COBRA-SFS Thermal Analysis of a Sealed Storage Cask for the Monitored Retrievable Storage of Spent Fuel

**D. R. Rector
C. L. Wheeler**

January 1986

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy	
Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

COBRA-SFS THERMAL ANALYSIS OF A SEALED
STORAGE CASK FOR THE MONITORED RETRIEVABLE
STORAGE OF SPENT FUEL

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Richland, Washington 99352

SUMMARY

The COBRA-SFS (Spent Fuel Storage) computer code was used to predict temperature distributions in a concrete Sealed Storage Cask (SSC). This cask was designed for the Department of Energy in the Monitored Retrievable Storage (MRS) program for storage of spent fuel from commercial power operations. Analytical results were obtained for nominal operation of the SSC with spent fuel from 36 PWR fuel assemblies consolidated in 12 cylindrical canisters. Each canister generates 1,650 W of thermal power. A parametric study was performed to assess the effects on cask thermal performance of thermal conductivity of the concrete, the fin material, and the amount of radial reinforcing steel bars (rebar). Seven different cases were modeled.

The results of the COBRA-SFS analysis of the current cask design predict that the peak fuel cladding temperature in the SSC will not exceed the 375°C design limit for the maximum spent fuel load of 19.8 kW and a maximum expected ambient temperature of 37.8°C (100°F). The results of the parametric analyses illustrate the importance of material selection and design optimization with regard to the SSC thermal performance.

ACKNOWLEDGEMENTS

The authors would like to thank the U.S. Department of Energy and the Monitored Retrievable Storage Program Office for the opportunity to perform this work. Special thanks are extended to Dr. Dennis Kreid for his support.

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COBRA-SFS THERMAL ANALYSIS OF A SEALED STORAGE CASK FOR THE MONITORED RETRIEVABLE STORAGE OF SPENT FUEL

1.0 INTRODUCTION

The Monitored Retrievable Storage (MRS) Program, which is managed for the Department of Energy (DOE) by the Pacific Northwest Laboratory, is preparing the necessary documents for support of the development of MRS facilities as a integral element of the Federal program for the management of nuclear wastes. The storage method chosen for the MRS facility is the concrete Sealed Storage Cask (SSC), designed by the Ralph M. Parsons Company, Architect/Engineer (A-E) for the MRS program. The SSC can accommodate 12 unconsolidated PWR fuel assemblies or 36 consolidated PWR fuel assemblies in 12 stainless steel canisters with total decay heat generation of up to 20 kW. A major design constraint on the cask is that the peak cladding (clad) temperature must not exceed 375°C in an inert gas atmosphere. (This is intended to ensure fuel integrity.)

This document presents the results of thermal analysis performed on the SSC with the COBRA-SFS (Spent Fuel Storage) subchannel thermal-hydraulic analysis code and includes a limited parameterization of important thermal and design parameters. The analysis was performed to provide an independent evaluation of the predicted SSC performance to support the analyses provided by the AE. Independent verification of the COBRA-SFS code for application to this and other spent fuel storage applications is proceeding through separate "benchmarking" activities under way in the MRS and Commercial Spent Fuel Management (CSFM) Programs.

2.0 CONCLUSIONS AND RECOMMENDATIONS

In this section, conclusions from the COBRA-SFS thermal analysis of the SSC monitored retrievable storage cask are presented. Recommendations are provided to improve the modeling accuracy and to improve the cask efficiency in maintaining the fuel rods at acceptable temperature levels. The conclusions and recommendations presented here are based on the results presented in Section 5.0.

2.1 CONCLUSIONS

1. The results of the COBRA-SFS analysis of the current SSC design predict that the peak fuel cladding temperature will be 380°C for the specified maximum spent fuel load (19.8 w) and a maximum ambient temperature of 51.7°C (125°F as specified in the pre-1985 version of 10CFR71 and used as a reference ambient conduction in this study). This exceeds the 375°C limit specified in the MRS Functional Design Criteria (Jackson 1985) by 5°C. However, when corrected to an ambient of 37.8°C (100°F as specified in the recently revised 10CFR71 and as was also used by the AE (Ralph M. Parsons Company 1985) as an expected maximum ambient temperature, the peak fuel cladding temperature predicted by COBRA-SFS is about 366°C, which is well within the 375°C limit.
2. The peak clad temperature can be effectively controlled within limits by modifying important cask thermal design parameters, such as the amount of radial rebar, the thermal conductivity of concrete, and the cavity fin design.
3. Cask thermal performance is also significantly dependent on thermal properties of the concrete. Changes to thermal and structural properties of concrete, due to exposure to high temperatures over extended periods of time, are therefore of potential concern.

2.2 RECOMMENDATIONS

1. If further optimization of the SSC design is pursued, the result of these analyses demonstrate that a number of design variables offer potential for performance enhancement and deserve further consideration. These are:
 - optimization of the amount of radial rebar in the cask wall
 - enhancement of the emissivity of the canisters, fins, and cavity liner
 - optimization of internal and external fin design to aid in heat removal
 - specification of a high-conductivity concrete to reduce wall thermal resistance
 - specification of a concrete with high shielding efficiency, thus reducing both the needed wall thickness and the resistance to heat transfer
 - provision of additional flow paths through the canister support plates to promote internal convection.
2. To reduce uncertainties in the COBRA-SFS predictions, the following thermal parameters must be characterized with greater precision:
 - component emissivities
 - concrete thermal conductivity
 - contact resistances fuel rod-to-rod, fuel rod-to-canister wall (fin-to-liner, liner-to-rebar, rebar-to-rebar)
 - the thermal boundary condition at the cask bottom.
3. To evaluate the accuracy of these COBRA-SFS predictions, experimental data in consolidated spent fuel rods should be obtained and COBRA-SFS predictions compared to the data.

3.0 CASK DESCRIPTION

The Sealed Storage Cask (SSC) described in this section is based primarily on design drawings provided by the Ralph M. Parsons Company, (cf. drawings H-3-54986, 54994, and 54999, Ralph M. Parsons Co., 1985). A preliminary design, based on a smaller content of radial reinforcing steel bars (rebar), was also analyzed in the study. Other than the rebar content and the internal fin attachment, the preliminary design was essentially the same as the current SSC design.

A simplified cut-away view of the SSC is presented in Figure 1. The cask is a cylindrical, reinforced concrete structure with a carbon-steel-lined cavity for storing spent fuel canisters. A steel-encased, cylindrical concrete shield plug fits into the open top of the cavity, and a steel cover plate is seal-welded to the liner flange to close the cask. The cask is 22 ft high and 12 ft in diameter. The upper 36 in. of the cask exterior is stepped to 152 in. in diameter to provide a circumferential lifting in surface for handling the cask.

A horizontal cross section of the cask is shown in Figure 2. The cavity liner is carbon steel with an outside diameter of 72 in. and a 2-in.-thick wall. The cavity is divided into quadrants by aluminum fins that are 2 in. thick and 31 in. long. Each quadrant contains three stainless steel spent fuel canisters for a total of 12 canisters per cask. Each quadrant also contains a smaller aluminum fin 11 in. in length to aid in removing heat from the cavity. The fins are bolted to the inside of the liner.

The concrete portion of the cask contains an embedded structural rebar cage, which is used for structural support and to aid heat transfer through the cask walls. The vertical and circumferential rebar is attached to the cavity liner fins, which extend 3.5 in. outward from the cavity liner. The outer rebar hoops are located in 3 in. in from the outside surface of the cask. The circumferential and radial rebar is located axially on 6-in. centers from cask top to bottom. The vertical and radial rebar is located on 8° and

FIGURE 1. Cut-Away View of the Sealed Storage Cask

FIGURE 2. Sealed Storage Cask Horizontal Cross Section

5° segments, respectively, in the circumferential direction around the cask. Rebar extends to the center of the bottom of the cask to support the concrete below the liner. The radial rebar, extending from the linear fins to 3 in. from the cask surface, is a major contributor in removing heat from the cask cavity. In the current design, the radial rebar makes 4 percent of the total radial cross sectional area at the end of the external liner fins. The preliminary design, which was analyzed first, had just under 1 percent rebar as a fraction of area at the end of the external liner fins.

The spent fuel is encapsulated for storage in sealed stainless steel canisters, which are illustrated in Figure 3. The canisters are designed to contain either unconsolidated spent fuel assemblies or compacted, consolidated

spent fuel rods. In this analysis, each canister was assumed to contain consolidated fuel rods from three 15x15 pressurized water reactor (PWR) assemblies. Only the PWR case was analyzed because of its higher heat load per canister. The spent fuel canister considered has no internal partitions, and the rods are in a loose bundle arranged on a triangular pitch. The canisters are filled with a gas mixture of 90% argon and 10% helium. The atmosphere in the cask cavity is air.

All calculations for this reference cased assumed the fuel had been discharged from the reactor with 33,000 MWD/MTU burnup, and that it cooled 10 years before being placed in dry storage. The heat generation rate corresponding to these conditions is 1,650 watts per canister (Jackson 1985). The axial power profile assumed in this analysis is shown in Figure 4.

FIGURE 3. Cross Sectional View of Spent Fuel Canister

FIGURE 4. Axial Power Profile of the Prototypic PWR Spent Fuel Assembly

FIGURE 1. Axial power profile of the prototypic fuel assembly

4.0 ANALYSIS METHOD

In this section, a description of the COBRA-SFS code is provided along with a description of the modeling assumptions used in the SSC thermal cask simulation.

4.1 COBRA-SFS CODE

COBRA-SFS is a combination of codes from the COBRA family [COBRA-IIIC (Rowe 1973), COBRA-VI-I (Wheeler et al. 1973) and COBRA-WC (George et al. 1985)], which have been extensively evaluated using both out-of-pile and in-pile thermal-hydraulic data under a wide range of flow and power conditions (Khan et al. 1981). COBRA-SFS is a finite-difference subchannel analysis code that predicts flow and temperature distributions in spent fuel storage systems and individual fuel assemblies. It was chosen because of the need to address natural convection heat transfer as well as radiation and conduction. COBRA-SFS retains all the important features of the parent COBRA codes and extends the range of application to include analysis of problems with three-dimensional conduction and two-dimensional radiation heat transfer.

The COBRA-SFS code solves equations for the conservation of mass, momentum, and energy in storage systems containing spent fuel assemblies. The equations have been derived by performing suitable mass and momentum balances on finite-control volumes, defined as subchannels, and energy balances on the subchannels, the adjacent fuel rods, and assembly walls. The equations for mass, axial momentum, and transverse momentum are solved using an implicit method that allows recirculating flows to be calculated. Boundary conditions used to define the field may be either specified flow rate or total pressure drop. An additional option adjusts the total pressure drop until the two following conditions are met simultaneously: 1) the pressure drop is equal across all subchannels, and 2) the total net flow rate for the problem is zero.

The energy equations for fuel, clad, fluid, and structure members are solved simultaneously at each axial level. The fuel rod model used in COBRA-SFS

can be either one- or two-dimensional (radial and circumferential). In addition, two-dimensional radiation heat transfer in the assembly and between walls is modeled. Axial conduction heat transfer is also included in the wall model.

The radiation heat transfer model employed in COBRA-SFS is implicitly coupled to the rod and wall energy equations. Rod-to-rod, rod-to-wall, and wall-to-wall radiative exchange in a plane is described using graybody exchange factors, which include the effect of multiple reflections (Cox 1977). Exchange factors are either computed internally (based on blackbody view factors and surface emissivities input to the code) or are specified by input.

4.2 COMPUTATIONAL MODEL

A three-dimensional, one-eighth sector model of the SSC was used for the COBRA-SFS analysis. A radial cross section of the computational cell arrangement is presented in Figure 5. The fluid flow region is divided into three zones, one zone for each of the spent fuel canisters and one which represents the region between the canisters and the cavity liner. The solid regions are represented by 25 radial wall nodes, including the zero-thickness nodes which represent the temperatures on the outside surface of the cask. The large aluminum fin is modeled by three wall nodes and the small fin by one node.

Each canister contains fuel rods from three 15x15 PWR assemblies. A detailed subchannel nodalization of each canister would require 624 rods and 1164 subchannels. A detailed one-eighth sector model of the SSC cask would consist of 1261 rods and 2333 subchannel nodes at each axial level. To reduce the model to a manageable size, several rods and subchannels are combined into groups which are linked by composite conduction and radiation connections. The interior of a single canister is modeled using 86 subchannel groups and 81 rod groups. A cross section of a one-sixth sector of a spent fuel canister indicating rod and subchannel groups is presented in Figure 6. The outside surface of the canister is divided into six equal wall segments.

FIGURE 5. One-Eighth Section, COBRA-SFS Nodal Representation of the Sealed Storage Cask

FIGURE 6. Cross Section of Canister One-Sixth Sector Indicating Rod and Subchannel Groups

Plenum models were used to describe the heat transfer through the top and bottom of the cask. Eighteen uniform axial nodes were used to model the cavity region of the cask. A description of how radiation, conduction, and convection are modeled within the cask follows.

4.2.1 Radiation Heat Transfer Model

Rod-to-rod, rod-to-wall, and wall-to-wall radiation heat transfer within each enclosure is prescribed using graybody exchange factors. The exchange factors within each spent fuel canister are based on one-sixth pin surface segments, a more exact approach to the assumption of uniform radiosity over a surface. Proper subdivision of the fuel rod surface when determining view factors has been previously shown to be significant in determining the proper radiative heat transfer from a radiation enclosure (Cox 1977). The individual graybody exchange factors are then combined to form composite rod exchange factors.

In the region between the canisters and the cavity surface, graybody exchange factors describe the radiation heat transfer between each wall node and every other wall node in the enclosure. The surface emissivities were specified as a function of material. The surface emissivities used for both rods and walls are listed in Table 1 and were obtained primarily from Touloukian and Ho (1970).

4.2.2 Conduction Heat Transfer Model

Wall conduction heat transfer in the radial, circumferential, and axial directions is modeled by specifying the appropriate thermal resistance terms between nodes in the COBRA-SFS model. The input value of resistance may reflect a composite of materials and parallel and/or series heat transfer paths. For example, concrete and radial rebar act as parallel heat transfer paths in the radial direction.

The fluid thermal properties were defined as a function of temperature; properties for all materials except concrete were obtained from Touloukian and Ho (1970). The thermal properties of concrete vary as a function of several

characteristics, including aggregate composition and water content. The thermal conductivities of concrete were chosen to be 1.05 Btu/hr-ft-°F and 0.75 Btu/hr-ft-°F for the best-estimate and worst-case values, respectively (Allen 1984). The solid material thermal conductivities are listed in Table 1.

TABLE 1. Thermal Properties

	<u>Best Estimate</u>	<u>Worst Case</u>
<u>Thermal Conductivity</u>		
k (aluminum)	133 Btu/hr-ft-°F	same
k (stainless)	10.9	same
k (steel)	25	same
k (concrete)	1.05	0.75
<u>Surface Emissivity</u>		
ε (rods)	0.8	same
ε (aluminum)	0.2	same
ε (stainless)	0.2	same
ε (steel)	0.6	same
ε (concrete)	0.9	same
<u>Contact Conductance</u>		
h (fin-liner)	500 Btu/hr-ft ² -°F	100 Btu/hr-ft ² -°F
h (liner-rebar)	∞	∞

Additional thermal resistances occur in regions where different solid materials are not in perfect thermal contact. For example, the fins in the cask interior are mechanically attached to the cavity liner. The contact conductances associated with this connection were chosen to be 500 Btu/hr-ft²-°F and 100 Btu/hr-ft²-°F for the best-estimate and worst-case values, respectively. Perfect thermal contact was assumed for the liner-rebar and rebar-rebar connections.

The COBRA-SFS code is capable of modeling rod-to-rod and rod-to-wall thermal contact conduction. However, it was conservatively assumed that the

rods were infinitesimally close to each other but not in thermal contact. It was also assumed that the canisters were filled with argon instead of argon-helium mixture. Conduction through the gas between adjacent fluid subchannels was included.

4.2.3 Convection Heat Transfer Model

The fluid in the one-eighth section model is divided into three independent flow regions. Both spent fuel canisters (zones 1 and 2) are sealed, and so the fluid in them is isolated from the rest of the cavity (zone 3) in terms of flow paths. The COBRA-SFS code is currently capable of modeling only flow region at a time. However, previous analysis of consolidated fuel bundles has shown that flow rates in the bundle region (e.g., inside the canisters) for typical storage conditions are negligible (Cuta, Rector and Creer 1984). Therefore, the friction parameters in the canister assemblies were increased so that the flows were conservatively reduced to very low values. The flow distribution in the cask cavity was determined using the normal COBRA solution procedure.

The overall contribution of convective heat transfer is dependent on the flow field established. For these simulations the flow field outside the canisters is obtained by adjusting the total pressure drop until: 1) the pressure drop across all channels is equal, and 2) the total net flow rate is zero. Thus, the flow resistance in the cavity between the canister and the cask becomes an important convection component parameter.

The overall flow resistance is assumed to be a combination of:

- canister, fin, and liner wall drag in the cavity region
- orifice losses through the top and bottom canister spacer plates.

The wall friction in the cavity region was modeled using the standard friction factor expression for fully developed laminar pipe flow; $f = 64/Re$ (Kays and Crawford, 1980). The top and bottom canister spacer plates have 33.3-cm (13.12-in.)-diameter holes through which the spent fuel canisters are positioned. The loss coefficient for the annular gap between the hole and

the canister was determined to be $K = 798.8$ from an expression for square-edged orifices taken from the Crane Technical Paper No. 410 (1979).

Heat transfer from the rods and walls to the coolant was prescribed through the use of a film coefficient of the form $Nu = 4.364$ (Kays and Crawford 1980). This formulation is an exact solution of the energy equation for a constant heat rate and fully developed velocity and temperature profiles in a circular tube. The film coefficient was evaluated as a function of temperature at each location.

4.2.4 Boundary Specifications

The computational model described earlier extends radially outward to the cask surface. Within this region, the wall and fluid energy equations are solved simultaneously; heat transfer coefficients are specified to describe the heat transport from the cask surface to the ambient air. The two coefficients of interest are: 1) heat transfer from the cask radial boundary to the ambient air and 2) heat transfer from the cask lid to the ambient air (the cask bottom was initially assumed adiabatic). The axial and radial heat transfer correlations are summarized in Table 2. They were obtained for vertical cylinders and horizontal plates in air at 1 atm (Lindeburge 1981).

The radiation component indicated in Table 2 is based on radiative heat exchange between the graybodies and is determined as a function of heat transfer and cask emissivity. For all cases the ambient air was assumed to be a blackbody ($\epsilon = 1.0$), at the temperature limit of 51.7°C specified by pre-1985 version of 10CFR71.

TABLE 2. Boundary Heat Transfer Correlations

<u>Type</u>	<u>Region</u>	<u>Natural Convective Component</u>	<u>Radiation Component</u>
Radial	Air	$Nu = 0.13 (Gr Pr)^{0.33}$	Yes
Axial	Air	$Nu = 0.14 (Gr Pr)^{0.33}$	Yes

5.0 RESULTS AND DISCUSSIONS

A thermal analysis of the SSC was performed using COBRA-SFS and the three-dimensional model presented in Section 4.0. A description of seven simulations and their results are presented in this section along with an evaluation of the modeling assumptions used.

5.1 CASE DESCRIPTIONS

The analysis of the SSC was based on drawings supplied by the Ralph M. Parsons Company and on prototypic spent fuel heat generation rates and power profiles. In developing the model, significant uncertainties were identified in several important heat transfer parameters, including the following:

- concrete thermal conductivity
- internal fin-to-liner contact thermal resistance
- fin material (e.g., thermal conductivity)
- cask bottom thermal boundary condition.

It was subsequently decided to bound the above parameters to provide estimates of the thermal performance of the as-built cask. The best-estimate and worst-case values of the primary thermal properties are shown in Table 1.

As stated earlier, in the preliminary design the radial rebar made up less than 1 percent of the total radial cross sectional area at the end of the liner fins. Subsequent simulations were performed assuming an increase in the radial rebar to 4 percent of the cross-sectional area (the current design) to illustrate the effect of radial rebar on the temperature profile. Both the preliminary and current designs also specified the internal fins to be aluminum. However, one simulation was performed with carbon steel fins to determine the importance of the fin material.

A summary of the parameters used in the five SSC parametric cases is presented in Table 3. The first three cases are based on the preliminary cask design, but the thermal properties and cask bottom boundary condition

TABLE 3. Parametric Case Definition

<u>Case No.</u>	<u>Thermal Properties</u>	<u>Cask Bottom Boundary</u>	<u>% Rebar^(a)</u>	<u>Fin Material</u>	<u>Design Parameters Fin-Liner Conductance (Btu/ft²-hr-°F)</u>
1	Best Estimate	Adiabatic	1%	Aluminum	500
2	Worst Case	Adiabatic	1%	Aluminum	100
3	Best Estimate	Ambient	1%	Aluminum	500
4	Best Estimate (current design)	Adiabatic	4%	Aluminum	500
5	Best Estimate	Adiabatic	4%	Steel	500
6	Best Estimate	Adiabatic	4%	Aluminum	100
7	Best Estimate	Adiabatic	4%	Aluminum	25

(a) % of cross-sectional area

are allowed to vary. In the next two cases (Case 4 and 5), the thermal property parameters are held fixed and only the cross-sectional rebar area and fin material are varied. Case 4 is the best-estimate analysis of the performance of the current SSC design with 4% rebar and aluminum internal fins. The final two cases (Cases 6 and 7), are identical to the current design case (Case 4) except that the fin-to-liner contact conductance is reduced from a nominal 500 Btu/hr-ft²-°F to values of 100 and 25 Btu/hr-ft²-°F, respectively.

5.2 RESULTS

The peak clad temperatures calculated for the seven simulations are summarized in Table 4. The radial location of the maximum clad temperature for all cases occur in the center rod of the canister identified as Zone 1. Peak clad temperatures for all cases are located at an elevation of 2.0 m from the bottom of the cask, which is 1 m from the bottom of the canisters.

TABLE 4. Predicted Peak Cladding Temperatures

<u>Case</u>	Temperature (°C)	
	<u>As-calculated</u>	<u>Adjusted</u> ^(a)
1 Best Estimate, Preliminary Design	408	394
2 Worst Case, Preliminary Design	442	428
3 Best Estimate, Ambient Temperature Bottom	381	367
4 Best Estimate, 4% Rebar, Current Design	380	366
5 Best Estimate, 4% Rebar, Carbon Steel Fins	402	388
6 Best Estimate, 4% Rebar, Reduced Fin-Liner Conductance	386	372
7 Best Estimate, 4% Rebar, Reduced Fin-Liner Conductance	395	381

(a) Adjusted for an ambient air temperature of 37.8°C (100°F)

5.2.1 Comparison of Best-Estimate and Worst-Case Temperatures Predicted for the Preliminary SSC Design

The axial temperature profiles at different locations within the cask for the preliminary design are shown in Figure 7 for Case 1 (best-estimate) and in Figure 8 for Case 2 (worst-case). The primary differences in the two cases are the concrete conductivity and the fin-to-liner contact coefficient. The locations Rod 1-1 and 2-1 indicate the center rod in the canisters designated Zone 1 and 2, respectively. The difference in thermal parameter for the two cases results in a change of peak clad temperature from 408°C to 442°C, an increase of 34°C.

The radial temperature profiles along the diagonal at the peak axial level are shown in Figure 9 for these two cases. From the liner to the center of the cask, the profiles are approximately parallel. The primary difference between the best estimate and worst case appears in the concrete portion of

FIGURE 7. Axial Temperature Profiles for the Best-Estimated Case, Preliminary Design (Case 1)

FIGURE 8. Axial Temperature Profiles for the Worst Case, Preliminary Design (Case 2)

FIGURE 9. Radial Temperature Profiles for the Best Estimate (Case 1), and Worst Case (Case 2), Preliminary Design

the cask. For the best-estimate case, the temperature difference between the liner and cask surface is 181°C (51% of the difference between the peak cladding and ambient temperatures), and it is 231°C (59% of the total temperature difference) for the worst case. Since over 50% of the peak temperature rise occurs across the concrete portion of the cask, it is imperative that the concrete properties used in the final analysis be representative of those occurring in the cask over its lifetime. Transverse temperature profiles along a line drawn through two adjacent canisters are shown in Figure 10. The peak clad temperatures in both canisters are nearly identical, because the aluminum fins are very efficient in removing heat from the innermost canister.

Both the best-estimate (Case 1) and worst-case (Case 2) calculations for the preliminary design were made using an adiabatic boundary at the bottom of the cask. In reality, some heat will be lost through the bottom. The amount of heat transferred depends on the surface material supporting the cask and the thermal contact between cask and surface. An additional calculation using best-estimate thermal parameters (Case 3) was performed with the bounding assumption that the bottom is perfectly connected to air at the ambient temperature. The axial temperature profiles for this case are given in Figure 11. The predicted clad temperature for the case is about 28°C cooler than the adiabatic bottom case reflecting a relatively large heat loss out the bottom. The actual peak clad temperature profiles will fall between the adiabatic boundary case (Case 1) and the ambient temperature boundary case (Case 3), with the adiabatic case being the more representative of the two for equilibrium conditions.

5.2.2 Best-Estimate Temperatures Predicted for the Current SSC Design

The first three simulations were performed assuming the preliminary cask design. In the preliminary design, the radial rebar makes up just less than 1 percent of the total radial cross sectional area at the end of the liner fins. A subsequent case (Case 4) was run using best-estimate thermal properties for the current design where the radial rebar was increased to 4 percent of

FIGURE 10. Transverse Temperature Profiles for the Best Estimate (Case 1), and Worst Case (Case 2), Preliminary Design

FIGURE 11. Axial Temperature Profiles for the Best-Estimate Case with Ambient Bottom (Case 3)

the cross-sectional area at the end of the exterior liner fins. The predicted axial temperature profiles for this case are shown in Figure 12. The peak clad temperature is 380°C , a reduction of 28°C from the preliminary design with 1% rebar. The radial temperature profile along the diagonal for this case is compared with that for the preliminary design in Figure 13. As in the concrete conductivity comparison, the primary change occurs in the concrete portion of the cask wall.

The results of the simulation for Case 4 are very similar to that performed by AE for the cask. Figure 14 shows selected temperature comparisons between the AE thermal analysis and the COBRA-SFS simulation. The principal difference between the two analyses is that the AE analysis used an ambient temperature of 37.8°C (100°F), whereas the COBRA-SFS analyses were done using an ambient temperature of 51.7°C (125°F), a difference of 13.9°C . To compensate for this difference and facilitate comparison of the results of the two analyses, a constant convection of 13.9°C was subtracted from the COBRA-SFS predicted temperatures to obtain the values shown in Figure 15. Although this procedure is not exact, it can be demonstrated that the magnitude of any uncertainty this introduced is a small fraction of the convection factor and thus well within the bounds of other uncertainties in these results. The value of this peak fuel temperature predicted by COBRA-SFS, similarly adjusted, is 366°C (not shown in Figure 14), which is well within the 375°C design limit. Another difference in the two analyses is that the AE analysis assumed the bottom of the cask to be connected to a finite soil base with an adiabatic boundary. This difference should not have effected the peak clad temperature by more than a few degrees, as indicated in a preceding discussion.

In the cavity, the AE analysis used an effective conductivity to model the conduction, convection, and radiation in air. In comparing the plenum and axial temperature profiles, it appears that natural convection, which tends to heat the upper portion of the cavity and cool the lower portion, is important and should not be neglected.

FIGURE 12. Axial Temperature Profiles for the Best-Estimate Case, Current Design (Case 4)

FIGURE 13. Radial Temperature Profiles for the Best Estimate, Preliminary Design (Case 1), and Current Design (Case 4)

FIGURE 14. Comparison of AE Thermal Analysis Results with Current Design, COBRA-SFS Results (Case 4)

FIGURE 15. Axial Temperature Profiles for the Current Design with Carbon Steel Cavity Fins (Case 5)

5.2.3 Predicted Effects of Varying the Fin Material and the Fin-Liner Contact Conductance

Both the preliminary design and the current design utilize aluminum cavity fins. A simulation was also made with carbon steel fins (Case 5) to determine the importance of the fin material. For this case, the amount of radial rebar was assumed to be 4 percent as in the current SSC design. The resulting axial temperature profiles are shown in Figure 15. The calculated peak clad temperature is 402°C, an increase of 22°C from the equivalent aluminum fin case (Case 4). This indicates that the fin material has a significant impact on the peak clad temperature.

Although thermal parameter studies were conducted in this analysis, the effect on the cask temperature distribution of changing the contact conductance between the aluminum fins and cavity liner wall was not studied independent of other parameters. Therefore, two additional simulations were performed, specifying the fin-liner contact conductance from a nominal 500 Btu/hr-ft²-°F to values of 100 Btu/hr-ft²-°F (Case 6) and 25 Btu/hr-ft²-°F (Case 7), respectively. The peak clad temperature results are listed in Table 4. Note that the peak temperatures range from 380°C (Case 4) to 396°C (Case 7), a difference of 16°C. Therefore, the reduction in contact conductance results in a moderate increase in peak temperature.

In the comparison of the preliminary best-estimate and worst-case simulations, it was demonstrated that the majority of the total temperature drop is across the cask wall. The concrete thermal conductivity is thus extremely important in determining the peak clad temperature, and selection of a high-conductivity concrete is thus highly advantageous. When concrete is exposed to high temperatures over an extended period of time, both the thermal and structural properties may degrade. Therefore, concrete temperature should be kept to a minimum. The peak concrete temperature was 262°C for the preliminary best estimate (Case 1) and 308°C for the worst case (Case 2).

The current design case (Case 4) reduces the peak concrete temperature to 222°C, which is a substantial improvement. Additional gain might be possible by optimization of the concrete for shielding and heat transfer effectiveness.

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