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**ASPECTS OF NUCLEAR WASTE MANAGEMENT
VOLUME 1: PRE-EMPLACEMENT RISKS**

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ABSTRACT

This report describes studies of technical issues relating to nuclear waste management. It supplements previous TASC reports on this topic. Volume 1 addresses events occurring before emplacement of the waste in a repository. The subjects addressed are thermal analysis of interim storage accidents and doses to the worst-situated individual in all types of pre-emplacement accidents. Volume 2 deals with the possible release of waste from a geologic repository. Aspects of long-term repository performance which are discussed include water flow around shafts and boreholes and use of water from contaminated wells. New methods and results pertaining to the analysis of uncertainties in long-term risk predictions are also presented.

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1. INTRODUCTION

1.1 BACKGROUND

This report describes work done between February 1978 and June 1978 as part of a continuing program of systematic analysis of nuclear waste management issues. The purpose of this report is to record the results of analyses of some specific issues relating to the estimation of hazards to the public which might arise from the geologic disposal of high-level nuclear wastes.

These analyses are aimed at checking the accuracy of the models presented in Reference 1 and at broadening their scope. In this volume of the report, studies of events which could occur before disposal of the wastes are described. In Volume Two, the results of studies of long-term hazards from waste emplacement in a deep geologic repository are presented.

1.2 ORGANIZATION OF THIS VOLUME

Two aspects of the subject of pre-emplacement accidents involving high-level nuclear waste are addressed in this volume:

- Development of a methodology for a thermal analysis of an interim storage basin after an accident which has caused drainage of its cooling water
- Doses to the worst-situated individual in accidents.

Chapter 2 of this volume describes an analysis of a storage basin after a loss-of-coolant accident. This analysis is not intended to be a rigorous thermal analysis of the subject, but rather an evaluation of a two-dimensional, calculational approach to the problem.

In Chapter 3, the procedures used for computing radiological dose to the "maximum" exposed individual from pre-emplacement accidents involving solidified, high-level waste are presented. The measure of risk to the worst-situated individual averaged overall scenarios including both accident occurrence and non-occurrence is evaluated.

Finally, Chapter 4 summarizes the principal findings of these studies and presents recommendations for necessary research.

2. THERMAL ANALYSIS OF INTERIM STORAGE ACCIDENTS

This chapter describes heat transfer calculations for estimating the thermal response of high-level solid waste (HLSW) canisters in an interim storage basin after a loss-of-coolant accident (LOCA). The principal modes of heat transfer from canister walls considered were convection to air and radiation to space. Calcine, borosilicate glass, and supercalcine multi-barrier waste forms with ages ranging from 1 year to 10 years after irradiation were considered.

The primary objectives of this analysis were:

- To extend previous one-dimensional interim storage LOCA thermal analyses (Ref. 1, Appendix B) by the use of a two-dimensional model
- To estimate the effects of canister spacing on waste and canister temperatures.

The HEATING5 computer code was used to estimate the maximum waste centerline and canister wall temperatures for steady-state conditions after the LOCA. Results were obtained as a function of:

- Waste form and age
- Canister spacing
- Boundary conditions.

The primary objective of extending the previous one-dimensional thermal analysis with a two-dimensional one was accomplished. The maximum canister wall temperatures computed were found not to differ significantly from previous results. However, in accomplishing the second objective, it was observed that the accuracy of the thermal analysis could be greatly improved by incorporating a more sophisticated air flow model into the analysis. Thus our results should be viewed as a development of methodology rather than a rigorous thermal analysis of the problem.

2.1 DESCRIPTION OF PROBLEM AND BACKGROUND

For the purposes of this study, it was assumed that during interim storage at a surface storage facility, high-level wastes are contained in stainless steel canisters. Large numbers of canisters are grouped in a square array and are located in a concrete basin filled with water to remove heat generated by the waste itself. A seismic event or other catastrophic accident could cause rupture of the basin and loss of the coolant water. As a consequence, failure of the canisters could well occur due to corrosion or melting of the canister wall; both are thermally induced effects. The rapidity of failure depends upon the heating rate of the wastes and on the geometry of the canister array.

In a previous TASC study (Ref. 1, Appendix B), the transient temperature response of a canister array following an instantaneous loss of cooling water was analyzed. The facility modeled closely paralleled that suggested in Reference 2. It was assumed to consist of 506 10-ft long waste canisters set into a rectangular concrete basin. The top of the basin was assumed to be open so that heat could be completely removed from the vicinity of the canister array. The canisters were

vertical in two layers, one directly above the other, with a 1-ft gap between. The canisters were taken to be 1 ft in diameter on a 1.5-ft center-to-center spacing.

The one-dimensional study used a lumped-parameter model in which the canister array was represented by a single node in a one-dimensional geometry. Radiation to space from the canister ends and convection to naturally circulating air were the principal heat transfer mechanisms treated. Computations were performed with the HEATING5 computer code (Ref. 3) to solve the finite difference heat flow equations.

The results obtained provided information on:

- Canister temperature-time histories for various waste ages
- Sensitivity of steady-state canister temperatures to canister spacing
- Sensitivity of canister failure probabilities to the distribution of waste ages in the storage facility.

A recommendation made at the conclusion of the one-dimensional study was to improve the accuracy of the results by means of a two-dimensional analysis of heat transfer through the waste canister array.

More recently, Lawrence Livermore Laboratory (LLL) (Ref. 4) performed preliminary analyses with the TRUMP code on the interim storage IOCA. The study examined the steady-state axial temperature gradients in a canister. It obtained higher temperatures than were produced by the lumped waste model and concluded that there was a potential for more serious accident consequences. The model used in the LLL study features the following heat transfer paths:

- Axial conduction in the waste
- Radiation from canister top to space
- Convection from canister sides to air
- Radiation from canister bottom to basin.

The waste and canister regions were together represented by a single node at each axial position; hence, radial conduction effects in the canister were ignored. Material properties were assumed to be constant with temperature.

The purpose of the work reported here was to extend the prior studies by considering:

- A two dimension steady-state treatment of the LOCA problem, including axial conduction
- Waste and canister as separate components including radial conduction
- Radiation heat transfer from canister sides
- Temperature-dependent material properties
- Various waste forms and ages at the time of the LOCA

Primary emphasis in this work was placed on developing a methodology for addressing the above elements. While this was accomplished, it was discovered that a much more rigorous approach must be used to produce an accurate, comprehensive thermal analysis of this LOCA problem. Certain elements of the work reported here would provide an important contribution to such an analysis.

2.2 WASTE FORMS

Calcine, borosilicate glass, and supercalcine multi-barrier waste forms were included in the study, with ages ranging from 1 to 10 years after irradiation. The waste was taken to be diluted to the extent that all 10-yr wastes produced 3.5 kW of heat per canister. The heat generation rates per canister at other ages for the same dilution were:

- 5-yr: 7.4 kW
- 2-yr: 18.1 kW
- 1-yr: 32.0 kW.

The matrix of wastes and ages for baseline cases addressed in this study are represented in Table 2.2-1.

TABLE 2.2-1
WASTE FORMS AND AGES FOR BASELINE CASES

WASTE FORM	WASTE AGES (yr)			
Calcine	1	2	5	
Glass	1	2	5	10
Multibarrier	1	5		

2.3 GEOMETRY

Figure 2.3-1 depicts the assumed geometry for LOCA calculations. The two-dimensional HEATING5 model consisted of the following material regions:

Figure 2.3-1 Geometry and Principal Heat Transport Mechanisms for the 2D HEATING5 LOCA Model

- A waste canister with appropriate boundary conditions
- A concrete basin underlying the canister
- An earth layer beneath the concrete slab.

No attempt was made here to model the concrete sides of the basin -- i.e., the canister array was taken to be infinitely large and without edge effects. The air gap between vertical canisters was not modeled separately; the stacked canisters were assumed to act as one continuous medium. Heat transfer to the flowing air was treated in terms of a boundary condition, as discussed in Section 2.4.

Figure 2.3-2 depicts the arrangement of nodes that constitute the HEATING5 model.* The waste canister was taken to be 20 ft in length to represent the two-layer stack of canisters, each 10 ft long.[†] Nodes in the waste region were spaced vertically every 0.5 ft. In the radial direction the waste region nodes were spaced every 0.25 ft.

The stainless steel canister was similarly divided axially into 40 zones. Further radial subdivisions in the canister were not deemed necessary since the canister is only 3/8 in. thick.

Below the canister region were located a 1-ft thick concrete slab (the basin) and 8 ft of earth. Node spacing in the earth layer was at 2-ft intervals in the axial (z) direction.

*This diagram represents R-z (cylindrical) coordinates with the canister centerline coinciding with the z axis.

†The term "canister" in the subsequent text will refer to the 20-ft long canister region although strictly a single canister is but 10 ft long.

Figure 2.3-2 Node Structure for 2D HEATING5 Code Loss-of-Coolant Accident Model

2.4 HEAT TRANSFER MECHANISMS AND BOUNDARY CONDITIONS

The principal heat transfer mechanisms taking place during a LOCA are indicated schematically in Fig. 2.3-1. These mechanisms may be divided into two categories: conduction within solid material regions -- i.e., the waste canister and the underlying basin and earth -- and boundary conditions on the waste canister that include both convection and radiation. For steady-state conditions, conduction is simply a function of the thermal conductivity of the materials and the geometry. The convection and radiation boundary conditions are more involved and are discussed in some detail below.

Convection to Air from Canister Sides - Heat was assumed to be transferred from the canister wall to the surrounding air by convection. A rigorous approach to this thermal analysis would employ a free convection heat transfer model using appropriate mass, momentum, and energy balances on the air stream and waste canisters. However, such an approach was beyond the scope and resources of this task. Therefore, a simplified and admittedly non-rigorous approximation was used to model the convective heat transfer. As will be seen, this approximation, while not strictly rigorous, satisfies the limited objectives of this analysis.

The approach chosen to obtain a convective heat transfer coefficient for the transfer of thermal energy from the waste canisters to the air stream was a modification of the method employed by LLL in related studies (Refs. 4 and 5). A value of air flow rate was arbitrarily but carefully chosen. Previous results from similar analysis (Refs. 2, 4, and 5) guided this choice of air flow rate. This fixed value of air flow was then used in conjunction with a forced convection heat transfer coefficient to model the heat transfer to the air in the vertical channels between the waste canisters.

For this analysis, the physical and thermal properties of the air stream were evaluated at the film temperature, roughly equal to the arithmetic mean of the canister wall temperature and the bulk air temperature. Based upon these properties (taken from Ref. 6), values of the convection heat transfer coefficient, h_c , were computed as a function of the film temperature. A linear fit to the h_c versus temperature over the temperature range of interest for the chosen air mass flow rate yielded the following expression for the temperature dependence of the convection coefficient:

$$h_c = 0.475 + 1.05 \times 10^{-4} T_f \quad (2.4-1)$$

where T_f is the film temperature in °F and h_c has units of Btu/hr-ft²-°F. As a matter of perspective, this expression for the heat transfer coefficient yields values which are typical of free convection heat transfer coefficient for gases (Ref. 7).

The convective heat transfer coefficient was used by HEATING5 to determine the heat flux, q_c , for each axial zone along the length of the canister according to

$$q_c = h_c(T_w - T_a) \quad (2.4-2)$$

where

T_w = canister wall temperature (°F)

T_a = air (bulk) temperature (°F)

Both T_w and T_a depend upon the axial position, z .

The bulk air temperature as a function of z is not known except at the bottom of the canister array where it has been assumed to be 120° F (Refs. 1 and 4). Appendix A outlines a modification made to the HEATING5 computer code to handle the type of situation where heat exchange is accomplished by the flow of a coolant. The new subprogram determines the air temperature and an effective value of h_c by solving the air heat balance equation numerically.

Radiation From Canister Sides --Two separate 2D radiation problems were considered here:

- Radiation from canister sides to space
- Inter-canister radiation.

The information needed for HEATING5 to compute radiation-to-space heat fluxes was the following:

- The view factors from various zones along the canister length to space. Determination of these view factors is discussed in Appendix B
- The emissivity of the canister, assumed to be $\epsilon = 0.45$ (Ref. 2)
- The equivalent blackbody temperature of space, assumed to be 75°F (Ref. 2).

The inter-canister radiation problem was not treated. Such calculations might have proved whether or not multiple reflections would lead to a net transfer of heat by radiation in an upward direction, thus reducing the axial canister temperature gradients. However, with a geometry consisting of a square array of finite length circular cylinders, tracing the multiple reflection paths to determine gray body shape factors was judged to be too complicated a mathematical exercise to pursue. Neglect of this effect is conservative; that is, it leads to canister maximum temperatures that may be somewhat too high.

Convection to Air from Canister Bottom - The heat transfer mode for convection from air to the canister bottom remains the same as in the previous study. The natural convection coefficient for flat plates (Ref. 8):

$$h = 0.1375 (\Delta T)^{1/3} \quad (2.4-3)$$

was employed, with ΔT expressed in $^{\circ}F$. Convection to air from the canister was determined to be an unimportant mechanism (see Section 2.8).

Radiation to Basin from Canister Bottom - The following assumptions, identical to those in the previous work, were made:

- View factor = 1.0
- Canister bottom emissivity = 0.45
- Concrete emissivity = 1.0.

Radiation to Space from Canister Top - The radiation heat losses from the canister top were computed using:

- A view factor of 1.0. In Reference 1 a view factor of 0.5 was used for canister tops to space. An additional radiation interchange term to the sides of the concrete basin was included also with a view factor of 0.5. No provision in this study was made for the concrete basin sides above the level of the canister tops; hence all radiation was considered to be directed to space. Refer to Section 2.8 for further discussion of this point
- An emissivity of canister tops equal to 0.45
- A space equivalent black body temperature of $75^{\circ}F$.

2.5 MATERIAL PROPERTIES

Table 2.5-1 gives the thermal conductivities for all materials used in these calculations, plus the sources of the data. The HEATING5 code interpolates linearly between tabulated entries. At temperatures outside the range indicated in

the tabulation, conductivities are taken to be constant at the lower or upper limit values. Since the calculations were all performed for steady-state conditions, density and specific heat information were not required for solid materials. The properties of air used in calculating the convective heat transfer coefficient are standard (Ref. 6) and are not repeated here.

TABLE 2.5-1
THERMAL CONDUCTIVITIES

MATERIAL	THERMAL CONDUCTIVITY (Btu/hr-ft-°F)	REFERENCE
Calcine HLSW	32°F 0.097	9
	1652°F 0.226	9
Glass HLSW	77°F 0.488	9
	1112°F 0.810	9
	1346°F 1.44	9
Multibarrier HLSW	5.76	9
Stainless Steel	9.8	9
Concrete	0.25	4
Earth	0.85	4

2.6 THE BASELINE CASE

A baseline case was established whose geometry and heat transfer parameters had reasonable nominal values and that could be used to compare the effects of different waste forms and waste ages on equilibrium temperatures. The following key parameters characterize the baseline case:

- Air mass flow rate of 500 lb/hr. This value was chosen to match that recommended by LLL in Ref. 4; it is discussed further in Section 2.7
- 1.5-ft canister center-to-center spacing (Ref. 2).

The waste forms and ages treated were presented in Table 2.2-1.

2.7 RESULTS OF BASELINE CASE ANALYSIS

The HEATING5 code provided maps of the steady-state temperatures in the waste canister and basin materials at each of the 188 nodes indicated in Fig. 2.3-2, and the air temperatures associated with each of the 40 nodes along the canister wall. For purposes of judging the canister failure temperatures, however, just two locations were of vital interest. These locations were where the maximum temperatures occurred anywhere along the length of the canister:

- In the waste material (at the canister center-line)
- At the stainless steel canister inner wall surface.

For a potential canister corrosion failure the canister wall temperature is the more important.

Table 2.7-1 presents the baseline case maximum waste-centerline and canister wall temperatures. For reference, the canister temperature failure criteria based upon internal corrosion (Refs. 9 and 10) for the three waste forms are:

TABLE 2.7-1
MAXIMUM AND CANISTER TEMPERATURES
FOR BASELINE CASES

WASTE		MAX. WASTE TEMPERATURE (°F)	MAX. CANISTER TEMPERATURE (°F)
MATERIAL	AGE (yr)		
Calcine	1	****	****
	2	****	****
	5	2415	1520
Glass	1	****	****
	2	****	****
	5	1660	1520
	10	990	860
Multibarrier	1	****	****
	5	1550	1510

Air Flow: 500 lb/hr
Canister Spacing: 1.5 ft

***Canister wall temperatures beyond the ~2600°F stainless steel melting point.

- Calcine: $2370 \pm 90^{\circ}\text{F}$
- Glass: $2190 \pm 90^{\circ}\text{F}$
- Multibarrier: $2370 \pm 180^{\circ}\text{F}$.

The following observations are of interest:

- Radial temperature gradients in the calcine are large owing to the low thermal conductivity of that waste form. Calcine centerline temperatures are near the melting point (2550°F) for 5-yr waste and greatly exceed it for younger wastes. Use of internal fins would obviate this problem, as discussed in References 9 and 10
- Maximum canister wall temperatures exceed the failure criteria for all three waste forms aged 1-yr and 2-yr

- Maximum canister wall temperatures do not depend significantly upon the waste form. In Table 2.7-1 temperature differences among the three waste forms at the same age reflect numerical errors in the code finite difference solutions. Thus, for a given age, the wide differences in the thermal conductivity between calcine and multibarrier will not affect canister failures by corrosion.

A demonstration of the axial position dependence of temperatures in the waste, canister, and the air predicted by HEATING5 is given in Figs. 2.7-1 through 2.7-5 for 5-yr calcine; 1-yr, 2-yr, and 10-yr glass; and 5-yr multibarrier. Features of these plots are:

- Sharp temperature gradients at both ends of the canister (due to radiation and convection at the ends), with relatively broad maxima
- Maximum wall and waste centerline temperatures occurring toward the bottom of the canister, a result of side radiation heat losses
- Air temperature rising monotonically and then leveling off near the top of the canisters where the air and canister-wall temperatures approach the same value.

Table 2.7-2 compares maximum canister wall temperatures for 1-yr to 10-yr glass wastes computed by the two-dimensional HEATING5 model with results obtained from previous models. These results are assumed independent of waste form, as indicated in the discussion of Table 2.7-1. Referring to Table 2.7-2 for each waste age:

Figure 2.7-1 Axial Temperature Profiles for 5-yr Calcine Waste

Figure 2.7-2 Axial Temperature Profiles for 1-yr Glass Waste

Figure 2.7-3 Axial Temperature Profiles for 2-yr Glass Waste

Figure 2.7-4 Axial Temperature Profiles for 10-yr Glass Waste

Figure 2.7-5 Axial Temperature Profiles for 5-yr Multibarrier Waste

TABLE 2.7-2

COMPARISON OF HEATING5 2D MAXIMUM CANISTER TEMPERATURES WITH PREVIOUS 1D AND TRUMP RESULTS

WASTE AGE (yr)	HEATING5 MODELS		
	1D (Ref. 1)	2D CONSTANT MASS FLOW RATE	TRUMP (Ref. 4)
1	****	****	****
2	****	****	****
5	1720	1520	2200
10	970	860	1100

Temperatures in °F

***Canister wall temperatures beyond the ~2600°F stainless steel melting point.

- Column 2 repeats the results presented in Reference 1 for the lumped-parameter 1D HEATING5 model. The 1D temperatures computed were uniform over the canister region because of the nature of the simple model. They represent average canister wall temperatures that cannot be easily related to 2D model results because of the non-linear processes involved.
- Column 3 repeats the baseline glass results from Table 2.7-1 of this report for a constant value of the air mass flow rate of 500 lb/hr.
- Column 4 presents the findings of the preliminary TRUMP studies. These temperatures are radially averaged over the waste canister region for calcine and, therefore, are not directly comparable to the canister wall temperatures of the three previous columns.

The principal conclusion derived from Table 2.7-2 is that the 2D HEATING5 results compare well with the previous 1D results. Both 1D and 2D HEATING5 temperatures are considerably lower than the corresponding TRUMP temperatures. Three reasons can be advanced for these differences:

- TRUMP-computed temperatures for the waste canister are radially averaged temperatures, which are higher than the canister wall temperatures
- TRUMP did not account for heat loss by side radiation
- The TRUMP convective heat transfer coefficient h_c was a constant (at 0.46 Btu/hr-ft²-°F). The HEATING5 h_c was temperature-dependent and slightly higher than the TRUMP value (see Eq. 2.4-1).

Table 2.7-3 compares the relative importance of the various radiation and convection heat loss mechanisms from the waste canister for glass waste aged 1, 2, 5, and 10 years. Heat losses from the canister sides dominate end effects under all circumstances. Except for the 1-yr waste, side convection is the chief heat transfer mode. Hence, canister wall temperatures in the threshold failure regime, i.e., wastes aged 2 to 5 years, will be most sensitive to model parameters that affect convection rather than those that affect radiation.

TABLE 2.7-3
HEAT LOSS MECHANISMS AND RATES FOR GLASS WASTE
(AIR FLOW OF 500 lb/hr)

HEAT LOSS MECHANISM		LOSS RATES FOR GLASS HLSW			
PROCESS	LOCATION	1 YR	2 YR	5 YR	10 YR
Convection	Side	52,800	38,300	19,400	9,900
Radiation	Side	56,500	21,600	5,200	1,300
Radiation	Top	2,700	900	400	100
Convection	Bottom	2,200	1,300	200	200
Radiation	Bottom	100	100	0	0
TOTAL HEAT LOSS		114,300	62,200	25,200	11,500

Heat losses are expressed in units of
Btu/hr per 10 ft of canister length

2.8 SENSITIVITY STUDIES

Canister Spacing Sensitivity - One option for reducing waste and canister temperatures in a LOCA is to increase the inter-canister spacing. In the current work, temperatures were compared at the nominal 1.5-ft spacing and at a greater, 3.0-ft spacing. The results are shown in Table 2.8-1 for maximum canister wall and waste centerline temperatures using 1, 2, 5, and 10-yr glass.

TABLE 2.8-1
MAXIMUM TEMPERATURES FOR TWO CANISTER SPACINGS

SPACING (ft)	LOCATION	TEMPERATURE FOR GLASS HLSW			
		1 YR	2 YR	5 YR	10 YR
1.5	Canister	****	****	1520	860
	Waste Centerline	****	****	1660	990
3.0	Canister	****	2230	1260	730
	Waste Centerline	****	2575	1400	865

Temperatures in °F

***Canister wall temperatures beyond the ~2600°F stainless steel melting point.

There does appear to be a moderate temperature decrease due to doubling of the spacing. The main reason for the reduction in canister maximum temperature at a 3-ft spacing is the increased view factor for radiation to space from the canister sides, particularly near the canister mid-plane where maximum temperatures generally occur.

In this sensitivity study the air flow rate was maintained at 500 lb/hr. Physically this is not a realistic assumption; a change in flow rate is intuitively expected for larger unit cells because of the greater volume of air present. It is a consequence of the constant flow rate model that heat losses due to convection actually were decreased by going to a larger canister spacing. With a model that allowed flow rate to increase with spacing, temperature differences between the 1.5-ft and 3.0-ft cases would have been even greater.

In Reference 1 it was concluded that canister temperature sensitivity to spacing was low. For instance, with 2-yr glass waste the previous 1D results showed a decrease in canister temperature of 490°F between 1.5-ft and 3.0-ft spacing. The present 2D results indicate a 600°F canister wall temperature difference. Again, the inclusion of side radiation effects is the cause.

Sensitivity to Boundary Conditions - A sensitivity study was performed to determine whether the assumption of an end radiation view factor to space of 1.0 compared to the view factor of 0.5 used in the previous 1D work would affect maximum canister temperatures. In addition, the assumption at the canister top of no convection to air in the current calculations was tested against an upper bound end convection heat transfer coefficient equal to twice the value given by Eq. 2.4-3. In neither case did maximum canister wall or waste centerline temperatures change. These studies were carried out with 5-yr calcine; over a variety of top boundary conditions the maximum canister wall temperatures only varied from 1520°F to 1527°F. Similar results would be expected for younger wastes because canister top heat losses are comparably small.

Also evaluated was the sensitivity of maximum canister temperatures to side radiation. Steady-state calculations were performed for 2, 5, and 10-yr glass with no side radiation allowed. The results are compared in Table 2.8-2 to the base-line cases with side radiation.

Where canister failures will clearly occur -- i.e., for 2-yr waste -- neglect of side radiation gives a significant temperature increase. For 5-yr waste the effect of side radiation is considerably less, and the computed 230°F temperature difference does not take the canister wall over the failure

TABLE 2.8-2
EFFECT OF SIDE RADIATION ON MAXIMUM
CANISTER WALL TEMPERATURE

GLASS HLSW AGE (yr)	MAXIMUM CANISTER TEMPERATURES (°F)	
	WITH SIDE RADIATION	WITHOUT SIDE RADIATION
2	****	****
5	1520	1750
10	860	940

****Canister wall temperatures beyond the ~2600 °F stainless steel melting point.

threshold of 2200°F. Thus, any uncertainties in the side radiation view factors are more important for the younger waste, but in any event they are unlikely to significantly affect failure conclusions.

2.9 SUMMARY

The two-dimensional thermal analysis reported here was conducted primarily to evaluate methodology. The analysis permits some general conclusions concerning the usefulness of these methods. However, these conclusions should be evaluated in the light that they are drawn from a simplified, parametric analysis. Their use therefore should be restricted to definition and scoping of potential future research and analysis topics. Our conclusions and observations are summarized below.

- The current 2D HEATING5 maximum canister wall temperatures are in the same range as those of the previous 1D calculations
- Convection from the canister sides to circulating air is the predominant heat transfer mechanism for all but very young wastes

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- The thermal conductivity of the waste form in the axial conduction model does not significantly affect maximum canister wall temperatures
- Sharp temperature gradients occur at both ends of waste canisters for all three waste forms studied. Temperature maxima tend to be broad and to be located near or below the interface between the two layers of canisters
- Uncertainties in canister side radiation view factors are not likely to alter canister failure probabilities substantially, although they will affect canister temperatures, for young wastes especially
- Canister and waste temperatures are somewhat sensitive to changes in canister spacing
- Details of canister top boundary conditions do not significantly influence maximum waste or canister temperatures.

The following additional studies are recommended to extend the work reported in this section:

- A much more detailed set of air flow calculations involving mass, momentum, and energy balances should be carried out to characterize the convective heat transfer process more completely
- The current two-dimensional studies were performed for an open storage basin where heated air and thermal radiation leave the storage area. The calculations should be redone for a basin with a pool that would recirculate cooling air and reflect radiation, thus increasing canister temperatures.
- A catastrophic accident during interim storage less severe than a LOCA could cause a loss of coolant circulation and

also compromise the capability of the facility to contain airborne radioactive particles without necessarily destroying the integrity of the basin itself. A study should be undertaken to determine the transient thermal response of the basin during the boil-off period. Times-to-failure would be longer than for a LOCA.

3. INDIVIDUAL DOSES FROM PRE-EMPLACEMENT ACCIDENTS

This chapter outlines the procedures used for computing radiological dose to the "maximum" individual from pre-emplacement accidents involving high-level solidified waste from the Pu-storage fuel cycle. The risk measure adopted here is that of expected dose to a worst-situated individual. This is, therefore, a measure of risk to the worst-situated individual averaged over all possible scenarios including both accident occurrence and non-occurrence.

An alternate approach could have been to compute per-accident doses to individuals exposed to radiation from "maximum-severity" accidents. This would have required a determination of how severe an accident would be appropriate in each case. Also, the use of a per-accident risk measure for each pre-emplacement accident would render comparison of risk among accident types and waste forms meaningless, since the probability of accident occurrence would not be considered.

Note that a substantial portion of this section's mathematical analysis is based on the work reported in Reference 1. This reference should be consulted as supplementary material.

3.1 DEFINITION OF THE MAXIMUM INDIVIDUAL AND OTHER ASSUMPTIONS

The maximum individual is assumed to behave as follows for each of the pre-emplacement accidents:

- He initially stands 100 m downwind of the accident site for one hour. This distance corresponds to the inner limit of calibration of the Gaussian diffusion air transport model and is considered a reasonable distance from which a spectator might view the accident. During this time he is exposed to direct gamma radiation from the canisters in certain accidents, as described in Section 3.2, and inhales contaminated air from all accidents.
- After an hour, he moves far enough away from the accident site to eliminate gamma radiation from the accident site as a dominant factor. He continues to inhale contaminated air at this distance for a total of one day* and experiences a 50-yr dose commitment from this radiation. (Since inhalation makes only a small contribution compared to ingestion dose, this distance need not be more precisely defined.)
- He drinks contaminated milk obtained from cows grazing on contaminated grass at a distance 100 m downwind of the accident for a continuous period of 50 yr following the accident, and receives a dose from this radiation. He also consumes a "maximum" diet of water, meat, vegetables, and seafood that have been contaminated via waterborne radioactivity for a continuous period of 50 years following the accident, and receives a dose from this radiation.

In addition, the following assumptions and those listed in Chapter 2 of Reference 1 apply to the calculation of maximum individual dose from pre-emplacment accidents:

*For accidents having instantaneous releases, such as truck and train impact accidents, the period of inhalation is the time of passage of the contaminated air mass.

- No consideration is given to 50-year chronic external exposure to gamma radiation from the ground when computing dose to the maximum individual, since a single individual is assumed to be able to evacuate the contaminated area after his initial exposure.
- Dose due to direct gamma radiation from the passing cloud is considered negligible compared to exposure via other assumed pathways.

3.2 COMPONENTS OF THE MAXIMUM INDIVIDUAL DOSE CALCULATION

Changes made to the Pre-employment Risk Calculations of Reference 1 - Expected dose to the maximum individual is computed in a manner identical to that depicted in the pre-employment risk flow chart (Fig. 2.1-1 of Ref. 1), reproduced here for convenience in Fig. 3.2-1. There are several important changes within the components of this flow chart, however:

- The event tree is enlarged to include the scenario of loss of gamma shielding in severe truck and rail fire accidents (see discussion to follow in this section).
- The meteorology and demography models are altered as follows:

The average air concentration factors in the meteorology model are evaluated at 100 m directly downwind of the accident, instead of over an area

The only demography is that of the single individual

Figure 3.2-1 Sequence of Calculations in the Pre-Emplacement Risk Assessment Model (From Ref. 1, Fig. 2.1-1)

- The dose models are changed as follows:

The deposition dose due to chronic 50-year exposure to gamma radiation on the ground is removed, due to the assumption that the individual is free to move out of the contaminated area

The dose due to gamma radiation from a transportation cask that has lost its gamma shielding in a fire accident is added to the calculations.

Gamma Radiation from the Accident Site - In severe transportation fire accidents, loss of the cask's gamma shielding can occur, thus allowing gamma radiation to escape from the canisters even if the canisters remain unbreached and in the cask. (In all impact accidents, the cask's gamma shield is assumed to continue to protect against exposure of individuals to gamma radiation from the canisters.) Gamma radiation from the wreck, while unimportant when computing population dose from pre-emplacment accidents, can be significant when computing doses to the maximum individual at a distance of 100 meters.

The important assumptions implicit in these calculations are:

- The point-source formula in air is valid for computing gamma dose at 100 m from a canister of waste, given a loss of cask gamma shielding. Attenuation of this radiation by the canister's stainless steel is assumed to cancel the additional contribution from ground-reflected radiation not accounted for by the point source formula.
- The fraction of canister gamma radiation emitted from the cask in the direction of the receptor is modeled as a ramp-step function of fire temperature for the truck and rail cask:

For the truck cask, the lead gamma shield melts at 327°C and the surrounding stainless steel softens at 1400°C (Ref. 1). The fraction of gamma radiation emitted from the cask, F_γ , is assumed to rise linearly from 0 at the former temperature to 1 at the latter, and then to remain at 1 for all temperatures greater than 1400°C.

For the rail cask, the depleted-uranium gamma shield melts at 1100°C and the surrounding stainless steel softens at 1400°C (Ref. 1). The release fraction, F_γ , again is assumed to rise linearly from 0 to 1 between these temperatures and then to level off at 1.

- The fire temperature probability density function (pdf) used is that given in Appendix A, Reference 1, namely:

$$p(T) = \begin{cases} 0, & T \leq 1400^\circ\text{F} \\ 1.5 \times 10^{-3} - 6.0 \times 10^{-9}(T-1900)^2, & 1400^\circ\text{F} < T \leq 2400^\circ\text{F} \\ 0, & T > 2400^\circ\text{F} \end{cases} \quad \begin{matrix} (A.3-25) \\ (Ref. 1) \end{matrix}$$

The following equations are used for computing expected gamma-radiation dose to the maximum individual from exposure to unshielded canisters in transportation fire accidents:

$$D(R) = \phi_1 \phi_2 D'(R) T \quad (3.2-1)$$

$$\phi_1 = P_1 P_2 P_3 P_4 / N_C N \quad (3.2-2)$$

$$\phi_2 = N_C \phi_\gamma N \quad (3.2-3)$$

$$\phi_\gamma = \int_0^\infty p(T) F_\gamma(T) dT \quad (3.2-4)$$

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where:

$D(R)$ = expected gamma-radiation dose to an individual from unshielded canisters in transportation fire accidents located R meters away. (Units are rem per MWe-yr of waste produced.)

ϕ_1 = probability of a truck or train urban or rural fire accident per MWe-yr of waste produced.

ϕ_2 = expected amount (MWe-yr) of waste emitting gamma radiation due to a loss of cask gamma shielding, given a truck or train fire accident.

ϕ_Y = expected gamma-radiation transmission factor given exposure to cask gamma shielding loss (dimensionless).

$D'(R)$ = the unattenuated gamma radiation dose rate to the maximum individual from bare canisters located R meters away (rem/hr per MWe-yr of unshielded waste).

T = the maximum individual's exposure time (hr).

P_1 = probability per mile of a train or truck accident of any kind.

P_2 = probability of a fire accident, given an accident.

P_3 = probability that the fire accident occurs in an urban (or rural) location.

P_4 = number of miles traveled per truck or rail car shipment.

N_C = number of canisters carried per truck or rail car (also the number of canisters assumed to be exposed to shielding loss per accident).

N = number of MWe-yr of waste per canister.

$p(T)$ = probability density function of fire temperature ($1/^\circ F$).

$F_{\gamma}(T)$ = fraction of canister gamma radiation emitted from cask due to loss of shielding at a given fire temperature T (dimensionless).

The value of $D'(R)$ is taken to be 0.14 rem/hr-MWe-yr and the value of T to be 1 hr. $F_{\gamma}(T)$ is defined according to the assumptions listed earlier in this section, while values for P_1 , P_2 , P_3 , P_4 , N_C , N , and $p(T)$ may be found in Reference 1. The resulting expected gamma-radiation doses are $\sim 10^{-6}$ rem/MWe-yr for truck fire accidents and $\sim 10^{-7}$ rem/MWe-yr for train fire accidents at a distance of 100 m. These gamma-dose figures are preliminary and should be used with caution.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The analyses described in this report have extended the previous work reported in References 1 and 12. Among the principal conclusions are:

- The results of the previous one-dimensional thermal analysis of interim storage accidents are confirmed by more detailed two-dimensional calculations.
- Waste temperatures calculated for interim storage accidents are moderately sensitive to assumptions concerning canister spacing and are much less sensitive to boundary conditions at the canister top.
- For an individual 100 m from a transportation accident involving solidified high-level waste, the expected dose from gamma radiation is on the order of or smaller than the other possible exposures in the same accident.
- For the calculation of expected doses to the worst-situated individual in accidents:
Expected population dose should remain
the primary measure of pre-emplacment risk in order to maintain comparability of consequences of different types of accidents.

4.2 RECOMMENDATIONS

The following studies are recommended to extend the work covered in this report:

- A much more detailed set of air flow calculations involving mass, momentum, and energy balances should be carried out to characterize the convective heat transfer process more completely
- The current two-dimensional studies were performed for an open storage basin where heated air and thermal radiation leave the storage area. The calculations should be redone for a basin with a pool that would recirculate cooling air and reflect radiation, thus increasing canister temperatures.
- A catastrophic accident during interim storage less severe than a LOCA could cause a loss of coolant circulation and also compromise the capability of the facility to contain airborne radioactive particles without necessarily destroying the integrity of the basin itself. A study should be undertaken to determine the transient thermal response of the basin during the boil-off period. Times-to-failure would be longer than for a LOCA.

APPENDIX A
CONVECTIVE HEAT TRANSFER FROM THE CANISTER WALL

A.1 DESCRIPTION OF PROBLEM

The primary mode of heat transfer from HLSW canisters in an interim storage loss-of-coolant accident is convection to the surrounding air. The scenario for air motion adopted in previous studies first by ARHCO (Ref. 2) and later by TASC (Ref. 1) consists of the following elements:

- Air moves rapidly downward along the sides of the interim storage basin
- At the bottom of the canister array near the concrete basin floor, air is at a temperature of 120°F
- Air is heated by the canister walls and rises due to buoyancy effects; the velocity of air determines the magnitude of the convective heat transfer coefficient between the air and the canister wall
- The heated air forms a thermal plume that leaves the storage basin area, i.e., it does not recirculate.

For the current two-dimensional problem, heat transfer along the length of the canister is of interest. To describe the convective process adequately requires knowledge of the canister wall temperatures, the air temperatures, and the appropriate heat transfer coefficients as a function of axial position. The HEATING5 computer code cannot explicitly handle the type of heat transfer problem that involves mass transfer (i.e., air flow) into and out of the boundaries of the problem space. Code material regions are fixed in space; their motion is not

allowed. However, by treating convective heat transfer simply as a boundary condition to the HLSW canisters without having to represent the air space between canisters as a separate material region, an effective method has been found to model the convective process. The purpose of this Appendix is to describe the approach used to compute the needed convection boundary condition parameters.

A.2 HEAT TRANSFER MODEL

Consider a unit cell in the canister array consisting of a waste canister surrounded by air flowing upward at a constant flow rate. The following assumptions have been invoked:

- Steady-state (time-independent) conditions prevail
- The convective heat transfer can be described as a forced convection process
- The air flow is sufficiently turbulent that complete radial mixing is promoted, i.e., there are no radial temperature gradients in the air stream.

At a small section of the canister (see Fig. A-1) at height z whose width is dz , the rate of heat transfer by convection to air, dq_c , is

$$dq_c = 2\pi r h_c (T_w(z) - T_a(z)) dz \text{ (Btu/hr)} \quad (\text{A-1})$$

where

r = outer radius of the canister (ft)

h_c = forced convection heat transfer coefficient
(Btu/hr-ft²-°F)

Figure A-1 Sketch of Convective Heat Transfer Process

T_w = canister wall temperatures ($^{\circ}\text{F}$)

T_a = air temperature ($^{\circ}\text{F}$)

The air, in flowing across this section, will experience a temperature rise given by

$$dq_c = \dot{m} C dT_a \quad (\text{Btu/hr}) \quad (\text{A-2})$$

with $\dot{m}$ = mass flow rate of the air per canister (lb/hr)

C = heat capacity of the air (Btu/lb- $^{\circ}\text{F}$)

Equating these expressions then yields the air heat balance equation

$$\frac{dT_a}{dz} = \frac{2\pi r h_c}{\dot{m} C} (T_w(z) - T_a(z)) \quad (A-3)$$

Associated with the differential equation Eq. A-3 is the air temperature at the bottom of the basin

$$T_a(0) \approx 120^\circ\text{F} \quad (A-4)$$

A.3 TREATMENT OF CONVECTION IN HEATING5

To treat the convection process as a boundary condition on the canister it is necessary, at each zone along the canister length, to input the following parameters:

- A heat transfer coefficient, h_c
- The temperature of the heat sink.

Given this information, the code provides the canister surface temperature and the area over which the heat transfer takes place to complete the heat transfer calculation.

For simplicity, it was decided to instruct HEATING5 to transfer heat by convection to a heat sink at a constant temperature, T_o , instead of at T_a , and to adjust the heat transfer coefficient accordingly (T_o was arbitrarily selected to be 75°F). Computation of an "effective" heat transfer coefficient was accomplished by a subroutine written specifically for this problem. The major steps in the subroutine are described in the following paragraphs.

At each axial zone the heat transfer process by convection is given by Eq. A-1, which can be rewritten using a heat transfer area, A, as

$$q_c = Ah_c(T_w - T_a) \quad (A-5)$$

To base the heat transfer on a sink temperature, T_o , in lieu of the actual air temperature, T_a , requires the use of an adjusted convection coefficient, h' , found from

$$h' = h_c \frac{T_w - T_a}{T_w - T_o} \quad (A-6)$$

The special subroutine determined the air temperature, T_a , in Eq. A-6 by solving Eq. A-3 using an iterative process. The canister was partitioned axially into N zones of equal length Δz . As indicated in Fig. 2.3-2, 40 zones were employed. The position of the k^{th} zone is

$$z_k = k\Delta z; k = 1, 2, \dots, N \quad (A-7)$$

The derivative of the left-hand side of Eq. A-1 was approximated by a backward difference of the form

$$\frac{dT_a}{dz}(z_{k+1}) = \frac{T_a(z_{k+1}) - T_a(z_k)}{\Delta z} \quad (A-8)$$

Using Eq. A-8 in Eq. A-3 gives

$$T_a(z_{k+1}) = \frac{2\pi r h_c \Delta z T_w(z_{k+1}) + \dot{m} C T_a(z_k)}{2\pi r h_c \Delta z + \dot{m} C} \quad (A-9)$$

which expresses the air temperature at zone $k+1$ in terms of the air temperature of zone k and the wall temperature at zone $k+1$. Substitution of this result into Eq. A-6 then provides the effective coefficient, h' , at zone $k+1$. Note that h_c is not necessarily a constant but may be input as a function of air temperature (see Eq. 2.4-1).

APPENDIX B
RADIATION VIEW FACTORS

B.1 DESCRIPTION OF PROBLEM

An important heat transfer mechanism from HLSW canisters in a loss-of-coolant accident is radiation to space from the hot canister walls. In the prior one-dimensional studies and in the current two-dimensional work, heat loss by radiation from the canister ends is easily computed. The view factors (i.e., the fraction of radiation emitted to space) were essentially unity. Radiation from the canister sides, on the other hand, is much more complicated to determine. The geometry consists of a square array of circular cylinders. The view factors depend on z , the coordinate in the axial direction -- the closer to the canister top, the larger the view factor to space. The problem addressed in this appendix is that of determining, approximately, the radiation view factors from the sides of waste canisters to space as a function of distance along the length of the canister.

B.2 DETERMINATION OF VIEW FACTORS

A typical pathway for radiation from a canister side wall to space was illustrated in Fig. 2.3-1. If one draws a square array of cylinders it is apparent that the solid angle subtended by all other cylinders from a point on the wall of a given canister is difficult to calculate. The approach taken here was to assume that the net effect of all surrounding cylinders, due to intercepting radiation from the sides of a given

cylinder, could be represented by enclosing the latter by a concentric cylinder of larger radius.

The simplified geometry is shown in Fig. B-1. If this representation is valid, the problem is reduced to computing the view factor from a region on the inner cylinder, indicated as Region 2, to space, indicated as a planar Region 7. Radiation that intercepts the sides of the outer cylinder -- i.e., Regions 4, 5, and 6 -- and the concrete bottom of the pool -- i.e., Region 10 -- is ignored. Selection of an appropriate radius, R , for the outer cylinder is important and will be discussed later; the radius of the inner cylinder, r , and the cylinder length, L , are the actual physical dimensions of the waste canisters. The regions, such as Region 2, for which the view factors are to be determined have been chosen to be horizontal rings so as to coincide with acceptable regions for the HEATING5 code in an R-z geometry (that is, regions whose boundaries are parallel to curves of constant R and z).

Following the nomenclature from Holman (Ref. 6) we define $F_{a,b,c-x,y,z}$ as the view factor, or shape factor, from a surface consisting of subsurfaces a , b , and c to another surface consisting of subsurfaces x , y , and z .

Consider again Fig. B-1; it is desired to calculate the view factor F_{2-7} , which can be accomplished by use of reciprocity and conservation of energy relationships.

From Surface 1 we have

$$F_{1-7} + F_{1-4} + F_{1-8} = 1 \quad (B-1)$$

By symmetry

$$F_{1-7} = F_{1-8} \quad (B-2)$$

REGIONS 1, 2 AND 3 ARE ON INNER VERTICAL CYLINDER
 REGIONS 4, 5 AND 6 ARE ON OUTER VERTICAL CYLINDER
 REGIONS 7, 8, 9 AND 10 ARE HORIZONTAL PLANES

Figure B-1 Geometry for Determining Radiation View Factors to Space from Regions on the Inner of a Pair of Concentric Cylinders

Therefore,

$$F_{1-7} = 1/2 [1 - F_{1-4}] \quad (B-3)$$

By a similar argument for composite surface 1, 2

$$F_{1,2-7} + F_{1,2-4,5} + F_{1,2-9} = 1 \quad (B-4)$$

and

$$F_{1,2-7} = F_{1,2-9} \quad (B-5)$$

Therefore,

$$F_{1,2-7} = 1/2 \left[1 - F_{1,2-4,5} \right] \quad (B-6)$$

The total radiation arriving at surface 7 from the combined area $A_{1,2}$ is the sum of the radiations from surfaces 1 and 2. Thus,

$$A_{1,2} F_{1,2-7} = A_1 F_{1-7} + A_2 F_{2-7} \quad (B-7)$$

Next, Eqs. B-3 and B-6 were substituted into Eq. B-7, using

$$A_{1,2} = A_1 + A_2 \quad (B-8)$$

to obtain, after some algebra,

$$F_{2-7} = 1/2 \left[1 + \frac{A_1}{A_2} F_{1-4} - \left(1 + \frac{A_1}{A_2} \right) F_{1,2-4,5} \right] \quad (B-9)$$

In the limit of thin regions where $A_2 \rightarrow 0$,

$$A_2 F_{2-7} = \frac{A_1}{2} \left[F_{1-4} - F_{1,2-4,5} \right] \quad (B-10)$$

The quantities F_{1-4} and $F_{1,2-4,5}$ appearing in Eq. B-9 are simply the view factors between two concentric, coaxial cylinders of equal length. Hottel (Ref. 11) gives that view factor relationship from the surface of the outer cylinder to the inner cylinder as

$$F_{o-i} = \frac{r}{R} - \frac{1}{\pi} \frac{r}{R} \cos^{-1} \left[\frac{(L/R)^2 + (r/R)^2 - 1}{(L/R)^2 - (r/R)^2 + 1} \right] \\ + \left[\left(\frac{1}{2\pi} \frac{L}{R} + \frac{R}{L} + \frac{r^2}{RL} \right)^2 - \left(\frac{2r}{L} \right)^2 \right]^{1/2} \cos^{-1} \left[\frac{(L/R)^2 + (r/R)^2 - 1}{(L/R)^2 - (r/R)^2 + 1} \frac{r}{R} \right] \\ + \left(\frac{1}{2\pi} \frac{L}{R} - \frac{R}{L} + \frac{r^2}{RL} \right) \sin^{-1} \frac{r}{R} - \frac{1}{4} \left(\frac{L}{R} + \frac{R}{L} - \frac{r^2}{RL} \right) \quad (B-11)$$

The corresponding relationship for the view factor from the inner to the outer cylinder is

$$F_{i-o} = \frac{R}{r} F_{o-i} \quad (B-12)$$

In terms of the present problem (see Fig. B-1) the ratio A_1/A_2 is given by

$$A_1/A_2 = z_1/(z_2 - z_1) \quad (B-13)$$

and F_{1-4} is evaluated at $L = z_1$, while $F_{1,2-4,5}$ is evaluated at $L = z_2$ using Eq. B-11 and Eq. B-12.

B.3 NUMERICAL RESULTS OF VIEW FACTOR CALCULATIONS

For calculation of radiation heat transfer in HEATING5 from canister sides the 20-ft long canisters were divided axially into 10 2-ft long zones. The radius r of the inner cylinder for each zone was 0.5 ft. The radius, R , of the outer cylinder was assumed to be 1.5 ft. This distance was selected because it represents exactly the canister center-to-center spacing and, roughly, it should correspond to an average distance from the center of the inner cylinder to the outer walls

of the surrounding cylinders (the actual range of these distances varies from 1 ft to about 3 ft). Table B-1 gives the computed view factors F_{2-7} with a 1.5-ft canister spacing for each of the 10 zones; note that distances are measured from the top of the canister.

In order to check whether the computed view factors were sensitive to the somewhat arbitrary choice of outer radius, F_{2-7} was recalculated for reasonable lower and upper bounds on R and compared to the nominal (R=1.5 ft) view factor.

TABLE B-1
RADIATION VIEW FACTORS FROM CANISTER SIDES

ZONE LOCATION (ft)	VIEW FACTOR F_{2-7}
0-2	0.3426
2-4	0.0735
4-6	0.0272
6-8	0.0140
8-10	0.0085
10-12	0.0057
12-14	0.0040
14-16	0.0030
16-18	0.0024
18-20	0.0019

These results are presented in Table B-2 for two typical zones located at 2 to 4 ft and 16 to 18 ft from the top of the canisters.

TABLE B-2
SENSITIVITY OF COMPUTED VIEW FACTORS TO
SELECTION OF OUTER RADIUS, R

OUTER RADIUS (ft)	F ₂₋₇ AT ZONE 2 TO 4 ft	F ₂₋₇ AT ZONE 16 TO 18 ft
1.0 (lower bound)	0.058	0.0018
1.5 (nominal)	0.073	0.0024
2.0 (upper bound)	0.076	0.0025

As can be seen, the sensitivity of the view factor calculation on the assumed equivalent outer radius is not large, giving greater confidence to the results.

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