HIGH LEVEL WASTE CANISTER
THERMAL CHARACTERIZATION FOR THE
SEALED STORAGE CASK CONCEPT

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INTRODUCTION

High level waste, generated by the chemical reprocessing of commercial nuclear reactor fuels, will be converted to a stable solid, packaged in a high integrity metal container (canister), and transferred to a Federal repository for storage. The waste and canister properties pertinent to storage require definition to assure that the filled canister will be compatible with the storage concept. The purpose of this study is to characterize the waste storage unit thermal behavior for normal and accident situations so that safe acceptance limits on heat content can be established for canisters received at the Retrievable Surface Storage Facility. The storage method used for the analyses is the Sealed Storage Cask Concept. Storage unit radiation shielding requirements for various waste and canister characteristics are also reviewed.

SUMMARY

A study was performed to determine the compatibility of various high level commercial radioactive waste and canister characteristics with the Sealed Storage Cask Concept (SSCC) for the Retrievable Surface Storage Facility (RSSF). The parameters included were waste form (calcine and glass), heat generation rate (0.25-5 kilowatts per hour per cubic foot), radiation generation rate (0-10 year old reference waste), and canister diameter (6-24 inches) and length (10-15 feet). The canister was assumed to be a right circular cylinder with sufficient internal finning to maintain the waste centerline temperature below the maximum stable waste temperature under normal operating conditions. The storage unit components were a simplified generic design of a reference case. The situations studied for conceptual compatibility were storage unit temperature limits for normal operations and air flow blockage in the unit. Unit burial cases were also examined. Shielding requirements and storage unit weights were determined for the various filled canisters.

Material properties at elevated temperatures are limiting conditions for concept compatibility. As the waste specific heat generation rate or canister diameter increases, storage unit temperatures increase significantly. The storage cask temperature of 1200°F; encountered in the air flow stoppage situation; is the limiting credible heat transfer accident condition for determining filled canister acceptability. Under limiting cask temperature conditions the concrete temperature is above 900°F, where significant spalling will occur. This is acceptable under accident conditions as long as the cask integrity is not impaired. Almost any size canister is conceptually compatible with the SSCC providing the

specific heat of the waste is low enough. Storage unit temperatures for the situations studied do not increase substantially as the canister length is increased from 10 to 15 feet.

An optimum canister for the reference waste, from Pressurized Water Reactor-Uranium (PWR-U) fuel exposed to 33,000 megawatt days per metric ton at 2 cubic feet per metric ton and 10 years old, has an 18.5 inch internal diameter and is 15 feet long. This represents 15.4 kilowatts of heat in a 28 cubic foot volume. Another optimum would be the maximum heat which can be placed in a reference canister, 10 feet long and 12 inches internal diameter. The maximum amount of heat is 10.1 kilowatts in this case. Results show that these canisters can be safely overpacked in up to three additional overpacks and casks and still be safely stored. The economic optimum canister may be determined after additional studies are performed to find minimum storage unit material requirements, establish canister acceptance costs, and account for fuel reprocessor costs for high level waste handling, storage and transportation.

Cask shield design is somewhat insensitive to canister and waste characteristics except for Pressurized Water Reactor-Plutonium (PWR-Pu) fuel derived waste. Minimal shield thickness required for all waste, cask and canister combinations, varies between 34 and 44 inches for non-PWR-Pu derived waste. The associated storage unit weights may vary significantly between about 53 and 160 tons. The PWR-Pu derived waste could require up to 20 inches additional concrete shielding to adequately attenuate the neutrons. The most significant neutron shielding parameter is the effect of waste fuel type (PWR-Pu versus other) and exposure history followed by waste

form and canister diameter. The storage unit for the reference waste in the 18.5 inch diameter and 15 feet long optimum canister requires 40 inches of concrete shielding, which includes a modest contingency and results in a total unit weight of 120 tons.

CANISTER AND STORAGE UNIT DESIGN

BASES

For a waste filled canister to be compatible with the Sealed Storage Cask Concept, it and the storage cask shall be able to maintain their integrity under all credible conditions. The concrete radiation shield is required to maintain its integrity, no gross cracks or spalling, only under normal operating conditions and to protect cask integrity under all credible conditions. The conditions considered for the heat transfer analyses are defined as follows:

- Normal Operating Conditions

A single storage unit is placed outdoors in 80°F air with zero wind velocity. Solar heating is neglected.

- Air Coolant Flow Blockage (Steady State)

The air inlet and outlet ports are plugged with concrete of the same thickness and properties as the concrete radiation shield. Other conditions are the same as the "Normal Storage Operation."

Solar heating effects are neglected on the following bases. The radiation shield thermal capacity is large, and the day time heating and night time heat loss sufficiently average each other such that the net thermal effects on the unit interior is small.

The condition of storage unit burial is included in the analyses, although this situation is not considered of sufficient probability as to deem credible. This case consists of a storage unit buried in the earth with the top of the storage cask 5 feet below the ground surface. The concrete shield maintains its integrity and has the same thermal properties as the ground. The storage unit temperatures encountered at this depth approach those for an infinitely deep buried unit.

STORAGE UNIT CHARACTERISTICS

A simplified generic storage unit design was used for this parametric study. The design used is shown in Figure 1, and the design and material assumptions are indicated in Table 1. The canister is 6 to 24 inches in diameter and 10 and 15 feet in length. A maximum canister length of 15 feet was selected since this is about the length of Light Water Reactor fuel assemblies, and experience exists for shipping and handling these assemblies in fuel reprocessor facilities and reactors. All material thicknesses and gap widths, except for the waste canister diameter and height, were held constant. Material characteristics were considered constant for computations, and average properties were used.

Solidified waste characteristics were assumed to be a hypothetical glass or calcine with variable heat generating capacity. The waste properties are indicated in Table 1. A heat generation range of 0.25-5 kilowatts per cubic foot was selected to cover a wide range of variables such as fuel exposure, waste age, the cubic feet of waste per equivalent metric ton of fuel, and the type of fuel from which the waste was generated. For the reference fuel types and characteristics indicated in Table 2 the heat generation rates of the high level wastes for various times after fuel discharge are shown in Figure 2. The effects of different fuel exposure on waste heat generation characteristics are shown in Appendix A.

For the reference optimum cases (maximum heat in reference canister and maximum canister size for reference waste which is discussed later) heat transfer calculations were also performed. Additional calculations for these cases include the following multiple overpack configurations.

Canister + Cask + Cask

Canister + Overpack + Cask

Canister + Overpack + Cask + Cask

The overpack possesses the same material properties and thickness as the canister. The additional cask has the same material characteristics and thickness as the first cask. Gaps between all metal containers are maintained at 1.5 inches. The spacings between the outer metal container and the concrete shield are 6 inches. The multiple overpack configurations are shown in Figure 3.

HEAT TRANSFER

Detailed results of the heat transfer analyses for the generic storage units are contained in Appendix B. These studies indicate that the size and heat generation limitations imposed on a filled canister, which may be received at the RSSF, are determined by a cask temperature limit of 1200°F encountered in the air flow stoppage cases. Also, there is no major increase in storage unit temperatures whether the canister is 10 or 15 feet long for acceptable, equivalent specific waste heat generation and canister diameter. For instance, the maximum temperature differences of similar storage unit components is less than about 50°F for normal operating conditions and 100°F for an accident situation. Thus significantly more waste, up to 50 percent, could be stored in a 15 foot canister rather than a 10 foot one.

More waste heat can be stored in a larger diameter canister, although the specific heat generation rate will have to be reduced. In a 10 foot long canister, 11.7 kilowatts can be stored in an 18 inch diameter canister whereas about 10 kilowatts of heat can be placed in a 12 inch diameter canister based on the no air flow condition. But, the specific heat generation rate would be 1.3 versus 0.65 kilowatts per cubic foot for the 12 and 18 inch diameter cases respectively.

Two reference optimum cases were established with regard to waste heat storage. These were the maximum heat generation rates that could be placed in a reference canister and the largest canister volume that can be filled with reference waste. The reference canister is 10 feet long and 12 inches internal diameter. The reference waste is 2 cubic feet per metric ton and comes from PWR-U fuel which was exposed to 33,000 megawatt days per metric ton and is 10 years old. The

maximum allowable heat generation which can be placed in a filled reference canister is 10.1 kilowatts, and the maximum size canister that can be filled with reference waste is 15 feet long and 18.5 inches internal diameter, which will hold 15.4 kilowatts of heat.

Additional calculations were performed for the reference optimum cases to determine the effects of overpacking these canisters. The normal operation, air flow stoppage, and burial calculations were performed for the optimum cases for the following multiple overpack arrangements.

Canister + Cask

Canister + Overpack + Cask

Canister + Cask + Cask

Canister + Overpack + Cask + Cask

These multiple overpack situations would occur where there has been failure of one or more storage unit waste barriers. The results of these calculations are summarized in Tables 3 through 8 for the optimum reference canister and reference waste cases respectively. These computations show that if the canister is overpacked the outer barrier is within acceptable temperature limitations, and the inner barrier temperatures do not increase significantly. This is due to the efficient heat transfer by radiation at the temperatures experienced and the increased heat transfer area of the outer overpacks and shield.

RADIATION SHIELDING

An additional consideration for receiving filled waste canisters at the RSSF is the shielding necessary for the facility and storage unit to assure the safety of operating personnel. Shielding requirements will have a significant impact on facility and storage unit costs but little effect on normal storage unit operating temperatures. Shielding thickness significantly affects heat removal from the storage unit only in the air flow stoppage cases where the heat must be conducted through the shield. Temperature changes for shield thicknesses modestly deviating from 40 inches would probably not be significant.

Shield thicknesses required to reduce the gamma and neutron dose rates to 1 millirem per hour for a storage unit with variable canister dimensions, waste types, and waste characteristics are shown in the figures indicated below.

<u>Situation</u>	<u>Figure Number</u>
Gamma Radiation: Calcine and Glass Waste	
Canister Diameters, inches: 6-24	4
Neutron Radiation: Calcine and Glass Waste	
Canister Diameters, inches: 6-24	5

The concrete used for the reference shield is ordinary concrete containing 2 weight percent water. The water content is conservatively low which may be representative of concrete encountering a high temperature environment.

The gamma shielding data indicate that shield thickness varies moderately with waste and canister characteristics. The inclusion of the 2 inch steel cask between the canister and

the shield reduces the concrete shield requirements by about 6 inches. Over the entire spectrum of waste and canister characteristics, the concrete thickness requirement varies over about a 10 inch thickness range for a storage unit.

The neutron shielding data indicates that the concrete shield thickness requirements vary significantly due to waste properties and canister design. Neutron shielding needs for the waste from PWR-Pu fuels are about 20 inches more concrete than for other fuels due to the high neutron generating curium-244 content. The overall shield thickness increase, over that required for gamma radiation shielding, may be up to 20 inches. The presence of the cask reduces the neutron dose rate from the canister by a factor of two or represents about 3 to 4 inches of dehydrated concrete.

The primary use of the shielding data is to determine the thickness of the concrete shield. If the shield exterior is designed for a dose rate other than 1 millirem per hour, the appropriate shield thickness can be determined from the shielding figures. It requires roughly 3.5 and 1.5 inches of reference concrete to reduce the shield exterior dose rate by a factor of two for neutron and gamma radiation, respectively. Also, excess concrete should be provided in the initial storage units to allow for some uncertainties in the shielding calculations.

The weight of the storage unit as a function of canister height and diameter, and shield thickness is shown in Figure 6. Greater than 94 percent of the storage unit weight is the shield weight, excluding the base. The storage unit weight increases significantly with increases in canister length and

diameter, and shield thickness. The weight is primarily a design and handling problem and not a concept consideration, but at some weight there is an upper practical limit which has not yet been established.

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TABLE 1

SEALED STORAGE CASK CONCEPT
GENERIC STORAGE UNIT
HEAT TRANSFER CHARACTERIZATION

WASTE

Heat Generation Per Unit Volume = 0.25-5 kw/ft³ (0.25, 0.5, 1, 2, 5)

	<u>Calcine</u>	<u>Glass</u>
Thermal Conductivity, Btu/hr-ft-°F	0.2	0.7
Heat Capacity, Btu/lb-°F	0.2	0.2
Density, lb/ft ³	81	187
Maximum Stable Temperature, °F	1500	1900

CANISTER

Shell: Material of Construction: 304-L stainless steel
Internal Diameter: 0.5-2 ft (0.5, 1.0, 1.5, 2.0)
Internal Height: 10-15 ft (10, 15)
Thickness: 0.375 in.
Thermal Conductivity: 10 Btu/hr-ft-°F
Emissivity: 0.45
Heat Capacity: 0.12 Btu/lb-°F
Density: 500 lb/ft³

Fins: Material of Construction: Carbon Steel
Length: Full
Penetration: 2/3
Thickness: 0.25 in.
Weld: Full weld at root
Thermal Conductivity: 23 Btu/hr-ft-°F
Heat Capacity: 0.15 Btu/lb-°F
Density: 490 lb/ft³

Canister Fill Height: Full (neglect fin volume)

TABLE 1 (Continued)

CASK

Material of Construction: Carbon Steel
Internal Diameter: Allow a 1.5 inch gap between cask and canister
Internal Height: Allow a 6 inch gap between cask and canister
Thickness: 2 in.
Thermal Conductivity: 26 Btu/hr-°F-ft
Emissivity: 0.6
Heat Capacity: 0.14 Btu/lb-°F
Density: 490 lb/ft³

SHIELD

Material of Construction: Concrete
Internal Diameter: Allow a 6 inch gap between concrete and cask
Internal Height: Allow 1 foot between floor and cask and 6 inches between cask and lid
Thickness: 40 in.
Thermal Conductivity: 0.5 Btu/hr-°F-ft
Emissivity: 0.7
Heat Capacity: 0.2 Btu/lb-°F
Density: 143.5 lb/ft³

AIR

Ambient Temperature: 80°F
Thermal Conductivity: 0.015 Btu/hr-ft-°F
Heat Capacity: 0.25 Btu/lb-°F
Density: 0.072 lb/ft²

BURIAL EARTH

Thermal Conductivity: 0.3 Btu/hr-ft-°F
Soil Thermal Diffusivity: 0.0083 ft²-°F
Heat Capacity: 0.2 Btu/lb-°F
Density: 180 lb/ft³

TABLE 2

COMMERCIAL NUCLEAR FUELS
REFERENCE EXPOSURE CONDITIONS

Exposure Conditions	FUEL			
	PWR-U	PWR-Pu	GEFO	HTGR
Burnup (MWD/MT)	33,000	33,000	41,500	94,300
Power (MW/MT)	30	30	48.5	64.6
Flux (N/cm ² -sec)	2.9×10^{13}	1.5×10^{13}	2.7×10^{15}	6.5×10^{13}
Enrichment				
WT% ²³⁵ U	3.3	0.68	0.19	4.6
WT% ²³⁹⁺²⁴¹ Pu	-	3.1	4.3	-
Other	-	-	-	2.3 ²³³ U

TABLE 3

NORMAL OPERATING TEMPERATURES FOR
MULTIPLE BARRIER STORAGE UNIT
CONTAINING OPTIMUM REFERENCE CANISTER

CANISTER: Diameter: 12 in
Length: 10 ft
Volume: 7.8 ft³

Specific Heat Generation: 1.3 kw/ft³
Total Heat Generation: 10.1 kw

CONFIGURATION	MAXIMUM COMPONENT TEMPERATURE - °F								
	Waste C ⁽¹⁾	Canister	Overpack	Storage Cask		Inner Shield	Outer Shield	Ambient Air	Air Flow CFH ⁽²⁾
				1	2				
Canister + Cask	2060	665	-	390	-	255	95	80	50,000
Canister + Cask + Cask	2120	725	-	515	320	205	91	80	74,000
Canister + Overpack + Cask	2220	825	630	355	-	230	93	80	55,000
Canister + Overpack + Cask + Cask	2270	875	695	495	305	195	90	80	80,000

(1) Canister has no fins and contains calcine

(2) At average annulus temperature

TABLE 4

AIR FLOW BLOCKAGE TEMPERATURES FOR
MULTIPLE BARRIER STORAGE UNIT
CONTAINING OPTIMUM REFERENCE CANISTER

CANISTER: Diameter: 12 in
Length: 10 ft
Volume: 7.8 ft³

Specific Heat Generation: 1.3 kw/ft³
Total Heat Generation: 10.1 kw

CONFIGURATION	MAXIMUM COMPONENT TEMPERATURE - °F								
	Waste $\epsilon^{(1)}$	Canister	Overpack	Storage Cask		Inner Shield	Outer Shield	Ambient Air	Air Flow $\text{CFH}^{(2)}$
				1	2				
Canister + Cask	2695	1310	-	1230	-	1195	139	80	0
Canister + Cask + Cask	2625	1240	-	1145	1090	1050	135	80	0
Canister + Overpack + Cask	2700	1315	1225	1150	-	1115	137	80	0
Canister + Overpack + Cask + Cask	2655	1270	1165	1080	1030	990	133	80	0

(1) Canister has no fins and contains calcine

(2) At average annulus temperature

TABLE 5

BURIAL TEMPERATURES AT ONE MONTH FOR
MULTIPLE BARRIER STORAGE UNIT
CONTAINING OPTIMUM REFERENCE CANISTER

CANISTER: Diameter: 12 in
Length: 10 ft
Volume: 7.8 ft³

Specific Heat Generation: 1.3 kw/ft³
Total Heat Generation: 10.1 kw

CONFIGURATION	MAXIMUM COMPONENT TEMPERATURE - °F					
	Waste $\bar{Q}$ ⁽¹⁾	Canister	Overpack	Storage Cask		Inner Shield
				1	2	
Canister + Cask	3375	1990	-	1965	-	1950
Canister + Cask + Cask	3080	1695	-	1655	1630	1615
Canister + Overpack + Cask	3230	1845	1805	1775	-	1760
Canister + Overpack + Cask + Cask	2990	1605	1550	1505	1480	1465

(1) Canister has no fins and contains calcine

TABLE 6

NORMAL OPERATING TEMPERATURES FOR
MULTIPLE BARRIER STORAGE UNIT
CONTAINING OPTIMUM MAXIMUM CANISTER SIZE

CANISTER: Diameter: 18.5 in
Length: 15 ft
Volume: 28 ft³

Specific Heat Generation: 0.55 kw/ft³
Total Heat Generation: 15.4 kw

CONFIGURATION	MAXIMUM COMPONENT TEMPERATURE - °F								
	Waste $\bar{C}$ ⁽¹⁾	Canister	Overpack	Storage Cask		Inner Shield	Outer Shield	Ambient Air	Air Flow CFH (2)
				1	2				
Canister + Cask	1955	560	-	355	-	240	92	80	70,000
Canister + Cask + Cask	2035	640	-	470	305	200	89	80	76,000
Canister + Overpack + Cask	2080	685	525	330	-	225	91	80	103,000
Canister + Overpack + Cask + Cask	2135	740	600	440	285	190	89	80	109,000

20

(1) Canister has no fins and contains calcine

(2) At average annulus temperature

TABLE 7

AIR FLOW BLOCKAGE TEMPERATURES FOR
MULTIPLE BARRIER STORAGE UNIT
CONTAINING OPTIMUM MAXIMUM CANISTER SIZE

CANISTER: Diameter: 18.5 in
Length: 15 ft
Volume: 28 ft³

Specific Heat Generation: 0.55 kw/ft³
Total Heat Generation: 15.4 kw

CONFIGURATION	MAXIMUM COMPONENT TEMPERATURE - °F								
	Waste ϕ ⁽¹⁾	Canister	Overpack	Storage Cask		Inner Shield	Outer Shield	Ambient Air	Air Flow CFH ⁽²⁾
				1	2				
Canister + Cask	2595	1200	-	1135	-	1105	135	80	0
Canister + Cask + Cask	2545	1150	-	1080	1035	1000	132	80	0
Canister + Overpack + Cask	2610	1215	1140	1080	-	1045	134	80	0
Canister + Overpack + Cask + Cask	2575	1180	1095	1030	985	950	131	80	0

(1) Canister has no fins and contains calcine

(2) At average annulus temperature

TABLE 8

BURIAL TEMPERATURES AT ONE MONTH FOR
MULTIPLE BARRIER STORAGE UNIT
CONTAINING OPTIMUM MAXIMUM CANISTER SIZE

CANISTER: Diameter: 18.5 in
Length: 15 ft
Volume 28 ft

Specific Heat Generation: 0.55 kw/ft³
Total Heat Generation: 15.4 kw

CONFIGURATION	MAXIMUM COMPONENT TEMPERATURE - °F					
	Waste $\zeta^{(1)}$	Canister	Overpack	Storage Cask		Inner Shield
				1	2	
Canister + Cask	3070	1675	-	1650	0	1635
Canister + Cask + Cask	2850	1455	-	1410	1385	1370
Canister + Overpack + Cask	2965	1570	1530	1500	-	1485
Canister + Overpack + Cask + Cask	2785	1390	1335	1295	1270	1250

(1) Canister has no fins and contains calcine

* ONE-HALF OF TOROID VOLUME
FILLED WITH CONCRETE

FIGURE 1
SEALED STORAGE CASK CONCEPT
GENERIC WASTE STORAGE UNIT
NORMAL OPERATION

FIGURE 2
HIGH LEVEL WASTE HEAT GENERATION
FOR REFERENCE FUELS

FIGURE 3

MULTIPLE OVERPACK CONFIGURATIONS

FUEL TYPE	FT ³ /MT	YEARS AFTER FUELS DISCHARGE									
PWR-U	1										
	2										
	3										
	5										
	7										
PWR-Pu	1										
	2										
	3										
	5										
	7										
HTGR	1										
	2										
	3										
	5										
	7										
GEFO	1										
	2										
	3										
	5										
	7										

FIGURE 4
CONCRETE SHIELDING REQUIRED
TO REDUCE CANISTER AND CASK
GAMMA DOSE RATE TO ONE MILLIREM PER HOUR

FIGURE 5

CONCRETE SHIELDING REQUIRED
TO REDUCE CANISTER AND CASK
NEUTRON DOSE RATE TO ONE MILLIREM PER HOUR

FIGURE 6
SEALED STORAGE CASK CONCEPT
STORAGE UNIT WEIGHT FOR
VARIABLE CANISTER DIMENSIONS

APPENDIX A

EFFECTS OF NUCLEAR FUEL PROPERTIES ON WASTE HEAT GENERATION

The effects of four different fuel types and their degree of burnup on waste heat generation was determined. The heat generation was determined as a function of time after fuel discharge. Calculations were made with the "ORIGN" computer code assuming average fuel properties and constant exposure conditions. The heat generation data was translated into waste heat generation properties by assuming that all radiation and other energy from the fission products and actinides in the waste are converted to thermal energy in the waste and generated from it. It was assumed that 0.5 percent of the uranium and plutonium from the fuels was in the waste for all cases except the High Temperature Gas Cooled Reactor waste where 0.5 percent of the uranium and thorium was in the waste. The results are shown in the figures indicated below.

<u>Fuel Type</u>	<u>Figure</u>
Pressurized Water Reactor - Enriched Uranium Fuel (PWR-U)	A-1
Pressurized Water Reactor - Equilibrium Recycle Enriched Plutonium Fuel (PWR-Pu)	A-2
High Temperature Gas Cooled Reactor - Equilibrium Recycle Fuel (HTGR)	A-3
Liquid Metal Fast Breeder Reactor - Equilibrium Recycle Fuel (GEFO)	A-4

Equilibrium recycle fuel characteristics were used since they represent worst case properties for heat generation and radiation characteristics. The effect of different enrichments of PWR-U fuels on heat generation characteristics at various fuel exposures was reviewed, Table A-1. It is seen that enrichment does not significantly affect the heat generation rate. The effect of power level on fuel heat generation was not investigated,

but it would be expected that the heat generation would be somewhat higher at short times out of the reactor for higher levels and constant burnup.

TABLE A-1

EFFECT OF ENRICHMENT ON EXPOSED PWR-U FUEL
HEAT GENERATION AND RADIATION PROPERTIES

Power Level - 30 MW/MT

Exposure MWD/MT	Enrichment % U-235	Property								
		Heat Generation KW/MT			Gamma Radiation Mev/sec-MT			Neutron Generation N/sec-MT		
		Years After Discharge			Years After Discharge			Years After Discharge		
		1	3	10	1	3	10	1	3	10
15,000	3.3	6.12	1.66	0.484	9.5×10^{15}	3.1×10^{15}	1.1×10^{15}	9.9×10^6	5.2×10^6	3.8×10^6
	2.05	6.64	1.82	0.475	1.1×10^{16}	3.7×10^{15}	1.2×10^{15}	3.9×10^7	2.6×10^7	1.9×10^7
20,000	3.3	7.50	2.18	0.646	1.2×10^{16}	4.6×10^{15}	1.5×10^{15}	3.9×10^7	2.4×10^7	1.8×10^7
	2.4	7.99	2.35	0.644	1.4×10^{16}	5.2×10^{15}	1.6×10^{15}	9.5×10^7	6.7×10^7	5.1×10^7
40,000	3.3	12.6	4.47	1.42	2.7×10^{16}	1.2×10^{16}	3.4×10^{15}	9.9×10^8	8.3×10^8	6.3×10^8
	3.8	12.1	4.28	1.39	2.5×10^{16}	1.2×10^{16}	3.4×10^{15}	7.0×10^8	5.7×10^8	4.4×10^8

FIGURE A-1

HIGH LEVEL WASTE HEAT GENERATION
WASTE SOURCE: PWR-U FUEL

FIGURE A-2

HIGH LEVEL WASTE HEAT GENERATION
WASTE SOURCE: PWR-Pu FUEL

FIGURE A-3

HIGH LEVEL WASTE HEAT GENERATION
WASTE SOURCE: GEFO FUEL

FIGURE A-4
HIGH LEVEL WASTE HEAT GENERATION
WASTE SOURCE: HTGR FUEL

APPENDIX B

HIGH LEVEL WASTE STORAGE UNIT THERMAL ANALYSES RESULTS

Three situations, normal operation, air flow stoppage and burial, were analyzed for material temperature limitations that may be encountered in the storage unit. The limitation for these circumstances is the storage unit material property which would impair the storage unit integrity. For an abnormal situation the radiation shield integrity was not considered necessary for waste containment and is not considered limiting. The materials limitations and the associated bases are shown in Table B-7. Storage unit assumptions and characteristics are stated in Table 1. The canister heat generation rate range of 0.25 to 3 kilowatts per cubic foot is presented. Models used for calculations were two dimensional and included conduction, convection, and radiation heat transfer modes.

The results are shown in the figures indicated below for the appropriate situations.

<u>Situation</u>	<u>Figure</u>
Normal Operation (Figure B-19)	
Canister:	
<u>Length, 10, 15 feet</u> <u>Diameter, inches</u>	B-2
6	B-1
12	B-2
18	B-3
24	B-4
Air Flow Stoppage (Figure B-5)	
Canister:	
<u>Length, feet</u> <u>Diameter, inches</u>	
10 6	B-6
12	B-7
18	B-8

Situation Figure

Air Flow Stoppage (continued)

Canister:

<u>Length, feet</u>	<u>Diameter, inches</u>	
10	24	B-9
15	6	B-10
	12	B-11
	18	B-12
	24	B-13

Burial (Figure 14)

Canister:

<u>Length, feet</u>	<u>Diameter, inches</u>	
10	6	B-15
	12	B-16
	18	B-17
	24	B-18

The results for the buried storage unit containing the 15 foot long canister are essentially the same as for the 10 foot long canister and are not included.

To determine the filled waste canister characteristics that may be received at the RSSF, based on materials limitations, the following scheme may be used with the above figures. In the appropriate figure find the maximum allowable material temperature furthest toward the left hand side of the figure. Then all the waste types at the cubic foot per metric ton and waste age to the left of that temperature are allowable for reception at the RSSF. The exposure and fuel assumptions from which the waste came are indicated in Table B-8. The burial case conditions are not considered limiting since this accident is not deemed credible. It should be noted that for the burial cases considered which are more restrictive than the no air

flow cases on canister heat content, that there is a time period over which the canister can be exhumated intact.

For normal operating situation, waste temperatures in canisters without fins, air flow rates through the storage unit, and the number of canister fins required to maintain the waste below its maximum stable temperature are shown in Table B-2 through B-6 for calcine and glass waste in 10 and 15 foot long canisters. The waste temperatures encountered at the canister wall is below the maximum stable waste temperature for credible situations encountered in the RSSF. Additional studies are needed to determine if this is adequate. That is, verification is needed to establish that pressurization and increased corrosion rates will not be significant under abnormal conditions due to the high waste centerline temperature, possibly above the maximum stable temperature of the waste.

TABLE B-1

SEALED STORAGE CASK CONCEPT
MATERIAL TEMPERATURE LIMITATIONS IN AIR

	<u>Normal Operation</u> ⁽¹⁾	<u>Abnormal Operation</u> ⁽²⁾
Concrete: Structure Shield	500°F ⁽³⁾	900°F ⁽⁴⁾
Carbon Steel: Cask	600°F ⁽⁵⁾	1200°F ⁽⁶⁾
Stainless Steel: Canister Overpack	800°F ⁽⁷⁾	1500°F ⁽⁸⁾

- Bases:
- (1) Maximum allowable temperatures during 100 year design life that will not compromise containment integrity;
 - (2) Maximum allowable temperature for up to one year where immediate containment integrity would not be impaired, but integrity could not be assured for 100 years;
 - (3) Twenty percent loss of strength;
 - (4) Extensive cracking with significant loss of strength. Concrete would require replacement;
 - (5) Maximum oxidation rate of 2 mils/year;
 - (6) Upper limit of carbon steel usefulness in air, however, under zero air flow conditions oxidation rate would be low. There would be some loss of ductility due to carbide spheroidation;
 - (7) Grain boundary attack by cesium oxide in calcine waste would be accelerated above 850°F;
 - (8) Mechanical and fatigue properties decreased significantly.

TABLE B-2

CALCINE WASTE CANISTER THERMAL DATA
AND STORAGE UNIT AIR FLOW RATES
CANISTER LENGTH - 10 ft

Waste Heat Generation Rate (kw/ft ³)	Storage Unit Data	Canister Diameter (inches)			
		6	12	18	24
0.25	Maximum Temp. - Canister Wall, °F	151	294	341	408
	- Waste $\bar{C}$, °F	218	516	941	1,474
	Fins Required, No. (1)	0	0	0	0
	Storage Unit Air Flow, CFH (2)	13,900	27,500	42,400	58,500
0.50	Maximum Temp. Canister Wall, °F	213	317	514	613
	- Waste $\bar{C}$, °F	346	910	1,714	2,747
	Fins Required, No. (1)	0	0	2	11
	Storage Unit Air Flow, CFH (2)	17,900	35,400	54,500	75,400
1.0	Maximum Temp. - Canister Wall °F	321	568	753	889
	- Waste $\bar{C}$, °F	588	1,635	3,153	5,157
	Fins Required, No. (1)	0	2	15	~45
	Storage Unit Air Flow, CFH (2)	23,000	45,400	70,300	97,900
2.0	Maximum Temp. - Canister Wall, °F	490	822	1,069	
	- Waste $\bar{C}$, °F	1,023	2,956	5,870	
	Fins Required, No. (1)	0	14	~50	
	Storage Unit Air Flow, CFH (2)	29,600	58,700	91,700	
5.0	Maximum Temp. - Canister Wall, °F	813			
	- Waste $\bar{C}$, °F	2,147			
	Fins Required, No. (1)	6			
	Storage Unit Air Flow, CFH (2)	41,400			

(1) To reduce $\bar{C}$ temperature to 1500 °F

(2) At average annulus temperature

TABLE B-3

CALCINE WASTE CANISTER THERMAL DATA AND
STORAGE UNIT AIR FLOW RATES
CANISTER LENGTH - 15 ft

Waste Heat Generation Rate (kw/ft ³)	Storage Unit Data	Canister Diameter (inches)			
		6	12	18	24
0.25	Maximum Temp.-Canister Wall, °F	161	261	356	427
	- Waste $\bar{C}$, °F	228	528	956	1,493
	Fins Required, No. (1)	0	0	0	0
	Storage Unit Air Flow, CFH (2)	21,000	36,000	55,000	76,000
0.50	Maximum Temp. - Canister Wall, °F	225	393	535	639
	- Waste $\bar{C}$, °F	358	926	1,735	2,773
	Fins Required, No. (1)	0	0	2	12
	Storage Unit Air Flow, CFH (2)	25,000	46,000	70,000	98,000
1.0	Maximum Temp. - Canister Wall, °F	335	587	780	
	- Waste $\bar{C}$, °F	602	1,654	3,180	
	Fins Required, No. (1)	0	2	15	
	Storage Unit Air Flow, CFH (2)	30,000	59,000	91,000	
2.0	Maximum Temp. - Canister Wall, °F	506	848		
	- Waste $\bar{C}$, °F	1,039	2,982		
	Fins Required, No. (1)	0	14		
	Storage Unit Air Flow, CFH (2)	38,000	76,000		
5.0	Maximum Temp. - Canister Wall, °F	831			
	- Waste $\bar{C}$, °F	2,165			
	Fins Required, No. (1)	6			
	Storage Unit Air Flow, CFH (2)	53,000			

(1) To reduce $\bar{C}$ temperature to 1500 °F

(2) At average annulus temperature

TABLE B-4

GLASS WASTE CANISTER THERMAL DATA AND
STORAGE UNIT AIR FLOW RATES
CANISTER LENGTH - 10 ft

Waste Heat Generation Rate (kw/ft ³)	Storage Unit Data	Canister Diameter (inches)			
		6	12	18	24
0.25	Maximum Temp. - Canister Wall, °F	151	249	341	408
	- Waste $\bar{C}$, °F	170	325	512	713
	Fins Required, No. (1)	0	0	0	0
	Storage Unit Air Flow, CFH (2)	13,900	27,500	42,400	58,500
0.50	Maximum Temp. - Canister Wall, °F	213	377	514	613
	- Waste $\bar{C}$, °F	251	529	857	1,223
	Fins Required, No. (1)	0	0	0	0
	Storage Unit Air Flow, CFH (2)	17,900	35,400	54,500	75,400
1.0	Maximum Temp. - Canister Wall, °F	321	568	753	889
	- Waste $\bar{C}$, °F	397	872	1,439	2,108
	Fins Required, No. (1)	0	0	0	4
	Storage Unit Air Flow, CFH (2)	23,000	45,400	70,300	97,900
2.0	Maximum Temp. - Canister Wall, °F	490	822	1,069	
	- Waste $\bar{C}$, °F	642	1,431	2,441	
	Fins Required, No. (1)	0	0	7	
	Storage Unit Air Flow, CFH (2)	29,600	58,700	91,700	
5.0	Maximum Temp. - Canister Wall, °F	813			
	- Waste $\bar{C}$, °F	1,194			
	Fins Required, No. (1)	0			
	Storage Unit Air Flow, CFH (2)	41,400			

(1) To reduce $\bar{C}$ temperature to 1900 °F

(2) To average annulus temperature

TABLE B-5

GLASS WASTE CANISTER THERMAL DATA AND
STORAGE UNIT AIR FLOW RATES
CANISTER LENGTH - 15 ft

Waste Heat Generation Rate (kw/ft ³)	Storage Unit Data	Canister Diameter (inches)			
		6	12	18	24
0.25	Maximum Temp. - Canister Wall, °F	161	261	356	427
	- Waste $\bar{C}$, °F	180	337	527	732
	Fins Required, No. (1)	0	0	0	0
	Storage Unit Air Flow, CFH (2)	21,000	36,000	58,000	76,000
0.50	Maximum Temp. - Canister Wall, °F	225	393	535	639
	- Waste $\bar{C}$, °F	263	545	878	1,249
	Fins Required No. (1)	0	0	0	0
	Storage Unit Air Flow, CFH (2)	25,000	46,000	70,000	98,000
1.0	Maximum Temp. - Canister Wall, °F	335	587	780	927
	- Waste $\bar{C}$, °F	401	892	1,466	2,146
	Fins Required, No. (1)	0	0	0	4
	Storage Unit Air Flow, CFH (2)	30,000	59,000	91,000	127,000
2.0	Maximum Temp. - Canister Wall, °F	506	848	1,112	1,339
	- Waste $\bar{C}$, °F	658	1,457	2,484	3,778
	Fins Required No. (1)	0	0	7	~30
	Storage Unit Air Flow, CFH (2)	38,000	59,000	118,000	166,000
5.0	Maximum Temp. - Canister Wall, °F	831	1,337		
	- Waste $\bar{C}$, °F	1,212	2,861		
	Fins Required, No. (1)	0	12		
	Storage Unit Air Flow, CFH (2)	53,000	108,000		

(1) To reduce $\bar{C}$ temperature to 1900 °F.

(2) At average annulus temperature.

FIGURE B-1
STORAGE UNIT TEMPERATURES
SEALED STORAGE CASK CONCEPT
NORMAL OPERATION
CANISTER DIAMETER = 6 IN.

FIGURE B-2

STORAGE UNIT TEMPERATURES
SEALED STORAGE CASK CONCEPT
NORMAL OPERATION
CANISTER DIAMETER = 12 IN.

FIGURE B-3

STORAGE UNIT TEMPERATURES
SEALED STORAGE CASK CONCEPT
NORMAL OPERATION
CANISTER DIAMETER = 18 IN.

FIGURE B-4

STORAGE UNIT TEMPERATURES
SEALED STORAGE CASK CONCEPT
NORMAL OPERATION
CANISTER DIAMETER = 24 IN.

FIGURE B-5
SEALED STORAGE CASK CONCEPT
GENERIC WASTE STORAGE UNIT
AIR FLOW STOPPAGE

FIGURE B-6

STORAGE UNIT AIR FLOW STOPPAGE TEMPERATURES
SEALED STORAGE CASK CONCEPT

CANISTER DIAMETER = 6 IN
CANISTER LENGTH = 10 FT.
CANISTER VOLUME = 2.0 FT³

FIGURE B-7

STORAGE UNIT AIR FLOW STOPPAGE TEMPERATURES
SEALED STORAGE CASK CONCEPT

CANISTER DIAMETER = 12 IN.

CANISTER LENGTH = 10 FT.

CANISTER VOLUME = 7.8 FT.³

FIGURE B-8

STORAGE UNIT AIR FLOW STOPPAGE TEMPERATURES
SEALED STORAGE CASK CONCEPT

CANISTER DIAMETER = 18 IN.
CANISTER LENGTH = 10 FT
CANISTER VOLUME = 18 FT³

FIGURE B-9

STORAGE UNIT AIR FLOW STOPPAGE TEMPERATURES
 SEALED STORAGE CASK CONCEPT

CANISTER DIAMETER=24 IN.
 CANISTER LENGTH=10 FT.
 CANISTER VOLUME=31 FT.³

FIGURE B-10

STORAGE UNIT AIR FLOW STOPPAGE TEMPERATURES
SEALED STORAGE CASK CONCEPT

CANISTER DIAMETER = 6 IN.
CANISTER LENGTH = 15 FT.
CANISTER VOLUME = 3.0 FT.³

FIGURE B-II

STORAGE UNIT AIR FLOW STOPPAGE TEMPERATURES
 SEALED STORAGE CASK CONCEPT

CANISTER DIAMETER = 12 IN.
 CANISTER LENGTH = 15 FT.
 CANISTER VOLUME = 12 FT.³

FIGURE B-12

STORAGE UNIT AIR FLOW STOPPAGE TEMPERATURES
SEALED STORAGE CASK CONCEPT

CANISTER DIAMETER = 18 IN.
CANISTER LENGTH = 15 FT.
CANISTER VOLUME = 26 FT³

FIGURE B-13

STORAGE UNIT AIR FLOW STOPPAGE TEMPERATURES
SEALED STORAGE CASK CONCEPT

CANISTER DIAMETER = 24 IN.
CANISTER LENGTH = 15 FT.
CANISTER VOLUME = 47 FT³

FIGURE B-14
SEALED STORAGE CASK CONCEPT
GENERIC WASTE STORAGE UNIT
BURIAL

FIGURE B-15

STORAGE UNIT BURIAL TEMPERATURES
SEALED STORAGE CASK CONCEPT
CANISTER DIAMETER=6 IN.
CANISTER VOLUME=2.0 FT.³

FIGURE B-16

STORAGE UNIT BURIAL TEMPERATURES
 SEALED STORAGE CASK CONCEPT
 CANISTER DIAMETER = 12 IN.
 CANISTER VOLUME = 7.8 FT³

FIGURE B-17

STORAGE UNIT BURIAL TEMPERATURES
SEALED STORAGE CASK CONCEPT
CANISTER DIAMETER=18 IN.
CANISTER VOLUME=18 FT.³

FIGURE B-18

STORAGE UNIT BURIAL TEMPERATURES
SEALED STORAGE CASK CONCEPT
CANISTER DIAMETER=24 IN.
CANISTER VOLUME=31 FT³

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