COBRA-SFS Thermal-Hydraulic Analyses of the CASTOR-1C and REA 2023 BWR Storage Casks Containing Consolidated Spent Fuel

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COBRA-SFS THERMAL-HYDRAULIC ANALYSES OF THE
CASTOR-1C AND REA 2023 BWR STORAGE CASKS
CONTAINING CONSOLIDATED SPENT FUEL

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EXECUTIVE SUMMARY

Consolidation of spent nuclear fuel rods is being considered as one option for more efficient and compact storage of reactor spent fuel assemblies. In this concept, rods from two disassembled spent fuel assemblies will be consolidated in a space originally intended to store a single unconsolidated assembly. The thermal performance of consolidated fuel rods in dry storage, especially in multiassembly storage systems, is one of the major issues that must be addressed prior to implementation. In this study, Pacific Northwest Laboratory researchers performed thermal-hydraulic analyses for both the REA 2023 cask and the CASTOR-1C cask containing either unconsolidated or consolidated BWR spent fuel assemblies. The objective was to determine the effect of consolidating spent fuel assemblies on the temperature distributions within both types of casks.

The COBRA-SFS (Spent Fuel Storage) computer code, used to perform the cask thermal-hydraulic analyses, predicts steady-state three-dimensional velocity, pressure, and temperature distributions within spent fuel storage systems. COBRA-SFS uses an iterative procedure to solve finite-difference equations for mass, momentum, and energy conservation for an interconnected array of channels and structural members. It uses subchannel representations with arbitrary flow and thermal connections; therefore, the user has a great deal of flexibility in modeling complex geometries. Although COBRA-SFS assumes that the backfill medium is incompressible, it uses a thermally expandable model to produce buoyancy-driven circulating flows within a system. Heat is transported throughout the system by conduction (fluid-to-fluid and solid-to-solid), natural convection, and planar radiation (rod-to-rod, rod-to-surface, and surface-to-surface).

Due to the size of the subchannel models required for multiassembly analyses, the development of simpler models, which accurately represent unconsolidated and consolidated spent fuel assemblies, was investigated. To evaluate unconsolidated assembly models, calculations were first made for detailed rod-and-subchannel models of a single assembly containing a typical

8x8 BWR fuel assembly. Several models with varying degrees of detail were investigated. The results from these models are compared to the detailed model results in Figures S.1 and S.2.

In Figure S.1, the peak cladding temperature in air is compared for the various assembly models. The results for only one model, consisting of one rod and one subchannel, disagreed significantly from the detailed calculation (64 rods, 77 subchannels). The results from all the other models agreed to within 3°C of that for the detailed model.

The radial temperature profiles across the unconsolidated assembly in air resulting from the various assembly models are compared in Figure S.2. These results indicate that significant radial temperature gradients exist, and that the most important gradient is that between the outer row of rods and the wall. If the gradients are preserved, the interior of the array can be modeled with a single rod and only one or two subchannels, and still yield a peak cladding temperature in reasonable agreement with the detailed 64-rod/77-subchannel case.

Based on the results obtained in the single-assembly calculations, the modeling study was continued in a multiassembly storage system--the REA 2023 cask. The REA 2023 spent fuel storage cask consists of a double containment design with silicone rubber O-rings for sealing the primary lid of the inner cavity and a welded final closure on the secondary cover. The cask has a smooth, painted, stainless steel outer skin; a lead/stainless steel gamma shield; and an ethylene glycol/water neutron shield. The fuel basket is constructed of stainless steel clad Boral for criticality control, copper plates for heat conduction to the cask wall, and stainless steel for structural strength. The loaded cask is approximately 5 m (16 ft) long and 2.25 m (8 ft) in diameter, and weighs approximately 100 tons when loaded with 52 unconsolidated BWR spent fuel assemblies. The REA 2023 BWR spent fuel storage cask design and manufacturing rights have been acquired by Mitsubishi Heavy Industries of Japan, and the cask model designation has been changed to MSF IV.

FIGURE S.1. Predicted Peak Cladding Temperatures in Air for Various Geometry Models

FIGURE S.2. Comparisons of Radial Temperature Profiles Across An Unconsolidated Fuel Assembly in Air Calculated with Various Geometry Models

A reference calculation was made using a detailed 64-rod/77-subchannel model (SC1) for a nominal REA case. Subsequent calculations investigated the effects of various less-detailed assembly geometry models for unconsolidated 8x8 rod fuel assemblies. The resulting peak cladding temperatures are compared in Table S.1. Geometry model LC1 requires 22 rods and 15 subchannels per assembly. Geometry model LC2 requires 11 rods and 11 subchannels per assembly. The geometry model SLC1 is the same as the LC1 model except that a detailed rod-and-subchannel model is used for the hot assembly only.

The calculation with the coarser lumping model LC2 yielded predicted peak cladding temperatures that were 6°C to 8°C lower than the temperatures calculated with the detailed model, indicating that the model is a bit too coarse to satisfactorily resolve the flow and heat transfer gradients encountered. The calculation with the detailed subchannel model of the hot assembly (with all other assemblies modeled using 15 channels and 22 rods per assembly) is in very good agreement with the results for the detailed subchannel model in all assemblies. However, these results are not significantly better than those obtained with LC1 (22 rods/15 subchannels), so there is no particular virtue in using the more complicated model. A lumped model in all assemblies is good enough, so long as it is of sufficient detail to resolve the significant temperature gradients.

A similar modeling study was performed for consolidated fuel assemblies in the REA cask. A consolidated assembly is assumed to consist of a 14-cm-square (5.5-in.) canister filled with 126 BWR fuel rods on a triangular pitch. Calculations were first made using detailed rod-and-subchannel models of a single consolidated fuel canister. Models with varying degrees of detail were investigated.

Comparisons of detailed and coarse model radial temperature profiles with both nitrogen and helium backfill gases are shown in Figure S.3. The coarse assembly model used in the comparison required 9 rods and 10 subchannels. The maximum temperature difference between profiles is less than 5°C for both

TABLE S.1. Predicted Peak Cladding Temperatures in REA Cask With Unconsolidated Fuel in Nitrogen, °C

Assembly	Geometry Model			
	SC1	LC1	LC2	SLC1
1	226.4	225.1	217.8	224.8
2	225.6	224.2	218.4	223.4
3	228.7	229.9	222.4	228.6
4	221.7	219.6	214.1	218.8
5	230.8	230.1	221.5	232.1
6	228.4	230.8	221.5	229.3
7	214.0	216.7	210.6	215.6

FIGURE S.3. Comparisons of Detailed and Coarse Model Predicted Radial Temperature Profiles with Nitrogen and Helium Backfill Gases

media. The excellent agreement between profiles indicates that the coarse models accurately represent consolidated spent fuel assemblies.

Based on the results obtained in the single-assembly and the REA cask modeling studies, a series of REA 2023 and CASTOR-1C cask simulations was performed using the COBRA-SFS code for both unconsolidated and consolidated BWR fuel assemblies stored in nitrogen or helium. The analyses were performed in two parts. In the first part, the decay heat generation rate was assumed to be 0.8 kW per assembly or canister, and the predicted peak cladding temperature profiles were calculated for each case. In the second part, a set of operating temperature limits was identified for the cask, and the assembly or canister decay heat was adjusted to predict the maximum heat rate that satisfied the cask temperature constraints.

Peak cladding temperature profiles are presented in Figure S.4 for four different cases. Two of the simulations were performed with the cask containing unconsolidated fuel in nitrogen and helium. The peak cladding temperatures for these two cases were predicted to be 384°C for the nitrogen case and 304°C for the helium case. The temperature profile for the nitrogen case is skewed upward because of a significant amount of natural circulation occurring within the cask.

When consolidated fuel is used, the predicted peak cladding temperature for the nitrogen case is 484°C, an increase of 100°C over the case with unconsolidated fuel assemblies. The axial profile for the consolidated assemblies is less skewed, indicating that consolidating the fuel severely reduced the amount of predicted natural circulation within the cask. In addition, radiation heat transfer is reduced because of increased pin shadowing and the addition of a low-surface-emissivity canister.

The peak cladding temperature for consolidated fuel assemblies in helium is 324°C, an increase of only 20°C over the case with unconsolidated assemblies. Although convection and radiation heat transfer are reduced, conduction, which is important in the helium case, is enhanced because of having high-conductivity

FIGURE S.4. REA 2023 Cask Axial Temperature Profile Predictions

fuel rods replace relatively low-conductivity gas. However, comparisons of nitrogen and helium predictions indicate that the effect of consolidation on peak temperatures strongly depends on the storage medium used.

The assembly decay heat rates were adjusted to predict the maximum allowable cask heat dissipation rates for all four cases. The predicted maximum heat rate was subject to three temperature constraints:

- 400°C allowable peak cladding temperature
- 327°C lead melting point
- 148°C (50 psia) saturation temperature of the ethylene glycol/water in the neutron shield.

After a few iterations, a maximum allowable heat dissipation rate was identified along with the limiting constraint for each case. The results are presented in Table S.2. For the two nitrogen cases, the limiting temperature constraint was a peak cladding temperature of 400°C. For the two helium cases, however, the limiting constraint was a peak neutron shield temperature of 148°C.

TABLE S.2. REA 2023 Cask Predicted Maximum Allowable Heat Dissipation Rates

<u>Fuel</u>	<u>Storage Medium</u>	<u>Maximum Allowable Decay Heat Rate, kW/Ass.</u>	<u>Temperature Limit, °C</u>
Unconsolidated	Helium	0.84	Neutron shield = 148
Unconsolidated	Nitrogen	0.84	Peak cladding = 400
Consolidated	Helium	0.80	Neutron shield = 148
Consolidated	Nitrogen	0.60	Peak cladding = 400

The CASTOR-1C cask consists of a nodular cast-iron body that provides gamma and neutron shielding. Additional neutron shielding is provided in the wall of the cask with two concentric rings of axial holes containing polyethylene rods (moderator material). Longitudinal fins on the cask surface enhance heat transfer from the cask wall.

The cask inner cavity contains a borated stainless steel basket designed to contain 16 BWR spent fuel assemblies. The borated material reduces the possibility of criticality when loading fuel underwater in a spent fuel storage pool. The cask is sealed with a multiple-lid system consisting of a primary lid, a secondary lid, and a protection plate. The stainless steel primary and secondary lids contain elastomer and metallic O-ring seals which guarantee a high level of leak-tightness. The protection plate is made of carbon steel and serves as mechanical protection as well as a dust and humidity seal.

Peak cladding temperature profiles are presented in Figure S.5 for four different cases based on a decay heat generation rate of 0.8 kW per assembly

or canister. Two of the simulations were performed with the cask containing unconsolidated fuel in nitrogen and helium. The peak cladding temperatures for these two cases are predicted to be 400°C for the nitrogen and 365°C for the helium. As in the REA cask, the predicted temperature profile in unconsolidated fuel for the nitrogen case is skewed upward because of natural circulation. When consolidated fuel is used, the predicted peak cladding temperature for the nitrogen case is 498°C, an increase of 98°C. The axial profile for the consolidated case in nitrogen is less skewed, indicating a reduction in natural circulation. Also, radiation heat transfer has been reduced because of increased pin shadowing and the addition of a low-surface-emissivity canister.

The peak cladding temperature for the consolidated fuel assemblies in helium is 348°C, a decrease of 17°C from the unconsolidated assemblies. Although convection and radiation heat transfer have been reduced, conduction

FIGURE S.5. CASTOR-1C Cask Axial Temperature Profile Predictions

is enhanced because high-conductivity fuel pins replace relatively low-conductivity gas. Therefore, as in the REA cask, the effect of consolidation on peak temperature strongly depends on the storage medium used.

The assembly decay heat rates were adjusted to predict the maximum allowable cask heat dissipation rates for all four cases. The only temperature constraint considered for the CASTOR-1C cask was a 400°C allowable peak cladding temperature. After a few iterations, a maximum allowable heat dissipation rate was identified for each case. The results are presented in Table S.3. For unconsolidated fuel, the use of helium results in a 12% increase in heat rate compared to nitrogen. For consolidated fuel, the use of helium results in a heat rate nearly double that for nitrogen.

Two major conclusions resulted from this study. First, a lumping technique (combining rods and flow channels), which reduces the number of computational nodes required to model complex multiassembly geometries, could be used for both unconsolidated and consolidated rods with negligible effect on prediction accuracies. Second, with a relatively high thermal conductivity backfill gas (e.g., helium), the predicted peak fuel rod temperature in a canister of consolidated rods generating the same amount of heat as an unconsolidated assembly is essentially the same as the peak temperature in the unconsolidated assembly. In contrast, with a relatively low thermal conductivity backfill gas (e.g., nitrogen), the opposite is true and the predicted peak temperature in a consolidated canister is significantly higher than in an unconsolidated assembly. Therefore, when rods are consolidated, selection of the backfill gas is important in maintaining peak rod temperatures below allowable values for rods with relatively high decay heat generation rates.

TABLE S.3. CASTOR-1C Cask Predicted Maximum Allowable Heat Dissipation Rates

<u>Fuel</u>	<u>Storage Medium</u>	<u>Maximum Allowable Decay Heat Rate, kW/Ass.</u>	<u>Temperature Limit, °C</u>
Unconsolidated	Helium	0.90	400
Unconsolidated	Nitrogen	0.80	400
Consolidated	Helium	0.98	400
Consolidated	Nitrogen	0.52	400

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NOMENCLATURE

SYMBOLS AND NOTATIONS

α_m	- set of wall numbers that connect to wall node m
β_n	- set of wall numbers that connect to rod n
γ_n	- set of channel numbers for channels with a thermal connection to rod n
Δt	- time step
Δx	- axial step
ϵ	- surface emittance or a member of a set
S_n	- set of rod numbers with a thermal radiation connection to rod n
θ	- problem orientation, angle from vertical
κ_n	- set of rod numbers with a thermal radiation connection to wall n
λ_i	- set of rod numbers with a thermal connection to subchannel i
μ	- viscosity
ξ_m	- set of subchannel numbers with a thermal connection to wall m
ρ	- density
σ	- Stephan-Boltzmann constant
σ_m	- set of wall numbers with a thermal radiation connection to wall m
τ_i	- set of wall numbers for walls that connect to subchannel i
ϕ	- area fraction
ϕ_i	- rod to subchannel i heat fraction
ψ_i	- set of transverse gas connections to subchannel i
ℓ	- length of transverse momentum control volume
A	- area
C	- drag, axial loss coefficient, empirical coefficient, or specific heat

D	- Darcy and orifice drag
D_h	- hydraulic diameter
e_k	- multiplier (± 1) that gives the correct sign to the transverse connection terms
f	- friction factor
F_{ij}	- radiation exchange factor, surface i to j
g	- acceleration due to gravity
Gr	- Grashoff number
h, H	- fluid enthalpy, average film coefficient, or heat transfer coefficient
H_g	- fuel-cladding gap conductance
k, K	- thermal conductivity
L	- length
Nu	- Nusselt number
P, p	- pressure
Pr	- Prandtl number
$\dot{q}$	- heat generation rate
$\dot{q}_{rad}$	- thermal radiation transport
q'''	- volumetric heat generation in wall
R	- radial thermal resistance or radius
r	- radius
Ra	- Rayleigh number
R_c	- outer radius of the cladding
Re	- Reynolds number
R_f	- outer radius of the fuel material
S	- transverse gap width

T	- temperature
T_a	- ambient temperature
T_c	- cladding temperature
T_{fs}	- temperature of the fuel surface
T_s	- local surface temperature
T_w	- wall temperature
t	- time
t_w	- effective wall thickness for heat storage
U	- effective wall conductance
u	- transverse velocity
v	- axial velocity
w_T	- crossflow due to turbulent exchange
y_c	- cladding thickness
z	- factor for effective fluid radial conduction length

SUPERSCRIPTS

- n - time step level or Nusselt number exponent
- N - empirical coefficient
- * - donor cell quantity
- average value

SUBSCRIPTS

- a - ambient
- c - cladding or convection
- D - diameter
- f - friction or fuel

i	- subchannel number or generalized subscript for matrix notation
HTR	- heat transfer from a rod
HTW	- heat transfer from a wall
j	- axial level or generalized subscript for matrix notation
II	- refer to channel numbers on either side of a transfer gap
JJ	
k	- transverse gap number
L	- length
m	- mixed convection or wall number
n	- rod number
o	- outside
p	- pressure
r	- radiation
R	- rod
s	- surface
T	- transverse
w	- wall
X	- local parameter

COBRA-SFS THERMAL-HYDRAULIC ANALYSES OF THE
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CONTAINING CONSOLIDATED SPENT FUEL

1.0 INTRODUCTION

Consolidation of spent nuclear fuel rods is being considered as one option for more efficient and compact storage of reactor spent fuel assemblies. In this concept, the rods from two disassembled spent fuel assemblies are consolidated in a space originally intended to store a single unconsolidated assembly. Several important technical issues must be investigated in evaluating the merits of rod consolidation. The thermal performance of consolidated fuel rods in dry storage, especially in multiassembly storage systems, is one of the major issues that must be addressed prior to implementation.

The COBRA-SFS spent fuel storage thermal-hydraulic computer code has been used to calculate the thermal performance of spent nuclear fuel rods in a variety of dry storage environments for both consolidated and unconsolidated assemblies (Cuta, Rector, and Creer 1984). The ability of the COBRA-SFS code to predict the temperature distribution within multiassembly casks containing unconsolidated fuel assemblies was evaluated in tests involving the REA 2023 (Wiles et al. 1986) and CASTOR-1C casks (Rector et al. 1986). In addition, the ability to model the temperature field in unconsolidated and consolidated single assemblies was verified by comparing COBRA-SFS calculations to data from a test involving electrically heated unconsolidated and consolidated assemblies (Cuta and Creer 1986).

In this study, Pacific Northwest Laboratory researchers performed thermal-hydraulic analyses for both the REA 2023 cask and the CASTOR-1C cask containing either unconsolidated or consolidated spent fuel assemblies. The objective was to determine the effect of consolidating spent fuel on the temperature distributions within both types of cask. Due to the size of the subchannel

models required for the analysis, the development of simpler models, which accurately represent unconsolidated and consolidated spent fuel assemblies for use in the cask analysis, was investigated.

The conclusions and recommendations based on this study are presented in Section 2.0. A brief description of the COBRA-SFS code is presented in Section 3.0. In Section 4.0, unconsolidated assembly analysis results are presented, and the methodology for reducing the problem size by using coarse assembly models is introduced. In Section 5.0, analysis results for both the REA 2023 cask and the CASTOR-1C cask containing consolidated BWR spent fuel rods are compared to unconsolidated spent fuel assembly predictions.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations presented here are based on the single assembly, the COBRA-SFS simulations for the REA 2023 cask, and the simulations for CASTOR-1C cask results. Two major conclusions resulted from this study. One, a lumping technique (combining rods and flow channels), which reduces the number of computational nodes required to model complex cask assembly geometries, could be used for both unconsolidated and consolidated rods with negligible effect on prediction accuracies. Two, with a relatively high thermal conductivity backfill gas (e.g., helium), the predicted peak fuel rod temperature in a canister of consolidated rods generating the same amount of heat as an unconsolidated assembly is essentially the same as the peak temperature in the unconsolidated assembly. In contrast, with a relatively low thermal conductivity backfill gas (e.g., nitrogen), the opposite is true and the predicted peak temperature in a consolidated canister is significantly higher than in an unconsolidated assembly. Therefore, when rod consolidation is used, selection of the backfill gas may be important in maintaining peak rod temperatures below allowable values for rods with relatively high decay heat generation rates. Other specific conclusions and recommendations resulting from this analyses effort are listed in the following sections.

2.1 CONCLUSIONS

Six specific conclusions were drawn from this study:

- Both unconsolidated and consolidated assemblies may be represented by coarse assembly models using composite subchannels and rods. The results from simulations using coarse models compare well with those generated using detailed models. Therefore, coarse assembly models may be used to reduce the problem size for multiassembly storage system analyses.
- The effect of fuel rod consolidation on heat transfer within a single fuel assembly is dependent on the storage medium used. In consolidated assemblies, as compared to unconsolidated assemblies, conduction heat

transfer increases while radiation and convection heat transfer decrease. In high conductivity helium, where conduction and radiation are the primary modes of heat transfer in the unconsolidated case, the enhanced conduction and reduced radiation in the consolidated case results in essentially the same predicted peak temperature. The predicted peak temperature in relatively low conductivity nitrogen, which has radiation and convection as the primary modes of heat transfer in the unconsolidated case, increases dramatically in the consolidated case where conduction heat transfer is dominant.

- A series of simulations was performed for the REA 2023 cask containing both unconsolidated and consolidated fuel assemblies. For the cask containing unconsolidated fuel with an average assembly decay heat generation rate of 0.8 kW, the predicted peak cladding temperature is 384°C for the nitrogen case and 304°C for the helium case. For the cask containing consolidated fuel with the same average canister heat generation rate, the predicted peak cladding temperature is 484°C for the nitrogen case and 324°C for the helium case.
- A series of simulations was performed for the CASTOR-1C cask containing both unconsolidated and consolidated fuel assemblies. For the cask containing unconsolidated fuel with an average assembly decay heat generation rate of 0.8 kW, the predicted peak cladding temperature is 400°C for the nitrogen case and 365°C for the helium case. For the cask containing consolidated fuel with the same average canister heat generation rate, the predicted peak cladding temperature is 498°C for the nitrogen case and 348°C for the helium case.
- The predicted maximum allowable heat dissipation rate for the REA 2023 cask containing unconsolidated fuel is 0.84 kW per assembly for both helium and nitrogen backfill gases. For the cask containing consolidated fuel, the predicted maximum allowable heat dissipation rate is 0.80 kW per canister for helium and 0.60 kW per canister for nitrogen.

- The predicted maximum allowable heat dissipation rate for the CASTOR-1C cask containing unconsolidated fuel is 0.90 kW per assembly for helium and 0.80 kW per assembly for nitrogen. For the cask containing consolidated fuel, the predicted maximum allowable heat dissipation rate is 0.98 kW per canister for helium and 0.52 kW per canister for nitrogen.

2.2 RECOMMENDATIONS

Based on the outcome of this work, three recommendations are offered:

- The ability of the COBRA-SFS code to model the temperature fields in a consolidated single assembly was evaluated using data from an electrically heated assembly test (Cuta and Creer 1986). However, this test may not reflect the surface condition of the rods, the degree of rod distortion, or the amount of rod-to-rod contact that would occur in an actual consolidated spent fuel assembly. Therefore, temperature data from an actual consolidated spent fuel assembly test are necessary to fully evaluate the performance of the code.
- The design parameters for the consolidated fuel canister, such as dimensions, material type and surface, and emissivities, were assumed for this analysis. The temperature results may vary if a different canister design is used. Therefore, the actual values for these parameters would enhance a best-estimate analysis.
- COBRA-SFS should continue to be used to perform analyses of storage systems using unconsolidated and consolidated spent fuel. As more consolidated assembly test data are generated, more evaluations should be performed and, if necessary, refinements to COBRA-SFS implemented.

3.0 COBRA-SFS COMPUTER CODE

The COBRA-SFS code is a steady-state, lumped finite-volume computer code that predicts flow and temperature distributions in spent fuel storage systems and fuel assemblies under mixed and/or natural convection conditions. Derived from the COBRA family of codes (Rowe 1973; Stewart et al. 1977; George et al. 1980; Khan et al. 1981), which have been extensively evaluated against in-pile and out-of-pile data, COBRA-SFS retains all the important features of the COBRA codes and extends the range of application to problems with two-dimensional radiation and conduction heat transfer. This capability permits analyses of single- and multiassembly spent fuel storage systems with unconsolidated or consolidated fuel, with a variety of fill media (Creer 1984; Cuta, Rector, and Creer 1984; Wiles et al. 1986; Wheeler et al. 1986; Rector et al. 1986; Cuta and Creer 1986).

COBRA-SFS provides finite-difference solutions to the equations governing mass, momentum, and energy conservation for incompressible flows. Although it is assumed that the backfill medium is incompressible, COBRA-SFS uses a thermally expandable flow model to calculate buoyancy-driven circulating flows within a system. Analyses are conducted using a subchannel approach in which the flow areas of assemblies or storage systems are divided axially into discrete control volumes for which the conservation equations of mass, momentum, and energy are written. These equations are then solved using an iterative implicit method. The energy equations for the coolant, rod cladding, fuel, and structural members (walls) are solved simultaneously in a plane. Axial conduction in the structural members is included. A nonparticipating, gray body radiation heat transfer model also allows two-dimensional radiant heat exchange among all solid members in an enclosure and is iteratively coupled to the rod and wall energy equations.

The flow field may be either user-prescribed or internally calculated as a function of the gravitational and dynamic pressure losses. Specifications of heat losses from the boundary may vary circumferentially and axially, and can include both radiation and convection heat transfer. Axial heat transfer

from the subchannel model to plenum regions (regions above and below the fuel assemblies) also can be modeled.

In the following sections, the COBRA-SFS modeling capabilities are outlined, and a brief description of the conservation equations is given.

3.1 MODELING CAPABILITIES

COBRA-SFS allows simulations of a wide range of dry storage systems via input instructions. In addition to the multiassembly cask analysis described in this report, applications have included analyses of single-assembly spent fuel storage systems under multiple orientations and fill media (Lombardo et al. 1986) and analyses of both single- and multiassembly consolidated fuel storage systems (Creer 1984; Cuta, Rector, and Creer 1984; Wiles et al. 1986; Wheeler et al. 1986; Rector et al. 1986; Cuta and Creer 1986). The code contains thermal-hydraulic models for pressure drop, turbulent mixing, diversion crossflow, buoyancy-induced flow recirculation, and conduction and radiation heat transfer. A versatile fuel rod model allows simulation of consolidated fuel assemblies. The code's capabilities and limitations are outlined in Table 3.1.

3.2 CONSERVATION EQUATIONS

The COBRA-SFS code solves the conservation equations of mass, momentum, and energy in a fuel assembly or fuel storage system using finite difference equations derived by performing suitable balances on finite control volumes. Empirical relationships are used where needed to close the set of equations.

The fluid control volume for continuity, axial momentum, and energy is characterized by a flow cross-sectional area, A ; an axial length, Δx ; and a gap width, S , for the connection to adjacent control volumes. Figure 3.1 shows the relationship of a subchannel control volume to a fuel storage system; a typical subchannel control volume is also displayed. Any series of control volumes connected axially is considered a subchannel. In the following equations, the finite-difference terms are presented with the corresponding

TABLE 3.1. COBRA-SFS Capabilities and Limitations

Modeling Capabilities	<ul style="list-style-type: none"> Finite-Volume Steady State Triangular, square or consolidated rod arrays Recirculating flows Zero net flow solution Interassembly and intra-assembly heat transfer Nonparticipating radiation (planar) Mixed geometry Variable axial grid spacing 	<ul style="list-style-type: none"> Multiple flow regions Fluid conduction and turbulent mixing Pressure drop model (network and subchannel) Variable property rod model Variable boundary heat transfer Prescribed heat flux Plenum heat loss model Use of specified flow regions Variable fluid properties
Program and I/O Control	<ul style="list-style-type: none"> Constant prescribed flow Zero net flow Restart and post-processing dump Decoupled hydrodynamics (no buoyancy) Fully coupled hydrodynamics Echoed input Result execution and time monitoring Variable/constant fluid properties Pressure drop initialization scheme Data "roll" option for large problems 	
Limitations and Assumptions	<ul style="list-style-type: none"> Incompressible flow Finite-Volume approach No free-field capability One-dimensional boundary heat transfer

FIGURE 3.1. Subchannel Definition

word definitions given in brackets immediately below each equation. The list of symbols in the Nomenclature section of this document should be referred to for explanation of the notation.

Continuity Equation (for subchannel i)

$$\bar{A} \frac{(\rho - \rho^*)}{\Delta t} j = \frac{v_{j-1} A_{j-1} \rho_{j-1}^*}{\Delta x_j} - \frac{v_j A_j \rho_j^*}{\Delta x_j} + \sum_{k \in \Psi_i} e_k (u_k S_k \rho_k^*) j \quad (3.1)$$

$$\left[\begin{array}{c} \text{mass} \\ \text{storage} \end{array} \right] = \left[\begin{array}{c} \text{axial mass} \\ \text{transport} \end{array} \right] + \left[\begin{array}{c} \text{lateral mass} \\ \text{transport} \end{array} \right]$$

The asterisk denotes that donor cell values are convected by the velocity v .

Fluid Energy Equation (for channel i)

$$\begin{aligned}
 \bar{A} \frac{(\rho h - (\rho h)^n)}{\Delta t} \Big|_j &= \frac{v_{j-1} A_{j-1} \rho_{j-1}^* h_{j-1}^*}{\Delta x_j} - \frac{v_j A_j \rho_j^* h_j^*}{\Delta x_j} + \sum_{k \in \Psi_i} e_k (u_k S_k \rho_k^* h_k^*) \Big|_j \\
 \boxed{\text{energy storage}} &= \boxed{\text{axial energy transport}} + \boxed{\text{lateral energy transport}} \\
 &+ \sum_{n \in \lambda_i} \frac{A_{HTR} H_R}{\Delta x_j} (T_{Cn} - T) + \sum_{m \in \tau_i} \frac{A_{HTW} H_W}{\Delta x_j} (T_w - T_m) \\
 &+ [\text{rod heat flux}] + [\text{wall heat flux}] \\
 &+ \sum_{k \in \Psi_i} e_k S_k K_k \frac{T_{II} - T_{JJ}}{l_k z_k} + \sum_{k \in \Psi_i} \frac{e_k w_T}{\Delta x_j} (h_{II} - h_{JJ}) \\
 &+ \boxed{\text{lateral conduction heat transfer}} + \boxed{\text{turbulent energy exchange}}
 \end{aligned} \tag{3.2}$$

All other forms of energy transport that are not explicitly represented in Equation (3.2) (e.g., potential and kinetic energy) have been neglected.

Axial Momentum Equation (for channel i)

$$\bar{A} \frac{(\rho v - (\rho v)^n)_j}{\Delta t} = \frac{A_{j-1} v_{j-1} v_{j-1}^* \rho_{j-1}^*}{\Delta x_j} - \frac{A_j v_j v_j^* \rho_j^*}{\Delta x_j} + \sum_{k \in \Psi_i} e_k (u_k S_k v_k^* \rho_k^*)_j$$

$$\left[\begin{array}{c} \text{axial} \\ \text{momentum} \\ \text{storage} \end{array} \right] = \left[\begin{array}{c} \text{axial momentum} \\ \text{transported} \\ \text{axially} \end{array} \right] + \left[\begin{array}{c} \text{axial momentum} \\ \text{transported} \\ \text{laterally} \end{array} \right]$$

$$+ \bar{A}_j \frac{P_{j-1} - P_j}{\Delta x_j} + \sum_{k \in \Psi_i} \frac{e_k w_T}{\Delta x} (v_{II} - v_{JJ})$$

$$+ \left[\begin{array}{c} \text{pressure} \\ \text{gradient} \end{array} \right] + \left[\begin{array}{c} \text{turbulent momentum} \\ \text{exchange} \end{array} \right]$$

$$- \frac{1}{2} \left(\frac{f}{D_h} + \frac{C}{\Delta x_j} \right) \rho_j^* v_j |v_j| A_j - A \rho g \cos \theta$$

$$- \left[\begin{array}{c} \text{irreversible friction} \\ \text{and form losses} \end{array} \right] - \left[\begin{array}{c} \text{gravitational head} \end{array} \right] \quad (3.3)$$

In the derivation of the axial momentum equation, it is assumed that all irreversible losses can be obtained by use of suitable friction factors and loss coefficients applied to the bulk velocity. Also, it is assumed that pressure changes linearly along the control volume, and the shear stress terms due to flow in the adjacent subchannels can be neglected.

Transverse Momentum Equation

The momentum control volume length, ℓ , and gap width, S , define a transverse momentum control volume as shown in Figure 3.2. Inside this control volume, the transverse velocity is normal to the transverse gap; the flow is

assumed to have no transverse component outside the transverse momentum control volume.

$$S\Delta x_j \frac{(\rho^*u - (\rho^*u)^n)_k}{\Delta t} = S_k v_{j-1} (\rho u)_{k,j-1}^* - S_k v_j (\rho u)_{k,j}^*$$

$$\left[\begin{array}{c} \text{lateral} \\ \text{momentum} \\ \text{storage} \end{array} \right] = \left[\begin{array}{c} \text{transverse momentum} \\ \text{transported axially} \end{array} \right]$$

$$+ \frac{S_k \Delta x_j}{\ell_k} (P_{II} - P_{JJ})_{j-1} - C_T u_k u_k \frac{\rho S \Delta x_j}{2\ell_k}$$

$$+ \left[\text{pressure gradient} \right] - \left[\text{irreversible form and friction loss} \right] \quad (3.4)$$

FIGURE 3.2. Transverse Momentum Control Volume

A further assumption in the transverse momentum equation is that there are no applied body forces in the transverse direction.

Fuel Rod and Cladding Energy Equations

By assuming that 1) there is no heat transfer axially, 2) the heat is generated uniformly throughout the fuel at a given axial location, and 3) the fuel properties do not vary with the radial variation in temperature, the cladding temperature is obtained by performing a lumped energy balance on the cladding material at each axial level. The finite-difference form of the equation used is presented in Equation (4.5).

$$y_c \rho_c c_c \frac{T_c^n - T_c^{n-1}}{\Delta t} = H_R \sum_{i \in g_f} \phi_i (T_c - T_i) + H_g \frac{R_f}{R_c} (T_{fs} - T_c)$$

$$\boxed{\text{energy storage}} = \boxed{\text{convection transfer to fluid}} + \boxed{\text{heat transfer from fuel}}$$

$$+ \sigma \sum_{n \in \zeta_n} F_{in} (T_c^4 - T_{cn}^4) + \sigma \sum_{m \in \beta_m} F_{im} (T_c^4 - T_{wn}^4)$$

$$+ \boxed{\text{radiation heat transfer from rods}} + \boxed{\text{radiation heat transfer from walls}} \quad (4.5)$$

In Equation (4.5), it is assumed that the temperature is uniform around the circumference of the cladding. The film coefficient, H_R , is given by user-specified correlations, and the gap conductance between fuel pellet and cladding, H_g , is assumed constant. F_{in} and F_{im} are gray body radiation exchange factors that account for multiple reflections within an enclosure. F_{in} is a

coefficient for rod-to-rod heat transfer, while F_{im} is a coefficient for rod-to-wall heat transfer. Both are derived by assuming constant surface emissivity. The graybody exchange factors can be user-prescribed or calculated internally by specifying blackbody view factors and surface emissivity values.

Energy Equations

$$\rho_w c_w t_w \frac{T_w - T_w^n}{\Delta t} = \sum_{i \in \xi_i} U (T - T_w) + \sigma \sum_{m \in \sigma_m} F_{im} (T_w - T_m^4)$$

$$[\text{energy storage}] = [\text{heat transfer from adjacent channels}] + [\text{radiation heat transfer from walls}]$$

$$+ \sigma \sum_{n \in \kappa_n} F_{in} (T_w^4 - T_{cn}^4) + q'''$$

$$[\text{radiation heat transfer from rods}] + [\text{heat generation}]$$

$$+ U_{j-1} (T_w - T_{w_{j-1}}) + U_{j+1} (T_w - T_{w_{j+1}}) + \sum_{m \in \alpha_m} U (T_w - T_{w_m}) \quad (4.6)$$

$$+ [\text{axial conduction heat transfer}] + [\text{heat transfer from adjacent walls}]$$

As before, F_{im} and F_{in} are the gray body exchange factors from wall node i to wall node m and rod node n , respectively. Axial heat transfer from the walls to a plenum region can be included at the end axial levels.

4.0 UNCONSOLIDATED ASSEMBLY ANALYSES

The COBRA-SFS code, like all other COBRA codes, is designed to model fuel assemblies on a rod-and-subchannel basis. This modeling approach affords a very detailed look at the individual rod temperatures and the flow and enthalpy distributions in the coolant. The problem sizes for spent fuel analyses, however, tend to be very large--a typical unconsolidated 8x8 boiling water reactor (BWR) assembly requires a model consisting of 77 subchannels and 64 rods. A typical unconsolidated 15x15 pressurized water reactor (PWR) assembly requires a model consisting of 252 subchannels and 225 rods. With consolidated fuel, the required number of rods and subchannels per assembly more than doubles. When the calculation is for a multiassembly storage system such as a cask, the problem size can become exceedingly large. Although COBRA-SFS can handle very large problems (consisting of hundreds of subchannels and rods), there is a practical upper limit, generally dictated by computer memory requirements. Also, the larger the problem, the more expensive it is to run; thus, cost considerations provide an urgent incentive to limit problem size.

The level of detail provided by rod-and-subchannel modeling is not always required for flow and heat transfer problems in fuel assemblies. Experience with COBRA codes has shown that reasonable results can often be obtained with much coarser representations of the assembly geometry. A study of the results obtained with COBRA-SFS for less detailed geometry models of spent fuel assemblies shows that it is possible to obtain results that are comparable to those obtained with detailed rod-and-subchannel models.

Calculations were first made for detailed rod-and-subchannel models of a typical unconsolidated 8x8 fuel assembly. Several models with varying degrees of detail were investigated, and the results compared to the detailed model results. Section 4.1 describes these models, and presents the results of the comparisons.

Based on the results obtained in the single-assembly calculations, the modeling study was extended to a multiassembly storage system--the REA cask. A reference calculation was made using detailed rod-and-subchannel assembly models in a REA cask model. Subsequent calculations investigated the effect of various less-detailed assembly geometry models for unconsolidated 8x8 fuel assemblies. Section 4.2 describes the REA cask models used, and presents the results of the comparisons.

4.1 SINGLE UNCONSOLIDATED ASSEMBLY ANALYSIS

A detailed rod-and-subchannel model was set up for a typical 8x8 BWR fuel assembly as the reference case for comparison with various channel lumping schemes. Five different geometry models were investigated, each progressively less detailed, so that the range of models extended from complete detail in the rod-and-subchannel model to an essentially one-dimensional representation of the assembly as a single average rod and channel. A set of calculations was performed using a circumferentially uniform boundary temperature. A second set was performed with a circumferentially nonuniform boundary that simulated the radial temperature gradient an assembly was likely to encounter in a cask storage environment.

The basic geometric characteristics of an 8x8 BWR fuel assembly are summarized in Table 4.1. The fuel rods are 1.25 cm (0.493 in.) in diameter, on a 1.63-cm (0.640-in.) pitch, with one water tube. The decay heat generation rate was assumed to be 0.4 kW per assembly, with the nonuniform axial decay heat distribution listed in Table 4.1. Figure 4.1 shows a cross section of the assembly, with the rod and channel noding for the detailed model. This model has 64 rods and 77 channels. The boundary temperature profiles for the air and helium cases are listed in Table 4.2. The temperature profiles identified as B1 are used for calculations with circumferentially uniform boundary temperatures. Profiles B1 and B2 are used for calculations with circumferentially nonuniform boundary temperatures. The boundary temperature profile B₁ was imposed uniformly on all eight wall nodes (65 through 72), as indicated by the notation B₁ on the diagram in Figure 4.1.

TABLE 4.1. Typical 8x8 BWR Fuel Assembly Characteristics

Geometric parameters

Rod diameter	1.25 cm (0.493 in.)
Pitch	1.63 cm (0.640 in.)
Water tube diameter	1.50 cm (0.591 in.)
Number of active rods	63
Number of water tubes	1
Active length	366 cm (144.0 in.)
Total axial length	452 cm (177.8 in.)

Operating parameters

Residual heat rate	0.4 kW/assembly
Radial decay heat profile	uniform
Axial decay heat profile	

<u>X/L</u>	<u>Axial Decay Heat Factor</u>
0.0	0.0
0.0399	0.0
0.0400	0.481
0.112	1.00
0.180	1.11
0.247	1.12
0.315	1.11
0.450	1.09
0.585	1.07
0.652	1.04
0.720	0.97
0.789	0.78
0.855	0.29
0.8551	0.0
1.0	0.0

FIGURE 4.1. Detailed 64-Rod/and 77-Subchannel Model of an 8x8 Unconsolidated Fuel Assembly (Geometry S1)

TABLE 4.2. Boundary Temperature Profiles for Single-Assembly Calculations

Relative Axial Location X/L	Boundary Temperature B ₁ , °C (°F)		Boundary Temperature B ₂ , °C (°F)
	Air Cases	Helium Cases	Air Cases
0.0	160 (319)	99 (210)	154 (310)
0.0624	162 (324)	123 (254)	156 (314)
0.1040	168 (334)	157 (314)	161 (321)
0.1457	174 (345)	185 (364)	160 (321)
0.1873	181 (358)	205 (400)	170 (339)
0.2292	187 (369)	218 (424)	175 (348)
0.2711	193 (380)	225 (437)	180 (356)
0.3127	199 (389)	229 (444)	184 (363)
0.3543	203 (398)	231 (448)	188 (370)
0.3960	208 (406)	232 (450)	191 (376)
0.4376	212 (413)	232 (450)	194 (381)
0.4792	215 (419)	232 (450)	197 (386)
0.5208	218 (425)	231 (448)	199 (390)
0.5624	221 (430)	230 (444)	201 (397)
0.6040	223 (434)	229 (444)	203 (397)
0.6457	225 (437)	226 (439)	204 (399)
0.6873	226 (439)	222 (432)	205 (400)
0.7292	226 (440)	215 (420)	205 (401)
0.7711	225 (437)	205 (400)	204 (399)
0.8127	221 (430)	186 (367)	201 (394)
0.8543	214 (417)	159 (317)	195 (383)
0.8960	204 (399)	127 (261)	187 (369)
0.9376	196 (384)	106 (224)	180 (357)
1.0	188 (371)	95 (202)	175 (346)

The subchannel noding shown in Figure 4.1 models the continuous flow field in the assembly as an array of discrete control volumes defined by the rod array. This noding is based on the assumption that the gradients of interest--i.e., velocity, temperature, and density--are small enough across the distance of the rod-to-rod pitch that each can be reasonably represented by a single average value. A subchannel can be defined over any geometric area of the flow field where the assumption of relatively insignificant gradients is reasonable.

A rod in a COBRA-SFS model is an arbitrarily defined heat transfer surface, just as a channel is an arbitrarily defined control volume in the flow field. In the subchannel model, a COBRA rod models a single fuel rod. However, a COBRA rod can model any heat transfer surface or collection of surfaces. The criterion for determining which surface or surfaces can be modeled by a single COBRA rod is the surface temperature. Surfaces at the same temperature, or nearly the same temperature, can usually be modeled with a single COBRA rod.

The detailed S1 subchannel model indicated significant gradients in fluid temperature, density, and velocity existed only in the radial direction. The fluid conditions were relatively uniform circumferentially, because of the uniform boundary imposed by specifying temperature profile B_1 (listed in Table 4.2) on all eight boundary nodes. Figure 4.2 shows a diagram of a subchannel noding pattern, referred to as geometry L1, determined after examining the results of the calculation with the detailed subchannel model. There are 17 COBRA rods in the model; fuel rods that are modeled by the same COBRA rod are labeled with the same index number. In the outer ring of the fuel rods, the rods facing a wall were at essentially the same temperature, except for the corner rods. The corner rods were significantly cooler than the adjacent rods, probably because they see so much more of the wall for radiation exchange. From this temperature distribution, it was deemed reasonable to combine the fuel rods along each face (minus the corner rods) into a single COBRA rod, while modeling each corner fuel rod as a separate COBRA rod.

FIGURE 4.2. Lumped 17-Rod/5-Subchannel Model (Geometry L1)

The internal fuel rods were combined by lumping them in groups of four, as illustrated in Figure 4.2. This pattern was selected because the four center fuel rods (modeled by COBRA rod 1) were at essentially the same temperature in the detailed subchannel calculation, and the remaining rods, when examined in groups of four, had temperatures within 2°C (3°F) of each other.

Radiation heat transfer is a major mode of heat transfer in spent fuel assemblies, so it is important that the geometry model take proper account of the exchange factors between heat transfer surfaces. In the detailed subchannel model, the exchange factors are calculated, rod-to-rod, rod-to-wall, and wall-to-wall, from black body view factors determined using Hottel's crossed-string correlation method for quarter-sections of the rod surfaces (Cox 1977). The individual rod surface view factors are obtained by summing the gray body factors for the constituent quarter-section surfaces. When several individual fuel rods are modeled as a single COBRA rod, the view factors for the individual rod surfaces are summed in much the same manner, to preserve the exchange factor relationships for all surfaces involved. If the surface temperature of the COBRA rod that models several fuel rods is essentially the same as the surface temperatures of those individual fuel rods, then the heat exchange by radiation will be satisfactorily modeled.

The key phrase here is "essentially the same." One of the questions addressed in this study is how far one can go in lumping rods before resultant calculated temperatures drift too far from detailed rod-to-rod temperature predictions.

Figure 4.3 shows another rod model used with the five-subchannel flow field model. This case represents the 64 fuel rods with only five COBRA rods, and is referred to as geometry L2. It is based on the observation that all the corner rods are essentially at the same temperature in the detailed calculation, so it should be possible to represent them as a single COBRA rod. The rods facing the walls (except the corner rods) are also all at nearly the same temperature, and can be modeled as a single rod. The same is similarly true for each radial ring of rods within the array.

The rod-and-subchannel models illustrated in Figures 4.2 and 4.3 represent what might be considered reasonable approximations of the detailed subchannel model. Although some smearing out of the gradients is inevitable with the lumped models, it is expected that these models will yield results in reasonable

FIGURE 4.3. Lumped 5-Rod/5-Subchannel Model (Geometry L2)

agreement with the detailed subchannel case. Figure 4.4 shows a rod-and-subchannel model designed to see how far one can go in simplifying the geometry model and still obtain meaningful results. The flow field is defined with only three subchannels--an outer ring that sees the wall, a ring between the outer two rod rows, and a uniform internal region. The fuel rods are modeled with

FIGURE 4.4. Lumped 2-Rod/3-Subchannel Model (Geometry L3)

two COBRA rods--one rod modeling the outer ring of fuel rods, and one rod modeling the interior fuel rods of the array. This rod-and-subchannel lumping pattern is referred to as Geometry L3.

A final lumping model considered was a one-dimensional representation of the assembly, with one channel and one rod. It is referred to as geometry

L4. It was not expected that this case would yield anything approaching a reasonable approximation of the results for the detailed subchannel model; it was included only to determine how discrepant the results would be for this simplest possible geometry model.

Table 4.3 lists the calculations made with the geometries described. Five different geometries were considered, each with air and helium as the storage medium, for a total of ten calculations. In all calculations, the same boundary and operating conditions were used; the only factor changing between cases was the degree of detail in the geometry model. The results of the calculations are presented in Table 4.4, and in Figures 4.5 and 4.6 with plots of peak cladding temperature calculated for each geometry.

TABLE 4.3. Summary of Cases for Unconsolidated Single Assembly with Circumferentially Uniform Boundary Temperatures

<u>Case No.</u>	<u>Geometry</u>	<u>Storage Medium</u>	<u>Assembly Decay Heat, kW</u>
1	Detailed subchannel (S1)	Air	0.4
2	5 subchannels, 17 rods (L1)	Air	0.4
3	5 subchannels, 5 rods (L2)	Air	0.4
4	3 subchannels, 2 rods (L3)	Air	0.4
5	One-dimensional (L4)	Air	0.4
6	Detailed subchannel (S1)	Helium	0.4
7	5 subchannels, 17 rods (L1)	Helium	0.4
8	5 subchannels, 5 rods (L2)	Helium	0.4
9	3 subchannels, 2 rods (L3)	Helium	0.4
10	One-dimensional (L4)	Helium	0.4

TABLE 4.4. Peak Cladding Temperatures Calculated in the Unconsolidated Single Assembly with Circumferentially Uniform Boundary Temperatures

Geometry	Peak Cladding Temperature, °C(°F)		Radiation Heat Transfer	
	In Air	In Helium	In Air	In Helium
S1	503 (262)	497 (258)	55%	28%
L1	499 (260)	493 (256)	59%	28%
L2	507 (264)	500 (260)	55%	24%
L3	499 (259)	490 (254)	63%	29%
L4	456 (236)	454 (235)	22%	7%

With air as the storage medium, a peak cladding temperature of 262°C was calculated with the detailed subchannel model with the boundary temperature defined uniformly around the canister by profile B₁. With helium as the storage medium, the calculated peak cladding temperature was 258°C (with the boundary defined by profile B₁ for helium from Table 4.2). In the air case, 45% of the heat was transferred from the rods by conduction or convection, and 55% was transferred by radiation. In the helium case, 72% of the heat was transferred from the rods by conduction or convection, with only 28% being transferred by radiation. These two detailed subchannel calculations served as the base cases with which the calculations for the lumped geometry models were compared.

The results are summarized in Table 4.4 by comparing the peak cladding temperatures calculated for each case. Surprisingly, the results for only one case--the one-dimensional geometry L4--disagreed significantly from the detailed calculation. Even the very simple model in geometry L3 (three subchannels, two rods) yields a peak cladding temperature in reasonable agreement with that of the detailed calculation; the results were within 2°C for the air case and 4°C for the helium case.

FIGURE 4.5. Predicted Peak Cladding Temperatures in Air for Various Lumping Patterns with Uniform Boundary Temperature

FIGURE 4.6. Predicted Peak Cladding Temperatures in Helium for Various Lumping Patterns with Uniform Boundary Temperature

These results indicate that the significant gradients are radial, and that the most important gradient is that between the outer row of rods and the wall. If these gradients are preserved, the interior of the array can be modeled with a single rod and only one or two subchannels, and still yield a peak cladding temperature in reasonable agreement with the detailed case.

The effect of the lumped geometry models on the radial temperature profile across the assembly is illustrated in Figure 4.7 for the air cases and in Figure 4.8 for the helium cases. These illustrations graph the cladding temperatures at the axial location of the peak cladding temperature for the fuel rods lying along the diagonal line of symmetry across the assembly cross section. Cases L1 and L2 match the profile from the detailed geometry S1 quite well in the calculations for both air and helium. The simpler model L3 (with only three channels and two rods) has a much flatter profile--as might be expected, because in this model all of the inner fuel rods in the assembly are at the same temperature.

These results show that with a circumferentially uniform boundary, there are significant gradients in the fuel assembly only in the radial direction. However, in multiassembly storage systems, the assemblies will probably encounter different temperatures on different faces of the assembly canister. In such cases, there could be significant gradients across the assembly.

To investigate the effect of a circumferentially nonuniform boundary, a base-case calculation was made using the detailed subchannel model with boundary temperature profile B_1 imposed on nodes 64 through 69, and 72, while the corner formed by nodes 70 and 72 was given the boundary temperature profile B_2 (from Table 4.2). Figure 4.9 shows a cross section of the assembly, with the nonuniform boundary conditions indicated. Calculations were performed using these boundary conditions with the geometry models L1, L2, and L3, and with two new lumped models that accounted for the circumferentially nonuniform boundary. Air was the only storage medium considered, because the results from the calculations with symmetrical boundary conditions indicate that helium would yield the same trends, only at different temperatures.

FIGURE 4.7. Comparisons of Radial Temperature Profiles Across the Unconsolidated Fuel Assembly in Air Calculated with the Various Geometry Models

FIGURE 4.8. Comparisons of Radial Temperature Profiles Across the Unconsolidated Fuel Assembly in Helium Calculated with the Various Geometry Models

FIGURE 4.11. Lumped 13-Rod/8-Subchannel Model (Geometry L6)

5-subchannel, 5-rod symmetrical model, L2, divided in half along the line of symmetry. Table 4.5 summarizes the calculations made for these six geometries with the circumferentially nonuniform boundary temperatures. The results are presented in Table 4.6 as peak cladding temperatures calculated in each case, and are compared graphically in Figure 4.12.

TABLE 4.5. Summary of Cases for Unconsolidated Single Assembly with Circumferentially Nonuniform Boundary Temperatures

<u>Case No.</u>	<u>Geometry</u>	<u>Storage Medium</u>	<u>Assembly Decay Heat, kW</u>
1	Detailed subchannel (S1)	Air	0.4
2	5 channels, 17 rods (L1)	Air	0.4
3	5 channels, 5 rods (L2)	Air	0.4
4	3 channels, 2 rods (L3)	Air	0.4
5	14 channels, 21 rods (L5)	Air	0.4
6	8 channels, 13 rods (L6)	Air	0.4

TABLE 4.6. Peak Cladding Temperatures in Air Calculated for the Unconsolidated Single Assembly with Circumferentially Nonuniform Boundary Temperatures

<u>Geometry</u>	<u>Peak Cladding Temperature, °C</u>	<u>Radiation Heat Transfer, %</u>
S1	496 (258)	55
L1	492 (255)	60
L2	500 (260)	55
L3	462 (239)	25
L5	501 (261)	58
L6	498 (259)	54

With air as the storage medium, the peak cladding temperature was calculated at 258°C in the detailed subchannel model, for the circumferentially nonuniform boundary. This calculation served as the base case to which the five lumped models considered here were compared. Of the symmetrical geometry models (L1, L2, and L3), the two with five subchannels (L1 and L2) match the predicted peak cladding temperature in the detailed case reasonably well. In both cases, the predicted peak temperature is within 3°C of the peak temperature

FIGURE 4.12. Predicted Peak Cladding Temperatures in Air, with Nonuniform Boundary, for Various Geometries

for geometry S1. The very simple geometry L3 (with only three subchannels and two rods), however, gives unacceptable results. The peak cladding temperature for this case is 19°C below that for the detailed case, even though it gave reasonable results for the subchannel case with uniform boundary temperatures. In the nonuniform boundary case, significant gradients are ignored by modeling the assembly on such a coarse mesh, and the results are correspondingly discrepant.

Examination of the radial temperature profiles for the uniform boundary models shows that, even for the cases in which the predicted peak cladding temperature is essentially correct, the overall results are not in good agreement with the detailed subchannel calculation. Figure 4.13 shows the predicted radial temperature profile across the assembly from the upper right-hand corner to the lower left-hand corner, where the nonuniform boundary is imposed. Results are plotted for the three uniform boundary geometries, L1, L2, and L3. These profiles are too symmetrical compared to the results for the detailed subchannel case, S1.

As shown in Figure 4.14, the predicted peak cladding temperatures for geometries L5 and L6 are in good agreement with the peak temperatures for the detailed case. In addition, Figure 4.14 shows that results for these two geometries yield temperature profiles that are reasonable approximations of the profile for the detailed subchannel case.

These results indicate that the geometry model selected for a spent fuel assembly must accommodate not only radial temperature gradients--from the center to the canister wall--but also any transverse gradients caused by circumferentially nonuniform temperatures on the canister or fuel tube walls.

4.2 REA 2023 CASK UNCONSOLIDATED ASSEMBLY ANALYSIS

The REA 2023 cask was designed by Ridihaigh, Eggers & Associates (REA) to safely store BWR spent fuel assemblies for extended periods. A description of the cask is presented in Section 4.2.1. Based on this description and on

FIGURE 4.14. Comparisons of Radial Profiles Across the Unconsolidated Fuel Assembly Calculated with Nonuniform Boundary Models

the experience gained from conducting the thermal-hydraulic analysis for the cask performance test performed at General Electric-Morris Operation (Wiles et al. 1986), COBRA-SFS models of varying degrees of detail were developed to represent the REA 2023 cask containing unconsolidated spent fuel assemblies. The objective of evaluating the various models was to prepare for analyses of consolidated spent fuel where discrete rod analyses may not always be practical. Descriptions of these models are presented in Section 4.2.2. Using these models, simulations were performed for spent fuel stored in a nitrogen or helium storage medium. The results are summarized in Section 4.2.3.

4.2.1 REA 2023 Cask Description

The REA 2023 BWR spent fuel storage cask is shown in Figures 4.15 and 4.16 and is discussed in detail in the REA topical report submitted to the U.S. Nuclear Regulatory Commission (NRC) (REA 1983). The cask is of the double containment design, with silicone elastomer O-rings used to seal the inner cavity and a seal-welded final closure as a secondary cover. The cask has a smooth, painted outer shell, an ethylene glycol/water neutron shield, and a lead gamma shield. The spent fuel basket is constructed of stainless steel clad Boral for criticality control, copper plates to conduct heat to the cask inner wall, and stainless steel for structural strength. The cask is approximately 2.25 m (8 ft) in diameter and 5 m (16 ft) long, and weighs approximately 100 tons when loaded with 52 unconsolidated BWR spent fuel assemblies.

The inner cask containment shell is 1.91-cm-thick (0.75-in.) stainless steel. The cask inner bottom plate, outer bottom plate, and outer shell are 5-cm-thick (2-in.) stainless steel. Lead gamma shielding, 10.8 cm (4.25 in.) thick in the sidewall, 8.26 cm (3.25 in.) thick in the bottom, and 7.62 cm (3.0 in.) thick in the primary lid, is provided.

Dimensions are in Meters

*Rotated From True Position

FIGURE 4.15. REA 2023 BWR Spent Fuel Storage Cask

FIGURE 4.16. Plan View of Quarter Section of REA 2023 BWR Cask

Each of two 1.27-cm-diameter (0.50-in.) drain lines, which penetrate the cavity bottom plate and the lead, terminates at the outer wall of the cask, where it is sealed by a 1.27-cm (0.5-in.) pipe plug and a 1.91-cm (0.75-in.) pipe plug in series. Both plugs are recessed into the 5.08-cm-thick (2.0-in.) outer shell.

Near the top of the cask, slightly below the primary cover, a 1.27-cm (0.5-in.) vent/sampling line penetrates the cask wall and lead, and terminates with a dual plug arrangement at the outer wall of the cask similar to that for the drain lines.

The cask body has eight attachment points or trunnion supports for bolt-on trunnions. Four of these are located near the top, spaced 90 degrees apart, and may be used for lifting the cask while in the vertical position. Two trunnion supports, 180 degrees apart, are located at an elevation slightly above the center of gravity of the cask when the cask is vertical. These trunnions are used when lifting the cask in the horizontal position and for rotating the cask from a vertical to a horizontal position, or vice versa. The two trunnion supports near the bottom may be used when rotating the cask, and can be used together with those at the top for supporting the cask in a horizontal position during transport or storage on a skid.

The neutron shield outer shell is a 0.64-cm-thick (0.25-in.) stainless steel plate approximately 399 cm (157 in.) long. The shield contains 15.24 cm (6 in.) of 50/50 ethylene glycol/water solution. Within the neutron shield are trunnion supports, to which the trunnions may be externally bolted. The neutron shield is divided into two sections. When the cask is positioned vertically, the bottom section (expansion tank) begins 0.64 cm (0.25 in.) from the cask bottom and extends up to 4.44 cm (15.75 in.). The adjoining top section (neutron shield cavity) is 398 cm (156.75 in.) long. The only connection between the two sections is a 1.91-cm (0.75-in.) schedule 40 stainless steel siphon pipe. This pipe runs from the top of the neutron shield cavity to the bottom of the expansion tank when the cask is in either the vertical or horizontal orientation. The neutron shield cavity has top and

bottom fill and drain plugs. The expansion tank has a bottom drain plug and a liquid-level indicating plug.

The inner or primary lid, which is recessed into the cask cavity, has a bottom plate 2.54 cm (1.0 in.) thick and a top plate 5.08 cm (2.0 in.) thick, with 7.62 cm (3.0 in.) of lead between the plates. The lid is secured to the cask body with 36 high-strength bolts 3.18 cm (1.25 in.) in diameter. Sealing is accomplished by two silicone elastomer O-rings. A hole through the top plate and between the O-rings is tapped for a 0.32-cm (1/8-in.) pipe plug that permits checking for leak tightness.

The outer or secondary lid, of 5.08-cm thick (2.0-in.) stainless steel, has a stainless steel angle welded around its circumference, to mate with a similar angle at the top of the outer wall of the cask body. These angles are seal-welded, after loading, to provide high integrity, long-term leak tightness. The angles are of such size that they may be ground and rewelded twice before requiring replacement.

The basket is fabricated in four sections, which are located in the cask inner cavity as shown in Figures 4.16 and 4.17. Contact is made with the inner wall of the cask, thus minimizing thermal resistance. Each basket section has thirteen 15.2-cm (6-in.) square Brooks and Perkins fuel tubes, each of which contains one BWR spent fuel assembly. These fuel tubes are essentially identical to the fuel tubes currently licensed for use in spent fuel storage pools. Each tube consists of concentric inner and outer square "shrouds", which integrally encapsulate Boral neutron absorber plates. Boral is a neutron poison material consisting of boron carbide uniformly dispersed within a matrix of aluminum alloy. The Boral neutron absorber plates extend above and below the active length of the fuel and are 0.185 cm (0.073 in.) thick and contain a boron-10 content of 0.02 g/cm^2 to provide adequate neutron attenuation.

The outer shell of each basket section and two internal ribs are constructed of 0.64-cm (0.25-in.) copper plates for conduction of heat to the

FIGURE 4.17. REA 2023 Cask Basket for 52 BWR Fuel Assemblies

inner wall of the cask (Figure 4.17). Other structural members of the basket are fabricated from stainless steel. The basket rests on the bottom of the cask, and has cutouts to permit water drainage and gas circulation.

4.2.2 COBRA-SFS Cask Model

COBRA-SFS models of varying degrees of detail were developed to represent the REA 2023 cask containing unconsolidated spent fuel assemblies. The basic cask geometry model is presented in Section 4.2.2.1. The lumped subchannel assembly models used in the analysis are described in Section 4.2.2.2. The material properties and correlations used are discussed in Section 4.2.2.3.

4.2.2.1 Cask Geometry Model

The unconsolidated fuel analysis used a three-dimensional, one-eighth-symmetry model of the cask. A cross section of the computational cell arrangement for the unconsolidated cask model is presented in Figure 4.18.

FIGURE 4.18. One-Eighth Section, COBRA-SFS Nodal Representation of the REA Cask

Solid structural wall nodes were used to model the cask body and basket and the stainless steel canisters. Radiation and/or conduction heat transfer between wall nodes was accounted for within a plane by specifying the appropriate thermal wall conductance terms. Wall axial conduction was also accounted for. Within the basket, the fuel tube walls and adjacent heat conduction strips were split into two nodes, allowing development of circumferential temperature gradients. For the complex geometry of the basket/cask interface, finer meshing was employed to allow more rigorous conduction and radiant heat exchange within this region. Coarser meshing was employed within the relatively simple geometry of the cask body. The cask body and basket were modeled using 106 wall nodes.

The radiant heat exchange between rods and walls in a fuel tube was computed from user-prescribed gray body exchange factors based on one-quarter rod surface segments, a more exact approach to the assumption of uniform radiosity over a surface. Proper subdivision of fuel rod surface has been previously shown to be significant in determining the proper radiative heat exchange within an enclosed assembly (Cox 1977). All gaseous fill media were considered nonparticipating.

The computational model described above extends into the cask body, terminating at the inner boundary of the ethylene glycol/water chamber. Within this region, the mass, momentum, and energy conservation equations were solved, resulting in predicted velocity and temperature distributions. To describe the heat transfer from the glycol inner boundary to the ambient, a boundary heat transfer model was employed. To determine the temperature distribution within the boundary regions, a one-dimensional energy equation was solved. Heat transfer between boundary regions can include forms of radiation and natural or forced convection. Four boundary regions were employed--a single region each for the neutron shield liner and outer boundary, the ethylene glycol/water mixture, and the ambient air.

To describe the heat transfer from the recirculating fluid in the regions immediately above and below the fuel tubes, through the lid and cask bottom to the ambient, an optional plenum model was employed. As with the boundary region model, only a one-dimensional energy equation was solved. The upper lid was modeled with 10 nodes; five nodes apiece were used to describe heat transfer in the axial and radial directions. For the bottom of the cask, only five nodes were used, as the bottom surface of the lid was assumed adiabatic. The overall heat transfer from the lid and bottom was modeled by specifying the thermal resistance between each region. Conduction heat transfer between the basket and cask body to the lid and bottom were also simulated via the plenum model.

4.2.2.2 Lumped Subchannel Assembly Models

The results of the calculations for single-assembly unconsolidated fuel indicate that the COBRA-SFS code can produce reasonable results with a relatively coarse representation of spent fuel assemblies. The temperature boundary conditions on the walls of the canister enclosing the fuel, however, have a significant influence on what constitutes an adequate level of detail in the geometry model. Calculations were made in the REA cask to investigate the effect of subchannel-and-rod noding detail in a multiassembly storage system with unconsolidated assemblies to prepare for consolidated fuel analysis. Helium and nitrogen were considered as storage media. A base-case calculation was made with a detailed rod-and-subchannel model for each fuel assembly in the cask. A nominal REA run was selected for these calculations, with an ambient boundary temperature of 52°C, a painted cask surface, and nominal decay heat of 0.4 kW per unconsolidated assembly.

The COBRA-SFS model uses a one-eighth section of symmetry containing three full assemblies and three half-assemblies divided on the line of symmetry. Figure 4.18 shows a cross section of the REA cask model. The detailed subchannel model for the assemblies in the REA cask is essentially identical to geometry S1 for the single assembly described in Section 4.1. This model is designated as geometry SC1. Figure 4.19 diagrams the model for a full

FIGURE 4.19. Detailed 64-Rod/77-Subchannel Model of Fuel Assembly in the RCA Cask

assembly, and Figure 4.20 illustrates a model for an assembly cut along the diagonal for a half-section of symmetry. The wall nodes (labeled W_1 through W_8) correspond to the nodes modeling the walls of the assembly canisters in the REA cask.

The lumped subchannel model LC1 selected for the cask calculations is shown in Figure 4.21 for a full assembly, and in Figure 4.22 for a half-section of symmetry. This model was selected based on the results of the single-assembly calculations, which indicated that circumferential as well as radial gradients needed to be accommodated in the geometry model. The model consists of 15 subchannels and 22 rods and is similar to the model that yielded the best comparison with the detailed subchannel case for the single assembly with nonuniform skewed boundary temperatures.

The results obtained with the LC1 geometry were in good agreement with the results of the detailed SC1 subchannel calculation in the REA cask, so a second lumping scheme, LC2, was selected to try out a somewhat coarser noding. (This geometry was run in nitrogen only, as the results with this fill medium are more sensitive to the hydrodynamics than are those with helium.) The selected subchannel and rod noding is illustrated in Figure 4.23 for a full assembly, and in Figure 4.24 for a half section of symmetry. This model consisted of only 11 subchannels and 11 rods in a full assembly, and attempts to account for circumferential gradients primarily with the ring of 8 channels around the wall. The rod noding pattern also helps preserve any circumferential gradients, but the model assumes relative circumferential uniformity in the interior fluid subchannels by modeling the flow field with subchannels in radial rings.

As a further check on the feasibility of lumping subchannels in assembly models within the cask, calculations were performed using a detailed rod-and-subchannel model in the hot assembly, with all other assemblies modeled with the lumping pattern developed for the LC1 geometry. This case is referred to as SLC1, and was run in both air and helium.

FIGURE 4.20. Detailed 36-Rod/42-Subchannel Model of Half Assembly in the REA Cask

4.2.2.3 Material Properties and Correlations

Except for emittances, the material properties used in the model were well defined. Fluid properties were input as functions of temperature and continuously updated during the simulation. Property values for the solids and for the ethylene glycol/water mixture (Curme and Johnston 1982) remained

FIGURE 4.21. Lumped 22-Rod/15-Subchannel Model (Geometry LC1) for Full Assemblies in the REA Cask

constant and were evaluated based on a preliminary predicted cask temperature distribution. Wall heat transfer in the radial and circumferential directions was modeled by specifying appropriate thermal resistances. The input value of resistance for a composite of materials is a combination of parallel and/or series paths. The resistances were obtained as functions of temperature, but remained constant during the simulation. As-measured emissivity values were

FIGURE 4.22. Lumped 14-Rod/9-Subchannel Model (Geometry LC1) for Half Assembly in the REA Cask

provided for the fuel tube and the high-emissivity paint used to coat the outer surface of the neutron shield (Taylor 1983, 1984). A wide range of emittances is possible for the other cask components; these emittances are dependent on fabrication technique, temperature, and oxidation buildup. A tabulation of the emittances used in the analysis is presented in Table 4.7; emittances not experimentally determined were assumed values.

FIGURE 4.23. Lumped 11-Rod/11-Subchannel Model (Geometry LC2) for Full Assembly in the REA Cask

Heat transfer from the rods and walls to the gas coolant was prescribed using a film coefficient of $Nu = 3.658$ (Kays and Crawford 1980). The film coefficient was evaluated as a function of temperature at each location.

The overall contribution of convective heat transfer is dependent in part by the flow field established. For these simulations the flow field is

FIGURE 4.24. Lumped 8-Rod/7-Subchannel Model (Geometry LC2) for Half Assembly in the REA Cask

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 approximately zero. Thus, the flow resistance of the cask becomes an important convection parameter. The overall cask flow resistance is assumed to be a combination of:

TABLE 4.7. Material Emittance Values

Component	Emittance
Fuel rods	0.8
Fuel tubes (stainless steel)	0.2 (measured)
Other stainless steel surfaces	0.2
Copper	0.5
Lead	0.6
High emissivity paint	0.78 (measured)
Cask surface (stainless steel)	0.3

- rod and wall surface drag
- spacer losses
- fuel tube inlet and exit losses
- fuel assembly inlet and outlet losses.

Rod and wall friction were modeled using an analytical solution for fully developed laminar flow along cylinders arranged in a square array, $f = 100/Re$ (Sparrow and Loeffler 1959). Spacer and fuel assembly inlet and outlet losses were included by specification of a pressure loss coefficient of 1.0. The major source of uncertainty, however, was the fuel tube inlet and outlet flow resistances. Loss coefficients for the fuel tube inlet and outlet were obtained from a handbook of hydraulic resistance (Idel'Chik 1966); uniform values of $K = 9$ and $K = 3$ were assigned for the fuel tube inlets and outlets, respectively.

Heat transfer from the subchannel model to the boundary requires specification of the heat transfer across the glycol/water annulus, and from the cask surface to the ambient. Heat transfer from natural convection in the partitioned glycol/water annulus was modeled as a function of the temperature difference across the annulus using

$$Nu = 0.22A^{-1/4} \left(\frac{Pr}{0.2 + Pr} Pr Gr \right)^{0.28} \quad (4.1)$$

where Pr is the Prandtl number, Gr the Grashof number, and A the annulus aspect ratio, L/D (Catton 1978). Because of uncertainties associated with application of this correlation to the neutron shield, Equation (4.1) was assumed to apply with the cask oriented either horizontally or vertically.

Heat transfer from the cask surface to the ambient included both radiation and convection components. The cask surface natural convection film coefficients were evaluated from an expression obtained for vertical cylinders and horizontal plates in air at atmospheric conditions, given as

$$Nu = C(Gr Pr)^{0.33} \quad (4.2)$$

where $C = 0.13$ for vertical surfaces and $C = 0.14$ for horizontal surfaces (Lindeburge 1981). Radiation heat transfer to the ambient was included in addition to the natural convection component described above. The radiation component was based on radiative heat exchange between gray bodies and was determined as a function of heat transfer area and cask emissivity. Two cask surface emissivities were used: 0.78, an as-measured value of the high-emissivity paint used to cover the surface of the neutron shield (Taylor 1984), and 0.3, the assumed emissivity for the unpainted stainless steel cask surfaces. The ambient was assumed to be a black body ($\epsilon = 1.0$).

4.2.3 Simulation Results

The calculations made in the REA cask model using the assembly models described in Section 4.2.2.2 are listed in Table 4.8. The results obtained with the detailed subchannel model in all assemblies (Geometry SC1) served as the reference case for the calculations with lumped geometry models. Table 4.9 summarizes the results of the calculations with nitrogen as the storage medium for the various geometry models considered by comparing peak cladding temperatures calculated for each assembly. Table 4.10 presents a similar

TABLE 4.8. Summary of Calculations in the REA Cask

<u>Run No.</u>	<u>Assembly Geometry Model</u>	<u>Storage Medium</u>	<u>Decay Heat kW/assembly</u>	<u>Ambient Boundary Temperature, °C</u>
1	SC1	Nitrogen	0.4	52
2	LC1	Nitrogen	0.4	52
3	LC2	Nitrogen	0.4	52
4	SLC1	Nitrogen	0.4	52
5	SC1	Helium	0.4	52
6	LC1	Helium	0.4	52
8	SLC1	Helium	0.4	52

TABLE 4.9. Predicted Peak Cladding Temperatures in REA Cask With Nitrogen Backfill, °C

<u>Assembly</u>	<u>Geometry Model</u>			
	<u>SC1</u>	<u>LC1</u>	<u>LC2</u>	<u>SLC1</u>
1	226.4	225.1	217.8	224.8
2	225.6	224.2	218.4	223.4
3	228.7	229.9	222.4	228.6
4	221.7	219.6	214.1	218.8
5	230.8	230.1	228.4	232.1
6	228.4	230.8	221.5	229.3
7	214.0	216.7	210.6	215.6

TABLE 4.10. Predicted Peak Cladding Temperatures in REA Cask With Helium Backfill, °C

<u>Assembly</u>	<u>Geometry Model</u>		
	<u>SC1</u>	<u>LC1</u>	<u>SLC1</u>
1	205.8	203.3	202.4
2	204.6	202.4	201.3
3	205.4	209.1	207.9
4	199.1	196.7	195.4
5	211.1	208.1	212.4
6	207.4	206.8	205.9
7	189.0	186.2	185.2
8	194.1	190.7	189.8

comparison for the calculations with helium as the storage medium. With nitrogen as the storage medium, the peak cladding temperature was 321°C. With helium as the storage medium, the peak cladding temperature was 211°C.

The calculation with the detailed subchannel model of the hot assembly (with all other assemblies modeled using 15 subchannels and 22 rods per assembly) are in very good agreement with the results for the detailed subchannel model in all assemblies. However, these results are not significantly better than those obtained with the 22-rod/15-subchannel with LC1 assembly model (Geometry LC1), so there is no particular virtue in using the more complicated model. A lumped model in all assemblies is good enough, so long as it is of sufficient detail to resolve the significant temperature gradients.

5.0 CONSOLIDATED ASSEMBLY ANALYSES

Consolidation of spent nuclear fuel assemblies is being considered as one option for more efficient and compact storage of reactor spent fuel. One major issue that must be addressed prior to implementation is the thermal performance of consolidated fuel rods in dry storage. This section documents simulations performed to predict the thermal behavior of both the REA 2023 and CASTOR-1C casks containing unconsolidated and consolidated BWR fuel.

As stated in Section 4.0, the use of detailed rod and subchannel models to describe a spent fuel storage cask may result in an exceedingly large problem size. This is especially true for problems with consolidated assemblies. For this reason, calculations were first made using detailed rod-and-subchannel models of a single canister containing consolidated fuel from two 8x8 BWR assemblies. Models with varying degrees of detail were investigated, and the results compared to the detailed model results. Section 5.1 describes these models and presents the results of the comparisons.

Based on the results obtained in the single-assembly calculations, a series of simulations was performed for consolidated fuel in both the REA 2023 and CASTOR-1C casks. These results are compared with those from casks filled with unconsolidated assemblies generating the same total decay heat. A comparison of results for the REA 2023 cask is presented in Section 5.2, and that for the CASTOR-1C cask is presented in Section 5.3.

5.1 SINGLE CONSOLIDATED ASSEMBLY GEOMETRY MODELING

A consolidated assembly is assumed to consist of a square canister, designed to fit inside a typical cask fuel tube [approximately 15 cm (6 in.) on a side] and filled with close-packed BWR fuel rods. A 14-cm-square (5.5-in.) canister was selected, filled with 126 BWR rods on a triangular pitch. A cross section of the assembly with the detailed rod-and-subchannel model is shown in Figure 5.1. The detailed model consists of 126 rods and 230 subchannels. It is assumed that the canister is centered within the fuel

FIGURE 5.1. Detailed 126-Rod/230-Subchannel Consolidated Assembly Model

tube. It is conservatively assumed that, within the canister, there is no contact between the rods or between the rods and the canister. The canister is assumed to be 0.025 cm (0.010 in.) thick and have a surface emissivity of

0.2. There is no geometric symmetry about the diagonal, so that a one-half assembly model is not possible.

A consolidated assembly model is significantly larger than the unconsolidated model, with nearly twice as many rods and three times as many subchannels. For single-assembly analyses, this does not present a problem; for cask analyses involving several assemblies, this results in an unacceptably large problem size. But experience with COBRA-SFS (Section 4.1) has shown that reasonable results can often be obtained with much coarser representations of assembly geometries.

The subchannel noding shown in Figure 5.1 models the continuous flow field in a consolidated assembly as an array of discrete control volumes, based on the assumption that the gradients of interest are small enough within the volume that the primary variables--velocity, temperature, and density--can be reasonably represented by a single average value. A subchannel can be defined over any geometric area of the flow field where the assumption of relatively insignificant gradients is reasonable.

In a COBRA-SFS model, a rod is an arbitrarily defined heat transfer surface, just as a channel is an arbitrarily defined control volume in the flow field. In the detailed subchannel model, a COBRA-SFS rod models a single fuel rod. However, a COBRA-SFS rod can be used to model any heat transfer surface or collection of surfaces. The criterion for determining which surface or surfaces can be modeled by a single COBRA-SFS rod is the surface temperature. Surfaces at the same temperature, or nearly the same temperature, can be modeled with a single COBRA-SFS rod.

To select an appropriate coarse model to represent the consolidated assembly, detailed model simulations were performed based on the boundary conditions and axial decay heat profile given in Table 4.1 for both air and helium storage media. Based on the results from the simulation, several different coarse models were developed and tested to determine their consistency. As a result of this investigation, two coarse models were selected which accurately represent a consolidated spent fuel assembly.

Figure 5.2 shows a consolidated assembly model that requires 9 rods and 10 subchannels. The shading indicates how the rods are combined. This model is based on the assumption that the primary temperature gradient is in the radial direction, with negligible heat being transferred circumferentially around the assembly. This is especially true for casks that use a highly conducting basket to remove heat from the center of the cask instead of relying on heat transfer through the assemblies.

FIGURE 5.2. Consolidated Assembly Model Consisting of 9 Rods and 10 Subchannels

In situations where circumferential heat transfer is significant, the rod and subchannel rings must be subdivided to allow for circumferential temperature gradient. Because there is no symmetry about the diagonal, the model is divided into four quadrants as shown in Figure 5.3. This more detailed model requires 31 rods and 35 subchannels. The rod numbers indicate how the rods are combined. In both coarse models, the canister is divided into four wall nodes.

The coarse models were evaluated by performing single consolidated assembly simulations for both air and helium using the same boundary conditions as for the detailed model. The decay heat generation rate was assumed to be 0.8 kW per assembly, with the axial decay heat distribution listed in Table 4.1. The boundary temperature profiles for the air and helium cases are listed in Table 4.2. The boundary temperature profile B1 was imposed uniformly on the outer fuel tube walls.

Comparisons of radial temperature profiles for the detailed consolidated assembly model and smallest coarse model (9 rods, 10 subchannels) at the peak temperature axial level are shown in Figure 5.4 for both nitrogen and helium. The maximum temperature difference between profiles is less than 5°C for both media. The coarse model with 31 rods and 35 subchannels results in a radial temperature profile that compares even more closely with results from the detailed model. The excellent agreement between profiles indicates that the coarse models accurately represent consolidated spent fuel assemblies.

To understand the effect of fuel rod consolidation on the temperature distribution, each of the three heat transfer modes--conduction, convection, and radiation--must be examined separately. Conduction heat transfer is enhanced by consolidation because low conductivity gas is replaced by relatively high conductivity fuel rods and canister. The amount of convection heat transfer is reduced due to the reduction of the flow area. Because the canister is closed, only the annular region between the canister and fuel tube is available for natural circulation. Radiation heat transfer is also reduced between both the fuel rods and between the rods and the fuel tube. When the

FIGURE 5.3. Consolidated Assembly Model Consisting of 31 Rods and 35 Subchannels

fuel rods are consolidated, rod shadowing increases so that each rod sees only rods adjacent to it. In addition, the low emissivity canister provides an effective radiation barrier between the fuel rods and fuel tube. For this reason, the amount of radiation heat transfer that occurs is very sensitive to the surface emissivity of the canister.

FIGURE 5.4. Comparisons of Detailed and Coarse Model Radial Temperature Profiles

A comparison of the unconsolidated and consolidated radial profiles for both nitrogen and helium are shown in Figures 5.5 and 5.6, respectively. Note that in the nitrogen case, the peak cladding temperature is significantly higher in the consolidated case. This is because radiation, which is the dominant mode of heat transfer in the unconsolidated case, is dramatically reduced in the consolidated case. In contrast, the peak cladding temperature in the helium case is lower than in the consolidated case. This is because conduction, which is the dominant mode of heat transfer in the unconsolidated case, is enhanced in the consolidated case.

FIGURE 5.5. Comparison of Unconsolidated and Consolidated Single-Assembly Radial Temperature Profiles in Nitrogen

FIGURE 5.6. Comparison of Unconsolidated and Consolidated Single-Assembly Radial Temperature Profiles in Helium

5.2 REA 2023 CASK SIMULATION RESULTS

Using the cask model described in Section 4.2 and the fuel assembly models described in Sections 4.1 and 5.1, a series of REA 2023 simulations was performed using the COBRA-SFS code for both unconsolidated and consolidated BWR fuel assemblies in a nitrogen or helium storage medium. The cases for which calculations were performed are described in Section 5.2.1. The results from these simulations are discussed in Section 5.2.2.

5.2.1 Case Descriptions

Ten simulations were performed to characterize the thermal performance of the REA 2023 cask under various conditions. Each of these simulation cases is described in Table 5.1. In all cases it was assumed that the cask was vertical and the ambient temperature was the current 10 CFR 71 limit of 100°F (38°C). Four simulations (Cases 1 through 4) were performed in which the cask contained unconsolidated fuel assemblies. In these cases the cask model

TABLE 5.1. REA 2023 Simulation Case Description

Case No.	Fuel Model			Storage Medium		Assembly Power	
	Uncon.	Consol., Coarse	Consol., 1 Detailed	Nitrogen	Helium	0.8 kW	Q_{max} for 400°C
1	X			X		X	
2	X				X	X	
3	X			X			X
4	X				X		X
5		X		X		X	
6		X			X	X	
7		X		X			X
8		X			X		X
9			X	X		X	
10			X		X	X	

was small enough that no simplification of the detailed fuel model was required. In the first two cases, simulations were performed assuming an assembly decay heat of 0.8 kW and storage media of nitrogen and helium, respectively. Based on the temperature results from these simulations, an additional two cases (Cases 3 and 4) were simulated to predict the maximum allowable assembly heat generation rate for both storage media. The predicted maximum heat rate was determined subject to temperature constraints for peak cladding temperature, melting point of the lead gamma shield, and saturation temperature of the ethylene glycol/water neutron shield. After a limited number of iterations, a maximum heat load was identified along with the limiting constraint.

Six simulations (Cases 5 through 10) were performed in which the cask contained consolidated fuel assemblies. Because of the prohibitively large number of subchannels required for detailed models of the consolidated assemblies, a coarse model was used for the REA cask. Figure 5.3 shows the 31-rod/35-subchannel coarse model for a full assembly. In two cases (5 and 6), simulations were performed assuming a canister decay heat of 0.8 kW and storage media of nitrogen and helium, respectively. To verify that the coarse assembly models accurately predicted the temperature distribution, two additional simulations (Cases 9 and 10) were performed in which the canister containing the peak temperature fuel rod was modeled using the detailed consolidated assembly model. Based on the results from these simulations, two additional cases (7 and 8) were performed to predict the maximum allowable heat generation rate for both storage media.

5.2.2 Simulation Results

Ten simulations were performed to characterize the thermal performance of the REA 2023 cask under various conditions. Of these, six simulations (Cases 1, 2, 5, 6, 9, and 10) were performed to predict the peak cladding temperature obtained with an assembly/canister heat generation rate of 0.8 kW. The predicted peak cladding temperatures for the six cases are given in Table 5.2.

TABLE 5.2. Predicted REA 2023 Cask Peak Cladding Temperatures

Case No.	Case Description	Peak Cladding Temperature, °C
1	Unconsolidated, nitrogen	384
2	Unconsolidated, helium	304
5	Consolidated (coarse), nitrogen	484
6	Consolidated (coarse), helium	324
9	Consolidated (1 detailed), nitrogen	486
10	Consolidated (1 detailed), helium	325

The remaining four simulations (Cases 3, 4, 7, and 8) were performed to determine the maximum allowable heat generation rates that would still meet the temperature limitations of the cask and fuel assembly/canister. The results of each simulation are discussed in more detail below.

The first two simulations (Cases 1 and 2) were performed with the REA 2023 cask containing unconsolidated fuel in both nitrogen and helium storage media. Axial temperature profiles of the peak temperature rod for both cases are shown in Figure 5.7. The peak cladding temperature is determined to be 384°C for the nitrogen case and 304°C for the helium case, a difference of 80°C. The elevation of the peak temperature in the nitrogen case is approximately 3.2 m as compared to 2.5 m for the helium case. The temperature profile for the nitrogen case is skewed upward due to a significant amount of natural circulation occurring within the cask. To illustrate the difference, the maximum predicted assembly average velocity is approximately 22 cm/sec (0.71 ft/sec) in the nitrogen case as compared to 8 cm/sec (0.26 ft/sec) in the helium case.

The radial temperature profile, taken along the diagonal from the center of the cask, is shown in Figure 5.8 for both locations. The differences between the two profiles occur in two regions: 1) in the gaps between structural members that are filled with storage medium and 2) within the individual fuel

FIGURE 5.7. Comparison of REA 2023 Cask Axial Temperature Profile Predictions for Unconsolidated Fuel in Nitrogen and Helium

FIGURE 5.8. Comparison of REA 2023 Cask Radial Temperature Profile Predictions for Unconsolidated Fuel in Nitrogen and Helium

assemblies. The temperature differences in these regions are reduced in the helium case due to a thermal conductivity that is significantly higher than that for nitrogen.

Based on the temperature results from these two simulations, two additional cases (3 and 4) were performed to predict the maximum allowable assembly heat generation rate for both storage media. The predicted maximum heat rate was determined subject to three temperature constraints:

- 400°C allowable peak cladding temperature

- 327°C lead melting point
- 148°C (50-psia) saturation temperature of the ethylene glycol/water in the neutron shield.

After a limited number of iterations, a maximum assembly heat rate was identified along with the limiting constraint. These results are shown in Table 5.3. For the nitrogen case, the maximum allowable heat rate was determined to be approximately 0.84 kW/assembly, with the limiting constraint being a peak cladding temperature of 400°C. For the helium case, the maximum allowable heat rate was determined to be approximately 0.84 kW/assembly, with the limiting constraint being an ethylene glycol saturation temperature of 148°C. The peak cladding temperature in this case was 312°C.

TABLE 5.3. Predicted REA 2023 Maximum Assembly Decay Heat Generation Rate for Unconsolidated Fuel

<u>Case No.</u>	<u>Case Description</u>	<u>Assembly Decay Heat Power, kW</u>	<u>Temperature Limit, °C</u>
3	Unconsolidated, nitrogen	0.84	Peak cladding = 400
4	Unconsolidated, helium	0.84	Neutron shield = 148

Following completion of the unconsolidated fuel assembly simulations, a set of six simulations (Cases 5 through 10) was performed with the REA 2023 cask containing consolidated fuel. Using the 9-rod/10-subchannel coarse assembly model described in Section 5.1, cask simulations (Cases 5 and 6) were performed assuming a heat generation rate of 0.8 kW/canister. The axial temperature profiles of the peak temperature rod for both nitrogen and helium are compared with the corresponding unconsolidated assembly profiles in Figures 5.9 and 5.10, respectively.

The predicted peak cladding temperature for the consolidated nitrogen case is 484°C compared to 384°C in the unconsolidated case, an increase of 100°C. The axial temperature profile for the consolidated case is considerably

FIGURE 5.9. Comparison of REA 2023 Cask Axial Temperature Profile Predictions for Consolidated and Unconsolidated Fuel in Nitrogen

FIGURE 5.10. Comparison of REA 2023 Cask Axial Temperature Profile Predictions for Consolidated and Unconsolidated Fuel in Helium

less skewed upward than it was in the unconsolidated case. This indicates that consolidating the fuel severely reduced the amount of natural circulation occurring within the cask. In addition, radiation heat transfer was reduced due to increased rod shadowing and the addition of a low-surface-emissivity canister. Therefore, the two primary modes of heat transfer in the nitrogen case, convection and radiation, were impeded by the consolidated geometry, resulting in a dramatic temperature increase.

By contrast, the predicted peak cladding temperature for the consolidated helium case is 324°C as compared to 304°C in the unconsolidated case, an increase of only 20°C. As in the nitrogen case, radiation heat transfer was reduced due to consolidation of the fuel. However, conduction heat transfer was enhanced because the low conductivity gas was replaced with the high conductivity fuel rods and canister. Therefore, of the two primary modes of heat transfer in the helium case, conduction was enhanced and radiation was reduced, resulting in a relatively small temperature increase.

To verify that the 9-rod/10-subchannel coarse consolidated canister models used in the cask analysis adequately represented the consolidated fuel assemblies, the coarse model used to represent the geometry of the canister containing the rod with the peak temperature was replaced with a detailed 126-rod/230-subchannel consolidated model. (Due to problem size limitations, it was not possible to develop a cask model with detailed 126-rod/230-subchannel representations of all canisters). Simulations were performed for both nitrogen and helium. In both cases (9 and 10), the resulting predicted peak axial temperature profiles with and without a detailed canister model were within 2°C throughout the profile. This indicates that the coarse model adequately predicts the temperature distribution in the consolidated fuel canisters.

Based on the temperature results from the consolidated fuel simulations, two additional cases (7 and 8) were performed to predict the maximum allowable canister heat generation rate for both storage media. The temperature constraints considered were the same as those used for the unconsolidated assembly simulations. After a small number of iterations, a maximum canister

heat rate was identified along with the limiting constraint. The results are shown in Table 5.4. For the nitrogen case, the maximum allowable heat rate was determined to be approximately 0.60 kW/canister, with the limiting constraint being a peak cladding temperature of 400°C. For the helium case, the maximum allowable heat rate was determined to be approximately 0.80 kW/canister; the limiting constraint was an ethylene glycol/water saturation temperature of 148°C. The peak cladding temperature in this case was 332°C.

TABLE 5.4. Predicted REA 2023 Maximum Assembly Decay Heat Generation Rate for Consolidated Fuel

Case No.	Case Description	Canister Decay Heat kW	Temperature Limit, °C
7	Consolidated, nitrogen	0.60	Peak cladding = 400
8	Consolidated, helium	0.80	Neutron shield = 148

5.3 CASTOR-1C CASK ANALYSIS

The second cask analysis performed was the CASTOR-1C BWR spent fuel storage cask. The cask is described in Section 5.3.1. Based on this description and on the experiences gained from performing the thermal-hydraulic analysis for the cask test conducted at the Wurgassen Nuclear Power Plant (Rector et al. 1986), a COBRA-SFS model was developed to represent the CASTOR-1C cask and is presented in Section 5.3.2. Using this model, a set of simulations was performed for the cask containing either consolidated or unconsolidated spent fuel assemblies. The results from these simulations are summarized in Section 5.3.3.

5.3.1 CASTOR-1C Cask Description

The CASTOR-1C cask (GNS 1983, 1985) is designed to safely store and remove the decay heat from 16 BWR spent fuel assemblies for extended periods. A cut-

away drawing of the CASTOR-1C cask is shown in Figure 5.11. The cask consists of a thick-walled nodular cast-iron body, cast in one piece. The body serves to physically protect the fuel assemblies and to provide radiation shielding. The central cavity of the cask contains a borated stainless steel basket that separates and supports the spent fuel assemblies. The top of the cask is sealed with a multiple-cover system. The overall cask dimensions and design specifications are summarized in Table 5.5. Each region of the cask is described in more detail below.

5.3.1.1 Cask Body

A cross section of the CASTOR-1C cask is shown in Figure 5.12. The cast-iron body of the cask has an overall length of 5510 mm (18.1 ft) and a maximum outside diameter of 1730 mm (5.7 ft). The side wall thickness (without fins) is approximately 440 mm (1.4 ft). Gamma and neutron radiation are shielded by the cast-iron wall of the cask. For improved neutron shielding through the side, two concentric rows of axial holes in the wall of the cask body are filled with polyethylene rods (moderator material). The rods are 60 mm (2.4 in.) in diameter and extend axially from the bottom of the cask to above the top elevation of the fuel assemblies. The maximum dose rate (gamma and neutron) on the cask surface is designed to be 200 mrem/hr or less. The maximum value for the average surface dose rate is 20 mrem/hr.

The outside surface of the cask varies as a function of axial level. Near the top and bottom of the cask, the surface is a cylinder (1905 mm, 6.25 ft in diameter) with four flat surfaces machined so the minimum flat-to-flat distance is 1730 mm (5.7 ft). In the axial region of the fuel assemblies, a set of 48 axial cooling fins enhances the removal of heat by natural convection. A cross section of the CASTOR-1C cask illustrating the cooling fin geometry is shown in Figure 5.13. The fins are 120 mm (4.7 in.) long, 50 mm (2 in.) wide at the base, and spaced approximately 112 mm (4.4 in.) apart. The outside of the cask is protected by an epoxy resin coating in the fin area. The fins

FIGURE 5.11. Elevation View of CASTOR-1C Cask

TABLE 5.5. CASTOR-1C Cask Dimensions and Design Specifications

Cask overall length, mm (ft)	5510 (18.0)
Cross section, mm (ft)	1730 (5.7)
Cask cavity width, mm (ft)	666 (2.2)
Cavity length, mm (ft)	4560 (15)
Sidewall thickness without fins, mm (ft)	440 (1.4)
Lid thickness, mm (ft)	
Primary lid	340 (13.4)
Secondary lid (incl. moderator)	130 (5.1)
Protection plate	80 (3.1)
Bottom thickness, mm (in.)	447 (17.6)
Moderator dimensions, mm (in.)	
Number of polyethylene moderator rods	80
Rod diameter	6 (2.4)
Moderator thickness sec. lid	6 (2.4)
Moderator thickness bottom	42 (1.7)
Number of cooling fins	48
Cask fuel assembly capacity	16
Cask atmosphere	helium
Cavity pressure, bar	0.8 (11.8)
Weight, tonne	
Empty cask	76.6
Loaded cask	81.1

FIGURE 5.12. Cross Section of CASTOR-1C Cask

FIGURE 5.13. Cooling Fin Geometry

are also covered with a high emissivity paint to aid in transferring heat from the cask surface. The remainder of the cask surface is covered with a corrosion-resistant nickel coating.

The thickness of material from the bottom of the inner cavity to the bottom of the cask is approximately 450 mm (17.7 in.). The major portion of this is cast iron. However, some of the cast iron is machined from the bottom of the cask and is replaced by concentric rings of polyethylene which serve as neutron shields. A semi-permanent steel cover plate is secured over the rings to hold them in place.

5.3.1.2 Cask Cavity and Basket

The cask inner cavity is square, 666 mm (2.2 ft) wide, and 4560 mm (15 ft) long. The bottom of the cavity is sloped slightly to enhance the draining of fluid. The inside of the cask, including the sealing surfaces, has a nickel

coating for corrosion protection. A support plate placed on the bottom of the cavity provides a level support for the basket and fuel assemblies.

The welded basket is made of borated stainless steel to reduce the possibility of criticality. The basket divides the cavity into 16 regions, each designed to contain a single BWR spent fuel assembly. A cross section of the fuel basket can be seen in Figure 5.13. The stainless steel plates used to construct the basket are 10 mm thick, and the overall basket width is 640 mm (2 ft). This leaves a gap between the basket and cavity wall of approximately 13 mm (0.5 in.) on all sides. The basket is designed to allow the top and bottom portions of the cavity to be open. This allows communication between adjacent assembly tubes and the possibility of natural circulation to occur inside the cavity. The basket also serves as a conduction heat transfer path from the center assemblies to the cask body.

During normal operation the cask is filled with helium. The inert gas inhibits corrosion and results in a higher peak cladding temperature limit. Helium also has a high conductivity, which enhances heat transfer in the cavity. The primary disadvantage is that an extensive sealing system is required to contain the gas. The cask cavity pressure during normal operation is 0.8 bar (11.8 psia).

5.3.1.3 Cask Lid System

The CASTOR-1C cask is sealed with a multiple-cover system comprising a primary lid, a secondary lid, and a protection plate. The three lids are shown in Figure 5.11. The stainless steel primary cover has an outside diameter of 1200 mm (3.9 ft) and an overall thickness of about 340 mm (13.3 in.). The secondary cover is made primarily of stainless steel and has a 1415 mm (4.6 ft) diameter and a 130-mm (5.1-in.) thickness. Some portion of the stainless steel in the secondary cover is replaced with concentric polyethylene rings that act as neutron shields. The protective plate, made of carbon steel, serves as a general mechanical protection against outside forces, as well as against dust and humidity. Each lid is bolted directly to the cask body. A combination of multiple elastomeric and metallic seals for each cover guarantees

a high level of leak-tightness. The maximum leak rate is designed to be 10^{-7} millibar litre per second.

5.3.2 COBRA-SFS CASK MODEL

Two models of the CASTOR-1C cask were developed for the COBRA-SFS analysis, one for the cask containing unconsolidated fuel assemblies and one for the cask containing consolidated fuel canisters. Each is a three-dimensional one-quarter-symmetry model of the cask. These models, along with the boundary specifications and properties used, are described in detail below.

5.3.2.1 Cask Body

A horizontal cross section of the computational cell arrangement used to represent the cask body for both cask models is presented in Figure 5.14. A total of 68 wall nodes at each axial level are used to model the heat transfer through the cask body. Of these, 20 are zero-thickness nodes that represent the temperatures on the outside and inside surfaces of the cask body. These surface nodes are necessary to accurately calculate the radiation heat transfer at the cask surfaces. The modeling of the surface fins is described in Section 5.3.2.3.

Wall conduction heat transfer in the radial, circumferential, and axial directions is modeled by specifying the appropriate thermal resistance terms between adjacent nodes. The input thermal resistance values may reflect a composite of materials and parallel and/or series heat transfer paths. For example, wall nodes containing both polyethylene neutron absorber rods and cast iron are modeled using a composite conductivity. Axial heat transfer is modeled in a similar manner.

5.3.2.2 Cask Cavity and Basket

A horizontal cross section of the computational cell arrangement used to represent the cask cavity and basket in the unconsolidated fuel model is presented in Figure 5.15. The subchannel and rod noding used in modeling the spent fuel assemblies is illustrated along with the assembly basket. The

FIGURE 5.14. COBRA-SFS Quarter-Symmetry Model of CASTOR-1C Cask Body

stainless steel basket is represented by 20 wall nodes at each axial level. The 8x8 BWR fuel assemblies in the unconsolidated fuel model were represented by 256 individual rods and 304 detailed subchannels. Each fuel rod was composed of five radial nodes, four for the fuel and a single node for the cladding.

For the consolidated fuel cask model, the consolidated fuel canisters were assumed to consist of fuel rods from two 8x8 BWR assemblies contained in a closed square stainless steel canister. The spent fuel canisters were

FIGURE 5.15. COBRA-SFS Quarter-Symmetry Model of CASTOR-1C Cask Cavity and Basket

represented by consolidated fuel models using 31 composite fuel rod nodes and 35 fluid subchannels per canister. In addition to the 20 wall nodes representing the assembly basket, 16 wall nodes are used to represent the stainless steel canisters. In both the unconsolidated and consolidated fuel models, 18 uniform nodes in all were used in the axial direction.

Heat is removed from the fuel assemblies in the cavity region by all three heat transfer modes: conduction, convection, and radiation. Conduction heat transfer through the basket is modeled by specifying the appropriate thermal

resistance terms between adjacent wall nodes. It was assumed that there is no additional thermal resistance at the welded junctions between basket plates. Heat transfer from the basket to the cavity wall was modeled using a thermal resistance that assumes a 13-mm (0.5-in.) helium gap. Fluid conduction is modeled based on a transverse control volume of gap width and subchannel centroid-to-centroid length. The conduction shape factor, which is defined in Section 3.0 as characterizing the amount of heat conduction between adjacent subchannels, was assigned a value of 1.0.

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 of the cask becomes an important convection component parameter. The rod and wall friction for all subchannels except those adjacent to the cavity surface are modeled using a friction factor expression of $f = 100/Re$, which is for a square rod array with typical BWR pitch-to-diameter ratios (Sparrow and Loeffler 1959). The wall friction for subchannels adjacent to the cavity surface is modeled using the standard friction factor expression for fully developed laminar pipe flow, $f = 64/Re$ (Kays and Crawford 1980).

Heat transfer from the rods and walls to the coolant was prescribed through the use of a film coefficient of the form $Nu = 3.658$. The film coefficient was evaluated as a function of temperature at each location.

Each BWR spent fuel assembly and surrounding basket and cavity walls is treated as a separate thermal radiation enclosure. Rod-to-rod, rod-to-wall, and wall-to-wall radiative heat transfer within each radiation enclosure is prescribed using gray body exchange factors. The exchange factors for each BWR spent fuel assembly are based on one-quarter rod 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).

5.3.2.3 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. To provide boundary conditions to the model, 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 and 2) heat transfer from the cask lid to ambient air (the cask bottom is assumed adiabatic).

The outside surface geometry of the cask varies as a function of axial level. In the axial region of the fuel assemblies, a set of 48 axial cooling fins is provided to assist in removing heat by natural convection. The amount of heat being removed by natural convection from a finned surface is calculated using the Nusselt number expression (Chaddock 1970)

$$Nu = 0.112 (Ra \cdot b/L)^{0.534} [1 - e^{-129/(Ra \cdot b/L)}]^{0.284} \quad (5.1)$$

where Ra is the Rayleigh number, b is the distance between vertical fins, and L is the total vertical length.

Heat is also removed from the fins by thermal radiation. The amount of heat removed is calculated using a composite gray body exchange factor. This factor is calculated using Hottel's method (Cox 1977) and is based on the surface emissivities and the black body view factors between the cask and fin surfaces and ambient air. The ambient air was assumed to be a black body surface at 26.7°C (80°F).

Near the top and bottom of the cask, the side surface of the cask is essentially a smooth cylinder. The amount of heat being removed by natural convection is calculated using the Nusselt number expression for vertical cylinders in air at 1 atm (Lindeburge 1981):

$$Nu = 0.13 (Gr Pr)^{0.33} \quad (5.2)$$

The top of the cask can be represented by a horizontal flat plate. The Nusselt number expression for this geometry in air at 1 atm (Lindeburge 1981) is

$$Nu = 0.14 (Gr Pr)^{0.33} \quad (5.3)$$

The radiation heat transfer from the top and smooth side surfaces is based on surface emissivities and the expression for heat transfer between parallel plates and the cask. As before, the ambient air is assumed to be a black body at 26.7°C (80°F).

The bottom of the CASTOR-1C cask rests on a supporting surface. Because the surface temperature and contact resistance are not known, the bottom surface of the cask is conservatively assumed to be an adiabatic boundary. The heat transfer correlations used are summarized in Table 5.6.

TABLE 5.6. Boundary Heat Transfer Correlations

<u>Type</u>	<u>Region</u>	<u>Natural Convective Component</u>
Radial	Fins	$Nu = 0.112 (Ra \cdot b/L)^{0.534} [1 - e^{-129/(Ra \cdot b/L)}]^{0.284}$
Radial	Smooth	$Nu = 0.13 (Gr Pr)^{0.33}$
Axial	Top	$Nu = 0.14 (Gr Pr)^{0.33}$
Axial	Bottom	Adiabatic

5.3.2.4 Properties

Most of the material properties (Table 5.7) used to develop the CASTOR-1C model were obtained from the GNS (GNS 1983, 1985). Constant value thermal conductivities are specified for cast iron and the neutron moderator. However, the thermal conductivity for the fuel basket is specified as a function of temperature. As stated earlier, the thermal conductivities are not used in the COBRA-SFS code directly but are used to determine the resistance terms

between adjacent wall nodes. A preliminary CASTOR-1C simulation was performed using an average value for the thermal conductivity, to estimate the specific temperatures for use in evaluating the thermal conductivity for each connection.

A list of surface emissivities is also provided in Table 5.7. The nickel-plated surfaces correspond to both the inside surface of the cavity and the outside surface of the cask above and below the fin region.

TABLE 5.7. Material Properties and Surface Emissivities

Thermal Conductivities

(nodular cast iron) = 0.35 W/cmK

(neutron moderator) = 0.15×10^{-2} W/cmK

(fuel basket) = $(9.503 + 1.445 \times 10^{-2}T - 4.989 \times 10^{-2}T^2 + 3.33 \times 10^{-9}T^3) \times 10^{-2}$ W/cmK

where T is temperature in °C

Surface Emissivities

Fuel rods	0.8
Fuel basket	0.4
Nickel-plated surfaces	0.25
Painted fins	0.93 (measured)

5.3.3 CASTOR-1C Cask Simulation Results

Using the cask model described in Section 5.3.2 and the fuel assembly models described in Sections 4.1 and 5.1, a series of CASTOR-1C simulations was performed using the COBRA-SFS code for both unconsolidated and consolidated BWR fuel assemblies in a nitrogen or helium storage medium. The simulation cases that were performed are described in Section 5.3.3.1. The results from these simulations are discussed in Section 5.3.3.2.

5.3.3.1 Case Descriptions

Ten simulations were performed to characterize the thermal performance of the CASTOR-1C cask under various conditions. Each of these cases is described in Table 5.8. In all cases it was assumed that the cask was vertical and that the ambient temperature was the current 10 CFR 71 limit of 38°C (100°F).

Four simulations (Cases 1 through 14) were performed in which the cask contained unconsolidated fuel assemblies. For the unconsolidated geometry, all assemblies in the cask were modeled with a detailed 64-rod/77-subchannel model. No simplification of the model was required. The first two simulations (Cases 1 and 2) were performed assuming assembly decay heat rates of 0.8 kW and storage media of nitrogen and helium, respectively. Based on the temperature results from these simulations, another two simulations (Cases 3 and 4) were performed to predict the maximum allowable assembly heat generation rate for both storage media. The predicted maximum heat rate was determined subject to a maximum allowable peak cladding temperature of 400°C. After a limited number of iterations, a maximum heat load was identified for both storage media.

TABLE 5.8. CASTOR-1C Simulation Case Description

Consol., Case No.	Fuel Model			Storage Medium		Assembly Power	
	Consol., Uncon.	Coarse	1 Detailed	Nitrogen	Helium	0.8 kW	Q_{max} for 400°C
1	X			X		X	
2	X				X	X	
3	X			X			X
4	X				X		X
5		X		X		X	
6		X			X	X	
7		X		X			X
8		X			X		X
9			X	X		X	
10			X		X	X	

A set of six simulations (Cases 5 through 10) was performed in which the cask contained consolidated fuel assemblies. Due to the large size of the detailed 126-rod/230-subchannel consolidated assembly model, a coarse 31-rod/35-subchannel model similar to that described in Section 5.1 was used in the cask model. As in the unconsolidated cases, simulations were performed assuming a canister decay heat of 0.8 kW and storage media of nitrogen and helium, respectively. To verify that the coarse assembly models were accurately predicting the temperature distribution, two additional simulations (Cases 9 and 10) were performed in which the canister containing the peak temperature fuel rod was modeled using the detailed 126-rod/230-subchannel consolidated canister model. Based on the results from these simulations, two additional cases (7 and 8) were simulated to predict the maximum allowable canister heat generation rate for both storage media.

5.3.3.2 Simulation Results

Of the 10 simulations, six (Cases 1, 2, 5, 6, 9, 10) were performed to determine the peak cladding temperature given an assembly/canister decay generation rate of 0.8 kW. The predicted peak cladding temperatures for the six cases are given in Table 5.9. The remaining four simulations (Cases 3, 4, 7, 8) were performed to determine the maximum allowable assembly/canister heat generation rate subject to the temperature limitations of the cask and fuel assembly. The results of each simulation are discussed in more detail below.

TABLE 5.9. Predicted CASTOR-1C Peak Cladding Temperatures

<u>Case No.</u>	<u>Case Description</u>	<u>Peak Cladding Temperature, °C</u>
1	Unconsolidated, nitrogen	400
2	Unconsolidated, helium	365
5	Consolidated (coarse), nitrogen	498
6	Consolidated (coarse), helium	348
9	Consolidated (1 detailed), nitrogen	500
10	Consolidated (1 detailed), helium	349

The first two simulations (Cases 1 and 2) were performed with the CASTOR-1C cask containing unconsolidated fuel, one in nitrogen and one in helium. The axial temperature profile of the peak temperature rod for both cases is shown in Figure 5.16. The peak cladding temperature is determined to be 400°C for the nitrogen case and 365°C for the helium case, a difference of 35°C. Note that the elevation of the peak temperature in the nitrogen case is approximately 3.7 m as compared to 2.8 m for the helium case. The temperature profile for the nitrogen case is skewed upward due to a significant amount of natural circulation occurring within the cask. To illustrate the difference, the maximum assembly average velocity is approximately 12 cm/sec (0.74 ft/sec) in the nitrogen case as compared to 8 cm/sec (0.27 ft/sec) in the helium case.

The radial temperature profiles, taken along the diagonal from the center of the cask, are shown in Figure 5.17 for both cases. The differences between the two profiles occur in two regions: 1) in the gap between the basket and cask wall member filled with storage medium, and 2) within the individual fuel assemblies.

Based on the temperature results from these two simulations, an additional two cases (3 and 4) were performed to predict the maximum allowable assembly heat generation rate for both storage media. The predicted maximum assembly heat rate was determined subject to a 400°C allowable peak cladding temperature. After a limited number of iterations, a maximum heat rate was identified. The results are shown in Table 5.10. For the nitrogen case, the maximum allowable heat rate was determined to be approximately 0.80 kW/assembly. For the helium case, the maximum allowable heat rate was determined to be approximately 0.90 kW/assembly.

Following completion of the unconsolidated fuel assembly simulations, a set of six simulations (Cases 5 through 10) was performed with the CASTOR-1C cask containing consolidated fuel. Using the 31-rod/35-subchannel coarse assembly model described in Section 5.1, cask simulations (Cases 5 and 6) were performed assuming a heat generation rate of 0.8 kW/canister. The axial temperature profiles of peak cladding temperatures for nitrogen and helium

FIGURE 5.16. Comparison of CASTOR-1C Axial Temperature Profile Predictions for Unconsolidated Fuel in Nitrogen and Helium

FIGURE 5.17. Comparison of CASTOR-1C Radial Temperature Profile Predictions for Unconsolidated Fuel in Nitrogen and Helium

TABLE 5.10. CASTOR-1C Maximum Assembly Decay Heat Generation Rates for Unconsolidated Fuel

Case No.	Case Description	Decay Heat Assembly kW	Peak Cladding Temperature, °C
3	Unconsolidated, nitrogen	0.80	400
4	Unconsolidated, helium	0.90	400

are compared with the corresponding unconsolidated assembly profiles in Figures 5.18 and 5.19, respectively.

The peak cladding temperature for the consolidated nitrogen case is 498°C , an increase of 98°C as compared to 400°C in the unconsolidated case. Note that the axial temperature profile for the consolidated case is skewed considerably less upward than in the unconsolidated case. This indicates that consolidating the fuel has severely reduced the amount of natural circulation occurring within the cask. In addition, radiation heat transfer has been reduced due to increased rod shadowing and the addition of a low-surface-emissivity canister. Therefore, the two primary modes of heat transfer in the nitrogen case, convection and radiation, have been reduced, resulting in a dramatic temperature increase.

The peak cladding temperature for the consolidated helium case is 348°C , a decrease of 17°C as compared to 365°C in the unconsolidated case. As in the nitrogen case, radiation heat transfer has been reduced due to consolidation of the fuel. However, conduction heat transfer is enhanced due to replacement of relatively low-conductivity gas with high-conductivity fuel rods and canister. Therefore, of the two primary modes of heat transfer in the helium case, conduction is enhanced and radiation is reduced, resulting in a relatively small temperature decrease.

To verify that the 31-rod/35-subchannel coarse consolidated assembly models used in the cask analysis adequately represent the consolidated fuel assemblies, representation of the canister exhibiting the peak cladding temperature was replaced with a detailed 126 rod/230 subchannel model. (Because of problem size limitations, it was not possible to develop a cask model with detailed 126-rod/230-subchannel representations of all canisters.) Simulations were performed for both nitrogen and helium. In both cases (9 and 10), the resulting peak axial temperature profiles for models with and without a detailed canister were within 3°C throughout the profile. This indicates that the coarse model adequately represents the consolidated fuel canisters.

FIGURE 5.18. Comparison of CASTOR-1C Axial Temperature Profiles for Consolidated and Unconsolidated Fuel in Nitrogen

FIGURE 5.19. Comparison of CASTOR-1C Axial Temperature Profiles for Consolidated and Unconsolidated Fuel in Helium

Based on the temperature results from the consolidated fuel simulations, two additional calculations (Cases 7 and 8) were performed to predict the maximum allowable canister heat generation rate for both storage media. The temperature constraints considered were those used for the unconsolidated simulations. After a limited number of iterations, a maximum heat rate was identified. The results are shown in Table 5.11. For the nitrogen case, the maximum canister allowable heat rate was determined to be approximately 0.52 kW/canister with the limiting constraint being a peak cladding temperature 400°C. For the helium case, the maximum allowable heat rate was determined to be approximately 0.98 kW/canister.

TABLE 5.11. CASTOR-1C Maximum Assembly Decay Heat Generation Rates for Consolidated Fuel

Case No.	Case Description	Canister Decay Heat kW	Peak Cladding Temperature, °C
7	Consolidated, nitrogen	0.52	400
8	Consolidated, helium	0.98	400

REFERENCES

- Catton, I. 1978. "Natural Convection in Enclosures." In Proceedings Sixth International Heat Transfer Conference, Vol. 6, p. 13-31.
- Chaddock, J. B. 1970. "Free Convection Heat Transfer from Vertical Rectangular Fin Arrays." ASHRAE Journal. August 1970: 53-60.
- Cox, R. L. 1977. Radiative Heat Transfer in Arrays of Parallel Cylinders. ORNL-5293, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Creer, J. M. 1984. "Decay Heat and Heat Transfer Predictions for Spent Fuel Storage Systems." In Proceedings, International Irradiated Fuel Storage: Operating Experience and Development Program Workshop, pp. 157-209. Ontario Hydro, Toronto, Ontario, Canada.
- Curme, G. O., and F. Johnston. 1952. Glycols. Waverly Press.
- Cuta, J. M., D. R. Rector and J. M. Creer. 1984. Thermal-Hydraulic Analysis of Consolidated Spent PWR Fuel Rods. EPRI-NP-3764, Electric Power Research Institute, Palo Alto, California.
- Cuta, J. M., and J. M. Creer. 1986. Comparisons of COBRA-SFS Calculations to Data from Electrically Heated Test Sections Simulating Unconsolidated and Consolidated BWR Spent Fuel. EPRI-NP-4593, Electric Power Research Institute, Palo Alto, California.
- Idel'Chik, I. E. 1966. Handbook of Hydraulic Resistance, Coefficients of Local Resistance and of Friction. AEC-TR-6630, U.S. Atomic Energy Commission and the National Science Foundation, Washington, D.C.
- Kays, W. M., and M. E. Crawford. 1980. Convective Heat and Mass Transfer. McGraw-Hill, Inc., New York, New York.
- Lindeburge, M. R. 1981. Mechanical Engineering Review Manual, 6th ed., The Professional Engineering Registration Program, San Carlos, California.
- Lombardo, N. J., T. E. Michener, C. L. Wheeler, and D. R. Rector. 1986. COBRA-SFS Predictions of Single-Assembly Spent Fuel Heat Transfer Data. PNL-5781, Pacific Northwest Laboratory, Richland, Washington.
- McKinnon, M. A., J. W. Doman, J. E. Tanner, R. J. Guenther, J. M. Creer, and C. E. King. 1986. BWR Spent Fuel Storage Cask Performance Test: Volume I - Cask Handling Experience, Decay Heat, Heat Transfer and Shielding Data. PNL-5777 Vol. I, Pacific Northwest Laboratory, Richland, Washington.

- Rector, D. R., R. A. McCann, U. P. Jenquin, C. M. Heeb, J. M. Creer and C. L. Wheeler. 1986. CASTOR-1C Spent Fuel Storage Cask Decay Heat, Heat Transfer, and Shielding Analysis. PNL-5974, Pacific Northwest Laboratory, Richland, Washington.
- Rector, D. R., J. M. Cuta and J. M. Creer. 1986. "Cask Consolidation Spent Fuel Thermal Analyses Using the COBRA-SFS Code." In Proceedings, Third International Spent Fuel Storage Technology Symposium/Workshop, Vol. 1, pp. S378-S397. CONF-860417, National Technical Information Service, Springfield, Virginia.
- Sparrow, E. M., and A. L. Loeffler, Jr. 1959. "Longitudinal Laminar Flow Between Cylinders Arranged in Regular Array." AIChE Journal. 5(3):325-330.
- Taylor, R. E. 1983. Hemispherical Total Emissivity of Stainless Steel. TPRL 364, School of Mechanical Engineering, Purdue University, West Lafayette, Indiana.
- Taylor, R. E. 1984. Hemispherical Total Emissivity of Stainless Steel. TPRL 364, School of Mechanical Engineering, Purdue University, West Lafayette, Indiana.
- Wheeler, C. L., R. A. McCann, N. J. Lombardo, D. R. Rector, and T. E. Michener. 1986. "HYDRA and COBRA-SFS Temperature Calculations for CASTOR-1C, REA-2023, CASTOR-V/21, and TN-24P Cask." In Proceedings, Third International Spent Fuel Storage Technology Symposium/Workshop, Vol. 1, S77-S98. CONF-960417, National Technical Information Service, Springfield, Virginia.
- Wiles, L. E., et al. 1986. BWR Spent Fuel Storage Cask Performance Test: Volume II - Pre- and Post-Test Decay Heat, Heat Transfer and Shielding Analysis. PNL-5777 Vol. II, Pacific Northwest Laboratory, Richland, Washington.

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