Sensitivity Analyses to Investigate the Influence of the Container Spacing and Tunnel Spacing on the Thermal Response in a Deep Geological Repository

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R. Guo

Atomic Energy of Canada Limited

NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Nuclear Waste Management Organization
22 St. Clair Avenue East, 6th Floor
Toronto, Ontario
M4T 2S3
Canada

Tel: 416-934-9814
Web: www.nwmo.ca

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ABSTRACT

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Author(s): R. Guo
Company: Atomic Energy of Canada Limited
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Abstract

This report describes the numerical modelling of a method for placing used-fuel containers in a horizontal tunnel in a deep geological repository (DGR). A series of thermal sensitivity analyses was carried out using the CODE_BRIGHT finite-element program to investigate the influence of tunnel spacing and container spacing on the development of the container-surface temperature and the tunnel-wall temperature in a conceptual repository located at a depth of 750 m in a limestone geosphere. The influence of buffer thermal conductivity on container- and tunnel-wall temperatures in a repository was also studied in this report.

The thermal analyses found that the buffer thermal conductivity does not significantly influence the tunnel-wall temperature. However, the analyses show that the buffer thermal conductivity does have a significant influence on the container-surface temperature during the first 100 years after waste placement.

The results demonstrate that the buffer composition and the resulting thermal conductivity is an important design consideration to optimize container and tunnel spacing within a Horizontal Tunnel Placement DGR, and to limit the container-surface temperature.

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM), the approach accepted by the Government of Canada (NRCan 2007) for the long-term management of Canada's used nuclear fuel. APM has, as its end-point, the containment and isolation of used fuel in a deep repository constructed in a suitable host rock formation such as crystalline or sedimentary rock (NWMO 2005). Crystalline rock and sedimentary rock are considered to be potential host geologic media in the current Canadian deep geological repository (DGR) conceptual design studies.

The thermal and mechanical response of a DGR situated in crystalline rock has been numerically evaluated by CTECH (2002), RWE NUKEM Limited (2003, 2004) and Guo (2007). Sedimentary rock is being studied by some international nuclear waste management organizations (e.g., NAGRA, ANDRA, ONDRAF/NIRAS) as the host medium for their deep geological repositories (DGRs). NAGRA has proposed an in-room placement method for a used-fuel/high-level waste repository (NAGRA 1985; NAGRA 2002). A scoping-level investigation was performed by Baumgartner (2005) to assess the feasibility of applying a NAGRA-type in-room placement method in a DGR for Canadian used nuclear fuel in representative shale and limestone sedimentary formations in Canada. The NWMO refers to the NAGRA-type in-room used-fuel container placement method as the Horizontal Tunnel Placement (HTP) method.

In 2007, an assessment of the thermal and mechanical response of the in-floor borehole used-fuel container placement method for a deep geological repository in crystalline rock was performed using CODE_BRIGHT (Guo 2007). CODE_BRIGHT is a general-purpose finite element program for the analysis of coupled thermo-hydro-mechanical (THM) phenomena in geological media and developed by Universidad Politécnica de Cataluña (Olivella et al. 1996). In order to further develop the Canadian capability for modelling using CODE_BRIGHT, CODE_BRIGHT (version 23beta) will be used to assess the thermal and thermal-mechanical response of a used fuel DGR in limestone using the HTP method at an assumed depth of 750-m below ground surface. GiD is a universal, adaptive and user-friendly graphical user interface for geometrical modelling, data input and visualisation of results for all types of numerical simulation programs (http://gid/cimne.upc.es). It is developed by Universidad Politécnica de Cataluña. Version 8.0.9 of GiD will be used for pre-processing of modelling input and post-processing of modelling results. Both near-field and far-field thermal-mechanical analyses will be performed to assess thermally acceptable repository layouts, mechanical stability of the near-field rock at the walls of the placement room (tunnel), and evolution of the thermal response for various locations in a deep geological repository.

2. OBJECTIVE OF AND SCOPE OF THE ANALYSES

The coupled thermo-mechanical modelling of a deep geological repository in limestone using the HTP method was divided into several tasks. The objective of the task described in this report was to perform near-field numerical thermal analyses to establish the closest container spacing within a placement room that will produce a container-surface temperature, which will not exceed a specified maximum container-surface temperature for the repository arrangement described in Section 4.2. Based on design assumptions and input parameters from earlier modelling work, it is assumed that the container outer surface temperature limit of ≤100°C will not be achievable and a higher maximum container-surface temperature will result from these analyses. The sensitivity of container-surface temperature to placement room spacing (tunnel spacing) should be assessed for placement room spacing of 20 m and 70 m. The sensitivity of the thermal results to the use of two single value thermal conductivities for the buffer sealing materials in the placement room (i.e., 0.4 W/(m·°C) and 0.7 W/(m·°C))[1] should also be assessed. The temperature gradient from the container surface through the sealing material and into the near-field rock should be the output from each analysis. In order to achieve this objective, the following modelling was performed.

- Group 1: Investigated the influence of tunnel spacing on the maximum container temperatures by performing 10 near-field thermal analyses for an infinite repository with fixed centre to centre container spacing of 28 m and varying tunnel spacing of 20, 24, 28, 32, 36, 40, 50, 55, 60 and 70 m.

- Group 2: Two sets of thirty-six cases were conducted in order to investigate the detailed influence of tunnel spacing and container spacing on the container-surface temperature and tunnel-wall temperature with two values of 0.4 and 0.7 W/(m·°C) for the buffer thermal conductivity (Table 1).

Table 1: Modelling Cases for Group 2

Tunnel spacing (m) \ Cases \ Container spacing (m)	**12**	**14**	**18**	**20**	**24**	**28**
20	x	x	x	x	x	x
24	x	x	x	x	x	x
28	x	x	x	x	x	x
32	x	x	x	x	x	x
36	x	x	x	x	x	x
40	x	x	x	x	x	x

- Group 3: Six cases were performed to investigate the influence of the buffer thermal conductivity on container-surface temperatures. The six values of the thermal conductivity were 0.4, 0.46, 0.53, 0.6, 0.65, 0.7 W/(m·°C) for a horizontally infinite repository with a tunnel spacing of 24 m and a container spacing of 14 m.

[1] Buffer thermal conductivity of 0.4 W/(m·°C) is based on relatively dry, highly-compacted bentonite. Buffer thermal conductivity of 0.7 W/(m·°C) is based on 50/50 bentonite/sand mixture.

- Group 4: Based on the analyses from the above three groups, 20 additional cases (Table 2) were conducted to analyze the container- and tunnel-wall temperatures in a repository with container spacing of 10 m, 8 m and 6 m.

Table 2: Modeled Cases for a Repository with Container Spacings of 6 m, 8 m and 10 m

Container spacing (m) / Cases / Tunnel spacing (m)	**10 (Thermal conductivities of buffer are 0.4 and 0.7 W/(m·ºC))**	**8 (Thermal conductivities of buffer are 0.4 and 0.7 W/(m·ºC))**	**6 (Thermal conductivity of the buffer is 0.7 W/(m·ºC))**
20	x	x	x
24	x	x	x
28	x	x	x
32	x	x	x

3. REFERENCE GEOSPHERE

The DGR was assumed to be located in a representative limestone formation at a depth of 750 m.

For the purpose of this thermal assessment, the reference geosphere was taken from the Paleozoic sedimentary sequence of the Michigan Basin (Golder Associates 2003). The geological environment has several layers of formations comprising from top to bottom:

- 10 m of overburden soil (1 m to 10 m depth);
- 440 m of dolostone (10m to 450 m depth);
- 200 m of shale (450 m to 650 m depth);
- 200 m of limestone (650 m to 850 m depth);
- 10 m of sandstone (850 m to 860 m depth); and
- granite (>860 m depth).

The thermal material properties for these representative formations are summarized in Table 3.

Table 3: Thermal Material Properties for Rock Types of the Michigan Basin (after Baumgartner 2005)

Rock Type (from surface)	Thickness (m)	Dry Density* (Mg/m^3)	Porosity* (η) (%)	Thermal Conduct. (W/(m·°C))	Specific Heat (J/(kg·°C))
Soils	10	1.8	30	1.5	1500
Mixed Dolostone & Shales	440	2.6	7	2.3	920
Shale	200	2.6	11	2.1	975
Limestone	180	2.6	2	2.3	830
Sandstone	10	2.6	0.5	2.5	810
Granitic Gneiss	>100	2.8	<0.4	3.0	810

*Golder Associates (2003).

The specific gravity of the active clay particles within the buffer was 2780 kg/m^3. The porosity of the buffer was 0.4. The specific heat was 800 J/(kg·°C).

4. AN IN-ROOM HORIZONTAL PLACEMENT OPTION

4.1 USED-FUEL CONTAINER AND SEALING MATERIALS

The NAGRA-type in-room placement method applied in a Canadian context was adapted from the arrangement described by Baumgartner (2005). The reference container is the IV-324-Hex used-fuel container, which has an outside diameter of 1168 mm and a length of 3867 mm (Maak and Simmons 2001). The current cross-sectional arrangement in the placement room has a tunnel diameter of 2500 mm resulting in a cross-section annular thickness of 666 mm for the Highly Compacted Bentonite (HCB) blocks and bentonite pellets (Figure 1). The sealing materials between the container and the placement room wall are 100% HCB blocks supporting the container and 100% bentonite pellets in the region surrounding it. The pellet composition consists of 80% HCB granules and 20% powder. These analyses consider sensitivity of container temperature to sealing material thermal conductivities using:

- 0.4 (W/(m·°C)) assuming relatively dry HCB material (i.e., as placed moisture content or less); and

- 0.7 (W/(m·°C)) assuming a more thermally conductive material (e.g., 50/50 bentonite/sand buffer).

4.2 PLACEMENT ROOM AND REPOSITORY LAYOUT

The HTP method is being studied for application in Canadian sedimentary rock. The starting point for this study is the work of RWE NUKEM Limited (2004), which assessed the NAGRA-type in-room placement method. However, the diameter of the borehole is the same as described by Baumgartner (2005). Figure 2 shows the layout of a typical 305-m-long placement room, including the 7-m-diameter access zone, the used fuel containers (UFCs) and the sealing bulkheads, and Figure 3 shows one potential 2158-m x 2120-m repository layout. The placement rooms are spaced on 55-m centres and are grouped in 6 panels of 36 rooms each. The total number of rooms within this DGR layout is 216. The repository design parameters are shown in Table 4.

These arrangements represent the starting point for these analyses and the dimensions of the container spacing. The placement room spacing and hence the repository layout will change for each case analysed.

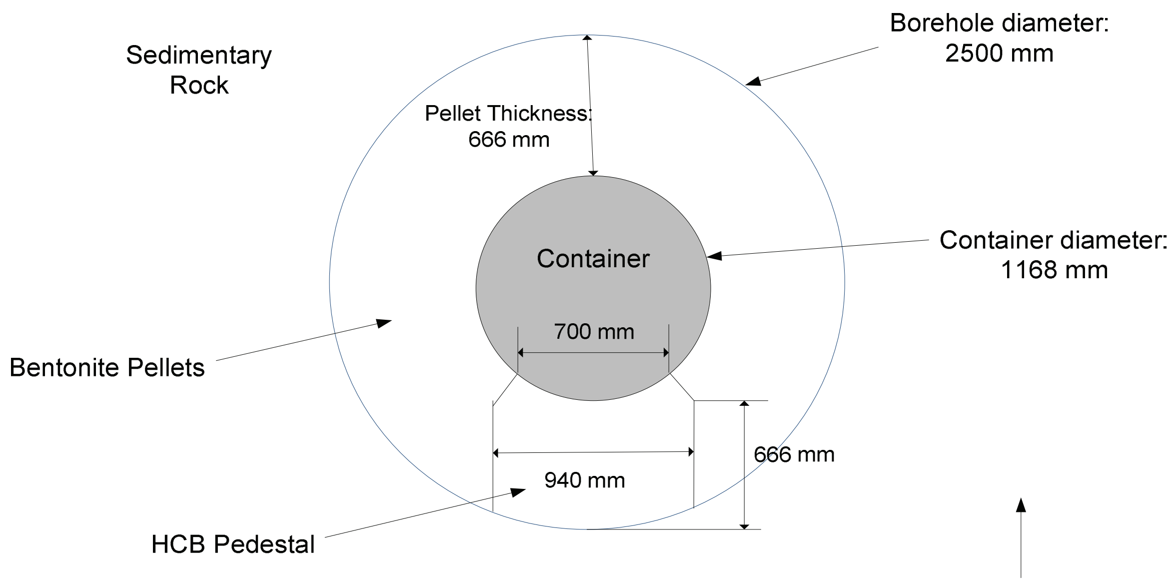

Figure 1: Cross-section of IV-324-Hex Used-Fuel Container within a Horizontal Tunnel Placement Room (NAGRA-type in-room placement after Baumgartner 2005)

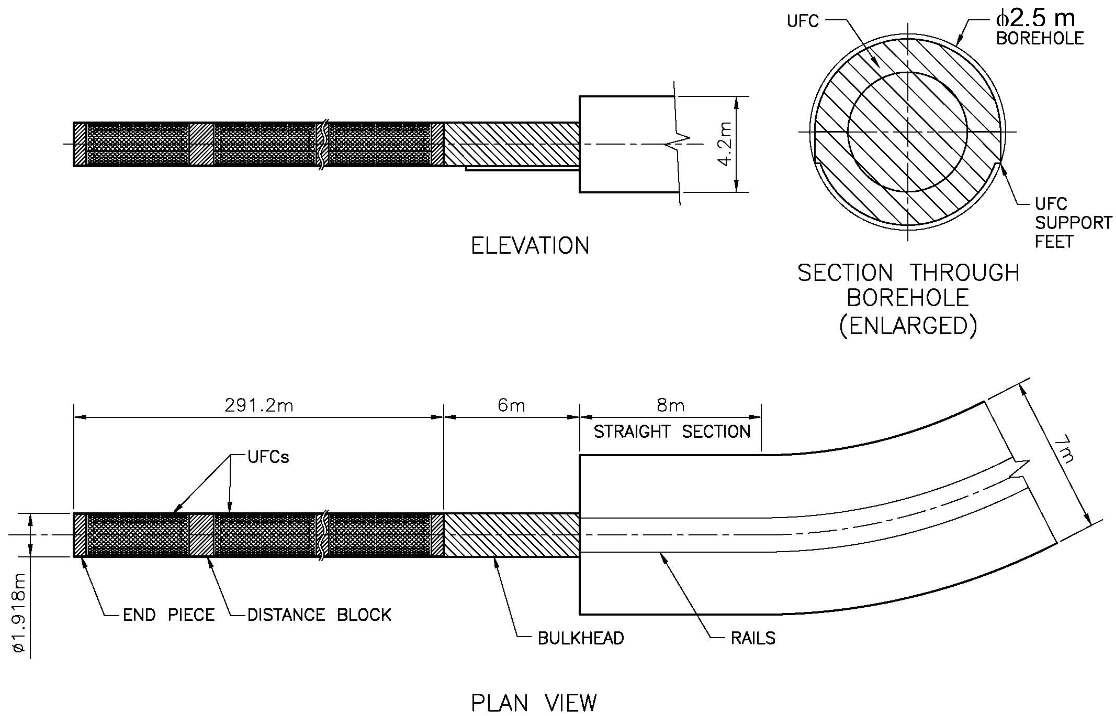

Figure 2: Plan View of a Horizontally Bored Placement Room (after RWE NUKEM Limited 2004). The difference between this plan view and RWE NUKEM Limited's plan view is the diameter of waste placement borehole. The diameter of the waste placement borehole in RWE NUKEM Limited is 1.918 m)

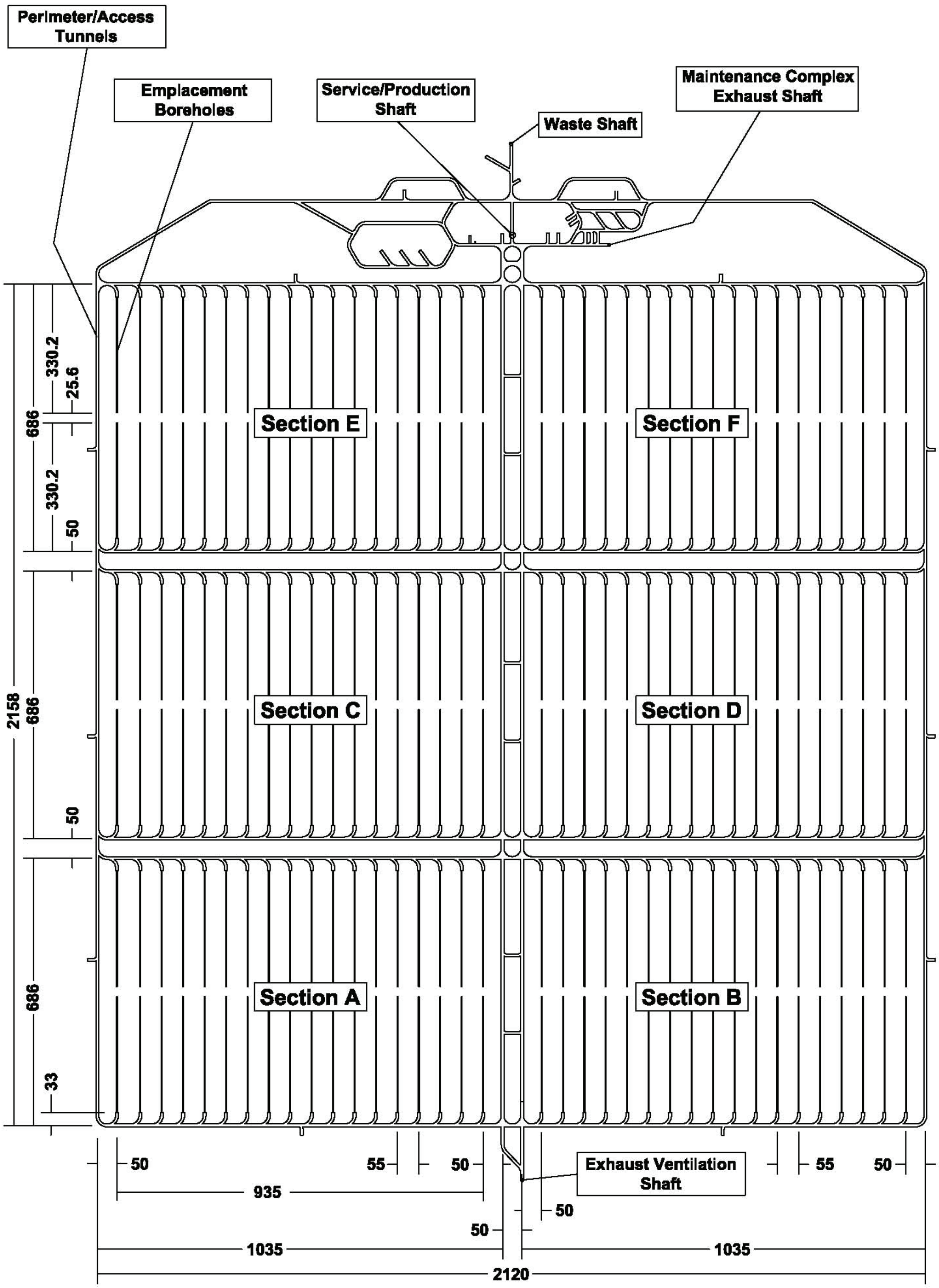

Figure 3: Plan View of the RWE NUKEM Repository Layout in Limestone (RWE NUKEM Limited 2004)

Table 4: Repository Design Parameters (Baumgartner 2005)

Number of Used-fuel Bundles[(1)]	3,600,280
Number of Used-fuel Containers[(2)]	11,112
Geothermal Gradient (°C/m depth)	0.019
Ground Surface Temperature (annual average) (°C)	7
Repository Depth	750
Maximum Extraction Ratio (ER_R)	0.25
Minimum Used-Fuel Post-reactor Discharge Time before Isolation (a)	30
Initial Heat Output (W)	1139
Placement Room (Tunnel) Diameter (mm)	2500
HCB Radial Thickness (mm)	666
HCB Pedestal Minimum Height (mm)	666
HCB Pedestal Length (mm)	3867

Notes: (1) Nominally 3.6 million used fuel bundles; number shown is rounded to an even number of IV-324-hex used-fuel containers in the design.
(2) Rounded up to provide an even number of containers per panel.

5. BOUNDARY CONDITIONS FOR NEAR-FIELD THERMAL MODELLING

5.1 MODEL GEOMETRY FOR NEAR-FIELD MODELLING

The near-field model considers a “unit cell” of the DGR. The cell consisted of a hexahedral portion of the repository and geosphere, bounded on the upper side by the Earth’s surface and on the lower side by a plane 10,000 m below the Earth’s surface and horizontally by two sets of vertical side surfaces. One set of opposing sides was the vertical mid-plane along the longitudinal axis of the placement room and the vertical mid-plane along the longitudinal axis of the inter-room pillar; and the second set of opposing sides was the vertical mid-plane between adjacent UFCs and the vertical mid-plane passing through the UFC (Figure 4). There were many types of materials in the reference geosphere: soil, mixed dolostone and shale, shale, limestone, sandstone, granitic gneiss; highly compacted bentonite, bentonite pellet backfill and container. The diameter of the borehole is 2.5 m. The horizontal dimensions of a unit cell were different for different modelling cases. The vertical depth of the model unit cell was 10,000 m. The depth from surface to the floor of the tunnel was 750 m.

5.2 THERMAL BOUNDARY CONDITIONS FOR NEAR-FIELD MODELLING

The thermal boundary conditions (Figure 4) were as follows:

- The ground-surface temperature (i.e., top surface of the model) was assumed to be 7°C;
- An isothermal condition of 197°C, assuming a geothermal gradient of 0.019°C/m of depth and an initial ground surface temperature of 7°C, was applied on the bottom surface of the model, resulting in an ambient temperature of 21.25°C at the repository level;

- An adiabatic condition was applied to all four vertical side surfaces of the model to represent the lack of lateral heat transfer due to the heat transfer from adjacent heat sources (i.e., other UFCs);
- A thermal load was applied to the nodes of the UFC. The total applied thermal load was one quarter of the container thermal load given in Table 5.

Table 5: UFC Heat Output after 30-Years of Post-Reactor Discharge Cooling

Time (years) after waste placement	Container heat output (W)	The heat applied in the model (W)
0	1138.6	284.65
1	1120.9	280.23
4	1067.7	266.93
10	961.4	240.35
20	821.1	205.28
40	622.4	155.60
70	440.8	110.20
105	349.0	87.25
140	289.2	72.30
190	250.5	62.63
300	215.0	53.75
420	190.9	47.73
570	169.9	42.48
770	147.6	36.90
970	125.3	31.33
1230	122.7	30.68
1500	120.2	30.05
2000	115.8	28.95
2500	111.3	27.83
3000	106.8	26.70
4200	96.0	24.00
6000	79.8	19.95
8000	61.9	15.48
10,500	44.3	11.08
13,000	43.1	10.78
16,000	41.7	10.43
20,000	39.8	9.95
25,000	37.5	9.38
40,000	30.5	7.63
60,000	21.2	5.30
85,000	9.5	2.38
100,000	2.6	0.65
300,000	2.2	0.55
500,000	1.8	0.45
1,000,000	0.9	0.23
3,000,000	0.9	0.23
10,000,000	0.6	0.15

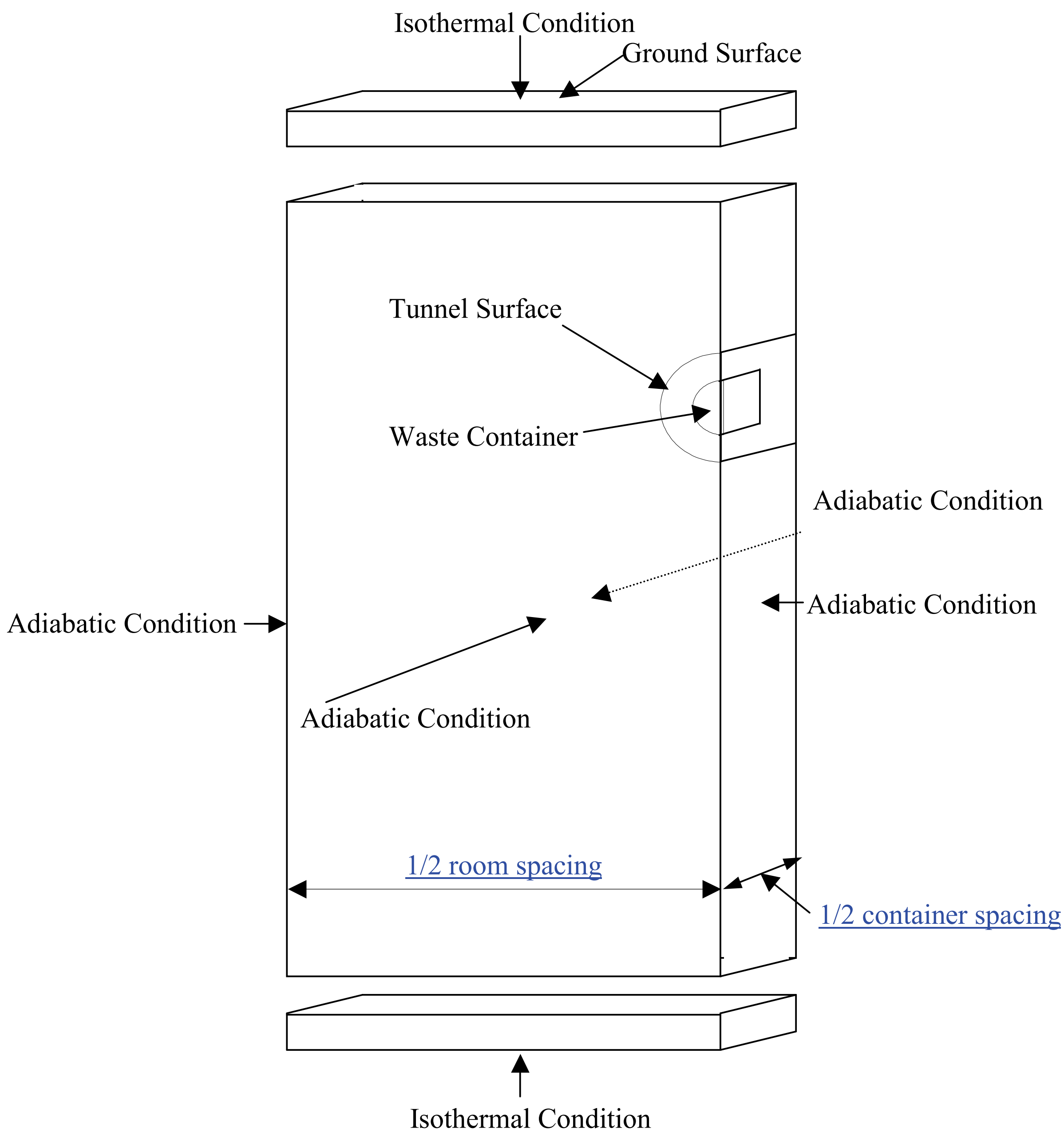

Figure 4: Thermal Boundary Conditions for Near-Field Modelling

6. MODELLING RESULTS

6.1 INFLUENCE OF TUNNEL SPACING ON CONTAINER-SURFACE TEMPERATURES

Figure 5 shows the container-surface temperature vs. time in an infinite repository with a centre-to-centre container spacing of 28 m, variable tunnel spacing and a buffer thermal conductivity of 0.4 W/(m·°C). In the scope of 20~70 m of tunnel spacing, the influences of tunnel spacing on the peak container-surface temperature was insignificant if container spacing was 28 m. The container-surface peak temperature in all cases was due to “self-heating” with very little thermal contribution from its nearest neighbours since the containers were spaced at relatively great distances in materials with relatively low thermal conductivity. However, the tunnel spacing did affect container surface temperature at times beyond the peak temperature by up to 10°C

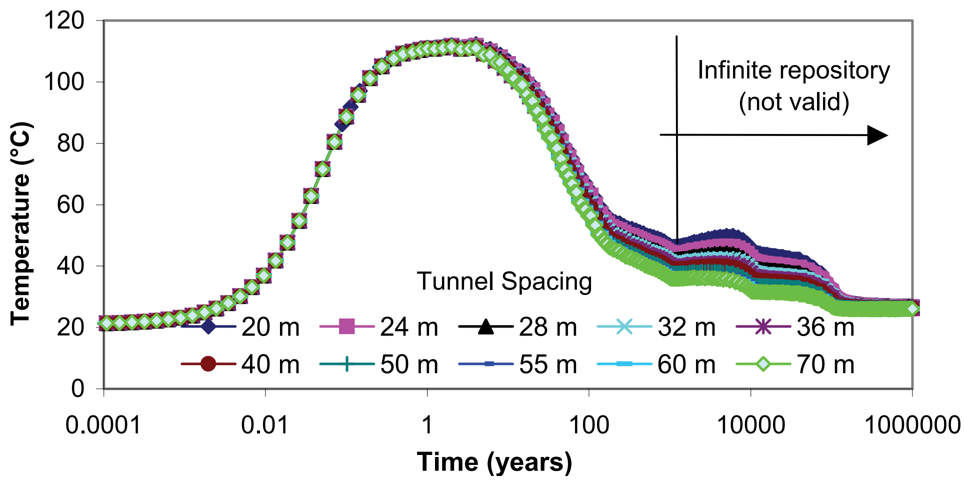

Figure 5: Container-Surface Temperatures vs. Time for Repositories with a Container Spacing of 28 m and Variable Tunnel Spacing (The buffer thermal conductivity is 0.4 W/(m·°C))

Figure 6 shows the influence of tunnel spacing on maximum container-surface temperature in a repository at a container spacing of 28 m and a thermal conductivity of 0.4 W/(m·°C). The maximum container-surface temperature decreased with increases in tunnel spacing. The maximum container temperature was 112°C at tunnel spacing of 20 m and decreased to 111°C at tunnel spacing of 70 m. When tunnel spacing exceeded 40 m, the maximum container-surface temperature was no longer affected since the arrival of the heat from its nearest neighbours occurred after its peak temperature was reached. Therefore, in the following section, the study focuses on 20~40 m of tunnel spacing.

6.2 USED FUEL CONTAINER-SURFACE TEMPERATURES IN A REPOSITORY WITH A BUFFER THERMAL CONDUCTIVITY OF 0.4 W/(m·°C)

Figure 7 to 12 show the container-surface temperature vs. time with a buffer thermal conductivity of 0.4 W/(m·°C) and variable container spacing in a horizontally infinite repository at variable tunnel spacing of 20 m, 24 m, 28 m, 32 m, 36 m and 40 m. For variable tunnel spacing, the container spacing did not have a significant influence on the maximum temperatures of container surface, but had a significant influence on the second peak temperatures. The maximum container-surface temperature occurred 4 years after waste placement. After 10 years of waste placement, the container-surface temperatures quickly decreased.

All analyses simulated a horizontally infinite repository. At times greater than 1000 years, the results in Figures 7 to 12 may not be valid for the case of a repository with finite horizontal dimensions. A thermal analysis of a repository with finite horizontal dimensions was performed using the analytical HOTROK computer program (Mathers 1985). The results from the finite-sized repository (Figure 13) do not show the same increase in temperature between 1,000 and 8,000 years as can be seen for the infinite repository (Figures 7 to 12). This indicates that the results after certain time (e.g., about 1,000 years) are not valid for a horizontally finite repository in the current analyses. This is indicated on the figures in this report.

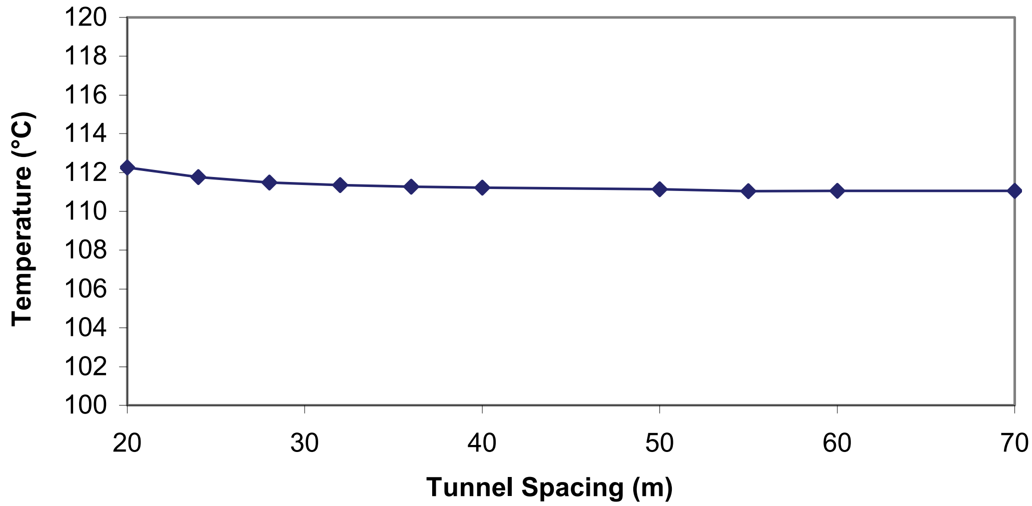

Figure 6: Maximum Container-Surface Temperatures vs. Tunnel Spacing with a Container Spacing of 28 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

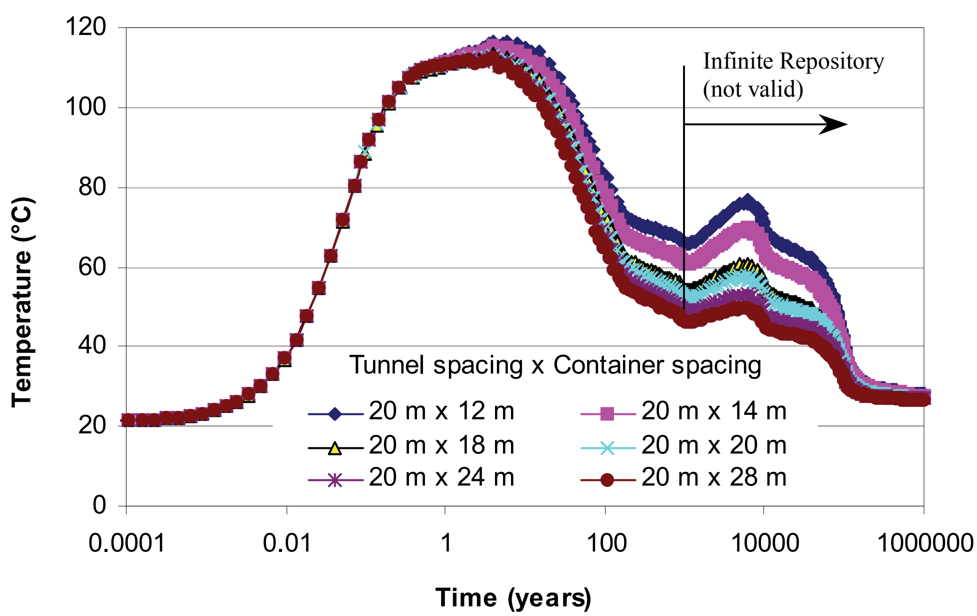

Figure 7: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 20 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

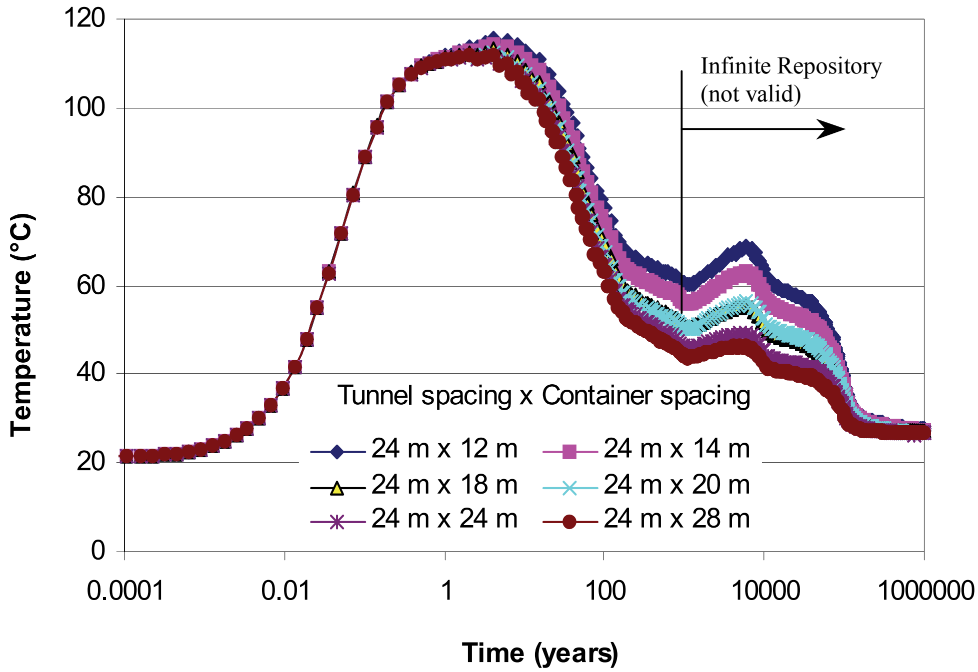

Figure 8: Container-Surface Temperature for a Horizontally Infinite Repository with a Tunnel Spacing of 24 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

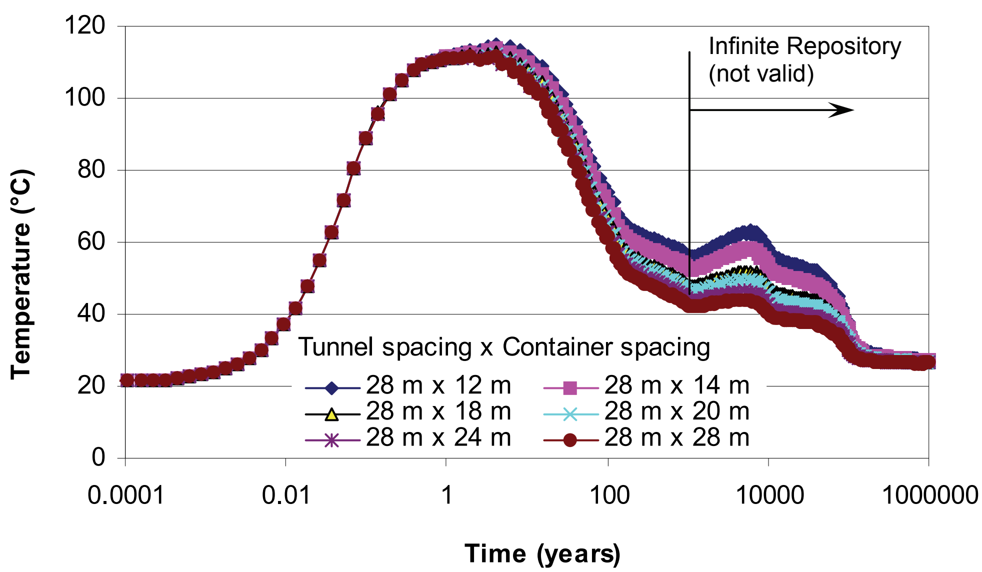

Figure 9: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 28 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

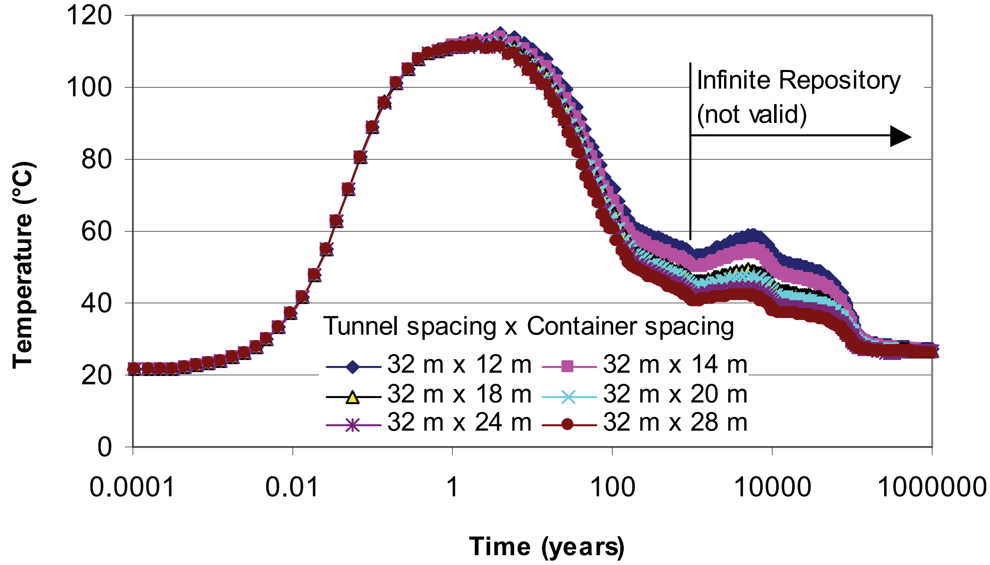

Figure 10: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 32 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

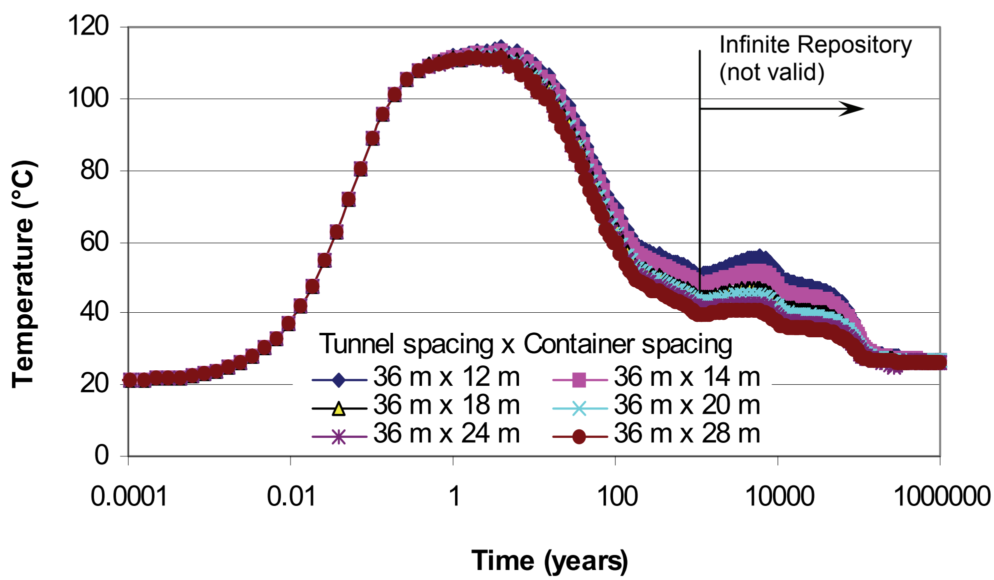

Figure 11: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 36 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

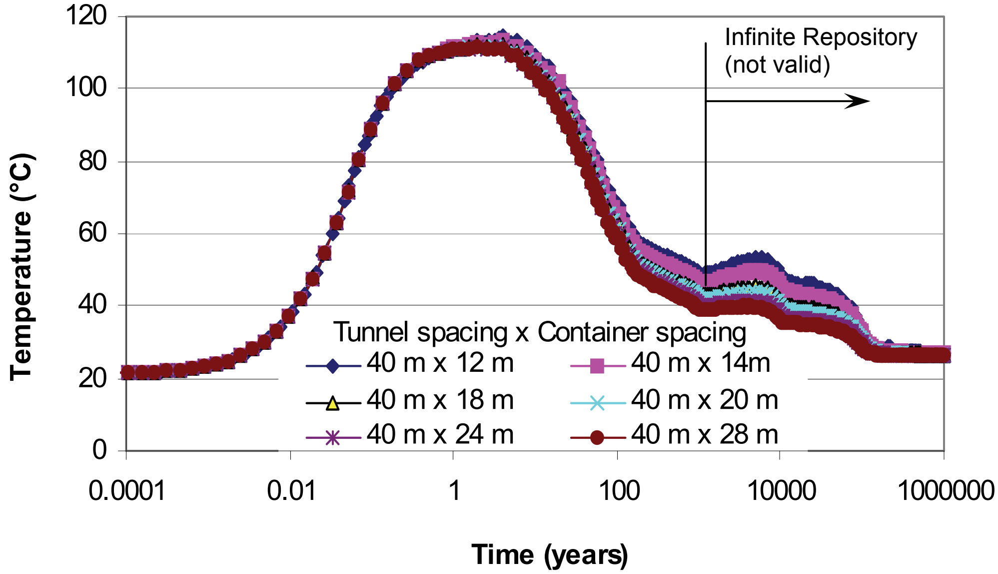

Figure 12: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 40 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

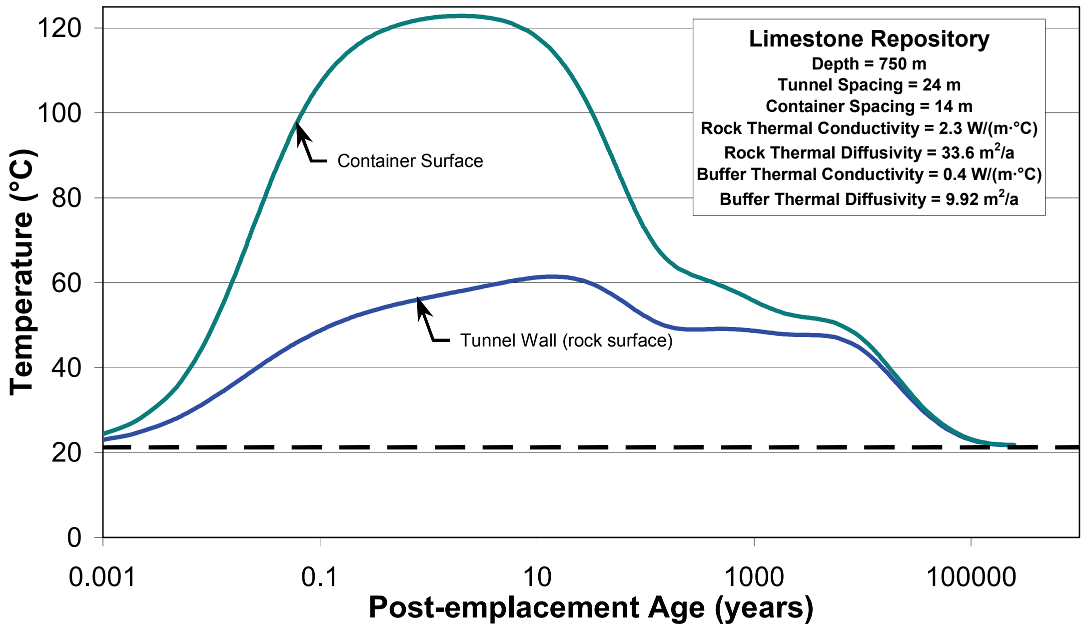

Figure 13: Container-Surface and Tunnel-Wall Temperatures vs. Time in a Finite Repository with a Tunnel Spacing of 24 m and a Container Spacing of 14 m from Calculation using HOTROK

Table 6 shows the simulated first peak temperatures, 500-year temperatures and 1,000-year temperatures on a container surface for variable tunnel spacing and container spacing when the value of 0.4 W/(m·°C) is used as the buffer thermal conductivity. For all cases, the first peak temperature happened 4 years after waste placement.

Table 6: Container-Surface Temperatures in a Horizontally Infinite Repository with a Buffer Thermal Conductivity of 0.4 W/(m·°C)

Tunnel Spacing (m)	Container Spacing (m)	Time for the first peak temperature (years)	First peak temperature (°C)	Temperatures after 500 years (°C)	Temperatures after 1,000 years (°C)
20	12	4	117	69	66
	14	4	115	64	62
	18	4	114	58	55
	20	4	113	55	53
	24	4	113	52	49
	28	4	112	50	47
24	12	4	116	63	61
	14	4	114	59	57
	18	4	113	54	51
	20	4	113	53	50
	24	4	112	50	46
	28	4	112	48	44
28	12	4	115	59	57
	14	4	114	56	53
	18	4	113	52	49
	20	4	112	50	47
	24	4	112	48	44
	28	4	111	46	43
32	12	4	115	57	54
	14	4	114	54	51
	18	4	113	50	47
	20	4	112	48	45
	24	4	112	46	43
	28	4	111	45	41
36	12	4	115	54	51
	14	4	113	52	49
	18	4	112	48	45
	20	4	112	47	44
	24	4	111	45	42
	28	4	111	44	40
40	12	4	114	53	50
	14	4	113	50	47
	18	4	112	47	44
	20	4	112	46	43
	24	4	111	44	41
	28	4	111	43	40

In summary, if the buffer thermal conductivity was 0.4 W/(m·°C), the first peak container-surface temperature fell in the range of 111°C to 117°C in a horizontally infinite repository with a tunnel spacing of 20~40 m and a container spacing of 12~28 m. The container temperature always exceeded 100°C due primarily to "self heating". "Self heating" may be reduced by increasing the time-out-of-reactor of the used fuel before placement within a repository.

6.3 TUNNEL-WALL TEMPERATURES IN A REPOSITORY WITH A BUFFER THERMAL CONDUCTIVITY OF 0.4 W/(m·°C)

Figure 14 to 19 show the temperatures on a tunnel wall vs. time with a buffer thermal conductivity of 0.4 W/(m·°C) for variable container spacing in a horizontally infinite repository with tunnel spacing of 20 m, 24 m, 28 m, 32 m, 36 m and 40 m. The first peak tunnel-wall temperatures were much lower compared to the first peak container-surface temperatures. Although the second peak temperatures were much higher than the first peak temperatures, they may not be the true temperatures for a finite repository because the results after 1,000 years of waste placement may not be valid for a finite repository as discussed in Section 6.2.

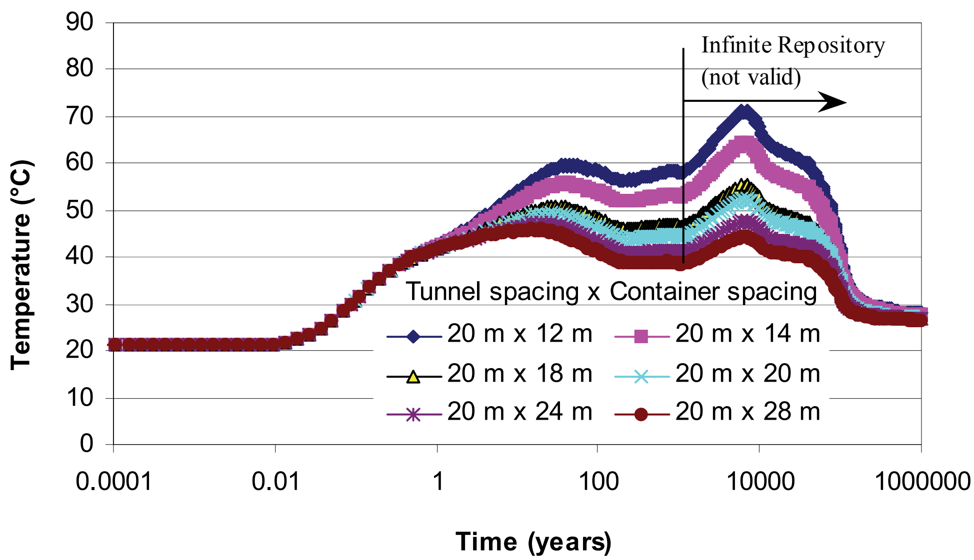

Figure 14: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 20 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

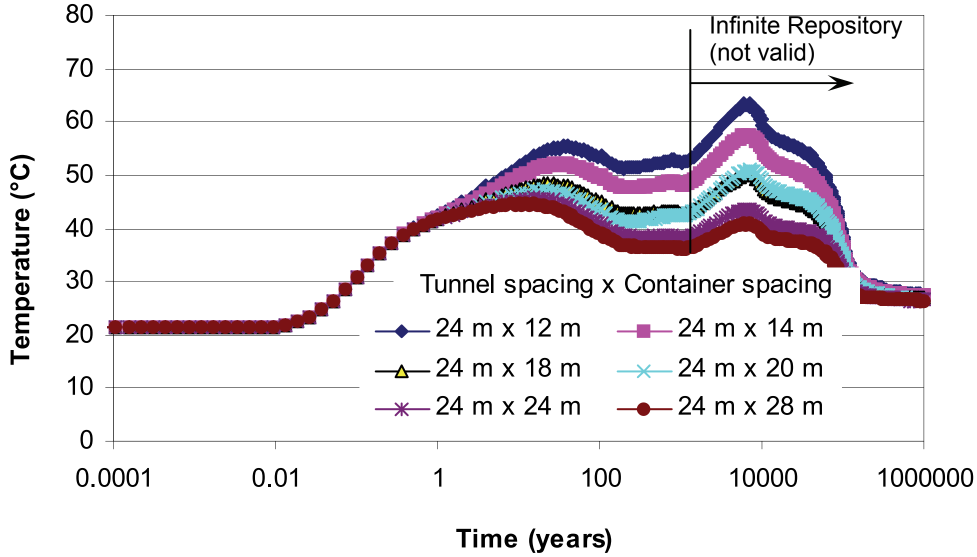

Figure 15: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 24 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

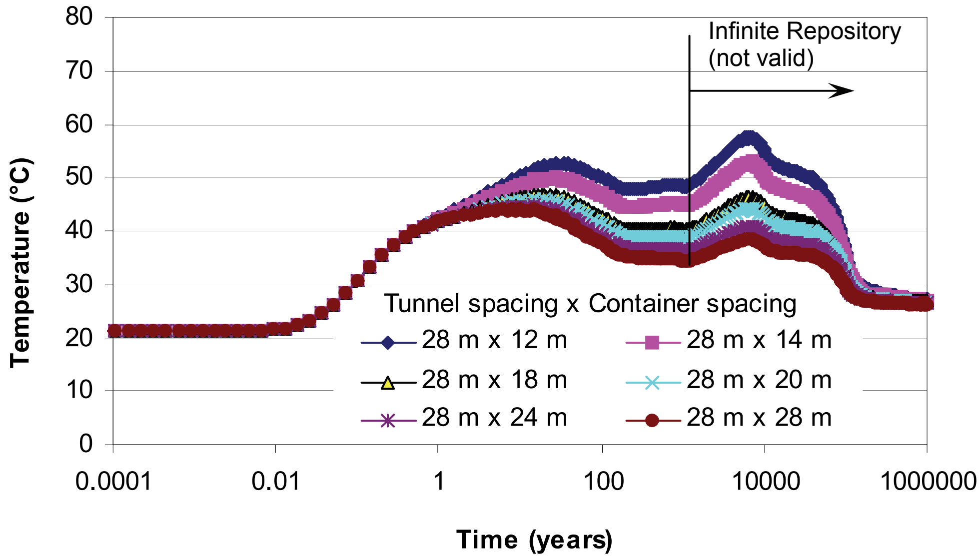

Figure 16: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 28 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

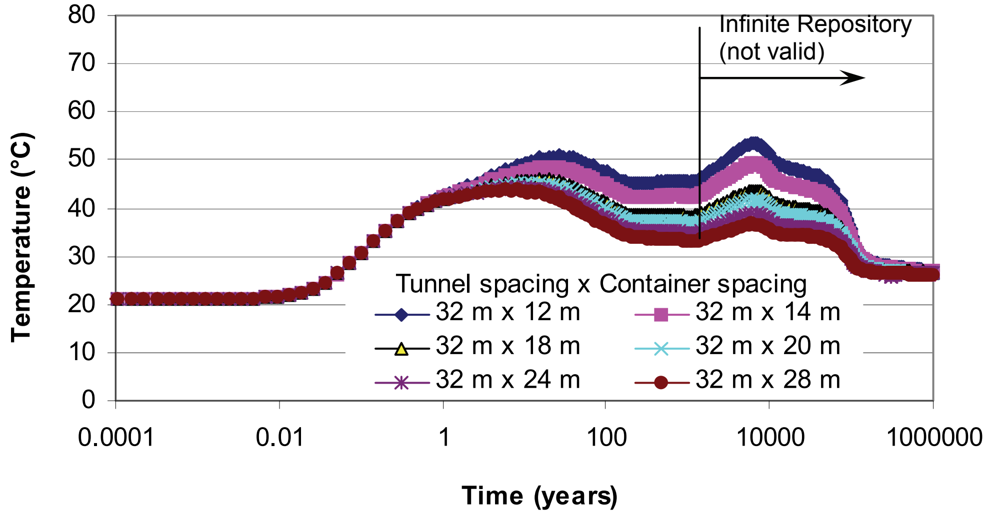

Figure 17: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 32 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

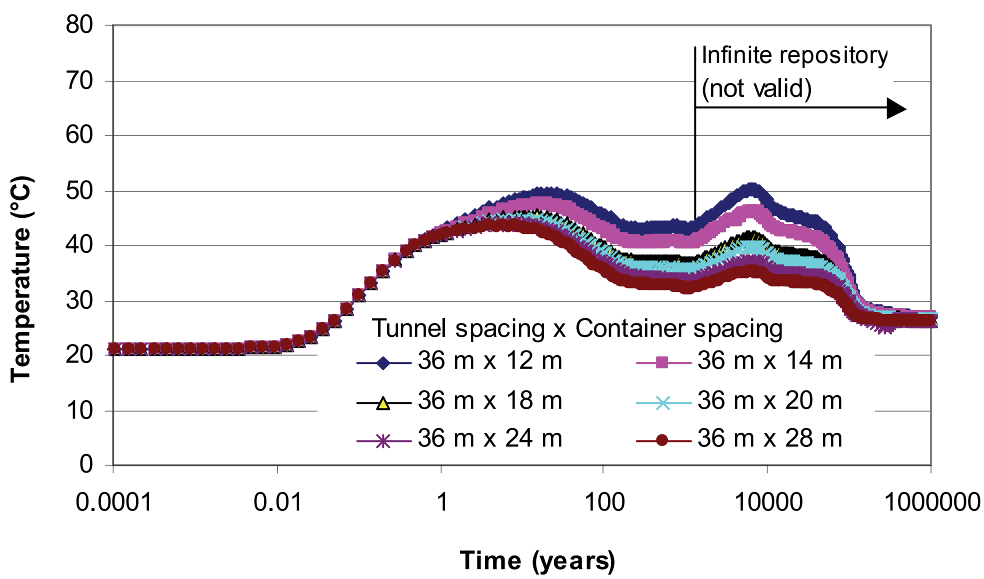

Figure 18: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 36 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

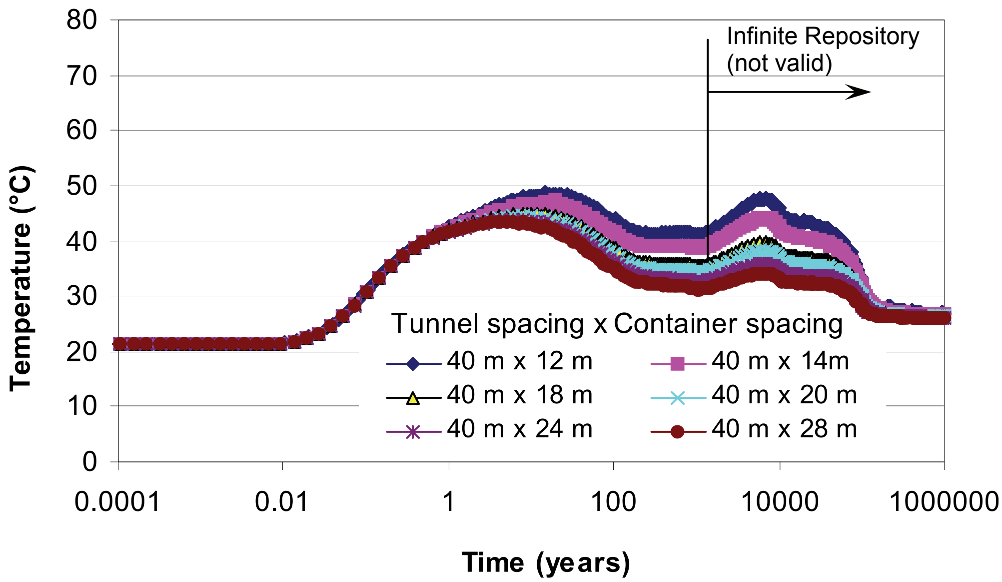

Figure 19: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 40 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

Table 7 shows the simulated first peak temperatures, 500-year temperatures and 1,000-year temperatures on a tunnel wall in a horizontally infinite repository with a buffer thermal conductivity of 0.4 W/(m·°C) for variable tunnel spacing and container spacing. The times for the first peak temperatures were different for different cases. With increased tunnel spacing and container spacing, the time for the first peak temperature decreased. The first peak tunnel-wall temperatures happened between 4 and 40 years for a repository with a tunnel spacing of 20 m to 40 m and a container spacing of 12 m to 28 m.

Table 7: Tunnel-Wall Temperatures in a Horizontally Infinite Repository with a Buffer Thermal Conductivity of 0.4 W/(m·°C)

Tunnel spacing (m)	Container spacing (m)	Time for the first peak temperature (years)	First peak temperature (°C)	Temperatures after 500 years (°C)	Temperatures after 1,000 years (°C)
20	12	40	60	58	58
	14	35	56	53	53
	18	27	51	47	47
	20	24	49	44	45
	24	15	47	41	41
	28	15	46	39	39
24	12	35	56	52	53
	14	30	52	48	48
	18	27	48	43	43
	20	20	47	42	43
	24	15	46	38	38
	28	15	45	36	36
28	12	27	53	48	49
	14	24	50	45	45
	18	15	47	40	40
	20	15	46	39	39
	24	15	45	36	36
	28	6	44	35	35
32	12	27	51	45	46
	14	20	49	42	42
	18	15	46	38	38
	20	15	45	37	37
	24	8	44	35	35
	28	6	44	34	33
36	12	20	50	43	43
	14	15	48	41	40
	18	15	45	37	37
	20	8	45	36	36
	24	6	44	34	34
	28	6	44	33	32
40	12	15	49	41	41
	14	15	47	39	39
	18	8	45	36	36
	20	8	45	35	34
	24	6	44	33	33
	28	4	44	32	31

In summary, the first peak tunnel-wall temperatures ranged between 44°C and 60°C if the buffer thermal conductivity was 0.4 W/(m·°C) in a horizontally infinite repository with a tunnel spacing of 20 to 40 m and a container spacing of 12 to 28 m. After 1,000 years of waste placement, the temperatures decreased from 60°C to 58°C for close tunnel and container spacing (20 and 12 m respectively)) and from 44°C to 31°C for the largest tunnel and container spacing (40 and 28 m respectively). From Section 6.2, it is clear that the tunnel spacing and container spacing did not have significant influence on the peak container-surface temperature. However, the data in Table 7 show that the tunnel spacing and container spacing affected the peak tunnel-wall temperatures.

6.4 HORIZONTAL TEMPERATURE PROFILES FROM MID-CONTAINER INTO MID-PILLAR

Figure 20 to 25 show the temperatures along a horizontal line from mid-container to mid-pillar between the adjacent placement rooms in a horizontally infinite repository after 4 years of waste placement with a buffer thermal conductivity of 0.4 W/(m·°C) for variable tunnel spacing of 20 m, 24 m, 28 m, 32 m, 36 m and 40 m, respectively. The temperature profiles along the horizontal line decreased very quickly from the surface of the container to the tunnel wall. Then, the temperatures continued to decrease from the tunnel wall to the midpoint of the two tunnels, but not significantly 4 years after waste placement. Figure 26 shows the temperatures along a horizontal line from mid-container to mid-pillar between the adjacent placement rooms in a horizontally infinite repository with a tunnel spacing of 24 m and a container spacing of 14 m at different times. Early on (e.g., 2 years or 4 years), the temperatures in the buffer were very high and in the rock the temperatures were very low. After 100 years following waste placement, the temperatures on a container surface and at mid-pillar were 74°C and 43°C, respectively. After 500 years, the container-surface temperature was 59°C and the temperature at mid-pillar was 45°C.

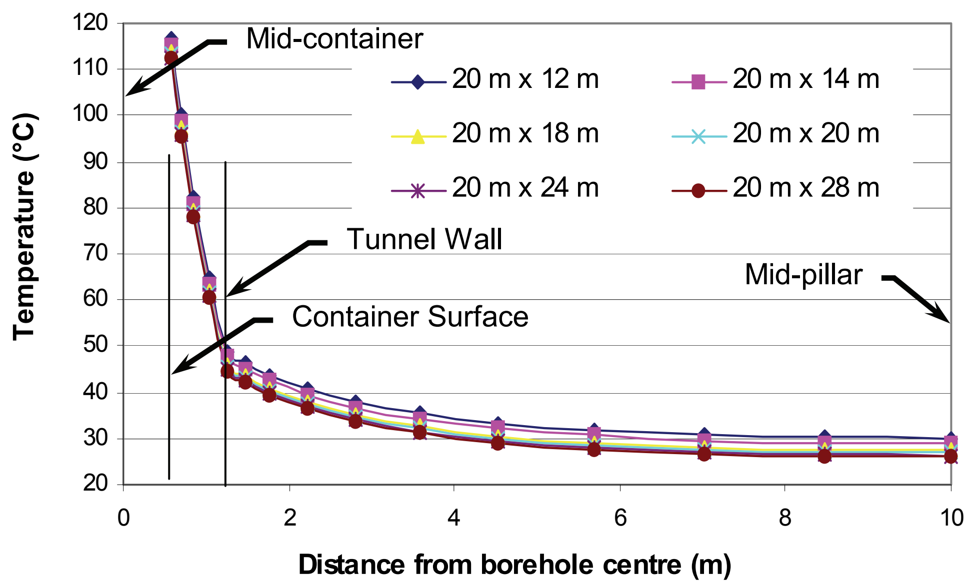

Figure 20: Temperature along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 20 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

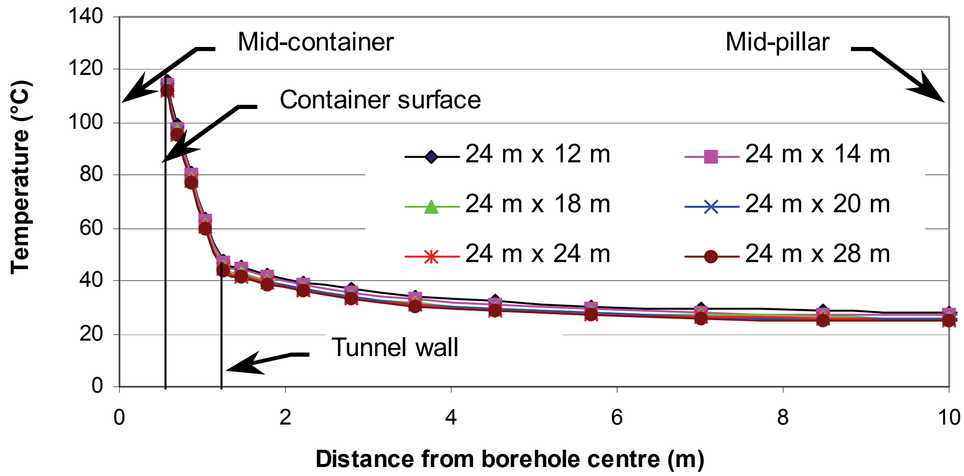

Figure 21: Temperatures along a Horizontal from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 24 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

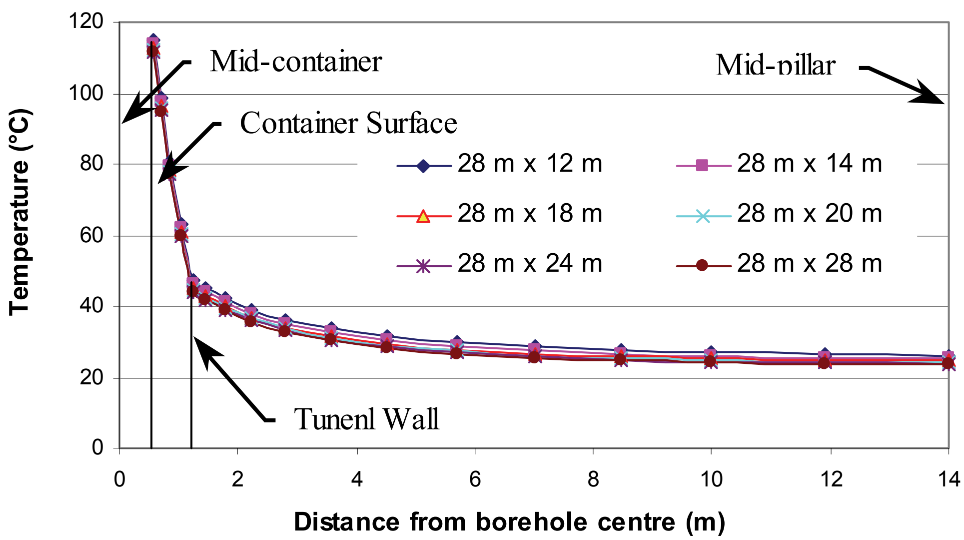

Figure 22: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 28 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

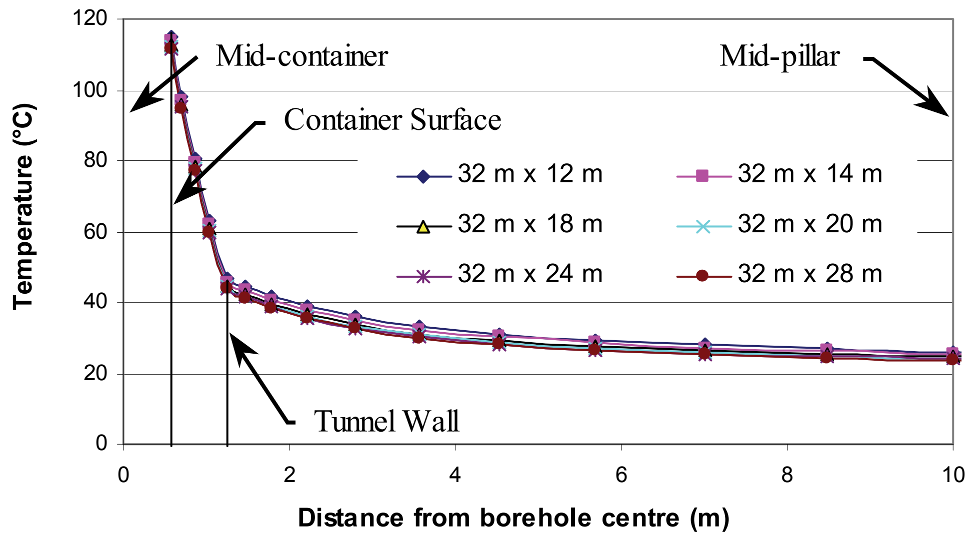

Figure 23: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 32 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

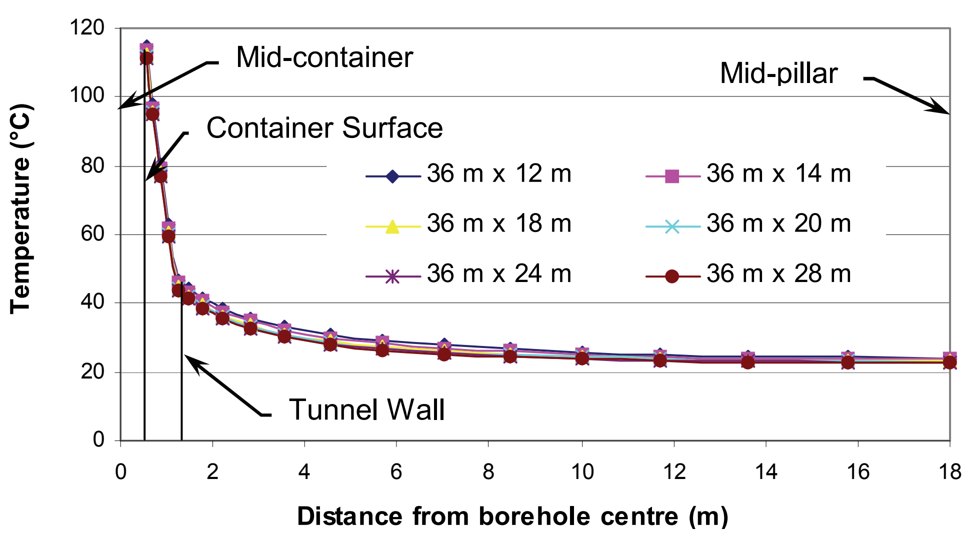

Figure 24: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 36 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

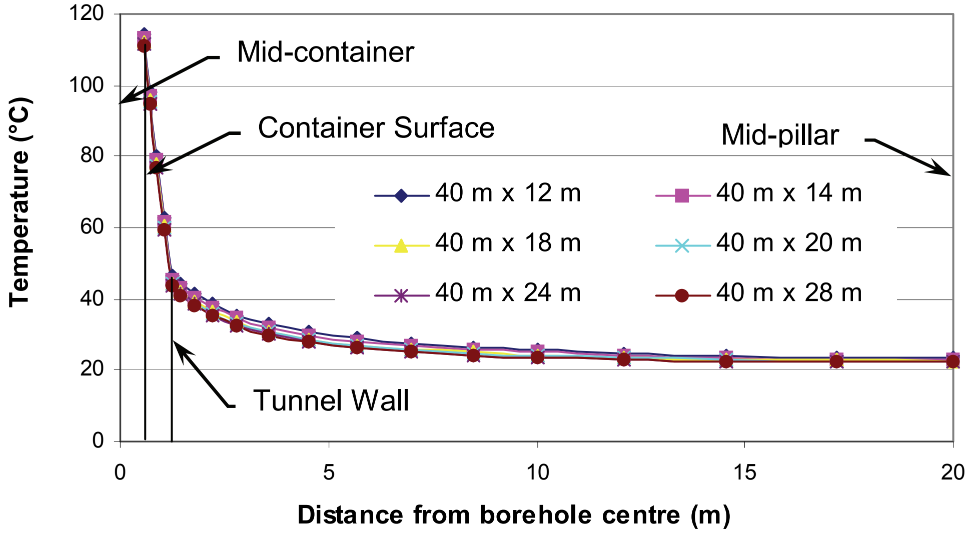

Figure 25: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 40 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

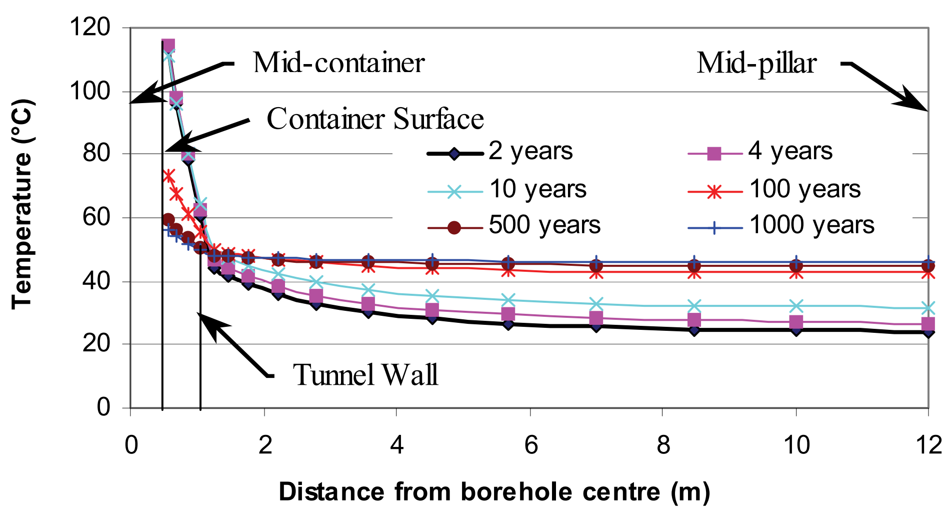

Figure 26: Temperatures at Various Times along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository with a Tunnel Spacing of 24 m and a Container Spacing of 14 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

In summary, soon after waste placement, the higher temperatures occurred largely in the buffer. After 100 years, the temperatures in the buffer dropped due to radionuclide decay and the temperatures in the rock increased to a near-uniform value of about 45°C.

6.5 CONTAINER-SURFACE TEMPERATURES IN A REPOSITORY WITH A BUFFER THERMAL CONDUCTIVITY OF 0.7 W/(m·°C)

Figure 27 to 32 show the container-surface temperature vs. time with a buffer thermal conductivity of 0.7 W/(m·°C) for variable container spacing in a horizontally infinite repository with tunnel spacing of 20 m, 24 m, 28 m, 32 m, 36 m and 40 m. For variable tunnel spacing, container spacing did not have a significant effect on the maximum temperatures on the container surface during the first year, but did have a significant effect at later years. The maximum container-surface temperature occurred at 4 to 15 years following waste placement.

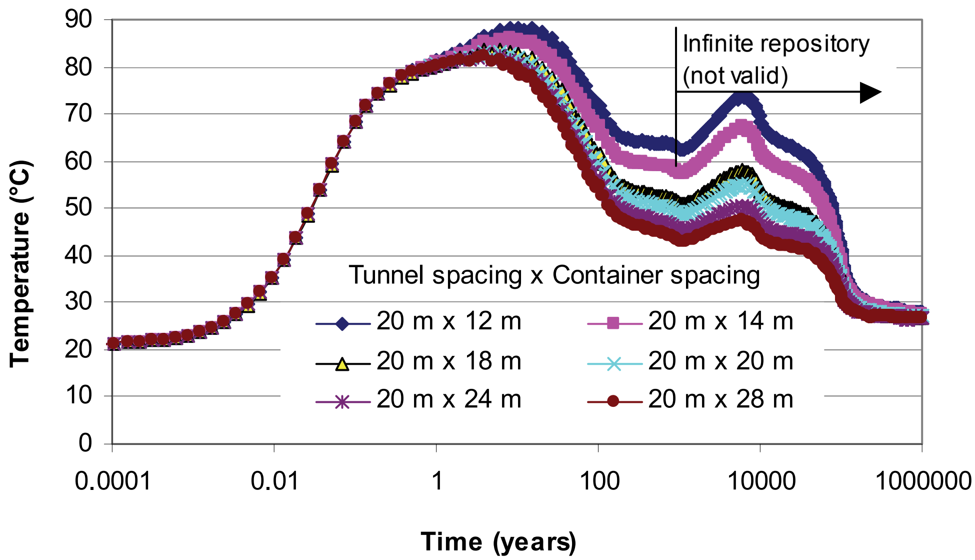

Figure 27: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 20 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

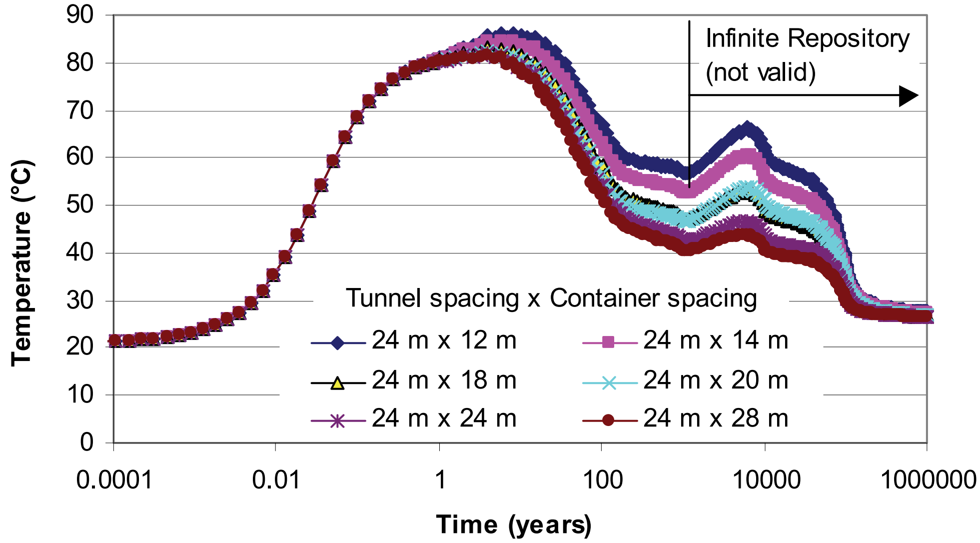

Figure 28: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 24 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

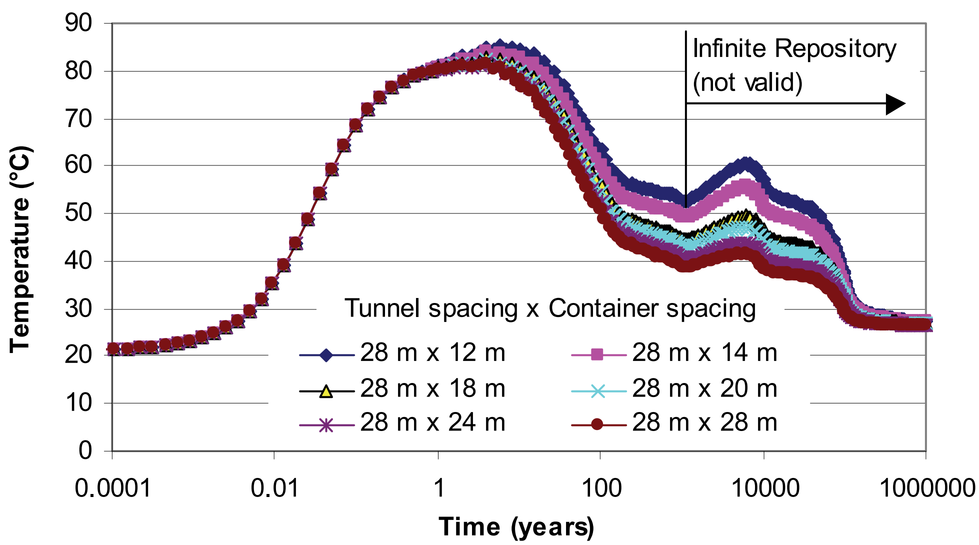

Figure 29: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 28 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

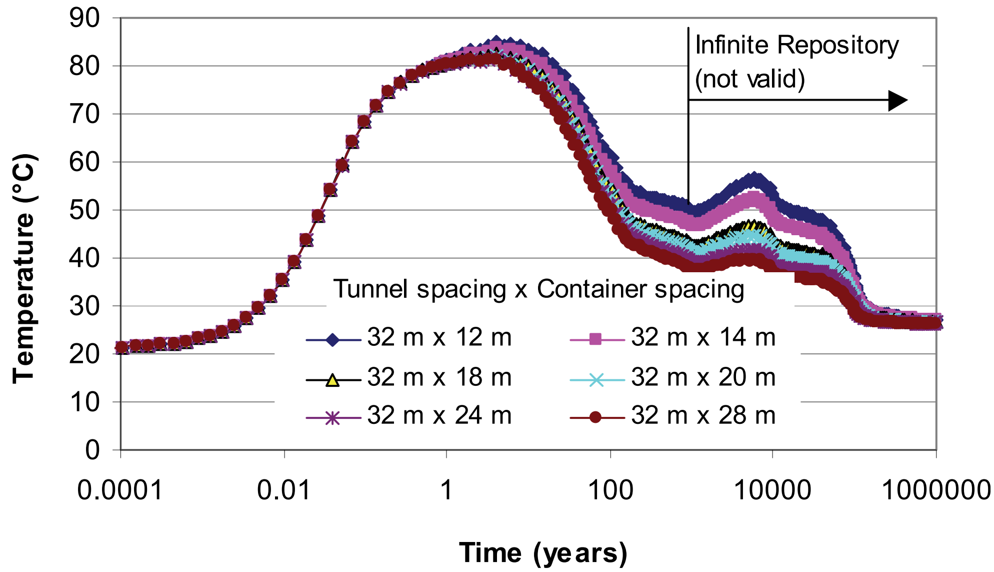

Figure 30: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 32 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

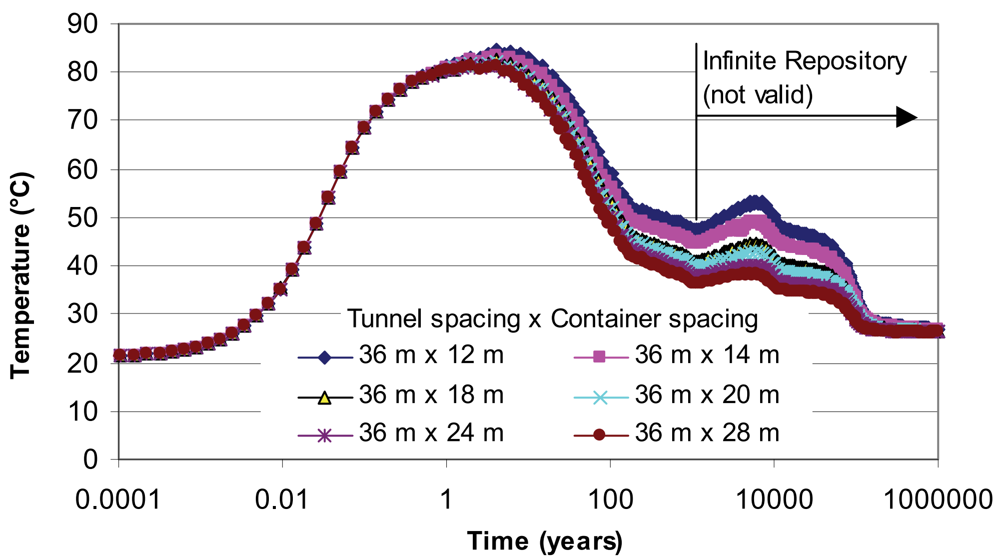

Figure 31: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 36 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

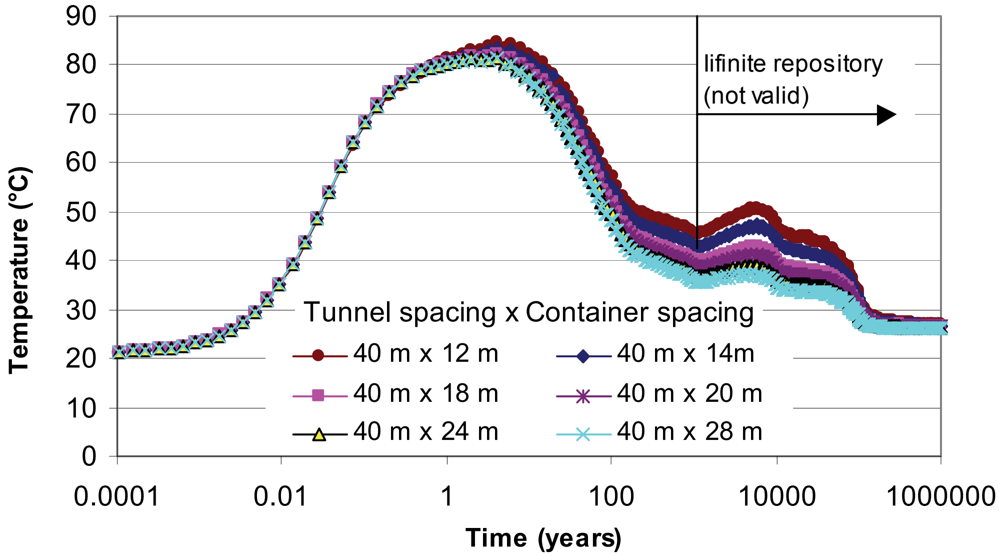

Figure 32: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 40 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

Table 8 shows the simulated first peak temperatures, 500-year temperatures and 1,000-year temperatures on container surfaces in a horizontally infinite repository with variable tunnel spacing and container spacing when a value of 0.7 W/(m·°C) was used as the buffer thermal conductivity. Comparing these data to those in Table 6, it can be seen that the time for the first peak temperature was the same or greater when the thermal conductivity of the buffer was higher. Also, the magnitude of the first peak container-surface temperature was less when the buffer thermal conductivity was greater. For example, a peak container temperature of 88°C was obtained for a 12 m container spacing and a 20 m tunnel spacing using a thermal conductivity of 0.7 W/(m·°C) 8 years after container placement, compared with a peak temperature of 117°C after 4 years of container placement when 0.4 W/(m·°C) was used as the buffer thermal conductivity.

Table 8: Container-Surface Temperatures in a Horizontally Infinite Repository with a Buffer Thermal Conductivity of 0.7 W/(m·°C)

Tunnel spacing (m)	Container spacing (m)	Time for the first peak temperature (years)	First peak temperature (°C)	Temperatures after 500 years (°C)	Temperatures after 1,000 years (°C)
20	12	8	88	64	63
	14	8	86	59	58
	18	6	84	53	51
	20	5	83	51	49
	24	4	83	47	46
	28	4	82	45	43
24	12	6	86	58	57
	14	6	85	54	53
	18	5	83	49	48
	20	4	83	48	47
	24	4	82	45	43
	28	4	82	43	41
28	12	6	85	54	53
	14	5	84	51	50
	18	4	83	47	45
	20	4	82	45	43
	24	4	82	43	41
	28	4	82	41	39
32	12	4	85	52	50
	14	4	84	49	47
	18	4	83	45	43
	20	4	82	43	41
	24	4	82	41	39
	28	4	81	40	38
36	12	4	85	49	48
	14	4	84	47	45
	18	4	82	43	41
	20	4	82	42	40
	24	4	82	40	38
	28	4	81	39	37
40	12	4	85	48	46
	14	4	83	45	43
	18	4	82	42	40
	20	4	82	41	39
	24	4	82	39	37
	28	4	81	38	36

In summary, for a buffer thermal conductivity is 0.7 W/(m·°C), the first peak container-surface temperature falls in the range of 81°C to 88°C in a horizontally infinite repository with a tunnel spacing of 20 to 40 m and a container spacing of 12 to 28 m. This is much lower than the design requirement of maximum temperature of ≤100°C on the container surface. The potential for reducing container spacing to more closely approach the maximum temperature of ≤100°C on the container surface for a buffer thermal conductivity of 0.7 W/(m·°C) is assessed in Section 7.

6.6 TUNNEL-WALL TEMPERATURES IN A REPOSITORY WITH A BUFFER THERMAL CONDUCTIVITY OF 0.7 W/(m·°C)

Figure 33 to 38 show the temperatures on a tunnel wall as a function of time for a buffer thermal conductivity of 0.7 W/(m·°C) at variable container spacing in a horizontally infinite repository and variable tunnel spacing of 20 m, 24 m, 28 m, 32 m, 36 m and 40 m.

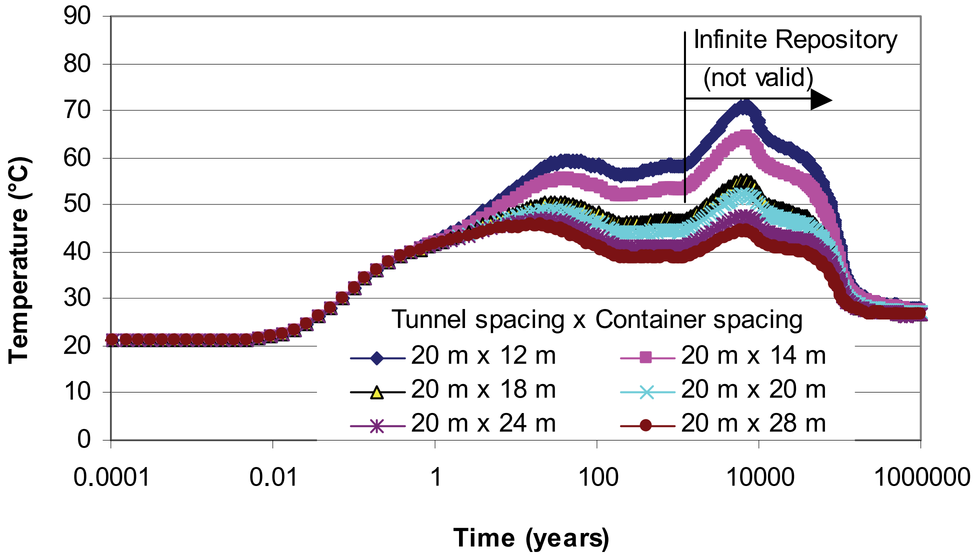

Figure 33: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 20 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

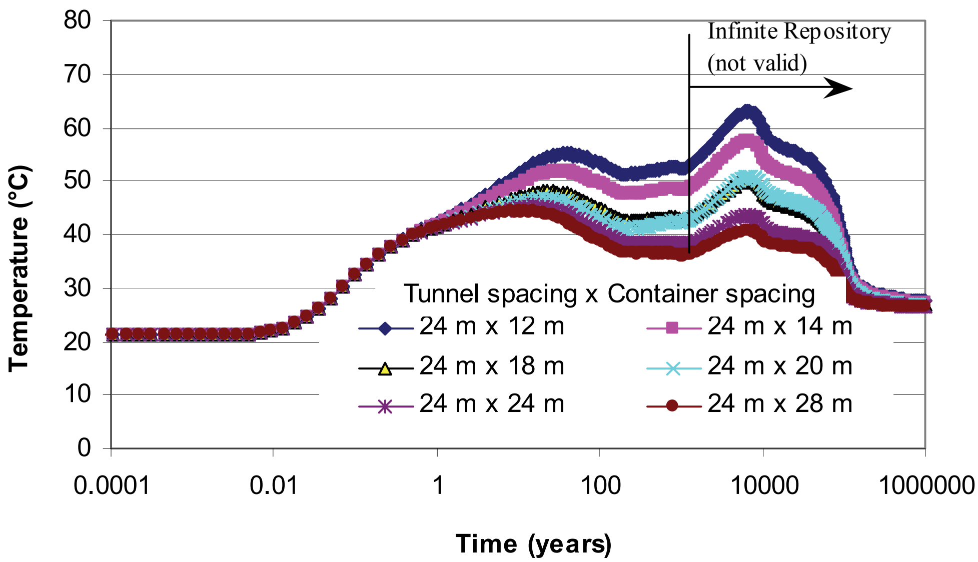

Figure 34: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 24 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

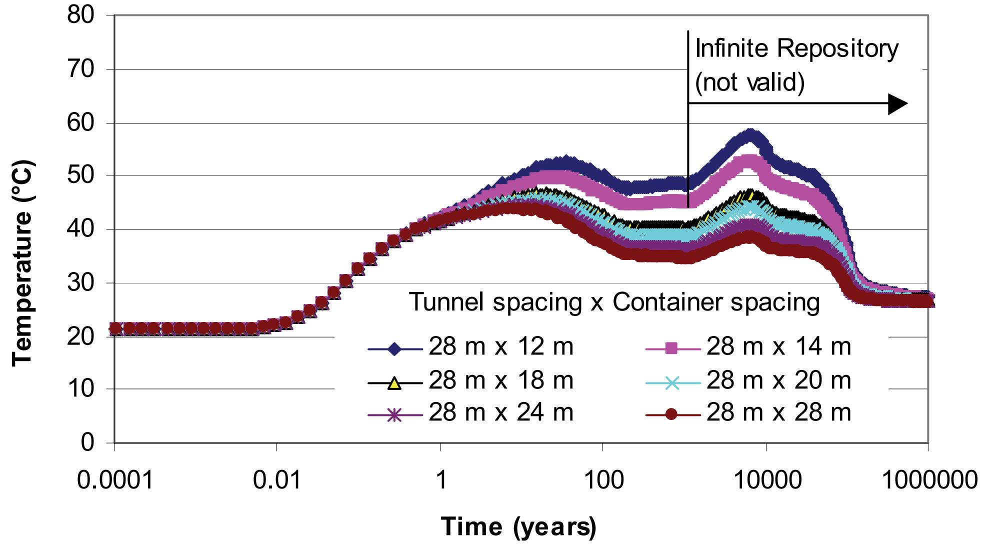

Figure 35: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 28 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

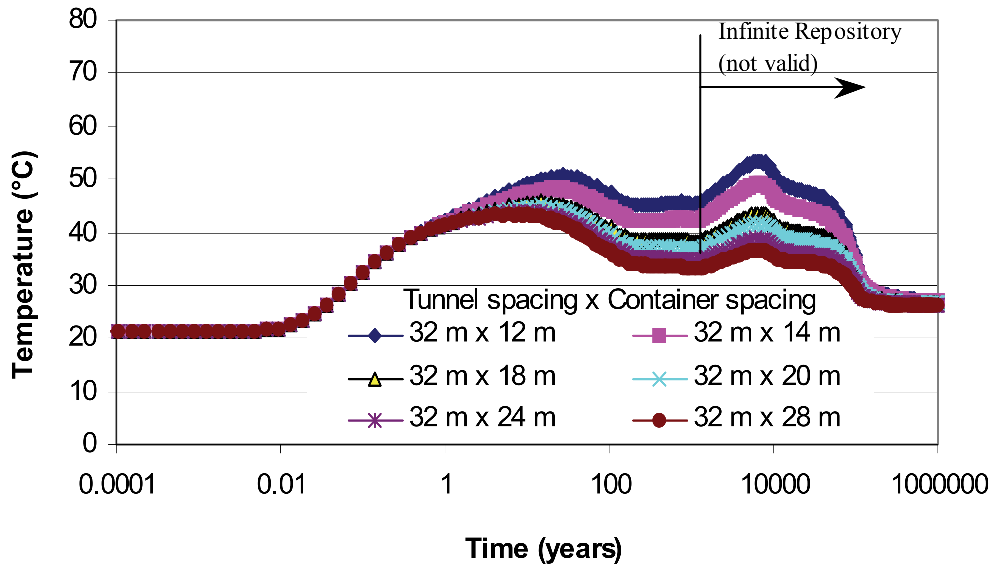

Figure 36: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 32 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

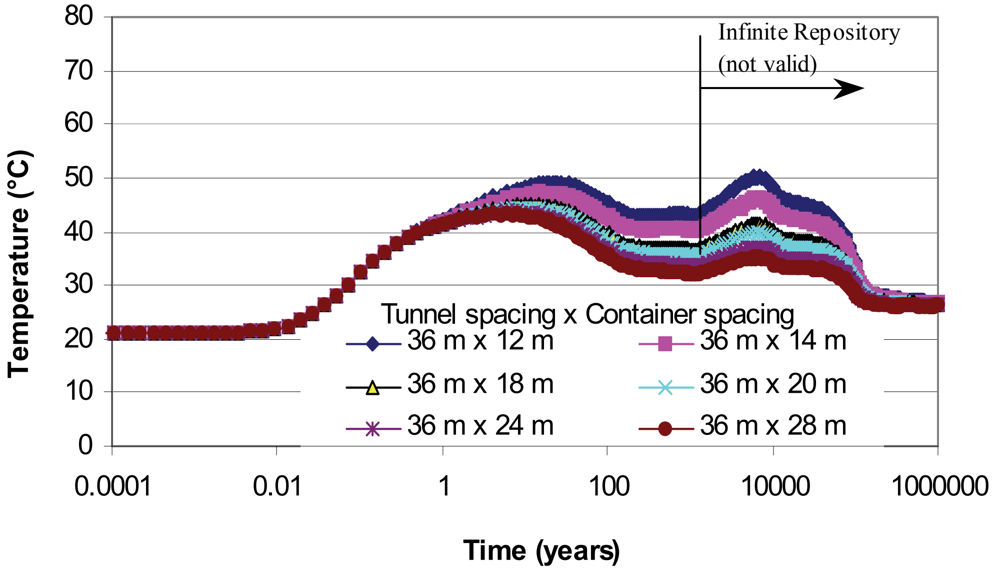

Figure 37: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 36 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

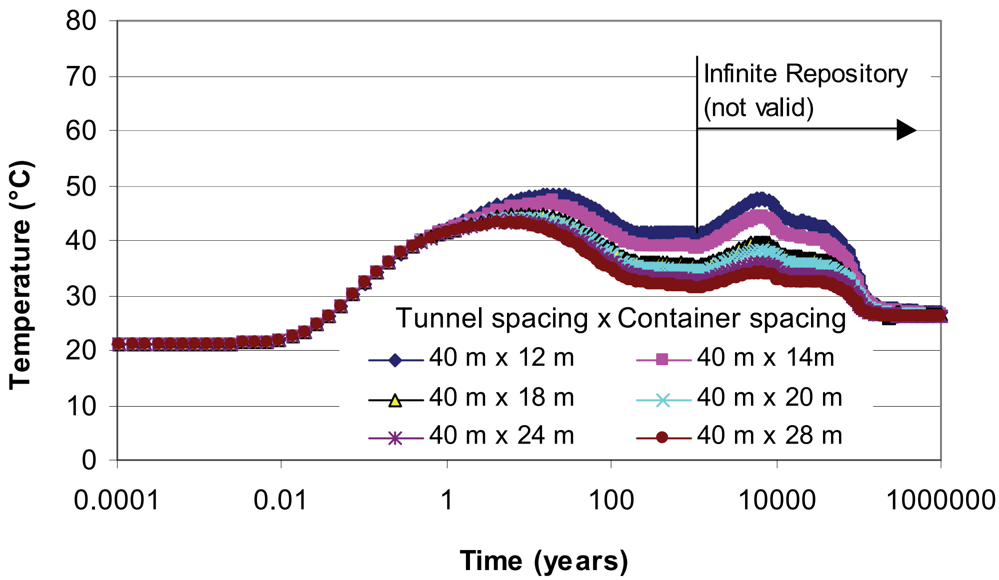

Figure 38: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 40 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

Table 9 shows the simulated first peak temperatures, 500-year temperatures and 1,000-year temperatures on a tunnel wall in a horizontally infinite repository with a buffer thermal conductivity of 0.7 W/(m·°C) and variable tunnel spacing and container spacing. The time for the first peak temperatures ranged from 4 to 40 years. For the tunnel and container spacings analyzed, the first peak temperatures on the tunnel wall ranged from 43°C to 60°C and after 1,000 years of waste placement, the temperatures ranged from 31°C to 58°C.

Table 9: Tunnel-Wall Temperatures in a Horizontally Infinite Repository with a Buffer Thermal Conductivity of 0.7 W/(m·°C)

Tunnel spacing (m)	Container spacing (m)	Time for the first peak temperature (years)	First peak temperature (°C)	Temperatures after 500 years (°C)	Temperatures after 1,000 years (°C)
20	12	40	60	57	58
	14	40	56	53	53
	18	27	51	46	47
	20	27	49	44	45
	24	20	47	41	41
	28	15	46	39	39
24	12	35	55	52	53
	14	35	52	48	48
	18	27	48	43	43
	20	15	47	42	42
	24	15	46	38	38
	28	15	45	36	36
28	12	27	53	48	49
	14	27	50	45	45
	18	15	47	40	40
	20	15	46	39	39
	24	15	45	36	36
	28	8	44	35	35
32	12	27	51	45	46
	14	20	48	42	42
	18	15	46	38	38
	20	15	45	37	37
	24	8	44	35	35
	28	6	44	34	33
36	12	20	49	43	43
	14	15	47	40	40
	18	15	45	37	37
	20	8	44	36	35
	24	6	44	34	34
	28	6	43	33	32
40	12	15	49	41	41
	14	15	47	39	39
	18	8	45	36	36
	20	6	44	35	34
	24	6	44	33	33
	28	4	43	32	31

In summary, the first peak temperatures on the tunnel wall ranged from 43°C to 60°C using a buffer thermal conductivity of 0.7 W/(m·°C) in a horizontally infinite repository with a tunnel spacing of 20 to 40 m and a container spacing of 12 to 28 m. Comparing the temperature data in Table 9 with the data in Table 7 (buffer thermal conductivity of 0.7 W/(m·°C) and 0.4 W/(m·°C), respectively), the rock surface temperatures differed by less than 1°C although there was a small difference in the time to the first peak. It can be concluded that the buffer thermal conductivity had little influence on tunnel-wall temperature."

6.7 TEMPERATURES ALONG A HORIZONTAL LINE PERPENDICULAR TO AND THROUGH THE CENTRE OF A CONTAINER WITH A BUFFER THERMAL CONDUCTIVITY OF 0.7 W/(m·°C)

Figure 39 to 44 show the temperatures along a horizontal line through the mid-point of a container in a horizontally infinite repository after 4 years of waste placement with a buffer thermal conductivity of 0.7 W/(m·°C) and a tunnel spacing of 20 m, 24 m, 28 m, 32 m, 36 m and 40 m, respectively. The temperatures along the horizontal line decreased very quickly from the surface of the container to the wall of the tunnel. Then, the temperatures continued to decrease from the tunnel wall to the mid-pillar between the adjacent placement rooms, but not significantly at 4 years after waste placement. For a repository with a tunnel spacing of 20 m, the maximum difference in the temperatures on the tunnel wall was 4°C. The maximum difference in the temperature in the rock along the horizontal line was 4°C.

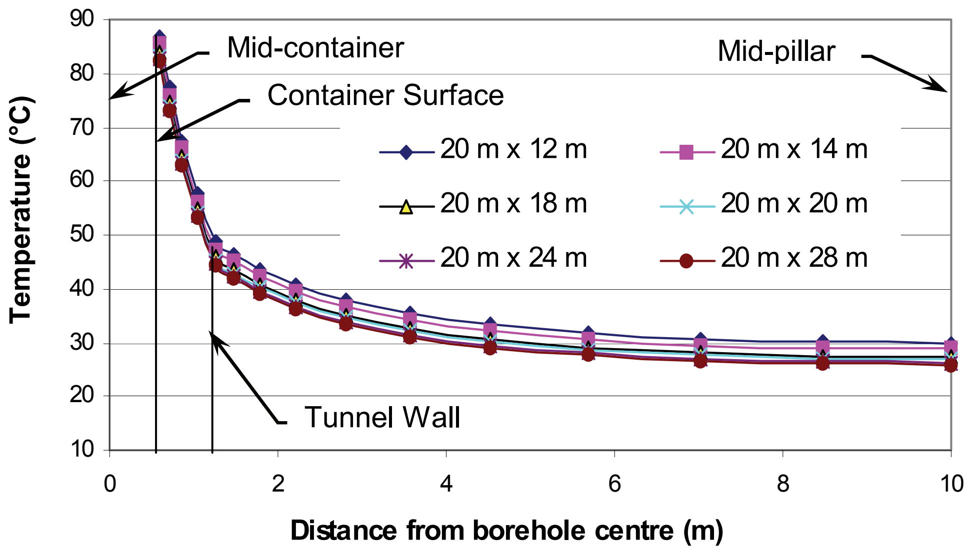

Figure 39: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 20 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

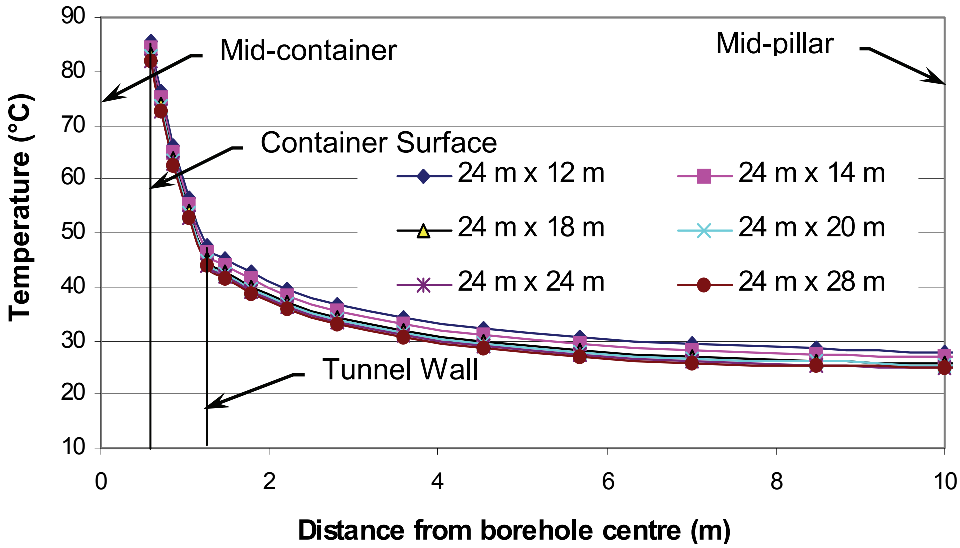

Figure 40: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 24 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

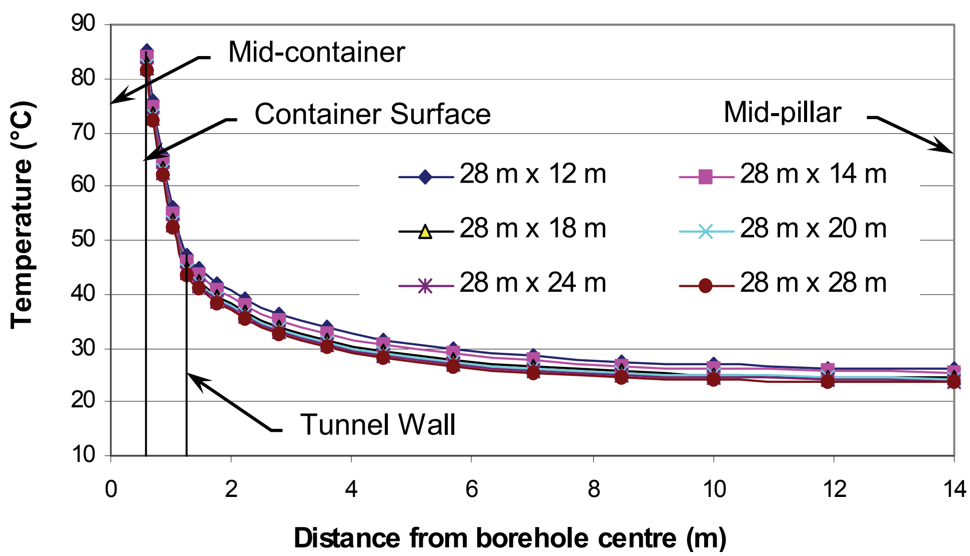

Figure 41: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 28 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

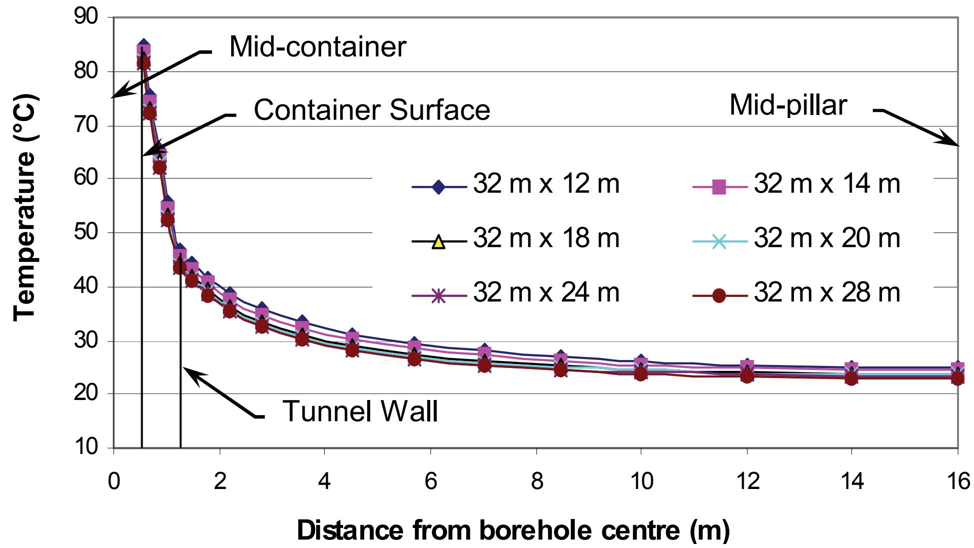

Figure 42: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 32 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

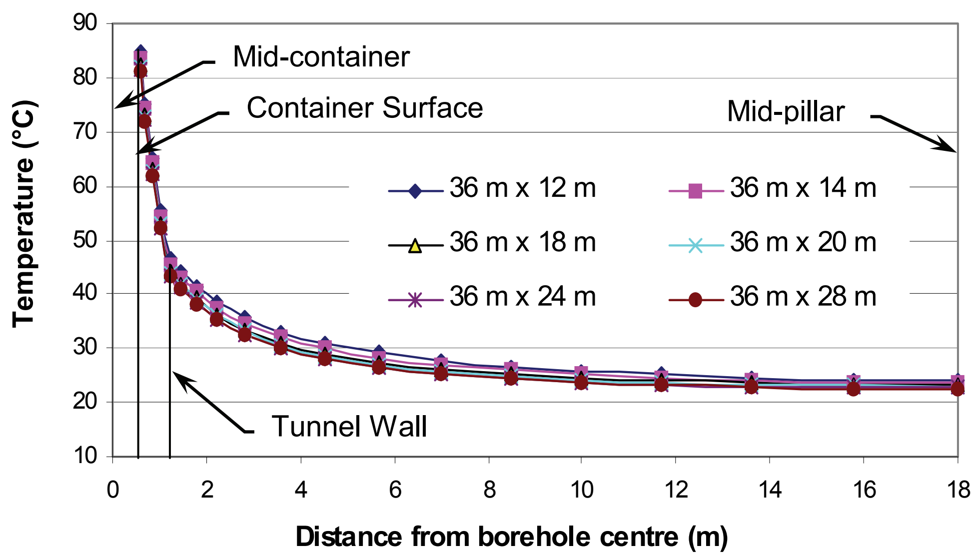

Figure 43: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 36 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

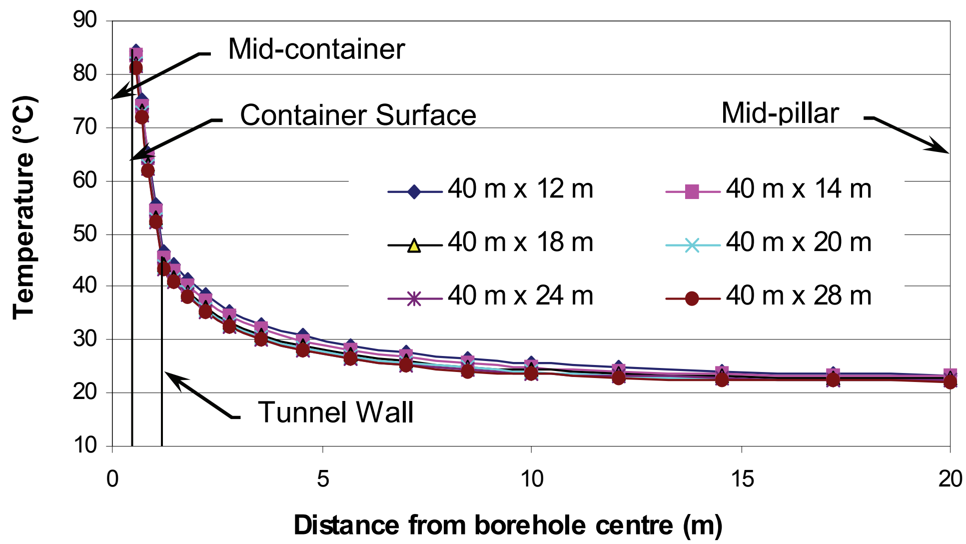

Figure 44: Temperatures along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository 4 Years after Container Placement with a Tunnel Spacing of 40 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

Figure 45 shows the temperatures along a horizontal line from mid-container to mid-pillar between the adjacent placement rooms in a horizontally infinite repository with a tunnel spacing of 24 m and a container spacing of 14 m and a buffer thermal conductivity of 0.7 W/(m·°C). It shows similar characteristics to those in Figure 26. The difference was that the temperature near the container surface in Figure 26 was higher than that in Figure 45 and the reason for the difference was the use of different values of buffer thermal conductivity in the two calculations.

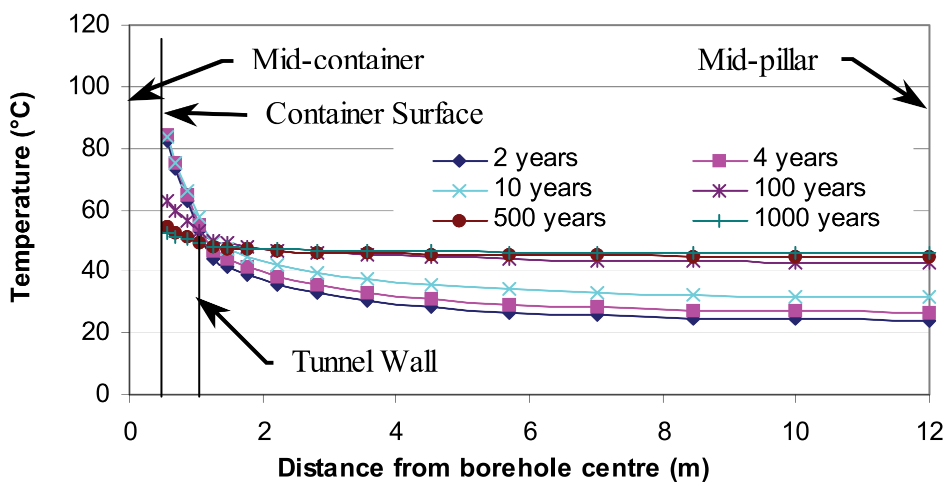

Figure 45: Temperatures at Various Times along a Horizontal Line from Mid-container to Mid-pillar in a Horizontally Infinite Repository with a Tunnel Spacing of 24 m and a Container Spacing of 14 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

In summary, soon after waste placement, the higher temperatures occurred only in the buffer near the container and the temperature decreased very quickly with distance from the container. With time, the temperatures along the horizontal line increased and became more uniform. One hundred years after waste placement, the temperatures in the buffer dropped significantly, while the temperatures in the rock increased to about 45°C. The temperatures in the rock in a repository using a buffer thermal conductivity of 0.7 W/(m·°C) were not significantly different from those using a thermal conductivity of 0.4 W/(m·°C).

6.8 THERMAL RESPONSE TO VARIABLE CONTAINER SPACING AND TUNNEL SPACING

Figure 46 shows the maximum temperatures on the container surfaces *vs.* tunnel spacing (20 m to 40 m) and container spacing (12 m to 28 m) with a buffer thermal conductivity of 0.4 W/(m·°C). The highest first peak container-surface temperature was 117°C and the lowest first peak temperature was 111°C. Beyond a tunnel spacing of 28 m, the container-surface temperature did not decrease significantly. Similarly, container spacing greater than 18 m did not produce a significant decrease in container temperature. The container-surface temperature exceeded 100°C for all cases analysed. One solution for decreasing the container-surface temperature would be to permit more radionuclide decay prior to placements (used-fuel time-out-of-reactor before placement >30 years).

Figure 47 shows the maximum temperatures on a tunnel wall in a repository for variable tunnel spacing (20 m to 40 m) and container spacing (12 m to 28 m) with a buffer thermal conductivity of 0.4 W/(m·°C). The first peak temperatures on the tunnel wall ranged from 43°C to 60°C. This means that the temperature increase induced in the rock by the heat released from waste in a repository is about 22~39°C.

Figure 48 is a container-surface temperature-contour plot based on tunnel spacing (TS) and container spacing (CS) in a horizontally infinite repository with a buffer thermal conductivity of 0.4 W/(m·°C). When container spacing is greater than 18 m and the tunnel spacing is greater than 24 m, the container-surface temperature does not decreased very much with increases in container or tunnel spacing.

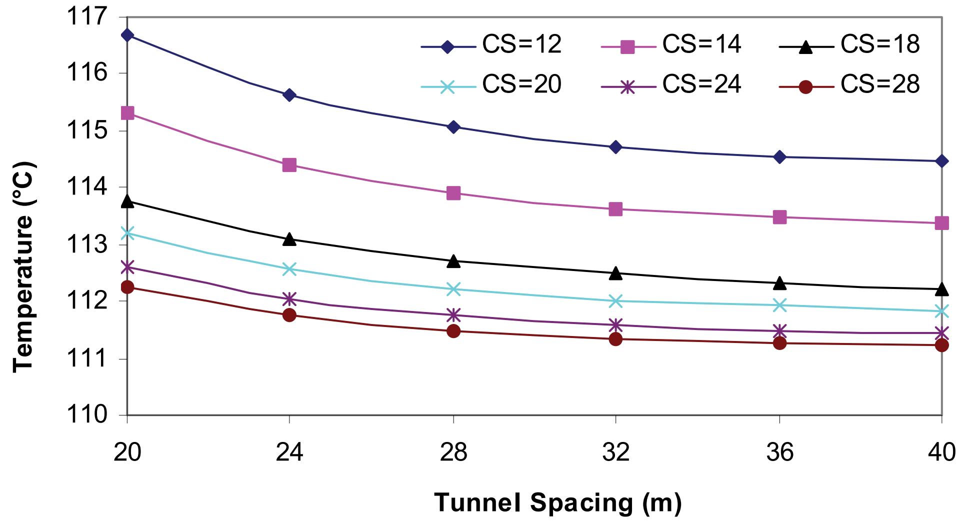

Figure 46: Maximum Container-Surface Temperatures vs. Tunnel Spacing and Container Spacing (The buffer thermal conductivity is 0.4 W/(m·°C))

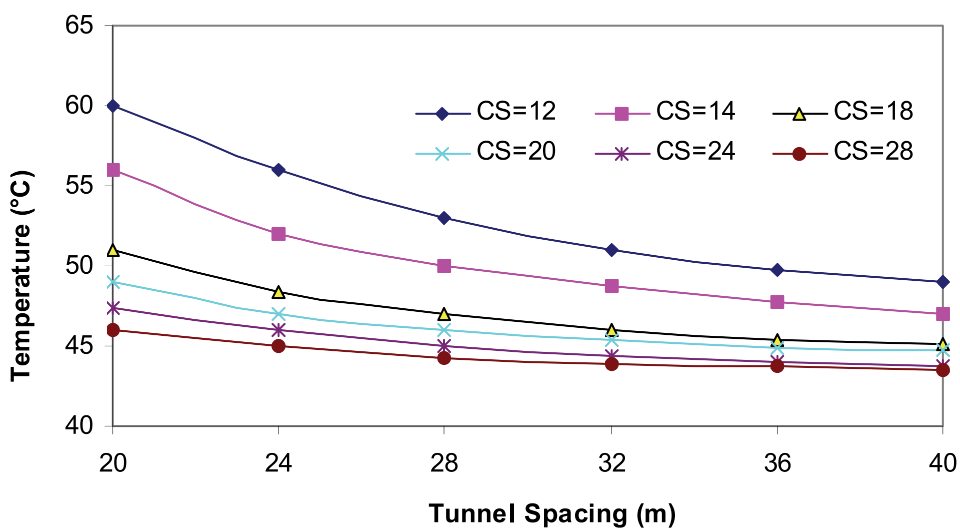

Figure 47: First Peak Tunnel-Wall Temperatures vs. Tunnel Spacing and Container Spacing (The buffer thermal conductivity is 0.4 W/(m·°C))

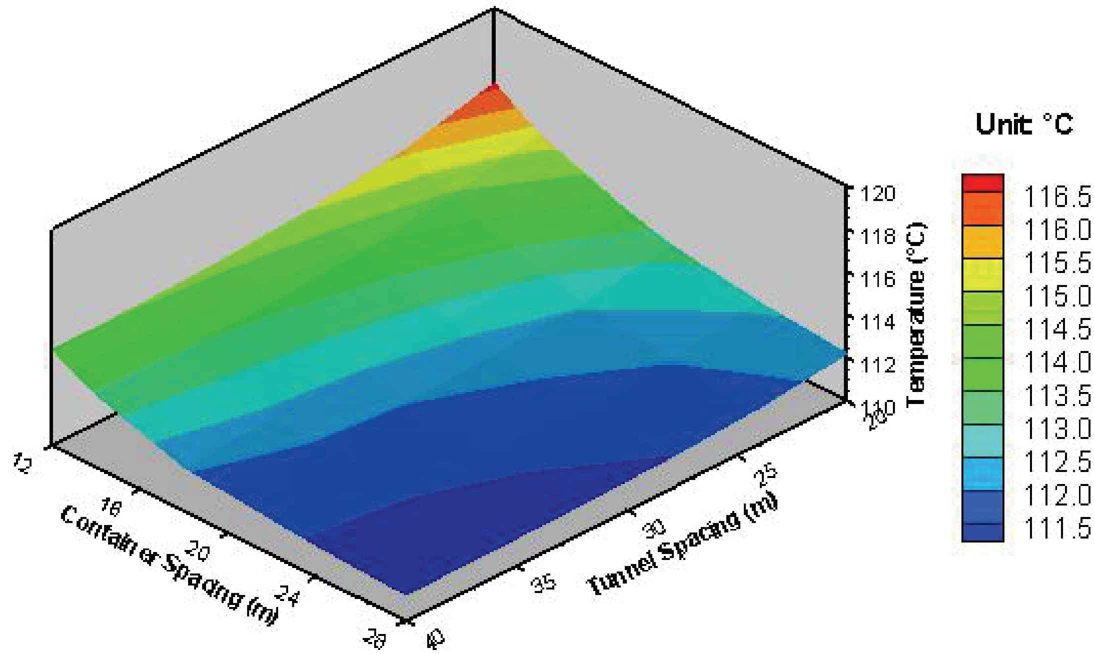

Figure 48: Maximum Container-Surface Temperatures (The buffer thermal conductivity is 0.4 W/(m·°C))

Figure 49 is a tunnel-wall first-peak temperature-contour plot based on tunnel spacing and container spacing in a horizontally infinite repository with a buffer thermal conductivity of 0.4 W/(m·°C). The temperatures in Figure 49 are the temperatures at location of tunnel wall directly opposite of the horizontal line from the container mid-plane to the pillar mid-plane.

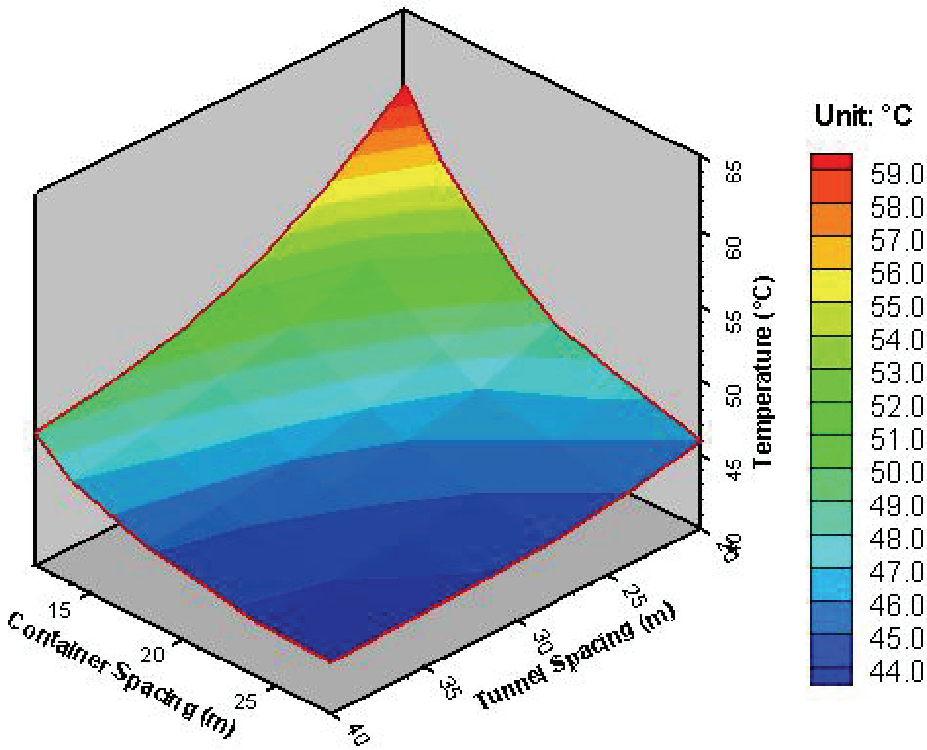

Figure 49: First Peak Tunnel-Wall Temperatures corresponding to the Centre of Container along Tunnel (The buffer thermal conductivity is 0.4 W/(m·°C))

Figure 50 shows the maximum first peak temperatures on the container surface in a horizontally infinite repository with variable tunnel spacing (20 m to 40 m) and container spacing (12 m to 28 m) and a buffer thermal conductivity of 0.7 W/(m·°C). The highest first peak container-surface temperature was 88°C and the lowest first peak temperature was 81°C. The container-surface temperature was lower than 100°C for all analyses performed using 0.7 W/m·°C as the buffer thermal conductivity, and was much lower than the container temperatures derived using 0.4 W/m·°C as the buffer thermal conductivity (Figure 46). The thermal conductivity had a significant influence on the container-surface temperature. Therefore, an accurate estimation of the buffer thermal conductivity is very important to the predication of container-surface temperature in a repository.

Figure 51 shows the maximum first peak temperatures on the tunnel wall in a horizontally infinite repository with variable tunnel spacing (20 m to 40 m) and container spacing (12 m to 28 m) and a buffer thermal conductivity of 0.7 W/(m·°C). The highest first peak container-surface temperature was 60°C and the lowest first peak temperature is 43°C. Compared with Figure 47, the buffer thermal conductivity did not significantly influence the tunnel-wall temperature.

Figure 52 shows the maximum container-surface temperature in a repository with variable tunnel spacing and variable container spacing and a buffer thermal conductivity of 0.7 W/(m·°C). When the container spacing was greater than 14 m and the tunnel spacing was greater than 24 m, the container-surface temperature did not decrease significantly with increased spacings.

Figure 53 shows the first peak tunnel-wall temperature with a buffer thermal conductivity of 0.7 W/(m·°C) as a function of tunnel and container spacing.

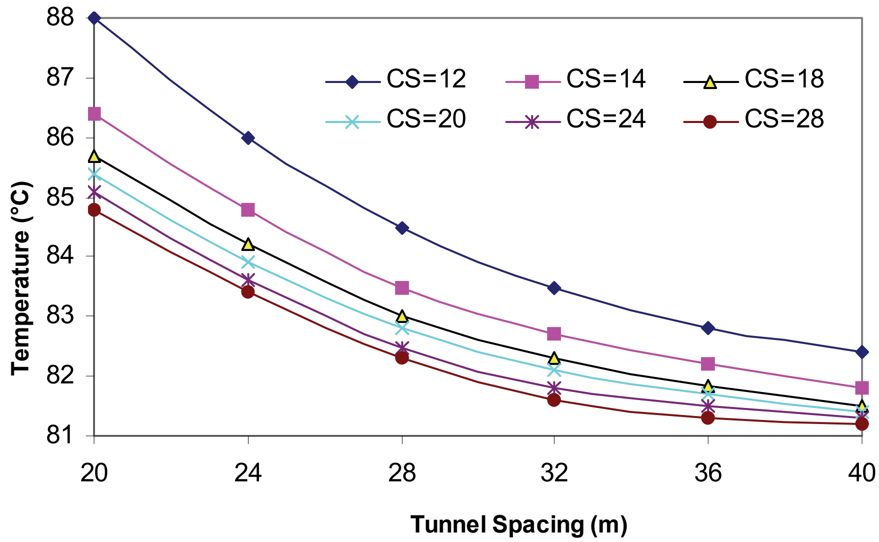

Figure 50: Maximum Container-Surface Temperatures vs. Tunnel Spacing and Container Spacing (The buffer thermal conductivity is 0.7 W/(m·°C))

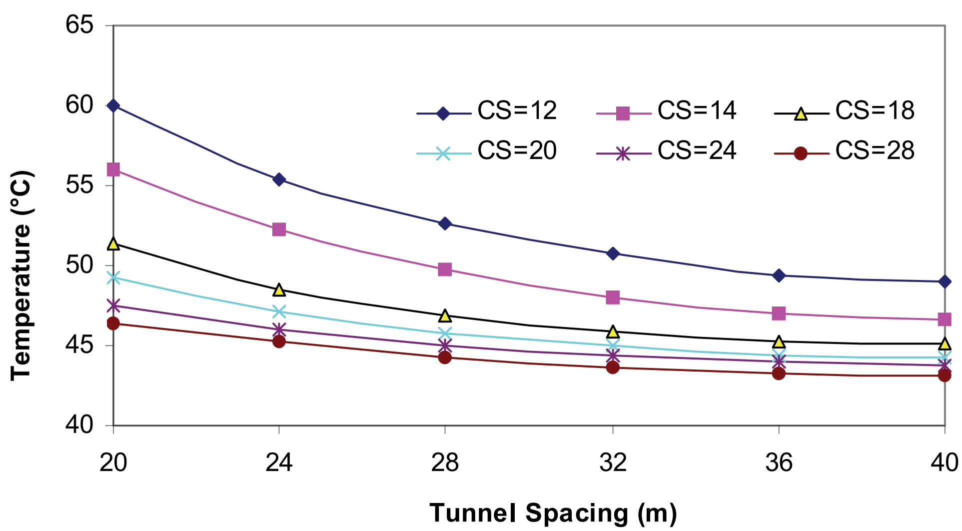

Figure 51: First Peak Tunnel-Wall Temperatures vs. Tunnel Spacing and Container Spacing (The buffer thermal conductivity is 0.7 W/(m·°C))

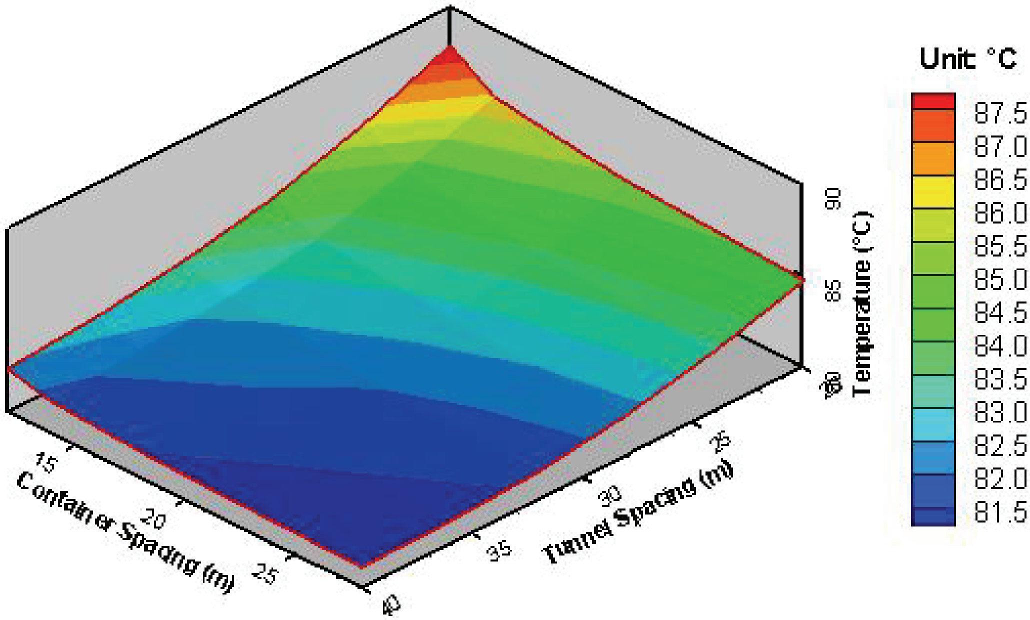

Figure 52: Maximum Container-Surface Temperatures (The buffer thermal conductivity is 0.7 W/(m·°C))

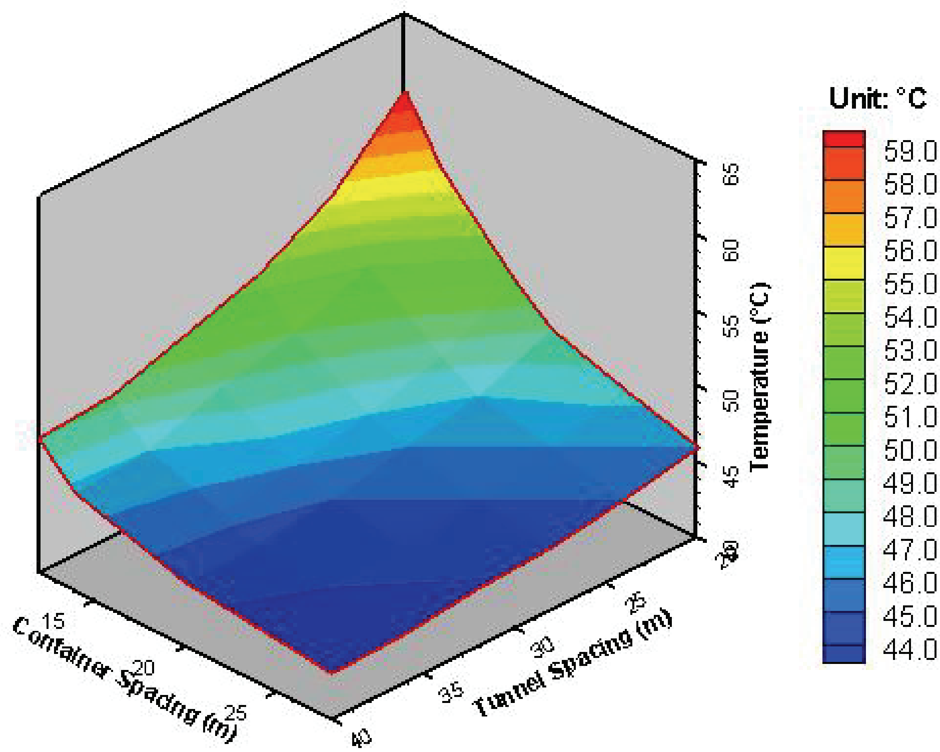

Figure 53: First Peak Tunnel-Wall Temperatures corresponding to the Centre of Container along Tunnel (The buffer thermal conductivity is 0.7 W/(m·°C))

In order to compare the influence of excavated volume on the container surface temperature for different tunnel spacing and container spacing, Figure 54 and 55 show the container surface temperatures vs. excavated volume for repositories with a buffer thermal conductivity of 0.4 and 0.7 W/(m·°C), respectively. In the calculation of excavated volume, it was assumed that there were 6 panels in a repository, 88 rooms in each panel and 21 containers in each room. The excavated volume provided is an index number only for comparing options for tunnel spacing and container spacing and is not considered to be valid for any other use. Generally, the container surface temperature decreased with excavated volume. However, the container surface temperature did not significantly decrease with excavated volume when the excavated volume was greater than 1.25 Mm^3 as shown in Figure 55.

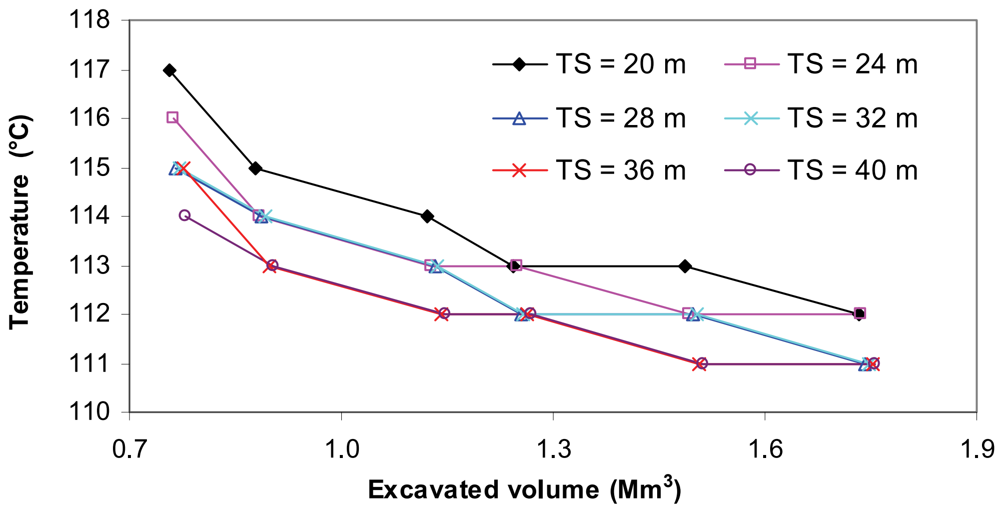

Figure 54: **Container-Surface Temperatures vs. Excavated Volume for Repositories with a Buffer Thermal Conductivity of 0.4 W/(m·°C)**

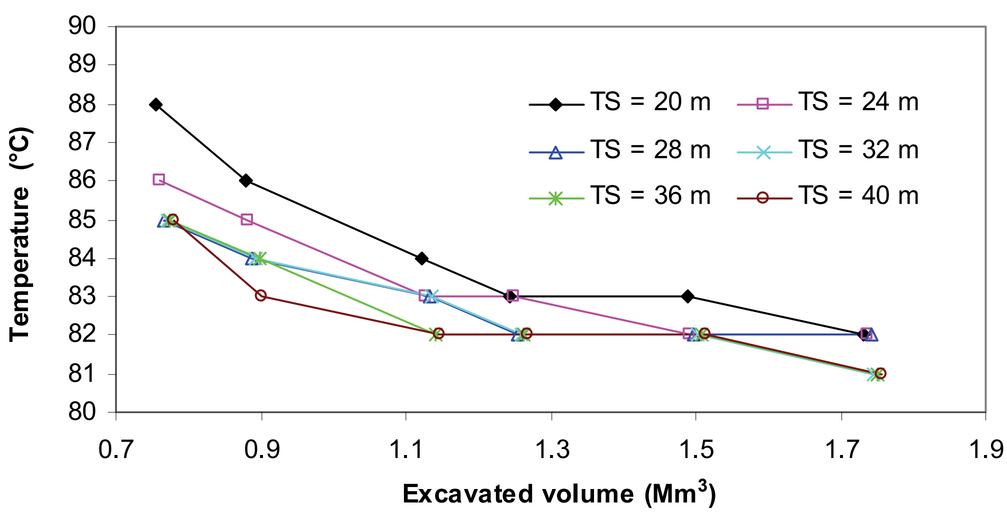

Figure 55: **Container-Surface Temperatures vs. Excavated Volume for Repositories with a Buffer Thermal Conductivity of 0.7 W/(m·°C)**

The container surface temperature is much higher than 100°C in a repository with a buffer thermal conductivity of 0.4 W/(m·°C) and with the range of 20 to 40 m for tunnel spacing and 12 to 28 m for container spacing. The container temperature is much lower than 100°C for a repository if the buffer thermal conductivity is 0.7 W/(m·°C). In Section 7 of this report, some cases with smaller container spacing are presented to assess the effect of smaller spacings on maximum container temperature for buffer thermal conductivity of 0.4 W/(m·°C) and 0.7 W/(m·°C).

6.9 INFLUENCE OF BUFFER THERMAL CONDUCTIVITY ON THERMAL RESPONSE IN AN INFINITE REPOSITORY

Figure 56 shows container-surface temperature vs. time in a repository for the case of a tunnel spacing of 24 m and a container spacing of 14 m as a function of the buffer thermal conductivity. The buffer thermal conductivity has a very significant influence on container-surface temperatures during the first 100 years after waste placement.

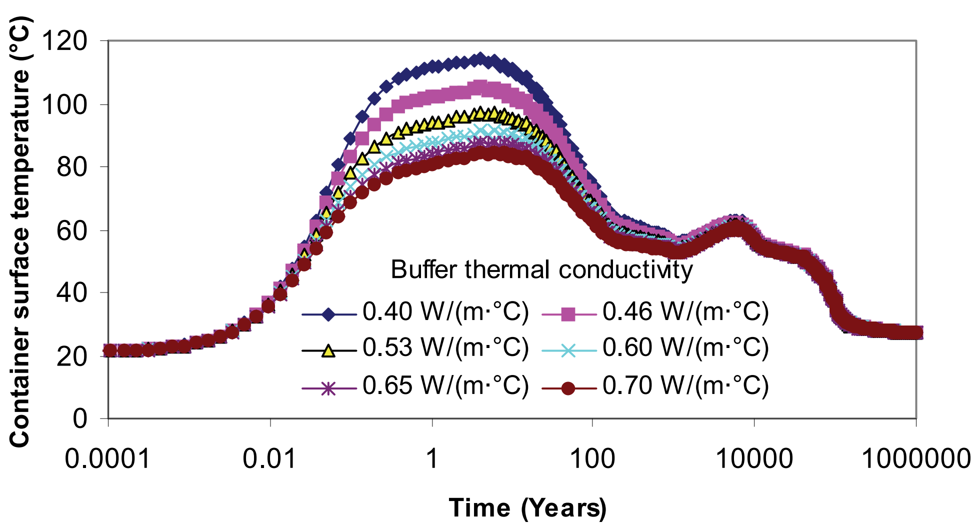

Figure 56: Container-Surface Temperatures vs. Time for Different Buffer Thermal Conductivities in a Horizontally Infinite Repository with a Tunnel Spacing of 24 m and a Container Spacing of 14 m

Figure 57 shows the tunnel-wall temperatures vs. time in an infinite repository for the case of a tunnel spacing of 24 m and a container spacing of 14 m as a function of the buffer thermal conductivity. For this tunnel and container spacing, buffer thermal conductivity had no effect on the tunnel-wall temperatures despite very different container temperatures.

Figure 58 shows the influence of buffer thermal conductivity on the maximum container-surface temperature in a horizontally infinite repository with a tunnel spacing of 24 m and a container spacing of 14 m. The maximum container-surface temperature decreased significantly with increasing buffer thermal conductivity. The results suggest that a buffer thermal conductivity of about 0.51 W/(m·ºC) would be required to meet the 100°C temperature limit on the used fuel container surface.

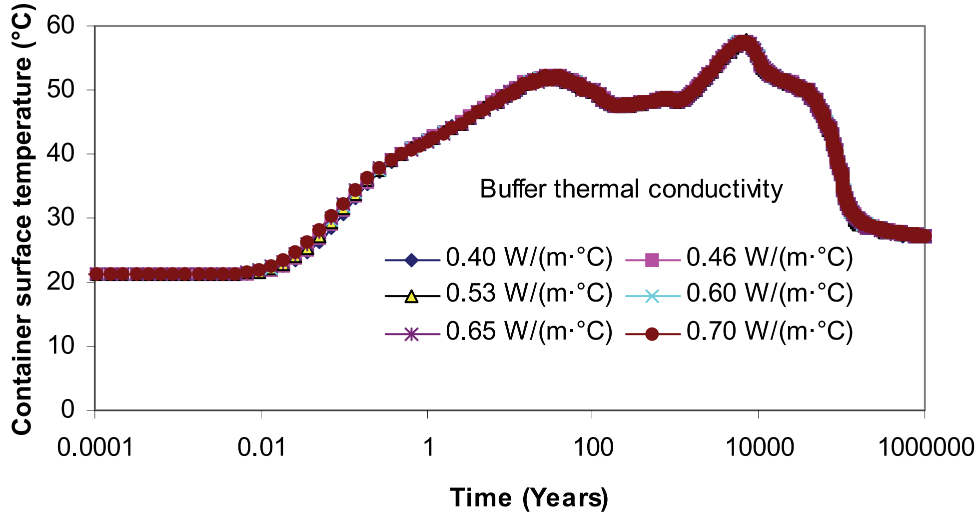

Figure 57: Tunnel-Wall Temperatures vs. Time for Different Buffer Thermal Conductivities in a Horizontally Infinite Repository with a Tunnel Spacing of 24 m and a Container Spacing of 14 m

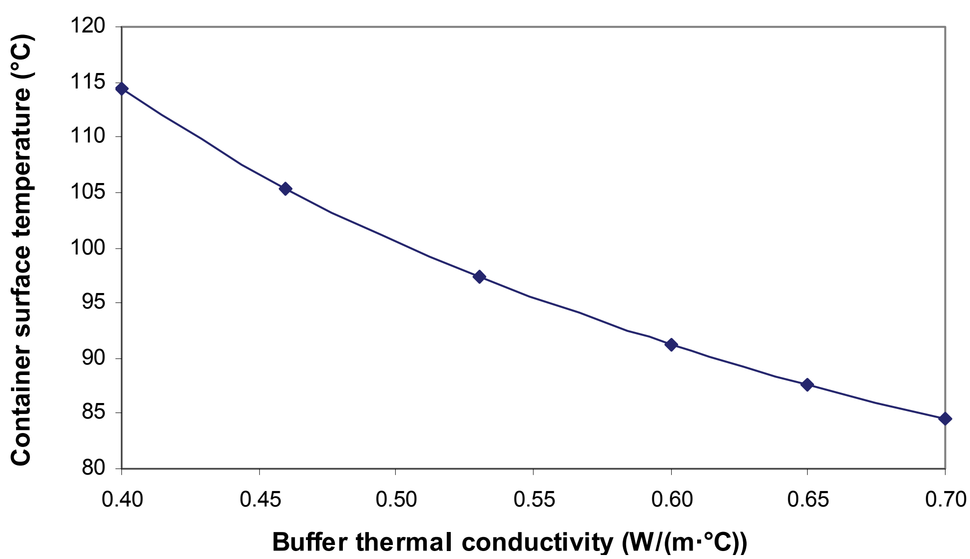

Figure 58: Maximum Container-Surface Temperatures vs. Buffer Thermal Conductivity for a Case with a Tunnel Spacing of 24 m and a Container Spacing of 14 m

7. ADDITIONAL MODELLING RESULTS

This section presents the results from the additional cases shown in Table 2 to check the container- and tunnel-wall temperatures in a repository with container spacing of 10 m, 8 m and 6 m using buffer thermal conductivities of both **0.4 W/(m·ºC) and 0.7 W/(m·ºC)**.

7.1 CONTAINER-SURFACE TEMPERATURES IN AN INFINITE REPOSITORY WITH CONTAINER SPACINGS OF 8 m AND 10 m WITH A BUFFER THERMAL CONDUCTIVITY OF 0.4 W/(m·°C)

Figure 59 and 60 show the container-surface temperatures in an infinite repository with a buffer thermal conductivity of 0.4 W/(m·°C) and with variable tunnel spacing and container spacing of 8 m and10 m, respectively. Compared with Figures shown in Section 6.2, the second peak temperatures were much higher than those in a repository with greater container spacing for a horizontally infinite repository.

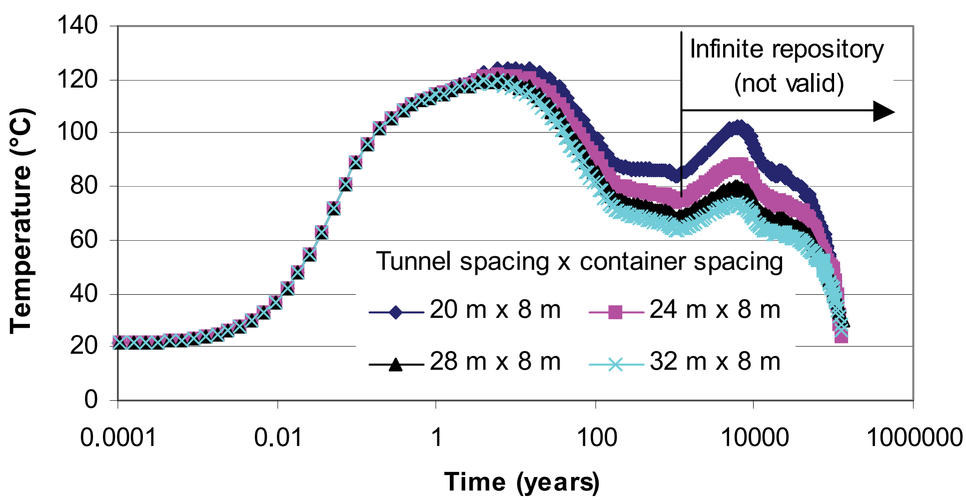

Figure 59: **Container-Surface Temperatures for a Horizontally Infinite Repository with a Container Spacing of 8 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)**

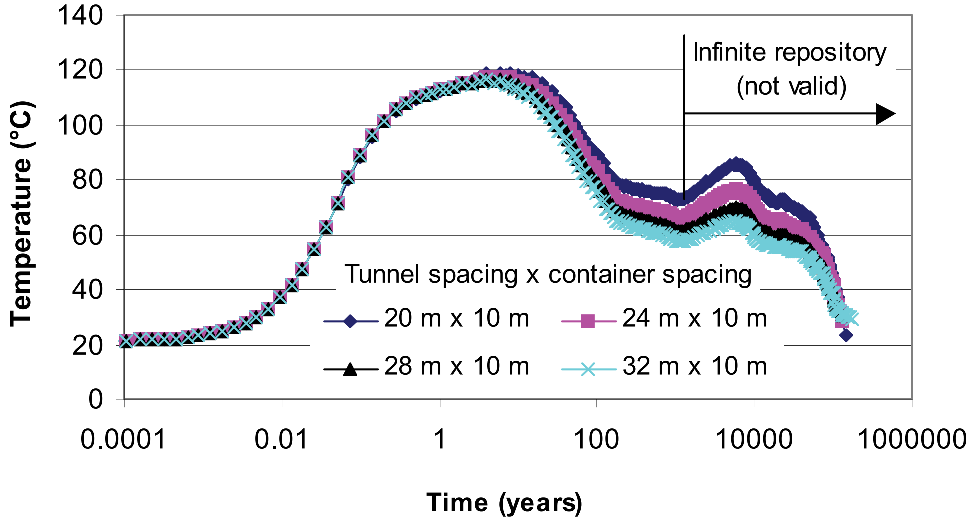

Figure 60: **Container-Surface Temperatures for a Horizontally Infinite Repository with a Container Spacing of 10 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)**

Table 10 shows the first peak temperatures, 500-year temperatures and 1,000-year temperatures on container surface in an infinite repository with a buffer thermal conductivity of 0.4 W/(m·°C) and with variable tunnel spacing and container spacing of 8 m and10 m. The first peak temperatures were much higher than 100°C in a repository with container spacing of 8 and 10 m if the buffer thermal conductivity is 0.4 W/(m·°C). The first peak container-surface temperature for different tunnel spacings occurred at the same time (4 years after waste plancement).

Table 10: Container-Surface Temperatures in a Horizontally Infinite Repository with a Buffer Thermal Conductivity of 0.4 W/(m·°C) for Additional Cases

Container Spacing (m)	Tunnel Spacing (m)	Time for the first peak temperature (years)	First peak temperature (°C)	Temperatures after 500 years (°C)	Temperatures after 1,000 years (°C)
8	20	4	123	86	84
	24	4	121	77	75
	28	4	120	71	69
	32	4	120	67	64
10	20	4	119	75	73
	24	4	118	69	66
	28	4	117	64	61
	32	4	117	61	58

7.2 CONTAINER-SURFACE TEMPERATURES IN AN INFINITE REPOSITORY WITH CONTAINER SPACINGS OF 6 m, 8 m AND 10 m AND WITH A BUFFER THERMAL CONDUCTIVITY OF 0.7 W/(m·°C)

Figure 61, 62 and 63 show the container-surface temperatures in an infinite repository with a buffer thermal conductivity of 0.7 W/(m·°C) and with variable tunnel spacing and container spacing of 6 m, 8 m and 10 m, respectively. Compared with Figures in Section 6.4, the second peak temperatures were much higher. Table 11 shows the first peak temperatures, 500-year temperatures and 1000-year temperatures on the container surface in a repository with container spacings of 6 m, 8 m and 10 m and various tunnel spacing and a buffer thermal conductivity of 0.7 W/(m·°C). The temperatures on the container surface were lower than 100°C in a repository with container spacings of 8 m and 10 m if the buffer thermal conductivity is 0.7 W/(m·°C). For a repository with container spacing of 6 m, the first peak container-surface temperatures were 99 and 101°C with tunnel spacings of 32 and 28 m, respectively. The tunnel spacing also influenced the time for the first peak container-surface temperatures.

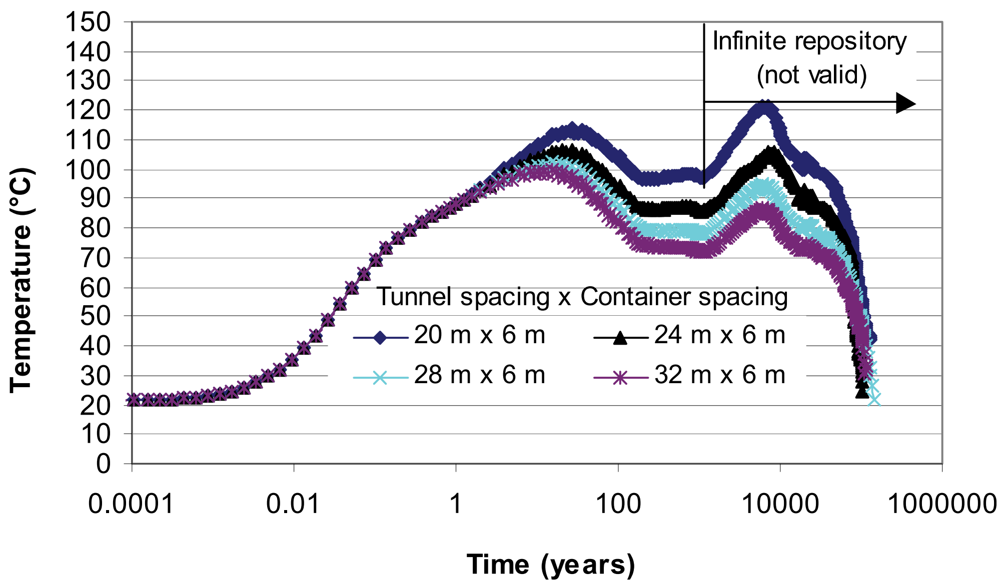

Figure 61: Container-Surface Temperatures for a Horizontally Infinite Repository with a Tunnel Spacing of 6 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)

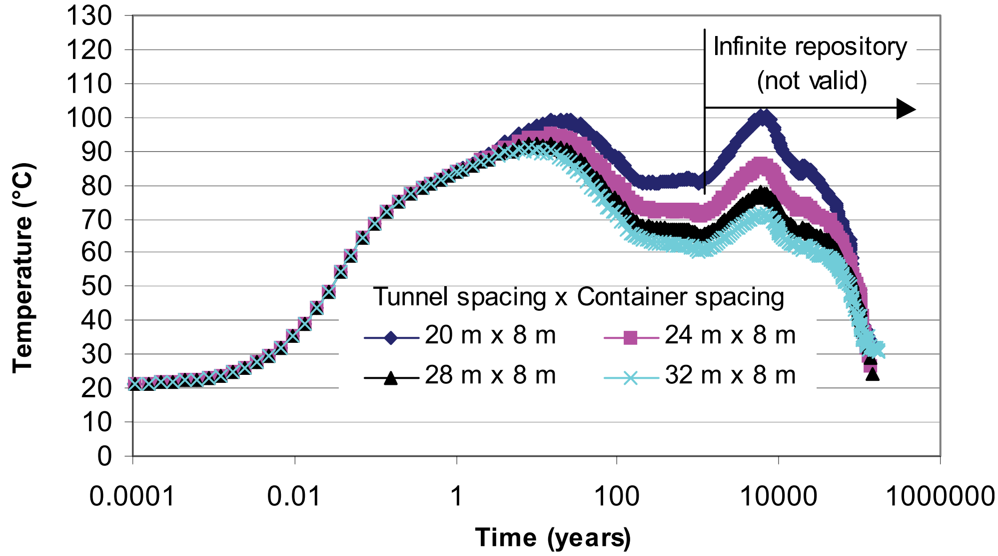

Figure 62: **Container-Surface Temperatures for a Horizontally Infinite Repository with a Container Spacing of 8 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)**

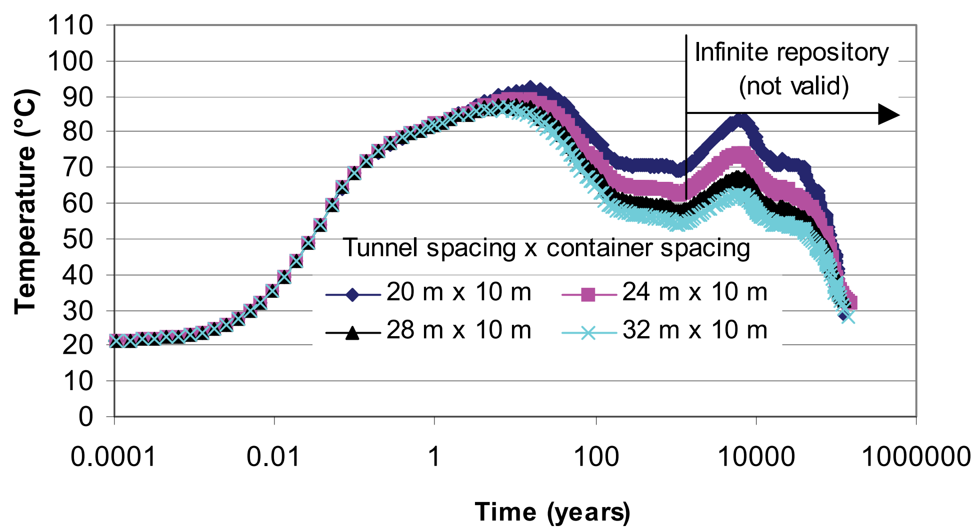

Figure 63: **Container-Surface Temperatures for a Horizontally Infinite Repository with a Container Spacing of 10 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)**

Table 11: Container-Surface Temperatures in a Horizontally Infinite Repository with a Buffer Thermal Conductivity of 0.7 W/(m·°C) for Additional Cases

Container Spacing (m)	Tunnel Spacing (m)	Time for the first peak temperature (years)	First peak temperature (°C)	Temperatures after 500 years (°C)	Temperatures after 1,000 years (°C)
6	20	27	114	97	97
	24	20	106	87	86
	28	15	101	79	78
	32	15	99	73	72
8	20	20	99	81	81
	24	15	95	72	71
	28	12	92	67	65
	32	12	90	62	61
10	20	15	93	70	69
	24	10	89	64	62
	28	8	88	59	58
	32	6	87	56	54

7.3 TUNNEL-WALL TEMPERATURES IN AN INFINITE REPOSITORY WITH CONTAINER SPACINGS OF 8 m AND 10 m AND WITH A BUFFER THERMAL CONDUCTIVITY OF 0.4 W/(m·°C)

Figures 64 and 65 show the tunnel-wall temperatures in an infinite repository with a buffer thermal conductivity of 0.4 W/(m·°C) and with variable tunnel spacing and container spacing of 8 m and10 m, respectively.

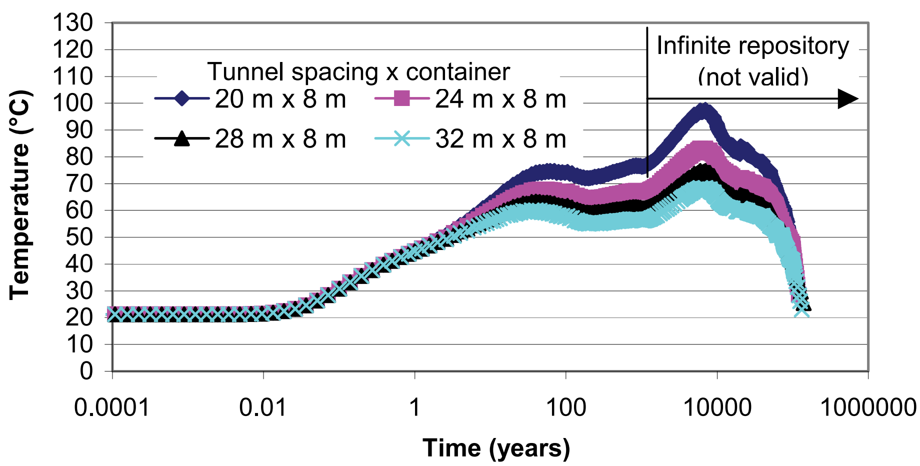

Figure 64: Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Container Spacing of 8 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)

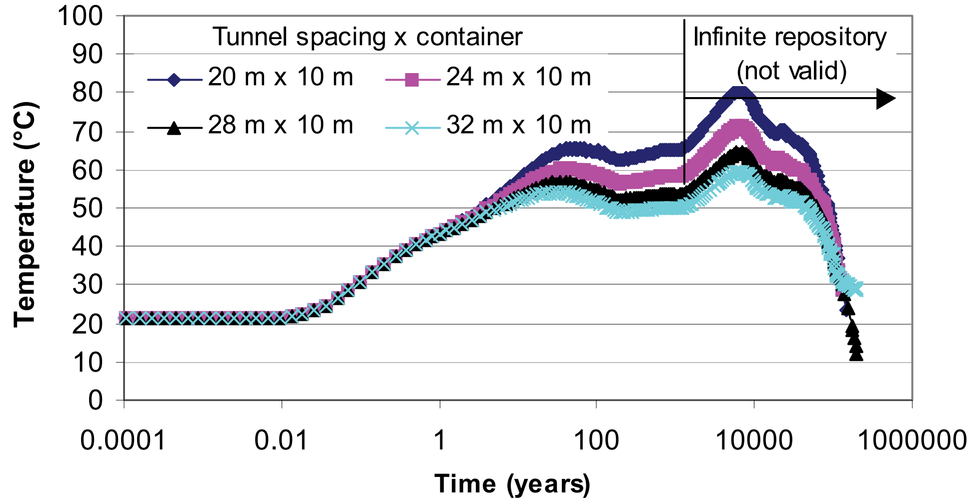

Figure 65: **Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Container Spacing of 10 m and a Buffer Thermal Conductivity of 0.4 W/(m·°C)**

Table 12 shows the first peak temperatures, 500-year temperatures and 1000-year temperatures on the tunnel wall in a repository with container spacings of 8 and 10 m and a buffer thermal conductivity of 0.4 W/(m·°C). The first peak temperatures were in a range of 54 to 75°C. This indicates that waste produced heat induced temperature increase was about 33 to 54°C.

Table 12: Tunnel-Wall Temperatures in a Horizontally Infinite Repository with a Buffer Thermal Conductivity of 0.4 W/(m·°C) for Additional Cases

Container Spacing (m)	Tunnel Spacing (m)	Time for the first peak temperature (years)	First peak temperature (°C)	Temperatures after 500 years (°C)	Temperatures after 1,000 years (°C)
8	20	56	75	75	76
	24	45	68	66	67
	28	38	63	60	61
	32	35	60	56	56
10	20	40	65	64	65
	24	35	60	58	58
	28	27	57	53	53
	32	25	54	50	50

7.4 TUNNEL-WALL TEMPERATURES IN AN INFINITE REPOSITORY WITH CONTAINER SPACINGS OF 6 m, 8 m AND 10 m AND A BUFFER THERMAL CONDUCTIVITY OF 0.7 W/(m·°C)

Figure 66, 67 and 68 show the tunnel-wall temperatures in an infinite repository with a buffer thermal conductivity of 0.7 W/(m·°C) and with variable tunnel spacing and container spacing of 6 m, 8 m and 10 m, respectively. Table 13 shows the first peak temperatures, 500-year temperatures and 1000-year temperatures on the container surface in a repository with container spacings of 6 m, 8 m and 10 m and various tunnel spacing and a buffer thermal conductivity of 0.7 W/(m·°C). Compared with Table 13, there was no difference in the tunnel-wall temperatures in an infinite repository whether using 0.4 W/(m·°C) or using 0.7 W/(m·°C) as the buffer thermal conductivity.

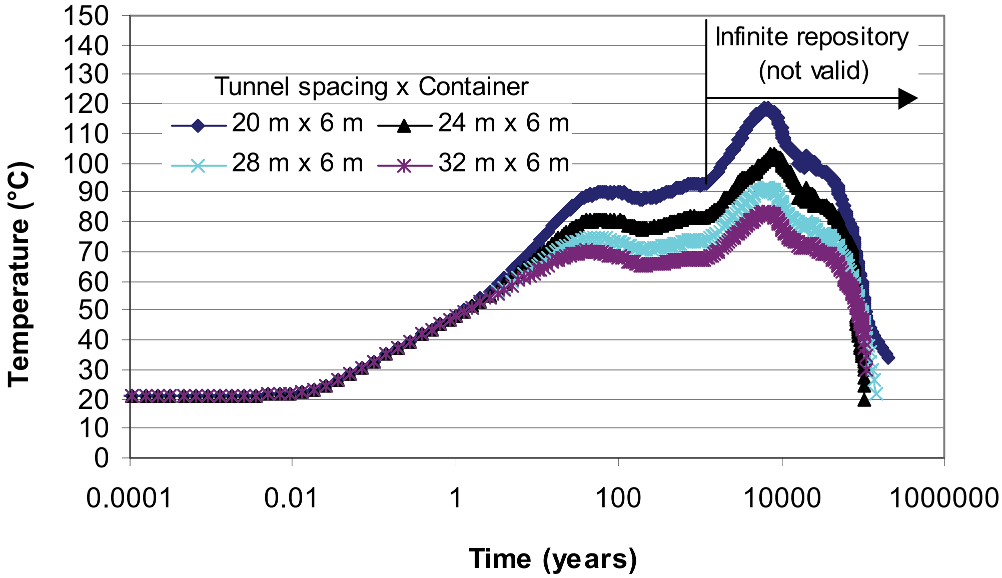

Figure 66: **Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Container Spacing of 6 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)**

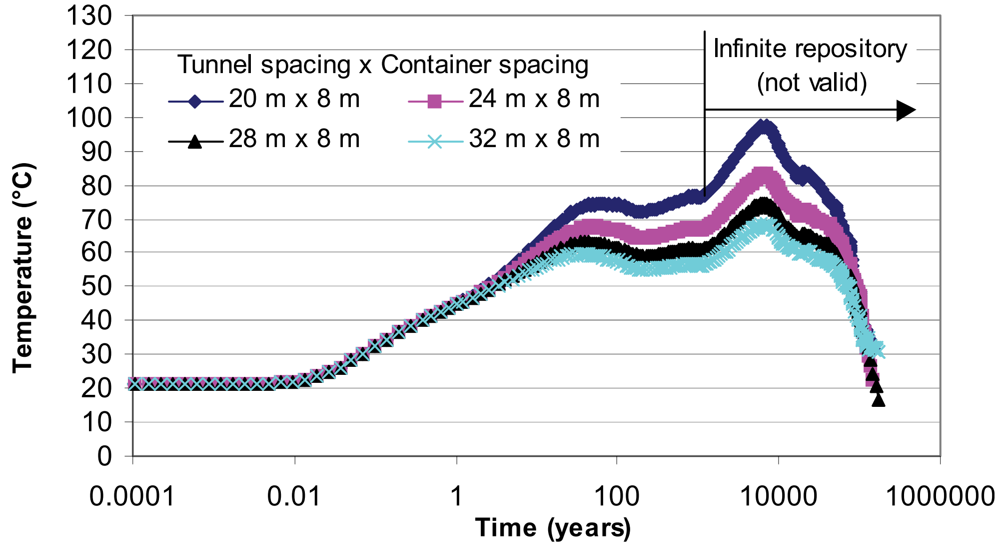

Figure 67: **Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Container Spacing of 8 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)**

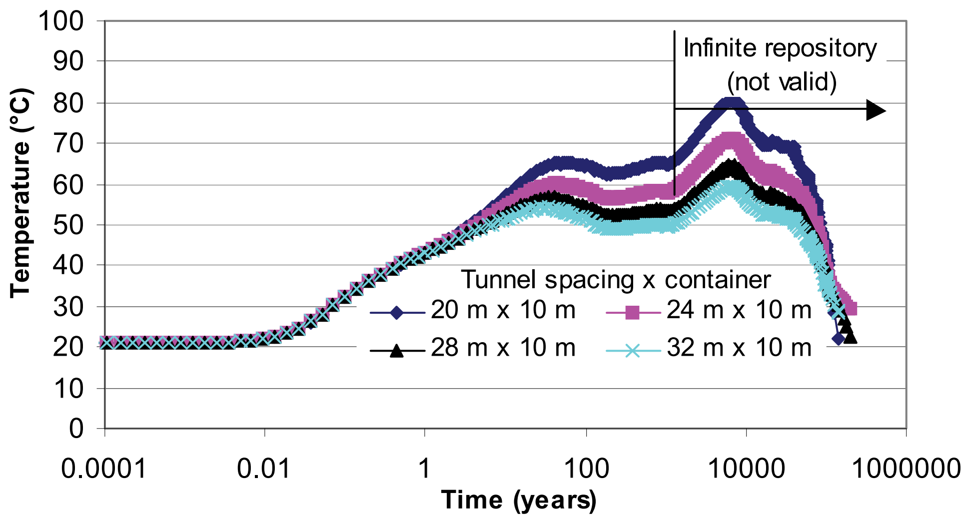

Figure 68: **Tunnel-Wall Temperatures for a Horizontally Infinite Repository with a Container Spacing of 10 m and a Buffer Thermal Conductivity of 0.7 W/(m·°C)**

In summary, the container-surface temperature can be less than 100°C in a repository with tunnel spacing of 32 m and container spacing of 6 m if the buffer thermal conductivity is 0.7 W/(m·°C),

Table 13: Tunnel-Wall Temperatures in a Horizontally Infinite Repository with a Buffer Thermal Conductivity of 0.7 W/(m·°C) for Additional Cases

Container Spacing (m)	Tunnel Spacing (m)	Time for the first peak temperature (years)	First peak temperature (°C)	Temperatures after 500 years (°C)	Temperatures after 1,000 years (°C)
6	20	70	91	91	93
	24	56	81	80	81
	28	50	75	72	73
	32	40	70	67	67
8	20	56	75	75	76
	24	45	68	66	67
	28	40	63	60	61
	32	35	60	56	56
10	20	45	65	64	65
	24	40	60	58	58
	28	35	57	53	53
	32	27	54	50	50

8. CONCLUSIONS

The CODE_BRIGHT finite-element program was successfully used to perform thermal analyses to assess the sensitivity of temperature to changes in the dimensions of a used-fuel deep geological repository. The modelling in this report identifies tunnel and container spacings beyond which little benefit is obtained in terms of decreasing container- or tunnel-wall temperature.

If the buffer thermal conductivity is 0.4 W/(m·°C), the modelling results are summarized as follows:

- For each case modelled the first peak container-surface temperature is above 100 °C, and ranges from 125°C when tunnel spacing is 20 m and container spacing is 8 m; to 111°C when tunnel spacing is 40 m and container spacing is 28 m.
- Once tunnel spacing is greater than 24 m, the container-surface temperature does not significantly decrease with container spacing.
- The container-surface temperature did not significantly decrease with container spacing when the container spacing is greater than 18 m.
- The highest first peak tunnel-wall temperature is 60°C and the lowest first peak temperature is 44°C. This means that the temperature increase induced by the heat released from waste in a repository is about 23~39°C.

If the buffer thermal conductivity is 0.7 W/(m·°C), the modelling results are summarized as follows:

- The highest first peak container-surface temperature is 114°C when tunnel spacing is 20 m and container spacing is 6 m. The lowest first peak temperature is 81° when tunnel spacing is 40 m and container spacing is 28 m.
- Once tunnel spacing is greater than 24 m, the container-surface temperature does not significantly decrease with container spacing.
- The container-surface temperature does not significantly decrease with container spacing when the container spacing is greater than 14 m.
- The container-surface temperature is less than 100°C in a repository with a tunnel spacing of 20 m to 40 m, a container spacing of 8 m to 28 m.
- The first peak container-surface temperature is 100°C when tunnel spacing is 32 m and container spacing is 6 m.
- The highest first peak tunnel-wall temperature is 91°C when tunnel spacing is 20 m and container spacing is 6 m. The lowest first peak tunnel-wall temperature is 43°C. This indicates that the temperature increase induced by the heat released from used fuel waste in a repository is about 22~70°C.

For a tunnel spacing of 24 m and a container spacing of 14 m, a buffer thermal conductivity of about 0.51 W/(m·°C) would be required to meet the 100°C temperature limit on the used fuel container surface.

The buffer thermal conductivity does not significantly influence the tunnel-wall temperature. However, the thermal conductivity does have a significant influence on the container-surface temperature during the first 100 years after waste placement. Therefore, an accurate estimation of the buffer thermal conductivity is important in calculating the container-surface temperature and the buffer adjacent to the containers in a repository.

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