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2D and 3D Thermal Simulations for Storage Systems with Internal Natural Convection for Canistered Spent Fuel

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1. Introduction

In the US, the number of nuclear plants expected to implement on-site dry storage is increasing each year. As reactors burn advanced fuel assemblies to higher burnups, the dry storage systems will be required to accommodate higher heat loads. This is due to the increasing capacity of the systems and the need to store higher burnup fuel with reasonable cooling periods (i.e., five to six years). As the storage systems heat rejection design must be passive, natural convection is an efficient means for rejection of heat from the spent fuel to the surface of the canister boundary. The design presented in this paper is a canistered system that employs conduction, radiation and convection to reject heat from the canister, which is stored in a vertical concrete cask. The canister containing the spent fuel in this design is a right circular stainless steel vessel capable of storing 37 PWR fuel assemblies with a total canister heat load of 40 kW.

Accompanying any design effort is the use of a numerical methodology that can accurately predict the peak-clad temperatures of the fuel and the structural components of the system. The main challenge to any analysis employing internal natural convection may be perceived as a practical limitation due to the size of the model. Since canisters are typically cylindrical, a two-dimensional model can be used to represent the canister. The fuel basket structure, which maintains the configuration of the spent fuel, is an array of square tubes, and is non-axisymmetric. Flow up through the fuel region in the basket encounters a complex cross section due to the fuel assembly rod array (up to 17×17). The flow region of the heated gas down the outside of the basket in the annulus between the canister shell and the basket assembly (downcomer) is also an irregular shaped area. To confirm that a two-dimensional (2D) modelling methodology is appropriate, a benchmark using results from a thermal test is required. The thermal test focuses on the accuracy of the simulation internal to the canister. The actual design of a canistered system inside a concrete cask requires additional modelling effort, since the flow along the external surface of the canister must be included. The target design, however, employs a nonuniform heating of the PWR fuel assemblies, which permits the heat load of an individual PWR assembly to range from .88 kW to 1.35 kW in a zoned configuration. As nonuniform loading adds more complication to the 2D model, an additional confirmation of the 2D modelling methodology may be obtained by performing a three-dimensional (3D) simulation of a simplified version of the target design.

2. Thermal Benchmark

Thermal testing was performed for a vertical metal cask containing 24 PWR (15×15 rod array) assemblies with a total heat load of 20.6 kW at the Idaho National Engineering Laboratory and documented in [1]. The variation of the heat loads between the assemblies was less than 6%, which can be approximated as a uniform heat load. The internal fuel basket was comprised of an array of 24 square slots constructed of aluminum. The test of interest for this evaluation was the test corresponding to vertical orientation of the cask in which the cask was backfilled with nitrogen. Axial profiles of the temperature data were obtained in the tests for the inner surface of the cask, as well as for various radial locations on the basket.

The two-dimensional axisymmetric model incorporates the cask inner surface axial temperature profile from the test as the boundary conditions for the model. The regions of the 2D model for the test are shown in Figure 1. Regions 2 through 5 comprise the full length of the basket. Regions 2 through 4 represent the fuel in the basket, and Region 3 corresponds to the 144-inch active fuel region. The heat generation applied in this region corresponds to the power distribution with a 1.2 peaking factor as identified in the physical test heat load [1]. Region 5 is considered to be within the length of the basket, but outside the length of the fuel assembly. Regions 1,6 and 7 correspond to the backfill gas, nitrogen. The backfill gas is modeled as an ideal gas and all regions in the model utilized laminar flow conditions. The pressure reported from the thermal test at steady state conditions was applied as the operating conditions for the nitrogen. Model generation and simulations were performed using FLUENT [2].

For the regions corresponding to the basket, two types of effective properties are employed in the analysis. To model the flow resistance of the fuel rods and the fuel assembly grids, the porous media option in FLUENT is used. This option permits the effect of the wetted perimeter and reduced flow area due to the fuel rods to be represented as a pressure drop. The methodology for computing the parameters for the porous media is available in the literature [3]. Separate calculations for the porous media input are made for the fuel rods and the fuel assembly grids.

The effective thermal properties for the basket regions are computed using an ANSYS [4] model shown in Figure 2 and follows the methodology presented in [5]. This methodology incorporates the conduction properties of the basket and fuel in the radial and axial directions. Additionally, it includes the contribution of radiation within the fuel region and from the fuel to the walls of the basket. The thermal test model contains an aluminum basket and the fuel regions, which are modeled with homogeneous orthotropic thermal conductivities. To determine the temperature-dependent effective thermal conductivity of the basket region, a series of temperatures is applied to the boundary of the model in Figure 2. Solutions for each boundary condition determine the maximum temperature of the basket and the associated change in temperature from the boundary to the maximum temperature location. These data are used to compute the temperature dependent effective thermal conductivity. Axial properties are based on component thermal conductivity weighted averaging.

For Region 7 (the downcomer) effective properties are not required and radiation across Region 7 is included in the solution using the Discrete Ordinate methodology [2].

The temperature contours calculated by the above model are shown in Figure 3, and the maximum temperature is identified to be 233°C. Data and results from the test reported in [1] recorded a maximum temperature of 232 °C. The solution was repeated using the K-ω turbulence model [2] and the maximum temperature decreased by 27°C indicating that the use of laminar flow model provided the best comparison with the test data. The guidelines for the use of the K-ω turbulent model direct that the y+ parameter must be on the order of unity. Review of this parameter for the converged solution indicated that y+ was unity confirming the acceptability of the analytical model of the boundary layer near the wall.

3. 2D Simulation of a Canistered System in a Concrete Cask

Using the methodology developed for the simulation of the physical thermal test, a model was developed for the target design of a vertical concrete cask storage system containing up to 37 PWR assemblies with a maximum heat load of 40 kW. The heat generation of the assemblies varies from .88 kW to 1.35 kW per assembly in a zoned arrangement with the highest heat loads arranged in an intermediate zone to avoid localized heating at the center of the basket. The schematic for the model is shown in Figure 4. The heat transferred to the inner canister surface from the internal gas flow is rejected into the annulus between the canister and the vertical concrete cask. Air is supplied to the annulus region by four inlets at the base of the cask.

Since the model is axisymmetric, the height of the vents in the model was altered to allow the modeled cross sectional area to correspond to the cross sectional area of the vents in the physical design. The analytical model size increased significantly since the flow of air up the annulus region was included in the model. The backfill gas for the canister is helium at an elevated pressure to permit the helium density to be increased to enhance the buoyancy driven flow. Specifying a pressure for the closed canister region simulated the increased density. The internal flow of helium is simulated using a laminar model. The cell divisions employed in the initial analysis were used as a guideline for the new model. To confirm the acceptability of the cell divisions, a mesh sensitivity study was performed in which the radial density of the cells in the downcomer region was increased by a factor of two, and the peak clad temperature changed by less than 0.5 °C.

The annulus region between the canister and the concrete cask corresponded to air being supplied to the inlets at 38°C (100°F) with a density and pressure corresponding to atmospheric conditions. Film coefficients from [6] and [7] were applied to the surface in conjunction with solar insolance. The flow model employed in the annulus region was the k-ε turbulence model, which has been use in simulation of similar storage system designs [5].

Temperature measurements of operating spent fuel storage systems show acceptable performance of this turbulence model. The Reynolds number computed at the midradius of the annulus region shown in Figure 5 provides further confirmation validating the use of a turbulent model. Using the average gas temperature in the annulus, a Rayleigh number [7] of 3×10^{11} was computed which is two orders of magnitude above the threshold value associated with turbulent flow and natural convection from vertical surfaces [8]. The velocity profile across the annulus corresponds to the typical trapezoidal profile for turbulent flow and the y+ parameter controls acceptable performance for the analytical model. Values of y+ determined using the converged solution were observed to be acceptable over the active fuel region, thus confirming the adequacy of the cell size adjacent to the wall.

The temperature results for the 38°C (100°F) ambient condition produced a temperature profile very similar to that of Figure 3 with a maximum temperature of 356°C. Velocity contours are shown in Figure 6 where the change in the direction of the flow near the base corresponds to the increased Reynolds number presented in Figure 5.

System performance is evaluated relative to helium pressure to define system sensitivity of the peak-clad temperature. Additional solutions were generated using lower canister pressures. At 75% of the helium pressure that produced the 356°C peak clad temperature, the clad temperature increased to 390 °C. Additional decrease in the pressure showed an increase in the peak clad temperature. The relationship of the temperature to the pressure is nonlinear such that at higher pressures, such as 8 atm (103 psig), the corresponding increase in pressure did not result in a commensurate decrease in the clad temperature. This behaviour is expected as the external flow, which provides the means to reject heat into the ambient, is relatively insensitive to the velocity of the helium internal to the canister. Consequently, as the pressure is increased, the ability to reject heat to the ambient is still limited by the annulus flow, which results in a decreased affect of the helium buoyancy on the peak-clad temperature.

To confirm the adequacy of the thermal test for use with an increased heat load and with the change in the basket design, a Rayleigh number was computed for the 37 PWR assembly design and the thermal benchmark. An average gas temperature was used to evaluate the gas properties. The temperature difference for the Rayleigh number was taken to be the difference between the maximum centerline temperature and the minimum downcomer temperature. With the increased heat load, the use of this difference would tend to over estimate the Rayleigh number for the 37 PWR assembly design. Using these parameters, the Rayleigh number for the PWR 37 assembly design and the thermal test were computed to be 2×10^{11} and 4.3×10^{11}, respectively. Even though the temperature difference is larger for the higher heat load, the properties of the backfill gas resulted in a larger value for Rayleigh number. This provides additional confirmation of the acceptability of using the thermal test [1] to provide guidance in the thermal simulation of storage systems utilizing internal convection heat transfer in the canister.

4. 3D Simulation of a Canistered System

A 3D model was generated corresponding to the 37 PWR assembly design. To maintain a reasonable model size, a 1/8 th symmetry model was generated including specified simplifications. While the model corresponding to Figure 4 included both the canister and the concrete cask, the 3D model only considers the canister and its internals. The film coefficients computed in the 2D model were applied as a boundary condition to the 3D model. The 3D model included two important features. The first feature was that each fuel assembly region was modeled explicitly, which allowed the effect of the nonuniform heat load to be observed directly. In this approach, the axial power distribution, as well as the nonuniformity in the radial direction, is taken into account in the simulation. Secondly, the carbon steel fuel basket structure was modeled explicitly as shown in Figure 7. To account for the resistance of the individual fuel rods and grid assemblies, the porous media option was used to represent the fuel inside each basket location. The methodology employed for the calculation of the porous media option in the previous two models was utilized. The effective thermal properties corresponding to the fuel were recomputed. The other conditions for the specification of the laminar flow and the pressure condition followed that of the previous models.

The results of the radial temperature distribution for both the 2D and the 3D model at the elevation of the maximum temperature is shown in Figure 8. The results of the 3D model show a localized temperature increase corresponding to the center of the fuel region, which is typical of heat generation regions. The region of the greatest difference between the 2D and 3D models corresponds to the center of the fuel assemblies with the largest heat load, 1.35 kW per fuel assembly. The center region of the basket, which has the median heat load, shows a minimal discrepancy between the two models. The maximum temperature reported in the 3D and 2D models were 348°C and 346°C, respectively. This difference is minimal based on the differences in the models and leads to a conclusion that the 2D modelling methodology for storage systems including a nonuniform heat load and irregular geometries is acceptable.

5. Conclusions

The use of natural convection to reject heat from the spent fuel storage canister having heat loads in the range of 40 kW has been incorporated into a design for a canister storing 37 PWR fuel assemblies. The methodology utilized to predict the peak-clad temperatures has been evaluated against published results. In comparing the Rayleigh number normally associated with natural convection from the thermal test and the PWR 37 assembly design, the thermal test is considered to be bounding for this application. The modelling methodology included the effect of the additional resistance to flow associated with the large wetted perimeter and the irregular shaped areas of the fuel assemblies and basket structure. The thermal properties of the basket also included both conduction and radiation. The 2D analysis of the system used in the thermal test showed excellent agreement with the reported thermal test data. To confirm the acceptability of the methodology for systems with nonuniform heat loading, an additional series of analyses was performed. A 3D model was generated which employed the same basket design as the 37 PWR assembly design. To ensure an accurate comparison with the 2D modelling methodology, a corresponding 2D model was also generated. Both models incorporated a 40 kW heat load with nonuniform loading. A comparison of the analysis results from both models showed excellent agreement. These evaluations confirmed that the use of 2D modelling methodology is acceptable in predicting the peak clad temperatures of the stored fuel assemblies utilizing passive convection heat transfer and nonuniform decay heat distribution.

6. References

[1] EPRI NP-5128, “The TN-24P PWR Spent-Fuel Storage Cask: Testing and Analyses,” Pacific Northwest Laboratory, Virginia Power Company and EG&G, Idaho National Engineering Laboratory, April 1987

[2] FLUENT, Revision 6.1, Fluent Inc, Lebanon, NH, USA

[3] “A Physical Introduction to Fluid Mechanics,” 1st Edition, Alexander J. Smits, 2000.

[4] ANSYS, Revision 6.0, ANSYS INC, Canonsburg, PA, USA

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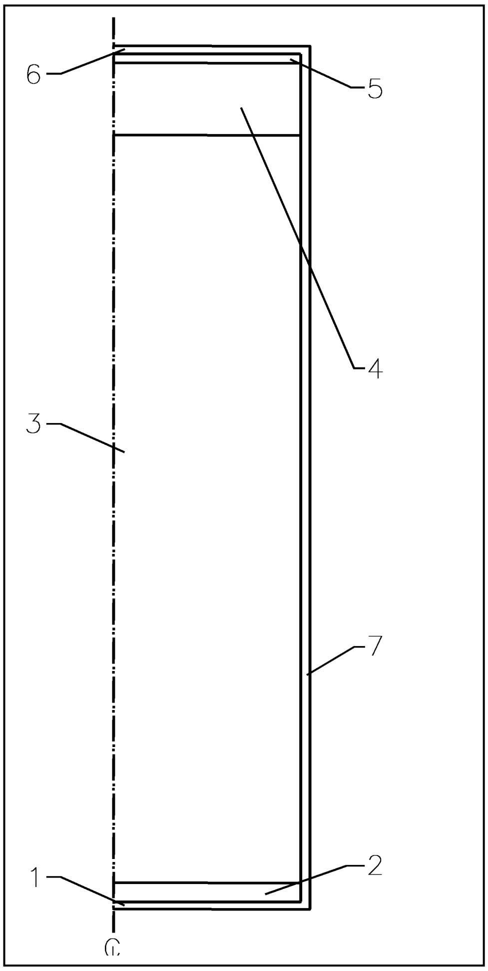
[6] “Principles of Heat Transfer,” Krieth F., Bohn M.S., Fifth Edition, West Publishing Company.

[7] “Fundamentals of Heat and Mass Transfer,” F.P. Incropera and D.P. DeWitt, 1981.

[8] “Convective Heat Transfer”, Second Edition, Louis C. Burmeister, 1993



Region Number	Description
1	Bottom nitrogen region
2	Region below active fuel region in the basket
3	Active fuel region
4	Region above active fuel region in the basket
5	Basket region without fuel
6	Top nitrogen region
7	Equivalent radial gap (downcomer region)

Figure 1. Schematic of the Model for the Thermal Test

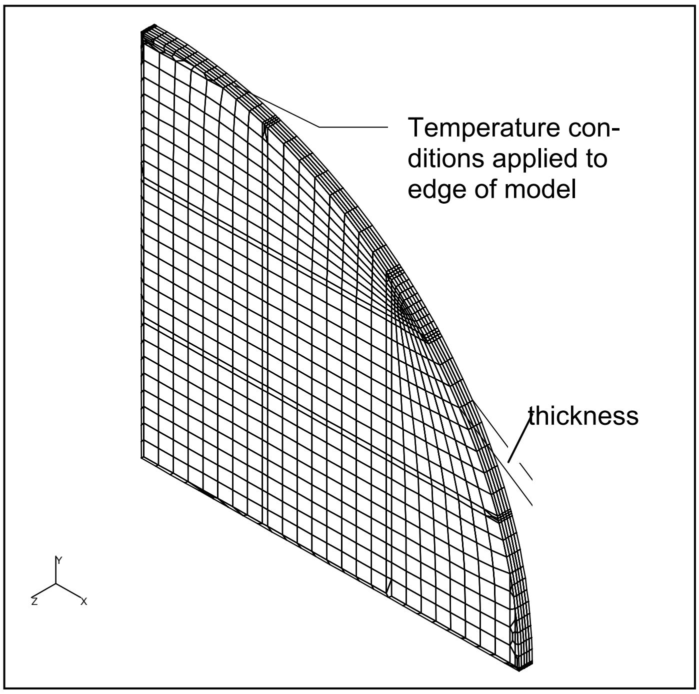


Figure 2. ANSYS Model for the EffectiveThermal Properties Calculation

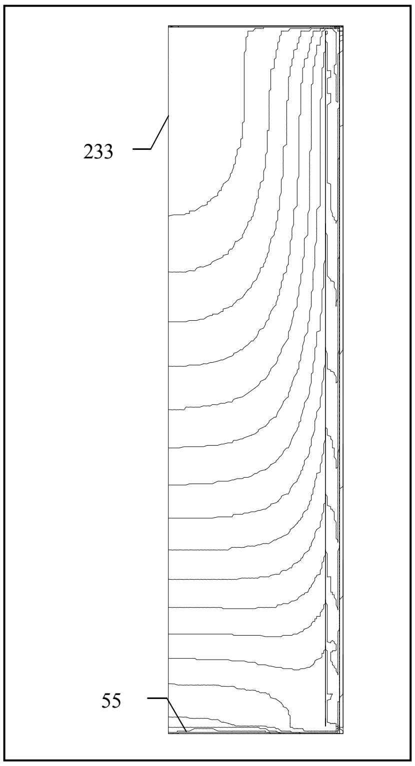


Figure 3. Temperature Contours (°C) for the Analysis of the Thermal Test [1]

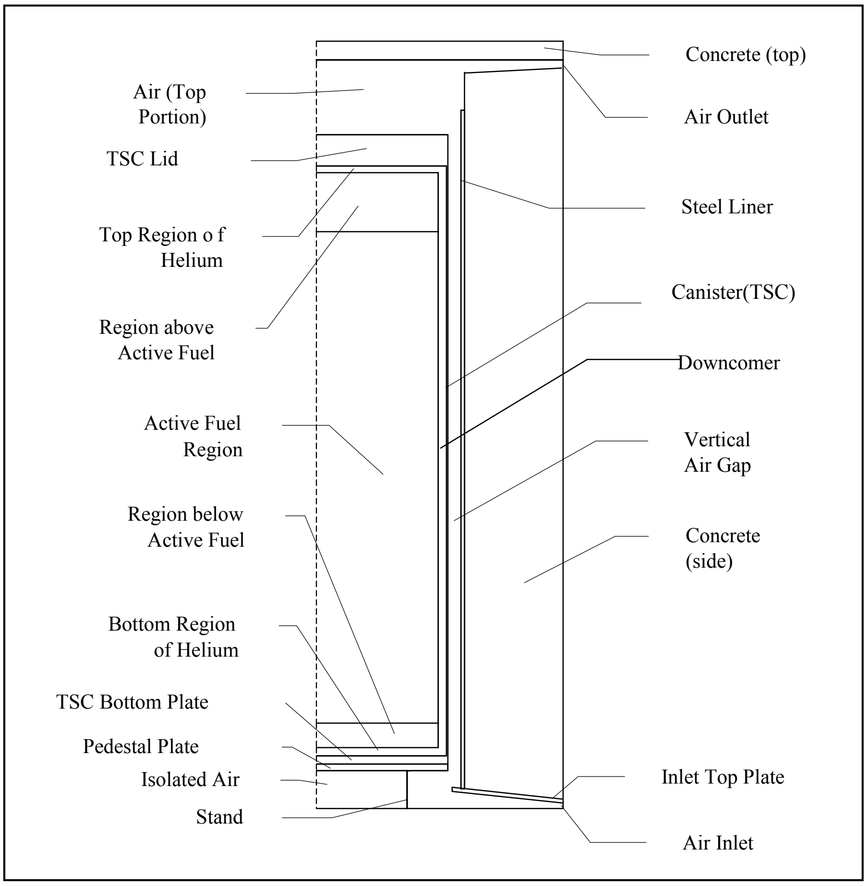


Figure 4. Schematic for the Model of the 37 PWR Fuel Assembly Canister in the Cask

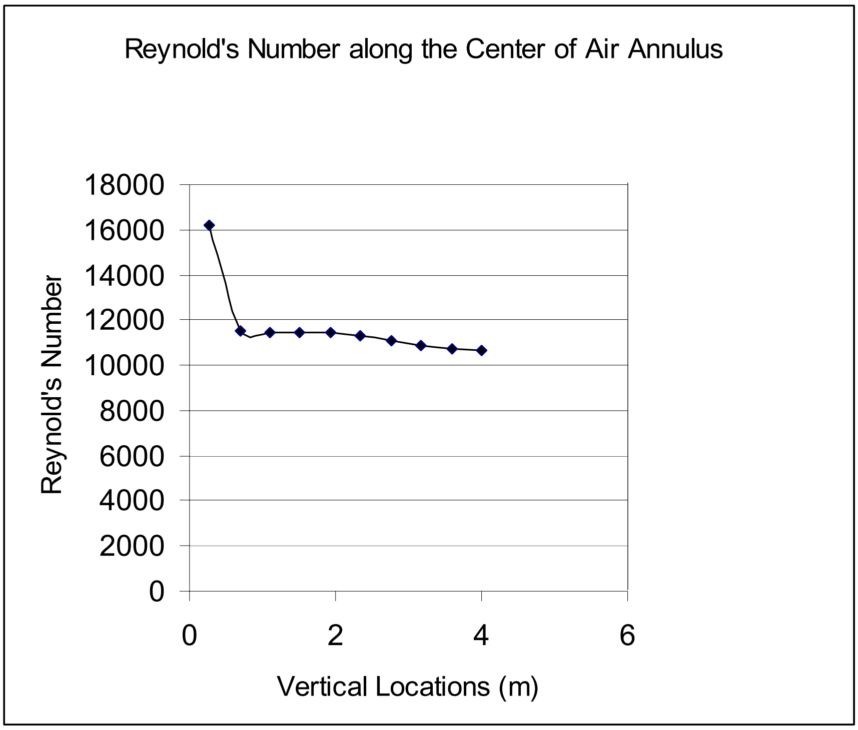


Figure 5 Reynold’s Number at the Radial Mid-Point of the Concrete Cask Annulus

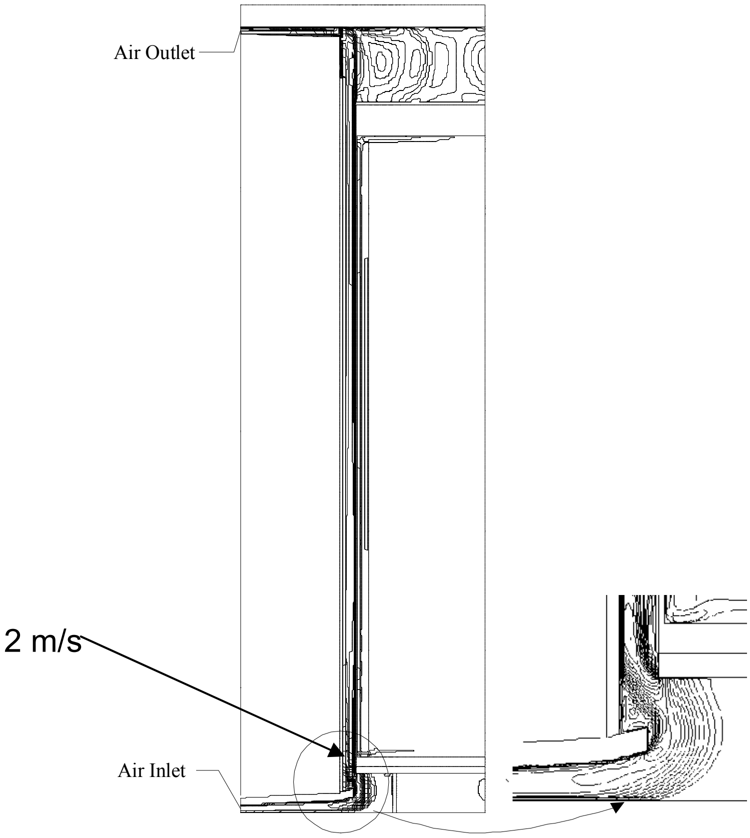
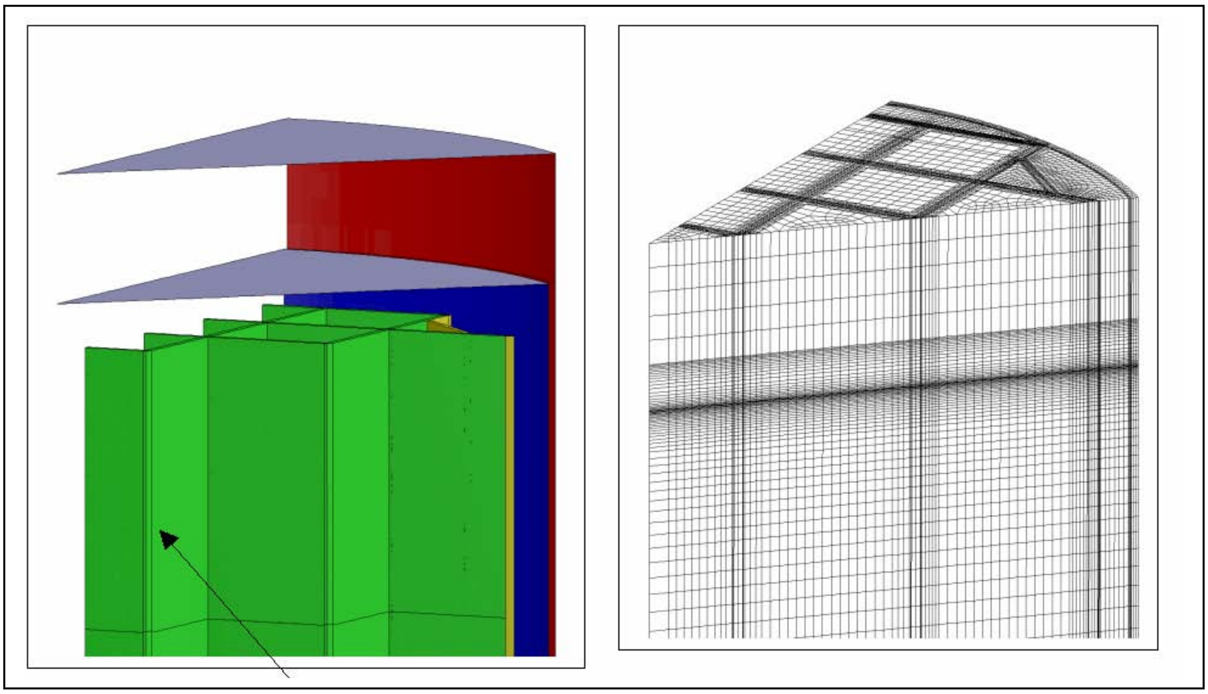


Figure 6 Velocity Contours (m/s) for the 37 PWR Fuel Assembly Design

Figure 6. Velocity Contours (m/s) for the Analysis of the 37 PWR Assembly Design



Basket
Cells for gas, closure lid and fuel
are not shown

Complete mesh for the 3D model

Figure 7 3D Fluid Flow Model for the 37 PWR Assembly Design

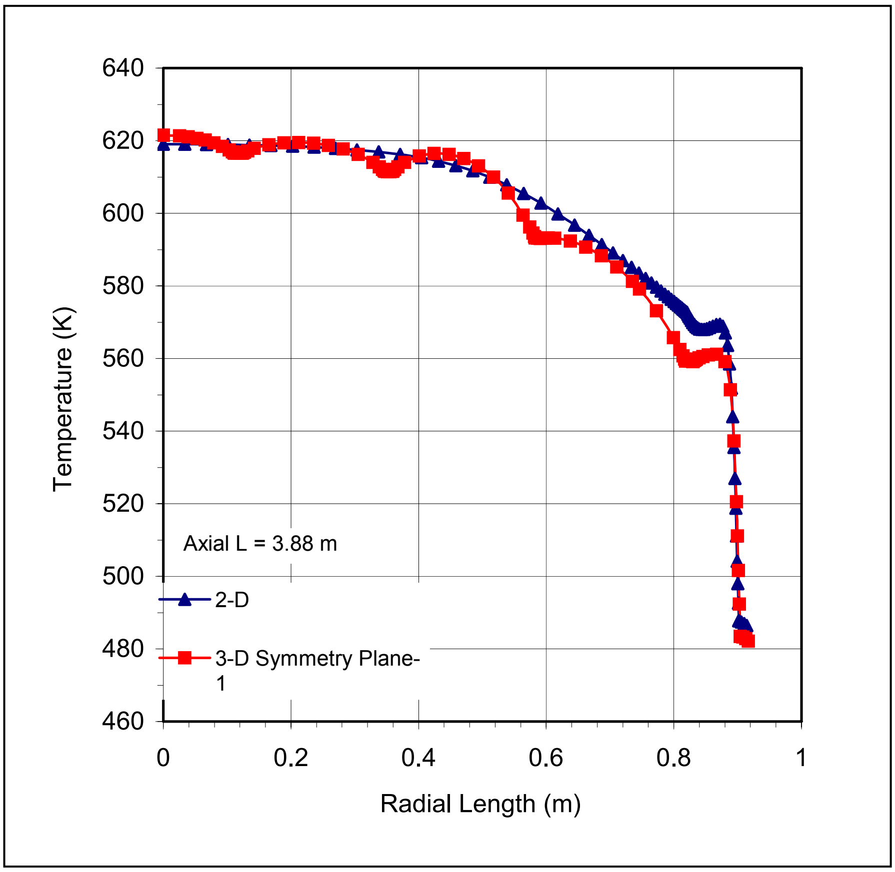


Figure 8 Comparision of the Radial Temperature Profile for the 2D and 3D Models