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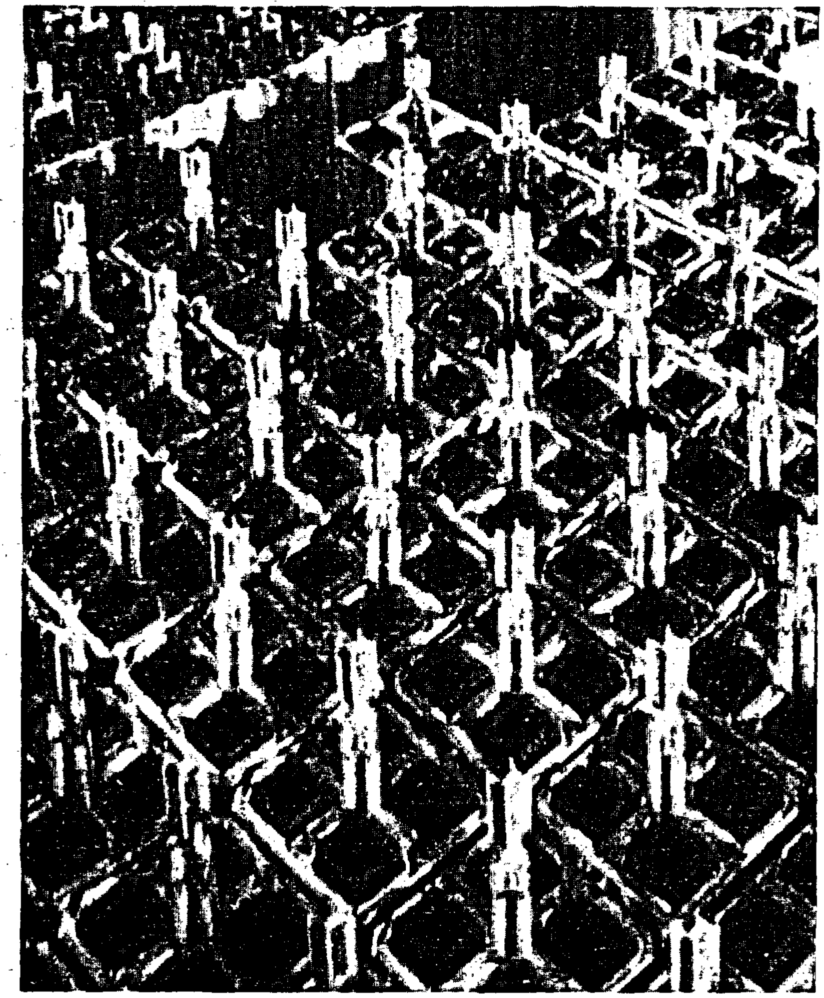
UC-85

HYDRA-II: A Hydrothermal Analysis Computer Code

Volume III

Verification/Validation Assessments



October 1987

Prepared for the U.S. Department of Energy
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HYDRA-II: A HYDROTHERMAL ANALYSIS COMPUTER CODE

VOLUME III

VERIFICATION/VALIDATION ASSESSMENTS

R. A. McCann
P. S. Lowery

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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

HYDRA-II is a hydrothermal computer code capable of three-dimensional analysis of coupled conduction, convection, and thermal radiation problems. This code is especially appropriate for simulating the steady-state performance of spent fuel storage systems. The code has been evaluated for this application for the U.S. Department of Energy's Commercial Spent Fuel Management Program.

HYDRA-II provides a finite difference solution in cartesian coordinates to the equations governing the conservation of mass, momentum, and energy. A cylindrical coordinate system may also be used to enclose the cartesian coordinate system. This exterior coordinate system is useful for modeling cylindrical cask bodies.

The difference equations for conservation of momentum are enhanced by the incorporation of directional porosities and permeabilities that aid in modeling solid structures whose dimensions may be smaller than the computational mesh. The equation for conservation of energy permits modeling of orthotropic physical properties and film resistances. Several automated procedures are available to model radiation transfer within enclosures and from fuel rod to fuel rod.

The documentation of HYDRA-II is presented in three separate volumes. Volume I - Equations and Numerics describes the basic differential equations, illustrates how the difference equations are formulated, and gives the solution procedures employed. Volume II - User's Manual contains code flow charts, discusses the code structure, provides detailed instructions for preparing an input file, and illustrates the operation of the code by means of a model problem. This volume, Volume III - Verification/Validation Assessments, provides a comparison between the analytical solution and the numerical simulation for problems with a known solution. This volume also documents comparisons between the results of simulations of single- and multiassembly storage systems and actual experimental data.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

HYDRA-II is a finite difference hydrothermal computer code that predicts the temperature and velocity distribution in a wide variety of systems. HYDRA-II was evaluated and documented for the U.S. Department of Energy's Commercial Spent Fuel Management Program. One of the program's objectives was the evolution of a mechanistically-based computer code that could be used for accurate analyses of complex spent fuel dry storage systems.

To demonstrate the capability of HYDRA-II as a computational tool, a significant effort was expended to assess both the code's performance and the validity of the computed results. Validation results using earlier versions of HYDRA are provided in McCann (1986), Rector et al. (1986), and Dziadosz et al. (1986).

Validation of the HYDRA-II code is presented in this report, the final in a series of three HYDRA-II documentation volumes. The first, Volume I - Equations and Numerics (McCann 1987), is a description of the theory behind the code. The second, Volume II - User's Manual (McCann, Lowery, and Lessor 1987), provides instructions and guidance for input to the code.

The validation assessment documented herein is based on comparison of code predictions with spent fuel heat transfer test data. Eleven case comparisons are reported using the results obtained from experiments employing four unique spent fuel storage tests. The tests used in the comparisons include all of the combined heat transfer effects expected to occur within spent fuel storage systems. The verification assessment is based on comparison of code predictions with the analytical solution to a simple pure-conduction problem (no fluid transport), and with detailed data obtained both experimentally and from separate numerical simulations for a geometrically-simple buoyancy-driven cavity problem.

The conclusions and recommendations based on these verification/validation assessments are presented in Chapter 2.0. Chapter 3.0 provides a brief overview of the HYDRA-II code's current capabilities and limitations. The uncertainties inherent in the modeling process are described in Chapter 4.0. The single- and multiassembly evaluation tests are documented in Chapters 5.0 and

6.0, respectively. Chapter 7.0 presents the verification assessments. The HYDRA-II input files for four spent fuel storage test simulations appear in Appendixes A through D.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The HYDRA-II computer code was used to predict the hydrothermal performance of two single-assembly and two multiassembly spent fuel storage cask heat transfer tests. Comparison of the computed temperature distributions with those obtained from the tests provided the basis for validating HYDRA-II. Two additional test cases were used to verify HYDRA-II. In the first, the computed solution was compared with a known analytical solution. The second verification test involved comparison of the HYDRA-II computed results with the extensive data obtained from an experiment and separate numerical simulations of that experiment. Important conclusions and recommendations established from the work described in this report are presented in this section.

2.1 CONCLUSIONS

Four principal conclusions were drawn from the work described herein:

- HYDRA-II successfully performed predictions for the two single-assembly validation tests. The deviation between predictions and data was ±10°C in ~200°C, in the worst case, for these tests.
- HYDRA-II successfully performed predictions for the two multiassembly validation tests. The deviation between predictions and data was ±25°C in ~300°C, in the worst case, for these tests.
- HYDRA-II results compared very well with the analytical solution for the pure-conduction verification test.
- HYDRA-II results agreed well with the results obtained from two separate numerical simulations and one set of experimental data for the buoyancy-driven cavity problem.

2.2 RECOMMENDATIONS

The results of, and conclusions drawn from, this work support two main recommendations. First, HYDRA-II should continue to be used to predict the hydrothermal performance of spent fuel dry storage systems as well as other closed, natural convection systems.

Second, if better prediction accuracies or enhancements to the capabilities of HYDRA-II are desirable, the following are recommended:

- More complete data sets (e.g., velocity fields) should be obtained in future cask tests for comparison with computer-simulated results.
- A turbulence model should be implemented in HYDRA-II to extend the range of its applicability.
- HYDRA-II should be modified to allow inflow/outflow boundary conditions for fluid transport.
- HYDRA-II should be modified to accommodate fully three-dimensional cavity radiation heat transfer.

3.0 HYDRA-II DESCRIPTION

HYDRA-II is a fully three-dimensional hydrothermal computer code that solves the equations of motion, continuity, and energy using finite difference techniques. The code solves the mass, momentum, and energy conservation equations for a region containing both fluid and solid materials. These equations are solved using finite difference representations on a cartesian grid. The cartesian-grid region represents a closed system to fluid transport and an open system for heat transfer. The boundaries of this grid may be in contact with the environment directly, or through an intermediate body. If present, the intermediate body is represented with a cylindrical grid that envelops the cartesian-grid region. Only the energy equation is solved in this intermediate-body region. Energy transfer by conduction, convection, and radiation is allowed from the cartesian-region grid to the cylindrical-region grid. Energy transfer to the environment by either of these grids is effected by natural convection and/or radiation. The numerics incorporated in HYDRA-II are described in detail in Volume I - Equations and Numerics (McCann 1987).

HYDRA-II does not currently provide a turbulence model to represent sub-grid scale motion of the fluid. Therefore, the Reynolds/Rayleigh numbers realized in the simulation must be sufficiently low so that all the scales of motion are resolved by the computational grid.

3.1 MODELING CAPABILITIES

The modeling capabilities available in HYDRA-II are summarized in Table 3.1.

3.2 LIMITATIONS

Limitations of the HYDRA-II code include:

- no explicit turbulence model
- no mass inflow/outflow boundary conditions
- "planar" or "two-dimensional" cavity radiation heat transfer.

TABLE 3.1. HYDRA-II Modeling Capabilities

Category	Capabilities
Geometry and Numerics	• fully three-dimensional • variable grid spacing in both cartesian and cylindrical grids • several rebalance schemes available to speed convergence of the momentum and energy solutions • several iterative schemes for use, alone or in combination, in obtaining solution for the fluid pressure field • "time" advance to steady state
Fluid Solution	• finite-difference on a cartesian grid • modeling a closed system • compressible, ideal gas • orifice- and Darcy-flow models • user-specified, orthotropic fluid permeabilities and subgrid scale obstructions • user-specified temperature-dependent viscosity • fixed system-pressure or total-mass operation conditions
Thermal Solution	• finite-difference on a cartesian grid and, if desired, an enveloping cylindrical grid • modeling an open system • conduction, convection, and radiation heat transfer modes; correlation for natural convection heat transfer to the environment • user-specified, temperature-dependent and orthotropic conductivity • user-specified, spatially-dependent energy-source terms • several models for radiation heat transfer
Program and Input/Output Control	• variably-dimensioned arrays (required core size specified by the user through PARAMETER statements) • restart and post-processing dumps • echoed input • user-specified convergence history monitoring

4.0 VALIDATION MODELING UNCERTAINTIES

Typical spent fuel storage casks and canisters are large and complex thermohydraulic systems, and some uncertainty about how best to construct an accurate overall model will always be present. These uncertainties lead inevitably to approximations, some of which may be difficult to quantify. Most uncertainties may be placed within one of three broad categories:

1. basic information that is application-specific and measurable (e.g., container dimensions, heat generation rates, ambient conditions)
2. information generic to most applications (e.g., property values, correlations)
3. decisions about how to achieve the best match between a particular code and the application (e.g., computational mesh, internal algorithms).

For the HYDRA-II validation, some of the more important factors falling within these categories are:

- The information shown on the furnished cask or canister drawings may not accurately reflect the as-built structure.
- Dimensional tolerances may be particularly significant when they influence small gaps with important thermal resistances. The input to HYDRA-II specified nominal dimensions.
- Potential eccentricities, such as the actual placement of the basket or fuel assembly support structure within the container cavity, are a source of uncertainty. Other eccentricities, such as the placement of a fuel assembly within the basket, are certain to occur and can substantially alter some thermal and flow resistances. The input to HYDRA-II specified no eccentricity.
- The total heat generation rate and the generation rate axial profile of spent fuel assemblies have a direct effect on predicted cladding temperatures. Both the total generation rate and the axial profile can be determined experimentally, and that is the preferred approach.

- All material property values possess a range of uncertainty, although the range for most well-characterized materials is usually not significant. Exceptions include the emittance of some materials, especially if the surface has been altered by some process (e.g., cladding corrosion or basket structure sandblasting). Values used in the simulations are believed to be typical. The potential consequences of a range of values on the temperature field have not been investigated.

- Some boundary conditions are difficult to determine. Examples include sparse temperature data for the external cask or canister body and means for determining the total mass or pressure of the gas within the cask or canister.

- Some uncertainties are inherent in the use of discrete solution methods. An example is the trade-off between mesh coarseness and accuracy. Because the conservation equations have been formulated within HYDRA-II in an entirely consistent fashion, any desired numerical accuracy may be achieved by using a sufficiently large number of computational cells. The practical trade-off is between accuracy and computer time and costs. The optimum is difficult to determine a priori.

- Another source of uncertainty results from limitations of internal code models. Thermal radiation models are a good example. All radiation enclosures within the cask are three-dimensional. Two-dimensional radiation models are used extensively within HYDRA-II for practical reasons. The errors associated with this approximation can be reduced, but not eliminated, by careful selection of a computational mesh.

5.0 SINGLE-ASSEMBLY EVALUATION TESTS

An important step in the evaluation of HYDRA-II was to analyze single-assembly storage systems. Conduction, convection, and radiation heat transfer mechanisms must be properly modeled to accurately predict the thermal performance of these systems. To demonstrate the effectiveness of the HYDRA-II models for single-assembly spent fuel heat transfer, predictions of two unique single-assembly spent fuel tests were compared. The first test was the Pressurized Water Reactor (PWR) Single-Assembly Spent Fuel Heat Transfer Test. The second test involved an electrically-heated single-assembly configuration. These tests and the comparisons are documented in the following sections.

5.1 PWR SINGLE-ASSEMBLY SPENT FUEL HEAT TRANSFER TEST

In this test, the effect of fill media on thermal performance of an actual PWR spent fuel assembly was examined. The test hardware and test conditions needed for numerical simulation are described in Section 5.1.1. Section 5.1.2 explains computational models for this application. Section 5.1.3 presents HYDRA-II predictions and comparisons to data.

5.1.1 Test Description

This section contains a brief description of the test hardware and test conditions needed for numerical simulation. A full account of all test details is given by Unterzuber et al. (1982). A condensed but complete summary of details needed for simulation is contained in Bates (1986).

5.1.1.1 Hardware Description

The hardware consisted of a main test assembly with a number of auxiliary systems and components. The main test assembly, illustrated in Figure 5.1, consisted of 1) a test stand supporting a representative storage cell liner, 2) a seismic restraint fixture providing test stand lateral support, 3) a test canister (representative of a storage canister), 4) a canister lid assembly containing instrumented tubes that were inserted into the spent fuel assembly, and 5) a PWR spent fuel assembly. Auxiliary equipment included 1) an evacuation and backfill system, 2) test stand electric heater controls, 3) thermocouples, and 4) a data acquisition system to record thermocouple data.

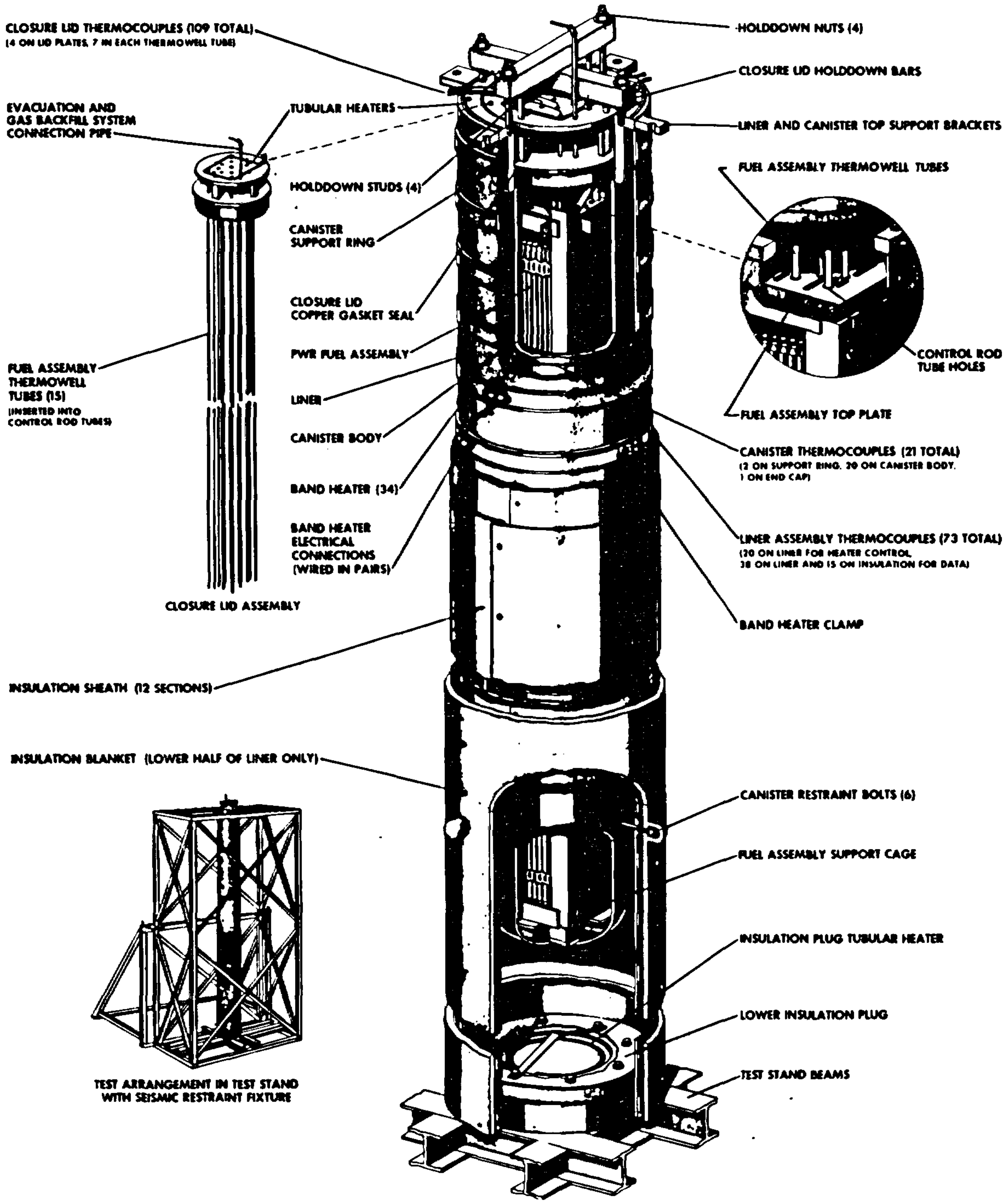


FIGURE 5.1. Fuel Temperature Test Assembly

Source: Unterzuber et al. (1982)

Figure 5.2 shows a vertical cross section of the test stand. The general configuration of liner and canister is indicated, along with the position of the fuel assembly. The fuel assembly consists of a 15x15 array of 204 fuel rods, 20 control rod guide thimbles, and one instrumentation tube.

A horizontal cross section of the test stand is shown in Figure 5.3. The positions of thermocouple tubes are indicated. These tubes hang from the canister lid and slide into control rod guide thimbles and the center instrumentation tube. Each thermocouple tube contains seven axially spaced thermocouples. Geometrical information for the fuel assembly and canister is given in Table 5.1.

5.1.1.2 Test Conditions

The test operating conditions used to construct the input file for the HYDRA-II code are given in Table 5.2. The test conditions include decay heat generation, type of fill gas, fill gas pressure, and canister temperature.

The canister surface temperature at a given elevation shown in Table 5.2 represents, in general, the average reading of several thermocouples located around the circumference of the canister at that elevation. The axial distribution of decay heat was obtained by interpreting data given in Davis (1980). The relative axial activity is plotted in Figure 5.4.

5.1.2 Computational Model Description

The computational mesh and material properties contained on the input file are described in this section. The complete HYDRA-II input file for the helium backfill case is provided in Appendix A.

5.1.2.1 Computational Mesh

The horizontal cross section presented in Figure 5.3 shows the fuel assembly inside a circular canister. The symmetrical location of unheated guide thimbles within the fuel assembly and the centered position of the fuel assembly within the canister allow the use of a one-quarter symmetry model.

Figure 5.5 shows the computational mesh employed for the simulations. Figure 5.6 indicates the alignment of the computational mesh with the fuel assembly and canister inside surface. Each rod is contained within a single

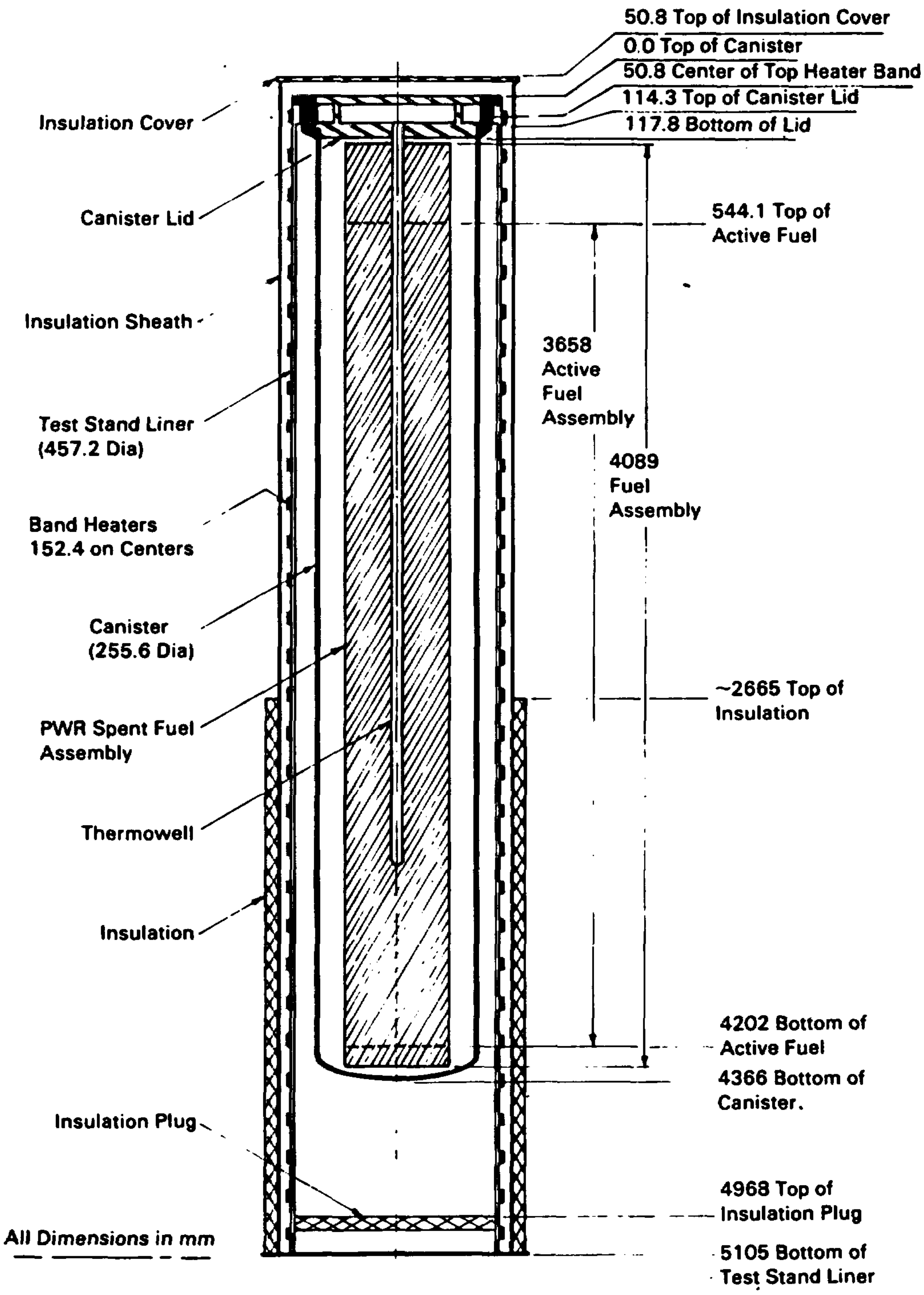


FIGURE 5.2. Test Stand Vertical Cross Section

Source: Bates (1986)

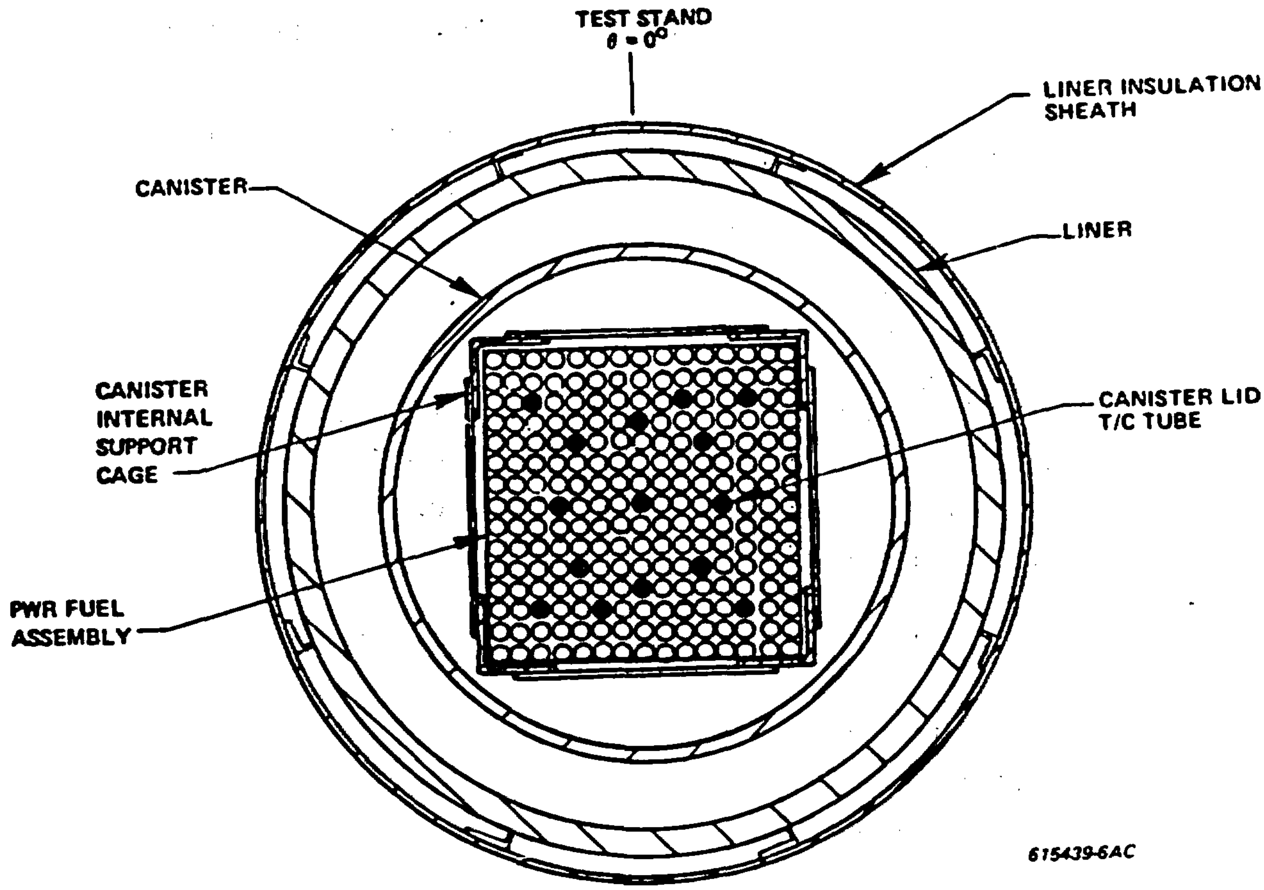


FIGURE 5.3. Test Stand Horizontal Cross Section

Source: Unterzuber et al. (1982)

square cell except along the boundaries representing planes of symmetry. The boundary cells contain half of a rod. The central boundary cell contains one quarter of the instrumentation tube.

A vertical cross section of the canister appeared in Figure 5.2. A corresponding cross section of the computational mesh is shown in Figure 5.7 for the simulations. Figure 5.8 indicates the location of the fuel assembly relative to the canister inside surface.

5.1.2.2 Material Properties

Material properties for the PWR spent fuel assembly were obtained from Touloukian and Ho (1970). Table 5.3 lists the material properties used for all simulations. Effective thermal conductivities were estimated for those

TABLE 5.1. Geometrical Parameters for Fuel Assembly/Canister

Fuel Assembly	
Number of rods	225 (15x15 array)
Fuel rods	204
Control rod guide thimbles	20
Instrumentation tube	1
Rod diameter	1.072 cm
Control rod guide thimble and instrumentation tube diameters	1.387 cm
Cladding thickness	0.062 cm
Fuel pellet diameter	0.948 cm
Pitch-to-diameter ratio	1.334
Active fuel length (includes swelling)	367.0 cm
Canister	
Inside diameter	33.7 cm
Outside diameter	35.6 cm
Outside length	436.6 cm

TABLE 5.2. Test Operating Conditions

Test Medium	Decay Heat Generation Rate	Pressure
Air	1.17 kW	1.0 atm
Vacuum (low-pressure air)	1.16 kW	0.2 atm
Helium	1.16 kW	1.07 atm

Canister Temperature Profiles

Top of Canister, cm	Average Measured Temperature, °C		
	Air	Vacuum	Helium
41.9	138.8	114.7	116.5
129.5	159.5	149.8	150.0
217.2	160.8	158.9	159.7
304.8	156.1	157.8	157.5
392.4	127.8	127.8	128.8
435.9	88.8	90.5	91.3

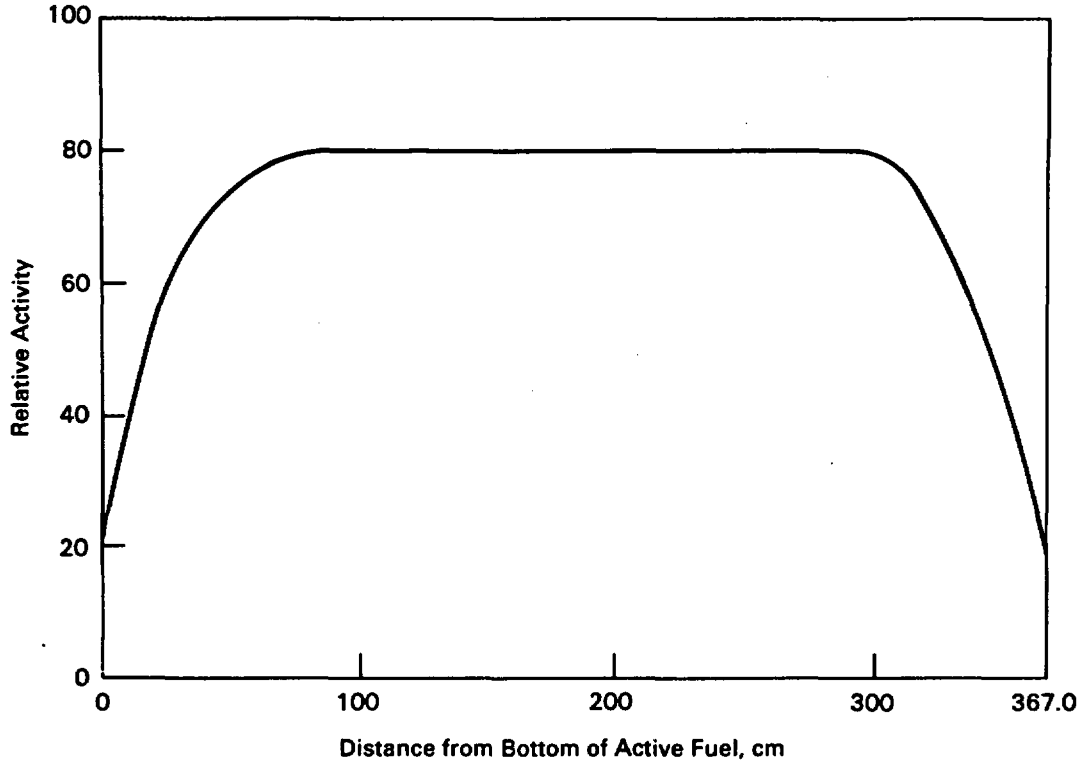


FIGURE 5.4. Relative Axial Activity Profile

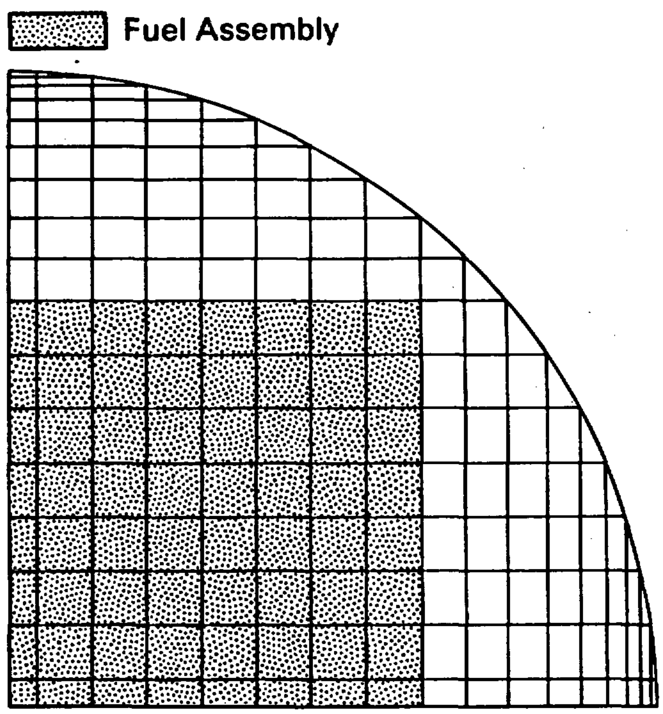


FIGURE 5.5. Horizontal Computational Mesh for PWR Single-Assembly Spent Fuel Heat Transfer Test Simulation

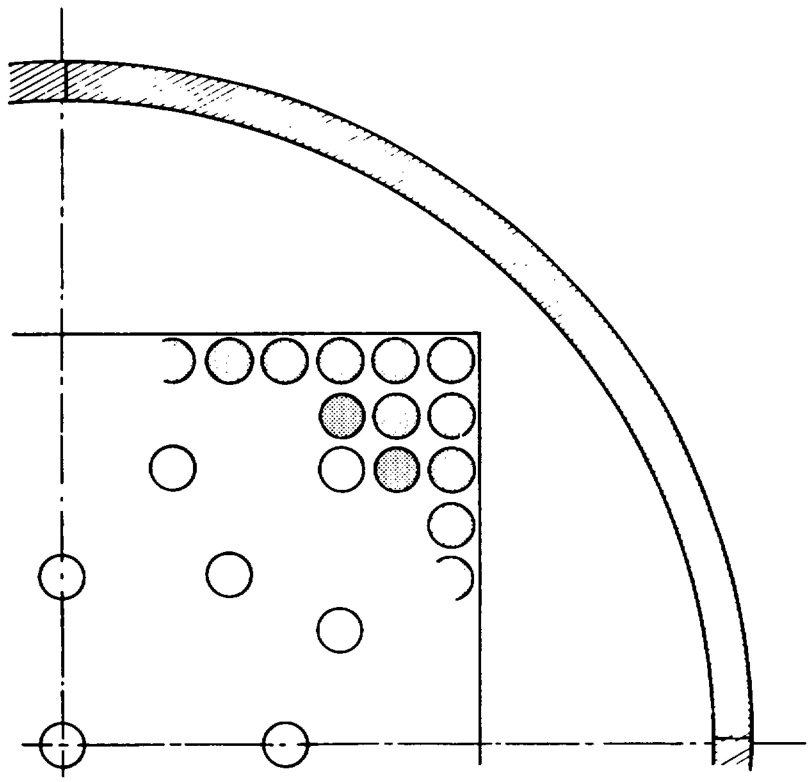


FIGURE 5.6. Physical Features Modeled in Horizontal Cross Section

computational cells containing more than one material. For the simulation denoted as low-pressure (0.2-atm) air, the mean free path is less than any significant length. The properties used for the low-pressure simulation are, therefore, those of air.

The emittance of the canister surface and support structure was specified as 0.3 for the simulations. Data given in Peterson (1975) and in EG&G (1980) suggest that rod emittances may vary over a considerable range of values. For very clean, nonoxidized rods, the emittance may be below 0.3. For oxidized rods described as having considerable surface crud, the emittance may be above 0.9. Visual examinations of spent fuel assemblies reported in Davis (1980) identified the presence of crud that varied somewhat with axial position. The fuel assembly used in the test was from the same reactor as the assemblies examined by Davis. As a result of this review, a rod emittance of 0.8 was used.

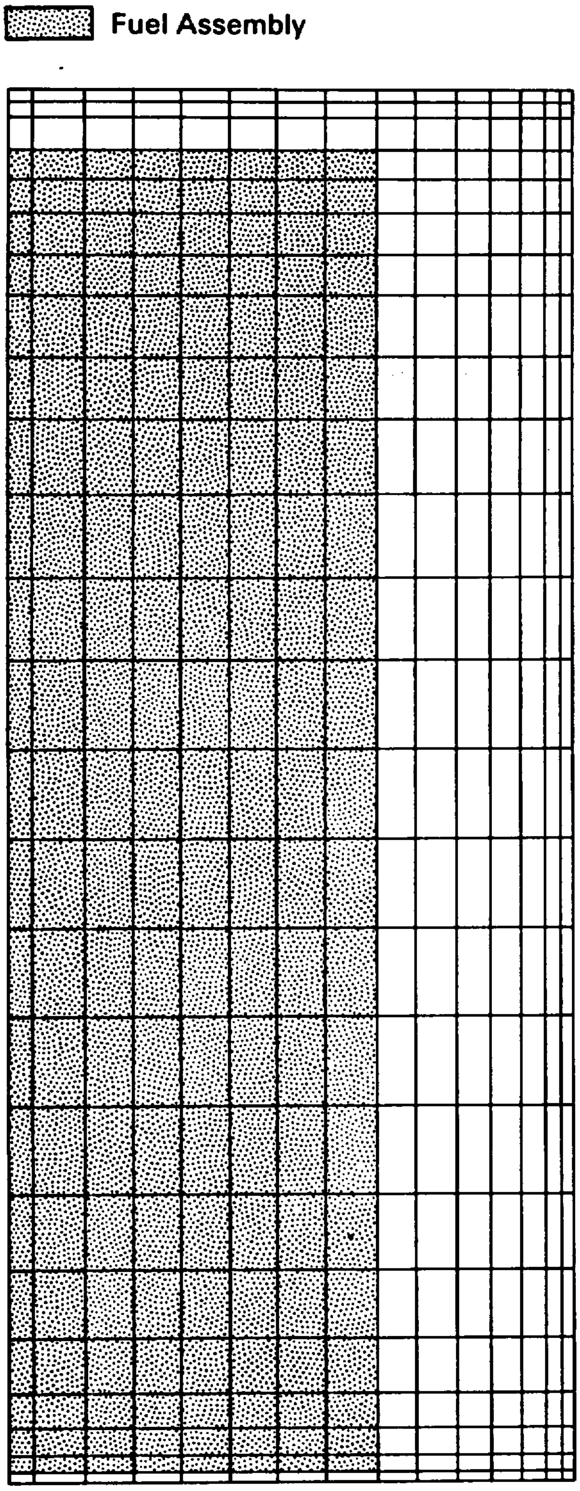


FIGURE 5.7. Vertical Computational Mesh for PWR Single-Assembly Heat Transfer Test Simulation

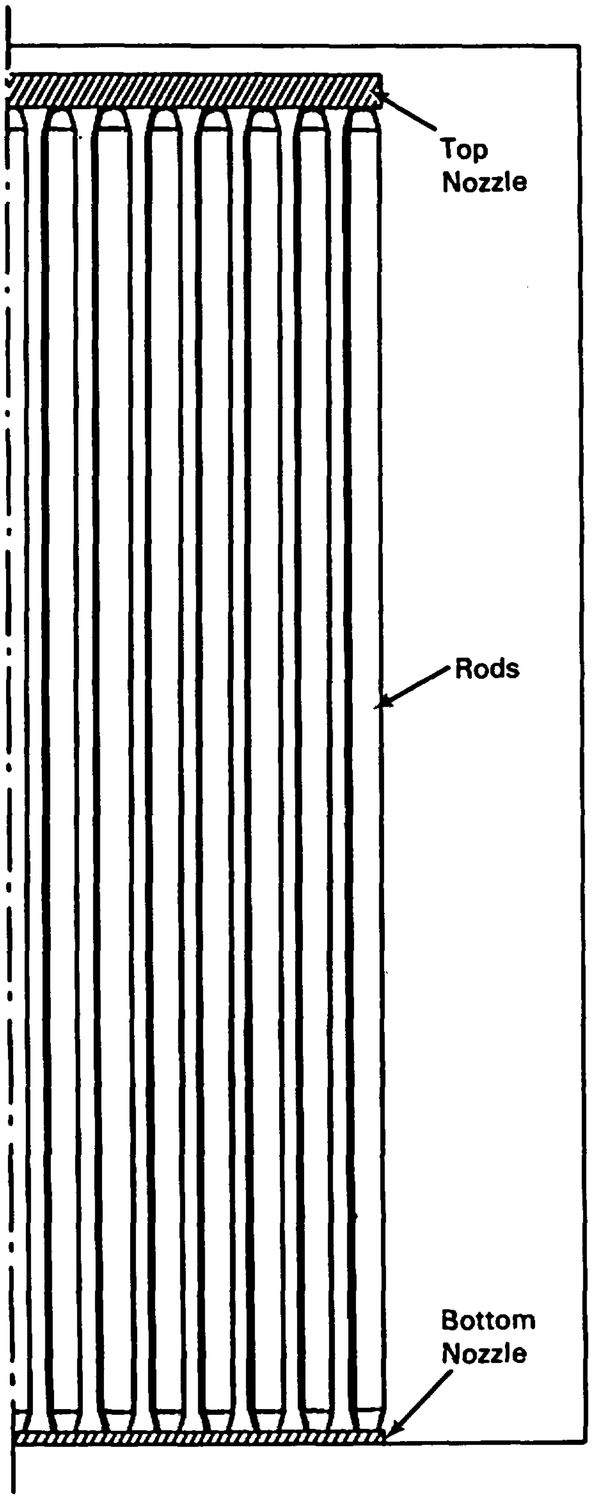


FIGURE 5.8. Fuel Assembly Position Relative to Canister Inside Surface - Vertical Cross Section

TABLE 5.3. Single-Assembly Spent Fuel Test Material Properties

Thermal conductivity, W/cm^2°K	
Stainless steel	0.09215+(0.1465E-3)T
Air	0.688E-4+(0.634E-6)T
Helium	0.52E-3+(0.32E-5)T
Specific heat, W sec/g°K	
Air	1.0
Helium	5.234
Viscosity, g/cm sec	
Air	0.608E-4+(0.400E-6)T
Helium	0.700E-4+(0.400E-6)T
Emittance	
Fuel cladding	0.8
Stainless steel	0.3

5.1.3 Predictions Compared to Data

Predictions of computed temperatures are compared to experimentally measured test data in this section. Three backfill environments were considered in these simulations:

- air at 1.0 atm
- vacuum (low-pressure air) at 0.2 atm
- helium at 1.07 atm.

Predicted and measured temperatures for the canister with an air backfill are shown in Figure 5.9. The comparison is favorable in the central range of axial elevations; however, there is a growing discrepancy toward the ends of the assembly. The underprediction of temperature near the bottom of the assembly and overprediction near the top suggest too much convection. The predicted maximum cladding temperature is 266°C. The corresponding measured value for this case is 255°C.

The natural convection flow field within the canister is driven by buoyancy forces resulting from temperature-dependent density variations in the fluid. As the fluid is heated within the fuel assembly, the fluid density

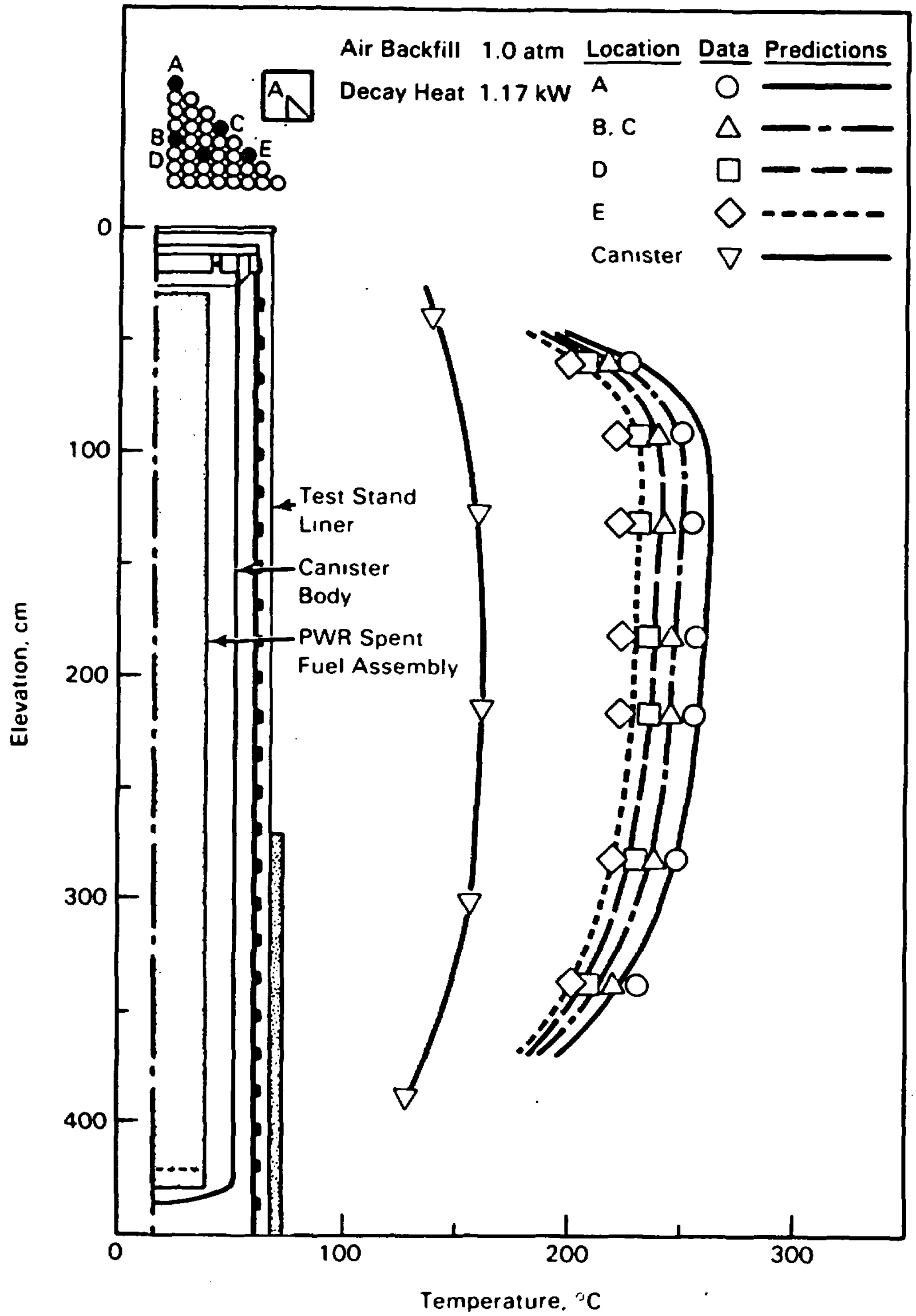


FIGURE 5.9. Predictions of Temperatures Compared to Data for Air Backfill Case

decreases and the fluid rises toward the top of the fuel assembly. The heated fluid exits the fuel assembly at or near the top of the fuel assembly. The fluid flows outward and transfers heat to the cooler canister wall. This causes the fluid density to increase. The denser fluid flows downward in the open region between the fuel assembly and the canister wall. Near the bottom of the canister, the fluid flows back into the fuel assembly to complete the recirculation pattern. The horizontal flow component into the fuel assembly is at maximum near the bottom of the fuel assembly. On a relative basis, the horizontal flows into or out of the fuel assembly are significant only over the bottom or top 20% of the fuel assembly. Superimposed on this overall recirculating flow is some predicted small-scale recirculation, particularly near the top of the canister. This secondary recirculation is much less apparent for the low-pressure air and helium simulations.

The predicted velocities in the free field are high enough to indicate that turbulence is present in the air test. An effective thermal conductivity may be computed based on an estimated Rayleigh number for the free field. The effective conductivity may be an order of magnitude larger than the molecular conductivity. If a turbulent Prandtl number analogy exists, then a turbulent viscosity value may also be an order of magnitude greater than the molecular viscosity. HYDRA-II does not currently incorporate a turbulence model. Therefore, the effective conductivity and viscosity were intentionally adjusted for this simulation (this would be done automatically by some turbulence models). The results for this simulation are shown in Figure 5.10. The predicted maximum cladding temperature is 258°C, and, again, the measured value is 255°C. The maximum vertical mass flux in the free field is approximately 17.7×10^{-3} g/cm^2-sec (velocity of 23 cm/sec). The maximum upward mass flux within the fuel assembly is approximately 27.1×10^{-4} g/cm^2-sec.

Figure 5.11 shows the comparison between predictions and data for the low-pressure air backfill test. The axial profiles are in excellent agreement with the data over the full length of the assembly. The maximum centerline temperature predicted by HYDRA-II (267°C) is very close to the experimentally measured maximum centerline temperature of 266°C. The maximum vertical mass flux in the

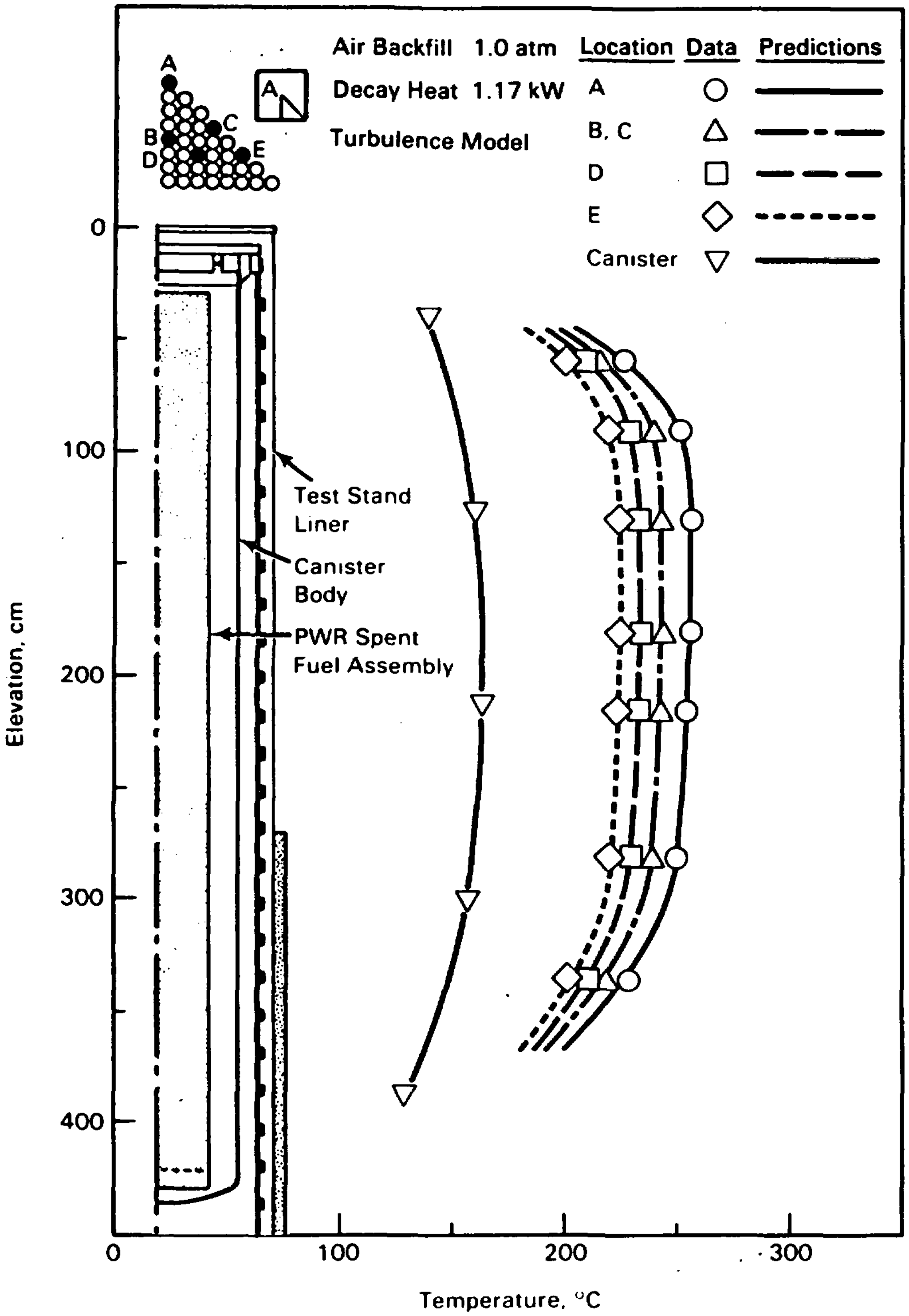


FIGURE 5.10. Comparison of Predicted and Measured Temperatures After Applying Turbulent Property Model to Air Backfill Case

free field between the fuel assembly and canister is approximately 9.4 x 10^{-3} g/cm^2-sec (velocity of 59 cm/sec). The maximum vertical mass flux within the assembly is approximately 1.3 x 10^{-4} g/cm^2-sec.

The results for the helium case are shown in Figure 5.12. The maximum centerline temperature predicted by HYDRA-II (226°C) is equal to the experimentally measured temperature. As can be seen in Figure 5.12, the comparison between predicted and measured temperatures at other locations is also very good. Maximum upward mass flux in the open region between the fuel assembly and the canister wall is predicted to be about 4.1 x 10^{-3} g/cm^2-sec (velocity of 32 cm/sec). Maximum upward mass flux within the fuel assembly is predicted to be about 0.5 x 10^{-4} g/cm^2-sec. These relatively small velocities suggest that, in this case, convection provides only a minor heat transfer component when helium is the backfill medium.

The difference between peak cladding temperature and the canister temperature is significantly lower for this helium test compared to the air tests. The lower temperatures are primarily the result of conduction by helium. The major benefit that helium offers to heat transfer is its relatively high thermal conductivity (roughly five times greater than air in the temperature range of interest). The observation that helium conduction is more important than convection applies only to this single-assembly test and will not necessarily be valid for other fuel assembly/canister configurations.

5.2 ELECTRICALLY-HEATED SINGLE-ASSEMBLY SIMULATIONS

The single-assembly heat transfer tests discussed in this section were performed as part of the DOE Commercial Spent Fuel Management Program. The tests were executed at the Pacific Northwest Laboratory using hardware designed and assembled by Allied General Nuclear Services at the Barnwell Nuclear Fuel Plant in Barnwell, South Carolina.

The primary objective of these tests was to provide experimental data for a variety of controlled conditions that would be characteristic of dry storage of spent light water reactor fuel. This data could then form a partial basis on which to evaluate the predictive capability of hydrothermal computer codes used to simulate spent fuel dry storage systems.

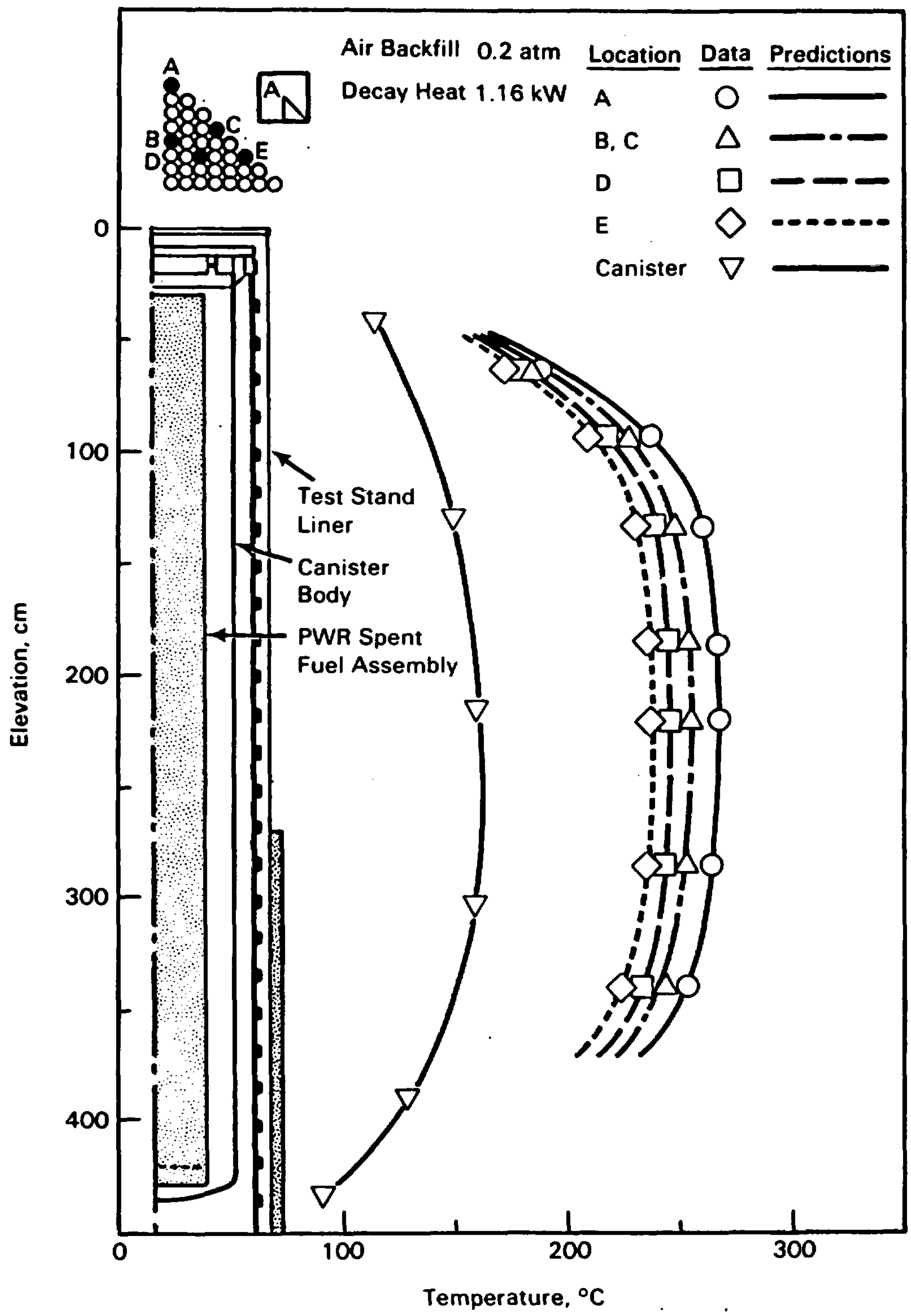


FIGURE 5.11. Predictions of Temperatures Compared to Data for Vacuum Backfill (Low-Pressure Air) Case

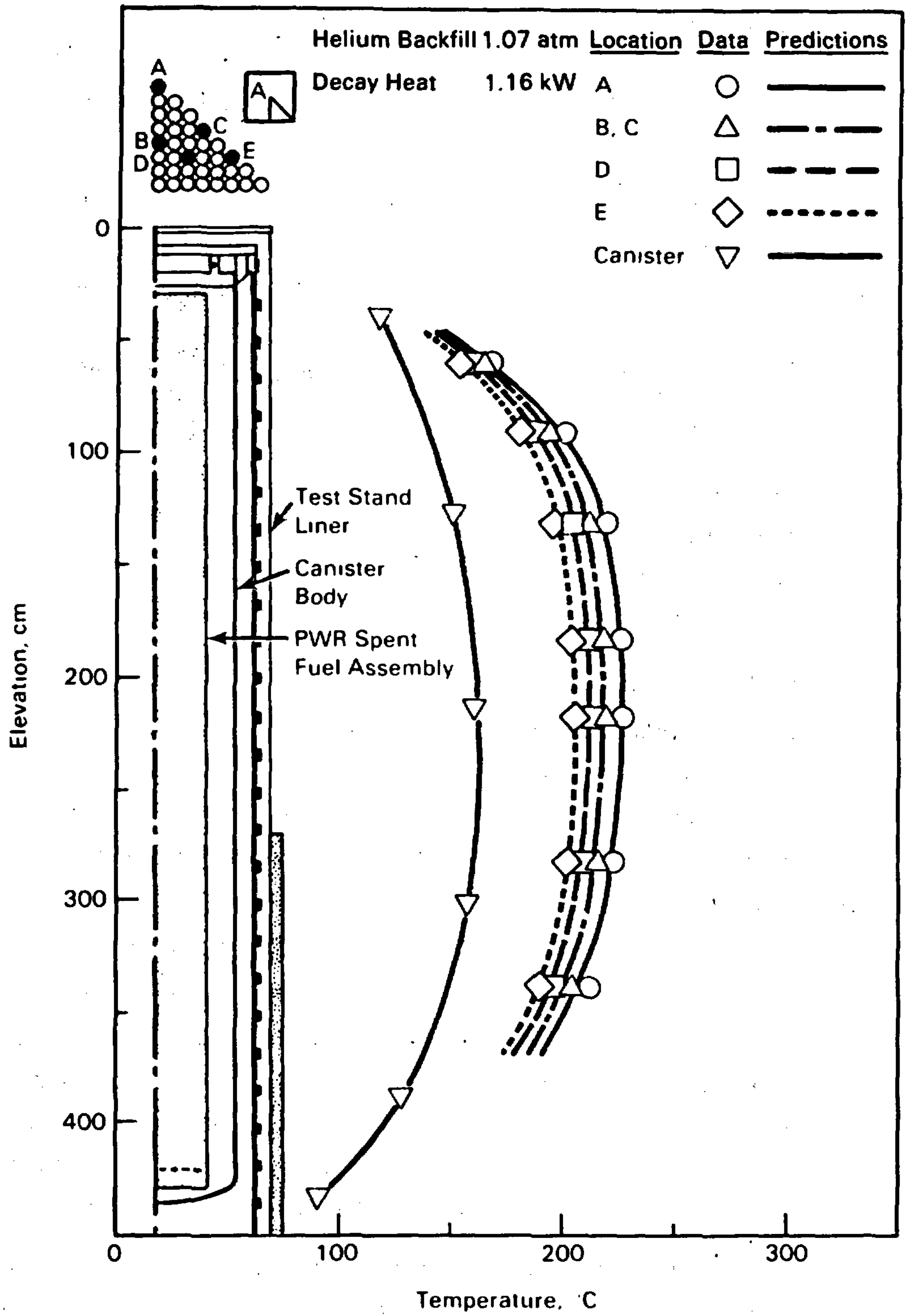


FIGURE 5.12. Predictions of Temperatures Compared to Data for Helium Backfill Case

The test hardware and test conditions needed for numerical simulation are described in Section 5.2.1. Section 5.2.2 contains computational models for this application. Section 5.2.3 presents HYDRA-II predictions and comparisons to data.

HYDRA pre-look and post-test predictions were previously performed for most of the test matrix described in Section 5.2.1. The results of these simulations are reported in detail in McCann (1986). Only the 1-kW, air-backfill simulation results will be discussed here. These cases are sufficient to illustrate the capabilities of HYDRA-II for predicting the unique aspects of these test conditions.

5.2.1 Test Description

This section contains a brief description of the test hardware and test conditions needed for numerical simulation. A full account of all test details is available in Bates (1986).

5.2.1.1 Hardware Description

The hardware consisted of the test assembly with a number of auxiliary systems and components. The test assembly comprised 1) a pressure/vacuum vessel (cask), 2) a transition piece and fuel tube, and 3) an electrically-heated model spent fuel assembly. Auxiliary equipment included 1) an evacuation and backfill system, 2) test assembly electric heater power supplies, controls, and transducers, 3) thermocouples, and 4) a data acquisition system.

Figure 5.13 shows an external view of the test assembly mounted on its skid. Electrical resistance heaters were spirally wound along the length of the cask. The heaters were connected to a temperature feedback controller and used to maintain a specified cask interior wall temperature (approximately 178°C) independent of the model fuel assembly power. An insulating blanket was placed over the cask body and guard heaters to minimize heat losses.

Figures 5.14 and 5.15 illustrate cross sections of the cask across its diameter and along its length, respectively. The transverse cross section of the cask illustrated in Figure 5.14 shows the double-wall construction, the location of thermocouples on the cask inside diameter, and the fuel tube location. The annulus bounded by the inner and outer cask walls was filled with

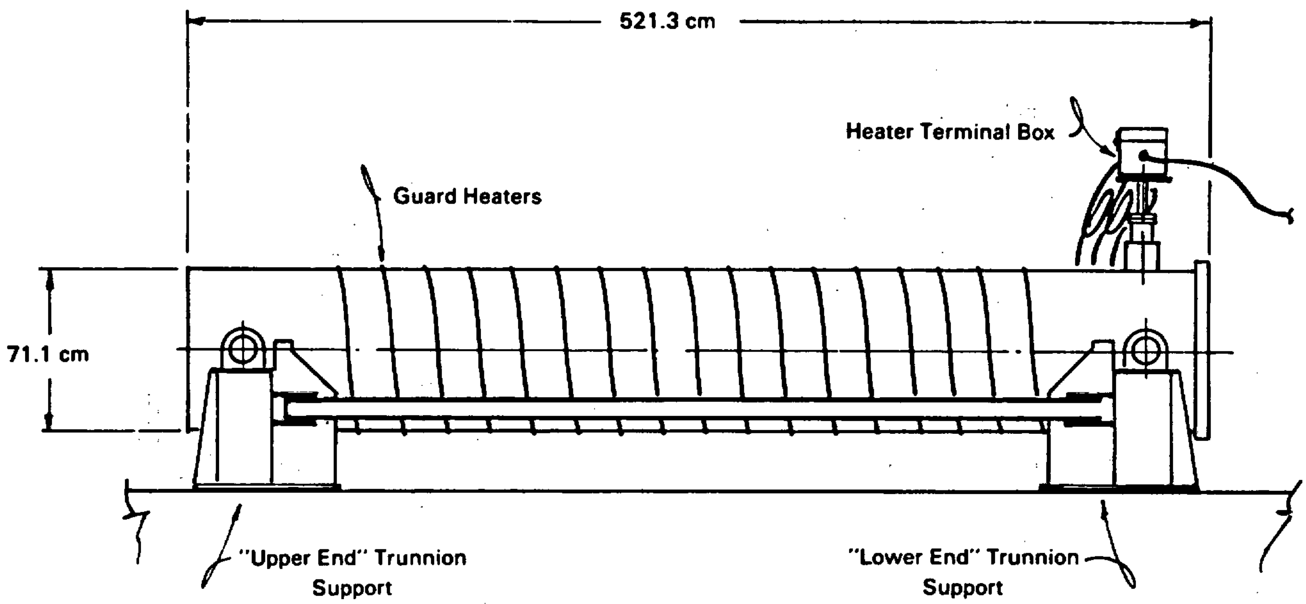


FIGURE 5.13. Test Assembly Mounted on Skid

air and sealed. The temperatures of the inside cask wall were used as boundary conditions for all simulations. These temperatures were estimated from thermocouples located near the inside cask wall. Four thermocouples were placed at each axial level. The five axial levels were approximately 1 m apart.

The fuel tube shown in Figures 5.14 and 5.15 is constructed in the form of a long box with a square cross section and open ends. The sides of the fuel tube are fabricated from Boral with stainless steel cladding. The fuel tube (and model fuel assembly) is intended to be concentrically located within the cask cavity. Post-test disassembly and inspection revealed that the upper end of the fuel tube/rod assembly centerline was offset from 1.25 to 2 cm. In addition, it was found that the composite fuel tube had delaminated and the inner stainless steel cladding pressed against the rod assembly in places.

Figure 5.16 shows a cross section of the electrically-heated model fuel assembly. It was designed and built to be physically and thermally characteristic of a typical 15x15 commercial light water reactor PWR fuel assembly. Of the total of 225 rods, 214 are electrically heated; the remaining 11 are unheated stainless steel rods.

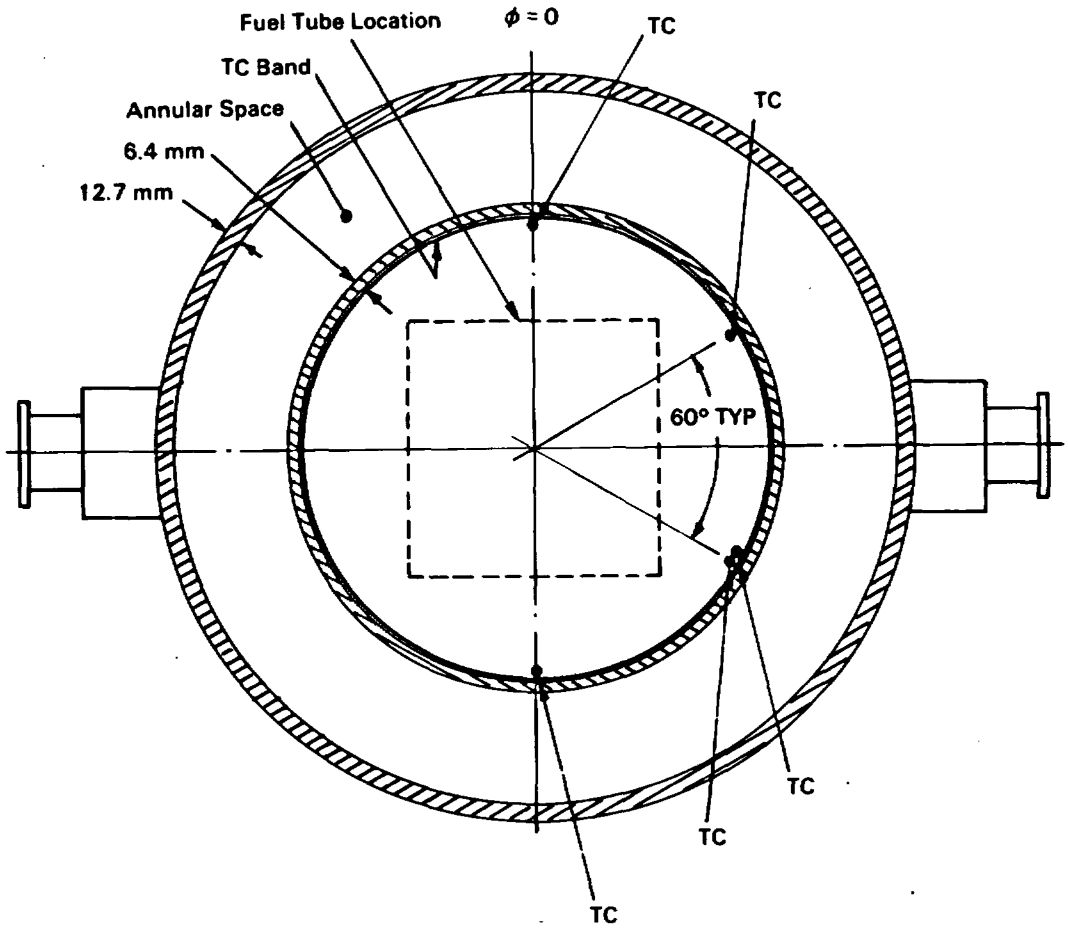


FIGURE 5.14. Electrically-Heated Cask Transverse Cross Section

The heater rods have a 366-cm heated length containing a single spirally wound nichrome wire insulated from the cladding by magnesium oxide powder. The power generation was assumed to be uniform along the length. Several of the heater rods were disconnected as indicated in Figure 5.16 to mirror failed and unheated stainless steel rods and, by this means, to provide half symmetric power generation.

The square cross section of the assembly was maintained by a series of spacer grids positioned along the length of the assembly (see Figure 5.15). Four of the spacer grids were fabricated as an array of 222.2 x 25.4 x 3.2-mm (8.75 x 1.0 x 0.125-in.) stainless steel flat bars. The remaining four spacer grids were of the more conventional "egg-crate" design used on PWR assemblies. The use of the spacer grids made from flat bars resulted in a variable rod

FIGURE 5.15. Electrically-Heated Cask Longitudinal Cross Section

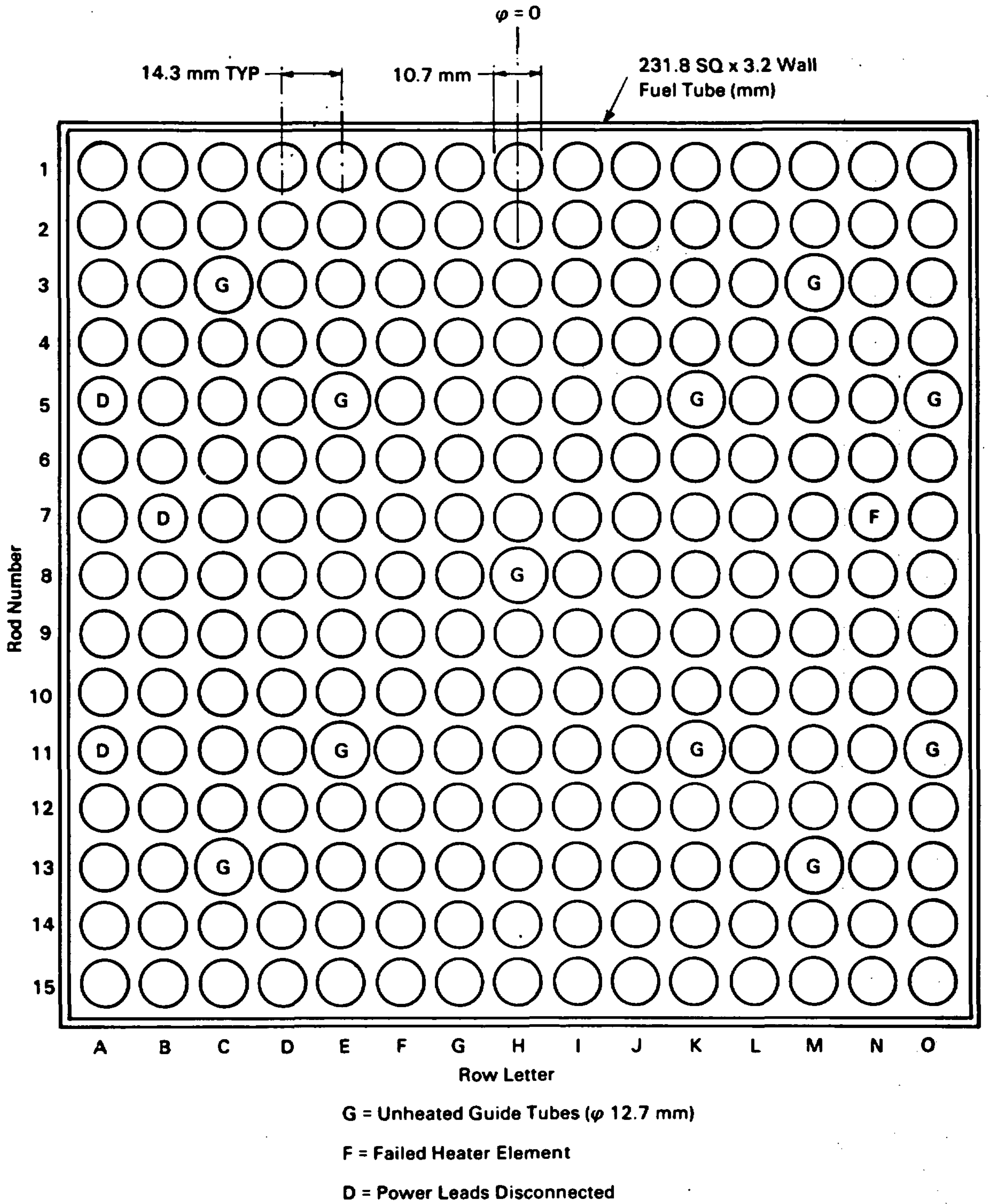


FIGURE 5.16. Cross Section of 15x15 Electrically-Heated Model Fuel Assembly

pitch. The rod assembly was instrumented with 57 thermocouples, although not all were functional. These thermocouples were apportioned over seven different axial planes. Some of the thermocouples were clipped to a rod surface. Others were attached to a stainless steel pad that was designed to be wedged between two neighboring rods. Post-test inspection revealed that some of the pads were loosely positioned near their original location.

The fuel tube was also instrumented with thermocouples at axial positions corresponding to those in the rod assembly. The thermocouples were welded to pads that were, in turn, welded to the outside surface of the fuel tube.

5.2.1.2 Test Conditions

Three independent primary parameters were selected to form a test matrix:

- cask orientation
  --horizontal
  --25° inclination from horizontal
  --vertical
- cask backfill medium
  --air at atmospheric pressure
  --air at approximately 0.1 atmosphere
  --helium at slightly above atmospheric pressure
- assembly power
  --0.5 kW
  --1.0 kW.

The resultant test matrix is shown in Table 5.4.

The test matrix was devised to exercise a range of code modeling capabilities appropriate to dry storage casks. Thus, the three cask orientations require a corresponding specification of the gravitational vector within the code, which directly affects the gas flow field. The three different backfill media promote a different relative contribution from conduction, convection, and thermal radiation heat transfer mechanisms. The heat generation level employed reflects typical 5- and 10-year-old PWR fuel.

TABLE 5.4. Electrically-Heated Single-Assembly Test Matrix

Run Number	Cask Orientation	Guard Heater Control Temp, °C	Nominal Power, kW	Actual Power, kW	Backfill	Pressure, mm Hg abs	Test Date
1	Inclined	178	1.0	0.951	Air	744.0	08/09/84
2	Inclined	178	1.0	0.940	Vacuum	83.3	08/10/84
2 repeat #1	Inclined	178	1.0	0.956	Vacuum	88.9	08/24/84
2 repeat #2	Inclined	178	1.0	0.960	Vacuum	85.3	09/14/84
2 repeat #3	Inclined	178	1.0	0.944	Vacuum	84.1	10/19/84
3	Inclined	178	1.0	0.956	Helium	789.4	08/22/84
4	Inclined	178	0.5	0.501	Helium	789.9	08/20/84
5	Inclined	178	0.5	0.484	Vacuum	82.6	08/16/84
6	Inclined	178	0.5	0.477	Air	746.8	08/15/84
7	Horizontal	178	0.5	0.487	Air	749.8	09/04/84
8	Horizontal	178	0.5	0.486	Vacuum	87.6	09/05/84
9	Horizontal	178	0.5	0.500	Helium	795.5	09/07/84
10	Horizontal	178	1.0	0.964	Helium	787.4	08/30/84
11	Horizontal	178	1.0	0.949	Vacuum	87.1	08/28/84
12	Horizontal	178	1.0	0.943	Air	743.2	08/27/84
13	Vertical	178	1.0	0.994	Air	746.3	09/21/84
14	Vertical	178	1.0	0.977	Vacuum	79.2	09/25/84
15	Vertical	178	1.0	0.995	Helium	787.4	09/28/84
16	Vertical	178	0.5	0.501	Helium	785.6	10/01/84
17	Vertical	178	0.5	0.496	Vacuum	81.3	10/03/84
18	Vertical	178	0.5	0.515	Air	749.8	10/05/84
19	Vertical	178	1.0	0.981	Vacuum	29.2	09/26/84
20	Horizontal	Off	0.5	0.497	Air	750.3	09/12/84
21	Vertical	Off	0.5	0.515	Air	747.3	10/09/84
22	Horizontal	On	0.0	0.0	Helium	787.9	10/23/84

The inside surface temperature of the cask cavity served as a boundary condition for all simulations. The temperature at one point on the surface was held constant by adjusting power to the external guard heaters. Temperatures at other positions did vary, depending on the particular parameters of a given test. A list of temperatures and their respective locations for each run may be obtained from Bates (1986).

5.2.2 Computational Model Description

The computational mesh and material properties contained on the input file are described in this section. The complete HYDRA-II input file for the air backfill, inclined orientation, 1-kW case is provided in Appendix B.

5.2.2.1 Computational Mesh

Transverse cross sections of the cask and rod assembly were illustrated previously in Figures 5.14 and 5.16, respectively. These figures show the rod assembly within the square fuel tube, both of which are symmetrically positioned within the circular cask. The half-symmetrical heat generation allows the use of a half symmetry model regardless of cask orientation.

Figure 5.17 shows the transverse computational mesh employed for all simulations. The straight-line segments approximating the cask inside diameter were introduced to reduce computer storage without significantly affecting predicted rod assembly or fuel tube temperatures. Figure 5.18 indicates the alignment of the computational mesh with the rod assembly, fuel tube, and cask inside surface.

A longitudinal cross section of the cask was shown in Figure 5.15. A corresponding cross section of the computational mesh is shown in Figure 5.19. Figure 5.20 indicates the location of the rod assembly, fuel tube, and cask inside surface relative to the computational mesh.

5.2.2.2 Material Properties

Material properties were obtained from Touloukian and Ho (1970). Table 5.5 lists the material properties used for all simulations. Effective thermal conductivities were estimated for those computational cells containing more than one material.

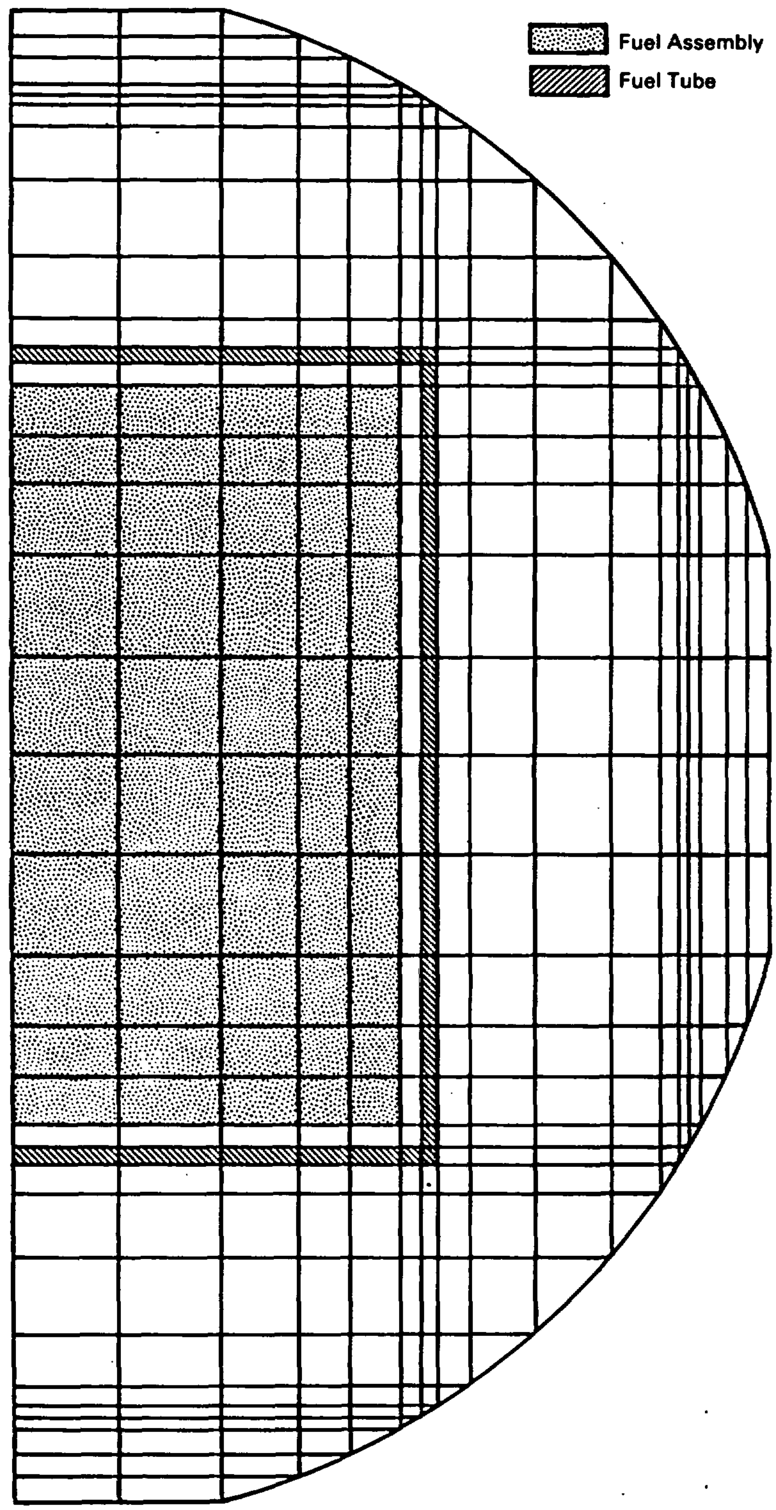


FIGURE 5.17. Transverse Computational Mesh for Simulating Electrically-Heated Cask Tests

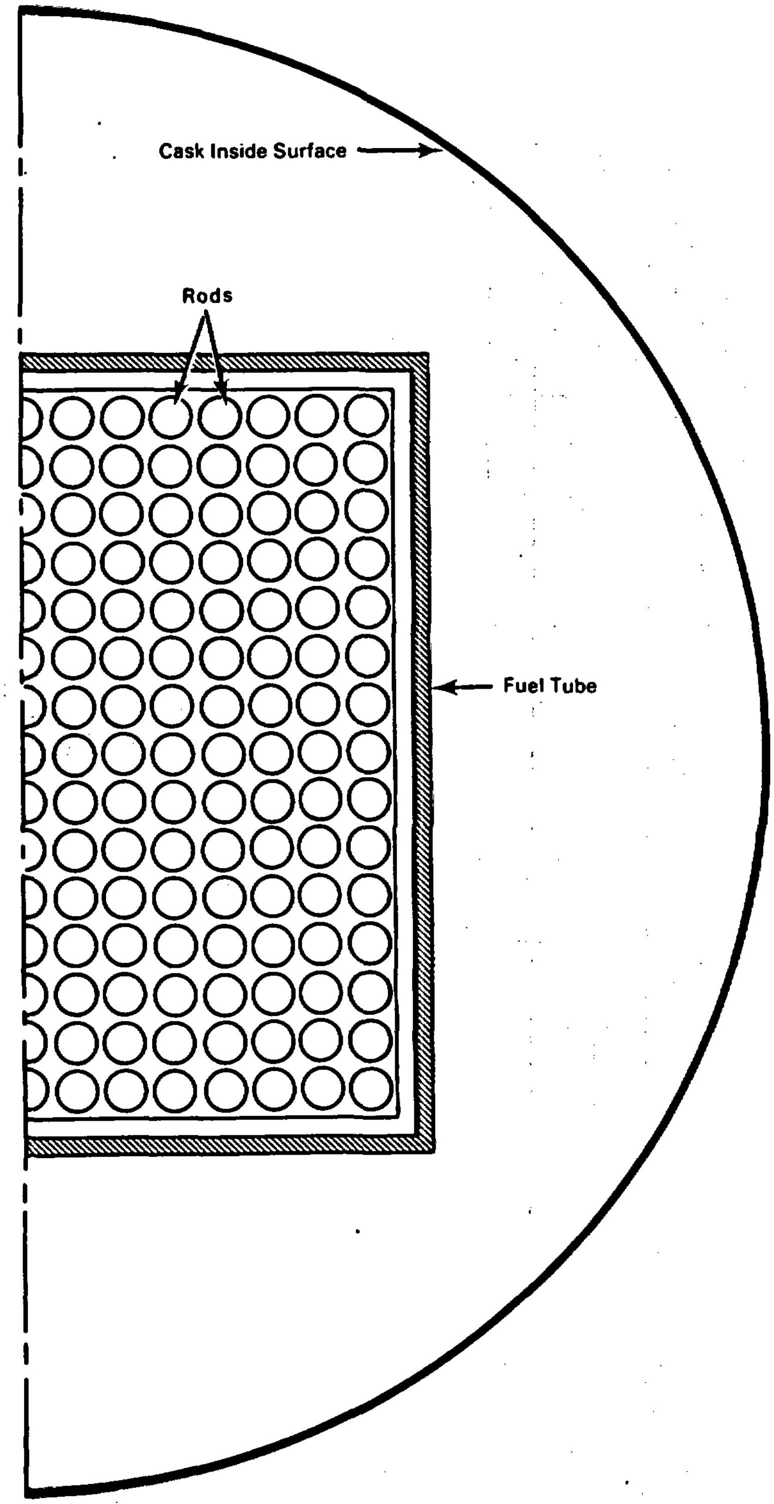


FIGURE 5.18. Alignment of Transverse Cross Section Computational Mesh with Electrically-Heated Cask Physical Features

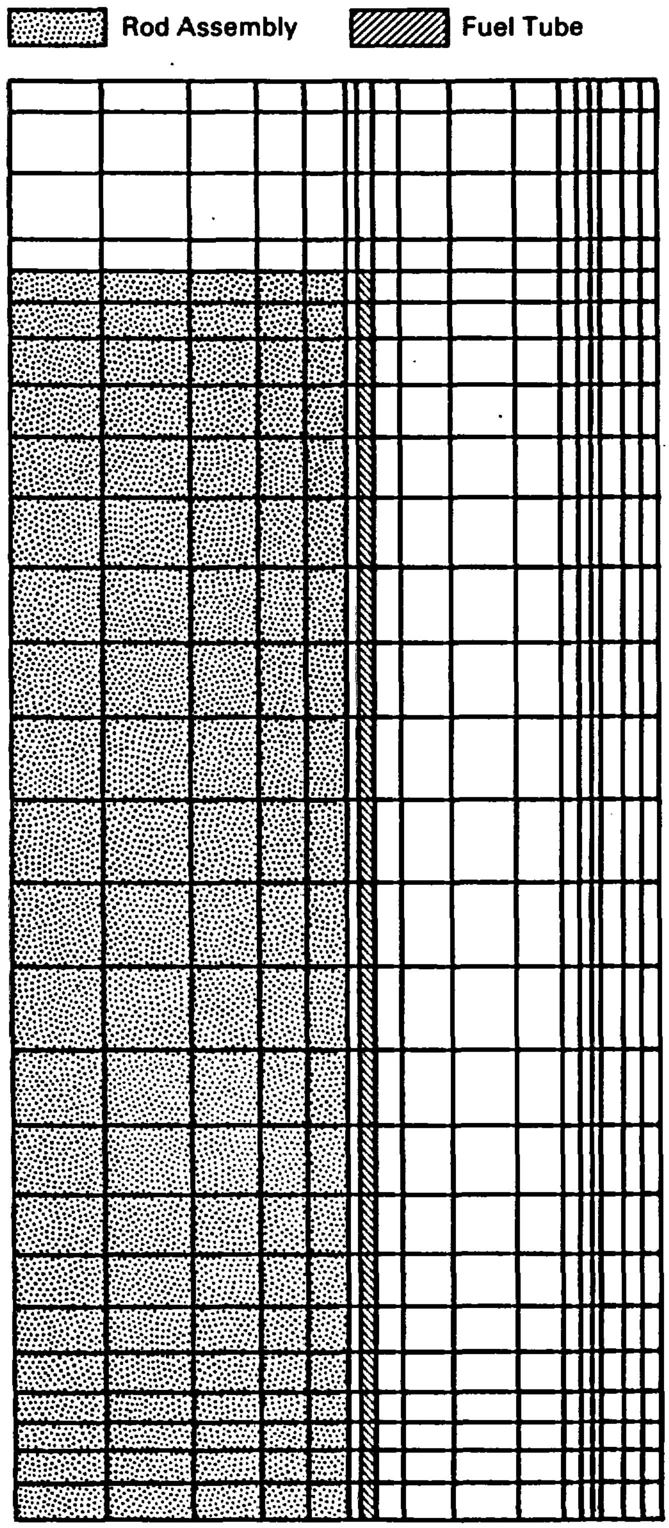


FIGURE 5.19. Longitudinal Computational Mesh for Simulating Electrically-Heated Cask Tests

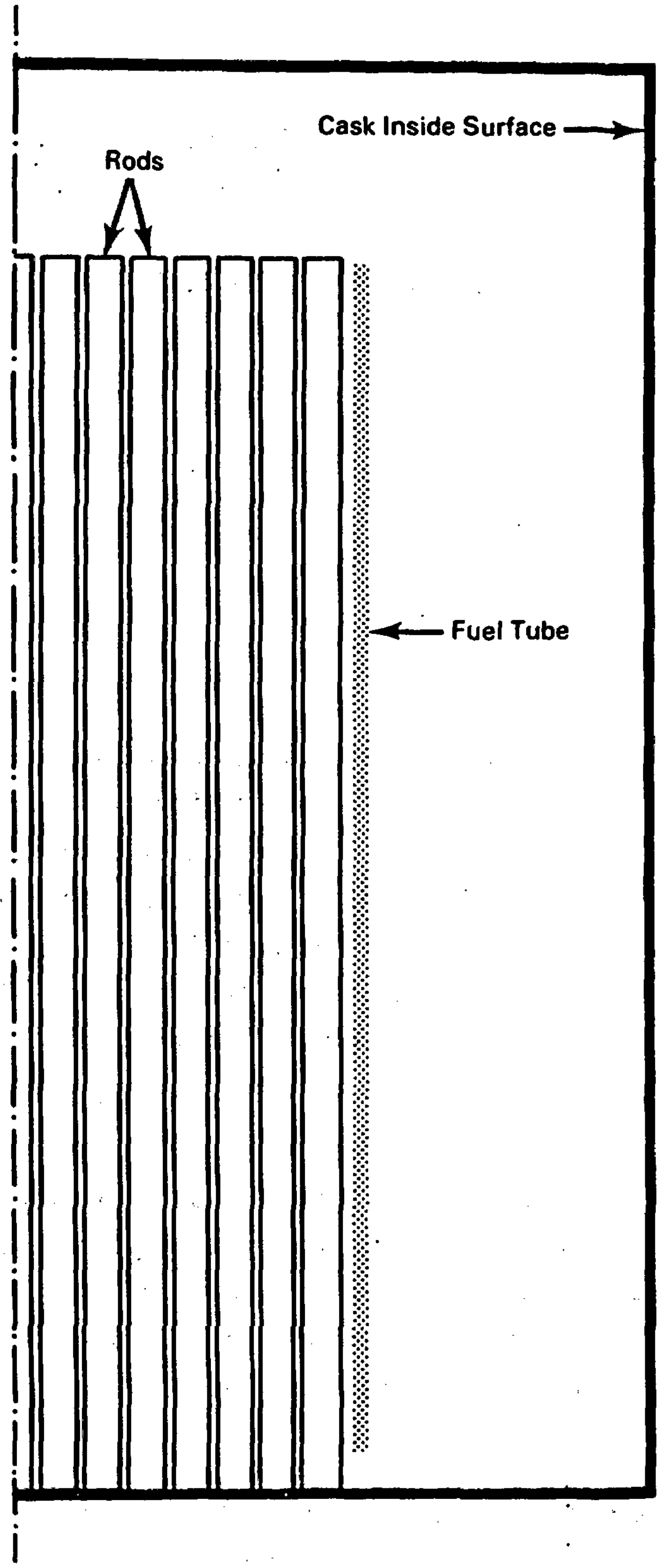


FIGURE 5.20. Physical Features Modeled in Longitudinal Cross Section

TABLE 5.5. Electrically-Heated Single-Assembly Test Material Properties

Thermal conductivity, W/cm^{2}°K	
Stainless steel	0.09215+(0.1465E-3)T
Boral	0.677-(0.667E-3)T
Magnesium oxide	0.16
Air	0.688E-4+(0.634E-6)T
Specific heat, W sec/g°K	
Air	1.0
Viscosity, g/cm sec	
Air	0.608E-4+(0.400E-6)T
Emittance	
Rods	0.6
Fuel tube	0.2
Cask inside surface	0.6

The range of uncertainty for most of the property values used is not considered significant. The exceptions are the thermal conductivity of magnesium oxide and the emittances. The thermal conductivity of the magnesium oxide insulation used in the heater rods depends on its initial compacted state and its subsequent thermal history. It is believed that the rods (and the cask) had repeatedly been at relatively high temperatures before the start of this series of tests. For this reason, the thermal conductivity of magnesium oxide was selected toward the high end of potential values that span a range of over an order of magnitude.

The emittance of the fuel tube is probably reliable because a similar but slightly less oxidized specimen had been measured previously by Taylor (1983). The emittance of 0.2 falls within the measured range. An emittance of 0.6 was selected for both the stainless steel rod cladding and cask inside surface because of their repeated exposure to relatively high temperatures.

5.2.3 Predictions Compared to Data

Figure 5.21 illustrates the results obtained from the HYDRA pre-look simulations of McCann (1986). These results indicate the comparison between

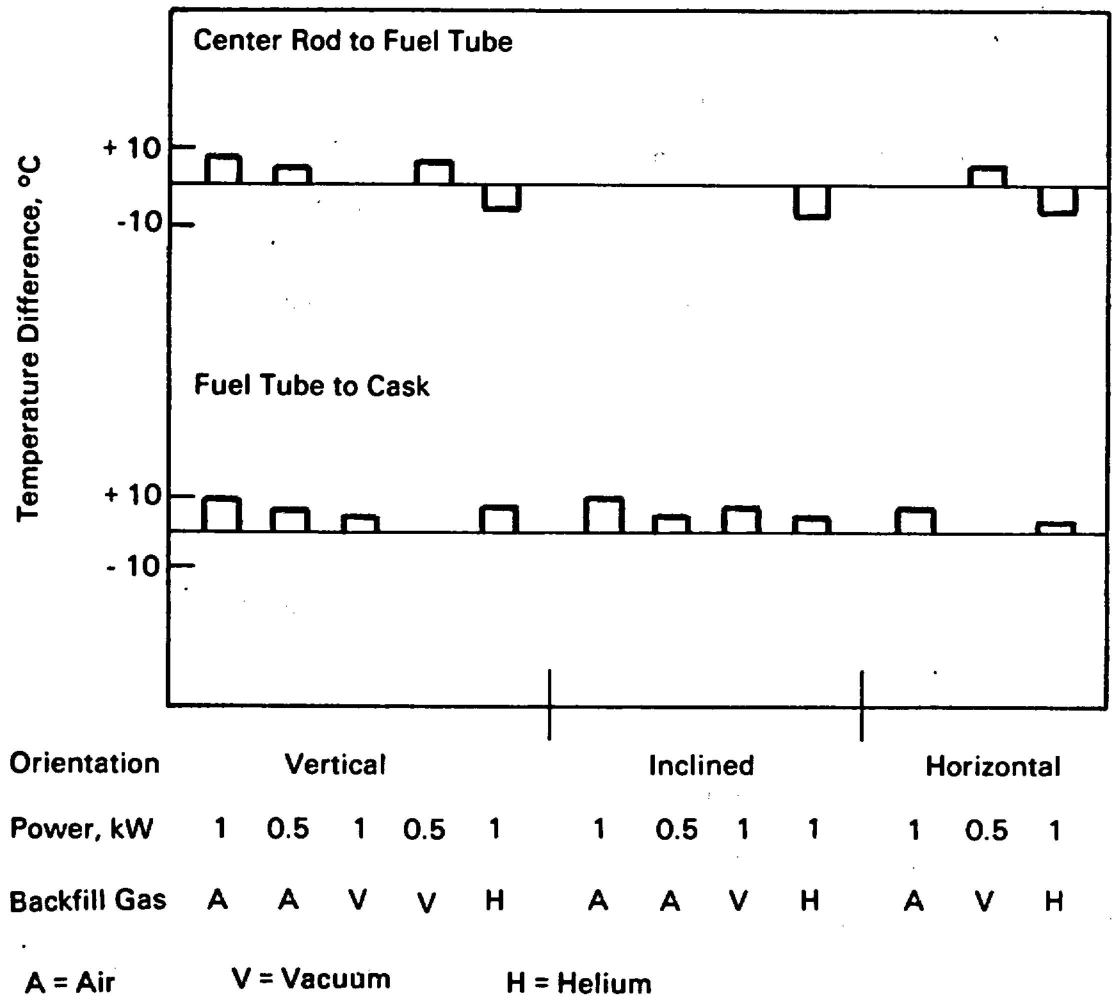


FIGURE 5.21. Summary of Predictions Compared to Data Showing Temperature Differences

predictions and data for virtually the entire spectrum of cases listed in the test matrix of Table 5.4. Figure 5.21 shows the comparison between predictions and data by means of 1) the temperature difference between the center rod and fuel tube and 2) the temperature difference between the fuel tube and cask. For example, the first simulation shown in Figure 5.21 is for a vertical orientation, 1-kW power generation rate, and air backfill. The temperature difference of approximately +8°C for center rod to fuel tube means that the predicted temperature difference is 8°C higher than what was measured. Similarly, the temperature difference of +10°C for fuel tube to cask means that the code prediction is 10°C greater than the measured temperature difference.

Predictions of temperatures are compared to experimentally measured 1-kW, air-backfill test data in this section. As indicated in Figure 5.21, these represent the worst cases of deviation between computed and measured results. All predictions were generated initially without access to the experimental results (except cask internal gas pressure, heat generation rate, and temperature boundary conditions), to ensure an unbiased evaluation of the HYDRA-II code. An additional simulation demonstrates the important benefits that turbulence modeling may provide.

All simulations were conducted with the same version of HYDRA-II, and all input files were identical except for the unique parameters of each test. The input files were prepared according to the best available information from cask drawings and private communications. After all tests were concluded, the cask was disassembled and inspected. It was found that the as-tested cask did not conform in all respects to the pretest information. The cask description given in Section 5.2.1.1 reflects the as-tested cask. The code input files, however, were based on pretest information. A discussion of the possible consequences of this mismatch is included in Section 5.2.3.2.

5.2.3.1 Predictions Compared to Data

Comparison between predictions and data can be made in the same manner as was done for Figure 5.21. For the vertical orientation case, a temperature difference of approximately +8°C resulted between the center rod and fuel tube. The computed fuel tube-to-cask temperature difference was +10°C. For the inclined and horizontal orientation cases, the fuel tube-to-cask temperature differences were +10°C and +8°C, respectively. These temperature differences are derived from average temperatures at the elevation nearest to the peak rod temperature where experimental data exists.

The fuel tube represents a barrier to both convective and radiative energy transport. Furthermore, the energy transport within the fuel tube (i.e., within the rod assembly) is characterized and modeled differently than is the transport external to the fuel tube (i.e., a free field). The temperature differences for these two regions might therefore be used as an indicator of the correctness of the separate models and heat transfer modes.

The results of the simulations are presented according to cask orientation. The results for the vertical orientation are presented first, followed by the inclined and then the horizontal orientation. Four axial temperature profiles are shown for each simulation: center rod, corner rod, fuel tube, and cask inside surface. These transverse locations were selected because of their significance to cask designers, because they provide a good measure of the code's predictive capability, and because they have the largest amount of experimental data. The legend on each figure shows the precise locations.

5.2.3.1.1 Vertical Orientation Results. Figure 5.22 shows the results for the vertical orientation case. These results display the largest discrepancy between predictions and data of all the simulations. One of the most striking aspects of the profiles is the shift in peak temperatures to nearly the top of the heated length. This shift does not reflect the heat generation rate, which is believed to be nearly uniform over the length of the rod assembly. The general shape of the profiles indicates that strong convection currents were present. Moreover, the predicted velocities are high enough so that appreciable turbulence is expected. The agreement between predictions and data will be shown to be greatly improved by the use of an appropriate turbulence model.

5.2.3.1.2 Inclined Orientation Results. Figure 5.23 shows the inclined orientation case results. These results are much improved over the vertical orientation simulation. The influence of axial convection is still apparent but much reduced. This is as it should be because the axial component of gravity has been reduced from 1.0 to approximately 0.4 (sin 25°).

It is interesting that the measured data indicates little change in the magnitude of peak temperatures for fuel tube and rod assembly as the inclination changed from vertical to 25° from horizontal. Some shift in axial location does, however, occur.

5.2.3.1.3 Horizontal Orientation Results. Figure 5.24 shows the results for the horizontal orientation case. These results demonstrate a consistent trend in passing from the vertical orientation to inclined and finally to the horizontal. The effects of axial convection, so marked in the vertical orientation, are no longer apparent, although axial convection is still present.

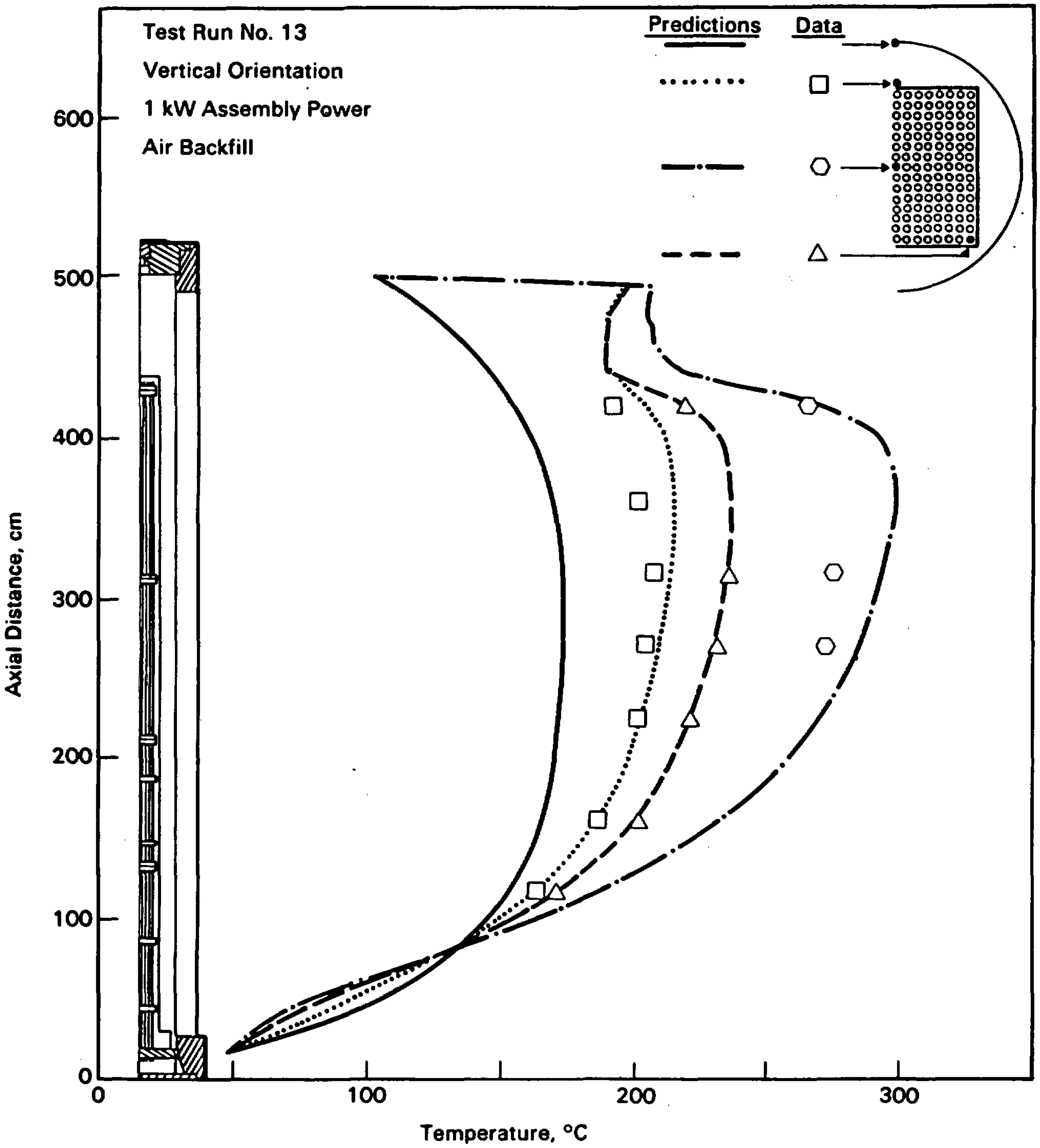


FIGURE 5.22. Predictions of Temperatures Compared to Data for Vertical Orientation Case

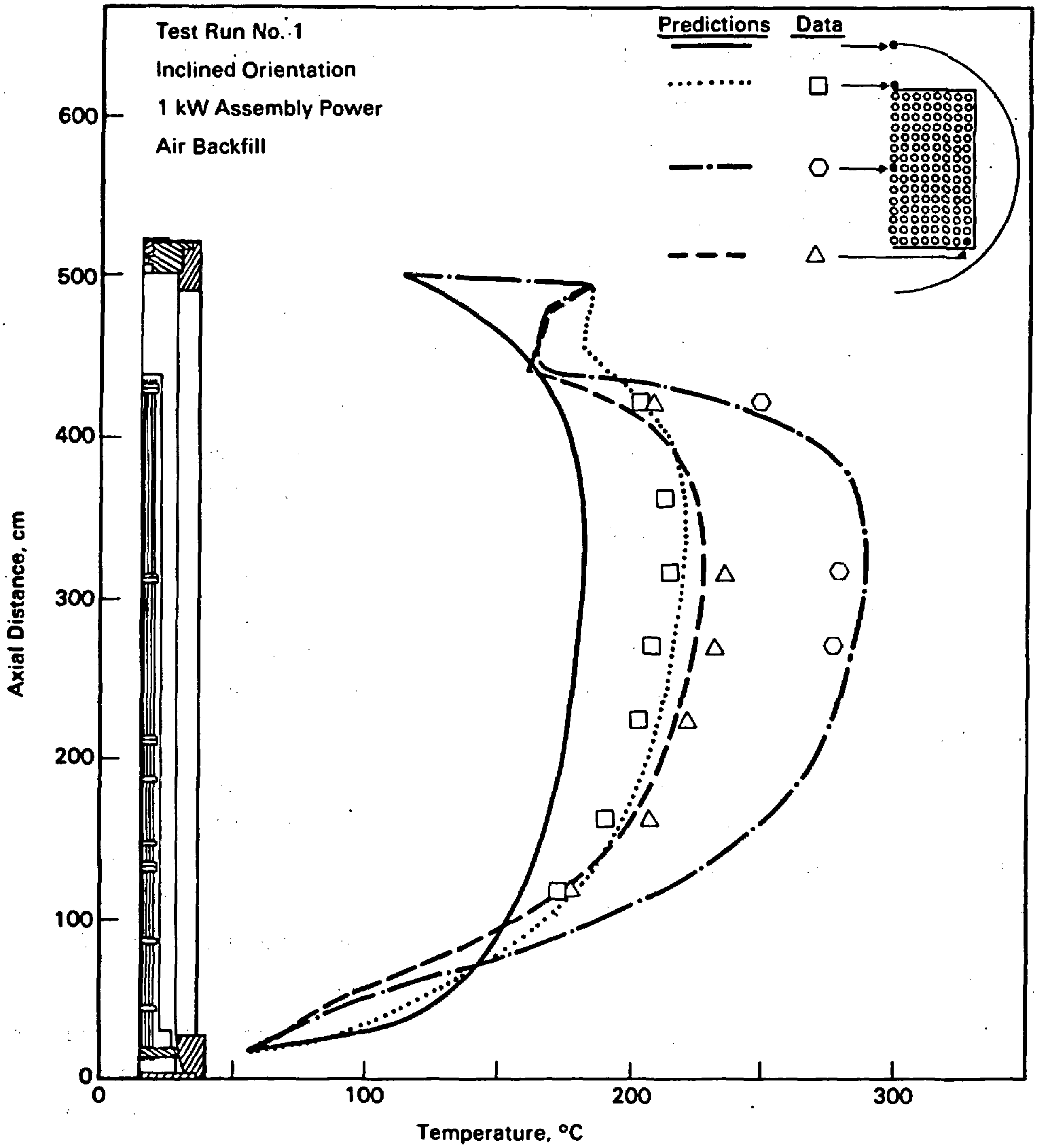


FIGURE 5.23. Predictions of Temperatures Compared to Data for Inclined Orientation Case

The temperature difference between the center rod and the fuel tube has remained nearly constant. Further, the temperature difference in the free field between the fuel tube and cask has continued to drop with the increasing gravitational component in the transverse direction.

5.2.3.1.4 Results Summary. The comparison between predictions and measured data was favorable for most of the simulations. An exception is the simulation for the vertical orientation case. It has been suggested that significant turbulence was present in this test. This matter and other factors influencing the results will be taken up in Section 5.2.3.2.

5.2.3.2 Additional Predictions Compared to Data

The input files for the simulations were constructed based on the best available information before the conclusion of the tests. After the tests were concluded, the cask was disassembled and inspected. Thermocouple locations and their method of attachment were verified. Important dimensions were measured. Some of the materials used in the rod assembly were confirmed, and the general condition of the cask interior was noted. The as-tested cask was found to not conform entirely to pretest information in some respects. The more significant findings are summarized below.

The fuel tube and rod assembly were intended to be centered within the cask and held in that position at both ends. It was found that the upper end had not been securely supported, resulting in an offset from the centerline estimated to be from 1 to 2 cm when in the horizontal position. The offset when the cask was in the vertical position is unknown. The input specified that both the fuel tube and rod assembly were centered.

The fuel tube walls were constructed as a sandwich with a Boral interior and two stainless steel sheets as cladding. It was observed that the fuel tube had delaminated and that the inside cladding appeared to press against the rod assembly in places. The time at which this structural change occurred within the test series is unknown. The input specified a bonded sandwich construction and a uniform gap between fuel tube and rod assembly.

Two types of spacer grids are used in the rod assembly. One type is similar to the conventional design used in PWR fuel assemblies; the other was

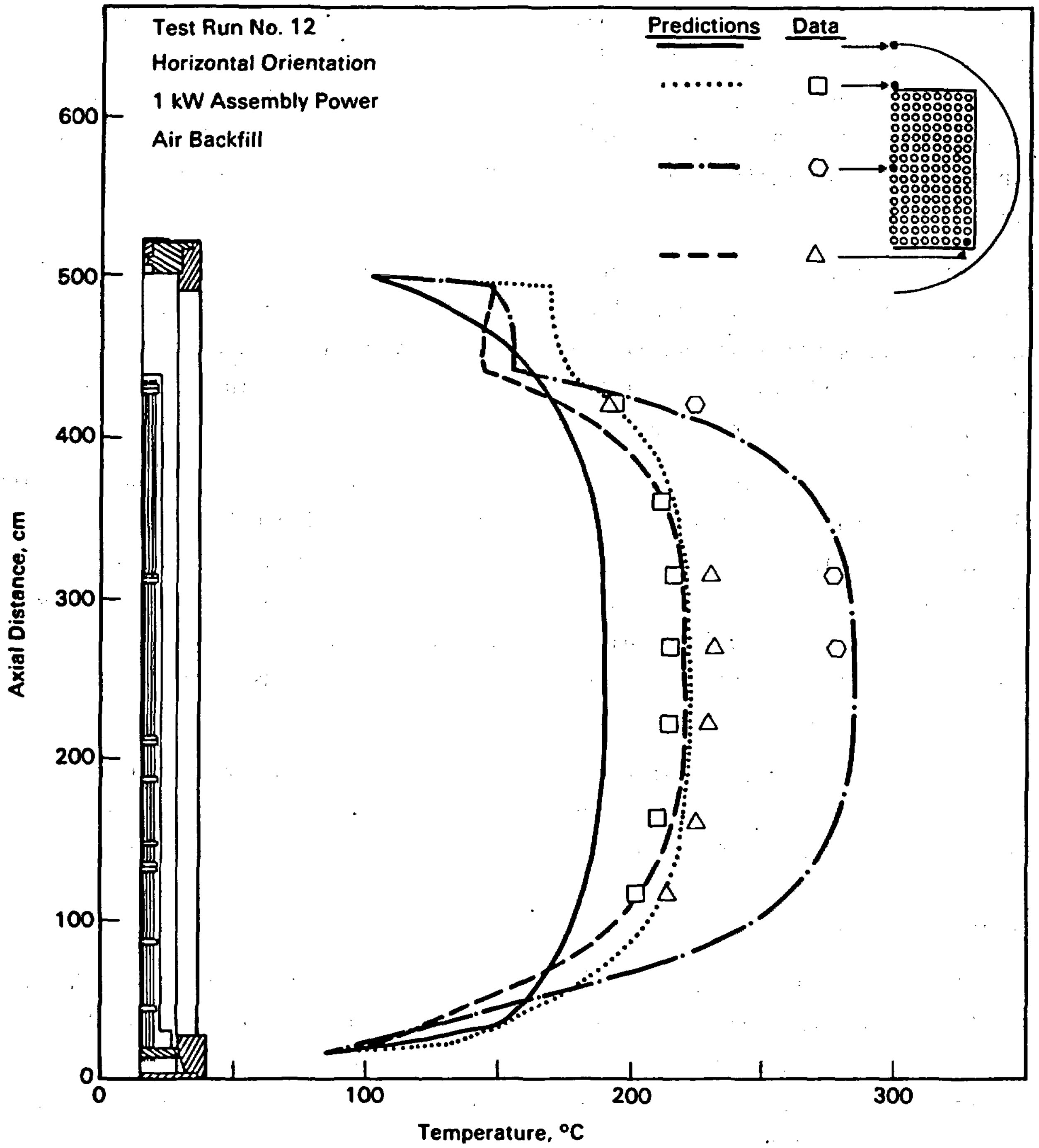


FIGURE 5.24. Predictions of Temperatures Compared to Data for Horizontal Orientation Case

fabricated from flat bars. The use of flat bars results in a rod pitch that varies in both the transverse and axial directions. The rod pitch influences conduction, convection, and thermal radiation transfer within the rod assembly in a complex fashion. The net effect on predicted temperatures is different for each cask simulation. The input to HYDRA-II specified a single nominal pitch.

The uncertainty in some thermophysical properties was mentioned previously in Section 5.2.2.2. The thermal conductivity of the magnesium oxide used in the heater rods has a potential range of over an order of magnitude. The emittances of the rods in the model fuel assembly and the cask inside surface were also not measured and thus are uncertain.

The physical locations of temperature data furnished as a boundary condition for the cask inside surface were rather sparse. The data planes were spaced approximately 1 m apart, and temperature differences exceeding 80°C were common near the ends of the cask. Temperature boundary conditions are required for the solution of the internal temperature field and have a direct impact on the internal temperatures. Temperature boundary conditions were estimated where measured data was not available.

Finally, measured temperatures at some nominally symmetric locations differed by 8°C or more. A comparison between predictions and data was summarized for all simulations in Section 5.2.3.1. This asymmetry in data is comparable to the temperature differences between predictions and data for all simulations as discussed in Section 5.2.3.1.

Considering all of the above factors, the agreement between the HYDRA-II predictions and the measured data is good. There appears to be no need to modify the algorithms or models currently in HYDRA-II. The agreement between predictions and data could, however, be improved by adjusting some property values used in the input.

Figure 5.25 shows the comparison between additional predictions and data for the vertical orientation, air backfill simulation. The superior agreement was achieved by incorporating a turbulent-transport mechanism in the upper half

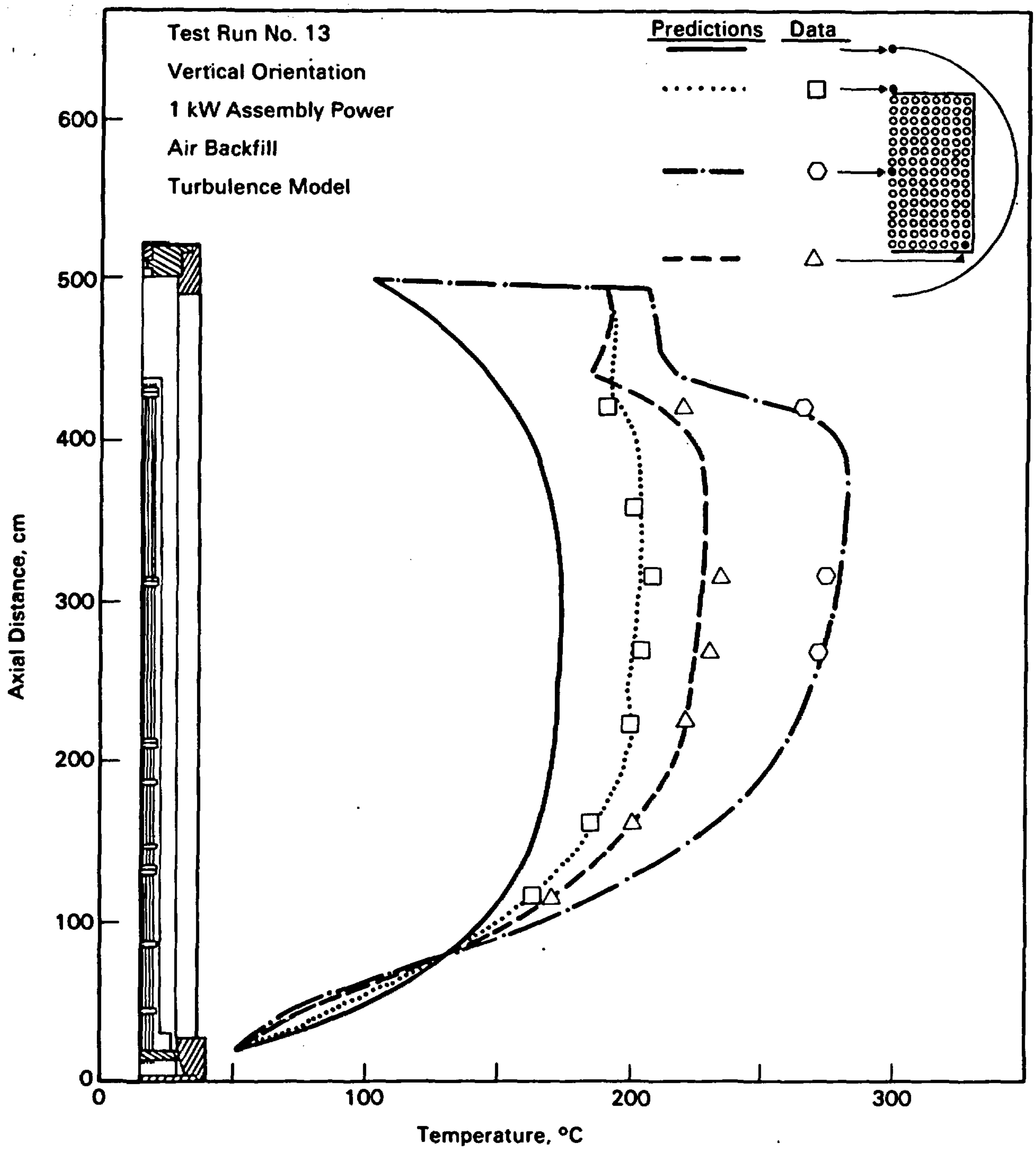


FIGURE 5.25. Comparison of Predicted and Measured Temperatures After Applying Turbulent Property Model to Vertical Orientation, Air Backfill Case

of the cask where velocities are greatest. The benefits of an appropriate turbulence model can be appreciated by comparing the results shown in Figure 5.25 with their counterparts shown in Figure 5.22.

6.0 MULTIASSEMBLY EVALUATION TESTS

HYDRA-II was also validated against multiassembly storage systems. As with the single-assembly validation cases considered in Chapter 5.0, conduction, convection, and radiation heat transfer mechanisms must be properly modeled to accurately predict the thermal performance of these systems. Two multiassembly storage systems will be considered for this purpose--the CASTOR-1C and CASTOR-V/21 spent fuel storage casks. Section 6.1 presents a comparison of the HYDRA-II predictions with data obtained experimentally for the CASTOR-1C configuration. A similar comparison for the CASTOR-V/21 configuration is presented in Section 6.2.

6.1 CASTOR-1C SPENT FUEL STORAGE CASK

The Gesellschaft fur Nuklear Services (GNS) CASTOR-1C cask (GNS 1983, 1985a) is designed to safely store 16 BWR spent fuel assemblies for extended time periods while dissipating their decay heat. A cutaway drawing of the CASTOR-1C cask is shown in Figure 6.1. The cask consists of a thick-walled nodular cast-iron body, which is cast in one piece. The body physically protects the fuel assemblies and provides radiation shielding. The central cavity of the cask contains a stainless steel basket that separates and supports the spent fuel assemblies. The top of the cask is sealed using a multiple-lid system. The overall cask dimensions and design specifications are summarized in Table 6.1. The major cask components are described in Section 6.1.1. The HYDRA-II model is described in Section 6.1.2. A series of tests and numerical simulations was performed for the CASTOR-1C cask. The effects of variations in backfill gas, backfill gas pressure, decay heat generation rate, and cask orientation were simulated. The complete computational and experimental results are provided in Rector et al. (1986). Only the case of the helium-filled, vertically-oriented cask (for which there is test data) is presented here. The comparison of computation with experiment for this case is presented in Section 6.1.3.

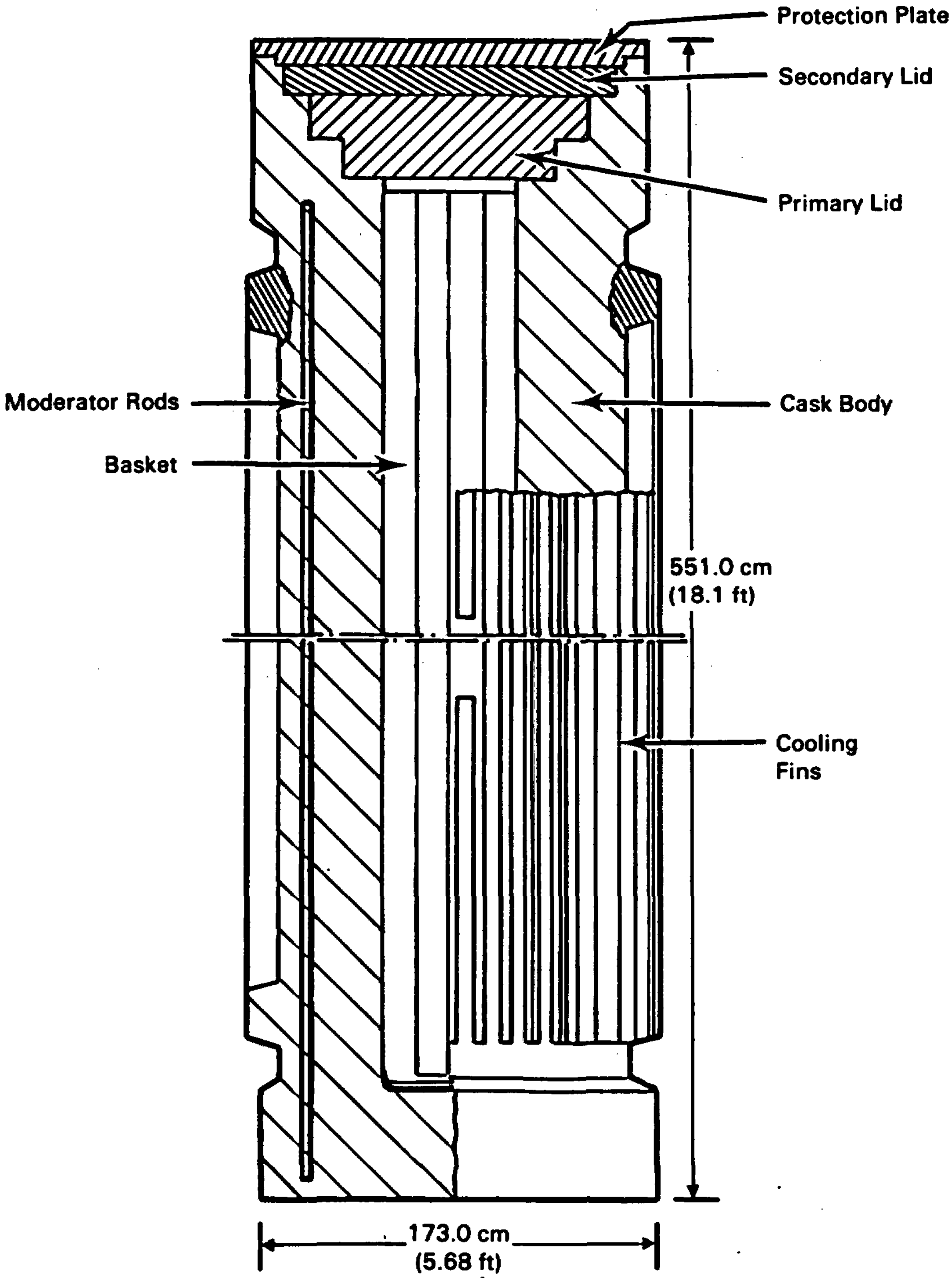


FIGURE 6.1. CASTOR-1C Cask Elevation View

TABLE 6.1. CASTOR-1C Cask Dimensions and Design Specifications

Cask overall length	551 cm (18 ft)
Cross section	173 cm (5.7 ft)
Cask cavity width	66.6 cm (2.2 ft)
Cavity length	456 cm (15 ft)
Side wall thickness without fins	44 cm (17 in.)
Lid thicknesses	
Primary lid	34 cm (13 in.)
Secondary lid (including moderator)	13 cm (5 in.)
Protection plate	8 cm (3 in.)
Bottom thickness	44.7 cm (18 in.)
Moderator dimensions	
Number of polyethylene moderator rods	80
Rod diameter	6 cm (2.4 in.)
Thickness, secondary lid	6 cm (2.4 in.)
Thickness, bottom	4.2 cm (1.7 in.)
Number of cooling fins	48
Cask fuel assembly capacity	16
Cask atmosphere	helium
Cavity pressure	0.8 bar (11.76 psia)
Weight	
Empty cask	76.6 ton
Loaded cask	81.1 ton

6.1.1 Test Description

This section contains a brief description of the test hardware and conditions needed for numerical simulation. More detailed documentation is available in Rector et al. (1986).

6.1.1.1 Body

A cross section of the CASTOR-1C cask is shown in Figure 6.2. The nodular cast-iron body has an overall length of 5510 mm (18 ft) and a maximum outside diameter of 1730 mm (5.7 ft). The side wall thickness (without fins) is approximately 440 mm (17.3 in.). Gamma-ray and neutron radiation are shielded

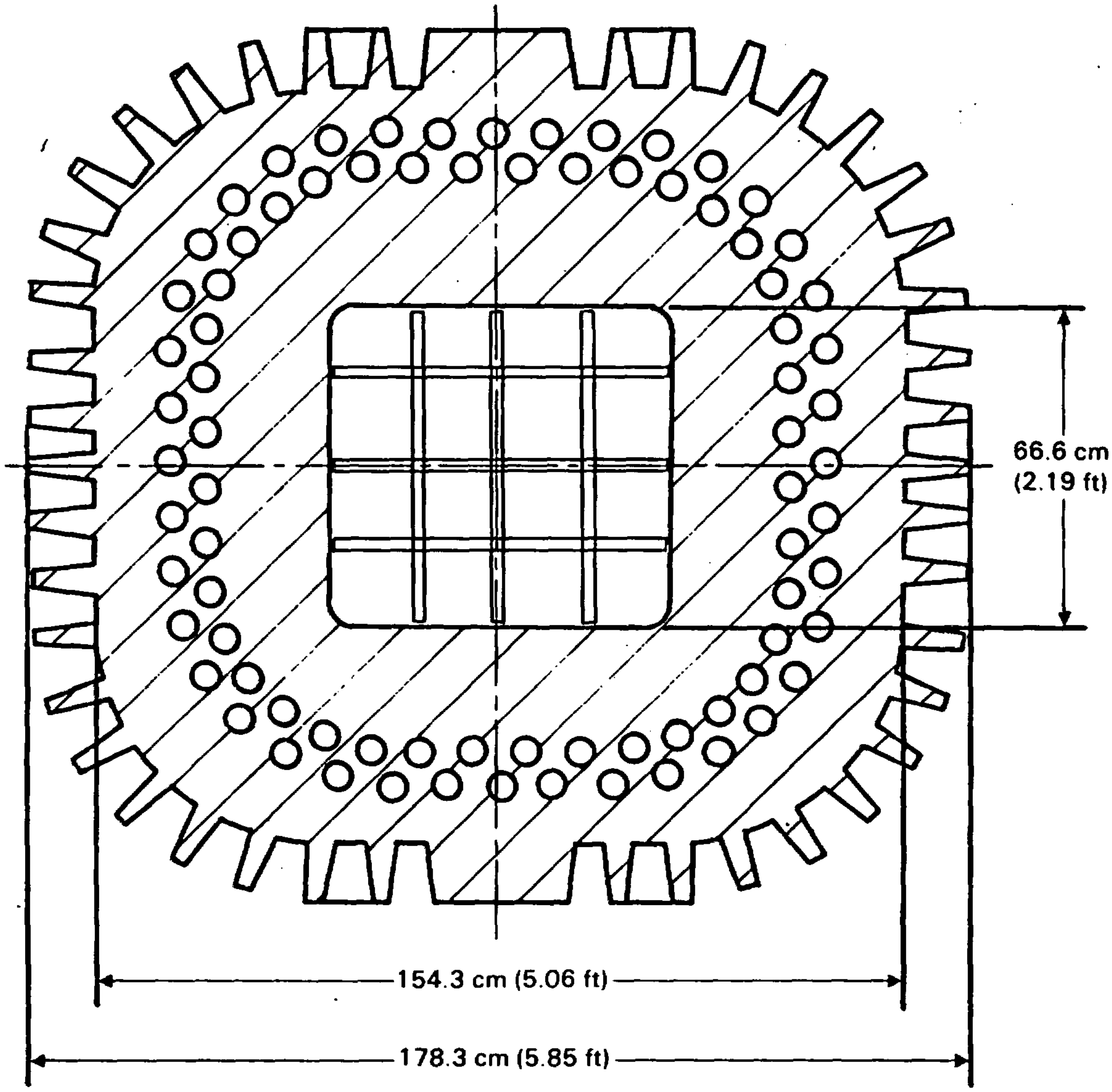


FIGURE 6.2. CASTOR-1C Cask Cross Section

by the cast-iron wall of the cask. For improved neutron shielding through the side, two concentric rows of axial holes in the cask body wall 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-ray and neutron) on the cask surface is designed to be 200 mrem/hr or less. The maximum design 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 is provided to enhance the removal of heat by natural convection. A cross section of the CASTOR-1C cask illustrating the cooling fin geometry is shown in Figure 6.3. The fins are 120 mm (4.7 in.) long and 50 mm (1.97 in.) wide at the base, and are 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 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 exterior 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 that serve as neutron shields. A semi-permanent steel cover plate is secured over the rings to hold them in place.

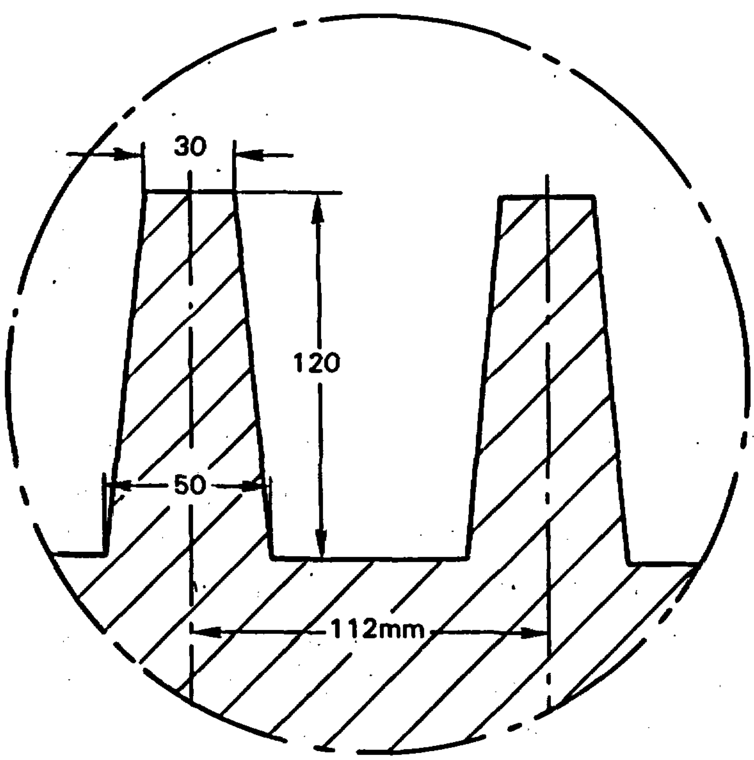


FIGURE 6.3. Cooling Fin Geometry

6.1.1.2 Cavity and Basket

The cask inner cavity is square, 666 mm (26.2 in.) wide, and 4560 mm (15 ft) long. The bottom of the cavity is sloped slightly to enhance draining of fluid. The inside of the cask, including the sealing surfaces, has a nickel coating for corrosion protection. A support plate is placed on the bottom of the cavity to provide a level support for the basket and fuel assemblies.

The basket is of welded construction and 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 is visible in Figure 6.2. The stainless steel plates used to construct the basket are 10 mm (0.4 in.) thick, and the overall basket width is 640 mm (25 in.). 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 gas flow between adjacent assembly tubes and natural circulation inside the cavity. The basket also serves as a path for conduction heat transfer from the center assemblies to the cask body.

During normal operation the cask is filled with helium. The use of this inert gas inhibits corrosion and results in a higher peak cladding temperature limit. In addition, helium 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 cavity pressure during normal cask operation is 0.8 bar (11.76 psia).

6.1.1.3 Lid System

The CASTOR-1C cask is sealed with a multiple-lid system consisting of a primary lid, a secondary lid, and a protection plate. The three lids are shown in Figure 6.1. The primary cover, constructed of stainless steel, has an outside diameter of 1200 mm (3.9 ft) and an overall thickness of about 340 mm (13.4 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 of the stainless steel in the secondary cover is replaced with concentric polyethylene rings that act as neutron shields. The protective plate is made of carbon steel and provides general mechanical protection against outside forces as well as 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} ℓ/s.

6.1.1.4 Spent Fuel Assemblies and Decay Heat

The 16 spent fuel assemblies used in the Wurgassen CASTOR-1C cask test were GE 7x7 and 8x8 assembly types. The design characteristics of these two assembly types are listed in Table 6.2. Each fuel assembly contained fuel rods

TABLE 6.2. Characteristics of Typical General Electric BWR Fuel Assemblies

	7x7 Assembly	8x8 Assembly
Assembly length	4354 mm (171.40 in.)	4354 mm (171.40 in.)
Fuel rods		
Number	49	63
Length	3964 mm (156 in.)	3964 mm (156 in.)
Active length	3683 mm (145 in.)	3733 mm (147 in.)
Outside diameter	14.3 mm (0.563 in.)	12.5 mm (0.493 in.)
Wall thickness	0.89 mm (0.035 in.)	0.86 mm (0.034 in.)
Pitch	18.7 mm (0.738 in.)	16.3 mm (0.640 in.)
Material	Zircaloy-2	Zircaloy-2
Tie rods - fueled		
Number	8	8
Outside diameter	14.3 mm (0.563 in.)	12.5 mm (0.493 in.)
Wall thickness	0.89 mm (0.035 in.)	0.86 mm (0.034 in.)
Material	Zircaloy-2	Zircaloy-2
Spacer capture rods		
Number	1	1
Outside diameter	14.3 mm (0.563 in.)	12.5 mm (0.493 in.)
Material	Zircaloy-2	Zircaloy-2
Spacers		
Number	7	7
Material	Zircaloy-4	Zircaloy-4
Springs	Inconel-X	Inconel-X
Tie plate material	304 stainless steel	304 stainless steel

(and one center water rod in the 8x8 assembly only), spaced and supported in a square array by the lower and upper tie plates. A typical GE 8x8 fuel assembly is shown in Figure 6.4. Besides the standard fuel rods, two other rod types are used in the fuel assembly: tie rods and a nonfuel water rod. The eight tie rods in each assembly have lower end plugs that thread into the lower tie plate casting and upper end plugs extending through the upper tie plate casting. These tie rods support the weight of the assembly only during fuel handling when the assembly hangs by the handle; during operation, the fuel rods are supported by the lower tie plate.

The ORIGEN2 code (Croff 1980a, 1980b) was used to predict decay heat generation rates of the 16 Wurgassen BWR spent fuel assemblies used in the CASTOR-1C cask performance test. Decay heat rates for the assemblies were determined from end-of-cycle burnup values and from the reactor operating history (Rector et al. 1986). The predicted assembly decay heat generation rates

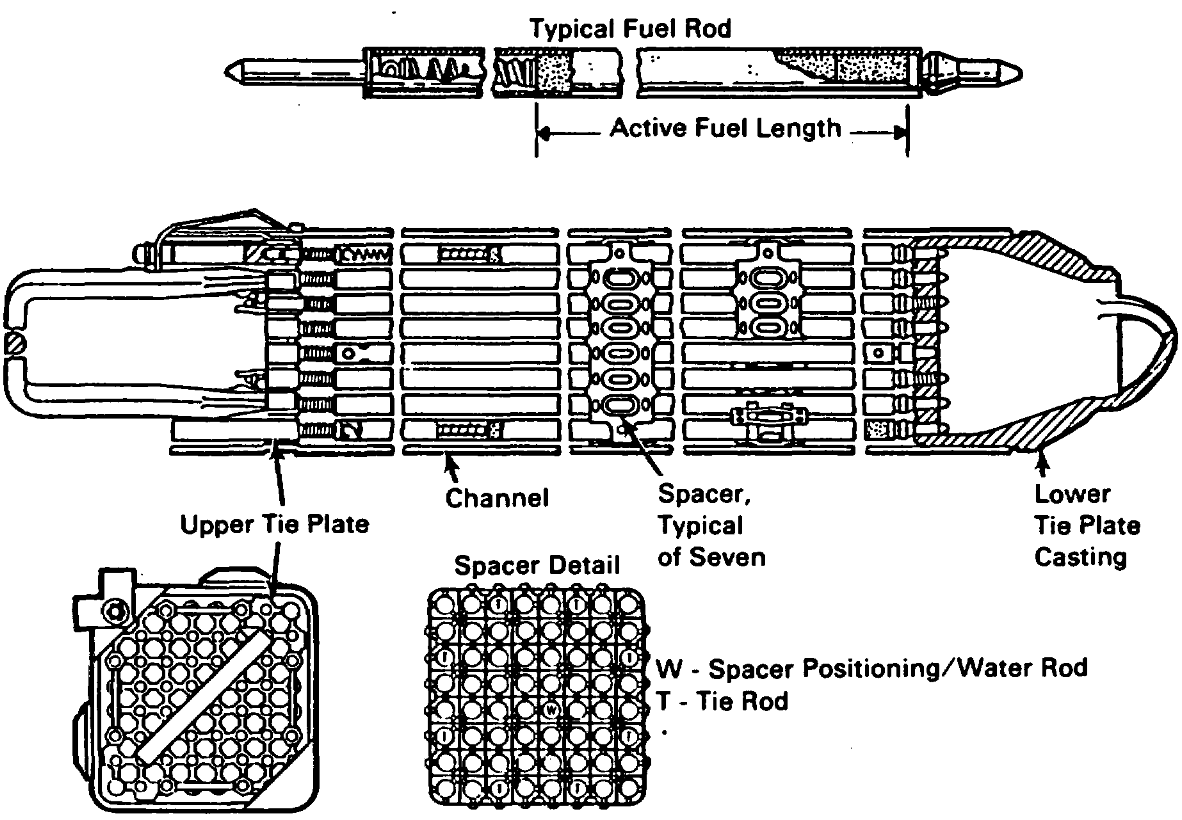


FIGURE 6.4. Typical General Electric 8x8 Fuel Assembly

for three dates are shown in Table 6.3 for each of the 16 Wurgassen BWR assemblies. The average predicted assembly decay heat rates were 837 W, 452 W, and 369 W, for the three dates, corresponding to cooling times of 434, 887, and 1100 days, respectively. At 434 days cooling time, the standard deviation of the predicted decay heat rate is ±6.0%, which reduces to ±4.4% for the longest

TABLE 6.3. Predicted Wurgassen BWR Assembly Decay Heat Rates

Assembly ID[(a)]	Burnup, GWD/MTU	Cooling Time, Days 434 — Predicted Decay Heat Rate, W 03/10/82	887 — 06/06/83	1100 — 01/05/84
B476	27.6	846	456	373
B471	27.6	851	460	376
B472	27.8	852	461	377
B476	27.6	851	460	376
B486	27.6	846	460	373
B489	27.8	852	454	377
B490	27.5	846	460	373
B493	27.5	841	454	371
BZ701	27.2	717	452	329
BZ703	28.5	838	398	369
BZ704	28.3	877	467	379
BZ706	27.2	712	396	328
BZ707	28.3	877	467	379
BZ708	28.5	838	452	369
BZ709	28.3	877	467	379
BZ710	28.3	877	467	379
Total		13,398	7,231	5,907
Average	28.8	837	452	369
Std. Dev:	±0.45	±50	±22	±16
%SD of Avg:	±1.6	±6.0	±4.9	±4.4

(a) Identification numbers starting with B denote 7x7 rod assemblies; numbers starting with BZ denote 8x8 rod assemblies.

cooling period. The associated axial decay heat profile used for the simulations is presented in Figure 6.5 and was determined using reactor activity scans and ORIGEN2.

6.1.2 HYDRA-II Models and Input

This section describes some of the information on the input file: the computational mesh, material properties, and correlations. The complete HYDRA-II input file for the helium backfill, vertical orientation case is provided in Appendix C.

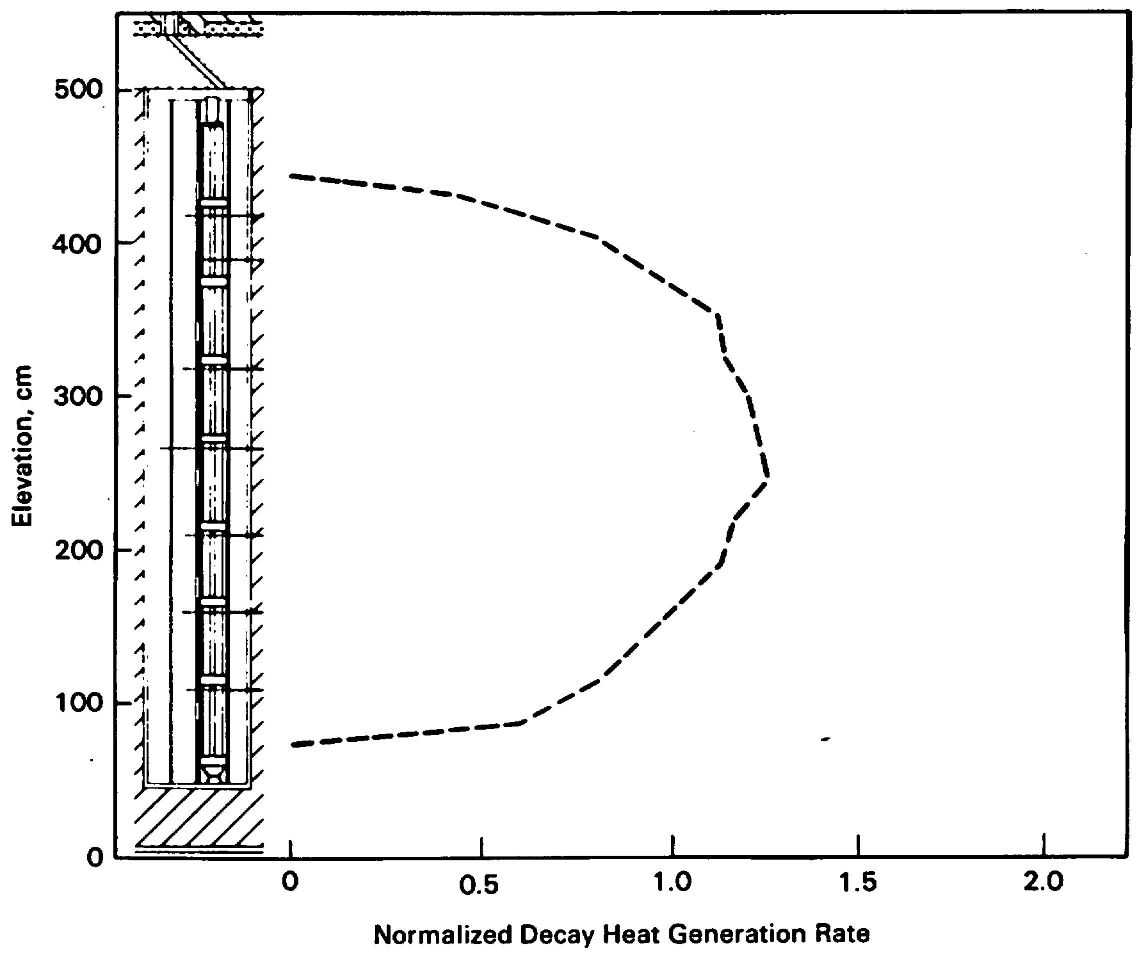


FIGURE 6.5. Axial Decay Heat Profile Used for CASTOR-1C Analysis

6.1.2.1 Computational Mesh

A transverse cross section of the cask was illustrated previously in Figure 6.2. This cross section shows a square cavity inside the cask whose outside surface is approximately cylindrical. Figure 6.6 shows the corresponding computational mesh employed and indicates the alignment of the computational mesh with various physical features of the cask. Cartesian coordinates are used in the cask cavity. A cylindrical coordinate system is used to represent the cask body.

An elevation-view section of the cask is seen in Figure 6.1. The corresponding axial cross section of the computational mesh is shown in Figure 6.7 and indicates the location of physical cask features relative to the computational mesh.

The code computes a temperature and three mass fluxes (if a fluid is present) corresponding to each computational cell. The shape and location of each cell is selected, insofar as practical, to coincide with physical structures or boundaries of the cask and its contents. The accuracy of predicted temperatures and mass fluxes is influenced significantly by how well the computational mesh is aligned with the physical structure.

6.1.2.2 Material Properties and Correlations

Material properties were obtained from the cask topical safety analysis report (GNS 1983, 1985a) and from Touloukian and Ho (1970). The material properties used for all simulations are listed in Table 6.4. Effective thermal conductivities were estimated for those computational cells containing more than one material.

The total heat transfer from the external surface of the cask to ambient was computed by HYDRA-II for both convection and radiation modes acting in parallel. Heat transfer correlations were used to predict convection heat transfer from the external surface of the cask to ambient. The correlations used for all external surfaces relate the Nusselt number, Nu, to the Rayleigh number, Ra, and are of the form $Nu = C[Ra(L)]^n$. The values of C, n, and the significant length, L, are listed in Table 6.5. Correlations for smooth surfaces were taken from Sissom and Pitts (1972); the correlations for finned surfaces were estimated from Chaddock (1970).

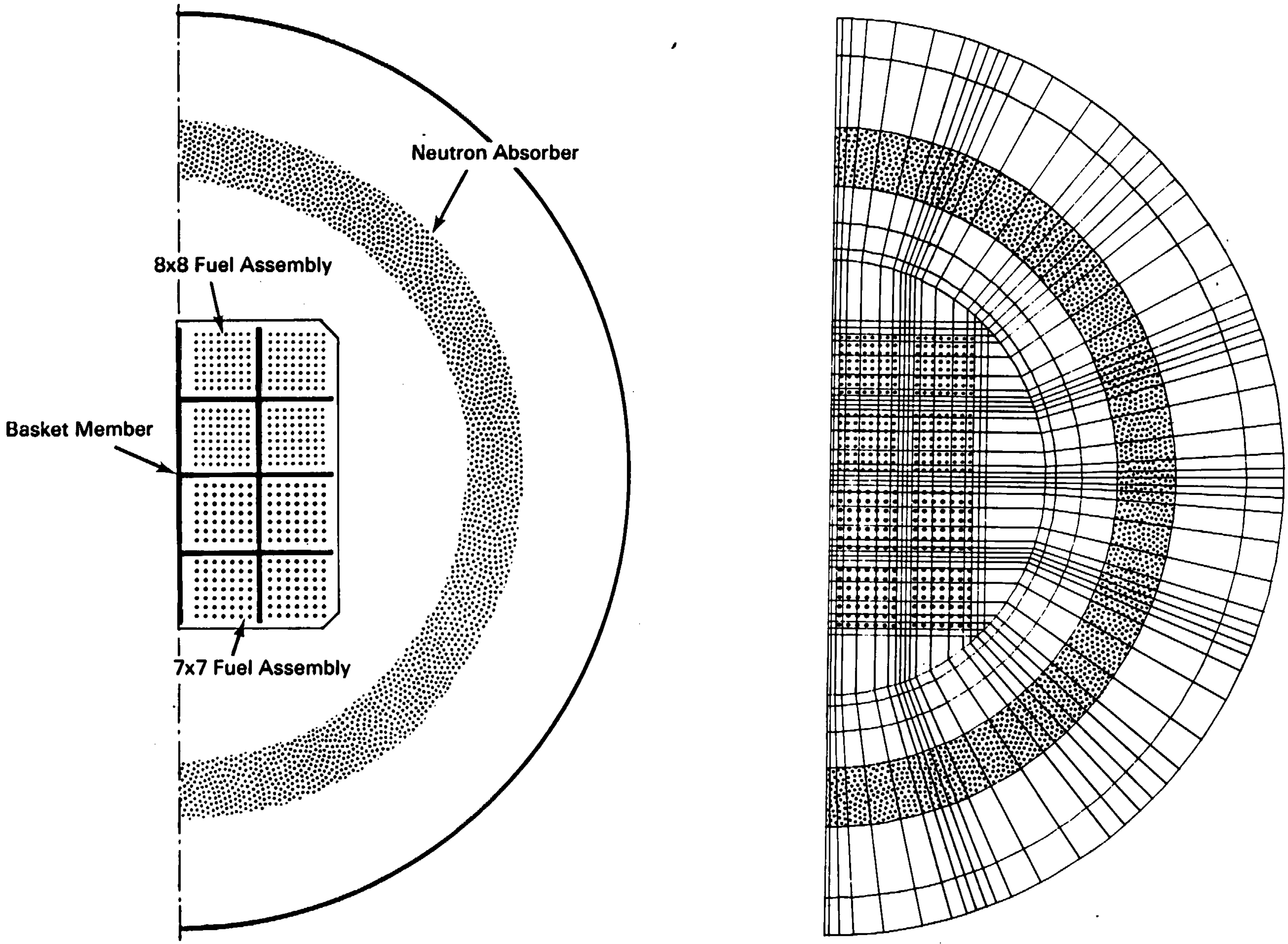


FIGURE 6.6. Transverse Computational Mesh and Alignment of Mesh with Physical Cask Features

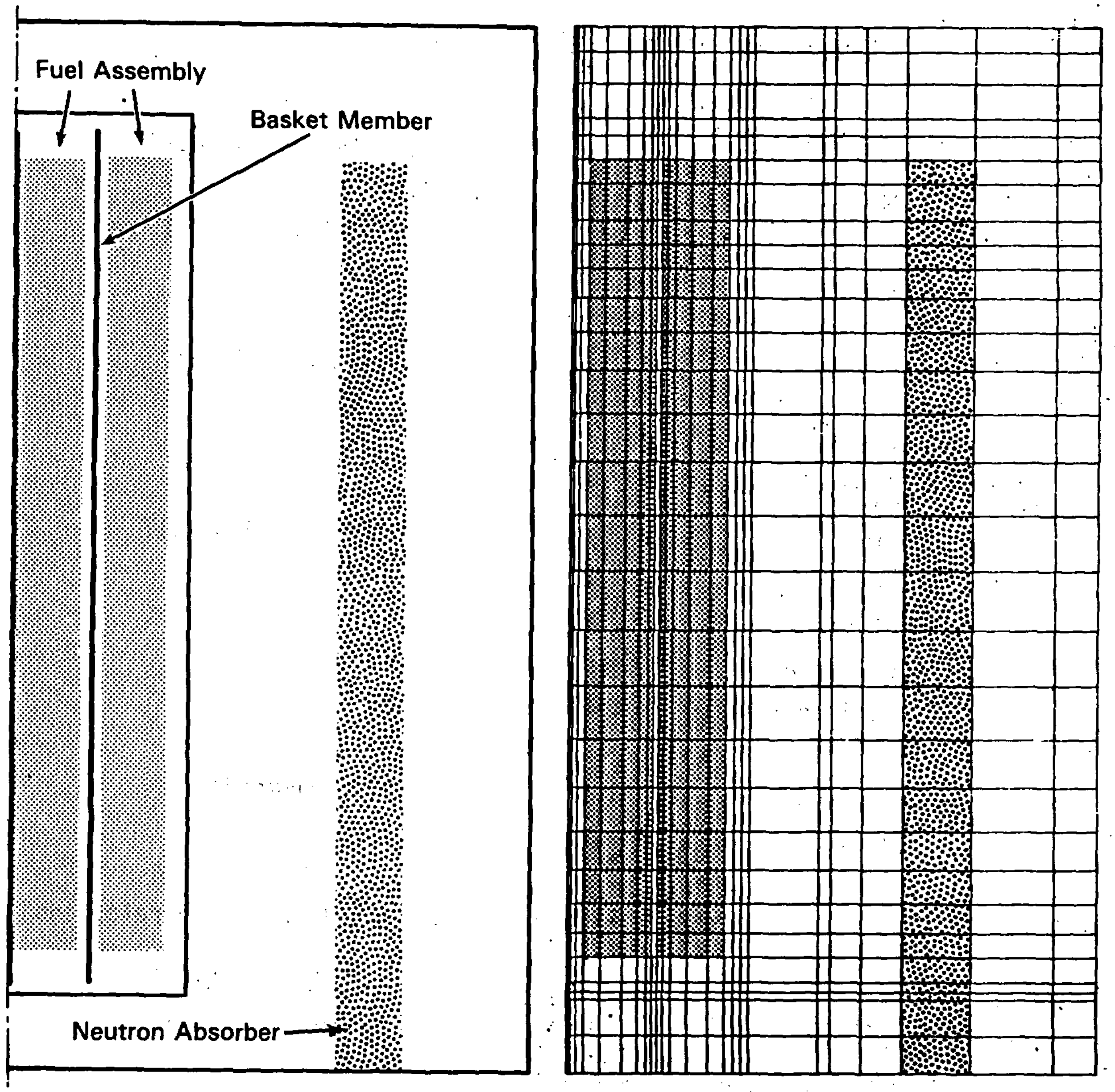


FIGURE 6.7. Axial Computational Mesh and Alignment with CASTOR-1C Physical Cask Features

6.1.3 HYDRA-II Predictions

Selected predicted and measured axial temperature profiles are shown in Figure 6.8. The largest discrepancy, 12°C, occurs in the peak cladding temperatures.

TABLE 6.4. CASTOR-1 Cask Test Material Properties

Thermal conductivity ($W/cm^{2}{}^\circ K$)	
Stainless steel	0.09215+(0.1465E-3)T
Boron steel (Radionox)	0.079+(0.21E-3)T
Nodular cast iron	0.5162-(0.3205E-3)T
Epoxy	0.15E-2
Concrete	0.017
Helium	0.52E-3+(0.32E-5)T
Specific heat (W sec/g°K)	
Helium	5.234
Viscosity (g/cm sec)	
Helium	0.700E-4+(0.400E-6)T
Emittance	
Fuel cladding	0.8
Fuel basket	0.4
Cast iron (nickel-plated)	0.25
Cast iron (smooth)	0.3
Cast iron (painted fins)	0.92 (Measured)
Stainless steel	0.2

TABLE 6.5. CASTOR-1C Cask Test Convection Heat Transfer Correlations

Surface	C	n	L, cm
Vertical	0.13	1/3	172.0
Horizontal; heated surface facing up	0.14	1/3	172.0
Vertical fins	0.75	1/4	8.0
Horizontal fins	0.5	1/4	8.0

Figure 6.9 shows predicted and measured radial temperature profiles at an axial elevation of 266 cm. The deviation between predictions and data (15°C) is acceptable over the radius from cask center to external surface.

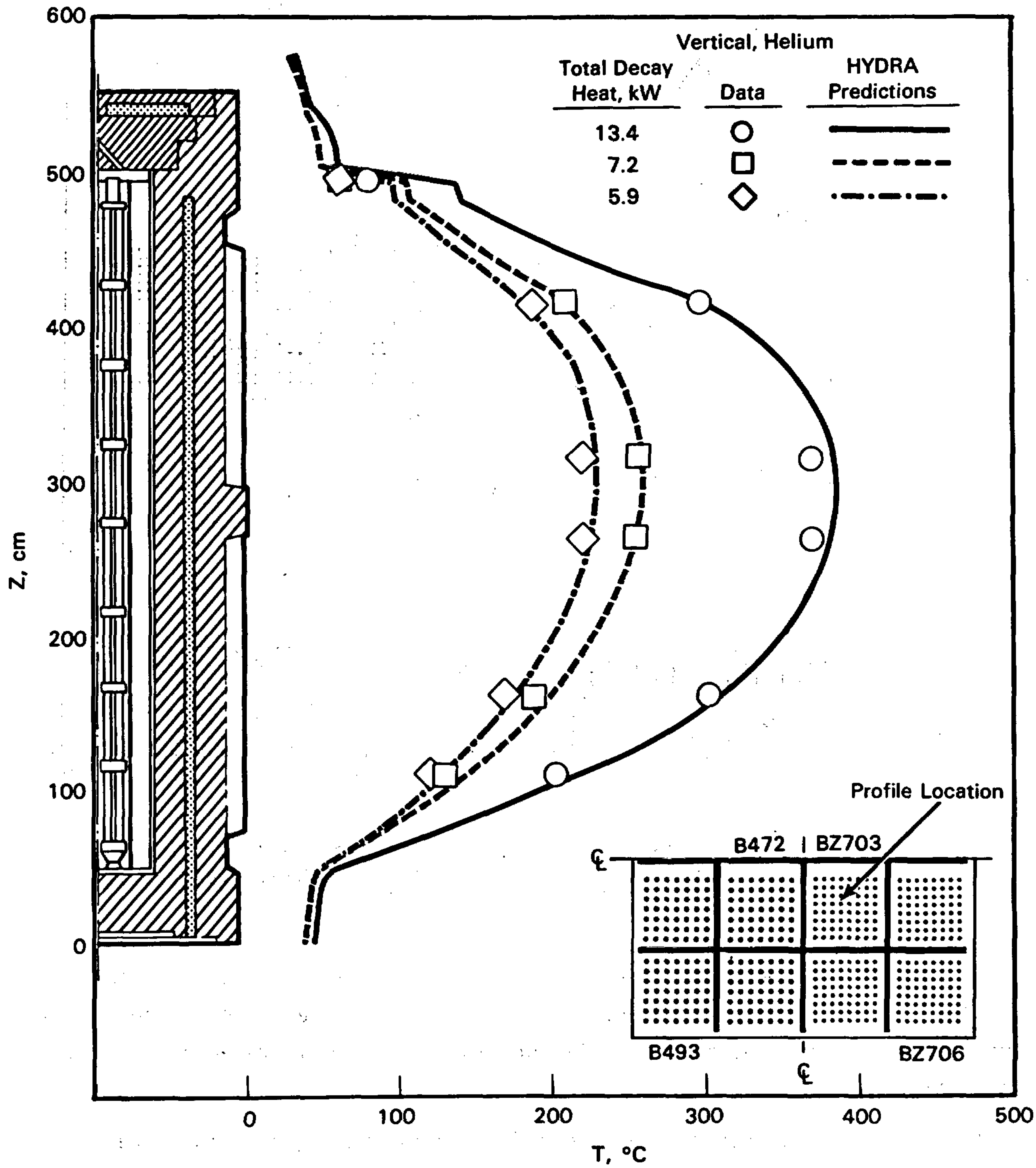


FIGURE 6.8. HYDRA-II Temperature Profile Predictions Compared to Vertical, Helium CASTOR-1C Test Data

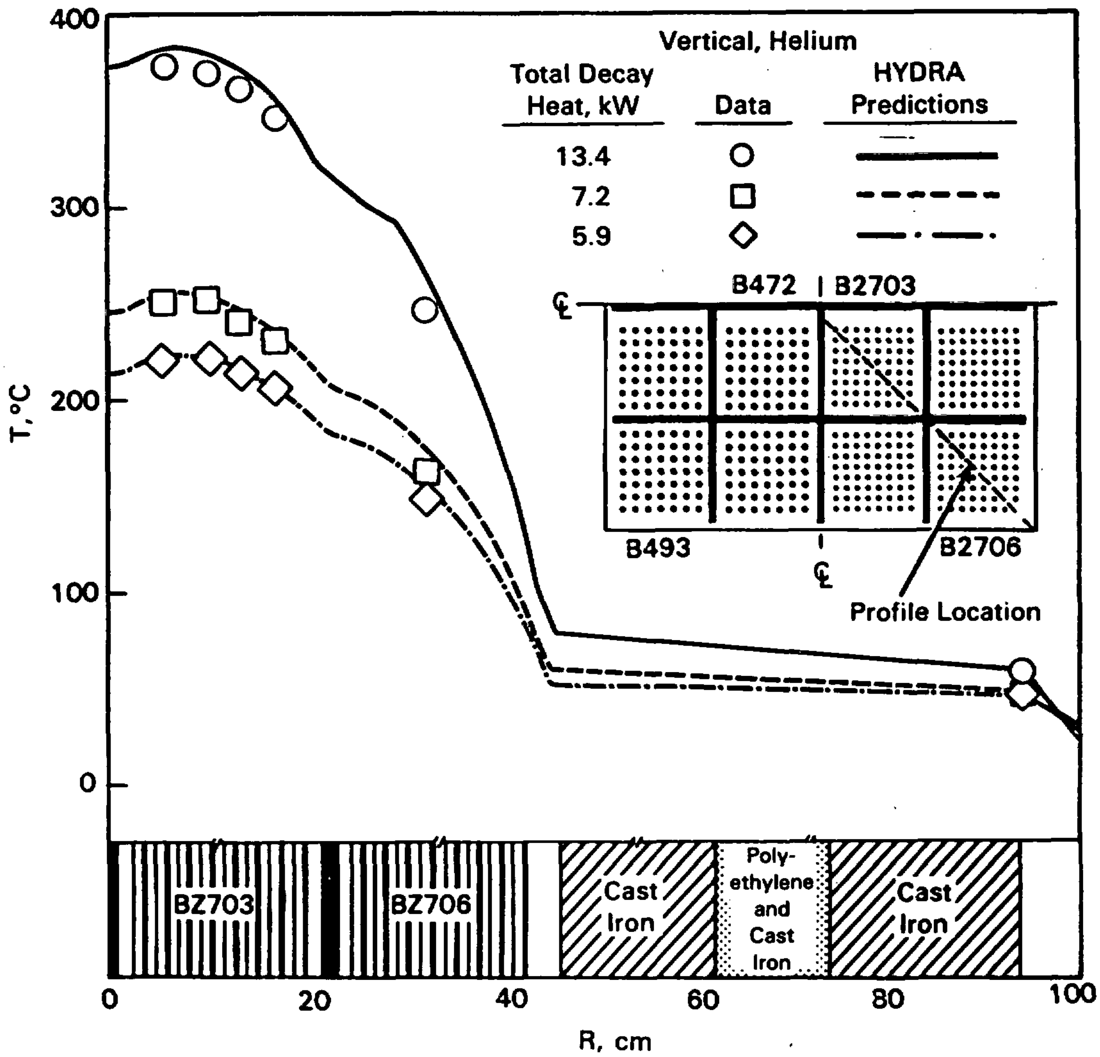


FIGURE 6.9. HYDRA-II Radial Temperature Profile Predictions Compared to Vertical, Helium CASTOR-1C Test Data at 266-cm Axial Location

Some observations are in order regarding the simulations. In Chapter 4.0, potential uncertainties inherent in any application were listed. The uncertainty having the most significance for CASTOR-1C is repeated here for emphasis:

- The total heat generation rate and the axial heat generation rate profile have a direct impact on predicted cladding temperature. Both the total generation rate and the axial profile can be determined experimentally, and that is the preferred approach.

This concern also applies to assembly heat generation rates. Because the values were calculated by ORIGEN2 rather than measured, it is estimated that the percentage uncertainty in the predicted total decay heat generation rate is ±5% (one sigma confidence level). The percentage uncertainty in the profile is similarly estimated at ±10%. Considering these uncertainties, the agreement between predicted temperatures and measured data is satisfactory.

6.2 CASTOR-V/21 SPENT FUEL STORAGE CASK

The CASTOR-V/21 spent fuel storage cask components are briefly discussed in Section 6.2.1. The corresponding HYDRA-II model used to simulate the hydrothermal response of this cask is described in Section 6.2.2. A complete series of tests and numerical simulations was performed for the CASTOR-V/21 cask. The backfill gas, gas pressure, and cask orientation were among the control parameters in the test matrix. The computational and experimental results obtained for each of these cases are provided in Dziadosz et al. (1986). Only the vertical orientation cases are presented here. The comparisons of computation with experiment for these cases are presented in Section 6.2.3.

6.2.1 Test Description

This section contains a brief description of the test hardware and conditions needed for numerical simulation. A more complete account of the details is available in Dziadosz et al. (1986).

6.2.1.1 Cask Body

The cask body is a one-piece cylindrical structure composed of ductile cast iron in nodular graphite form. This material exhibits good strength and ductility, as well as providing effective gamma shielding. Overall, the cask body exterior is 4886 mm (16 ft) high and 2385 mm (8 ft) in diameter (Figure 6.10). The external surface has 73 heat transfer fins that run circumferentially around the cask, and is coated with epoxy paint for corrosion protection and ease of decontamination.

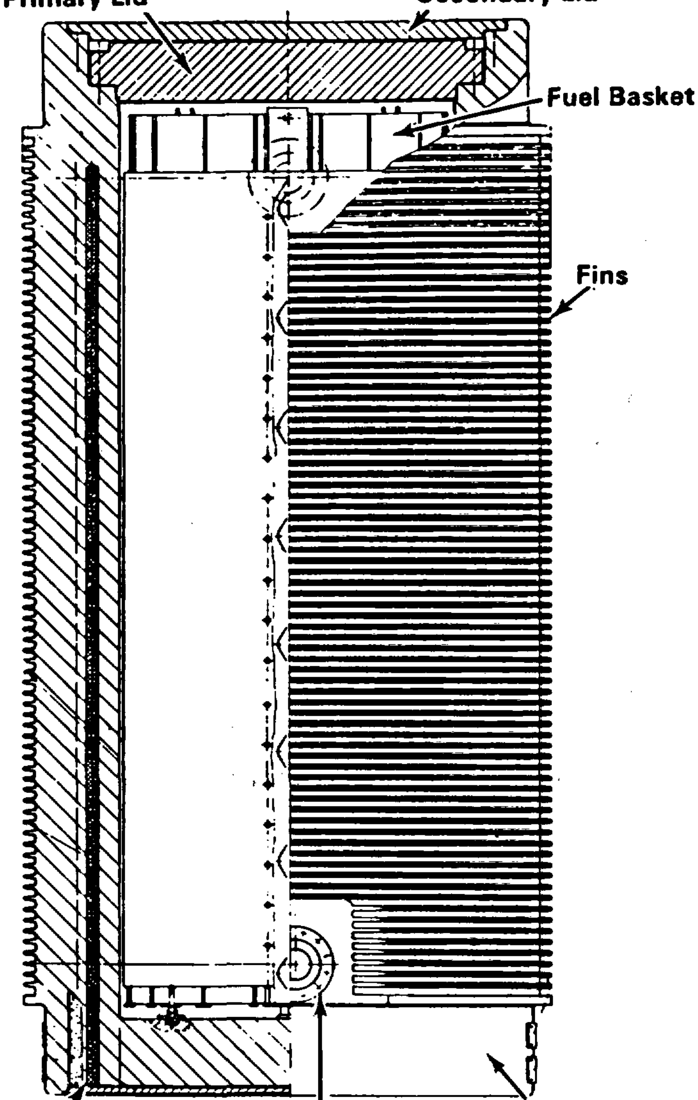


FIGURE 6.10. CASTOR-V/21 PWR Spent Fuel Storage Cask

The cask body wall, excluding fins, is 380 mm (15 in.) thick. Incorporated within the wall of the body are polyethylene moderator rods to provide neutron shielding. Two concentric rows of these 60-mm (2.3-in.) nominal diameter rods are distributed around the cask perimeter (Figure 6.11). Two lifting trunnions are bolted on each end of the cask body.

The diameter of the inner cavity is 1527 mm (5 ft), and the overall inner cavity length is 4152 mm (163 in.). Precision-machined surfaces are provided

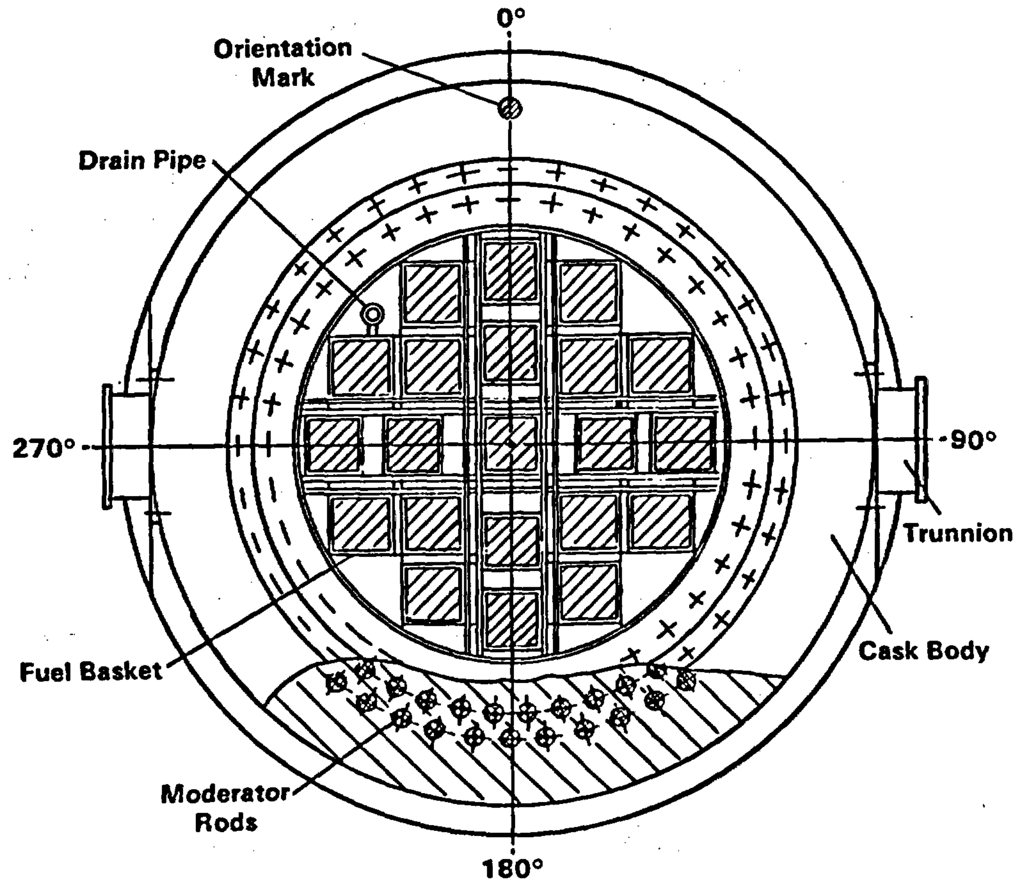


FIGURE 6.11. CASTOR-V/21 Cask Cross Section

at the open end of the cask cavity for positive gasket sealing, and bolt holes are included at these locations to secure the two cask lids. The interior cavity surfaces, including sealing surfaces, have a galvanic-applied nickel plating.

6.2.1.2 Spent Fuel Basket

The cylindrical spent fuel basket (Figure 6.11) is made of welded stainless steel plate and borated stainless steel plate with a boron content of approximately 1% for criticality control. The basket comprises an array of 21 square fuel tubes/channels that provide structural support and positive positioning of the fuel assemblies. The basket overall height is 4110 mm (13.5 ft) including the four 130-mm-diameter (5-in.) pedestals that support the basket and fuel weight on the bottom of the cask cavity. The basket outside diameter of 1524 mm (5 ft) fits tightly in the cask cavity inner diameter of 1527 mm (5 ft). The depth of each fuel tube is 4050 mm (13.3 ft). A spacing of 74 mm (3 in.) is present between the top of the basket cavity and the underside of the primary lid, thus accommodating a fuel assembly length of 4124 mm (162 in.) and supporting convection heat transfer. The final assembly results in a clearance of approximately 60 mm (2.3 in.) between the top of the fuel assemblies and the bottom of the primary lid, for a reference fuel assembly of 4064 mm (160 in.).

6.2.1.3 Primary Lid

A stainless steel primary lid, 1785 mm (6 ft) in diameter and 290 mm (12 in.) thick, is provided (Figure 6.12). Forty-four bolt holes are machined near the lid perimeter to secure the lid to the cask body. Two grooves machined around the lid underside, inside the bolt circle, are provided for O-ring gaskets (Figure 6.13). The inner groove accepts a metal O-ring, which

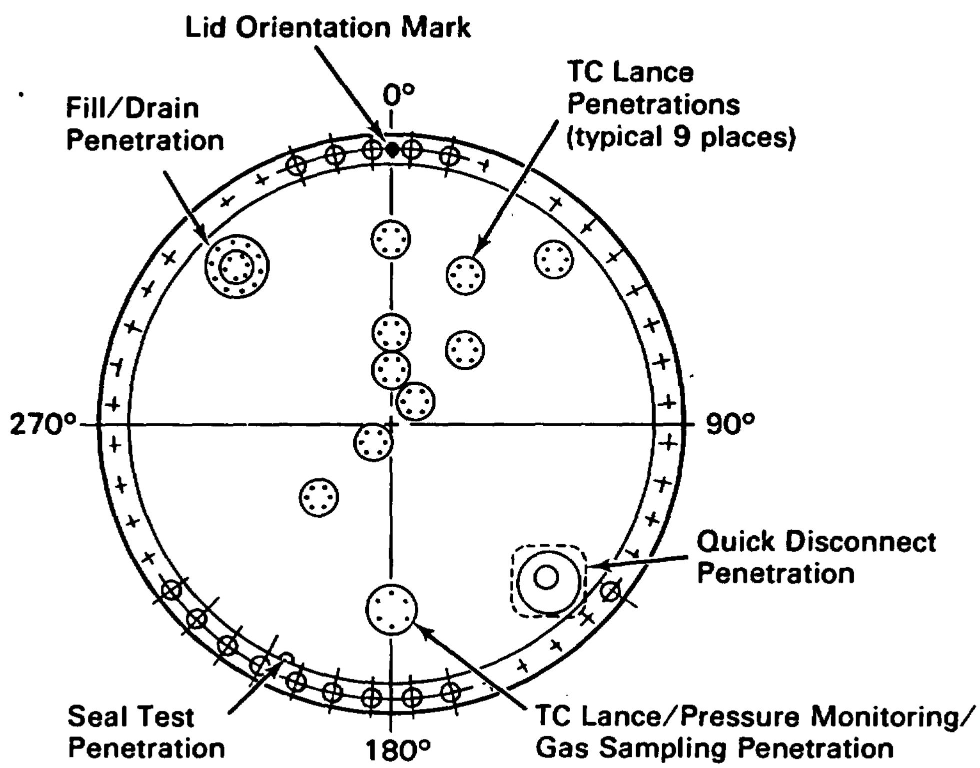


FIGURE 6.12. CASTOR-V/21 Cask Primary Test Lid

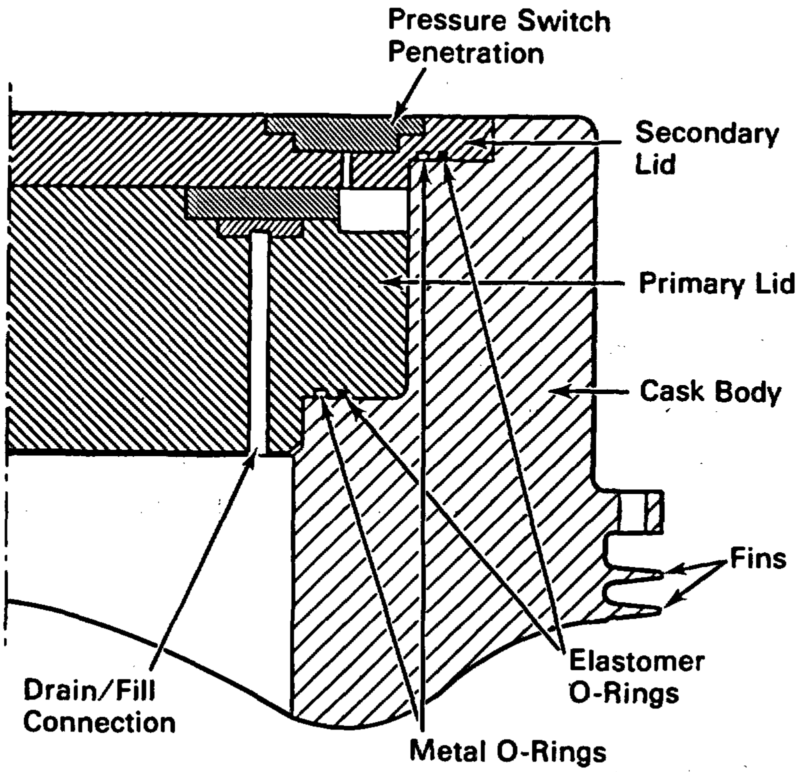


FIGURE 6.13. CASTOR-V/21 Cask Lid System

serves as the first barrier between stored fuel and the environment. The outer groove accepts an elastomer O-ring. A 10-mm-diameter (0.5-in.) penetration through the lid provides access to the annulus between the two seals to perform post-assembly leak testing. This penetration is plugged when not in use.

The primary lid used during testing was not a standard lid and has 10 additional penetrations for fuel assembly guide tube instrumentation [thermocouple (TC) lances]. Nine of the penetrations are machined with 18-mm (0.7-in.) holes through the lid and countersunk (20 mm, 0.8 in.) to accept the TC lances and 105-mm-diameter (4-in.) flanges. The tenth penetration has a hole through the lid for a TC lance and accepts a 140-mm-diameter (5.5-in.) flange. The pattern of the 10 fuel assembly instrumentation penetrations was selected to measure radial temperature profiles across the basket in the spent fuel assemblies.

6.2.1.4 Secondary Lid

The stainless steel secondary lid is 2007 mm (79 in.) in diameter and 90 mm (3.5 in.) thick (Figure 6.13). Forty-eight bolt holes are machined near the lid perimeter to secure the lid to the cask body.

The secondary lid was not used during the CASTOR-V/21 cask performance test because of interference with fuel assembly instrumentation leads.

6.2.1.5 Surry PWR Spent Fuel Assemblies and Decay Heat

The fuel assemblies are square in cross section, nominally 214 mm (8.426 in.) on a side, and have a total length of 4058 mm (159.765 in.). The fuel column is 3658 mm (144 in.) long. The overall configuration is shown in Figure 6.14.

The fuel rods in a fuel assembly are arranged in a square array with 15 rod locations per side and a nominal rod-to-rod centerline pitch of 14.3 mm (0.563 in.) as shown in Figure 6.15. Of the total possible 225 rod locations per assembly, 20 are occupied by guide tubes for the control rods and burnable poison rods, and one central thimble is reserved for incore instrumentation. The remaining 204 locations contain fuel rods. In addition to fuel rods, a fuel assembly also includes a top nozzle, a bottom nozzle, and seven grid assemblies.

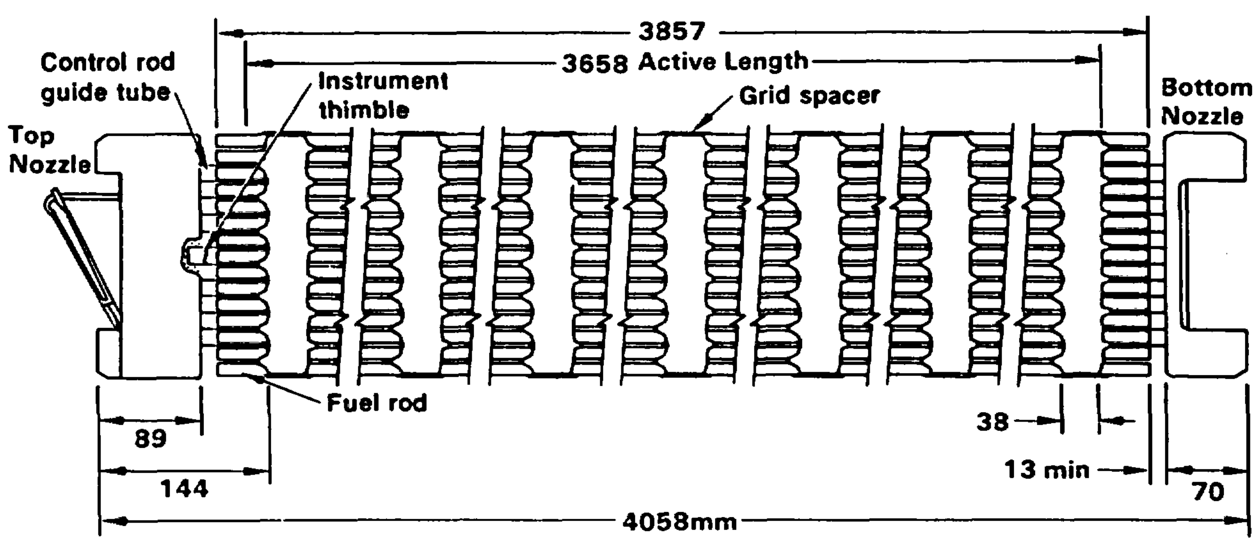


FIGURE 6.14. Surry 15x15 PWR Fuel Assembly

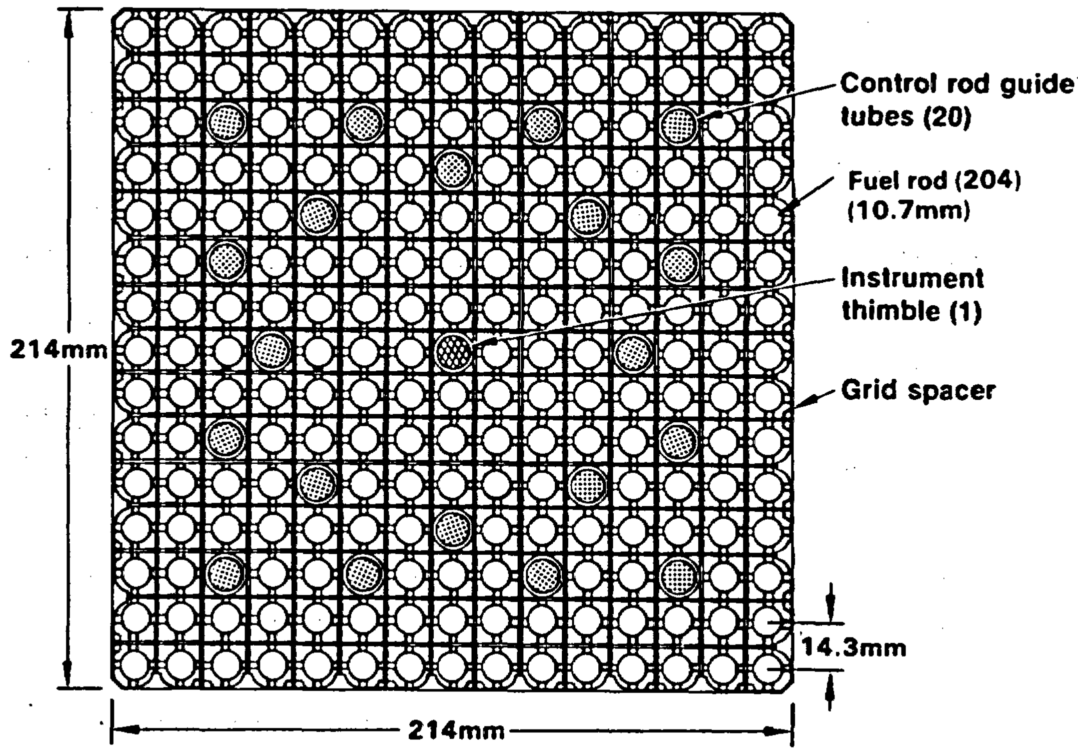


FIGURE 6.15. Surry 15x15 PWR Fuel Assembly Cross Section

The 21 guide tubes, in conjunction with the grid assemblies and the top and bottom nozzles, comprise the basic structure of the fuel assembly. The top and bottom ends of the guide tubes are fastened to the top and bottom nozzles, respectively. The grid assemblies are fastened to the guide tubes at each location along the length of the fuel assembly at which lateral support for the fuel rods is required. The fuel rods are contained and supported, and the rod-to-rod centerline spacing is maintained along the assembly, within this skeletal framework.

The fuel rods consist of uranium dioxide ceramic pellets contained in slightly cold-worked and partially annealed Zircaloy-4 tubing, which is plugged and seal-welded at the ends to clad the fuel. Nominal dimensions include 9.29-mm (0.3659-in.) pellet diameter, 10.71-mm (0.422-in.) tube OD, and 0.62-mm (0.0243-in.) tube thickness.

The ORIGEN2 code (Croff 1980a, 1980b) was used to predict decay heat generation rates of the Surry PWR spent fuel assemblies used in the CASTOR-V/21 cask performance test. The results of these calculations are given in Table 6.6 for the 21 assemblies that were used in the CASTOR-V/21 cask during performance testing. Fuel assembly decay heat generation rates were predicted to total 28.4 kW at the start of testing and 27.5 kW at the end of testing. Thirteen of the twenty-one fuel assemblies had decay heat rates near 1 kW, and the remaining eight assemblies had decay heat rates of 1.8 kW at the start of the month-long test.

The load pattern for the cask is shown in Figure 6.16. Assembly placements were selected to create quarter symmetry of heat generation within the basket and to produce a relatively flat temperature profile across the fuel assemblies.

Measured axial decay heat profiles or gamma scans for the Surry spent fuel assemblies were not available as input data to the ORIGEN2 computer code to predict axial decay heat profiles. Axial gamma radiation scans previously obtained on Turkey Point reactor spent fuel assemblies were therefore used to develop a typical assembly axial burnup distribution. The Turkey Point and Surry PWR reactors and spent fuel assemblies are of the same designs, so axial decay heat profiles should be very similar.

The axial burnup distribution required as input to ORIGEN2 consisted of an average from gamma scans of 25 rods from five Turkey Point assemblies. ORIGEN2, with the measured gamma distribution and the appropriate Surry operating history, was then used to predict the relationship between burnup values

TABLE 6.6. Surry PWR Spent Fuel Characteristics

Assembly	Burnup, GWD/MTU	Cooling Time, months	Initial Enrichment, wt%	Sept. 1985 Pred. Decay Heat, kW Start	Sept. 1985 Pred. Decay Heat, kW End
V04, V08, V12, V24	31.1	46	2.91	1.00	0.98
V05	31.5	46	2.91	1.02	0.99
T03, T07, T08, T09, T11, T12, T13, T16	35.7	46	3.11	1.11	1.09
V11, V13, V14, V15	29.8	26	2.91	1.79	1.72
V01, V09, V25, V27	30.2	26	2.91	1.83	1.75
			Total	28.4	27.5

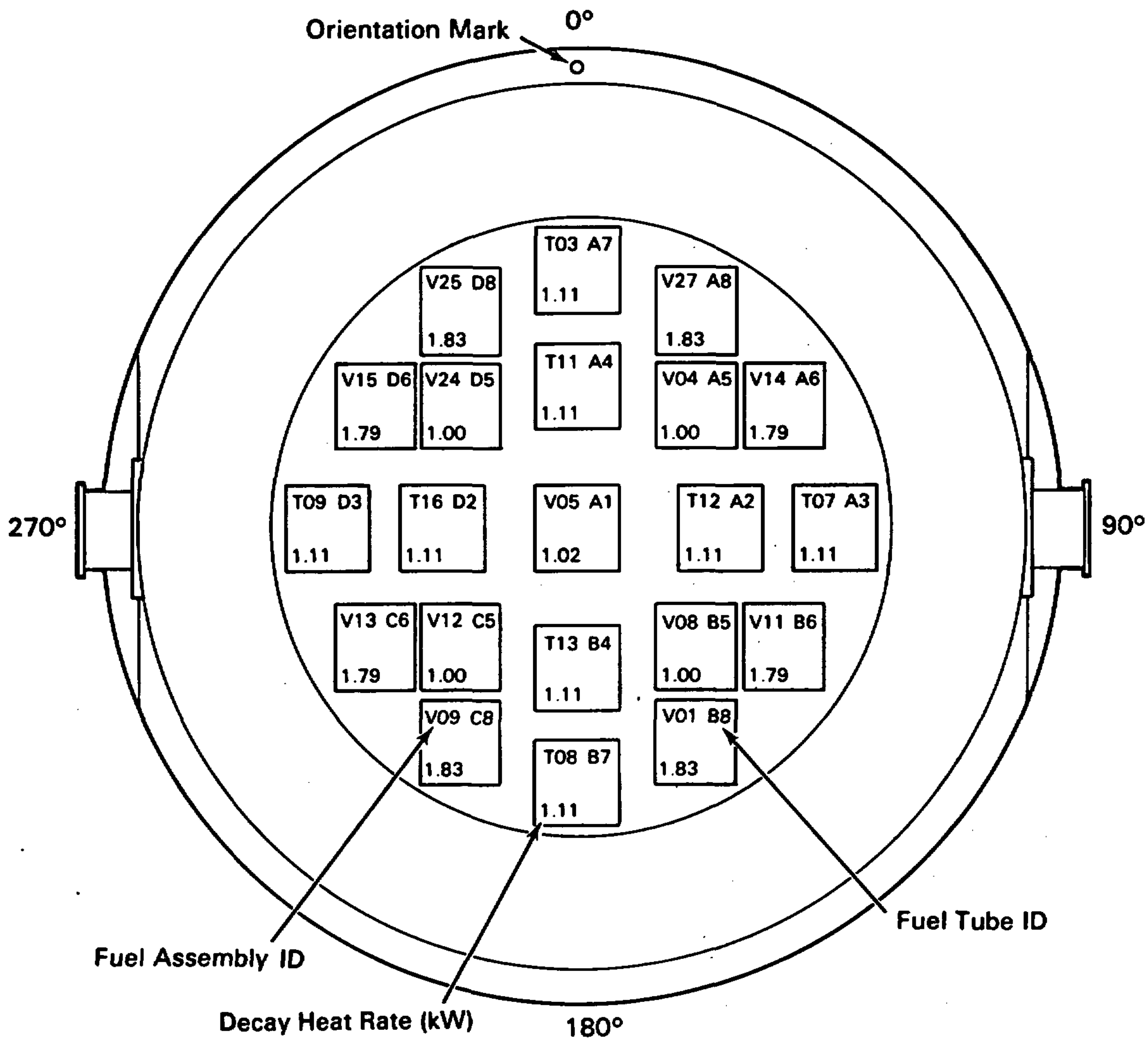


FIGURE 6.16. Spent Fuel Load Pattern

and decay heat rates in specific axial regions (nodes) along the length of a fuel assembly. The measured gamma activity from Turkey Point assemblies and predicted Surry assembly decay heat axial profiles are shown in Figure 6.17. Both profiles are typical of those for spent fuel assemblies from PWR reactors. The dips in the profiles are a result of grid spacers at those locations.

Axial decay heat profiles are important because they strongly influence the shape of axial temperature profiles in the fuel assemblies, especially in vacuum and in a horizontal orientation where convection heat transfer is

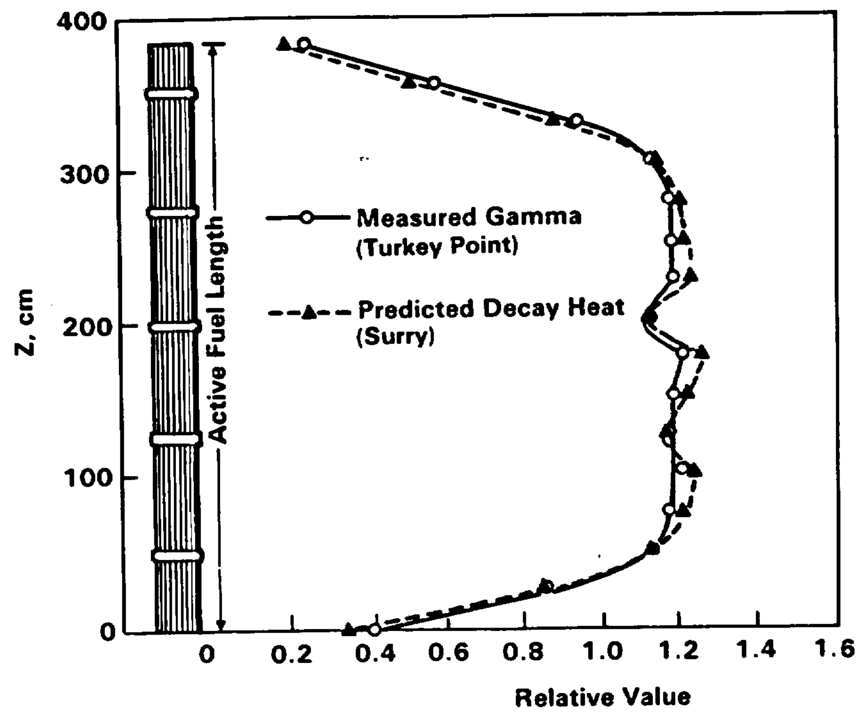


FIGURE 6.17. Predicted Axial Decay Heat Profile

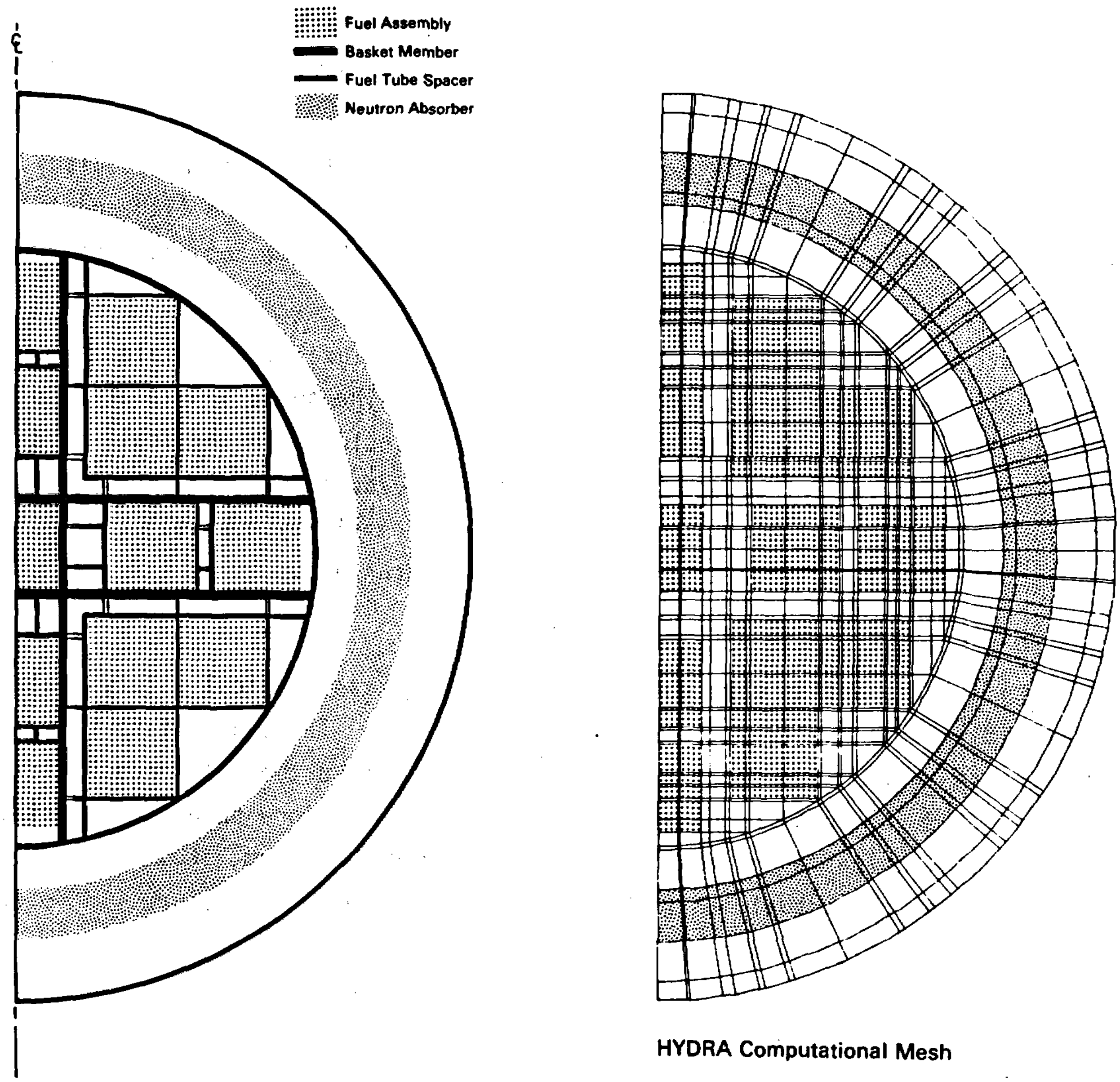
minimized. A smoothed representation of the predicted axial decay heat profile (Figure 6.17) was used as input to the HYDRA-II heat transfer computer program to facilitate temperature predictions.

6.2.2 HYDRA-II Models and Input

This section describes some of the information on the input file: the computational mesh, material properties, and correlations. The complete HYDRA-II input file for the vacuum, vertical orientation case is provided in Appendix D.

6.2.2.1 Computational Mesh

A radial cross section of the cask has been illustrated previously in Figure 6.11. This cross section shows a cylindrical cavity inside the cask whose outside surface is approximately cylindrical. Figure 6.18 shows the corresponding radial computational mesh employed and indicates the alignment of



a. Cask Cross Section   b. HYDRA Computational Mesh

FIGURE 6.18. Transverse Computational Mesh and Alignment of Mesh with CASTOR-V/21 Cask Physical Features

the mesh with various physical features of the cask. Cartesian coordinates are used in the cask cavity, and a cylindrical coordinate system is used to represent the cask body.

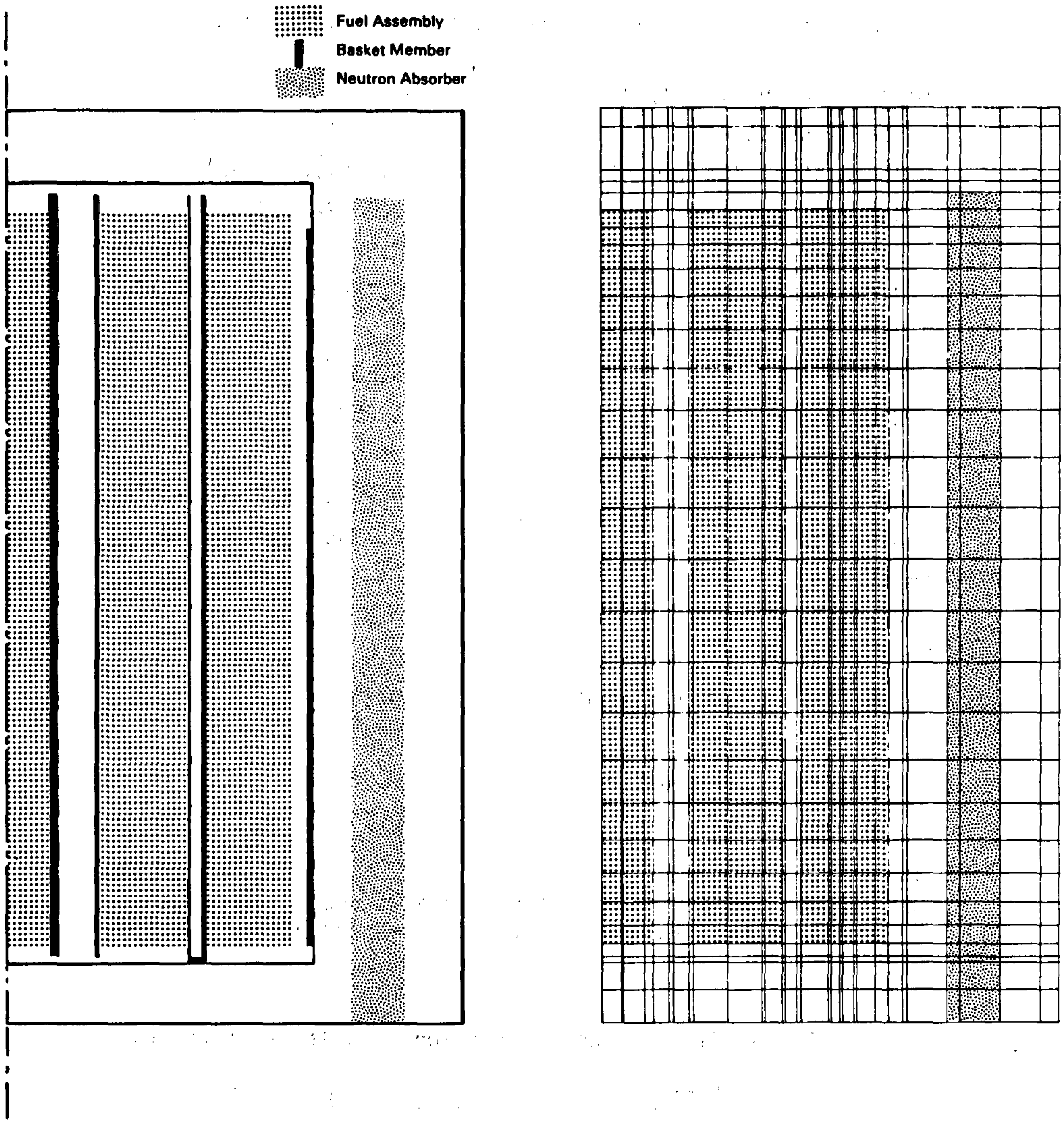
An elevation view of the cask is seen in Figure 6.10. A corresponding cross section of the axial computational mesh is shown in Figure 6.19 and indicates the location of physical cask features relative to the computational mesh.

The code computes a temperature and three mass fluxes (if a fluid is present) corresponding to each computational cell. The shape and location of each cell is selected, insofar as practical, to coincide with physical structures or boundaries of the cask and its contents. The accuracy of predicted temperatures and mass fluxes is influenced significantly by how well the computational mesh is aligned with the physical structure.

6.2.2.2 Material Properties and Correlations

Material properties were obtained from the GNS cask topical safety analysis report (1985b) and from Touloukian and Ho (1970). Table 6.7 lists the material properties used for all simulations. Effective thermal conductivities were estimated for those computational cells containing more than one material. For those simulations where the backfill is denoted as vacuum, it is to be understood that the actual backfill was nitrogen gas at low pressure. However, the pressure was high enough so that the mean free path of the gas was less than any significant lengths (gaps). Hence, the properties used for the vacuum simulations were those of nitrogen.

The total heat transfer from the external surface of the cask to ambient was computed by HYDRA-II for both convection and radiation modes acting in parallel. Heat transfer correlations were used to predict convection heat transfer from the external surface of the cask to ambient. The correlations used for all external surfaces relate the Nusselt number, Nu, to the Rayleigh number, Ra, and are of the form $Nu = C[Ra(L)]^n$, with coeffients C, n, and L for this analysis defined as listed in Table 6.8. Correlations for smooth surfaces



a. Cask Cross Section

b. HYDRA Computational Mesh

FIGURE 6.19. Axial Computational Mesh and Alignment of Mesh with CASTOR-V/21 Cask Physical Features

TABLE 6.7. CASTOR-V/21 Cask Test Material Properties

Thermal conductivity, W/cm^2°K	
Stainless steel	0.09215+(0.1465E-3)T
Boron steel (Radionox)	0.079+(0.21E-3)T
Nodular cast iron	0.5162-(0.3205E-3)T
Helium	0.52E-3+(0.32E-5)T
Nitrogen[(a)]	0.75E-4+(0.6167E-6)T
Specific Heat, W sec/g°K	
Helium	5.234
Nitrogen	1.053
Viscosity, g/cm sec	
Helium	0.700E-4+(0.400E-6)T
Nitrogen	0.794E-4+(0.355E-6)T
Emittance	
Fuel cladding	0.8
Fuel basket	0.4
Cast iron (nickel-plated)	0.25
Cast iron (smooth)	0.3
Cast iron (painted fins)	0.92
Stainless steel	0.2

(a) Vacuum properties were the same as those for nitrogen because the vacuum was actually low-pressure nitrogen.

TABLE 6.8. CASTOR-V/21 Cask Test Convection Heat Transfer Correlations

Surface	C	n	L, cm
Vertical	0.13	1/3	220.0
Horizontal; heated surface facing up	0.14	1/3	220.0
Horizontal; heated surface facing down	0.27	1/4	220.0
Vertical fins	0.6	1/4	3.5
Horizontal fins	0.45	1/4	3.5

were taken from Sissom and Pitts (1972), and the correlations for finned surfaces were estimated from Chaddock (1970). The lead coefficients, C, for the finned surfaces are modified from those found in the references to more accurately reflect the actual configuration.

6.2.3 HYDRA-II Predictions

Axial temperature profile predictions are compared to data for the vertical, helium test run in Figure 6.20. Temperatures on the exterior surface of the cask are satisfactorily predicted. It will be seen in subsequent figures that satisfactory surface temperature predictions occur for all test runs.

Also shown in Figure 6.20 are the axial temperature profiles for an outer fuel assembly and the center fuel assembly. The deviation between predictions and data is small (15°C) for the outer assembly, and slightly larger (25°C) for the center assembly. The axial profile indicates the influence of convection; i.e., hotter temperatures occurred in upper regions of the assemblies and cooler temperatures occurred in lower regions.

As seen in Figure 6.20, temperatures at locations below the peak are slightly overpredicted and temperatures at locations above the peak are slightly underpredicted. It is speculated that the predicted axial decay heat generation rate profile is in error for some or all of the fuel assemblies. This source of uncertainty has been encountered in previous comparisons with cask data and could be reduced by experimental measurement (Creer 1984; Rector et al. 1986). This trend is common to all axial profile predictions presented in this section.

Figure 6.21 shows axial temperature profile predictions compared to data for the vertical, nitrogen test run. The worst-case deviation between data and computation in the fuel assemblies is 15°C. The influence of upward convection in the fuel assemblies is again indicated.

Figure 6.22 shows axial temperature profile predictions compared to data for the vertical, vacuum test run. The lack of significant convection for this test run results in peak temperatures being located near the axial elevation of peak decay heat generation.

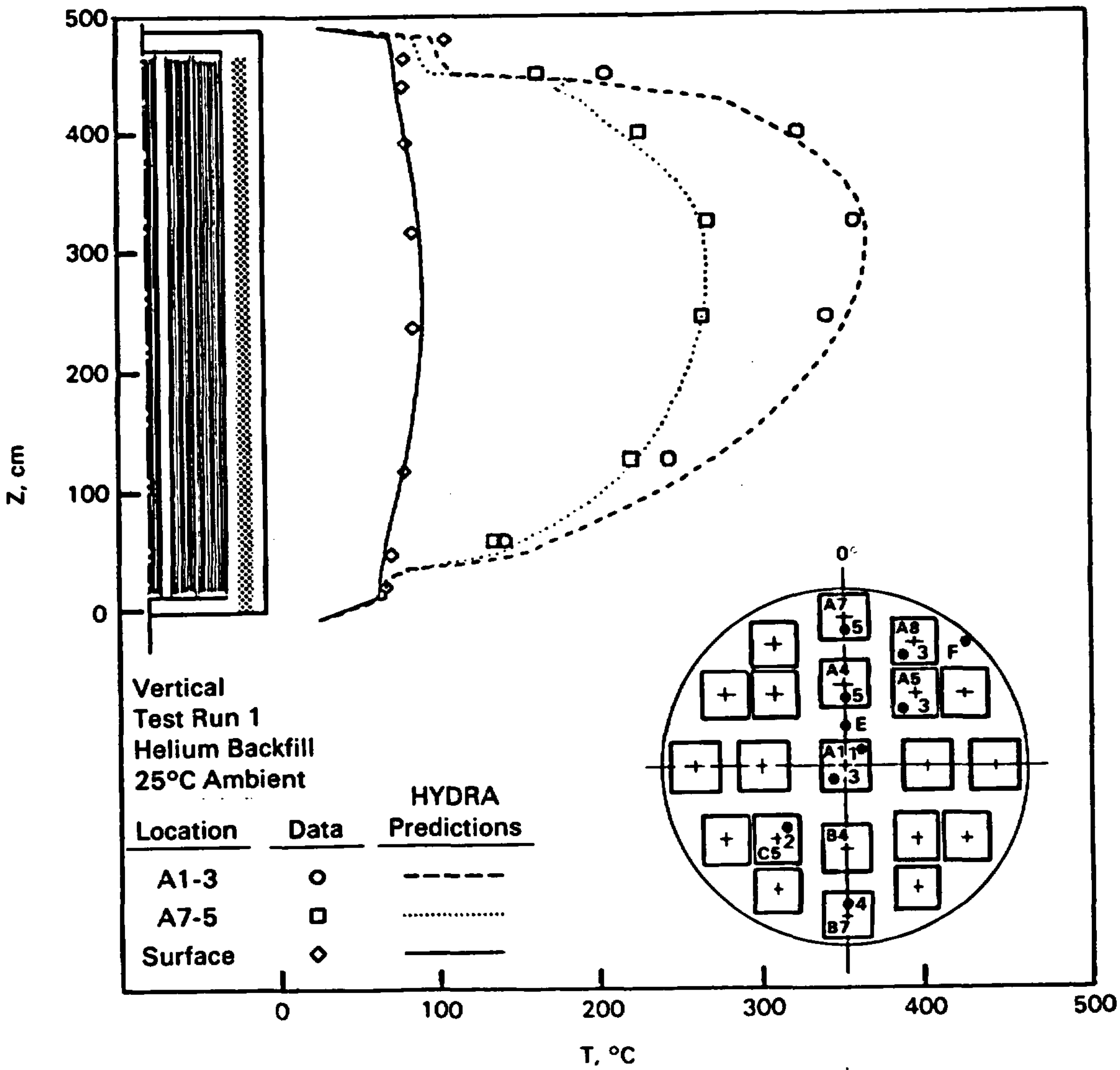


FIGURE 6.20. Axial Temperature Profile Predictions Compared to Vertical, Helium Test Data from CASTOR-V/21 Cask

Figure 6.23 shows axial temperature profile predictions compared to data for an outer fuel assembly generating 1.8 kW of heat. The results for the three vertical test runs are presented for comparison. Predictions agree exceptionally well with data for all three backfills. The effect of convection is seen in the helium and nitrogen test runs, but not in the vacuum run.

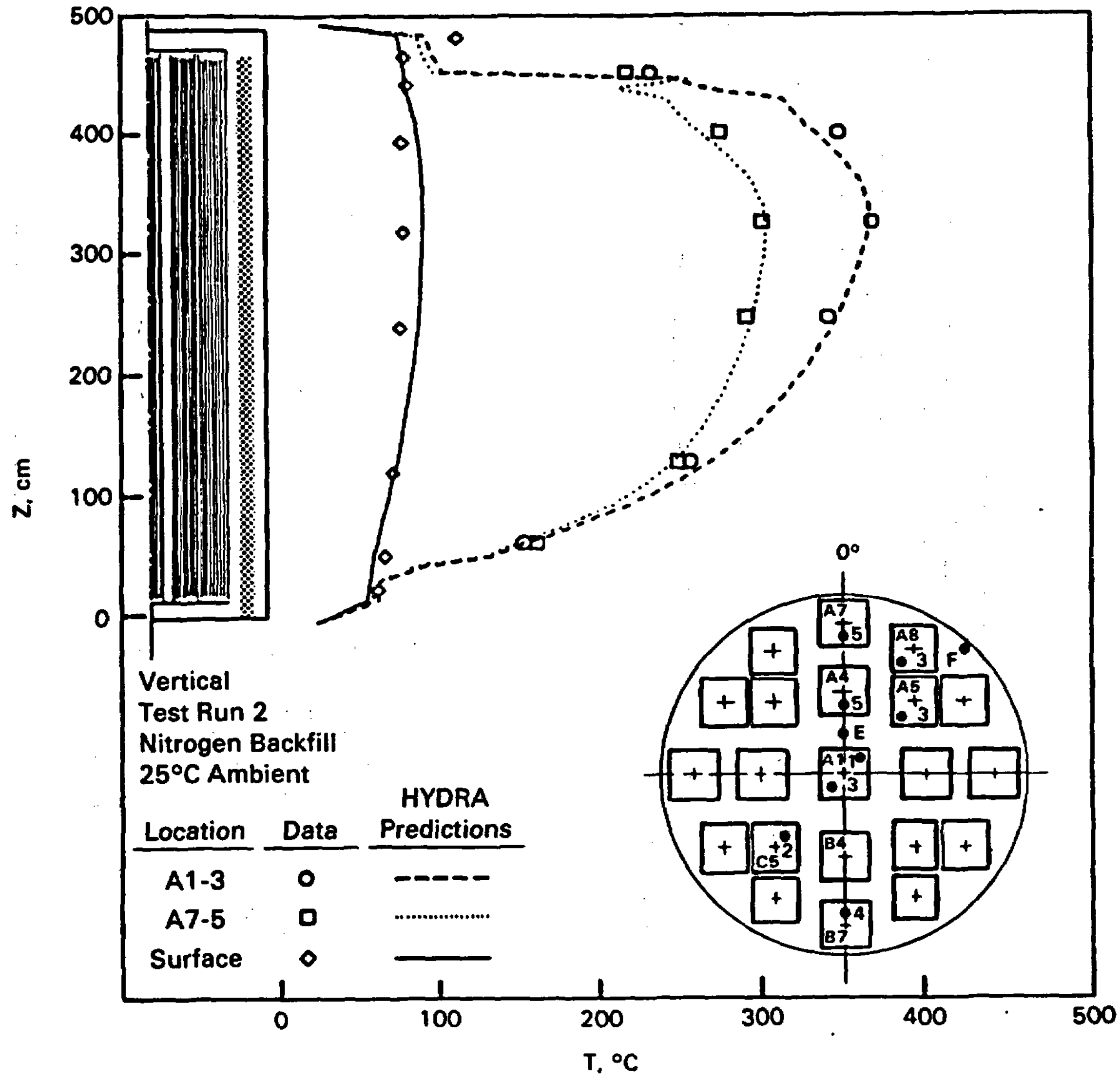


FIGURE 6.21. Axial Temperature Profile Predictions Compared to Vertical, Nitrogen Test Data from CASTOR-V/21 Cask

Radial temperature profiles for the three vertical test runs from the center fuel assembly out to the cask surface are shown at the respective axial planes of peak guide tube temperature in Figure 6.24. Again, the collective results demonstrate that the predicted and measured temperatures in the fuel assemblies are in good agreement. The disagreement between predicted and measured gas temperatures between assemblies A1 and A4 is probably caused by

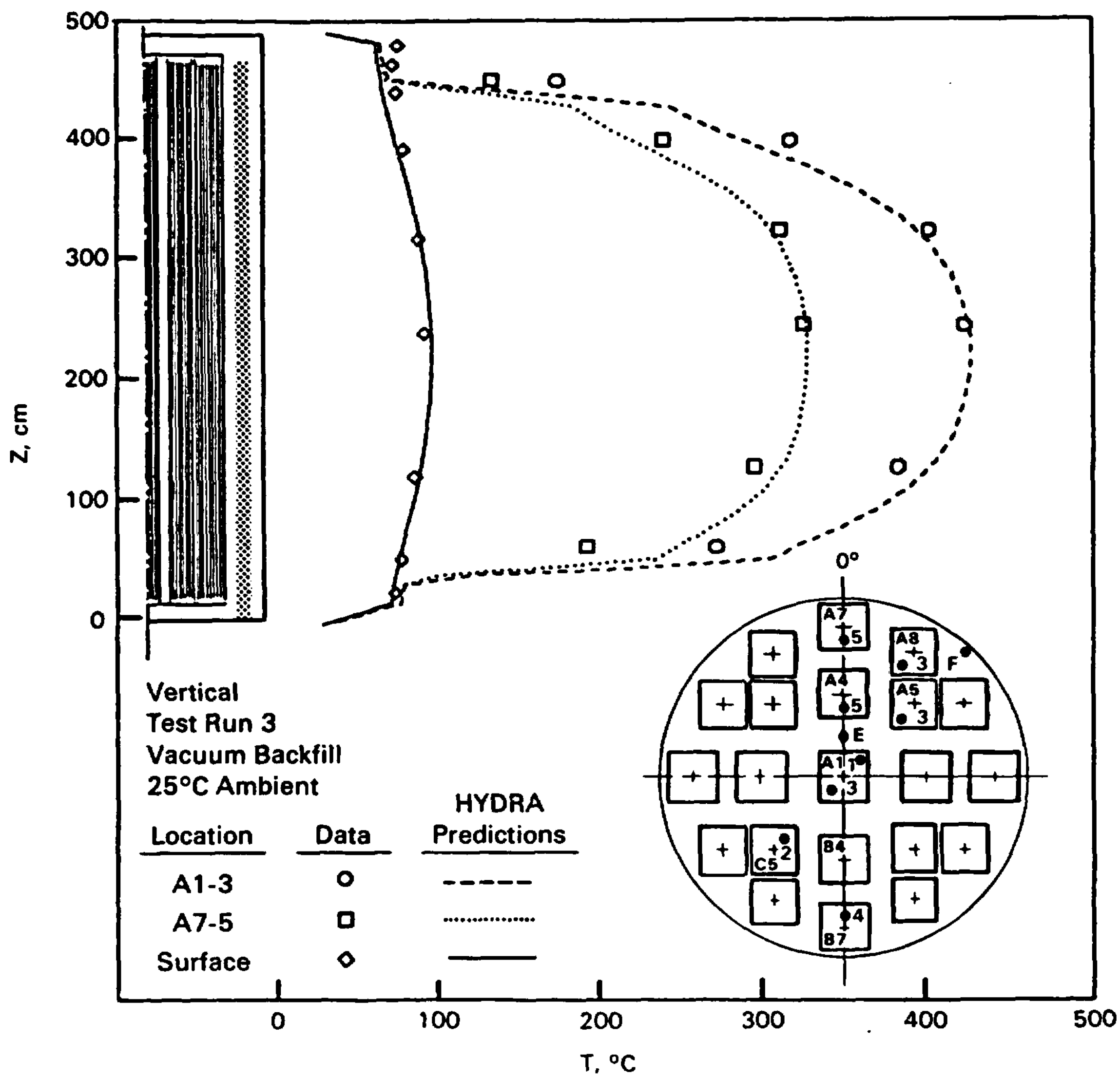


FIGURE 6.22. Axial Temperature Profile Predictions Compared to Vertical, Vacuum Data from CASTOR-V/21 Cask

the uncertain location of the TC lances. The lances may have been touching the basket, resulting in measured temperatures greater than predicted temperatures.

Figure 6.25 shows axial mass fluxes at the plane of peak guide tube temperature for the vertical, nitrogen test run. Relatively high flows are seen in the channels adjacent to the basket fuel tubes. Flow is generally

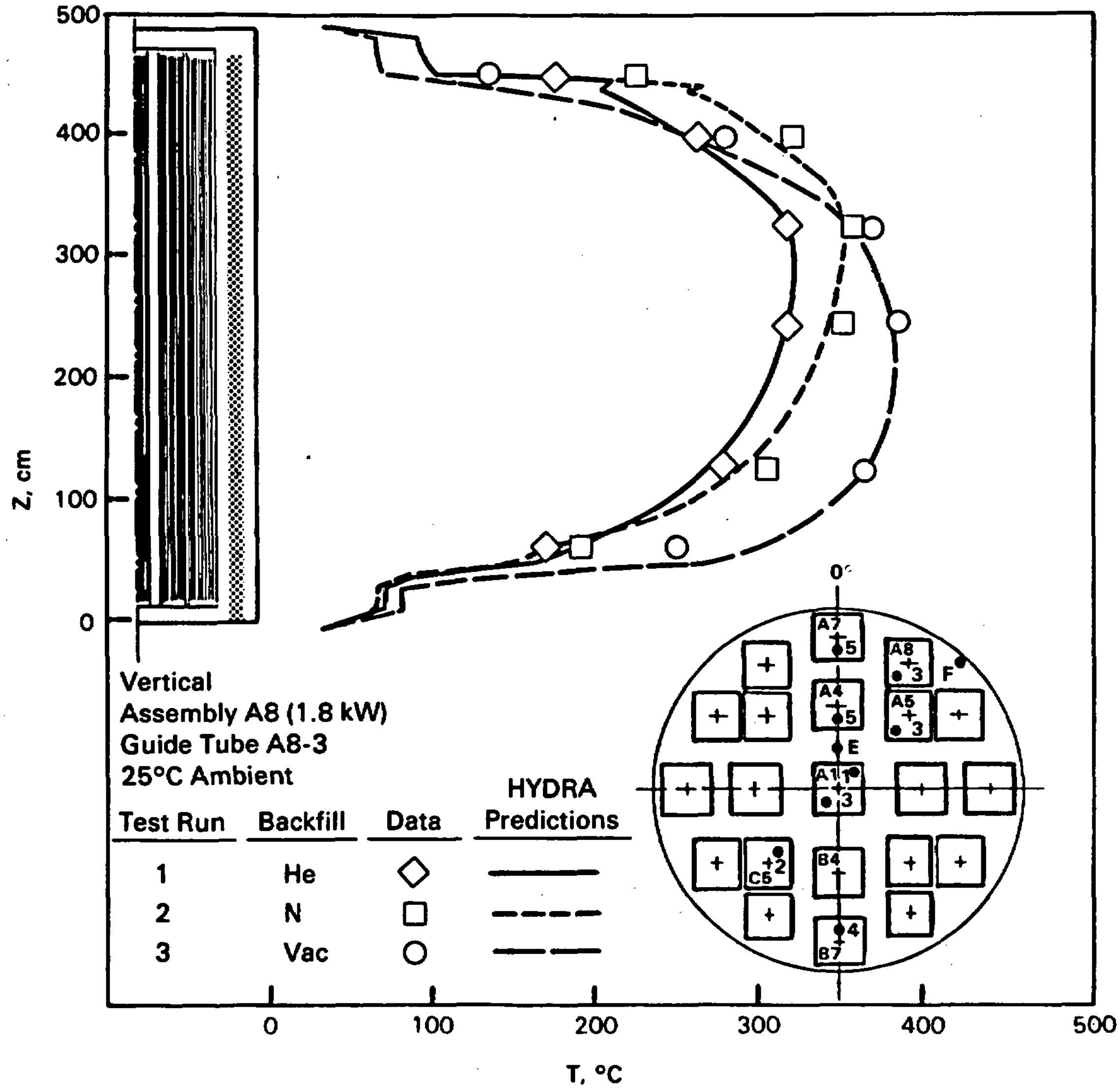


FIGURE 6.23. Axial Temperature Profile Predictions Compared to Vertical, Helium, Nitrogen, and Vacuum 1.8-kW Outer Fuel Assembly Data

upward in the interior regions of the basket and downward near the inner cask wall. A peak mass flux of approximately 0.03 g/sec-cm^2 can be seen from Figure 6.25 to be flowing down the cavity wall. The corresponding velocity is approximately 60 cm/sec. Upward mass fluxes in the fuel assemblies are approximately 0.001 g/sec-cm^2 with corresponding average assembly velocities of

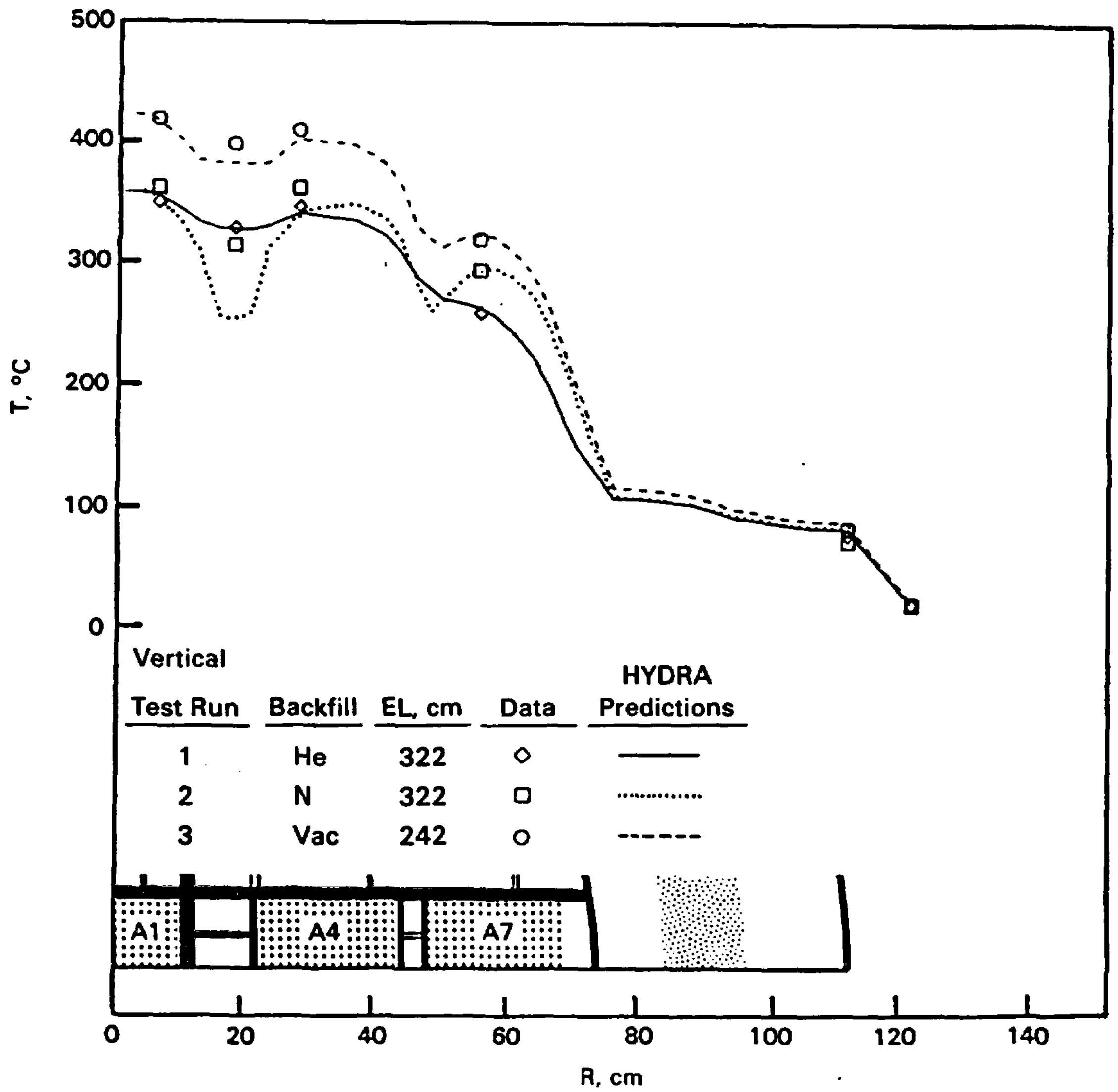


FIGURE 6.24. Radial Temperature Profile Predictions Compared to Vertical, Helium, Nitrogen, and Vacuum Data at Axial Planes of Peak Guide Tube Temperatures

2 cm/sec. A display of mass fluxes for the vertical, helium test run looks qualitatively similar to Figure 6.25 except that the mass fluxes are an order of magnitude less. The convection flow in the vertical, vacuum test run also has a similar appearance, but the negligibly low mass fluxes are of no consequence to the temperature field.

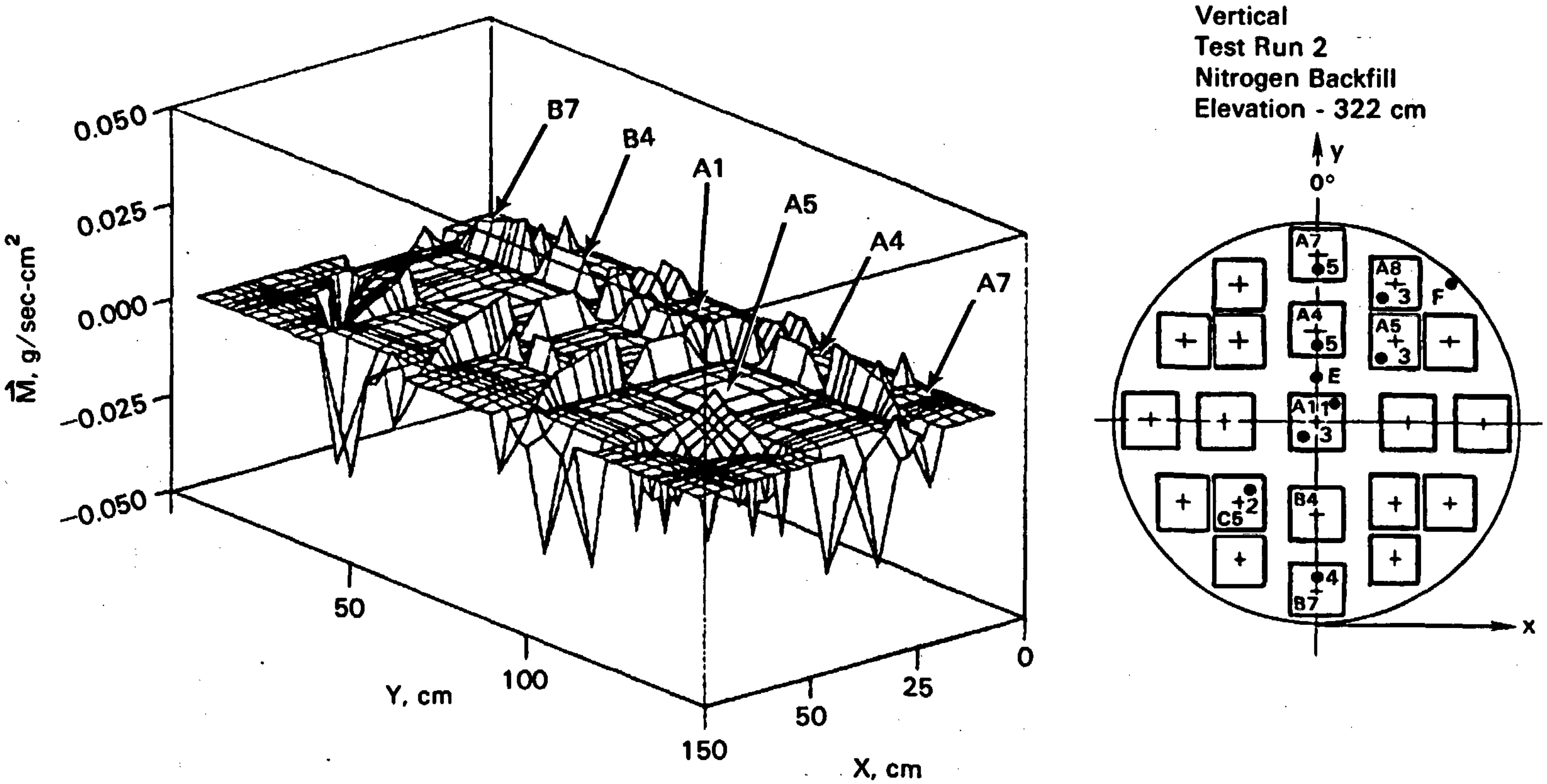


FIGURE 6.25. Axial Mass Fluxes at Plane of Peak Guide Tube Temperature for Vertical, Nitrogen Test Run

Figure 6.26 shows a vector plot of mass fluxes for the vertical, nitrogen test run. The X-Z plane selected is one of the channels adjacent to basket fuel tubes and is identified in Figure 6.26. There is a general mass flow upward in the interior of the basket and downward next to the inner wall. The largest mass fluxes in this plane are horizontal and occur at the bottom of the cavity.

Figure 6.27 shows the flow pattern across the bottom of the cavity for the vertical, nitrogen test run. The largest mass flux is approximately 0.03 g/sec-cm^2. The results for helium are qualitatively similar but smaller by about an order of magnitude.

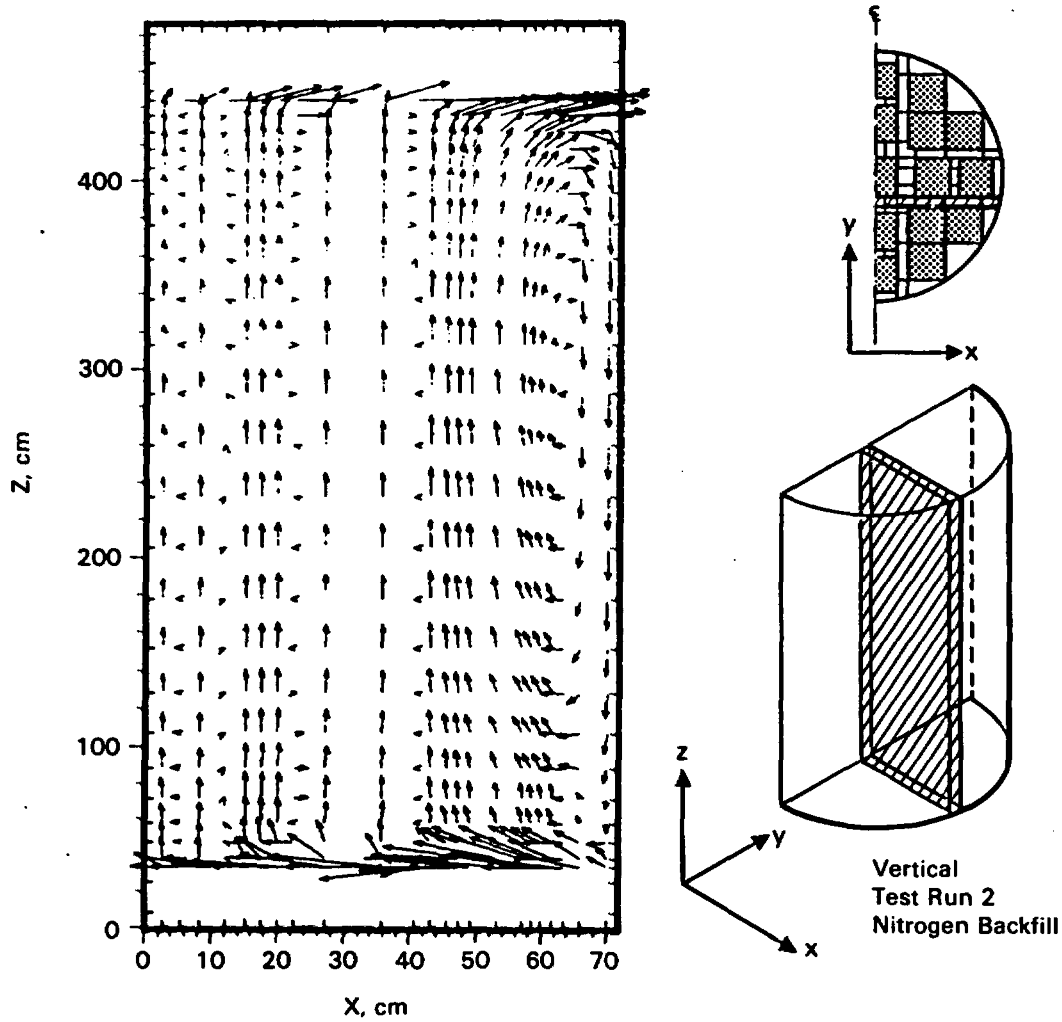


FIGURE 6.26. Vector Plot of Mass Fluxes in X-Z Plane for Vertical, Nitrogen Test Run

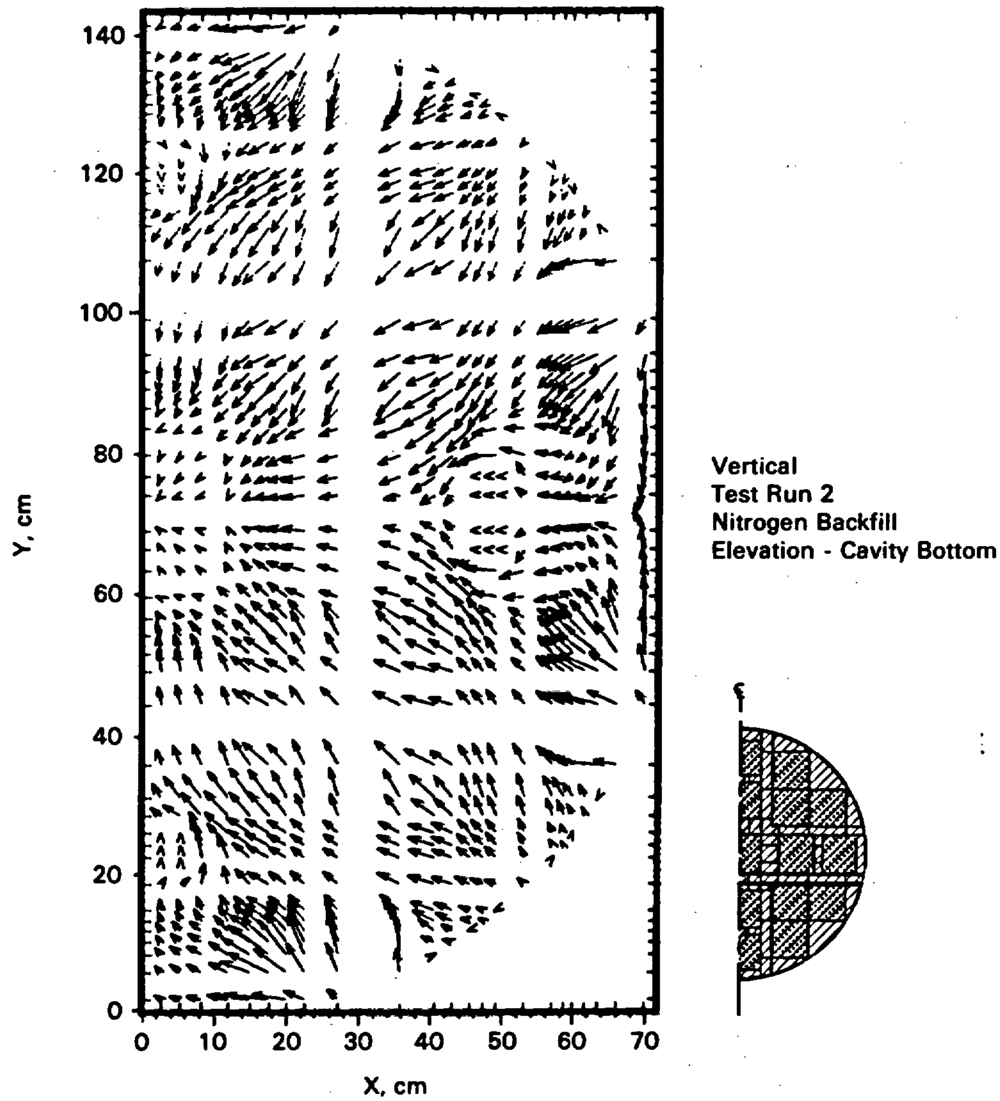


FIGURE 6.27. Vector Plot of Mass Fluxes in X-Y Plane at Bottom of Cavity for Vertical, Nitrogen Test Run

The mass flux maps presented in this section were constructed from local vector components in the respective planes. Mass flux maps of local vector components for the entire cask inner cavity flow channels are available in HYDRA-II output. These vector plots (maps) can be appropriately selected to clearly indicate both local and global mass fluxes necessary to obtain a better understanding of cask performance and to identify promising approaches to cask optimization.

Heat fluxes in the X-Y plane at the axial location of peak guide tube temperature for the vertical, helium test runs are shown in Figure 6.28. The highest heat fluxes are directed along the solid borated stainless steel basket members next to the inner cask wall (e.g., in the region 40< x <70, Y~55 and 85). Their magnitude is approximately 1.0 W/cm^2. Heat fluxes in the two large channels next to the inner cask wall (X = 45, Y = 25 and 115) are seen to be directed inward (at this axial plane). This reflects convection heat transfer. A vector plot of heat fluxes for the vertical, nitrogen test run is qualitatively similar.

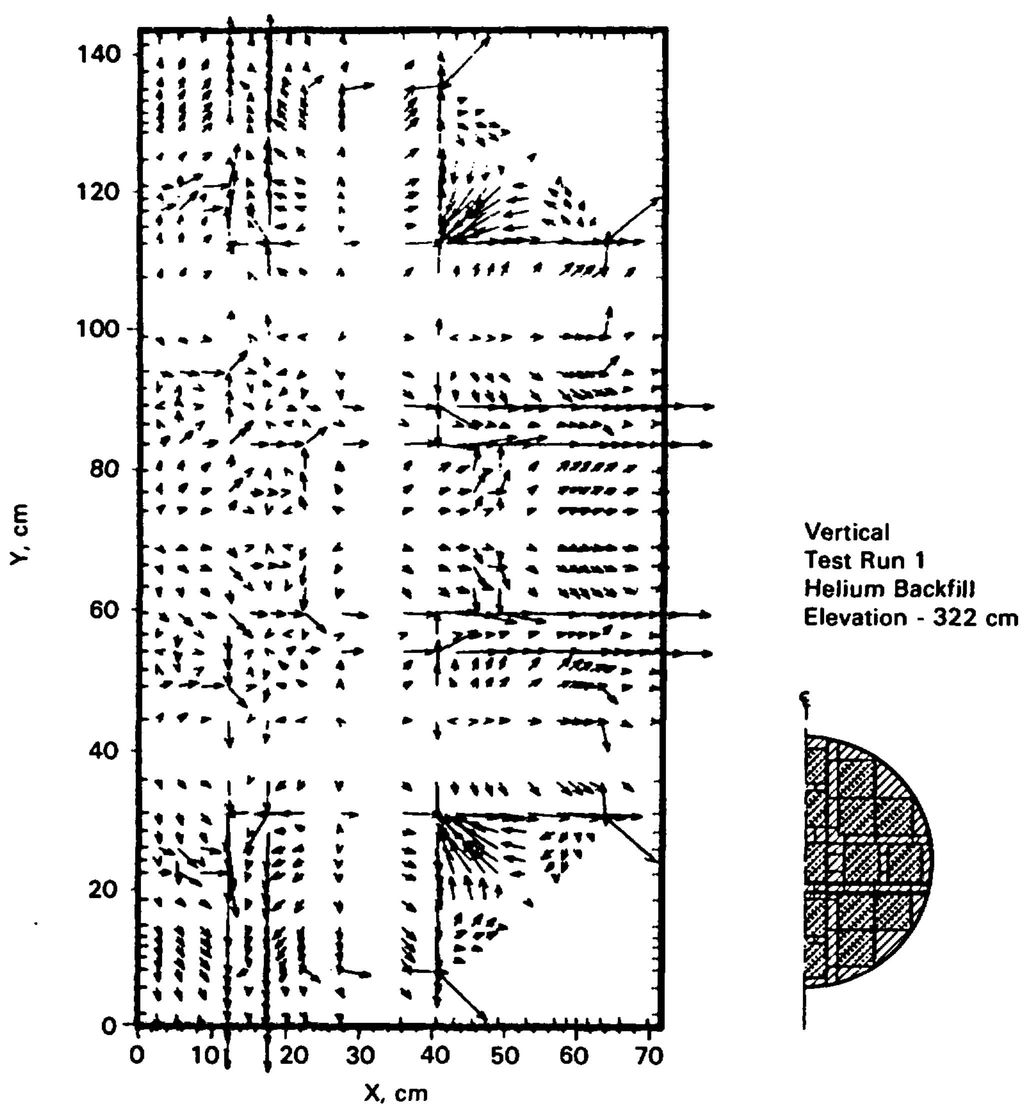


FIGURE 6.28. Vector Plot of Heat Fluxes in X-Y Plane at Axial Position of Peak Guide Tube Temperature for Vertical, Helium Test Run

7.0 VERIFICATION SIMULATIONS

Code verification has been a continuing activity during the evolution of HYDRA-II. The purpose of verification is to establish correctness of the code logic and the numerically modeled physics. The use of simple problems that individually contain separate effects of more complex problems is especially helpful. Code predictions for these simple problems can be compared to known analytical solutions or published experimental data. In some cases it is useful to compare results with those of other codes.

This chapter presents code predictions for two problems. The first problem is steady-state heat conduction in a square with orthotropic properties and heat generation. Code predictions for this problem are compared to the analytical solution. The second problem is buoyancy-driven convection in a rectangular cavity, where code predictions are compared to experimental data and to the predictions generated by two other codes.

7.1 STEADY TEMPERATURE IN A SQUARE WITH HEAT GENERATION

The problem is steady-state heat conduction in a square with uniform heat generation. The thermal conductivity in one coordinate direction is unity; in the other coordinate direction, it is 1/16. The boundary temperatures on all four sides are zero. For computational purposes, use was made of quarter symmetry so two sides became adiabatic boundaries as shown in Figure 7.1.

As expected, the results shown in Figure 7.1 indicate good agreement between predictions and the analytical solution along the coordinate axes even for the relatively coarse mesh used. The locally one-dimensional difference scheme employed in the code is especially appropriate in these directions for this problem. Good agreement is also achieved along the diagonal where heat transfer is clearly not one-dimensional.

This problem was also run with the conducting square oriented in the X-Z plane and the Y-Z plane. The results were identical to those shown in Figure 7.1, indicating consistent coding for all three directions. The favorable results shown in Figure 7.1 provide evidence that the heat conduction portion of the code is working as intended.

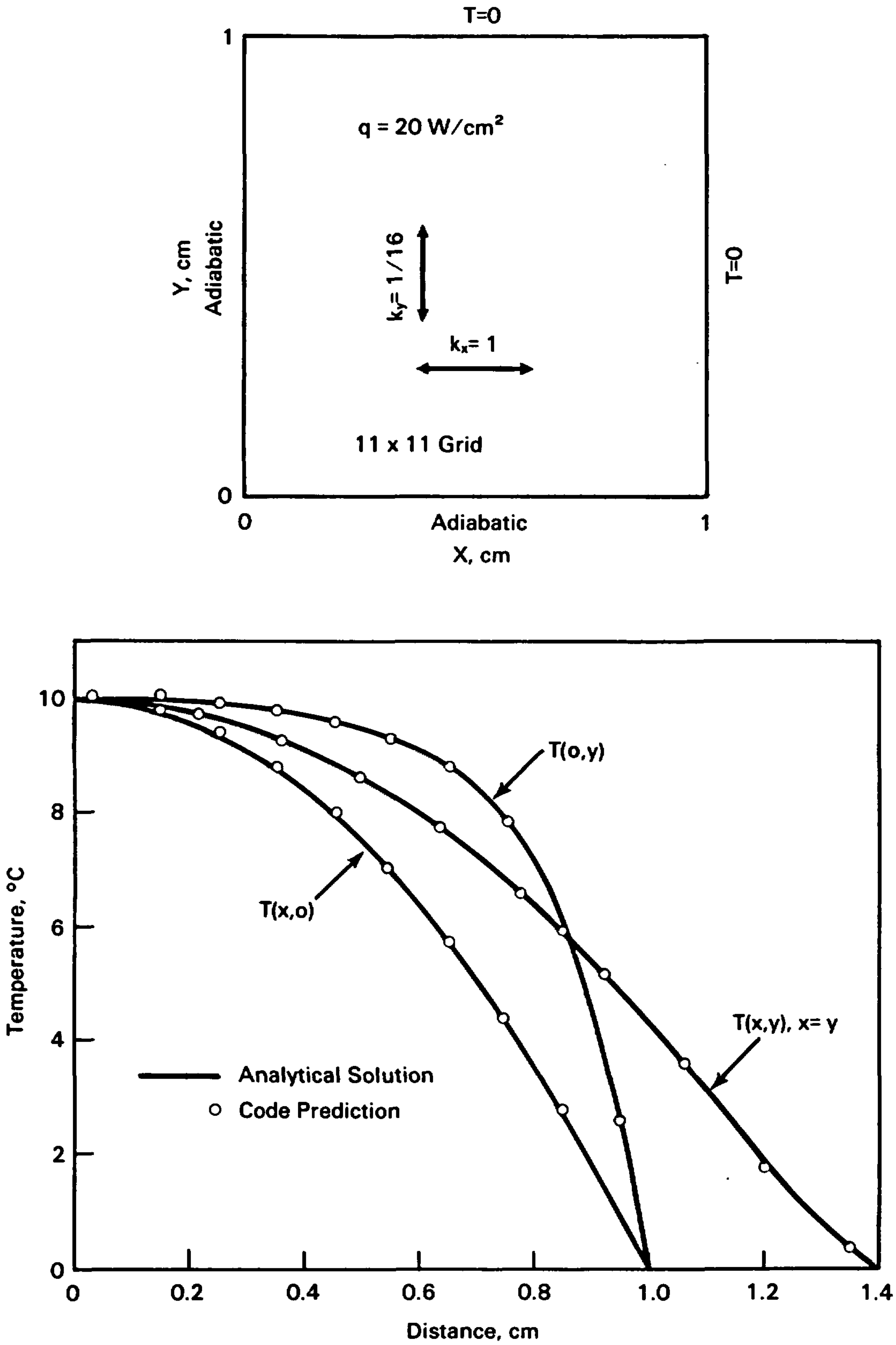


FIGURE 7.1. Steady Temperature in a Square with Heat Generation

7.2 BUOYANCY-DRIVEN CAVITY CONVECTION

The problem is buoyancy-driven convection in a rectangular cavity, where the momentum equation is coupled with the energy equation.

The cavity configuration, which has an aspect ratio of 10:1, is shown in Figure 7.2. The vertical walls are constant temperature boundaries; one is hot and the other is cold. The top and bottom surfaces are insulating material. The medium in the cavity is air at atmospheric pressure. Variable mesh spacing was used in HYDRA-II to enhance resolution of the boundary layer next to the walls.

The results are shown in Figure 7.2. Predictions are compared to the experimental data of Eckert and Carlson (1961). Also shown are the code predictions of TEMPEST (Eyler, Trent, and Budden 1983) and VECTRA (Hjelm and Donovan 1979). The general agreement among the three codes and the experimental data is good.

This problem was also run with the two-dimensional cavity oriented in the other two mutually orthogonal directions. The results were identical to those shown in Figure 7.2, indicating consistent coding for all three directions. The favorable results shown in Figure 7.2 provide evidence that the coupled energy energy, momentum, and continuity equations are working as intended.

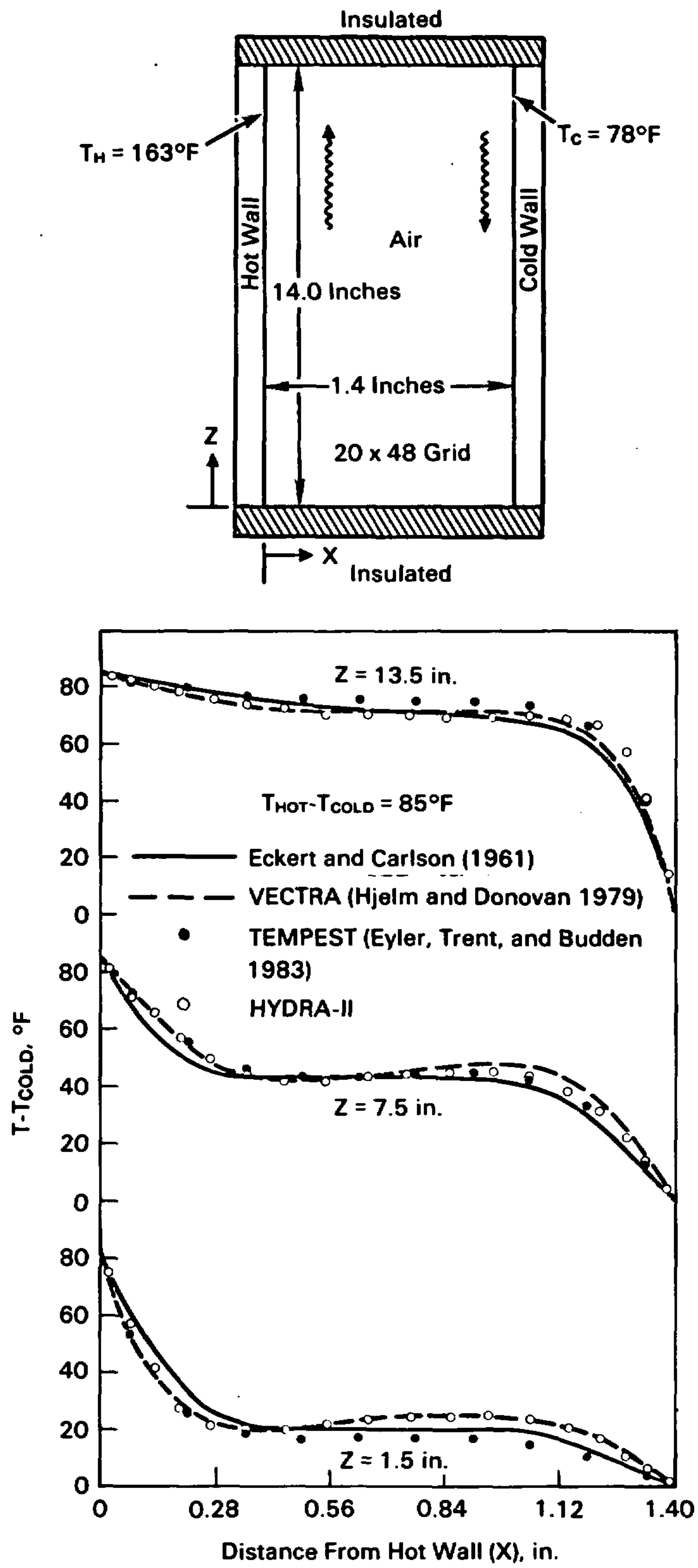


FIGURE 7.2. Natural Convection in a Rectangular Cavity

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APPENDIX A

HYDRA-II INPUT FILE FOR THE PWR SINGLE-ASSEMBLY SPENT FUEL TEST -- HELIUM BACKFILL CASE

APPENDIX A

HYDRA-II INPUT FILE FOR THE PWR SINGLE-ASSEMBLY SPENT FUEL TEST -- HELIUM BACKFILL CASE

```
1/main
7
so they chop and change, and each fresh move
  is inly a fresh mistake.
                              robert service

input for e-mad 2/27/84
quarter symmetry, helium
Re-run using HYDRA-II in July 1987
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0
0,0.1,0.5,0.010
1,1,1
1.0,100,1
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2
1,3
2,5,2
1 /MAIN/Print Arrays or info
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0,0 /ptsl
1 /pqbnd
1,2 /pql
0,0 /pqrad
0,0 /ptsl
1,0 /pt
0,0 /pts
1,0 /pmx
1,0 /pmy
1,0 /pmz
0,0 /pdpf
0,0 /ppf
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1/grid/jeend
16*16
1/grid/imend
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high conductivity
0.1e+20,0.0,0
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sst
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air (backfill gas)
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18*393, 18*387, 18*381, 18*377, 18*375, 18*373
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0,0,0,0,.25 /sideh,sidel,sidev,sidec,siden
```

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high conductivity
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air (ambient gas)
0.6880e-4,0.6340e-6,0
copper
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lead
0.392,-1.333e-4,0
sst
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0
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1 /HYDRO/monmz
4
4,5,5
4,5,17
11,11,3
11,11,21
0,0,0
1/hydro/specs vis boundary
2
1.0e-20,2.0,16.0,17.0,17.0,2.0,26.0,
1.0e-20,1.0,1.0,2.0,16.0,2.0,26.0,
28*0.0
1/hydro/specs vis inside
2
0.1e+10,7.0,10.0,8.0,8.0,2.0,23.0,
0.1e+10,10.0,10.0,9.0,11.0,2.0,23.0,
```

```
28*0.0
1/propm/perm0
1.0e+4
1/propm/ax
0
-1,6*0
1/propm/ay
0
-1,6*0
1/propm/az
0
-1,6*0
1/propm/axl
0
0.25, 9,9,9,16,2,23
0.1e-6, 9,9,9,16,24,24
-1,6*0
1/propm/ayl
0
0.25, 2,9,8,8,2,23
0.1e-6, 2,9,8,8,24,24
-1,6*0
1/propm/azl
0
0.559, 2,9,9,16,23,23
0.294, 8,8,10,16,24,24
0.294, 2,7,10,10,24,24
0.1e-6, 9,9,9,16,24,24
0.1e-6, 2,8,9,9,24,24
-1,6*0
1/propm/por
0
0.559, 2,9,9,16,2,23
0.927, 2,9,9,16,24,24
0.600, 10,10,8,11,2,23
0.600, 7,9,8,8,2,23
-1,6*0
1/propm/permx
0
0.00466, 2,9,9,16,2,23
-1,6*0
1/propm/permy
0
0.00466, 2,9,9,16,2,23
-1,6*0
1/propm/permz
0
0.0098, 2,9,9,16,2,24
-1,6*0
1/pdg
0.8,0.5e-6
1/piter
4,25
1.0,0.0,1.0
1/piter/norder
4
2,4,1,0
1/piles
0.1e-7,1.25,4,0
1 /REBQ/necho
0,0 /REBQ/nmax,info
1,1,1 /REBQ/kbound,jbound,ibound
0.1e-20, 0.1e-20, 0.1e-20 /REBQ/akkmin,ajjmin,aiimin
1 /REBQ/necho
0 /REBQ/kreg
1 /REBQ/necho
0 /REBQ/kbida
```

```
1 /REBQ/necho
0 /REBQ/jreg
1 /REBQ/necho
0 /REBQ/jblda
1 /REBQ/necho
0 /REBQ/lreg
1 /REBQ/necho
0 /REBQ/lblda
1/af
6,0
1/avg
0,1082179.0
```

APPENDIX B

HYDRA-II INPUT FILE FOR THE ELECTRICALLY-HEATED, SINGLE-ASSEMBLY TEST -- AIR BACKFILL, INCLINED ORIENTATION, 1-kW CASE

APPENDIX B

HYDRA-II INPUT FILE FOR THE ELECTRICALLY-HEATED, SINGLE-ASSEMBLY TEST -- AIR BACKFILL, INCLINED ORIENTATION, 1-kW CASE

```
1/main
7
so they chop and change, and each fresh move
  is inly a fresh mistake.
                              robert service

input for agns 5/9/85
source is h2ag, input file is inh2ag1
1/2 symmetry, inclined, air, 1.0kw, run 1
6,4,1
1,1,50
1.0,1,0,0
0
0,0.1,1.0,0.01
1.0,1.0,0.0
0.0,30,1
1/main/print plane options
2
1,17
2,27,2
1/main/print arrays or info
0.0,0/pti
0.0,0/ptsi
1.0/pqbnd
1.0,1/pqi
0.0,0/pqrad
0.0,0/pts1
1.0,0/pt
0.0,0/pts
1.0,2/pmx
0.0,0/pmy
1.0,1/pmz
0.0,0/pdpf
0.0,0/ppf
1/grid
2.0,3,3,17,20
1/grid/ieend
1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,18,
18,18,17,16,15,14,13,12,11,10,9,8,7,6,5,4,3,1
1/grid/jebeg
2,2,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17
1/grid/jeend
35,35,35,34,33,32,31,30,29,28,27,26,25,24,23,22,
21,20
1/grid/imend
3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,6*18,
17,16,15,14,13,12,11,10,9,8,7,6,5,4,3
1/grid/jmbeg
2,2,2,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16
1/grid/jmend
35,35,35,35,34,33,32,31,30,29,28,27,26,25,24,23,
22,21
1/grid/icart
```

```
2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,
4*19,18,17,16,15,14,13,12,11,10,9,8,7,6,5,4,3,2
1/grid/jcart
1,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,
18,19,20,21,22,23,24,25,26,27,28,29,30,31,
32,33,34,35,36,36
1/grid/isend
28*2
1/grid/dx
1.0,2*2.9464,2.2098,2*1.4732,0.381,0.5334,0.889,1.6002,
2.431504306,1.247813387,0.598477002,0.3301857,0.223356546,
0.772350835,0.63908606,0.734174295,1.0
1/grid/dy
1.0,0.734174295,0.63908606,0.772350835,0.223356546,0.3301857,
0.598477002,1.247813387,2.431504306,1.6002,0.889,0.5334,0.381,
2*1.4732,2.2098,4*2.9464,2.2098,2*1.4732,
0.381,0.5334,0.889,1.6002,2.431504306,1.247813387,0.598477002,
0.3301857,0.223356546,0.772350835,0.63908606,0.734174295,1.0
1/grid/dz
1.0,12.3825,11.1125,2*10.16,12.7,15.24,17.78,20.32,22.86,25.4,
26.67,3*27.94,26.67,25.4,
22.86,20.32,17.78,15.24,12.7,2*10.16,2*21.43125,10.16,1.0
1/grid/dr
22.225,2*1.0
1/prop
-1,-1,-1,-1,-1,-1,0
0.0,0.0,0.0,0.0,0.0
0.0,0.0,0.0,0.0,0.0
1/prop/ccon0,ccon1,ccon3
6
low conductivity
0.1e-20,0.0,0.0
high conductivity
0.1e+20,0.0,0.0
air (backfill gas)
0.6880e-4,0.6340e-6,0.0
sst
0.09215,0.1465e-3,0.0
boral
0.677,-0.667e-3,0.0
helium (not used)
0.52e-3,0.32e-5,0.0
1/prop/specs def. 01 isotropic and 11 parallel
6
1.0,1.0,1.0,1.0,
2.0,1.0,2.0,1.0,
3.0,1.0,3.0,1.0,
4.0,2.0,4.0,0.3480,
 5.0,0.1854,
5.0,2.0,4.0,0.3480,
 3.0,0.1854,
6.0,1.0,4.0,1.0,
72*0.0
1/prop/specs def. 21 series
5
10.0,4.0,0.3480,0.0,0.0,0.0,
11.0,5.0,0.1854,0.0,0.0,0.0,
12.0,3.0,0.795,0.0,0.0,0.0,
13.0,3.0,0.398,0.0,0.0,0.0,
14.0,3.0,0.9,0.0,0.0,0.0,
70*0.0
1/prop/specs def. 31 fuel assembly
1
20.0,3.0,0.889,1.077,1.453,0.16,0.16,0.6,0.95,
91*0.0
1/prop/index
30,46
```

```
1,1,2,35,2,27,1,1,1,
2,6,14,23,2,23,1,31,20,
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6,6,14,23,2,23,1,41,14,
2,7,13,13,2,23,1,4,3,
2,7,24,24,2,23,1,4,3,
7,7,14,23,2,23,1,4,3,
2,8,12,12,2,2,2,4,3,3,6,
2,8,25,25,2,2,2,4,3,3,6,
8,8,13,24,2,2,2,4,3,3,6,
2,7,12,12,3,23,4,12,4,15,4,22,10,22,11,
2,7,25,25,3,23,4,12,4,15,4,22,10,22,11,
8,8,13,24,3,23,4,14,4,16,4,21,10,21,11,
8,8,12,12,3,23,3,12,5,14,5,15,5,
8,8,25,25,3,23,3,12,5,14,5,15,5,
2,13,2,11,2,23,1,4,3,
2,13,26,35,2,23,1,4,3,
9,18,12,25,2,23,1,4,3,
2,10,10,10,2,2,1,3,6,
2,10,27,27,2,2,1,3,6,
10,10,11,26,2,2,1,3,6,
2,18,2,35,24,27,1,4,3,
2,2,1,1,2,27,1,42,12,
3,3,1,1,2,27,1,42,13,
2,2,35,35,2,27,1,42,12,
3,3,35,35,2,27,1,42,13,
18,18,17,17,2,27,1,41,13,
18,18,18,19,2,27,1,41,12,
18,18,20,20,2,27,1,41,13,
53*0
1/therm
0.5,1.0,0.5
1.0,100,1
1/therm/monitor/t
0
0,0,0
1/therm/q weighting factor
1.0,2,6,14,23,
0.9375,2*2,18,19,
0.75,2*3,2*17,
0.75,2*3,2*20,
0.555555556,2*4,2*16,
0.555555556,2*4,2*21,
0.5,2*5,2*19,
0.5,2*6,2*17,
0.5,2*6,2*20,
0.0,4*0
1/therm/group power
475.5,2,6,14,23,
0.0,4*0
1/therm/relact
4*0.0,17*1.0,5*0.0
1/therm/pqgen
0.0
1/therm/tcen
0,18.5
340.0,360.0,380.0,410.0,440.0,460.0,480.0,500.0,
510.0,520.0,7*530.0,520.0,510.0,500.0,480.0,
450.0,430.0,410.0,390.0,370.0
1/therm/ts1
0,0
 331.9,331.9,331.9,331.9,331.9,331.9,331.9,331.9,331.9,331.9,331.9,331.9,
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422.0,421.9,
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428.5,428.5,
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436.3,436.5,436.6,437.0,437.4,437.8,438.0,438.1,438.1,438.2,438.4,438.5,
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456.8,456.9,

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0.                 ,0.                 ,0.                 ,
0.                 ,0.                 ,0.                 ,
1/radp/iregs
0
1/radp/jregs
0
1/radp/kregs
4
0.806,0.9,2,6,14,23,23,28
0.2,0.9,2,8,12,12,23,28
0.2,0.9,2,8,25,25,23,28
0.2,0.9,8,8,13,24,23,28
1/radr/notes
2
agns does not use the
radr radiation model
1/radr/h
0
1/radr/ireg
0
1/radr/it4
0
1/reba
20.0,0
1/hydro
1.0,0.2e-7,0,0.5,1.0,-0.05
0,0.1e-3,0.4
0,0,1.0
1013250.0,440.0,0.80219e-3
```

```
0.0,-0.906308,-0.422618
0.608e-4,0.4e-6
1/hydro/monitor/mx
0
0,0,0
1/hydro/monitor/my
0
0,0,0
1/hydro/monitor/mz
0
0,0,0
1/hydro/specs vis boundary
1
0.1e-19,1.0,1.0,2.0,35.0,2.0,27.0,
14*0.0
1/hydro/specs vis inside
3
0.1e+10,2.0,8.0,12.0,12.0,3.0,23.0,
0.1e+10,2.0,8.0,25.0,25.0,3.0,23.0,
0.1e+10,8.0,8.0,13.0,24.0,3.0,23.0
1/propm
1.0e+4
1/propm/ax
0
-1.0,6*0
1/propm/ay
0
-1.0,6*0
1/propm/az
0
-1.0,6*0
1/propm/axi
0
0.227,10,10,10,27,2,2,
-1.0,6*0
1/propm/ayi
0
0.227,2,10,9,9,2,2,
0.227,2,10,27,27,2,2,
-1.0,6*0
1/propm/azi
0
0.1e-6,2,10,10,11,2,2,
0.1e-6,2,10,26,27,2,2,
0.1e-6,9,10,12,25,2,2,
-1.0,6*0
1/propm/por
0
0.580,2,6,14,23,2,23,
0.1e-4,2,8,12,12,3,23,
0.1e-4,2,8,25,25,3,23,
0.1e-4,8,8,13,24,3,23,
-1.0,6*0
1/propm/permx
0
0.0065,2,6,14,23,2,23,
-1.0,6*0
1/propm/permy
0
0.0065,2,6,14,23,2,23,
-1.0,6*0
1/propm/permz
0
0.015,2,6,14,23,2,23,
-1.0,6*0
1/pdg
0.8,0.5e-5
```

```
1/plter
8,25
0.0,1.0,1.0
1/plter/norder
3
3,4,1,0
1/plles
0.1e-7,1.3,4,0
1/rebq
2,0
1,1,1
0.1e-20,0.1e-20,0.1e-20
1/rebq/krid
18
1,2,2,7,2,11,
2,2,8,8,6,11,
3,1,9,13,7,11,
4,2,2,7,12,12,
5,2,8,8,12,12,
6,1,9,14,12,12,
7,2,2,7,13,18,
8,2,8,8,13,18,
9,1,9,18,13,18,
10,2,2,7,19,24,
11,2,8,8,19,24,
12,1,9,18,19,24,
13,2,2,7,25,25,
14,2,8,8,25,25,
15,1,9,14,25,25,
16,1,2,7,26,35,
17,1,8,8,26,31,
18,0,9,13,26,30
1/rebq/kbld
71
1,2,1,4,2,
2,3,1,5,2,
3,6,2,
4,5,1,7,2,
5,6,1,8,2,
6,9,2,
7,8,1,10,2,
8,9,1,11,2,
9,12,2,
10,11,1,13,2,
11,12,1,14,2,
12,15,2,
13,14,1,16,2,
14,15,1,17,2,
15,18,2,
16,17,1,
17,18,1
1/rebq/jrid
12
1,2,2,7,2,2,
2,2,8,8,2,2,
3,1,9,18,2,2,
4,2,2,7,3,14,
5,2,8,8,3,14,
6,1,9,18,3,14,
7,2,2,7,15,23,
8,2,8,8,15,23,
9,1,9,18,15,23,
10,1,2,7,24,27,
11,1,8,8,24,27,
12,0,9,18,24,27
1/rebq/jbld
45
```

```
1,2,1,4,3,
2,3,1,5,3,
3,6,3,
4,5,1,7,3,
5,6,1,8,3,
6,9,3,
7,8,1,10,3,
8,9,1,11,3,
9,12,3,
10,11,1,
11,12,1
1/rebq/lrld
24
1,2,2,11,2,2,
2,2,12,12,2,2,
3,2,13,18,2,2,
4,2,19,24,2,2,
5,2,25,25,2,2,
6,1,26,35,2,2,
7,2,2,11,3,14,
8,2,12,12,3,14,
9,2,13,18,3,14,
10,2,19,24,3,14,
11,2,25,25,3,14,
12,1,26,35,3,14,
13,2,2,11,15,23,
14,2,12,12,15,23,
15,2,13,18,15,23,
16,2,19,24,15,23,
17,2,25,25,15,23,
18,1,26,35,15,23,
19,1,2,11,24,27,
20,1,12,12,24,27,
21,1,13,18,24,27,
22,1,19,24,24,27,
23,1,25,25,24,27,
24,0,26,35,24,27
1/rebq/lbld
99
1,2,2,7,3,
2,3,2,8,3,
3,4,2,9,3,
4,5,2,10,3,
5,6,2,11,3,
6,12,3,
7,8,2,13,3,
8,9,2,14,3,
9,10,2,15,3,
10,11,2,16,3,
11,12,2,17,3,
12,18,3,
13,14,2,19,3,
14,15,2,20,3,
15,16,2,21,3,
16,17,2,22,3,
17,18,2,23,3,
18,24,3,
19,20,2,
20,21,2,
21,22,2,
22,23,2,
23,24,2
1/af
5,0
1/avg
0.0,991914.9
```

APPENDIX C

HYDRA-II INPUT FILE FOR THE CASTOR-1C SPENT FUEL TEST -- HELIUM BACKFILL, VERTICAL ORIENTATION CASE

APPENDIX C

HYDRA-II INPUT FILE FOR THE CASTOR-1C SPENT FUEL TEST -- HELIUM BACKFILL, VERTICAL ORIENTATION CASE

```
1/main
7
so they chop and change, and each fresh move
  is inly a fresh mistake.
                              robert service

input for castor-1c 2/1/85
source is h21c, input file is inh21c4
1/2 symmetry, vertical, he, wrgssn pwr, case 4
5,4,1
1,1,50
1.0,0,0,0
0
0,0.1,1.0,0.01
1.0,1.0,0.0
1.0,50,1
1/main/print plane options
2
1,16
2,26,2
1/main/print arrays or info
0.0,0/ptl
0.0,0/ptsl
1.0/pqbnd
1.0,1/pql
0.0,0/pqrad
0.0,0/pts1
1.0,0/pt
1.0,0/pts
1.0,2/pmx
0.0,0/pmy
1.0,1/pmz
0.0,0/pdpf
0.0,0/ppf
1/grid
2.0,17,17,3,33
1/grid/leend
1,17,31*18,17,1
1/grid/jebeg
17*2,3
1/grid/jeend
17*34,33
1/grid/imend
16,33*18,16
1/grid/jmbeg
18*2
1/grid/jmend
18*34
1/grid/icart
2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,31*19,
18,17,16,15,14,13,12,11,10,9,8,7,6,5,4,3,2
1/grid/jcart
16*1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,
20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,16*35
1/grid/isend
```

```
32*7
1/grid/dx
1.0,0.5,1.0,1.5,3.0,4.0,3.0,1.5,3*1.0,
1.5,3.0,4.0,3.0,2*1.5,1.3,1.0
1/grid/dy
1.0,1.3,2*1.5,3.0,4.0,3.0,1.5,3*1.0,1.5,
3.0,4.0,3.0,1.5,3*1.0,1.5,3.0,4.0,3.0,1.5,
3*1.0,1.5,3.0,4.0,3.0,2*1.5,1.3,1.0
1/grid/dz
1.0,20.0,18.5,4.0,5.0,13.0,12.5,15.0,17.5,20.0,22.5,
25.0,27.5,29.0,30.0,29.0,27.5,25.0,22.5,20.0,17.5,15.0,2*12.5,
19.0,2*12.5,9.0,18.0,16.5,13.0,1.0
1/grid/dr
46.1832221,2.3167779,5.5,7.65,12.5,15.1,8.0,1.0
1/prop
-1,-1,-1,-1,-1,-1,0
1.0,172.0,0.0,0.14,0.333
0.0,0.0,0.0,0.0,0.0
1/prop/ccon0,ccon1,ccon3
10
low conductivity
0.1e-20,0.0,0.0
high conductivity
0.1e+20,0.0,0.0
helium (backfill gas)
0.52e-3,0.32e-5,0.0
sst
0.09215,0.1465e-3,0.0
boron steel (radionox)
0.079,0.21e-3,0.0
nodular cast iron
0.5162,-0.3205e-3,0.0
epoxy
0.15e-2,0.0,0.0
nitrogen
0.075e-3,0.6167e-6,0.0
concrete
0.017,0.0,0.0
air (not used)
0.6880e-4,0.6340e-6,0.0
1/prop/specs def. 01 isotropic and 11 parallel
9
1.0,1.0,1.0,1.0,
2.0,1.0,2.0,1.0,
3.0,1.0,3.0,1.0,
4.0,1.0,4.0,1.0,
5.0,1.0,5.0,1.0,
6.0,2.0,4.0,2.0,
        3.0,2.0,
8.0,1.0,4.0,0.62,
9.0,1.0,6.0,1.0,
10.0,2.0,4.0,7.0,
         7.0,6.0,
60*0.0
1/prop/specs def. 21 series
8
14.0,4.0,2.0,0.0,0.0,0.0,
15.0,3.0,2.0,0.4,0.25,0.0,
16.0,7.0,4.0,0.0,0.0,0.0,
17.0,8.0,0.6,0.2,0.2,1.0,
18.0,4.0,7.0,0.0,0.0,0.0,
19.0,7.0,6.0,0.0,0.0,0.0,
20.0,1.0,1.0,0.2,1.0,0.5,
21.0,9.0,20.0,0.0,0.0,0.0,
52*0.0
1/prop/specs def. 31 fuel assembly
2
```

```
22.0,3.0,1.267,1.429,1.875,0.0209,0.1150,0.8,0.95,
23.0,3.0,1.080,1.250,1.625,0.0209,0.1150,0.8,0.95,
82*0.0
1/prop/index
68,77
1,1,2,34,2,31,1,1,1,
2,18,2,34,4,28,1,4,3,
4,8,4,8,5,6,1,4,8,
12,16,4,8,5,6,1,4,8,
4,8,12,16,5,6,1,4,8,
12,16,12,16,5,6,1,4,8,
4,8,20,24,5,6,1,4,8,
12,16,20,24,5,6,1,4,8,
4,8,28,32,5,6,1,4,8,
12,16,28,32,5,6,1,4,8,
5,7,5,7,5,6,1,4,3,
13,15,5,7,5,6,1,4,3,
5,7,13,15,5,6,1,4,3,
13,15,13,15,5,6,1,4,3,
5,7,21,23,5,6,1,4,3,
13,15,21,23,5,6,1,4,3,
5,7,29,31,5,6,1,4,3,
13,15,29,31,5,6,1,4,3,
2,2,3,33,5,27,1,4,5,
10,10,3,33,5,27,1,4,5,
3,17,10,10,5,27,1,4,5,
3,17,18,18,5,27,1,4,5,
3,17,26,26,5,27,1,4,5,
3,12,10,10,5,5,1,4,3,
3,12,18,18,5,5,1,4,3,
3,12,26,26,5,5,1,4,3,
2,2,8,28,5,5,1,4,3,
10,10,8,28,5,5,1,4,3,
2,17,3,33,4,4,5,11,6,13,6,3,2,23,14,23,15,
5,7,6,6,4,4,1,4,3,
6,6,5,7,4,4,1,4,3,
13,15,6,6,4,4,1,4,3,
14,14,5,7,4,4,1,4,3,
5,7,14,14,4,4,1,4,3,
6,6,13,15,4,4,1,4,3,
13,15,14,14,4,4,1,4,3,
14,14,13,15,4,4,1,4,3,
5,7,22,22,4,4,1,4,3,
6,6,21,23,4,4,1,4,3,
13,15,22,22,4,4,1,4,3,
14,14,21,23,4,4,1,4,3,
5,7,30,30,4,4,1,4,3,
6,6,29,31,4,4,1,4,3,
13,15,30,30,4,4,1,4,3,
14,14,29,31,4,4,1,4,3,
9,11,9,11,4,4,1,4,4,
9,11,25,27,4,4,1,4,4,
10,10,7,7,4,4,1,3,4,
10,10,29,29,4,4,1,3,4,
13,13,10,10,4,4,1,3,4,
13,13,26,26,4,4,1,3,4,
10,10,7,7,3,3,1,43,15,
10,10,29,29,3,3,1,43,15,
13,13,10,10,3,3,1,43,15,
13,13,26,26,3,3,1,43,15,
4,8,4,8,7,26,1,31,22,
12,16,4,8,7,26,1,31,22,
4,8,12,16,7,26,1,31,22,
12,16,12,16,7,26,1,31,22,
4,8,20,24,7,26,1,31,23,
12,16,20,24,7,26,1,31,23,
4,8,28,32,7,26,1,31,23,
```

```
12,16,28,32,7,26,1,31,23,
2,18,2,34,2,3,1,4,9,
2,18,2,34,1,1,2,43,16,43,21,
2,18,2,34,29,30,1,4,4,
2,18,2,34,30,30,2,43,17,43,19,
2,18,2,34,31,31,4,11,10,13,10,23,18,51,20,
2*0
1/therm
0.5,5.234,0.5
1.0,50,20
1/therm/monitor/t
0
0,0,0
1/therm/q weighting factor
1.0,4,8,4,8,
1.0,12,16,4,8,
1.0,4,8,12,16,
1.0,12,16,12,16,
1.0,4,8,20,24,
1.0,12,16,20,24,
1.0,4,8,28,32,
1.0,12,16,28,32,
0.0,4*0
1/therm/group power
848.25,4,8,4,8,
843.55,12,16,4,8,
852.3,4,8,12,16,
848.25,12,16,12,16,
837.5,4,8,20,24,
877.1,12,16,20,24,
877.1,4,8,28,32,
714.65,12,16,28,32,
0.0,4*0
1/therm/relact
5*0.0,0.16,0.5,0.69,0.81,0.91,1.0,1.12,1.17,1.27,1.24,
1.22,1.15,1.14,1.01,0.88,0.75,0.57,0.35,0.15,0.03,5*0.0
1/therm/pqgen
0.0
1/therm/tcen
0,18.0
310.0,320.0,340.0,360.0,380.0,400.0,420.0,440.0,450.0,
470.0,490.0,510.0,5*520.0,510.0,500.0,490.0,480.0,
470.0,460.0,450.0,420.0,390.0,360.0,340.0,320.0,310.0
1/therm/tsl
0,0
2080*299.0
1/therm/delta
0
2,18,2,34
2*10.0,25*20.0,3*0.0
1/rebt
0.1e+6,6,1
1/props
-1,-1,-1,-1,-1,-1,0
1.0,172.0,0.0,0.14,0.333
0.0,0.0,0.0,0.0,0.0
1.0,8.0,0.0,0.75,0.25
1/props/ccon0,ccon1,ccon3
9
low conductivity
0.1e-20,0.0,0.0
high conductivity
0.1e+20,0.0,0.0
sst
0.09215,0.1465e-3,0.0
nodular cast iron
0.5162,-0.3205e-3,0.0
```

```
epoxy
0.15e-2,0.0,0.0
helium
0.52e-3,0.32e-5,0.0
nitrogen
0.075e-3,0.6167e-6,0.0
air
0.688e-4,0.634e-6,0.0
concrete
0.017,0.0,0.0,0.0
1/props/specs def. 01 isotropic and 11 parallel
14
1.0,1.0,1.0,1.0,
2.0,1.0,2.0,1.0,
3.0,1.0,3.0,1.0,
4.0,1.0,3.0,0.852,
5.0,1.0,3.0,1.166,
6.0,1.0,4.0,1.0,
7.0,1.0,4.0,0.852,
8.0,1.0,4.0,1.166,
9.0,1.0,4.0,0.230,
10.0,1.0,4.0,0.431,
11.0,1.0,4.0,0.5187,
12.0,2.0,3.0,5.964,
         5.0,5.112,
13.0,2.0,3.0,8.162,
         5.0,6.996,
14.0,1.0,3.0,1.857,
40*0.0
1/props/specs def. 21 series
10
20.0,5.0,4.0,0.0,0.0,0.0,
21.0,6.0,0.1,0.25,0.2,0.5,
22.0,7.0,0.7,0.2,0.2,0.5,
23.0,5.0,6.0,0.0,0.0,0.0,
24.0,7.0,0.1,0.2,0.25,0.5,
25.0,8.0,0.1,0.2,0.25,0.5,
26.0,1.0,1.0,0.2,1.0,0.5,
27.0,1.0,1.0,0.3,1.0,0.5,
28.0,1.0,1.0,0.96,1.0,0.5,
29.0,9.0,20.0,0.0,0.0,0.0,
40*0.0
1/props/index
19,40
1,1,2,66,2,31,1,1,1,
2,7,1,1,2,31,1,2,1,
2,7,67,67,2,31,1,2,1,
2,7,2,66,2,31,3,1,7,2,8,3,6,
5,5,2,66,2,26,3,1,9,2,10,3,11,
2,7,2,66,1,1,1,43,29,
2,4,2,66,1,1,1,43,20,
2,2,2,66,28,28,1,43,21,
2,2,2,66,29,29,4,1,4,2,5,3,3,41,21,
3,3,2,66,29,29,1,43,21,
2,3,2,66,30,30,5,1,4,2,5,3,3,43,22,43,23,
4,4,2,66,30,30,5,1,4,2,5,3,3,41,24,43,24,
2,3,2,66,31,31,4,11,12,13,13,3,14,51,26,
4,5,2,66,31,31,4,1,4,2,5,3,3,51,26,
5,5,2,66,31,31,1,41,25,
6,7,2,66,31,31,1,51,27,
7,7,2,66,2,6,1,53,27,
7,7,2,66,7,25,1,53,28,
7,7,2,66,26,31,1,53,27,
17*0
1/tside
0,299.0,1.0
1/tside/monitor/ts
```

```
0
0,0,0
1/tside/delta
0
30*10.0
1/radc
0
1/radc/index
32
21,1,16,1,1,1
21,1,16,2,2,1
21,1,16,1,3,1
21,1,16,2,4,1
21,1,16,1,5,1
21,1,16,2,6,1
21,1,16,3,7,1
21,1,16,3,8,1
21,1,16,4,9,1
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0.1e+5,14,14,29,31,2,2,
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-1.0,6*0
1/propm/permz
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0.1e+5,3,16,18,18,4,24,
0.1e+5,3,16,26,26,4,24,
-1.0,6*0
1/pdg
0.8,0.5e-5
1/plter
8,25
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1/plter/norder
3
3,4,1,0
1/plles
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1/rebq
2,0
1,1,1
0.1e-20,0.1e-20,0.1e-20
1/rebq/krld
20
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18,1,2,9,27,34,
19,1,10,10,29,34,
20,0,11,18,27,34
1/rebq/kbld
101
1,2,1,4,1,5,2,
2,3,1,4,2,
3,4,-1,5,2,6,2,
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7,8,1,10,2,
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20
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1/rebq/jbld
83
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19,20,1
1/rebq/lrld
30
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26,1,2,9,26,26,
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28,1,18,18,26,26,
29,1,19,26,26,26,
30,0,27,34,26,26
1/rebq/ibfd
135
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24,25,2,29,3,
25,30,3,
26,27,2,
27,28,2,
28,29,2,
29,30,2
1/af
5,0
1/avg
0.0,0.75e+6
```

APPENDIX D

HYDRA-II INPUT FILE FOR THE CASTOR-V/21 SPENT FUEL TEST--VACUUM, VERTICAL ORIENTATION CASE

APPENDIX D

HYDRA-II INPUT FILE FOR THE CASTOR-V/21 SPENT FUEL TEST--
VACUUM, VERTICAL ORIENTATION CASE

```
1/main
15
official classification of this report is
unclassified although the markings have not
been removed from each page. authorized by
s. e. gydesen, pnl classification officer and
b. j. merrill, manager, security on 10/3/85.
markings removed by r. a. mccann
                                      date

so they chop and change, and each fresh move
  is inly a fresh mistake.
                              robert service

input for castor-v/21 11/14/85
source is h2v, input file is inh2v8
1/2 symmetry, vert., vac., n, 27.94kw, case 8
6,4,1
1,1,100
1.0,0,0,0
0
0,0.1,1.0,0.01
1.0,1.0,0.0
1.0,100,1
1/main/print plane options
2
1,15
2,25,2
1/main/print arrays or info
0.0,0/pti
0.0,0/ptsi
1.0/pqbnd
1.0,1/pqi
0.0,0/pqrad
0.0,0/pts1
1.0,0/pt
1.0,0/pts
1.0,2/pmx
0.0,0/pmy
1.0,0/pmz
0.0,0/pdpf
0.0,0/ppf
1/grid
2.0,9,9,17,32
1/grid/ieend
1,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,16*24,
23,22,21,20,19,18,17,16,15,14,13,12,11,10,9,1
1/grid/jebeg
9*2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17
1/grid/jeend
9*47,46,45,44,43,42,41,40,39,38,37,36,35,34,33,32
1/grid/imend
9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,18*24,
23,22,21,20,19,18,17,16,15,14,13,12,11,10,9
1/grid/jmbeg
```

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10*2,3,4,5,6,7,8,9,10,11,12,13,14,15,16
1/grid/jmend
10*47,46,45,44,43,42,41,40,39,38,37,36,35,34,33
1/grid/icart
2,3,4,5,6,7,8,9,
10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,16*25,
24,23,22,21,20,19,18,17,16,15,14,13,12,11,10,
9,8,7,6,5,4,3,2
1/grid/jcart
8*1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,
21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,
37,38,39,40,41,42,43,44,45,46,47,8*48
1/grid/isend
31*7
1/grid/dx
1.0,5.0,0.5,5.5,2.0,4.02422514,1.0,3.97577486,1.0,
2*8.51211257,1.0,3.97577486,1.0,2.59636862,1.0,
6.93008731,0.8619833,2.10139183,0.75998222,2.77441184,
0.63974744,4.61506347,3.31733259,1.0
1/grid/dy
1.0,3.31733259,4.61506347,0.63974744,2.77441184,
0.75998222,2.10139183,0.8619833,6.93008731,1.0,
2.59636862,1.0,3.97577486,1.0,2*8.51211257,1.0,
3.97577486,1.0,4.02422514,2.0,5.5,0.5,2*5.0,0.5,
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1.0,3.97577486,1.0,2.59636862,1.0,6.93008731,
0.8619833,2.10139183,0.75998222,2.77441184,
0.63974744,4.61506347,3.31733259,1.0
1/grid/dz
1.0,18.0,14.0,3.0,7.0,10.0,12.5,15.0,17.5,20.0,
22.5,25.0,27.0,27.3,27.4,27.3,27.0,25.0,22.5,20.0,
17.5,15.0,12.5,9.5,9.0,9.0,6.5,5.5,23.5,9.3,1.0
1/grid/dr
75.2,1.0,10.0,3.2,2*10.0,4.8,1.0
1/prop
-1,-1,-1,-1,-1,-1,0
1.0,220.0,0.0,0.14,0.333
1.0,220.0,0.0,0.27,0.25
1/prop/ccon0,ccon1,ccon3
9
low conductivity
0.1e-20,0.0,0.0
high conductivity
0.1e+20,0.0,0.0
nitrogen (backfill gas)
0.075e-3,0.6167e-6,0.0
sst
0.09215,0.1465e-3,0.0
boron steel (radionox)
0.079,0.21e-3,0.0
nodular cast iron
0.5162,-0.3205e-3,0.0
epoxy (not used)
0.15e-2,0.0,0.0
helium (not used)
0.52e-3,0.32e-5,0.0
air (not used)
0.6880e-4,0.6340e-6,0.0
1/prop/specs def. 01 isotropic and 11 parallel
27
1.0,1.0,1.0,1.0,
2.0,1.0,2.0,1.0,
3.0,1.0,3.0,1.0,
4.0,1.0,4.0,1.0,
5.0,1.0,5.0,1.0,
6.0,2.0,3.0,1.0,
        5.0,1.0,
```

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7.0,1.0,5.0,0.7816,
8.0,2.0,3.0,0.5,
        5.0,0.5,
9.0,1.0,3.0,2.0,
10.0,1.0,3.0,0.5,
11.0,1.0,5.0,2.0,
12.0,1.0,5.0,0.5,
13.0,2.0,3.0,0.6444,
        4.0,0.3556,
14.0,1.0,3.0,1.552,
15.0,2.0,3.0,1.289,
         4.0,0.7112,
16.0,2.0,3.0,0.3222,
         4.0,0.1778,
17.0,1.0,3.0,3.104,
18.0,1.0,3.0,3.190,
19.0,1.0,3.0,1.431,
20.0,2.0,3.0,0.7221,
         4.0,0.2779,
21.0,2.0,3.0,0.8222,
         4.0,1.778,
22.0,1.0,3.0,1.355,
23.0,1.0,3.0,1.276,
24.0,2.0,3.0,4.669,
         4.0,1.143,
25.0,2.0,3.0,7.366,
         4.0,0.7366,
26.0,1.0,6.0,1.0,
27.0,1.0,4.0,8.0,
24*0.0
1/prop/specs def. 21 series
11
32.0,3.0,1.0,0.0,0.0,0.5,
33.0,3.0,0.5,0.0,0.0,0.5,
34.0,4.0,4.572,0.0,0.0,0.0,
35.0,3.0,4.669,0.0,0.0,0.0,
36.0,4.0,2.946,0.0,0.0,0.0,
37.0,3.0,7.366,0.0,0.0,0.0,
38.0,3.0,0.3,0.2,0.2,0.5,
39.0,1.0,1.0,0.2,1.0,0.5,
40.0,3.0,0.35,0.83,0.45,0.0,
41.0,3.0,0.35,0.83,0.45,1.0,
42.0,1.0,1.0,0.8,1.0,0.5,
84*0.0
1/prop/specs def. 31 fuel assembly
1
45.0,3.0,0.9484,1.072,1.430,0.0209,0.1150,0.8,0.95,
141*0.0
1/prop/index
158,332
1,1,2,47,2,30,1,1,1,
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2,24,2,47,30,30,3,51,39,1,1,2,1,
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2,24,28,28,5,26,1,4,5,
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2,4,28,28,5,26,2,12,6,15,6,
5,5,22,27,5,26,2,14,6,16,6,
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sst
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nodular cast iron
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air
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epoxy (not used)
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