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ANNULAR AIR SPACE EFFECTS ON NUCLEAR
WASTE CANISTER TEMPERATURES IN A DEEP
GEOLOGIC WASTE REPOSITORY

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ABSTRACT

Air spaces in a deep geologic repository for nuclear high level waste will have an important effect on the long-term performance of the waste package. The important temperature effects of an annular air gap surrounding a high level waste canister are determined through 3-D numerical modeling. Air gap properties and parameters specifically analyzed and presented are the air gap size, surfaces emissivity, presence of sleeve, and initial thermal power generation rate; particular emphasis was placed on determining the effect these variables have on the canister surface temperature. Finally a discussion based on modeling results is presented which specifically relates the results to NRC regulatory considerations.

1.0 INTRODUCTION

Containing and isolating nuclear waste material from man and his environment until its radioactivity has decayed to a harmless level is the aim of Nuclear Waste Management. Commensurate with this, programs sponsored by the Nuclear Regulatory Commission are designed to develop and organize knowledge pertaining to the dynamics associated with the management and ultimate disposal of waste materials. The knowledge gained through such programs must form the basis for written guidelines and regulations for use in licensing other organizations/agencies to dispose of nuclear waste in such a manner that the health and safety of the general public is assured.

1.1 Purpose and Scope of this Report

The purpose of this report is to document important findings determined through an extensive 3-D numerical analysis of the effects of an air gap around a nuclear waste canister emplaced in a deep geologic repository. The independent effects dealt on the canister temperature and the near-field temperature gradients in the host rock are examined/analyzed in detail. Particular emphasis is placed on quantitative assessment and unambiguous documentation of the temperature of a waste canister in response to variations of several parameters which may lead to relevant NRC regulations. These are:

- a) the surface properties of the gap
- b) the size of the annular air gap
- c) presence/absence of a sleeve
- d) the canister and areal initial thermal power levels.

1.2 Relevance of these Results to NRC Regulations

A preliminary assessment of the thermal effects of an annular air space surrounding an emplaced nuclear waste canister was made by Davis [1]. That analysis was limited to the consideration of a single initial power generation

rate (4.61 kW) and fixed gap surface emittance properties of 0.9. The conclusion reached was that air gaps could have a significant effect on the long term performance of the waste package.

Annular air spaces around the waste canister will be unavoidable. A qualitative analysis of the mechanics of drilling a large diameter hole (1 ft. or .3 m) in the floor of a repository corridor to a depth of approximately 26 ft. (7.9 m), with sufficient diametral clearance to avoid binding, leads to the realization that air gaps will be unavoidable. If no sleeve is used, ultimate closure due to creep will likely occur but the macrovoids at the canister/host rock interface will never completely be erased by the creep process. Likewise, macro-air spaces will result if backfilling were to occur.

Since it is certain that air spaces are unavoidable, an understanding of air gap effects is essential; regulation of the air gap specifications, including size and surface properties, should be based on principles of engineering analysis to optimize the long-term thermal performance of the waste package. It is essential that this is assured by NRC regulations because temperature is the primary source potential determining corrosion rate, brine migration rate, and thermo/mechanical package response. These coupled mechanisms will determine the life span of the metal barriers which prevent release of the radionuclides housed in the waste packages.

1.3 Physical Characteristics of the Conceptual Repository

Most of this analysis addressed a repository mined in bedded salt. However, basalt was also modeled so that some determination of host rock/air gap interaction could be quantified. The thermal sources were modeled to have the characteristics of spent fuel aged from 3 to 10 years prior to emplacement. (This is consistent with Presidential policy announced April 7, 1977 deferring indefinitely the reprocessing of commercial nuclear waste.)

A conceptual model of a spent fuel nuclear waste repository is illustrated in Figure 1. It consists of a series of long parallel corridors (rooms) mined in

FIG. 1. Conceptual model of a nuclear high level waste repository in salt.

a layer of rock. The size of the corridors will ultimately be determined by the final design of waste handling equipment and they may have cross-sectional dimensions as large as 18 x 26 ft. (5.49 x 7.92 m). The modeling analysis performed herein assumed a cross section of 18 x 18 ft. (5.49 x 5.49 m). Waste canisters would be emplaced in drilled holes equally spaced 17.3 ft. (5.27 m) apart along the floor centerline. The rooms were modeled as being 88 ft. (26.82 m) center to center. Following emplacement, a plug would be inserted atop the canister and the cavity above the plug would be filled to floor level. The top of the canister was modelled as being 10 ft. (3.05 m) below the floor level.

Prior analysis has shown that the room air space will have a significant effect on the repository thermal environment. Altenbach [2] employed the TRUMP [3] thermal code to compare the effect of room ventilation* vs. non-ventilation. He showed that the canister temperature will be more than 300°F (148.9°C) cooler if the repository rooms are ventilated.** Davis [4] showed that the presence of a large air space in close proximity to an emplaced waste canister could result in the canister being cooler. (This effect would be much more dramatic if the host rock were of a less conductive material than salt.)

1.4 Characterisitics of the Modeled Thermal Source

In all of the cases modeled, the thermal source had the decay characteristics of spent fuel. The size of the canister modeled was the same: 1 ft. diameter by 16 ft. long (.3m x 4.8m). Three different initial power levels were modeled. They were:

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*A ventilated room is one which is cooled by means of an externally powered air moving system.

**The waste in Altenbach's study was solidified high level waste in a canister which was 8 ft. long x 1 ft. (2.44 x .3 m) diameter. The SHLW was modeled as 10-year-old waste having an initial power of 3.5 kW per canister. Spacing was such that an areal loading of 100 kW per acre resulted.

- a) The equivalent of three PWR assemblies aged 3.4 years from time of removal from a reactor; they collectively generated 4.61 kW per canister at the time of modeled emplacement. The thermal decay characteristics are tabulated below (time is referenced to emplacement) [5].

TIME (YRS.)	POWER (kW)
0	4.61
2	2.81
7	1.81
27	1.13
97	0.4

- b) The equivalent of three PWR assemblies aged 10 years from time of removal from a reactor; they collectively generated 1.65 kW per canister at the time of modeled emplacement. The thermal decay characteristics are tabulated below, and are time-referenced to emplacement [6].

TIME (YRS.)	POWER (kW)
0	1.65
15	1.12
20	1.02
35	0.72
85	0.36
285	0.014

- c) The equivalent of one PWR assembly aged 10 years from time of removal from a reactor; it generated 0.55 kW per canister at the time of modeled emplacement. The thermal decay characteristics are tabulated below and time referenced to emplacement [6].

TIME (YRS.)	POWER (kW)
0	0.55
15	0.37
20	0.34
35	0.24
85	0.12
285	0.005

Average thermodynamic properties of UO_2 were assumed for the waste package and modeling was executed assuming temperature-independent properties for the waste. The important properties were:

thermal conductivity = 4.62 Btu/hr-ft- $^{\circ}$ F (8.0 W/m $^{\circ}$ C)
specific heat capacity = 0.059 Btu/lbm- $^{\circ}$ F (246.62 J/kg $^{\circ}$ C)
mass density = 655. lbm/ft. ^{3} (1.049 x 10 ^{4} kg/m ^{3})

1.5 Unit Cell and Host Rock Properties

The assumption of simultaneous emplacement of the waste canisters in a uniformly spaced horizontal plane leads to the modeling simplicity of a unit cell containing one waste canister.

Figure 2 illustrates the unit cell, which is identical to that employed by Altenbach [2] and Davis [4]*. For the purpose of analyzing the air gap effects, the time period of interest was 0-2 years because peaking of the canister temperature occurred within that modeled time frame. A special purpose 1-D finite difference code was developed which verified the validity of fixing the upper and lower boundary temperatures at constant values consistent with the geothermal gradient. (A unit cell of 1000 ft. (304.8 m)

*Rooms were modeled as being continuously ventilated so as to maintain an average air temperature of 79 $^{\circ}$ F (26.1 $^{\circ}$ C). The full unit cell size was 88 x 17.3 x 1000 ft. (26.8 x 5.27 x 304.8 m).

Figure 2. Quarter-symmetry 3-D unit cell utilized in air gap analysis.

height will retain constant temperature boundaries for a period of at least four years after waste emplacement).

The properties of modeled salt and basalt are listed in Table 1.

2.0 SUMMARY OF RESULTS AND CONCLUSIONS

Key statements which summarize the most important results of this study are presented below.

2.1 Air Gap Size

A critical gap size at which canister temperatures will be highest has been identified. This occurs at roughly one inch for most cases, and should be avoided by design. Large gaps can conceivably maintain the canister at temperatures lower than those obtained from zero gap (perfect thermal contact) simulations.

2.2 Temperature Dependence of Air Gap Effects

Gap effects are magnified when local geo-medium temperatures are increased. This can be caused by higher areal power loadings and emplacement media with low thermal conductivities.

2.3 Emissivity

The emissivities of the gap surfaces should be as close to unity as is feasible, to enhance the heat transfer process. Raising the canister surface emissivity has the most influence.

2.4 Sleeve

The presence of a loosely inserted retaining sleeve will increase the canister temperature significantly.

Table 1. Thermal Properties of Salt and Basalt

	<u>SALT</u> [5]		<u>BASALT</u> [7]	
Conductivity:	<u>(Btu/hr-ft-°F)</u>	<u>(W/m-°C)</u>	<u>(Btu/hr-ft-°F)</u>	<u>(W/m-°C)</u>
	3.09 (32°F)	5.35 (0°C)	.67 (32°F)	1.16 (0°C)
	2.61 (122°F)	4.52 (50°C)	.69 (122°F)	1.19 (50°C)
	2.23 (212°F)	3.86 (100°C)	.73 (212°F)	1.26 (100°C)
	1.94 (302°F)	3.36 (150°C)	.76 (302°F)	1.32 (150°C)
	1.70 (392°F)	2.94 (200°C)	.79 (392°F)	1.37 (200°C)
	1.53 (482°F)	2.65 (250°C)	.86 (572°F)	1.49 (300°C)
	1.39 (572°F)	2.41 (300°C)	.90 (752°F)	1.56 (400°C)
	1.18 (752°F)	2.04 (400°C)	.95 (952°F)	1.64 (511°C)
Specific Heat				
Capacity:	<u>(Btu/lbm-°F)</u>	<u>(J/kg-°C)</u>	<u>(Btu/lbm-°F)</u>	<u>(J/kg-°C)</u>
	.204 (32°F)	853. (0°C)	.17 (32°F)	711. (0°C)
	.230 (752°F)	961. (400°C)	.23 (752°F)	961. (400°C)
Density:	135. lbm/ft ³	(2160 kg/m ³)	180. lbm/ft ³	(2880 kg/m ³)

3.0 NUMERICAL MODELING RESULTS

In the absence of specific regulatory direction it is certain that wide variations will occur in surface properties of the waste canister as well as the size of air gaps surrounding the canister. The potential effects of such variations are detailed in this chapter. Except where it is specifically stated to the contrary all graphical results pertain to a repository in bedded salt.

3.1 Effect of Air Gap Size

It has been estimated that a radial clearance of 2.5 inches (6.35 cm) would be necessary for a retrieval tool to access a waste package. (This assumes that the over-coring option is a second choice, should a retrieval operation be required.) Backfilling of the annular space with mined loose rock has been shown by Davis [1] to have serious negative thermal consequences* because of poor conductivity of the loose rock.

The sensitivity of the waste canister temperature to air gap size was evaluated by using the 3-D TRUMP numerical code. The time-dependent temperature distributions for air gaps of 3, 6, 18, and 42 inches (7.6, 15.2, 45.7, and 106.7 cm) were determined.

Figures 3 and 4 show that the size of the air gap has a dramatic effect on the temperature response of the waste canister, especially when the initial thermal power generation rate is high. The peak canister "relative" temperature** is plotted in Figure 4 as a function of gap size for the same

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*The canister temperature can be as much as 350°F (177°C) hotter than would result if the air gap is left unfilled. This calculation was based on a 3" (7.6 cm) air space and an initial power generation rate of 4.61 kW/canister.

**The canister "relative" temperature is referenced to what the temperature would be if perfect thermal contact existed between the salt and the canister (i.e., 0-gap and perfect thermal contact). For example, if the gap size is 0.81 ft. (.25 m) and the initial generation rate is 4.61 kW, the peak temperature for the air gap case will be the same as the perfect thermal contact case.

-11-
GAP SIZE (cm)

Figure 3. Larger thermal power levels produce conditions which result in greater canister temperature sensitivity to air gap size. The emissivities of the gap surfaces were modeled as 0.9.

Figure 4. Higher power level waste canisters show a greater sensitivity to air gap effects when referenced to expected temperatures from perfect thermal contact cases. ΔT is the temperature relative to perfect thermal contact: $\Delta T = T - T_{ptc}$.

three different initial power levels. The trend is the same regardless of the magnitude of the power level: as the gap size increases from zero gap, the temperature rapidly approaches a peak at the critical width. Beyond this width, larger gaps produce lower temperatures.

3.1.1 Discussion of the Air Gap Effect

The results presented show that the canister temperature initially rises to a maximum as the air gap size increases from "perfect thermal contact". If the gap size is increased beyond this critical dimension the temperature of the canister will begin to drop. The characteristics of the temperature versus gap size can be understood by examining the three heat transport mechanisms governing the heat flow from the canister surface to the host rock; they are conduction, convection, and radiation. When the gap is small (less than 0.5 inch or 1.27 cm) pure conduction and radiation account for the heat transport.* When the gap is large enough to allow convection circulation to develop, the pure conduction component becomes insignificant and the heat transport is accounted for through combined convection and radiation.

For very small gaps (less than .5 inch or 1.27 cm) the overall "conductance" of the gap is a function of the air conductivity, the gap width (heat transfer path), and the gap's radiation exchange properties. Over this range of gap sizes the radiation properties are relatively constant. Therefore, the gap conductance decreases (and resistance to heat flow increases) as the width increases, until the point at which convection replaces conduction in the heat transfer (between .5 and 1.0 inch, or 1.27 and 2.54 cm). At this critical gap size the canister surface can be expected to reach its highest temperature, as indicated in Figures 3 and 4. Beyond this width the convection and radiation mechanisms provide a conductance which is relatively independent of gap size [1], but greater than the conductance of a dead (non-convecting) air space.

*For a 1.65 kW initial power source the Grashof number is less than 20,000 for the annular air space; for such conditions convection heat transport is insignificant [10] (i.e., pure conduction and radiation govern heat flow.)

The net effect, then, of a small gap is to replace a relatively poor thermal conductor (rock or salt) with a worse conductor (dead air). A large gap (greater than one inch), however, replaces the emplacement medium with radiation and convection mechanisms which are markedly more "conductive" than dead air, and may even be more conductive than the emplacement medium for certain conditions.

3.1.2 Concept of Perfect Thermal Contact

Perfect thermal contact is an analytical idealization which can be regretfully misleading. Even if it were possible to have the canister in physical contact with the host rock, the unavoidably rough drill hole surface would produce a very large number of isolated macro-air pockets leading to a large thermal contact resistance. Furthermore, the thermal condition of the waste package would be in even worse condition if backfilling were to take place around the canister with loose rock [1]. These certainties behoove NRC guidelines be written such that the design of repository air spaces be carefully regulated.

3.2 Effects of Surface Emissivity

The thermal resistance to radiation heat exchange between two diffuse surfaces is given by

$$R_{rad} = \frac{1 - \epsilon_1}{\epsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1 - \epsilon_2}{\epsilon_2 A_2} \quad (1)$$

where ϵ is the surface's spectral emissivity, A is surface area, and F_{12} corresponds to the view factor between surface 1 and 2. The first and last terms are surface resistances and the middle term is a space resistance which is a function only of the heat exchange system. From equation (1) it is seen that the contribution to resistance of the first and last terms approaches zero as the surface emissivities approach the classical "black body" value of 1. The importance of surface emissivity is made apparent quickly by

considering the sensitivity of the relative magnitudes of the three terms in equation (1) to changes in emissivity. If the areas are approximately equal, the resistance will be made to double by reducing the surface emissivity from 1.0 to 0.67 (the view factor, F_{12} , will be approximately 1.0 for all gap sizes).

The canister surface and the host rock surface (or drill hole surface) comprise the two surfaces of primary interest. In the absence of regulatory constraints it is possible that these heat exchange surfaces could have an emissivity as low as 0.1 [8]. A simple comparison through Equation (1) will show that the radiation heat exchange resistance will be more than one order of magnitude greater if the emissivity is 0.1 instead of 0.8. An emissivity of 0.8 or greater is economically achievable by superficial sandblasting followed with surface oxidation.

3.3 Temperature/Emissivity Modeling Results

The interactive effects on the canister surface's peak temperature of initial power generation rate and surface emissivities are illustrated in Figure 5. The repository geometry was identically modeled for all three power levels. The emissivity is important at all power levels but is more significant at higher power levels.

The interactive effects of air gap size and emissivity are illustrated in Figure 6. These results show that emissivity is most critical for smaller gap sizes. It should be noted that the power level modeled in Figure 6 results was very low (0.55 kW per canister--16 kW/acre). The emissivity effects would be significantly greater for higher heat generation rates.

3.4 The Relative Importance of Emissivity of the Two Radiation Exchange Surfaces

It is more important to have a high emissivity for the canister surface than for the salt (or sleeve) surface, although it would be desirable for both

Figure 5. The surface emissivity effects the canister temperature at all power levels, but has the greatest influence at higher levels. The gap size for this case is 3 in. (7.6 cm).

Figure 6. The three curves show the relative effect of surface emissivity for three different air gap sizes (all other parameters are the same). If the gap is large enough surface emissivity effects are practically negligible. Initial power level in each case was .55 kW per canister.

surfaces to have high emissivities. This conclusion is derivable from equation (1), where it is noted that the area in the canister surface resistance term is less than that of the salt surface. Consequently, the magnitude contribution to total radiation resistance is greater for the canister surface than the larger salt surface. Since emissivity appears in the same functional form in both of the surface resistance terms of equation (1), it is apparent that the response of the total thermal radiation resistance will be greater for changes in ϵ_1 than for similar changes in ϵ_2 .

This conclusion is supported by numerical modeling results shown in Figure 7. The temperature response was first determined for a canister surface emissivity of 0.2 and a salt surface emissivity of 0.9; subsequently the temperature response was determined for the case where emissivity values were switched on the two surfaces. The two responses are superimposed on the same coordinate set in Figure 7, showing the second case produce a peak temperature 25°F (13.9°C) lower than the first.

3.5 Influence of a Sleeve on the Temperature Response of the Canister

Intuitive considerations could mislead an investigator to think that adding a retaining sleeve around the waste canister within the annular drill hole air space would increase the effective conductivity of the air space and consequently lead to lower canister temperatures because steel is a good conductor relative to air and salt. Just the opposite occurs; a steel sleeve placed in the radial middle of a 6-inch (15.2 cm) annular air space will cause a dramatic temperature increase in the canister surface. The magnitude of the increase is highly sensitive to the surface emissivities. Figures 8 and 9 illustrate the sleeve effect on the canister surface temperature for respective emissivities of 0.4 and 0.9.

The responses shown in Figure 8 indicate that insertion of a sleeve into a 6" (15.2 cm) air gap will result in the surface temperature of the canister peaking more than 80°F (44.4°C) higher than it would without a sleeve (all surfaces were modeled with $\epsilon = 0.4$). Similarly, Figure 9 shows that a sleeve

Figure 7. The canister surface temperature is more sensitive to the emissivity of the can surface than the receiving surface (in this case salt). Thermal loading is 4.61 kW per canister (132 kW/Acre), with a 3 in. (7.6 cm) air gap.

Figure 8. The temperature response of the canister surface is shown for two cases: a) No sleeve and a 6 in (15.2 cm) air gap, b) A thin sleeve placed concentrically in the middle of a 6" annular gap (which results in partitioning the 6" air space into two 3" (7.6 cm) spaces). The results show that a sleeve will cause a dramatic temperature increase ($\epsilon = 0.4$, initial canister power was 1.65 kW).

Figure 9. The temperature response of the canister surface is shown for two cases: a) No sleeve and a 6" (15.2 cm) air gap, b) A thin sleeve placed concentrically in the middle of a 6" annular gap (which results in partitioning the 6" air space into two 3" (7.6 cm) spaces). The results are essentially the same as that shown in Figure 8, except that the effect is somewhat less due to the higher value of emissivity used ($\epsilon = 0.9$). Initial canister power was 1.65 kW.

inserted in a 6-inch (15.2 cm) air gap will cause the canister surface temperature to peak 40°F (22.2°C) higher when all surface emissivities are 0.9. Both cases described by Figures 8 and 9 had thermal sources of 1.65 kW/canister initial power.

The cause of such a dramatic increase in temperature of the canister is explained by considering equation (1), which defines the resistance of a single air gap. The insertion of a sleeve partitions one 6-inch (15.2 cm) air gap into two 3-inch (7.6 cm) air gaps. The heat rejection path from the canister surface to the host rock is, consequently, through two series resistances instead of a single air space resistance. The end result is that of approximately doubling the thermal radiation resistance across the 6-inch (15.2 cm) space. A similar doubling effect on the convection heat transfer resistance also occurs.

3.6 Influence of Host Rock Property

The magnitude of air gap effects depends greatly on host rock properties--particularly on the thermal conductivity. The scope of this current effort addressed only bedded salt in detail. However, one specific case involving basalt was modeled for the purpose of illustrating how much more important air gap effects are if repository sites are chosen in media less conductive than bedded salt.

The peak canister surface temperature is plotted as a function of air gap sizes for basalt and salt as shown in Figure 10. Compared with salt, the temperature drops dramatically in basalt with increasing air gap sizes. The power level for this comparison is relatively low (1.65 kW/canister or 47 kW/acre). Effects at higher power levels would be even more dramatic. The plot shows that for those geometry and power conditions modeled the peak canister temperature would be 32°F (17.8°C) less than the "perfect thermal contact" case if a 6-inch (15.2 cm) gap were provided. Emissivity effects would be similarly more important if the host rock were less conductive.

Figure 10. Effect of air gap size is much more significant if the repository host rock is a poor thermal conductor like basalt. Plotted here are results for both salt and basalt over a range of gap sizes. Surface emissivities were set at .9.

4.0 REGULATORY CONSIDERATIONS

NRC guidelines should require the licensee to assure that his proposed design will preclude the canister surface temperature from exceeding a specified maximum. In light of results of modeling presented in this report the guidelines should require assurance on the part of the licensee that air gaps and gap surface properties have been considered in design detail. It is recommended that the spectral emissivity for the canister surface be in the range of .8 or greater. Gap sizes on the order of one inch (2.54 cm) should be avoided. As a consequence of the negative thermal effects shown to result from a retaining sleeve it is recommended that the use of a loosely inserted sleeve should be precluded in the absence of outweighing advantages to structural or retrievability considerations. Backfilling with loose salt should be prohibited by regulation (see reference [1]).

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APPENDIX A

TEMPERATURE RESPONSE OF THE AIR GAP SURFACES

A series of temperature responses of the two annular air gap surfaces are shown in Figures 11 - 15. The surface emissivities are varied as noted on each plot. The air gap size and the power generation rate are constant at 3" (7.6 cm) and 1.65 kW/canister as noted on each plot.

Figure 11. The temperature responses of the two gap surfaces above result when the surface emissivities are 1.0 and the power generation rate is 1.65 kW and the gap size is 3" (7.6 cm).

Figure 12. The temperature responses of the two gap surfaces above result when the surface emissivities are 0.9, the power generation rate is 1.65 kW and the gap size is 3" (7.6 cm).

Figure 13. The temperature responses of the two gap surfaces above result when the surface emissivities are 0.75, the power generation rate is 1.65 kW and the gap size is 3" (7.6 cm).

Figure 14. The above temperature response of the two gap surfaces results when the surface emissivities are 0.6, the power generation rate is 1.65 kW, and the gap size is 3" (7.6 cm).

Figure 15. The temperature responses of the two gap surfaces above result when the surface emissivities are 0.4, the power generation rate is 1.65 kW, and the gap size is 3" (7.6 cm).

APPENDIX B

TEMPERATURE RESPONSE OF THE CANISTER SURFACE

The peak temperature response of the canister surface was plotted as a function of gap size in Figures 3 and 4 for different power levels. Figure 16 shows the surface temperature response of the canister for four gap sizes. The initial power generation rate and the surface emissivities are the same in all cases.

Figure 16. Temperature response of the canister surface is shown for four different gap sizes. Initial thermal power was 1.65 kW/canister and surface emissivities were 0.9.