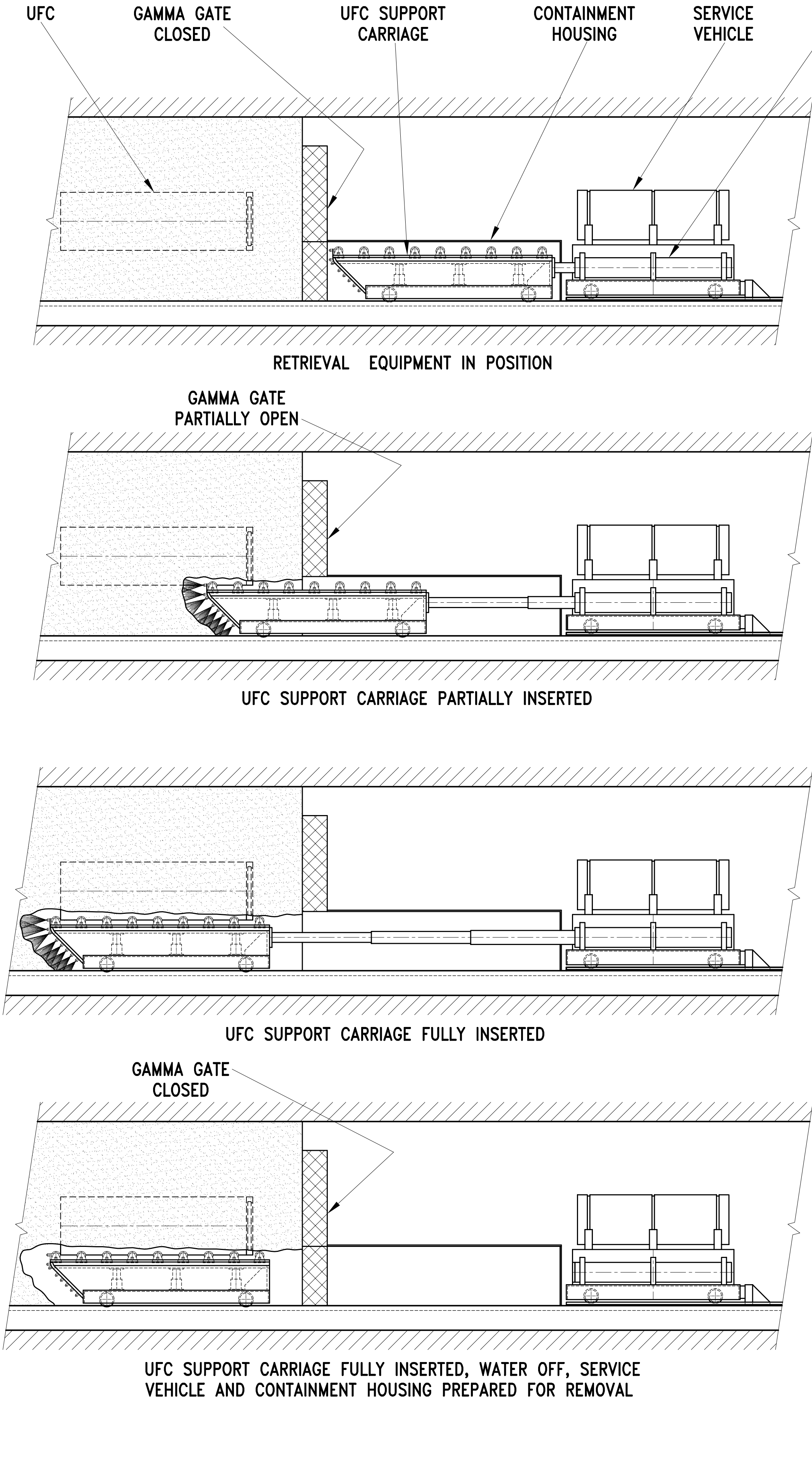


FIGURE 36 RECOVERY EQUIPMENT FOR REMOVAL OF LOWER SEALING MATERIALS

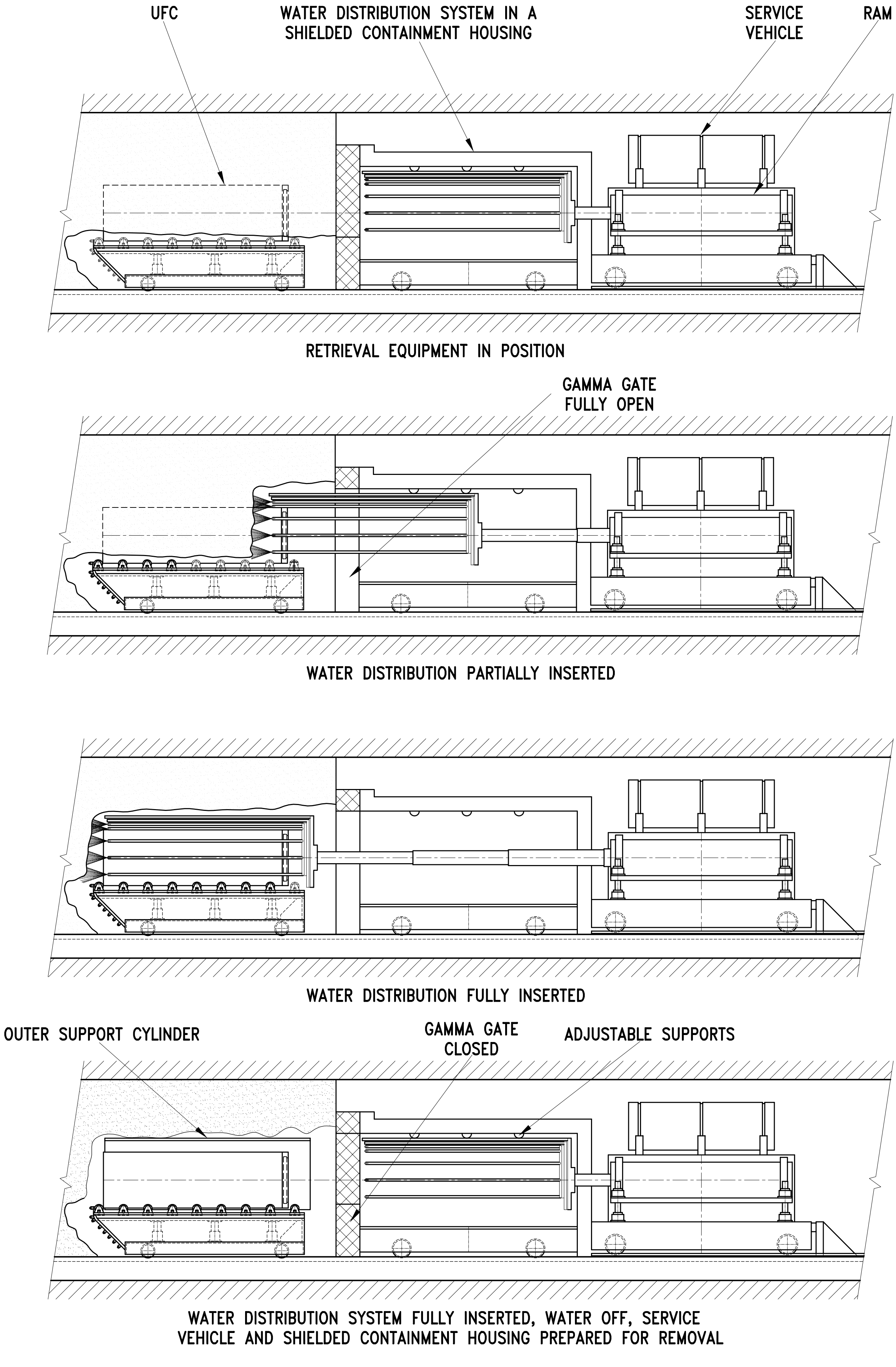


FIGURE 37 RECOVERY EQUIPMENT FOR REMOVAL OF UPPER SEALING MATERIALS

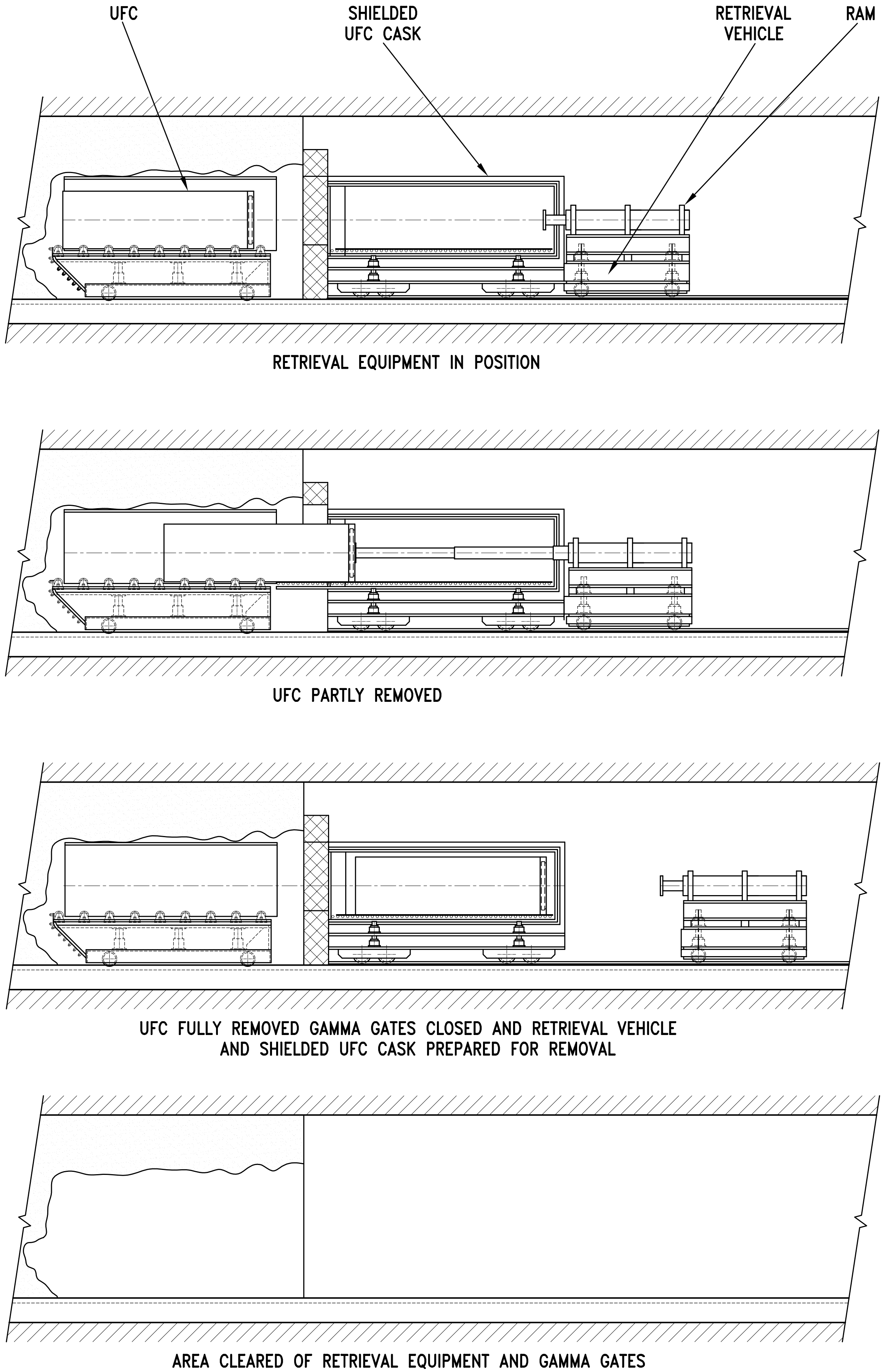


FIGURE 38 RECOVERY EQUIPMENT FOR REMOVAL OF UFC

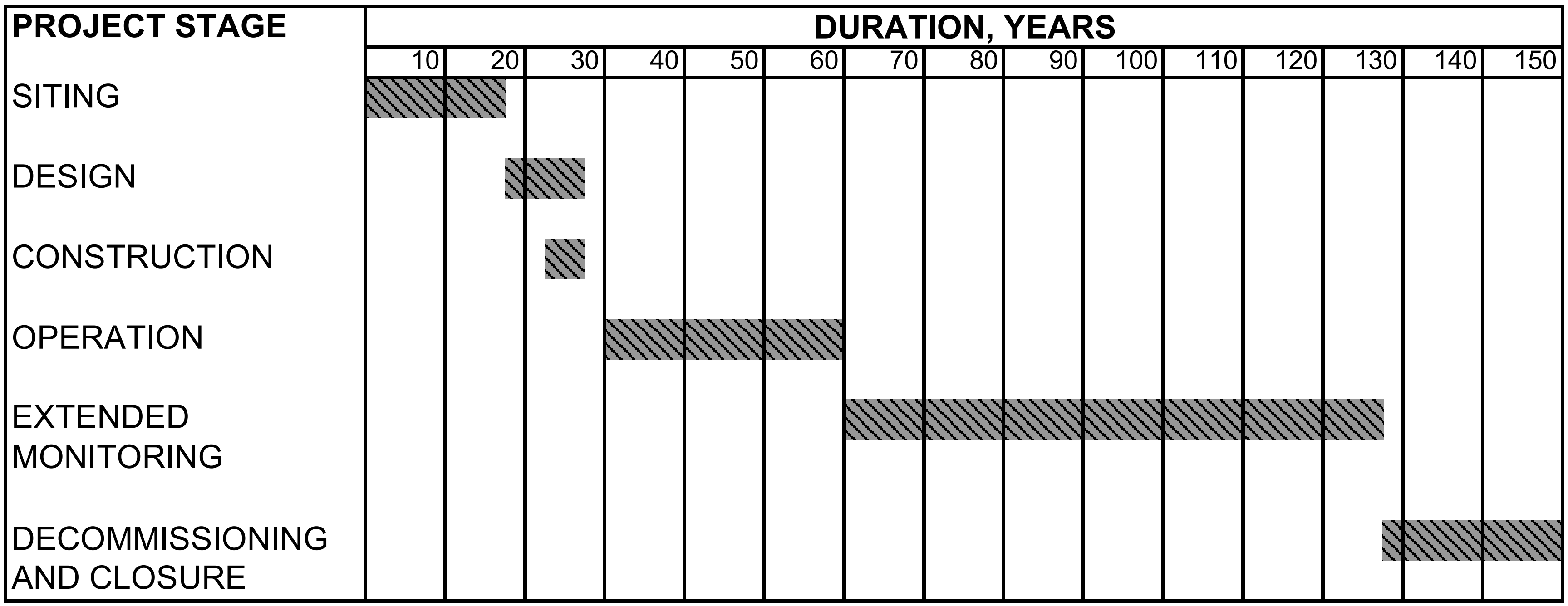


FIGURE 39 – SUMMARY DGR SCHEDULE

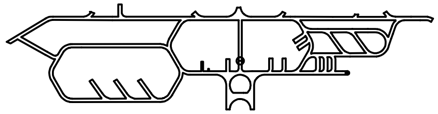


Fig. 1e (i)

Initial Exploration Development
Developing a Test Component Area and determining the proper Repository orientation.

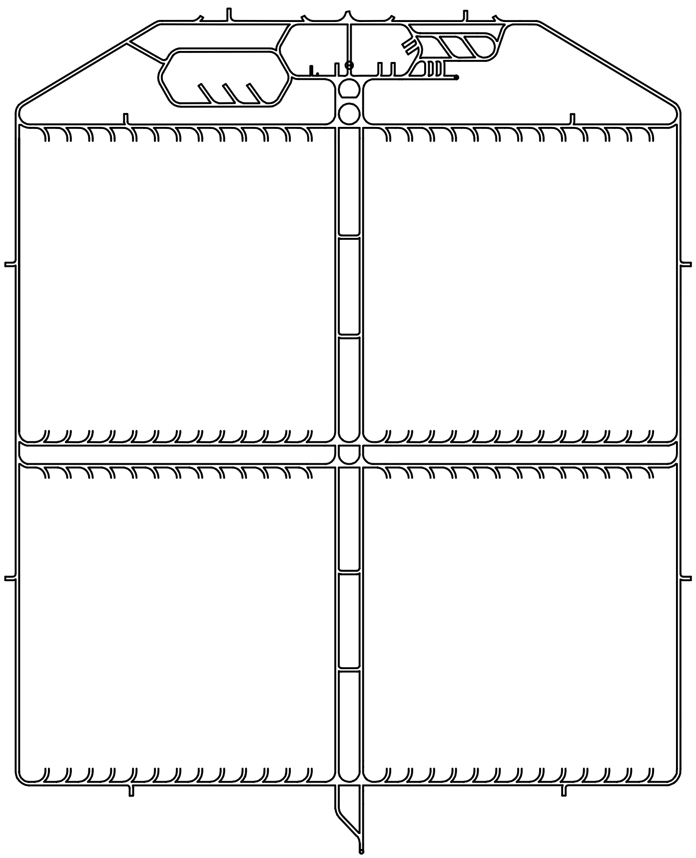


Fig. 1e (ii)

Repository Development
Establishing the perimeter, central and repository panel access drifts, plus the waste fuel transport repair facility and exhaust ventilation shaft.

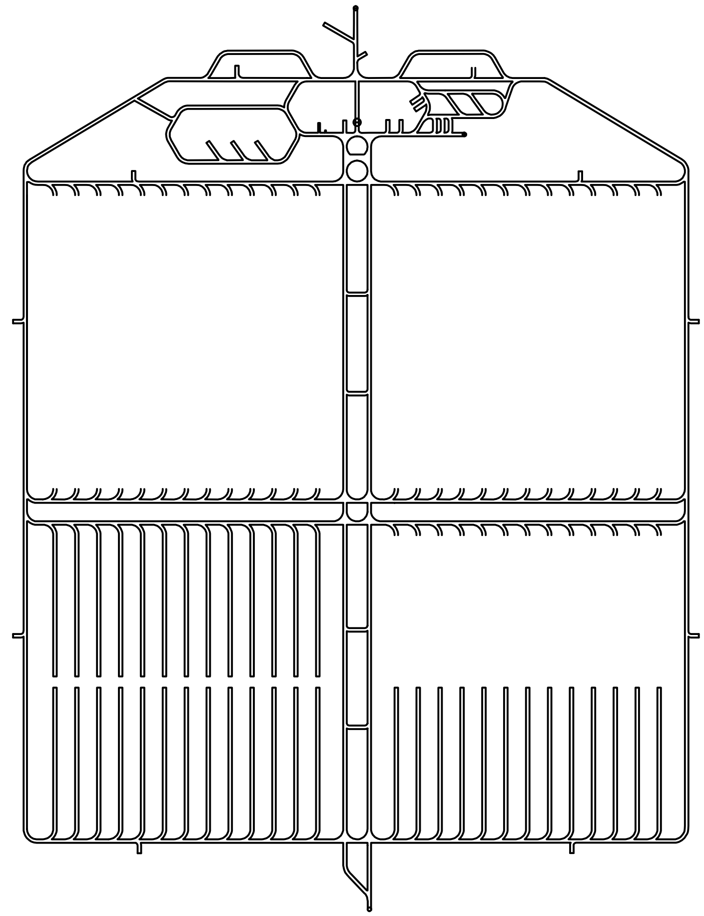


Fig. 1e (iii)

Repository Development - Repository Panel Development
Establish the Waste Shaft, empty and loaded rail car areas and 39 emplacement rooms.

FIGURE 40 DGR DEVELOPMENT STAGES

APPENDIX A

Logistics Study

A1 Introduction

The major processes associated with the receipt of used fuel, its packaging and emplacement are summarised in this document with an initial assessment of the durations for these activities. There are a number of activities that will be carried out in parallel with these main activities but as these will not affect the throughput capability of the DGR they have not been listed at this stage. Examples of these would be operations associated with placing used fuel storage/shipping modules in the storage pool, supplying new empty UFCs or baskets into the packaging process and handling/exporting scrap used fuel basket components.

The aim of this assessment is to establish that the required throughput can be achieved and to ensure that there are no major constraints imposed by the proposed used fuel packaging plant (UFPP) and DGR layouts.

The initial assessments were carried out based on information given in the request for proposal [1]. However, additional information was subsequently provided and the implications of this are addressed in Section A11.

A2 Facility Throughput for Used Fuel

The specified throughput for the DGR was set at 120,000 used fuel bundles per year with a total requirement of 3,600,000 fuel bundles over the 30 year operating period of the facility. It has been assumed that the facility will operate 230 days per year.

The following Table summarises the key data used in the assessment.

	Bundles per Unit	Total Throughput	Annual Throughput	Daily Throughput
Total Used Fuel Bundles	1	3,600,000	120,000	522
Fuel Received in Sealed Baskets (8.1%)	60 (54)	4,935	165	0.72
Number of Basket Casks	180	1645	55	0.24
Fuel Received in Modules (91.9%)	96	34,453	1148	5
Number of IFTCs for Modules	192	17,227	574	2.50
Number of UFCs	324	11,111	371	1.61

A3 Cask Receipts

Used fuel bundles will be received in two cask types, Basket Casks and Irradiated Fuel Transport Casks (IFTCs) for modules. The total cask receipts will be less than 3 per day (2.74 averaged over the 30 years) and the operations will be similar for both cask types.

From	To	Duration (Minutes)	Comment
Road Transport	Cask Buffer Store	20	Using Crane
Cask Buffer Store	Cask Transporter	15	Using Crane
Remove Impact Limiter		10	Using Crane
Impact Limiter moved	Parking Position	10	Using Crane
Cask Transporter	Vent/Unbolt Cell	10	Using Transporter
Vent and Remove Bolts		50	On Transporter
Vent/Unbolt Cell	Receipt Cell	10	Using Transporter
Remove Lid and Contents (2 Modules or 3 Used Fuel Baskets)		60	Using In Cell Crane
Load Modules (2 empty modules into IFTC only)		60	Using In Cell Crane
Receipt Cell	Vent/Bolt Cell	10	Using Transporter
Bolt Lid and Test		50	On Transporter
Vent/Bolt Cell	Cask Transporter	10	Using Transporter
Cask Transporter	Cask Buffer Store	15	Using Crane
Cask Buffer Store	Road Transport	20	Using Crane
Total		350	5hr 50 mins

The total utilisation for the different handling features will be:

Module/Basket Transport Cask Crane	60 minutes per Cask
Cask Transporter	260 Minutes per Cask
In Cell Crane	130 minutes per Cask

It may be necessary to decontaminate casks on occasions and this will increase the utilisation of the Cask Transporter by some 240 minutes.

Utilising only one Process Line will result in a total utilisation of the Transporter of (3 x 260 + 240 for decontamination) 1020 minutes or 17 hours. It is assumed that a double shift system will be employed, therefore more than one process line will be required to meet the throughput. Assuming an operational efficiency of 85%, one line would be able to cater for two Casks being processed with one requiring decontamination [(2 x 260 + 240)/0.85 = 895 minutes or 15 hours].

It has been assumed that both modules can be removed from the Cask and placed on the Transporter, or in a park position in the receipt cells i.e. there is no need to await processing of the first module before the second can be unloaded.

A4 Module Processing

The required throughput for modules equates to an average of 5 per day. It has been assumed that up to three IFTCs per day will be unloaded, leading to six modules per day being processed. A number of these modules may be transferred to the buffer storage pool for short term storage; however, this operation will be carried out in parallel with other modules being processed.

From	To	Duration (Minutes)	Comment
Receipt Cell	Receipt Cell Cart Park	15	Unload Using In Cell Crane
Receipt Cell Cart Park	Fuel Module Handling Cell	15	Transfer Using Cart
Transfer Fuel to UFC Basket		180	Cart being Utilised
Transfer Basket to UFC or Storage Position	(Assuming basket is full part way through emptying module)	20	Using Fuel Handling Cell Crane
Fuel Module Handling Cell	Receipt Cell Cart Park	15	Return Empty Module on Cart
Remove and Decontaminate Module			Off Line Activity
Receipt Cell Module Store	Receipt Cell	15	Load Module into IFTC Using In Cell Crane
Total		260	3 hrs 20 mins

The total utilisation for the different handling features will be:

Used Fuel Handling Cell Crane	20 minutes per module
Transfer Cart	230 Minutes per module
In Cell Crane	30 minutes per module

The utilisation of the Transfer Cart will limit the number of modules capable of being processed in two shifts to 3.5 [(16 x0.85 x 60)/230 = 3.55]. This indicates that two process lines will be required to meet the module processing requirements.

Therefore, two Fuel Handling Cell fuel transfer machines will be required.

A5 Sealed Storage Basket Processing

To satisfy throughput requirements less than one Sealed Storage Basket (SSB) per day on average will be received at the UFPP. However, for the purposes of this assessment a throughput of one SSB per day has been assumed.

From	To	Duration (Minutes)	Comment
Receipt Cell	Receipt Cell SSB Rail Car Park	15	Unload Basket using Receipt Cell Crane
Receipt Cell SSB Rail Car Park	Cutting and Fuel Bundle Transfer Cell	10	Transfer using SSB Rail Car
Cut SSB and dispose of waste		150	SSB Rail Car in use
Transfer Fuel to UFC Basket		120	UFC Basket and SSB Rail Car in use
Cutting and Fuel Bundle Transfer Cell	Fuel Basket Handling Cell	10	Transfer using UFC Basket Rail Car
Transfer UFC Basket to UFC or Storage Position	(Assuming UFC Basket is full part way through emptying SSB)	20	Using Fuel Handling Cell Crane
Fuel Basket Handling Cell	Cutting and Fuel Bundle Transfer Cell	10	Transfer an empty UFC Basket using UFC Basket Rail Car
Remove and decontaminate SSB, dispose of waste	(Decontaminate off line)	30	Using Cutting and Fuel Bundle Transfer Cell Crane and SSB Rail Car
Cutting and Fuel Bundle Transfer Cell	Receipt Cell SSB Rail Car Park	10	Transfer Empty SSB Rail Car
Total		375	6 hr 15 mins

The total utilisation for the different handling features will be:

Receipt Cell Crane	15 minutes per SSB
SSB Rail Car	360 minutes per SSB
Cutting Cell Crane	30 minutes per SSB
Fuel Handling Cell Crane	20 minutes per SSB
UFC Basket Rail Car	160 minutes per SSB

From this analysis it is possible to process one SSB per day and it may be possible to carry out this operation within a single shift.

A6 UFC Filling, Sealing, Welding and Inspection

The UFPP will be provided with two independent UFC filling lines. It has been assumed that each line will process up to one UFC per day.

From	To	Duration (Minutes)	Comment
UFC Store Cart	Receipt Station	10	Transfer UFC using Cart
Load into Shielded Cart		15	Using Receipt Cell Crane
Receipt Station	Fuel Handling Cell	15	Using Shielded Cart
Open gate, raise UFC and remove steel inner lid		20	Using Fuel Handling Cell equipment/Cart
Load UFC with three UFC Baskets	(See Below*)	45	Using Fuel Handling Cell Crane/Cart
Replace steel lid, lower UFC and close gate		20	Using Fuel Handling Cell equipment/Cart
Fuel Handling Cell	Venting/Sealing Cell	10	Transfer full UFC on Shielded Cart
Raise UFC, vent and seal inner container, lower UFC		80	Using Shielded Cart
Venting/Sealing Cell	UFC Welding Cell	10	Transfer full UFC on Shielded Cart
Raise UFC, vacuum area, weld copper lid, lower UFC		180	Using Shielded Cart, welding equipment
UFC Welding Cell	UFC Inspection Cell	10	Transfer full UFC on Shielded Cart
Raise UFC, inspect weld, lower UFC	Radiography followed by Ultrasonic NDT	240	Using Shielded Cart
UFC Inspection Cell	UFC Receipt Cell	10	Transfer full UFC on Shielded Cart
Raise UFC into Receipt Cell		15	Using Receipt Cell Crane
UFC Receipt Cell	Receipt Station	10	Transfer empty Shielded Cart
Total		690	11 hr 30 mins

The total utilisation for the different handling features will be:

Receipt Cell Crane	15 minutes per UFC
Shielded Transfer Cart	680 minutes per UFC
Posting in Cell Crane	15 minutes per UFC
Welding Equipment	180 minutes per UFC

NDT Inspection equipment 240 minutes per UFC

The utilisation of the Shielded Cart extends to the bulk of the operations, although a number of the durations are determined by other activities. The Shielded Cart will be utilised for 680 minutes and with an operational efficiency of 85% will result in over 13.3 hours to process a UFC. A two shift system on each line will provide adequate capacity to process two UFCs per day, with the third shift available for such tasks as re-work of welds or additional NDT, if required.

* The foregoing times are based on filled baskets being stored in the Fuel Handling Cell until three baskets are available for loading in to a UFC. The baskets are then loaded into the UFC consecutively.

A7 UFC Monitoring and Decontamination

One UFC per day will be required to be processed through each of the two facilities.

From	To	Duration (Minutes)	Comment
Raise UFC into UFC Receipt Cell		15	Using In Cell Crane
Receipt Location	Monitoring Station	10	Using In Cell Crane
Swab and Monitor UFC		30	
Monitoring Station	Decontamination Booth	10	Using In Cell Crane
Spray UFC and dry		60	
Decontamination Booth	Monitoring Station	10	Using In Cell Crane
Swab and Monitor UFC		30	
UFC Receipt Cell (Monitoring Station)	Jacketing and Dispatch Cell	10	Using In Cell Crane
Open gate, lower UFC and close gate		15	Using In Cell Crane
Total		190	3 hr 10 mins

The total utilisation for the different handling features will be:
In Cell Crane 70 minutes per UFC
Spray Booth 60 minutes per UFC
Swab and Monitor Equipment 60 minutes per UFC

As only one UFC needs to be processed per day through each monitoring and decontamination line, ample capacity is available to satisfy the throughput requirements.

A8 UFC Jacketing

One UFC per day will be required to be processed through each of the two facilities.

From	To	Duration (Minutes)	Comment
Sealing Materials Compaction Plant	Dispatch Cell	10	Bentonite Blocks on Railcars
Offload Blocks and assemble in Support Frames		60	Using In Cell Crane and Support Frame
Withdraw Railcar and personnel		10	Support Frame in Use
UFC Receipt Cell, open gate, lower UFC and close gate	Jacketing and Dispatch Cell	15	Using In Cell Crane and Support Frame
Raise Support Frames to vertical and encase UFC		30	Use Support Frame
Lower to the horizontal and remove top support		30	Using Support Frame
UFC Cask Storage Area	Dispatch Cell Location	15	Transfer empty UFC Cask on Railcar
Open gate, transfer UFC and close gate		15	On roller bed into Cask
Dispatch Cell Location	Waste Shaft	15	Transfer full UFC Cask on Railcar
Total		200	3 hr 20 mins

The total utilisation for the different handling features will be:

In Cell Crane	75 minutes per UFC
Support Frame	175 minutes per UFC

The UFC jacketing support frame will be utilised for the majority of the operations. However, with an estimated overall duration of some 4 hours, allowing for an operational efficiency of 85%, ample capacity is available to meet throughput requirements.

A9 UFC Cask Movements

Although on average only 1.61 UFCs need to be emplaced per day, for the purpose of the following assessment two UFCs per day have been assumed as the maximum DGR throughput. It is proposed that the Cask used to transfer UFCs from the UFPP to the underground emplacement rooms will have a capacity of one UFC. Movements of UFCs and associated items are listed below, together with an estimate of their durations:

A9.1 UFC Cask Movements (Two cask movements per day required)

From	To	Duration (minutes)	Comment
UFPP Storage	Waste Shaft	10	Full
Waste Shaft	Underground Storage	15	Full
Underground Storage	Emplacement Room	20	Full
Unload Cask		60	Emptying
Emplacement Room	Underground Storage	20	Empty
Underground Storage	Waste Shaft	15	Empty
Waste Shaft	UFPP Storage	10	Empty
Total		**150**	
UFPP Storage	UFPP	10	Empty
Load Cask		60	Filling
UFPP	UFPP Storage	10	Full
Total		**80**	

A9.2 Buffer Plug Cask Movements (One cask movement per day required)

The following assessment assumes that the Buffer Plug Cask will be loaded at the Sealing Materials Compaction Plant (SMCP), located at the DGR surface facilities.

From	To	Duration (minutes)	Comment
Load Cask		30	Filling
SMCP	Waste Shaft	10	Full
Waste Shaft	Underground Storage	15	Full
Underground Storage	Emplacement Room	20	Full
Empty Cask		30	Emptying
Emplacement Room	Underground Storage	20	Empty
Underground Storage	Waste Shaft	15	Empty
Waste Shaft	SMCP	10	Empty
Total		150	

A9.3 Buffer and Dense Backfill Blocks (Eight rail car movements per day required)

Total volume of sealing materials required for the emplacement of two UFCs will be approximately 94 m^3 (3.2m x 5.73m x 5.13m). It has been assumed that sealing material pre-compacted blocks will be transported underground using flatbed railcars, each with a capacity of approximately $12m^3$ (2m by 2m by 5m with a 60% packing fraction). This assumption will result in the requirement for 8 railcar movements between surface and underground to satisfy the emplacement of two UFCs.

Railcars may be assembled underground and transferred to the emplacement room as a train. However, each railcar will still have to be moved into the emplacement room individually. Individual movements for all operations have therefore been assumed.

From	To	Duration (minutes)	Comment
Load Rail Car		30	Filling
SMCP	Waste Shaft	10	Full
Waste Shaft	Underground Storage	15	Full
Underground Storage	Emplacement Room	20	Full
Empty Rail Car		30	Emptying
Emplacement Room	Underground Storage	20	Empty
Underground Storage	Waste Shaft	15	Empty
Waste Shaft	SMCP	10	Empty
Total		150	

A9.4 Light Backfill Hopper (One hopper/railcar movement per day required)

Approximately 12.5 m^3 of light backfill will be required per day. It has been assumed that this will be mixed (crushed granite and bentonite) at an appropriate surface facility and transported underground in a railcar mounted hopper. It has also been assumed that the hopper will accommodate the required 12.5 m^3 of material.

From	To	Duration (minutes)	Comment
Storage Area	Sealing Materials Plant	10	Empty
Load Hopper		30	Filling
Sealing Materials Plant	Waste Shaft	10	Full
Waste Shaft	Underground Storage	15	Full
Underground Storage	Emplacement Room	20	Full
Empty		30	Emptying
Emplacement Room	Underground Storage	20	Empty
Underground Storage	Waste Shaft	15	Empty
Waste Shaft	Storage Area	10	Empty
Total		160	

A9.5 **Ventilation Ducting, Rails and Services** (Four movement per day required)

From	To	Duration (minutes)	Comment
Parking	Emplacement Room	10	Empty
Load		30	Loading
Emplacement Room	Spare Emplacement Room	15	Loaded
Unload		30	Emptying
Spare Emplacement Room	Parking	10	Empty
Total		95	

A10 Summary of Movements in Different Areas

A10.1 Waste Shaft Movements

Item	No of Movements	Duration (minutes)	Comment
UFC Cask	4	88	Two full, two empty
Buffer Plug Cask	2	44	One full, one empty
Pre-compacted Blocks	16	352	Eight full, eight empty
Light Backfill Hopper	2	44	One full, one empty
Total	24	528	

Assuming an Waste Shaft operating efficiency of 85%, the 528 minutes given above will equate to 10.4 working hours. The travel time for a single waste shaft journey of 22 minutes is similar to that used for previous DGR studies and includes nominal waiting time.

A10.2 Perimeter Road Operations

Item	No of Movements	Duration (minutes)	Comment
UFC Cask	4	80	2 full, 2 empty
Buffer Plug Cask	2	40	1 full, 1 empty
Pre-compacted Blocks	16	320	8 full, 8 empty – may be moved in trains
Light Backfill Hopper	2	40	1 full, 1 empty
Redundant Equipment	8	120	4 full, 4 empty
Personnel	6	120	Assume 3 shifts, using perimeter road.
Total	38	720	

Not all movements will be between the waste shaft and emplacement rooms. Therefore, it may be possible to undertake a number of the movements simultaneously. The individual movements would therefore need to be defined in greater detail to ensure traffic conflicts do not occur.

A10.3 Emplacement Room Movements

A four day cycle has been assumed for filling each emplacement room, to emplace two UFCs (one day), the required sealing materials (two days) and one day free to complete operations elsewhere. Four emplacement rooms will be worked on in parallel using the emplacement sequence shown in Figure A1.

Item	No of Movements	Duration (minutes)	Comment
Unload UFC Cask	2	120	60 minutes each
Transfer UFC to Emplacement Location	2	120	60 minutes each
Unload Buffer Plug Cask	2	60	30 minutes for each pair
Transfer Buffer Plugs to Emplacement Location	2	60	30 minutes per UFC
Unload Light Backfill Hopper	1	30	
Strip Out Redundant Equipment		180	Allow 3 hours
Load Redundant Equipment	4	120	30 minutes per railcar
Sub-total		**690**	11.5 hours
Place Pre-compacted Blocks	120 blocks (2 teams)	**1200**	See Below
Total	16 (8 round trips)	**1890**	31.5 hrs

A detailed analysis of block placement was undertaken to establish the likely number of blocks and their configuration to determine realistic placement durations.

Based on Figure 1 in the main report, it is envisaged that the cross section of the emplacement room will be made up using 7 Dense Backfill Blocks and 9 Buffer Material Blocks. It is assumed that the blocks will all be approximately 0.9m long requiring 6 layers to accommodate each pitch along the emplacement room. This equates to 42 dense backfill Blocks and 54 Buffer Material Blocks, 96 in all. The lower areas under each UFC will be filled with a total of 12 Dense Backfill Blocks and 12 Buffer Material Blocks giving a grand total of 120 blocks to be placed.

Assuming 20 minutes to offload and position each block the overall duration would be 2400 minutes (40 hours). Based on 85% operating efficiency this would require an operational period of 47.0 hours.

Once the blocks are offloaded it will be possible to utilise two sets of lifting equipment to place blocks in parallel. This would result in an overall duration of 1200 minutes (20 hours) and taking into account 85% efficiency would result in 23.5 hours of operational time. This could be achieved using four teams on a two shift system with the two teams on each shift working in different emplacement rooms. Such a scenario would provide 28 hours of effort, assuming 7 hours per shift allowing for underground operators travel time. This would allow a time of just over 25 minutes to place each block, rather than the 20 minutes originally assumed.

UFC emplacement operations require 11.5 hours per day. Taking into account an efficiency of 85% this results in 13.5 hours per day being required; a time that can be achieved during two shifts.

From the above It is proposed that there will be a total of four teams of sealing materials placement workers and two teams of UFC emplacement workers. The emplacement sequence shown in Figure A1 outlines how the work would be organised, based on working a double shift system.

This would involve two sealing materials teams installing blocks in Rooms 1 and 2 on the first shift of Day 1, followed by a further two sealing materials teams carrying on with the installation of blocks in both Rooms 1 and 2 in the second shift. On Day 2 the same pattern would be used resulting in the completion of block installation in both Rooms 1 and 2 by the end of Day 2.

On Days 3 and 4 the sealing materials teams would complete installation of blocks in Rooms 3 and 4. In parallel the first emplacement team would install the first UFC in Room 1 on Day 3, shift 1 and the second UFC would be installed by the second emplacement team on shift 2 of Day 3. On Day 4, shift 1 the first emplacement team would install the first UFC on shift 1 and the second emplacement team would install the second UFC on the second shift of Day 4.

On Days 5 and 6 the teams would install blocks in Rooms 1 and 2 and UFCs in Rooms 3 and 4. The teams would continue to alternate between rooms in this manner until the rooms were filled. The same procedure would then be used for the next four rooms.

A11 Amended Delivery Rates

The information supplied in [2] gives details of the expected rate of deliveries for sealed baskets and modules.

The implications of this are that up to approximately 30,000 fuel bundles may arrive in sealed baskets for the years 2040 to 2046, the remaining 90,000 arriving in modules. During this period approximately 500 sealed storage baskets would have to be handled per year, equating to 2.17 per day. This would result in two basket casks per day being received and two (1.8) IFTCs.

From Section A3 it can be seen that there is sufficient capacity to handle four casks per day working on a two shift system, two of these would be on the basket line and two on one of the module lines. Occasionally a third shift may be required to receive and process a basket flask to maintain throughput. From Section A5 it can be seen that two sealed baskets can be processed in 12.5 hours. Assuming an efficiency of 0.85, this results in a 15.5 hours duration that can be accommodated by working a double shift system. A third shift may be required occasionally to accommodate the fact that just over two modules need to be processed per day on average. The module throughput is less than shown in Section A4.

Section A4 considers that six modules may need to be handled each day and the revised requirement from the above equates too less than this figure.

It is concluded that accommodating these revised figures, the fuel bundle delivery rates shown in [2] can be achieved by working a double shift, rather than a single shift in the basket handling line.

A12 Benchmarking

All durations assumed in this logistics study have been determined by assessing the tasks involved and allocating a time for each based either on the speed of the equipment envisaged, or on operational experience from previous projects where similar activities are involved. It is not possible to give definitive times for all operations as the level of detail is not available to carry out a full operational research study at this time. However, the durations arrived at for a number of the major activities have been compared with those determined for previous projects and have been found to be consistent.

Cask receipt, unloading and despatch times have been used to establish the validity of the derived DGR throughput rates compared with other facilities where information is available.

Typical turnround times for casks at UK nuclear facilities such as BNFL, Sellafield and UKAEA, Dounreay tend to be in the order of one to three days. These durations are based on the time for loading radioactive materials into casks rather than removing the contents from a previously checked and approved source, as is the case for the DGR. Quality Assurance and monitoring checks at the example facilities were also more involved than those envisaged for receipt of already certified casks. In addition, the nuclear utilities specified do not have a major driver to decrease the turnround times quoted, as it is normally other operations within the processes that influence the overall operational times.

Experience at Fort St Brain indicates that a turnround time of two days to load and unload a cask is typical. This involves 1.5 days to load and 0.5 days (4 hours) to unload.

For the Idaho Spent Fuel (ISF) Project in the USA, the design has assumed a cask turnround time of approximately 4 hours, this involves removing a single canister from the cask and replacing the cask lid.

At Hanford, also in the USA, within their canister store building, a turnround time of 8 hours has been achieved to receive, dock, unload, transfer the canister from a cask and place it in a storage tube.

One of the most appropriate benchmark in the UK would be the Nirex Deep Waste Repository for ILW, which is still at a design stage but where substantial work has been undertaken. From published information it is apparent that the repository will receive approximately 2,500 casks per year, where it is intended to process through either a single or double line facility. This number of casks equates to approximately 50 casks per week being processed as opposed to the 14 that are necessary for the DGR.

A13 Summary

This logistics study demonstrates that the required throughput can be achieved through all the process areas. This conclusion has been based on a requirement to process two UFCs per day, whereas the actual requirement is 1.61 UFCs per day on average. The study also demonstrates that the peak throughput for sealed storage baskets can be achieved between the years 2040 and 2047.

The study indicates that the most critical operations, from a throughput perspective, are those associated with installing pre-compacted sealing material blocks within the emplacement rooms. However, based on the assumptions made in the study the proposed method of UFC emplacement is viable. To ensure that satisfactory phasing of UFC emplacement and sealing materials is possible, emplacement of UFCs needs to be considered in parallel with sealing material block placement.

A14 References

[1] 2001. Technical Specification for Updating the Conceptual Design and Cost Estimate for a DGR for Used Nuclear Fuel. Ontario Power Generation, Nuclear Waste Management Division, Document No 06819-UFM-03789-0001-R00, Rev 0. Toronto, Ontario.

[2] Garamszeghy, M. 17 April 2002. Updated Shipping logistics and Fuel Age. OPG internal e-mail to T Kempe, R Heystee & J Villagran. Ontario Power Generation, Toronto, Ontario.

	Day 1			Day 2			Day 3			Day 4			Day 5			Day 6			Day 7			Day 8			Day 9			Day 10		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2		S1	S2	S3
ROOM 1	**A1**	**B1**		**A1**	**A2**		**E1**	**E2**					**A1**	**B1**		**A1**	**B1**		**E1**	**E2**					**A1**	**B1**		**A1**	**B1**	
ROOM 2	**A2**	**B2**		**A2**	**B2**					**E1**	**E2**		**A2**	**B2**		**A2**	**B2**					**E1**	**E2**		**A2**	**B2**		**A2**	**B2**	
ROOM 3							**A1**	**B1**		**A1**	**A1**		**E1**	**E2**					**A1**	**B1**		**A1**	**B1**		**E1**	**E2**				
ROOM 4							**A2**	**B2**		**A2**	**A2**					**E1**	**E2**		**A2**	**B2**		**A2**	**B2**					**E1**	**E2**	

S1 First Shift
S2 Second Shift
S3 Third Shift (Not Used)
A1 First Shift, First Backfill Team
A2 First Shift, Second Backfill Team
B1 Second Shift, Third Backfill Team
B2 Second Shift, Fourth Backfill Team
E1 First Shift, First Emplacement Team
E2 Second Shift, Second Emplacement Team

FIGURE A1 - EMPLACEMENT ROOM SEQUENCE

1106/MD18085/REP/01

Radioactive Materials Management

Conceptual Design for a Deep Geologic Repository for Used Nuclear Fuel

Annex 1

Metallurgical Aspects of Used Fuel Container Design

December 2002

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 .

This document is written solely for the benefit of the Client, for the purpose stated in the Agreement, and the Consultant's liabilities are limited to those set out in the Agreement."

Summary

The overall objective of the work described in this document is to confirm that the materials and design proposed for the Used Fuel Container (UFC) are reasonable to use as the basis for the conceptual design for the Deep Geologic Repository (DGR). Ontario Power Generation (OPG) have selected oxygen-free phosphorus-doped (OFP) copper as the preferred option for constructing the outer shell of the UFC. One factor in making this selection was the fact that there is a large existing body of knowledge about the behaviour of copper in repository environments and about techniques for constructing and inspecting large copper vessels, based mainly on work carried out for the Swedish, Finnish and Canadian authorities. This document presents a summary view of the key metallurgical aspects of using copper for the outer shell of the UFC. It deals with:

- behaviour of the specified UFC materials under the conditions expected in the DGR
- assessing the constructability and inspection of the UFC design.

The document outlines the environments that the UFCs will encounter and discusses the various modes of corrosion that might affect the copper shell during each stage of operation. The role of creep in the deformation of the outer copper shell is reviewed. Studies carried out to investigate methods for constructing the outer copper container are reviewed and recent discussions with potential manufacturers of the copper shell are summarised. Possible methods for inspecting the seal weld are reviewed. It is concluded that it is reasonable to use the proposed UFC design as the basis for the conceptual design of the DGR

Contents

1 Introduction

The overall objective of the work described in this report is to confirm that the materials and design proposed for the Used Fuel Container (UFC) are reasonable to use as the basis for the conceptual design of the Deep Geologic Repository (DGR). The specific aims of this document are to address the requirements stated in the technical specifications for the project [1], namely:

- to assess the compatibility of the specified materials under the conditions expected in the DGR
- to assess the constructability of the UFC design.

In line with the customer's guidelines the task is based on the following assumptions and principles. A factor in OPG's selection of copper for the corrosion barrier of the UFC was the existence of a large knowledge base on copper behaviour and fabrication technology which derives from years of R&D work done by Sweden and Finland, to which OPG has also contributed. Selecting copper gives the benefit of using a well-known material and utilising existing technologies specially developed for nuclear waste applications. Other material choices (such as titanium) would require the commitment to carry out an extensive R&D programme in order to be able to obtain equivalent data to that already available for copper.

Therefore, CTECH was not requested to carry out any additional investigations on copper behaviour but to use the information available from recent research. Accordingly, this assessment draws heavily on the literature provided by OPG and the documents published by SKB and Posiva. For example, SKB have recently published a comprehensive review of the large body of information available about the corrosion of copper [2].

This report presents only a summary view and makes references to the extensive literature base. It is divided as follows. In Section 2 the materials proposed for the UFC are outlined and a brief description of the environmental conditions expected during the waste management process is given. Section 3 deals with the compatibility of the UFC materials with the environmental conditions expected during the used fuel management process. In Section 4 the feasibility of constructing and inspecting the proposed UFC design is discussed.

2 UFC Materials and Environment in a Deep Geologic Repository

The purpose of this section is to outline the materials that will be used for the UFC and to describe the environments that the containers are expected to encounter. In assessing the performance of the UFC materials it is important to characterise the environment at each stage of the operations. Details of the proposed design of the UFC, and the processes by which the UFCs will be handled and placed in the repository, are given in the body of the main report [3].

2.1 UFC MATERIALS

The outer container will be manufactured from oxygen-free phosphorus-doped (OFP) copper [4]. The phosphorus is added to improve creep ductility (see Section 3.3) and it is oxygen-free to confer superior resistance to uniform and localised corrosion processes. SKB has compiled a technical specification for the OFP copper [5], which gives the chemical composition for the material (see Table 1 below). The material may obey either of the specifications given in the table, but in addition trace impurities should be in the following ranges: O<5 ppm, P 40-60 ppm, H<0.6 ppm, S<8 ppm. It is specified that the grain size for the lid and copper tubes shall be less than 360 µm.

	Cu	**Ag**	**As**	**Fe**	**S**	**Sb**	**Se**	**Te**	**Pb**
UNS C10100	99.99%	25	5	10	15	4	3	2	5
EN 133/63 Cu-OF1	rem	25	5	10	15	4	4	4	5
	Bi	**Cd**	**Mn**	**Hg**	**Ni**	**O**	**Sn**	**Zn**	
UNS C10100	1	1	0.5	1	10	5	2	1	
EN 133/63 Cu-OF1									

Table 1. Composition of material selected by SKB (max ppm) for outer copper shell

The inner container will be made from carbon steel (typically SA516 grade 70 for shell plate (C 0.28 wt%; Mn 0.85% wt% [6,7]) and SA105 for the ends).

2.2 ENVIRONMENT DURING MANUFACTURE AND STORAGE

During manufacture and storage the vessels will be exposed to an atmospheric environment. The humidity and atmospheric composition are unknown at present. It is possible that the units will be manufactured remotely, before being transferred to a storage area at the packaging plant. It is understood that the UFCs will be used and transferred to the DGR within a short period of being received at the packaging plant (up to 6 weeks based on first in, first out). The heat emitted from the surface of the container will raise the surface temperature, which will reduce the local relative humidity and prevent any condensation forming on the container surface.

2.3 ENVIRONMENT DURING FILLING, SEALING AND REPOSITORY EMPLACEMENT

After loading the UFC, the inner (steel) lid will be bolted in place, sealing the inner vessel. Following this operation, the UFC will be moved to the electron beam (EB) welding station, where the copper lid will be placed on the container and seal welded. Since the EB welding operation is carried out under vacuum, the interstitial space between the UFC inner and outer shells will remain at vacuum. The inert gas used to fill the inner vessel may diffuse into the annulus after a long period of time, once the mechanical seal of the inner vessel has failed. Steps will be taken to dry the gas used to fill the inner vessel, to avoid hydrogen generation by anaerobic corrosion of steel. During these operations the surfaces of the UFC components will be exposed to indoor atmospheric conditions.

After sealing, the UFC will be placed on to the lower part of the bentonite sleeve and the upper bentonite sleeve will be added, so that in effect all the outer copper surfaces will be placed in contact with oxygenated bentonite. The moisture content of the precompacted bentonite blocks will initially be 85% saturated [2,8] corresponding to a moisture content of 17%, but a moisture profile is expected to develop near the surface of the UFC due to the elevated surface temperature of the UFC (i.e. the moisture level will be lower near the UFC surface than the bulk concentration in the bentonite). Initially the surface temperature will be of the order of 30ºC, but this will increase after the bentonite shell has been placed around the container. The design limit for the temperature of the outer surface of the UFC has been set at 100ºC. Thermal analysis predicts a peak temperature of 97ºC, which will occur sixteen years after emplacement in the repository [9]. The elevated surface temperature may lead to local evaporation and precipitation of dissolved species such as sodium chloride and gypsum (calcium sulphate).

The bentonite sleeve will be 250 mm thick. The complete assembly will then be placed in a repository emplacement room, within a pre-assembled structure constructed with buffer and dense backfill blocks. The buffer material surrounding the bentonite shell will be composed of 50% silica sand and 50% bentonite. Outside the buffer material will be a layer of dense backfill (a compacted mixture of crushed granite aggregate, glacial lake clay and sodium bentonite clay), followed by light backfill (a compacted mixture of crushed granite aggregate and sodium bentonite clay) and finally the host rock. It is expected that the two halves of the bentonite shell will seal together after being saturated with groundwater [14].

2.4 ENVIRONMENT AFTER SEALING IN REPOSITORY

2.4.1 Groundwater composition

The site of the DGR has not been agreed and so it is not possible to be precise about the groundwater composition. However, data are available for the crystalline rock formations in the Canadian Shield. Gascoyne has published compositional data for a range of locations at depths up to 1000m [10]. Shallow fracture groundwaters are generally dilute calcium-sodium-bicarbonate waters (TDS <0.3 g/L). At greater depths (200-400m below surface) there is a chloride and sulphate component in the formation water and at still greater depths (>500m), waters of increasing salinity are found (>50 g/l salinity). Below 200m, the pH is typically in the range 7.5 to 8.8.

2.4.2 Buffer materials

The major components of a typical bentonite, Wyoming bentonite MX-80, and one which is a candidate buffer material for the DGR and has been used in research programmes by SKB, is as follows [11]:

Element	Percentage
SiO_2	66.9
Al_2O_3	20.8
Fe_2O_3	4.7
TiO_2	0.2
MgO	3.1
CaO	1.9
K_2O	0.6
Na_2O	0.6
P_2O_5	0.1
unknown	1.1

A typical sodium bentonite composition is as follows: Si 29.5; Al 8.4; Fe 3.0; Na 1.6; Ca 1.3; Mg 1.3; K 0.5; C 0.4; Ba 0.4; S 0.3; H 0.8; O 52.5%. Details of the other sealing materials are given in reference [12].

2.4.3 Composition of conditioned groundwater

For the purposes of assessing the corrosion behaviour of the UFC materials it is necessary to estimate the composition of the aqueous phase in contact with the metal surfaces. The composition will be derived from equilibration of the groundwater with the chemical components of the sealing materials (i.e. the groundwater will be ‘conditioned’ by the sealing materials before it reaches the surface of the container).

After each emplacement room is closed the groundwater will gradually resaturate the sealing materials. SKB [2] have estimated that this process is most likely to occur over a period of six to thirty five years, but periods up to several hundred years cannot be ruled out. As groundwater saturates the bentonite, it is likely that the clay will expand inhomogeneously, so there will be uneven contact between the bentonite and the surface of the copper. SKB assume that contact between the bentonite porewater and the UFC will not occur until the bentonite is fully saturated [2]. In the SKB situation, it is estimated that total porewater replacement will occur within ~14,000 years.

The pH of the saturated bentonite porewater is expected to be mildly alkaline. While calcite is present the pH will be ~8.4 decreasing to about ~6.8 after removal of the calcite [2].

The ammonia concentration is expected to be low (a few mg/litre [2]); it is possible that it may be removed by an irreversible cation exchange process but this has not been verified experimentally [2].

The chloride concentration will depend on the specific chloride concentration in the groundwater. For the purposes of assessing materials compatibility it is necessary to assess the corrosion behaviour in groundwaters with a chloride concentration up to 50 g/litre.

The sulphate concentration in the porewater will increase when it comes into contact with the groundwater due to dissolution of gypsum (calcium sulphate) [2].

The predominant cations will be sodium, calcium, magnesium and silicon [10].

Some concentration of groundwater constituents is expected at the surface of the UFC as a result of the elevated temperature [2].

2.4.4 Temperature and degree of oxygenation

During the exposure period in the repository the temperature and oxidising ability of the environment will change with time, as shown graphically in reference [13]. The major oxidant will be residual oxygen, which will be consumed by reaction with the minerals in the sealing materials, by microbial activity [2], as well as by reactions with the UFC copper shell. Some oxidising species may be formed by radiolysis of the trapped water and oxygen, but these will decrease with time as the radioactivity decays. SKB predict negligible concentrations of radiolysis products on the external surface of the UFC.

The length of the aerated period has been modelled by taking account of the various mechanisms for consumption of oxygen, and it has been estimated that the maximum duration of the aerated period will be 670 years. SKB have estimated that the aeration period in their repository will be between 7 and 290 years. The temperature of the UFC surface will reach a maximum value of approximately 97°C after about16 years, following which it will fall to the ambient temperature, 20-30°C, after 10^4-10^5 years.

The waters tested in the Canadian shield are anoxic, with Eh values typically in the range 0 to 200 mV in near surface waters, falling to a range of –50 to -250 mV at depths greater than 600m [10]. The oxygen content of the water decreases rapidly with increasing depth. At 60m the oxygen concentration has decreased by 99.98% compared to the oxygen concentration of water at the surface. At depths of several hundred metres, dissolved oxygen is virtually absent due to reaction with iron-bearing minerals, and the Eh is believed to be controlled by the Fe(II)/Fe(III) couple [10]. UFCs in the deep repository will first be exposed to oxidising conditions, owing to the residual air trapped in the repository. During this period, aerobic corrosion of the UFCs would be possible. As time passes, the residual oxygen will be consumed by reaction with the minerals and the copper outer shell of the UFCs, and when full groundwater resaturation has occurred, the conditions will be fully anoxic with negative Eh values applying.

2.4.5 Microbial activity

Microbial activity is likely in the repository, as deep granitic groundwaters have been found to contain diverse, metabolically active bacteria [2]. Swedish and Canadian studies [2,14] have shown that the level of microbial activity close to the UFC will be determined by the availability of water in the bentonite. Below a certain thermodynamic water activity, a_w, (i.e. a thermodynamic term used to describe the effective concentration or availability of water in the bentonite clay [15]; the lower the value of a_w the lower the concentration of available water) the microbial populations cannot survive. The threshold a_w for microbial activity has been measured as 0.96 and studies have shown that this activity cannot be sustained in partially saturated or fully saturated bentonite. Furthermore the drying effect of the heat emitted from the UFCs will reduce the local water activity still further around the UFC and lead to a microbiologically inactive zone.

In the fully compacted state the bentonite blocks will have a water activity below that required to allow microbial growth [14]. SKB and OPG results indicate that the number of micro-organisms will decrease rapidly during swelling of the bentonite [2] and that only spores will remain after the full expected swelling pressure has been achieved. Eventually even viable spores will be eradicated from fully compacted buffer and repopulation by microbes is unlikely due to the small pore space in the bentonite clay. The fully compacted bentonite blocks will not allow permeation of new fresh microbes from outside the vicinity.

The radiation levels at the surface of the copper containers will be too low to reduce any microbial activity [14] because of the attenuation of the radiation by the thick inserts and the copper walls (see Section 2.4.6). The temperature of the UFCs will not be high enough to kill any naturally occurring microbial populations in the bentonite [14], although the populations will be reduced at the highest expected temperatures.

Microbial activity will be possible in the 50%/50% bentonite/sand mixture because the water activity will be higher than the threshold value but is unlikely that it will be sustainable within the 100% bentonite jacket of the UFC. Activity will likely be viable in the outer regions of the emplacement room and at the interface between the sealing materials and rock [14].

Microbial activity remote from the surface of the UFCs, particularly that of sulphate reducing bacteria during the early post-closure phase, may result in the formation of sulphide, which is a potential corrodent for copper (see Section 3.2.2.4). SRB activity correlates well with the presence of pyrite (iron sulphide) in geological formations at the Finnish sites [2], indicating that there had been long-term SRB activity leading to the reduction of sulphate to sulphide. SRB activity was observed at many of the depths investigated at Finnish sites. The concentration of sulphate in the bentonite can be up to tens of mmol/litre [2] and this could be a nutrient source for SRB activity.

The production of nitrite, ammonia and organic acids (e.g. acetate) by bacterial action is possible. These species are all known agents for the stress corrosion cracking of copper. Their probable concentration is taken into account when assessing the risk of stress corrosion cracking occurring [2].

2.4.6 Radiation levels

The gamma absorbed dose rates at the surface of a range of container designs were evaluated by Hanna [16]. If it was assumed that fuel bundles were cooled for a period of thirty years before packaging, and that the UFC had a lid thickness of 3.2 cm and a shell thickness of 2.5cm, the maximum predicted contact dose rate at the surface of the UFC was 0.908 Gy/hour.

2.4.7 External pressure on UFC

An external pressure will develop on the exterior of the UFC due to the hydrostatic head and bentonite swelling pressure. The normal isotropic pressure loading prior to glaciation is estimated to be ~15 MPa and the glaciation isotropic pressure loading is estimated to be up to ~45 MPa [17]. The pressure will cause the outer copper vessel to deform collapsing onto the inner carbon steel vessel.

3 Compatibility of Container Materials with DGR Environment

In this section the effect of the environments that will be experienced by the UFC on the various possible types of corrosion affecting the UFC are discussed.

3.1 CORROSION DURING MANUFACTURE, STORAGE, FILLING AND SEALING

During this period the container materials will undergo atmospheric corrosion. The critical relative humidity for corrosion is generally believed to be in the range 50-70% for metals [2];

below this value there is insufficient water to form a continuous electrolyte film on the surface. The elevated surface temperature of the UFCs will tend to reduce the local humidity below the critical relative humidity for corrosion. Very little corrosion would be expected during these operations with a corrosion rate of <1 µm yr^{-1} expected [2], provided cleanliness is preserved. It is assumed that steps will be taken to prevent surface contamination.

3.2 CORROSION AFTER EMPLACEMENT IN THE REPOSITORY

3.2.1 Atmospheric corrosion prior to saturation

It is predicted that it could take several thousand years to resaturate the repository with groundwater [2]. While the bentonite is unsaturated the surfaces of the UFC will be exposed to a gaseous environment, whose water content would be expected to be low as moisture will be adsorbed by the bentonite clay. There will be a moisture gradient away from the surface, due to the heat produced by the UFC [2,18] and it is difficult to predict the concentration of water at the surface of the UFC. If the activity of water is low, the rate of gas phase oxidation will be slow, with the most probable corrosion product being Cu_2O. The predicted depth of attack due to this form of corrosion is negligible (<1 µm over 10,000 years).

If sufficient moisture were available to form a thin continuous surface electrolyte film, which is unlikely due to the elevated temperatures of the UFC, the rate of corrosion could be more rapid given the rapid supply of oxygen through a porous sealing material layer and the possibility of forming concentrated solutions on the surface. There are no data for the atmospheric corrosion rate of copper at elevated temperatures but it is likely to be considerably less than 1 µm yr^{-1} [2,18], even with an unlimited supply of oxygen to the surface. The rate is likely to decrease with time due to the build up of a protective corrosion product film [18], which will mainly be formed from cuprous oxide.

Regardless of the exact corrosion mechanism, the total amount of corrosion would be restricted by the limited inventory of oxygen in the repository. On mass balance considerations, the maximum depth of corrosion would be expected to be approximately 300 µm over the entire surface of the container [2]. The actual value is likely to be considerably less than 300 µm because some of the oxygen would be consumed by reaction with the sealing materials. More detailed modelling shows that the total depth of attack due to corrosion in a thin liquid film is likely to be <90 µm [18]. In summary, atmospheric corrosion is unlikely to have a significant impact on the integrity of the UFC.

3.2.2 Aqueous corrosion after saturation

After repository closure, groundwater will eventually permeate through the sealing materials and come into contact with the surface of the UFC. There are two main types of attack to consider, namely general corrosion and pitting corrosion.

3.2.2.1 General corrosion

On the basis of the Pourbaix diagrams for copper in a range of chloride concentrations, it can be seen that the potential range for thermodynamic stability extends from above the hydrogen evolution potential to more negative electrochemical potentials. This shows that in the absence of oxidising species copper will be stable. This has been demonstrated by the study of natural analogues, such as native deposits of copper. In the absence of oxygen the corrosion of copper will be extremely slow and the corrosion process will produce no hydrogen. The period of greatest risk to the copper is when it is exposed to oxygenated conditions, before oxygen is consumed by corrosion reactions or by reaction with surrounding minerals. The question that needs to be addressed therefore is whether the corrosion rate of copper during this period will be sufficiently low to provide the necessary protection of the interior of the UFC. This question has been addressed in the work carried out by OPG and partners. The detailed mechanism of general corrosion of copper and the supporting experimental evidence is thoroughly reviewed in reference [2] and there is no need to cover it in detail here. The key points are summarised below.

A mechanism has been proposed for the general corrosion of copper [13,19,20]. In essence, in highly oxygenated conditions and/or low chloride concentrations the final corrosion product contains cupric ions (Cu(II)) in the form of mixed chloride/hydroxide species ($CuCl_2.3Cu(OH)_2$), whereas in low oxygen concentrations and/or low chloride concentrations the final corrosion product will be predominantly cuprous oxide, $Cu(I)_2O$. The predominant cathodic reaction is reduction of oxygen.

Corrosion experiments in bentonite buffer have shown that the corrosion rate is controlled by diffusion of oxygen and chloride through the bentonite [2]. In well aerated buffer material the corrosion rate is determined by the rate of transport of Cu(II) away from the surface and in low oxygen conditions it is controlled by diffusion of oxygen to the surface of the copper. Good agreement is claimed between measured values of Ecorr and the values predicted on the basis of electrochemical models.

In the presence of Cu(II), the copper concentration near the surface is high, because it is readily absorbed by the bentonite, whereas in the presence of Cu(I) the concentration profiles are shallow, because its complexes are less readily absorbed by the clay.

Experiments on corrosion coupons and heated copper tubes embedded in bentonite have yielded average corrosion rates of 3 $\mu m\ yr^{-1}$ [21]. Other experiments in compacted bentonite / sand mixtures have given corrosion rates in the range 30-50 $\mu m\ yr^{-1}$ [22,23].

As oxygen within the repository is consumed the rate of general corrosion will decrease and eventually cease unless it is supported by reduction of water on a sulphide film.

A detailed mechanism has been proposed for the corrosion of copper and this has formed the basis of a predictive 1-dimensional model . The modelling shows that the oxygen available in the repository will be consumed after 670 years at which point the depth of attack due to general corrosion will be 11 µm [13,20,24].

3.2.2.2 Pitting corrosion

A number of experimental studies have been carried out to investigate the possible pitting of copper in a bentonite environment. In experiments carried out with bentonite-filled, groundwater-saturated, small-scale copper containers [25], Aaltonen did not find any pitting after 12 months' exposure at 80ºC. The Eh value inside the container decreased to below -300 mV. In other experiments [21,26] on heated copper tubes in bentonite the attack was uneven, but there were no indications of pitting. Brennenstuhl et al [27] carried out experiments to investigate the corrosion of copper under deposits of bentonite. Some roughening of the copper surfaces was observed, but no pitting. It was concluded that although under-deposit corrosion was a possible degradation mechanism for UFCs its rate and extent would be very small and would cease when the oxygen in the repository has been consumed.

During resaturation, following a period in which a layer of bentonite next to the container was desiccated, the contact between the copper surface and the bentonite may not be uniform. Points of contact may be possible pit initiation sites [2].

Type I and Type II pitting of copper is well known to occur in potable water, as discussed in reference [13], but such pit morphologies have not been observed on copper embedded in bentonite.

The extreme value statistics approach has been applied to the prediction of the long-term behaviour of copper [2,13]. The probability of a pit exceeding 9 mm depth during a million years was predicted to be $<10^{-21}$; the probability of exceeding 5 mm in 1,000 years was $<10^{-11}$ [13].

3.2.2.3 Stress corrosion cracking

It is necessary to demonstrate that stress corrosion cracking (SCC) of copper is not possible in the predicted repository conditions. The two primary requirements for stress corrosion cracking to occur are tensile stresses exceeding a certain threshold value and the presence of an SCC agent. The possible causes of stress cracking of copper in the repository have been thoroughly reviewed in reference [2]. It is concluded [2] that the risk of SCC will diminish with time as the repository environment evolves. The most likely time for SCC to occur is during the early period when oxygen and other oxidants such as Cu(II) from corrosion of the UFC, will be present. A number of reasons are postulated for the chemistry of the environment not being conducive to SCC. These include:

- the short period over which oxygen will be available to support SCC;
- the high concentration of chloride is expected to lead to the formation of a $CuCl_2.3Cu(OH)_2$ film, which will cause general corrosion and prevent SCC;
- the concentrations of SCC agents will be too low.

Laboratory experiments are in progress to establish the risk of SCC over short time periods. It is suggested that the stresses and strain rates required for SCC will not occur on the copper outer shell [17], even during the early stage of repository life, when the external hydrostatic pressures will increase and the copper outer shell will deform to fit around the inner steel component.

Finite element analysis (FEA) [17] has shown that the external isotropic pressures in a DGR would cause the copper shell to collapse on to the carbon steel inner vessel by plastic deformation. This would result in closure of the gap between the inner and outer containers. The FEA shows that the external surfaces in the regions around the welded lid closure would always be subject to compressive stress, thus minimising the risk of the initiation and propagation of SCC near the electron-beam lid closure welds. The FEA also predicts that there would be some regions of tensile stress in the surface of the UFC, but that there would always be sub-surface regions of compressive stress, which would tend to prevent stress corrosion cracks penetrating the full thickness of the walls. Furthermore, it is postulated that crack tip creep processes will relieve the stresses in the container surface and relieve crack tip stresses before crack advance can occur [2].

There are a number of unresolved questions in the field of SCC of copper, including the effect of electrochemical potential on the SCC of copper in ammonia solutions and how this relates to the corrosion potential in the repository, the effect of acetate on the SCC of copper and the effect of welds on SCC susceptibility. Further work may be needed in this area [2,28].

3.2.2.4 Microbially influenced corrosion

Microbially influenced corrosion (MIC) of copper can occur in conditions that are conducive to growth, of a number of different species, leading to increased general corrosion rates or SCC [14,29]. Possible causes of MIC are SRBs, which form sulphides, organic acids produced by anaerobes, and nitrogen-metabolising microbes, which form species such as nitrate, nitrites and ammonia. The nitrogen-containing species are potential agents for SCC of copper.

The effect of a range of possible microbial metabolites on the corrosion of copper in simulated groundwater was investigated by Jain and Ogundele [14]. Sulphide, and to a slight extent nitrite, were found to increase the corrosion rate of copper in simulated groundwater. The results with other metabolites were inconclusive, but did not appear to cause a significant increase in corrosion rate. The situation with polysaccharides may warrant further investigation.

A strong argument against the possibility of MIC of the copper containers is that microbes will not be viable in the region of the buffer surrounding the container, due to the low water activity (see Section 2.4.5), provided that the density of the bentonite is sufficiently high. Furthermore it is believed that cycled aerated-deaerated conditions are required for SRB-induced MIC [14] to occur.

In the longer-term it is postulated that the most important effect of microbial activity in the repository would be the production of sulphide by SRB activity in regions which are remote to the container [2,14]. Microbial activity will be possible in the 50%/50% bentonite/sand mixture because the water activity will be higher than the threshold value, but activity will be severely limited. The HS^- ions produced by the SRBs could diffuse through the sealing material and react with the surface of the copper however, the maximum predicted corrosion rate due to this mechanism is only 0.001 µm/yr. On this basis the additional corrosion damage caused by microbial activity has been modelled and shown to be negligible [29].

3.2.2.5 Galvanic corrosion

Where two dissimilar metals come into contact in the presence of an electrolyte there is the possibility of enhanced corrosion occurring due to galvanic corrosion. If there were a leak of groundwater into the annulus between the inner and outer containers there would be a possibility of galvanic interactions between the copper and the carbon steel insert. This is an issue that is not addressed in the OPG corrosion studies because it is assumed that there will be no perforations in the outer copper container.

3.2.2.6 Crevice corrosion

Crevice corrosion in copper is believed to be self-limiting because it is driven by a concentration cell which disappears when the concentrations of Cu(I) ions at the anodic and cathodic sites become equivalent [2]. It is assumed that as the lid and base will be welded on to the body of the UFC, there will be no crevices exposed externally to the repository environment and therefore crevice corrosion is not an issue.

3.2.2.7 Weld corrosion

No preferential corrosion of welds has been found in tests to date [30].

3.2.3 Radiolysis effects

There is literature evidence that SCC of brasses can occur at high dose rates (e.g. 6×10^{-4} Gy hr^{-1}) in moist air at ambient temperature, due the formation of radiolysis species, particularly NH_3 and NO_2^-. However, no positive shifts in corrosion potential were observed when copper was exposed to a dose rate higher than that expected in the repository and it was concluded that there was no significant formation of oxidising radiolysis products at such dose rates [18].

Because of the low dose rate, due to the internal shielding by the carbon steel inner container, it is predicted that the concentrations of radiolysis products such as NO_2^- would not be sufficient to cause SCC of copper [18]. Combined crevice corrosion / U-bend tests [18] in an irradiated (5 Gy hr^{-1}) groundwater vapour phase did not result in any crevice corrosion or SCC, but general corrosion resulted in the formation of a green patina.

3.2.4 Natural analogues

Measurements on natural analogue artefacts support the corrosion rate estimates for copper and provide supporting evidence for the proposed corrosion mechanisms. Extreme value statistics have been applied to predict the maximum pit depth based on archaeological analogues (in particular the *Kronan* cannon and naturally occurring deposits of native copper [8]). They are consistent with laboratory data and modelling predictions.

3.3 CREEP DEFORMATION OF THE UFC COPPER SHELL

It is anticipated that the copper outer shell of the UFC will be subjected to creep deformation. At the expected maximum temperature of ~100°C and an external pressure of about 15 MPa, the external copper shell will undergo plastic deformation and creep while collapsing onto the inner load-bearing steel vessel. Through this process, the total elastic and plastic strain developed in the copper vessel must not exceed the minimum value for creep strain-to-failure of the material [31].

Extensive R&D efforts in the Swedish, Finnish and Canadian nuclear used fuel management programmes have been made to improve the creep properties of the copper material, to ensure that creep rupture can be ruled out as a failure mode for their used fuel containers. Creep data have been collected and analytical methods have been developed for predicting the long-term creep behaviour of the copper vessel in a DGR.

3.3.1 Development of a Copper Material with Improved Creep Ductility

Early SKB creep test results indicated that standard oxygen-free copper (ASTM UNS C10100) exhibited unacceptably low creep strain to failure. The poor creep ductility of this material was believed to be caused by segregation of sulphur (S) to the grain boundaries where it forms films that lead to embrittlement of the matrix [32]. A sulphur content in OFP copper higher than 7 ppm, was found to result in reduced creep strain to failure. SKB tests indicated that the addition of a small quantity of phosphorus (P) (40 to 60 ppm) resulted in significant improvement of creep ductility and an increase in the creep strain to failure [33-36]. It was also demonstrated that electron beam welding does not affect the creep ductility of OFP-Cu [37].

Based on the above reported results, an oxygen-free phosphorus-doped (OFP) copper material was developed by the Swedish and Finnish nuclear fuel waste management programmes [38,39]. This material conforms to the specifications of the oxygen-free copper ASTM UNS C10100 and meets additional requirements which include: S content < 8 ppm, P content from 40 to 60 ppm and grain size from 180 to 360 µm. The requirement for creep ductility has been specified to be a minimum strain-to-failure of 10% at a temperature of 100°C. This material is currently the reference corrosion-barrier material for used-fuel containers adopted by the Swedish, Finnish and Canadian used nuclear fuel programmes [39-41]. *#Note: Raiko and Salo 1999 was referenced here in the addendum but not given in the reference list – it has been assumed that it should have been 1996.*

3.3.2 Calculated Maximum Creep Strain

Structural analyses were carried out by OPG for the Canadian UFC case to estimate the extent of radial, axial and hoop creep strains of the copper vessel over the UFC design life in a DGR. The maximum accumulated creep strain in the copper corrosion barrier is determined by the size of the gap between the outer copper shell and the inner steel vessel and by the thickness of the copper shell [42]. Maximum strain values were calculated for the Canadian UFC, with a 25-mm-thick copper vessel, gap values of 1 mm and 1.75 mm. These values corresponded to maximum accumulated creep strains of 4% and 7%, respectively, which are less than the minimum 10% elongation of the strain-to-failure requirement for OFP copper.

3.3.3 Development of Creep Data for OFP-Cu Material

Extensive creep tests were carried out by the Swedish/Finnish and Canadian programmes to improve understanding and the capability for predicting the long-term creep behaviour of the copper vessel of a UFC during its design lifetime in a DGR.

Extensive creep tests were carried out by SKB on OF copper material and OFP-Cu materials in air at relatively high temperatures (175-300°C) and stresses (60-160 MPa) [43-46]. Full creep curves were obtained in these tests, providing strain rates, creep strain and creep rupture data for the primary, secondary and tertiary stages of creep. These data are used to assess the effects of the material chemical composition, grain size, manufacturing and closure welding processes on the creep behaviour of OFP copper.

Copper creep studies in the Canadian programme included tests in air and in simulated Canadian groundwater, at temperatures in the range of 95 to 150°C and stresses from 20 to 100 MPa [47]. Creep rates in the range of 2.8×10^{-13} to 9.9×10^{-11} s^{-1} were obtained, which could be considered as approximate upper bound limits for creep processes of the UFC copper shell in a DGR. For the range of temperatures and stresses investigated, the dominant creep deformation mechanism is grain boundary controlled diffusion.

Detailed analyses of the OPG data and of SKB data obtained at higher temperatures (175-300 °C) and stress conditions (60-160 MPa) indicate that the two data sets are complementary, and constitute a good creep data base for OFP copper, applicable over a relatively wide range of stresses and temperatures [47]. At the higher temperatures and stresses investigated by SKB, the steady-state creep behaviour follows a power-law relationship.

The test results obtained in the Canadian studies indicate that the simulated Canadian groundwater environment has insignificant effect on creep rates for the OFP copper, with respect to those observed in an air environment [47].

3.3.4 Methods for Predicting the Creep Behaviour of the UFC Copper Shell

Creep tests carried out at high temperatures (175-300°C) and stress (60-160 MPa) have indicated that OFP copper would meet the creep ductility requirement of having a minimum value of 10% strain-to-failure. However, it is known that the ductility of copper decreases with decreasing creep strain rate. In comparison with the experimental creep test conditions, the copper vessel would be subjected to lower temperatures and stresses in a DGR and the creep rates that would be experienced by the copper vessel are expected to be lower than those observed in the experimental creep tests. Analytical methods are required for extrapolating the experimental creep data to repository conditions.

An analytical approach that could potentially be used for quantifying the long-term creep properties of the container material was described by Dutton [48]. His study presented an analytical scheme that adopted the Theta Projection Concept for the extrapolation of experimental creep data for long-term prediction of creep behaviour. Another analytical method has been described by Sandstrom [49] for extrapolating experimental creep strain data to longer times. These data could potentially be used for predicting the long-term creep behaviour of the copper vessel of a UFC.

4 Constructability and Inspection of UFCs

4.1 CONSTRUCTION OF A UFC

The proposed UFC is an assemblage of two major components:

- the inner carbon steel vessel with a bolted lid
- the outer copper shell with a welded lid.

The ability to manufacture and assemble these two items using currently available techniques is discussed in this section.

4.1.1 UFC Copper Shell

Trials to manufacture copper containers with wall thicknesses of 50 mm have been carried out by SKB [5]. This work has extended to the manufacture of copper containers with 30 mm thick walls. Further developments in this area on behalf of SKB are presently examining the benefits of producing seamless tubes by extrusion and pierce and draw techniques, rather than the hot rolling, bending and longitudinal electron beam welding investigated in earlier work [50,51]. Initial problems associated with the integrity of the longitudinal welds of these tubes have been reduced as a result of further development work. Carrying out the welding process at reduced pressure rather than high vacuum, together with using a reduced copper wall thickness, may well result in the hot roll and weld process providing an acceptable solution. Lids and bottoms for containers manufactured using this method have been made by forging continuous-cast bars and this results in a larger grain size than that produced in the container walls.

In both the Swedish and Finnish container development programmes, electron beam welding is a well-established technique for attaching the copper lid to the container shell [51,52,53]. However, friction stir welding has been investigated as an alternative sealing method, with further development work currently being undertaken [5,8].

During the preparation of this report discussions have taken place between CTECH and two potential manufacturers of copper tubes, in order to determine the viability of manufacturing seamless copper containers to the dimensions required for the proposed UFC design. The two techniques considered were the extrusion process, which produces an open ended tube, and the pierce and draw method, which provides a tube with an integral base and open top.

Wyman Gordon Limited of Steventon, Scotland, manufacture extruded tubes and have provided a number of copper extrusions for SKB using the process described in [5]. Mr Bob Collins of Wyman Gordon confirmed that the company has the capability to extrude tubes with an internal diameter of 1092 mm, external diameter of 1194 mm and a length of 3780 mm [54], to allow machining to the required rough machining dimensions. The base of the container, made by forging continuous-cast bars, would be rough machined and then welded to the tube, followed by final machining. The container lid would be made by forging continuous-cast bar and then machining to suit the individual UFC shell, to be ready for welding to the container following loading with used fuel baskets within the DGR facility.

Vallourec and Mannesmann Tubes (V & M Tubes) have manufactured copper tubes with integral bases, using the pierce and draw method, to similar dimensions as those of the proposed UFC design, for Posiva and SKB [5]. During discussions between CTECH and Messrs Wolfgang Grummer and Douglas Crooks of V & M Tubes, confirmation was given that V & M Tubes have the capability at their Reisholz Works in Germany to pierce and draw copper tubes to the required dimensions. In addition, similar tubes had been made for Posiva and SKB; the entire surface of the tubes has been examined using ultrasonic techniques. Further development work is required to ensure that the grain size of the integral base is kept within acceptable limits and V & M Tubes have made proposals to SKB on how this may be achieved. V & M Tubes also have the capability to machine the drawn copper tubes and have undertaken trials for SKB using different machine speeds and feeds to determine their effect on tube surface finish. Tolerances on the finished container required by SKB were achieved within the machining capabilities available to V & M Tubes.

As a result of the above discussions and the work undertaken by SKB and Posiva, CTECH believe that it is viable to produce the proposed UFC copper shell design utilising one (or all) of the manufacturing methods described. The selection of the method to be employed may be influenced by the limited number of suppliers that are able to provide extrusions or pierce and draw tubes. However, this may be balanced by the ability to achieve repeatable high quality longitudinal welds using the roll and weld method.

4.1.2 UFC Inner Carbon Steel Vessel

Costs have been obtained from Babcock & Wilcox (B & W) of Cambridge Ontario [55] to manufacture steel inner vessels to a range of different dimensions. It is assumed that B & W have satisfied themselves that these configurations can be manufactured successfully, giving confidence that the same techniques could be used for the current UFC inner vessel design.

During discussions with V & M Tubes it became apparent that the company had the capability to manufacture a carbon steel vessel sized to fit within the proposed UFC. As with the outer copper container, V & M Tubes believed that the pierce and draw method was a viable method to produce a steel tube with an integral base to the dimensions required. V&M Tubes had previously produced tubes for the German 'Pollux' container that had finished dimensions of 1012 mm outside diameter, 690 mm inside diameter and 5086 mm long and which weighed approximately 17.2 tonnes.

4.1.3 Summary

The assembly of the two major components of the proposed UFC will require accurate handling of the individual components due to the small dimensional clearance between the two items. V & M Tubes have confirmed that diametral dimensions of copper tubes with a finished wall thickness of 50 mm will remain stable for a considerable period, therefore not presenting additional problems during the UFC assembly process. However, adopting a thinner wall for the copper tube may result in the open-end diameter of the tube distorting with time, due to its self-weight when laid horizontally, or during transport. Such distortion may be overcome by either, assembling the two components soon after the copper tube is finish machined, or introducing temporary support within the open end(s) of the copper tube.

From information reported by OPGI, together with discussions held with Wyman Gordon Limited and V & M Tubes, it is concluded that a number of techniques are available that may be used to manufacture UFCs to the current design. Development work will be required to ensure that repeatable, good quality welds can be achieved for the copper container, either using electron beam or friction stir welding techniques.

4.2 INSPECTION OF UFC

Validation of the UFC closure weld will be carried out using both radiography and ultrasonic non-destructive testing (NDT) techniques. It is proposed to deploy both systems from within the same DGR used fuel packaging plant shielded cell into which the lidded end of the UFC will be raised. Because the ultrasonic testing method requires the introduction of a liquid coupling medium, the weldment will be radiographed prior to deploying the ultrasonic equipment. To simplify the equipment necessary within the cell to undertake both NDT operations the UFC will be rotated past the inspection heads. Furthermore, the equipment within the cell will be kept to a minimum so as to not to expose it to damaging radiation fields. For this reason, as much NDT ancillary equipment as possible will be located outside the cell to provide ease of access for hands on maintenance.

The UFC copper lid weld will be inspected for porosity, a measure of weld quality, and possible sites for localised corrosion [2] and other defects such as cracks. Radiography [8] will be used to detect weld pores, however, the size of pore that can be detected with this type of inspection technique is limited. To extend the scope of weld defects that can be identified, an ultrasonic phase array system will be used. Although this system can detect small pores and cracks, reflection of the ultrasonic beam from large grains within the weld material presents difficulties. The feasibility of using an ultrasonic array technique to inspect container welds for discontinuities that lack volume (e.g. lack of penetration) has been demonstrated [56].

Radiography and ultrasonic inspection are complementary techniques [57]. SKB are also working on the use of the eddy current technique to detect near-surface discontinuities [8].

The grain structure in the lid and base area of the copper container is affected by the fabrication and sealing processes employed. The impact of the grain structure on the ultrasonic inspection of the copper container will need to be investigated further during future container development.

5 Conclusions

The main conclusions from the review of the metallurgical and constructability aspects of the proposed UFC design covered by this report are as follows.

1. Based on the existing body of knowledge, there is a high level of confidence in the use of copper as the outer shell material for the UFC, in terms of its likely corrosion resistance as well as the methods available for its construction and subsequent inspection.

2. Areas of further work to confirm the suitability of copper as the UFC outer shell material have been identified. These include the effect of chemical conditions on copper SCC susceptibility, the effect of grain size on UFC inspection and the significance of microbially-induced corrosion [2].

3. From a review of the metallurgical information currently available the proposed UFC design is viable.

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1106/MD18085/REP/01

Radioactive Materials Management

Deep Geologic Repository Conceptual Design

Annex 2

Finite Element Analysis

December 2002

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 .

This document is written solely for the benefit of the Client, for the purpose stated in the Agreement, and the Consultant's liabilities are limited to those set out in the Agreement."

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1 Introduction

A design concept for deep geologic emplacement of used CANDU fuel was first developed by Atomic Energy of Canada Ltd (AECL) during the period 1978-1996, under the Canadian Nuclear Fuel Waste Management Program. Following an extensive review under the federal Environmental Assessment and Review Process, a number of changes were recommended to address comments from a broad range of stakeholders, including the public. Since then, the four owners of used nuclear fuel in Canada [Ontario Power Generation (OPG), Hydro-Québec (HQ), New Brunswick Power (NBP) and Atomic Energy of Canada Ltd (AECL)] have continued, jointly, to develop the deep geologic repository (DGR) concept for the long-term safe management of the used fuel.

This has led to the work currently being undertaken by CTECH, to update the conceptual design for a deep geologic repository facility, and to prepare a corresponding cost estimate for designing, building and operating a DGR for the long-term storage of used nuclear fuel from all Canadian reactors. As a part of this work, a number of finite element analyses have been carried out in order to provide confidence in the feasibility of the proposed concept to provide a safe long-term solution. This report summarises the results of these investigations.

2 Description of Proposed DGR

The design concept developed as a part of this contract is appropriate for a hypothetical site with geologic and hydro-geologic conditions similar to those of the sparsely fractured rock of the Whiteshell Research Area. The emplacement room is designed to be located at a depth of 1000m, in relatively impermeable, sparsely fractured granite pluton. A complete design description for the proposed used-fuel emplacement facility has been presented in Reference 1 however this section of this report gives a brief outline of the proposed design.

The used fuel will be placed in a used fuel container (UFC), which will accommodate 324 fuel bundles. The proposed UFC has an overall diameter of 1168 mm and overall length of 3867 mm. Remaining key dimensions of the UFC are shown in Figure 1, and are consistent with those quoted by OPG in Reference 2.

The UFC design consists of an outer copper corrosion-barrier vessel and an inner, carbon steel load-bearing component. The selected material for construction of the outer corrosion barrier is the reference material developed by the Swedish nuclear fuel waste management programme. It is a high purity, oxygen-free copper with a low phosphorus content of 40 to 60 ppm (OFP copper), specifically chosen to give the copper matrix the required ductility to meet the DGR performance demands. The inner load-bearing component is in the form of a carbon steel inner vessel capable of withstanding all external pressure loads expected in a hypothetical geologic repository. It has been designed such that it will not be subjected to yielding or creep failure during the UFC design lifetime.

The UFCs are protected with a bentonite jacket, and placed in the DGR emplacement room. The emplacement room comprises three main components; the opening excavated within the rock mass, the permanent furnishings required to conduct emplacement operations, and the sealing materials. The arrangement of the various room components is shown in Figure 2.

Following work by Baumgartner *et al* [3], the profile of the emplacement room was specified as having an elliptical cross-section with the major axis in the horizontal plane and an aspect ratio of approximately 1.7. The emplacement-room should be oriented such that the room axis is parallel to the maximum principal stress direction, and the major axis of elliptical cross section is parallel to the intermediate principal stress direction. In comparison with other room shapes and orientations, this design minimises the tangential stress concentrations around the room perimeter. For ease of UFC and sealing material emplacement, a minimum centreline room height of 4.2 m was established, and consequently, a centreline room width of 7.14 m.

Low-heat, high-performance concrete is used for the construction of a uniform platform on the floor of the room to facilitate fuel emplacement. Although the rails and other temporary furnishings are removed as the room is filled, the concrete floor remains as a permanent structure. The voids around the UFC are filled with clay-based sealing materials of various densities.

The DGR arrangement for in-room emplacement of nuclear fuel waste is a system of access tunnels and emplacement rooms arranged into four distinct sections (Figure 3). Each section consists of a number of emplacement rooms, with 2 UFCs placed across the width of the room. The proposed design has a maximum total DGR capacity of 11,232 UFCs or 3,639,168 fuel bundles. In order to maintain rock formation stability, a minimum pillar width between adjacent emplacement rooms of three times the emplacement room width was specified. However, in practice a greater spacing was required to maintain DGR temperatures within the specified limits. Assuming an ideal site, with no faults or stress anomalies, the minimum overall dimensions of the UFC emplacement area are approximately 1.4 km by 1.4 km. These dimensions do not account for any adaptations that may be required at an actual site because of local conditions (e.g. specific rock structures, faults and stress anomalies).

3 Design Specification

A complete design specification for the DGR and associated UFC are given in References 4 and 5. For the purposes of the thermo-mechanical design assessments carried out as a part of the current work package, the key aspects of the specification are as follows:

- The UFC shall be designed with sufficient mechanical stability and strength to provide containment of the used fuel from the time of loading through handling, transportation, emplacement and potential retrieval operations and for its specified functional design life of not less than 1,000,000 years in the DGR.

- After emplacement in the emplacement room, the surface temperature of a UFC shall not exceed 100°C. This UFC surface temperature limit will avoid undesirable phase transformation of a bentonite based buffer, which may have an adverse effect on the swelling and self sealing properties of the buffer material [References 6, 7 and 8]. This temperature limit will also avoid boiling of groundwater that comes into contact with the UFC surface.

- The UFC shall withstand 15 MPa of external pressure loading with the usual safety margin that is employed in the ASME Boiler and Pressure Vessel Code, Section III (i.e. $2/3\sigma_{yield}$). This external load accounts for up to 1000 m of hydrostatic pressure (10 MPa) and a maximum buffer swelling pressure of up to 5 MPa.

- In addition to the normal external pressure loads prior to glaciation, the UFC shall withstand an increase in hydrostatic pressure of 30 MPa due to glaciation (i.e. corresponding to an additional hydraulic head due to the presence of a 3000 m thick ice cap). Therefore, the UFC shall withstand a maximum external pressure loading of 45 MPa (30 MPa from glacial loading and 15 MPa as described above) for the duration of the glacial episode. The glacial load is regarded as an extreme case for which no extra safety margin is required.

- An intact UFC shall withstand an internal pressure rise that may occur from gas production due to the corrosion of the UFC 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 UFC on sealing. The effect of temperature rise on the contained gases and water shall be included.

- The UFC shall withstand the static and dynamic loads associated with used fuel loading, handling in the packaging plant, transportation to the DGR, movements within the UFC cask, emplacement and potential retrieval operations in the DGR. For structural analysis of a UFC for the static and dynamic loads, analyses shall be performed at the appropriate temperatures.

- Total acceptable strain in the UFC - The total elastic and plastic strain developed in any part of the UFC shall not exceed the creep-rupture strain of the material over the design life of the UFC. The creep-rupture strain of the material(s) shall be determined for the as-fabricated condition of the material(s) and shall account for variations due to welding and other fabrication and heat treatment processes.

- The UFC geometry shall be such that the loading pressure imposed by the UFC on the buffer does not exceed the load bearing capacity of the buffer material supporting the UFC for the UFC design lifetime.

4 Material Properties

4.1 USED FUEL PROPERTIES

The DGR design is based on the reference CANDU fuel bundle, containing 19.25 kg of elemental uranium when initially inserted into the reactor. Each fuel bundle consists of 37 fuel elements and is 495 mm long and 102 mm in diameter. For the design scoping assessments carried out as a part of this programme of work, only the heat output from the waste fuel is required. It is assumed that neither the fuel, nor the fuel bundle contributes to the strength of the proposed design. The fuel decay has been calculated, Reference 9, from which heat output as a function of time has been derived (Table 1). It has been assumed that all fuel will undergo an initial cooling period of 30 years in surface facilities prior to emplacement within the repository.

4.2 ROCK MASS PROPERTIES

A volume of sparsely fractured granite was selected as the host medium for the waste emplacement area of the DGR. The rock mass material properties and the derived strength limits used in the design analyses are largely, based on measurements taken in the Underground Research Laboratory for Lac du Bonnet granite [Reference 10]. The sparsely fractured rock mass is assumed to be linearly elastic, isotropic and homogeneous. The assumed elastic constants and thermal properties for the rock mass are shown in Table 2.

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 [References 11 and 12]. At the nominal DGR depth of 1000m, this gives an ambient temperature of 17°C.

The ambient principal in-situ stresses assumed for the in-room emplacement repository can be defined by the following functions, originally presented in Appendix B of Reference 3.

$$\sigma_1 = 0.1345 MPa / m_{depth} + 18.5 MPa \quad < 300\text{m} \quad (1a)$$

$$\sigma_1 = 0.00866 MPa / m_{depth} + 56.3 MPa \quad \text{from 300 to 1400 m} \quad (1b)$$

$$\sigma_1 = 0.0403 MPa / m_{depth} + 12.1 MPa \quad > 1400\text{ m} \quad (1c)$$

$$\sigma_2 = 0.1112 MPa / m_{depth} + 9.9 MPa \quad < 300\text{ m} \quad (2a)$$

$$\sigma_2 = 0.00866 MPa / m_{depth} + 40.7 MPa \quad \text{from 300 to 1660 m} \quad (2b)$$

$$\sigma_2 = 0.0293 MPa / m_{depth} + 6.4 MPa \quad > 1660\text{m} \quad (2c)$$

$$\sigma_3 = \sigma_v = 0.0260 MPa / m_{depth} \quad (3)$$

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

The assessment of thermo-mechanical stability is made by calculating a factor of safety based on the Hoek and Brown empirical failure criterion model [Reference 13], defined as follows:

$$\sigma_{1f} = \sigma_{3f} + \left(m \cdot \sigma_c \cdot \sigma_{3f} + s \cdot \sigma_c^2\right)^{1/2} \quad (4)$$

where σ_{1f} = major principal stress at failure,
σ_{3f} = minor principal stress at failure,

σ_c = uniaxial compressive strength, and
m, s = empirical strength parameters.

Under uniaxial conditions, for this granite, the onset of stable crack initiation (σ_{ci}) is about 70 to 75 MPa. In comparison, the stress for the onset of unconfined unstable crack growth (σ_c) is about 150 MPa, and the peak unconfined compressive strength (σ_f) is about 210 MPa (i.e., the conventional value from laboratory testing) [Reference 10]. For the purposes of the current work, 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, rising to σ_c = 150 MPa, m = 25, s = 1 after the sealing materials have been placed. Note that the later 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 Underground Research Laboratory (Reference 14).

A criterion is also 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 disposed waste, 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; i.e. horizontal stress greater than or equal to zero for a “no-tension” analysis [Reference 15] 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 [Reference 10]

4.3 SEALING MATERIAL PROPERTIES

Following extensive research [Reference 16], three bentonite clay-based sealing materials have been specified for the in-room emplacement design: buffer material, dense backfill and light backfill. Bentonite clays are particularly attractive as sealing materials because of their swelling, and plasticity properties as well as their very low hydraulic conductivity. In addition, bentonite clay has the ability to sorb and retain cations.

The buffer [Reference 17] is a mixture of sodium-bentonite clay (a montmorillonite-rich clay found in commercial quantities in the central plains of North America) and well-graded silica sand mixed in a 1:1 dry mass ratio, giving a minimum dry bulk density of 1.67 Mg/m^3 and an optimum gravimetric moisture content of 17-19 wt%. For the in-room emplacement method, the buffer is placed around the UFC in the form of close-fitting, pre-compacted blocks.

The dense backfill material is a variant of the reference sealing material proposed for the reference borehole emplacement method [Reference 18]. It is a mixture of glacial lake clay (an illite-rich lake clay deposited in glaciated regions of North America), sodium-bentonite clay and crushed granite mixed in a proportion of 25/5/70% by dry weight, with a dry bulk density of about 2.1 Mg/m^3 and an optimum gravimetric moisture content of 8%. Like the buffer material, the dense backfill is placed as close-fitting blocks of highly pre-compacted sealing material [10].

In order to fill the upper perimeter of the emplacement room, a light backfill material, which can be blown into position is specified. The light backfill has a composition of 50% sodium-bentonite clay and 50% crushed granite, by dry weight. Based on the minimum dry density of this mix and the minimum clay dry density, it is judged that this material will yield about the same hydraulic conductivity as the dense backfill.

A mixture of dry granular bentonite and rounded sand is used to fill the gap between the buffer and the UFC's bentonite jacket, to provide for conductive heat transfer and to maintain the density of the clay-based sealing system. Rounded silica sand and granular bentonite, screened to specific sizes (i.e., fractionated) and dried, have good flow properties to fill the gap. Bentonite has been introduced to reduce the diffusion-controlled mass transport rate within the annulus around a defected UFC.

In addition to the bentonite clay based materials, low heat, high performance concrete is used for supporting rails and equipment and for placing and aligning pre-compacted dense backfill and buffer blocks, as well as the construction of bulkheads at the emplacement room entrances, in tunnels and in shafts. Cement based grouts may be used to control groundwater movement into the excavation and around seals. Recent test information suggests that these high-performance cements and concretes would have very low porosity, reduced pH and extremely low hydraulic conductivities. Microcracks generated in the high-performance materials would tend to self-seal [Reference 19].

The specifications for the basic physical properties of clay-based sealing materials are presented in Table 2. 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 UFC. Values for thermal conductivity of the jacket material have been derived, as a function of distance from the UFC, from References 20 and 21. The sealing materials are all assumed to have uniform, linear elastic, isotropic properties.

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 22. 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.

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = const \qquad (5)$$

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

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2 \cdot Y^2 \qquad (6)$$

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

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = k^2 + k^2 + 4k^2 \quad (7)$$

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

$$6k^2 = 2 \cdot Y^2 \qquad \text{or} \quad k = \frac{1}{\sqrt{3}} Y \quad (8)$$

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.

4.4 UFC PROPERTIES

4.4.1 Copper Properties

The outer corrosion barrier of the UFC is assumed to be OFP copper for which the material properties (Table 3) are taken from Reference 23:

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

The creep behaviour of the copper container will be assessed using the following empirical creep function for copper [Reference 24]:

$$\dot{\varepsilon} = 1.58 \cdot 10^{-17} \cdot \sigma_j^{3.4} \qquad \text{for } \sigma_j < 130 \text{ MPa.} \quad (9)$$

Where σ_j is the von Mises stress in MPa and

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

4.4.2 Carbon Steel Properties

The inner carbon steel vessel 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 4. Post yield properties for the steel will be modelled using a stress strain curve defined by the true stress strain data shown in Table 4b.

In comparison to the copper, creep of the steel at the anticipated peak DGR temperatures is negligible, and will not be taken into consideration.

5 Initial Emplacement Room Analysis

5.1 AIM

The aim of the initial emplacement room analysis was to provide confidence that the proposed DGR design would meet the thermal design requirements, before a more detailed analysis of the DGR was carried out. In addition, the model was used to determine the sensitivity of the repository temperature to room and UFC spacing, in order to assist with the development of the final proposed repository layout.

5.2 MODEL

For the initial assessments, a 2D cross-section through the emplacement room and UFC was considered. 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 [Reference 25]. The emplacement room layout considered was broadly similar to that considered in Reference 26, modified to accommodate the larger current design of UFC. Details of the cross-section considered are shown in Figure 5. Following an initial investigation, it was concluded that assuming the copper outer container is in intimate contact with the steel inner vessel 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 sealing materials swelling. The computer model therefore ignored the small gap between the inner and outer containers. The model geosphere was bounded on top by the Earth's surface and at the bottom by a plane 2000 m below the repository horizon; on the 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.

The ground surface temperature was modelled as an isothermal boundary condition, with a temperature of +5°C representing the average Canadian Shield surface temperature. After 10,000 years, the assumed surface temperature was reduced to 0°C, in order to account for a period of glaciation. The lower boundary was also modelled as isothermal, at a plane 2000 m below the repository horizon, such that a geothermal gradient of +0.012°C/m of depth was achieved. This results in an initial rock formation temperature at the DGR depth of 17°C. The vertical boundaries were modelled as adiabatic planes of symmetry to reflect the heat generated in the cell, Figure 6. In effect, therefore, the model replicates an infinite array of infinitely long parallel emplacement rooms. The condition modelled was thus representative of a UFC located in the centre of the DGR. The approach adopted is inherently conservative, in that the model considers a situation where all of the fuel is placed in the repository 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. A further inherent conservatism of the modelling approach adopted is that the heat lost from the ends of the UFCs was not considered; the model results therefore over predict the temperature profile.

The initial analysis only considered the thermal performance of the repository. The heat flux due to the radio-active 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 UFC, thus presenting a worst case, as far as the UFC temperature history is concerned. All voids were assumed to be filled with sealing materials and the DGR was considered to remain dry during the initial stages. As the thermal conductivity of the dry material is lower than that of partially saturated materials, this provides a conservative analysis. Furthermore, in the absence of water-flow, conduction was considered to be the dominant heat transfer mechanism, and radiation and convection heat transfer mechanisms were not considered, again yielding a conservative assessment.

5.3 INITIAL ANALYSIS RESULTS

The analysis predicted a peak copper temperature of 122.7°C, 26 years after emplacement, based on a UFC heat output of 1138.6 W at the point of emplacement, and a emplacement room separation of 45 m. The full temperature history is shown in Figure 7, for three locations within the emplacement room; the hottest point on the outer surface of the copper container, the uppermost point of the emplacement room (crown), and the horizontal extremity of the room (springline), at the granite surface, Figure 8. The thermal profile within the DGR geosphere at twenty years from emplacement is shown in Figure 9.

The results of the sensitivity analysis are summarised in Table 5. For these analyses, an earlier UFC heat loading of 993 W per UFC was used as a base case, with a emplacement room separation of 28.6 m. For this base case, the local heat flux at the surface of the UFC was used, with no attempt to account for the UFC axial spacing; this is the total heat load per UFC (993 W) divided by its internal surface area. This provides an upper bound to the predicted temperature. A lower bound value was obtained by using a reduced heat flux obtained by dividing the UFC heat load by the internal surface area of the UFC plus that of the end plug. In addition, a number of further analyses were carried out to determine the system's sensitivity to the assumed heat flux.

Subsequent analyses were used to determine the system sensitivity to the layout of the emplacement room. These considered a range of UFC separations, starting from the base case separation of 2.52 m (between centres), as well as a range of emplacement room separations.

Finally, analyses were carried out to determine the dependence on the sealing material properties. A range of light backfill thermal conductivity values were considered. The base case assessment used a light backfill conductivity of 0.7 W/m°C.

6 Near-field Analysis

6.1 AIM

The near-field analysis provides a more detailed assessment of the thermal and stress conditions in the material surrounding the emplaced UFC than that provided by the initial 2D assessment. The use of a 3D model allows the UFC longitudinal spacing to be more accurately taken into account. The results of this analysis will be used primarily to provide confidence that the proposed DGR design will meet the thermal design requirements; That is that the external surface temperature of the copper corrosion barrier will not exceed 100°C during the life of the DGR.

6.2 MODEL

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. Subsequent to the initial analysis work described in the previous section, the design of the emplacement room layout was reviewed in order to improve performance and operability. This resulted in several changes to the disposition of the various sealing materials. Details of the revised dimensions assumed for the near-field analysis are given in Figure 2, and the finite element model shown in Figure 10. The longitudinal spacing between UFCs was assumed to be 1.25 m (less than 1 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.

For the thermal portion of the analyses, the top boundary condition (representing ground surface) was modeled 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 modeled 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). All four vertical boundaries were modeled as adiabatic planes of mirror symmetry to reflect the heat generated within the cell (Figure 6). 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 representative of the conditions likely to be encountered in the middle of the DGR. As with the previous analysis, conduction was considered to be the dominant heat transfer mechanism, and therefore the effects of radiative and convective heat transfer were not considered. This is a conservative assumption.

For the structural analyses the boundary conditions are as follows. The top boundary is free to displace vertically, and the perimeter is rigidly constrained laterally. The bottom boundary is rigidly fixed against displacement, both vertically and laterally. The four vertical boundaries are fixed against out-of-plane lateral displacement and are attached to the top and bottom boundaries to maintain the appropriate continuity (Figure 6). 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 sealing materials, in view of the uncertainty and time dependence of this effect. Also, the stiffness of the sealing 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.

6.3 NEAR-FIELD ANALYSIS RESULTS

The results of the near-field thermal analysis are shown in Figures 11 to 15. The temperature history plots (Figures 11a) shows results at the same three locations used previously (Figure 8). The results indicate a rapid increase in the UFC temperature over the first decade, reaching a peak temperature of 97°C after 16 years for a UFC located at the center of the DGR, and given an ambient temperature of 17°C at the repository depth of 1000m. 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 fuel 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 the 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 repository. 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). 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 achieved 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 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 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. 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 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, thus the compressive strength capacity of the granite is not exceeded at any time.

Figure 16 shows the displacement of the emplacement room at various times. 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 therefore 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.

7 Far-field Analysis

7.1 AIM

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 repository depth is adequate to prevent cracking of the surrounding rock formation due to the thermal expansion of the formation local to the repository. 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.

7.2 MODEL

The model used a simplified representation of a quarter section of the repository, the extent of which was sufficient such that the temperature of the rock at the boundaries remained unaffected by the presence of the repository. 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 repository 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. 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 repository. 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 repository, based on an assumption of a full repository containing 3.6M 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 repository edge effects are explicitly considered. As discussed for the near-field assessment, in order to provide a conservative assessment of the peak temperature reached in the surrounding rock formation it was assumed that the DGR remains dry throughout the life of the repository, and 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. 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. The model is thus representative of a repository 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 DGR emplacement rooms are oriented with the room's longitudinal axis perpendicular to the highest principal stress. Between 10,000 and 100,000 years, an additional load due to 3000 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, such as the formation of local fault lines through an emplacement room, will be adequately buffered by the clay based sealing materials materials, and therefore do not need to be explicitly considered at this stage of the DGR design process.

7.3 FAR-FIELD ANALYSIS RESULTS

Figure 19 shows the thermal history for three locations within the DGR, the repository centre (equivalent to the previous near-field case), at the mid point along one edge of the repository, and at a corner location. In addition, Figure 20 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 center of the repository, with the peak rock temperature at a corner of the repository being only 33°C, compared with a peak temperature at center of the repository of 69.5°C. The far-field analysis predicts that the peak temperature will be developed at around 4000 years from waste emplacement, and it would take over 100,000 years to return to the initial ambient temperature,

Also shown in Figure 19 is the temperature history at the crown of a emplacement room at the center of the repository, 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 repository being averaged over the entire waste emplacement area, as defined by the initial gross thermal load. Between 100 years and 2000 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 2000 years in the immediate plane of the repository and earlier in time as the distance from the plane of the repository increases (i.e. the localized heating effects are "smeared" out). It is therefore considered that the DGR will initially reach a temperature of 70°C some 100 years after fuel emplacement. The rock temperature will then remain more or less constant for some 4000 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 1.27 MPa after 10,000 years, Figure 21. This is significantly below the quoted tensile strength for the homogeneous isotropic rock considered of 6 MPa, and indicates that new fracture zones will not be initiated as a result of the DRG. 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 metres vertically, in the vicinity directly above the DGR. This is significantly less than the specified depth of 100m, and negligible impact on groundwater flow is anticipated. The maximum uplift is about 247 mm on the ground surface above the centre of the DGR at about 10,000 years after waste emplacement, Figure 23.

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 worst-case conditions, 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 repository, 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 shows how temperature varies with distance from the edge of the repository, 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.

8 Pressure Analysis

8.1 AIM

One of the key requirements of the UFC is to withstand the pressure loading applied through a combination of sealing materials swelling 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 1000m). During periods of glaciation, it is assumed that the UFC 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 UFC design specification requires the stresses in the UFC to remain within ASME III design limits for Level A loading under normal conditions, and within ASME III design limits for Level D loading during periods of glaciation.

8.2 MODEL

An axisymmetric finite element model of the copper outer and carbon steel inner containers was created (Figure 25). 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. For the purposes of the current work, assessment of the creep behaviour of the copper container has not been included in the finite element analysis model.

8.3 RESULTS

8.3.1 External Pressure Cases

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). 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 proposed design for the carbon steel inner container is therefore considered satisfactory.

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 tensile stress in the copper, under external isotropic pressure loading of 15 MPa prior to glaciation, is 68.4 MPa (Figure 27). The creep rate at this stress level is typically less than $8x10^{-4}$ $year^{-1}$. The application of additional loading due to glaciation results in further localised collapse of the copper at the corners of the container, and a reduced residual stress of 46.7 MPa. This can be compared with an ultimate tensile strength for the copper of 200 MPa.

Under normal conditions, the maximum (localised) plastic strain in the copper outer barrier following its collapse against the steel liner is 6.6%, this rises to a strain of 9.5% at a pressure loading of 45 MPa following a period of glaciation, Figure 28. This compares with a plastic strain to failure of around 29% based on short term tensile testing [Reference 23]. 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 be carried out once information is available on the rate of swelling of the sealing materials materials.

8.3.2 Internal Pressure Case

In addition to the external pressure cases, due to formation pressure, the intact UFC is required to withstand an internal pressure rise that may occur from gas production due to the corrosion of the UFC 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 UFC on sealing. The analysis has determined the maximum theoretical internal pressure that can be retained by an unsupported copper container (i.e. assuming no support from the sealing materials). The absence of support from the sealing materials has been assumed because of the variation of sealing materials pressure with time, the fact that support in the region of the lifting feature is unlikely, and to cover the situation where a UFC is subsequently retrieved. The analysis indicates that initial yield occurs when the pressure reaches 0.6 MPa, with local yielding occurring in the UFC lid (Figure 29). Ultimate failure of the copper container is predicted at a pressure of approximately 2.3 MPa (Figure 30), when global yielding of the UFC lid occurs.

According to the reaction for anaerobic corrosion, [Reference 27] 1 mole of water gives rise to 1 mole of hydrogen. Using Boyle's law, the total volume of (liquid) water required to generate an internal pressure of 0.6 MPa is therefore 67 cc. With a long-term hydrogen production rate of 1 dm^3 per year at 1 standard atmosphere, this volume of water would be consumed in approximately of 2.8 years, this defining the rate of pressure build-up in the UFC under these circumstances. This therefore provides a specification for the maximum moisture content acceptable at the time of closing the UFC. In practice, because the void space between the outer copper and the inner steel containers will be evacuated in the electron beam welding cell, and will therefore not contain a significant volume of water vapor, the actual internal pressure is likely to be very much lower than 0.6 MPa.

9 Handling Load Analyses

9.1 AIM

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 typical of those likely to be encountered.

9.2 TWO-POINT LIFT

It is assumed that the UFC copper shell and it's steel inner container 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 UFC 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 [Reference 28]. Further conservatism was introduced by assuming a fully loaded UFC (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, Figure 33. 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.

9.3 VERTICAL LIFT

When fully loaded the UFC, with its inventory of three baskets containing spent CANDU fuel and with the inner vessel lid bolted and the copper container 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 [Reference 29].

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. ASME III Fig NB-3221-1 places a limit of 1.5x design allowable stress (giving a limit of 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 [Reference 30] 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 lid lifting feature design is satisfactory. Although the proposed grapple design is also adequate, the anticipated stresses in the UFC 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 UFC lifting feature is 75 tonnes, at which point the whole of the container wall has begun to yield, Figure 36. Changes in the design of the grapple will not result in an increase in the maximum load that can be applied to the UFC lid.

10 Emplacement Condition Analysis

To establish the integrity of the chosen emplacement room emplacement sealing materials 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 viability of the final design.

Before the UFC and jacket are placed in the emplacement room, the maximum displacement of the room is 1.46 mm, Figure 37. 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 sealing material blocks, and placing the UFC the actual deflections may be larger. Figures 38 to 40 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, which also shows the relevant design allowable 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 emplacement room in place, and the sealing materials in position, the maximum deformation is 1.27 mm, Figure 41. Figures 42 to 44 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 lower slot infill blocks to support the UFC. As previously, maximum stress values are summarised, by material in Table 6, 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.

11 Conclusions

A number of finite element analyses have been carried out by AEA Technology, in support of a programme of work being undertaken by CTECH to update the conceptual design for a DGR for the long-term storage of used nuclear fuel from all Canadian reactors. These analyses have established that the proposed design for the Canadian used nuclear fuel deep geological repository can meet the design specification.

The outer surface of the UFC will reach a maximum temperature of 97.2°C, 16 years after emplacement. The surrounding granite formation will reach a maximum temperature of 72.6°C after 57 years, that 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 DGR will have returned to near ambient temperature.

The UFC design has been shown to be able to satisfactorily withstand the design loading following saturation of the DGR, as well as any build-up of pressure within the UFC. 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 minimum yield stress.

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 (3x the self 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.

Analyses have been carried out to demonstrate the stability of the sealing material blocks at all times during the emplacement operation. Assessments were carried out both prior to UFC placement, and also after placement, but prior to placement of the lower slot infill blocks. In both cases, deformation of the sealing material blocks was negligible, <1.5 mm. Stresses in the sealing material blocks were also low and remained within the assumed allowable limits for the various sealing materials. It was therefore concluded that the proposed emplacement methodology would be feasible.

Stress analysis of the surrounding rock formation has shown that the emplacement room excavations are stable prior to the emplacement of the UFCs. Thereafter, stresses in small regions at the top and bottom of the emplacement room exceed the Hoek and Brown failure criterion used to determine rock stability. This is limited to a region extending less than 300 mm into the rock formation, and only occurs after the decay heat has built-up after the sealing materials have been placed. In practice, therefore, this is not considered to present a threat to the safety of the emplacement room. However, should a UFC require retrieval some years after emplacement, some additional roof support may be necessary.

The analyses carried out as a part of this programme of work have all confirmed that the proposed DGR and associated UFC design and the emplacement methodology, 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.

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The fuel decay has been calculated[1], from which the following heat outputs as a function of time have been derived for the reference CANDU fuel bundle

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 1. Used Fuel Heat Output.

1 JC Tait *et al*, "Characteristics and Radionuclide Inventories of Used Fuel from OPG Nuclear Generating Stations – Volume 3", 06819-REP-01200-10029-R00 Volume 3

Property	Lac du Bonnet Granite [1]	Low heat high performance concrete	Fractionated silica sand	Buffer	Bentonite jacket	Dense backfill
Thermal conductivity (W/m°C)	3.00	1.80	1.0 [2]	1.70	0.90 0-100mm 1.05 100 –200mm 1.15 200-250mm [3]	2.00
Specific heat (kJ/kg°C)	0.845	0.9	0.82	1.38	1.38	1.19
Density (kg/m^3)	2650	2430	1450	1970	1600	2270
Young's modulus (GPa)	60	50	0.10	0.10	0.10	0.20
Poisson's ratio	0.25	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
Swelling pressure (kPa)	0	0	0	800-2000	800-2000	<50

Table 2. Granite and Sealing Material Thermo-mechanical Properties.

1 P.Baumgartner *et al* "Engineering for a Disposal Facility Using the In-room Emplacement Method", AECL-11595, COG-96-223, June 1996

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Property[1]	
Thermal conductivity (W/m°C)	380
Specific heat (kJ/kg°C)	0.390
Density (kg/m^3)	8930
Young's modulus (GPa)	117
Poisson's ratio	0.3
Coefficient of thermal expansion (10^{-6}/°C)	16
Strain to failure	29%

Table 3a. Thermo-mechanical Properties for Copper

True stress (MPa)	**True plastic strain**
60	0.000
80	0.015
130	0.065
180	0.154
200	0.288

Table 3b. Post-Yield Copper Properties

1 AE Bond *et al* "Assessment of a Spent Fuel Disposal Container; Assessment Studies for a Copper Canister with Cast Steel Inner Component", SKB Technical report 97-19, May 1997.

Property	
Thermal conductivity (W/m°C)	59
Specific heat (kJ/kg°C)	0.460
Density (kg/m^3)	7800
Young's modulus (GPa)	200
Poisson's ratio	0.30
Coefficient of thermal expansion (10^{-6}/°C)	12
Yield Strength (MPa)	260
Tensile Strength (MPa)	485

Table 4a. Thermo-mechanical Properties for SA516-70 and SA105 Steels

Service Level	Design Stress Intensity
ASME III Service level A	161.7 MPa
Glaciation loading	260.0 MPa

Table 4b. Design Stress Intensity

Description	Max. Temperature (°C)
Base case (ignoring axial spacing, room spacing 28.6 m, 993 W per container).	115.7
As base case, but reduced heating to allow for axial spacing.	87.5
As base case, but with 875 W per container.	104.5
As base case, but with 1138.61 W per container	145.8
As base case, but increase spacing between containers by 500 mm	114.7
As base case, but increase spacing between containers by 2 metres.	106.7
As base case, but increase spacing between containers by 4 metres.	101.0
As base case, but with room spacing increased by 14.3 metres.	94.3
As base case, but with light backfill conductivity = 1.7 W/m K.	110.9
As base case, but with light backfill conductivity = 3.0 W/m K.	109.2
1138.61 W per container, 45 metres between room centres	122.7

Table 5. Summary of Sensitivity Study Results.

Material	Maximum principal stress (Tensile)	Maximum principal stress (Compressive)	Maximum shear stress
Jacket			
After UFC placement	**0.19 MPa**	**0.28 MPa**	**0.14 MPa**
Allowable	**250 kPa**	**0.9 MPa**	**520 kPa**
Buffer			
Prior to UFC placement	**0.023 MPa**	**0.127 MPa**	**0.064 MPa**
After UFC placement	**0.032 MPa**	**0.225 MPa**	**0.118 MPa**
Allowable	**125 kPa**	**0.4 MPa**	**260 kPa**
Dense Backfill			
Prior to UFC placement	**0.017 MPa**	**0.164 MPa**	**0.084 MPa**
After UFC placement	**0.009 MPa**	**0.0243 MPa**	**0.0123 MPa**
Allowable	**125 kPa**	**0.4 MPa**	**260 kPa**

Table 6. Summary of Emplacement Analysis Results.

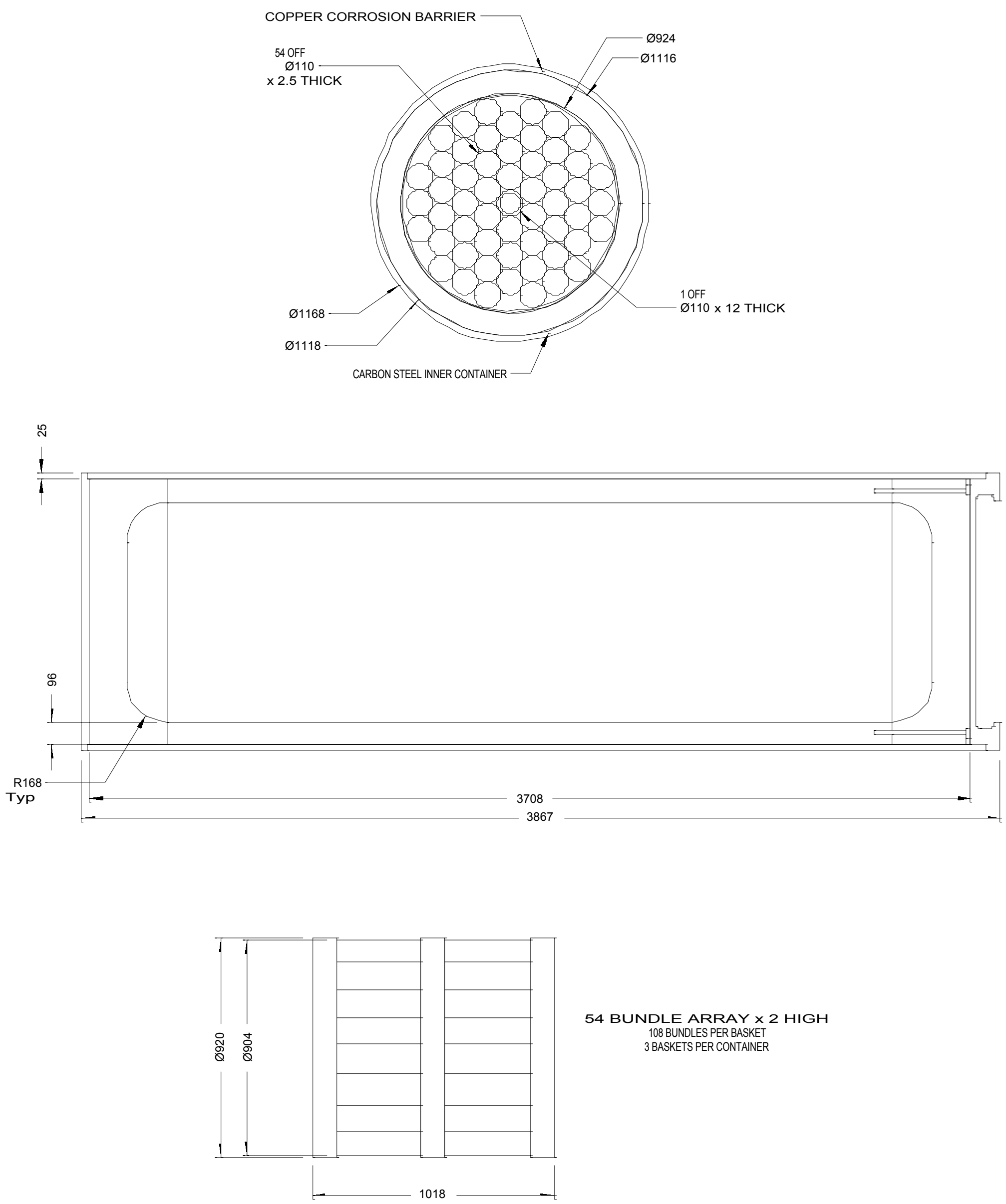


Figure 1 Used Fuel Container Design

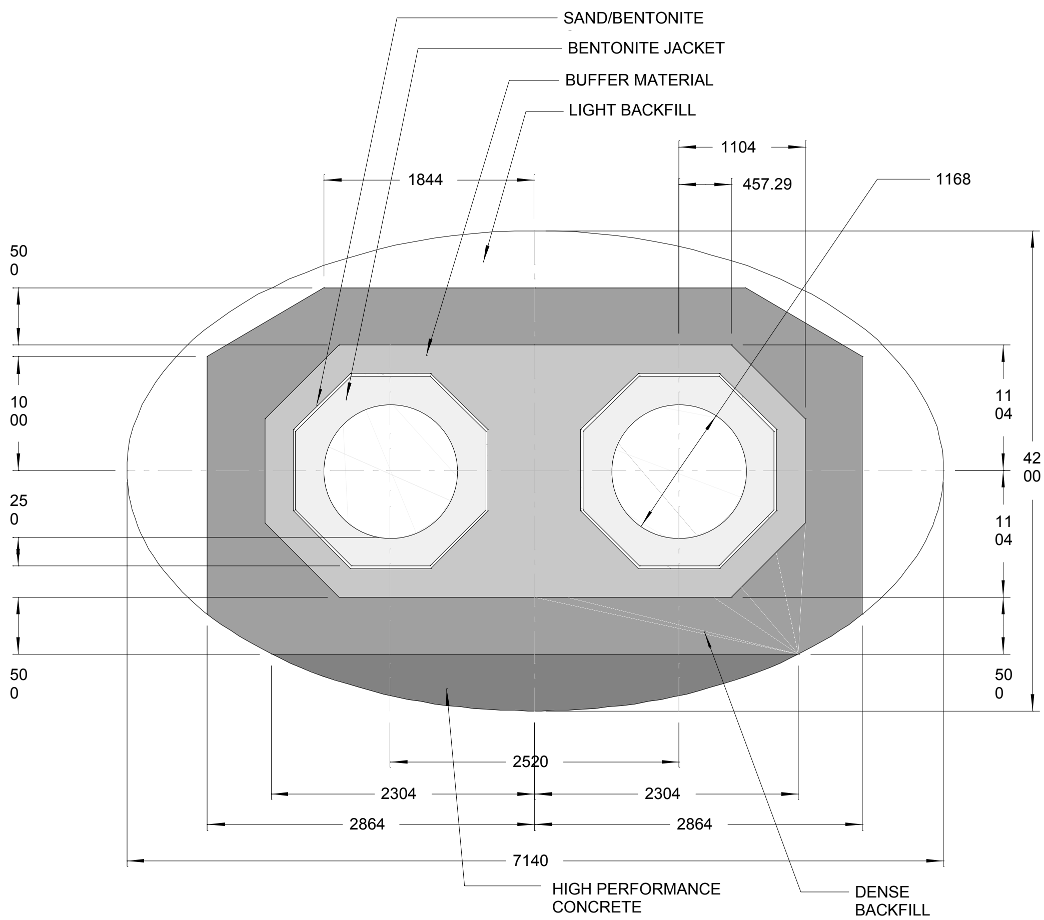


Figure 2. Sectional View of Emplacement Room (Revised Design).

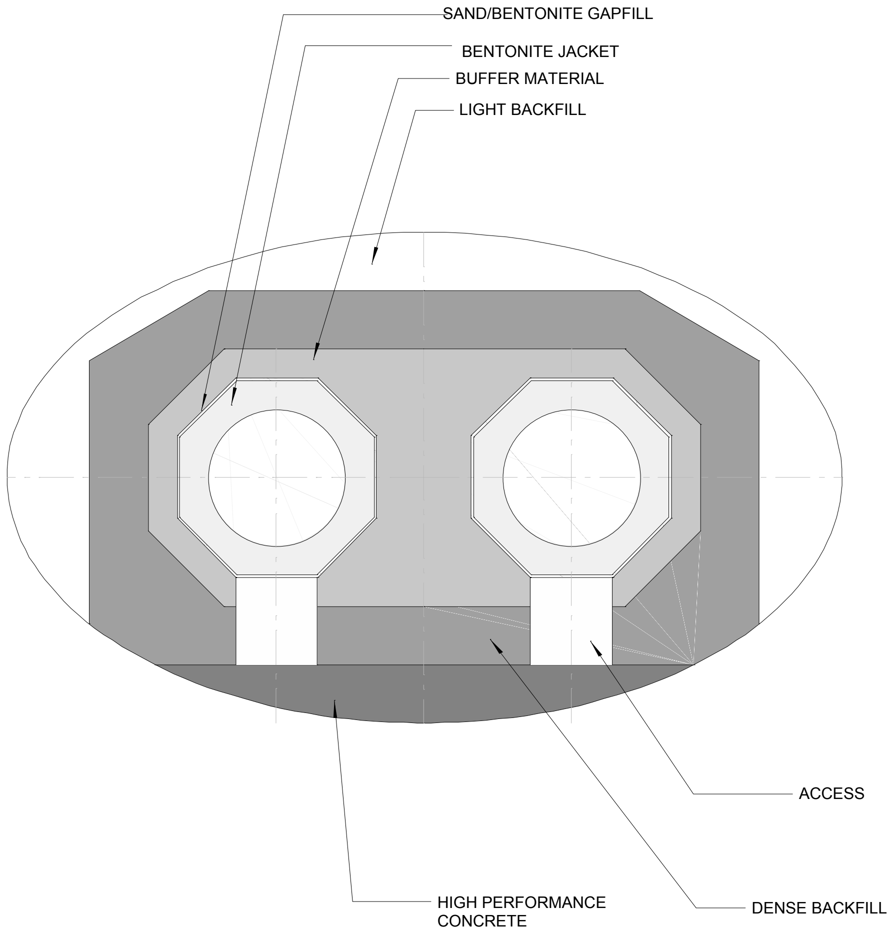


Figure 4. Sectional View of Emplacement Room (prior to UFC emplacement).

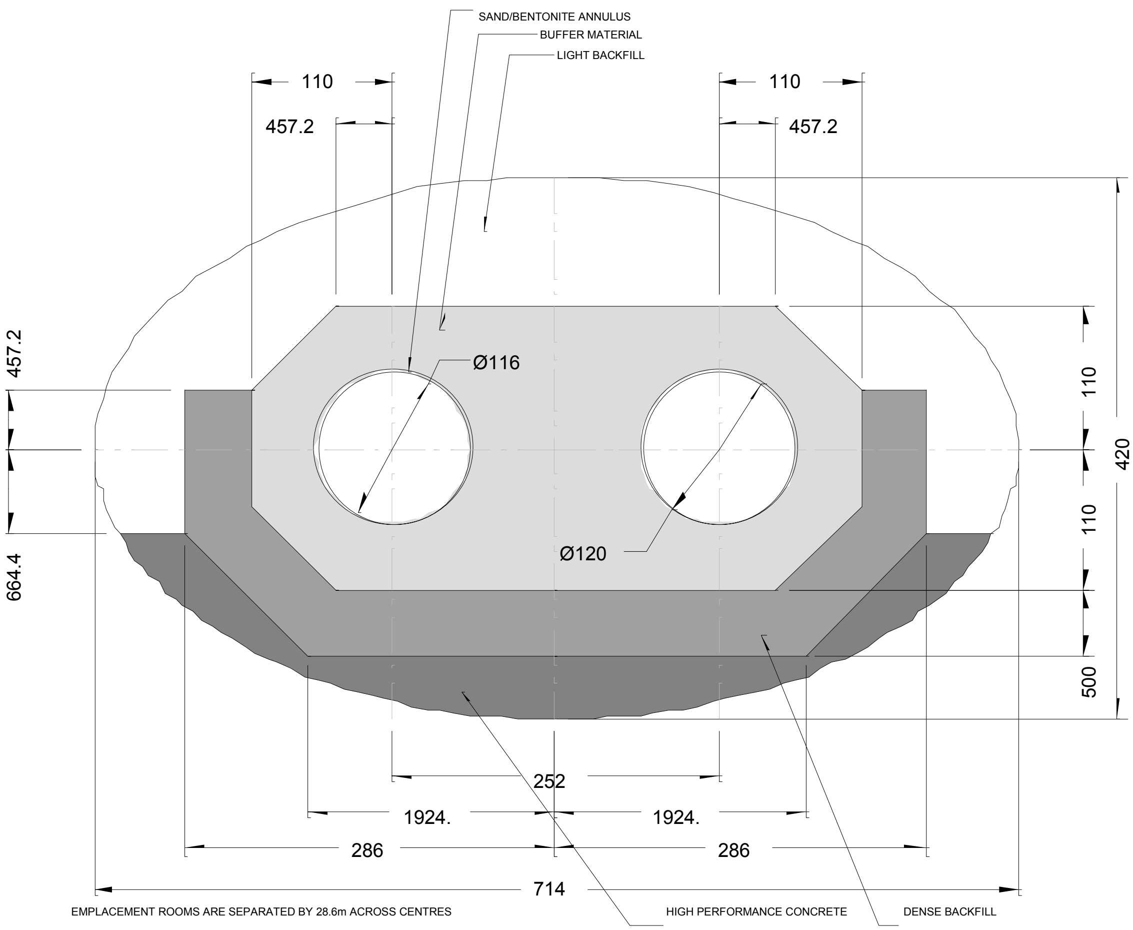


Figure 5. Sectional View of Emplacement Room (Initial design).

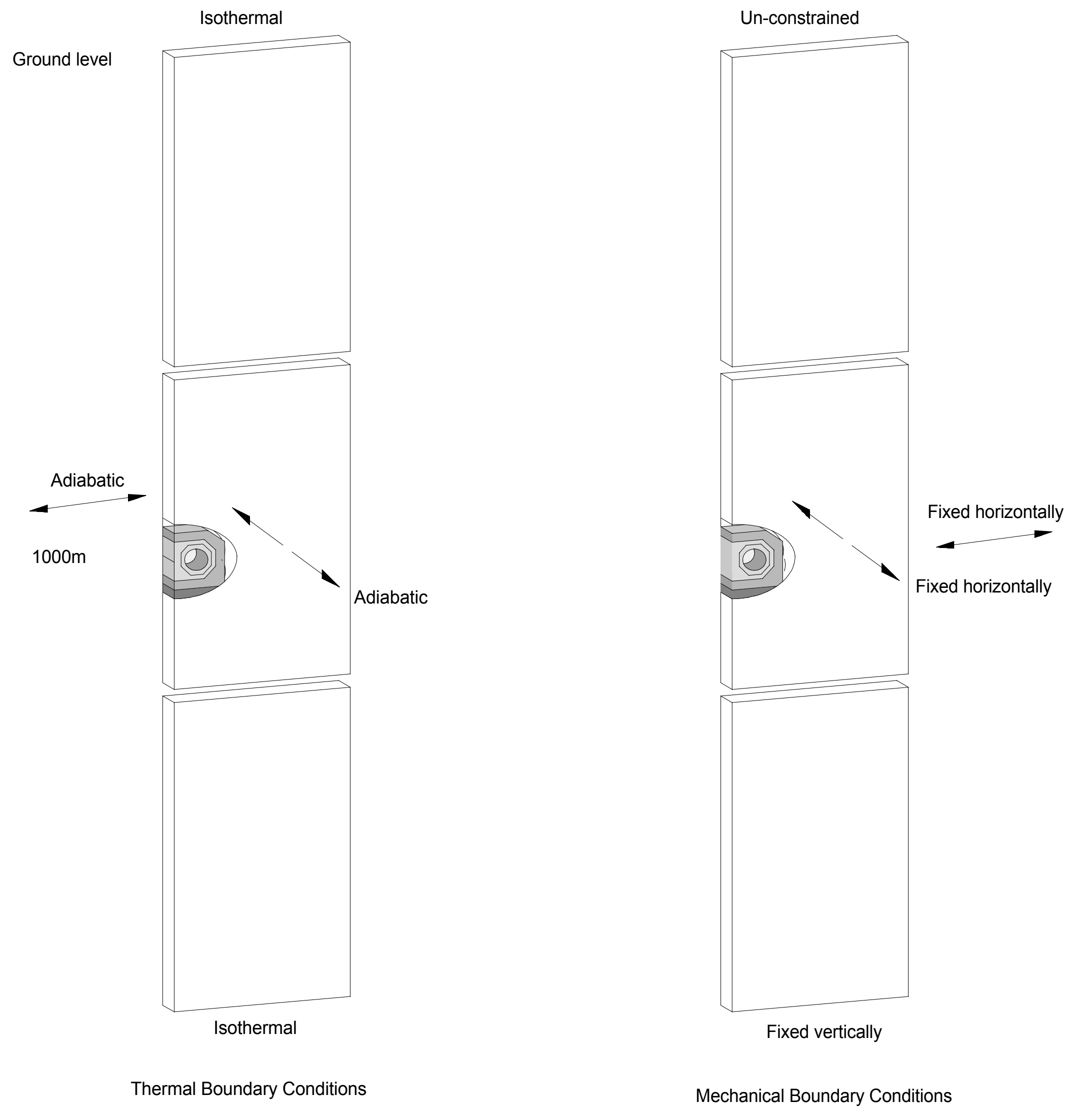


Figure 6. Thermal and Mechanical Boundary Conditions.

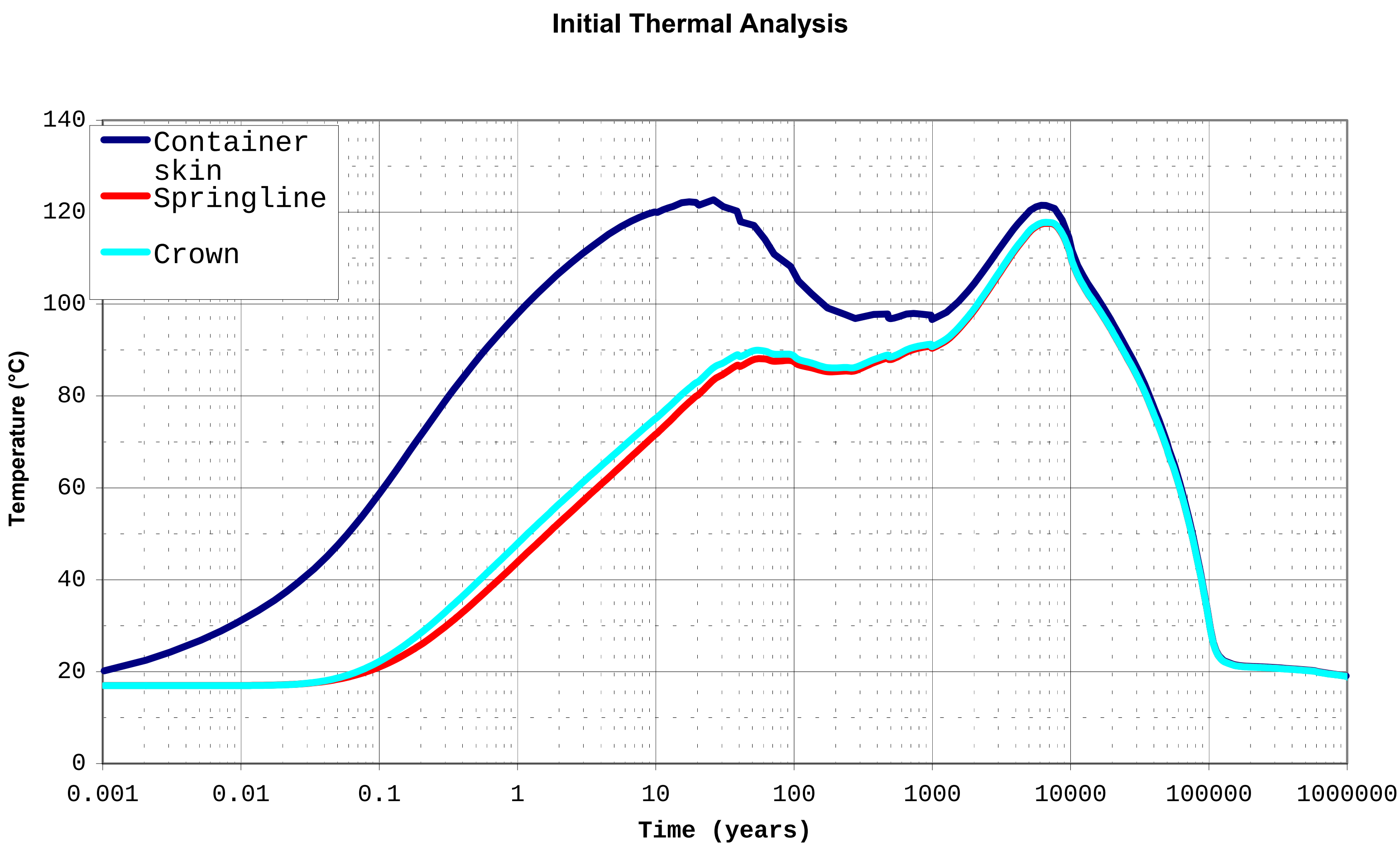


Figure 7 **Temperature History.**

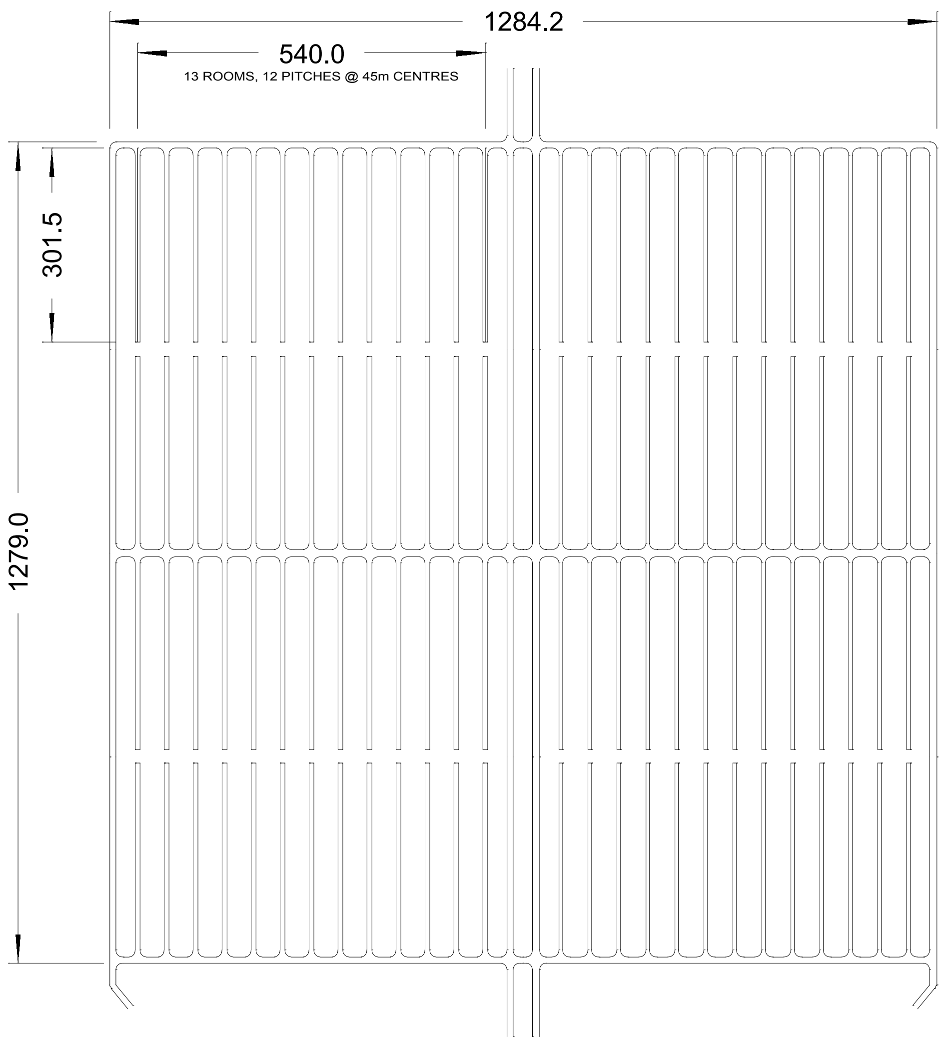


Figure 3. Proposed Plan of DGR.

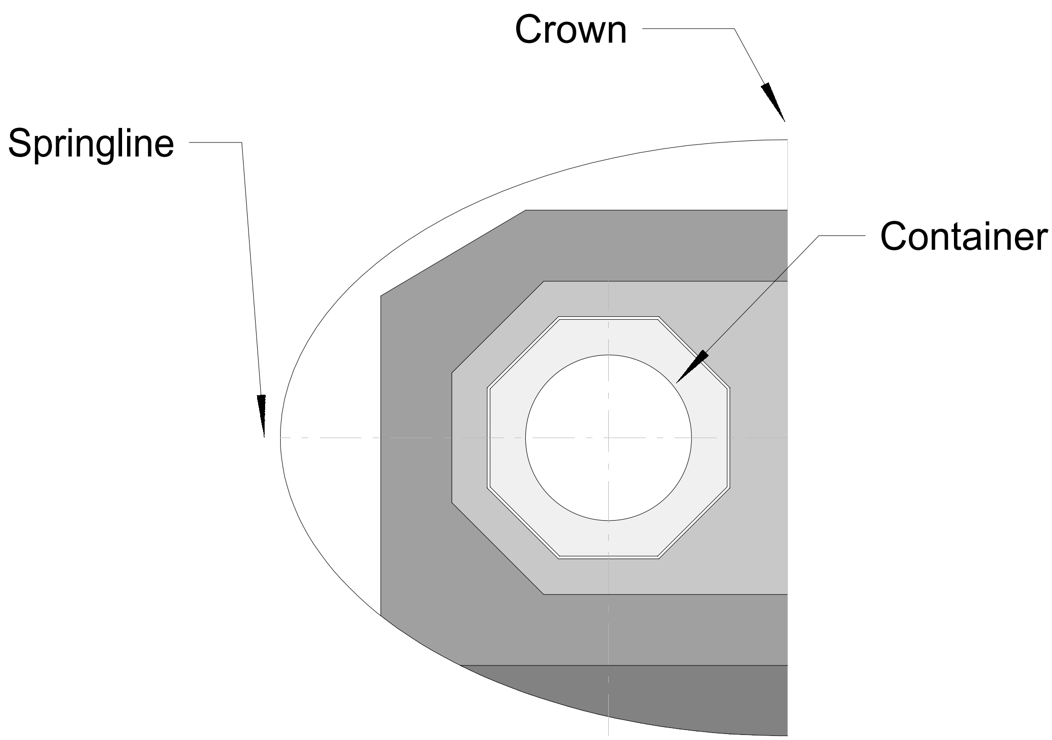


Figure 8. Monitoring Points for Temperature History Plots.

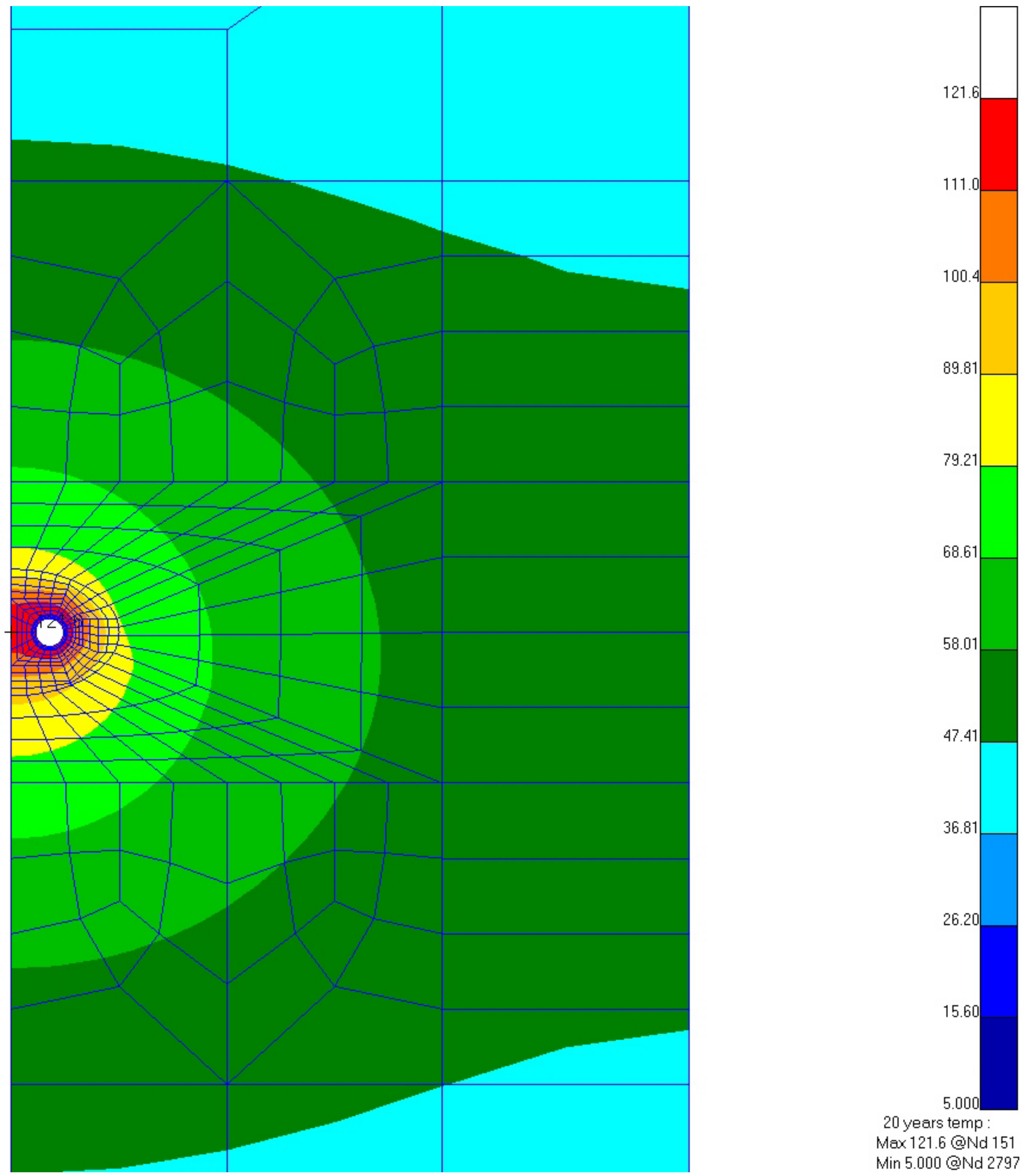


Figure 9. Temperature Profile 20 Years After Emplacement.

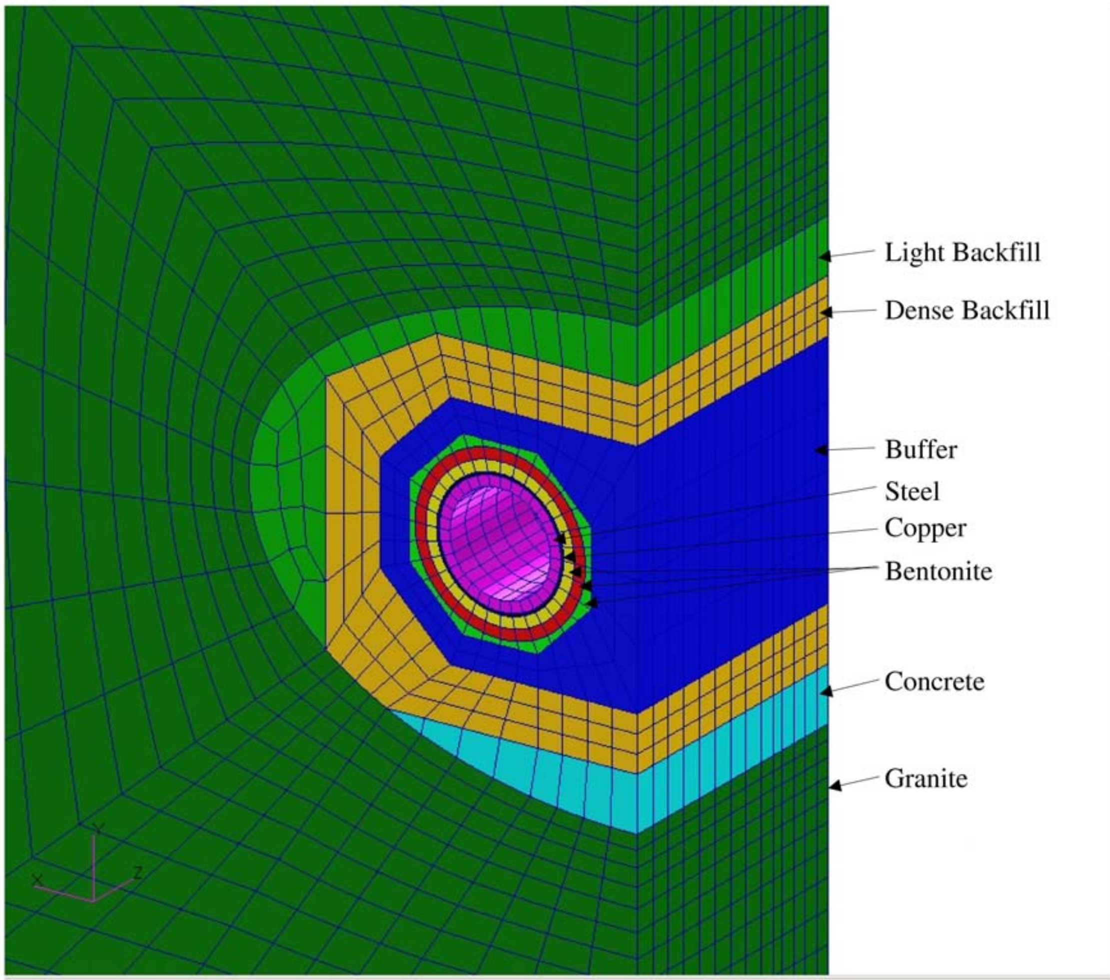


Figure 10. Finite Element Model of Emplacement Room (Revised design).

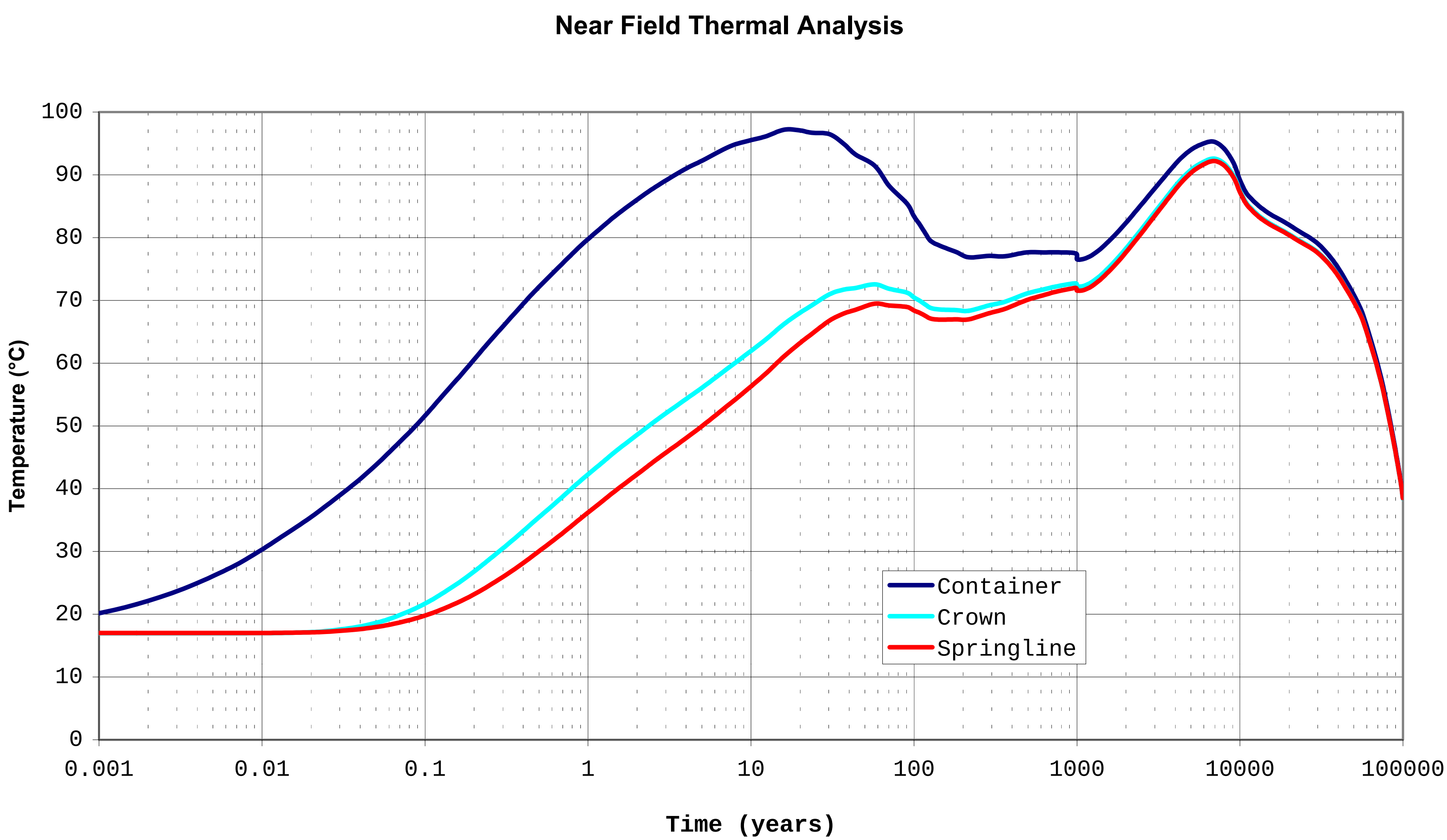


Figure 11a Temperature History.

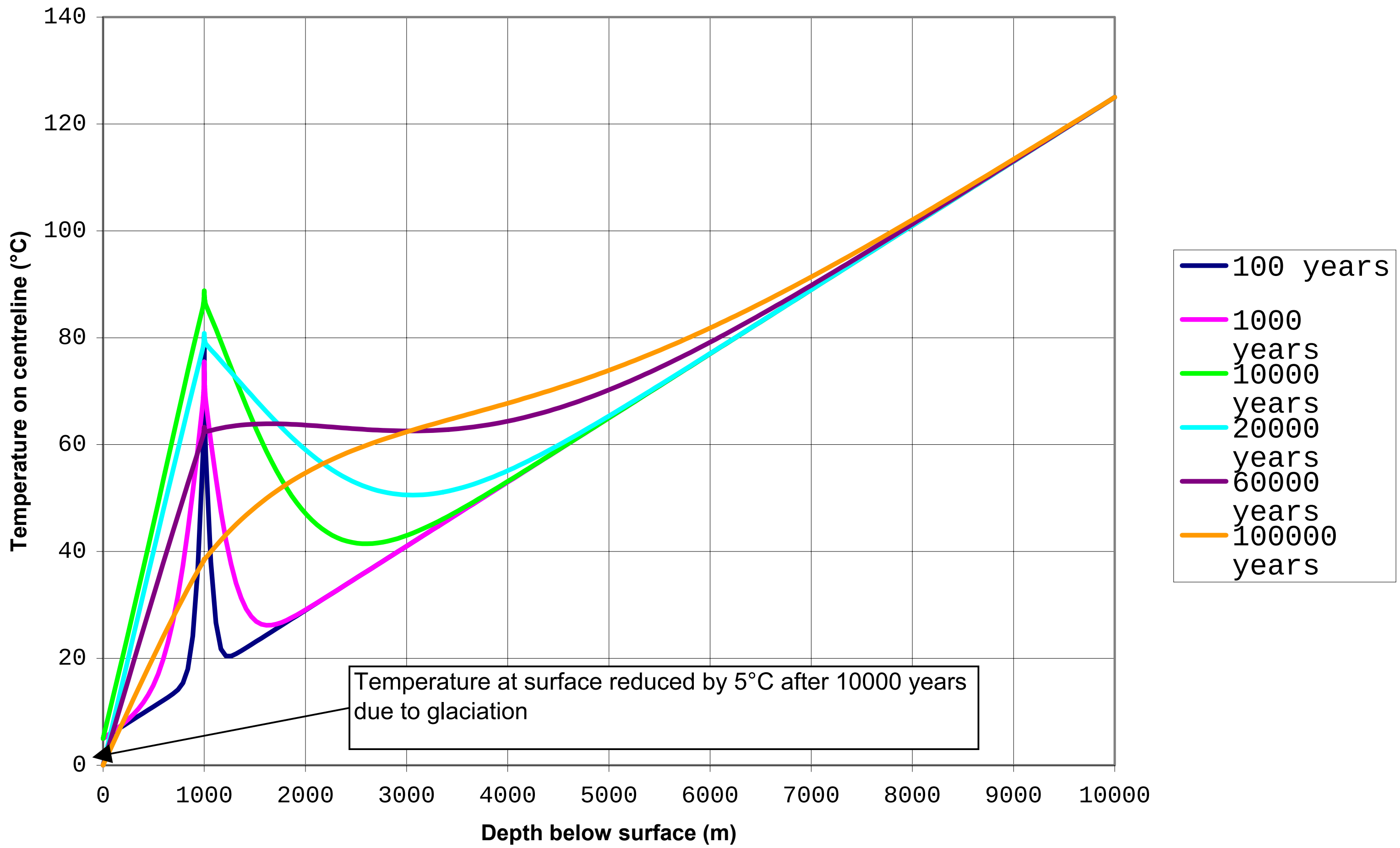


Figure 11b Temperature History.

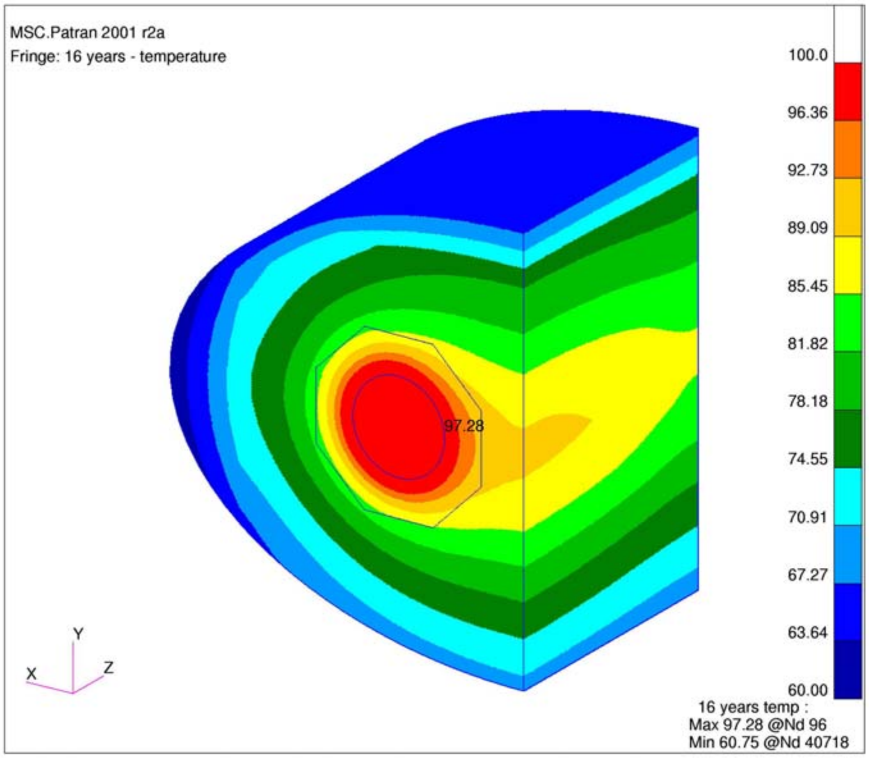


Figure 12a Temperature Profile – 16 Years (Peak container temperature).

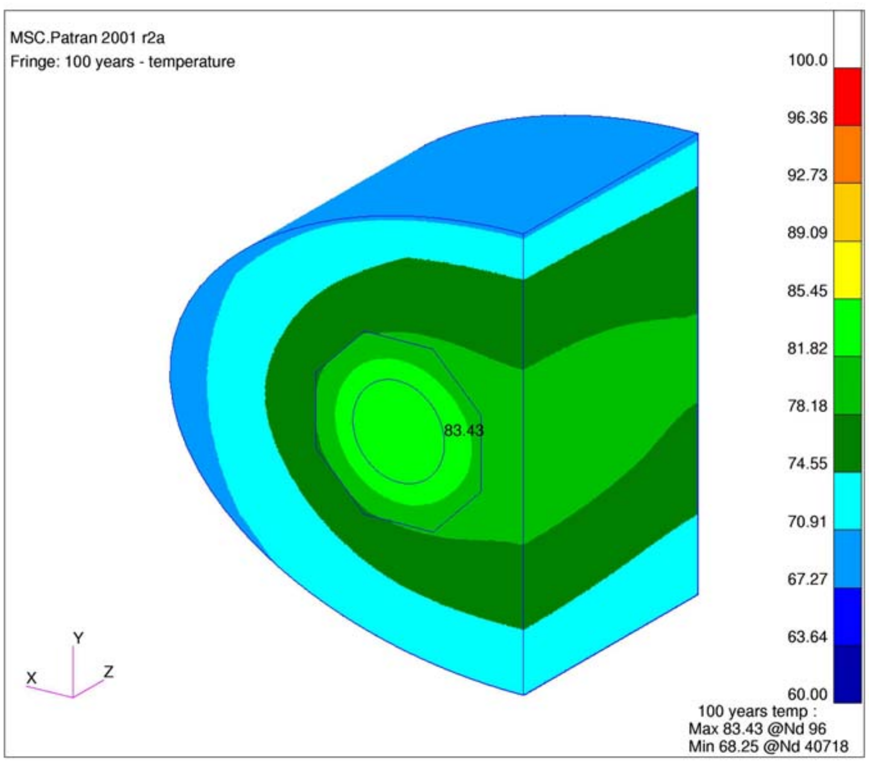


Figure 12b Temperature Profile – 100 Years

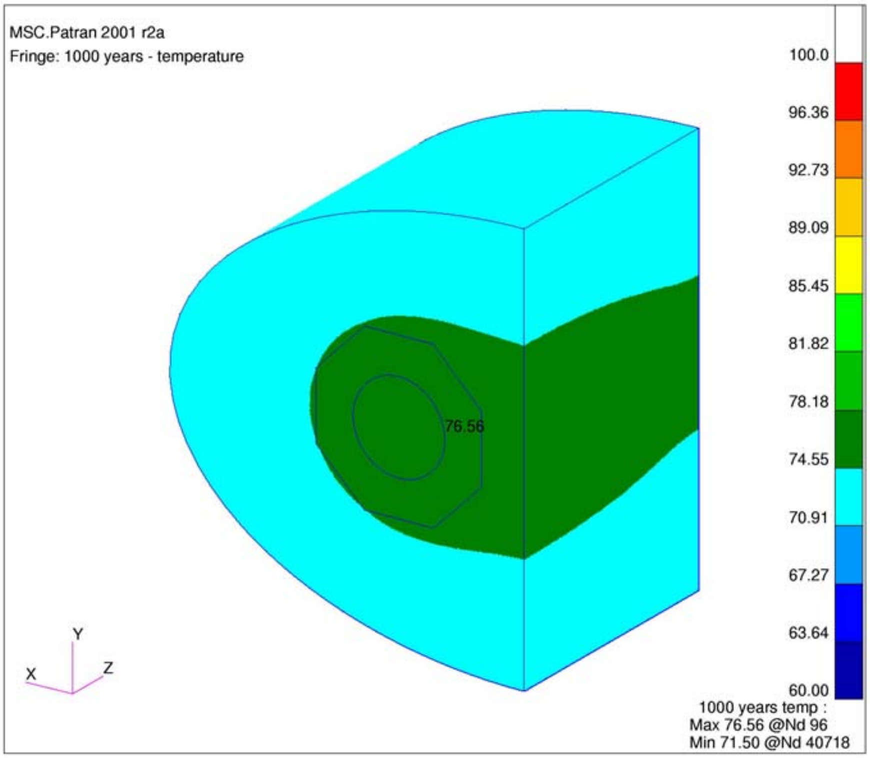


Figure 12c Temperature Profile – 1000 Years

Figure 12d Temperature Profile – 10,000 Years

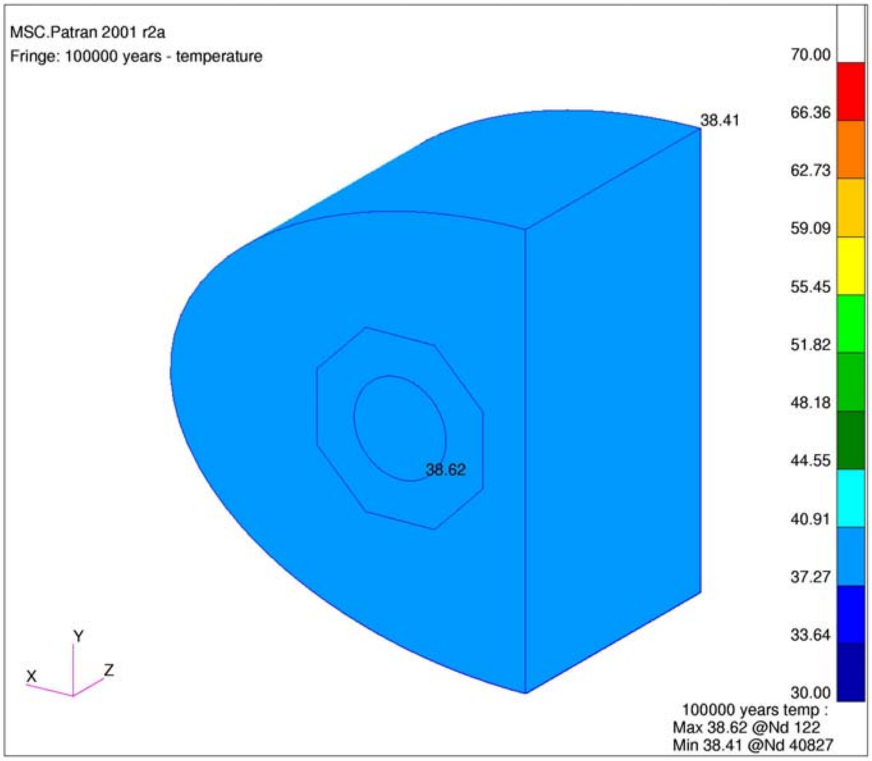


Figure 12e Temperature Profile – 100,000 Years

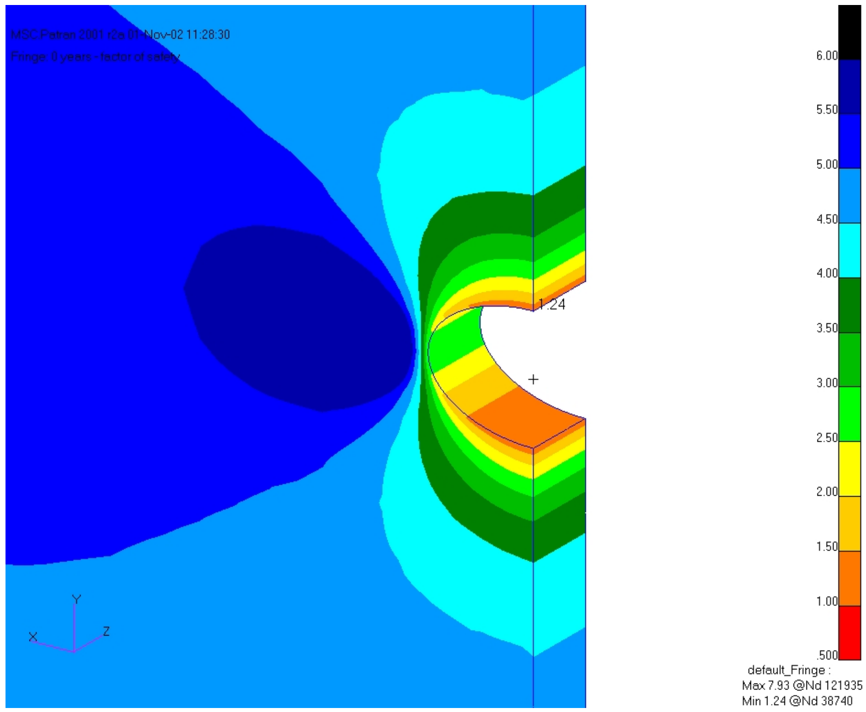


Figure 13a Emplacement Room Stability – **worst case orientation/ post excavation**

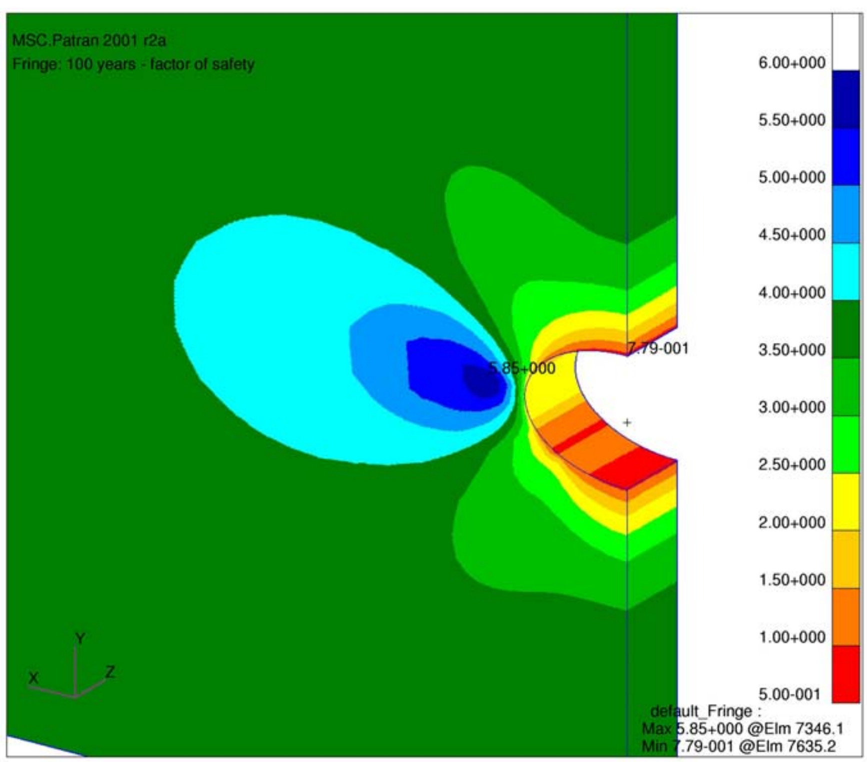


Figure 13b Emplacement Room Stability – **worst case orientation/ 100 years**

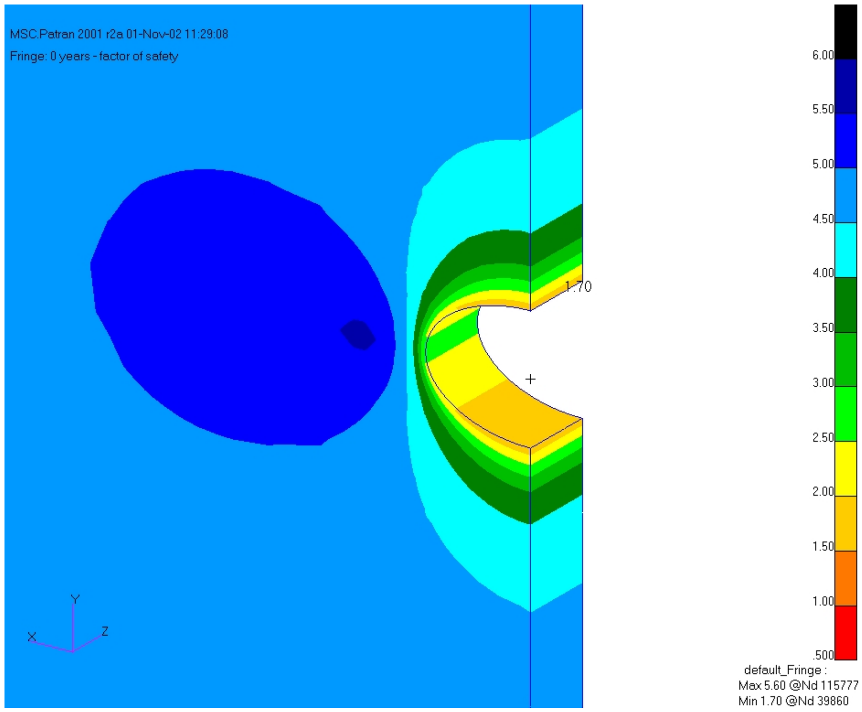


Figure 13c Emplacement Room Stability – preferred orientation/ post excavation

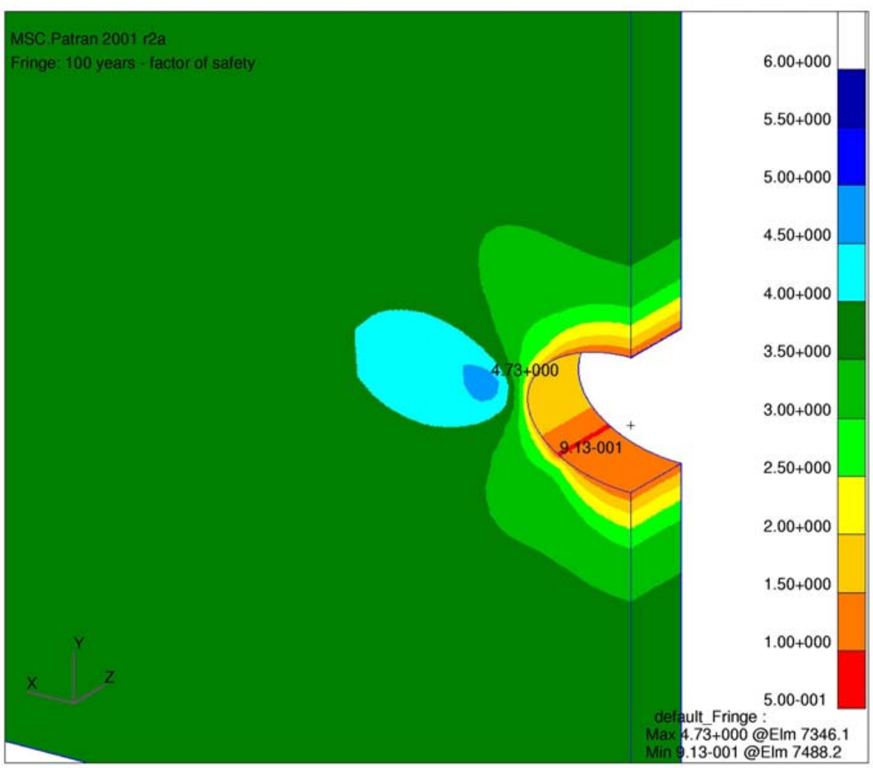


Figure 13d Emplacement Room Stability – preferred orientation/ 100 years

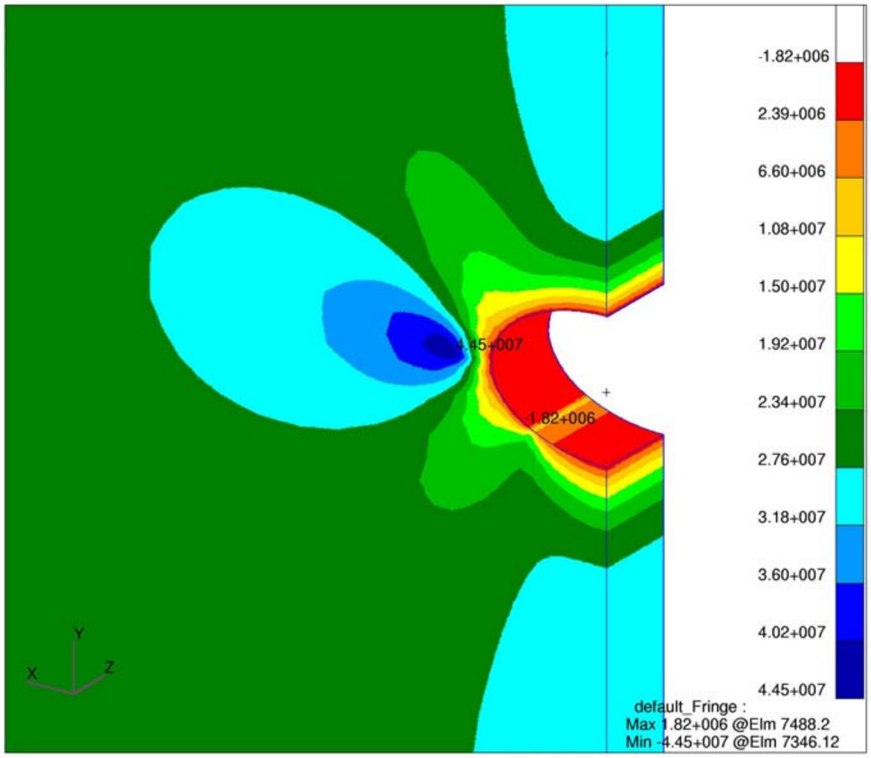


Figure 14a Maximum Tensile Principal Stress – 100 Years

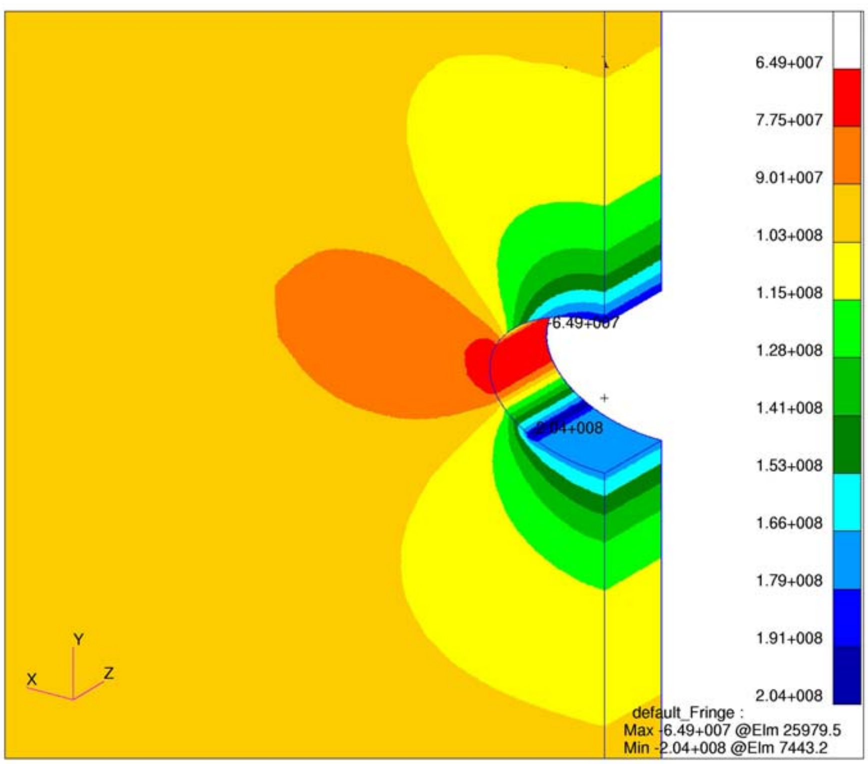


Figure 14b Maximum Compressive Principal Stress – 100 Years

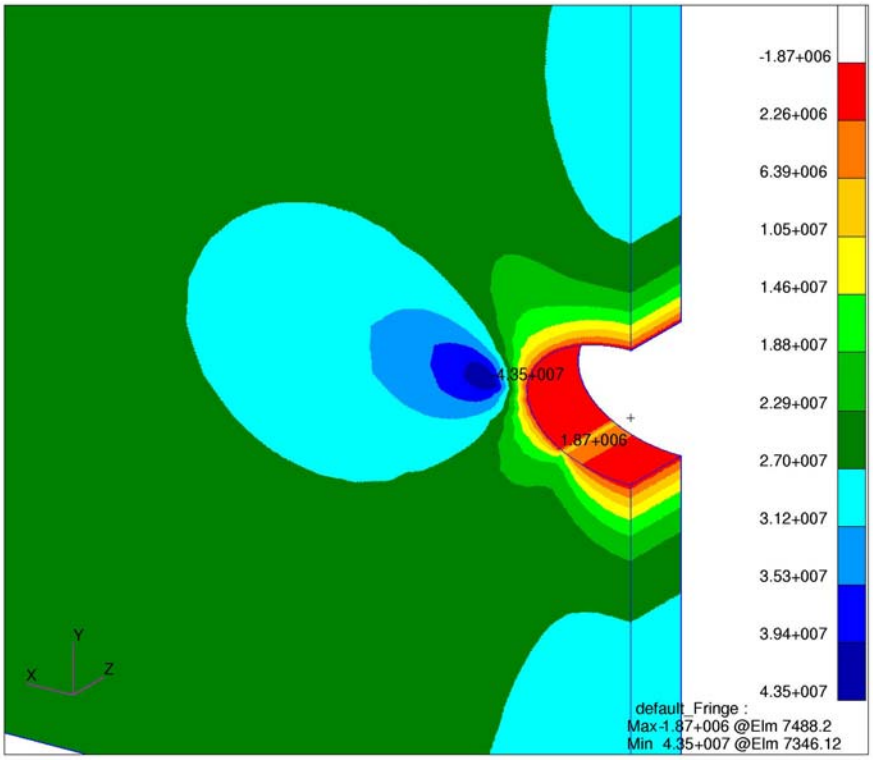


Figure 15a Maximum Principal Stress – 100 Years

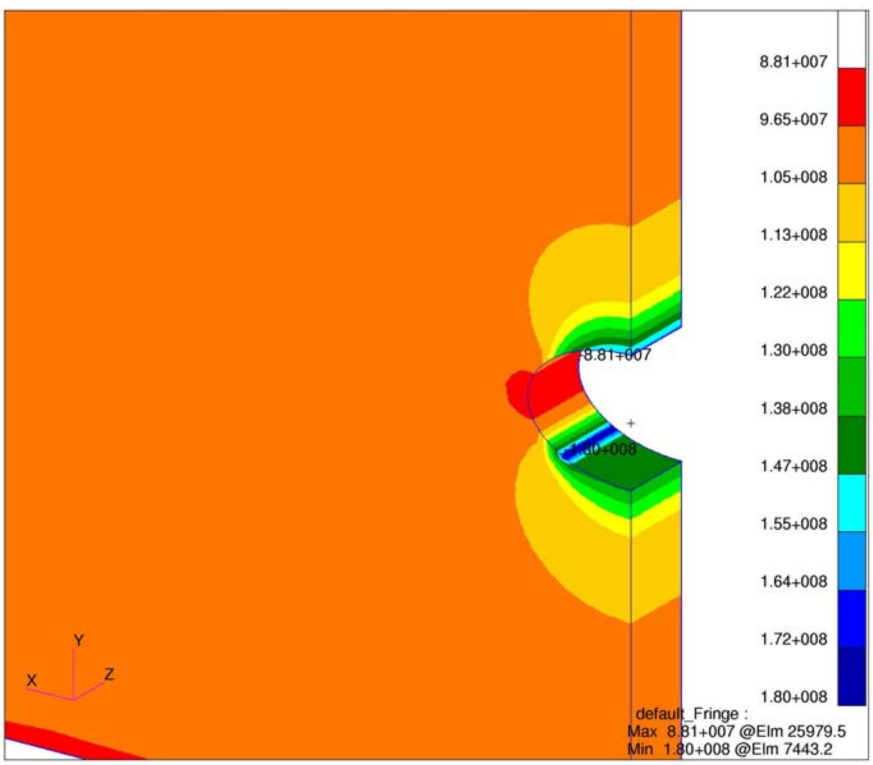


Figure 15b Minimum Principal Stress – 100 Years

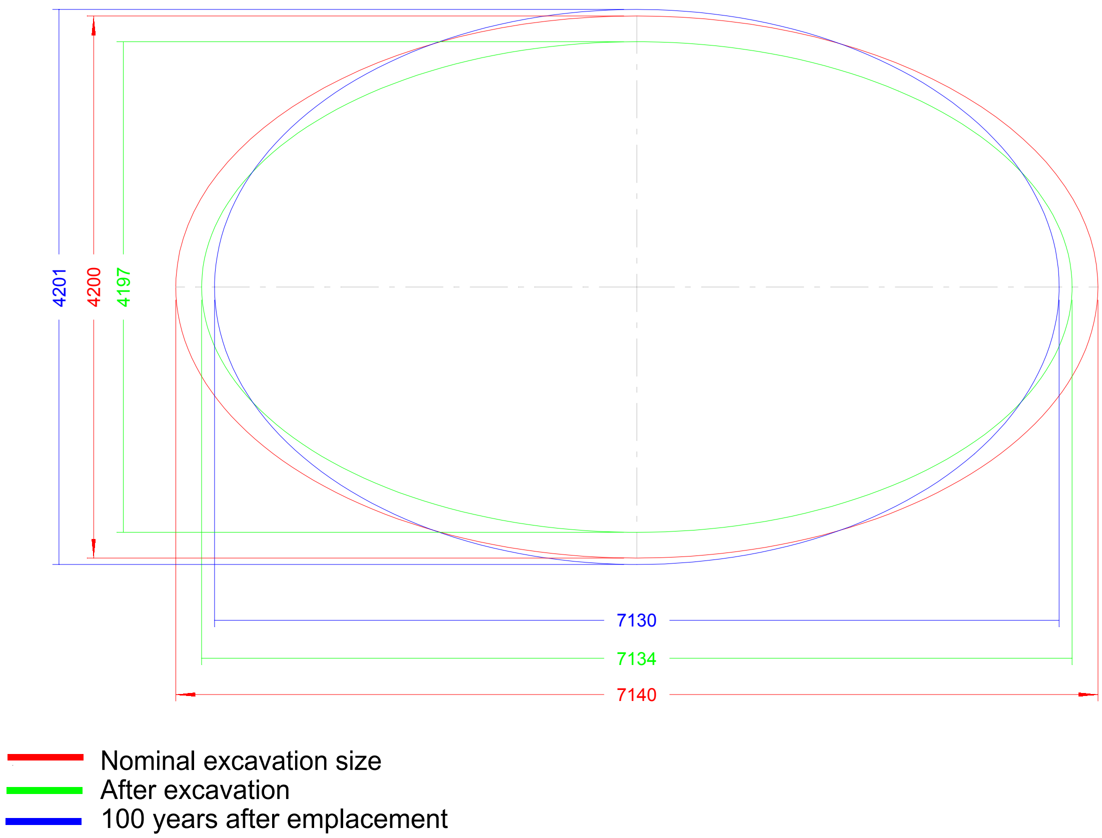


Figure 16 Emplacement Room Displacement

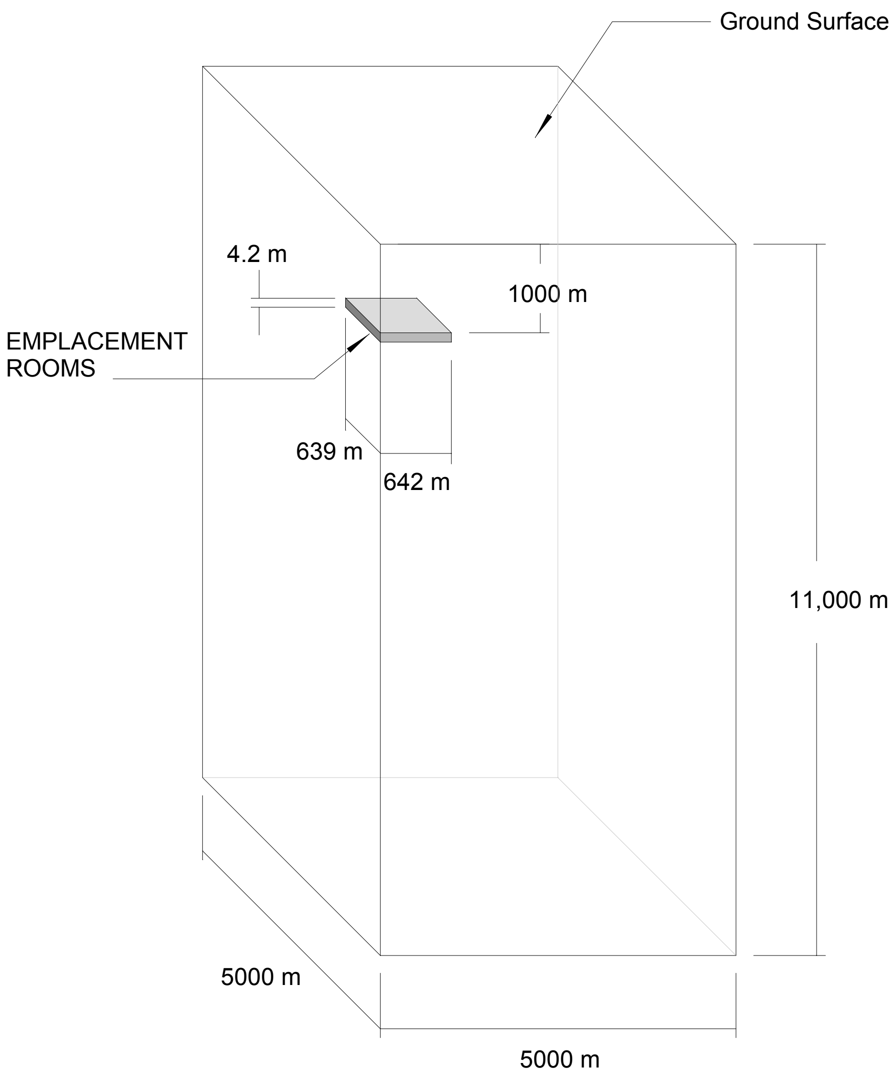


Figure 17. Perspective View of Far-Field Model

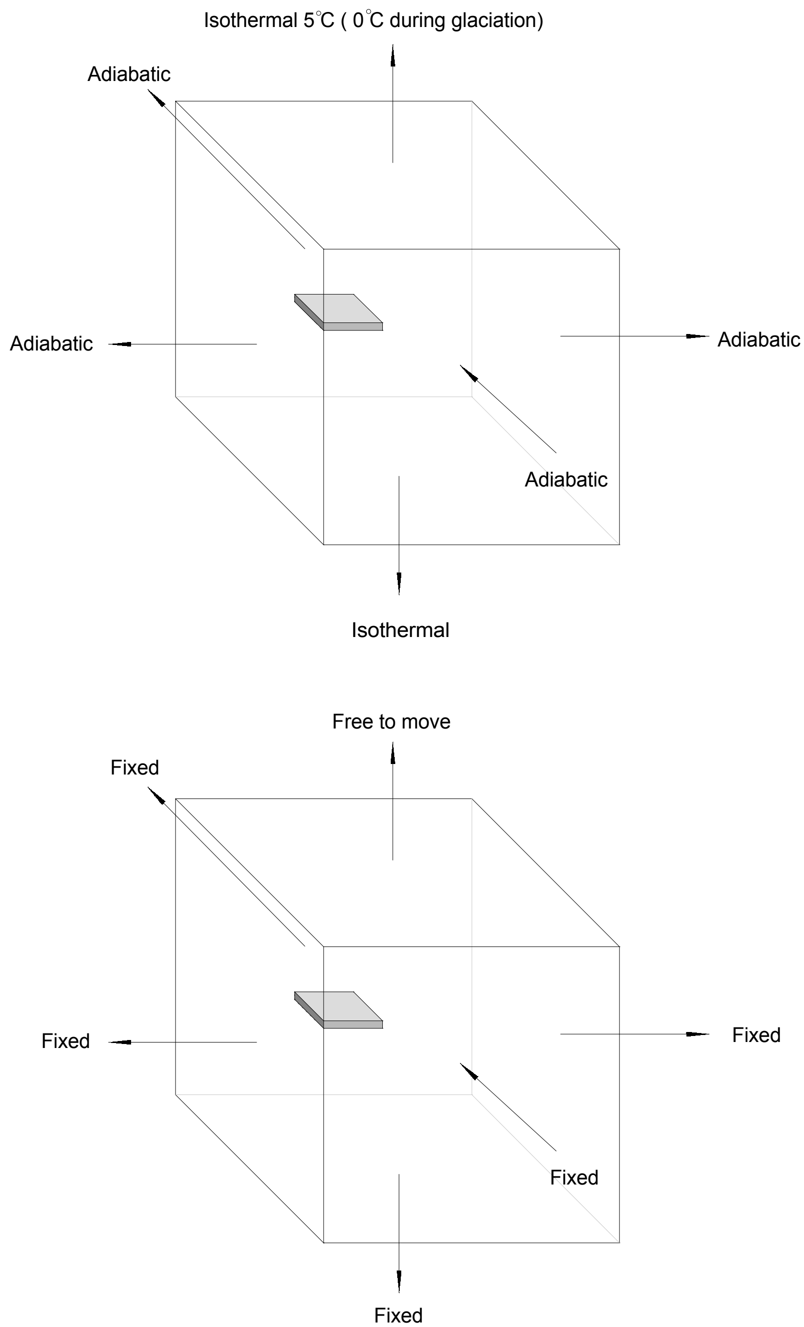


Figure 18. Thermal and Mechanical Boundary Conditions.

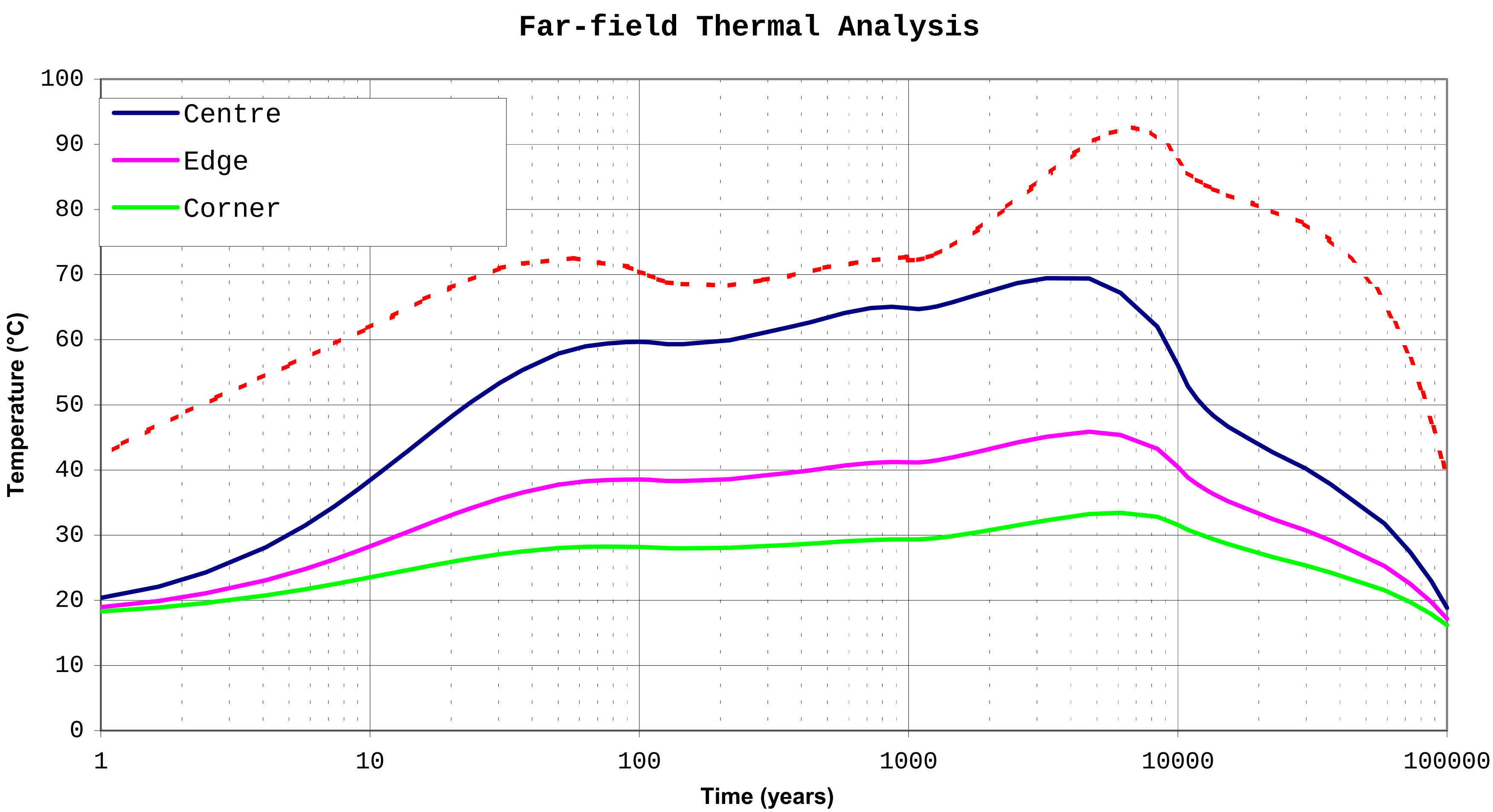


Figure 19 Temperature History.

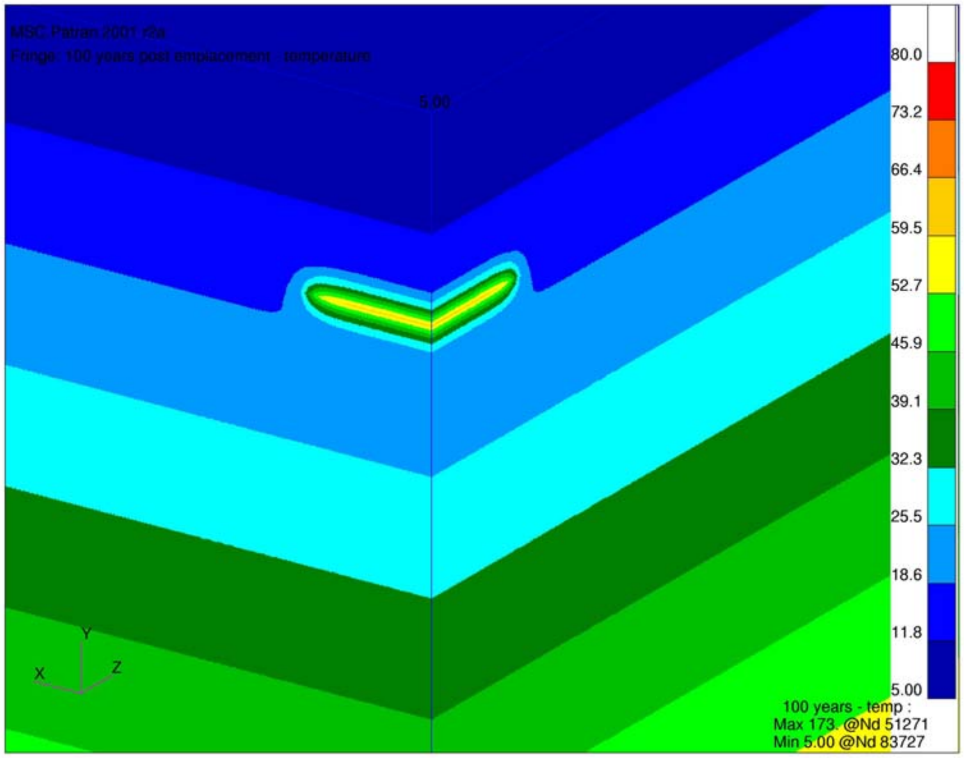


Figure 20a Temperature Profile – 100 Years.

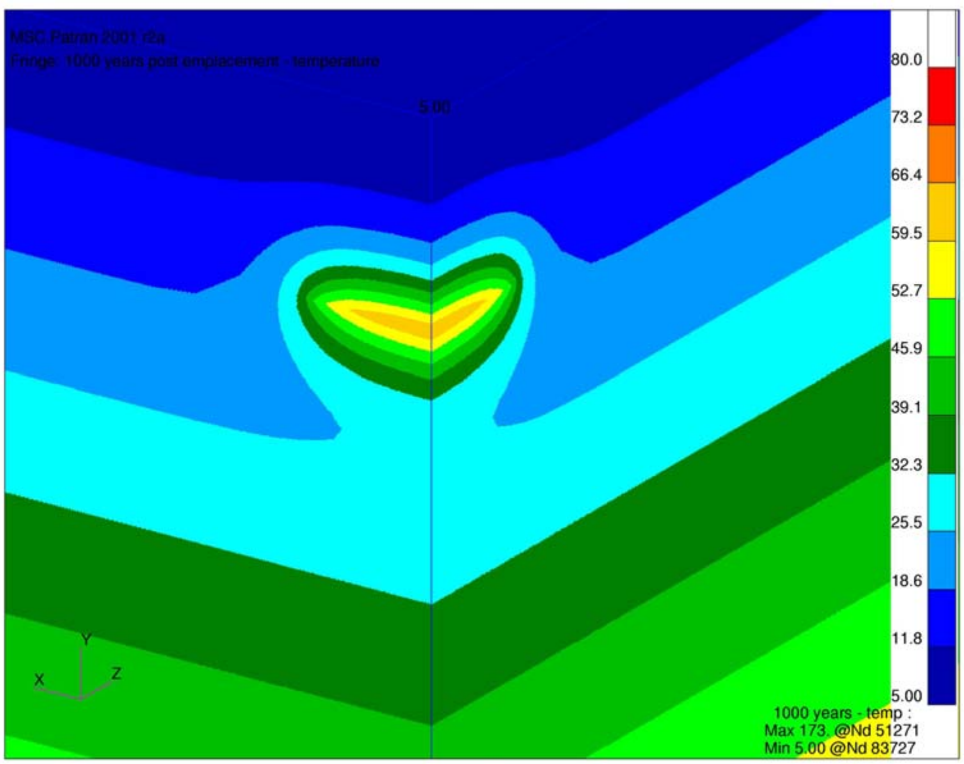


Figure 20b Temperature Profile – 1,000 Years.

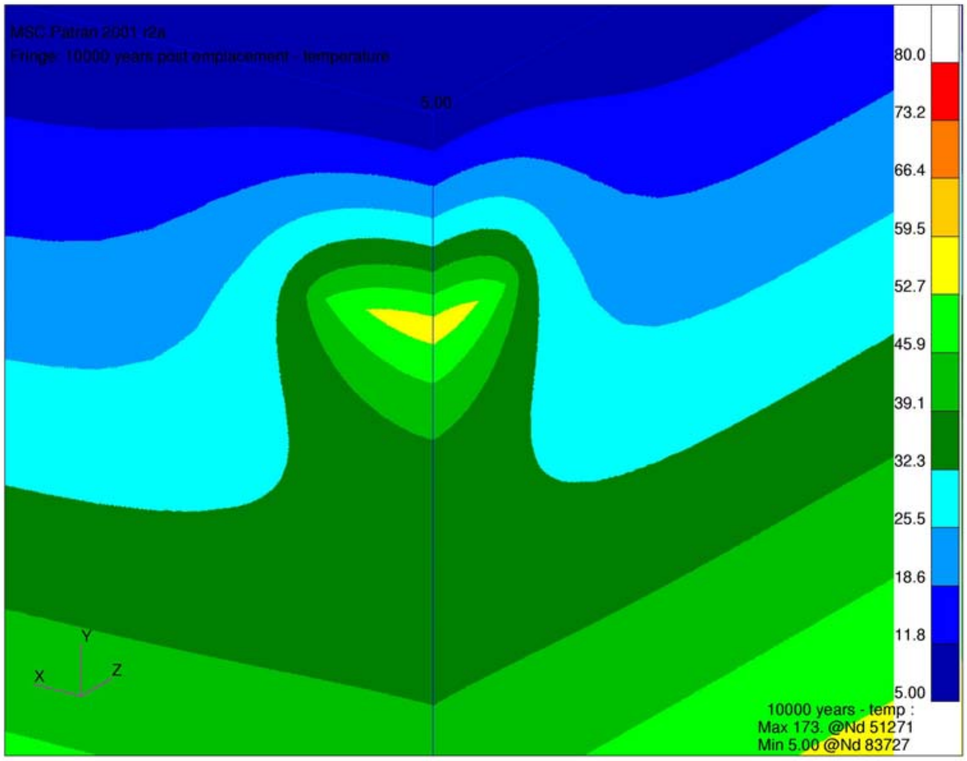


Figure 20c Temperature Profile – 10,000 Years.

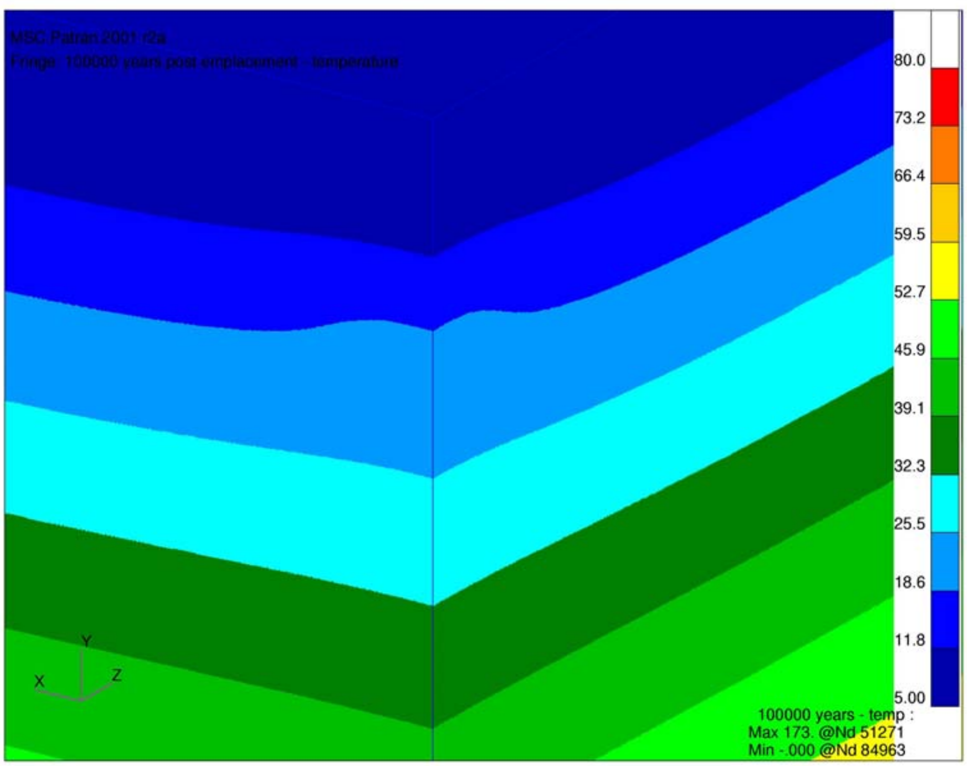


Figure 20d Temperature Profile – 100,000 Years.

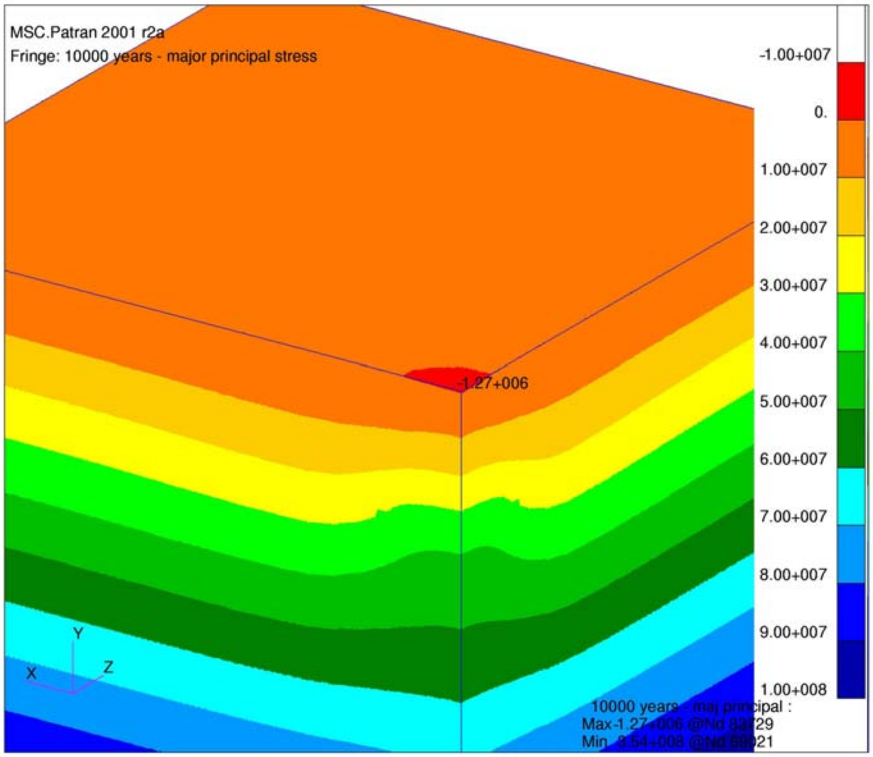
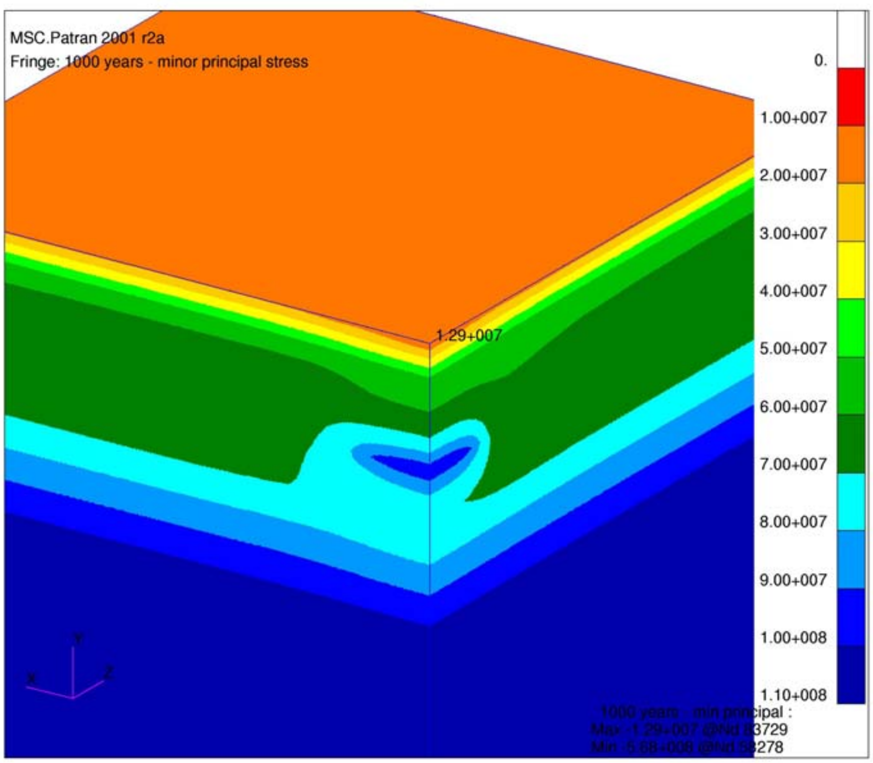


Figure 21 Maximum Tensile Principal Stress – 10,000 Years.



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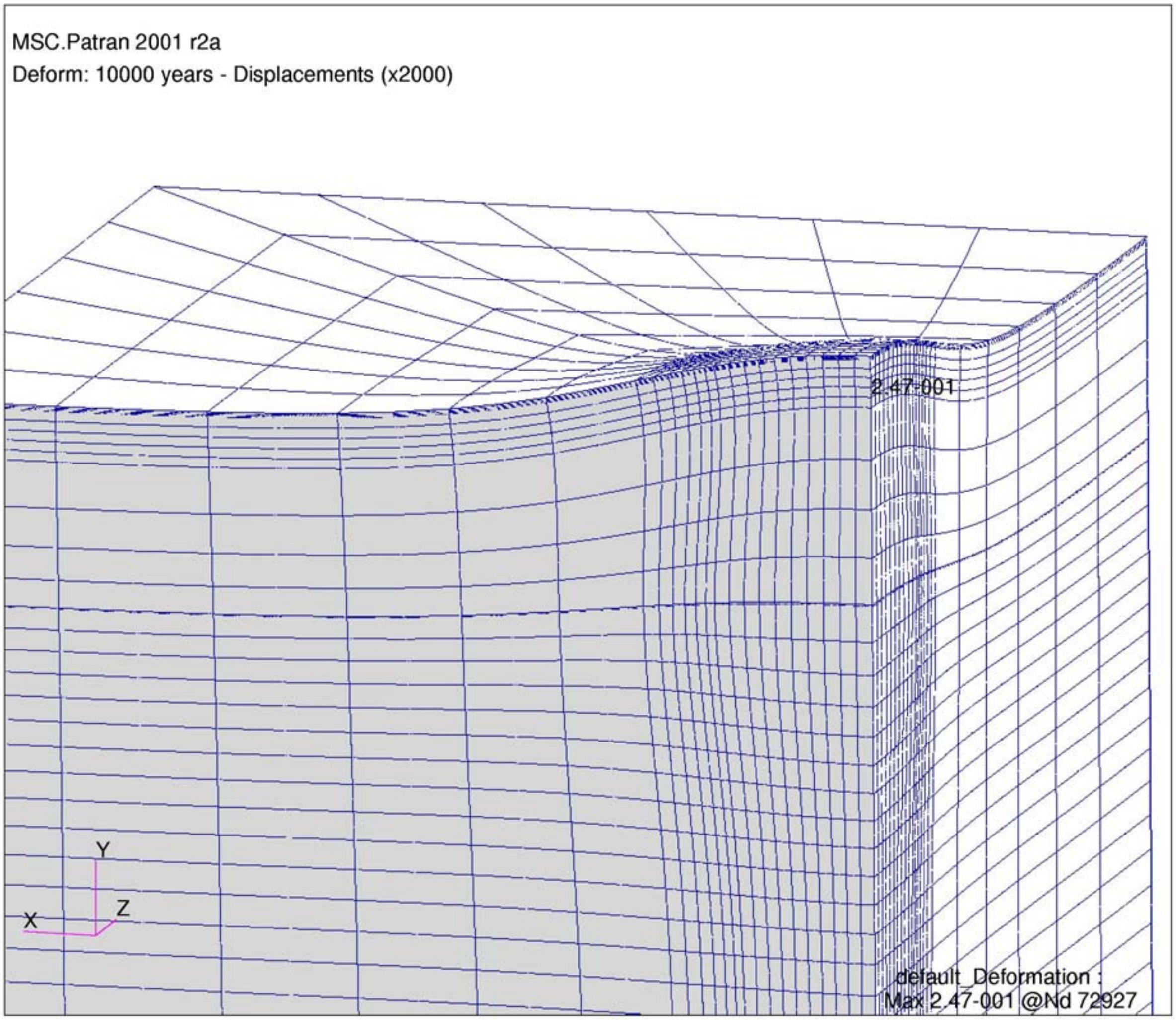


Figure 23 Ground Deformation (x2000) – 10,000 Years.

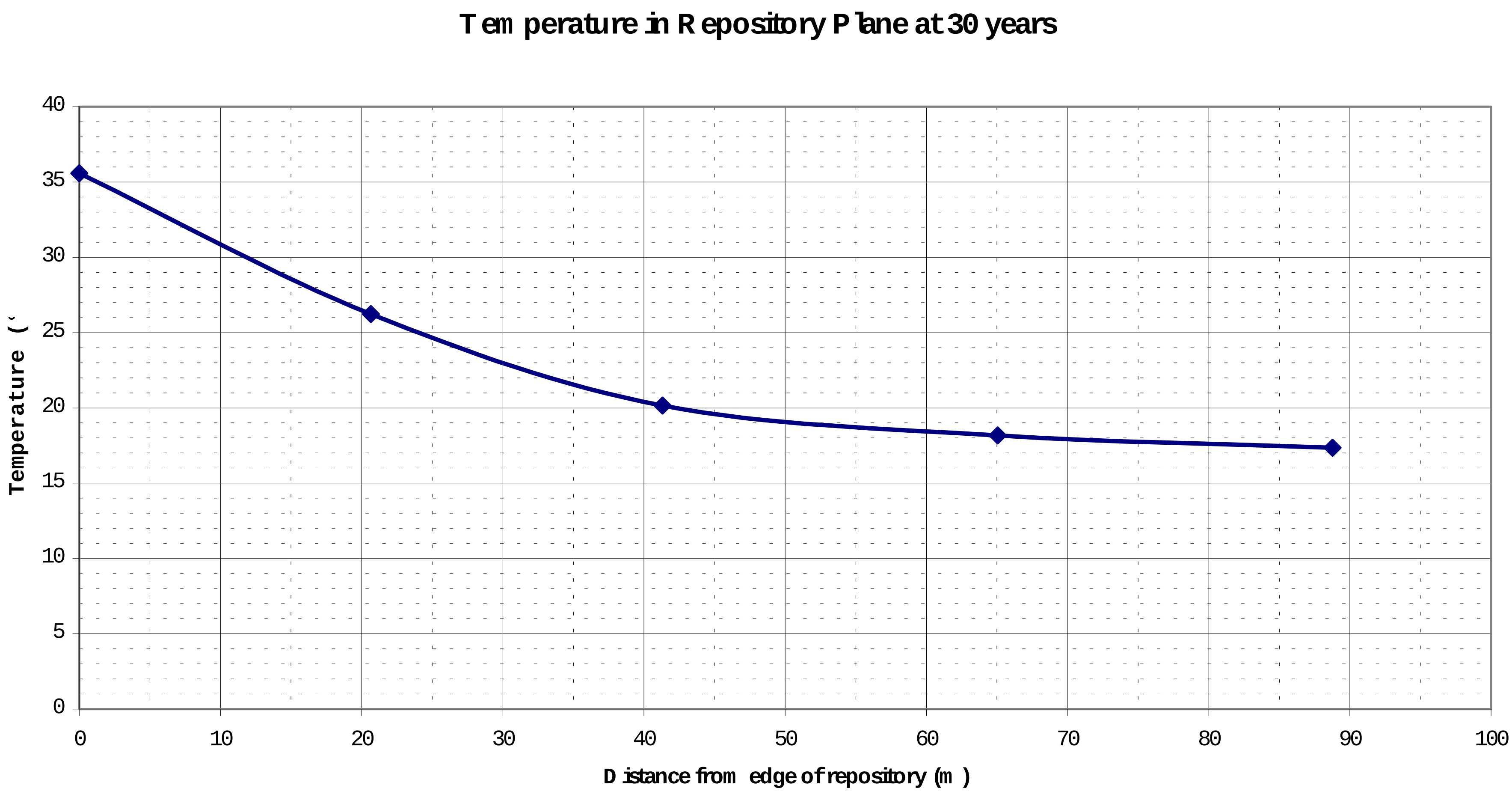
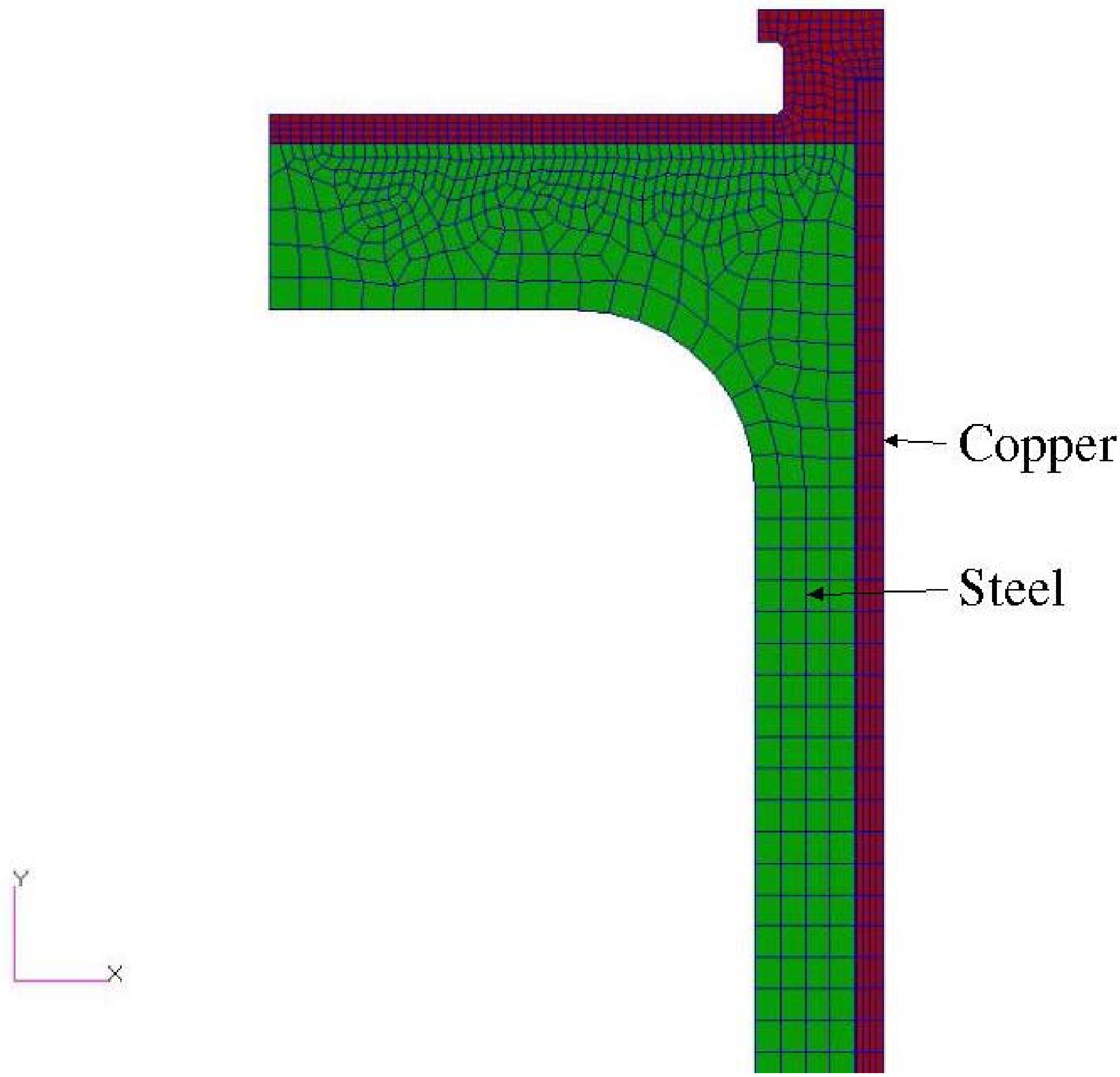


Figure 24 Temperature Profile at Edge of Repository.



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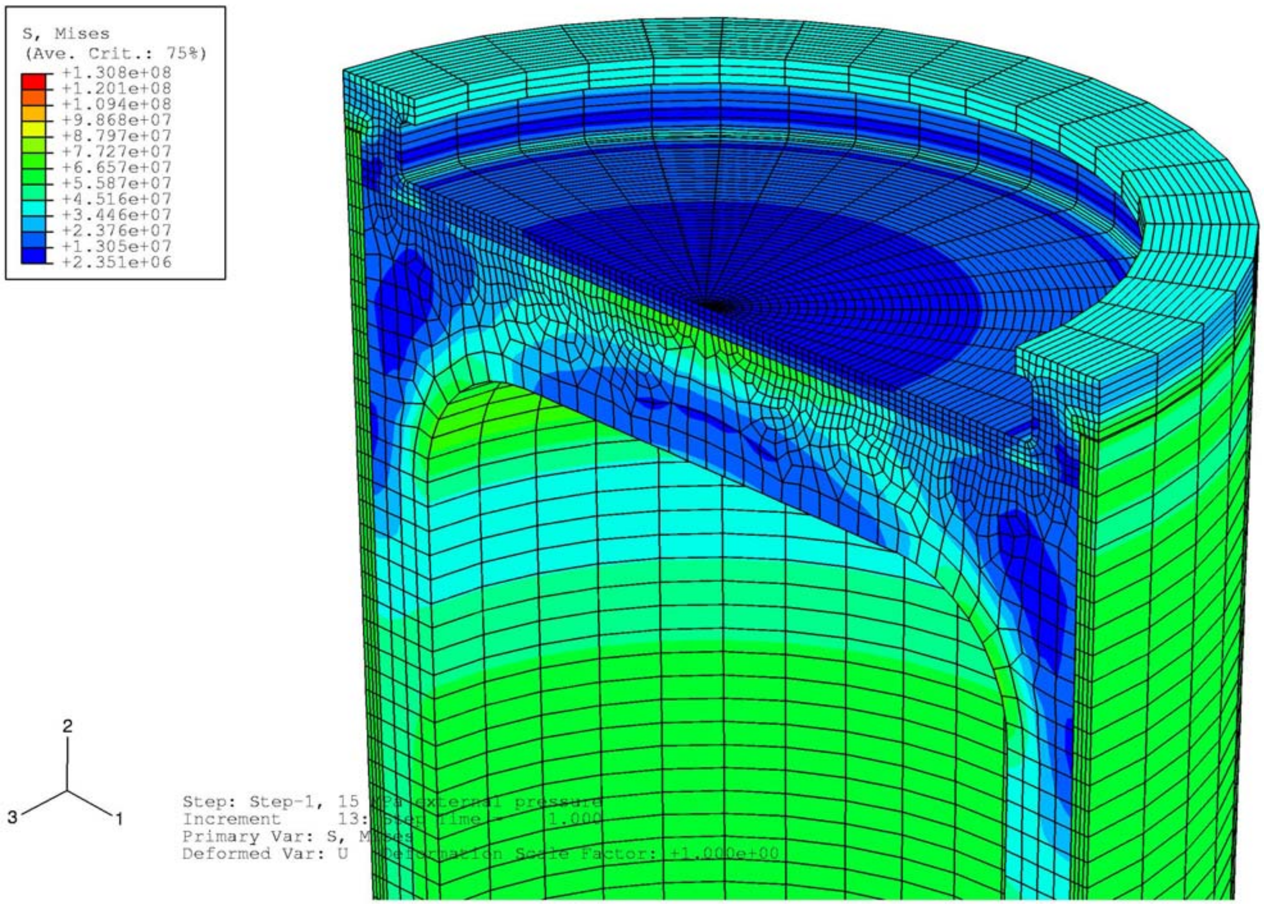


Figure 26a 15 MPa Pressure Loading (Von Mises stress).

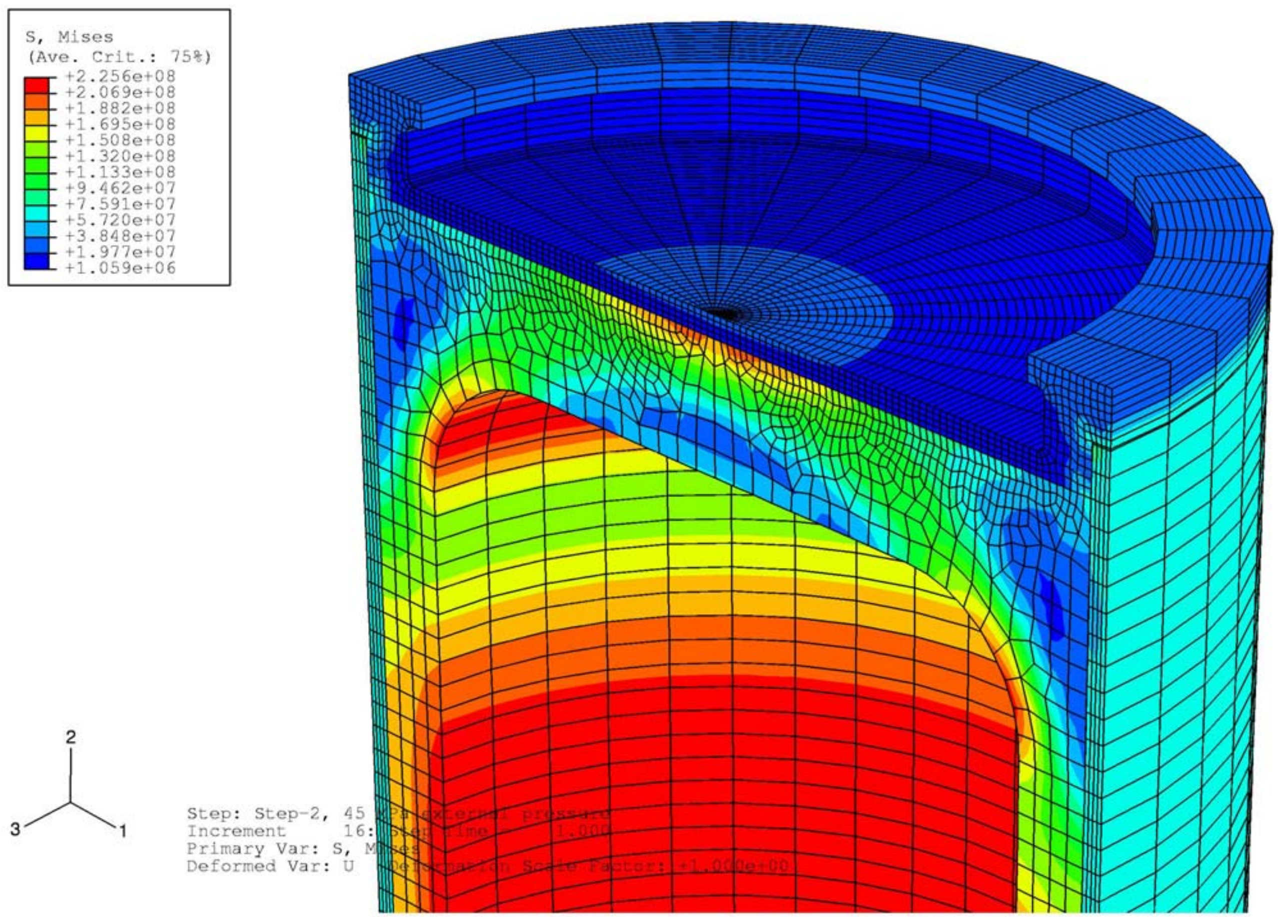


Figure 26b 45 MPa Pressure Loading (Von Mises stress).

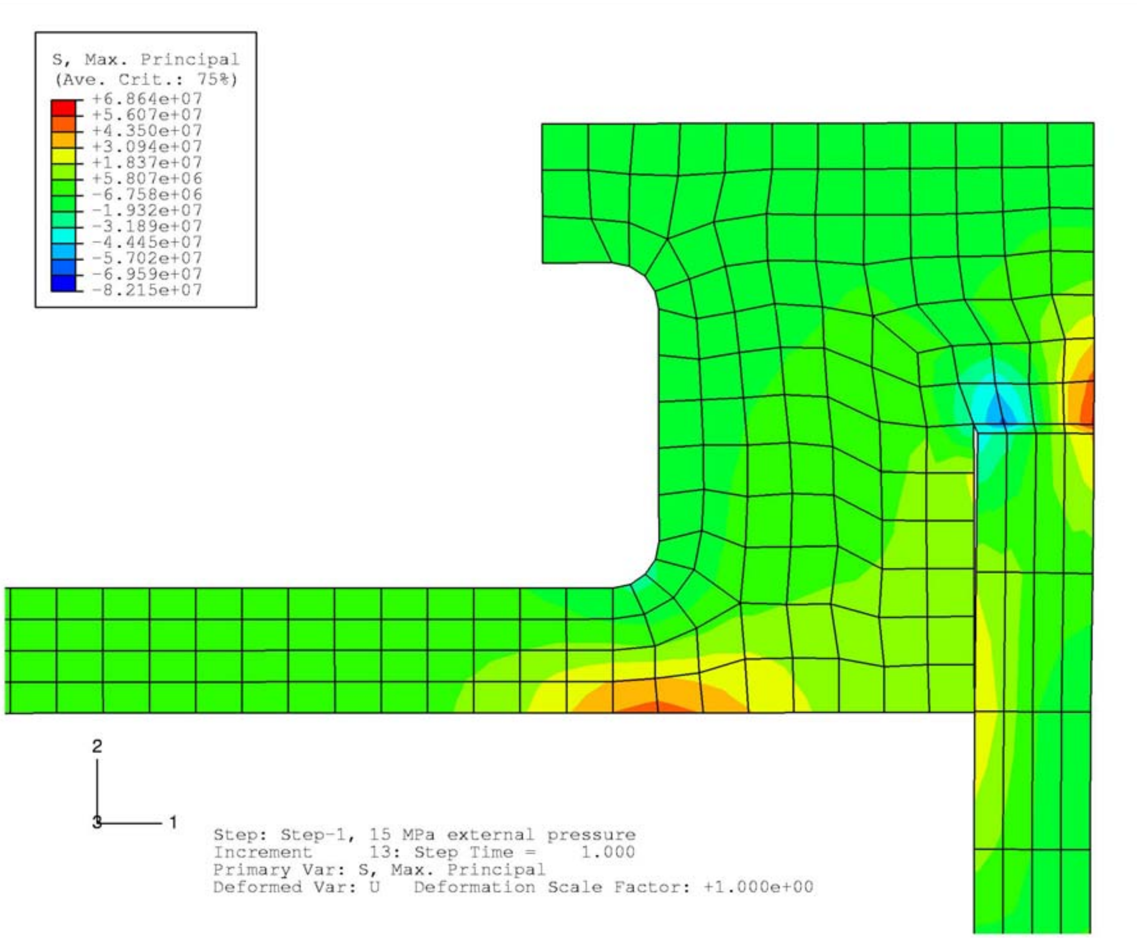


Figure 27a Copper Container Maximum Principal Stress (15 MPa).

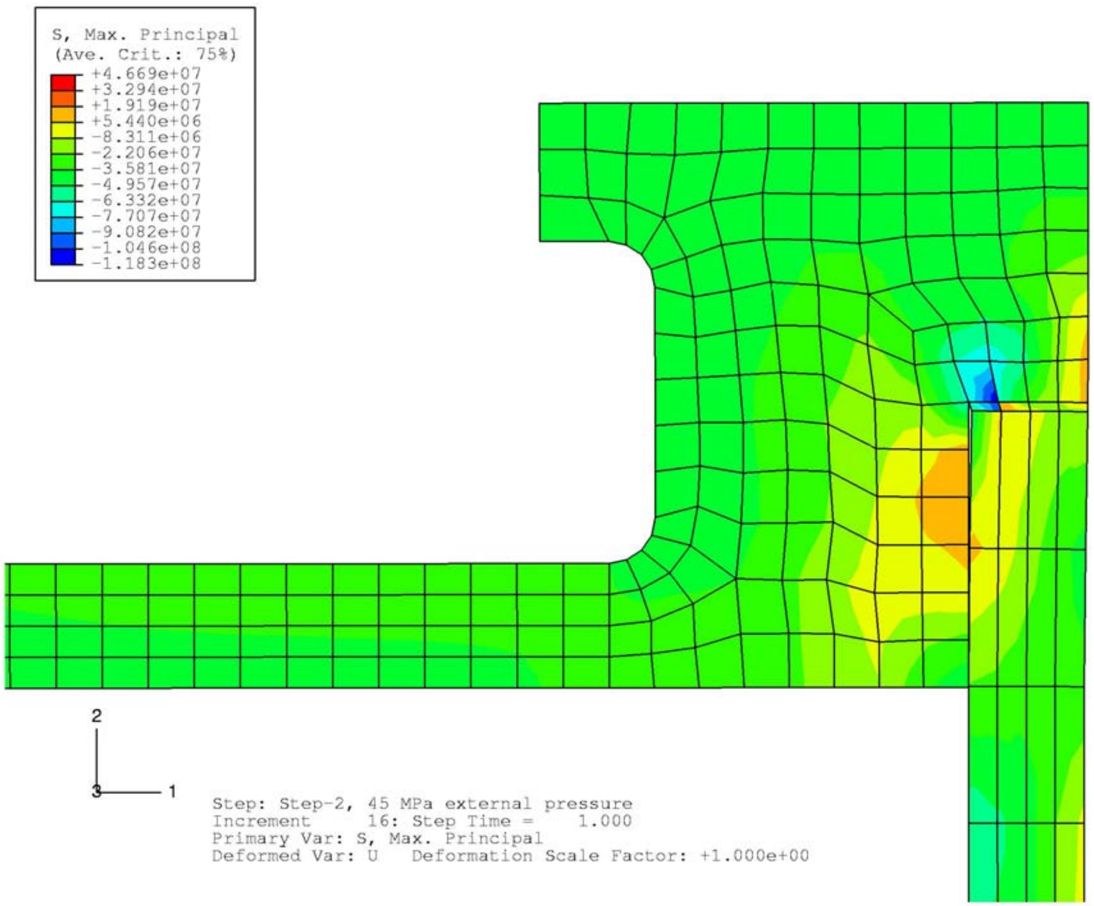


Figure 27b Copper Container Maximum Principal Stress (45 MPa).

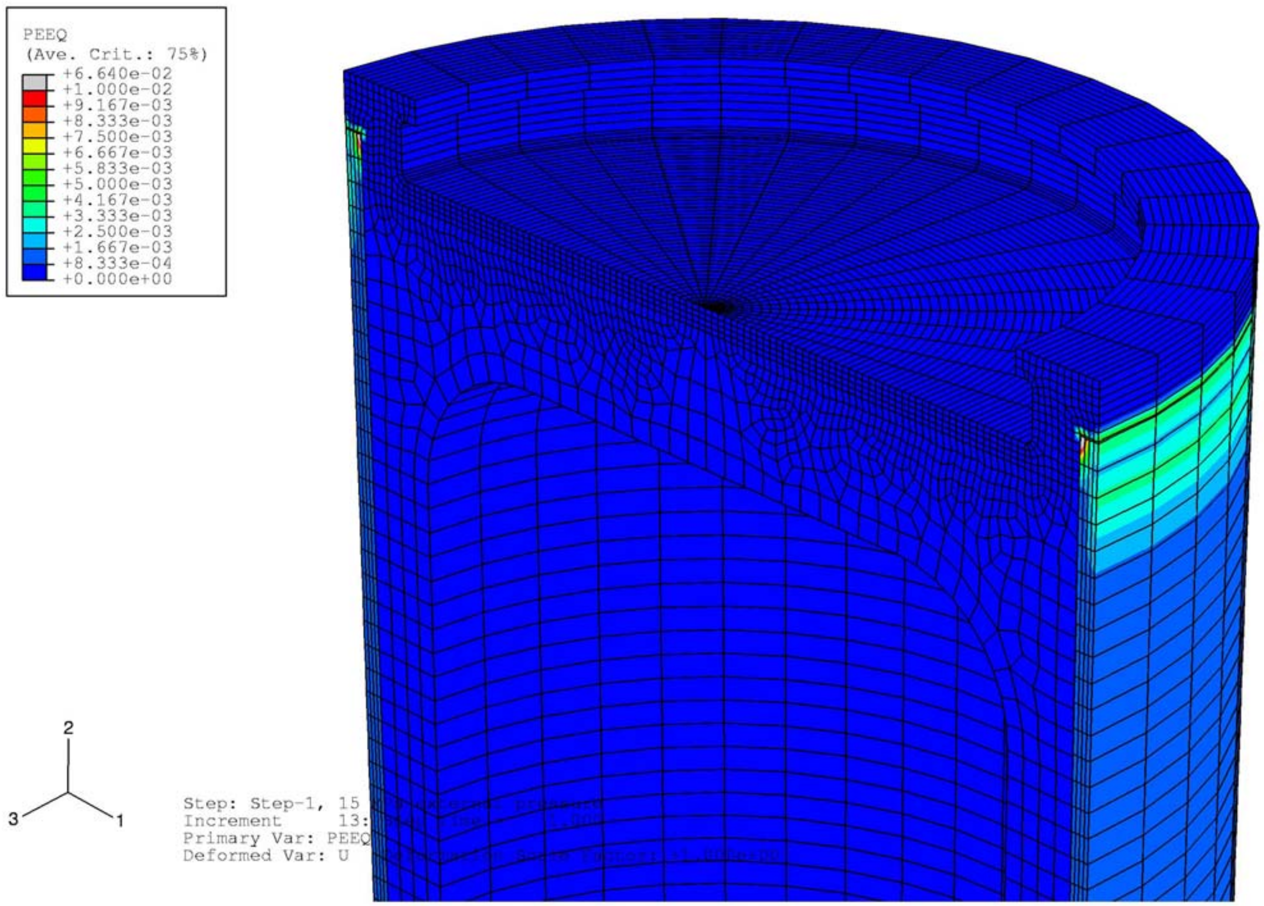


Figure 28a 15 MPa Pressure Loading (strain).

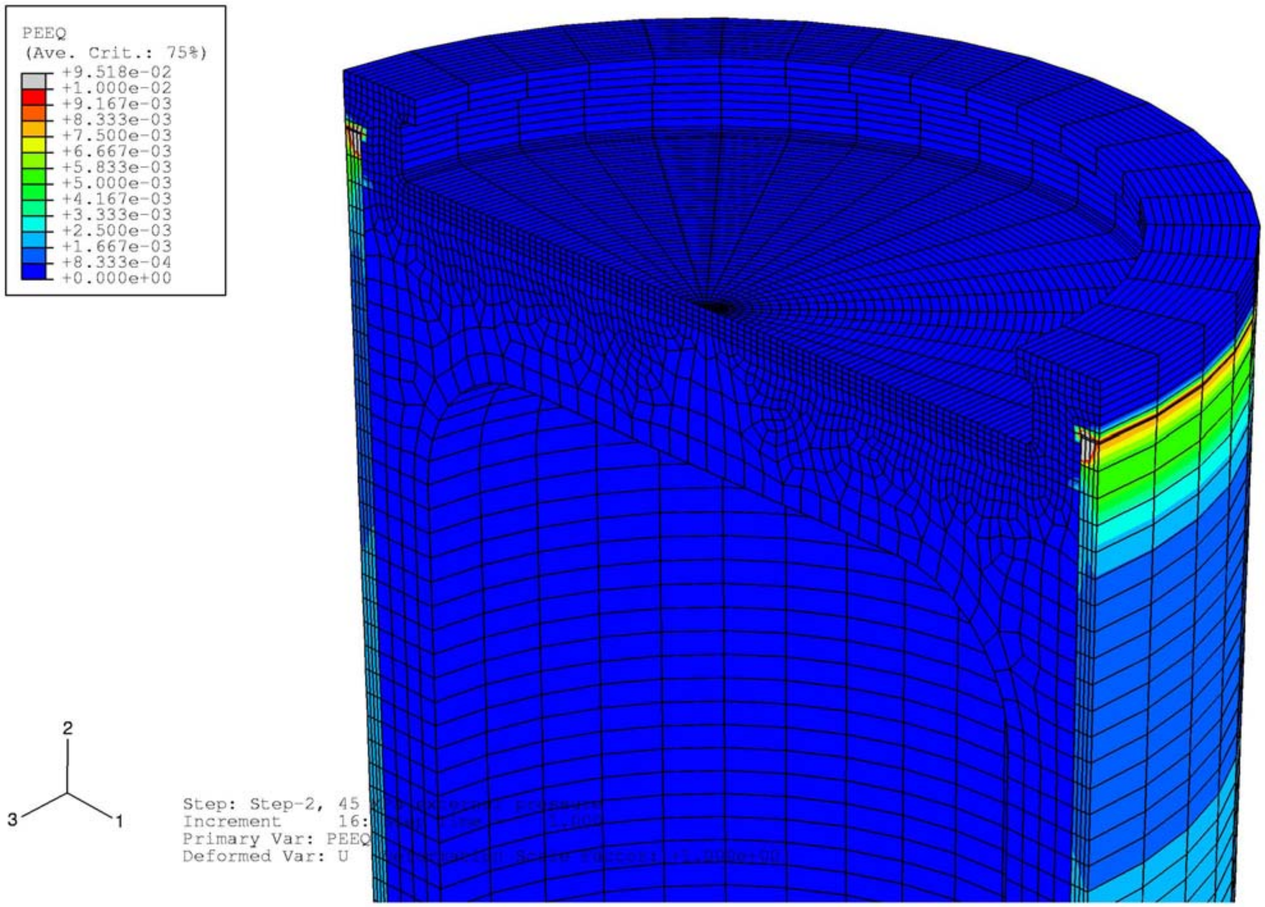


Figure 28b 45 MPa Pressure Loading (strain).

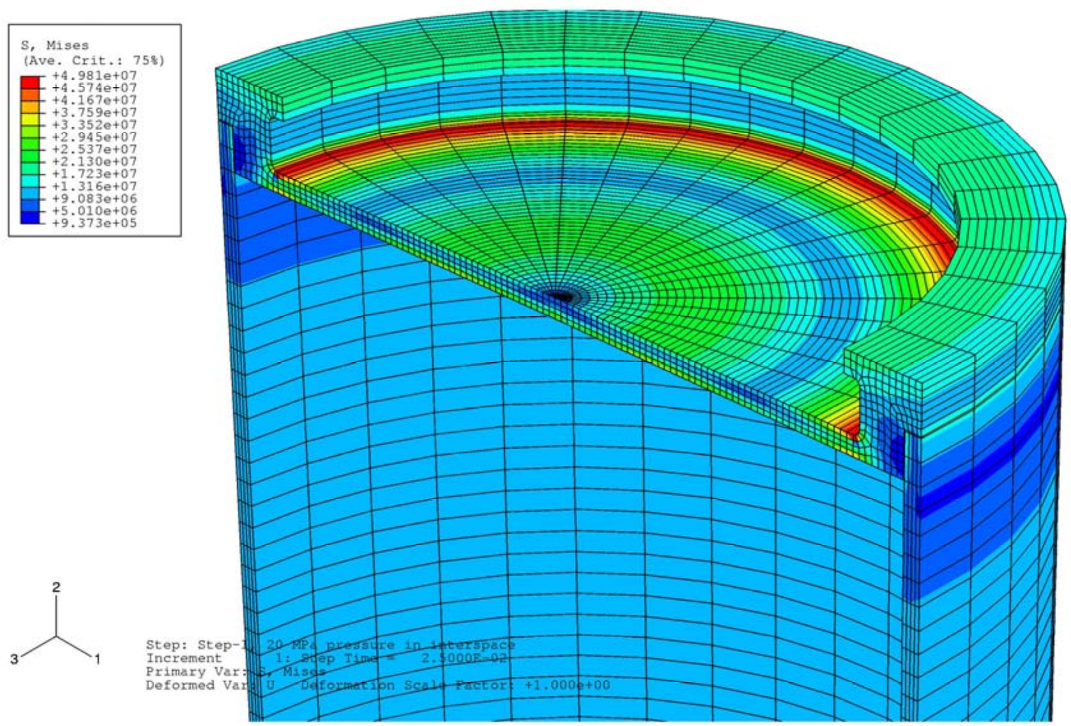


Figure 29. Internal Pressure Case (von Mises stress).

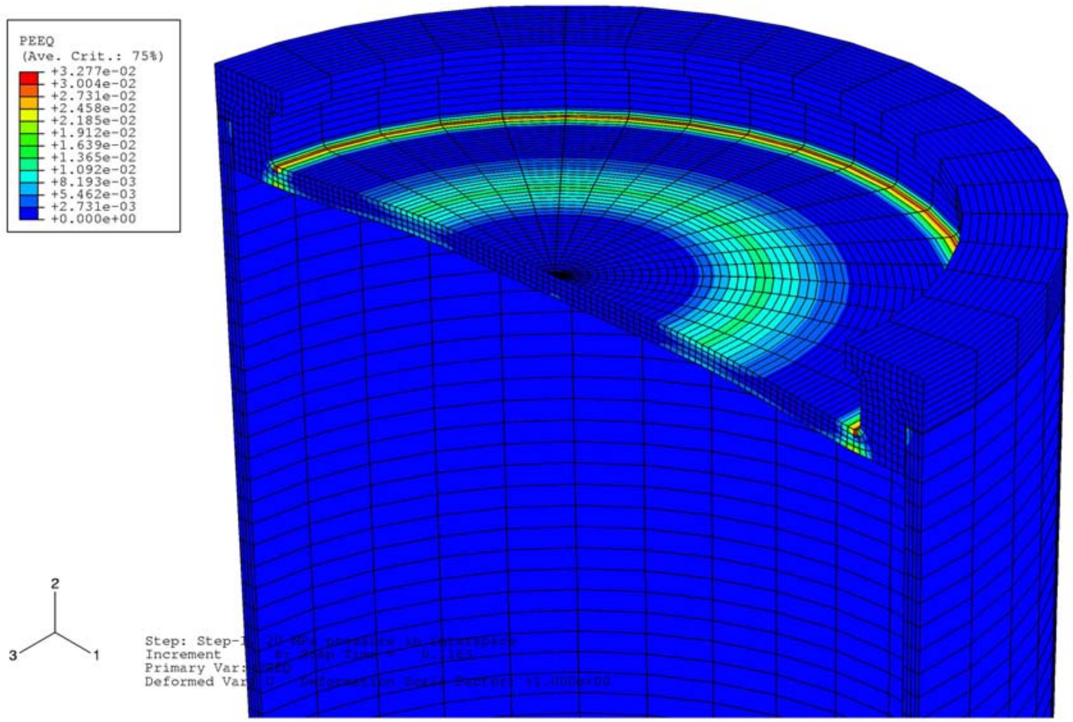
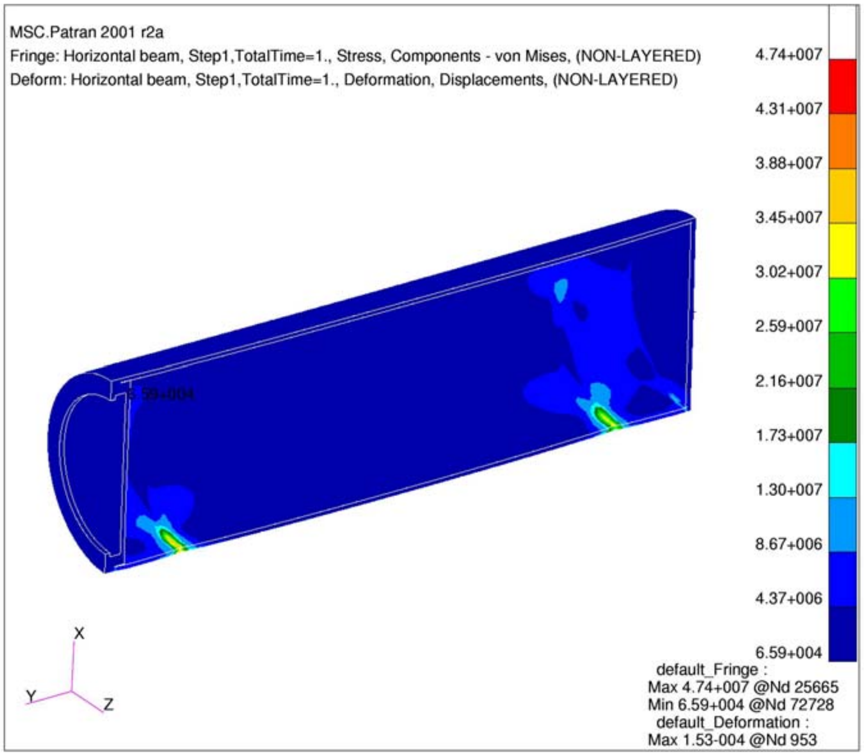


Figure 30. Internal Pressure Case (strain).



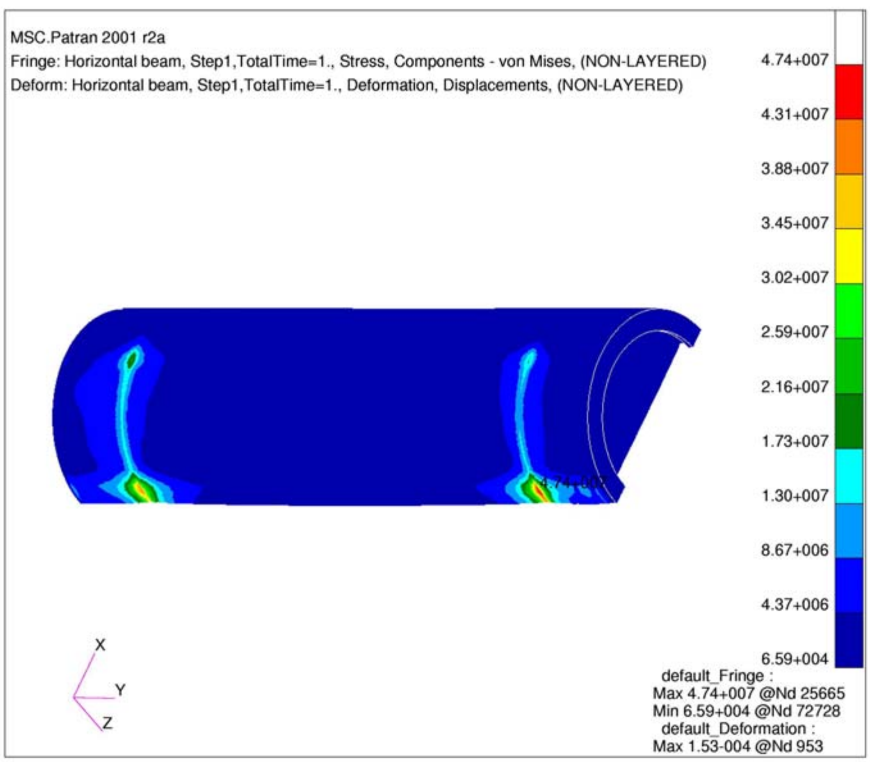


Figure 31. UFC Two-point Lifting Case – von Mises Stress (Copper)

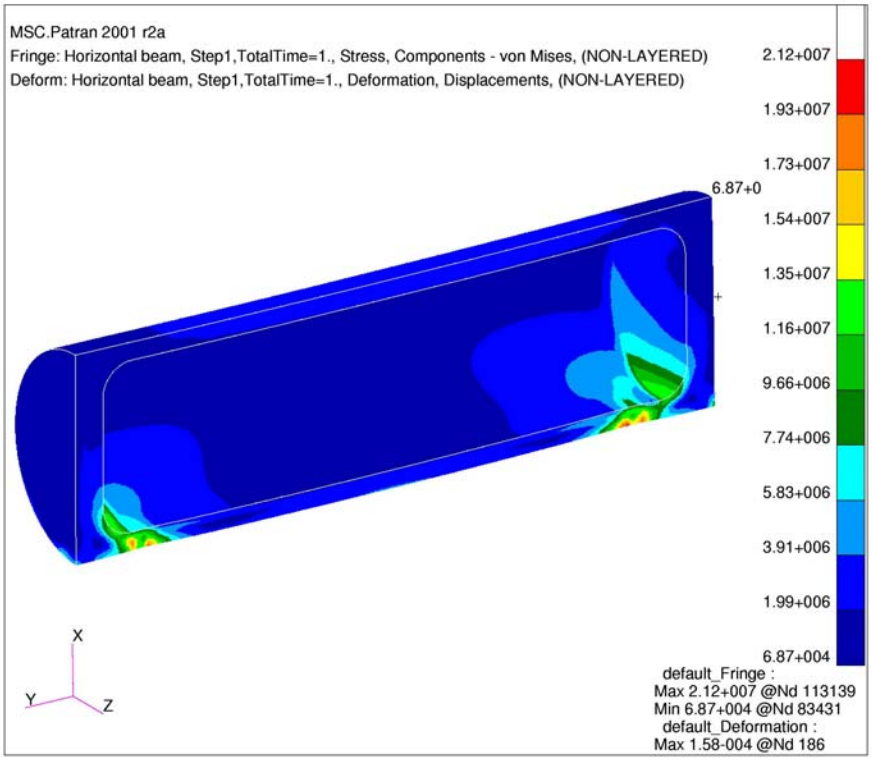


Figure 32. UFC Two-point Lifting Case – von Mises Stress (Steel)

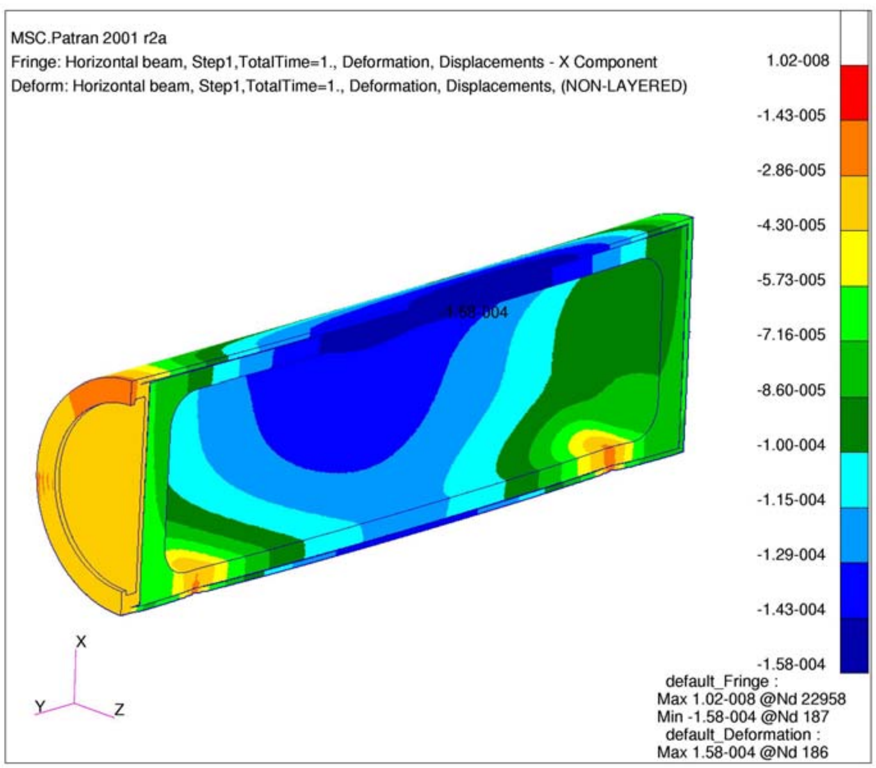
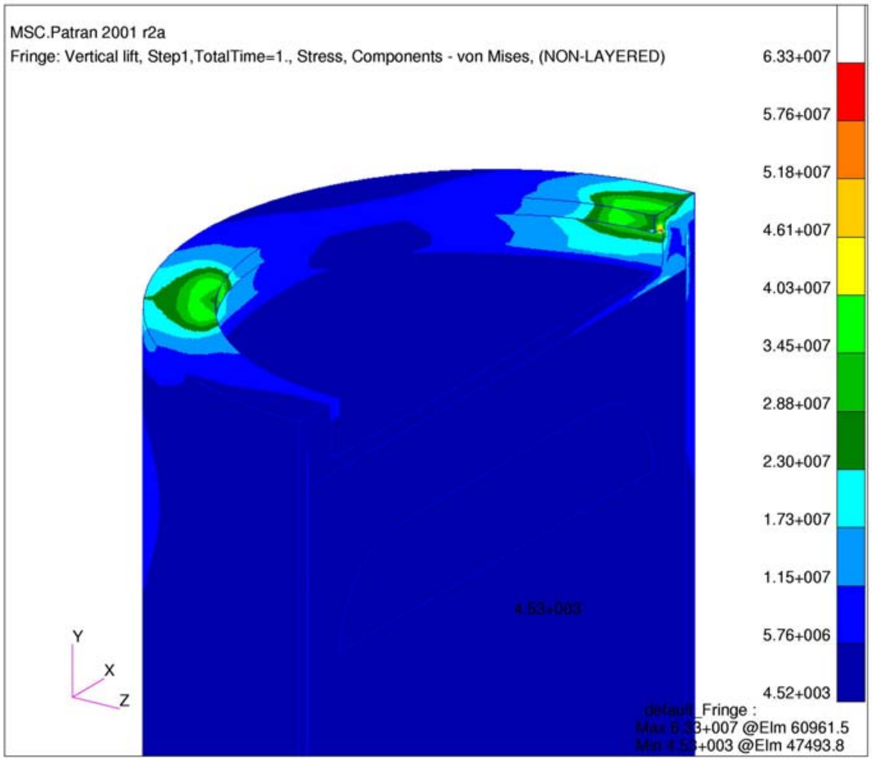


Figure 33. UFC Two-point Lifting Case – Deformation



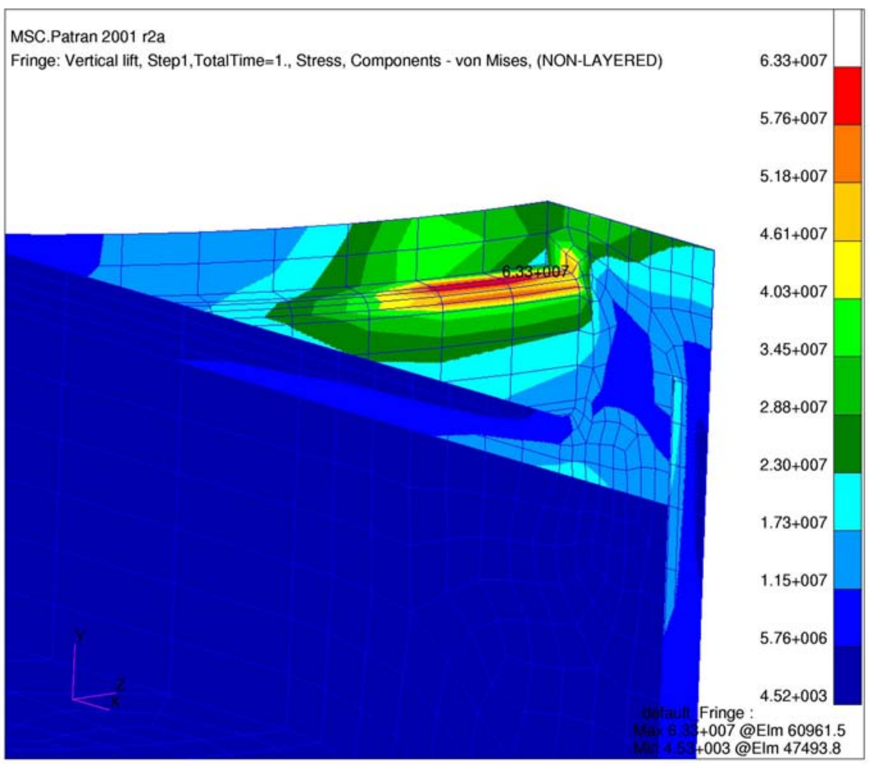


Figure 34. UFC Lifting Case – von Mises Stress

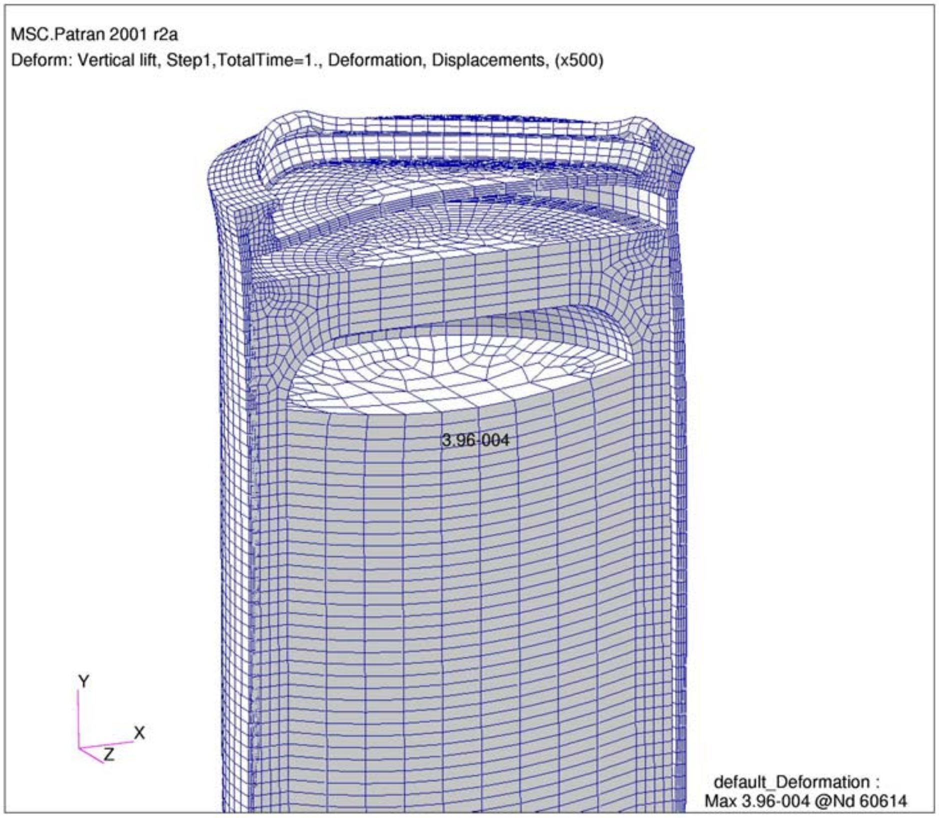


Figure 35. UFC Lifting Case – Deformation

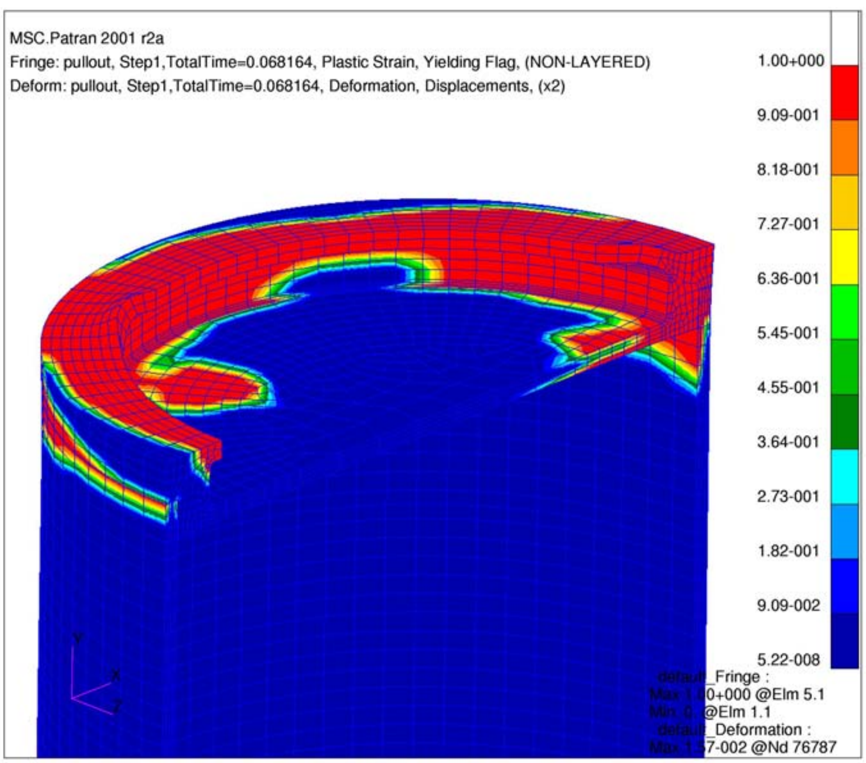


Figure 36. UFC Maximum Load Lifting Case – Yield

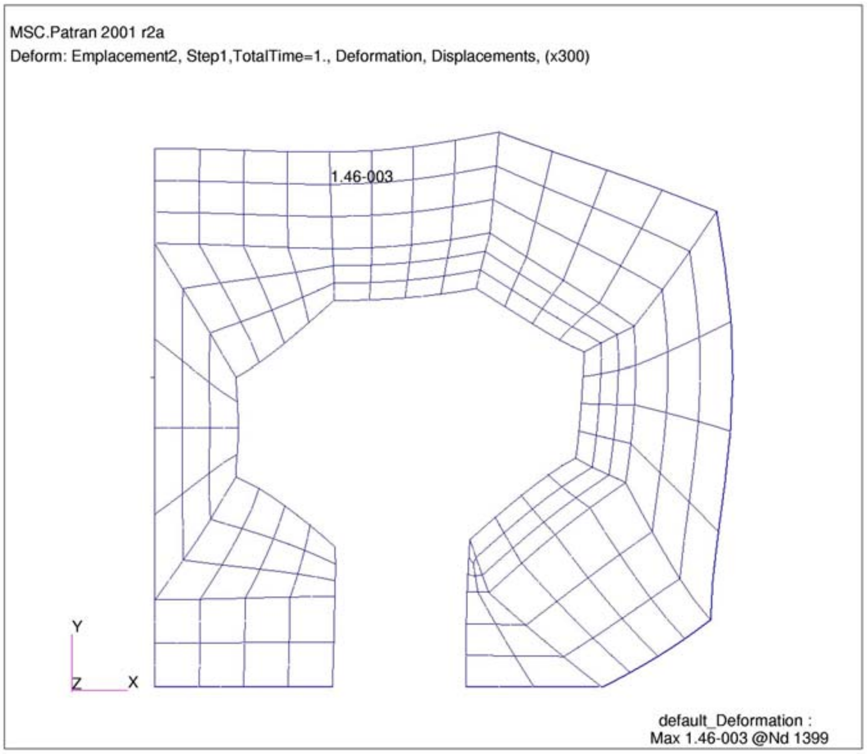


Figure 37. Emplacement Room Deformation – Prior to UFC placement

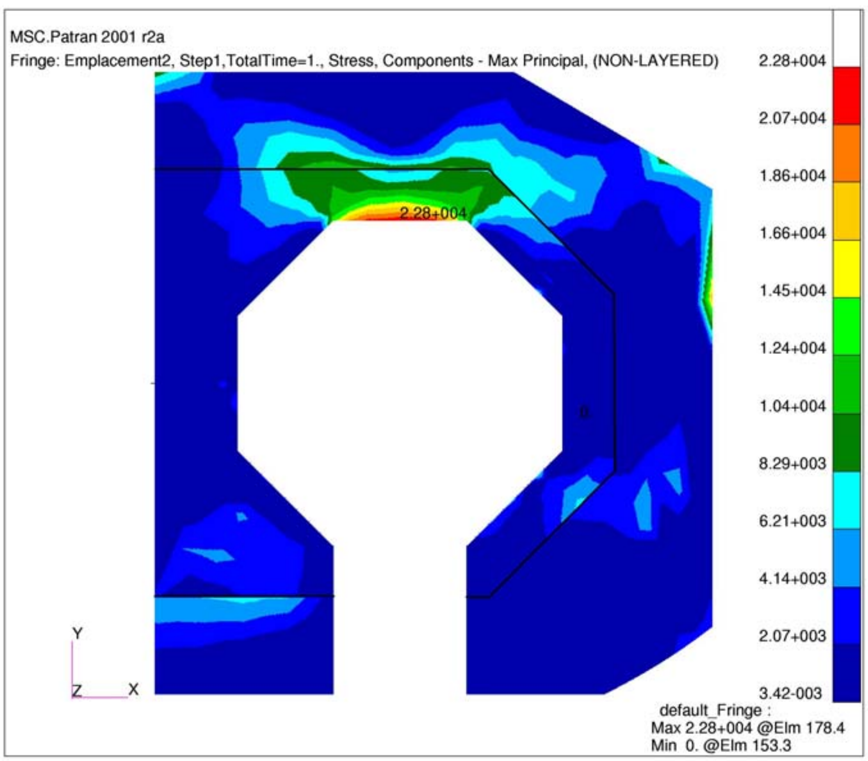


Figure 38. Emplacement Room prior to UFC placement (Maximum principal stress)

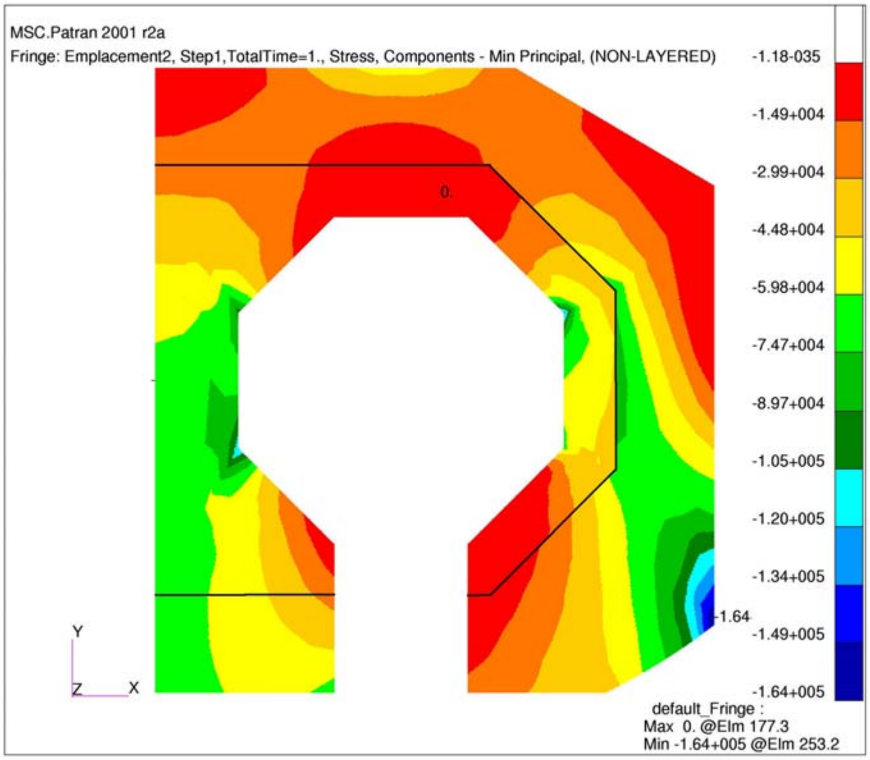


Figure 39. Emplacement Room prior to UFC placement (Minimum principal stress)

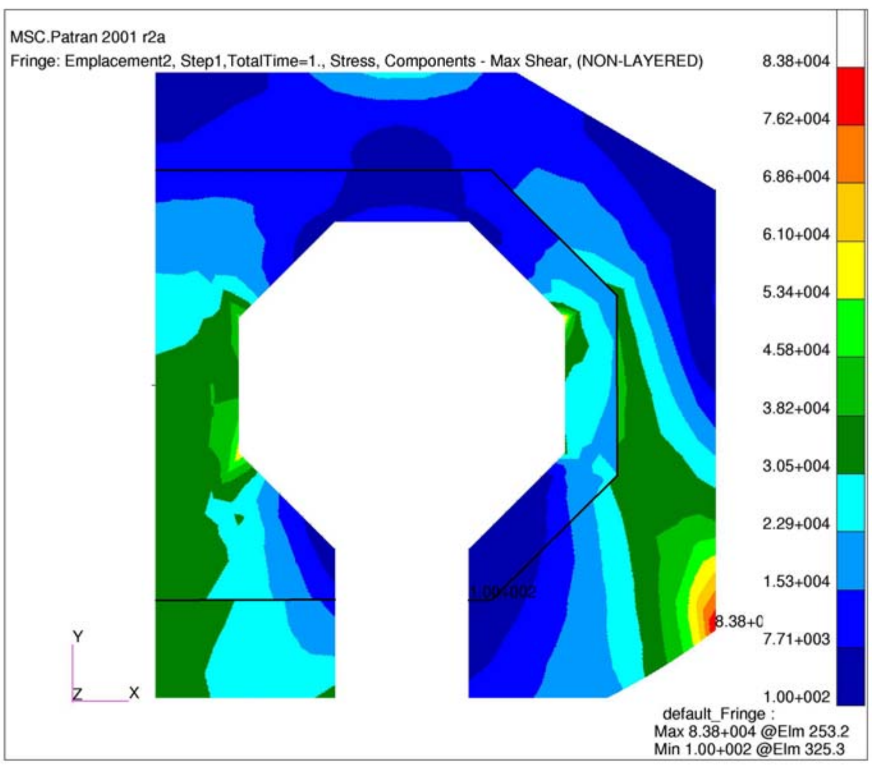


Figure 40. Emplacement Room prior to UFC placement (Maximum shear stress)

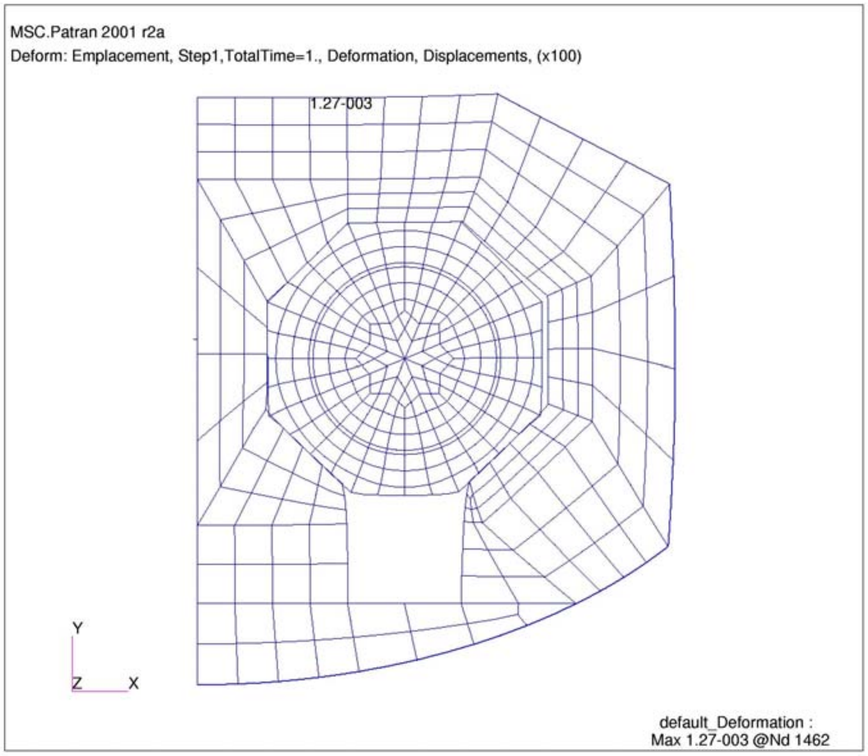


Figure 41. Emplacement Room Deformation after UFC placement

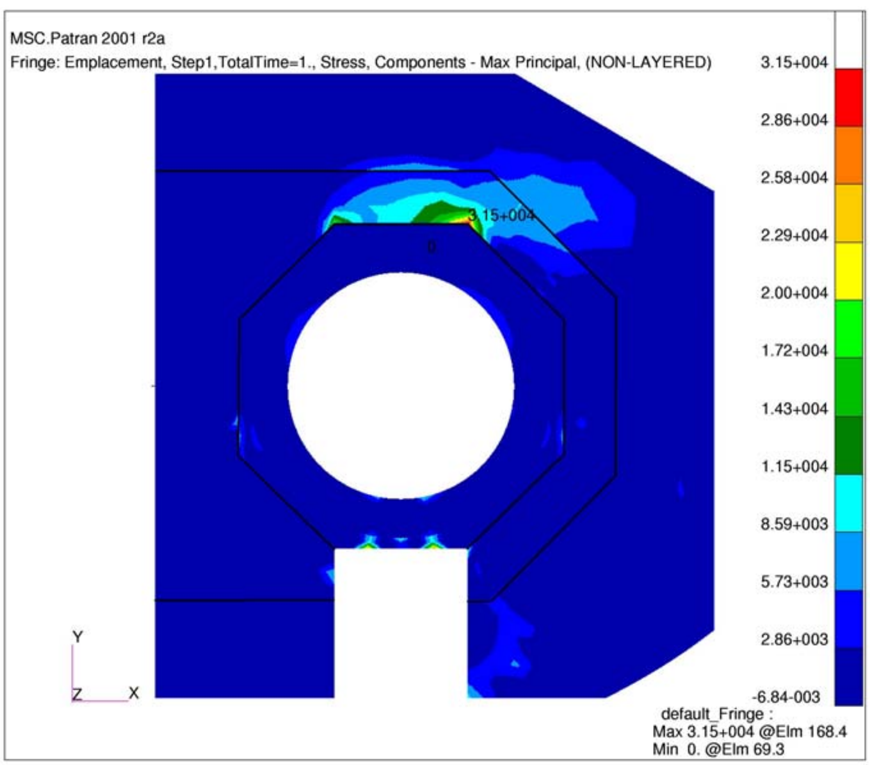


Figure 42. Emplacement Room after UFC placement (Maximum principal stress)

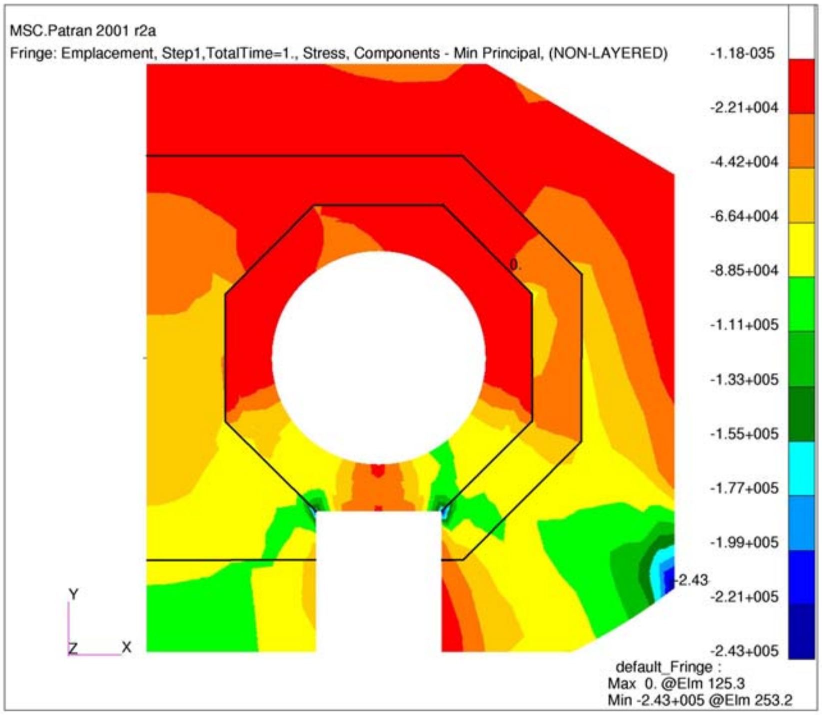


Figure 43. Emplacement Room after UFC placement (Minimum principal stress)

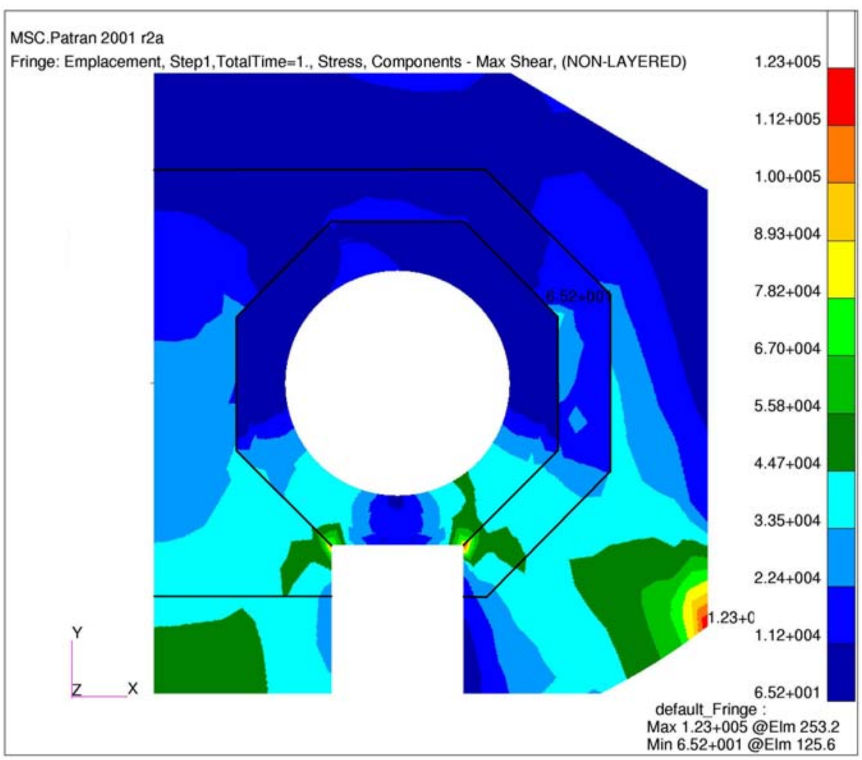


Figure 44. Emplacement Room after UFC placement (Maximum shear stress)

1106/MD18085/REP/01

Radioactive Materials Management

Deep Geologic Repository Conceptual Design

Annex 3

Shielding Calculations

December 2002

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 .

This document is written solely for the benefit of the Client, for the purpose stated in the Agreement, and the Consultant's liabilities are limited to those set out in the Agreement."

Summary

Scoping shielding calculations were required in support of the Deep Geologic Repository design, to ensure that the routine dose rate to an individual worker during normal operations is not more than 2 mSv/year. To achieve this, the dose rate at the working face of operating areas within the facility shall not exceed 1.0 μSv/h. Supporting shielding calculations detailed in this report demonstrate that this dose rate limit will not be exceeded, with the exception of handling the existing road transportation casks. The dose rate to operators from these casks will be mitigated by incorporation of local shielding and management procedures.

Contents

1 Introduction

Scoping shielding calculations were required in support of the Deep Geologic Repository (DGR) design. To ensure that the routine dose rate to an individual worker during normal operations is not more than 2 mSv/year the dose rate at the working face of operating areas within the facility should not exceed 1.0 μSv/h. Shielding assessments were performed to ensure that the plant design would meet this dose rate limit. The assessments included:

- Used Fuel Container (UFC) design including bentonite clay jacket and emplacement room spacer plugs
- UFC Transport Cask
- Bulk Shielding of the Used Fuel Packaging Plant (UFPP) including the storage pool
- UFPP UFC Shielded Cart
- DGR Emplacement Room
- End-Plug Cask
- Dose Burden.

2 Shielding Assumptions

The reference fuel for shielding calculations has a burnup value of 280 MWh/kgU and an age of 30 years [1]. The source terms for this reference were taken from Volume 3 of [2] and are given in Table 1. The model has not taken into account the effect of any fuel end plate. The fuel composition was based on data for a 37-element fuel bundle and was taken from Table 2 of [2]. The material compositions assumed are given in Tables 2 and 3 and were taken from [3 to 9].

Used fuel bundles enter the facility in road transport casks containing either CANDU irradiated fuel dry storage baskets or modules. The fuel is removed from the cask and then from the basket or module, placed in UFC baskets. The loaded UFC baskets are lowered into a UFC that is located within a shielded cart. The UFC is sealed and inspected, removed from the cart and placed within a bentonite clay jacket. The UFC and jacket are placed within a transport cask and transferred underground to an emplacement room for subsequent emplacement.

3 Computer Codes

The Monte Carlo code MCBEND [4] was used to perform the majority of gamma dose rate calculations. Results were verified using the RANKERN computer code [5]. MCBEND models the transport of individual particles accurately by using a fine energy group representation of nuclear data, but with the same flexible geometry modelling package used by the RANKERN code.

In effect, MCBEND simulates what happens in practice, and performs a numerical experiment of the system being analysed. In order to achieve reasonable accuracy with practical amounts of computing time, the code is provided with acceleration techniques. These effectively cause more particles, or fractions of particles to be tracked in the direction of interest, compared to directions of less importance. A simple adjoint diffusion calculation is used to define which directions and energies are important.

The point kernel RANKERN code was used to verify a number of the gamma dose rate calculations, as it provides an efficient way of determining the contribution to dose rates from scattered and reflected radiation. RANKERN starts its calculation by randomly sampling a point within the defined source and then performing a line of sight calculation to the defined dose point. The contribution from radiation that is initially travelling in a different direction, but is then scattered back toward the dose point is accommodated by the use of build-up factors, that are based upon the path length between the current source point and the dose point. Further random points within the source are sampled, so as to integrate over the source volume, until a calculated result with a predefined statistical uncertainty is achieved. RANKERN also includes the facility to define reflection surfaces, so that a two-stage calculation may be performed.

RANKERN and MCBEND have been successfully applied to such problems as:

- Design of nuclear plant
- Interpretation and analysis of measurements on operating plant and in experimental facilities
- Calculation of personnel dose levels and radiation induced material changes.

Both RANKERN and MCBEND have been developed by the ANSWERS software service which acts as a centrally controlled repository for all the major computer codes and data libraries used in the areas of criticality, shielding and reactor physics in the UK. The ANSWERS Service employs a comprehensive set of software management QA procedures, covering the entire software life-cycle, in the development and validation of its software. The Quality Management System provided by these procedures has been certified against the International Standard ISO 9001.

In all but one case dose rates were calculated using ICRP51 conversion factors for gammas and ICRP60 for neutrons. The exception was the UFC design assessment where the dose rate was required in Grays per hour (see Section 4).

4 UFC Design

4.1 INITIAL CALCULATIONS

The UFC was modelled as a carbon steel (density 7.86 g/cc) cylinder of outer diameter 1116 mm and height 3712 mm. The height of the UFC was later changed to 3708 mm but this does not affect the results of these calculations. The internal dimensions were 924 mm and 3512 mm respectively. The internal dished ends were neglected for computational ease and pessimism. The steel cylinder was housed in a copper jacket with a gap of 1 mm between copper (density 8.96g/cc) and steel at the sides and 2 mm at the top. There was no gap at the base. The copper was modelled as 25 mm thick at the sides and the base and 31.8 mm thick at the top.

The basket was modelled as 55 carbon steel tubes, each with a wall thickness of 2.5 mm, on a 110 mm pitch and each with an outer diameter of 110 mm. The centremost tube was modelled as empty giving a total of 54 fuel bundles per basket. The six baskets (later changed to three baskets) were stacked with a nominal 10 mm gap between them. The model for the fuel bundles was based on details taken from Table 4.1 of [10]. The fuel bundles were modelled as cylinders of height 500 mm and diameter 102.5 mm.

The gamma and neutron dose rates were calculated using the MCBEND computer code. The dose rates were calculated at contact with the sides and base of the UFC. Dose rates were not calculated above the lid as the shielding there was greater than at the base.

The results were initially calculated in Sv/h. The following assumptions were made to convert Sv/h to Gy/h. For the gamma dose rate the result in Sv/h (calculated using ICRP51) is broadly equivalent to Gy/h, so no conversion was required. For the neutron dose rate, 1.0 Sv/h (calculated using ICRP21) is approximately equivalent to 0.1 Gy/h, so the results were reduced by a factor of ten. The results of the calculations are given in the Table below. It can be seen that the total dose rate is considerably less than the limiting value of 15 Gy/h. Secondary gammas were not calculated for these preliminary scoping calculations as they were expected to be trivial compared to the primary gamma dose rates.

Results

Dose Point	Gamma Dose Rate Gy/h	Neutron Dose Rate Gy/h	Total Dose Rate Gy/h
Side of UFC	0.038	2.3E-5	0.038
Base of UFC	0.034	1.6E-5	0.034

4.2 LATER UFC DESIGN

Following completion of the preliminary scoping calculations, described in the previous section, the UFC was redesigned. The new design is similar to the old, with the exception that the thickness of the ends of the steel container was increased from 100 mm to 159 mm in the new design and the thickness of the copper lid was decreased from 31.8 mm to 25 mm. It was not necessary to repeat the above calculations because the increase in steel thickness meant that the initial calculations were pessimistic. The reduction in copper lid thickness does not affect the results as the original calculation was based on the 25 mm thick copper base. The fuel will now be stored in three taller UFC baskets rather than six shorter ones, but this will not significantly affect dose rates in any way.

5 UFC Jacket and Emplacement Room Spacer/Shield Plug

5.1 JACKET AND SHIELD PLUG

The UFC and its contents were modelled as described previously in Section 4. Initial calculations were carried out by modelling the proposed UFC jacket as a cylinder of buffer material 250 mm thick around the copper body of the UFC. The calculational model is shown in Figure 1. The composition of the buffer material is given in Table 2 and was taken from [3]. Dose rates were calculated at contact with the side of the 250 mm of buffer and the dose rates are summarised in the table below.

The UFC spacer/shield plug, positioned at the end of a UFC located within an emplacement room, was modelled as a buffer cylinder placed adjacent to the UFC copper lid. Dose rates were calculated at contact with the exposed surface of the buffer plug. 780 mm of buffer material was required to reduce the contact dose rate too less than 1.0 μSv/h. Neutron and secondary gamma contributions to the total dose rate were negligible.

To help ensure that the emplaced UFC temperature constraints were not exceeded, a UFC jacket end thickness of 256.5 mm was proposed followed by a buffer shield plug thickness of 750 mm. From the above shielding calculation results, it is evident that the proposed overall jacket/plug thickness will provide adequate shielding.

Jacket Results

	Gamma μSv/h	Neutron μSv/h	Secondary Gamma μSv/h	Total μSv/h
Radial dose rate after 250mm bentonite	1.35E3	3.71E0	1.82E0	1.35E3

5.2 BENTONITE CALCULATIONS

The initial UFC jacket calculations reported in the Section 5.1 were performed using buffer material for the jacket i.e. 50% bentonite clay and 50% silica sand. 100% bentonite is now proposed instead. To quantify the effect of changing materials the calculations for the 250 mm thick buffer jacket were repeated using 250 mm of bentonite. It is intended to use Wyoming bentonite, but as the composition for this was not available, the composition for sodium bentonite was used instead, as a sensitivity study. The compositions are given in Table 2 and the results are summarised in the table below. The surface gamma and total dose rates for bentonite are less than half the equivalent buffer dose rates. The increase in the small neutron dose rate does not present any problems. It is concluded that any calculations performed using buffer material for the jacket rather than bentonite are likely to be pessimistic, assuming that the composition of Wyoming bentonite is similar to that of sodium bentonite.

Bentonite/ Buffer Results

Jacket Material	Bentonite	Buffer
Gamma surface dose rate µSv/h	4.91E2	1.35E3
Neutron surface dose rate µSv/h	5.09E0	3.71E0
Total surface dose rate µSv/h	4.96E2	1.35E3

6 UFC Transport Cask

Once a UFC has been fitted with a bentonite jacketed, the whole assembly is placed within a transport cask for transfer underground to the repository. To control operator dose the transport cask's surface dose rate is limited to less than 1.0 µSv/h. Calculations were performed to determine the amount of shielding, additional to the 250 mm UFC jacket, required to achieve this dose rate. The layers of additional shielding required were: 50 mm air, 50 mm steel, 50 mm polythene and 100 mm steel.

The radial surface dose rates for this amount of shielding are given in the table below. These dose rates were based on the use of a buffer jacket. A 100% bentonite jacket will, from the evidence given in Section 5, reduce the total dose rate further.

Transport Cask Results

Calculation	Gamma µSv/h	Neutron µSv/h	Secondary Gamma µSv/h	Total µSv/h
Radial dose rate after cask shielding	0.61	0.11	Neg.	0.72

7 UFPP Bulk Shielding

7.1 STORAGE MODULES

Calculations were required to derive a bulk shielding thickness for remote operation cell walls within the UFPP i.e. the basket receipt and cutting cells, the module receipt and fuel module/basket handling cells, such that the dose rate to an operator working outside the cells was less than 1.0 µSv/h. The worst case for the majority of cells was assumed to be two storage modules at a distance of 500 mm from the inside of the cell wall. This stand off distance will be maintained by physically limiting the travel of the cells overhead cranes. The calculational model was set up as described in the following paragraph.

For pessimism two modules were modelled side by side at a distance of 500 mm from the shield wall, assumed to be constructed from ordinary concrete with a density of 2.32 g/cc. The fuel bundles were modelled as cylinders of height 500 mm and diameter 102.5 mm. The bundle composition is shown in Table 3 and was taken from Table 2 of [2]. One module contains 48 tubes that are 1000 mm long and each of which hold two fuel bundles. The amount of concrete required to reduce the operating face dose rate to 1.0 µSv/h was then calculated. The composition used for the concrete is shown in Table 2. The calculational model is shown in Figures 2 and 3.

Dose rates were calculated at contact with the operating face of the shield wall. The amount of concrete shielding required to reduce the dose rate to less than 1.0 µSv/h was calculated to be 1100 mm. Neutron and secondary gamma contributions to the total dose rate, for this thickness of concrete, were negligible.

7.2 UFPP FUEL MODULE SHIELDED TRANSFER TUNNEL

The fuel module shielded transfer tunnel is intended to shield a single module while it is transferred from the fuel module receipt bay to the fuel module/basket handling cell. Calculations were performed to determine the amount of steel and polythene shielding required for the tunnel wall. Concrete was not used due to the limited space available. The tunnel wall was modelled at a distance of 450 mm from a single module as shown in Figure 4. Results showed that the shielding required to reduce the cold side dose rate to less than 1.0 μSv/h was 300 mm of steel followed by 100 mm of polythene and another 50 mm of steel. The dose rates for the transfer tunnel wall with this shielding are shown in the table below.

UFPP Fuel Module Shielded Transfer Tunnel Dose Rates

Primary Gamma Dose Rate (μSv/h)	Neutron Dose Rate (μSv/h)	Secondary Gamma Dose Rate (μSv/h)	Total Dose Rate (μSv/h)
0.56	0.28	0.05	0.89

7.3 IRRADIATED FUEL DRY STORAGE BASKET UFPP RECEIPT BUFFER STORE

The basket receipt cell buffer store can hold a maximum of 32 irradiated fuel dry storage baskets stored in a double stacked array of 16. Calculations were required to determine whether the proposed 1100 mm thick concrete walls provided enough shielding to give a cold side dose rate of less than 1.0 μSv/h. The calculational model is shown in Figure 5. The primary gamma dose rate on the cold side of the wall was calculated to be 0.63 μSv/h and the neutron dose rate was negligible. It is concluded that the wall will provide adequate shielding.

7.4 UFPP UFC RECEIPT CELL

The UFC receipt cell has two separate UFC holding bays; one for passed UFCs and the other for failed UFCs. The bays are some 14 m apart to prevent contamination. Each bay can hold up to ten UFCs that are stored in a vertical orientation. Calculations were required to determine the thickness of the concrete cell wall that would give a cold side dose rate of less than 1.0 μSv/h. The calculational model is shown in Figure 6. The thickness of concrete required to reduce the surface dose rate to less than 1.0 μSv/h was 700 mm.

8 UFPP Storage Pool Depth

The storage modules were modelled as outlined in Section 7, but with their overall dimensions increased to 1.0 m x 1.3 m x 0.65 m as indicated in Figure 44 of [11]. It was assumed that the centres of the uppermost bundles lay some 140 mm below the top of the module. The storage pool was modelled as a 6x6x6 array of modules covered by water as shown in Figure 7. The model also included a raised module in transit. The depth of water was required to reduce the pool surface dose rate to less than 1.0 μSv/h.

Dose rates were calculated at contact with the surface of the pool water. The gamma dose rate from the raised module was found to dominate and 2300 mm of water was required above the raised module to reduce the pool surface dose rate to less than 1.0 μSv/h. This equates to 3250 mm of water above the main array. If the module were to be raised any higher then the pool surface dose rate would exceed the limit. Neutron and secondary gamma contributions to the total dose rate were negligible.

9 UFPP UFC Shielded Cart

9.1 SHIELDED CART BULK SHIELDING

The calculational model for the UFC was based on [6 and 7]. The UFC was modelled within the shielded cart and the amount of radial steel/polythene shielding was adjusted until the radial surface dose rate was calculated to be less than 1.0 μSv/h. The calculational model of the shielded cart is shown in Figure 8.

The shielding required to reduce the surface dose rate to less than 1.0 μSv/h was 160 mm steel, 120 mm polythene, 50 mm steel, moving radially outwards as shown in Figure 8.

9.2 TRANSFER TUNNEL ROOF THICKNESS

The thickness of the transfer tunnel roof above the shielded cart inner vessel is required to provide sufficient shielding to give a surface dose rate of less than 1.0 μSv/h.

The calculational model is shown in Figure 9. It was assumed that the copper lid had not yet been put on the UFC but that the steel lid was in place. The top of the fuel was assumed to lie 564 mm below the top of the transfer cart i.e. 589 mm below the concrete transfer tunnel ceiling.

The thickness of concrete required to reduce the surface dose rate to 1.0 μSv/h above the transfer tunnel ceiling was 600 mm.

9.3 SHIELDED CART SHINE CALCULATIONS

These calculations are concerned with radiation “shining” through the 25 mm gap between the top of the cart and the transfer tunnel ceiling and then being reflected towards an operator standing in the tunnel. The gap is provided to allow the shielded cart to travel along the tunnel without coming into contact with the transfer tunnel ceiling.

9.3.1 Shine From Top of UFC Within Shielded Cart

The first set of calculations considered the effect of shine from the top of the UFC within a shielded cart, as the shielded cart is moved into position beneath an access port too a process cell above the transfer tunnel. As the cart has no lid there is the possibility of radiation from the top of the UFC reflecting off the concrete ceiling down towards an operator standing close to the cart. The calculational model is shown in Figure 9.

Calculated dose rates adjacent to the cart and level with the gap between the top of the cart and the ceiling were 11.0 μSv/h for gammas and 1.0 μSv/h for neutrons. Predicted dose rates at operator head height (at any distance from the cart) were negligible.

9.3.2 Shine From Partially Raised UFC

The second set of calculations were concerned with radiation shine through the gap between the top of the cart and the ceiling whilst the UFC is partially raised up to the cell above (for example as it would be at the UFC inner vessel purging cell). The calculational model is shown in Figure 10. The model considered the effect of the radiation being scattered from the ceiling and walls of the transfer tunnel.

Calculated dose rates adjacent to the cart and level with the gap between the top of the cart and ceiling were high, 1.83E3 μSv/h for gammas and 12.5 μSv/h for neutrons. The gamma dose rate (due to radiation reflected from the transfer tunnel ceiling and walls) at operator head height was less than 0.4 μSv/h and the neutron dose rate was negligible.

9.3.3 Shine From Fuel Baskets

Finally the third set of calculations considered the same radiation shine as described in Section 9.3.2, but from baskets that were lowered into the UFC from the fuel module/basket handling cell. The calculational model is shown in Figure 11. The calculated gamma dose rate at operator head height was less than 2.0 μSv/h and again the neutron dose rate was negligible. As this dose rate is above the normal limit of 1.0 μSv/h, access in the transfer tunnel may require restricting whilst fuel is lowered into a UFC.

10 UFPP Sealing Cell

The UFPP sealing cell walls and ceiling are required to provide sufficient shielding to give an external surface dose rate of less than 1.0 μSv/h for the case when a UFC is partially raised into the cell.

The calculational model is shown in Figure 12. It was assumed that the steel and copper lids were removed from the UFC and that the top of the fuel and steel was flush with the cell floor as shown in Figure 12. All cell walls were assumed to be equidistant from the UFC centreline.

The dose point for the ceiling was situated directly above the open UFC. The wall dose points were taken vertically along one wall on the UFC centreline opposite the UFC floor opening. The ceiling thickness required to achieve a surface gamma dose rate of less than 1.0 μSv/h was 850 mm and the wall thickness was 750 mm. Neutron and secondary gamma dose rates were negligible.

11 DGR Emplacement Room Operator Dose

After the jacketed UFC (with shielding/spacer blocks in place at the end) is placed within the dense backfill/buffer material emplacement structure, the operator must insert the lower shielding blocks beneath the jacketed UFC. During this operation he will receive a dose due to radiation scattered from under the UFC. A barrier will be used to ensure that the operator does not approach the emplacement structure beyond a distance of 1.25 metres. Calculations were required to determine the dose rate to the operator during this procedure. Details of the calculations and assumptions are outlined below.

The calculational model was based on [8] and is shown in Figures 13 and 14. The end of the 1.00 m of shielding/spacer buffer blocks (actually 256.5 mm of bentonite followed by 750 mm of buffer material) was assumed to lie flush with the end of the dense backfill/buffer material emplacement structure as shown in Figure 13. For computational ease the hexagonal cross-section was modelled cylindrically as shown in Figure 14, this is a slightly pessimistic assumption. The minimum vertical distance between the jacket and the high performance concrete floor was 742 mm. The jacket material was modelled as buffer material and not bentonite that has superior shielding properties.

Primary gamma and neutron dose rates were calculated using the MCBEND computer code. The RANKERN computer code was also used to confirm the MCBEND results for reflected gamma radiation. The dose points were situated 1.25 metres from the end of the shielding/spacer blocks as shown in Figure 13. The peak primary gamma dose rate at that distance was 0.7 μSv/h and the neutron and secondary gamma dose rates were negligible.

12 DGR Emplacement Room Shielding/Spacer Plug Cask

After the jacketed UFC is placed in the emplacement room, the UFC transport cask is removed and a shielding/spacer plug cask is positioned next to the emplacement room shield wall gamma gate. Calculations were required to ensure that the shielding/spacer plug cask provided sufficient shielding to give an external dose rate of less than 1.0 μSv/h. The calculational model is shown in Figure 15. The emplacement room shield wall was assumed to have the same construction as the transport cask i.e. 100 mm steel, 50 mm polythene and 50 mm steel. During the transfer of the shielding/spacer plugs from the cask, both the cask and shield wall gamma gates are open. Therefore the subsequent space they took up was modelled as an air gap. The position of the shielding/spacer plugs within the cask varies, so for simplicity (and pessimism) the cask was modelled as being empty. Calculations determined that a 20 mm thick steel cask provided sufficient shielding to reduce the surface dose rate on the outside of the cask to less than 1.0 μSv/h.

13 Dose Burden

13.1 DURING USED FUEL HANDLING/EMPLACEMENT

The basis of design for the facility is such that the routine dose to an individual worker during normal operations is less than 2 mSv/year. This has been achieved by ensuring that throughout the facility, with the exception of handling the existing road transportation casks, an individual worker is not exposed to a dose rate greater than 1.0 μSv/h. Assuming a nominal time estimate for individual worker exposure of 2000 hours per year this gives a total dose of no more than 2 mSv/year. This section follows the used fuel route through the facility to demonstrate that, with the exception of handling the road transportation casks, the dose rate to any operator does not exceed 1.0 μSv/h.

The fuel arrives at the receipt area of the plant in either modules (approximately 90% of fuel volume) or irradiated fuel dry storage baskets (10%). As the modules form the bulk of the fuel, there are two lines dedicated to processing this container type and one line to baskets.

The modules are carried in road transportation casks; it is expected that the baskets will be transported in a similar type of cask. Historical operational data indicates that the contact dose rate of the road transport cask is 0.23 mSv/h which falls to 0.08 mSv/h at a distance of one metre. These dose rates are obviously not consistent with the design of the new facility and therefore present the potential for increased operator dose in this area.

The logistics study shown in Appendix A of the Design Report indicates a road transportation cask handling time of up to two hours from receipt of the cask on its transporter up to the point where it is handled remotely. In total 629 road transportation casks (plus basket casks which are assumed to be similar) are received per year and are handled over two separate shifts. Assuming that the operators handle the cask at a distance of one metre the total operator dose for handling the road transportation casks would be 50 mSv/year.

Should these flasks be used within the facility a number of mitigating measures should be employed such as: minimising occupancy times, increasing operator distance from the flask, use of localised shielding and diversification of operators.

13.1.1 Basket Line

The storage basket within its transport cask arrives at the transporter receiving/shipping area where the impact limiter is removed and the cask is placed on a cart. It is then taken to the cask cart decontamination cell where the cask is vented and the lid bolts removed. The cask passes through to the basket transport cask receipt cell where the cart scissor lift raises the cask to the basket receipt cell gamma gate.

All operations within the basket receipt cell are done remotely and the cell has 1100 mm thick walls that are sufficient to give a cold side surface dose rate of less than 1.0 µSv/h as shown in Section 7.1. Hence operators outside the cell will receive a dose rate of less than 1.0 µSv/h. Once within the cell, a double-lidding system is used to remove the cask lid while keeping it free of contamination, the basket is then removed and placed in the buffer store. The shielding provided by the basket receipt cell buffer store walls is described in Section 7.3. The cask lid is replaced, the empty cask is lowered back to the basket transport cask receipt cell where the bolts are replaced; the cask and cart are monitored and decontaminated if necessary.

The storage basket is removed from the buffer store and passes through a shield door to the basket cutting cell. This is also a remote operations cell with a wall thickness of 1100 mm. In this cell the top of the storage basket is removed and placed into a skip for subsequent disposal. Used fuel bundles are removed remotely from the now open storage basket and placed individually within a waiting UFC basket. The empty storage basket is placed in a skip for subsequent disposal, while full UFC basket is transferred through a shield door to the Fuel Module/Basket Handling Cell (FMBHC).

The FMBHC is a remote operations cell with 1100 mm thick walls. Here the UFC basket containing used fuel bundles is held pending transfer to a UFC. Empty UFC baskets are lifted into the FMBHC from the new UFC basket delivery tunnel. The basket delivery facility is an area that will be considered in the detailed design stage and is not expected to present any shielding weakness. Design solutions will be required to prevent contamination leaving the FMBHC.

At this point the waste skip in the basket cutting cell will contain the remains of the storage basket. Once full, the waste skip is lowered via a gamma gate to the used cask basket size reduction/drumming/export area where it is processed so that it is suitable for export.

13.1.2 Module Line

The module within its transport cask arrives at the transporter receiving/shipping area where the impact limiter is removed and the cask is placed on a cart. It is taken to the cask cart decontamination cell where the cask is vented and the lid bolts removed. The cask passes through to the module transport cask receipt cell where the cart scissor lift raises the cask to the basket receipt cell gamma gate.

All operations within the module receipt cell are done remotely and the cell has 1100 mm thick walls. Once within the cell a double-lidding system is used to remove the cask lid while keeping it free of contamination and the module is removed. Following the loading of an empty module (see below) the cask lid is replaced and the cask is lowered back to the module transport cask receipt cell where the bolts are replaced. The cask and cart are monitored and decontaminated if necessary.

The module has two possible routes from the module receipt cell. If temporary storage is required it will go to the inlet pool, having been cleaned if necessary, prior to placement within the storage pool.

The dose rate at the surface of the module buffer storage pool is less than 1.0 μSv/h (see Section 8) so that an operator working above the pool is protected. The transfer of the module from the module receipt cell to the storage pool will be considered at the detailed design stage. Design solutions will be required to reduce the potentially high transient dose rate to the operator at this point.

If it is to be processed immediately, the module passes along the fuel module shielded transfer tunnel (see Section 7.2) to the FMBHC.

The FMBHC is a remote operations cell with 1100 mm thick walls as already discussed in the previous section. Within this cell the fuel is removed from the module ready for placement in a UFC basket. The empty module is returned to the fuel module receipt cell. The module is decontaminated, dried and then replaced in a cask ready for return to the customer.

At this point in the process the fuel from either a basket or a module is in the FMBHC and has been placed in one of three UFC baskets ready to be loaded into the UFC. Two identical lines leave the FMBHC, one at each end of the cell.

13.1.3 UFC Lines

The UFC shielded cart stands in the shielded cart transfer tunnel under the UFC basket export port, where fuel baskets are lowered into it. Supporting calculations have shown that dose rates to an operator standing in the transfer tunnel, during this operation, would be just less than 2.0 μSv/h (Section 9.3.3). Therefore, man access at this point may require restriction while fuel is being placed into the cart. Once the baskets are in place the steel lid is put on the UFC inner vessel.

The cart shielding has been designed to give a surface dose rate of less than 1.0 μSv/h so that it is possible for an operator to approach a cart to facilitate remedial work if necessary. As the cart has no lid there is the possibility of radiation from the top of the UFC reflecting down from the concrete ceiling towards the operator. However, calculations (see Section 9.3.1) demonstrated that dose rates at operator level were negligible.

The ceiling of the shielded cart transfer tunnel is 600 mm thick. Supporting calculations in Section 9.2 have shown that this reduces the dose rate above the tunnel too less than 1.0 μSv/h. This enables operators to enter cells above the transfer tunnel to carry out maintenance operations whilst the shielded cart is positioned below.

The transfer cart takes the UFC along the transfer tunnel to the transfer ports for a series of cells. At each port the UFC is lifted so that the top of the UFC enters the cell above. The dose rate at operator height in the tunnel below is less than 1.0 μSv/h, provided that the top of the fuel within the UFC does not pass higher than the floor of the cell (See Section 9.3.2).

At the sealing cell the UFC is purged and the copper lid fitted. The lid is welded at the UFC lid welding cell with the weld checked at the UFC inspection cell. The thickness of the walls and ceilings for these cells was shown by calculation (See Section 10) to give external dose rates of less than 1.0 μSv/h.

After inspection the UFC is lifted remotely into the UFC receipt cell. If it has passed inspection it is stored in the "passed" UFC holding bay, otherwise it goes to the "failed" UFC holding bay. Separate grapples are used to handle passed and failed UFCs to prevent cross contamination. The cell has the facility to decontaminate and dry UFCs if necessary. All operations within the UFC receipt cell are done remotely and the cell has sufficiently thick walls to give a cold side surface dose rate of less than 1.0 μSv/h as shown in the supporting calculation (see Section 7.4).

Failed UFCs are returned via the transfer tunnel to the failed UFC lid removal cell where the lid is removed. Then the UFC moves back under the FMBHC port and the fuel lifted back into the cell to be placed later into a new UFC. The failed UFC goes to the shielded cart swabbing/decontamination and UFC loading area where it is cleaned and removed.

Passed UFCs are lowered into the UFC jacketing dispatch cell. Man access is permitted for this cell to put the UFC jackets in place on the support frame, but not when a UFC is in the cell. The UFC is lowered into the open support frame that is then closed around the UFC. The jacket end cap is put in place and the support frame rotated to a horizontal position. At this point the upper portion of the support frame is raised to allow the jacketed UFC to be transferred on a roller bed into the UFC transport cask via a gamma gate. The shielding provided by the transport cask has been designed to give a surface dose rate of less than 1.0 μSv/h (see Section 6). Therefore, man access is acceptable for any operation while the UFC is within the cask.

The transport cask is transferred to the waste shaft and lowered underground for onward movement to an emplacement room. The cask is then connected to a gamma gate at the emplacement room shielded wall. Following transfer from the cask to behind the shield wall, the jacketed UFC is placed into its final location within the emplacement room. The emplacement room shield door and gamma gate will be designed to provide the same shielding as the transport cask so that the dose rate throughout the operation will be less than 1.0 μSv/h.

The transport cask is removed and the shielding/spacer plug cask containing the buffer plugs is put in its place. The shielding provided by the shielding/spacer plug cask has been designed to give a surface dose rate of less than 1.0 μSv/h (see Section 12). The shielding/spacer plugs are added to the end of the UFC. The thickness of these shielding/spacer plugs is greater than that required by the supporting shielding calculations (see Section 5.1) for UFC spacing reasons.

Finally the remaining lower sealing material blocks are inserted beneath the jacketed UFC. Supporting calculations demonstrate that operator dose rate is below 1.0 μSv/h if the operation is carried out 1.25 m from the face of the emplacement structure (see Section 11).

13.2 DOSE UPTAKE BY CONSTRUCTION WORKERS

It is the current intention to excavate each new section of the emplacement facility while emplacement is taking place in a previously constructed section. The emplacement facility is designed such that workers will only receive a negligible dose. This is achieved in several ways:

- At all times workers are shielded from the active emplacement facility by 30 m of granite
- The underground facility is designed to be clean so there is no risk to workers from active contamination. This is achieved by having separate ventilation systems for both active and construction operations.

Procedures will be in place to ensure that personnel do not inadvertently enter the wrong area. Should accidental entry occur the maximum dose rate (by design) to the worker would be less than 1.0 μSv/h.

14 Conclusions

The facility has been designed such that the routine dose to an individual worker during normal operations is no more than 2 mSv/year. This is achieved by ensuring that throughout the facility an individual worker is not exposed to a dose rate greater than 1.0 μSv/h. The exception to this is the handling of existing road transportation casks. The dose rate to operators from these casks will be mitigated by incorporation of local shielding and management procedures, should a better design not be incorporated. The supporting shielding calculations detailed in this report demonstrate that this dose rate limit is not exceeded, except under non-routine operations and when handling the existing road transport casks.

15 References

1 Technical Specification for Updating the Conceptual Design and Cost Estimate for a Deep Geological Repository for Used Nuclear Fuel. 06819-UFM-03789-00010-R00.

2 Characteristics and Radionuclide Inventories of Used Fuel from OPG Nuclear Generating Stations. 06819-REP-01200-10029-R00-Vol 1.

3 Technical Specification for a Screening-Level Study to Select Preferred Used Fuel Disposal Container Geometries and Capacities. 06819-TS-01110-10000-R00.

4 MCBEND. A Monte-Carlo Program for General Radiation Transport Solutions. User Guide to Version 9E. ANSWERS/MCBEND(94)15.

5 RANKERN. A Point-Kernel Program for Gamma-Ray Transport Solutions. User Guide for Version 14. ANSWERS/RANKERN(95)03.

6 Figure 7 of Main Design Update Report – Assembly of Used Fuel Baskets and Container.

7 Figure 2 of Main Design Update Report – 108 Bundle Used Fuel Basket.

8 Figure1 of Main Design Update Report – DGR Emplacement Room showing General Arrangement of Emplaced Blocks and UFCs.

9 P. Baumgartner, 2000. Elemental Composition of Disposal Vault Sealing Materials. Report 06819-REP-01300-10015-R00, AECL, Toronto, Ontario.

10 Deep Geological Repository Facility and Packaging Requirements. 06819-PR-01110-10000-R01

11 Engineering for a Disposal Facility Using the In-Room Emplacement Method. AECL-11595, COG-96-223.

16 Tables

16.1.1 Table 1 UO2 Fuel Spectra for 280 MWh/kgU, 30 years cooling

Combined Photon Spectra (fission products and actinides)		Combined Neutron Spectra (Alpha-n and spontaneous fission)	
Mean Energy (MeV)	Photons/s/kgU	Boundaries (MeV)	Neutrons/s/kgU
5.500	9.50E+01	17.300-14.200	0.0
4.750	1.05E+02	14.200-12.200	1.022E+00
4.250	1.82E+02	12.200-10.000	8.923E+00
3.750	3.14E+02	10.000-8.610	1.377E+01
3.250	5.42E+02	8.610-7.410	4.372E+01
2.800	7.34E+05	7.410-6.070	1.322E+02
2.400	7.48E+03	6.070-4.970	2.638E+02
2.000	1.01E+07	4.970-3.680	7.372E+02
1.580	2.74E+08	3.680-3.010	8.553E+02
1.120	7.92E+09	3.010-2.730	5.007E+02
0.650	6.36E+11	2.730-2.470	5.507E+02
0.300	2.60E+10	2.470-2.370	2.306E+02
0.170	2.53E+10	2.370-2.350	4.579E+01
0.120	2.81E+10	2.350-2.230	2.667E+02
0.085	3.91E+10	2.230-1.920	7.694E+02
0.055	8.58E+10	1.920-1.650	6.976E+02
0.030	1.64E+11	1.650-1.350	8.467E+02
0.010	3.62E+11	1.350-1.000	1.066E+03
		1.000-0.821	5.232E+02
		0.821-0.743	2.469E+02
		0.743-0.608	4.372E+02
		0.608-0.498	3.492E+02
		0.498-0.369	4.027E+02
		0.369-0.297	2.092E+02
		0.297-0.183	9.715E-01
		0.183-0.111	6.141E-01
		0.111-0.067	9.450E-02

16.1.2 Table 2 Material Compositions

	Sodium Bentonite 2.703 g/cc	Buffer 1.954 g/cc	Dense Backfill 2.226 g/cc	High Performance Concrete 2.429 g/cc	Ordinary Concrete 2.32 g/cc
Element	Weight %	Weight %	Weight %	Weight %	Weight %
Si	29.5	32.6	29.6	37.6	15.5
Al	8.4	3.6	7.5	3.3	1.4
Fe	3.0	1.3	2.4	0.9	1.0
Na	1.6	0.7	2.2	1.4	
Ca	1.3	0.6	1.4	2.3	25.7
Mg	1.3	0.6	0.7	0.2	
K	0.5	0.2	3.1	1.7	
C	0.4	0.2	0.4	0.3	6.0
Ba	0.4	0.2			
S	0.3	0.1		0.1	2.0
Ti			0.2		
P			0.1		
Mn					
H	0.8	2.0	0.8	0.5	4.0
O	52.5	58.0	51.5	51.8	49.8

Data for Sodium Bentonite taken from [9].

Data for buffer, dense backfill and high performance concrete taken from [3].

Data for ordinary concrete taken from [4].

16.1.3 Table 3 Fuel bundle Composition

Fuel Bundle 5.85 g/cc	
Component	Volume Proportion
Uranium dioxide (10.6 g/cc)	0.501
Zircalloy (6.55 g/cc)	0.082
Void	0.417

Data taken from [2]

17 Figures

Figure 1 Calculational Model of UFC and Jacket (Not to Scale)

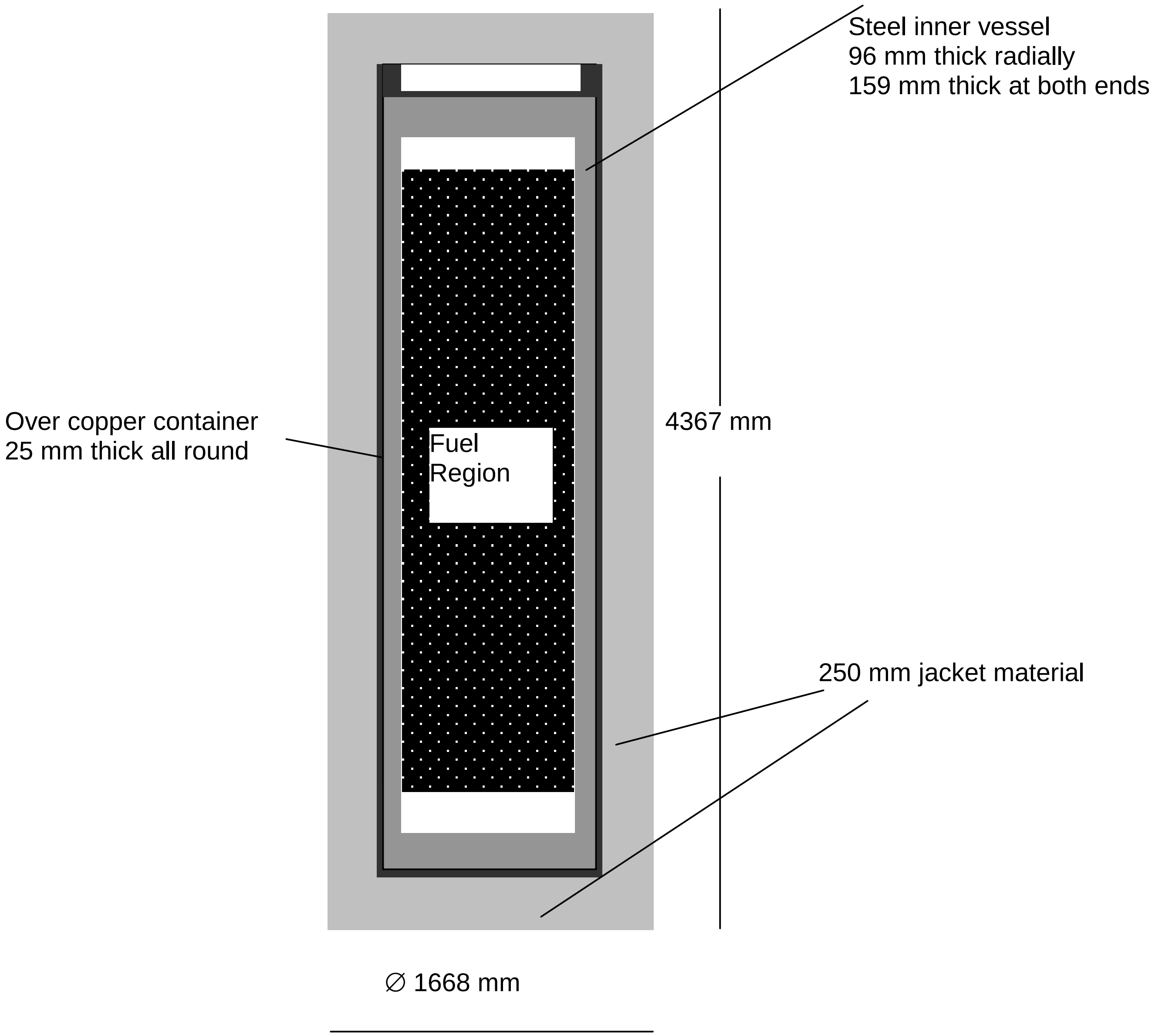


Figure 2 Calculational Model of Storage Modules (Not to Scale)

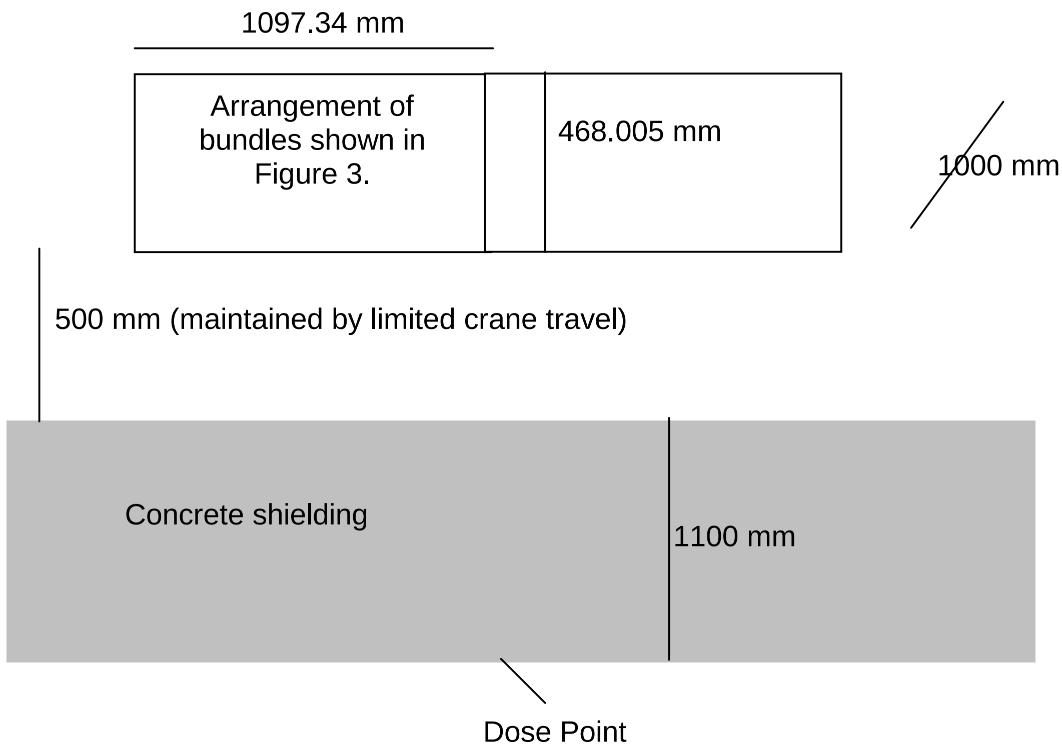


Figure 3 Arrangement of Fuel Bundles within Module (Not to Scale)

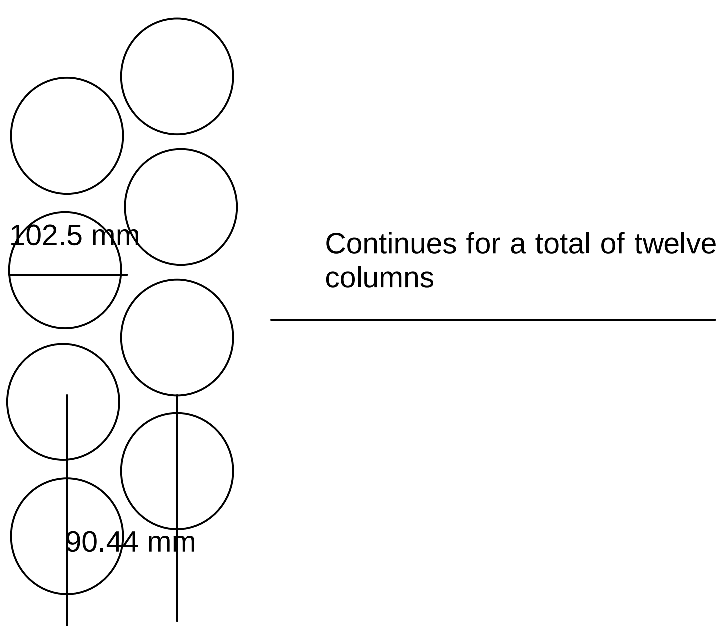


Figure 4 Calculational Model of Fuel Module Shielded Transfer Tunnel (Not to Scale)

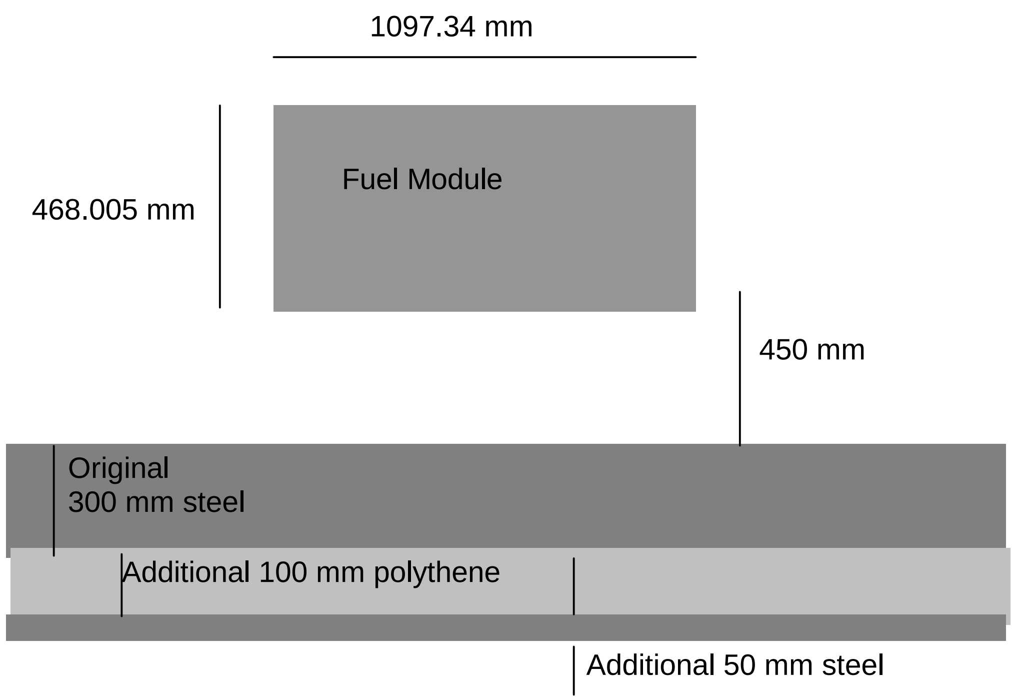
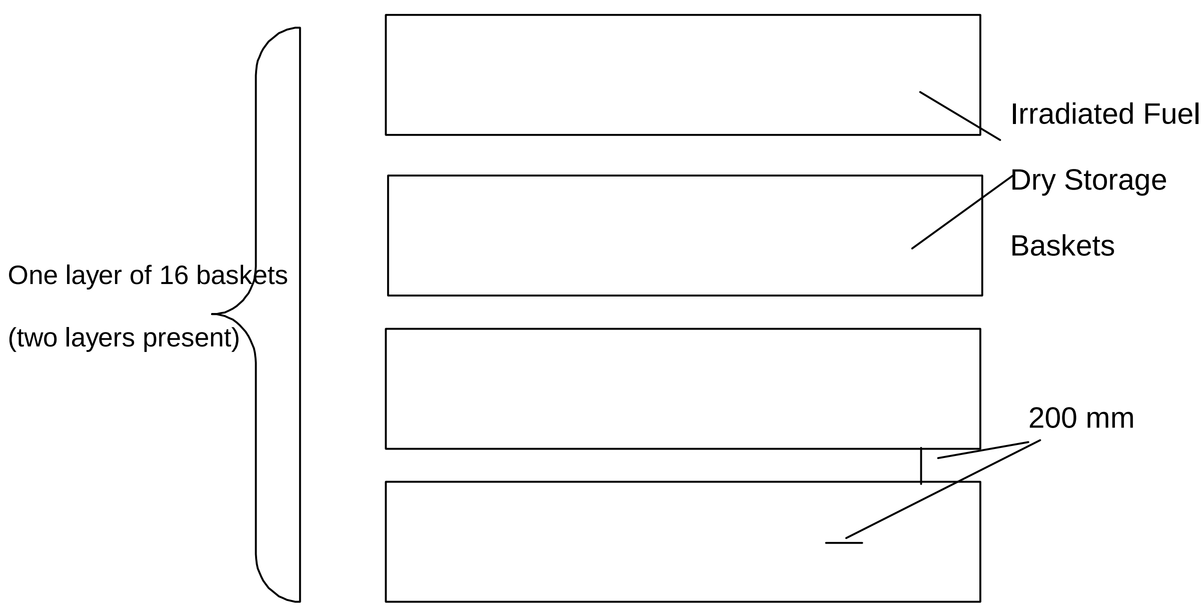


Figure 5 Calculational Model of Basket Receipt Cell Buffer Store (Not to Scale)



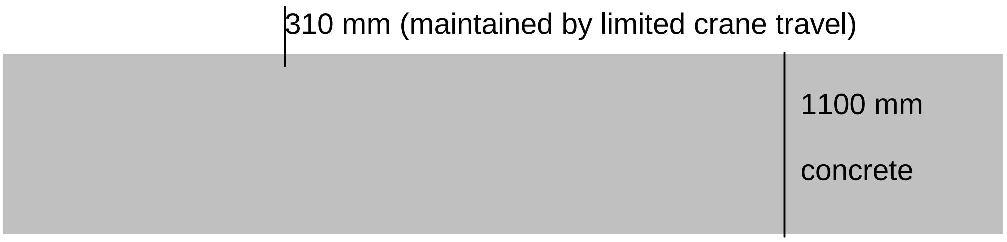


Figure 6 Calculational Model of UFC Receipt Cell (Not to Scale)

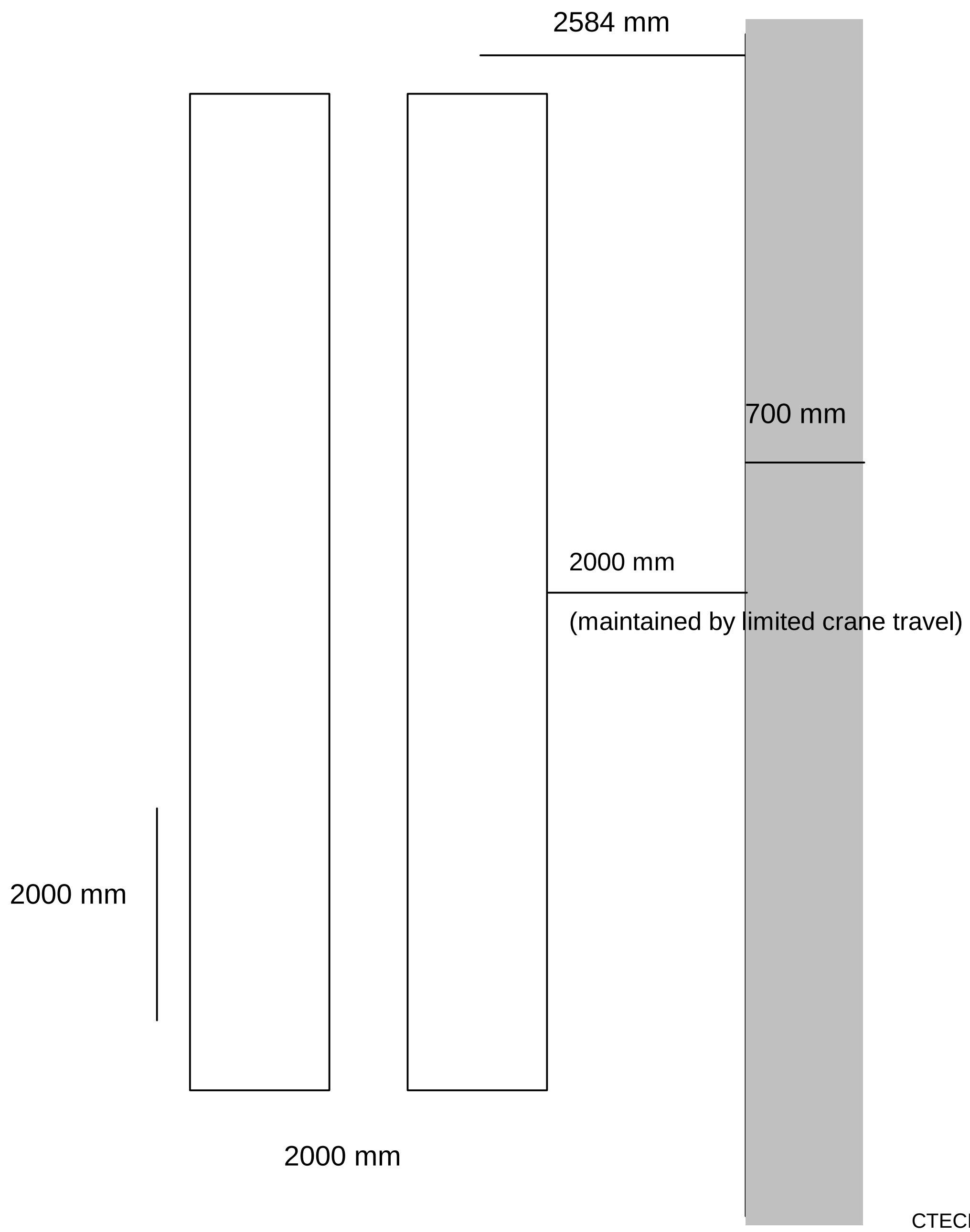


Figure 7 Calculational Model of Storage Pool (Not to Scale)

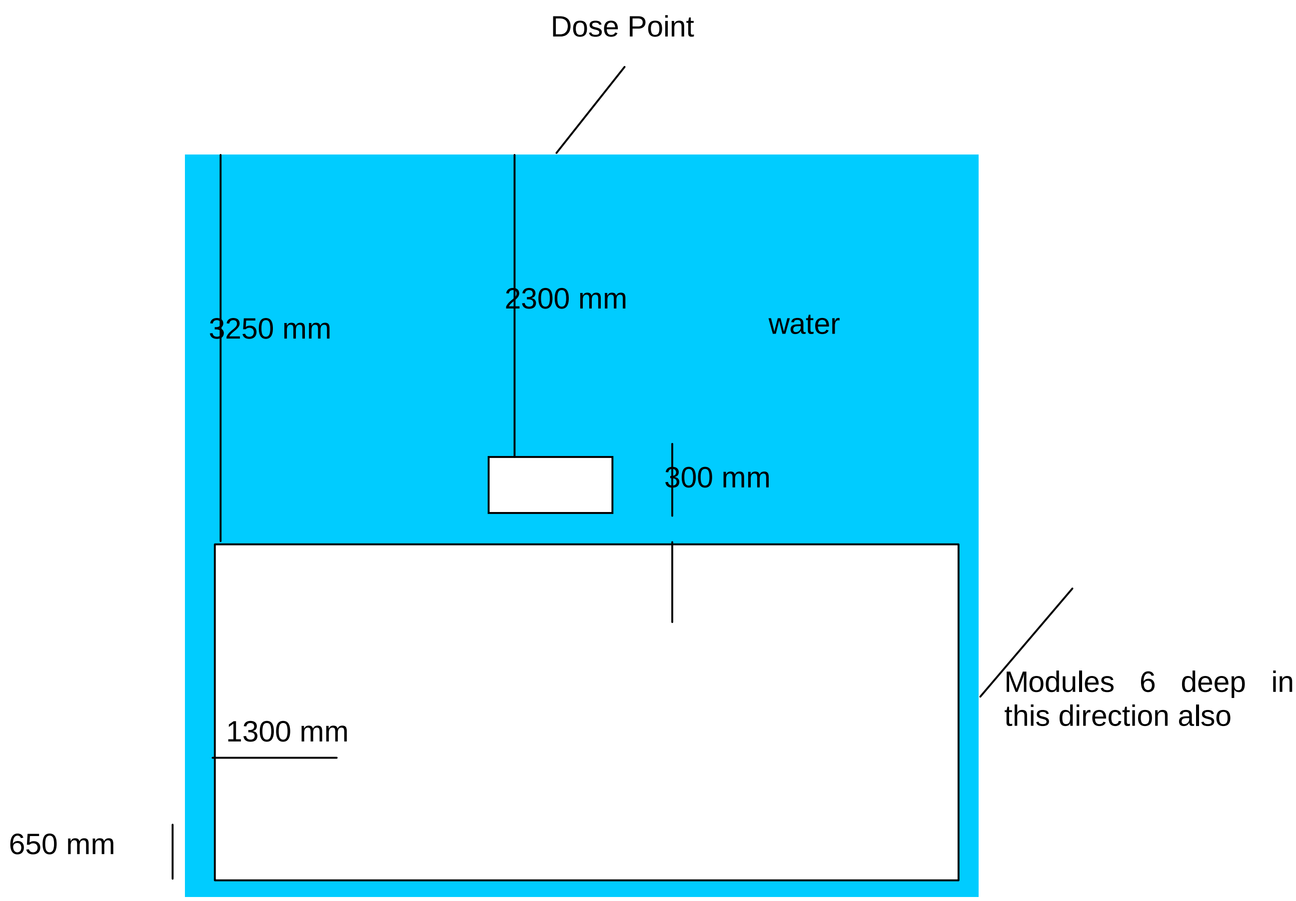


Figure 8 Section through Calculational Model of Shielded Cart (Not to Scale)

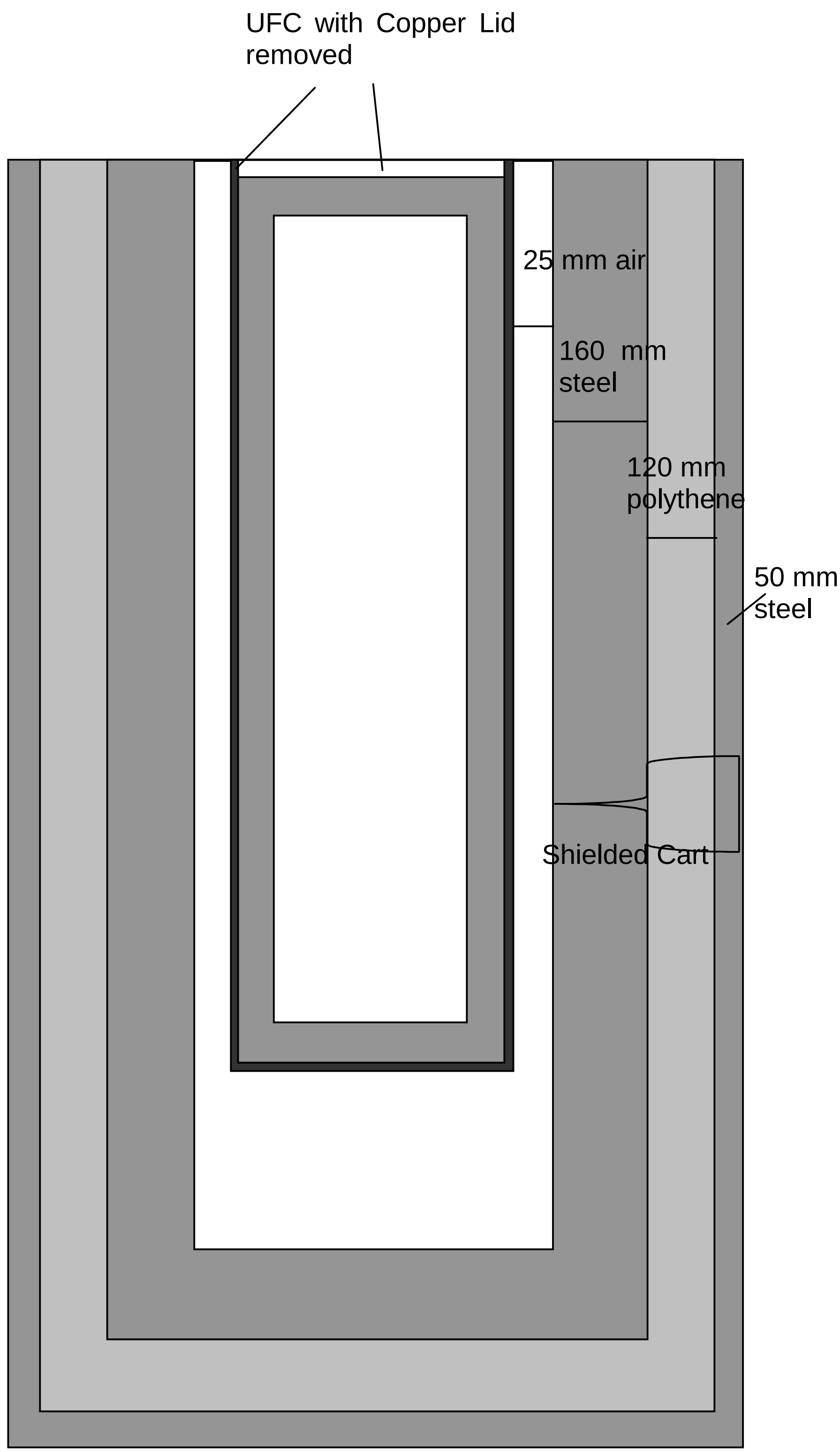


Figure 9 Section through Calculational Model of Shine from UFC in Shielded Cart and Transfer Tunnel Roof (Not to Scale)

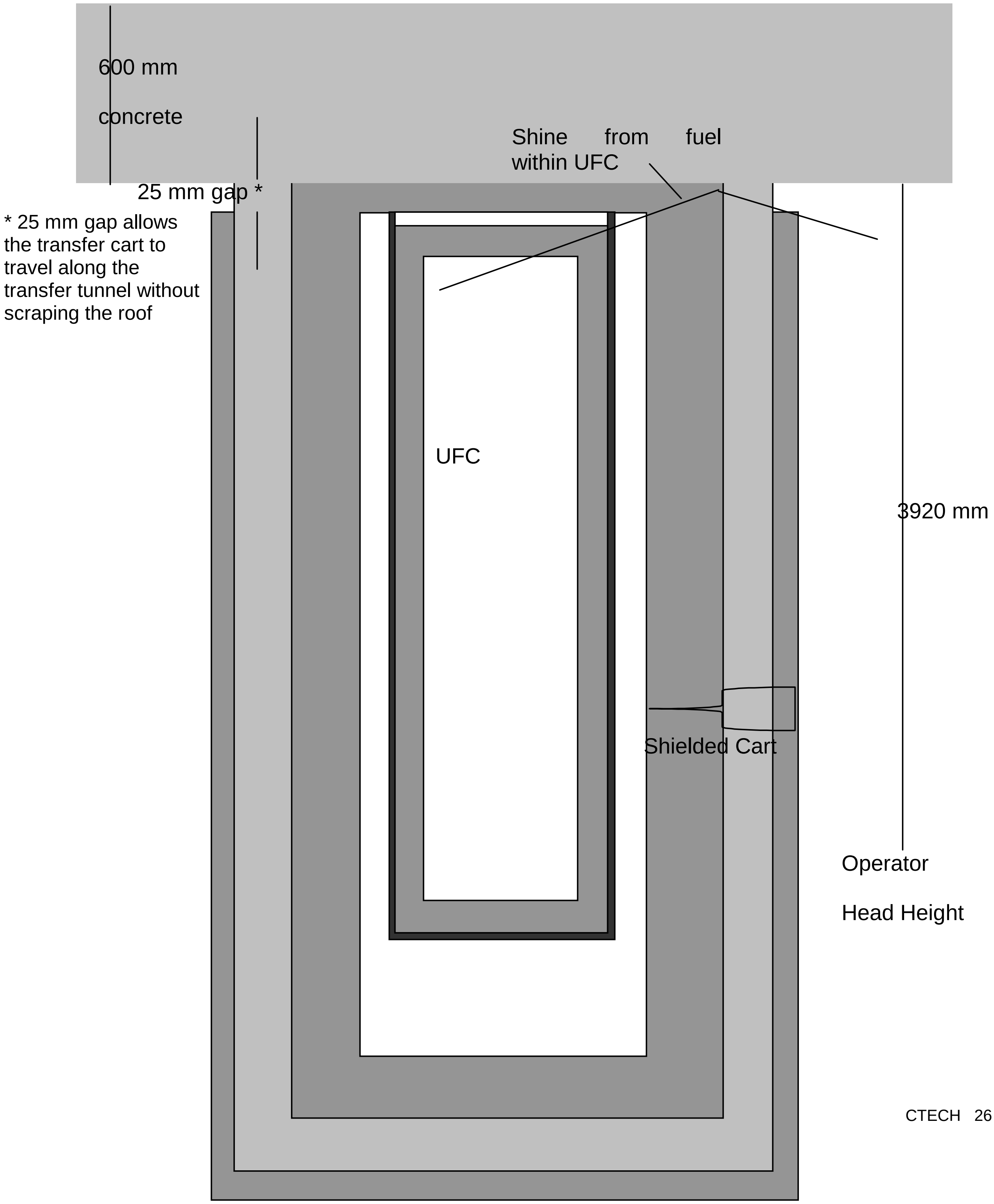


Figure 10 Section through Calculational Model of UFC Raised to Cell (Not to Scale)

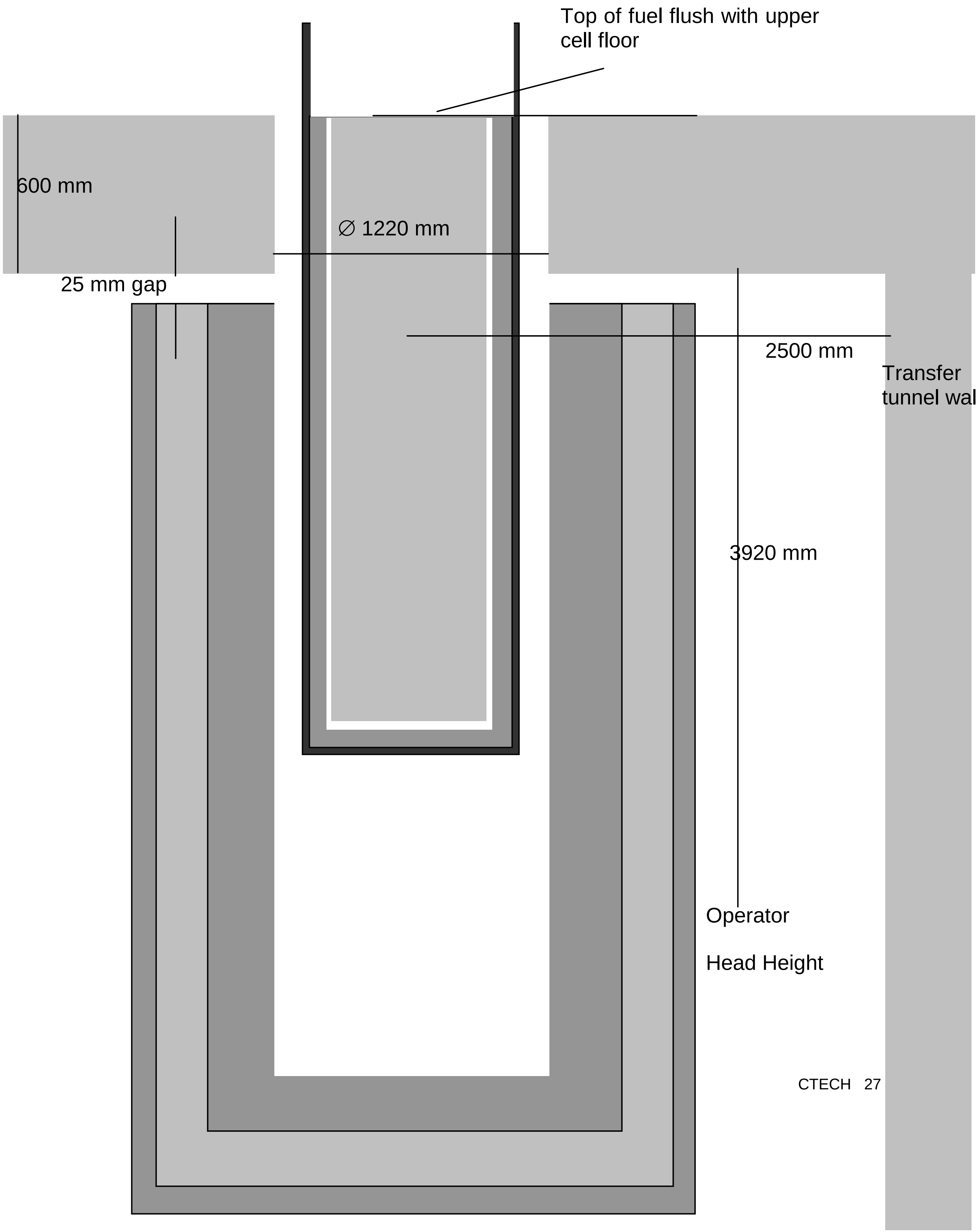


Figure 11 Section through Calculational Model of Baskets Lowered into UFC (Not to Scale)

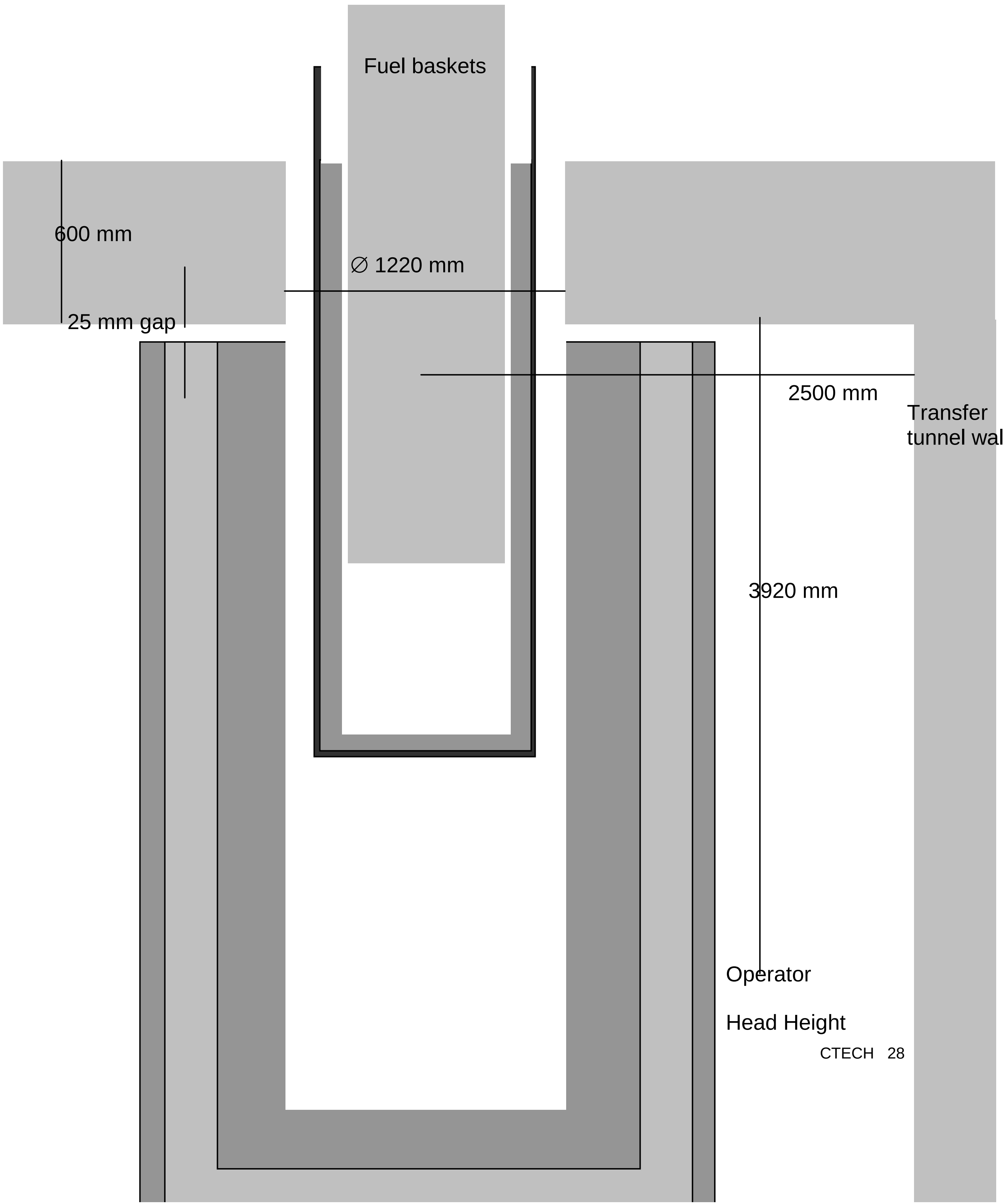


Figure 12 Section through Calculational Model of Sealing Cell (Not to Scale)

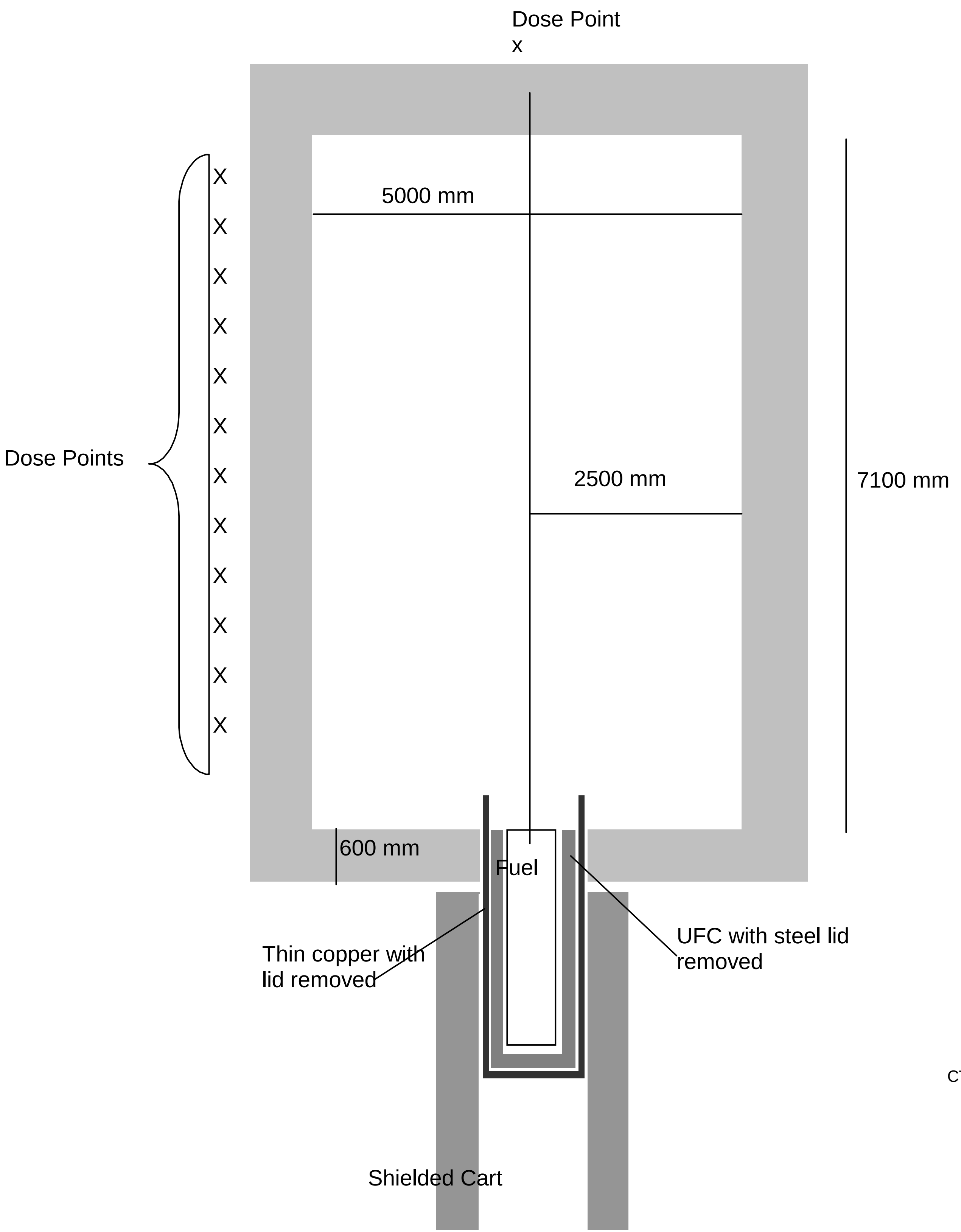


Figure 13 Axial Section through Calculational Model of Emplacement Room (Not to Scale)

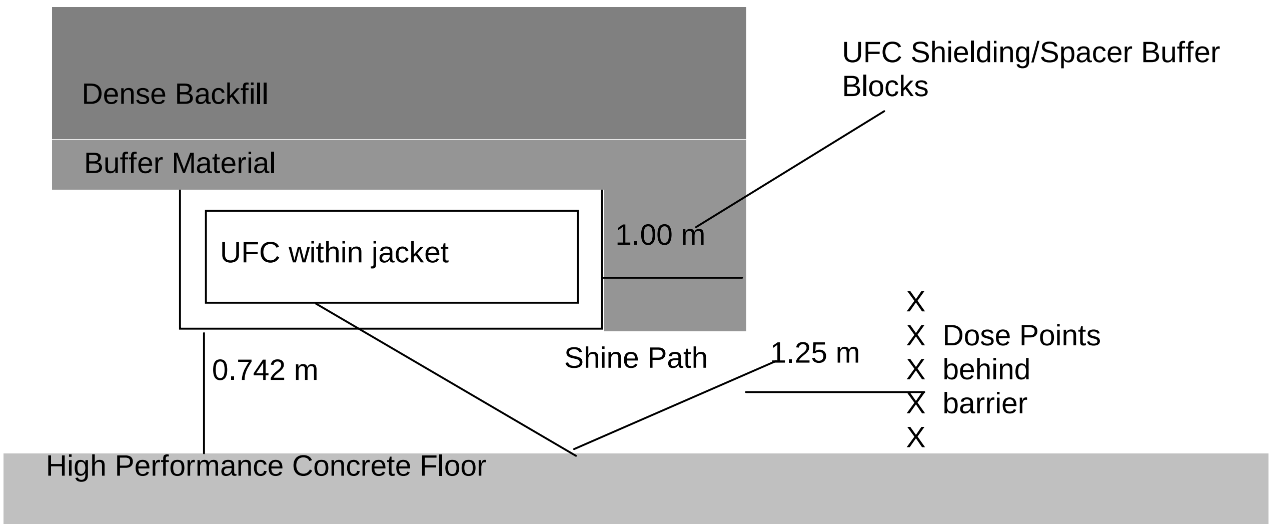


Figure 14 Radial Section through Calculational Model of Emplacement Room (Not to Scale)

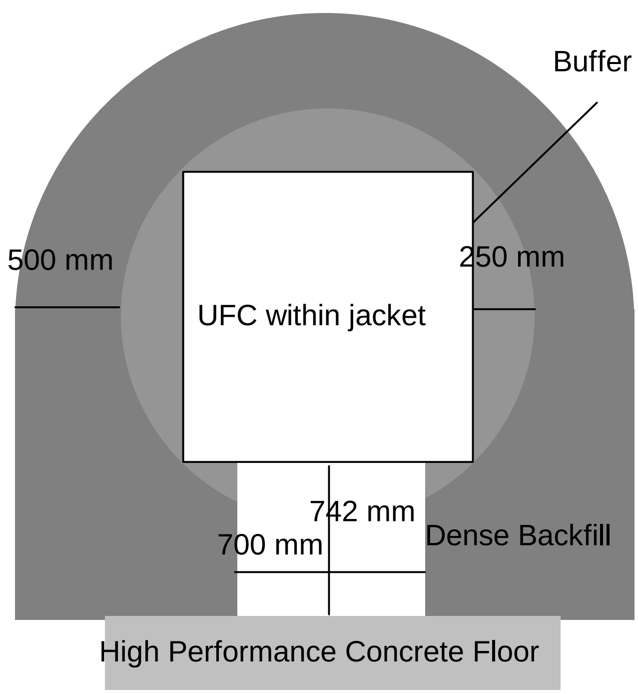
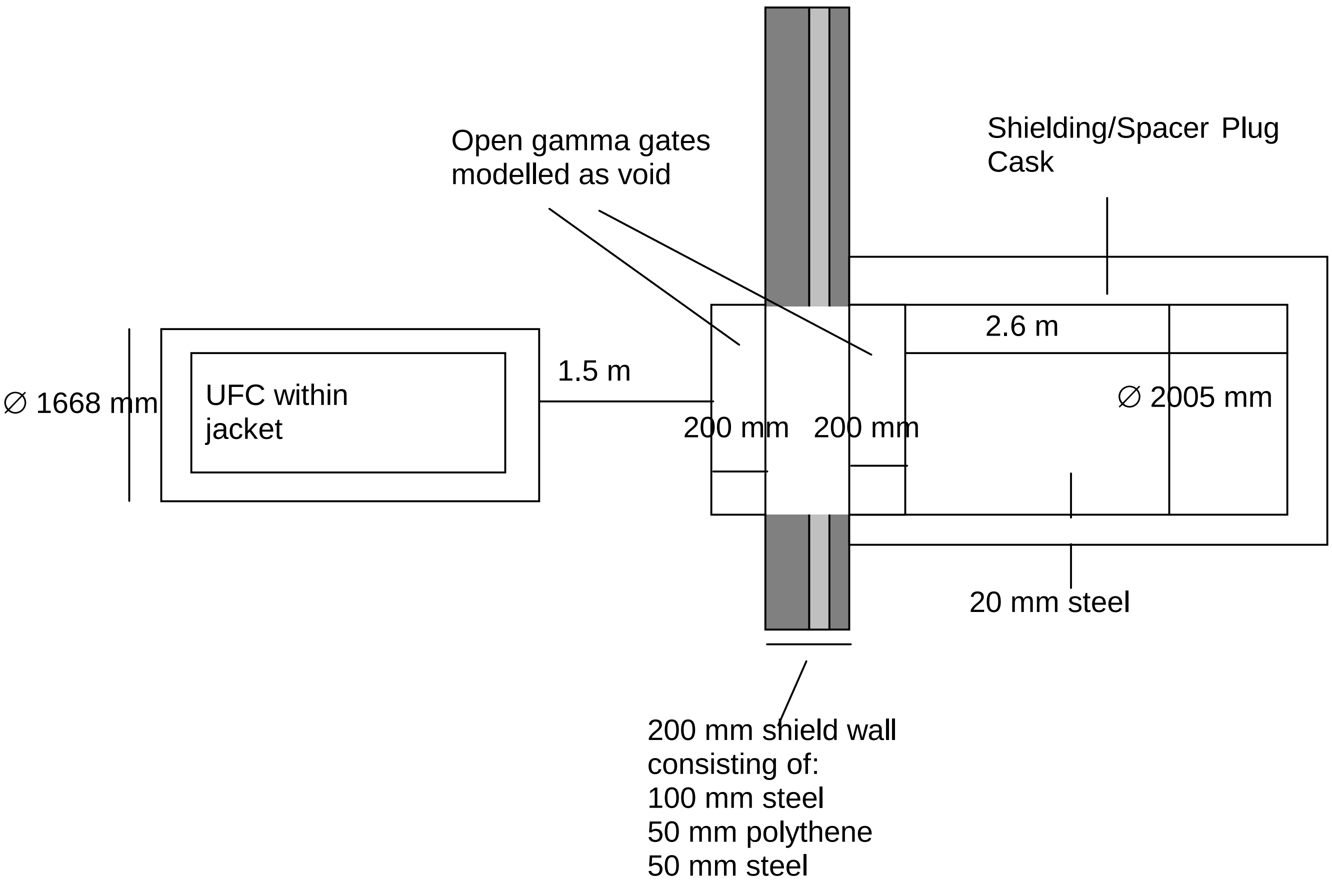


Figure 15 Section through Calculational Model for Shielding/Spacer Plug Cask (Not to Scale)



1106/MD18085/REP/01

Radioactive Materials Management

Deep Geologic Repository Conceptual Design

Annex 4

Repository Layout and Excavation Methods

December 2002

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 .

This document is written solely for the benefit of the Client, for the purpose stated in the Agreement, and the Consultant’s liabilities are limited to those set out in the Agreement.”

Summary

It is proposed that the emplacement of CANDU used nuclear fuel will be undertaken in a deep geologic repository (DGR) excavated in crystalline rock in the Canadian Shield. CTECH has been contracted by Ontario Power Generation (OPG) to review the existing repository design, update the layout and construction method, and prepare a cost estimate for construction of the underground repository.

This report discusses the design and construction of the underground repository. Access to and from the underground facility will be by vertical shaft, with four shafts being constructed in total. The current design concept includes a repository designed to accommodate 3.6 million used fuel bundles excavated at a depth of 1000 m below surface in a sparsely-fractured granite pluton. The repository consists of the waste emplacement area and underground accessways and infrastructure to safely conduct emplacement operations of used fuel in Used Fuel Containers (UFCs) and comprises a system of tunnels and emplacement rooms arranged in four distinct sections in an area of about 1.4 km by 1.4 km. The central access drifts and perimeter tunnels join at opposite ends of the repository where the shafts are located. The shafts comprise:

- Service/Production shaft for transportation of personnel, equipment and supplies
- Maintenance Facility Exhaust Raise
- Primary Exhaust Raise
- Waste Shaft for transportation of the used fuel

All the shafts, except the Primary Exhaust Raise, are located in relatively close proximity to one another in an area designated as the Service Shaft Complex. The Primary Exhaust Raise is located approximately 1.4 km from the Service Shaft Complex at the opposite end of the repository.

Excavation will be by drill and blast methods utilizing engineered blast designs to provide for very smooth wall blasting to minimize the excavation damage zone (EDZ). A comparison of drill and blast techniques and tunnel boring machines (TBMs) has resulted in the conclusion that drill and blast techniques will provide satisfactory EDZ characteristics and provide a more flexible tool than TBMs. Innovative TBMs are being developed, that provide greater flexibility with reduced turning radii compared to conventional TBMs, but these are still considered to be at the prototype stage and are not sufficiently proven in the field to be considered for the development of the DGR at this time.

Excavation will be carried out in phases. The first phase will be an exploration phase involving site selection and construction of an exploration shaft that will later serve as the Service/Production shaft for transport of personnel, equipment and supplies. A second shaft to serve as the Maintenance Facility Exhaust Raise is also constructed during this period, together with other underground facilities and infrastructure including a component test area.

The second phase of construction comprises pre-emplacement development where the main access drifts and perimeter of the repository is developed, the Primary Exhaust Raise and

Waste Shaft constructed and the first campaign of emplacement room excavation completed that consists of 39 rooms. The mining contractor will complete the balance of 65 emplacement rooms over three subsequent campaigns for a total of 104 rooms.

The emplacement room will be 315 m in length and accommodate 108 UFCs in each. The rooms will be 4.2 m high and 7.14 m wide and elliptical in shape. Accessways and other tunnels will be 4.2 m high by 7.0 m wide and rectangular in shape with an arched back.

Emplacement of UFCs and the schedule for campaign mining of the emplacement rooms has been carefully scheduled and planned to permit concurrent activity. Excavation and emplacement both retreat towards the Service Shaft complex with the general airflow being from the Service Raise Complex to the Primary Exhaust Raise. Airflows for emplacement and excavation operations are always maintained separate.

Cask and buffer block movement is planned always to be uni-directional in a clockwise direction. Such an arrangement, as opposed to an unrestricted flow of traffic, is a more safe arrangement and reduces excavation requirements for emplacement room access.

Ventilation requirements for the DGR have been estimated on a basis of the airflows required for a drill and blast method of excavation and air velocities to control the heating effect from the stored UFCs. During emplacement activities the estimated airflow requirement is 240 m^3/s, whereas only 140 m^3/s is required for emplacement activities only.

Although normal excavation strategy will provide for excavation and emplacement activities always to take place at opposite sides of the repository, blast vibration concerns are discussed and possible blast vibration levels estimated. The concern principally relates to potential damage to emplaced UFCs and associated clay-based sealing materials during blasting operations or the likely potential for such damage if professional blasting standards and engineered blasts are not followed. It was concluded that no problem should exist for normal blasting operations when engineered blast designs are used.

Contents

Tables

Appendices

1 Introduction

Within the framework of a project to update the design concept for emplacement of CANDU used nuclear fuel in a deep geologic repository (DGR) excavated in crystalline rock in the Canadian Shield, CTECH has been contracted by Ontario Power Generation (OPG) to review the existing repository design described in documentation prepared by the AECL and Baumgartner et al[1], update the layout and construction method, and prepare a cost estimate for construction of the underground repository.

The current design concept includes a repository designed to accommodate 3.6 million used fuel bundles excavated at a depth of 1000 m below surface, in a sparsely-fractured granite pluton. Access to and from the underground facility will be by shaft.

The updated DGR design concept and cost estimate will be used for a comparison of options for the long-term management of used nuclear fuel in Canada and to initiate a siting process for such a facility, if the government selects the DGR option as the approach to long-term management of used nuclear fuel in Canada.

Following a site selection process, once experimental data is confirmed and the design of the facility is finalized, excavation of an underground repository would commence.

The actual repository excavation process would continue over many years. The repository layout described here consists of four repository sections each containing two emplacement panels. Each panel consists of 13 emplacement rooms connected by a common access drift, with each of the rooms having a capacity of 108 Used Fuel Containers (UFC).

The completed DGR layout as illustrated in Figure 1a indicates the four repository sections to be located adjacent to each other in an overall rectangular shape. In reality, the four repository sections would likely not be laid-out in a regular pattern, but may be separated because of structural discontinuities in the rock mass or other geotechnical considerations. The four sections are bounded by a pillar created by dual access drifts where the sections share a common boundary. The pillars will reduce rock temperatures at the boundaries of the repository sections after UFC emplacement. As rock stability and degradation is a function of temperature, the pillars so created will reduce the temperature of the access drift from which emplacement has not yet taken place and provide a safer working environment that will be of particular value in the case of UFC retrieval. Controlled ventilation airflows will mitigate the temperature increase in the access drifts.

On a basis of operating 230 days per year, it will take approximately 7.5 years to fill each section (26 emplacement rooms) of the repository. On a basis of mining 365 days per year, excavating and preparing 26 rooms for emplacement will require approximately 2.5 years. As a result, a "campaign" mining regime, utilizing mine contractors, has been proposed to excavate and prepare the emplacement rooms on an "as needed" basis.
Excavation of the DGR will utilize mechanized drill and blast mining techniques, with the broken material transported back to a central rock dump located on the surface within the perimeter fence of the DGR. The arrangement of the underground excavations are such that:

[1] Engineering for a Disposal Facility Using the In-Room Emplacement Method, P. Baumgartner, D.M. Bilinsky, Y. Ates, R.S. Read, J.L. Crosthwaite, D.A. Dixon, AECL-11595-96-223, June 1996.

- The transport of all UFCs, and unit trains containing the clay-based sealing materials will be in a clockwise direction to the emplacement rooms. If in the event that campaign mining and used fuel emplacement coincides, the separation of emplacement and excavation activities will minimize the interaction of each activity's traffic flows. The common uni-directional aspect of both activities will provide for ease of traffic flow and will facilitate operation of the facility providing an inherently safer material flow compared to the omni-directional flow described in Reference Document 4[2].
- The ventilation of the repository will allow for the emplacement of UFCs whilst campaign excavation proceeds. In each instance, potential contaminants from both activities will be contained in separate ventilation circuits to provide a safe working environment. In this respect, the ventilation system maintains the concepts developed in Reference Document 4.

2 Design Parameters

2.1 SUMMARY OF DESIGN PARAMETERS

A summary of design parameters is provided in Table 1a and Table 1b.

2.2 EXCAVATION DIMENSIONS

As indicated in Table 1a, the perimeter drifts, emplacement room access drifts and the central access drifts are 7.0 m wide by 4.2 m in height. They are rectangular in shape, with the roof of the tunnels being slightly arched. These dimensions are based upon:

- The provision of adequate and safe clearances for the combined rail car and used fuel cask.
- The provision of adequate clearances for equipment and services used during excavation (compressed air, water, electrical, auxiliary ventilation).

The emplacement rooms are 7.14 m in width and 4.2 m in height. The individual emplacement rooms will be elliptical in shape consistent with the aspect ratio recommended by Baumgartner of 1.7 between the major and minor axes. With this aspect ratio in mind, the dimension of the emplacement room becomes a function of the height requirement to safely transport the used fuel cask within the emplacement room.

Shaft dimensions are also indicated in Table 1a.

[2] Engineering for a Disposal Facility Using the In-Room Emplacement Method, pg. 39, P. Baumgartner, D.M. Bilinsky, Y. Ates, R.S. Read, J.L. Crosthwaite, D.A. Dixon, AECL-11595-96-223, June 1996.

Table 1 a – Excavation Design Parameters

Item		Unit	Comment
Contractor Excavation Schedule			
Number of Days per Year	365	Days	
Shifts per Day	3	Shifts	
Hours per Shift	8	Hours	
Excavation Data			
Waste Shaft	6.15	m	Circular, internal diameter
Service/Production Shaft	7.3	m	Circular, internal diameter
Maintenance Facility Exhaust Raise	3.96	m	Circular, internal diameter
Primary Exhaust Shaft	3.66	m	Circular, internal diameter
Perimeter Access Drift Dimension	4.2 x 7.0	m	Rectangular, arched back
Central Access Drift Dimension	4.2 x 7.0	m	Rectangular, arched back
Panel Access Drift Dimension	4.2 x 7.0	m	Rectangular, arched back
Emplacement Room Dimension	4.2 x 7.14	m	Elliptical
UFC Transport Turning Radius	25	m	Centreline
Minimum Distance Emplacement Rooms to Perimeter Access Drift	45	m	Centreline to centreline
Minimum Distance Emplacement Rooms to Central Access Drift	45	m	Centreline to centreline
Distance between Emplacement Rooms	45	m	Centreline to centreline
Distance between Emplacement Room Ends	22.7	m	Centre to centre perimeter drifts
Total Width of Emplacement Area	1358	m	Centre to centre upper-most panel
Total Length of Emplacement Area	1343	m	access to lower-most panel access drift

Table 1b – UFC Emplacement Parameters

Item		Unit	Comment
UFC Emplacement Schedule			
Number of Days per Year	230	Days	46 Weeks at 5 days per week
Shifts per Day	2	Shifts	
Hours per Shift	8	Hours	Shift duration reduced by 1 hour to 7 hours to accommodate underground travel time
UFC Emplacement Data			
Number of Emplacement Rooms per Section	26	Room	As per CTECH Document[3]
Number of UFCs per Emplacement Room	108		
Average Number of UFCs per Day	1.6		
Emplacement Room Data			
Container and Buffer Material Length (pairs)	5.13	m	As per CTECH Document
Number or Pairs per Emplacement Room	54	m	
Length of Room for UFCs and Buffer Blocks	277.02	m	
Buffer Block Shielding at End of Room	1	m	
Concrete Bulkhead	12	m	
Room Access Turning Radius	25	m	
Total Room Length	**315.02**	**m**	

[3] Initial UFC Design Outline (Rev. C), January 2002

3 DGR Excavation Development

3.1 SITING PHASE PLAN

The Siting Phase would 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 would 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 characterization activities would 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 characterization activities would 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 would be prepared for each site being evaluated. Design work would be completed for the surface and underground facilities primarily to establish the access, utility and infrastructure requirements. These requirements would be considered during site screening to ensure that they could be met at potentially suitable site locations in the areas selected for detailed evaluation. Details of the environmental and repository monitoring programme would also be developed, and the plan to incorporate this programme into subsequent site evaluation activities would be prepared during site screening. Following the selection of a preferred site, a preliminary repository design specific for the site would be completed and approved prior entering into the environmental assessment process.

The implementing agency would be required to demonstrate, during the environmental assessment process, that there would be no adverse impact on the environment resulting from the construction, operation, decommissioning and closure of the repository, and during the post-closure period. Whilst there would inevitably be much focus on the radiological components of environmental impact, the more conventional environmental concerns would also be addressed. A comprehensive environmental survey to measure and record the current background conditions at the proposed site would be conducted.

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

3.2 CONSTRUCTION PHASE PLAN

The Construction Phase would involve constructing the infrastructure and surface facilities needed to dispose of nuclear fuel waste, the underground access ways and service areas, and a portion of the underground disposal rooms. However prior to the start of full-scale construction there would be a period of underground evaluation in the Underground Characterization Facility (UCF). 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 repository. The Construction Phase would begin with the receipt of regulatory approval to start construction and would end when the first used fuel is received at the site.

3.2.1 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 would 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 waste emplacement
- To perform geotechnical mapping, characterization and component testing for deriving engineering design values and constraints, and
- To develop final construction and operation designs for the repository and its component that may differ from the symmetrical layout indicated in Figure 1a due to the presence of faults or other geological features.

The underground evaluation will be accomplished in three phases. Figure 1e (i) demonstrates the initial phase to establish the infrastructure for test work to be undertaken to determine the characteristics of the rock mass. From a logistics perspective approximately 3700 m 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
- Mechanized 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 vault 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 disposal 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 that pass through and around the repository, 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 characterize 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

- Characterization 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 approximately 2,000 m of exploration sized tunnels and begin rock mass behavioural testing in the CTA

- Conduct appropriate research and development as needed, and

- Produce the detailed engineering specifications and plans for the construction of the DGR facility.

After the completion of the characterization studies of the underground facility, in which the central access, perimeter and panel access tunnels are developed (Figure 1e(ii)) 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 1b demonstrates the support infrastructure that will be in place in the Service Shaft Area, whilst Figure 1c 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 (characterization 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 repository and its components after excavation of the CTA and prior to completion of this project phase.

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

3.2.2 Facility Construction

After the underground evaluation studies have been carried out and the final designs completed the construction of the full-scale repository facility can begin. The purpose of the construction is to build all the facilities necessary for the operation of the repository 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 Used Fuel Packaging Plant (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 disposal rooms (i.e. 1.5 panels), 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

- Characterize 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, as needed, and development, and

- Prepare the detailed safety assessment 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 1e(iii) shows the vault layout at the end of the Construction Phase.

3.3 OPERATION PHASE PLAN

The Operation Phase would involve receiving nuclear fuel waste 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 repository there would be a period of extended monitoring.

3.3.1 Emplacement of Disposal Containers

The purpose of the Operation Phase is to emplace and seal the UFCs in the repository. 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), and

- 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 panel, on one side of the central access tunnel, room preparation and room excavation takes place in another panel on the other side of the central access tunnel. It is envisaged that room preparation and excavation will be of shorter duration than emplacement and therefore there will be periods where ongoing construction is suspended with the construction being carried out on a campaign basis. Two separate ventilation systems are 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 are 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 A and all the rooms in Section B will have been excavated and prepared. At the beginning of the Operation Phase, block placement and waste emplacement starts 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, followed by the lower panel of Section D (see Figure 2a).

The principle of segregating the radiological operations from the non-radiological operations is maintained. The central access tunnels are twinned to reduce the potential for traffic accidents, particularly with radioactive materials and to provide a secondary route for worker and material transport. The emplacement operations retreat from the Upcast Shaft Complex towards the Service Shaft Complex. Thus the work progresses from potentially contaminated areas towards clean areas with a fresh air source, enhancing the environment for workers.

At the end of each cycle when the waste emplacement operations are completed in a room panel, each functional activity is moved to the next sequence of rooms in the opposite Section across from the central access tunnels. Figure 2a through to Figure 2d.

3.3.2 Extended Monitoring

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

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

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

3.4 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 repository, 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 collar houses, and

- 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 and the 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 and install shaft sealing bulkheads at strategic locations

- Decontaminate and dismantle the UFPP and associated facilities

- Dismantle all other surface facilities, services and infrastructure, and

- Prepare the 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.

3.5 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 post-closure period

- Recondition the site surface to a state suitable for public use with the provision that subsurface use be restricted, and

- Prepare the safety assessments and apply for approval to release the site.

The activities and related data for this phase is the same as described for the facility described in **Annex 3** and as previous studies[4] Closure work is assumed to occur over 1 shift/day, 230 days per annum.

4 Emplacement Room Development and Used Fuel Emplacement Sequencing

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

- The excavation must be done in such a manner that the structural integrity of the adjacent panel is not compromised
- The emplacement, hence excavation, will retreat towards the Service Shaft Complex
- Separated ventilation flows from emplacement and mining operations, isolating the blasting fumes, diesel fumes and dust from the excavation process are all key issues
- Initially the mining contractor would excavate 39 emplacement rooms. The location of these rooms would be in the upper and lower half of Section A and the lower half of Section B (see Fig. 2a). Task allotment in the excavation process includes:
- Pouring of concrete floors in all excavated emplacement rooms
- Establishing rail track access across the emplacement panel and a minimum of four 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 is isolated to the left of the central access corridor (Fig. 2b), allowing the campaign excavation to proceed on the right-hand side of the repository.

During the second excavation campaign (Fig. 2b) an additional 26 rooms will be provided. The excavation activity will be isolated to the upper panel of Section B and the lower panel of Section D. As in the first excavation campaign, completion of the excavation work will include:

- Pouring of concrete floors in all excavated Emplacement Rooms.
- Establishing rail across the Emplacement Panel and a minimum of four Emplacement Rooms.

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

[4] Engineering for a Disposal Facility Using the In-Room Emplacement Method, pg. 39, P. Baumgartner, D.M. Bilinsky, Y. Ates, R.S. Read, J.L. Crosthwaite, D.A. Dixon, AECL-11595-96-223, June 1996.

The time differential will allow emplacement activities to be completed in Section A and move into the upper Section B/lower Section D emplacement area.

When the third excavation campaign commences (Fig. 2c), Section C will be the centre of mining activity. Since the excavation takes place along two emplacement panel accessways excavation time will be 15 days longer at 949 days (Appendix C), but well within the time required to emplace 2,808 UFCs in Section B/D. In providing an additional 26 emplacement rooms, Figure 2d demonstrates the excavation sequence recommended by Baumgartner et al[5] in relation to the emplacement activity, and those portions of the repository that are filled and sealed to entry. The central access corridor will be utilized for fresh air delivery, with fresh air splitting from this central airway to the perimeter drifts (Fig 1d).

The final section to be excavated will be the upper panel of Section D. Since only 13 Emplacement Rooms are to be excavated, approximately 1.2 years on a basis of operating 365 days per year, will be required to complete the facility excavation.

For safety purposes, the ventilation in areas of the facility where UFCs are being transported or handled during emplacement is completely separate from that of the areas where excavation activities are in progress.

5 Cask and Buffer Block Movement

Due to the size of the UFC, casks to the emplacement room will require a 25 m centreline turning radius. Entrance to the emplacement room will not be “Y” shaped as described in previous documentation[6] so as to prevent the creation of zones of potential rock weakness within the DGR. Therefore, ingress and egress to and from the emplacement room panels will be in one direction. For safety reasons, to the extent possible, traffic flow will be uni-directional, moving in a clockwise direction to eliminate the possibility of head on collisions with other rail traffic (buffer material, concrete, etc.).

In transporting the casks and materials to the emplacement site, rail cars will be towed. Since each emplacement panel will have its own access drift (Figure 1a), the combination of single emplacement room access and uni-directional traffic flow, will allow the cask and buffer material train to be drawn past the entrance, then backed in.

Upon dispatching its material, the train will return to the Waste Shaft area either by the central access or perimeter drift in a clockwise direction, according to the established uni-directional flow of the cask transportation system. Figure 2e illustrates traffic flows during room emplacement activities in the Upper and Lower Panels of Section B and D respectively, whilst emplacement room excavation is being undertaken in Section C.

Marshalling drifts have been established above the Waste Shaft’s perimeter access drift, to provide space for organizing “unit trains” of clay-based sealing material. The marshalling drift to the right of the Waste Shaft will be for full rail cars, whilst the marshalling yard to the left of the Waste Shaft will be utilized as a temporary storage area for empty rail cars returning from the emplacement room. Within the Waste Shaft Station there is a cask car storage area, sized to

[5] Engineering for a Disposal Facility Using the In-Room Emplacement Method, pg. 39, P. Baumgartner, D.M. Bilinsky, Y. Ates, R.S. Read, J.L. Crosthwaite, D.A. Dixon, AECL-11595-96-223, June 1996.
[6] Engineering for a Disposal Facility Using the In-Room Emplacement Method, Fig. 37, pg. 130, P. Baumgartner, D.M. Bilinsky, Y. Ates, R.S. Read, J.L. Crosthwaite, D.A. Dixon, AECL-11595-96-223, June 1996.

provide sufficient storage for the UFC cask and clay-based sealing material cars required on a daily basis.

6 Ventilation

6.1 VENTILATION REQUIREMENTS

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

- The air volume requirement to provide proper dilution of excavation contaminates
- Air velocities to control the heating effect from emplaced UFCs on the exposed tunnel surfaces.

Based upon CTECH's experience, should sufficient fresh air be supplied to ventilate operating diesel powered equipment underground, then the issues pertaining to radioactive materials (radon gas and radon daughter by-products) will also be met.

In Reference 4, the underground facility ventilation rate was not specified. In addition, with the current preference for a "campaign" excavation process, where a mining contractor would be mobilized/demobilized as required, the quantity of diesel powered mining and excavation equipment may vary. On the basis of the equipment fleet proposed on page 51 of 443 (WEDS) of the November 14, 2001 Cost Estimate[7] prepared by the Nuclear Waste Management Division of OPG, approximately 1125 kW of equipment is listed. Utilizing Ontario Government legislated air requirements[8] of 0.06 $m^3/s/kW$, 67.5 m^3/s of air will be required for diesel-powered equipment utilized in the excavation process. Since this equipment may not be centralized along one emplacement panel access drift and because of its highly mobile nature, CTECH recommends increasing this air volume required by approximately 50% to 100 m^3/s. As this equipment is expected to work in more than one emplacement panel, equal amounts of air must be allotted to each panel.

Utilizing heat stress tables[9] and reviewing temperature data for Pinawa, Manitoba and Kenora, Ontario, the highest average daily maximum surface air temperature[10,11] recorded during the "summer months" – May through September was 25^o C (77^o F).

In this instance, if input air temperatures were 25^o C, and ambient tunnel wall temperatures were 35^{o}C, maintaining a minimum air velocity of 0.5 m/s in the central and perimeter drift accesses would keep the effective temperature (air) in the drift below 27^o C[12,13]. Considering cross-

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[7] Cost Estimate for Disposal Facility for Used Fuel Owned by Ontario Power Generation, New Brunswick Power, Hydro Quebec and Atomic Energy of Canada Limited – Detailed Cost Information at Lowest Level of WBS File: 06819-03780 (UFM) T10, 14 November 2001

[8] Occupational Health and Safety Act and Regulations for Mines and Mining Plants, Section 183.1(3), Ontario Ministry of Labour, 1996

[9] Fan Engineering – An Engineers Handbook On Fans and Their Applications, R. Jorgensen – Editor, 8th Edition, Buffalo Forge Company, Buffalo, New York, 1984.

[10] Pinawa WNRE, Manitoba Temperature Data, Environment Canada, 1963 to 1990

[11] Kenora A, Ontario Temperature Data, Environment Canada, 1938 to 1990

[12] Industrial Ventilation – A Manual of Recommended Practice, 13th Edition, American Conference of Governmental Hygienists, Lansing Michigan, pg. 3-1 – 3-7.

sectional area of these drifts, the 0.5 m/s velocity is equivalent to air volumes of 15 m^3/s. Emplacement worker exposures to these "hot" areas would be minimal, since these "hot" areas are on the "exhaust" side of the repository where air velocities would be in excess of 0.5 m/s, and ventilation for temperature control becomes less demanding.

During the actual UFC emplacement activity, the elliptical shaped room would require 12 m^3/s of airflow utilizing the 0.5 m/s velocity criteria. It is noted that the Reference 4[14] documentation specifies 14 m^3/s. Utilizing the Reference Document 4 air volume and assuming five (5) emplacement rooms are being ventilated at any one time, 70 m^3/s would be a minimum air volume required per emplacement panel. The 14 m^3/s ventilation rate would allow the operation of 233 kW of diesel-powered locomotives to operate in each emplacement room.

Allowing for room excavation and emplacement to take place simultaneously and considering the air requirements of the Service Shaft Complex, the DGR's air volume requirements of the DGR is provided in Table 2.

Table 2 DGR Estimated Air Volume Requirements

Location	Emplacement Activities Only	Emplacement and Excavation Activities
Service Shaft Complex Waste Shaft (upcast) Maintenance Complex Shaft (upcast)	 20 m^3/s 50 m^3/s	 20 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**

6.2 VENTILATION FACILITIES

With respect to the positioning of the main fans, exhaust fans will be required on:

- Maintenance Facility Exhaust Raise
- 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

[13] Fan Engineering – An Engineers Handbook On Fans and Their Applications, R. Jorgensen – Editor, 8th Edition, Buffalo Forge Company, Buffalo, New York, 1984 pg. 20-2 – 20-8.
[14] Engineering for a Disposal Facility Using the In-Room Emplacement Method, pg. 41, P. Baumgartner, D.M. Bilinsky, Y. Ates, R.S. Read, J.L. Crosthwaite, D.A. Dixon, AECL-11595-96-223, June 1996.

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.

Estimated duties are:

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

During the non-heating season the surface Service Shaft fan will be turned off.

6.3 DISCUSSION ON THE PRIMARY EXHAUST VENTILATION RAISE

The maximum air volumes to be exhausted, estimated in Section 5.1, are approximately half those reported in the 1992 AECL Report[15] (240 m^3/s versus 462 m^3/s). For most part of the operating life of the facility the 140 m^3/s required during "emplacement activities only" represents approximately 30% of the previously prescribed air requirement.

Differences occur due to:

- A change in emplacement method
- A change in backfilling methods utilizing bulldozers to place and wheeled compactors to prepare the bentonite cover
- Method of cask transportation (track versus trackless)
- Cask size and weight
- DGR development (continuous versus campaign extraction) involving development of more rooms at any one time across more panels, which requires more diesel powered equipment. In the AECL 1992 report, 3,471 containers[15] per year were to be placed underground. Presently less than 400 cask movements per year are now required.

With the reduction in air volume requirements, CTECH recommends eliminating one of the primary exhaust raises. With the advent of the "campaign excavation" concept, the requirement for a dual exhaust raise system becomes unnecessary.

Utilizing the "campaign excavation" methodology, where continual on-going mining is not taking place, the need for a separate exhaust raise system for each activity (excavation and UFC emplacement) becomes redundant. In Figures 2a through 2d, in which the ventilation air flows are superimposed on the excavation, UFC emplacement and emplacement room sealing process, it is demonstrated that the separation of exhaust airflows from each activity are achieved. During the initial UFC emplacement sequence, UFC emplacement is such that the emplacement process retreats from exhaust towards fresh air (Service Shaft Complex). When campaign mining recommences, the emplacement activity is over 1.3 km from where the two exhaust flows merge, prior to exhausting up the single ventilation raise, which now serves as the Exhaust Shaft Complex described in Reference 4.

[15] Used Fuel Disposal Centre – A Reference Concept Vol. I, II, III, AECL-CANDU, J.S. Redpath Mining Consultants, Golder Associates, The Ralph M. Parsons Company, April 1992, pg. 103 and 54.

In the AECL 1992 Report, the emplacement room excavation and preparation were on going, requiring increased air volume requirements. Under this operating plan the dual primary exhaust raises serve two purposes:

- Provided a “clean” exhaust air flow to the HEPA (High Efficiency, Particulate Air) radioactive filters, whilst allowing the “dirty” exhaust airflow from the continuous excavation process not to blind the pressure sensitive HEPA filtration system
- Reduced the underground facility’s airflow resistance.

HEPA air filtration systems are capable of filtering sub-micron particulate matter. These filters are made of porous paper containing a high percentage of glass fibres less than 1 μm in diameter, pleated into a rigid frame. Special HEPA filters are guaranteed to be 99.9999% efficient for 0.3 μm particles. To achieve this kind of filtering efficiency HEPA filters are limited to a 1.27 m/s face velocity at 250 Pa.

On the basis of the AECL 1992 report, the emplacement panels’ exhaust shaft will handle 178 m^3/s, whilst the excavation panel exhaust fan will handle 190 m^3/s. In this instance, the minimum surface area of approximately 140 m^2 of filtration-media area would be required to handle the 178 m^3/s. If a single raise was utilized with the AECL 1992 airflows, the HEPA filter would require at least 290 m^2 (~3,120 ft^2) of filtration-media area. In addition, a pre-filter would also be required to eliminate excessive dust loading and premature ‘blinding” on the HEPA filter from the excavation process, resulting in a large, cumbersome facility. CTECH would not recommend this configuration for the airflows specified in the AECL 1992 report.

With the underground facility’s reduced air volume requirements, the maximum air volume exhausting a single raise would be 170 m^3/s when “emplacement and excavation activities” coincided, and reducing to 70 m^3/s when “emplacement activities only” were in progress. Under this operating regime, the HEPA filtration system would be constructed in such a manner that a variable speed, variable pitch fan could, if the need arose, exhaust into the HEPA filter system. This would be controlled by a series of control gates or dampers directing the facility’s exhaust to the HEPA filtration system. Since the air volume is less than what was to be handled by the AECL 1992 reports emplacement panels’ exhaust shaft, a slightly smaller or similarly sized emergency (stand-by) HEPA filtration system would be activated as air exhaust volumes and conditions demanded.

6.4 MINE EGRESS

In addition, the AECL 1992 report indicated that the upcast ventilation shaft that provides ventilation to the excavation panels would be equipped with an emergency evacuation hoisting system[16], thereby providing an alternate means of egress from the DGR.

In the AECL 1992 report, the Excavation Panel Exhaust Raise was used as a second means of egress. CTECH is of the opinion that an exhaust raise, which may be contaminated with smoke and blasting fumes**,** should not be used for this purpose. An alternate means of egress is required for various circumstances, including:

[16] Used Fuel Disposal Centre – A Reference Concept Vol. I, II, III, AECL-CANDU, J.S. Redpath Mining Consultants, Golder Associates, The Ralph M. Parsons Company, April 1992, pg. 53.

- Access to Normal Egress: In this example the Service Shaft hoist/conveyance is not available for service due to mechanical problems
- Emergency Situation (life threatening): In this example a mine fire isolates the workforce underground
- Location of Workers with respect to the Underground Workings: In this example the need would be based upon logistics and perhaps a life-threatening situation. It may be cheaper to provide an alternate means of ingress and egress versus extended travel times to the jobsite. Alternatively, if the majority of workers are in an area of limited egress opportunities, an approved man-cage for emergency egress can be fitted to the Waste Shaft conveyance or the skip compartment in the Service Shaft. In the event of an emergency situation such as a mine fire, utilizing an exhaust shaft/raise as a means of escape is not the preferred choice.

To safeguard underground miners and emplacement workers in the advent of an underground fire or other emergency situation, CTECH recommends the use of strategically placed permanent and portable refuge stations. Such facilities are mandatory in an underground facility according to Ontario's Occupational Health and Safety Act and Regulations for Mines and Mining Plants R.R.O. 1990, Regulation 654, and are recommended for the DGR. The strategic placement of refuge stations will reduce worker risk in the event of an underground fire providing a means of retreat to a safe location, especially when, for instance, the workers may be trapped behind a fire. The affected workers, upon notification would retreat to such a facility and wait either for rescue or release from the refuge station by properly trained (Ontario Mine Rescue) individuals.

> *Note - The Ministry of Labour have been demonstrating the use of portable refuge stations in Provincial Mine Rescue competitions since 1991.

With respect to the location of the workforce, as the OPG's operation proceeds, the workforce, emplacement and excavation personnel will be retreating from the Exhaust Shaft Complex towards the Service Shaft Complex. As a result, CTECH recommends that an alternate means of egress be established in the Service Shaft Complex by providing the ability for the Service Shaft Skip Compartment and for the Waste Shaft UFC conveyance to be quickly converted to "man-carrying" status in the event of unusual circumstances. In the case of the Service Shaft's skip compartment conversion, a man-carrying insert can be placed and secured within the rock skip and manual conveyance signals installed at each loading and unloading station. In the case of the Waste Shaft conveyance, an appropriate sized "man-cage" could be positioned and secured within the confines of the Waste Shaft conveyance.

7 Conclusions and Recommendations

Excavation of the DGR is recommended to be by drill and blast methods utilizing engineered blast designs to provide for very smooth wall blasting to minimize the EDZ. A comparison of drill and blast techniques and TBMs has resulted in the conclusion that drill and blast techniques will provide satisfactory EDZ characteristics and provide a more flexible tool than TBMs.

Excavation is recommended to be carried out in three phases. The first phase will be an underground evaluation phase involving site selection and construction of an exploration shaft, CTA and other underground infrastructure. The second phase comprises the balance of the planned shafts and access tunnels and the commencement of emplacement room excavation and installation of services for emplacement. The third phase comprises the operations phase of the DGR when the remaining emplacement rooms are constructed. Excavation of the emplacement rooms in the third phase is intermittent and conducted by means of mining campaigns by a mine contractor.

The emplacement rooms are recommended to be 315 m in length and accommodate 108 UFCs in each. The rooms will be 4.2 m high and 7.14 m wide and elliptical in shape. Accessways and other tunnels will be 4.2 m high by 7.0 m wide and rectangular in shape with an arched back.

The DGR construction schedule calls for concurrent emplacement of UFCs and campaign mining. Excavation and emplacement will both retreat towards the Service Shaft complex with the general airflow being from the Service Raise Complex to the Primary Exhaust Raise. Airflows for emplacement and excavation operations will always be maintained separate.

Cask and buffer block movement will always be uni-directional in a clockwise direction. Such an arrangement, as opposed to an unrestricted flow of traffic, is a more safe arrangement and reduces excavation requirements for emplacement room access.

Ventilation requirements for the DGR will be based on the airflows required for a drill and blast method of excavation and air velocities to control the heating effect from the stored UFCs.

Although normal excavation strategy will provide for excavation and emplacement activities always to take place at opposite sides of the repository, there is a concern related to potential damage to emplaced UFCs and associated clay-based sealing materials during blasting operations or the likely potential for such damage if professional blasting standards and engineered blasts are not followed. Accordingly, it is recommended that blast vibrations be monitored as a precautionary measure.

APPENDIX A

Mining Construction Techniques

APPENDIX A

Mining Construction Techniques

Introduction

The Deep Geologic Repository (DGR) is proposed to comprise of a series of underground rooms and access tunnels excavated in a granitic pluton at a depth of 1000 m below surface. Geotechnical studies have recommended that the storage rooms cross section be elliptical to minimize the effect of the expected non-isotropic rock stresses.

The DGR Design Update Report has chosen an elliptical cross-section emplacement room with approximate internal dimensions of 7.14 m along the horizontal axis and 4.20 m along the vertical axis, resulting in an aspect ratio of 1.7.

The access tunnels linking the container emplacement rooms are, for the purposes of this study, assumed to be rectangular in shape 10.00 m wide by 4.40 high with an arched back (i.e. of similar dimensions to those assumed in the Baumgartner et al 1996 study). Several factors, including a different assumed fuel inventory, have, however, resulted in different repository dimensions for the current study.

The proposed layout of the DGR (Figure 1a) has an area of 1.78 km^2. The repository is now subdivided into four (4) Sections having each 26 emplacement rooms with a length of approximately 315.02 m.

The purpose of this analysis is to compare the merits of drill and blast (D&B) mining techniques with tunnel boring machine (TBM) techniques, and to recommend which technique should be reflected in the DGR Design Update report.

Geotechnical Considerations

A listing of the major geotechnical considerations is provided below. This report excludes a detailed discussion of these areas.

Important geotechnical factors in selecting a method of excavation relate to:

- Rock mass quality with Rock Mass Rating (RMR) or similar rating system identified
- Rock strength
- Rock stress state
- Water pressure/inflows.

TBM or D&B techniques both require knowledge of these parameters. Important D&B considerations are water inflows, grouting requirements (if any) and ground support.

Practical and Technical Considerations

Rate of Progress

The rate of progress of a D&B, which can range from 3 m to 5 m per day, is dependent on many factors. Holen[17] has expressed the general statement that a good weekly advance for cross sections of 50 m^2 would be 80m and more than 100 m for smaller cross-sections. For TBM, a good production rate per week may be in the range between 150 m and 400 m dependent on the rock conditions, machine parameters and diameter.

D&B can be undertaken on as many fronts as the layout and logistics allows with the use of additional equipment sets. This would be advantageous if speed of construction was of prime importance. However, this is unlikely to be the case. Similar flexibility would also be possible using mobile mining equipment. However, increased capitalization would be necessary.

Rock hardness and degree of fracturing are important factors in determining the rate of progress of a TBM, as are the logistics that accompany the machine. The utilization of the TBM, i.e., actual time spent boring rather than maintenance or other activities, significantly affects overall progress. If rate of progress were solely dependent upon penetration rate (mm/revolution) it would be relatively simple to determine the rate of progress. In papers published by Holen, Bruland[18] and Cigla et al[19], determination of penetration rate in all three papers were a function of:

- Intact rock properties
- Rock mass properties
- Cutter and cutting geometry
- Machine specifications
- Operational parameters.

The first three items are dependent on detailed rock analysis, which is not currently available for the DGR. The assumed uniaxial compressive strength of the granites in which the DGR will be excavated can provide tunnel bore manufacturers insights into expected penetration rates. However, Cigla cautions that mechanical cutting predictions relying only on the compressive strength alone may provide inaccurate results.

In foliated/bedded rock, according to Bruland and referenced by Cigla, the orientation of the foliation planes with respect to the machine advance direction can have a significant effect on advance rates. Lovat of Toronto[20] was contacted by CTECH to discuss TBM advance rates. Lovat reported that it had had some experience in tunnel boring in granites, and taking a conservative approach, thought that with proper geotechnical analysis, penetration rates of approximately 0.6 m/hr could be achieved for circular openings.

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[17] TBM vs. Drill and Blast Tunnelling, H. Holen, Statkraft AS

[18] Prediction Model for Performance and Cost, A. Bruland, The Norwegian University of Science and Technology, Norway

[19] Application of Tunnel Boring Machines in Underground Mine Development, M. Cigla, S. Yagiz, L. Ozdemir, Excavation Engineering and Earth Mechanics Institute, Department of Mining Engineering, Colorado School of Mines, Golden, Colorado, USA

[20] Lovat, 441 Carlingview Drive, Toronto, Ontario

Items that can affect the borer's performance are:

- Assembly and disassembly of the TBM and back-up (discharge conveyors)
- Excavation of tip stations, niches and branchings
- Rock support in zones of poor quality
- Time for dealing with unexpected rock mass conditions
- Complimentary rock support and lining
- Major TBM breakdowns
- Invert cleanup
- Haulage capacity.

In modeling exercises referenced in the Colorado School of Mines paper (Cigla et al.) a utilization factor of 30% is attributed to boring through granite producing a 5 m per day advance rate.

Downtime on a drill jumbo can be extensive as well, but the cost differential between that of a drill jumbo and a TBM or Mobile Miner is such that it provides the excavation contractor opportunity to have numerous jumbos available as spare units, thereby increasing drilling time at the face.

Experience in Norway[21], and elsewhere, indicates that TBM advance rates can significantly exceed those of D&B, but rates are clearly a function of rock type and ground conditions.

Status of Technology

Control of the excavation damage zone (EDZ) is one of the most significant aspects of DGR design. TBMs will provide very good EDZ characteristics, but D&B can also limit EDZ to acceptable limits through engineered blast designs to provide very smooth walls. According to the published literature, experiments at the Underground Research Laboratory in Pinawa have demonstrated the ability of D&B techniques to provide very good excavation control with relatively little blast damage when controlled blasting techniques and well-designed perimeter blasting techniques are used.

Elliptical shaped rooms are required for stability purposes. Circular shaped emplacement rooms are not an option for the DGR. According to Lovat, the present ability of conventional TBMs to provide an elliptical cross section is limited to those ellipses with a major/minor axis aspect ratio of 2.0 or less. The elliptical shape is accomplished by mounting two smaller cutting wheels outboard of the main cutting wheel. Unfortunately, the shape would not be perfectly elliptical. Lovat suggested a road header might be used to complete the desired shape.

According to a literature search by CTECH, two Japanese[22] [23] companies have applied for patents on a tunnel bore machine with an angled cutting face. The rationale is that when a

[21] TBM vs Drill & Blast Tunnelling, Holen, Statkraft Anlegg AS
[22] Shield Boring Machine, K. Katsumi, Taisei Corp., Patent Number JP 1193691, Application Number JP-19970398929-19971226

sphere is sliced at an angle other than 90^o to one's plane of sight, an ellipse is produced. In reviewing their patent application it seems feasible for soft rock formations, but CTECH is hesitant to recommend this approach for hard ground, where the machines cutter thrust in the advancing direction would be diminished.

According to a literature search carried out by CTECH, Mitsubishi Heavy Industries of Japan has experimented with a twin head TBM. The unit consists of two overlapping heads with cutters in both heads being limited to two diametrically opposed sectors covering approximately 15% of the TBM face area. The spacing is such that there is no interference between the two heads when boring. In 1999, the device was described as experimental[24].

The Mobile Miner produced by Robbins and the Continuous Mobile Miner build by Wirth are more flexible machine that are reported to be able to turn in approximately 11 m. However, both machine have had limited use and in the opinion of CTECH would require more field experience before either could be considered for the DGR application.

Excavation System Flexibility

Holen[25] in his paper cites the conventional TBMs turning radius as the greatest hindrance to flexibility of use. A stripped down TBM can pass a minimum radius of 40 to 80 m, but, with its trailing gear in place, turning radii of 150 to 450 m can be expected. In addition, it can be expected that an additional 3 to 6 weeks of non-production time would be required for each move and re-assembly, once a starting chamber was made available for the re-assembly (Holen). As a result, conventional TBMs are best suited for "line drive" tunnelling, going from point A to B, and according to Holen and Bruland, the minimum economic length of drive for choosing a conventional TBM excavation method is 5 to 6 km.

The Mobile Miner produced by Robbins and Wirth are more flexible tunneling machines compared to conventional TBMs and can turn in approximately 11 m radii. However, in the opinion of CTECH, these machines have had limited use and thus at this time would require more field experience before being considered for the DGR.

The Japanese have also developed TBMs that can turn very tight radii, including right-angle turns. However, as the production machines have only been soft ground and only a few prototype hard rock machines have been build, CTECH considers these machines are not sufficiently proven to be considered for the DGR.

In general, drill jumbos are more flexible than conventional TBMs. The turning radius of a 3-boom jumbo will range from 9 to 11 m depending on boom length. Once on the level and assembled no further work is required other than normal maintenance procedures. Since the drill unit is small in comparison to the TBM, it can excavate the rock mass on many fronts.

D&B techniques allow virtually any underground design to be constructed with there being no impediment to the establishment of relatively tight turning radii to provide an effective 90^o turn-off. It is on this premise that the current layout is based. Although Mobile Miners can turn tight curves, they must still be considered in the prototype arena for hard rock use. Conventional

[23] Large Section Shield Boring Machine, M. Setsuo, Ohbayashii Corp., Patent Number JP 2000120386, Application Number JP-19980298058-19981020

[24] Development of Non-circular Section Mechanism for Hard Rock, F. Ishise et al. Mitsubishi Heavy Industries 1999

[25] TBM vs. Drill and Blast Tunnelling, H. Holen, Statkraft SA

TBM techniques, by contrast, require a turning radius of 150 m or more and thus using such approaches, it will not be possible to excavate emplacement rooms out from the main access in the layout proposed with D&B.

Considering the issues raised by the TBMs turning radius assuming the use of a conventional TBM with no special turning characteristics, a re-assessment of the DGR layout is in order with more continuous tunnels and less right angle turns if TBM methods were to be adopted. A preliminary review of potential layouts by CTECH using TBMs indicates that an efficient design would be difficult to achieve.

Problems that are immediately apparent are:

- Large area and length of tunnel required to turn at 90^o
- Intersections of tunnels need to be at 90^o or thereabouts in order to avoid the very wide cross-over spans resulting from tangential or near-tangential intersections
- According to conventional wisdom, in a normal commercial environment, the economics of tunnel boring only become advantageous when continuous drives of more than 5 km are considered. In the case of development of the DGR, cost is not the most critical item.

Relative to proven conventional TBMs, the drill jumbo is flexible in respect of conformance with typical mine designs. The conventional TBM is inflexible.

Transportation

According to the United States Department of Energy (DOE) website[26] [27], the TBM used for excavation at its Yucca Mountain NWF, with its trailing equipment in place, weighted 860 tons and measured 140 m in length. Although it is larger in gross diameter than what is envisaged for the DGR with the outboard cutting wheels for the elliptical shape, CTECH estimates a conventional TBM of similar magnitude would be required. Transportation of the TBM to the DGR site would be achieved by special transports. Transportation underground would require breaking the unit down into parts and a re-build once located on the repository level. The degree of dismantling required is a function of the size of the shaft conveyance compartment and the shaft's hoisting capacity.

The drill and blast equipment (drill jumbos, load-haul dump, haulage trucks, etc.) would also require dismantling and re-assembly underground.

Phased Approach to Development

Currently it is intended to carry out an underground evaluation of the proposed DGR site prior to licensing and construction of the full-scale facility DGR. This will involve the excavation of a shaft to the required depth of 1000 m and some geotechnical and excavation work being carried out. This will allow construction and operation designs to be completed.

Regardless of whether D&B or boring is carried out, the initial underground excavation probably will be carried out using D&B techniques, as up to 100 m of development will be required in which the TBM would be set up. If the underground evaluation phase of the construction were

[26] http://www.ymp.gov/factsheets/doeymp0001.htm
[27] http://www.ymp.gov/factsheets/images/tbmgraphics.htm

being carried out by D&B techniques, the use of TBM techniques would not be hindered. Initial excavation by D&B would be necessary for the TBM designer and manufacturer to gather data for the design of the TBMs, if such were being contemplated. The layout selected for the underground evaluation phase would be designed to be used in the later operations, with enlargement if necessary.

Excavation Damage

The major concern with respect to excavation damage for drill and blast technology is the creation of stress fractures emanating from the rock face back into the rock mass providing a zone of weakness, and vibration (shock-wave) through the rock mass caused during blasting. The effect of blasting will generate an EDZ.

Recent developments in drill technology, combined with planned and engineered drilling, hole loading and stemming can minimize the stress fractures normally associated with hard rock mining. Many of the drill manufacturers provide on-board computerized drilling capability, in which not only allows the operator to correctly position the drill, but will also log all pressures related to drilling and the position of the drilled holes. This would be very useful in designing explosive and stemming loads for the emplacement room.

Once a site is selected and during the exploration phase[28] of the DGR, excavation damage data can be updated and assessed on a regular basis and modification of drilling parameters can be made accordingly.

The on-going development of actual excavation damage data during the “exploration phase” may affect the timely transition from exploration to DGR facility development if tunnel boring is chosen. Once all the rock parameters are determined delivery time of a new TBM can vary between 6 to 12 months.

[28] Engineering for a Disposal Facility Using the In-Room Emplacement Method, P. Baumgartner et al., AECL-11595, COG-96-223, June 1996

Health and Safety

Ventilation

For the purpose of this Appendix, CTECH comments on ventilation pertain to the issue of D&B versus tunnel boring excavation methods, rather than any issues related to radiation effects and temperature, which are important considerations during emplacement activities.

In D&B excavation methods, two potential health concerns are:

- The generation of diesel fumes and particulate matter
- The generation of blasting fumes.

The effects of the first concern can be minimized by:

- Providing proper dilution rates for the operating diesel fleet
- Minimizing the effect of the diesel fleet on the project by utilizing electric load-haul-dump machines and electric trolleys back to the service shaft.

The impact of blasting gases on the facility during the placement of the UFC can be minimized by:

- Providing dedicated exhaust routes for radionuclide and blasting fume production
- Ensuring the excavation and preparation of the emplacement rooms take place on the opposite side of the repository from emplacement.

TBM methods do not generate the blasting and diesel contaminates as D&B. Dust control is a problem common to both methods, but dust can be a particular problem for the TBM technique with dust being generated from the rotation of the cutting heads. In the opinion of CTECH it is likely that by the very nature of the boring process a higher portion of the dust generated in TBM methods will be in the respirable range (< 5 μm), and therefore could present a potential health hazard. However, good engineering design practice and the implementation of dust control procedures should essentially eliminate hazards arising from dust for both TBM and D&B methods.

Current Practice by Active Nuclear Fuel Waste Disposal Authorities

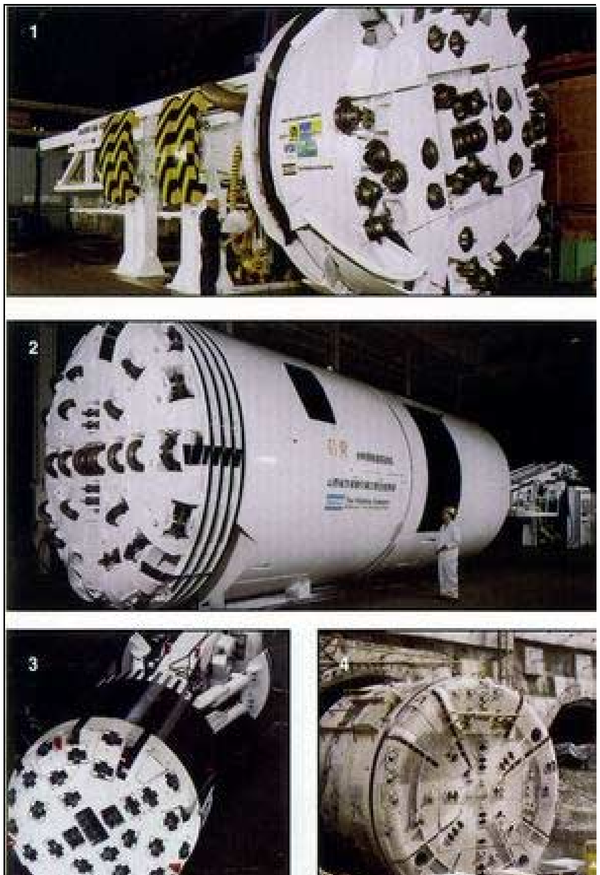
An investigation carried out by Golder Associates (Golder) on behalf of CTECH, on the current directions being considered by various agencies worldwide for excavating emplacement rooms and ancillary underground facilities for the DGR has revealed that the major focus on method selection of most agencies is not on cost nor on rate of progress (although both are important) but is primarily on wall control and secondly on flexibility for achieving desired excavation geometries.

Excavation using D&B methodology is still being considered by a number of agencies, as they have long experience in its use and consider it as more flexible than machine methods. However modern advances using non-circular mobile mining machines as illustrated in the right hand photographs in Figure 1 (overleaf), rather than the conventional civil tunnel boring machines (TBMs), as illustrated in the left illustrations, is leading to changes in appreciation of the flexibility and performance available from machines.

Based on an overview assessment of the various available techniques the advantages and disadvantages of each major method has been summarized, as per the following matrix table:

Table 1 –Comparison Matrix of Drill and Blast approaches with Machine Methods

	ADVANTAGES							DISADVANTAGES						
	Quality Profile	Flexibility	High Speed	Low Cost	Tight Curves	Fast Set-up	Proven Technology	Vibrations	Fumes	Slow Speed	High Cost	Slow Set-up Time	Low Flexibility	Prototype
Drill & Blast		☑	▪		☑	☑	☑	☒	☒	☒				
Conventional TBM	☑		☑				☑				☒	☒	☒	
Mobile Miner	☑	☑	☑	☑	☑	☑								☒
Esoteric Machines	☑	☑	☑								☒	☒		☒



Various conventional CIVIL-type TBM's with long trailing equipment. High quality wall control but limited flexibility and turning radii (150m)

Traditional Drill Jumbo for D&B excavation. Significant flexibility, but reduced wall control compared with machine mined

Continuous Mobile Miner, capable of tight (11m) radius turns, good wall profile control and mining non-circular shapes

Commercial Mobile Miner, capable of tight radius turns and mining non-circular shapes

Figure 1 – Comparative Illustrations of Available Excavation Equipment

In the above Table 1 the term Esoteric Machine refers to the various hybrid and complex machines that are currently in use or in development in countries such as Japan, a few of these types of machine are illustrated in Figure 2.

Figure 2 – Various types of esoteric multi-face machines mainly for soft ground excavation. Note: some multi-face prototypes are already in development for hard-rock utilization.

None of the agencies consulted has as yet completed a thoroughly rigorous review of the advantages and limitations of each of the newer approaches as a means for optimizing the selection. However, the Japanese, Swedes, Americans and the Swiss have advanced further than the Canadian program in conducting at least partial trials of a number of methods. These trials and the various studies that have followed have lead to their programs at least having tentative ideas on methodologies. Table 2 summarizes the information collected from the various agencies, while the following discussion sheds some light on the currently very diverse viewpoints on the best and most appropriate selection of methodology.

Table 2 –Comparison Matrix of Nuclear Agencies Excavation Method Selections

	DRILL & BLAST							TBM							SELECTION		
	Primary Design	Alternative	Considerations	... Cost	... EDZ Minimization	... Rate of Progress	... Flexibility	Primary Design	Alternative	Considerations	... Cost	... EDZ Minimization	... Rate of Progress	... Flexibility			
Sweden (SKB)	☑	▪	▪		②	▪	❶	▪	☑	▪		❶		▪	☑	|	
US (Yucca Mtn)			▪				▪	☑		▪		❶	▪	▪		|	☑
Finland (Okiluoto/Posiva)	☑	▪	▪	▪	②	▪	❶		▪	▪	▪	▪		▪	☑	|	
Korea (KAERI/Kigam)	☑	▪	▪						▪	▪				▪	☑	|	
Switzerland (Grimsel)	▪	▪	▪	▪	▪	▪		☑	▪	▪		❶		▪		|	☑
JNC (Japan)		☑	▪	▪	▪	▪	②	☑	▪	▪	▪	❶		▪		|	☑
Enresa (Spain)	▪	▪	▪					☑	▪	▪		❶		▪		|	☑

Note: The table indicates the ranking of the factors by the agencies, with ❶ being most important and ② being next important.

JNC (Japan) indicate that their preference will be to use TBM methods for the repository, but they indicate that are not committed to it. Their rock lab (which is due to start into construction in 2005) will use D&B methods due to logistical constraints.

The Swedes have done extensive comparisons of D&B versus TBM, with specific comparison testing conducted in the ASPO hard rock laboratory. These tests indicated a net penetration rate of 1.36 m/hour (1-3 m/hour is an industry standard) with an average utilization ot the TBM when boring of 30% (again well within the industry range of 20 - 60 %). For the trials it was found that at these utilizations the advance rates for the TBM per week were of the order of 30 - 50 m, and that almost the same was achieved by D&B methods. On the basis of these comparisons SKB have decided tentatively that the use of TBM technologies may be unnecessarily restrictive in flexibility and may not necessarily produce a significantly safer repository. However, they are still carrying forward use of TBMs as an option.

Currently, the US is the only agency that is firmly committed to use of TBM methods (ref Figure 3 – which shows the Yucca Mountain machine – which is basically of the conventional circular face Civil–type of construction). This decision was based almost entirely on Performance Assessment and Safety considerations mainly related to the depth of the EDZ created around a machine driven excavation versus that created by D&B methods.

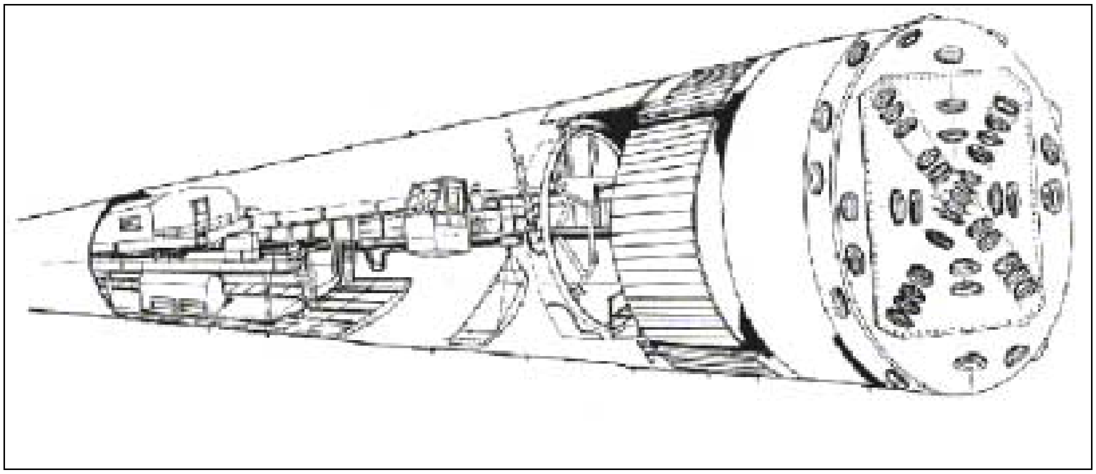


Figure 3 - Yucca Mountain TBM Concept

Enresa, for the Spanish program view the decision in much the same way, and as a consequence are focusing their development concepts on use of TBM techniques because of the evidence that it produces a smaller EDZ. Although, they have not undertaken an independent financial evaluation of TBMs versus D&B they maintain that the decision must be based on Performance Assessment (PA) of which method constitutes the better safety case. Based on their studies of the available evidence they have concluded that machine excavation methods create less damage to the rock mass walls, thus they consider D&B an unacceptable option for the repository.

At the opposite end of the scale, by contrast, at the present time the Finnish program uses 100% D&B, and has no plans for TBM usage. This decision is partly historical, as all the ILW/LLW repositories that have been constructed in Sweden and Finland were built using D&B methods, so there is a fair degree of familiarity and comfort with the technology. In general, the rock is good (mainly self supporting), and smooth wall blasting leaves little damage. Further, the SKB and Posiva programs have quite specific and particular requirements for the shapes and sizes of their repository openings, for which D&B is ideally suited.

As is evident from Table 3, both TBM and D&B methods have been selected as the approach of choice by different DGR programs. However with the advent of significant and novel technological developments in machine mining which aid performance and flexibility it is clear that more refinement and optimization of selection decisions is still needed, and that changes in direction may yet occur with several of the programs. The Swiss program, provides an insight into the thrust of current focus, as this program is already advancing along optimization lines on the basis of risk minimization decision analysis approaches, with suggestions of a hybrid of various approaches as being the optimum way forward. Based on trials undertaken at the rock laboratory at Grimsel where both blasting and TBM were used to investigate drilling technologies and their implications on PA issues, the Swiss are currently considering use of three different excavation methodologies for the proposed LLW repository at Wellenberg (marl formation, central Switzerland), as follows:

- For the access tunnels and entranceways / and in adjacent rock formations: - D&B (using smooth blasting methods)

- Within the repository host rock: - a combination of TBM (operational tunnels) and "Teilschnitt-Maschine" (mobile miner/road-header)
- For the emplacement caverns: - smooth-wall blasting or road-header.

Ongoing work is focussing on optimizing the selection criteria on the basis of cost and time optimization for the access tunnels; and on EDZ minimization for the emplacement rooms and tunnels

Similar, but very preliminary, optimization planning studies are in progress related to the methodologies likely for use for the proposed HLW/ILW repository proposed for construction in a clay formation in northern Switzerland (reference level of the repository: 650 m below ground). For this planned facility, concept planning is currently considering:

- For the access tunnels / ramp: - road header or soft blasting
- For the access shafts: - raise boring or conventional shaft sinking (depending on evaluation of expected mining risks)
- For the ILW-emplacement tunnels: - smooth-wall blasting
- For the HLW-emplacement tunnels: - TBM.

In this case, again, ongoing studies are continuing focusing on optimizing the selection criteria, with current thinking being that cost / time optimization and minimization of engineering risks will dominate the selection procedures for the access tunnels; while EDZ minimization will be the sole constraint for the emplacement tunnels

The Canadian program can and should benefit from these types of risk minimization studies and the long and extensive hard-rock mining experience embodied in the Canadian mining industry. The increased use of advanced mechanized mining in ore extraction and the thrust of the civil tunnel boring machine manufacturers towards more functionality of their high end machines gives confidence that much more flexible, high performance mining TBMs will be available that will be better suited to excavating the required repository room complexes.

Conclusions

Currently, the technical feasibility of boring an elliptically shaped heading in hard rock has not been proven, although machine excavation equipment is certainly capable of cutting typical high strength plutonic rock as demonstrated by the successful raise boring completed at AECL's URL facility.

D&B techniques are more flexible than TBM techniques.

TBM techniques eliminate the inherent hazards of blasting and ventilation of blasting fumes, but good design and proper procedures can reduce this potential hazard to acceptable limits.

Although rock disturbance is minimized by the use of boring methods, the damage resulting from D&B techniques can be minimized by good blast design.

The requirement of an underground evaluation phase of the construction most likely being carried out by D&B techniques would not necessarily hinder the use of TBM techniques and would be necessary for the TBM designer and manufacturer to complete the design of the TBMs, if such were being contemplated.

Recommendation

In the opinion of CTECH and at this time, the technical feasibility of boring an elliptically shaped heading has not been demonstrated to the level that the method can be recommended with certitude in respect of construction of the DGR.

APPENDIX B

Blasting Vibration Control

APPENDIX B

Blasting Vibration Control

Purpose of Blasting Vibration Control

According to the normal excavation strategy, blasting operations will not take place near emplacement operations. However, the possibility exists that during on-going excavation activities, the vibration created by blasting may affect adjacent emplacement rooms in which either emplacement activities are on-going or UFCs have been emplaced.

The purpose of this Appendix is to suggest a practical method to limit ground movement within the repository during the excavation process, especially in the vicinity of emplaced UFCs. There is no discussion on the effect of blast design and blast vibration on the EDZ arising from development activities.

CTECH suggests the use of Peak Particle Velocity (PPV), frequency and Scaled Distance Factor to determine the possible seismic effects in design and monitoring of the blasts.

The scaled distance is related to the weight of explosive charge and the distance from the blast. These parameters influence seismic effects and therefore the ground vibration resulting from the blasts.

Description of Methodology

According to literature, most of the experiments examining PPV, a particle velocity of less than 51 mm/s (~2 in/sec) has been shown to create no damage[29]. This assumes frequency is greater than about 50 Hz. Therefore, CTECH will utilize a 51 mm/s velocity as a maximum allowable PPV in determining the weight of explosives per detonation.

For the purpose of PPV and Scaled Distance Factor determinations:

- If the Charge Length/Charge Diameter ratio is greater than 6, it is defined as a Cylindrical Charge
- If the length of Charge/Charge Diameter ratio is less than 6, it is defined as a Spherical Charge.

The drill holes produced in the excavation process are therefore considered cylindrical charges. The scaled distance equation[30] used to maintain PPV below 51 mm/s for a cylindrical charge is:

$$D_s = D/(W)^{1/2} \qquad (1)$$

Where D_s is scaled distance, D is distance from blast and W is weight of explosive.

Therefore, manipulating Equation 1, the weight of the explosive can be estimated by:

$$W = (D/D_s)^2 \qquad (2)$$

[29] Explosives and Rock Blasting, Field Technical Operations, Atlas Powder Company, 1987, pg. 332, 333
[30] Explosives and Rock Blasting, Field Technical Operations, Atlas Powder Company, 1987, pg. 333 - 339

Further limitations[31] are provided for the Equation 2, as to whether the blast site is monitored utilizing seismic equipment or not.

A. Seismic Instrumented Site:

Use of a D_s factor of 13.44 m/(kg)$^{1/2}$ (20 ft/(lb)$^{1/2}$) is recommended for sites using the seismic measurement instruments if a peak particle velocity of less than 51 mm/s is to be obtained.

B. Non-seismic Instrumented Site:

Use of a D_s factor of 33.61 m/(kg)$^{1/2}$ (50 ft/(lb)$^{1/2}$) is recommended for sites that are not instrumented. This factor includes a factor of safety to allow high seismic energy generation.

Estimation of the Maximum Explosives Charge

It is recommended that instrumentation be installed to monitor PPV for the OPG project. Table 1 indicates the maximum allowed charge per blast where at least an 8 ms delay occurs between adjacent hole detonations.

> *Note: As the time increases between adjacent hole detonations PPV is reduced. The 8 ms delay between adjacent is an explosive industry minimum norm[32] used in blast design. However, depending upon OPG's requirements the time delay between adjacent holes may be greater than 8 ms.

Assuming a 3.65 m (~12 ft) round is drilled for the panel access drifts and emplacement rooms, with a 0.61 m (~2 ft) collar (i.e. the unloaded portion of a hole), a 3.04 m (~10 ft) hole length will be charged. Holes that are to be charged are typically 38 mm in diameter.

[31] Explosives and Rock Blasting, Field Technical Operations, Atlas Powder Company, 1987, pg. 338
[32] Explosives and Rock Blasting, Field Technical Operations, Atlas Powder Company, 1987, pg. 284

Table 1: Maximum Allowed Explosives Charge

Distance from blast		D_s factor of 33.61		D_s factor of 13.44	
M	Ft	w (lb)	w (kg)	w (lb)	w (kg)
5	16.4	0.11	0.05	0.67	0.31
10	32.8	0.43	0.20	2.69	1.22
15	49.2	0.97	0.44	6.05	2.75
20	65.6	1.72	0.78	10.76	4.88
25	82.0	2.69	1.22	16.82	7.63
30	98.4	3.87	1.76	24.22	10.99
35	114.8	5.27	2.39	32.96	14.95

W = Maximum weight of explosive charge

Assuming that ammonium nitrate fuel oil (ANFO) type explosives are utilized as the blasting agent, which is a conservative assumption as less powerful explosives are likely to be used, the mass of the explosive will vary with the drilled hole diameter. In this example that does not represent an actual blast hole loading design, since the diameter of the drill holes are 38 mm (~1 ½"), the density of ANFO is 0.8 g/cc [33] and the charged length of the drill hole is 3.04 m (10 ft). The resultant weight of explosives determined from explosive loading density tables[34] is 0.91 kg/m (0.61 lb/ft). Therefore each drill hole will contain 2.77 kg (~6.1 lb) of explosive.

Figure 1: Maximum Allowed Explosives Charge

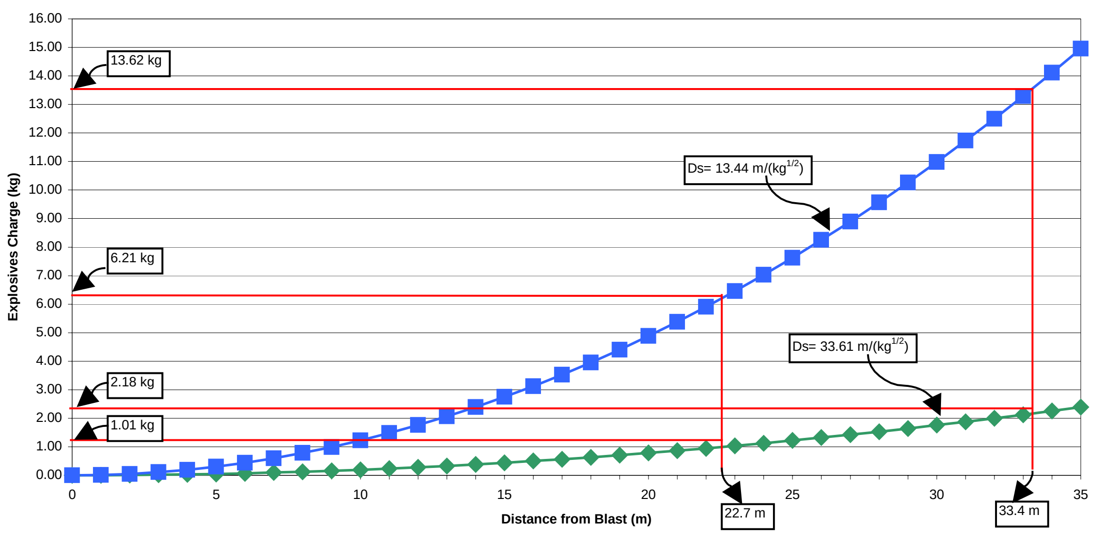


Table 1 is represented graphically in Figure 1, demonstrating the Amount of Explosive Charge versus Distance from Blast, to maintain PPV below 51 mm/s. From Figure 1:

[33] Explosives Handbook, E.I Dupont, 1974, pg 41.
[34] Explosives and Rock Blasting, Field Technical Operations, Atlas Powder Company, 1987, Appendix C pg. 582

- If a non-seismic monitored blast occurs during emplacement room excavation, explosive charges must be kept below 1.01 kg per detonator when approaching an excavated emplacement room (i.e. 22.7 m)
- If seismic monitored blast occurs during emplacement room excavation, explosive charges must be kept below 6.21 kg per detonator when approaching an excavated emplacement room (i.e. 22.7 m).

According to the normal excavation strategy, blasting operations will not take place near emplacement rooms which have been already filled or those where emplacement operations are in progress. However, if blasting was necessary near to the concrete bulkhead and grout zone sealing of an emplacement room, the following guidelines should be observed, while recognizing that regulators may demand more stringent factors:

- If a non-seismic monitored blast occurs during excavation, explosive charges must be kept below 2.18 kg per detonator
- If seismic monitored blast occurs during excavation, explosive charges must be kept below 13.62 kg per detonator.

Recommendations

CTECH recommends:

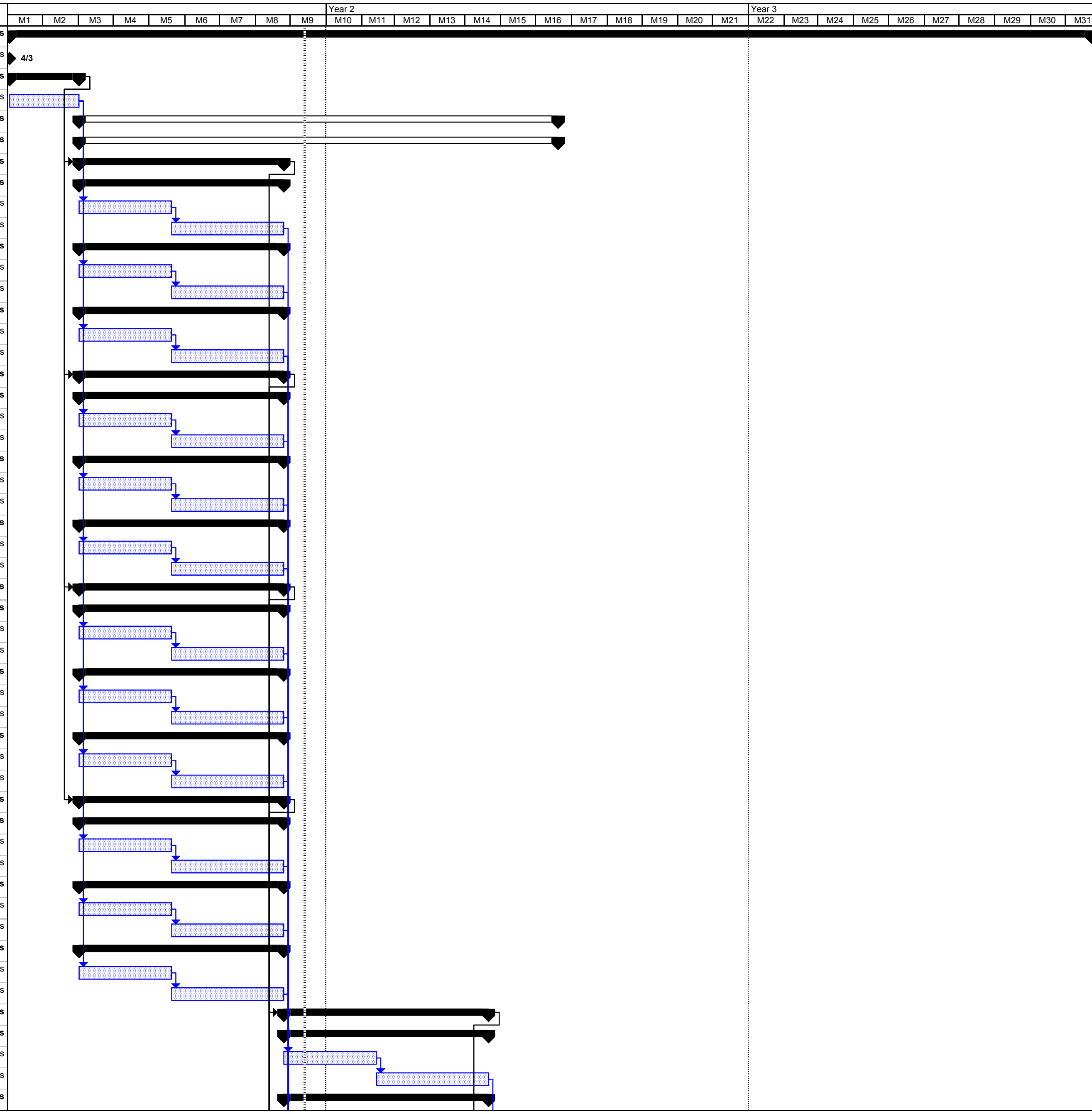
- Monitoring of the blasts for Peak Particle Velocity, to ensure the PPV does not exceed 51 mm/s, thereby allowing normal blasting advance and procedure
- For non-monitored blasting, reduce the hole length, hence explosive charge, if the excavation activity were to take place near an emplacement room or concrete/grout seal.

APPENDIX C

Campaign Mining Schedules

OPG-DGR Vault Excavation -Upper Half Section B/Lower Half Section D

ID	Task Name	Duration
1	**OPG-DGR Vault Excavation Project**	**935 days**
2	Award Contract	0 days
3	**Vault Excavation Mobilization**	**60 days**
4	Mobilization	60 days
5	**Vault Excavation Upper B/Lower D**	**414 days**
6	**Mine Block B/D**	**414 days**
7	**Jumbo No. 1**	**177 days**
8	**Mine Emplacement Room Upper B1 (UB1)**	**177 days**
9	Develop 290 m Pilot	80 days
10	Slash290 m Emplacement Room	97 days
11	**Mine Emplacement Room Upper B2 (UB2)**	**177 days**
12	Develop 290 m Pilot	80 days
13	Slash 290 m Emplacement Room	97 days
14	**Mine Emplacement Room Lower D1 (LD1)**	**177 days**
15	Develop 290 m Pilot	80 days
16	Slash 290 m Emplacement Room	97 days
17	**Jumbo No. 2**	**177 days**
18	**Mine Emplacement Room Lower D2 (LD2)**	**177 days**
19	Develop 290 m Pilot	80 days
20	Slash 290 m Emplacement Room	97 days
21	**Mine Emplacement Room Lower D3 (LD3)**	**177 days**
22	Develop 290 m Pilot	80 days
23	Slash 290 m Emplacement Room	97 days
24	**Mine Emplacement Room Upper B3 (UB3)**	**177 days**
25	Develop 290 m Pilot	80 days
26	Slash 290 m Emplacement Room	97 days
27	**Jumbo No. 3**	**177 days**
28	**Mine Emplacement Room Upper B4 (UB4)**	**177 days**
29	Develop 290 m Pilot	80 days
30	Slash 290 m Emplacement Room	97 days
31	**Mine Emplacement Room Upper B5 (UB5)**	**177 days**
32	Develop 290 m Pilot	80 days
33	Slash 290 m Emplacement Room	97 days
34	**Mine Emplacement Room Lower D4 (LD4)**	**177 days**
35	Develop 290 m Pilot	80 days
36	Slash 290 m Emplacement Room	97 days
37	**Jumbo No. 4**	**177 days**
38	**Mine Emplacement Room Lower D5 (LD5)**	**177 days**
39	Develop 290 m Pilot	80 days
40	Slash 290 m Emplacement Room	97 days
41	**Mine Emplacement Room Lower D6 (LD6)**	**177 days**
42	Develop 290 m Pilot	80 days
43	Slash 290 m Emplacement Room	97 days
44	**Mine Emplacement Room Upper B6 (UB6)**	**177 days**
45	Develop 290 m Pilot	80 days
46	Slash 290 m Emplacement Room	97 days
47	**Jumbo No. 1**	**177 days**
48	**Mine Emplacement Room Lower D7 (LD7)**	**177 days**
49	Develop 290 m Pilot	80 days
50	Slash 290 m Emplacement Room	97 days
51	**Mine Emplacement Room Upper B7 (UB7)**	**177 days**

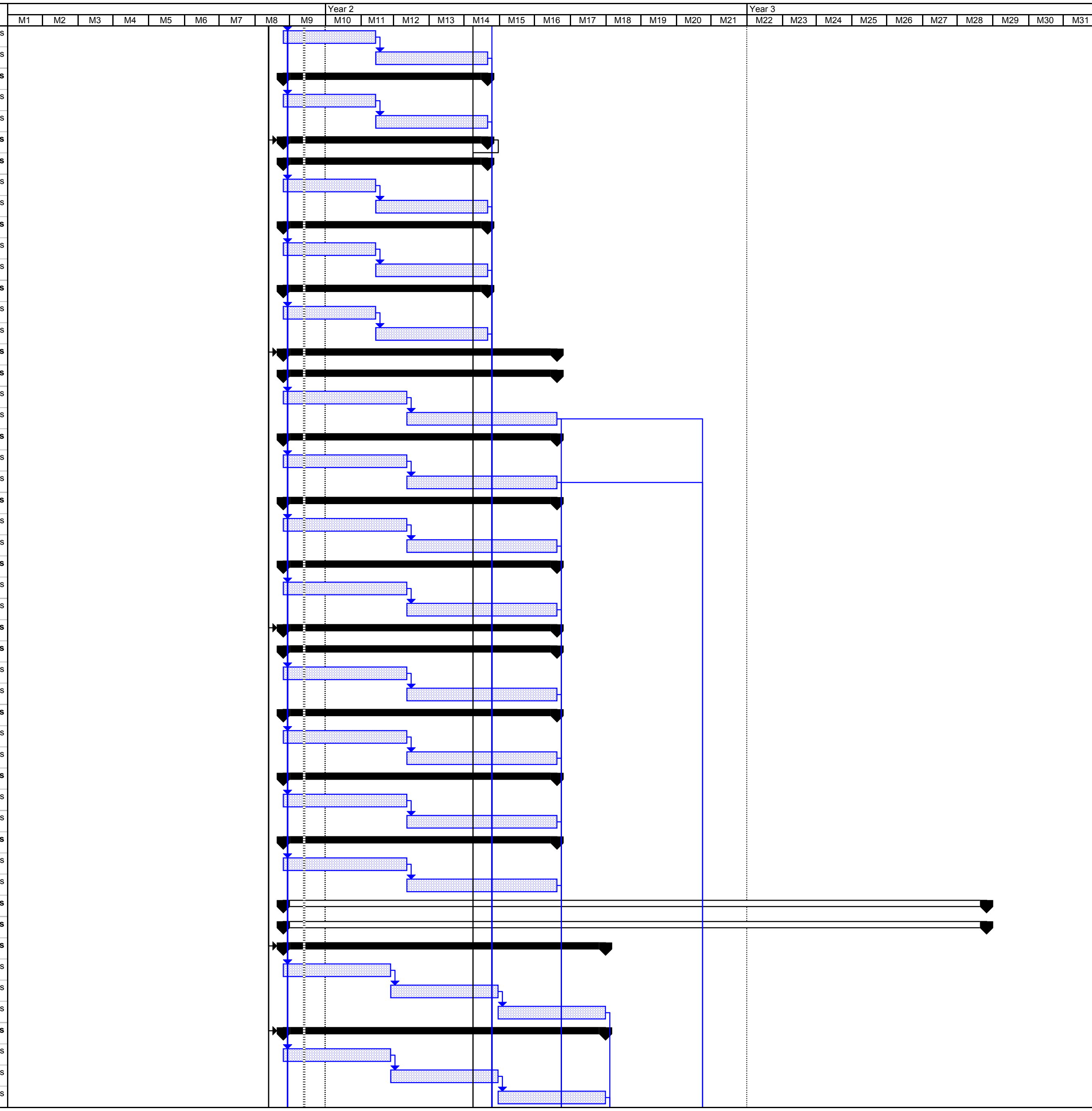


Project: OPG Project1
Date: Fri 12/13/02

Task | Split | Progress | Milestone | Summary | Rolled Up Task | Rolled Up Split | Rolled Up Milestone | Rolled Up Progress | External Tasks | Project Summary

OPG-DGR Vault Excavation -Upper Half Section B/Lower Half Section D

ID	Task Name	Duration
52	Develop 290 m Pilot	80 days
53	Slash 290 m Emplacement Room	97 days
54	**Mine Emplacement Room Upper B8 (UB8)**	**177 days**
55	Develop 290 m Pilot	80 days
56	Slash 290 m Emplacement Room	97 days
57	**Jumbo No. 2**	**177 days**
58	**Mine Emplacement Room Upper B9 (UB9)**	**177 days**
59	Develop 290 m Pilot	80 days
60	Slash 290 m Emplacement Room	97 days
61	**Mine Emplacement Room Lower D8 (LD8)**	**177 days**
62	Develop 290 m Pilot	80 days
63	Slash 290 m Emplacement Room	97 days
64	**Mine Emplacement Room Lower D9 (LD9)**	**177 days**
65	Develop 290 m Pilot	80 days
66	Slash 290 m Emplacement Room	97 days
67	**Jumbo No. 3**	**237 days**
68	**Mine Emplacement Room Lower D10 (LD10)**	**237 days**
69	Develop 290 m Pilot	107 days
70	Slash 290 m Emplacement Room	130 days
71	**Mine Emplacement Room Upper B10 (UB10)**	**237 days**
72	Develop 290 m Pilot	107 days
73	Slash 290 m Emplacement Room	130 days
74	**Mine Emplacement Room Upper B11 (UB11)**	**237 days**
75	Develop 290 m Pilot	107 days
76	Slash 290 m Emplacement Room	130 days
77	**Mine Emplacement Room Upper B12 (UB12)**	**237 days**
78	Develop 290 m Pilot	107 days
79	Slash 290 m Emplacement Room	130 days
80	**Jumbo No. 4**	**237 days**
81	**Mine Emplacement Room Lower L11 (LD11)**	**237 days**
82	Develop 290 m Pilot	107 days
83	Slash 290 m Emplacement Room	130 days
84	**Mine Emplacement Room Lower D12 (LD12)**	**237 days**
85	Develop 290 m Pilot	107 days
86	Slash 290 m Emplacement Room	130 days
87	**Mine Emplacement Room Lower D13 (LD13)**	**237 days**
88	Develop 290 m Pilot	107 days
89	Slash 290 m Emplacement Room	130 days
90	**Mine Emplacement Room Upper B13 (UB13)**	**237 days**
91	Develop 290 m Pilot	107 days
92	Slash 290 m Emplacement Room	130 days
93	**Concrete Emplacement In Upper B/Lower D**	**609 days**
94	**Concrete Emplacement**	**609 days**
95	**Concrete Crew No. 1**	**279 days**
96	UB1	93 days
97	UB2	93 days
98	UB3	93 days
99	**Concrete Crew No. 2**	**279 days**
100	UB4	93 days
101	UB5	93 days
102	UB6	93 days

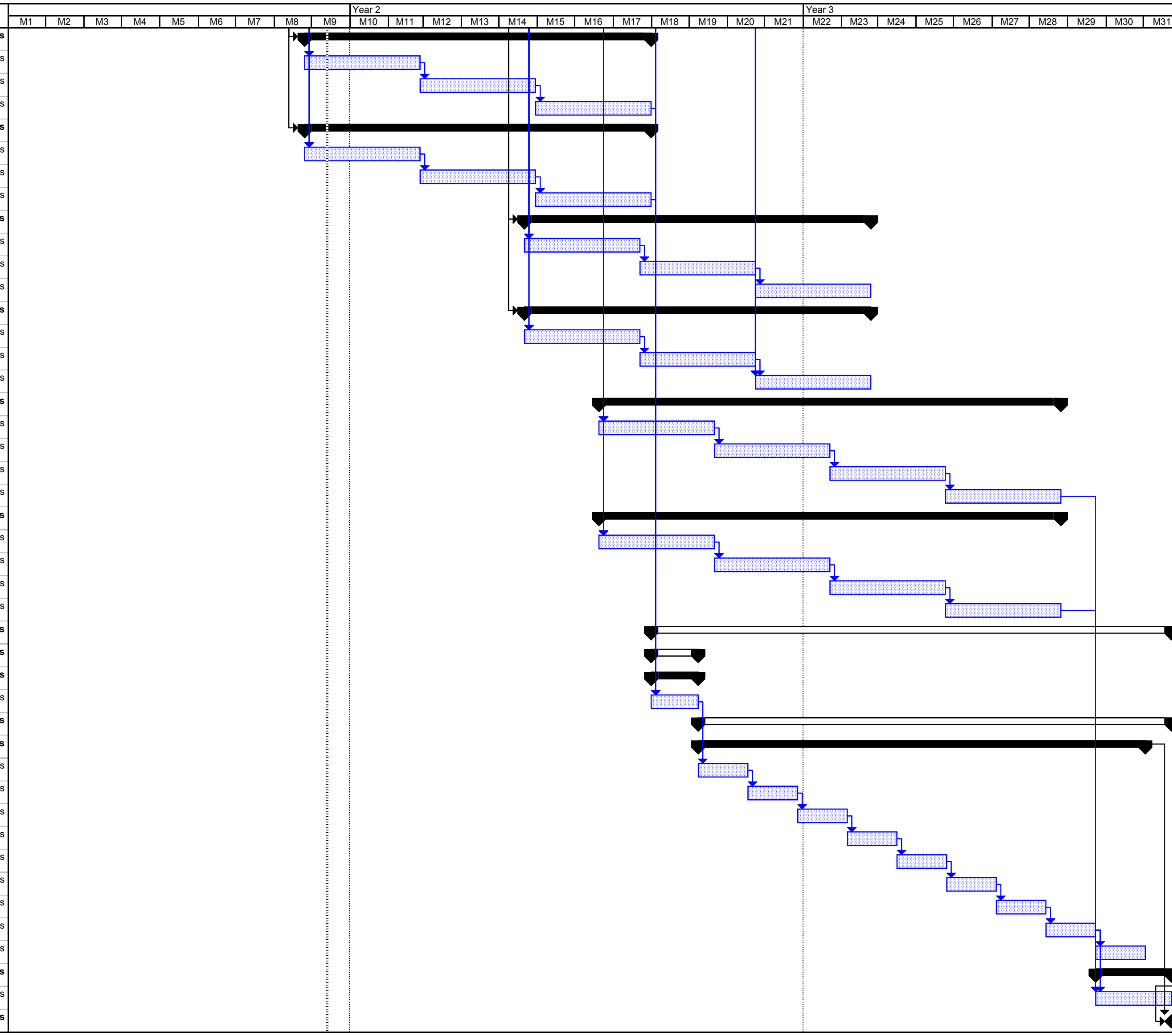


Project: OPG Project1
Date: Fri 12/13/02

Task	Progress	Summary	Rolled Up Split	Rolled Up Progress	Project Summary
Split	Milestone	Rolled Up Task	Rolled Up Milestone	External Tasks	

OPG-DGR Vault Excavation -Upper Half Section B/Lower Half Section D

ID	Task Name	Duration
103	**Concrete Crew No. 3**	**279 days**
104	LD1	93 days
105	LD2	93 days
106	LD3	93 days
107	**Concrete Crew No. 4**	**279 days**
108	LD4	93 days
109	LD5	93 days
110	LD6	93 days
111	**Concrete Crew No. 1**	**279 days**
112	LD7	93 days
113	LD8	93 days
114	LD9	93 days
115	**Concrete Crew No. 2**	**279 days**
116	UB7	93 days
117	UB8	93 days
118	UB9	93 days
119	**Concrete Crew No. 3**	**372 days**
120	LD10	93 days
121	LD11	93 days
122	LD12	93 days
123	LD13	93 days
124	**Concrete Crew No. 4**	**372 days**
125	UB10	93 days
126	UB11	93 days
127	UB12	93 days
128	UB13	93 days
129	**Prepare SectionB/D for Emplacement (Track, Vent, etc)**	**419 days**
130	**Install Track Across Emplacement Rooms**	**38 days**
131	**Install Track and Switch Gear Between Vault Upper B/Lower D**	**38 days**
132	Across Emplacement Rooms LD/UB1 - LD/UB 6 (12 Rooms)	38 days
133	**Install Track in 9 out of 26 Emplacement Rooms**	**381 days**
134	**Track Crew No. 1**	**360 days**
135	UB1	40 days
136	UB2	40 days
137	UB3	40 days
138	UB4	40 days
139	UB5	40 days
140	LD1	40 days
141	LD2	40 days
142	LD3	40 days
143	LD4	40 days
144	**Install Track and Switch Gear Between Vault Upper B/Lower D**	**61 days**
145	Across Emplacement Rooms LD/UB7 - LD/UB 13 (14 Rooms)	61 days
146	**End of Mining - 26 Rooms ready for Emplacement**	**0 days**

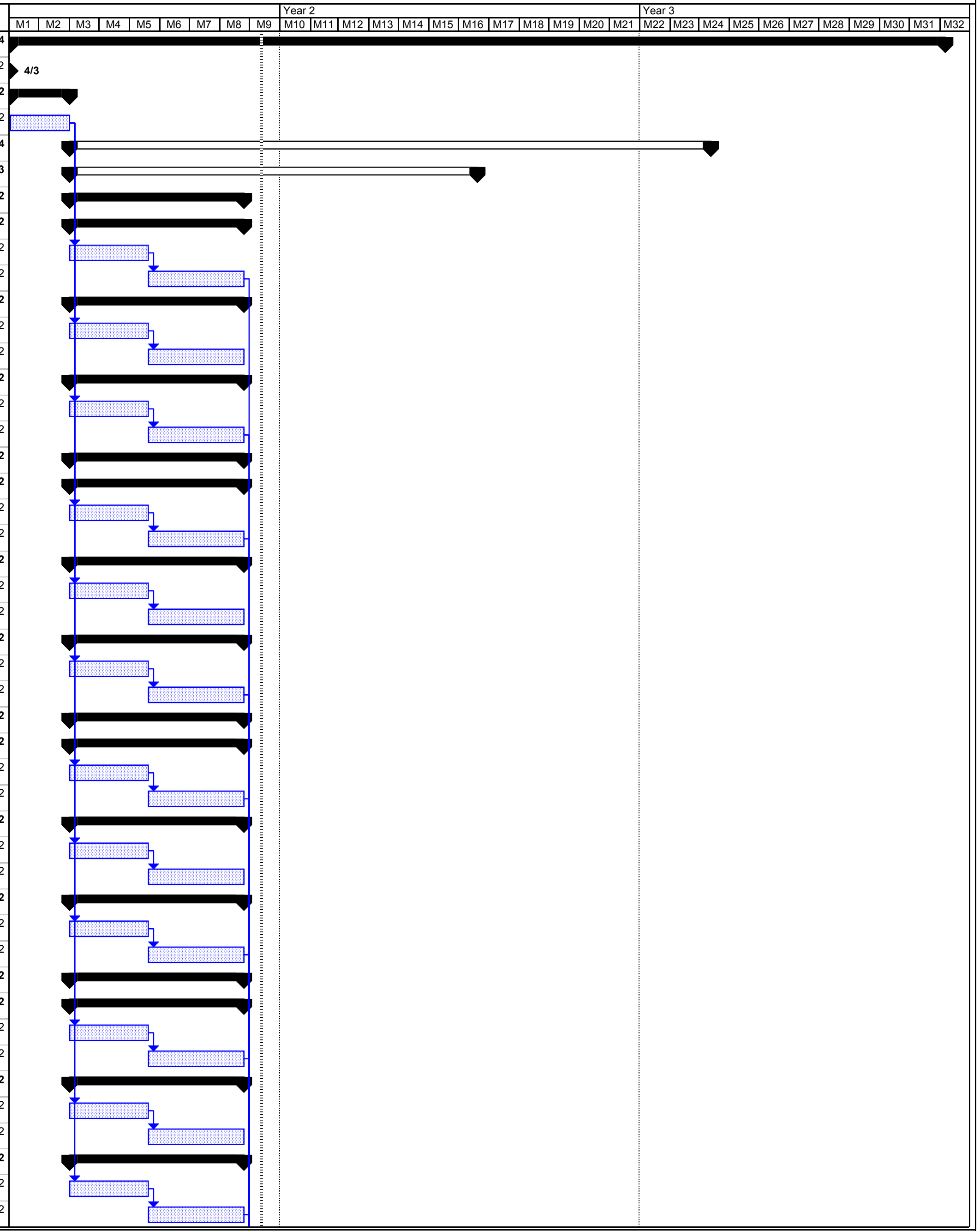


Project: OPG Project1
Date: Fri 12/13/02

Task | Progress | Summary | Rolled Up Split | Rolled Up Progress | Project Summary
Split | Milestone | Rolled Up Task | Rolled Up Milestone | External Tasks

OPG - DGR Vault Excavation - Upper Half Section A/Section B

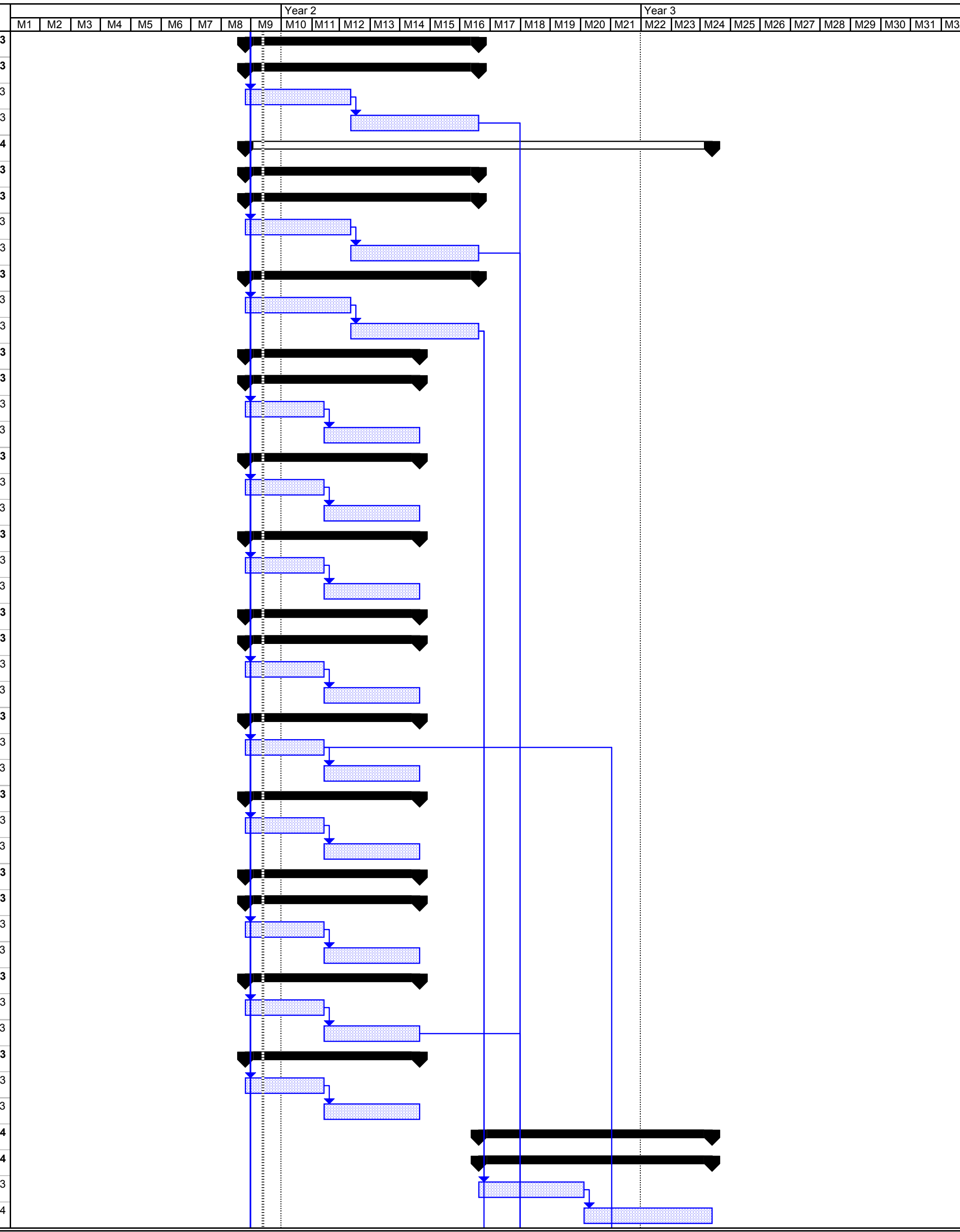
ID	Task Name	Duration	Start	Predecessors	Finish
1	**OPG-DGR Vault Excavation Project**	**949 days**	**Wed 4/3/02**		**Sat 11/6/04**
2	Award Contract	0 days	Wed 4/3/02		Wed 4/3/02
3	**Vault Excavation Mobilization**	**60 days**	**Wed 4/3/02**		**Sat 6/1/02**
4	Mobilization	60 days	Wed 4/3/02		Sat 6/1/02
5	**Vault Excavation Upper/Lower C**	**651 days**	**Sun 6/2/02**		**Sat 3/13/04**
6	**Mine Lower C**	**414 days**	**Sun 6/2/02**		**Sun 7/20/03**
7	**Jumbo No. 1**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
8	**Mine Emplacement Room Lower C1 (LC1)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
9	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
10	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	9	Mon 11/25/02
11	**Mine Emplacement Room Lower C2 (LC2)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
12	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
13	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	12	Mon 11/25/02
14	**Mine Emplacement Room Lower C3 (LC3)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
15	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
16	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	15	Mon 11/25/02
17	**Jumbo No. 2**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
18	**Mine Emplacement Room Lower C4 (LC4)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
19	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
20	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	19	Mon 11/25/02
21	**Mine Emplacement Room Lower C5 (LC5)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
22	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
23	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	22	Mon 11/25/02
24	**Mine Emplacement Room Lower C6 (LC6)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
25	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
26	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	25	Mon 11/25/02
27	**Jumbo No. 3**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
28	**Mine Emplacement Room Lower C7 (LC7)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
29	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
30	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	29	Mon 11/25/02
31	**Mine Emplacement Room Lower C8 (LC8)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
32	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
33	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	32	Mon 11/25/02
34	**Mine Emplacement Room Lower C9 (LC9)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
35	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
36	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	35	Mon 11/25/02
37	**Jumbo No. 4**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
38	**Mine Emplacement Room Lower C10 (LC10)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
39	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
40	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	39	Mon 11/25/02
41	**Mine Emplacement Room Lower C11 (LC11)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
42	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
43	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	42	Mon 11/25/02
44	**Mine Emplacement Room Lower C12 (LC12)**	**177 days**	**Sun 6/2/02**		**Mon 11/25/02**
45	Develop 290 m Pilot	80 days	Sun 6/2/02	4	Tue 8/20/02
46	Slash 290 m Emplacement Room	97 days	Wed 8/21/02	45	Mon 11/25/02



Project: OPG Project1
Date: Fri 12/13/02

Task | Progress | Summary | Rolled Up Split | Rolled Up Progress | Project Summary
Split | Milestone | Rolled Up Task | Rolled Up Milestone | External Tasks

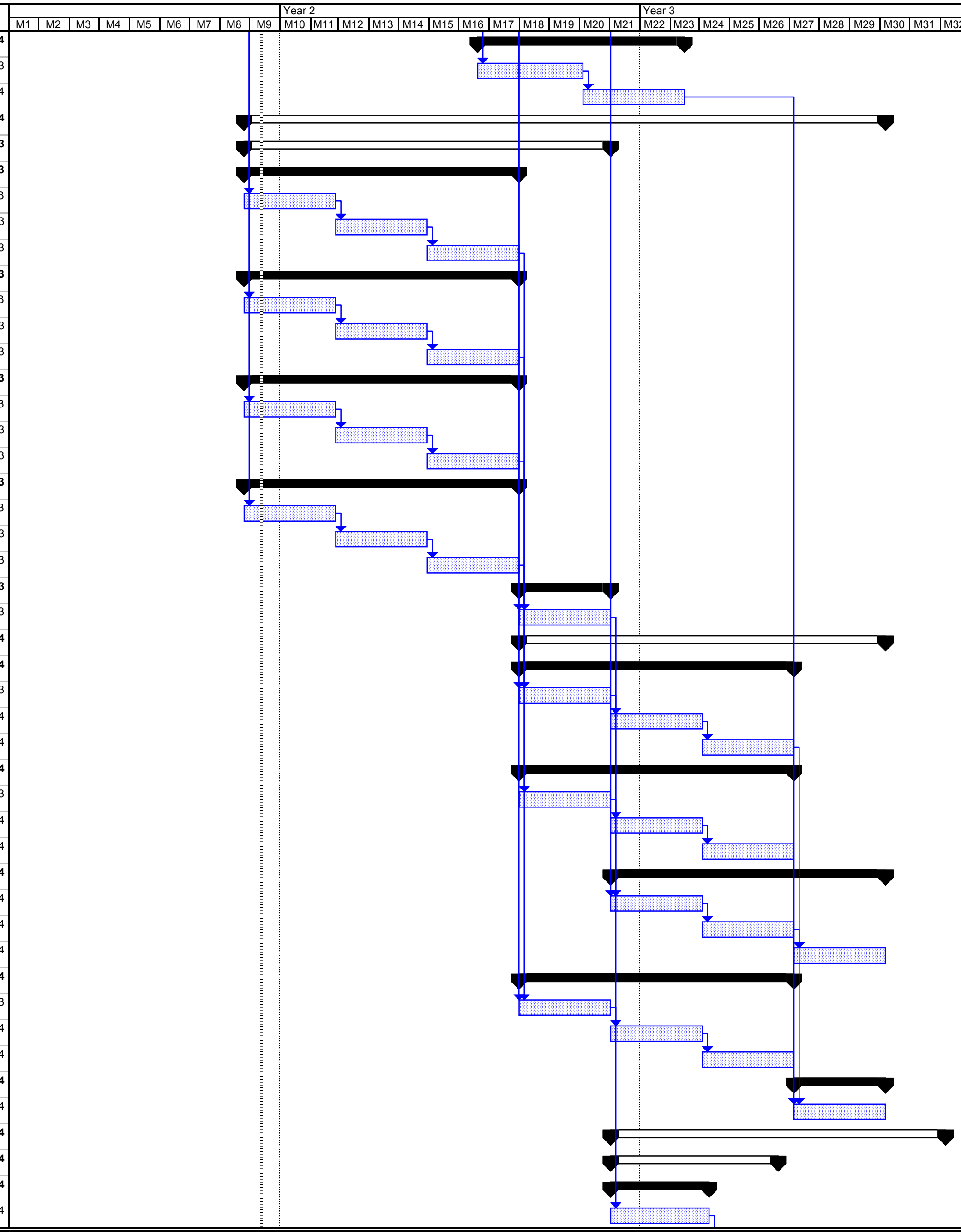
ID	Task Name	Duration	Start	Predecessors	Finish
47	**Jumbo No. 1**	**237 days**	**Tue 11/26/02**		**Sun 7/20/03**
48	**Mine Emplacement Room Lower C13 (LC13)**	**237 days**	**Tue 11/26/02**		**Sun 7/20/03**
49	Develop 290 m Pilot	107 days	Tue 11/26/02	16	Wed 3/12/03
50	Slash 290 m Emplacement Room	130 days	Thu 3/13/03	49	Sun 7/20/03
51	**Mine Upper C**	**474 days**	**Tue 11/26/02**		**Sat 3/13/04**
52	**Jumbo No. 1**	**237 days**	**Tue 11/26/02**		**Sun 7/20/03**
53	**Mine Emplacement Room Upper C1 (UC1)**	**237 days**	**Tue 11/26/02**		**Sun 7/20/03**
54	Develop 290 m Pilot	107 days	Tue 11/26/02	16	Wed 3/12/03
55	Slash290 m Emplacement Room	130 days	Thu 3/13/03	54	Sun 7/20/03
56	**Mine Emplacement Room Upper C2 (UC2)**	**237 days**	**Tue 11/26/02**		**Sun 7/20/03**
57	Develop 290 m Pilot	107 days	Tue 11/26/02	16	Wed 3/12/03
58	Slash 290 m Emplacement Room	130 days	Thu 3/13/03	57	Sun 7/20/03
59	**Jumbo No. 2**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
60	**Mine Emplacement Room Upper C3 (UC3)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
61	Develop 290 m Pilot	80 days	Tue 11/26/02	26	Thu 2/13/03
62	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	61	Wed 5/21/03
63	**Mine Emplacement Room Upper C4 (UC4)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
64	Develop 290 m Pilot	80 days	Tue 11/26/02	26	Thu 2/13/03
65	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	64	Wed 5/21/03
66	**Mine Emplacement Room Upper C5 (UC5)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
67	Develop 290 m Pilot	80 days	Tue 11/26/02	26	Thu 2/13/03
68	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	67	Wed 5/21/03
69	**Jumbo No. 3**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
70	**Mine Emplacement Room Upper C6 (UC6)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
71	Develop 290 m Pilot	80 days	Tue 11/26/02	36	Thu 2/13/03
72	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	71	Wed 5/21/03
73	**Mine Emplacement Room Upper C (UC7)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
74	Develop 290 m Pilot	80 days	Tue 11/26/02	36	Thu 2/13/03
75	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	74	Wed 5/21/03
76	**Mine Emplacement Room Upper C8 (UC8)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
77	Develop 290 m Pilot	80 days	Tue 11/26/02	36	Thu 2/13/03
78	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	77	Wed 5/21/03
79	**Jumbo No. 4**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
80	**Mine Emplacement Room Upper C9 (UC9)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
81	Develop 290 m Pilot	80 days	Tue 11/26/02	46	Thu 2/13/03
82	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	81	Wed 5/21/03
83	**Mine Emplacement Room Upper C10 (UC10)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
84	Develop 290 m Pilot	80 days	Tue 11/26/02	46	Thu 2/13/03
85	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	84	Wed 5/21/03
86	**Mine Emplacement Room Upper C11 (UC11)**	**177 days**	**Tue 11/26/02**		**Wed 5/21/03**
87	Develop 290 m Pilot	80 days	Tue 11/26/02	46	Thu 2/13/03
88	Slash 290 m Emplacement Room	97 days	Fri 2/14/03	87	Wed 5/21/03
89	**Jumbo No. 1**	**237 days**	**Mon 7/21/03**		**Sat 3/13/04**
90	**Mine Emplacement Room Upper C12 (UC12)**	**237 days**	**Mon 7/21/03**		**Sat 3/13/04**
91	Develop 290 m Pilot	107 days	Mon 7/21/03	58	Tue 11/4/03
92	Slash 290 m Emplacement Room	130 days	Wed 11/5/03	91	Sat 3/13/04



Project: OPG Project1
Date: Fri 12/13/02

Task		Progress		Summary		Rolled Up Split		Rolled Up Progress		Project Summary	
Split		Milestone		Rolled Up Task		Rolled Up Milestone		External Tasks			

ID		Task Name	Duration	Start	Predecessors	Finish
93		**Mine Emplacement Room Upper C13 (UC13)**	**210 days**	**Mon 7/21/03**		**Sun 2/15/04**
94		Develop 290 m Pilot	107 days	Mon 7/21/03	58	Tue 11/4/03
95		Slash 290 m Emplacement Room	103 days	Wed 11/5/03	94	Sun 2/15/04
96		**Concrete Emplacement In Rooms**	**651 days**	**Tue 11/26/02**		**Mon 9/6/04**
97		**Lower C Rooms**	**372 days**	**Tue 11/26/02**		**Tue 12/2/03**
98		**Concrete Crew No. 1**	**279 days**	**Tue 11/26/02**		**Sun 8/31/03**
99		LC1	93 days	Tue 11/26/02	10	Wed 2/26/03
100		LC2	93 days	Thu 2/27/03	99	Fri 5/30/03
101		LC3	93 days	Sat 5/31/03	100	Sun 8/31/03
102		**Concrete Crew No. 2**	**279 days**	**Tue 11/26/02**		**Sun 8/31/03**
103		LC4	93 days	Tue 11/26/02	20	Wed 2/26/03
104		LC5	93 days	Thu 2/27/03	103	Fri 5/30/03
105		LC6	93 days	Sat 5/31/03	104	Sun 8/31/03
106		**Concrete Crew No. 3**	**279 days**	**Tue 11/26/02**		**Sun 8/31/03**
107		LC7	93 days	Tue 11/26/02	30	Wed 2/26/03
108		LC8	93 days	Thu 2/27/03	107	Fri 5/30/03
109		LC9	93 days	Sat 5/31/03	108	Sun 8/31/03
110		**Concrete Crew No. 4**	**279 days**	**Tue 11/26/02**		**Sun 8/31/03**
111		LC10	93 days	Tue 11/26/02	40	Wed 2/26/03
112		LC11	93 days	Thu 2/27/03	111	Fri 5/30/03
113		LC12	93 days	Sat 5/31/03	112	Sun 8/31/03
114		**Concrete Crew No. 3**	**93 days**	**Mon 9/1/03**		**Tue 12/2/03**
115		LC13	93 days	Mon 9/1/03	50,109	Tue 12/2/03
116		**Upper C Rooms**	**372 days**	**Mon 9/1/03**		**Mon 9/6/04**
117		**Concrete Crew No. 1**	**279 days**	**Mon 9/1/03**		**Sat 6/5/04**
118		UC1	93 days	Mon 9/1/03	55,101	Tue 12/2/03
119		UC2	93 days	Wed 12/3/03	118	Thu 3/4/04
120		UC3	93 days	Fri 3/5/04	119	Sat 6/5/04
121		**Concrete Crew No. 2**	**279 days**	**Mon 9/1/03**		**Sat 6/5/04**
122		UC4	93 days	Mon 9/1/03	105	Tue 12/2/03
123		UC5	93 days	Wed 12/3/03	122	Thu 3/4/04
124		UC6	93 days	Fri 3/5/04	123	Sat 6/5/04
125		**Concrete Crew No. 3**	**279 days**	**Wed 12/3/03**		**Mon 9/6/04**
126		UC7	93 days	Wed 12/3/03	115,74	Thu 3/4/04
127		UC8	93 days	Fri 3/5/04	126	Sat 6/5/04
128		UC9	93 days	Sun 6/6/04	127	Mon 9/6/04
129		**Concrete Crew No. 4**	**279 days**	**Mon 9/1/03**		**Sat 6/5/04**
130		UC10	93 days	Mon 9/1/03	113,85	Tue 12/2/03
131		UC11	93 days	Wed 12/3/03	130	Thu 3/4/04
132		UC12	93 days	Fri 3/5/04	131	Sat 6/5/04
133		**Concrete Crew No. 1**	**93 days**	**Sun 6/6/04**		**Mon 9/6/04**
134		UC13	93 days	Sun 6/6/04	120,95	Mon 9/6/04
135		**Prepare Section C for Emplacement (Track, Vent, etc)**	**340 days**	**Wed 12/3/03**		**Sat 11/6/04**
136		**Install Track Across Emplacement Rooms**	**170 days**	**Wed 12/3/03**		**Thu 5/20/04**
137		**Track Crew No. 1**	**100 days**	**Wed 12/3/03**		**Thu 3/11/04**
138		Repair Track and Switch Gear Across Vault Lower C	100 days	Wed 12/3/03	115	Thu 3/11/04

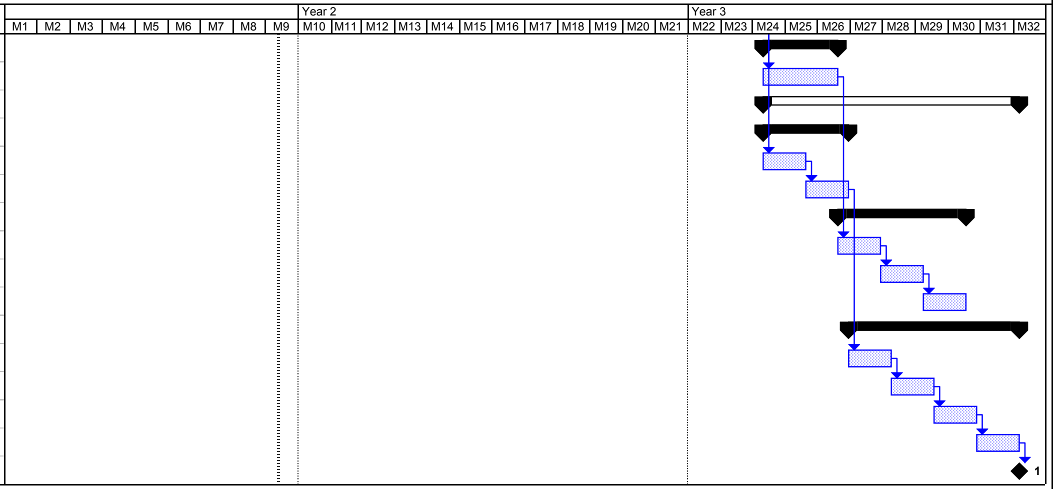


Project: OPG Project1
Date: Fri 12/13/02

Task	Progress	Summary	Rolled Up Split	Rolled Up Progress	Project Summary
Split	Milestone	Rolled Up Task	Rolled Up Milestone	External Tasks	

OPG - DGR Vault Excavation - Upper Half Section A/Section B

ID		Task Name	Duration	Start	Predecessors	Finish
139		**Track Crew No. 1**	**70 days**	**Fri 3/12/04**		**Thu 5/20/04**
140		Install Track and Switch Gear Across Vault Upper C	70 days	Fri 3/12/04	138	Thu 5/20/04
141		**Install Track in 9 out of 26 Emplacement Rooms**	**240 days**	**Fri 3/12/04**		**Sat 11/6/04**
142		**Track Crew No. 2**	**80 days**	**Fri 3/12/04**		**Sun 5/30/04**
143		LC1	40 days	Fri 3/12/04	138	Tue 4/20/04
144		LC2	40 days	Wed 4/21/04	143	Sun 5/30/04
145		**Track Crew No. 1**	**120 days**	**Fri 5/21/04**		**Fri 9/17/04**
146		LC3	40 days	Fri 5/21/04	140	Tue 6/29/04
147		LC4	40 days	Wed 6/30/04	146	Sun 8/8/04
148		LC5	40 days	Mon 8/9/04	147	Fri 9/17/04
149		**Track Crew No. 2**	**160 days**	**Mon 5/31/04**		**Sat 11/6/04**
150		LC6	40 days	Mon 5/31/04	144	Fri 7/9/04
151		LC7	40 days	Sat 7/10/04	150	Wed 8/18/04
152		LC8	40 days	Thu 8/19/04	151	Mon 9/27/04
153		LC9	40 days	Tue 9/28/04	152	Sat 11/6/04
154		End of Mining - 26 Rooms ready for Emplacement	0 days	Sat 11/6/04	153	Sat 11/6/04

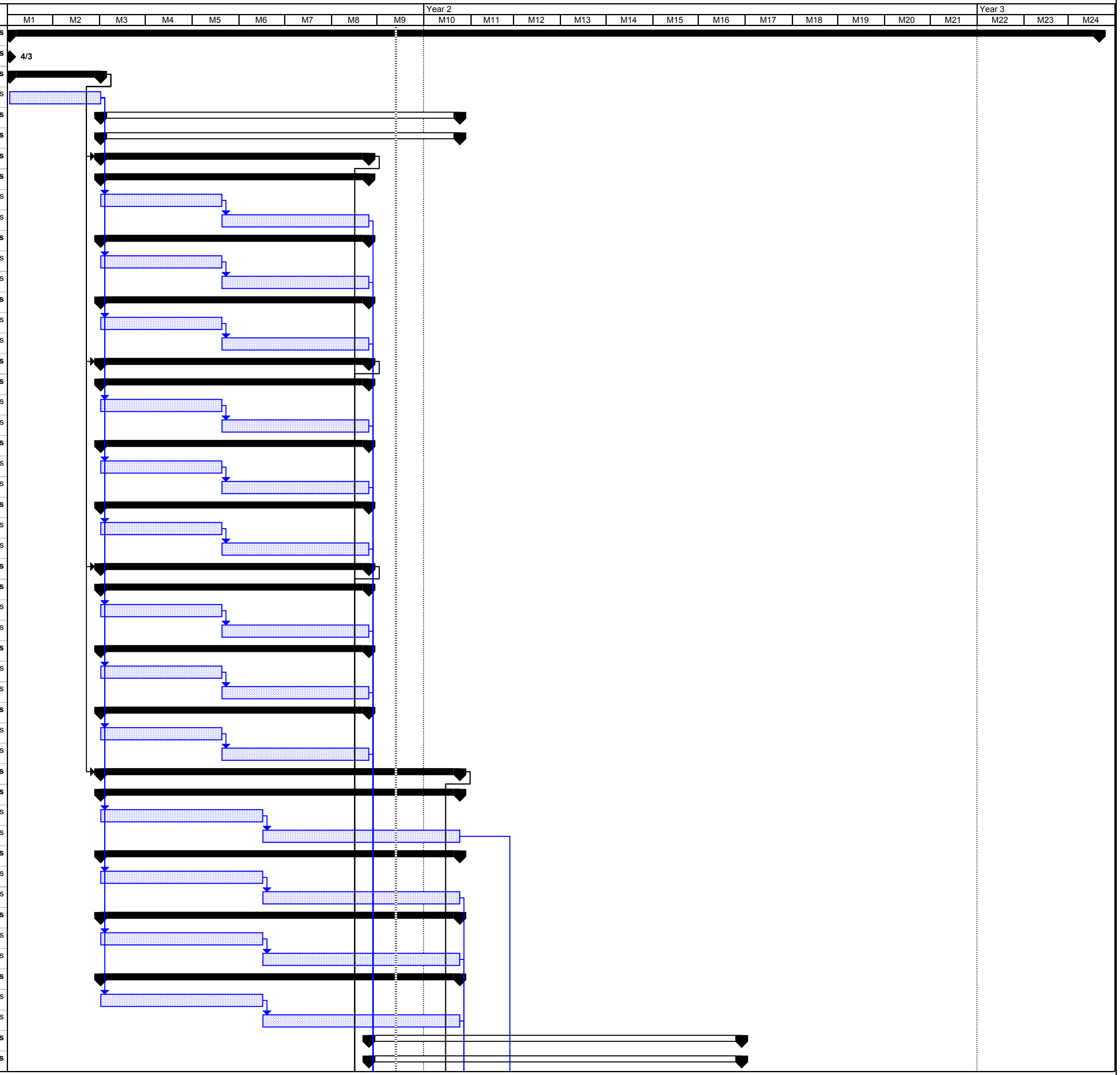


Project: OPG Project1
Date: Fri 12/13/02

Task		Progress		Summary		Rolled Up Split		Rolled Up Progress		Project Summary	
Split		Milestone		Rolled Up Task		Rolled Up Milestone		External Tasks			

OPG - DGR Vault Excavation - Upper Half Section D 13 Rooms

ID		Task Name	Duration
1		**OPG-DGR Vault Excavation Project**	**719 days**
2		**Award Contract**	**0 days**
3		**Vault Excavation Mobilization**	**60 days**
4		Mobilization	60 days
5		**Vault Excavation Upper D**	**237 days**
6		**Mine UpperD**	**237 days**
7		**Jumbo No. 1**	**177 days**
8		**Mine Emplacement Room Upper D1 (UD1)**	**177 days**
9		Develop 290 m Pilot	80 days
10		Slash290 m Emplacement Room	97 days
11		**Mine Emplacement Room Upper D2 (UD2)**	**177 days**
12		Develop 290 m Pilot	80 days
13		Slash 290 m Emplacement Room	97 days
14		**Mine Emplacement Room Upper D3 (UD3)**	**177 days**
15		Develop 290 m Pilot	80 days
16		Slash 290 m Emplacement Room	97 days
17		**Jumbo No. 2**	**177 days**
18		**Mine Emplacement Room Upper D4 (UD4)**	**177 days**
19		Develop 290 m Pilot	80 days
20		Slash 290 m Emplacement Room	97 days
21		**Mine Emplacement Room Upper D5 (UD5)**	**177 days**
22		Develop 290 m Pilot	80 days
23		Slash 290 m Emplacement Room	97 days
24		**Mine Emplacement Room UpperD6 (UD6)**	**177 days**
25		Develop 290 m Pilot	80 days
26		Slash 290 m Emplacement Room	97 days
27		**Jumbo No. 3**	**177 days**
28		**Mine Emplacement Room Upper D7 (UD7)**	**177 days**
29		Develop 290 m Pilot	80 days
30		Slash 290 m Emplacement Room	97 days
31		**Mine Emplacement Room Upper D8 (UD8)**	**177 days**
32		Develop 290 m Pilot	80 days
33		Slash 290 m Emplacement Room	97 days
34		**Mine Emplacement Room Upper D9 (UD9)**	**177 days**
35		Develop 290 m Pilot	80 days
36		Slash 290 m Emplacement Room	97 days
37		**Jumbo No. 4**	**237 days**
38		**Mine Emplacement Room Upper D10 (UD10)**	**237 days**
39		Develop 290 m Pilot	107 days
40		Slash 290 m Emplacement Room	130 days
41		**Mine Emplacement Room Upper D11 (UD11)**	**237 days**
42		Develop 290 m Pilot	107 days
43		Slash 290 m Emplacement Room	130 days
44		**Mine Emplacement Room UpperDA12 (UD12)**	**237 days**
45		Develop 290 m Pilot	107 days
46		Slash 290 m Emplacement Room	130 days
47		**Mine Emplacement Room UpperD13 (UD13)**	**237 days**
48		Develop 290 m Pilot	107 days
49		Slash 290 m Emplacement Room	130 days
50		**Concrete Emplacement In Rooms**	**246 days**
51		**Upper D Rooms**	**246 days**



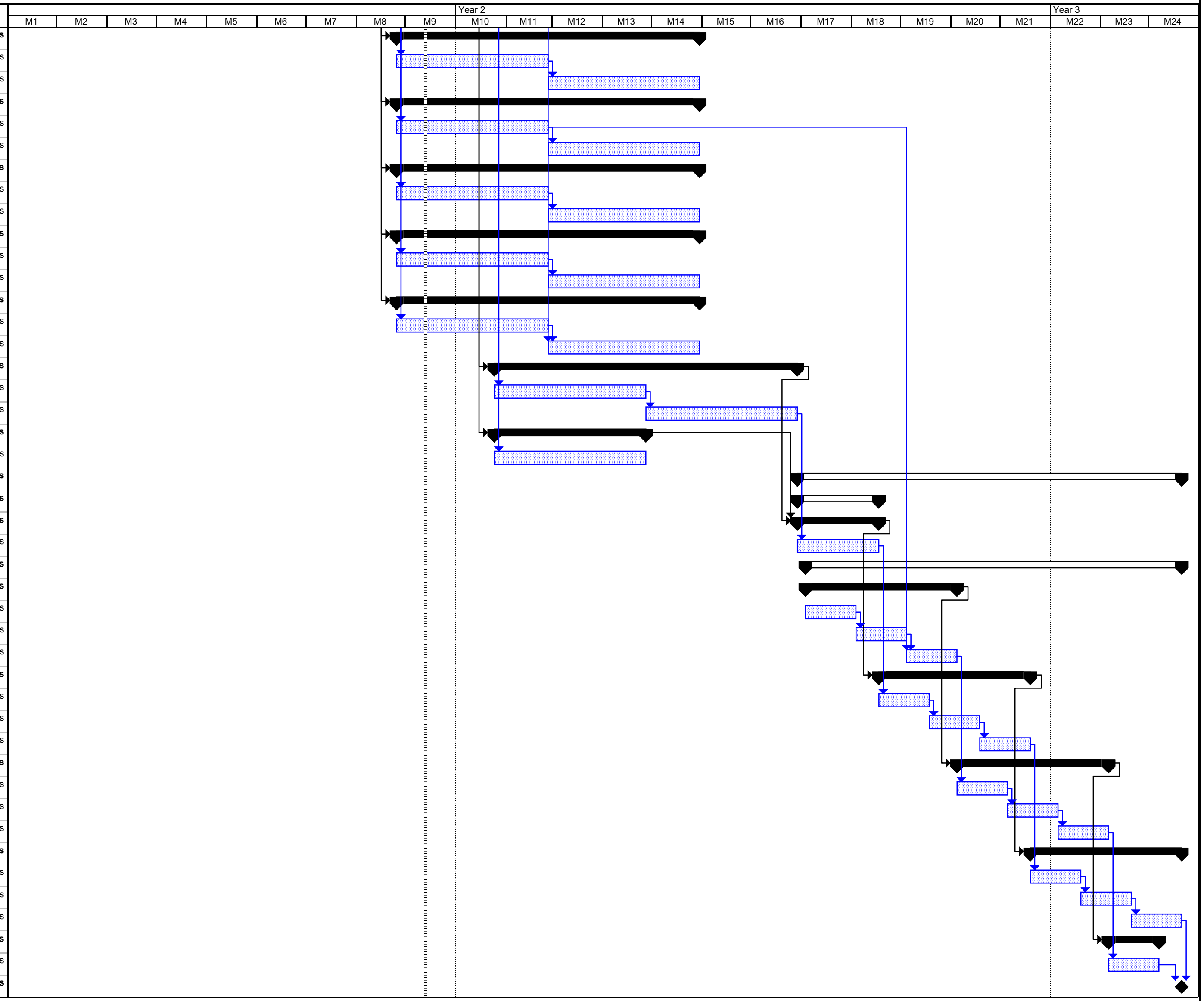
Project: OPG Project1
Date: Fri 12/13/02

Task		Progress		Summary		Rolled Up Split		Rolled Up Progress	
Split		Milestone		Rolled Up Task		Rolled Up Milestone		External Tasks	

Project Summary

OPG - DGR Vault Excavation - Upper Half Section D 13 Rooms

ID	Task Name	Duration
52	**Concrete Crew No. 1**	**186 days**
53	UD1	93 days
54	UD2	93 days
55	**Concrete Crew No. 2**	**186 days**
56	UD3	93 days
57	UD4	93 days
58	**Concrete Crew No. 3**	**186 days**
59	UD5	93 days
60	UD6	93 days
61	**Concrete Crew No. 4**	**186 days**
62	UD7	93 days
63	UD8	93 days
64	**Concrete Crew No. 5**	**186 days**
65	UD9	93 days
66	UD10	93 days
67	**Concrete Crew No. 6**	**186 days**
68	UD11	93 days
69	UD12	93 days
70	**Concrete Crew No.5**	**93 days**
71	UD13	93 days
72	**Prepare Upper Section D for Emplacement (Track, Vent, etc)**	**236 days**
73	**Install Track Across Emplacement Rooms**	**50 days**
74	**Track Crew No. 1**	**50 days**
75	Install Track and Switch Gear Across Vault Upper D	50 days
76	**Install Track in 13 Emplacement Rooms**	**231 days**
77	**Track Crew No. 2**	**93 days**
78	UD1	31 days
79	UD2	31 days
80	UD3	31 days
81	**Track Crew No. 1**	**93 days**
82	UD4	31 days
83	UD5	31 days
84	UD6	31 days
85	**Track Crew No. 2**	**93 days**
86	UD7	31 days
87	UD8	31 days
88	UD9	31 days
89	**Track Crew No. 1**	**93 days**
90	UD10	31 days
91	UD11	31 days
92	UD12	31 days
93	**Track Crew No. 2**	**31 days**
94	UD13	31 days
95	**End of Mining - 13 Rooms ready for Emplacement**	**0 days**



Project: OPG Project1
Date: Fri 12/13/02

Task | Progress | Summary | Rolled Up Split | Rolled Up Progress | Project Summary
Split | Milestone | Rolled Up Task | Rolled Up Milestone | External Tasks

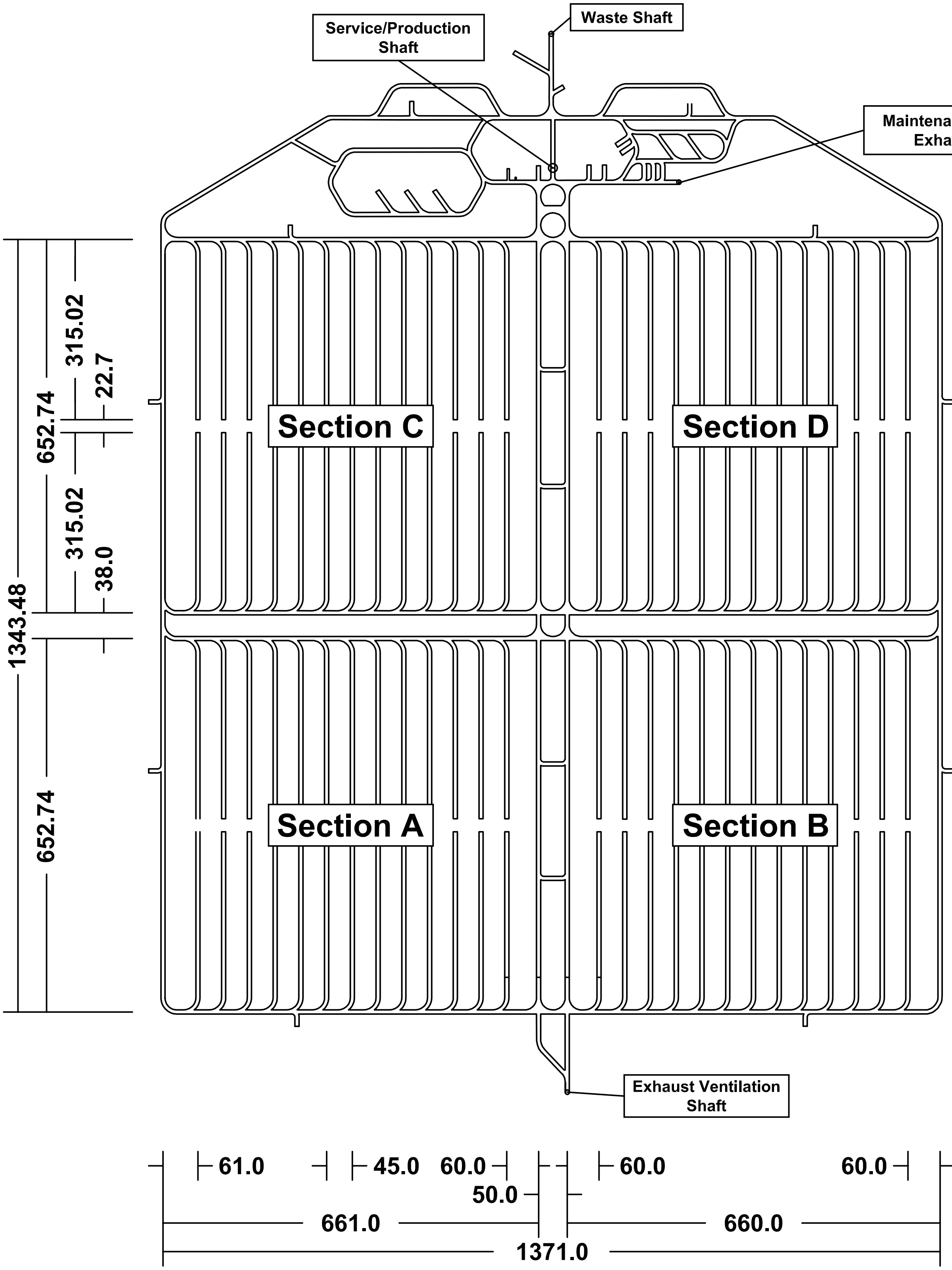


Fig. 1a - General Layout - Proposed Plan of Used Fuel Disposal Vault (Rev. 3)

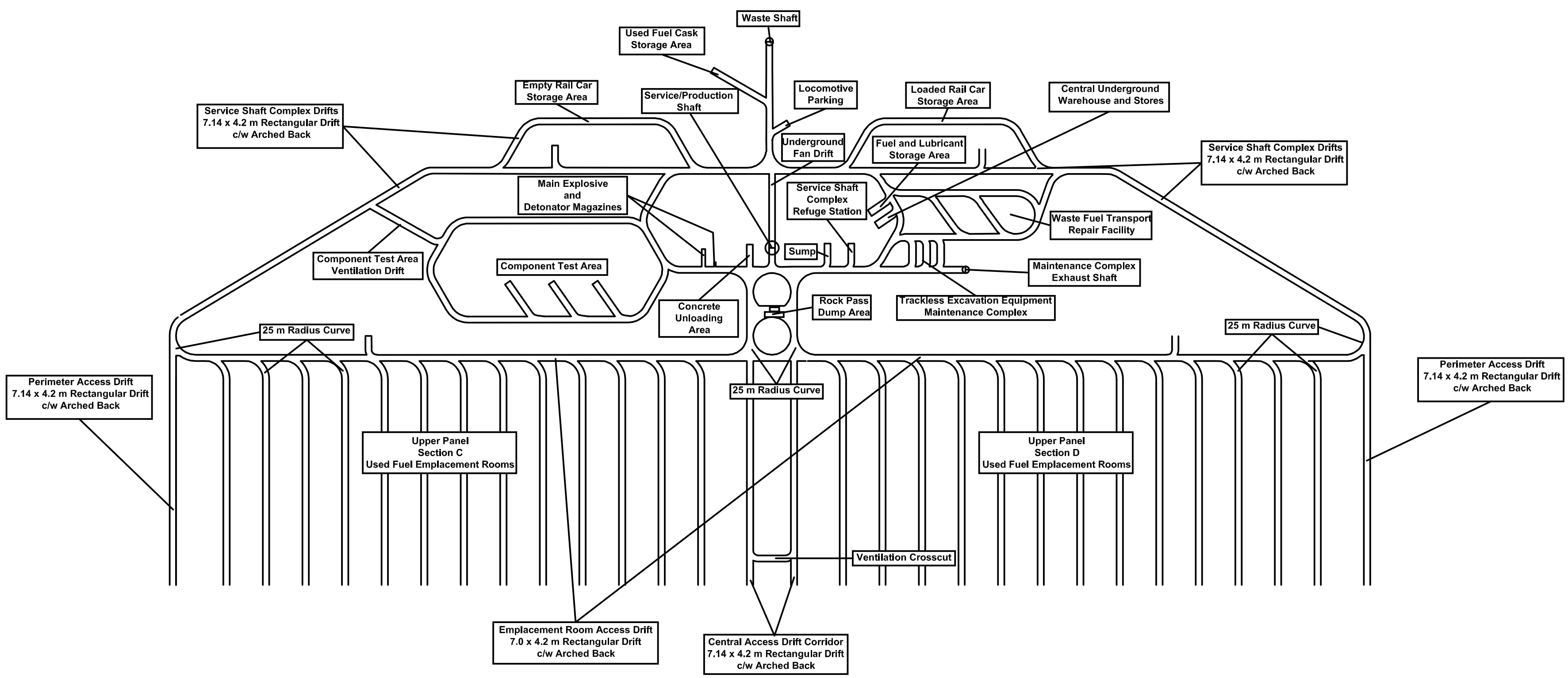


Fig. 1b - Detail of Service Shaft Area (Rev. 3)

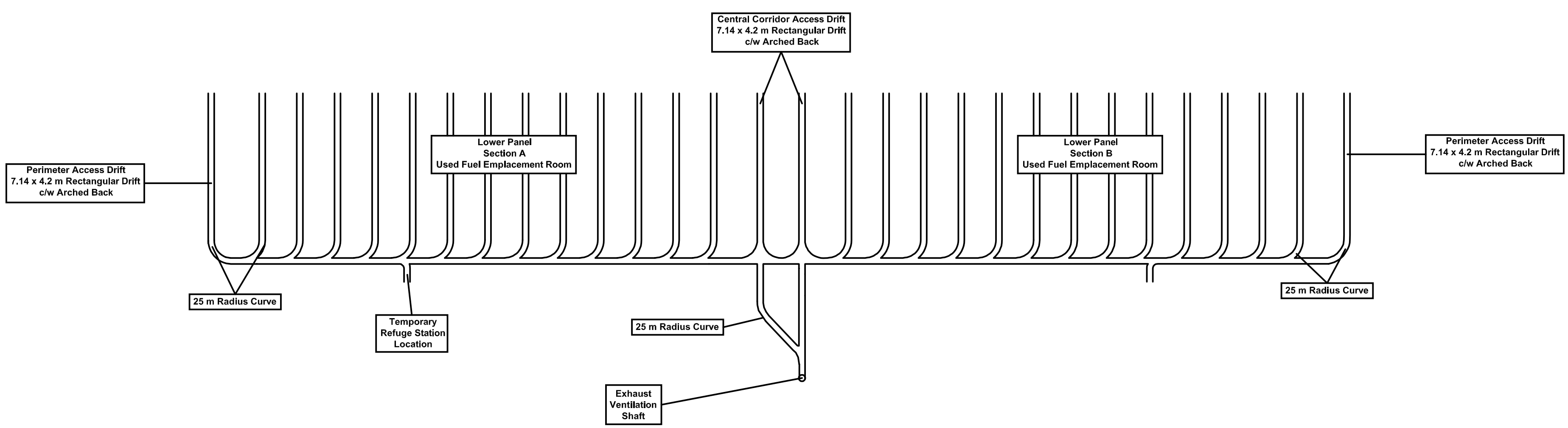


Fig. 1c - Detail of the Upcast Shaft Complex (Rev. 2)

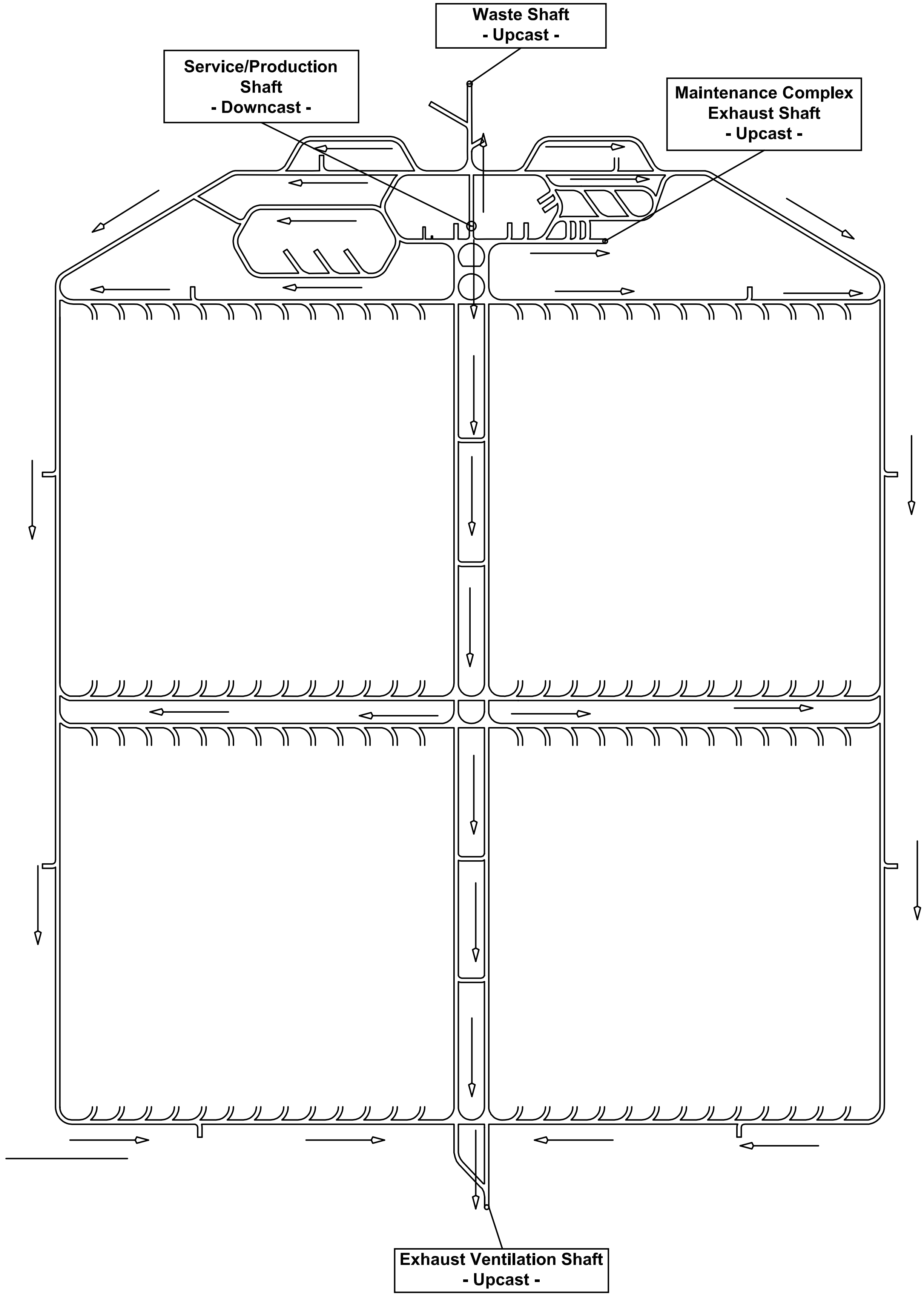


Fig. 1d - Ventilation Schematic for the Used Fuel Disposal Vault

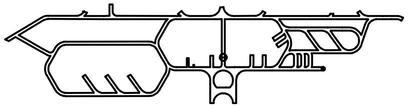


Fig. 1e (i)

Initial Exploration Development
Developing a Test Component Area and determining the proper Repository orientation.

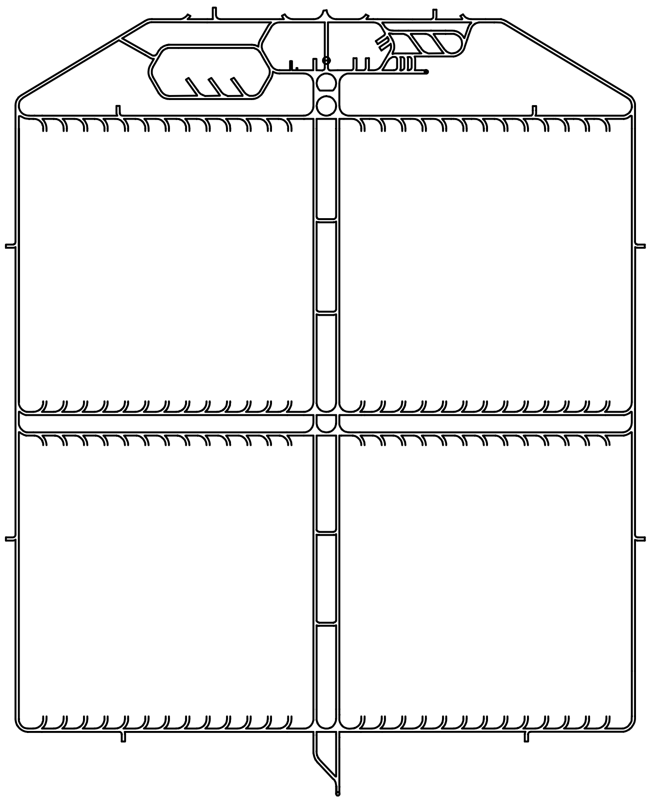


Fig. 1e (ii)

Repository Development
Establishing the perimeter, central and repository panel access drifts, plus the waste fuel transport repair facility and exhaust ventilation shaft.

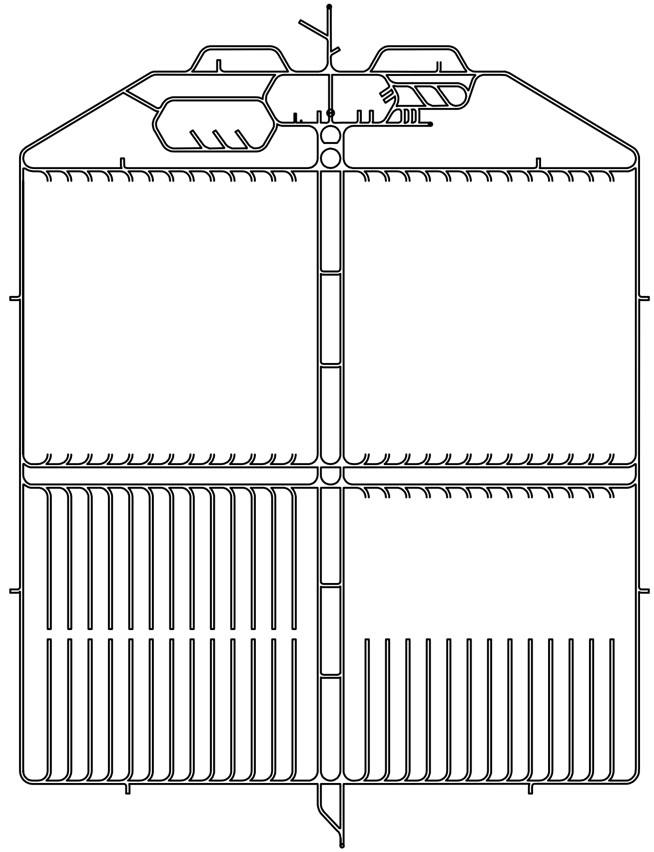


Fig. 1e (iii)

Repository Development - Repository Panel Development
Establish the Waste Shaft, empty and loaded rail car areas and 39 emplacement rooms.

Fig. 1e - Proposed Pre-Emplacement Development Sequence

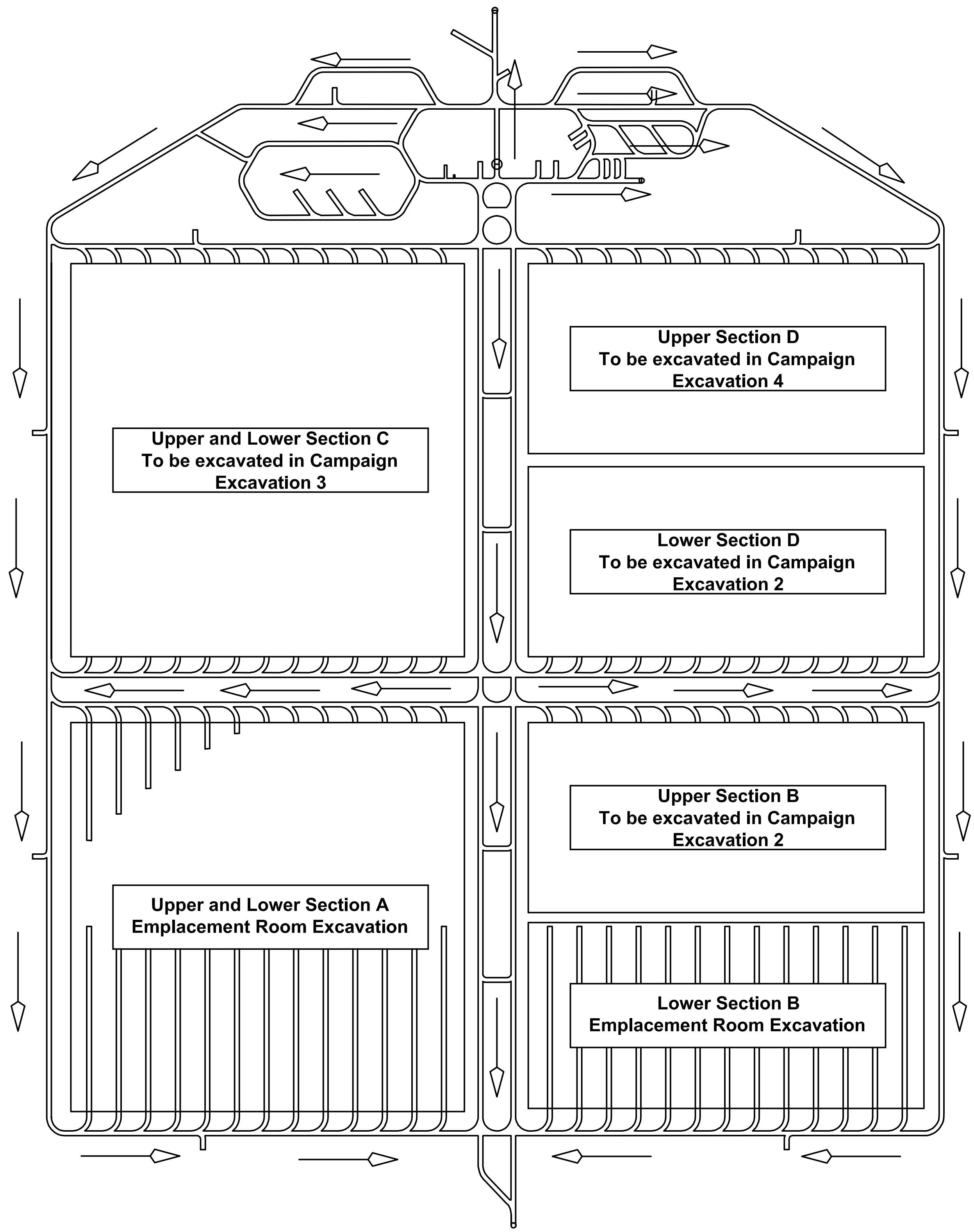
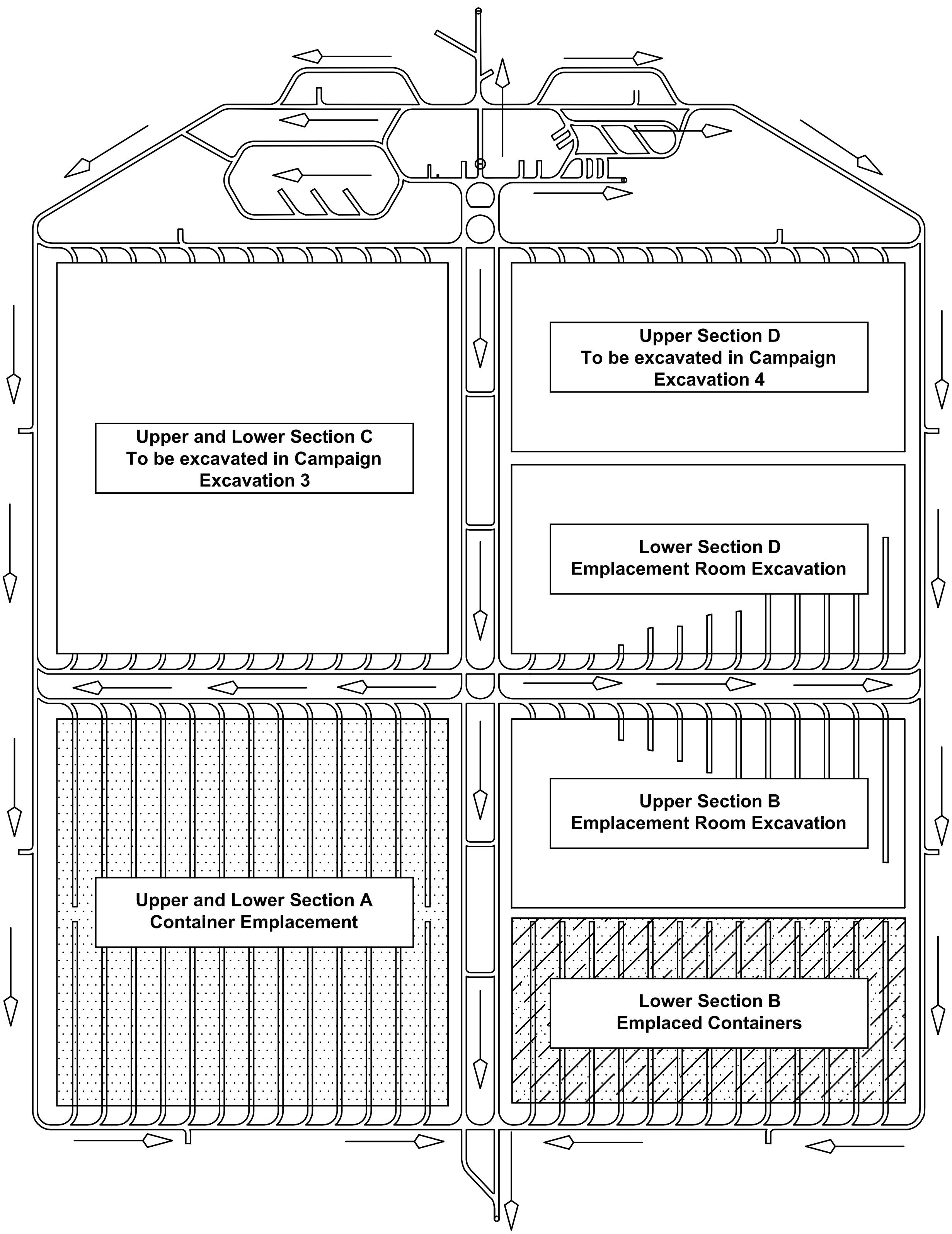
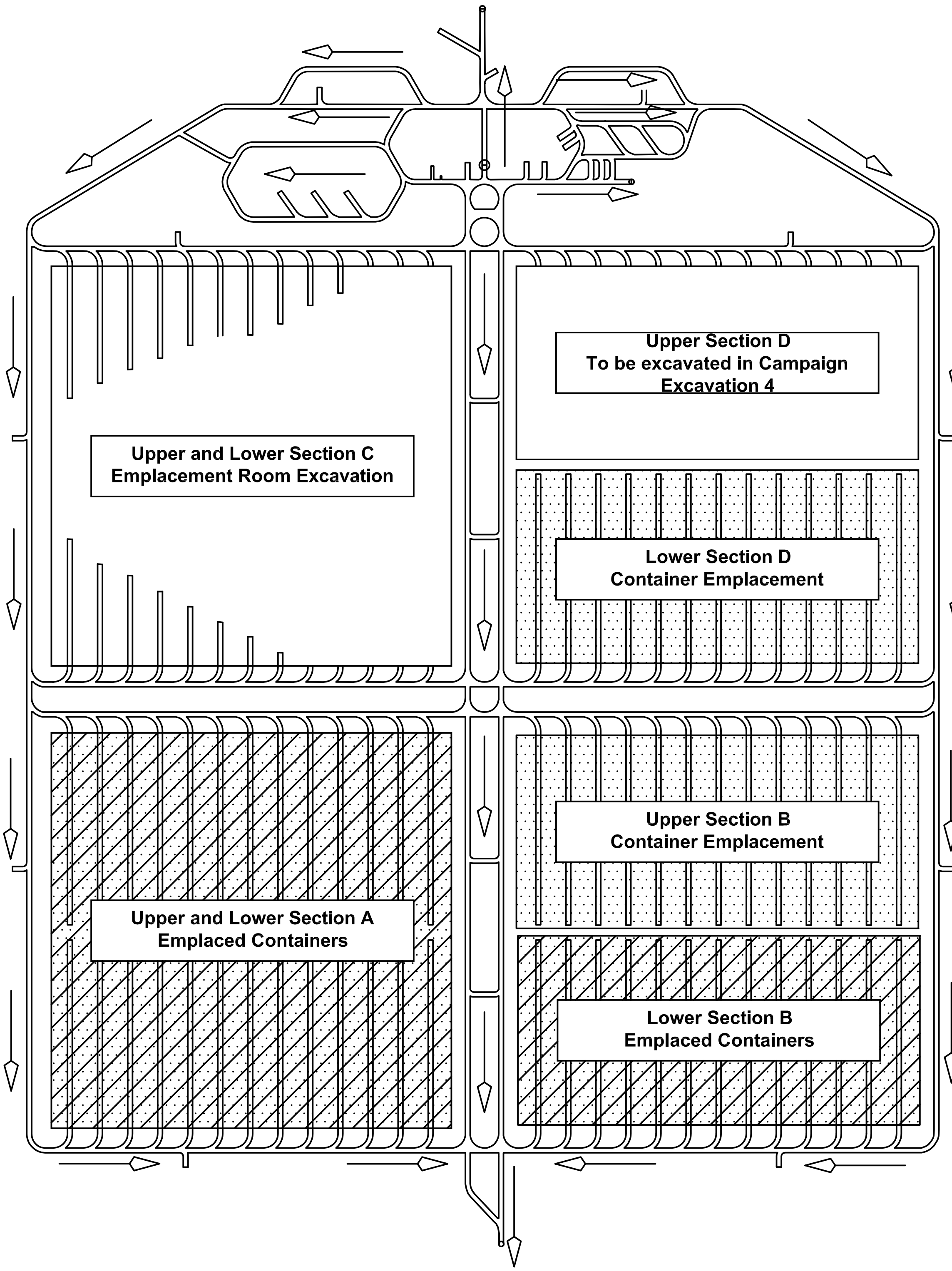


Fig. 2a - Demonstrating Initial Section Excavation Sequence
(Initial 39 emplacement room excavation)



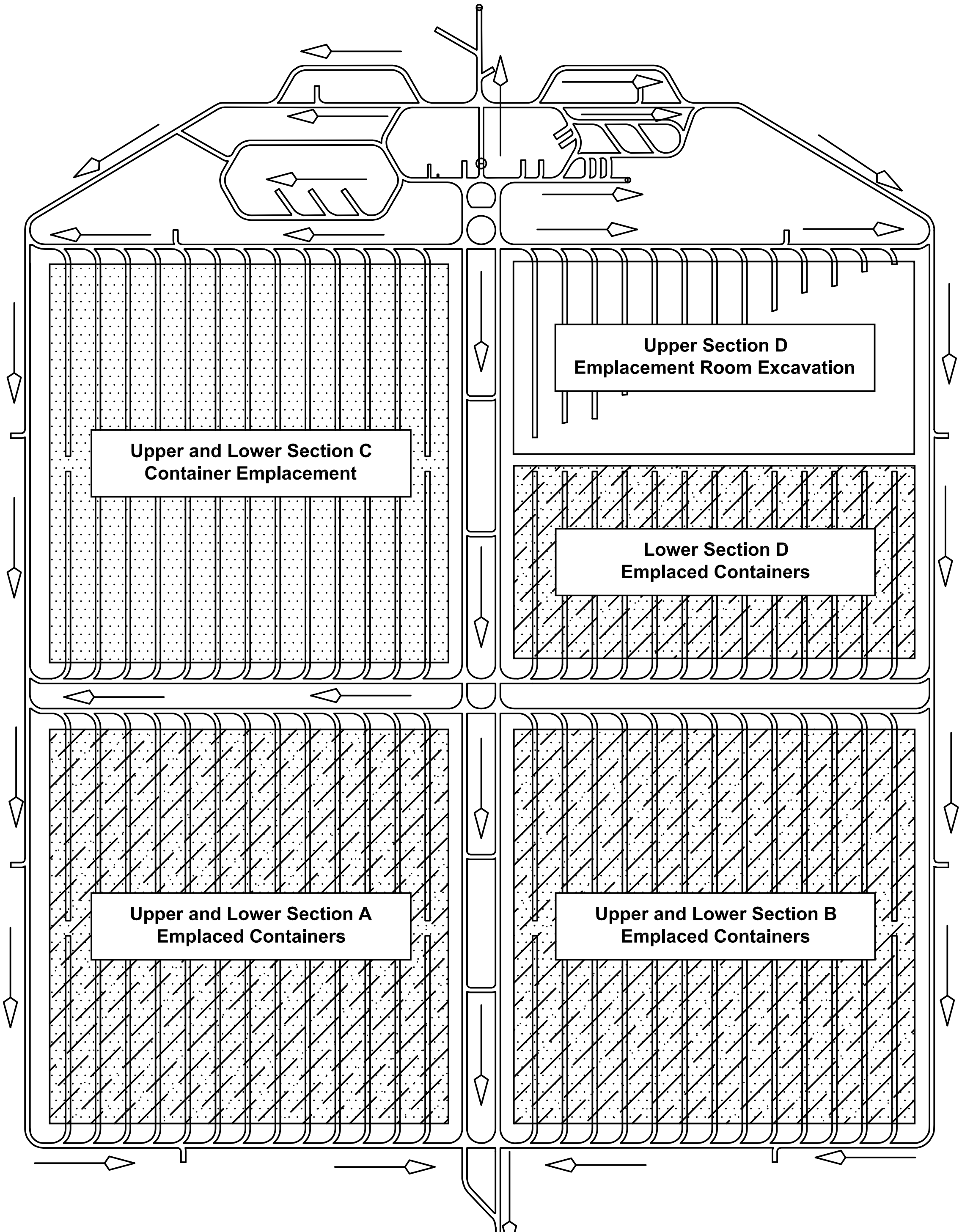
Note: Airflow direction demonstrates non-mixing of excavation and emplacement air.

Fig. 2b - Demonstrating Section Excavation and Waste Emplacement Sequence during Campaign Excavation 2 (26 emplacement rooms excavated)



Note: Airflow direction demonstrates non-mixing of excavation and emplacement air.

Fig. 2c - Demonstrating Section Excavation and Waste Emplacement Sequence during Campaign Excavation 3 (26 emplacement rooms excavated)



Note: Airflow direction demonstrates non-mixing of excavation and emplacement air.

Fig. 2d - Demonstrating Section Excavation and Waste Emplacement Sequence during Campaign Excavation 4 (13 excavation rooms excavated)

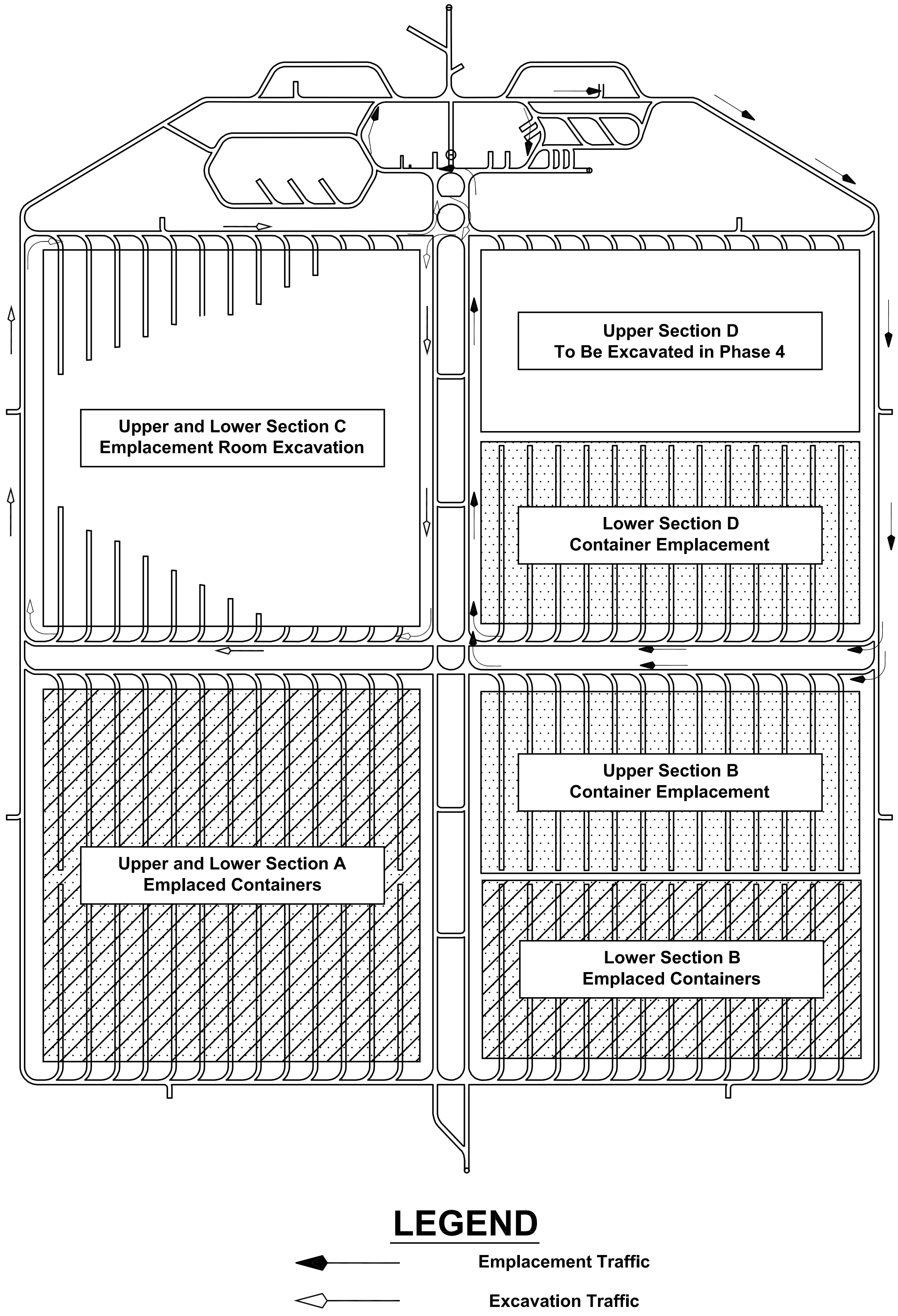
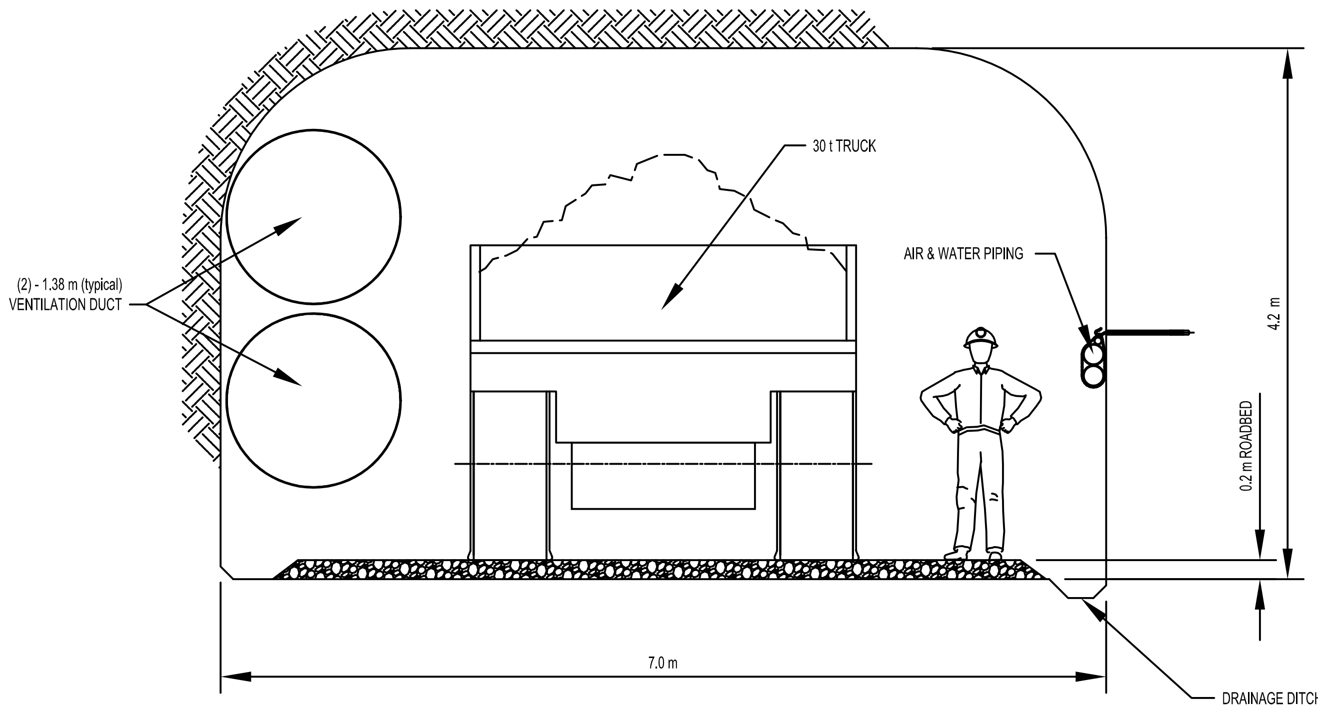


Fig. 2e - Demonstrating Clockwise movement of traffic during emplacement in Upper Panel B and Lower Panel D, whilst 26 emplacement rooms are excavated in Section C



NOTE:
- LAYOUT MAY BE MIRRORED DEPENDING ON WHETHER AN UPPER OR LOWER EMPLACEMENT PANEL IS BEING DEVELOPED.

FIG.3 7.0 m x 4.2 m WASTE FUEL REPOSITORY ACCESS DRIFT
(DEMONSTRATING THE SPATIAL RELATIONSHIPS)

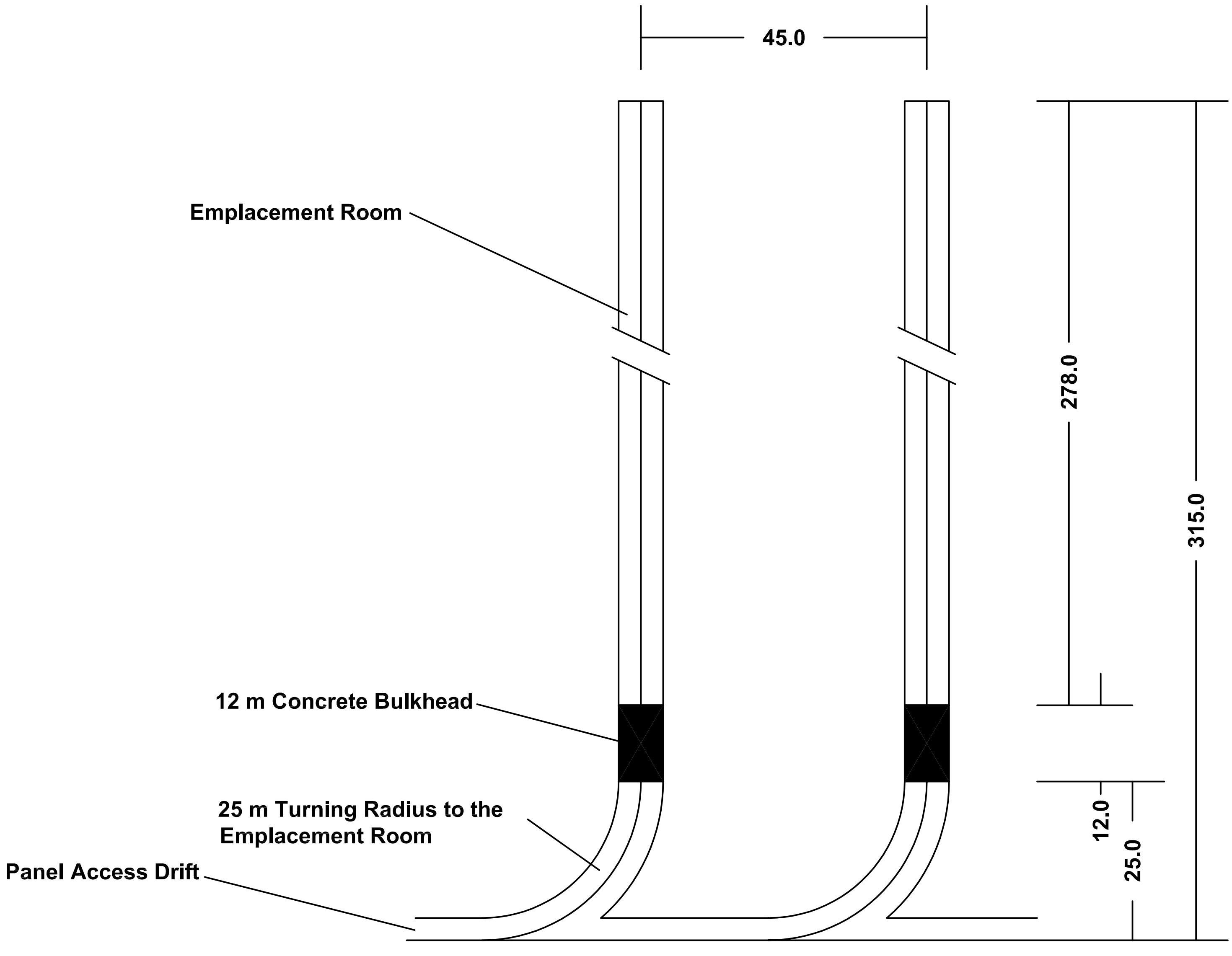


Fig. 4 - Demonstrating the position of the 12 m thick Concrete Bulkhead relative to the emplacement rooms and panel access drift.

1106/MD18085/REP/01

Radioactive Materials Management

Deep Geologic Repository Conceptual Design

Annex 5

NFOLD Numerical Analysis

December 2002

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 .

This document is written solely for the benefit of the Client, for the purpose stated in the Agreement, and the Consultant's liabilities are limited to those set out in the Agreement."

Contents

Tables

Figures

EXECUTIVE SUMMARY

Numerical analyses of the Deep Geologic Repository (DGR) concept layout design provided by CTECH, were undertaken using the displacement discontinuity program NFOLD. These analyses were carried out to assess three states during development and operation of the DGR, as follows:

1. to check overall stability conditions for the excavations prior to thermal loading,
2. to check overall stability conditions after all the emplacement vaults are filled, and
3. to check overall stability conditions during excavation of clay-based sealing materials to retrieve one or more containers, at various times after emplacement.

Based on the assumptions made regarding uniform in situ stresses and homogenous, sparsely fractured rock mass conditions as incorporated into the NFOLD model, the proposed emplacement vault layout at a depth of 1000 m is generally satisfactory from a global rock stability viewpoint for the creation of the excavations prior to thermal loading and also from the overall stability perspective once the emplacement rooms are filled.

The numerical results indicate that:

1. The 45m distance between centres of the emplacement rooms is adequate for maintaining stability of the sparsely fractured rockmass assumed to comprise the 38m wide rib pillars, between these rooms.
2. 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 optimization program is required to "calibrate" far-field stress conditions with the design aspect ratio. (The current study assumes a ratio of 1.7).
3. The emplacement rooms should be arranged parallel to the major horizontal far-field stresses, as this reduces the potential for rock damage and failure around the openings.
4. In situ stress measurements must be undertaken in the initial stages of design investigation at the actual chosen site to confirm magnitudes and orientations. Knowledge of the far-field stresses is paramount for selecting the best layout development.
5. Additional ground support will likely be required at the corners and entranceways to the emplacement rooms.
6. The intersections of proposed accessways located at the centre of the emplacement vault 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 60m to minimize super-position of stresses. This recommendation has been included in the revised repository layout.

1 Introduction

Golder Associates was retained by CTECH to carry out geotechnical numerical analyses for assisting in the conceptual design for a deep geologic repository (DGR) for used nuclear fuel, utilizing the in-room emplacement concept of the used fuel containers.

Numerical analyses of the concept layout design provided by CTECH, were undertaken using the displacement discontinuity program NFOLD. These analyses were carried out to assess three states during development and operation of the DGR, as follows:

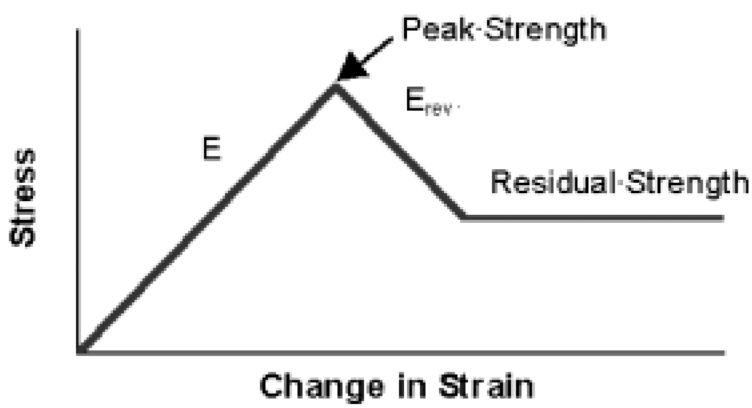
1. to check overall stability conditions for the excavations prior to thermal loading,
2. to check overall stability conditions after all the emplacement vaults are filled, and
3. to check overall stability conditions during excavation of clay-based sealing materials to retrieve one or more containers, at various times after emplacement.

This report presents the numerical analysis results and suggests an alternative for retrieving the containers, after they have been placed in the vaults.

2 NFOLD Model

Non-linear analyses of the DGR vault were conducted using the program NFOLD, which utilizes the displacement discontinuity (DD) stress analysis method. This method has its greatest application in the determination of stresses and displacements associated with excavation of tabular ore bodies in underground mines. For the analyses conducted for the DGR, the vault plan was represented as an infinitely thin, planar slit located within an infinite, elastic material (the host rock). The rock mass around the repository was modelled as equal sized rectangular elements in the plane of the emplacement vault. Each of these individual elements represents a portion of the emplacement vault plan as a compressible material.

The model assumes that these DD elements may yield, according to the deformation and failure characteristics of a typical element as represented by the following properties: linear elastic behaviour to a peak strength, followed by a falling load-deformation response to a residual strength plateau, as illustrated by the following stress-strain graph:



Although the placement of clay-based sealing materials (or bentonite jacket) into the vaults could be simulated with the introduction of a fill element to replace a previously excavated element, for conservatism at this concept analysis stage no bentonite jacket (i.e., the 100% bentonite clay used for the protective jacket around the UFC) was introduced into the NFOLD vault models.

In order to simulate the mining excavation process, blocks of displacement discontinuity elements were removed at each mining stage, with progressive mining being represented by a sequence of different mining patterns. For the current study, in order to examine the most critical areas of the vault from the stress-deformation viewpoint, attention was concentrated on the central area of the planned repository layout provided by CTECH.

For ease of the simulations, the repository configuration was modelled as a single, horizontal seam with a constant 4 m thickness. Elements were set as 3.5 m by 3.5 m in the NFOLD model, in order to represent each of the 7.14 m wide emplacement rooms with 2 elements.

Based on an assumption that the basic unconfined compressive strength of the rock mass (100 MPa) would be an appropriate value for replicating conditions at the room periphery, the peak and residual strengths of the rib pillars, located between the vaults, were assumed as follows:

Material Location	Peak Strength (MPa)	Residual Strength[1] (MPa)	Young's Modulus (loading) (GPa)	Young's Modulus (post peak) [2] (GPa)
Excavation without thermally induced stresses				
Core of Rib Pillars	120	60	60	42
Edge of Rib Pillars	100	50		
Partially Confined Elements	110	55		
Long-term Induced Stresses, Including Simulated Thermally Induced Stresses				
Core of Rib Pillars	180	90	60	42
Edge of Rib Pillars	150	75		
Partially Confined Elements	165	82		

[1] Residual strength arbitrarily assumed as 50% of the peak strength
[2] Post-peak Young's Modulus assumed as 70% of the pre-peak modulus

With no actual data available on confinement and strength relationships for the assumed sparsely fractured rock mass, assumptions on the internal strengths of the rib pillars for use in the NFOLD model were based on typical precedent experience with boundary and chain pillars for underground tabular mining situations. For such situations, as confinement away from the walls of the excavations into the interior of the rock mass increases, higher effective peak and residual strengths are applicable than at the edge of the rib pillars. For the emplacement room geometries being modelled in this case, it has been assumed that at a distance of about 1.75m (i.e., half the first DD element into the rock mass away from the room wall), where the confining stress is predicted to increase to more than 10 MPa, that the confined peak rock mass strength would likely be a minimum of 10% higher than at the pillar edge. Taking into account the further increase in confinement conditions to more than 20 MPa predicted to occur further into the rock mass away from the emplacement room walls, a conservative peak strength increment of 20% over the base strength at the wall zone has been assumed for representing the DD elements that are fully confined.

3 Rock Mass Material Properties and Design Limits

3.1 MATERIAL PROPERTIES

In order to incorporate appropriate characteristics for the rock mass and basic rock material within the NFOLD modelling configuration, rock mass material properties and derived strength limits were established using URL experience, as per the information published in Baumgartner et al. (1996) and summarized in Table 1.

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 σ_{ex} ***= 100 MPa***, and
b) Under Thermally-induced Loading Conditions,
   peak strength design limit, ***m = 25, s = 1*** and σ_{ti} ***= 150 MPa.***

Application of these criteria for evaluating the stability of the emplacement rooms has been applied as a two step procedure, such that the emplacement rooms first must satisfy criterion (a) during the excavation process and then only after (a) is satisfied, criterion (b) can then be used for checking the stability of the rock mass around the openings under applied thermal loading conditions.

These Hoek-Brown limit values have respectively been defined for case (a) based on URL experience and for case (b) on Baumgartner et al. (1996) thermal loading calculations for the equivalent "long-term" strength of the Lac du Bonnet granite. [Note - this latter case assumed unconfined peak strength value of σ_{ti} = 150 MPa also coincides with the threshold stress for initiation of unstable crack growth under these stress/temperature conditions (as determined from uniaxial compressive strength tests].

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 utilized 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:

- where $(\sigma_1 - \sigma_3) \geq$ ***100 MPa*** possible breakout formation likely initiated in that zone,
- with the $(\sigma_1 - \sigma_3)$ = ***75 MPa*** contour conservatively defining the depth/extent of maximum breakout.

3.2 IN SITU STRESSES

For evaluating the excavation phase for creating the DGR, which is assumed to be excavated 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), based on measurements from the URL (Martin 1990, Read 1994), the Medika pluton (Martino, unpublished memorandum, 1993) and from CANMET (Herget and Arjang, 1991). These assumed in situ stresses for the repository zone (as carried in the 1996 modelling and also assumed for the current study) are:

$$\boldsymbol{\sigma_3 = \sigma_v = 0.026\ \mathrm{MPa/m\ (depth)}}$$
$$\boldsymbol{\sigma_2 = 0.00866\ \mathrm{MPa/m} + 40.7\ \mathrm{MPa}}$$
$$\boldsymbol{\sigma_1 = 0.00866\ \mathrm{MPa/m} + 56.3\ \mathrm{MPa}}$$

where σ_v = vertical stress; and
$\sigma_1, \sigma_2, \sigma_3$ = major, intermediate and minor principal stresses, respectively

Based on these gradient relationships, stresses computed for a depth of 1000 m are:

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

with a maximum stress ratio (σ_1 / σ_3) = 2.5; where: σ_H, σ_h and σ_v, are the major and minor horizontal far-field stresses, and the vertical far-field stress, respectively.

4 Repository and Emplacement Room Layouts

4.1 EXTRACTION RATIO CONSIDERATIONS

As per the design document (OPG, 2001), maximum vault-level extraction ratios (ER), for the DGR concept layouts, as determined in a direction perpendicular to the axis of a panel of rooms, are required not to exceed 0.25, defined as follows:

ER = W/(W+P)

where: ER = extraction ratio

W = width of the emplacement rooms (m) and

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

In practice, to satisfy the thermal design specification, a lower extraction ratio was required and this was then incorporated into the CTECH layouts (as shown on Figure 1). This configuration, which was then utilized as the basis for the NFOLD analyses, was determined to exhibit an acceptable extraction ratio of 0.16 based on W = 7.14 m wide vaults spaced at 45 m centre to centre (i.e., P = (45 m - 7.14 m) ≈ 38 m).

4.2 OPTIMUM ROOM GEOMETRY

4.2.1 Initial Excavation Condition

The reference room shape being used for the current CTECH design concept is an ellipse based on the fact that Baumgartner et al. (1996) showed that stress concentrations at the perimeter of an excavation are lowest for an ellipse with a room width-to-height (i.e., W/H), or room aspect ratio, equal to the ratio of the major to minor principal far-field stresses acting in the plane of the ellipse section.

For the proposed DGR at 1000m, the ratio of the major horizontal to vertical far-field stresses (i.e., $\sigma_{H\ far\text{-}field} / \sigma_{Vertical}$) is equal to 2.5. Other conditions being ignored, at this depth, this aspect ratio should govern the "ideal" room shape for minimizing the stress concentrations acting on perimeter of the initially excavated rooms.

4.2.2 Thermal Effects

As a consequence of the anticipated increase in temperature shown on Figure 2 that will develop as the rock mass is heated, locally increased stresses will be generated. Due to the arrangement of the containers this stress increase will be non-symmetric with respect to the opening shape and, as a result, this increase will tend to create a more uniform far-field stress configuration around each emplacement room opening. This increase in stress state due to thermal effects effectively amounts to an equivalent increment in far-field stresses, which in turn would suggest a need to alter the geometry of the "ideal" room shape, by reducing the "ideal" elliptical aspect ratio to about 1.55 [i.e., $(\sigma_{H\ far\text{-}field} + \Delta\sigma_{Thermal})/(\sigma_{Vertical} + \Delta\sigma_{Thermal}) = 1.55$].

Based on the fact that the optimum ratio for the unheated rooms is 2.5 (as also shown in the previous analyses carried out by Baumgartner et al. in 1996), a compromise aspect ratio of 1.7 was stipulated by OPG for the layout of the rooms for the current design (ref. OPG, 2001 report). For this stipulated aspect ratio geometry, the proposed and analysed ellipse has a maximum width of 7.14 m and a maximum height of 4.2 m.

It will be clear from the above explanation that there can be no "perfect" or "ideal" shape that would provide "perfectly stable" rock mass behaviour for the loading conditions of both the excavation stage and the operation stage (thermal loading). A decision on critical shape requirements must therefore be made that compromises one or other or both end case conditions. By satisfying the stress configurations applicable for the excavation stage (i.e., by utilizing an elliptical room with an aspect ratio = 2.5), the potential for rock mass damage or failure would be minimized around the initially excavated opening walls; but in the long-term, some potential fracturing could develop as the temperature rises. This could, in the minimum case, locally increase the hydraulic conductivity of the rock mass more than would occur for an optimized ellipse for the thermal condition. By satisfying the long-term, thermal loading condition (i.e., by utilizing an elliptical room with an aspect ratio = 1.55), rock damage during thermal loadings could be reduced. This might assist with eventual retrieval of the containers without too adversely affecting the behaviour of the opening walls. However, extra rock support would be required in the short-term during the vault excavation stage.

Since the reference concept (OPG, 2001) stipulates an aspect ratio of 1.7 and the required height for placing the containers is 4.2 m, a 7.14 m wide x 4.2 m high elliptical shape was derived. It should be recognized, however, that no optimization of the vault shape was carried out. Once the far-field stress measurements and assessment of rock mass quality are undertaken for the selected site, then there could be significant local variability in stress conditions in proximity to zones where fracturing and/or regional faulting exists, optimized room dimensions may need to be varied across the final repository layout. With this proviso noted, it must also be recognized that under thermal loading conditions, even for the assumed idealized sparsely fractured rock mass, some localized areas (typically of about 0.5 m depth) around the openings are predicted to exhibit damage/failure (as factors of safety are calculated as being lower than 1 in such zones). In addition, as a result of the thermal overstress, some deeper disturbed zones may develop. Where areas of pervasive and hydraulically interconnected micro-cracking occur within such zones as a result of the thermal overstress effects, it is conceivable that the rockmass could locally exhibit enhanced permeabilities.

4.3 SHAFT AND ACCESSWAY LAYOUTS

As shown on Figure 1, it is proposed that the emplacement rooms in the repository vault be laid out on a grid pattern with a central cruciform access drift arrangement and an external perimeter drift. These drifts will provide access from the main service shaft. For the current concept, it is proposed that once a location is selected for the DGR, an initial exploration shaft will be sunk to a depth of approximately 1050 m, extending some 50 m below the DGR horizon for handling excavated rock (for loading and spill pockets, etc…). It is envisaged that this exploration shaft will eventually become the Service Shaft for the DGR presuming that conditions at repository level are as anticipated.

Access tunnels linking the shaft to the emplacement rooms and likely the rooms including the envisaged 25 m radius curves at the entrances to each room, for the purposes of the NFOLD modelling are assumed to be of rectangular section some 7.0 m wide and 4 m high (based on CTECH geometry).

5 Excavation Sequencing and DGR Development

5.1 INITIAL EXCAVATION STAGE

The proposed repository facility, which covers an area of approximately 1.8 km^2 is planned to be subdivided into four sections, each comprising 26 emplacement rooms with a length of approximately 315 m. The excavation and preparation of the 26 rooms for each emplacement panel is anticipated to require approximately 2.5 years. By contrast, utilizing average emplacement rates of 1.6 used fuel containers per day and operating on a 230 days per year basis, as outlined in Annex 4 it is anticipated that it will take approximately 7.5 years to fill a complete emplacement panel.

As shown in Figure 1, the four sections of the repository vault, which are labeled as A to D, are themselves each further subdivided in plan into an upper (more northern) and a lower (more southern) section allowing campaign mining to be undertaken to achieve excavation of 13 emplacement rooms at a time. It should be appreciated that the CTECH designation of upper and lower sections refers solely to plan location positions and not to any specific elevation difference between the sections.

At the initiation stage, before starting used fuel emplacement, it is planned that part of section B and all of section A will be excavated, in addition to all of the development accessways. The remainder of the vault would then be excavated sequentially, with used fuel emplacement following out of synch with the excavation process (see main text of Annex 4). In order to assess more fully the differences between pre- and post-thermal loading for the numerical analyses presented here, a simplification on this sequence has been adopted whereby excavation of the entire central area has been modelled in NFOLD using sufficient steps to properly replicate the mining and filling sequence. The two final excavation steps summarizing the maximum inferred differences, when one panel is excavated after three-quarters of the remainder of the panels have already been excavated is shown on Figure 3. As is evident the right hand diagrams show completion of the four panels by excavating the rooms in the lower section of panel C after the upper sections of panels A and B and the lower section of Panel D have already been mined.

5.2 USED FUEL EMPLACEMENT STAGE

Once initial excavations of a couple of panels have been completed, used fuel emplacement can be started. Based on the CTECH campaign mining strategy, it is planned that filling will start in the lower section B panel, then proceed on to the panel of rooms comprising the lower half of section A. Once the lower panels of sections A and B have been filled and sealed, emplacement activity will move to the upper panel of section A. At this stage used-fuel containers (UFCs) will have been emplaced into the rooms within the lower panels of sections A and B, while excavation will be continuing of the upper panel of section B and also of the lower panel of section D. Such excavation will be undertaken contemporaneously with filling of the upper panel of section A. Thermal loadings on the rock mass from the UFCs in the lower panels of sections A and B would by this time have been developing for about 6 and 10 years respectively.

As is expected, with initial placement of the containers, the rock mass will be heated, causing an induced increase in rock mass stresses. This thermal effect in the rock mass was "simulated" in the NFOLD models by applying a higher far-field stress regime, equivalent to the near-surface thermally induced stresses. The boundary conditions (i.e., modified far-field stresses) for use in the NFOLD modeling were obtained from evaluation of the results from the thermal and thermo-mechanical analyses described in Annex 2, based on the 3D finite element program Abaqus©. The 3D results suggest that, although locally to the rooms different conditions may pertain as discussed in Annex 2, globally the thermally induced stresses that will develop after 30 years of container emplacement will rise by about 45 MPa due to the rock mass temperature rise, which will reach a maximum of about 70°C at the walls. This temperature rise is quite gradual as shown on Figure 2, such that at 20 years the temperature at the walls would be approximately 66°C at the crown and invert and 64°C at the horizontal springline.

This assessment of a 45 MPa stress increase due to the temperature rise from ambient to 70° is based on results from a comprehensive series of analyses performed by Baumgartner et al. (1996), which established some basic relationships between thermal loadings and equivalent stress increases for the typical plutonic rocks at Lac du Bonnet. This work indicated a typical gradient of 0.84 MPa/degree for a 31°C rise in temperature with an equivalent increase in the far-field stresses of 26 MPa generated by the variation in the temperature. Using this gradient as a reference and considering that the original in situ rock temperature at the depth of the DGR would be about 17°C, then an increment of approximately 44.5 MPa would be estimated for a temperature rise of about 53°C (i.e., moving from 17°C to 70°C).

To mimic the effect of these thermal loadings on rock mass stresses, the NFOLD numerical models for the emplacement stage analyses were therefore prepared using modified artificially elevated far-field stresses (to reflect the equivalent thermally-induced increased stress state, post heating). These stresses were modelled using:

$$\sigma_{H'far\text{-}field} = 109.5 \text{ MPa} \quad \sigma_{h'\ far\text{-}field} = 94 \text{ MPa} \text{ and } \sigma_{V'\ far\text{-}field} = 70.5 \text{ MPa}$$

where: $\sigma_{H'}$, $\sigma_{h'}$ and $\sigma_{V'}$, are the major and minor horizontal far-field stresses, and the vertical far-field stress, respectively modified by the thermal effects [i.e., $\sigma_{H'\ far\text{-}field}$ = 109.5MPa = ($\sigma_{H\ initial\ far\text{-}field}$ = 65 MPa) + ($\Delta\sigma_{\ Thermal}$ = 44.5 MPa) and $\sigma_{V'\ far\text{-}field}$ = 70.5 MPa = ($\sigma_{V\ initial\ far\text{-}field}$ = 26 MPa) + ($\Delta\sigma_{\ Thermal}$ = 44.5 MPa)], with these values being applied uniformly throughout the NFOLD model as upgraded far field stresses (as a means to simulate the influence of the increased thermally induced stresses).

Again, the entire central area of the planned repository layout was modelled to examine the influence of the thermal effects, this time for the conditions existing once the used fuel had been placed into the vaults within sections A, B, C and D (i.e., equivalent to conditions after sufficient emplacement residence time that induced rock mass temperatures would have reached their maximum).

6 Analysis Results

Figures 3 to 5 present a summary of the NFOLD analysis results for (a) initial excavation conditions and (b) post-emplacement conditions.

6.1 STABILITY PRIOR TO THERMAL LOADING

Predicted normal stress conditions at the end of the initial stage of excavation (i.e., of the upper panels of sections A and B and the lower panels of sections C and D) are shown on Figure 3. These results are based on the assumptions of the initial stress shown in the rosette on the left side of the diagram with the major horizontal far-field principal stress oriented perpendicular to the emplacement room layouts in order to accommodate uncertainty in the magnitude of likely far-field stresses.

The NFOLD model layouts assume that these stresses are uniform across the entire width of the repository and that rock mass conditions are also uniform and not disturbed by areas with intense fracturing, such as may occur in the vicinity of significant geological structure. Obviously, by making these assumptions of uniformity of the deep geological conditions, some uncertainty is introduced that the results may not be truly valid and representative of actual most probable repository rock mass and stress conditions. These analyses should therefore be considered conceptual only, reflecting the fact that no provision has been made for likely geological and/or lithological variations, nor has any calibration been incorporated (such as would normally be undertaken by replicating observations during excavation and monitoring (convergence readings, microseismic data, etc.).

Despite these potential limitations on the reliability of the modelling results, some clear and useful inferences can be drawn from the results.

6.1.1 Initial As-Excavated Normal Stress Distributions

Figure 3, diagrams A) and B) show normal stress distributions for the central zone of the DGR for two steps in the excavation sequence assuming that the emplacement rooms in each step are excavated but not filled. As is evident, these figures indicate that even in the tightest intersection areas, maximum normal (compressive) stresses are less than 60 MPa in the pillar core areas, essentially suggesting that, at this stage, at least, the excavation of each emplacement room does not interfere with the next adjacent ones. In fact, even at the location with the highest induced normal stresses, at the centre of the emplacement vault where the four access drifts intersect (see insert diagram), at this stage conditions are not sufficiently adverse as to induce complete pillar failure, only edge damage. In the other locations where high stresses can be observed, such as the corners to the vaults in close proximity to the curved entranceways, where stresses reach magnitudes in excess of the threshold criteria of 75MPa, the zone of overstress into the rock mass can be seen to be of limited depth. [Note: it is standard in mining rock mechanics to quote compressive stresses as positive].

Based on these results, that suggest that near-surface localized stress levels are potentially high to give rise to rock mass damage, it is recommended that (i) provision be made for installing additional support into the highly stressed corner areas and (ii) that the drift configuration pillar widths in the centre of the repository layout be altered to locally reduce the induced stresses.

6.1.2 Factors of Safety for Initial Excavation

Figure 3 diagrams C) and D) show the factors of safety predicted for the same two panel excavation situations, again without any thermal loading effects. As is evident factors of safety greater than 2.5 are computed at the pillar corners (i.e., one-half room away from the wall of the adjacent room). The plots show that elsewhere than within the cruciform drift intersection zone in the centre of the planned repository, (see inset diagram) factors of safety in the core of the rib pillars, located between the rooms, are sufficiently high that, for this initial excavation stage, there would be no concerns regarding any potential for overall instability of the emplacement vault.

6.1.3 Tributary Area Check

As is evident from the above discussion, the numerical results generally suggest that, provided no adverse geological structures intersect the room layouts and complicate stress or rock quality conditions, there will be no significant initial problems with the planned excavation layouts. However, as a general check on the modelling results an estimate of the normal loading acting on the rib pillars has been conservatively calculated using tributary area theory, assuming that the induced pillar stress is expressed by:

$$\text{Pillar Stress (MPa)} = \gamma \times z \times \left(1 + \frac{Wo}{Wp}\right)$$

where: γ = rock density (MPa/m) = 0.026 MPa/m

z = pillar depth (m) = 1000 m

Wo = room width (m) = 7.14 m

Wp = pillar width (m) $\cong$ 38 m

For the DGR, at a depth of 1000 m, using the above expression, the estimated mid-pillar stress is calculated as approximately 31 MPa, a value very close to the NFOLD computed estimates for the mid rib pillar stresses, but approximately one-half of the maximum induced stresses computed by the NFOLD modelling for the most concentrated zones. However, even in these high stress margin zones to the pillars, inferred stress concentrations are still significantly lower than the estimated partially confined strength of 110 MPa suggesting that pillar edge damage will be of very limited depth extent. This suggests that pillar stability at the initial excavation stage is not an issue.

6.2 STABILITY POST THERMAL LOADING

6.2.1 Normal Stress Distribution

In order to model the possible effects of thermal loadings, as previously discussed a generally conservative assumption of imposing a general increase on the far-field stresses affecting all the openings has been incorporated into the NFOLD models. Although it is expected that the actual effect of the temperature rise inside the rock mass induced by the container heat will be to create additional induced stresses around the openings, which will be highest at the walls reducing with distance away from the emplacement vaults. Rather than replicating this "decay" in the NFOLD modelling, the more conservative assumption of a constant value of increased induced stress has been assumed throughout the model (including in the area of the access drifts). In fact, this can be considered a worse case scenario compared to reality because there will no heat generated from the access drifts.

In consequence of these conservatisms in the inferred stress state, it is likely that the results shown on Figure 4 for the normal stress distributions across the entire panel (i.e., simulating the effects created by increased induced stresses due to thermal loading effects) likely over-estimate the centre pillar induced stresses by some small percentage. Even with this over-estimation, the results indicate that only close to the room walls is any damage predicted. Here due to the geometry of the rooms, normal stresses increase to about 110 MPa, dropping to less than 80 MPa about 7 m away from the walls.

Again, as with the initial excavation stage, provided that there are no rock mass defects (joints/faults and such like) that intersect the rooms and compromise their integrity; these results suggest that each emplacement room can be considered to act individually. In fact, the plots suggest that no major interaction appears to develop between the rooms that would cause damage or failure to the rock mass between the vaults. This may not, however, be the case for the cross-over drift intersection area at the centre of the repository nor for the access entrance ways.

The results, however, do suggest that there may be localized wall damage that will develop due to the heating induced stress increases. This could complicate achieving effective room seals. Thus, in order to ensure the least disturbed as practically possible ground conditions around the 12 m long concrete bulkhead, it is recommended that a minimum distance of, say, 7 m (i.e., one-emplacement room diameter) be left between the last emplaced UFC and the emplacement room bulkhead. This recommendation is made based on the fact that the thermally induced stresses may cause some fracturing around the elliptical, emplacement rooms, which is unlikely to propagate more than 1 diameter away from the opening, but that this may be too deep a damage zone for successful placement of the bulkhead. Farther away from the heated zone conditions would be expected to be less affected.

Further, depending on the proximity of the last container (UFC) to the curved accessway to each emplacement room, there could also be high thermally-induced stresses developed at the entrance corners. At these locations, there is a possibility that the combined excavation and thermally induced stress loading effects may give rise to additional rock damage that would necessitate provision of site-specific additional rock support.

6.2.2 Factors of Safety after Used fuel Emplacement

Figure 5 replicates the configurations shown for normal stresses on Figure 4, but now presents factors of safety for the panel excavation layouts under thermal loading. As is evident, except at the vault walls and in the vicinity of the cruciform drift intersection (see insert diagram), factors of safety greater than 2 are generally observed, including within the core of the rib pillars. Based on the previously discussed criteria for rock strength under thermal loading conditions, this factor of safety is considered adequate for room and vault stability, suggesting that, provided that the DGR is excavated in a zone of uniform high quality rock devoid of any major geological discontinuity intersecting the vaults, it is likely that the proposed layouts will have adequate stability for the anticipated thermal loadings.

7 Container Retrieval Considerations

In concept, the proposed retrieval of the containers, as currently described in Section 3.5 of the main DGR report, requires significantly more detailed geotechnical evaluation from both the soil mechanics and rock mechanics perspectives than is within the scope of this report. From the soil mechanics perspective, maintaining the stability of the buffer and clay-based sealing materials during the proposed container retrieval procedure is an issue of concern to the viability of the proposed approach, and needs detailed assessment. From the rock mechanics viewpoint, the retrieval issue also needs more detailed examination from the perspective of potential build up of strain energy.

7.1 ROCK MECHANICS ISSUES

The analyses carried out to-date have indicated a potential for damage to occur within the rock mass at the crown and base of the emplacement rooms as a result of the thermally induced expansion of the rock. Whilst in general, this is not considered to affect the global stability of the DGR concept, because of the limited extent of the damage zone, and the time delay after emplacement of the used fuel prior to the initiation of damage, it will influence the positioning of emplacement room bulkheads and affect any retrieval procedures.

Current analyses have not considered in any detail the stress regimes at the ends of the emplacement rooms, or access roadways. These analyses will be required during the detailed design stage to establish the minimum spacing from the end of the last container to the emplacement room bulkhead, to avoid rockmass damage in areas where clay-based sealing materials will not be placed until the final stages of the vault closure. Based on interpolation from the current analyses, this distance is likely to be of the order of one room diameter. However, because this precise distance is unlikely to have a significant effect on the overall DGR layout (and hence ultimate cost), no alterations were made to the CTECH layouts or the NFOLD modelling to modify the original reference separation distance of 1 m.

As far as retrieval is concerned, any proposed methodology should take into account the potential for the rock mass to become fractured and unstable as a result of thermal expansion and stress increases. Furthermore, because such loading of the rock mass may still be continuing to increase even as the clay-based sealing materials are removed, there is potential for microseismic events to develop and possibly even for strainbursts to occur associated with re-excavation. Ideally, retrieval should be delayed sufficiently to allow the heating process to reach a steady state or be into the cooling phase, then if the clay-based sealing materials are excavated there will be less potential risk in inducing adverse levels of microseismicity and associated strainburst damage. Alternatively, where delay is not acceptable, some form of tunnel lining will be required.

Based on the above, from the rock mechanics perspective, it is suggested that:

1. A minimum period should be established before allowing any retrieval of the containers without tunnel lining. This period should be such that the rock mass would be either in a steady thermal condition (i.e., thermally induced stresses have reached their maximum) or, preferably, retrieval should only be attempted once cooling has started.

2. The bulkhead, placed at the end of the emplacement rooms, should be placed well beyond the location of the last container, to ensure that the bulkhead, access drifts or near by panels are not subjected to excessive induced stresses due to the adjacent heated rooms. It should also be placed distant enough from the end containers to avoid rock mass damage due to the heating process. As it must be positioned to contain (or enclose) potential damage zones that may develop around the emplacement rooms, it is recommended (prior to confirmatory analysis) that it be placed at least one room diameter from the last container.

Consideration should be given for creating the transition from the rectangular access drifts to the elliptical rooms well downstream of the bulkhead locations so as to minimize any corner or edge damage effects.

7.2 METHODOLOGY AND APPROACH

Finally, although from the rock mechanics viewpoint, retrieval of the containers during the period of increasing thermally-induced stresses increase may be more difficult than during the period of cooling, provided that adequate ground support procedures can be implemented, a conceivable concept can likely be devised. Because the magnitude of microseismic events that might be generated will be small (low Richter magnitude), given that the retrieval process would be undertaken semi-remotely (for human-health reasons), re-excavation and recovery would essentially pose no more significant risk than is routinely managed in the context of typical usage of currently-available tele-operated remote access mining equipment.

Further, should recovery of the containers ever prove to be necessary, it will likely only occur many years into the future, at a time when technological developments will potentially have made the operation of the tele-operated and computer-controlled equipment required for the retrieval process a matter of routine. Given that the reasons for retrieval of the containers would not be trivial, it is considered that overcoming the minor and manageable rock mechanics operational risks involved in the retrieval process will be comparatively insignificant.

7.3 ALTERNATIVES

As is evident from the foregoing discussion, verification of any chosen method of retrieval will require significant detailed technical and practical evaluation, which should incorporate development of alternative retrieval methods. This, however, is outside the scope of this particular project. Alternative schemes to that proposed in Section 3.5 of the main report (such as use of a pipe jack full length of the chambers to shroud the containers during retrieval) could have merit if concerns related to the stability of the clay-based sealing materials (as outlined in the introduction to section 7.0 of this report) are justified. Such a scheme may be more practical not only from the viewpoint of improving soil (clay-based sealing materials) stability, but also for mitigating some of the problems that might develop due to potential strain energy release (burst) problems, if all the clay-based sealing materials are removed.

8 Summary and Conclusions

1. Based on the assumptions made regarding uniform in situ stresses and homogenous, sparsely fractured rock mass conditions as incorporated into the NFOLD model, the proposed emplacement vault layout at a depth of 1000 m is satisfactory from a global rock stability viewpoint.

2. The elliptical cross-section shape, selected for the emplacement rooms, is endorsed as the most appropriate shape to achieve minimal stress concentrations at the excavation perimeter. The aspect ratio of 1.7, used throughout the analysis, however needs field verification and optimization, as it is not possible to analytically define the "ideal" aspect ratio that can satisfy both the excavation and thermal stability requirements.

3. The 45m distance between centres of the emplacement rooms appears adequate for the stability of the 38m wide rib pillars, created between the rooms, based on assumed homogenous rock mass conditions. However, geological structural factors (adversely oriented major jointing only, and not even faults) may necessitate utilization of wider pillars and/or alternative layouts.

4. The emplacement rooms should be arranged parallel to the major horizontal far-field stress so as to reduce the potential for rock damage and failure around the openings. In order to ensure that the repository is optimally laid out, more than one far-field stress measurement must be undertaken in the initial stages of design investigation at the actual chosen site. Multiple measurements are needed to confirm magnitudes and orientations and establish any variation that may exist due to changes in rock mass conditions across the width of the vault plane area.

5. For the assumed uniform stress conditions and with the assumption of a rock mass essentially devoid of major fracturing, local damage zones are predicted from the NFOLD modelling to occur only at two locations as a result of the high induced stresses

   (i) at the corners of the entranceways to the emplacement rooms. Here, additional surface support (e.g., fibre reinforced shotcrete and bolting) will likely be required to maintain rock mass stability, and

   (ii) within the block of ground bounded by the intersections of the accessway drifts at the centre of the emplacement vault. Here it is suggested that the chain rib pillars be widened to at least 60 m to minimize super-position of stresses.

6. 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 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.

7. Should retrieval of UFCs be required, it is probable that significant rock support will need to be installed so that the clay-based sealing materials can be removed. This is based on the fact that complete removal of the clay-based sealing materials will be necessary for container retrieval, and that residual stored thermally induced strain energy may complicate such removal. An examination of effective methods for sequencing the installation of appropriate rock support to allow UFC retrieval should be undertaken as part of detailed design engineering.

9 References

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TABLE 1: SUMMARY OF CURRENT AND PREVIOUS FACILITY DESIGN PARAMETERS

BASELINE PARAMETER (or ASSUMPTION)	PREVIOUS CONCEPTS		CURRENT CONCEPT	COMMENTS	
	1994 IN-FLOOR Emplacement Method (Simmons & Baumgartner, 1994)	**1996 IN-ROOM Emplacement Method (Baumgartner et al., 1996)**	**2002 IN-ROOM Emplacement Current Study for Updating the Conceptual Design and Cost Estimate**	**General**	**ASSUMPTION REPRESENTATIVENESS & RELIABILITY**
Emplacement Method	Single-level, room-and-pillar type of excavation, with in-floor 1.24 diameter and 5-m deep vertical boreholes	Single-level, room-and-pillar type of excavation	Single-level, room-and-pillar type of excavation		
Waste emplacement area	Plan area ≈ 4 km^2 416 emplacement rooms within 8 panels	Plan area ≈ 4 km^2 512 emplacement rooms within 8 panels	Plan area ≈ 1.8 km^2 104 emplacement rooms within 4 panels	Unlikely over this scale of area to have uniform geological features. This fact has been previously recognised by Canada and other international HLW programs and hence characteristic fractured domain approaches are being used.	
Depth	500 to 1000 m Nominal depth of 1000 m (i.e., 500 to 1000 m deep, but 1000 m was used for costing purposes)	(1) 500 to 1000 m - sparsely fractured rock (2) 750 m - low hydraulic conductivity (3) 500 m - higher conductivity - moderately fractured rock	1000 m in the plutonic rock of the Canadian Shield	Limited data is available on conditions at 1000 m depth. The choice of this depth must be confirmed through exploration. This depth may significantly increase costs due to higher stress-related damage effects.	1000 m depth is becoming an international reference standard vf. Japan, Sweden. However, generic fracture fabric is being utilised. It may be required that a more fractured rock mass also be examined with higher conductivity (as per 1996 study)
Excavation method	Drill-and-blast method	Drill-and-blast method, using perimeter blasting	Selected by the contractor, either drill-and-blast or a tunnel boring machine		TBM tunnels are preferred in Swedish and Japanese concepts. Degree of damage to rock during drill and blast could be problematic. The choice should be made by implementing agency. However, due to stress conditions non circular shaped drives may need to be examined.
Cross-section - Disposal Room	8 m wide, 5.5 m high and 129 m long. 138 boreholes drilled into the floor.	Finished cross-section elliptical-shaped, 3 m high, 7.3 m wide and 238 m long. [Drill-and-blast excavation = 3.3 m high by 7.6 m wide]	Elliptical cross-section with the major axis in the horizontal plane. Cross-section with 4.2 m high, 7.14 m wide and 315 m long.	Should a circular shape be considered for TBM application? TBM drives more commonly circular, but novel machines are now being produced that can excavate non-circular shapes. Assessment of double cutter head geometry effectiveness in high strength rock and high stress conditions needs consideration.	Shape is strongly dependent on construction method and stress field.
Aspect Ratio (major axis/minor axis)		**2.3**	**1.7**		
Nominal extraction ratio (ER) Centre-to-centre spacing between emplacement rooms and layout and spacing of rooms and pillars.	0.25 to 0.3 ER = W/(W+P) W (m) = width of the emplacement rooms and P (m) = width of the pillar between emplacement rooms	ER should not exceed 0.25, determined in a direction perp. to the axis of a panel of rooms at the repository mid-plane. Centre-to-centre between emplacement rooms set at 30 m	Same as 1996 ER ≤ 0.25	Scale of excavation of 1.8 km^2 area is significant and dependant on inferred geology. Appropriate extraction ratio is based on good rock conditions. In 1996 concept-barrier pillars widened to isolate conducting structures. If modifica-tions to pillar widths and/or design layouts are later required, it	Fracture pattern is assumed as sparse. Any realistic changes in density would affect optimized overall extraction ratios. Barrier pillars should be considered between each panel or X number of panels to avoid possible pillar chain reaction (or dominó effect). Note, however, that for the current planned layout, the NFOLD calculations do not suggest this type of

							could impact schedule and costs.	pillar failure.
Ambient In Situ Stresses (Emplacement rooms parallel or perp. to major principal in situ stress)	Average for Canadian Shield		Upper Range for Shield k_1 (σ_1/σ_3) = 2.5 k_2 (σ_2/σ_3) = 1.9			As per 1996	k ratios could vary depending on proximity to pluton margins and/or other structural control. Orientation of major in situ stress may also swing thus negating favourable orientation of room and pillar layout.	
Maximum Principal Stress σ_1 (MPa)	500 m 34.4 MPa	1000 m 52.6 MPa	500 m 60.6 MPa	750 m 62.8	1000 m 65 MPa	As per 1996, 1000 m	Given limited data at 1000 m, actual σ_1 could be greater	
Intermed. Principal Stress σ_2 (MPa)	22.4 MPa	36.5 MPa	45 MPa	47.2 MPa	49.4 MPa	As per 1996, 1000 m	Ratio of σ_1/σ_2 and orientation of stress fabric could vary and magnitude could differ in different parts of pluton.	
Minimum Principal Stress σ_3 (MPa)	13.3 MPa	26.5 MPa	13 MPa	19.5 MPa	26 MPa	As per 1996, 1000 m		
Rock Type	Granite (at the URL)		Granite (at the URL)			Plutonic Rock.	Rock material could be variable (from granite to gabbro) This could have a significant impact on properties and hence potentially on design layouts.	
Rock Mass Fabric	Uniform, sparsely fractured		1) Generic design - assuming the **sparsely fractured** granitic rock mass of the Whiteshell Research Area, depth from 500 to 1000m. 2) Favourable vault location at a depth of 750 m to ensure long groundwater travel time from the vault to the accessible environment. **Sparsely fractured** rock mass. 3) Specific design for a *permeable geosphere design objective*. **Moderately fractured** rock mass created by transecting low-angle fault (20 m thick, low angle 18° fault). See note 1.			**Sparsely fractured** plutonic rock mass will be considered.	Generic design is specified as assuming sparsely fractured rock mass. In view of scale of repository (1.8 km^2 scale is significant) the rock mass fabric should include definition of mini-mum distance from emplacement rooms to closest conductive fracture zone and/or the design should also consider moderately fractured by reducing generic parameters	JNC and SKB designs assume 50 to 100 m to conductive fracture zones. Currently no distance is specified for this design. There is a need to define (a) background fracture density and (b) spacing of fracture zones. These should be specified as ranges, since variation across the 1.8 km^2 scale repository would be expected. Alternative designs should be based on background fracture intensities as high as 5 per metre, and 100 to 200 m spacing of fracture zones.
Rock Strength - Excavation - Thermal - Rock Web - Factor of Safety	Hoek-Brown (1980) strength criterion $\sigma_{1f} = \sigma_{3f} + \sqrt{(m\sigma_c\sigma_{3f} + s\sigma_c}$ σ_c = 190 MPa, m=17.5, s=0.19 σ_c = 190 MPa, m=17.5, s=0.19 σ_c = 110 MPa, m=30, s=1 2 (avg. for web rock and pillars)		Hoek-Brown parameters adopted from the Deviatoric Stress Approach $\sigma_{1f} = \sigma_{3f} + \sqrt{(m\sigma_c\sigma_{3f} + s\sigma_c^2)}$ σ_c = 100 MPa, m=16.6, s=1 σ_c = 150 MPa, m=25, s=1 Not applicable ≥ 1 (at excavation perimeter) Note: The Hoek-Brown parameters (σ_c, m and s) were adjusted to implicitly consider the deviatoric stress approach (Castro et al., 1995, Martin, 1995), which is expressed as (σ_1 - σ_3) = 0.5 to 0.6 σ_c			Same as 1996. However, should also consider (σ_1 - σ_3) = 100 MPa for possible breakout formation and (σ_1 - σ_3) = 75 MPa for estimate of maximum depth of potential breakout (see Note 3)		Perhaps a range should be specified rather than single value strength parameters. In the absence of large scale rock mass strength measurements, values can be obtained by simulation with a range of Plutonic fracture fabrics. Although Baumgartner et al. (1996) reviewed strength variation, no detailed fabric analysis was completed at that stage or for the current update. Therefore, in the detailed analysis stage, consideration should be given to the influence on the strength of more fractured zones.
Young's Modulus / Poisson's ratio	35 GPa / 0.25		60 GPa / 0.25 (based on URL, Read and Martin, 1992)			Same as 1996. It considers that the rock mass is linearly elastic, isotropic and homogenous.	Rock mass Young's Modulus depends on rock type and degree of fracturing. Again single value assumptions may not be realistic. It may be more appropriate to consider ranges, viz. E ranges from 40 to 60 GPa.	
Shaft & Panel tunnels			7.9 m diameter shaft and 10 m wide by 4.4 m high tunnels			Same as 1996.	Location of shaft and initial access with respect to room and pillar layout are critical design issues, specially for any TBM or mechanised mining approach	
Monitoring System	Discussed in the Simmons and Baumgartner (1994)		Discussed in the Baumgartner et al. (1996) report as well as in other EIS support documents.			Monitoring system for verification of repository		

	report		performance for an extended period before the facility is finally closed		
Container Heat Output	297 W	330 W	1138 W		

BASELINE PARAMETER (or ASSUMPTION)	PREVIOUS CONCEPTS		CURRENT CONCEPT	COMMENTS	
	1994 IN-FLOOR Emplacement	1996 IN-ROOM Emplacement	2002 IN-ROOM Emplacement	General	ASSUMPTION REPRESENTATIVENESS & RELIABILITY
Number of fuel bundles per basket	72	72	324		
Maximum Container Outer Surface Temperature	100° C	90° C	97° C		
Minimum Buffer Thickness to surround each emplacement container	250 mm	> 500 mm (500 mm buffer + remaining void with backfill)	500 mm buffer backfill + 500 mm clay-based and cement-based sealing materials = 1000 mm total		
Radiation dose to workers placing sealing materials and emplacement containers		20 mSv (CNSC Radiation Protection Regulations) < 1 µSv/h	< 50 mSv (CNSC Radiation Protection Regulations) < 2.5 µSv/h		
Fuel Burn-up	685 GJ/kg U (190 MW h/kg U)	720 GJ/kg U (200 MW h/kg U)	1008 GJ/kg U (consider 280 MWh/kg U for shielding design)		
Fuel age	10 year cooled fuel	Same as 1994 - 10 years	30 years		
Geothermal gradient	+0.012°C/m of depth and the average ground surface temperature shall be assumed to be +5°C. Therefore, the resulting average rock and groundwater temperature at a depth of 1000 m will be 17°C	+0.012°C/m of depth and the average ground surface temperature shall be assumed to be +5°C. Therefore, the resulting average rock and groundwater temperature at a depth of 1000 m will be 17°C	Same as in 1996.		If 0.015 °C/m is assumed at 1000 m depth, then temperature would be 20°C This would be a conservative assumption.
Drainage Assumptions	Fully drained conditions for the vault sealing materials and the rock mass	Fully drained conditions for the vault sealing materials and the rock mass	Fully drained conditions for the vault sealing materials and the rock mass		
GRANITE PROPERTIES Thermal Conductivity (W/m°C) Specific Heat (kJ/kg°C) Mass Density (Mg/m^3) Coefficient of Thermal Expansion (10^{-6}/°C)	 3 0.845 2.65 10	 3 0.845 2.65 10	Same as in 1996 3 0.845 2.65 10	Thermal conductivity of 3 W/m°C is on the high end of measured values worldwide, but at AECL's URL, value is 3.5 W/m° C. Note also that most Canadian Shield rocks are of high quality because weathered materials have been eroded.	

NOTES:

1. The geosphere conditions for the 1996 studies were defined as a permeable, moderately fractured rock mass with a vault depth set at 500 m. The emplacement-room geometries that were assumed were for sparsely fractured rock (cases 1 and 2). These were retained for the moderately fractured rock mass assumed in case 3, as the specific rock strength and ambient in situ stresses were not as well defined. The total horizontal distance between the two vault sections separated by the transecting fault was set as 375 m (Stanchell et al., 1996).

2. IN SITU STRESS

The ambient principal in situ stresses assumed for the in-room emplacement vault within the Canadian Shield for the 1996 case were based on measurements from the URL (Martin 1990, Read 1994), the Medika pluton (Martino, unpublished memorandum, 1993) and from CANMET (Herget and Arjang, 1991). The assumed in situ stresses carried in 1996 were:

$\sigma_3 = \sigma_v$ = 0.026 MPa/m (depth)

σ_2 = 0.1112 MPa/m + 9.9 MPa, from **0 to 300 m** σ_2 = 0.00866 MPa/m + 40.7 MPa, from **300 to 1660 m** and σ_2 = 0.0293 MPa/m + 6.4 MPa, **greater than 1660 m**

σ_1 = 0.1345 MPa/m + 18.5 MPa from **0 to 300 m** σ_1 = 0.00866 MPa/m + 56.3 MPa, from **300 m to 1400 m**; and σ_1 = 0.0403 MPa/m + 12.1 MPa, **greater than 1400 m**

where σ_v = vertical stress; and

$\sigma_1, \sigma_2, \sigma_3$ = major, intermediate and minor principal stresses, respectively

For the 1996 study, the three depth conditions are summarized as follows:

SUMMARY OF THE IN SITU STRESSES (after Baumgartner et al., 1996)

Vault Depth (m)	Maximum Principal Stress σ_1 (MPa)	Intermediate Principal Stress σ_2 (MPa)	Minimum Principal Stress σ_3 (MPa)	Stress Ratio σ_1 / σ_3	Stress Ratio σ_2 / σ_3	Comments
500	60.6	45	13	4.7	3.5	Herget and Arjang, 1991
750	62.8	47.2	19.5	3.2	2.4	
1000	65	49.4	26	2.5	1.9	

3. ROCK MASS STRENGTH DESIGN LIMITS

For the based on uniaxial compressive strength of the Lac du Bonnet granite, the stress for the onset of stable crack growth initiation (σ_{ci}) is about 70 MPa to 75 MPa. The stress for the onset of unstable crack growth (σ_{usc}) is about 150 MPa, and the peak unconfined compressive strength (σ_f) is about 210 MPa. The factor of safety is defined as the ratio of the rock strength to the rock stress under triaxial conditions (Baumgartner et al., 1996).

The Hoek and Brown (1988) empirical criterion model is used, defined as follows:

$$\sigma_{1f} = \sigma_{3f} + \sqrt{(m\sigma_c\sigma_{3f} + s\sigma_c^{\ 2})}$$

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

Two peak strength, with associated empirical strength parameters, are used with this failure model to calculate the factors of safety in sparsely fractured rock, as follows:

1) The peak strength design limit of the rock mass under excavation mechanical (EX) load conditions is σ_{EX} = 100 MPa, m = 16.6 and s = 1;

2) The peak strength design limit of the rock mass under full thermal-mechanical ™ load conditions is σTM = 150 MPa, m = 25 and s = 1; if and only if, the peak strength under excavation load is not exceeded.

Note that this failure criterion reflects an intact rock tensile strength of 6 MPa, which is below the 10.4 MPa average value for wet Lac du Bonnet granite at the URL.

UPLIFT - The maximum depth of the near-surface extension zone, measured from ground surface, is set at 100 m. The near-surface extension zone (also called the perturbed fracture or perturbed fissure zone) is defined as the volume of rock overlying the emplacement vault that could experience uplift, loss of horizontal confining stresses (i.e., horizontal stress = zero for a "no-tension" analysis and potential opening and extension of subvertical fractures.

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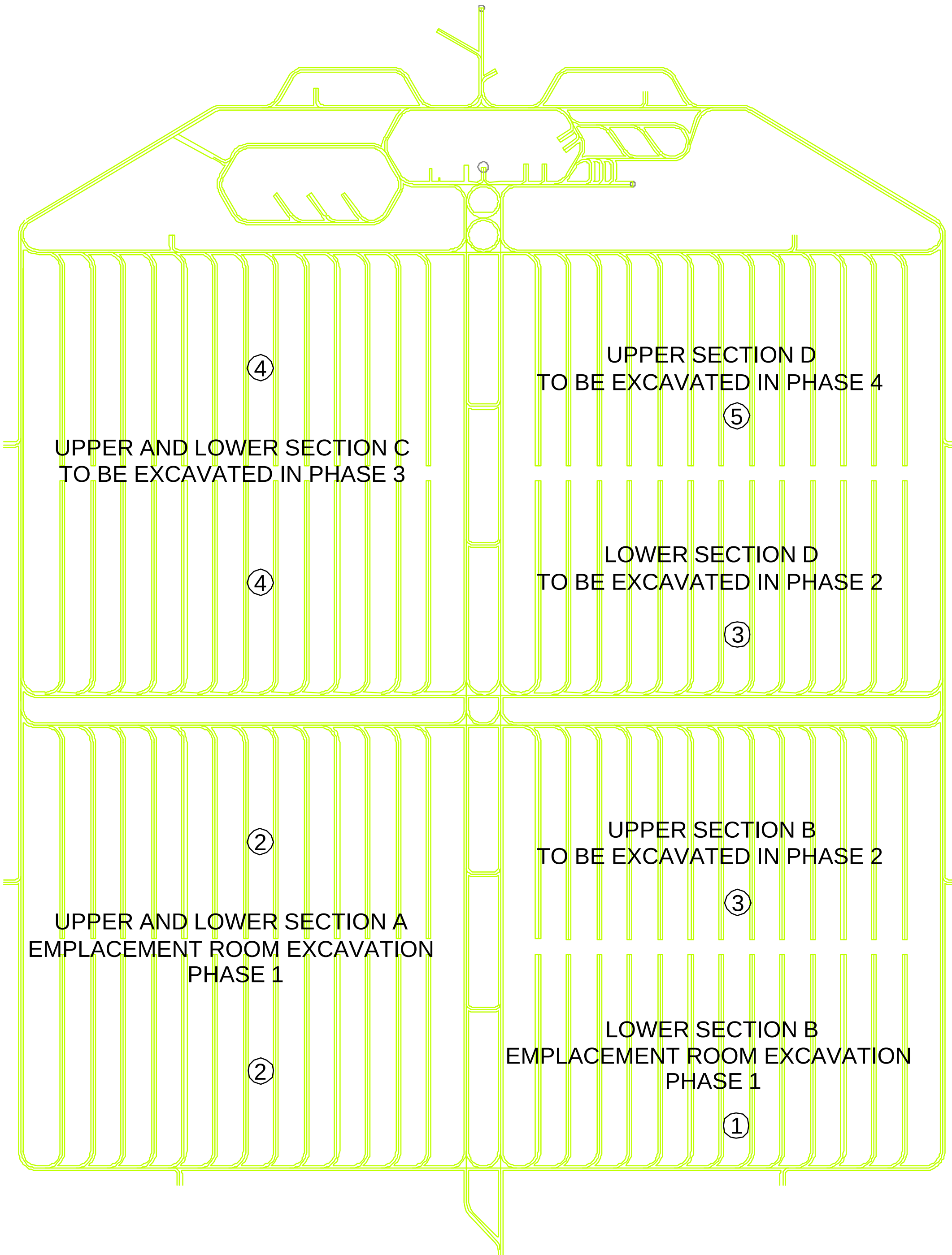
TYPICAL SECTION EXCAVATION AND WASTE EMPLACEMENT SEQUENCE

FIGURE 1



① EMPLACEMENT SEQUENCE

REV. 1

DATE: NOVEMBER 2002

PROJECT: 011-1667

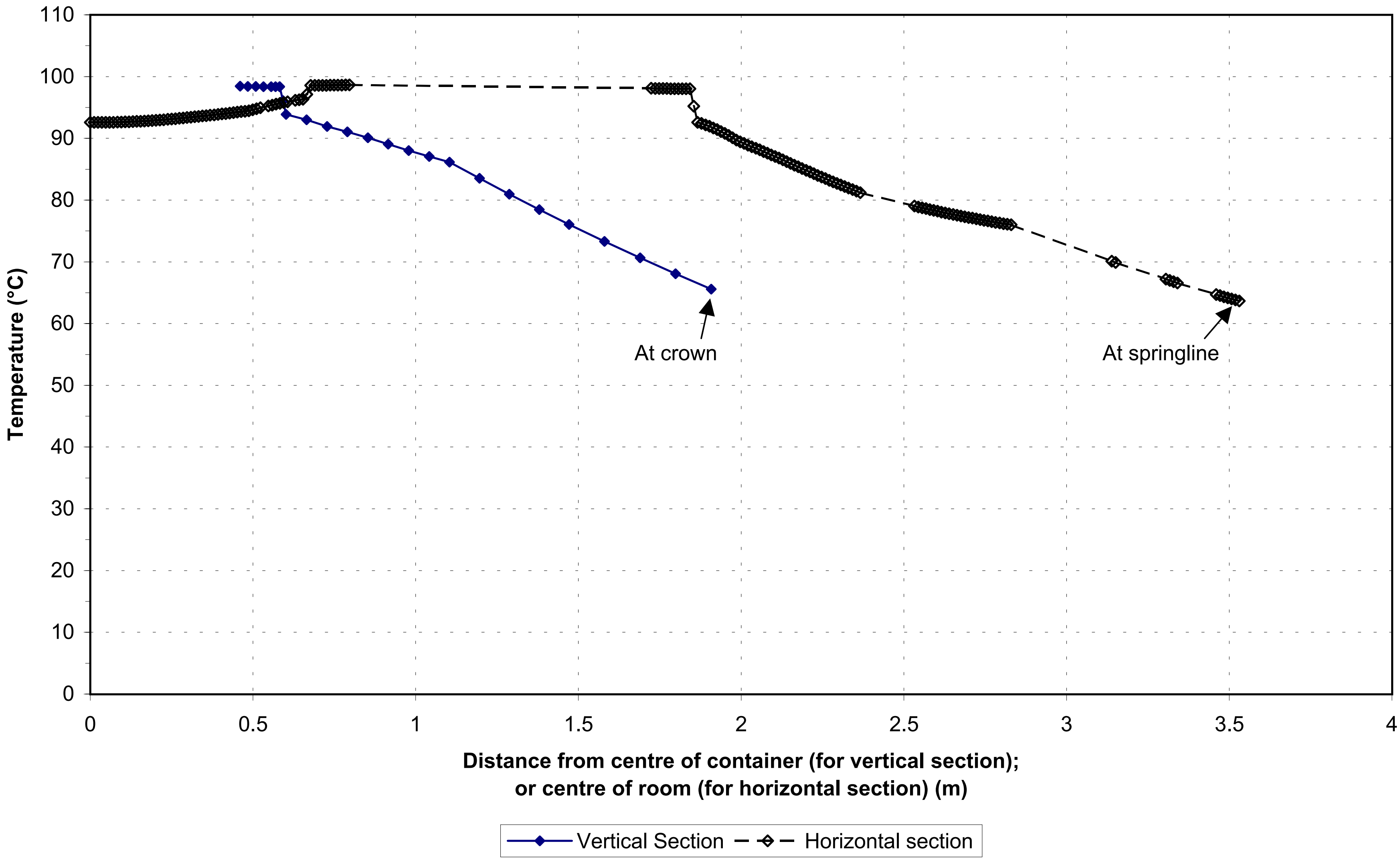
Golder Associates

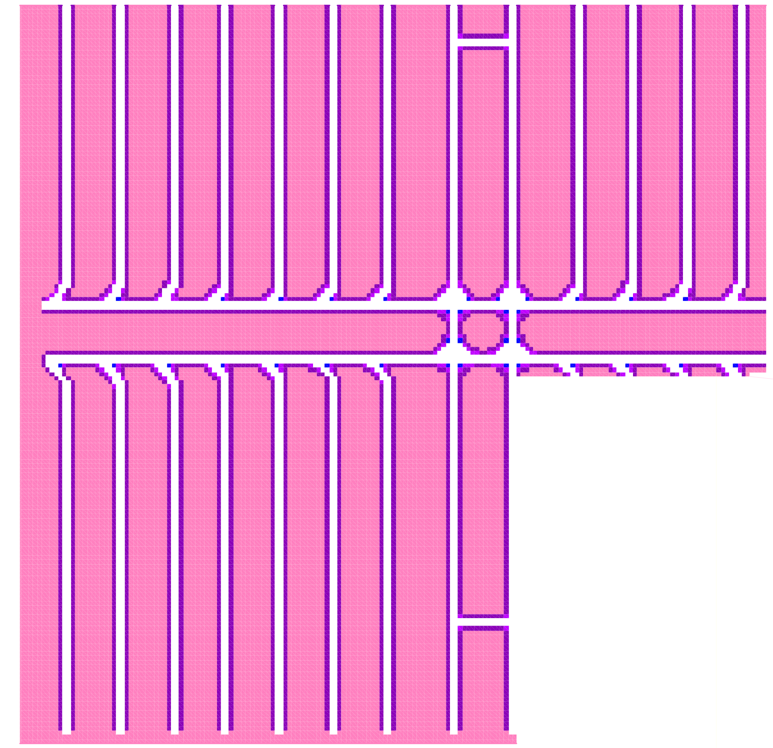
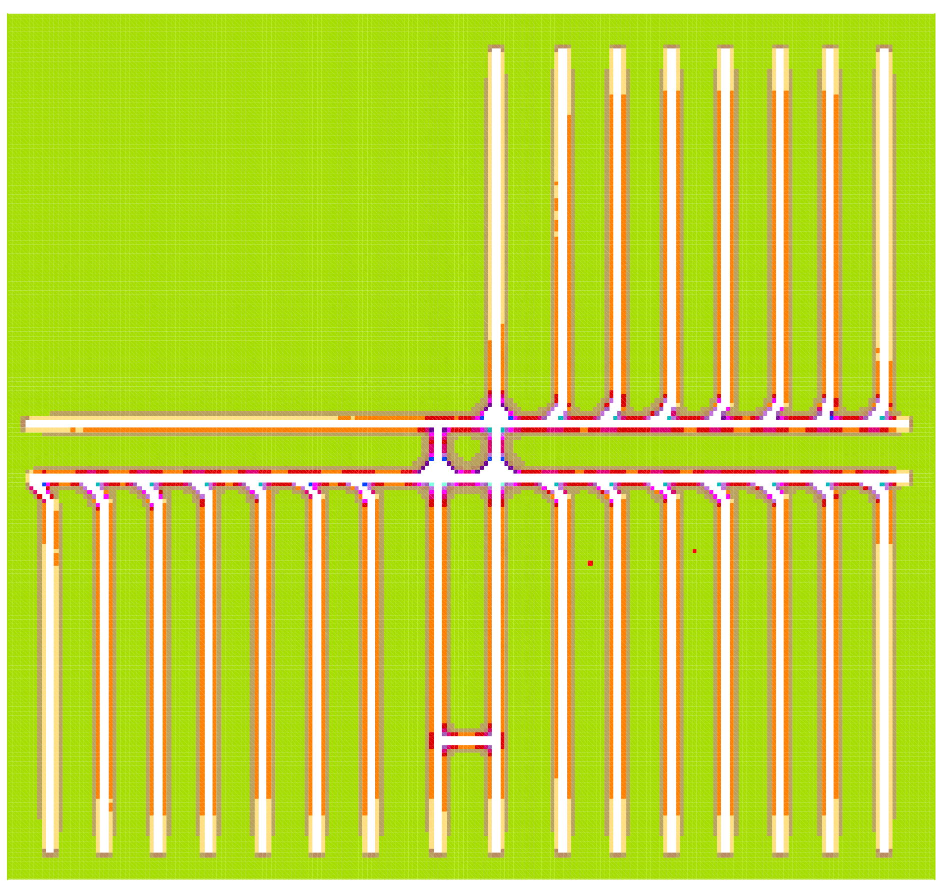
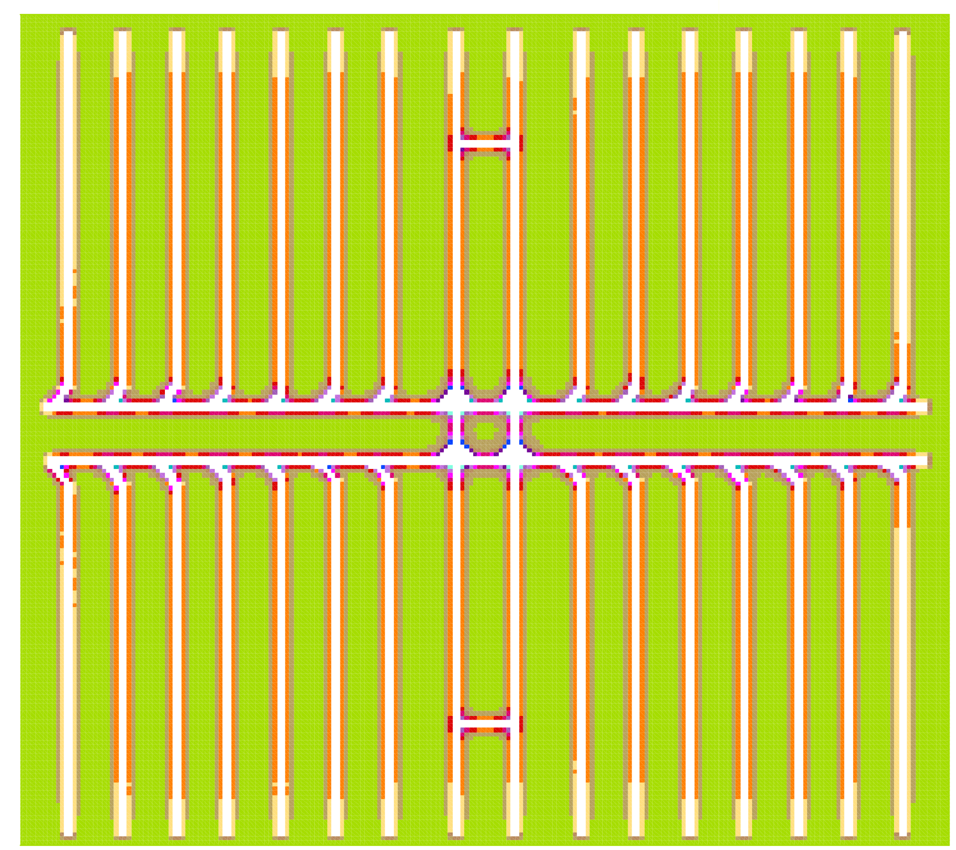
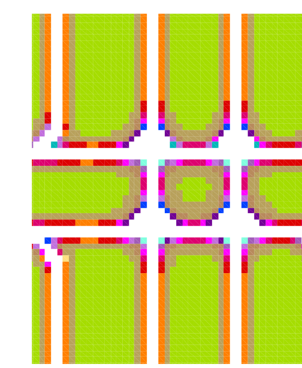
CAD: PS

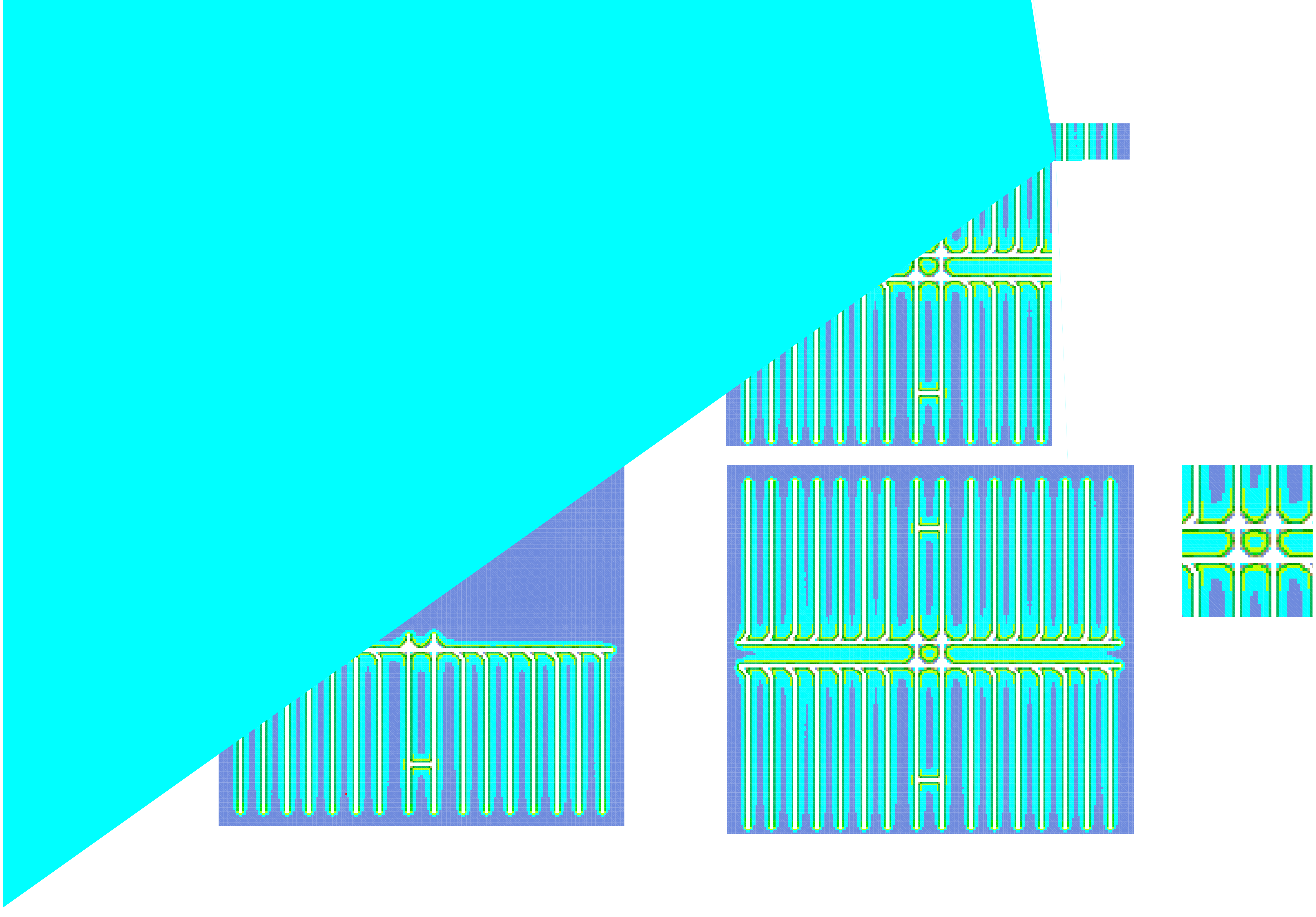
CHK:

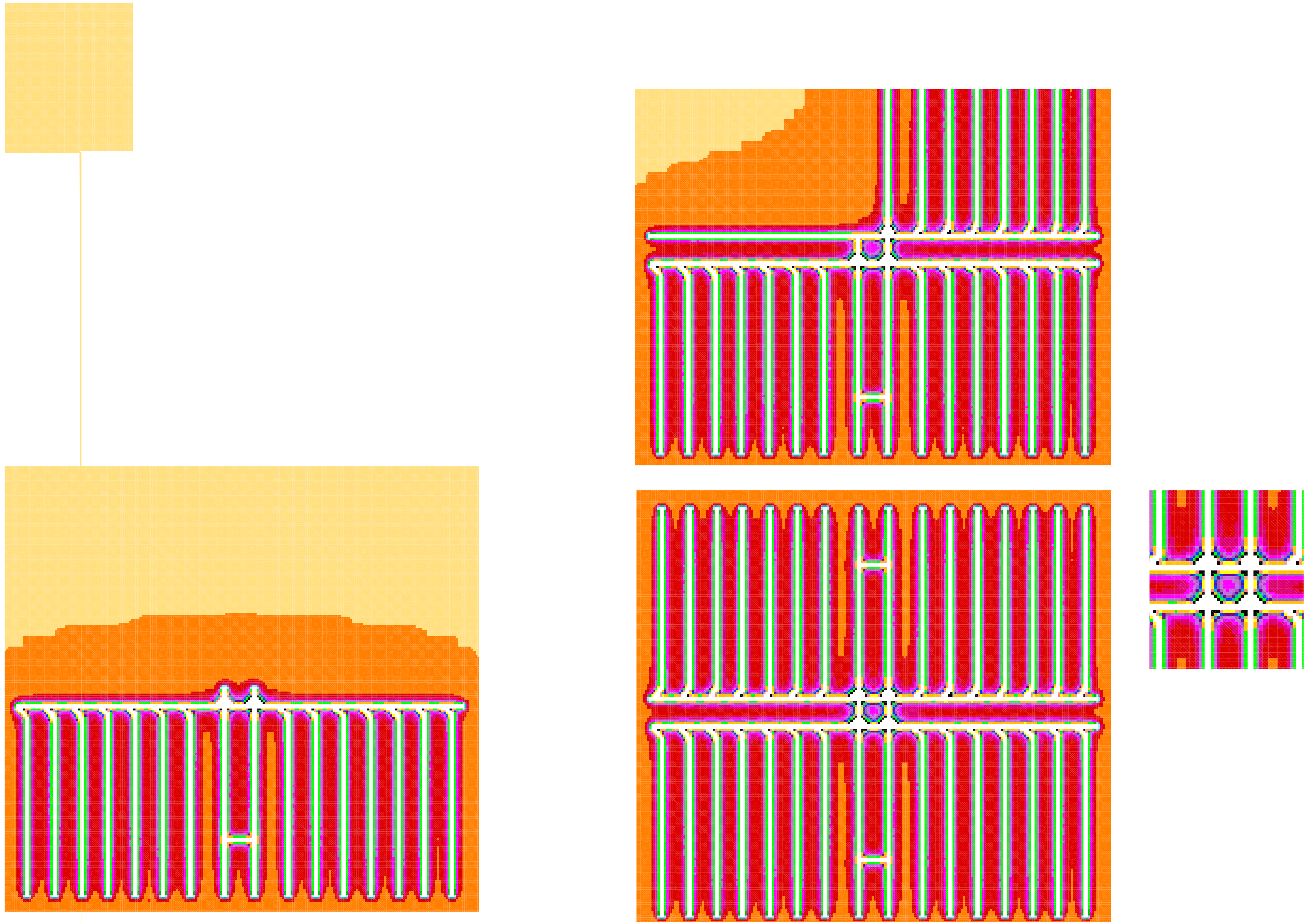
PLOT DATE: November 01, 2002
FILENAME: T:\Projects\2001\011-1667\RNOV2002\Q1667001a.dwg

FIGURE 2: TEMPERATURE VERSUS DISTANCE AFTER 20 YEARS
(modified buffer properties)







1106/MD18085/REP/01

Radioactive Materials Management

Deep Geologic Repository Conceptual Design

Annex 6

Environmental Monitoring

December 2002

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 .

This document is written solely for the benefit of the Client, for the purpose stated in the Agreement, and the Consultant's liabilities are limited to those set out in the Agreement."

Summary

This report addresses the requirements and the implementation of a monitoring programme designed to evaluate the environmental effects of the deep geological repository (DGR) facility.

The report describes the requirements and general framework for environmental monitoring of the DGR and includes the development of an environmental monitoring plan and the relevant sampling and analytical requirements.

Contents

1 Introduction

Possible approaches for the long-term management of used nuclear fuel are being reviewed in Canada. One of the options being considered is direct emplacement of the used fuel in a deep geologic repository (DGR) in a crystalline rock formation in the Canadian shield.

This option is based on a design concept that will ensure long-term isolation of the used fuel through a combination of engineered and natural barriers. The repository would be designed for passive safety so that no institutional controls would be necessary to ensure the safe, permanent isolation of the used fuel.

This report considers the requirements for environmental monitoring for the DGR facility from the start of the project and through its preclosure phase. This phase is defined to include all activities from siting through to decommissioning and closure of all components of the system. Preclosure monitoring is expected prior to and during the used fuel emplacement stage (approximately 30 years) and for up to 70 years following the completion of used fuel emplacement.

One of the requirements for the repository is that it must include comprehensive pre-operational environmental monitoring to gather information necessary to establish baseline conditions in the local environment.

The aims of this report are to describe and propose monitoring plans and systems that will demonstrate that the repository is not adversely effecting the environment and that its safety and performance targets are being met.

The report is structured as follows:

Section 2	Monitoring Objectives
Section 3	Environmental Monitoring Concepts
Section 4	Environmental Monitoring Plan
Section 5	Conclusions

2 Monitoring Objectives

Regular monitoring programmes, in respect to radioactive used fuel emplacement operations, are usually established to satisfy one or more of the following objectives:

(a) to estimate public radiation exposures, using appropriate additional data and models

(b) to comply with regulatory requirements

(c) to ensure that regulatory requirements have been met

(d) (for monitoring by regulators or local authorities) to check operators results

(e) to provide an independent means of surveillance for inadvertent or

unrecorded discharges

(f) to provide public reassurance

(g) (pre-operationally) to establish background levels

(h) to detect any long-term trends.

Usually, several of these objectives apply in the case of any given monitoring programme.

In addition, monitoring programmes may also be designed to provide information that can be used to quantify radiation exposure pathways and hence confirm the scientific basis of assessments of public radiation exposures.

The fundamental objective of repository environmental monitoring is to evaluate, quantitatively, the effect on the environment from the activities at the repository site. Such monitoring should ensure that the repository is compliant with regulatory targets.

During the preclosure period, parameters will be monitored both in and around the DGR to determine the effects of the facility on the environment. This will include the geosphere, atmosphere and the biological environment. Implications on humans and the social and economic effects of the project will also be considered.

It is expected that initially, during the siting phase, a parameter baseline will be established and, subsequently, the relevant environmental parameters will be monitored for a period of more than 100 years.

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 for environmental performance for the repository have been established.

The types of systems and instrumentation that might be used will depend on key issues such as the timescales over which the monitoring will be required and the frequencies with which they will be undertaken. 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 DGR operator will be required to demonstrate, prior to the construction of the repository, that there would be no significant adverse effects on the environment resulting from these activities that cannot be justified or mitigated by reasonable means. Whilst there would inevitably be much focus on the radiological aspects, the more conventional environmental concerns should also be addressed.

The environmental monitoring programme will be developed as part of the licensing process for the facility and in accordance with regulatory requirements.

The primary objectives of environmental monitoring in this context are therefore to:

- establish a baseline for the repository environment prior to construction
- quantify the effect of repository operations on the environment
- verify that radiation/hazardous material exposures to members of the public are compliant with operating targets and regulations
- demonstrate compliance with performance objectives and regulatory limits.

3 Environmental Monitoring Concepts

A comprehensive programme for environmental and radiation safety monitoring would be required as part of the licensing process for the facility and in accordance with regulatory requirements. As it is not clear at present what these requirements might be in detail, this section of the report has considered a generic approach that is likely to be broadly relevant.

A monitoring system would be established throughout all phases of the repository lifecycle. A comprehensive recording and reporting system that can be audited would be established. Independent verification programmes would also be established.

The monitoring system would provide a continuous review of radiation exposures and would demonstrate that all exposures are as low as reasonably achievable (ALARA) and that all dose limits and constraints are met. The monitoring results would be reviewed by both the operator of the facility and the regulators, on a regular basis, to determine whether safety and environmental objectives are being met.

The various requirements for environmental monitoring are described below:

1. Environmental monitoring baseline

During the operational and preclosure and postclosure surveillance phases of the repository, environmental monitoring would be conducted to determine whether any releases of radionuclides from the site are occurring and, if so, whether these are within the agreed limits. In order to judge this, the ambient background radiation levels of the site and its environs, need to be established. The baseline monitoring would address both the surface and subsurface environments. The programme would include the following environmental media:

- air
- surface water and groundwater
- soil
- flora
- fauna

The baseline monitoring would also identify the local ecosystems, and potential pathways for radionuclide transport through the environment and uptake by people.

Current surface water drainage patterns and habits of local flora/fauna and humans would be identified to aid the optimisation of the repository design, particularly with respect to the surface infrastructure arrangements.

2. Quantify the impact of repository operations on the environment

Operating procedures at the repository would be established to ensure that no unauthorised releases of radioactive material to the environment will occur. A monitoring programme would be established to confirm this. This programme would include routine measurements of:

- surface contamination (via instrument surveys and surface swabs)
- airborne contamination (via area monitoring with high-volume air samplers and personal air samplers)
- external radiation dose rates (via fixed monitoring/sampling stations and instrument surveys).

3. Demonstrate that radiation/hazardous material exposures to members of the public are compliant with objectives and that exposures are within regulatory limits

A dose assessment programme would be established for members of the public, which could include calculations of dose from dosimetric models and environmental data, the use of personal dosimeters or periodic (e.g. annual) urine sampling and analysis of a test group of individuals..

A dose assessment record would be generated for members of the public that can be reviewed by the operators, as well as the regulators..

4. Demonstrate compliance with performance objectives and regulatory limits.

The repository environment would be monitored during both the operational and the institutional control (post-closure) phases to ensure that any environmental effect is acceptable and meets all relevant requirements.

The monitoring system would include both sampling of the various media, as described in the baseline survey (i.e. air, surface water and groundwater, biota and soil) and their analysis for key contaminants.

4 Preparation of an Environmental Monitoring Plan

An environmental monitoring plan will be required for operations at the repository, covering both general environmental issues and the specific requirements of legislation and Codes of Practice in relation to radiation and radioactive used fuel repositories.

Development of the plan will take into account issues and responses raised in the environmental assessment process, as well as formal regulatory requirements.

The general aims of the monitoring plan will be to:

- Establish management processes and procedures that will ensure that environmental effects are minimized during construction, operation, surveillance and decommissioning

- Establish ongoing monitoring and reporting processes to follow the effects of the operation on the surrounding environment

- Establish audit processes for checking the implementation and effectiveness of management and monitoring systems.

4.1 MANAGEMENT AND MONITORING APPROACHES

A number of management and monitoring approaches will be required during the four key phases of the project i.e. construction, operation, the surveillance period and decommissioning.

4.1.1 Monitoring during Construction

This section describes the potential mechanisms for environmental effect during construction.

Table 1 Environmental issues during Construction

Area	Issue
Physical Environment	
	Surface water run-off, soil erosion and siltation of water courses
	Dust Generation
	Noise
	Release of pollutants to soil, surface water or groundwater
Vegetation and Flora	
	Potential for introduction and dispersal of weeds
	Damage/removal of native vegetation
	Accelerated soil erosion
	Threatened species
Fauna	
	Direct loss of individuals
	Loss of habitat
	Increased competition for resources and predation
	Threatened species
	Pest species
	Fencing
Socio-Economic	
	Construction vehicle traffic
	Unauthorised site access and attempted access
	Land use conflicts
Cultural Heritage	
	Consultation with claimant groups
	Access to the repository sites
	Infrastructure and access within the repository site
Radiation	
	Establish the preconstruction conditions.

The following table describes the monitoring requirements, where needed, for each of these areas.

Table 2 Environmental Monitoring Requirements during Construction

Issue	Monitoring Requirement
Physical Environment	
Surface water runoff, soil erosion and siltation of watercourses	• Regular inspection of drainage lines for evidence of sediment transport • Inspect bunded areas regularly to confirm integrity of bunds • Inspect and maintain erosion control measures • Clean up areas of accidental spillage of fuels and dispose appropriately
Dust	• Visual monitoring to determine areas of excessive dust generation and activities creating dust to ensure that any dust arising is minimal
Noise	• Measurement of noise levels during construction to ensure consistency with Industrial Noise Policy and OH&S requirements
Potential for release of pollutants to soil and surface water	• Ad hoc inspections following severe weather events • Ad hoc inspections following any fuel/oil spills and after cleanup activities • Opportunistic sampling of flowing surface water upstream and downstream of the site with analysis of salinity, turbidity/total suspended solids and selected radionuclides to build up background data set
Potential for release of pollutants to groundwater	• Continued analysis of existing monitoring wells to record any potential changes prior to emplacement of the used fuel
Vegetation and Flora	
Potential for introduction and dispersal of weeds	• Undertake preconstruction and postconstruction surveys of disturbed areas to identify the presence of any weeds, and remove and destroy any weeds found
Damage/removal of native vegetation	• Establish photopoint monitoring sites and baseline plans of existing conditions prior to construction • Undertake quantitative surveys to establish biodiversity indicators (including non-vascular plants) for future monitoring

Issue	Monitoring Requirement
Threatened species	• Maintain a watching brief for presence of rare species within the site • Monitor delineated populations (or individuals) for disturbance • Monitor implemented conservation measures for level of success
Accelerated soil erosion	• Undertake preconstruction and postconstruction surveys to identify areas of potential erosion • Monitor the effectiveness of water management techniques
Fauna	
Direct loss of individuals	• Monitor the presence of fauna in and around construction activities • Conduct daily checks for trapped animals. Trapped animals are to be captured and released nearby
Loss of habitat	• Monitor as per Vegetation and Flora, above
Threatened species	• Monitor areas defined as no-go areas for effects on threatened species
Pest species	• Monitor the site for vertebrate and invertebrate pests
Socio-Economic	
Unauthorised site access and attempted access	• Maintain a record of unauthorised or attempted unauthorised intrusion
Radiation	

Issue	Monitoring Requirement
Preconstruction conditions	• The baseline monitoring would address both the surface and sub-surface environments. The programme will include the following environmental media: • Air • Surface and Groundwater • Soil/Sediment • Flora • Fauna • The baseline monitoring would also identify the local ecosystems and potential pathways for radionuclide transport through the environment and uptake by people. The requirements for sampling and analysis are described in more detail in Section 4.

4.1.2 Monitoring During Operation

This section provides a summary of monitoring requirements during operation and includes the following in addition to those identified earlier:

Table 3 Potential Environmental Effects during Operation

Area	Issue
Vegetation and Flora	
	Movement of radionuclides
	Waste water and sewage management
Fauna	
	Disturbance associated with human activities
	Movement of radionuclides
	Waste water and sewage management
	Non-radioactive waste management
Socio-Economic	
	Protests and demonstrations
	Human intrusion

Area	Issue
	Effects of tourists on surrounding areas
Radiation	
	Used fuel transport to the site
	Routine operations at the repository (fuel handling, repackaging, on-site transport)

Table 4 Environmental Monitoring Requirements during Operation

Issue	Monitoring Requirement
Physical Environment	**As for construction phase**
Vegetation and Flora	**As for construction phase plus**
Introduction and dispersal of weeds	• Undertake annual (spring) and opportunistic monitoring
Native vegetation and threatened species	• Undertake photopoint monitoring and quantitative surveys • Undertake biodiversity indicator monitoring (including non-vascular plants), based upon the quantitative survey data
Waste water and sewage management	• Waste water to be controlled in a closed environment and disposed of appropriately to discourage weed establishment and vermin
Movement of radionuclides	• Radionuclide monitoring in target species
Fauna	**As for construction phase plus**
Waste water and sewage management	• Waste water is to be controlled in a closed environment and disposed of appropriately to discourage weed establishment and vermin
Non-radioactive waste management	• All waste is to be contained and disposed of off site • Recyclable waste is to be separated and transported to a recycling depot or other appropriate establishment
Movement of radionuclides	• Radionuclide monitoring in target species • Establish the existing incidence of mutations in appropriate species
Socio-Economic	
Protests and demonstrations	• Ongoing management of attempted unauthorised site access
Human intrusion	• Manage risk of human intrusion through use of security fences and surveillance
Effects of tourists on surrounding areas	• Monitor effects of tourist activity accessed via new road infrastructure
Radiation	

Issue	Monitoring Requirement
Used fuel Transport	• Monitor vehicles prior to transport from storage sites to repository • Monitor environment after any transport incidents
Routine operations	• A monitoring programme would be established to confirm that no releases of radioactive material to the environment occur. These would include routine measurements of: • Surface contamination (via instrument surveys and surface swabs) • Airborne contamination (via area monitoring with high volume air-samplers and personal air samplers) • External radiation dose rates (via instrument surveys). • The monitoring programme would also demonstrate that environmental effects are compliant with objectives and regulatory limits • The monitoring system will include both sampling of the various media as described in the baseline survey and their analysis for key contaminants and as such will cover air, surface and groundwater, biota and soil. • The logistics of the sample collection and analyses would be optimised. The analyses could take place on-site or off-site. An on-site facility would require appropriate infrastructure availability. • The requirements for sampling and analysis are described in more detail in Section 4.

4.1.3 Monitoring During Surveillance

This section provides a summary of monitoring requirements during surveillance. Thee are essentially the same as during operations with a reduction in frequency with time. For example:

Table 5 Environmental Monitoring Requirements during Surveillance

Issue	Monitoring Requirement
Physical Environment	
Surface water and erosion	• Prepare a surveillance and monitoring plan consistent with national/province policy
Potential for soil erosion / siltation of water courses	• Annual inspection reducing to five-yearly after five years
Potential for release of pollutants to soil	• Annual inspections reducing to five-yearly after five years
Potential for release of pollutants to surface water	• Annual inspection reducing to five-yearly after five years)
Potential for release of pollutants to ground water	• Annual monitoring of water levels in groundwater monitoring wells reducing to five-yearly after five years • Annual groundwater sampling for pH, electrical conductivity/salinity, major ions and selected radionuclides, reducing to five-yearly after five years
Radiation	
Routine surveillance	• Maintain all programmes as per Operation phase

4.1.4 Management and Monitoring during Decommissioning

The management and monitoring requirements during decommissioning are essentially the same as those for the operational phase.

4.2 ENVIRONMENTAL MONITORING PROGRAMMES

Appropriate environmental media and analytical requirements will be identified from an understanding and assessment of the site-specific characteristics and the operations at the repository. These will be based on the identification and assessment of potential release pathways and mechanisms for release of radioactive/contaminated material from the site.

It is expected that the environmental media requiring monitoring would include the following.

4.2.1 Airborne Particulate

Airborne particulate samples would be collected at a number of different locations around the repository site. This could be achieved using either high or low-volume continuous air samplers which collect samples on fiberglass filter paper. The samples are typically collected at a height of 2 to 3 m. Samples are typically collected weekly and composited quarterly.

The filters would be analysed for the radionuclides, and other hazardous materials, of concern. Typically these would include analyses for actinides and fission products using alpha and gamma spectrometry. Beta analyses could also be required if releases of tritium, carbon-14 and strontium–90 were of concern. Analyses for other hazardous or toxic materials will depend on the use of, and potential releases of these, from the repository.

4.2.2 Soil Samples

Soil samples are typically collected at the approximate locations of air particulate sampling. The soil samples are typically collected in three depth profiles: 0-2 cm, 2-5 cm and 5-10 cm. These depth profile measurements provide information to understand the vertical migration of radionuclides.

The frequency of sampling will normally alter throughout the programme, with more frequent (monthly) sampling at the beginning of the programme moving to less frequent sampling, quarterly or yearly, with time.

The analytical measurements will address the radionuclides and hazardous/toxic materials identified to be of concern. These may be as associated with the entire soil samples or as associated with various constituents of the soil, for example the more easily leachable components or organic fraction. Such measurements can indicate the bioavailability of the compound.

4.2.3 Groundwater

It is anticipated that there will be a number of monitoring boreholes around the repository site. The number, and location, of these will depend on the site-specific conditions and repository design.

Observations of groundwater levels and groundwater samples will be collected on a regular basis. The frequency of sampling, and in-situ observations and measurements, will depend on the site-specific hydrogeological conditions. The groundwater samples will be analysed for both radiological and non-radiological water quality parameters.

4.2.4 Surface Water

Surface water samples would be collected at regular intervals from various locations in the repository vicinity. The frequency of sampling, and in-situ observations and measurements, will depend on the site-specific hydrological conditions. The surface water samples will be analysed for both radiological and non-radiological water quality parameters.

4.2.5 Sediments

The majority of the sediment samples would be collected at the same locations as the surface water samples. The analytical measurements of these samples will address the radionuclides and hazardous/toxic materials identified to be of concern. These may be as associated with the entire sediment sample or as associated with various constituents of the sediment, for example the more easily leachable components or organic fraction. Such measurements can indicate the bioavailability of the compound.

4.2.6 Biota Samples

Uptake of radionuclides by plants and animals is an important factor in estimating the intake of radionuclides in humans through ingestion. Typically, vegetation samples are collected at the same locations that soil and air samples are taken. Fish/shellfish samples would be obtained from appropriate rivers/streams.

Animal samples would be obtained from locations adjacent to the repository site, for example, deer and rabbit samples. The appropriate species would be identified during the site characterisation phase and will typically be those who are part of the human food chain and those which might be responsible for the transfer of contaminated material throughout the environment.

4.3 SAMPLING AND ANALYTICAL REQUIREMENTS

The following sampling and analytical requirements will need to be defined for the environmental monitoring programme.

1. Sampling Frequency

This will depend on the type of media being sampled and the natural variation and cycles for that media. For example sampling could coincide with the Spring thaw and vegetation growth. Depending on the sensitivity of the analytical methods, samples might be aggregated prior to analysis.

2. Sampling procedure

Sampling procedures will need to be established and these should address the following:

- Equipment (e.g.soil/sediment corers, sample pots/bags)
- Conditions
    - Acidification (to prevent plating out onto the storage container walls)
    - Preservatives (to prevent decay/putrefaction)
- Storage prior to analysis
    - Light conditions

    - Temperature
- Identifiers
    - Unique labelling system

3. In-situ measurements/analysis

Some analyses/measurement will be done on site, for example:

- External dose rate
- Oxygen concentration (of water samples)
- Turbidity
    - Gamma spectrometry

Such measurements will require the same quality control and reporting systems as described below for off-site analyses

4. Off-site analysis

Procedures and methodologies will need to be developed for:

- Transport and handling
- Storage
- Pretreatment
    - drying
    - ashing
    - sieving
    - filtration

5. Analyses

Typical analytical requirements would be:

Water samples

Specific conductance, total dissolved solids, total suspended solids, density, pH, Eh, specific gravity, total organic carbon, total organic halogens, chloride, alkalinity, calcium, magnesium, potassium, iron, radionuclides (e.g. Pu isotopes, Am-241, U isotopes, Cs-137, Co-60, Sr-90, C-14, H-3), heavy metals (e.g. Cd, Pb, Hg), organics (humic acids, fulvic acids, organic contaminants).

Soil/Sediment samples

Density, porosity, total organic matter, dry weight, wet weight, leachable fractions, radionuclides (e.g. Pu isotopes, Am-241, U isotopes, Cs-137, Co-60, Sr-90, C-14, H-3), heavy metals (e.g. Cd, Pb, Hg), organics (humic acids, fulvic acids, organic contaminants)

Air samples

Particulate mass, radionuclides and metals as above (and including Be-7 as a natural tracer), volatile organics if appropriate

Flora/fauna

Dry weight, wet weight, specific organ weights, radionuclides, heavy metals and organics as above

6. QA/QC

Quality assurance and quality control will be required for the entire sampling and analytical process. This will include:

- Management systems
- Method statements for all processes
- Traceability from source to result
- Replicate analyses
- Intercomparisons
- Instrument calibration
- Validation

7. Statistics

An approach to the analysis of results will be established. This will include:

- Data handling, trends and variances
- Treatment of outliers

8. Records

Records of the entire process should be established and archived.

9. Reporting

The results of the environmental monitoring programme should be reported as appropriate at various levels of detail and complexity.

5 Conclusions

The operator will be required to demonstrate, prior to the construction of the repository that there would be no adverse effect on the environment resulting from these activities. Whilst there would inevitably be much focus on the radiological components on the environment, the more conventional environmental concerns should also be addressed.

A comprehensive programme for environmental and radiation safety monitoring will be required to demonstrate that no such adverse effects were observed. This programme would be developed as part of the licensing process for the facility and in accordance with regulatory requirements.

The general objectives of environmental monitoring are to:

- establish a baseline for the repository environment prior to construction
- quantify the effect of repository operations on the environment
- demonstrate that radiation/hazardous material exposures to members of the public are compliant with objectives and that exposures are within regulatory limits
- demonstrate compliance with environmental performance objectives and regulatory limits.

The environmental monitoring programme would address physical environment, vegetation and flora, fauna, socio-economic, cultural heritage and radiation.

The sampling and analysis requirements would address, sampling frequency and procedure, in-situ measurements/analysis, off-site analysis, analyses, QA/QC, statistics, records and reporting.

1106/MD18085/REP/01

CTECH

Radioactive Materials Management

Deep Geologic Repository Conceptual Design

Annex 7

Waste Shaft Hoisting System Used Fuel Container Design

December 2002

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 .

This document is written solely for the benefit of the Client, for the purpose stated in the Agreement, and the Consultant's liabilities are limited to those set out in the Agreement."

Contents

Figures

Appendices

1 INTRODUCTION

1.1 GENERAL

SNC-LAVALIN are providing engineering services to Ontario Power Generation (OPG) through CANATOM/CTECH to update the conceptual design for a deep geologic repository (DGR) for used nuclear fuel.

JR Morris Engineering is retained to provide specialist engineering services in the area of hoisting, shaft design, and related facilities. A report is to be developed comparing the conceptual designs for hoists, conveyances, and shafts, tabulation of design parameters, sketches of proposed arrangements, description of operating features, and estimates of marginal cost differences. SNC-Lavalin will be assisted in preparing more detailed designs and estimates for a selected base case.

1.2 DESIGN PARAMETERS

Spent fuel rod bundles will be received at the repository's surface facility where they will be packaged in special containers for emplacement. The loaded containers, encased in a bentonite jacket and suitably shielded, will be transported underground through the used fuel handling shaft. On the repository's emplacement level they will be transported by rail to the emplacement rooms.

The designs will be of a generic nature, with no specific site selected. The primary design criteria are as follows:

1. Repository depth 1000 m.
2. Used Fuel Container (UFC) 1168 mm diameter x 3867 mm long . Mass 24.7 Mg.
3. UFC encased in bentonite jacket (UFC/BJ), octagonal, 1670 mm over flats, 4380 mm long. Mass 36.7 Mg
4. Shielding cask, round, 2.305 m diameter x 5.0 m long. Mass, including UFC/BJ, 86.5 Mg.
5. Emplacement rate 371 containers/y, maximum 2 containers/d.
6. Preferred container attitude is horizontal during transport. Vertical attitude can be considered.
7. Containers may be transported down the shaft in shielding casks, or alternately without casks, but with shielding provided either by the cage structure or by fixed shielding at loading and unloading areas.
8. Transport of UFC/BJ's in the underground repository will be on railcars.
9. A steel thickness of 150 mm is required for gamma shielding, with the addition of 50 mm of polyethylene for neutron shielding.
10. Shaft and hoisting design will be according to Province of Ontario Occupational Health and Safety Act and Regulations for Mines and Mining Plants.
11. When the repository is decommissioned the shaft will be sealed and backfilled, using clay-based sealing material as used in UFC/BJ emplacement. Removal of

shaft lining will be required prior to backfilling to eliminate possible fluid passages at the concrete/rock interface.

1.3 PREVIOUS WORK

The project will be based on previous studies[1, 2], extending that work to accommodate redesigned fuel emplacement containers, modified storage rate, and other changes to operating concepts.

[1] Engineering for a Disposal Facility Using the In-Room Emplacement Method, P. Baumgartner, D.M. Bilinsky, Y. Ates, R.S. Read, J.L. Crosthwaite, D.A. Dixon, AECL-11595-96-223, June 1996.
[2] Used Fuel Disposal Centre – A Reference Concept Vol. I, II, III, AECL-CANDU, J.S. Redpath Mining Consultants, Golder Associates, The Ralph M. Parsons Company, April 1992

2 SUMMARY

2.1 THE FOLLOWING CASES WERE CONSIDERED:

Case #1 A cask containing a UFC/BJ is loaded on a railcar in the surface 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 on the repository level and moved to the emplacement location. Cage payload including railcar is maximum at 95.2 Mg, with estimated cage mass of 38.1 Mg.

Case #2 A UFC/BJ 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 repository level a crane beside the shaft transfers the UFC/BJ to another transport cask for travel to the emplacement location. Payload mass is reduced to 40.4 Mg, with a cage mass of 16.1 Mg.

Case #3 This is 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 Mg, but cage mass is increased to 60.0 Mg.

Case #4 A cask with UFC/BJ is brought to the shaft in horizontal position, 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. On the repository level the procedure is reversed, using another large crane to rotate the cask to horizontal position 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 Mg, with cage mass of 38.0 Mg.

Case #5 This is 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 Mg, with cage mass of 39.0 Mg.

- Case #1 is recommended as the base case for ongoing studies. This is the most expensive option, but it offers the simplest cask handling procedures. 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: this is not significant in the total project cost.
- The maximum payloads proposed can be handled by a Koepe hoist using currently catalogued hoist ropes.
- Blair-type drum hoists were briefly considered, but costs are high and the surface structures complex.
- 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 hoist will be driven through a two-stage reduction gear to obtain this low RPM. Transit time through the shaft will be

approximately seven minutes. Because of the low speed, electrical drive costs will be a relatively minor part of the total hoisting system and savings through further hoist speed reduction would be negligible.

- The vertical and unshielded UFC/BJ options markedly reduce shaft diameter, at the expense of more complex handling equipment and procedures. Hoist size is also reduced when handling unshielded UFC/BJ's in an unshielded cage. Although the capital cost differential in selecting one of these options is not considered significant at the present stage, these choices might be more attractive should an arrangement be selected which required more cask length.
- The Koepe hoist will be tower mounted in a concrete headframe. Protection against sabotage or terrorist attack should be considered: concrete construction is inherently damage-resistant as compared to steel, and can be easily strengthened to any desired specification by increasing wall thickness.
- Overall height will be approximately 38.0 m to the top of the roof parapet. Installation of the hoist will be done with a mobile crane; an overhead crane capable of maintenance lifts will be installed in the hoistroom.
- The electrical room will be at ground level, attached to the headframe. Reinforced concrete construction is recommended for security reasons.
- Hoist control will be from a central control room at the service shaft.
- The cage will be of steel construction. The floor will be designed as a bridge deck within the cage frame, able to slide vertically to isolate the effects of rope elasticity when landing on banking beams.
- Banking beams at collar will be retractable, while those at repository level will be fixed during operation. Special shock-absorbing systems will be included to handle the heavy loads.
- As this shaft will be sunk after repository access is available through the Service Shaft, excavation by raise-and-slash methods offers more economical sinking and potentially enhanced wall rock conditions compared with the use of pilot-and-slash blasting methods.
- Conventional shaft lining would consist of a nominal 300 mm thickness of concrete. In this shaft intermittent curbs are recommended, located at 5.5 m spacing to support the shaft sets. This will reduce initial cost slightly, and greatly reduce decommissioning work. It is also possible to omit lining entirely, using rock bolts and mesh for ground support; this is particularly appropriate if rope guides are used, eliminating the need for set support. The latter option will reduce the costs of stripping and sealing the shaft to a minimum.
- Additional grouting or other water control measures should be allowed for to ensure a clean working environment.
- The shaft was specified in the original study references as being dedicated to the handling of used fuel. The presently projected duty 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 of the primary requirement. These uses might include: transport of heavy excavation equipment: transport of clay-based sealing and other bulk materials from a surface preparation plant. The latter option would greatly simplify the

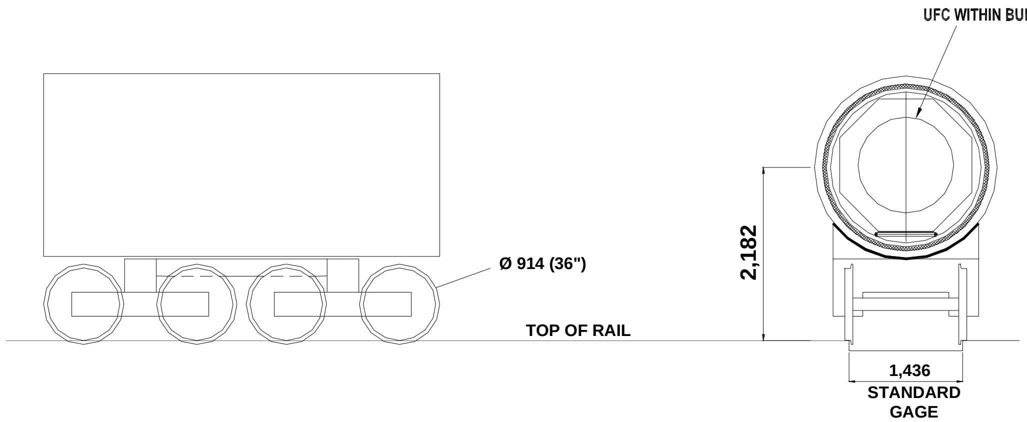


FIGURE 1
RAIL CAR USING ARTICULATED RAIL TRUCKS

underground arrangements, and would permit more flexibility in the block forming of the clay-based sealing material. This would be particularly valuable should extended curing of the blocks prove necessary before emplacement.

3 CASK AND RAILCAR ARRANGEMENTS

3.1 GENERAL

A single railcar will preferably carry the UFC/BJ from the packaging plant on surface to the emplacement location underground. The details of handling procedures, particularly during emplacement of the UFC/BJ in the repository, are not known at this time

3.2 BOGIE DESIGN WITH SEPARATE CASK

3.2.1 Horizontal Cask

The design shown in Figure 1 is based on conventional railcar design, with a chassis supported on two – four wheeled trucks, or bogies. The chassis pivots on the bogies when traversing curves. Wheel diameter and wheelbase (within each bogie) are reduced from standard railway practice for 100 ton cars to minimize shaft diameter and lower the height of the UFC/BJ. The chassis must be designed to cradle the cask, possibly with retaining catches. Wheel gauge is shown as railway standard, although increased gauge would increase stability and should be considered in final design.

3.2.2 Vertical Cask

The advantage of transporting the UFC vertically in the shaft is that it allows a smaller shaft diameter.

The disadvantages are:

- Additional activities and hoisting equipment are required to stand the cask vertically before entering the cage and to lay it horizontally after leaving the cage for underground transport.

- Trunnions for lifting and tilting the cask will increase width, possibly making the cask less

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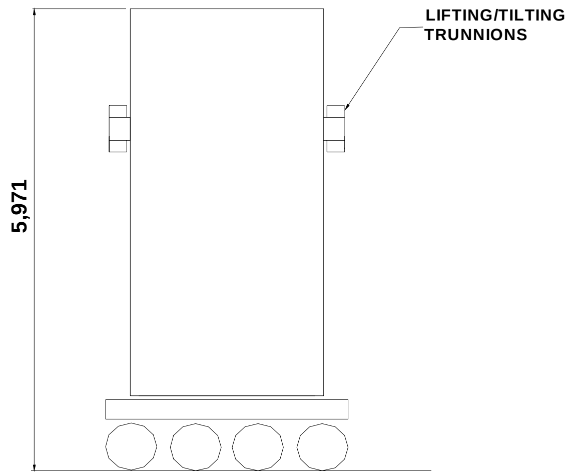


FIGURE 2
VERTICAL CASK/RAIL CAR DESIGN

3.2.3 Integrated Design with Wheels on Cask

Figure 3 shows a car design in which the axles attach directly to the cask structure. The primary purpose of this design is to reduce the height of the cask to reduce excavation requirements. There is also some reduction in overall weight.

The axles are supported on elastomeric pads which accommodate vertical discrepancies in rail elevation so as to share load on the wheels. They also provide lateral flexibility so the wheels can track around curves.

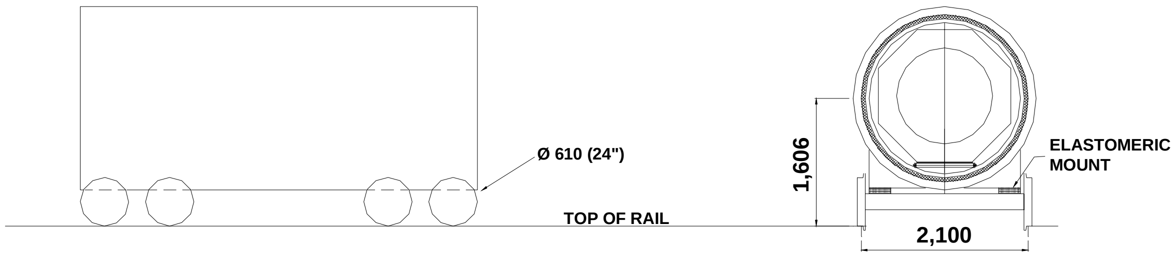


FIGURE 3
UNITIZED CASK/RAIL CAR DESIGN

4 HOISTING PLANT

4.1 HOIST SELECTION

4.1.1 General

Even the lightest payload considered is beyond the capacity of a single hoist rope as currently available. The two commonly accepted multi-rope hoisting systems are the Blair drum hoist system, which normally uses two ropes per conveyance, and the Koepe, or friction hoist, system, which can use as many ropes as can be attached in the available space on the conveyance centerline. More than eight ropes are seldom used.

Safety catches are not required by Ontario hoisting regulations when multiple ropes are used.

4.1.2 Drum Hoists

The Blair Multi-Rope (BMR) system provides two winding drums for each conveyance; for counterweighted hoisting this results in four drums connected to two conveyances. These four drums are normally mechanically linked together. Some installations have used electrical interlinking, but the electrical costs become very high. The tensions in the two ropes connected to each conveyance tend to vary because of differences in spooling on the winding drums, or variations in rope elasticity. The tensions must be equalized, normally by a floating headsheave arrangement supported by a hydraulic system linked between the two sheaves.

As in any drum hoist, rope handling is somewhat simpler than with a Koepe system, as all ropes can be wound to surface for changing.

The normal BMR could handle the loads in Case 3, UFC/BJ in unshielded cage, but at a cost probably $10,000,000 - $12,000,000 greater than would be needed for a friction hoist of the same capacity.

A four-rope BMR can be visualized, which would have no counterweight. Two mechanically connected drums would be mounted on either side of the shaft, with electrical linking between the two sides. The four ropes could handle the loads in Case 1, but at an additional cost of perhaps $15,000,000. The principal attraction in this system is that with a single conveyance and no tail ropes, the cage could be designed for pneumatic retardation in case of a runaway. This is a system which has been postulated previously, but has never been implemented; its pursuit cannot be recommended.

4.1.3 Koepe Hoists

The Koepe system leads the multiple ropes (head ropes) over a friction wheel, with a conveyance attached to each end; in this case there will be a cage on one end and a counterweight on the other. The load ratio (T1/T2) between the two sides of the friction wheel must be kept within certain limits. To assist with this, balance ropes (tail ropes) are hung from the bottom of one conveyance to the bottom of the other to compensate for the changing weights of the head ropes as the conveyances travel up and down the shaft.

Since none of the ropes are attached to the hoist, and tension ratios must always be observed, special procedures must be used for rope installation and changing. Special rope winders are often provided for this service. Although rope handling is more complicated, rope life is normally better than with a drum hoist, where wire damage from multi-layer spooling is common with highly tensioned ropes.

The Koepe hoist is often mounted in a headframe tower immediately over the shaft. All ropes are thus enclosed in the headframe, protected from weather and outside interference.
The principal features of the hoists calculated for the various cases are summarized below. Hoist diameters have not been rationalized.

CASE	ROPES Number x diameter, mm x kg/m	HOIST DIAMETER mm	RMS POWER kW
1	6 x 54.0 x 16.16	6210	1420
2	4 x 42.9 x 10.04	4934	510
3	6 x 46.0 x 11.67	5520	560
4	6 X 54.0 X 16.16	6210	1420
5	6 X 52.4 X 15.30	6026	1300

4.1.4 Hoist Control

The hoist will normally operate on automatic control. During shaft inspection and maintenance, while crew are riding on top of the cage, control will be by manual remote radio link. Special operations such as rope installation or changing will be manually controlled from an operating console. This hoist will be installed some years after commissioning of the Service Shaft. Assuming that the Waste Handling Shaft will be relatively close to the Service Shaft, it is anticipated that the control console for both will be located in the Service Shaft hoist control room.

4.1.5 Safety Features

Hoisting safety provisions fall into four main areas:

1. Structural/mechanical strength.

    - Regulations require the aggregate breaking strength of the hoist ropes to exceed the total suspended load by a large factor; at a depth of 1000 m the factor, for a Koepe hoist, is approximately 6.3:1.
    - Factors for conveyances and headframe structures are expressed differently, but the general principle is that these components of the system are able to survive a rope-breaking incident without catastrophic failure. Some repair of deformed members is accepted in such a case.
    - Hoist main shaft and wheel are designed for infinite fatigue life at the specified loads.

2. Mechanical Redundancy

    - Multiple hoist ropes on a Koepe hoist provide redundancy, since loss of up to half the ropes would not reduce the total rope breaking strength below the total suspended load. In the case of a single rope drum hoist, safety dogs are required for personnel hoisting, thus providing a redundant support system for the cage in case of a rope failure.
    - Braking systems are divided into two halves. Each has a separate brake disk, calipers, and application valves. Each half of the system has the capacity to stop and hold the greatest load to be carried. The brakes may be applied by pneumatic or hydraulic pressure in normal operation, but in an ultimate emergency situation will be applied by springs or weights, which are independent of any outside power source.

3. Control Redundancy

    - The primary hoist control provides a speed/position operating envelope within which the hoist must operate. This defines maximum speed, speed limits in specific areas such as when approaching a stopping point, acceleration and deceleration rates, and limits of travel distance. Stopping points are defined by the hoist control, but normally the final stopping point is controlled by a physical position switch in the shaft. The control system will normally have two inputs for critical items, such as dual encoders for conveyance position, or encoder with tachogenerator backup for conveyance speed. Various other items, such as correct release of brakes, correct system voltage, proper brake operating pressure, and motor current limits are fed into the system from external sensors; if these values breach the operating rules an emergency stop in invoked.
    - A hoist monitor follows the action of the primary control, providing a second speed/position envelope. If the operating envelope or values are breached an emergency stop is invoked. Modern digital hoist monitors provide many additional functions, such as recording performance during emergency stops.
    - Physical limit switches (track limits) in the conveyance travelway provide a third limit to conveyance travel. Additional switches are typically used to synchronize the control system digital position indicator with the actual conveyance position, and to check speed at a particular points in the shaft against the speed envelope at this position.

- The safety circuit, which invokes an emergency stop, consists of several contacts connected in series. Some of these are direct connections to sensors, such as the track limit switches, brake wear switches, position switches and pressure switches, or motor current limit. Others are activated by the hoist control or monitor Programmable Logic Controller (PLC) if the operating envelope or operating rules are breached. All contacts must be in closed condition if the hoist motor is to be energized and the brakes released; the loss of any circuit wiring causes the same result as the opening of a safety contact. Once the hoist is in motion, fault conditions handled through the PLC may invoke either an immediate stop or a preventive stop, in which the hoist is allowed to complete the current trip, but prevented from starting again. A preventive stop might be caused by such things as failure of a hoist motor cooling fan, which will not cause immediate danger or damage to the system.
- Some systems may provide an electrically controlled stop, much less stressful for the equipment than a full mechanically braked emergency stop, for some problems which are not immediately threatening.

4.2 HEADFRAME

The headframe can be either of steel or concrete construction; there is little to choose in terms of cost. The concrete tower is usually faster to enclose when weather is a schedule factor. It can also be economically reinforced against sabotage by increasing wall thickness. Concrete is proposed for this project.

Figure 4 is a section through the headframe showing principal features. Since the headframe is relatively low (38.0 m), hoist installation will be done with a mobile crane. A smaller crane will be installed over the hoist for maintenance tasks such as lifting bearing caps and brake units.
An electrical room will be built on ground level adjoining the headframe. This would typically be a steel-framed building, but in this case reinforced concrete is recommended.

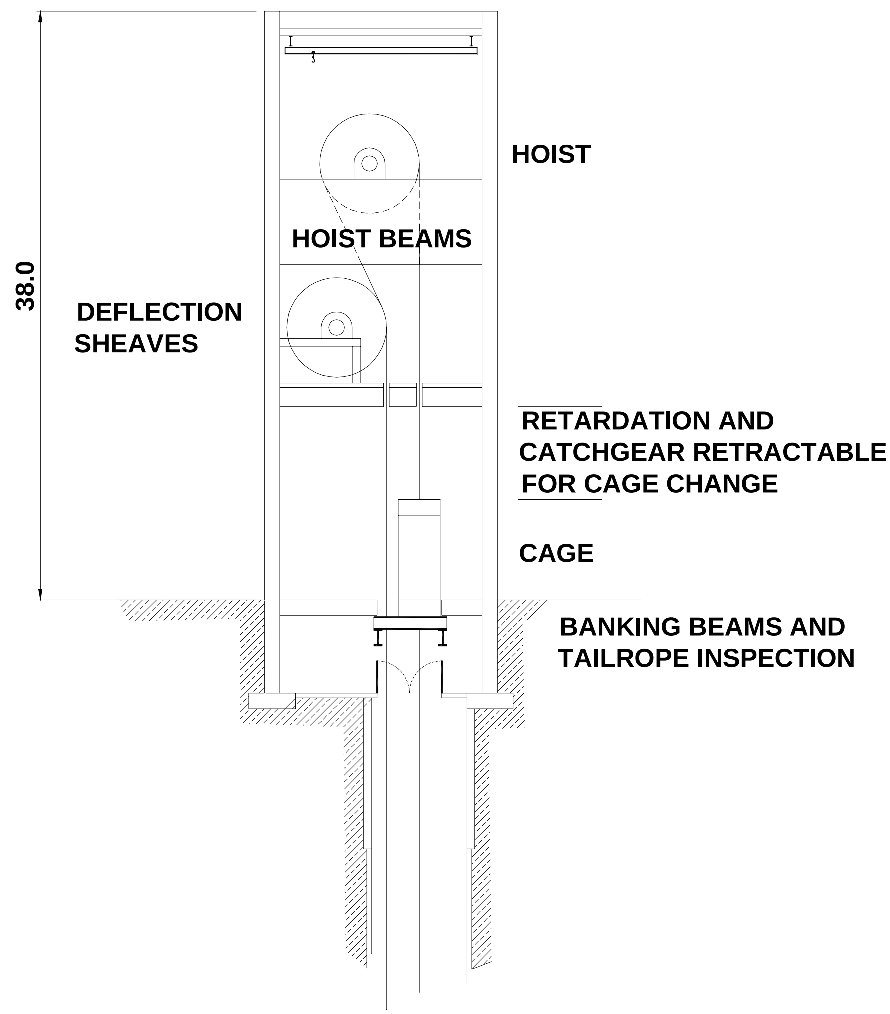


FIGURE 4
HEADFRAME
VERTICAL SECTION

4.3 END ZONE ARRANGEMENTS

4.3.1 Cage Banking Arrangements

The cage must be banked, or landed, on fixed supports when loading and unloading railcars so that the rails on the cage match closely with those on the station. A combination of elastomeric and hydraulic shock absorbers will be used to avoid impact as the cage is landed. The final landing onto the fixed supports will be done hydraulically, as this can be controlled more precisely than is possible with the hoist.

The payload will cause a rope stretch of approximately 0.7 m when the payload is at the repository level. The head rope tension must be released by an amount equivalent to the payload before the load is removed, otherwise the cage will rise violently as the wheels of the railcar leave the cage. Section 5.1 below describes the cage floor arrangement which will be used to isolate the effects of rope elasticity from the railcar loading/unloading.

Rope stretch is much less when loading at the collar, but is sufficient that, with the loads being considered, banking beams will be required. Collar banking beams must be retractable to let the cage pass. Banking beams at shaft bottom will be fixed in lateral position during operation, but will be retractable to allow the conveyances to be raised above collar level during installation and maintenance.

4.3.2 Retardation and Catchgear System

Regulations and good practice call for a retardation system at top and bottom of travel capable of stopping a conveyance traveling at full speed, and a catchgear system at the top of travel which will prevent a conveyance falling down the shaft in case of an incident which breaks the hoist ropes.

Because of the low speed in this case less than one meter of retardation distance is needed. Hydraulic retardation is proposed. At shaft bottom the retarder cylinders will support the banking beams, allowing them to sink sufficiently under heavy impact to stop the conveyance at a deceleration rate of approximately 0.9 g.

A similar retardation system will be used in the headframe, and will be incorporated with a catchgear system. The catchgear provides a latching system to engage the conveyance should it travel past the normal stopping point. Although catchgear is designed to minimize fallback of a conveyance, shock absorbers must also be provided to soften the impact of a conveyance dropping onto the latches.

The counterweight will be provided with retarders and catchgear similar to that for the cage.

4.4 ALTERNATE TECHNOLOGY

4.4.1 Block Hoist System

The 'Block Hoist' system has been used several times in South Africa for handling loads of up to 64 tonnes, at depths of over 300 m. It is more complex than an ordinary Koepe hoist, but allows smaller ropes to be used. At shallow depths the hoist wheel can also be smaller, but at the proposed depth of the repository the hoist diameter is governed by the number of turns required per trip, and would be approximately the same as the largest Koepe hoist being considered.

To maximize the advantages of this system it would be necessary to use stranded ropes rather than Full Locked Coil, which is not usual Canadian practice at the proposed depth. The layout would be improved if permission could be obtained to use sheave diameter:rope diameter (D:d) ratios of less than the 80:1 normally required.

The system would be a more attractive alternative if the repository was to be located at shallower depth. It is not recommended for the depth being considered.

Figure 5 shows the concept, using a D:d ratio of 60:1 for the sheaves on top of cage and counterweight. Shaft diameter would be approximately 7.0 m with this arrangement.

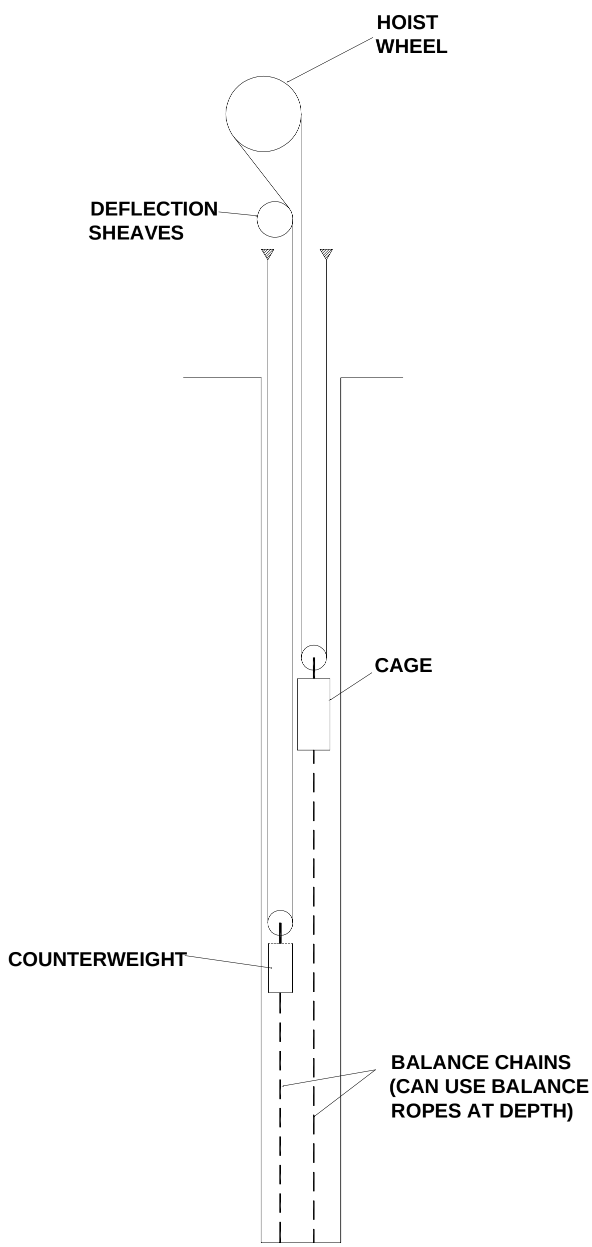


FIGURE 5
BLOCK HOIST SYSTEM ARRANGEMENT

5 CAGE

5.1 GENERAL

Three principal cage variants are considered, in various dimensions. All but one variant is designed for handling railcars. All cages are designed without doors, with the railcar locked into the cage by means of mechanized rail chocks, except in Case 3 where a door is provided for shielding. The variant without rails carries the cask vertically, suspended from saddles that engage trunnions on the cask.

All cages 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 removes from the ropes the elastic stretch due to payload, while maintaining an acceptable T1/T2 ratio. It provides a totally static situation while loading and unloading railcars. Other means of handling this problem have been used, but do not provide the simplicity of positively isolating rope tension and proving correct release by means of simple limit switches[3].

All cages are expected to have some powered devices onboard, such as rail chocks, other load retaining devices, or winches. Power will be provided by bayonet-style contacts that engage sockets on the cage when at loading/unloading position. Energization of the circuit will be controlled by interlocks; no voltage will be present unless the cage is in position and hoist brakes set. The devices will be activated by springs or weights to return to a locked or failsafe condition when power is removed.

5.2 HORIZONTAL CASK ATTITUDE

5.2.1 Unshielded Cage

5.2.1.1 Case #1

Figure 6 illustrates a cage sized to accept a cask of specified size and loaded weight. This represents the simplest shaft operating situation, as the load approaches and leaves the shaft in horizontal position and is fully shielded so that crew can work adjacent to a loaded cask in case of any emergency maintenance problem. The price of this convenience is large shaft diameter (6.15 m).

[3] Englemann, H.J., W. Filbert and C. Schrimpf. 1993. Demonstration tests for the simulation of shaft transfer. In Proceedings of the Symposium on Waste Management (WM'93). Tucson, Arizona. V2 pages 1311-1315.

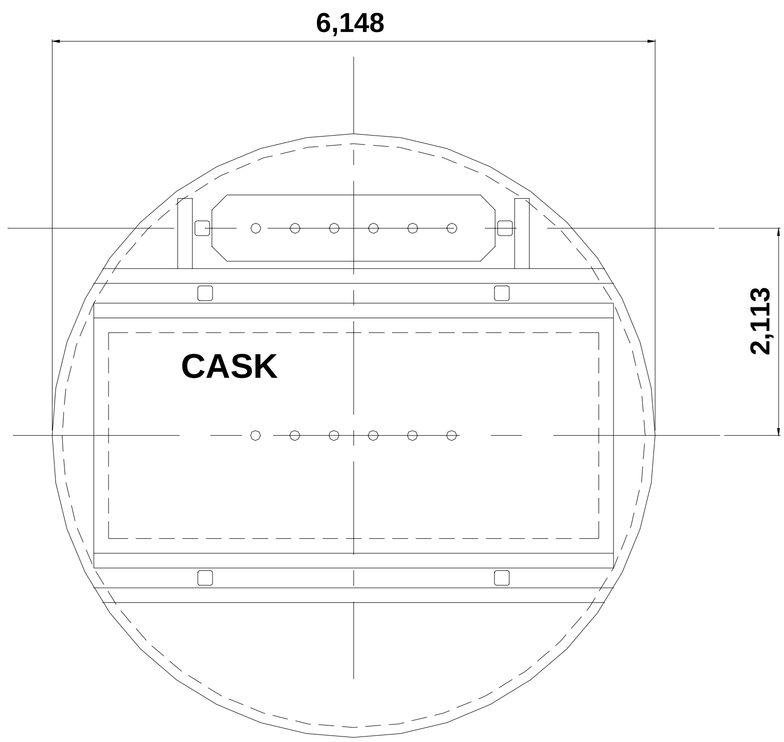


FIGURE 6
SHAFT PLAN FOR HORIZONTAL CASK TRANSPORT

5.2.1.2 Case #2

Figure 7a illustrates a cage sized to handle a UFC/BJ without shielding cask. In this case shielding will be provided on all vertical sides of the cage compartment at surface and repository level. Opening the compartment gate, and all subsequent activities until the UFC/BJ was transferred to and enclosed in a transport cask, would be conducted remotely. Note that in this case the number of hoist ropes is reduced because of the lesser payload.

Savings are obtained in shaft, hoist, ropes, and cage at the penalty of increased cost for remote operating devices, more complex handling activites, and limitations on emergency maintenance activities. Large cranes will be needed at shaft side to transfer the UFC/BJ into a shielded railcar. A possible advantage of this system lies in the ability to conveniently use different car styles on surface and underground, should the requirements of packaging and emplacement favor different designs.

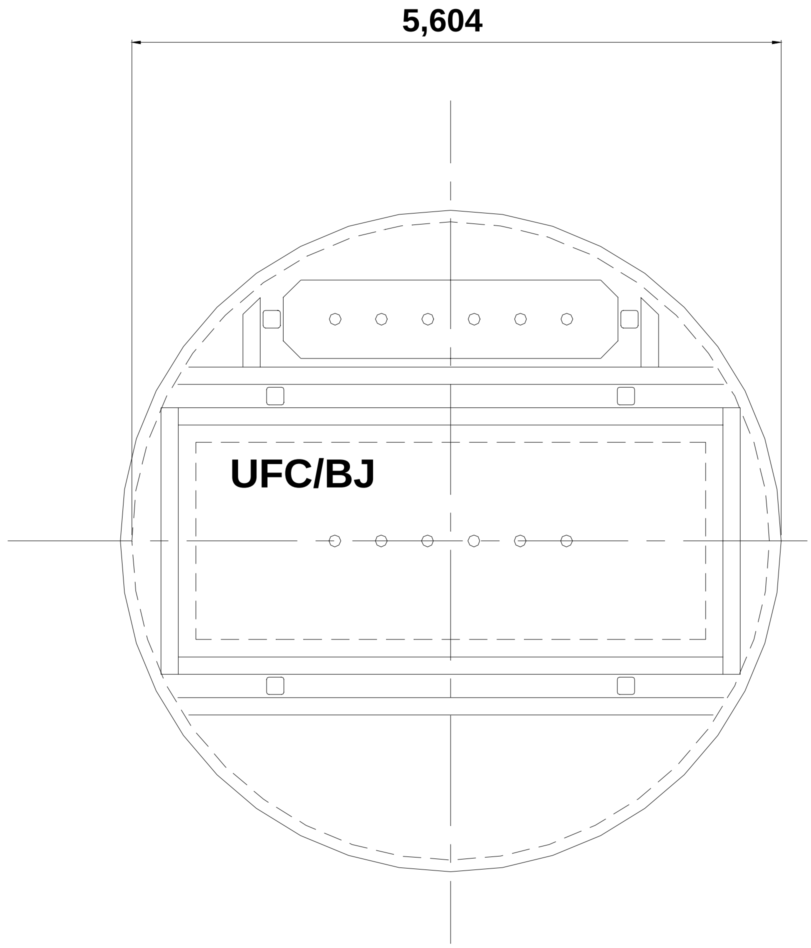


FIGURE 7b
SHAFT PLAN FOR UFC/BJ TRANSPORT
IN SHIELDED CAGE

5.2.1.3 Case #3 - Shielded Cage

Figure 7b illustrates a cage sized to handle a UFC/BJ without cask, as in 7a. However, in this case the cage structure is constructed of steel plate to provide shielding equivalent to a cask. Overall weight of cage and shielding is less than that of cage plus cask, since the shielding plates form major structural members. However, the hoist must still use six ropes, very nearly equal to the hoist used in case 4. This, together with additional cage length to provide heavy doors, results in a larger shaft than in 7a.

Although it would be possible to work around the shaft station with a loaded cage present, all activities to transfer the UFC/BJ to a transport container would still have to be done by remote operation. As in the previous case, large cranes would be needed at the shaft to transfer UFC/BJ's to and from the cage. The value of this approach as compared to case 7a is questionable.

5.3 VERTICAL CASK ATTITUDE

5.3.1.1 Case #4 - Cask Tilted Outside Shaft

The UFC/BJ is assumed to arrive at the shaft in horizontal position in a transport cask. The cask would be designed with trunnions, complete with bearings, so that it could be lifted by crane near the shaft, rotated to the vertical position, and set on a short-wheelbase car to be moved into the cage. This special car is visualized to move only a short distance in a straight line to and from the shaft, so that axle design can be very basic. The cage would be equipped with a yoke that lowers around the upper end of the vertical cask to secure it against any lateral impulses.

At the repository level the car would be pulled out of the shaft and the cask transferred to a transport car for the trip into the repository. Another large crane would be needed near the shaft, and additional excavation would be needed to accommodate it. The bentonite jacket on the UFC would experience some mechanical shearing forces during tilting that might be objectionable. The cage arrangement for this option is shown as Figure 8a.

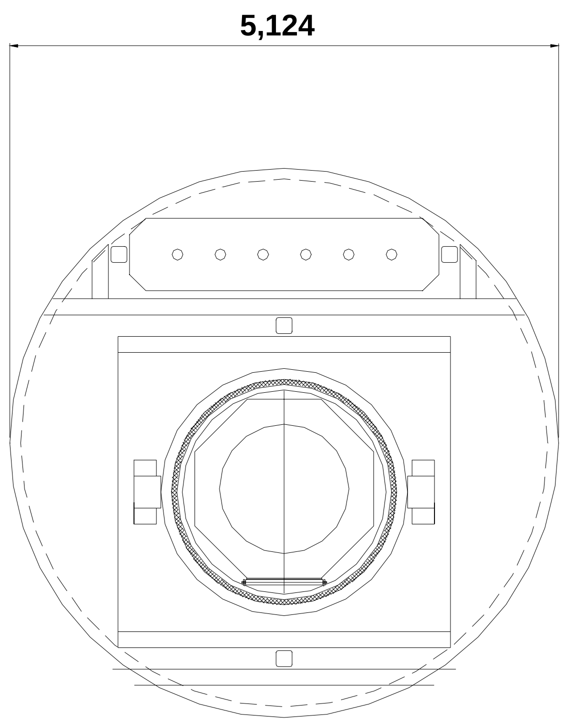


FIGURE 8a
SHAFT PLAN FOR TRANSPORT OF CASK LOADED VERTICALLY ON RAILCAR

5.3.1.2 Case #5 - Cask Tilted in Cage

The cage would be designed with saddles to engage the lifting trunnions on the casks. All tilting would be done within the cage using the main hoist. The cage floor would serve as a bridge so a standard car could enter the cage on surface to deliver the cask, and then be removed. The floor would be able to slide downwards a sufficient vertical distance to allow the cask to hang in the trunnions so that the car can be removed. An on-board winch would control cask movement during tilting, and would return the cask to horizontal position at the repository level. On the repository level the cask would be tilted horizontal, a similar car would enter the cage, and the cage would be lowered until the load rested on the car and the trunnions lifted clear of the saddles, at which time the car would be pulled out of the cage.

Figure 8b shows a slightly larger shaft than in 8a, due to the orientation of the cask trunnions. Handling arrangements would be simplified, since no additional major cranes would be needed for tilting the casks. Net rope loads would be slightly less, since the weight of the trunnion saddles is expected to be less than that of a short-wheelbase railcar and no retaining yoke would be needed for the top end of the cask.

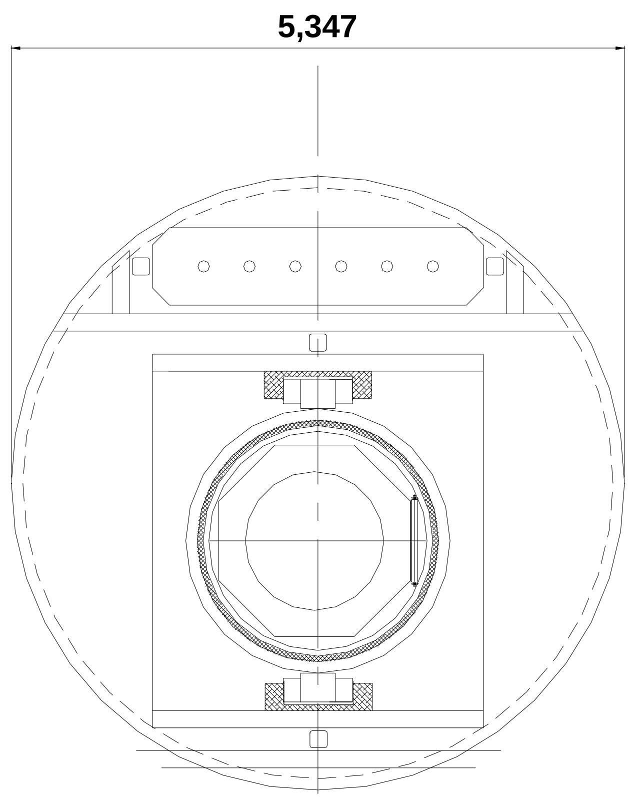


FIGURE 8b
SHAFT PLAN FOR TRANSPORT OF CASK SUSPENDED VERTICALLY IN CAGE

6 SHAFT

6.1 GENERAL

Shaft arrangements have been shown in Figures 6, 7a,b, and 8a,b.

CASE NO.	FINISHED DIAMETER m	EXCAVATED AREA m^2
1	6.15	35.8
2	5.45	28.7
3	5.61	30.3
4	5.13	25.8
5	5.35	27.8

The shaft is assumed to be in sound rock such that only nominal ground support is needed. Ground water will be controlled primarily by grouting, although short sections of hydrostatic lining might be included in the near surface sections where most water is encountered. A water collection ring will be provided immediately above the repository level; additional water rings could be provided at other shaft locations if needed.

Characterization of the shaft walls will be a significant time element in the sinking schedule. The schedule should allow one shift per day for characterization, with two shifts per day for sinking. Shaft cross-section is controlled by the cage floor plan and the number of hoist ropes needed to support the payload (influences counterweight width). A minimum clearance of 100 mm is allowed between cage and shaft walls.

No permanent pipes are expected in the shaft. Although this will be a rather critical operating system, the conditions in this shaft will be much safer than in any other shaft in the proposed complex, and electrical and communications cables can be routed through here. Communications cables for the hoist controls and cask handling equipment will be carried on the shaft walls. A leaky coaxial cable should be installed for reliable communications during shaft inspection.

6.2 SHAFT LINING AND FURNISHING

A concrete lining of 300 mm thickness would be conventional for a shaft of this nature. However, the necessity of sealing the shaft on decommissioning, probably with removal of the lining, may render other approaches more attractive. As the site will be chosen on the basis of good rock quality, continuous concrete lining can be dispensed with, and support provided by rock bolts and mesh, shotcrete, or by concrete curbs at each set location with bolts and mesh between. All these approaches have been previously used in mining shafts. There is a penalty in increased ventilation resistance, but this shaft is not intended to carry large volumes of air. If concrete curbs, one meter high, are installed at 5.0 m intervals, conventional steel sets and guides, as shown in the illustrations, can be readily installed. In planning for decommissioning, the argument could be made that having potential flow paths of one meter length behind the curbs, separated by 4.0 m lengths of clay-based sealing material, will provide sealing substantially equivalent to that which would be accomplished by removal of the curbs. The curbs would serve as excellent bases for the full concrete seals that will possibly be placed at three locations in the shaft.

Rope guides could be readily used at this depth, although wall clearances would have to be increased to 200 mm. Rope guides, together with an unlined shaft, would reduce excavation volume somewhat since the additional wall clearance needed would be more than offset by the elimination of the 300 mm concrete thickness. Guide rope life in the conditions envisaged in this shaft could exceed 25 years. Inspection and maintenance effort would be reduced as there are no structural connections to be checked within the shaft.

Concrete curbs with conventional steel sets are recommended for this shaft, subject to evaluation of the need for removal of the curbs on decommissioning.

6.3 SINKING ARRANGEMENTS

The Service Shaft will be the first shaft to be sunk, as it must support development of the repository and initial underground characterization. The Waste Handling Shaft and Ventilation Shafts are indicated to be relatively close to the Service Shaft, providing the opportunity to use the more economical raise and slash method for excavating these shafts. The raise and slash method is well suited to the pilot and slash blasting technique that was developed at WNRE. Long slash rounds can be broken to the pilot raise, potentially improving shaft wall conditions and promoting more effective sealing when decommissioning.

The shaft depth is excessive for single-lift raising, but the provision of a mid-shaft access level to support raise development may be justified.

The Koepe hoist could be rigged as a single drum hoist to service the slashing operation, eliminating the cost of installing a temporary sinking hoist.

6.4 VENTILATION

Downcast ventilation in the Canadian climate produces very dry shaft conditions in the winter, when heating is needed. This results in very good maintenance conditions with negligible corrosion. In summer, particularly if the site should be in the southern Precambrian Shield area where high humidity can occur, surface air tends to cool as it meets the shaft walls, and may condense substantial amounts of water. This may occur on relatively few days, depending on location, and under normal circumstances a slight downcast flow would be preferred that potentially could incorporate the use of a dehumidifying plant. However, because of radiological safety concerns, the Waste Shaft should be upcasting. In the event of a radioactive release resulting from an upset condition in the Waste Shaft, the upcast arrangement prevents the underground area from being contaminated.

7 ESTIMATES

7.1 GENERAL

These estimates are prepared for the purpose of ranking the options considered in this report, and are presented as marginal cost differences for the major cost categories in provision of shaft and hoisting plant. The least cost case for each cost category is assigned a value of zero; marginal cost differences are then calculated from historical factors for the other cases.

For example, the electrical costs associated with a hoist include control systems and area power and lights, which are essentially constant for each option, plus a variable amount for DC converters and motors.

Estimates are in Canadian dollars. Target accuracy is +25%, -50%.

7.2 SUMMARY OF MARGINAL COSTS

Amounts in thousands of dollars.

CASE	SHAFT	HOIST	CONVEY'CES	ROPES & ATTACHM'TS	UFC/BJ HANDLING	TOTAL MARGIN	MARGINAL DIFFERENCE
1	4,120	1671	494	460	0	6744	4600
2	1,195	0	0	0	1100[1]	2145	0
3	1,854	896	685	123	560[2]	3968	1823
4	0	1668	492	460	460[3]	3080	936
5	824	1507	481	396	0	3208	1063

Note:

1. Includes shaft side cranes for handling unshielded UFC/BJ's. Includes required surface structure and underground excavation. Allowance for fixed shielding around cage compartment at stations. Includes allowance for isolated control rooms and remote crane operating systems for handling unshielded containers.
2. Includes shaft side cranes for handling unshielded UFC/BJ's. Includes required surface structure and underground excavation. No allowance for fixed shielding as this is included in cage. Includes allowance for isolated control rooms and remote crane operating systems for handling unshielded containers.
3. Includes shaft side cranes for lifting/tilting loaded casks. Includes required surface structure and underground excavation.

APPENDIX

Hoist Design Calculations

Cost Parameters

JR MORRIS ENGINEERING
FRICTION HOIST DESIGN PROGRAM

CASE:	OGP-DGR, LOWERING UFC/BJ IN UNSHIELDED CAGE			DATE:	02-Jul-02
REFERENCE NUMBER:	02SNC-a				
SYSTEM TYPE:		Counterweighted Cage			
PRODUCTION RATE	tonnes/hour	400	PRODUCTIVITY FACTOR		1
HOISTING DISTANCE	m	1000	MINIMUM CONVEY'CE TARE FACTOR		0.4
SUSPENDED ROPE LENGTH	m	1015	COUNTERWEIGHT FACTOR		0.5
HOIST DIAMETER	mm	4934	HOIST/ROPE DIAMETER RATI		115
EQUIV EQUIPMENT MASS	kg	258	MECHANICAL EFFICIENCY	%	95
T1/T2 RATIO, allowable		1.40	TAIL LOOP LENGTH	m	10
TOTAL SUSPENDED LOAD	kN	1719	HEADROPE/TAILROPE WT RA		1.00
TREAD PRESSURE	kPa	2030	REVOLUTIONS/TRIP		64.5
T1/T2 RATIO		1.26	T2/T3		1.35
		SIDE ONE		SIDE TWO	
CONVEYANCE MASS	kg	16148			36333
PAYLOAD	kg	40370			
		HEADROPES		TAILROPES	
NUMBER OF HEADROPES		4	NUMBER OF TAIL ROPES		4
ROPE TYPE		FLC			
ROPE STRENGTH	kN	1564			
ROPE DIAMETER	mm	42.90			
ROPE UNIT WEIGHT	kg/m	10.04			10.04
SAFETY FACTOR AT SHEAVE, STATUTO		6.34			
ACTUAL		6.53			

					ROPE LOADS STATIC		ACC'L'N		HOIST EFFORT	POWER	
		RATE	TIME	DISTANCE	SIDE 1	SIDE 2	SIDE 1	SIDE 2	@ROPES		T1/T2
			sec	m	kN	kN	kN	kN	kN	kw	
ACCELERATE TO CREEP	m/s/s	0.25	2.00	0.50	958	760	24	-19	262	785	1.33
					958	760	24	-19	262	785	1.33
CREEP	m/sec	0.5	0.00	0.00	958	760			218	653	1.26
					958	760			218	653	1.26
ACCELERATE TO RUN	m/s/s	0.25	10.00	17.50	958	760	24	-19	262	785	1.33
					958	760	24	-19	262	785	1.33
RUN	m/sec	3	320.67	962.00	958	760			218	653	1.26
					958	760			218	653	1.26
DECELERATE TO CREEP	m/s/s	0.25	10.00	17.50	958	760	-24	19	174	522	1.20
					958	760	-24	19	174	522	1.20
CREEP	m/sec	0.5	4.00	2.00	958	760			218	653	1.26
					958	760			218	653	1.26
DECELERATE TO STOP	m/s/s	0.25	2.00	0.50	958	760	-24	19	174	522	1.20
					958	760	-24	19	174	522	1.20
LOAD/UNLOAD			60.00							0	
										0	
TOTAL			408.67	1000.00							
							POWER, fan-cooled			604	
							self-cooled			635	

JR MORRIS ENGINEERING
FRICTION HOIST DESIGN PROGRAM

CASE: OGP-DGR LOWERING UFC/BJ IN SHIELDED CAGE DATE: 02-Jul-02
REFERENCE NUMBER: 02SNC-b

SYSTEM TYPE:		CWTED CAGE	GUIDE MATERIAL:		STEEL
PRODUCTION RATE	tonnes/hour	NA	PRODUCTIVITY FACTOR		1
HOISTING DISTANCE	m	1000	MINIMUM CONVEY'CE TARE FACTOR		NA
SUSPENDED ROPE LENGTH	m	1015	COUNTERWEIGHT FACTOR		0.45
HOIST DIAMETER	mm	5520	HOIST/ROPE DIAMETER RATIO		120
EQUIV EQUIPMENT MASS	kg	474	MECHANICAL EFFICIENCY	%	95
T1/T2 RATIO, allowable		1.40	TAIL LOOP LENGTH	m	10
TOTAL SUSPENDED LOAD	kN	3160	HEADROPE/TAILROPE WT RAT		1.00
TREAD PRESSURE	kPa	2074	REVOLUTIONS/TRIP		57.7
T1/T2		1.15	T2/T3		1.14
		SIDE ONE			SIDE TWO
CONVEYANCE MASS	kg	60000			78167
PAYLOAD	kg	40370			
		HEADROPES			TAILROPES
NUMBER OF HEADROPES		6	NUMBER OF TAIL ROPES		6
ROPE TYPE		FLC			
ROPE STRENGTH	kN	1803			
ROPE DIAMETER	mm	46.00			
ROPE UNIT WEIGHT	kg/m	11.67			11.67
SAFETY FACTOR AT SHEAVE, STATUTO		6.34			
ACTUAL		6.41			

		RATE	TIME sec	DISTANCE m	ROPE LOADS STATIC SIDE 1 kN	STATIC SIDE 2 kN	ACC'L'N SIDE 1 kN	ACC'L'N SIDE 2 kN	HOIST EFFORT @ROPES kN	POWER kw	T1/T2
ACCELERATE TO CREEP	m/s/s	0.25	2.00	0.50	1689	1471	43	-37	318	955	1.21
					1689	1471	43	-37	318	955	1.21
CREEP	m/sec	0.5	0.00	0.00	1689	1471			238	713	1.15
					1689	1471			238	713	1.15
ACCELERATE TO RUN	m/s/s	0.25	10.00	17.50	1689	1471	43	-37	318	955	1.21
					1689	1471	43	-37	318	955	1.21
RUN	m/sec	3	320.67	962.00	1689	1471			238	713	1.15
					1689	1471			238	713	1.15
DECELERATE TO CREEP	m/s/s	0.25	10.00	17.50	1689	1471	-43	37	157	472	1.09
					1689	1471	-43	37	157	472	1.09
CREEP	m/sec	0.5	4.00	2.00	1689	1471			238	713	1.15
					1689	1471			238	713	1.15
DECELERATE TO STOP	m/s/s	0.25	2.00	0.50	1689	1471	-43	37	157	472	1.09
					1689	1471	-43	37	157	472	1.09
LOAD/UNLOAD			60.00								
TOTAL			408.67	1000.00							
							POWER, fan-cooled			661	
							self-cooled			694	

JR MORRIS ENGINEERING
FRICTION HOIST DESIGN PROGRAM

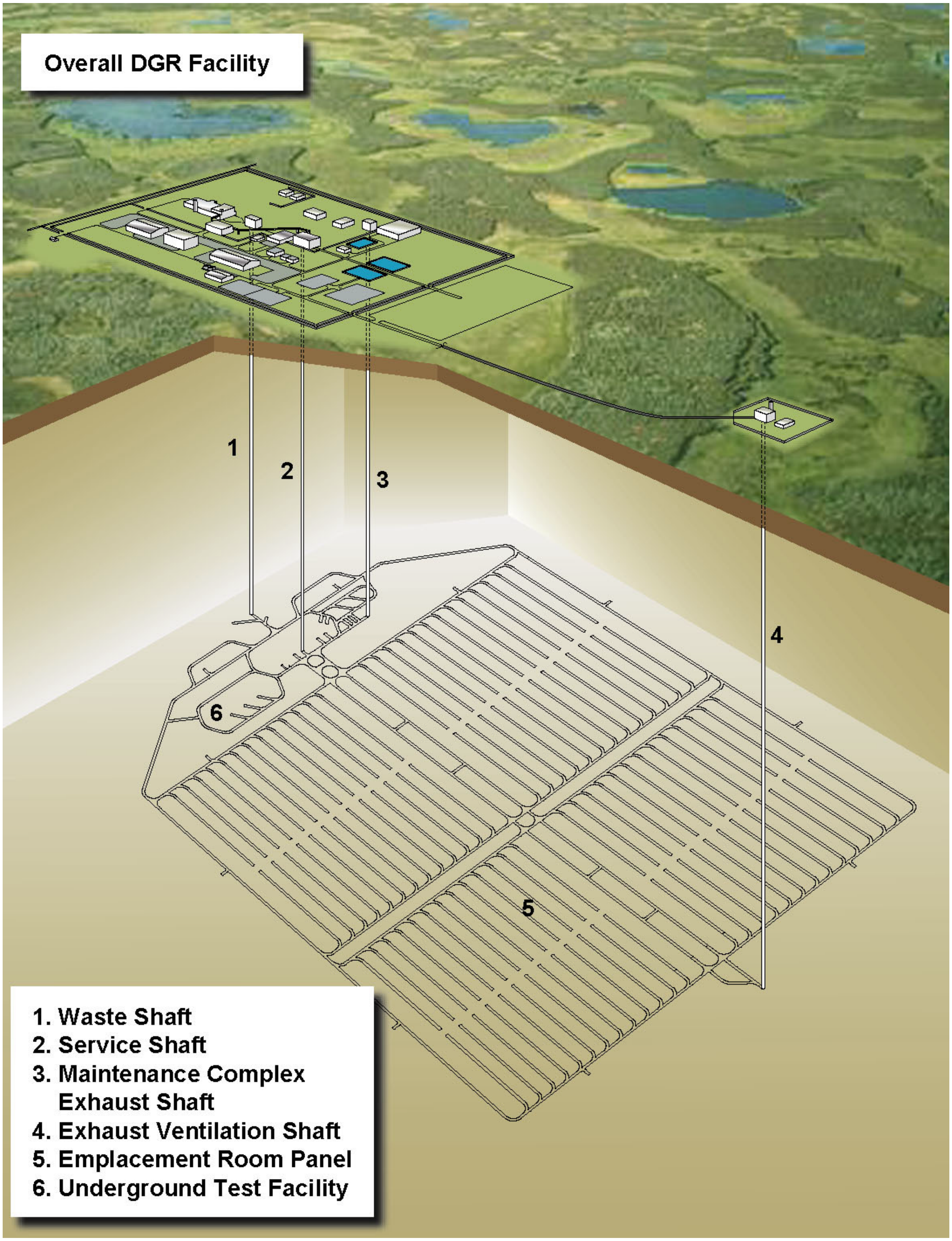
CASE:	OGP-DGR LOWERING WASTE CASK ON RAIL CAR			DATE:	02-Jul-02
REFERENCE NUMBER:	02SNC-C				

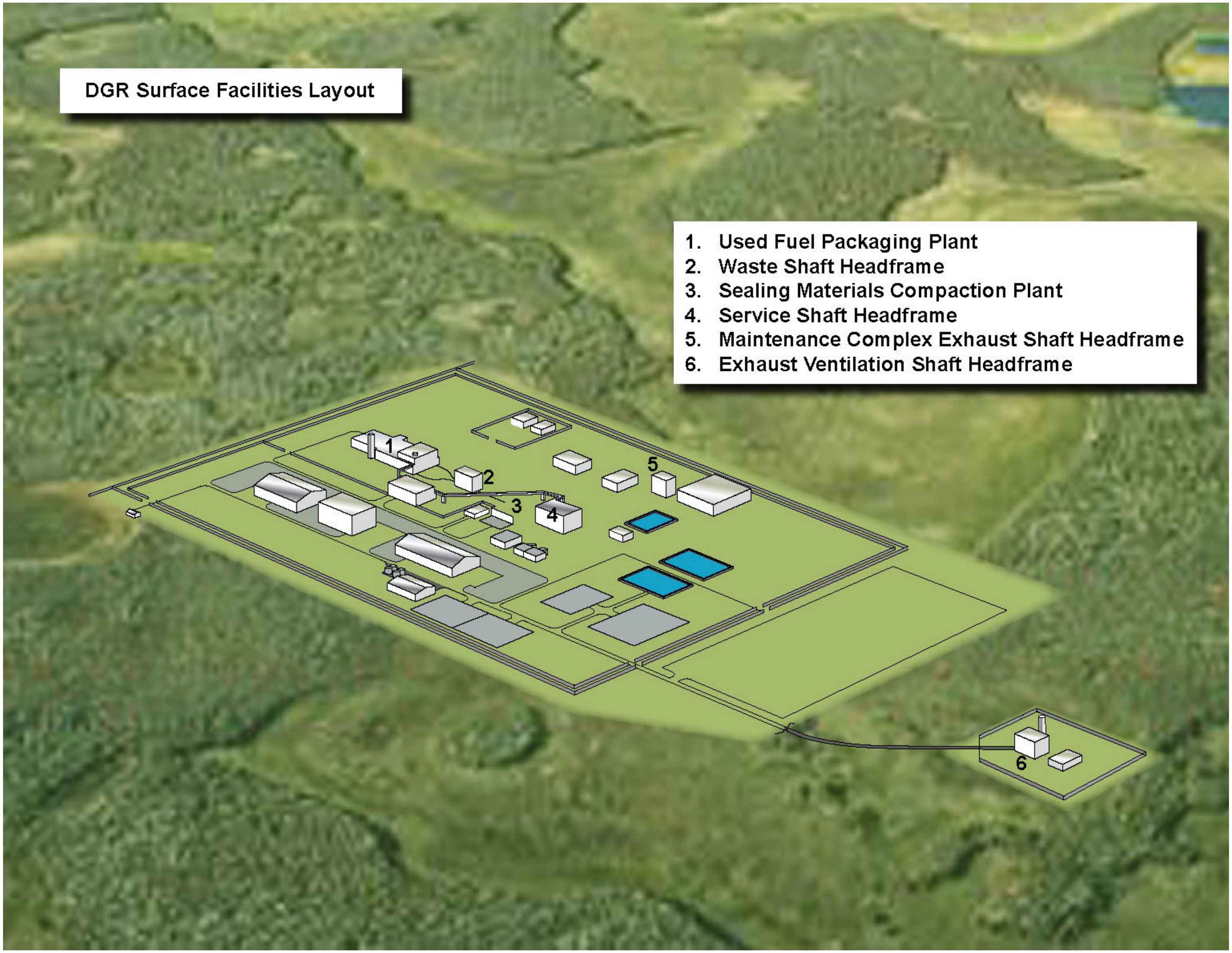
SYSTEM TYPE:		Counterweighted Cage			
PRODUCTION RATE	tonnes/hour	NA	PRODUCTIVITY FACTOR		1
HOISTING DISTANCE	m	1000	MINIMUM CONVEY'CE TARE FACTOR		0.4
SUSPENDED ROPE LENGTH	m	1015	COUNTERWEIGHT FACTOR		0.4
HOIST DIAMETER	mm	6210	HOIST/ROPE DIAMETER RATIC		115
EQUIV EQUIPMENT MASS	kg	601	MECHANICAL EFFICIENCY	%	95
T1/T2 RATIO, allowable		1.40	TAIL LOOP LENGTH	m	10
TOTAL SUSPENDED LOAD	kN	4003	HEADROPE/TAILROPE WT RAT		1.00
TREAD PRESSURE	kPa	1990	REVOLUTIONS/TRIP		51.3
T2/T3		1.33	T2/T3		1.28
		SIDE ONE		SIDE TWO	
CONVEYANCE MASS	kg	38060			76120
PAYLOAD	kg	95150			
		HEADROPES		TAILROPES	
NUMBER OF HEADROPES		6	NUMBER OF TAIL ROPES		6
ROPE TYPE		FLC			
ROPE STRENGTH	kN	2472			
ROPE DIAMETER	mm	54.00			
ROPE UNIT WEIGHT	kg/m	16.16			16.16
SAFETY FACTOR AT SHEAVE, STATUTOI		6.34			
ACTUAL		6.50			

					ROPE LOADS STATIC SIDE 1		ACC'L'N		HOIST EFFORT	POWER	
		RATE	TIME	DISTANCE	SIDE 1	SIDE 2	SIDE 1	SIDE 2	@ROPES		T1/T2
			sec	m	kN	kN	kN	kN	kN	kw	
ACCELERATE TO CREEP	m/s/s	0.25	2.00	0.50	2282	1722	58	-44	709	2127	1.39
					2282	1722	58	-44	709	2127	1.39
CREEP	m/sec	0.5	0.00	0.00	2282	1722			607	1820	1.33
					2282	1722			607	1820	1.33
ACCELERATE TO RUN	m/s/s	0.25	10.00	17.50	2282	1722	58	-44	709	2127	1.39
					2282	1722	58	-44	709	2127	1.39
RUN	m/sec	3	320.67	962.00	2282	1722			607	1820	1.33
					2282	1722			607	1820	1.33
DECELERATE TO CREEP	m/s/s	0.25	10.00	17.50	2282	1722	-58	44	505	1515	1.26
					2282	1722	-58	44	505	1515	1.26
CREEP	m/sec	0.5	4.00	2.00	2282	1722			607	1820	1.33
					2282	1722			607	1820	1.33
DECELERATE TO STOP	m/s/s	0.25	2.00	0.50	2282	1722	-58	44	505	1515	1.26
					2282	1722	-58	44	505	1515	1.26
LOAD/UNLOAD			60.00								
TOTAL			408.67	1000.00							
								POWER, fan-cooled		1683	
								self-cooled		1767	

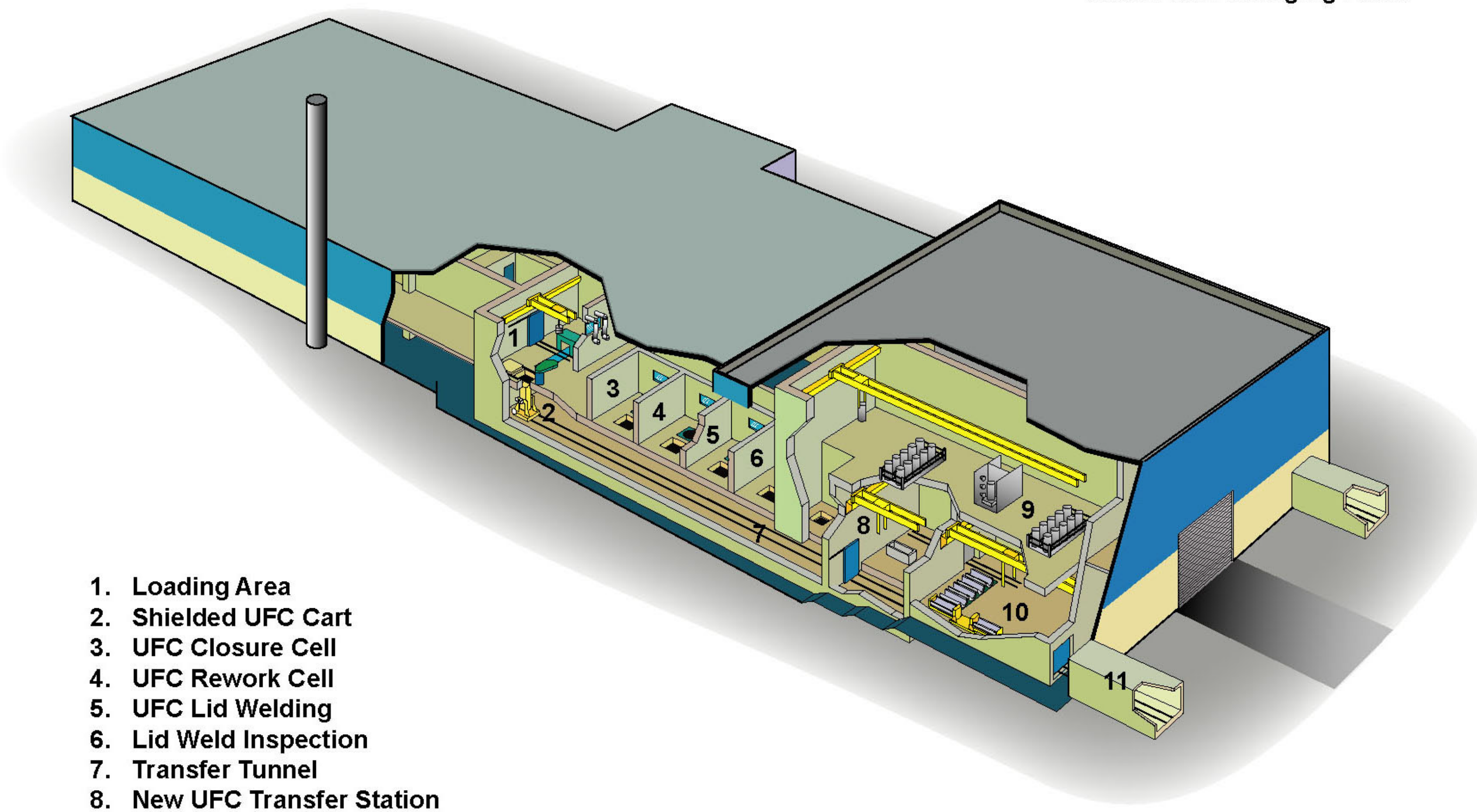
OPG-DGR Hoisting Tradeoff Estimates
Marginal Cost Basis
February
12,2002

	SHAFT			HOIST ELECTRICAL			HOIST MECHANICAL			HOIST TOTAL	CAGE & CWT			ROPES & ATTACHMENTS			UFC/BJ HANDLING	TOTAL MARGIN	MARGINAL DIFF
CASE	Area	Unit $	Marginal Cost $'000	kw	Unit $	Marginal Cost $'000	eem	Unit $	Marginal Cost $'000		Weight, kg	Unit $	Marginal Cost $'000	Rope wt kg	Unit $	Marginal Cost $'000	CRANES, EXCAVATION, STRUCTURE	$'000	$'000
1	35.8	400	4,120	1420	300	273	61215	40	1397520	1671	114180	8	494	223000	5.45	460	0	6744	4600
2	28.7		1,195	510		0	26277		0	0	52480		0	138550		0	950	2145	0
3	30.3		1,854	558		14	48312		881400	896	138167		685	161050		123	410	3968	1823
4	25.8		0	1418		272	61165		1395520	1668	114000		492	223000		460	460	3080	936
5	27.8		824	1291		234	58093		1272640	1507	112600		481	211140		396	0	3208	1063

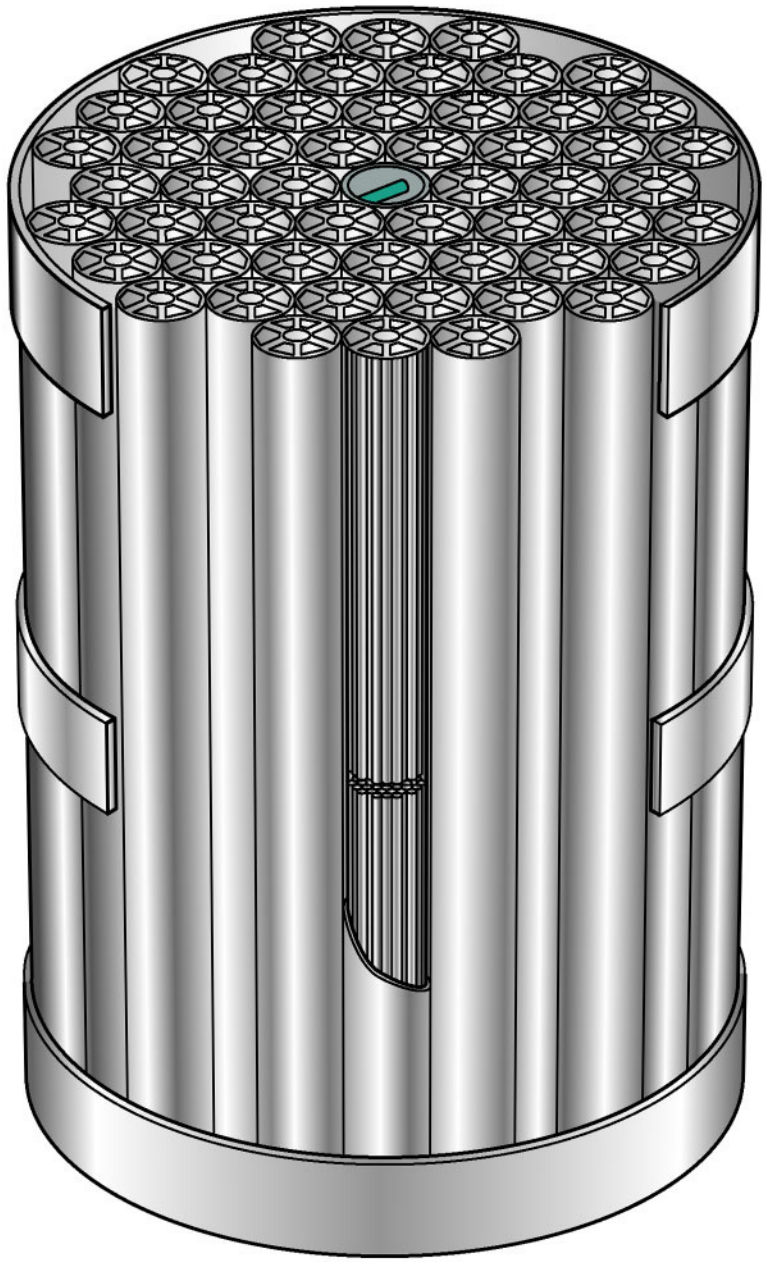

Overall DGR Facility
1
2
3
4
5
6
1. Waste Shaft
2. Service Shaft
3. Maintenance Complex Exhaust Shaft
4. Exhaust Ventilation Shaft
5. Emplacement Room Panel
6. Underground Test Facility


DGR Surface Facilities Layout
1. Used Fuel Packaging Plant
2. Waste Shaft Headframe
3. Sealing Materials Compaction Plant
4. Service Shaft Headframe
5. Maintenance Complex Exhaust Shaft Headframe
6. Exhaust Ventilation Shaft Headframe
1
2
3
4
5
6

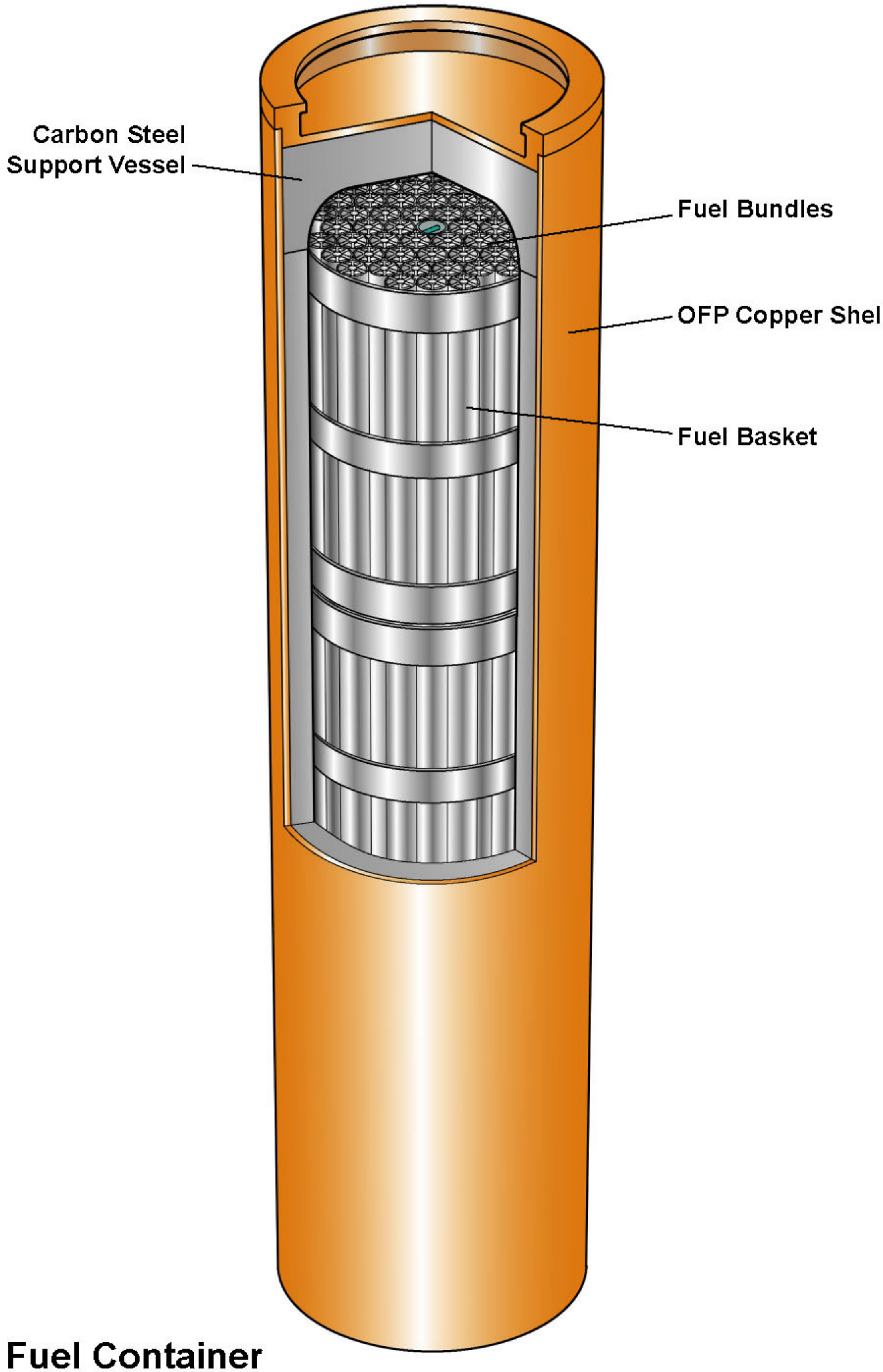
Used Fuel Packaging Plant



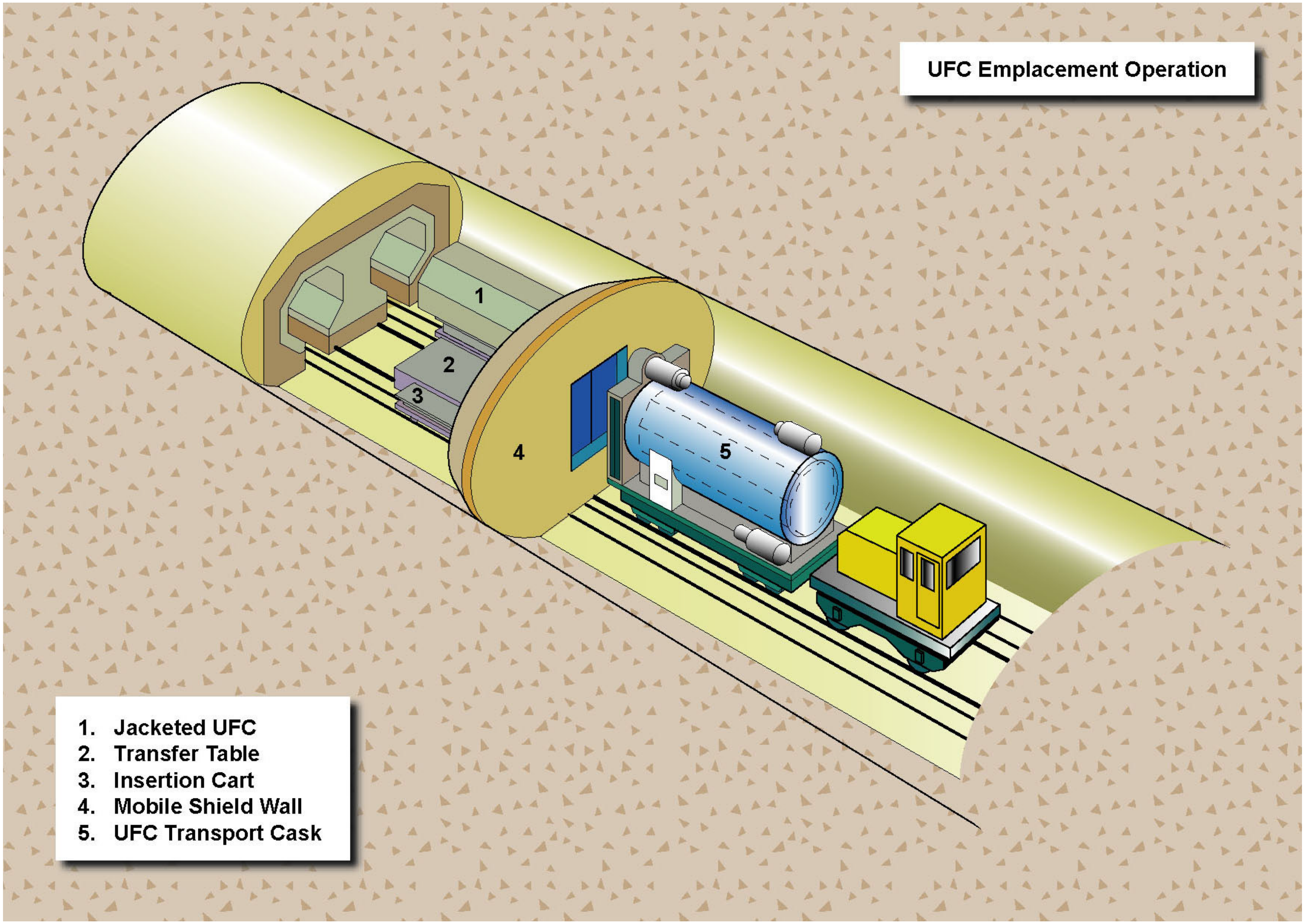
1. Loading Area
2. Shielded UFC Cart
3. UFC Closure Cell
4. UFC Rework Cell
5. UFC Lid Welding
6. Lid Weld Inspection
7. Transfer Tunnel
8. New UFC Transfer Station
9. UFC Decontamination
10. UFC Jacketing Area
11. UFC Export Tunnel

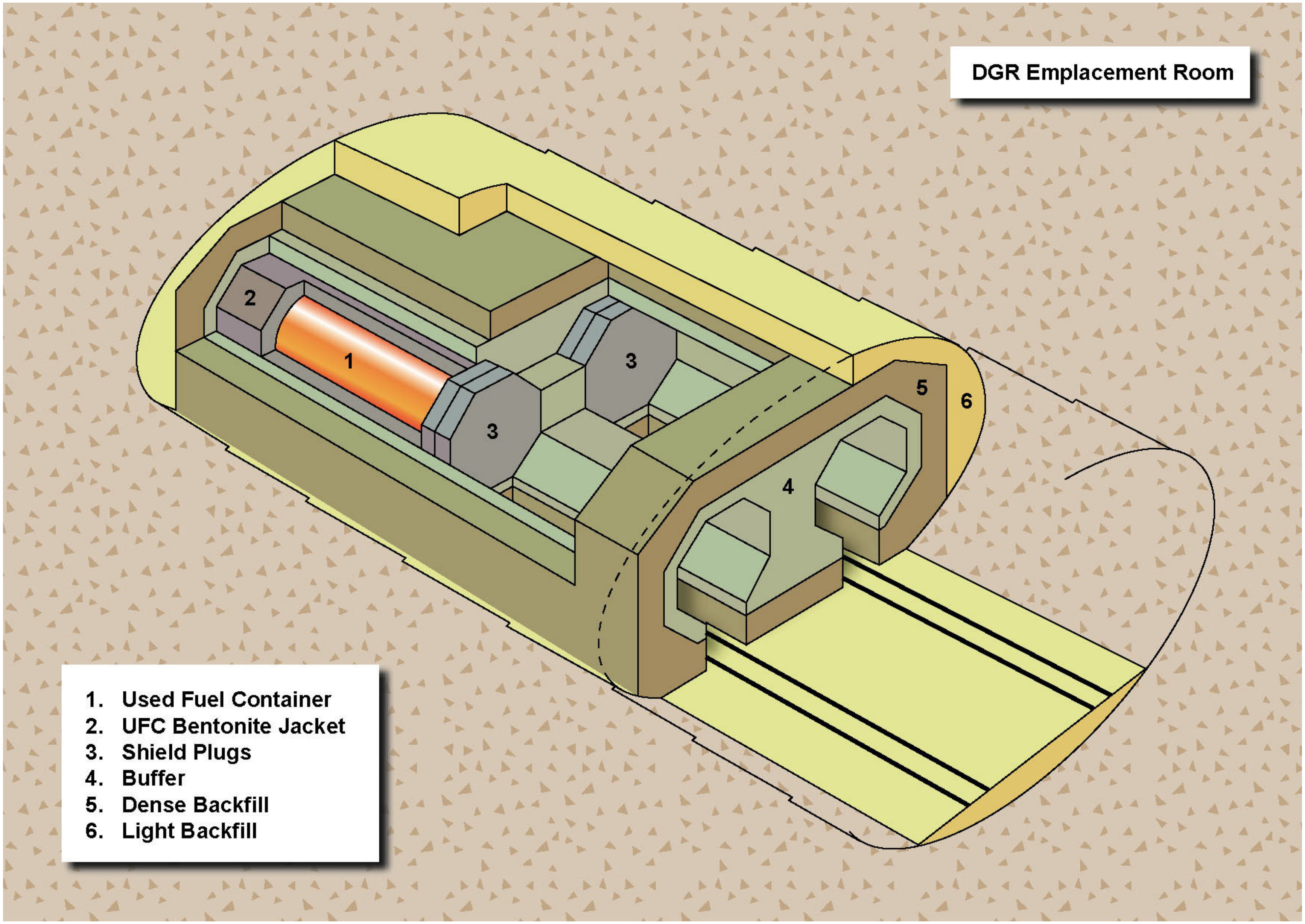


108-bundle Basket
for the Used Fuel Container



Used Fuel Container


UFC Emplacement Operation
1
2
3
4
5
1. Jacketed UFC
2. Transfer Table
3. Insertion Cart
4. Mobile Shield Wall
5. UFC Transport Cask



DGR Emplacement Room
1
2
3
3
4
5
6
1. Used Fuel Container
2. UFC Bentonite Jacket
3. Shield Plugs
4. Buffer
5. Dense Backfill
6. Light Backfill