THERMAL EVALUATION OF LOADING AND DRYING OPERATIONS OF A HIGH CAPACITY SPENT FUEL STORAGE CANISTER

Mike Yaksh, Ph.D., PE
NAC International INC
Norcross GA

Christine Wang, PhD
NAC International
Norcross GA

ABSTRACT

Higher capacity designs for storage of spent fuel provide an advantage of ALARA during loading operations and optimal use of space on the storage location. In this paper the thermal analyses for a transfer system to store 87 BWR fuel assemblies are presented. The assemblies are stored in a welded canister whose fuel assembly's positions are maintained by a non-welded basket configuration. The operations to complete the drying operations and to move the canister with in the plant employs a shielded transfer cask which also uses a cooling system to remove heat from the system. Heat rejection internal to the canister is primarily accomplished by natural convection, and heat rejection from the canister surface uses circulating water. Two separate thermal analysis models are employed for this evaluation. During the drying phase, a detailed three-dimensional model of the basket and canister determines the transient thermal response of the fuel. This defines the duration of the vacuum drying cycle. Segments of the operation permit the helium backfill in the canister to reject heat by convection from the fuel assembly to the canister surface. This is simulated using a two-dimensional CFD model which incorporates porous media modeling to represent the hydraulic resistance of the fuel rods and fuel assembly grids. Certain transient conditions require the results of the three-dimensional conduction model to define the initial conditions of the two-dimensional CFD transient model. The simulation methodology makes efficient use of both technologies to determine the thermal response of the system for all operational conditions. The results confirm that the maximum component temperatures remain within their allowable temperatures.

INTRODUCTION

Preparation of fuel for dry storage in a canistered system requires that the fuel be subjected to a drying process. Vacuum drying is commonly used to remove moisture from the fuel once the fuel has been loaded into a canister. The canister is a stainless steel right circular cylinder with a stainless steel lid that is approximately 230 mm thick. This lid thickness is required to minimize the radiation dose to personnel during the welding process of the lid to the canister. With in the canister the fuel position is maintained by a non welded basket which is comprised of an array of 87 cells which are defined by 45 tubes. Further details on the basket design can be found in Ref 1. Radiation protection and movement of the canister is accomplished with a shielded transfer cask. Since the fuel is loaded into the canister under water, the canister is filled with water when the lid is positioned onto the canister. The welding process requires that transfer cask be moved to allow access to the lid above the water level of the pool. Upon completion of the lid welding process, water is removed from the canister to initiate the vacuum drying process. Water is removed by purging the canister with helium followed by evacuation of the canister cavity to a pressure less than 10 Torr. Dryness verification is confirmed by isolating the vacuum pump and verifying that the pressure remains less than 10 Torr. The fuel of interest in this paper is BWR fuel having a maximum heat load of 33kW. There is a range of heat loads in which time limits of the drying operation are not required to maintain the fuel clad below 400°C (Ref 2). For heat loads approaching 33 kW, vacuum drying time limits are required to maintain the fuel clad temperatures less than 400°C. In such cases, the fuel must be subjected to a period of cooling prior to being subjected to an additional vacuum drying cycle, it is needed. During the vacuum drying, heat is rejected from the fuel to the canister surface by radiation and conduction. During the cooling cycle the canister is backfilled to 7 Atm of helium which permits the heat to the rejected from the fuel by convection, radiation, and conduction to the canister surface. For both conditions, the heat is rejected from the canister surface by water flowing in the annulus between the canister surface and the inner surface of the transfer cask. The following paper describes the thermal evaluations of the vacuum drying process for a canister containing 87 BWR fuel assemblies.

VACUUM DRYING THERMAL EVALUATION

During the time of vacuum, the heat is rejected from the fuel by radiation and conduction. While helium is present by virtue of the purging process, there is insufficient helium to support any significant convection. An overall view of the thermal finite element model for the vacuum evaluation is shown in Figure 1. ANSYS (Ref 3) is used to generate the model and the transient solutions. This corresponded to a $1/8^{th}$ of the entire cross of the 87 fuel assembly basket. The model reflects the gaps throughout the model, and as shown in Figure 1, this includes a small gap between the individual tubes. The outer surface of the model is the canister shell. Radiation is modeled from the outer surface of the basket tubes to the inner surface of the canister shell using a radiation matrix. The top and bottom surfaces of the model are conservatively assumed to be adiabatic.

In this model, the fuel is represented by temperature dependent effective properties for the conductivity, density and specific heat. A detailed two-dimensional planar model of a 10x10 BWR fuel assembly is shown Figure 2. The fuel model uses a radiation matrix methodology to determine the radiation between neighboring pins. The elements between the pins account for any contribution by conduction through the helium. The edge of the BWR fuel model corresponds to the inner surface of the BWR channel and the heat generation is applied to the elements representing the fuel pellets. The solution for this model leads to the effective conductivity in the X-Y plane (Figure 1). A separate set of effective thermal properties accounts for the heat rejection path from the BWR fuel assembly channel, intervening gaps, neutron absorber sheets to the inner surface of the tube.

A temperature boundary condition is applied to the outside of the canister shell which conservatively bounds the canister shell temperature in the transient condition. The heat generation is applied to the elements representing the fuel and the axial power distribution corresponds to that of a BWR fuel assembly with the maximum power density factor of 1.22.

The thermal transient evaluation was continued to steady state or until the maximum allowable clad temperature was reached. Figure 3 shows that the heat load of 29 kW permits in an indefinite time for the vacuum drying condition and at the maximum heat load of 33 kW, the time in vacuum must be limited to 35 hours.

COOLING EVALUATION

The objective of the thermal cooling evaluation was to identify the time to reduce the fuel clad temperatures to a level to allow the vacuum condition to be restarted, if required. The cooling process is initiated when the canister is backfilled to 7 Atm of helium. At this pressure, the density is increased to permit convection to be a significant heat rejection mode. The flow path of the helium is vertically up though the basket cells containing the fuel into the plenum region at the top of the canister. The heated gas then flows into the down comer which is the region of the canister volume outside the tubes and the heat is rejected through the canister shell to the water flowing in the annulus region. The plenum region at the bottom of the canister allows the gas from the down comers to be circulated back up through the tubes.

For the BWR fuel assembly, it is possible for the gas to flow inside the channel surrounding the fuel rods as well as outside the channel, but inside the wall defining the cell of the fuel. The approach employed here conservatively neglected the convection gas flow in the cell outside the channel. Helium is assumed to flow only internally to the channel surrounding the fuel rods. The flow restrictions up through the fuel are associated with the fuel rods and the fuel assembly grids. Instead of generating a detailed model for all the fuel rods which could be larger than 8,000 fuel rods, the flow resistance was represented by an orthotropic porous media model in Ref 4. The axial value for the porous media corresponded to the flow restrictions of the fuel rods and grid. Two separate models are required to determine the porous media data, which are shown in Figure 4. A quarter three dimensional model is used to determine the flow resistance due to the axial flow parallel to the fuel rods. Another three dimensional model is required for the fuel grid. Since these flow restrictions occurred in a serial manner, they are combined to determine the effective porous constant over the length of the fuel assembly.

In addition to representing vertical movement of the helium, the orthotropic properties can also be used to represent the radial conductance associated with conduction and radiation. A cross section of the model shown in Figure 1 was used to compute the orthotropic properties for conductivity corresponding to the region of the cells. The results from the porous calculations and thermal conductivities modeling were combined into a two-dimensional axisymmetric Fluent model of the fuel, basket, canister, and transfer cask shown in Figure 5. The gas flow internal to the canister and in the water annulus region (between the canister shell and the inner surface of the transfer cask) is modeled as being laminar. The walls of the transfer cask is comprised of a series of shells; carbon steel inner shell, NS4FR (polymer for neutron shielding), lead (gamma shielding) and the outer carbon steel shell. These were combined into a single effective orthotropic conductivity. The boundary condition for the outside of the transfer cask was the specification of a film coefficient for vertical plates. A film coefficient is also specified for the top of the canister lid, since it is a heated surface facing upward. Solar insolance is not applied to any surface since the operations are performed inside a building. The remaining boundary condition for the model is the water annulus inlet temperature specification of 100°F.

To perform the thermal transient using the axisymmetric model in Figure 5, a set of initial conditions is needed. The cooling operation is initiated after the system has reached it maximum temperature achieved during the vacuum condition. Consequently, the temperature varies through out the model in the axial, radial and circumferential directions (in Figure 1). The transient temperature distribution for the vacuum condition was determined using the model in Figure 1 which is a three dimensional model ANSYS model. To be consistent with the axisymmetric model in Figure 5, the temperatures from the last time step in the three dimensional model transient was mapped into the two dimensional Fluent model. To determine the location of the points of interest in the two dimensional Fluent model, the cell location data of the Fluent model was written to an ASCII file. ANSYS Parametric Design Language (APDL) was used to read these locations and determine an average temperature along a circumferential path corresponding to the radial and axial location in the Fluent model. APDL was then used to write the initial conditions at each cell location for Fluent to be used as the initial condition in the Fluent model.

Two system heat loads are evaluated using this methodology for 25 kW and 33 kW. This required that the ANSYS three dimensional model be first used to determine the maximum temperature of the model each of these heat loads. The maximum temperatures from the ANSYS model were then mapped into the Fluent model as the initial conditions. The Fluent thermal transient was then solved until steady state conditions were obtained.

The time histories for the maximum fuel clad temperatures are shown in Figure 6 for the 25kW and 33 kW cases. The additional 8 kW in the 33 kW case continues to increase the fuel clad temperature for an additional six hours due to the increased level of heat and the gradual increase of heat rejection by the helium convection inside the canister. This implies that the maximum system temperature may occur not during vacuum, but at some time during the cooling process. For both cases, the time to reach near steady state conditions is approximately 35 hours. At this time, the system could be subjected to another drying cycle if required.

CONCLUSIONS

Processing of fuel for dry storage requires that the moisture from the fuel be removed. During the vacuum drying and subsequent cooling of a canistered fuel system, it is necessary to confirm that the maximum fuel clad remains with the allowable temperature. A methodology has been described in this paper which used a three dimensional model to determine the maximum clad temperature for the vacuum evaluation. To reduce the fuel clad temperature, cooling is achieved by using convection with helium, and the evaluation of the system response was accomplished using a two dimensional model incorporating the flow resistance using a porous media model. A unique method was employed to map the three dimensional results into the initial conditions of the two dimensional model. The results confirm that the clad temperatures remained less than the 400°C through out the entire process.

REFERENCES

Ref 1 - MAGNASTOR Final Safety Analysis Report, Revision 0, NAC International, Norcross GA

Ref 2 - ISG-11, Revision 3 – “Cladding Considerations for the Transportation and Storage of Spent Fuel,” US Nuclear Regulatory Commission, Washington, DC, November 17, 2003.

Ref 3 - ANSYS Revision 10, ANSYS INC, Canonsburg PA, USA

Ref 4 - FLUENT, Revision 6.1, Fluent Inc, Lebanon, NH.

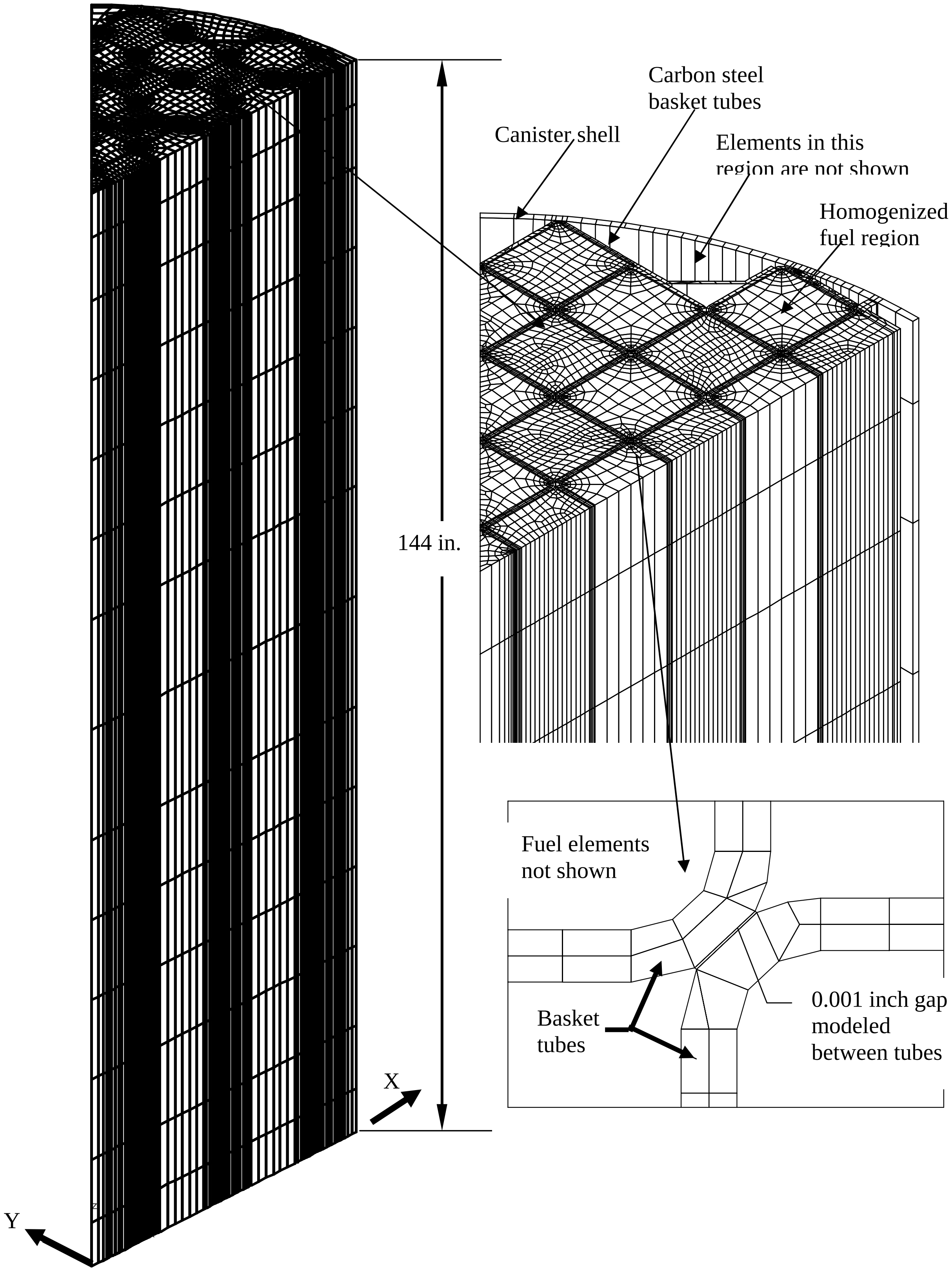

Figure 1 - Overall View of Canister Thermal Model

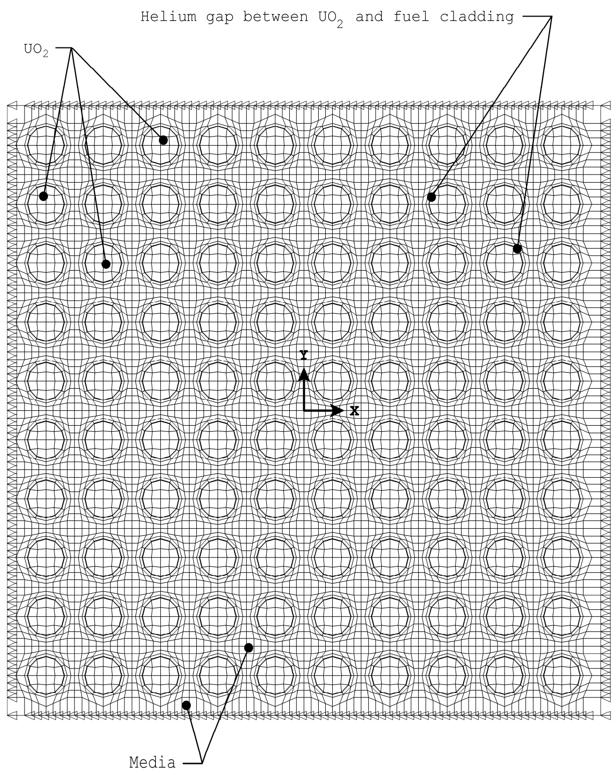

Figure 2 - Detailed Planar Model of a BWR 10x10 Fuel Assembly

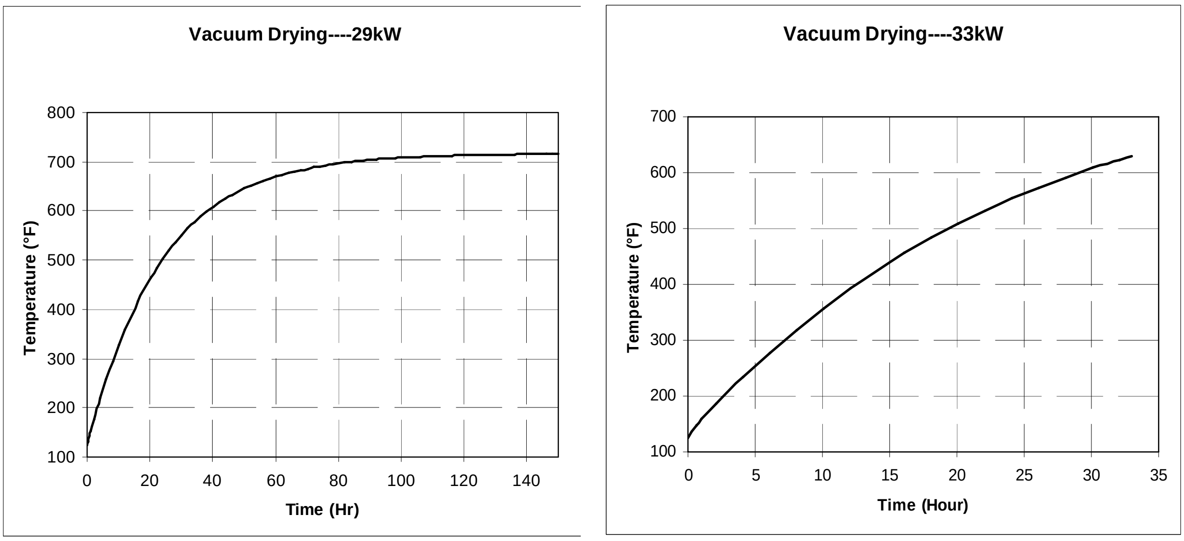

Figure 3 - Vacuum Drying Maximum Fuel Clad Temperature (ºF) for 29kW and 33 kW Cases

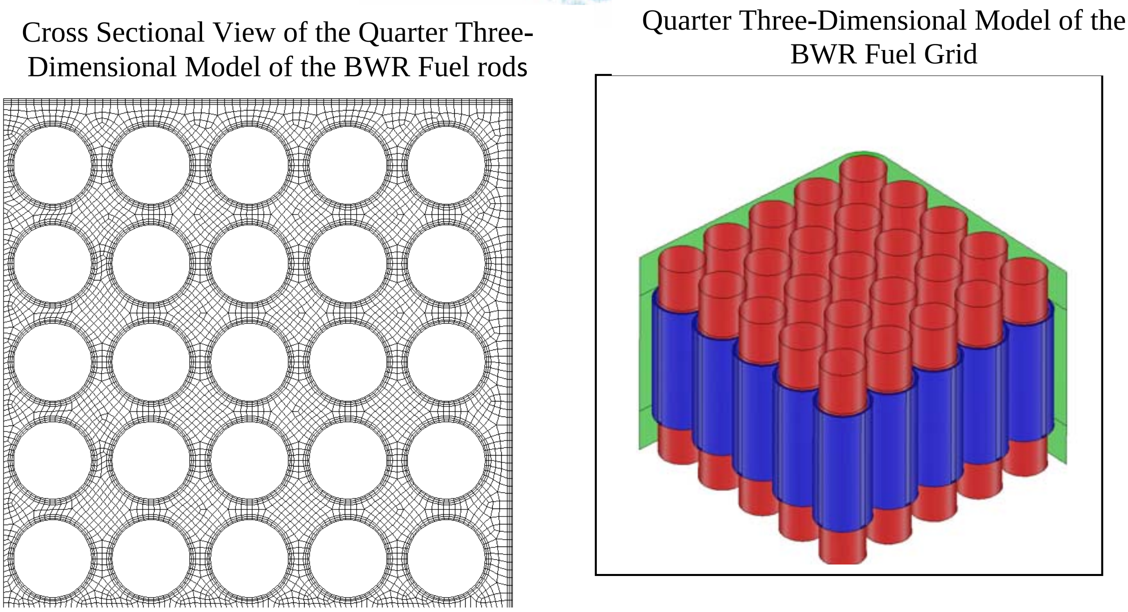

Figure 4 - CFD Models for the Porous Media Determination for the Fuel Rods and Fuel Grids

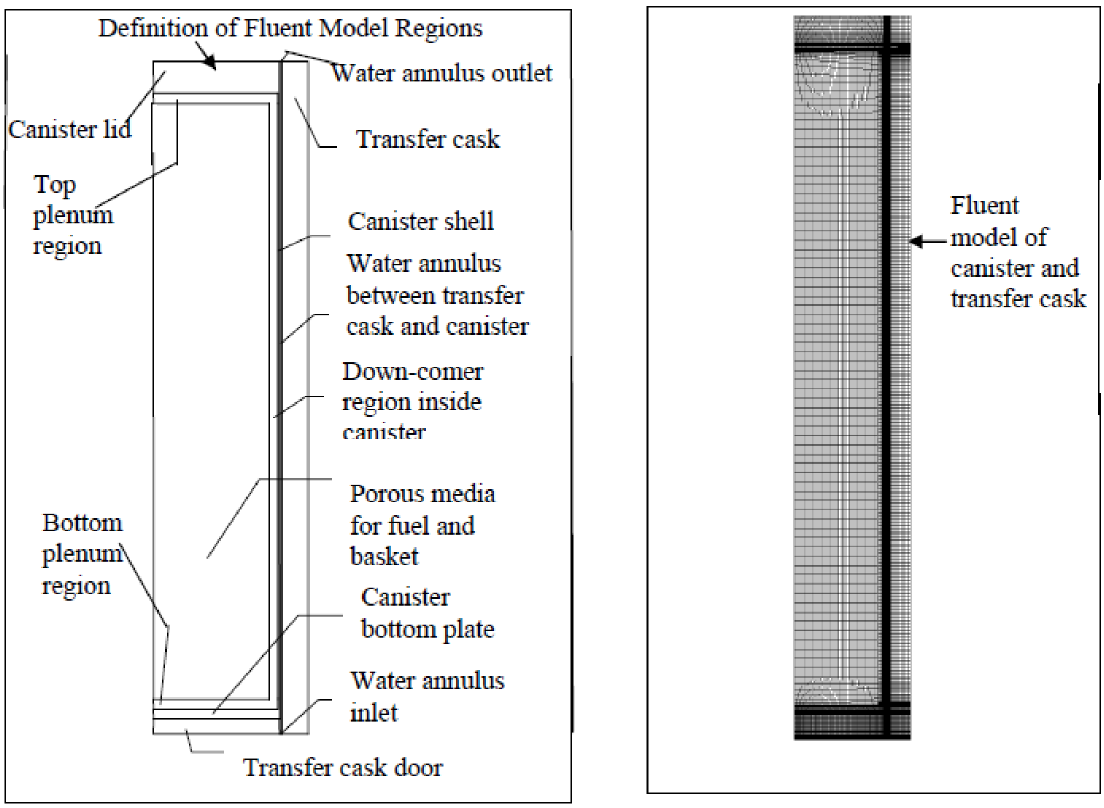

Figure 5 - Two-Dimensional Fluent Model for Loaded Canister and Transfer Cask

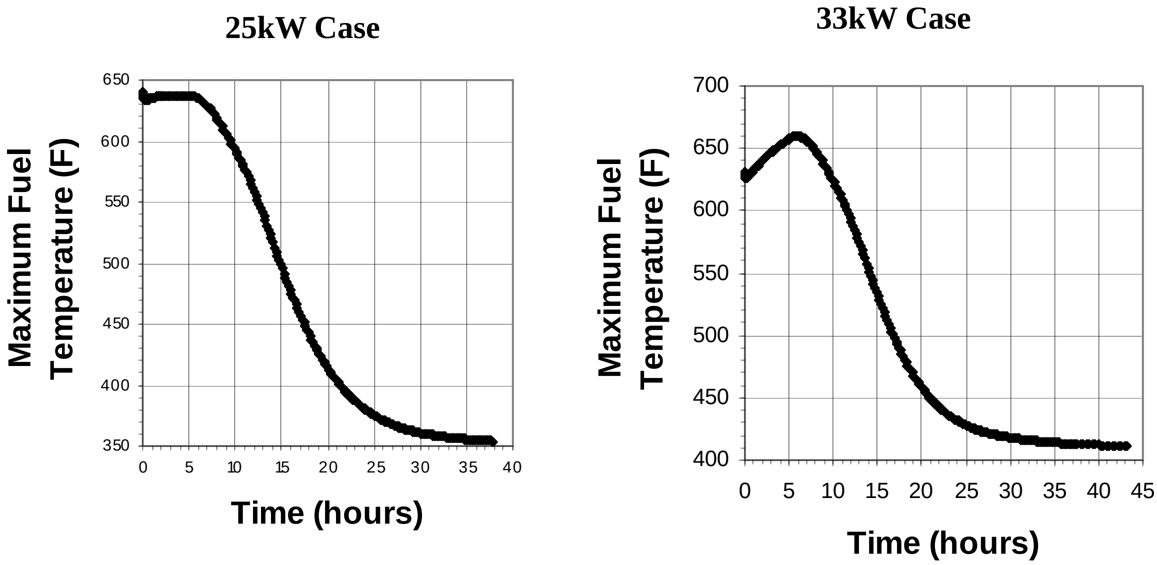

Figure 6 -Cooling Phase Maximum Fuel Clad Temperature (ºF) for 25 kW and 33 kW Cases