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Scoping Thermal Analysis of Alternative Dual-Purpose Canister Disposal Concepts

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SCOPING THERMAL ANALYSIS OF ALTERNATIVE DUAL-PURPOSE CANISTER DISPOSAL CONCEPTS

Used Fuel Disposition Campaign

Dual Purpose Canisters

(Work Package FT-13LL081609)

Level 4 Milestone (M4): M4FT-13LL0816091

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Revision History

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- Original document.

Tables

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Acronyms

32P	32 assembly PWR (32-PWR) waste package
BU	Burnup (GWd/MT)
CIS	Central Interim Storage Facility
DOE	U.S. Department of Energy
DPC	Dual-Purpose Canister (for storage and transportation)
DSEF	Disposal Systems Evaluation Framework
Dr Sp	Drift / borehole spacing (m)
EBS	Engineered Barriers System
FY	Fiscal Year
GWd/MT	Gigawatt (thermal) - days per Metric Ton
IHLRWM	International High-Level Radioactive Waste Management (Conference)
LLNL	Lawrence Livermore National Laboratory
MT	Metric Ton (used interchangeably with MTHM, MTIHM and MTU)
MTIHM	Metric Ton of Initial Heavy Metal
MTHM	Metric Tons of Heavy Metal
MTU	Metric Tons of Uranium
NE	DOE-Nuclear Energy
PWR	Pressurized Water Reactor
Src	Source (used on figures for central heat source)
TC	Temperature acceptance criterion (°C)
t-store	Surface storage time (years), sometimes referred to using the Mathcad variable name (t_store)
UFD	Used Fuel Disposition
WP	Waste Package
WP Sp	Waste package spacing (m)

Nomenclature

Cp	specific heat, J/kg-K
k	thermal conductivity, W/m-K
L	characteristic length, m
$q(t)$	continuous heat generation rate of the point source, W
$qL(t)$	continuous line heat source, W/m
r	radial distance, m
R	thermal resistance, m-K/W
t	time, s
t'	integration variable for convolution integral
T	temperature, K
α	thermal diffusivity, $m^2/s = k/(\rho\text{-}Cp)$
ρ	density, kg/m

1. **Introduction**

This Lawrence Livermore National Laboratory (LLNL) report is a Level 4 milestone deliverable M4FT-13LL081609 “Scoping Thermal Analysis of Alternative DPC Disposal Concepts”, which is a supporting document to a Level 2 Sandia National Laboratories milestone, M2FT-13SN0816112 "Preliminary Report on DPC Disposal Alternatives". For this study a 32-PWR package size is used as a bounding envelope surrogate for existing dual-purpose canisters (DPC), plus a 5-cm disposal overpack.

Abstract

This report evaluates the feasibility of disposing of large DPCs in a clay/shale geologic environment. It utilizes the thermal-analytical models developed over the past two years as part of the Disposal Systems Evaluation Framework (DSEF). It evaluates waste streams representative of existing SNF waste streams (at 40-GWd/MT burnup) and potential future waste streams (at 60 GWd/MT burnup). The analyses cover ventilated (open) repository concepts in clay/shale, where backfill may or may not be added to emplacement drifts at closure. The results show that repository concepts which meet a design thermal constraint of TC = 100°C at the drift wall are feasible with large drift spacing (70 to 90 m) and large waste package (WP) spacing (20 to 40 m).

Background

The trade studies presented in this report were facilitated by the results of a series of thermal modeling and thermal performance parametric sensitivity studies developed over a two-year period in Sutton (2011), Greenberg (2012a and 2012b), and utilized in Hardin (2011 and 2012) that evaluated both “enclosed” and “open” repository design concepts. The “enclosed mode” studies evaluated a range of repository design concepts derived from international repository programs in salt, clay/shale (sedimentary), granite (crystalline, hard rock), and deep-borehole (crystalline basement) environments for spent nuclear fuel (SNF) waste packages ranging in capacity from 1 to 12-PWR assemblies, and waste forms from once-through, partial recycle, and full recycle fuel cycles. The “open mode” studies evaluated repository design concepts in salt, sedimentary, and crystalline environments for larger waste SNF packages ranging from 4 to 32-PWR fuel assemblies. The 2012 analyses performed some sensitivity study calculations for the 32-PWR sized waste packages, but the reference repository design concepts were based on 4, 12, and 21-PWR assembly waste package capacities. The sensitivity studies contained in those reports pointed the way for the repository thermal analyses conducted in 2013 which identified potentially viable design options for 32-PWR capacity waste packages in several geologic media.

In 2013, previously developed modeling and analysis techniques were applied to study potential design concepts for the disposal of large dual-purpose canisters, which extended the analyzed waste package capacity to 32-PWR assemblies. Hardin (2013a) evaluated the following design alternatives:

- Crystalline Rock Enclosed Emplacement Concepts for HLW or SNF
- Generic Salt Repository Concepts for HLW or SNF
- Clay/Shale Enclosed, Borehole Emplacement Concept

- Sedimentary Unbackfilled, Open, In-Drift Emplacement Concepts for SNF
- Sedimentary Backfilled, Open, In-Drift Emplacement Concept for SNF
- Hard-Rock Open, In-Drift Emplacement Concepts for SNF
- Cavern-Retrievable Storage and Disposal Concept for SNF

LLNL also conducted thermal analyses of 32-PWR waste packages in sedimentary (clay/shale) open repository concepts in 2013 (Greenberg 2013a and 2013b), which examined the sensitivity of the required ventilation time to meet various thermal acceptance temperature criteria as a function of waste package (WP) and drift spacing.

Objective:

Explore repository layout concepts for large (32-PWR) WP disposal in a clay/shale host environment to minimize the layer of host rock around the emplacement drift that exceeds a defined set of thermal acceptance criteria. The primary temperature acceptance criteria (TC) considered in this study is 100°C, which would keep the host rock below the boiling point (for a pressure of 1 bar). Above 100°C, loss of inter-layer water may occur, potentially resulting in a change in the fracture pathways. A TC = 120°C criterion is also examined because temperatures significantly in excess of 120°C may cause chemical changes in the clay that alter sorption and desorption properties.

This report supplements and complements the analysis in Sections 4 and 5 of Hardin 2013a (Sedimentary Unbackfilled, Open, In-Drift Emplacement Concepts for SNF; and Sedimentary Backfilled, Open, In-Drift Emplacement Concepts for SNF), which assumed a repository layout with 70 m drift spacing and 20 m waste package spacing, and evaluated two repository operating modes – one with 50 years of surface storage and 100 years of ventilation, and another with 100 years of surface storage and 200 years of ventilation.

Assumptions:

- Clay/shale with host rock thermal conductivity of 1.75 W/m-K
- 32-PWR WPs with burnup of 40 GWd/MT and 60 GWd/MT
- 50 year surface storage
- 25, 50, 75, and 100 years ventilation time (after the end of surface storage) for the 40 GWd/MT analysis, and 150 years of ventilation for the 60 GWd/MT analysis
- 75% ventilation system thermal (heat removal) efficiency
- 70 m drift spacing for the 40 GWd/MT analysis; 70 and 90 m for the 60 GWd/MT analysis

Approach:

The Disposal Systems Evaluation Framework (DSEF) Mathcad thermal analytical component is used to analyze the design cases. The parametric sensitivity study capability of DSEF is used, which enables evaluating 10 different WP spacings at a time for a given combination of ventilation time and drift spacing.

Figure 1 shows the repository layout thermal model components. Each analysis case provides the peak temperature and transient temperature at the drift wall (compliance point $r = r_{DW}$, the radius of the drift wall), and at another location arbitrarily selected for analysis purposes, compliance point 2 (CP2) within the host rock. Figure 2 is a scale drawing of a cross-section of an emplacement drift showing the waste package, drift wall, and the depth of the CP2 locations (1 to 5 m from the surface of the drift wall) in the host rock. To develop a temperature gradient profile, multiple analysis cases are run, varying the value of CP2 from 1 to 5 m distance into the host rock from the surface of the drift wall. Since the thermal analytical model relies on symmetry to simplify the calculations, the gradient is along a line perpendicular to the plane of the repository, centered above the central WP finite line source.

The DSEF Mathcad model approach uses two analytical heat transfer solutions. A transient "outside" model was developed assuming a homogeneous infinite medium to portray the temperature transient in the host rock, and a quasi-steady-state multi-layer cylindrical "inside" model was developed to represent the thermal response of the Engineered Barriers System (EBS). (Sutton 2011; Greenberg 2012c)

The "outside" model calculates a temperature transient, given decay heat data for the waste form, at the borehole or drift wall of a geologic repository by assuming the uniform infinite medium extends both inside and outside the "calculation radius". The "inside" model uses the temperature calculated by the "outside" model at the host rock wall surface in conjunction with the transient heat source, and calculates the thermal gradient through the EBS using a steady-state multilayer cylindrical model solution. This approach is reasonable because the thermal mass of the EBS components is much smaller than the infinite mass of host rock surrounding the EBS. There is a short (on the order of weeks or months) transient in the EBS components when the waste is initially placed in the repository. After that, the component temperatures follow the continuing temperature transient in the surrounding host rock, which slowly evolves because of its large thermal mass.

For the cases presented in this report, the temperature gradient in the host rock is calculated using the "outside" model. Consequently, it is independent of heat flow within the EBS components, including any influence of backfill thermal conductivity. The addition of backfill at closure is included in the Mathcad model, but it only affects the surface temperature of the EBS components, primarily the WP surface temperature.

The "outside" model consists of three transient component equations representing the repository layout shown in Figure 1. The rectangular coordinates used in the equations relate to Figure 1 as follows: y runs from left to right, x runs up and down on the page, and z is the direction perpendicular to the plane of the repository. The coordinates (0, 0, 0) correspond to the middle of the central WP.

Equation (1) models the contribution of a finite line source representing the central WP (where $y = 0$ at the center of the central WP), Equation (2) models the adjacent WPs (4 on either side of the central WP) in the same drift as point sources, and Equation (3) represents the adjacent drifts (4 on either side of the central drift) as infinite line sources. Note that the equations are shown in rectangular coordinates, where $r^2 = x^2 + y^2 + z^2$ for radial distances.

Equation (1):

$$T_{line}(t,x,y,z) = \frac{1}{8\cdot\pi\cdot k}\cdot\int_0^t \frac{q_L(t')}{t-t'}\cdot e^{\frac{-\left(x^2+z^2\right)}{4\cdot\alpha\cdot(t-t')}}\cdot\left[\operatorname{erf}\left[\frac{1}{2}\cdot\frac{\left(y+\frac{L}{2}\right)}{\sqrt{\alpha\cdot(t-t')}}\right]-\operatorname{erf}\left[\frac{1}{2}\cdot\frac{\left(y-\frac{L}{2}\right)}{\sqrt{\alpha\cdot(t-t')}}\right]\right]dt'$$

Equation (2):

$$T_{point}(t,r) = \frac{1}{8\cdot\rho\cdot Cp\cdot(\pi\cdot\alpha)^{\frac{3}{2}}}\cdot\int_0^t \frac{q(t')}{(t-t')^{\frac{3}{2}}}\cdot e^{\frac{-r^2}{4\cdot\alpha\cdot(t-t')}}\,dt'$$

Equation (3):

$$T_{infinite\_line}(t,x,z) = \frac{1}{4\cdot\pi\cdot k}\cdot\int_0^t \frac{q_L(t')}{t-t'}\cdot e^{\frac{-\left(x^2+z^2\right)}{4\cdot\alpha\cdot(t-t')}}\,dt'$$

The temperature transients of EBS components within the emplacement drift are calculated by the "inside" model. Prior to emplacement of backfill, WP surface temperature rise (relative to the drift wall) is determined by radiation heat transfer; however, after the backfill is added, the thermal resistance between the WP and drift wall is greatly increased, causing an abrupt spike in WP surface temperature. The overall combination of the "outside" and "inside" analytical models shows no effect from the addition of backfill on the drift wall or host rock temperature transients. In a more detailed model there would be a transient reduction in the heat transfer from the WP to the drift wall and host rock until the thermal mass of the backfill was heated up and reached a quasi-steady state condition.

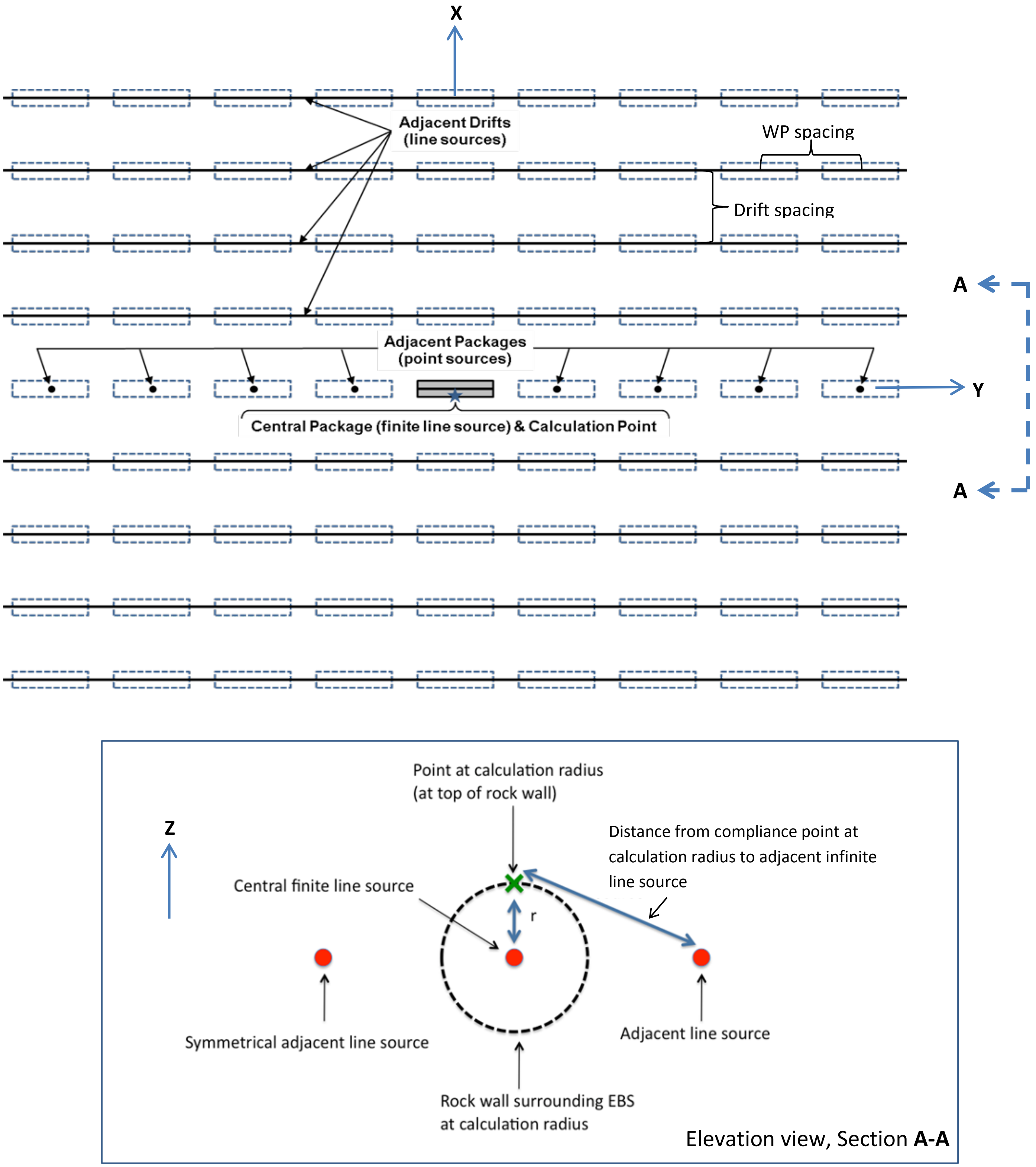


Figure 1 – Plan view and elevation view of the repository layout assumed in the thermal-analytical model

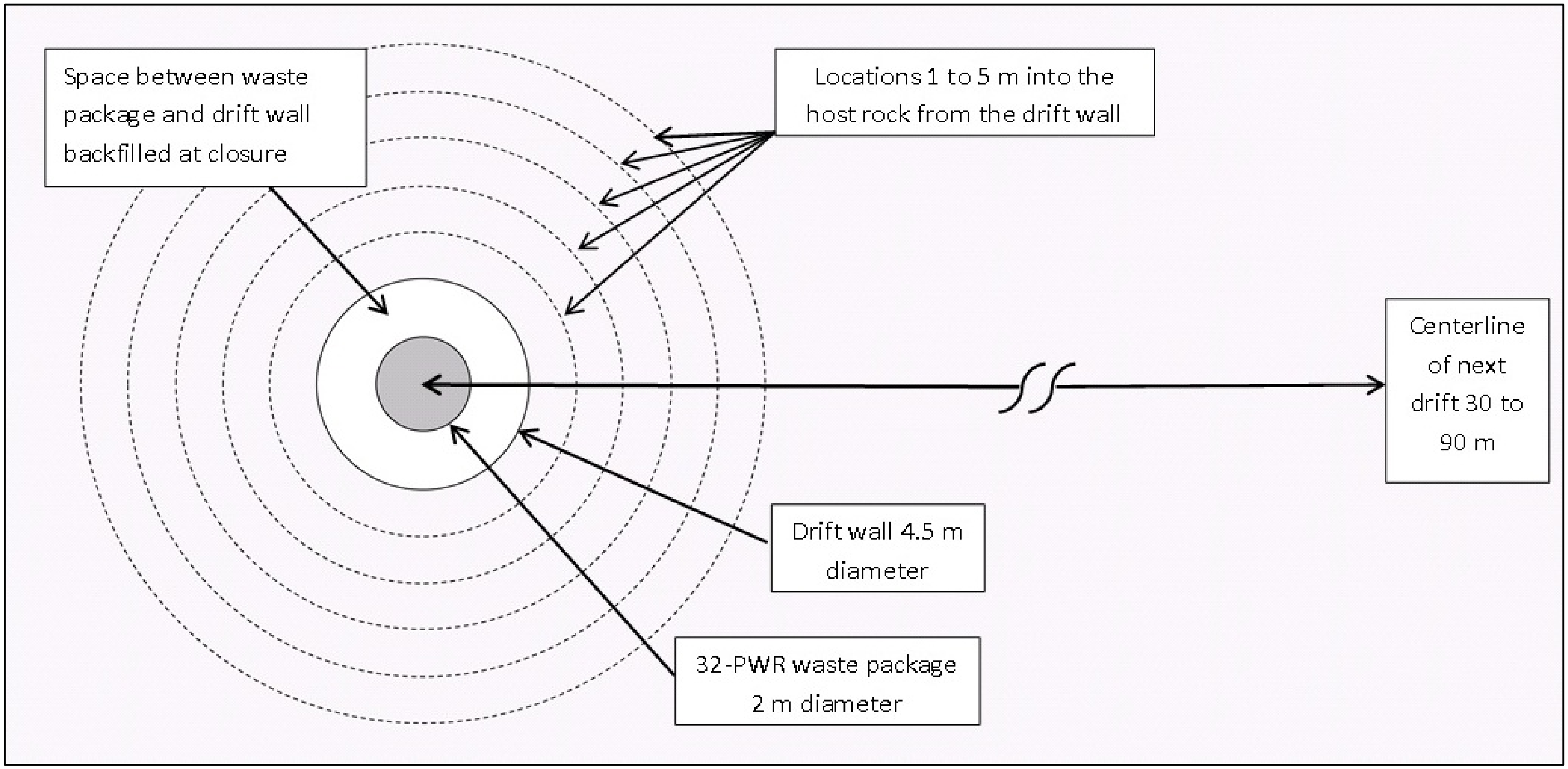


Figure 2 – Scale drawing example of repository cross-section showing compliance point and adjacent drift distances

Temperature buildup at a given WP location in a drift is the result of contributions from three generic sources of heat: (1) the adjacent drifts (lateral neighbors), (2) the adjacent WPs within that drift (axial neighbors), and (3) that WP itself. Insights gained from Greenberg (2013c) were used to develop the range of WP spacings for the 40 GWd/MT burnup spent fuel cases, and in selecting the drift spacing and WP spacing for the 60 GWd/MT burnup spent fuel cases.

A summary of the case numbers evaluated is given in Table 1, and a summary of peak temperature results and times at various locations for all of the analysis cases is presented in Appendix A.

Table 1 - Summary of clay/shale repository design cases evaluated and associated case numbers

Drift spacing = 70 m Parametric studies varying WP spacing (15 to 24 m)	**Case # Definition Table**	**32-PWR WP, 40 GWd/MT DSEF base case 229**			
		Ventilation Duration (yr)			
	CP2* (m)	**100**	**75**	**50**	**25**
Clay/Shale (sedimentary) (K_{th} = 1.75 W/m-K)	**1**	500-1	500-6	500-11	500-16
	2	500-2	500-7	500-12	500-17
	3	500-3	500-8	500-13	500-18
	4	500-4	500-9	500-14	500-19
	5	500-5	500-10	500-15	500-20

Drift spacing = 70 & 90 m Parametric studies varying WP spacing (16 to 34 m)	**Case # Definition Table**	**32-PWR WP, 60 GWd/MT DSEF base case 231**	
		Drift Sp / Vent time	
	CP2* (m)	**90 m / 150 yr**	**70 m / 150 yr**
Clay/Shale (sedimentary) (K_{th} = 1.75 W/m-K)	**1**	500-21 and 500-32**	500-26 and 500-27**
	2	500-22	500-28**
	3	500-23	500-29**
	4	500-24	500-30**
	5	500-25	500-31**

Notes:

* CP2 = Compliance point 2 – depth into the host rock from the surface of the drift wall

** Cases 500-27 to 500-32 extended WP spacing parametric study values to 50 m

2. Repository Layout and Operating Options for 32-PWR BU = 40 GWd/MT Design Cases

The sensitivity of required ventilation duration to design layout options presented in Figures 5 and 6 of Greenberg (2013c) are shown here in Figure 3 for cases meeting temperature acceptance criterion TC = 100°C at the drift wall, and in Figure 4 for cases meeting TC = 120°C at the drift wall. As can be seen by examining these figures, for WP spacing on the order of 20 m, there are diminishing returns for increasing the drift spacing beyond around 70 m. Therefore, the current analysis focuses on repository layout options for a range of WP spacings around 20 m and a drift spacing of 70 m.

Figure 3 indicates a range of design options can keep the drift wall and host rock below the TC = 100°C criterion provided the ventilation duration is at least 100 years.

The analysis results for the temperature gradient are plotted as a function of WP and drift spacing for ventilation times of 100, 75, 50, and 25 years in Figure 5 through Figure 8, respectively. In each of these figures, the top panel shows the locus of peak calculated temperature points for the drift wall, and at depths of 1 to 5 m into the host rock, for 70 m drift spacing and a range of WP spacing from 16 to 24 m. The data is drawn from the cases defined in Table 1, and the data for all of these cases is provided in Appendix A.

The data from the bottom panels of Figure 5 through Figure 8 is summarized concisely in Table 2 and Table 3 to show the host rock layer thickness outside of the drift wall that exceeds TC = 100 and 120°C, respectively, for ventilation times of 100, 75, 50, and 25 years.

Figure 5 shows that for 32-PWR WPs with a burnup of 40 GWd/MT, 70 m drift spacing and 23 m WP spacing, around 100 years of ventilation is required to meet TC = 100°C at the drift wall (so that there would be no boiling in the host rock at one bar pressure), and the figure also shows that TC = 120°C is met at the drift wall for WP spacing of around 14 m.

Figure 6 shows that, for the same 32-PWR WPs and 70 m drift spacing with only 75 years of ventilation, a WP spacing of 16 m is required to meet TC = 120°C at the drift wall. Figure 6 also shows that for 24 m WP spacing the drift wall would still be above the TC = 100°C acceptance criterion. Figure 6 and Table 2 show that for a WP spacing of 24 m, the temperature exceeds 100°C for about the first 0.4 m into the host rock.

Figure 7 shows that, for the same 32-PWR WPs and 70 m drift spacing with only 50 years of ventilation, a WP spacing of 24 m is required to meet TC = 120°C at the drift wall. Figure 7 and Table 2 show that at a WP spacing of 24 m, the temperature exceeds 100°C for about the first 0.9 m into the host rock.

Figure 8 shows that, for the same 32-PWR WPs and 70 m drift spacing with only 25 years of ventilation, even a WP spacing of 24 m is unable to prevent the drift wall from slightly exceeding 140°C. Figure 8 and Table 3 show that the temperature exceeds TC = 120°C for about the first 0.8 m into the host rock. Figure 8 and Table 2 show that the temperature exceeds TC = 100°C for about the first 1.8 m into the host rock.

As the ventilation time is progressively reduced from 100 years down to 25 years, the results show that for the fixed range of WP spacing (from 16 to 24 m) the drift wall temperature at the end of the ventilation period, as expected, is progressively hotter, and the thickness of the host rock layer that exceeds TC = 100°C or 120°C increases.

The optimal design for 32-PWR WPs and 40 GWd/MT burnup and 70 m drift spacing requires 100 years of ventilation and a WP spacing of 24 m to achieve TC = 100°C at the drift wall.

Figure 9 shows the calculated transient results for the design option of 100 years of ventilation and 23 m WP spacing. The upper panel of Figure 9 shows the transient temperatures at the drift wall and at depths into the host rock of 1, 2, 3, 4, and 5 m (from cases 500-1 through 500-5), and the lower panel shows the transient contributions to the drift wall temperature for Case 500-1 with 23 m WP spacing, which is the case where the drift wall temperature peaks at TC = 100°C. The data summarized in Table 2 and Table 3, as well as Figure 5 through Figure 8 only shows the peak temperature results for a range of waste package spacings with a drift spacing of 70 m, whereas the top panel of Figure 9 shows the full transient temperatures at the drift wall as well as at various depths into the host rock. The lower panel of Figure 9 shows that the relative contributions to the peak drift wall temperature due to adjacent WPs and adjacent drifts is relatively small compared to the contribution of the central waste package. This indicates that the drift spacing and WP spacing, if increased further, will only drop the peak drift wall temperature slightly.

Table 2 - Summary of host rock layer thickness (m) outside the drift wall required to meet TC = 100°C for 32-PWR WPs with BU = 40 GWd/MT and 70 m drift spacing, as a function of ventilation time and WP spacing

	WP Spacing (m)				
Ventilation Time (yr)	16	18	20	22	24
100	0.9	0.6	0.3	0.1	0.0
75	1.5	0.9	0.7	0.5	0.4
50	2.2	1.7	1.3	1.1	0.9
25	3.6	2.8	2.3	1.9	1.8

Table 3 - Summary of host rock layer thickness (m) outside the drift wall required to meet TC = 120°C for 32-PWR WPs with BU = 40 GWd/MT and 70 m drift spacing, as a function of ventilation time and WP spacing

	WP Spacing (m)				
Ventilation Time (yr)	16	18	20	22	24
100	0.0	0.0	0.0	0.0	0.0
75	0.0	0.0	0.0	0.0	0.0
50	0.7	0.4	0.3	0.1	0.0
25	1.6	1.2	1.0	0.8	0.8

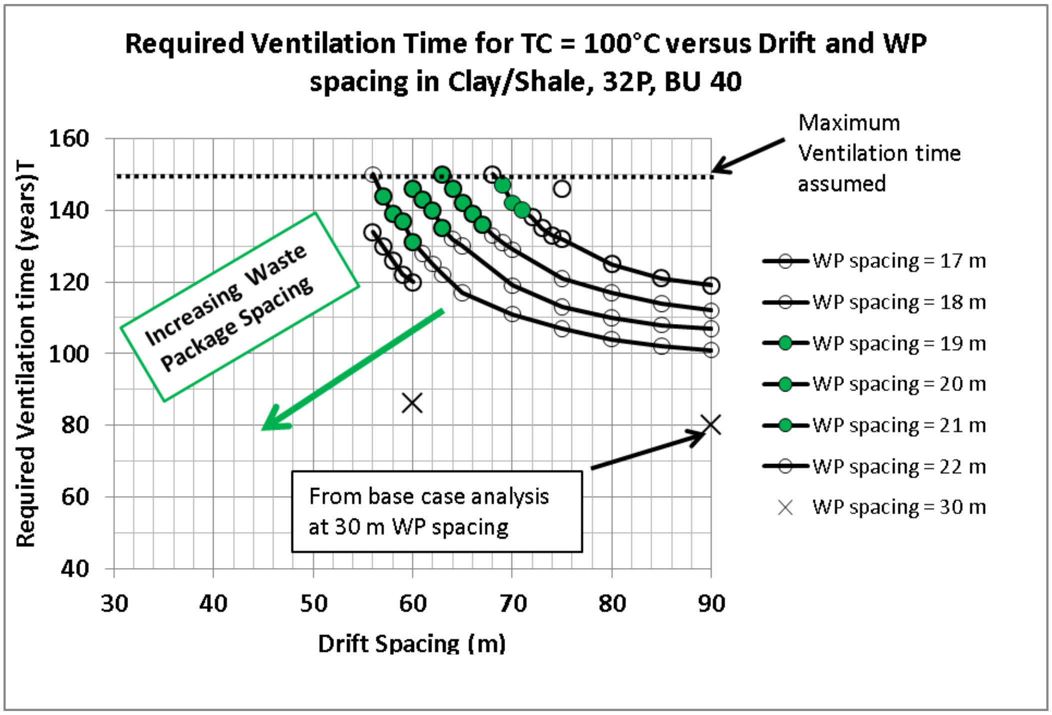


Figure 3– Required ventilation time in Clay/Shale for TC = 100°C versus WP and drift spacing

Note: Figure 3 is from Figure 5 of Greenberg (2013c)

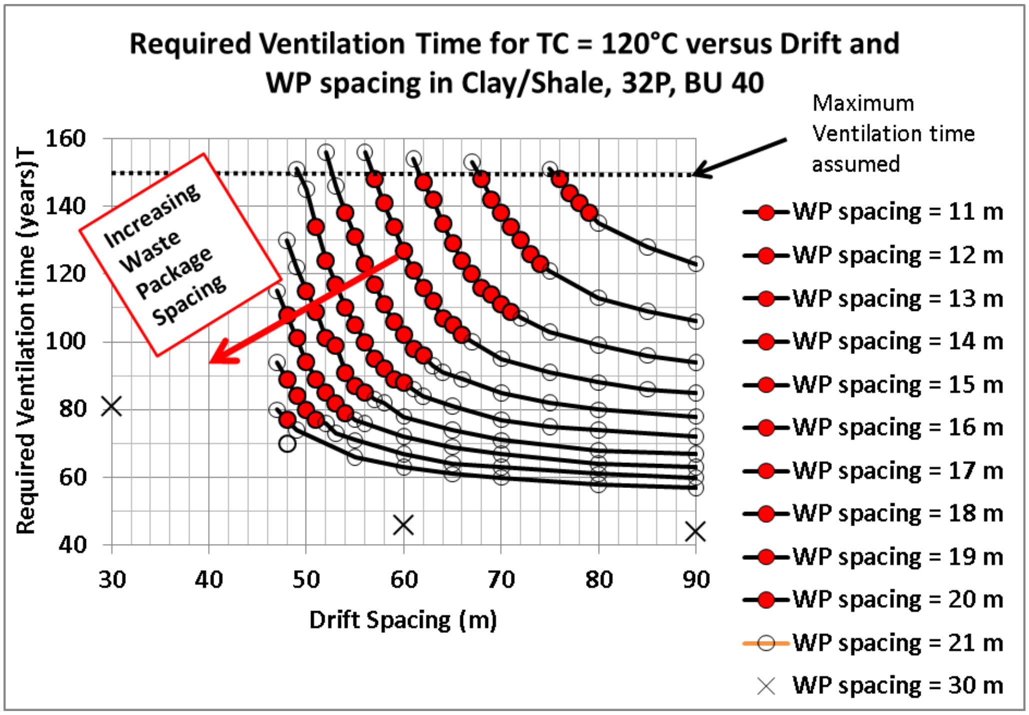
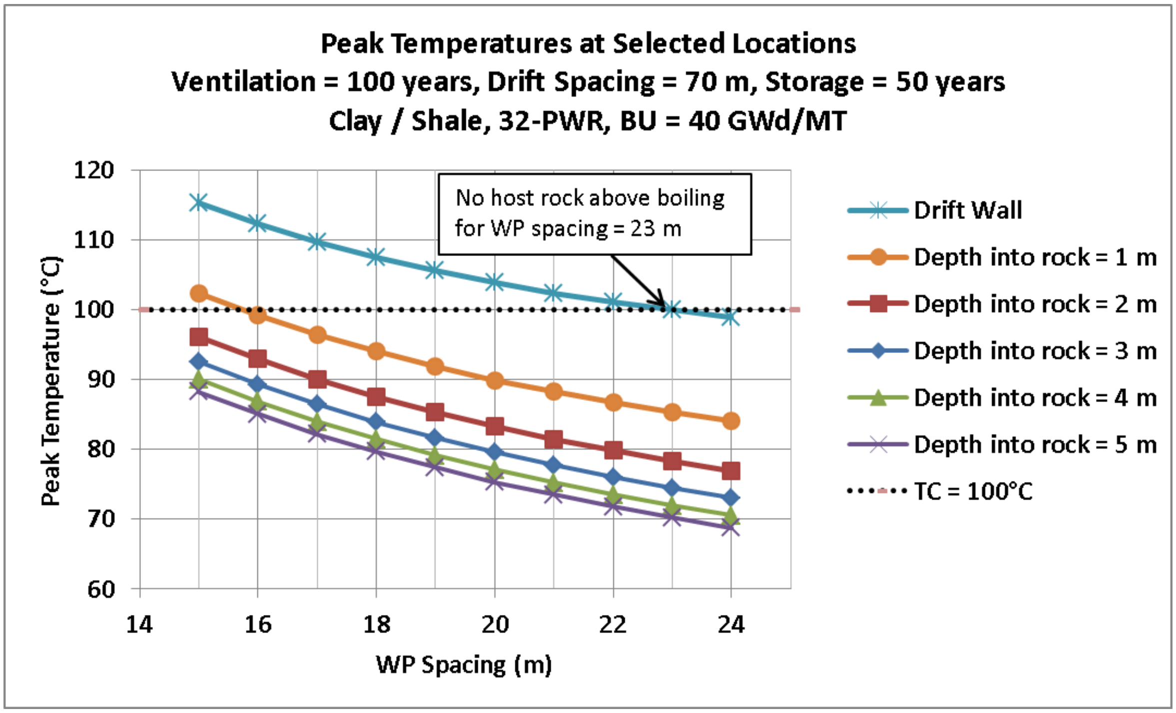


Figure 4– Required ventilation time in Clay/Shale for TC = 120°C versus WP and drift spacing

Note: Figure 4 is from Figure 6 of Greenberg (2013c)



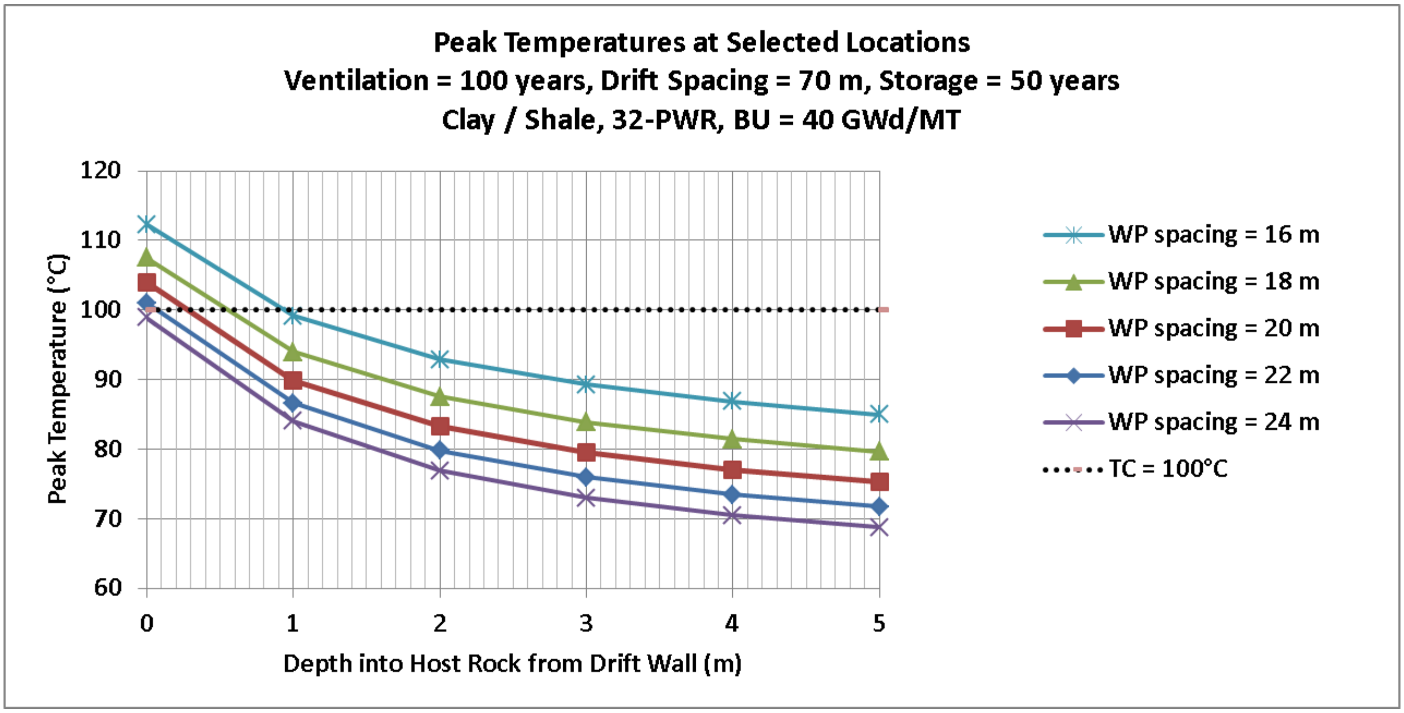
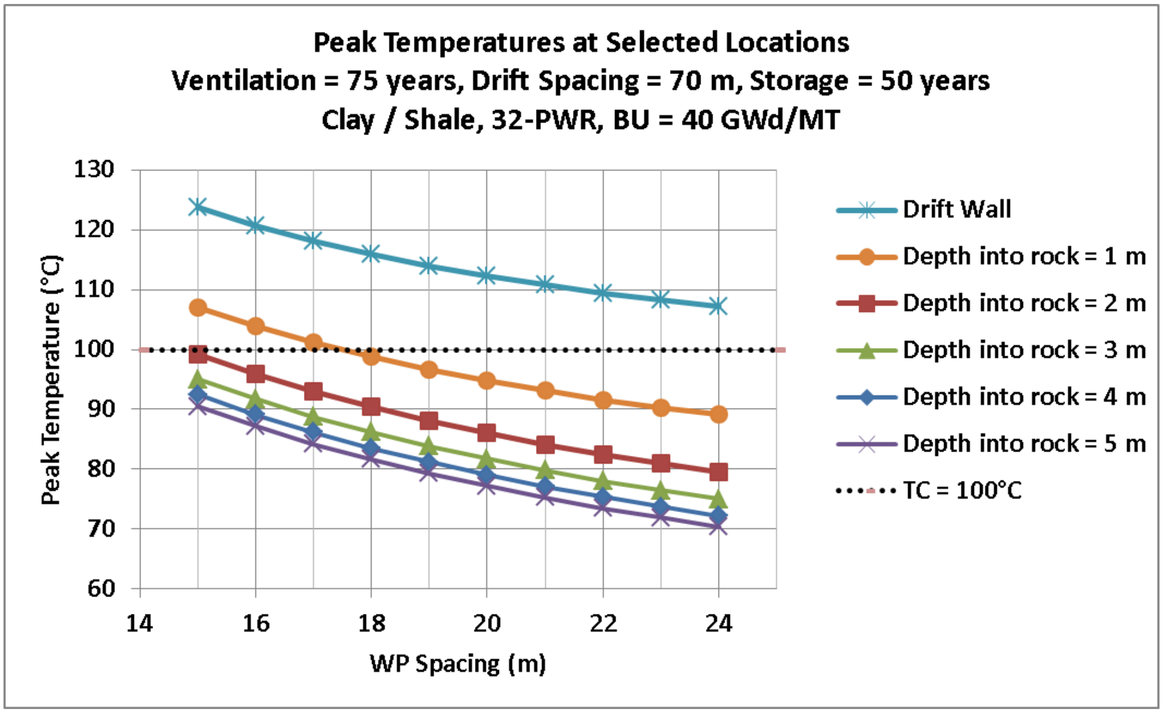


Figure 5 – Peak temperatures at selected locations for 32-PWR WPs with BU = 40 GWd/MT and ventilation duration = 100 years



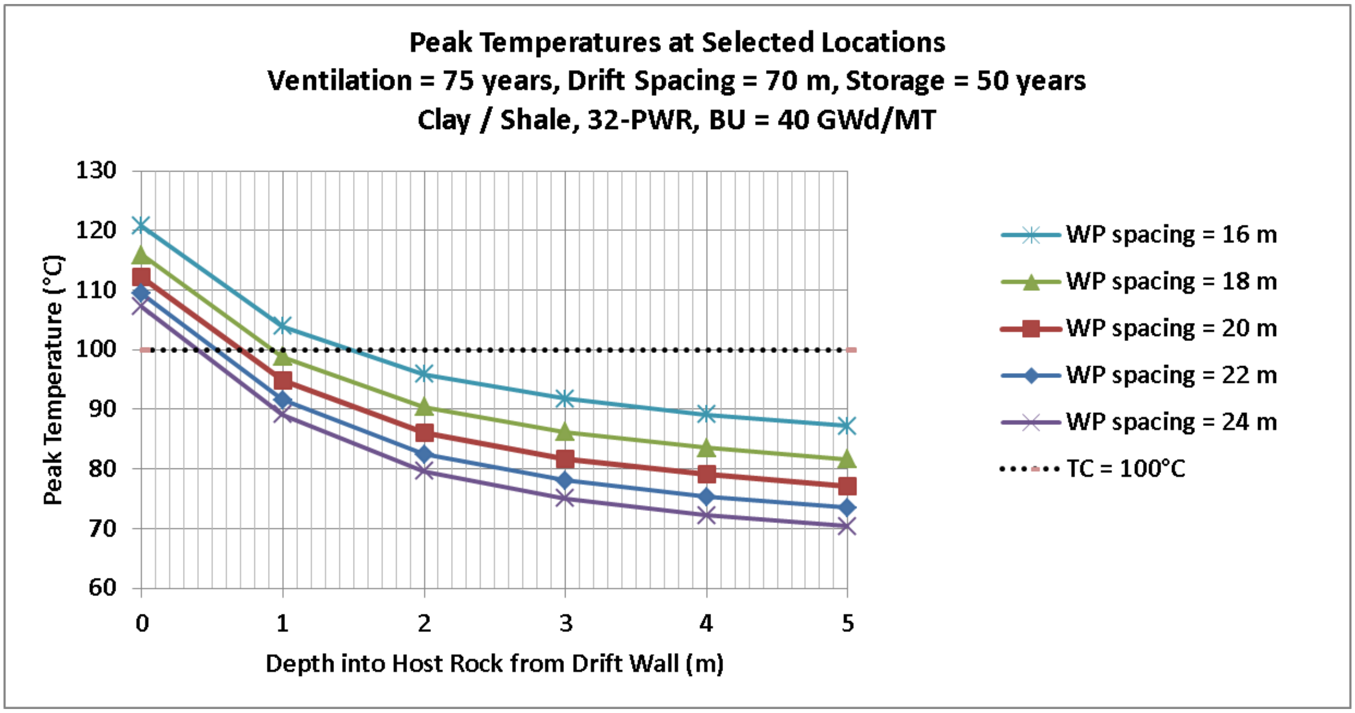
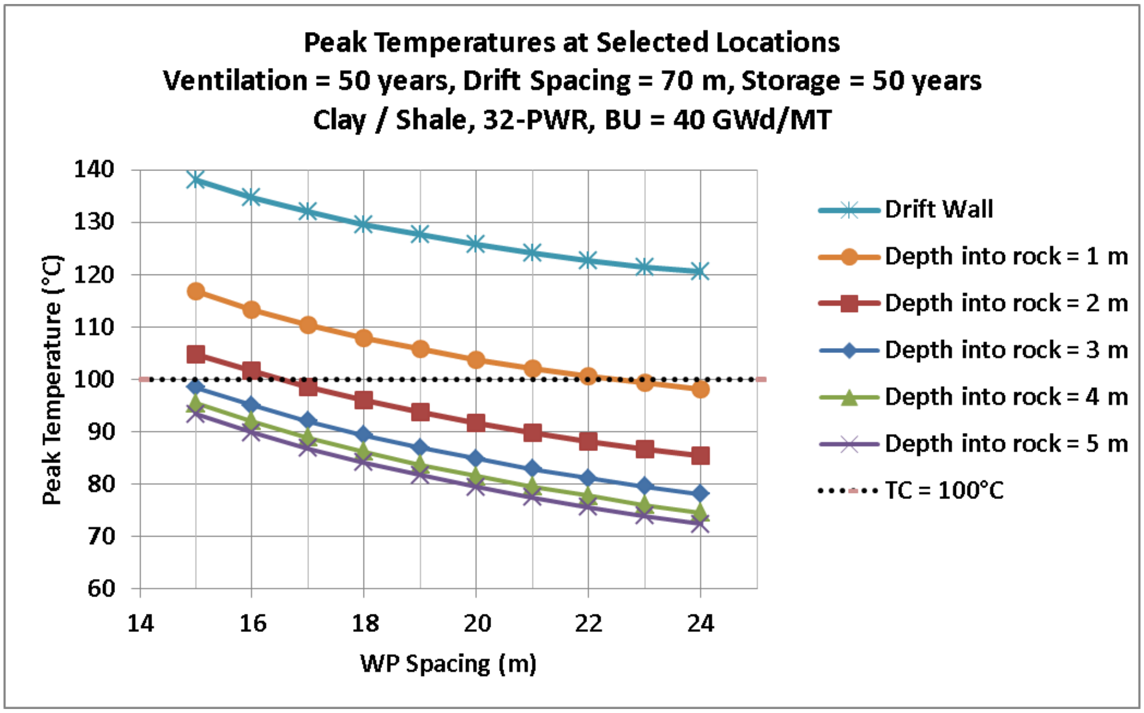


Figure 6 – Peak temperatures at selected locations for 32-PWR WPs with BU = 40 GWd/MT and ventilation duration = 75 years



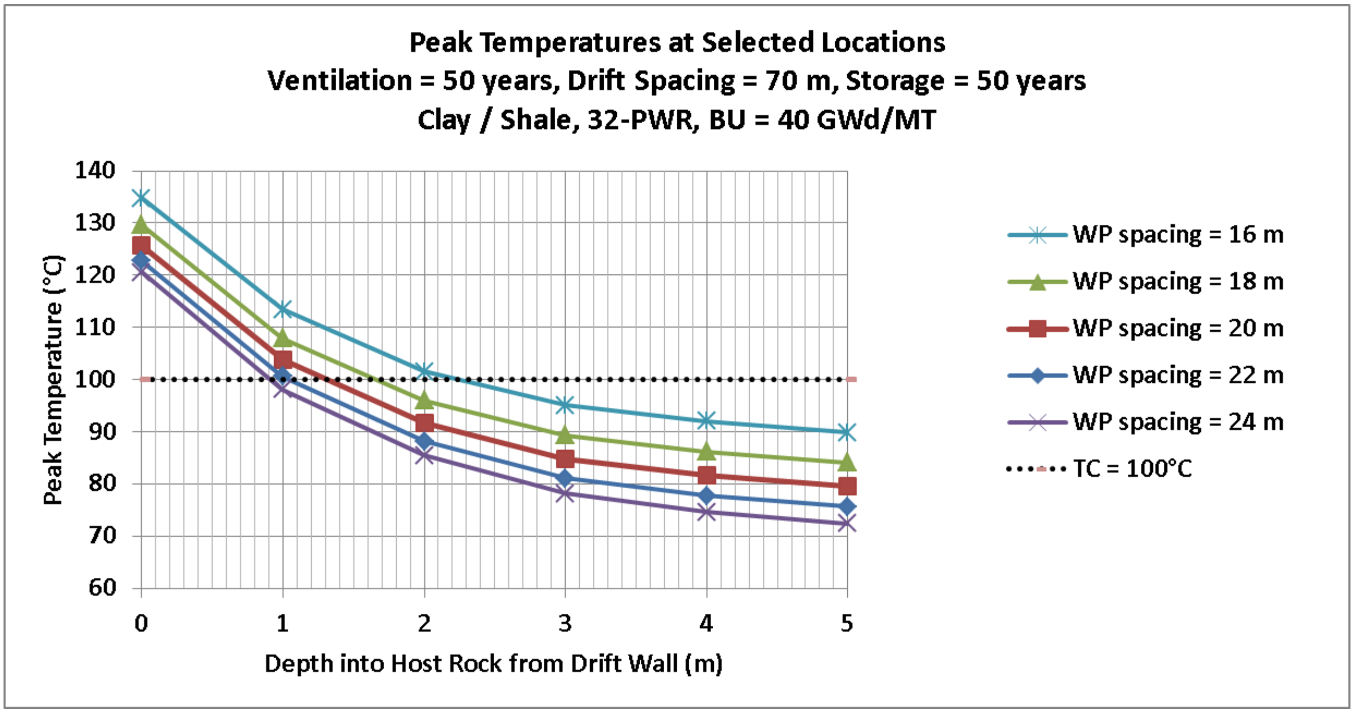
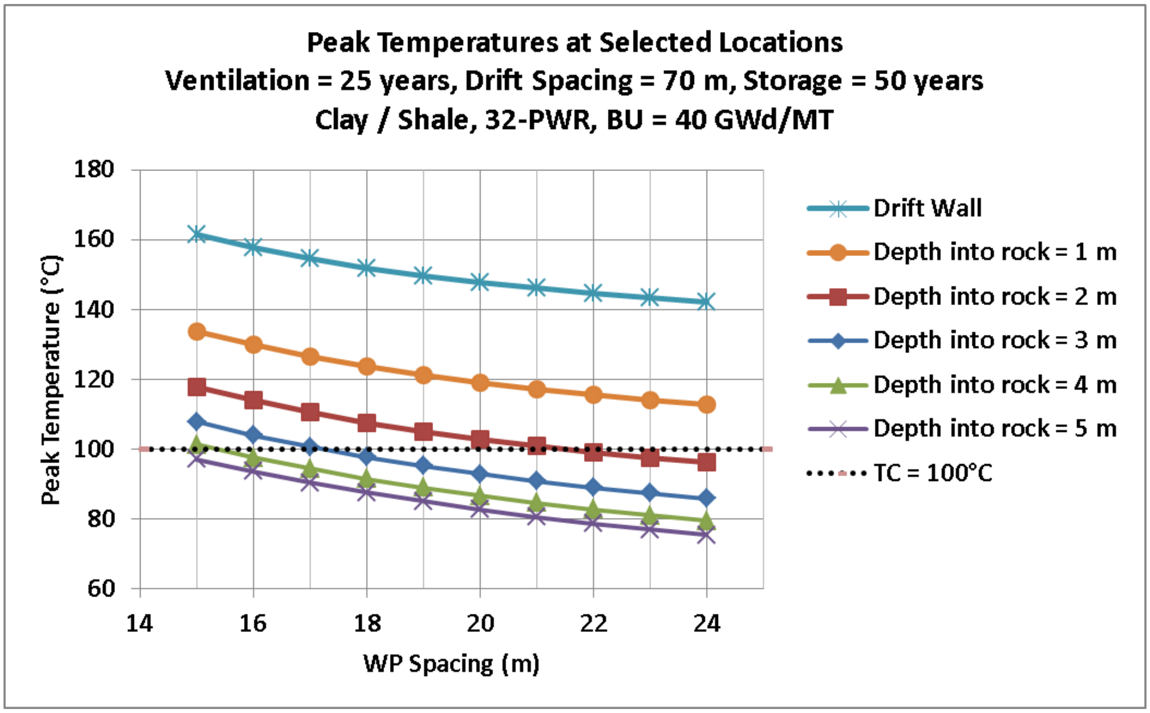


Figure 7– Peak temperatures at selected locations for 32-PWR WPs with BU = 40 GWd/MT and ventilation duration = 50 years



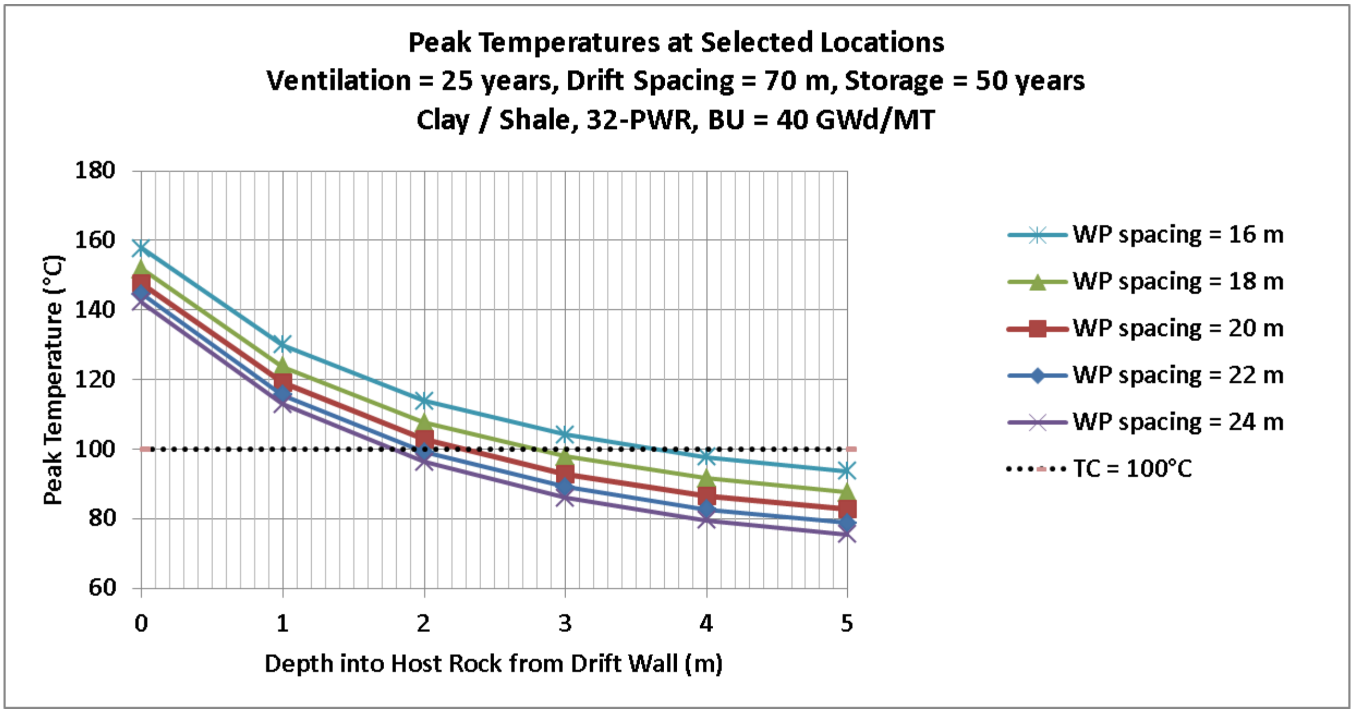
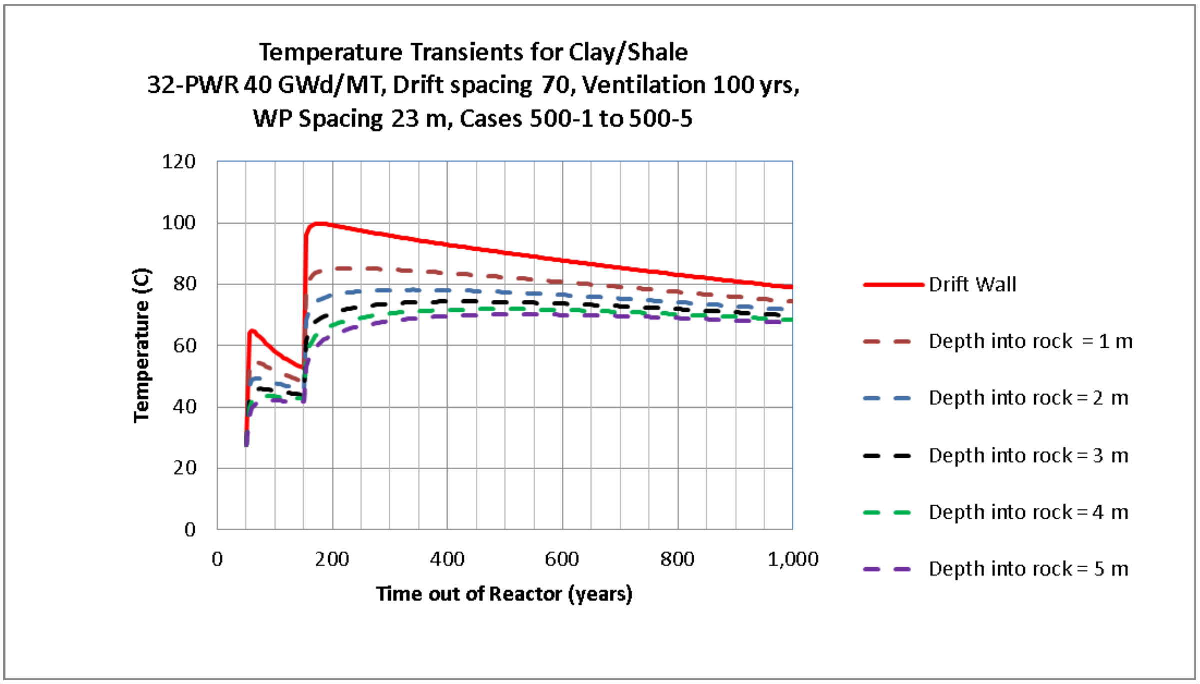


Figure 8 – Peak temperatures at selected locations for 32-PWR WPs with BU = 40 GWd/MT and ventilation duration = 25 years



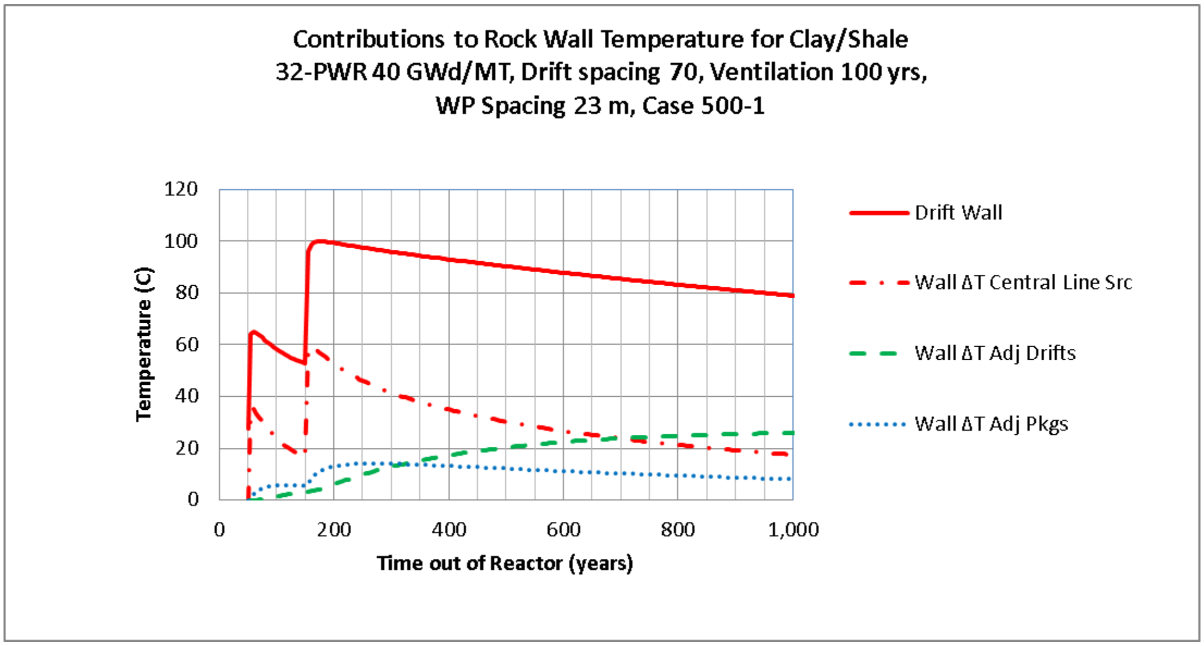


Figure 9 – Transient temperatures and transient contributions to drift wall temperature for 32-PWR WPs with BU = 40 GWd/MT (Cases 500-1 thru 500-5) with WP spacing = 23 m

3. Repository Layout and Operating Options for 32-PWR BU = 60 GWd/MT Design Cases

The decay heat for spent nuclear fuel with a burnup of 40 and 60 GWd/MT is given in Table 3.1-3 of Greenberg (2012b) on a per fuel assembly and per metric ton basis. At 50 years out of reactor (the time of emplacement assumed in this analysis), the decay heat for one spent fuel assembly (assuming 0.47 MT per assembly) is 317.6 and 675.7 W for a burnup of 40 and 60 GWd/MT, respectively. A 32-PWR WP has 32 times the heat of a single assembly, but because of pre-closure ventilation, with an assumed ventilation thermal efficiency of 75%, only 25% of the heat generated by a WP goes into the host rock wall. At the time of WP emplacement, this results in around 2,541 and 5,407 W going into the host rock for burnups of 40 and 60 GWd/MT, respectively.

As a consequence of the much higher decay heat, the 32-PWR, 60 GWd/MT waste stream needs a repository layout and operating concept with larger WP and drift spacing, and longer ventilation times than required for the 40 GWd/MT waste stream. Based on the results of previous analyses and the behavior shown in Figure 3 and Figure 5, a base case for the 32-PWR 60 GWd/MT waste stream of 150 years of ventilation, 90 m drift spacing, and around 30 m of drift spacing was selected to identify a design concept with the drift wall less than or equal to TC = 100°C.

Table 1 lists the case numbers evaluated for 90 m drift spacing and 150 years of ventilation. After examining the results of the analysis shown in Figure 10, it was clear that this option would meet the requirements with 34 m drift spacing. Comparing the results for the 40 GWd/MT at 100 years ventilation time (Figure 5), and the results for 60 GWd/MT with 150 years of ventilation time (Figure 10), the behavior looks very similar, but the WP spacing scales for these two plots are different. It takes a larger increase in WP spacing to obtain roughly the same drop in drift wall temperature for the hotter waste form, even with 50% more ventilation time. Specifically, starting at 16 m WP spacing, for 90 m drift spacing, 150 year ventilation, and a burnup of 60 GWd/MT, it takes a 6 m increase in WP spacing (16 to 22 m) to reduce drift wall temperature by 10°C (from 120 to 110°C), and it takes twice that increase in WP spacing (22 to 34 m) for an additional 10°C reduction (from 110 to 100°C). For 70 m drift spacing, 100 years of ventilation, and a burnup of 40 GWd/MT, it takes a 5 m increase (16 to 21 m) in WP spacing to reduce drift wall temperature by 10°C (from 112°C to 102°C), and it takes an additional 2 m increase in WP spacing (21 to 23 m) for an additional 2°C reduction (from 102°C to 100°C).

Based on the results presented in Figure 3, it appears reasonable that additional workable design concepts capable of meeting TC = 100°C at the drift wall could be found for 70 m drift spacing by slightly increasing the WP spacing .

Figure 11 shows a comparison of 70 and 90 m drift spacing for WP spacing ranging from 16 to 40 m. The results are only a few degrees hotter for the 70 m drift spacing layout, and with the additional analysis of case 500-27, it was shown that slightly more than 38 m WP spacing is required to meet TC = 100°C at the drift wall compared to 34 m needed for the 90 m drift spacing case. The detailed results for these cases are shown in tabular form in Appendix A.

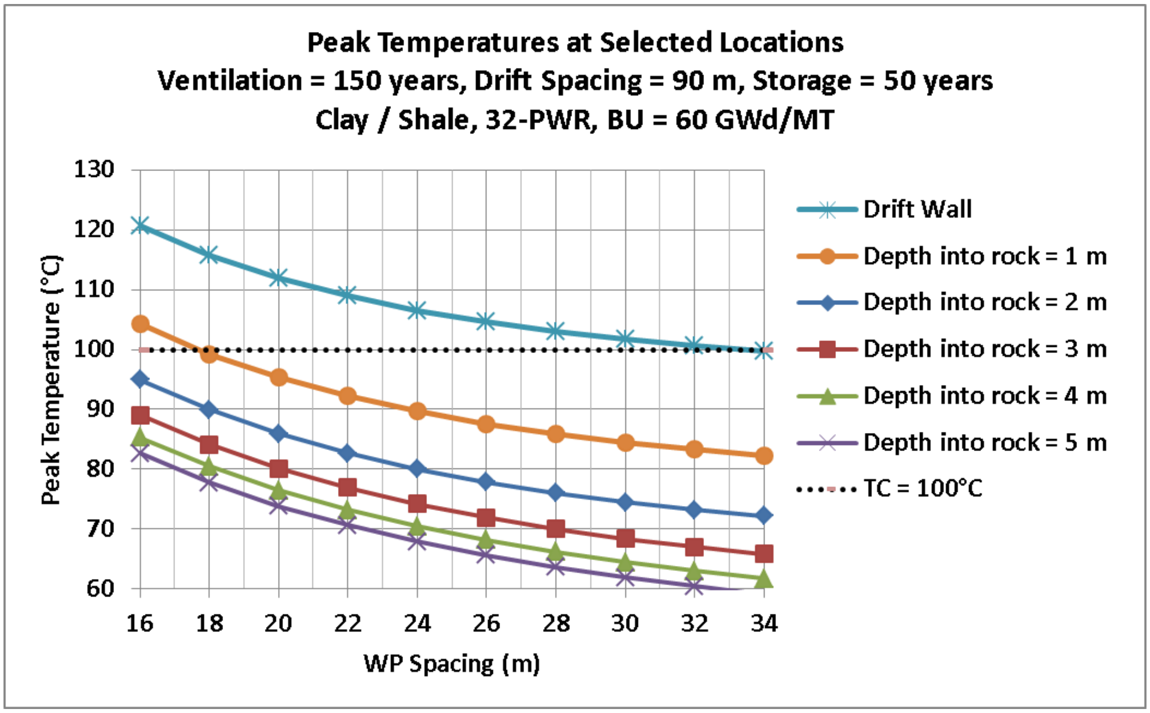
Figure 12 shows the results for 32-PWR WPs with a burnup of 60 GWd/MT, 70 m drift spacing and 100 years of ventilation, over a range of drift spacing from 32 to 50 m. This figure confirms that around 38 m WP spacing is required to meet TC = 100°C at the drift wall for this design concept. The rate of change of peak drift wall temperature drops much more slowly with increasing WP spacing, since 38 m WP spacing is already in the region of diminishing returns (beyond 30 m WP spacing) as was shown on Figure 3.

Figure 13 and Figure 14 show the transient temperatures and transient contributions to the drift wall temperature for Case 500-21 (with a drift spacing of 90 m and a WP spacing of 34 m), and for Case 500-27 (with a drift spacing of 70 m and a WP spacing of 38 m), respectively. These are both cases where the peak drift wall temperature coincides with TC = 100°C. The upper panels of these figures show the transient temperatures at the drift wall and at depths into the host rock of 1, 2, 3, 4, and 5 m (from cases 500-21 through 500-25 on Figure 13, and from cases 500-27 through 500-31 on Figure 14). The lower panels of these figures show the transient contributions to the drift wall temperature for Case 500-21 with 34 m WP spacing (Figure 13), and for Case 500-27 with 38 m WP spacing (Figure 14).

The data summarized in Table 4, as well as Figure 10 through Figure 12, only show the peak temperature results for a range of waste package spacing with a drift spacing of 90 m, whereas the top panel of Figure 13 and Figure 14 show the full transient temperatures at the drift wall and at various depths into the host rock. The lower panels of both of these figures show that the relative contributions to the peak drift wall temperature due to adjacent WPs and adjacent drifts is relatively small compared to the contribution of the central waste package. This indicates that the drift spacing and WP spacing if increased further will only drop the peak drift wall temperature slightly.

Table 4 - Summary of host rock layer thickness (m) outside the drift wall required to meet TC = 100°C for 32-PWR WPs with BU = 60 GWd/MT as a function of drift and WP spacing for ventilation duration = 150 years

	WP Spacing (m)						
Ventilation Time / Drift spacing	26	28	30	32	34	36	38
150 yr / 90 m	0.27	0.18	0.10	0.04	0.00	0.00	0.00
150 yr / 70 m	0.46	0.34	0.24	0.17	0.10	0.05	0.01



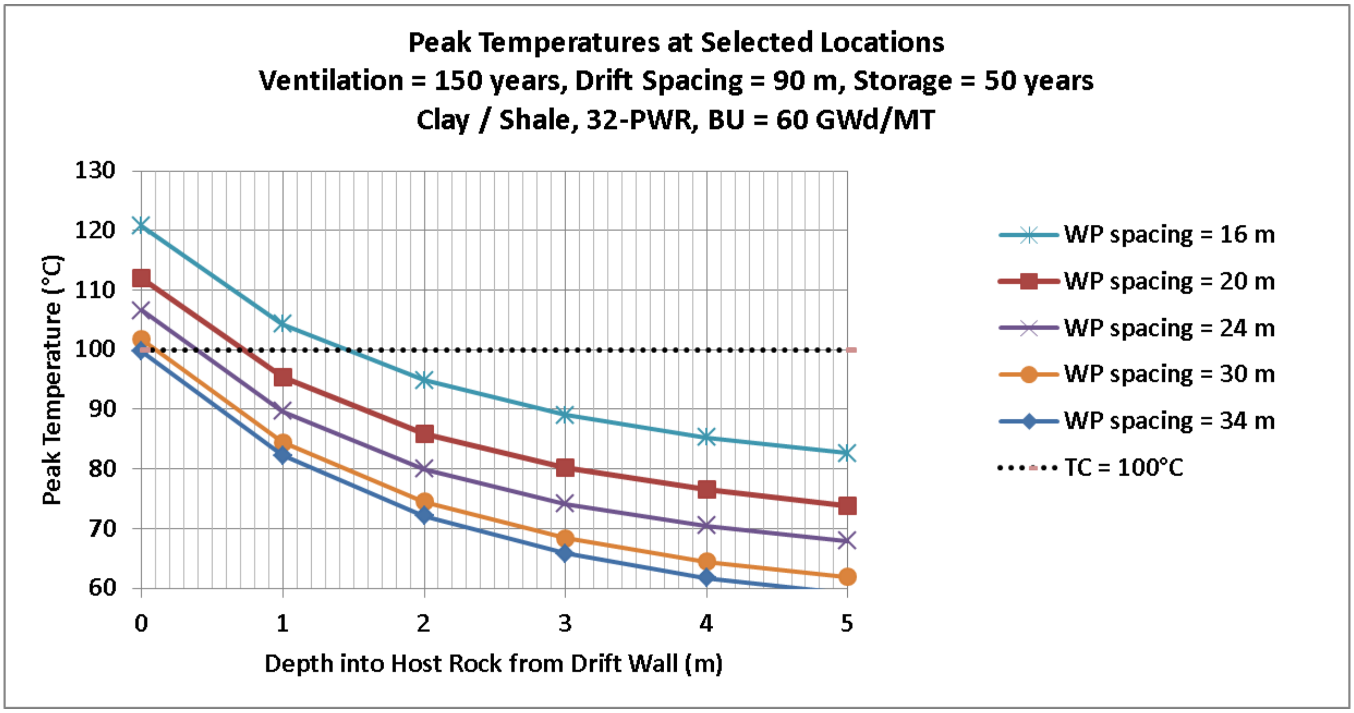


Figure 10 – Peak temperatures at selected locations for 32-PWR WPs with BU = 60 GWd/MT, ventilation duration = 150 years, and drift spacing = 90 m

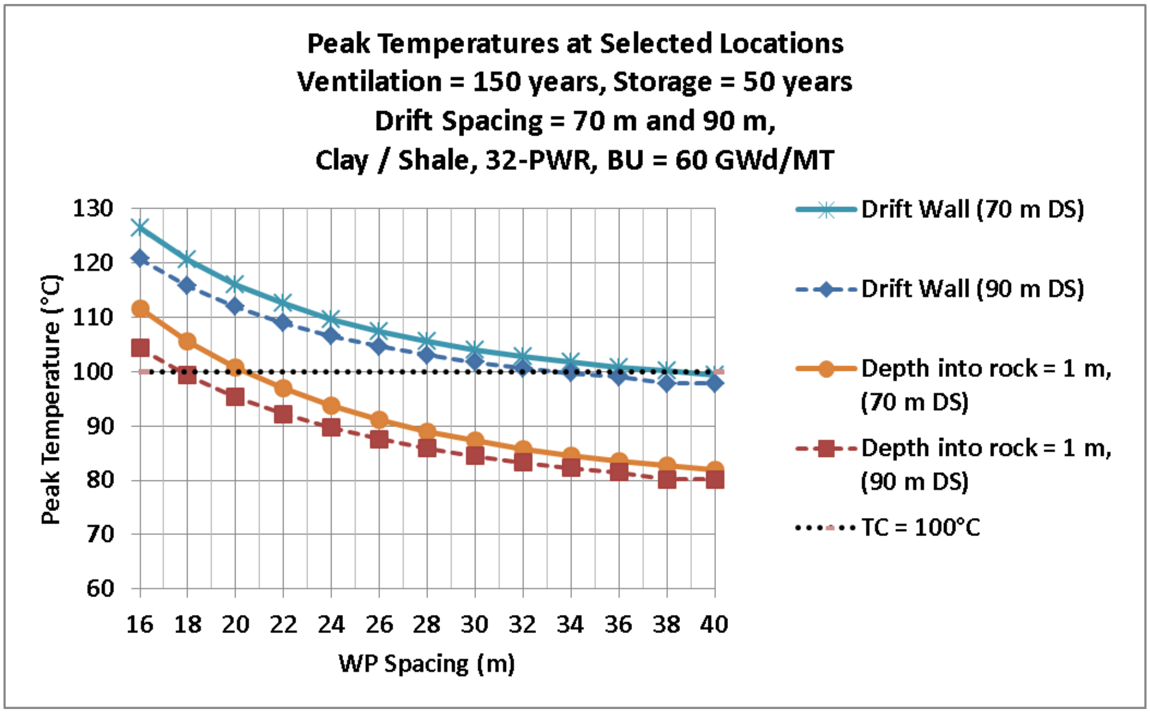
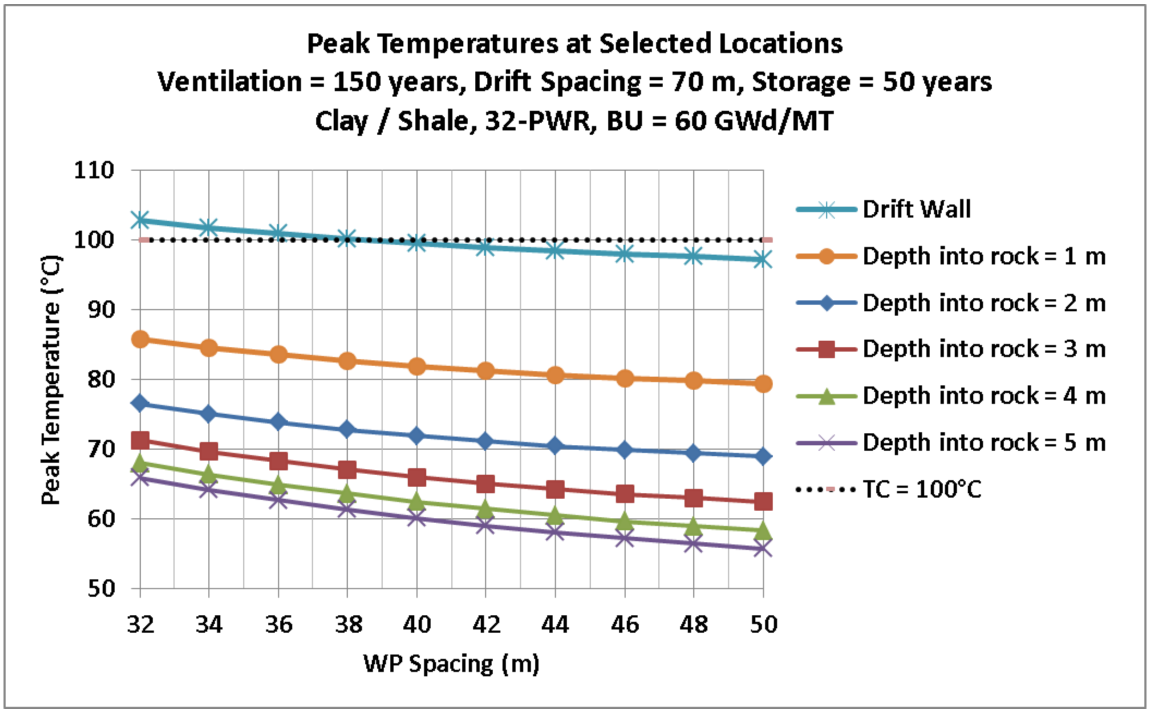


Figure 11 – Comparison of peak temperatures at selected locations for drift spacing of 70 and 90 m for 32-PWR WPs with BU = 60 GWd/MT and ventilation duration = 150 years



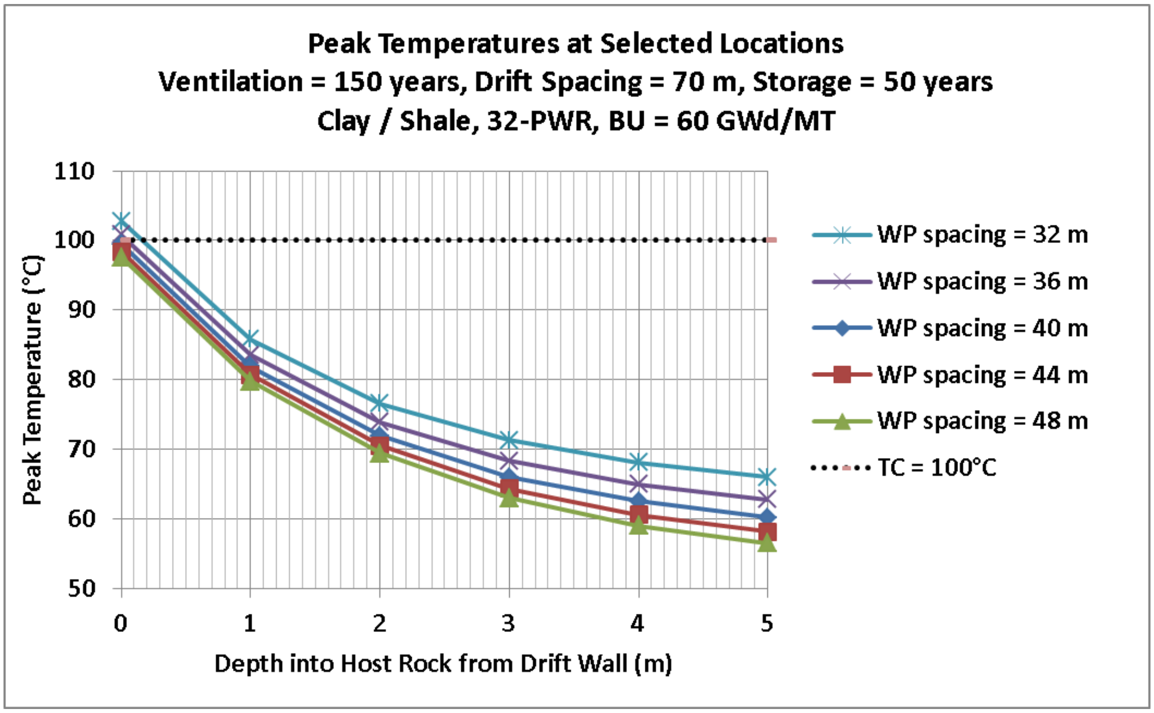
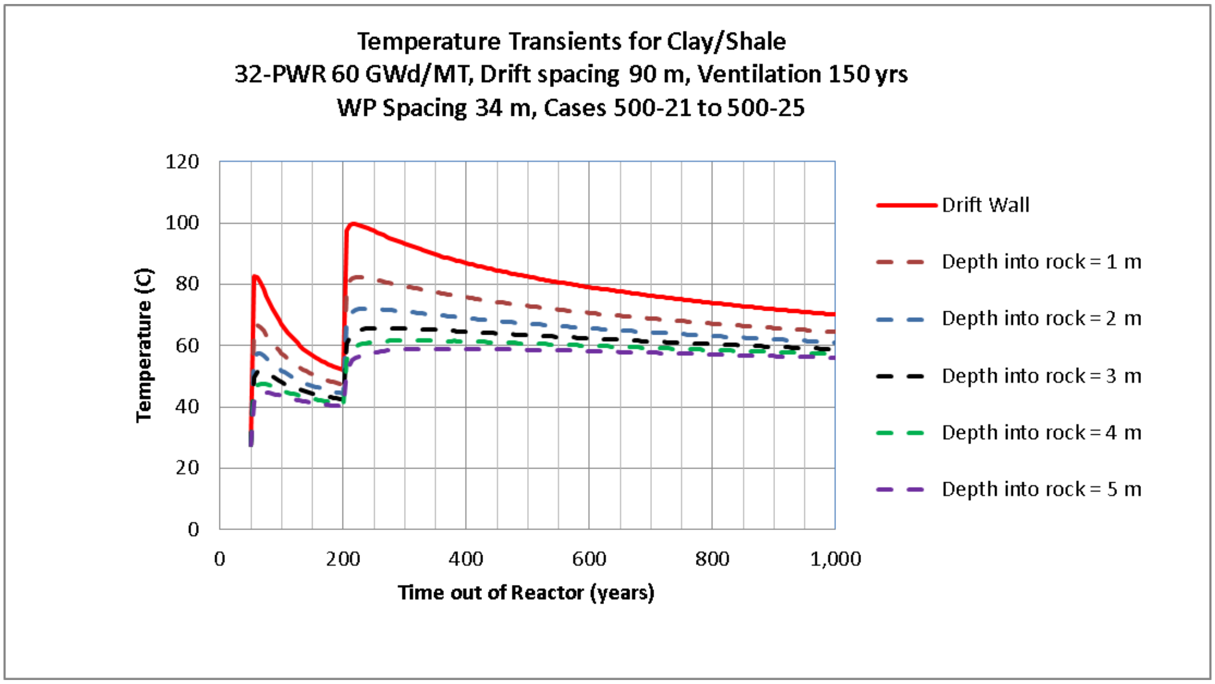


Figure 12 – Peak temperatures at selected locations for 32-PWR WPs with BU = 60 GWd/MT, ventilation duration = 150 years, and drift spacing = 70 m



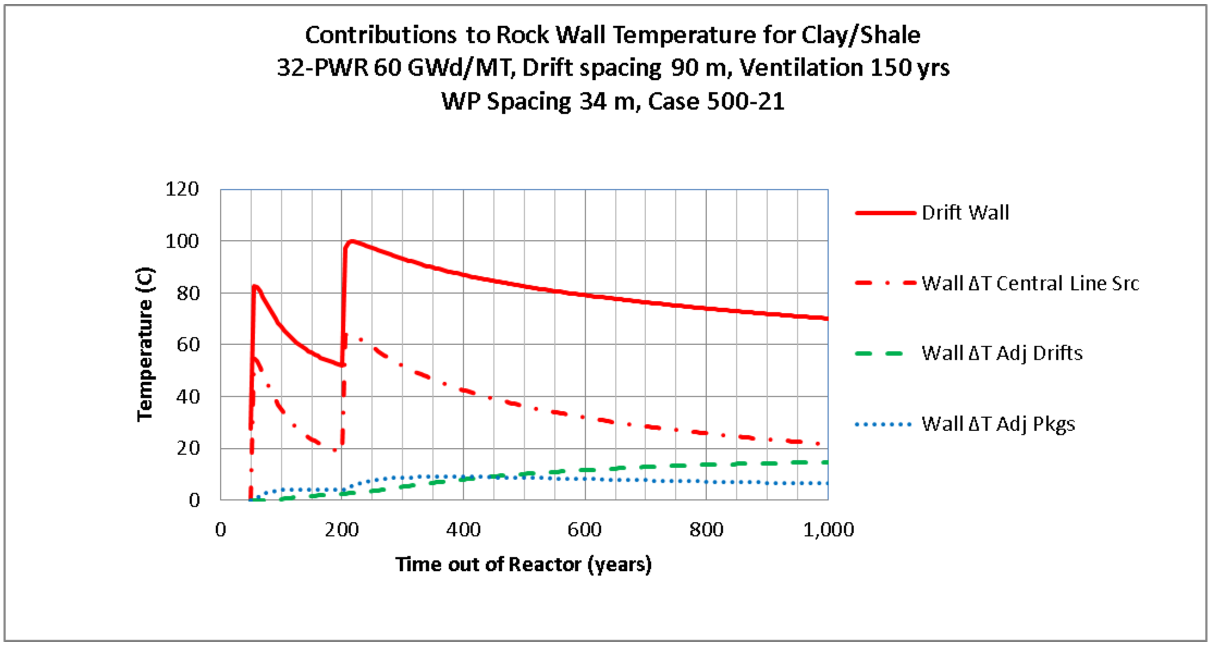
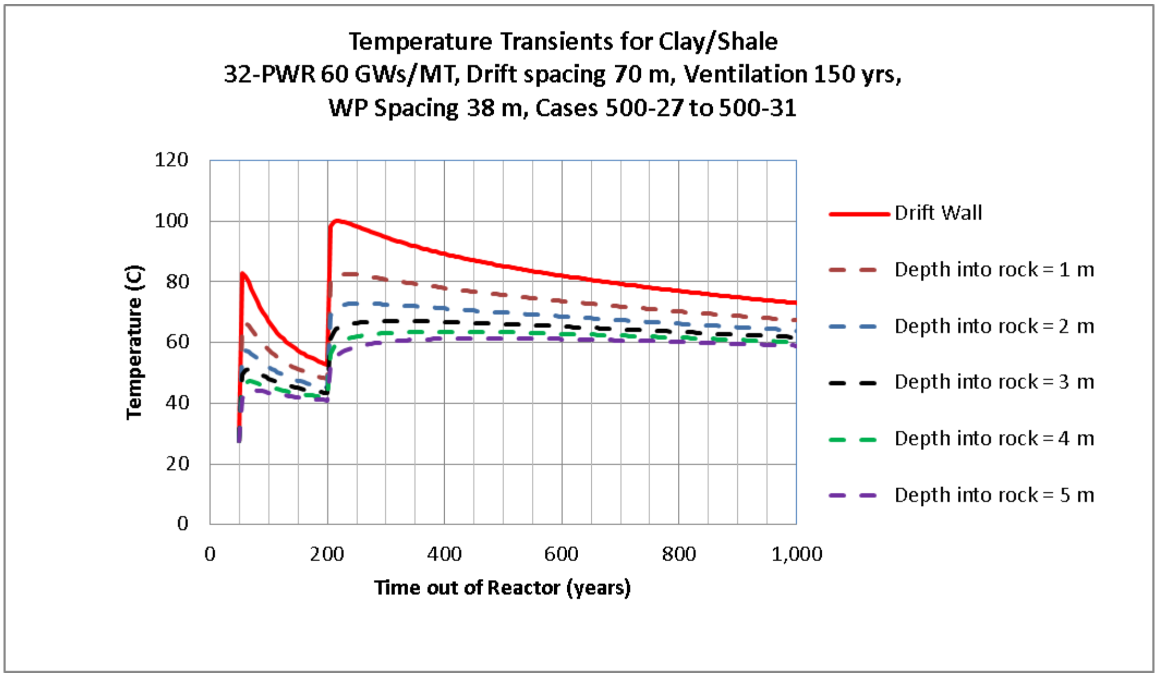


Figure 13 - Transient temperatures and transient contributions to drift wall temperature for 32-PWR WPs with BU = 60 GWd/MT (Cases 500-21 to 500-25), drift spacing = 90 m, and WP spacing = 34 m



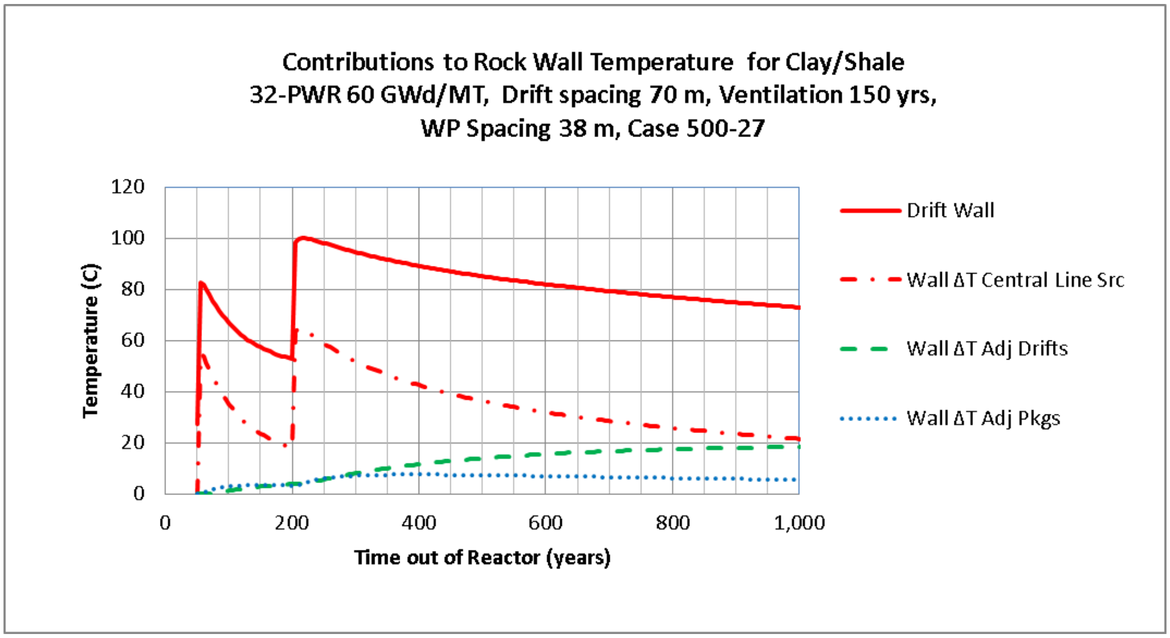


Figure 14 - Transient temperatures and transient contributions to drift wall temperature for 32-PWR WPs with BU = 60 GWd/MT (Cases 500-27 to 500-31), drift spacing = 70 m, and WP spacing = 38 m

4. Summary of Results

Section 2 discusses the analysis of the thermal performance for 32-PWR WPs with a burnup of 40 GWd/MT. Independent variables were the drift spacing and ventilation time, with results presented at five depth locations in the host rock, relative to the drift wall.

Section 3 discusses the analysis of the thermal performance for 32-PWR WPs with a burnup of 60 GWd/MT. Independent variables were the drift spacing and ventilation time, with results presented at five depth locations in the host rock, relative to the drift wall. In Section 3, two potentially workable design solutions were compared (a case with 90 m drift spacing and 34 m WP spacing, and a case with 70 m drift spacing and 38 m WP spacing) to illustrate the trade-off between drift and WP spacing.

Table 5 shows the required repository footprint area for the workable design solutions identified in Sections 2 and 3, based on the methodology defined in Appendix B.

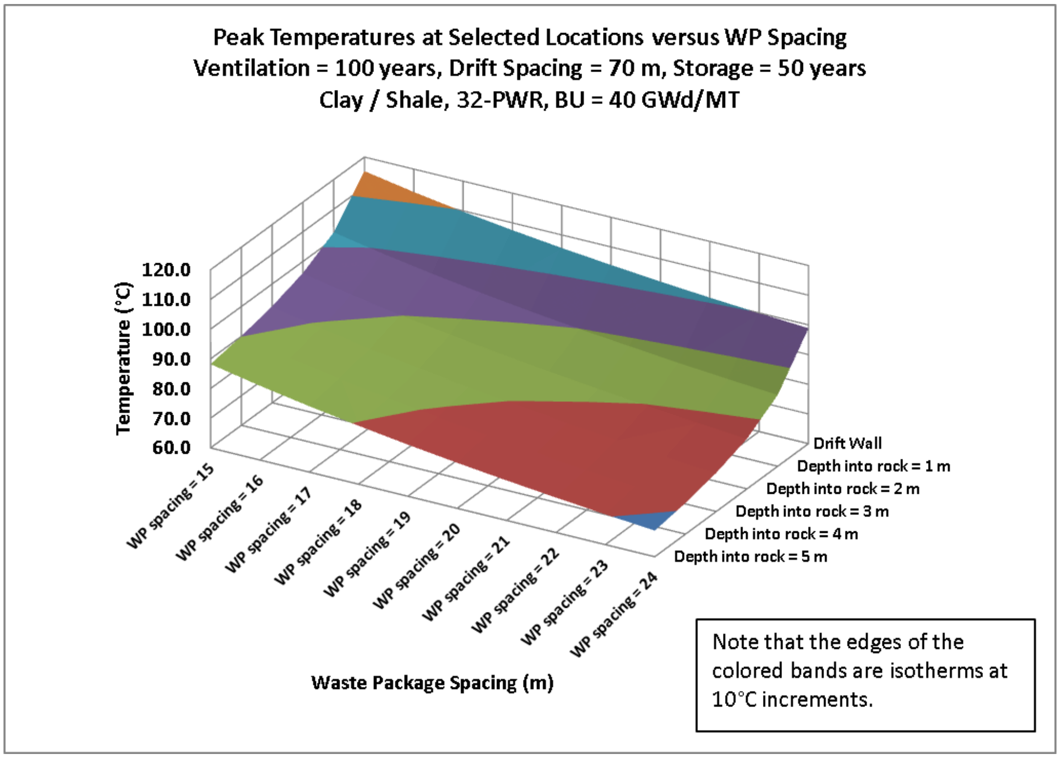
Table 5 - Repository footprint area and excavation drift length for design options identified

	Cases 500-1 to 500-5	**Cases 500-27 to 500-31**	**Cases 500-21 to 500-25**
Transient temperature and heat source contribution plots	Figure 9	Figure 14	Figure 13
Burnup (GWd/MT)	40	60	60
WP spacing (m)	23	38	34
Drift spacing (m)	70	70	90
Repository total area (km^2)	14.4	23.4	26.9
Areal mass loading (m^2/MT)	102.8	166.9	192.5
Total emplacement drift length (km)	209	339	305
Decay heat per WP (W) at time of emplacement	10,163	15,824	15,824
Decay heat per WP not removed by ventilation (W) at time of emplacement*	2,541	3,956	3,956
Areal heat load generated by WPs (W/m^2) at time of emplacement	6.6	6.3	5.5
Areal heat load into host rock (W/m^2) at time of emplacement	1.6	1.6	1.4
Time out of reactor (yr) when ventilation stops	150	200	200
Decay heat per WP (W) at end of ventilation	3,882	4,173	4,173
Areal heat load (W/m^2) at end of ventilation	2.5	1.7	1.4

Note: * based on 75% ventilation efficiency, only 25% of the decay heat goes into the host rock

Figure 15 summarizes many of the results shown in Section 2 and 3 in the form of 3D gradient plots. In this figure the edges of the colored bands are the isotherms (in 10°C increments) that show the temperature versus depth into the host rock and a range of WP spacing. The top panel of the figure (40 GWd/MT burnup) shows how the 100°C isotherm moves gradually from a depth of around 1.5 m inside the host rock at a waste package spacing of 15 m, to the surface of the drift wall when the waste package spacing is 23 m. The bottom panel of the figure (60 GWd/MT burnup) shows the increased waste package spacing required to lower the drift wall temperature to meet the 100°C temperature criterion.

It is clear from both the top and bottom panels of Figure 15 that to accommodate disposal of large DPCs in a clay / shale environment, both large drift spacing (between 70 and 90 m), and WP spacing (between 20 and 40 m) are needed to achieve 100°C drift wall temperatures. Figure 15 also shows that at 70 m drift spacing, and 15 m WP spacing, the drift wall temperature is only slightly reduced by doubling or tripling the waste package spacing.



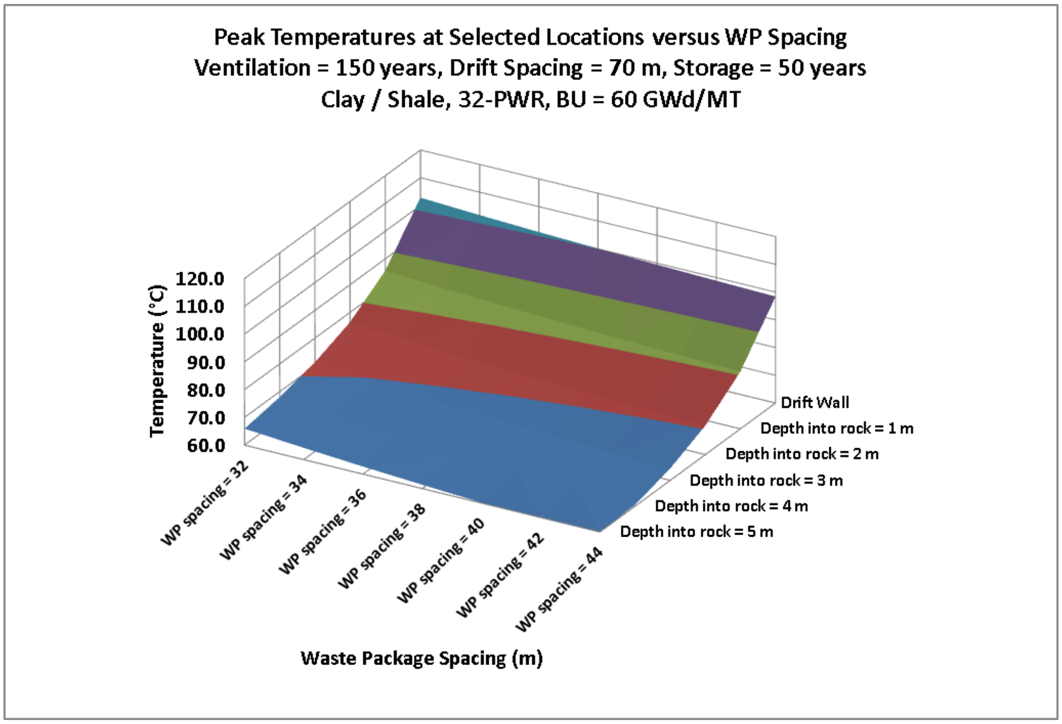


Figure 15 – 3D Thermal gradient results for the 70 m drift spacing cases with BU = 40 and 60 GWd/MT as a function of WP spacing

5. Benchmarking Analysis Performed by Argonne National Laboratory

Huff (2012) documented an Argonne National Laboratory benchmark of the Mathcad thermal-analytical model against a lumped-sum finite element model using the SINDAG thermal analysis code. Huff 2012 compared modeling results for both clay and salt enclosed mode repository models. They concluded that the Mathcad model was run with single tunnel and multiple tunnels (100 drifts modeled) cases, and concluded in Section 5 of Huff 2012:

> “The analytic model gave peak temperatures for all cases run which agreed with the numerical model within 4°C and, for calculation radii less than 5 meters, consistently reported peak temperature timing within 11 years of the SINDAG numerical model. In light of the magnitude of uncertainties involved in generically modeling a non-site-specific geologic repository, this sufficiently validated the analytical model with respect to its goals.”

The benchmark analysis also specifically compared the calculated temperature at various depths into the host rock. The results showed consistently higher peak temperatures at each depth with the SINDAG model. This was probably due in part to the location of the gradient calculation in the Mathcad model as perpendicular to the plane of the emplacement drifts, and partially due to the greater number of emplacement drifts in the multi-drift SINDAG model. However, Huff 2012 also included a calibration evaluation and concluded

> “The result of this calibration effort is a procedure for calibration of a rapid analytic heat transport model which improves peak temperature value and timing agreement with a more detailed, but more time intensive heat transport model. With a single calibration, it is possible for the disagreement between the two models to be alleviated for many configurations. It is recommended that for this and other analytic models which neglect rapid heat transport in engineered components near the calculation radius, the additional step will improve results near the area of interest.”

If more detailed or site specific analysis is required, a calibration procedure similar to that identified in Huff 2012 Section 6 could be applied to the analytical model to fine tune the design selection. Then final site specific design with detailed rock property data could be conducted with a finite element computer code.

6. Future Considerations

This report provided thermal gradients adjacent to the large 32-PWR WPs, and identified workable design concepts that can keep the host rock below a temperature criterion of TC = 100°C. It would be useful to be able to produce full 3D temperature profiles for the repository layout, in particular showing the maximum temperature between WPs in a given drift.

Potential future tasks:

- Revise DSEF Mathcad model to allow explicit output of thermal gradient between adjacent waste packages in an emplacement drift
- Using the new model explore effects of backfill thermal conductivity on keeping the regions between waste packages cool enough to maintain sealing and swelling behavior of the backfill

The thermal-analytical model approach has the potential to produce those types of results, but the combination and arrangement of heat sources, and the output data structure to retrieve the results and create the graphics needs further development. This will be a valuable task for future modeling and analysis.

Note that the CASE LIBRARY in DSEF has been updated to include all of the cases evaluated in this report, so that future analysis can take advantage of the results in developing future alternative design concepts.

7. Conclusions

The objective of this report was to explore repository layout concepts for large (32-PWR) WP disposal in a clay/shale host environment, with the goal of minimizing the layer of host rock that exceeds a defined set of thermal acceptance criteria. The primary temperature acceptance criteria (TC) considered in this study was 100°C, to maintain the host rock layer below the boiling point. The concern is that above 100°C, loss of inter-layer water may occur, potentially resulting in a change in the fracture pathways. A second temperature criterion (TC = 120°C) was also considered because temperatures in excess of 120°C may lead to the alteration of sorption and desorption properties.

The results showed that that large WPs representative of the existing waste inventory (32-PWR WPs with a burnup of 40 GWd/MT), and large WPs representative of future waste streams (32-PWR WPs with a burnup of 60 GWd/MT) could be accommodated in clay/shale repository concepts that meet the temperature acceptance criteria.

Given the large WP and drift spacing of the repository design solutions for 32-PWR WPs, the order of magnitude of the thermal gradients in the host rock in all directions around the WP are expected to be similar to the radial gradient above the top of the central waste package. As a result, the expected temperature at the mid-point between WPs in an emplacement drift should be well below 100°C when the drift wall temperature above the center of a WP equals 100°C.

The thermal gradient along the emplacement drift between WPs would drop more rapidly if the backfill thermal conductivity is less than the host rock, which would normally be the case. For example the host rock thermal conductivity in this report was assumed to be 1.75 W/m-K, and the backfill thermal conductivity based on an engineered backfill of 70% bentonite and 30% sand was assumed to be 1.2 W/m-K. The thermal conductivity of dry bentonite is around 0.6 W/m-K. Lower backfill thermal conductivity of the backfill leads to higher calculated WP surface temperatures, but would also lead to cooler temperatures in the emplacement drifts at the mid-point between WPs.

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Appendix A – Peak Temperature and Time of Peak Temperature Summary Tables for Cases Analyzed

The list of the 32 analyzed cases includes 270 sets of transients facilitated by the parametric study capabilities in DSEF. This appendix includes a summary of the peak temperatures and when they occur for six locations for each case including compliance point 2 (CP2), the drift wall, potentially three additional Engineered Barriers System (EBS) surfaces designated EBS-1, EBS-2, and EBS-3, and the WP surface as the innermost surface. The EBS design for ventilated open mode concepts only includes one EBS layer prior to closure, EBS-1 is a steel liner. As a result the radii and temperatures for EBS-2 and EBS-3 are the same as the surface of the WP. At closure, a layer of 70% bentonite and 30% sand is emplaced over a 10 year period as backfill. The peak temperature of the WP occurs after the emplacement of the backfill.

The definition of the 32 cases summarized in this appendix is as follows:

Drift spacing = 70 m Parametric studies varying WP spacing (15 to 24 m)	**Case # Definition Table**	**32-PWR WP, 40 GWd/MT DSEF base case 229**			
		Ventilation Duration (yr)			
	CP2* (m)	**100**	**75**	**50**	**25**
Clay/Shale (sedimentary) (K_{th} = 1.75 W/m-K)	**1**	500-1	500-6	500-11	500-16
	2	500-2	500-7	500-12	500-17
	3	500-3	500-8	500-13	500-18
	4	500-4	500-9	500-14	500-19
	5	500-5	500-10	500-15	500-20

Drift spacing = 70 & 90 m Parametric studies varying WP spacing (16 to 34 m)	**Case # Definition Table**	**32-PWR WP, 60 GWd/MT DSEF base case 231**	
		Drift Sp / Vent time	
	CP2* (m)	**90 m / 150 y**	**70 m / 150 y**
Clay/Shale (sedimentary) (K_{th} = 1.75 W/m-K)	**1**	500-21 and 500-32**	500-26 and 500-27**
	2	500-22	500-28**
	3	500-23	500-29**
	4	500-24	500-30**
	5	500-25	500-31**

Notes:

* CP2 = Compliance point 2 – depth into the host rock from the surface of the drift wall

** Cases 500-27 to 500-32 extended WP spacing parametric study values to 50 m

Appendix A - Mathcad Iterative Convergence Model

Summary of Peak Temperatures and Times, Ventilation time = 100 years

Case 500-1		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	3.25	102.3	315	99.1	285	96.4	285	94.0	285	91.8	260	89.9	250	88.2	235	86.7	235	85.3	230	84.0	230
Peak Rock	2.25	115.3	210	112.3	205	109.7	190	107.5	190	105.6	185	103.9	185	102.4	185	101.1	180	99.9	175	98.9	175
Liner inner surface	2.225	115.3	210	112.3	205	109.8	190	107.6	190	105.6	185	104.0	185	102.4	185	101.1	180	99.9	175	98.9	175
Backfill inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
Envelope inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
WP surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160

Summary of Peak Temperatures and Times, Ventilation time = 100 years

Case 500-2		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	4.25	96.1	425	92.9	410	90.1	390	87.6	385	85.3	360	83.3	360	81.5	360	79.8	360	78.3	340	76.9	315
Peak Rock	2.25	115.3	210	112.3	205	109.7	190	107.5	190	105.6	185	103.9	185	102.4	185	101.1	180	99.9	175	98.9	175
Liner inner surface	2.225	115.3	210	112.3	205	109.8	190	107.6	190	105.6	185	104.0	185	102.4	185	101.1	180	99.9	175	98.9	175
Backfill inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
Envelope inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
WP surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160

Summary of Peak Temperatures and Times, Ventilation time = 100 years

Case 500-3		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	5.25	92.5	470	89.3	475	86.4	465	83.9	465	81.6	465	79.6	465	77.7	465	76.0	465	74.4	465	73.0	420
Peak Rock	2.25	115.3	210	112.3	205	109.7	190	107.5	190	105.6	185	103.9	185	102.4	185	101.1	180	99.9	175	98.9	175
Liner inner surface	2.225	115.3	210	112.3	205	109.8	190	107.6	190	105.6	185	104.0	185	102.4	185	101.1	180	99.9	175	98.9	175
Backfill inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
Envelope inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
WP surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160

Summary of Peak Temperatures and Times, Ventilation time = 100 years

Case 500-4		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	6.25	90.1	525	86.8	540	84.0	515	81.4	515	79.1	515	77.1	485	75.2	475	73.5	475	71.9	465	70.5	475
Peak Rock	2.25	115.3	210	112.3	205	109.7	190	107.5	190	105.6	185	103.9	185	102.4	185	101.1	180	99.9	175	98.9	175
Liner inner surface	2.225	115.3	210	112.3	205	109.8	190	107.6	190	105.6	185	104.0	185	102.4	185	101.1	180	99.9	175	98.9	175
Backfill inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
Envelope inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
WP surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160

Summary of Peak Temperatures and Times, Ventilation time = 100 years

Case 500-5		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	7.25	88.2	605	85.0	605	82.2	580	79.7	545	77.4	540	75.3	535	73.5	555	71.8	525	70.2	540	68.8	525
Peak Rock	2.25	115.3	210	112.3	205	109.7	190	107.5	190	105.6	185	103.9	185	102.4	185	101.1	180	99.9	175	98.9	175
Liner inner surface	2.225	115.3	210	112.3	205	109.8	190	107.6	190	105.6	185	104.0	185	102.4	185	101.1	180	99.9	175	98.9	175
Backfill inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
Envelope inner surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160
WP surface	1	189.0	165	186.6	160	184.5	160	182.8	160	181.3	160	179.9	160	178.7	160	177.7	160	176.7	160	175.9	160

Summary of Peak Temperatures and Times, Ventilation time = 75 years

Case 500-6		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	3.25	107.0	190	103.9	185	101.2	175	98.8	180	96.6	170	94.8	170	93.1	165	91.6	160	90.3	160	89.2	155
Peak Rock	2.25	123.7	155	120.7	150	118.1	150	115.9	150	113.9	145	112.2	145	110.8	145	109.4	145	108.2	140	107.2	140
Liner inner surface	2.225	123.7	155	120.8	150	118.2	150	115.9	150	114.0	145	112.3	145	110.8	145	109.4	145	108.3	140	107.3	140
Backfill inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
Envelope inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
WP surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135

Summary of Peak Temperatures and Times, Ventilation time = 75 years

Case 500-7		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	4.25	99.1	335	95.9	320	93.0	300	90.4	320	88.0	280	86.0	285	84.1	255	82.5	240	81.0	230	79.6	215
Peak Rock	2.25	123.7	155	120.7	150	118.1	150	115.9	150	113.9	145	112.2	145	110.8	145	109.4	145	108.2	140	107.2	140
Liner inner surface	2.225	123.7	155	120.8	150	118.2	150	115.9	150	114.0	145	112.3	145	110.8	145	109.4	145	108.3	140	107.3	140
Backfill inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
Envelope inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
WP surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135

Summary of Peak Temperatures and Times, Ventilation time = 75 years

Case 500-8		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	5.25	95.1	425	91.7	425	88.8	415	86.2	390	83.8	390	81.7	375	79.8	375	78.1	375	76.5	375	75.0	355
Peak Rock	2.25	123.7	155	120.7	150	118.1	150	115.9	150	113.9	145	112.2	145	110.8	145	109.4	145	108.2	140	107.2	140
Liner inner surface	2.225	123.7	155	120.8	150	118.2	150	115.9	150	114.0	145	112.3	145	110.8	145	109.4	145	108.3	140	107.3	140
Backfill inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
Envelope inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
WP surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135

Summary of Peak Temperatures and Times, Ventilation time = 75 years

Case 500-9		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	6.25	92.5	500	89.1	480	86.2	475	83.5	465	81.2	460	79.0	460	77.1	440	75.3	440	73.7	425	72.2	430
Peak Rock	2.25	123.7	155	120.7	150	118.1	150	115.9	150	113.9	145	112.2	145	110.8	145	109.4	145	108.2	140	107.2	140
Liner inner surface	2.225	123.7	155	120.8	150	118.2	150	115.9	150	114.0	145	112.3	145	110.8	145	109.4	145	108.3	140	107.3	140
Backfill inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
Envelope inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
WP surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135

Summary of Peak Temperatures and Times, Ventilation time = 75 years

Case 500-10		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	7.25	90.5	515	87.2	515	84.3	515	81.6	515	79.3	500	77.2	500	75.3	500	73.5	500	71.9	500	70.4	510
Peak Rock	2.25	123.7	155	120.7	150	118.1	150	115.9	150	113.9	145	112.2	145	110.8	145	109.4	145	108.2	140	107.2	140
Liner inner surface	2.225	123.7	155	120.8	150	118.2	150	115.9	150	114.0	145	112.3	145	110.8	145	109.4	145	108.3	140	107.3	140
Backfill inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
Envelope inner surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135
WP surface	1	211.1	135	208.5	135	206.3	135	204.4	135	202.7	135	201.2	135	199.9	135	198.8	135	197.8	135	196.9	135

Summary of Peak Temperatures and Times, Ventilation time = 50 years

Case 500-11		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	3.25	116.8	130	113.4	130	110.5	125	108.0	125	105.7	125	103.8	125	102.1	120	100.6	120	99.3	120	98.1	120
Peak Rock	2.25	138.1	120	134.7	120	132.0	115	129.6	115	127.6	115	125.8	115	124.2	115	122.8	115	121.5	115	120.5	110
Liner inner surface	2.225	138.1	120	134.8	120	132.0	115	129.7	115	127.6	115	125.8	115	124.2	115	122.8	115	121.6	115	120.5	110
Backfill inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
Envelope inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
WP surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110

Summary of Peak Temperatures and Times, Ventilation time = 50 years

Case 500-12		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	4.25	104.9	150	101.6	145	98.6	145	96.0	145	93.7	145	91.6	140	89.8	140	88.2	135	86.8	135	85.5	130
Peak Rock	2.25	138.1	120	134.7	120	132.0	115	129.6	115	127.6	115	125.8	115	124.2	115	122.8	115	121.5	115	120.5	110
Liner inner surface	2.225	138.1	120	134.8	120	132.0	115	129.7	115	127.6	115	125.8	115	124.2	115	122.8	115	121.6	115	120.5	110
Backfill inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
Envelope inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
WP surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110

Summary of Peak Temperatures and Times, Ventilation time = 50 years

Case 500-13		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	5.25	98.5	335	95.1	310	92.0	310	89.3	240	86.9	215	84.8	240	82.9	240	81.1	195	79.5	175	78.1	170
Peak Rock	2.25	138.1	120	134.7	120	132.0	115	129.6	115	127.6	115	125.8	115	124.2	115	122.8	115	121.5	115	120.5	110
Liner inner surface	2.225	138.1	120	134.8	120	132.0	115	129.7	115	127.6	115	125.8	115	124.2	115	122.8	115	121.6	115	120.5	110
Backfill inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
Envelope inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
WP surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110

Summary of Peak Temperatures and Times, Ventilation time = 50 years

Case 500-14		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	6.25	95.4	395	92.0	395	88.9	395	86.2	355	83.8	375	81.6	365	79.6	350	77.7	350	76.1	350	74.6	355
Peak Rock	2.25	138.1	120	134.7	120	132.0	115	129.6	115	127.6	115	125.8	115	124.2	115	122.8	115	121.5	115	120.5	110
Liner inner surface	2.225	138.1	120	134.8	120	132.0	115	129.7	115	127.6	115	125.8	115	124.2	115	122.8	115	121.6	115	120.5	110
Backfill inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
Envelope inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
WP surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110

Summary of Peak Temperatures and Times, Ventilation time = 50 years

Case 500-15		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	7.25	93.4	470	89.9	470	86.8	470	84.1	470	81.7	470	79.5	470	77.5	415	75.6	415	73.9	415	72.4	415
Peak Rock	2.25	138.1	120	134.7	120	132.0	115	129.6	115	127.6	115	125.8	115	124.2	115	122.8	115	121.5	115	120.5	110
Liner inner surface	2.225	138.1	120	134.8	120	132.0	115	129.7	115	127.6	115	125.8	115	124.2	115	122.8	115	121.6	115	120.5	110
Backfill inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
Envelope inner surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110
WP surface	1	245.1	110	242.1	110	239.6	110	237.4	110	235.5	110	233.9	110	232.4	110	231.2	110	230.0	110	229.0	110

Appendix A - Mathcad Iterative Convergence Model

Summary of Peak Temperatures and Times, Ventilation time = 25 years

Case 500-16		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	3.25	133.8	95	130.0	95	126.6	95	123.8	95	121.2	95	119.0	95	117.2	90	115.6	90	114.2	90	112.9	90
Peak Rock	2.25	161.6	90	157.8	90	154.5	90	151.8	85	149.6	85	147.7	85	146.1	85	144.6	85	143.3	85	142.2	85
Liner inner surface	2.225	161.6	90	157.8	90	154.6	90	151.9	85	149.7	85	147.8	85	146.1	85	144.7	85	143.4	85	142.3	85
Backfill inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
Envelope inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
WP surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85

Summary of Peak Temperatures and Times, Ventilation time = 25 years

Case 500-17		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	4.25	117.8	105	113.9	105	110.6	105	107.6	100	105.1	100	102.9	100	100.9	100	99.2	95	97.7	95	96.3	95
Peak Rock	2.25	161.6	90	157.8	90	154.5	90	151.8	85	149.6	85	147.7	85	146.1	85	144.6	85	143.3	85	142.2	85
Liner inner surface	2.225	161.6	90	157.8	90	154.6	90	151.9	85	149.7	85	147.8	85	146.1	85	144.7	85	143.4	85	142.3	85
Backfill inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
Envelope inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
WP surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85

Summary of Peak Temperatures and Times, Ventilation time = 25 years

Case 500-18		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	5.25	107.8	115	104.1	115	100.8	115	97.8	115	95.2	115	92.9	115	90.9	110	89.1	110	87.4	110	86.0	105
Peak Rock	2.25	161.6	90	157.8	90	154.5	90	151.8	85	149.6	85	147.7	85	146.1	85	144.6	85	143.3	85	142.2	85
Liner inner surface	2.225	161.6	90	157.8	90	154.6	90	151.9	85	149.7	85	147.8	85	146.1	85	144.7	85	143.4	85	142.3	85
Backfill inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
Envelope inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
WP surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85

Summary of Peak Temperatures and Times, Ventilation time = 25 years

Case 500-19		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	6.25	101.3	130	97.7	135	94.4	135	91.5	135	89.0	135	86.7	135	84.6	135	82.7	130	81.0	130	79.5	125
Peak Rock	2.25	161.6	90	157.8	90	154.5	90	151.8	85	149.6	85	147.7	85	146.1	85	144.6	85	143.3	85	142.2	85
Liner inner surface	2.225	161.6	90	157.8	90	154.6	90	151.9	85	149.7	85	147.8	85	146.1	85	144.7	85	143.4	85	142.3	85
Backfill inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
Envelope inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
WP surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85

Summary of Peak Temperatures and Times, Ventilation time = 25 years

Case 500-20		WP Spacing 15, m		WP Spacing 16, m		WP Spacing 17, m		WP Spacing 18, m		WP Spacing 19, m		WP Spacing 20, m		WP Spacing 21, m		WP Spacing 22, m		WP Spacing 23, m		WP Spacing 24, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	7.25	97.2	365	93.6	355	90.4	355	87.6	355	85.1	235	82.8	235	80.7	235	78.8	210	77.0	210	75.4	210
Peak Rock	2.25	161.6	90	157.8	90	154.5	90	151.8	85	149.6	85	147.7	85	146.1	85	144.6	85	143.3	85	142.2	85
Liner inner surface	2.225	161.6	90	157.8	90	154.6	90	151.9	85	149.7	85	147.8	85	146.1	85	144.7	85	143.4	85	142.3	85
Backfill inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
Envelope inner surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85
WP surface	1	299.0	85	295.5	85	292.5	85	289.9	85	287.7	85	285.8	85	284.2	85	282.7	85	281.5	85	280.3	85

Appendix A - Mathcad Iterative Convergence Model

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 90 m drift spacing

Case 500-21		WP Spacing 16, m		WP Spacing 18, m		WP Spacing 20, m		WP Spacing 22, m		WP Spacing 24, m		WP Spacing 26, m		WP Spacing 28, m		WP Spacing 30, m		WP Spacing 32, m		WP Spacing 34, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	3.25	104.3	255	99.3	250	95.3	245	92.2	245	89.6	240	87.6	235	85.9	230	84.5	230	83.3	230	82.3	230
Peak Rock	2.25	120.7	235	115.8	230	112.0	230	108.9	230	106.5	225	104.6	220	103.1	220	101.8	220	100.7	220	99.8	215
Liner inner surface	2.225	120.8	235	115.8	230	112.0	230	109.0	230	106.6	225	104.7	220	103.1	220	101.8	220	100.7	220	99.8	215
Backfill inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
Envelope inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
WP surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 90 m drift spacing

Case 500-22		WP Spacing 16, m		WP Spacing 18, m		WP Spacing 20, m		WP Spacing 22, m		WP Spacing 24, m		WP Spacing 26, m		WP Spacing 28, m		WP Spacing 30, m		WP Spacing 32, m		WP Spacing 34, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	4.25	94.9	295	89.9	290	85.9	270	82.7	270	80.0	270	77.8	255	76.0	250	74.5	245	73.2	240	72.2	240
Peak Rock	2.25	120.7	235	115.8	230	112.0	230	108.9	230	106.5	225	104.6	220	103.1	220	101.8	220	100.7	220	99.8	215
Liner inner surface	2.225	120.8	235	115.8	230	112.0	230	109.0	230	106.6	225	104.7	220	103.1	220	101.8	220	100.7	220	99.8	215
Backfill inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
Envelope inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
WP surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 90 m drift spacing

Case 500-23		WP Spacing 16, m		WP Spacing 18, m		WP Spacing 20, m		WP Spacing 22, m		WP Spacing 24, m		WP Spacing 26, m		WP Spacing 28, m		WP Spacing 30, m		WP Spacing 32, m		WP Spacing 34, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	5.25	89.1	330	84.1	315	80.2	315	76.9	315	74.2	305	71.9	295	70.0	320	68.4	280	67.0	270	65.8	260
Peak Rock	2.25	120.7	235	115.8	230	112.0	230	108.9	230	106.5	225	104.6	220	103.1	220	101.8	220	100.7	220	99.8	215
Liner inner surface	2.225	120.8	235	115.8	230	112.0	230	109.0	230	106.6	225	104.7	220	103.1	220	101.8	220	100.7	220	99.8	215
Backfill inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
Envelope inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
WP surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 90 m drift spacing

Case 500-24		WP Spacing 16, m		WP Spacing 18, m		WP Spacing 20, m		WP Spacing 22, m		WP Spacing 24, m		WP Spacing 26, m		WP Spacing 28, m		WP Spacing 30, m		WP Spacing 32, m		WP Spacing 34, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	6.25	85.3	380	80.5	380	76.5	380	73.2	380	70.5	380	68.2	355	66.2	330	64.5	330	63.0	330	61.7	315
Peak Rock	2.25	120.7	235	115.8	230	112.0	230	108.9	230	106.5	225	104.6	220	103.1	220	101.8	220	100.7	220	99.8	215
Liner inner surface	2.225	120.8	235	115.8	230	112.0	230	109.0	230	106.6	225	104.7	220	103.1	220	101.8	220	100.7	220	99.8	215
Backfill inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
Envelope inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
WP surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 90 m drift spacing

Case 500-25		WP Spacing 16, m		WP Spacing 18, m		WP Spacing 20, m		WP Spacing 22, m		WP Spacing 24, m		WP Spacing 26, m		WP Spacing 28, m		WP Spacing 30, m		WP Spacing 32, m		WP Spacing 34, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	7.25	82.6	415	77.8	430	73.9	430	70.6	380	67.9	380	65.6	380	63.6	380	61.9	380	60.4	380	59.1	380
Peak Rock	2.25	120.7	235	115.8	230	112.0	230	108.9	230	106.5	225	104.6	220	103.1	220	101.8	220	100.7	220	99.8	215
Liner inner surface	2.225	120.8	235	115.8	230	112.0	230	109.0	230	106.6	225	104.7	220	103.1	220	101.8	220	100.7	220	99.8	215
Backfill inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
Envelope inner surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210
WP surface	1	202.2	215	197.7	215	194.4	210	192.0	210	190.0	210	188.4	210	187.1	210	186.0	210	185.1	210	184.3	210

Appendix A - Mathcad Iterative Convergence Model

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 70 m drift spacing

Case 500-26		WP Spacing 16, m		WP Spacing 18, m		WP Spacing 20, m		WP Spacing 22, m		WP Spacing 24, m		WP Spacing 26, m		WP Spacing 28, m		WP Spacing 30, m		WP Spacing 32, m		WP Spacing 34, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	3.25	111.6	305	105.6	305	100.8	290	96.9	290	93.8	270	91.2	265	89.0	255	87.3	245	85.8	240	84.6	235
Peak Rock	2.25	126.4	255	120.6	250	116.1	245	112.5	240	109.7	235	107.4	230	105.6	225	104.1	220	102.8	220	101.7	220
Liner inner surface	2.225	126.4	255	120.6	250	116.1	245	112.6	240	109.7	235	107.5	230	105.6	225	104.1	220	102.8	220	101.8	220
Backfill inner surface	1	206.3	215	201.4	215	197.7	210	194.9	210	192.7	210	190.9	210	189.4	210	188.1	210	187.1	210	186.2	210
Envelope inner surface	1	206.3	215	201.4	215	197.7	210	194.9	210	192.7	210	190.9	210	189.4	210	188.1	210	187.1	210	186.2	210
WP surface	1	206.3	215	201.4	215	197.7	210	194.9	210	192.7	210	190.9	210	189.4	210	188.1	210	187.1	210	186.2	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 70 m drift spacing

Case 500-27		WP Spacing 32, m		WP Spacing 34, m		WP Spacing 36, m		WP Spacing 38, m		WP Spacing 40, m		WP Spacing 42, m		WP Spacing 44, m		WP Spacing 46, m		WP Spacing 48, m		WP Spacing 50, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	3.25	85.8	240	84.6	235	83.5	230	82.6	230	81.9	230	81.2	220	80.7	220	80.2	220	79.8	220	79.4	220
Peak Rock	2.25	102.8	220	101.7	220	100.8	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Liner inner surface	2.23	102.8	220	101.8	220	100.9	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Backfill inner surface	1.00	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
Envelope inner surface	1.00	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
WP surface	1.00	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 70 m drift spacing

Case 500-28		WP Spacing 32, m		WP Spacing 34, m		WP Spacing 36, m		WP Spacing 38, m		WP Spacing 40, m		WP Spacing 42, m		WP Spacing 44, m		WP Spacing 46, m		WP Spacing 48, m		WP Spacing 50, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	4.25	76.5	290	75.1	280	73.8	270	72.8	255	71.9	250	71.1	245	70.5	240	69.9	235	69.4	230	69.0	230
Peak Rock	2.25	102.8	220	101.7	220	100.8	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Liner inner surface	2.225	102.8	220	101.8	220	100.9	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Backfill inner surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
Envelope inner surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
WP surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 70 m drift spacing

Case 500-29		WP Spacing 32, m		WP Spacing 34, m		WP Spacing 36, m		WP Spacing 38, m		WP Spacing 40, m		WP Spacing 42, m		WP Spacing 44, m		WP Spacing 46, m		WP Spacing 48, m		WP Spacing 50, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	5.25	71.3	380	69.7	340	68.3	345	67.1	315	66.0	305	65.1	290	64.3	280	63.6	270	63.0	260	62.5	250
Peak Rock	2.25	102.8	220	101.7	220	100.8	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Liner inner surface	2.225	102.8	220	101.8	220	100.9	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Backfill inner surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
Envelope inner surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
WP surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 70 m drift spacing

Case 500-30		WP Spacing 32, m		WP Spacing 34, m		WP Spacing 36, m		WP Spacing 38, m		WP Spacing 40, m		WP Spacing 42, m		WP Spacing 44, m		WP Spacing 46, m		WP Spacing 48, m		WP Spacing 50, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	6.25	68.0	440	66.4	420	64.9	380	63.6	380	62.5	380	61.5	380	60.5	380	59.7	330	59.0	330	58.3	320
Peak Rock	2.25	102.8	220	101.7	220	100.8	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Liner inner surface	2.225	102.8	220	101.8	220	100.9	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Backfill inner surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
Envelope inner surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
WP surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210

Appendix A - Mathcad Iterative Convergence Model

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 70 m drift spacing

Case 500-31		WP Spacing 32, m		WP Spacing 34, m		WP Spacing 36, m		WP Spacing 38, m		WP Spacing 40, m		WP Spacing 42, m		WP Spacing 44, m		WP Spacing 46, m		WP Spacing 48, m		WP Spacing 50, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Point	7.25	65.9	490	64.2	480	62.7	480	61.4	480	60.2	460	59.1	460	58.1	415	57.2	380	56.4	380	55.8	380
Peak Rock	2.25	102.8	220	101.7	220	100.8	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Liner inner surface	2.225	102.8	220	101.8	220	100.9	215	100.1	215	99.5	215	98.9	215	98.4	215	98.0	215	97.6	215	97.2	215
Backfill inner surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
Envelope inner surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210
WP surface	1	187.1	210	186.2	210	185.4	210	184.8	210	184.2	210	183.7	210	183.3	210	182.9	210	182.5	210	182.2	210

Summary of Peak Temperatures and Times, 60 GWd/MT burnup, Ventilation time = 150 years, 90 m drift spacing

Case 500-32		WP Spacing 32, m		WP Spacing 34, m		WP Spacing 36, m		WP Spacing 38, m		WP Spacing 40, m		WP Spacing 42, m		WP Spacing 44, m		WP Spacing 46, m		WP Spacing 48, m		WP Spacing 50, m	
Location	Radius, m	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr	Peak Temp, C	TooR, yr
Second Compliance Poin	3.25	83.3	230	82.3	230	81.4	225	80.7	220	80.1	220	79.6	220	79.1	220	78.7	220	78.4	215	78.1	215
Peak Rock	2.25	100.7	220	99.8	215	99.0	215	98.4	215	97.8	215	97.3	215	96.9	215	96.5	215	96.2	215	95.9	210
Liner inner surface	2.23	100.7	220	99.8	215	99.0	215	98.4	215	97.8	215	97.4	215	96.9	215	96.6	215	96.2	215	96.0	210
Backfill inner surface	1.00	185.1	210	184.3	210	183.6	210	183.1	210	182.6	210	182.2	210	181.8	210	181.5	210	181.2	210	180.9	210
Envelope inner surface	1.00	185.1	210	184.3	210	183.6	210	183.1	210	182.6	210	182.2	210	181.8	210	181.5	210	181.2	210	180.9	210
WP surface	1.00	185.1	210	184.3	210	183.6	210	183.1	210	182.6	210	182.2	210	181.8	210	181.5	210	181.2	210	180.9	210

Appendix B - Excavation Length and Repository Footprint versus Waste Package and Drift Spacing

The methodology for calculating repository subsurface excavation length and excavation volume is described in Section 9, and Figures 20 and 21 of the DSEF Version 2.1 User's Manual (Greenberg 2013b). The calculation is straight-forward, and is based on a set of repository-level input assumptions provided on the DSEF INPUTS worksheet. Given the total MTU for a repository, such as 140,000 MTU shown in Table 6, the MTU per assembly, and the WP capacity, the number of WPs can be calculated. Then, with some assumptions about spacing, emplacement drift and diameters, the emplacement drift excavation length and excavation volume can be calculated.

Emplacement panel dimensions are based on assumptions about the number of WPs per emplacement drift, and the number of emplacement drifts per panel. Given the definition of the number of WPs per emplacement panel, the total number of panels per repository is calculated. The current analysis assumes one access/service main per emplacement panel. The dimensions of a single panel are calculated as shown in Figure 16.

The specific repository-level input data used this report are shown in Table 6, and is based on a repository with a total capacity of 140,000 MTU. The example excavation length calculations were limited to the cases that assumed a WP capacity of 32-PWR assemblies. The green colored labels in the right-hand column of Table 6 show the variable range names used within the DSEF Excel workbook.

The thermal analysis is based on current PWR fuel design with 17x17 fuel rod assemblies and enrichments leading to 0.47 MTU per assembly. The average mix of existing spent fuel assemblies as per Table 4-1 of Hardin 2012 has a lower MTU per assembly because it includes the older fuel inventory. Assuming all of the 140,000 MTU is made up of 32-PWR WPs with 0.47 MTU/assembly yields 9,309 WPs per repository. Table 4-1 of Hardin 2012 shows an estimated number of WPs for the clay/shale open sedimentary design based on a mix of PWR and BWR fuel assemblies for 21-PWR or 44-BWR assembly WPs of 16,157 for proportionally larger WPs this would correspond to 10,603 WPs, which is roughly comparable to the number of waste packages considered for 140,000 MTU in this report.

Figure 17 shows the normalized total repository excavation length as a function of both WP and drift spacing, and Figure 18 shows the repository footprint area as a function of the same variables.

Note that the DSEF cost calculations first evaluate a raw calculated set of values, and then apply cost contingency factors to account for cost uncertainties. However, since the objective in these calculations was to compare relative excavation lengths of the various repository design options, the values were all normalized to the base case having a WP separation of 10 m, and a drift spacing of 30 m. Given this normalization approach, all of the contingency factors cancel out, and give the same result as a normalization based on the raw calculated values.

The raw calculated excavation lengths for the base cases analyzed for the clay/shale open repository layout are shown in Table 7, and the normalized values are shown in Figure 17. Note that the calculated excavation lengths include emplacement and service drifts, but do not include ramps and shafts.

Appendix B - Excavation Length and Repository Footprint versus Waste Package and Drift Spacing

Table 6 - DSEF input data for excavation length, excavation volume, and repository footprint area calculations

MTU per Repository	140,000	<-- Repository_MTU
MTU per assembly	0.47	<-- Repository_avg_MTU_per_assembly

WP/ (Emplacement Drift)	15	<-- Repository_WP_per_drift
# Emplacement Drifts / panel	48	<-- Repository_drifts_per_panel
Radius (m) of Access Main (r_{AM})	2.75	<-- Repository_access_main_r
Extra Spacing (m) at ends of Emplacement Drift	5	<-- Repository_drift_extra_length
Extra Spacing (m) at ends of Access Main	5	<-- Repository_access_extra_length

Repository Design Mode for Cost Calculation (Open or Enclosed)	OPEN	<-- Repository_design_mode

Waste Package Capacity	Waste Package Length (m)	WP Outer Radius (m)	WP Spacing (m)	Radius (m) of Emplacement Drift (r_{DW})	Emplacement Drift Spacing (m)
32	5	1	10	2.25	30

Table 7 - Total emplacement and service drift excavation length (km) summary table

Excavation Length (km) (for a 140,000 MTU repository)	Base Case Required Excavation Length Summary Table	32-PWR WP DSEF base case 229		
		WP Spacing (m)		
	Dr Sp (m)	10	20	30
Clay/shale (sedimentary)	30	115	201	288
	60	133	220	307
	90	151	238	325

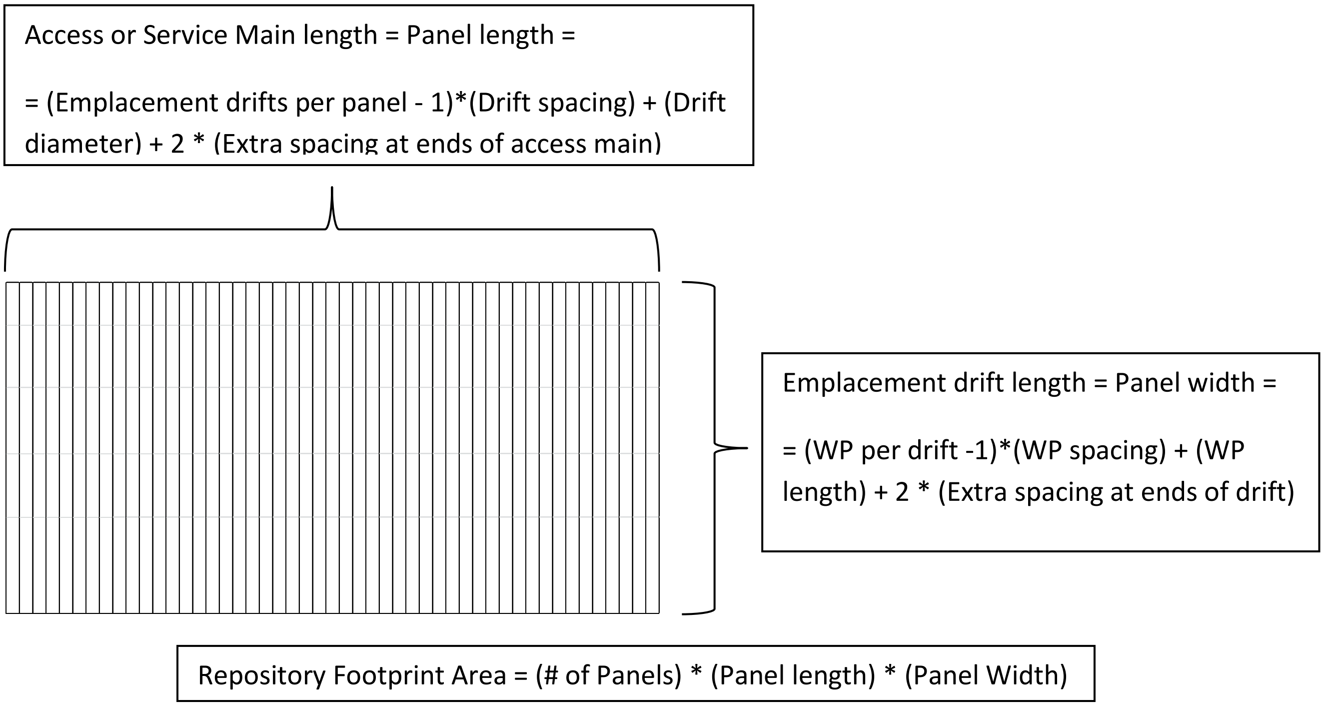


Figure 16 – Repository layout unit emplacement panel diagram for the footprint area calculation

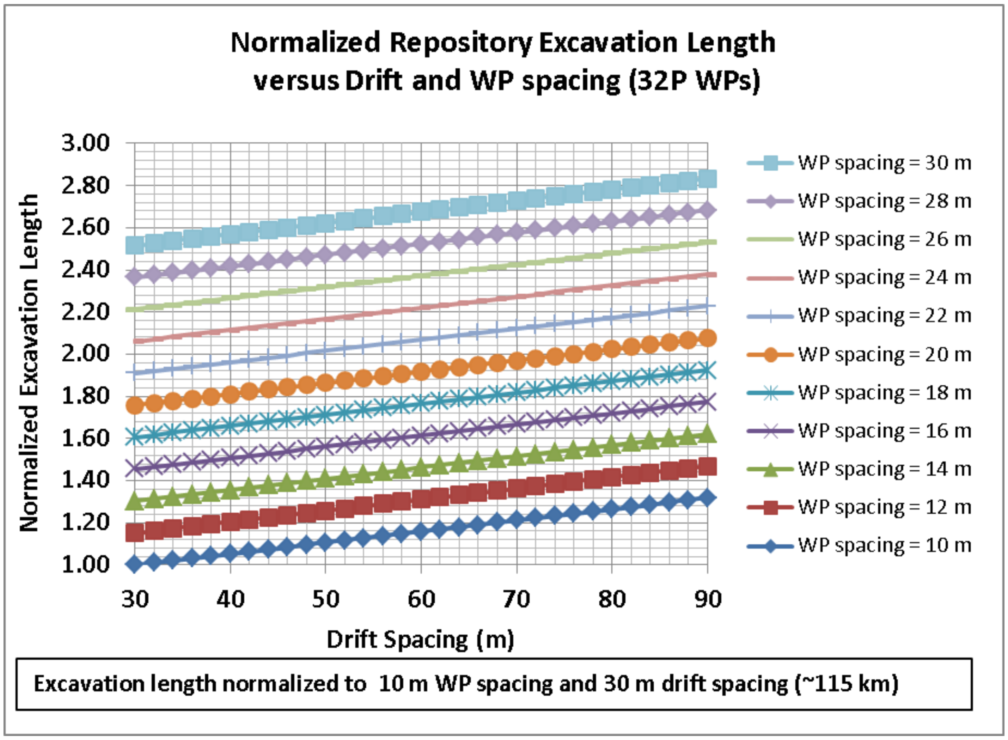
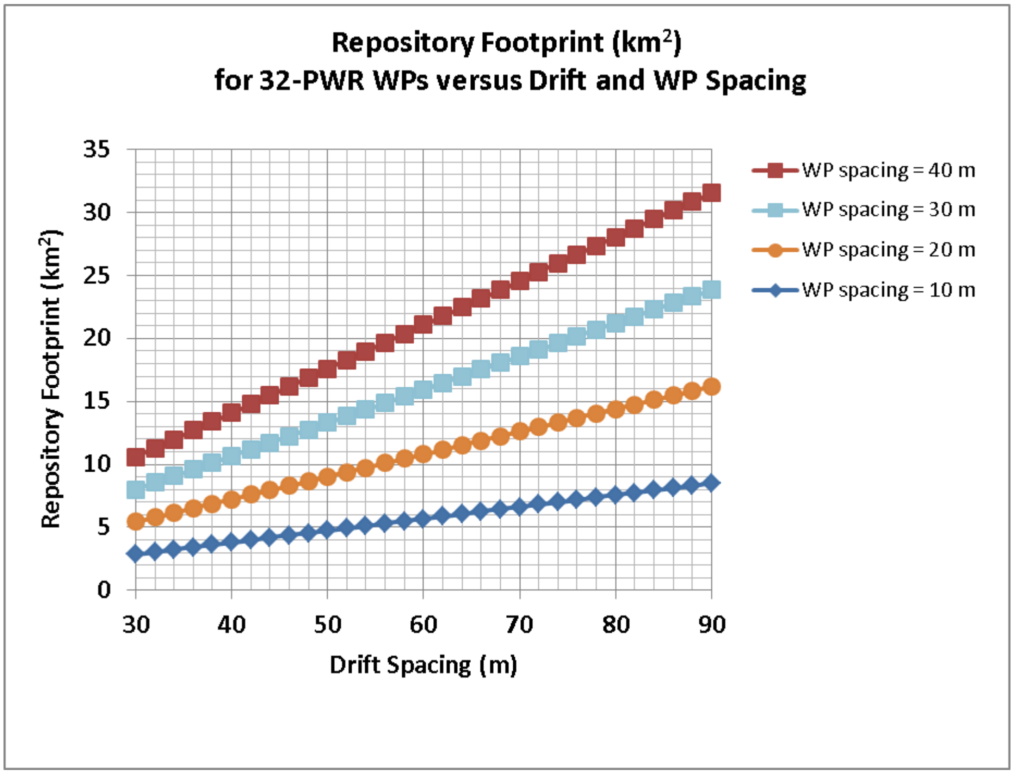


Figure 17 – Normalized repository excavation length versus drift and WP spacing for 32-PWR WPs

Note that the excavation length includes emplacement and service drifts, but does not include ramps and shafts.



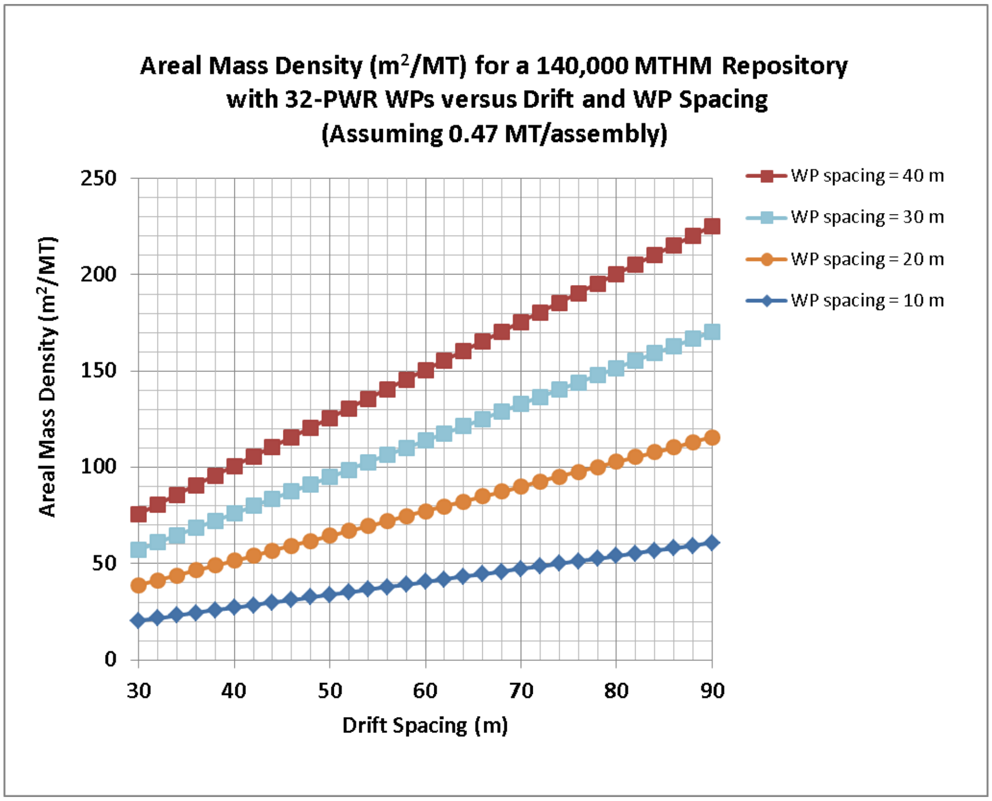


Figure 18 – Repository footprint area and areal mass loading for 32-PWR WPs versus drift and WP spacing