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

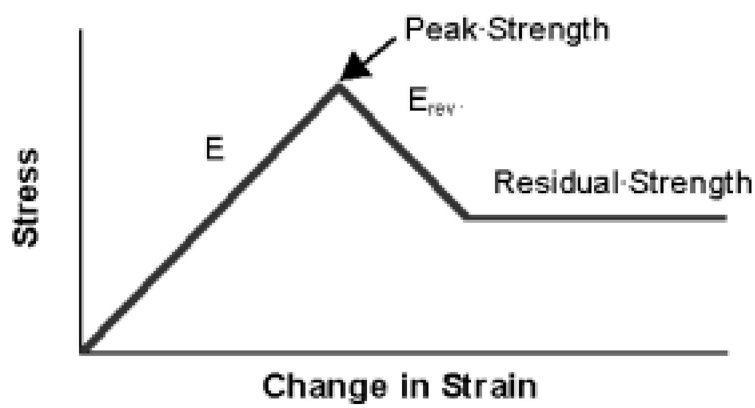
3. to check overall stability conditions during excavation of clay-based sealing materials to retrieve one or more containers, at various times after emplacement.

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:

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

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

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

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

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:

$$\sigma_{H'\text{far-field}} = 109.5 \text{ MPa} \quad \sigma_{h'\text{ far-field}} = 94 \text{ MPa} \text{ and } \sigma_{V'\text{ far-field}} = 70.5 \text{ MPa}$$

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., $\sigma_{H'\text{ far-field}}$ = 109.5MPa = ($\sigma_{H\text{ initial far-field}}$ = 65 MPa) + ($\Delta\sigma_{\text{ Thermal}}$ = 44.5 MPa) and $\sigma_{V'\text{ far-field}}$ = 70.5 MPa = ($\sigma_{V\text{ initial far-field}}$ = 26 MPa) + ($\Delta\sigma_{\text{ Thermal}}$ = 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:

$$\text{Pillar Stress (MPa)} = \gamma \times z \times (1 + \frac{Wo}{Wp})$$

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) ≅ 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

Annex 2 - Ontario Power Generation - Deep Geologic Repository Project - Abaqus Thermal Stress Analysis Report.

Annex 4 - SNC (2002). Ontario Power Generation - Deep Geologic Repository Project - Mining Method Discussion Paper. Report prepared by SNC-Lavalin, April 2002.

Anderson, J.A., Strom, C. Svemar and K-E Almen (2000). What requirements does the KBS-3 repository make on the host rock? Technical report TR-00-12. SKB, Stockholm.

Baumgartner, P.; Bilinsky, D.M.; Ates, Y.; Read, R.S.; Croshtwaite, J.L.; Dixon, D.A. (1996). Engineering for a Disposal Facility Using the In-Room Emplacement Method. AECL report # 11595, COG 96-223.

JNC (200). H12: Project to establish the Scientific and Technical Basis for HLW Disposal in Japan. Supporting Report 1, Geological Environment in Japan. Technical report JNC TN1410 2000-02. JNC, Tokyo, Japan.

Hoek, E., and Brown, E.T. (1988). The Hoek-Brown Failure Criterion - a 1988 update. In Rock Engineering for Underground Excavations. Proc. 15th Canadian Rock Mechanics Symposium (ed. J. Curran), 31-38. Toronto.

Martin, C.D. (1990). Characterizing In Situ Stress Domain at the AECL Underground Research Laboratory. Canadian Geotechnical Journal 27, 631-646.

Martin, D.R., Christiansson and J. SÖderhÄll (2001). Rock stability considerations for siting and constructing a KBS-3 repository based on experiences from ÄspÖ, HRL. AECL's URL, tunnelling and mining. Technical report TE-01-38. SKB, Stockholm.

OPG (2001). Technical Specification for Updating the Conceptual Design and Cost Estimate for a Deep Geologic Repository for Used Nuclear Fuel. Document # 06819-UFM-03789-0001 R00.

OPG (2001a). Cost Estimate for a Disposal Facility for Used Fuel Owned by Ontario Power Generation, New Brunswick Power, Hydro Québec and Atomic Energy of Canada Ltd. Ontario Power Generation (OPG) report #: 06819-Rep-00400-10012 R00.

Read, R.S. (1994). Interpreting Excavation-Induced Displacements Around a Tunnel in Highly Stressed Granite. Ph.D. Thesis, Department of Civil and Geological Engineering, University of Manitoba, Winnipeg, Manitoba.

Simmons, G.R.; Baumgartner, P. (1994). The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility. AECL report # 10715, COG 93-5.

Stanchell, F.W., Davison, C.C., Melnyk, T.W., Scheier, N.W., and T. Chan (1996). The Disposal of Canada's Nuclear Fuel Waste: A study of post closure safety of in-room emplacement of used CANDU fuel copper containers in permeable plutonic rock. Vol. 3: Geosphere Model, Atomic Energy of Canada Ltd. Report, AECL - 11494-3, COG - 95-552-3.

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)

$\sigma_2 = 0.1112$ MPa/m + 9.9 MPa, from **0 to 300 m** $\sigma_2 = 0.00866$ MPa/m + 40.7 MPa, from **300 to 1660 m** and $\sigma_2 = 0.0293$ MPa/m + 6.4 MPa, **greater than 1660 m**

$\sigma_1 = 0.1345$ MPa/m + 18.5 MPa from **0 to 300 m** $\sigma_1 = 0.00866$ MPa/m + 56.3 MPa, from **300 m to 1400 m**; and $\sigma_1 = 0.0403$ MPa/m + 12.1 MPa, **greater than 1400 m**

where σ_v = vertical stress; and

σ_1, σ_2, σ_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.

REFERENCES

Anderson, J.A., Strom, C. Svemar and K-E Almen (2000). What requirements does the KBS-3 repository make on the host rock? Technical report TR-00-12. SKB, Stockholm.

Baumgartner, P.; Bilinsky, D.M.; Ates, Y.; Read, R.S.; Croshtwaite, J.L.; Dixon, D.A. (1996). Engineering for a Disposal Facility Using the In-Room Emplacement Method. AECL report # 11595, COG 96-223.

JNC (200). H12: Project to establish the Scientific and Technical Basis for HLW Disposal in Japan. Supporting Report 1, Geological Environment in Japan. Technical report JNC TN1410 2000-02. JNC, Tokyo, Japan.

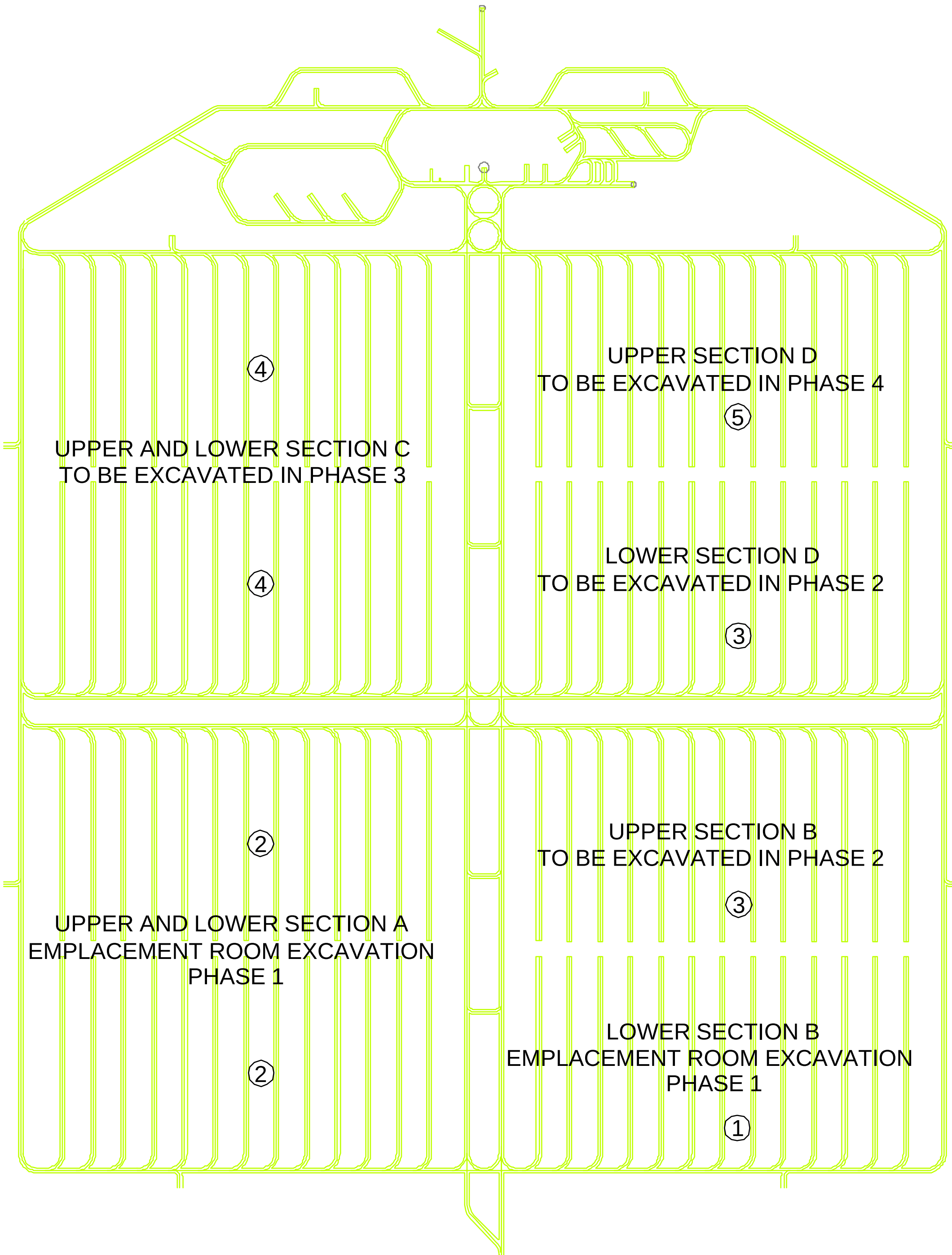
Martin, D.R., Christiansson and J. Söderhäll (2001). Rock stability considerations for siting and constructing a KBS-3 repository based on experiences from Äspö, HRL. AECL's URL, tunnelling and mining. Technical report TE-01-38. SKB, Stockholm.

Stanchell, F.W., Davison, C.C., Melnyk, T.W., Scheier, N.W., and T. Chan (1996). The Disposal of Canada's Nuclear Fuel Waste: A study of post closure safety of in-room emplacement of used CANDU fuel copper containers in permeable plutonic rock. Vol. 3: Geosphere Model, Atomic Energy of Canada Ltd. Report, AECL - 11494-3, COG - 95-552-3.

Simmons, G.R.; Baumgartner, P. (1994). The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility. AECL report # 10715, COG 93-5.

TYPICAL SECTION EXCAVATION AND WASTE EMPLACEMENT SEQUENCE

FIGURE 1



1 EMPLACEMENT SEQUENCE

REV. 1

DATE: NOVEMBER 2002

PROJECT: 011-1667

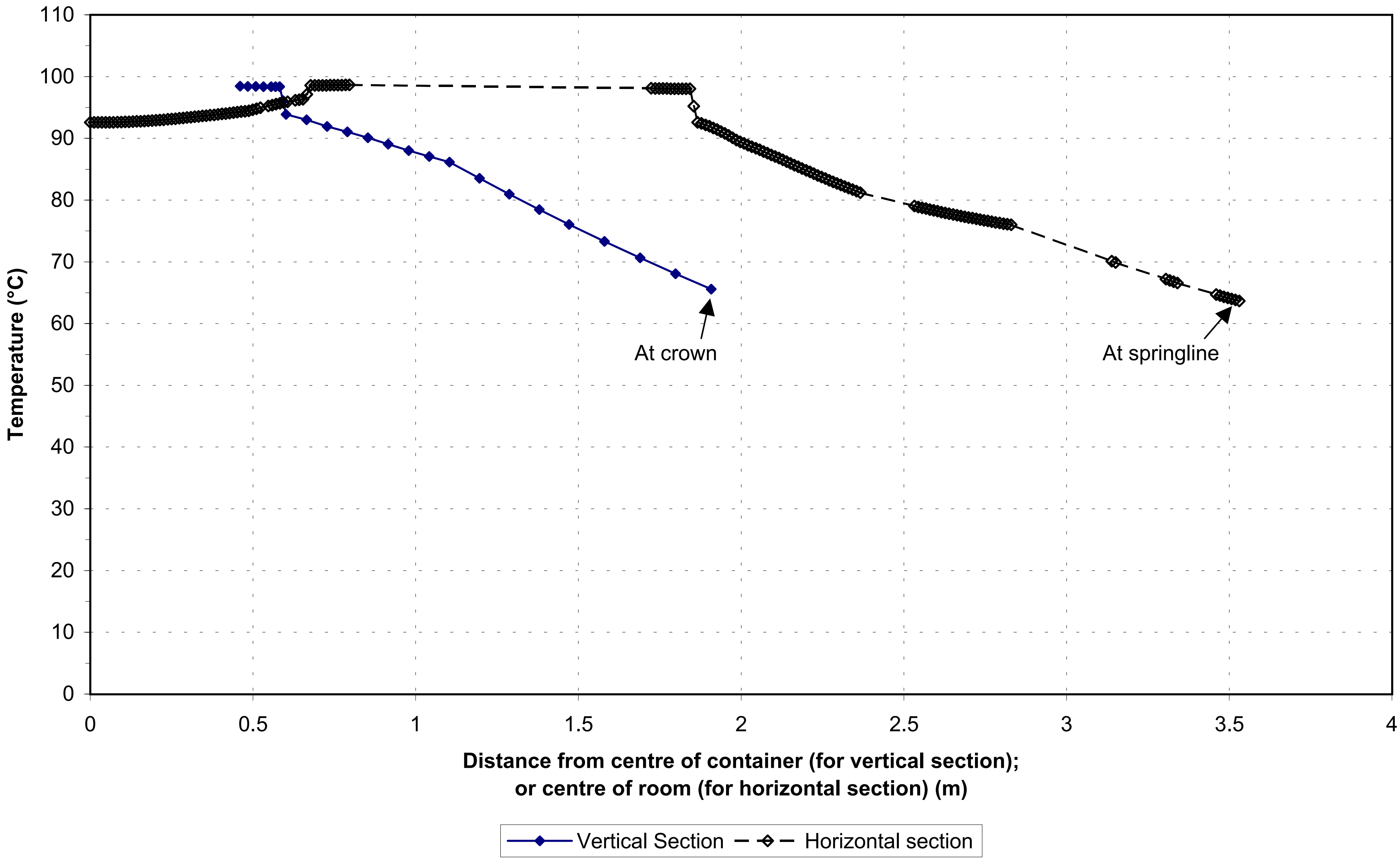
Golder Associates

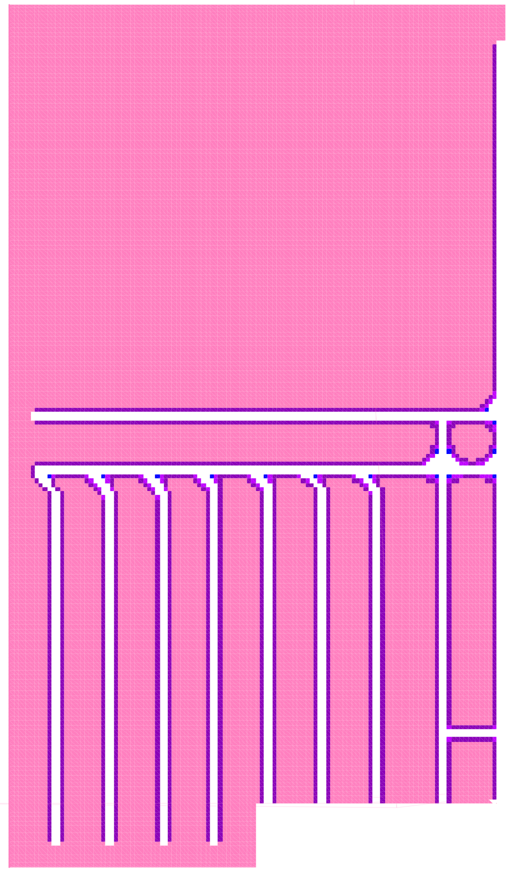
CAD: PS

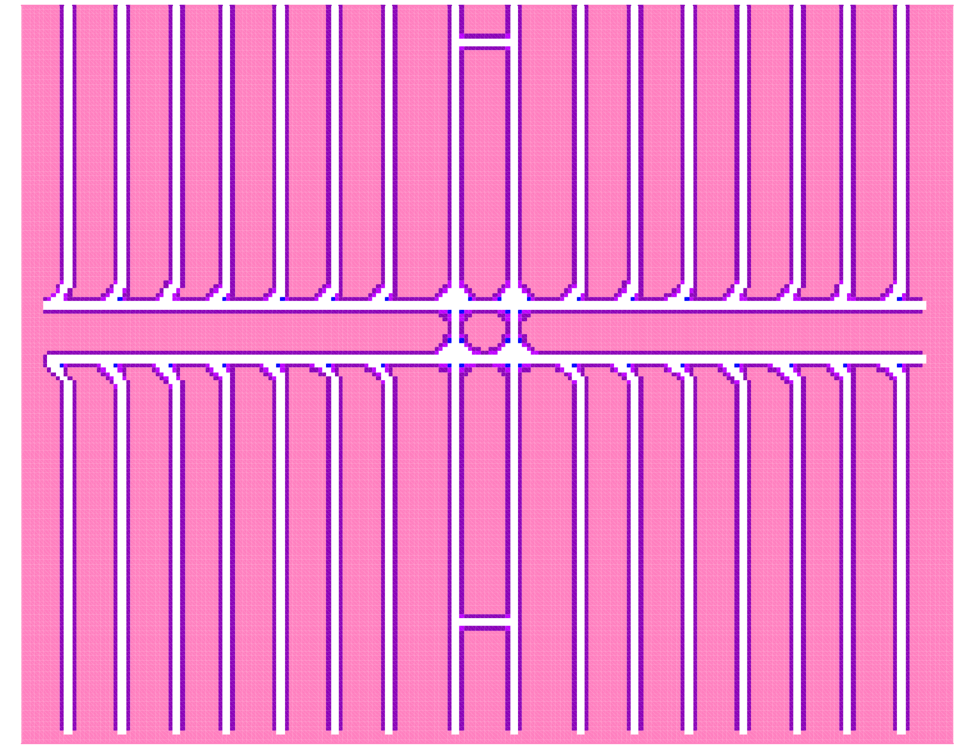
CHK:

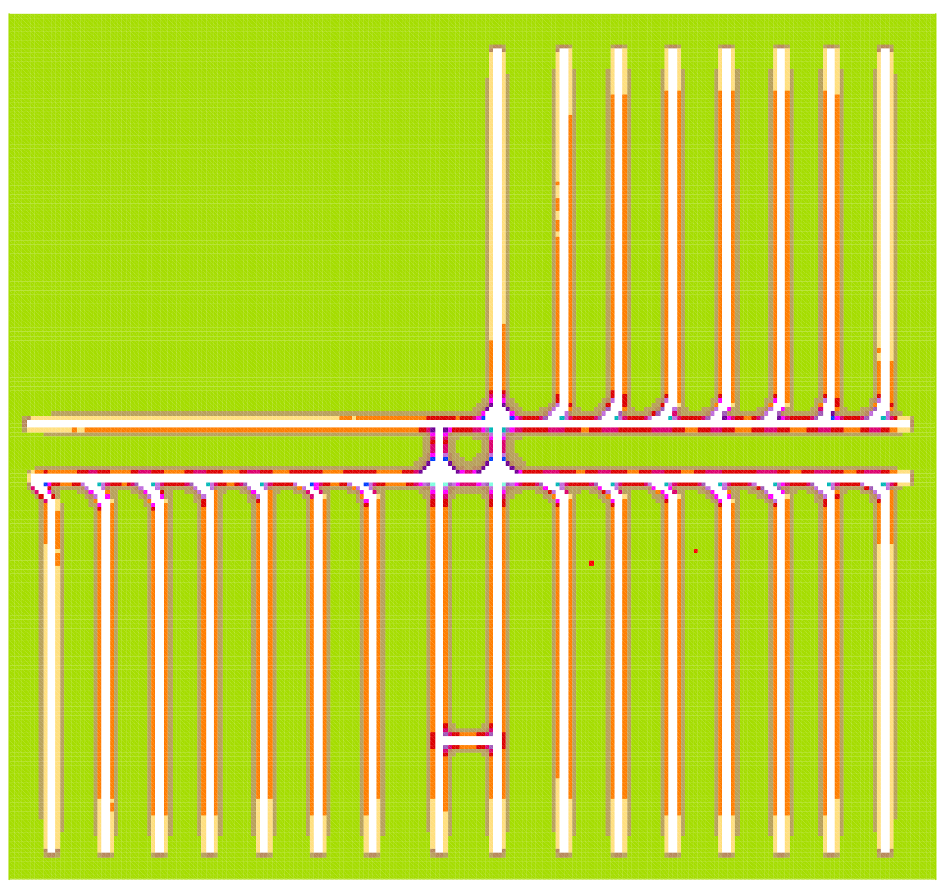
PLOT DATE: November 01, 2002
FILENAME: T:\Projects\2001\011-1667\RNOV2002\Q1667001a.dwg

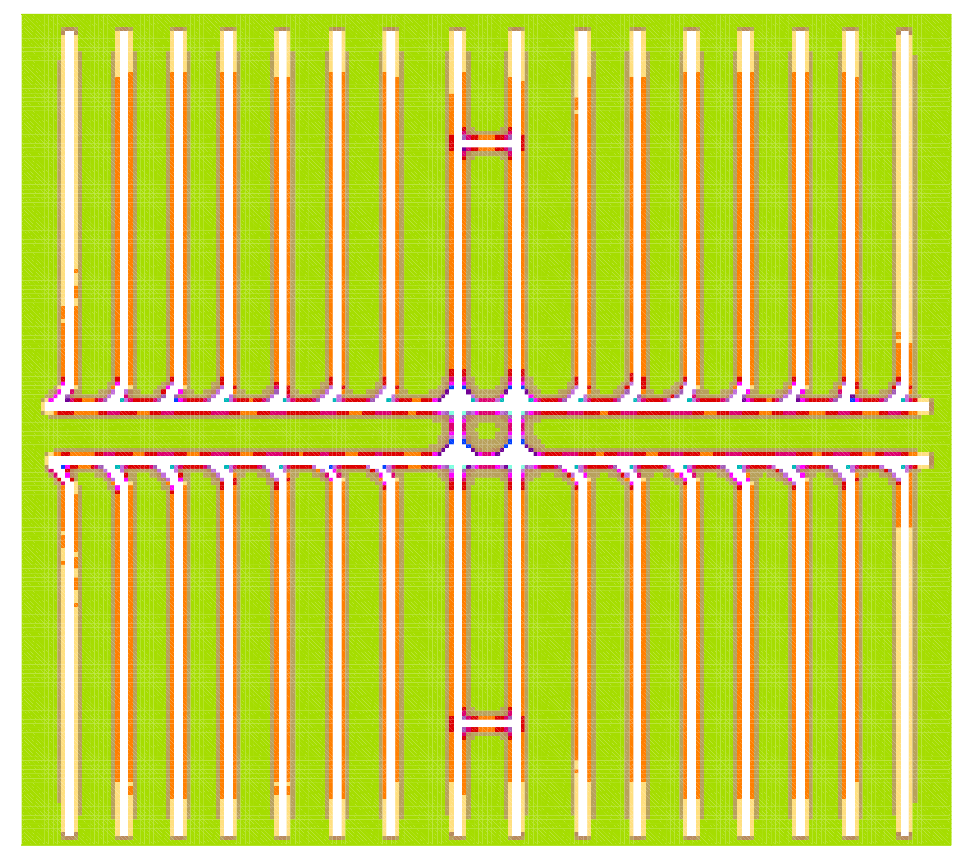
FIGURE 2: TEMPERATURE VERSUS DISTANCE AFTER 20 YEARS (modified buffer properties)

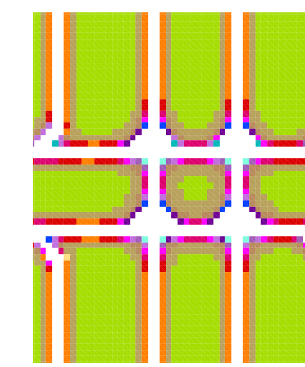


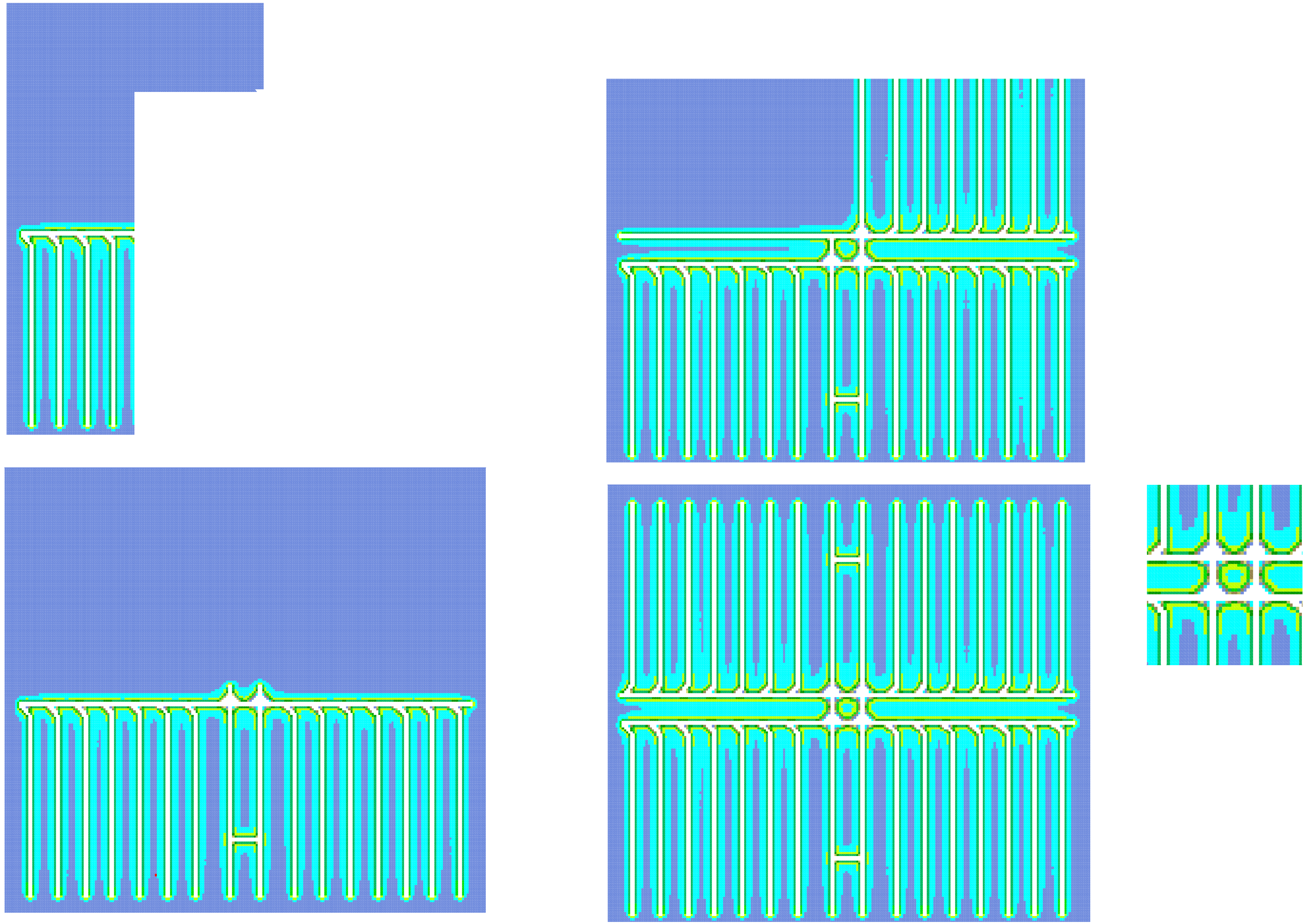


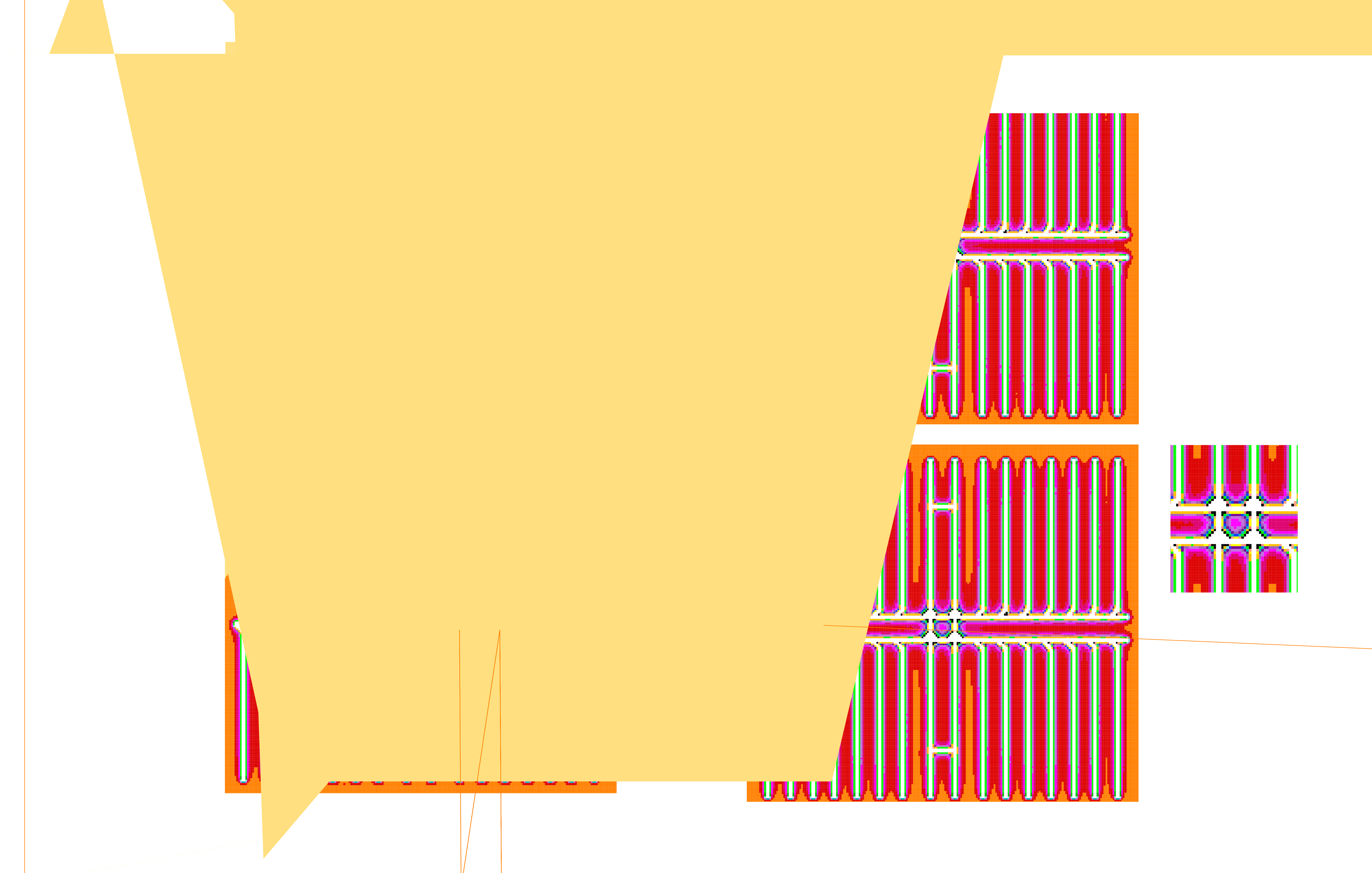












STEP 4 - PHASE 3. EXCAVATION AND FILLING OF SEWER SECTION C