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ANALYSIS OF A HYPOTHETICAL PARTIAL LOSS-OF-COOLANT ACCIDENT IN THE UNIVERSITY OF WISCONSIN TRIGA-FUELED RESEARCH REACTOR

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ABSTRACT

A hypothetical partial loss-of-coolant accident in the University of Wisconsin TRIGA-fueled research reactor is analyzed with the aid of a computational fluid dynamics (CFD) code. Because the vessel breach is assumed to be in a beam tube, water blocks the flow of air through the reactor inlet plenum. Decay heat is removed from the fuel rods by conduction to the water, which boils water and produces steam, and to the flowing steam. An axially-symmetric CFD model of the hottest fuel rod and its associated coolant is described. A peak fuel temperature of 578° C is predicted and is sufficiently low to preclude fuel failure. A simple approximate model is developed and used to demonstrate the reasonableness of the CFD peak temperature results.

1. Introduction

1.1 Description of a Partial Loss-of-Coolant Accident

A loss-of-coolant accident (LOCA) in a water-cooled research reactor in an open reactor vessel is an upset that is initiated by a leak in the reactor pool or tank. The reactor is shutdown by a scram initiated by a low water level trip when the level is a considerable distance above the top of the fuel. The analysis focuses on demonstrating that the decay heat can be removed by passive means without allowing fuel temperatures to reach values that cause clad failure.

If the water drains completely, then cooling is largely accomplished by air flowing upward through the fuel coolant channels in place of the water and the accident is considered to be a complete LOCA. In a partial LOCA, because of the location of the

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inlet plenum. Cooling of the fuel in the partial LOCA is accomplished by heat conduction to the water which generates steam that flow through the reactor coolant channels and provides additional cooling before exiting the top of the open vessel.

A beam tube failure is a potential cause of a partial LOCA. Beam tubes are horizontal tubes that traverse the reactor vessel and connect the periphery of the core to the reactor wall. Experiments can be performed using the emergent neutron beams.

1.2 The University of Wisconsin Nuclear Reactor (UWNR)

The UWNR is a pool-type TRIGA-fueled reactor with 83 low-enriched-uranium (LEU) fuel rods. The reactor was constructed as a plate-type Material Test Reactor (MTR) and subsequently was converted to a TRIGA-fueled reactor with a highly-enriched uranium (HEU) core. Recently, the HEU core was replaced with an LEU core. An idealized (not-to-scale) sketch of the cross section of a fuel rod is included in Figure 1. Each fuel rod is 30 inches long, including the end fittings. The fuel meat is 15 inches long. The rod diameter is 1.411 inches. Although the end fittings have a smaller diameter, in the figure they are shown with the same diameter. The clad thickness is 0.020 inches. There is a very small radial gap or a contact resistance between the fuel and the clad and a larger radial gap between each reflector and its adjacent clad. There is also a 1/8th-inch horizontal gap between the top of the upper reflector and the bottom of the upper end fitting. The maximum licensed power is 1.0 MW. The highest power rod produces 19.7 kW, which includes a 2% uncertainty on measured power. The fuel rods are arranged vertically on a 1.530-inch square pitch. In the conversion from MTR fuel to TRIGA fuel, each MTR fuel plate assembly was replaced with a 2-by-2 4-rod cluster. The pool surface area is about 85 ft^2.

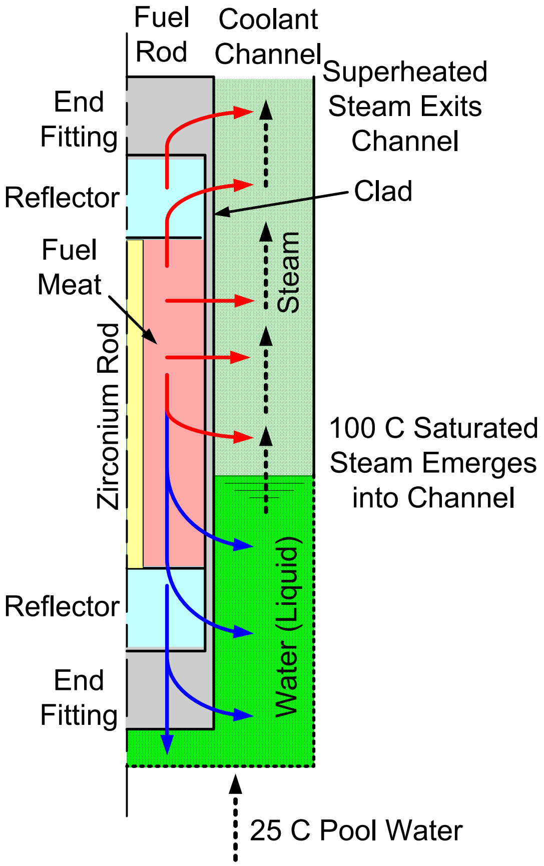

Figure 1 – Fuel Rod Conceptual Model for Decay Heat Removal

1.3 Fuel Temperature Limit

The maximum fuel temperatures during a LOCA must be sufficiently low to prevent clad failure. During a LOCA, the relatively poor heat transfer to the flowing air at the exposed surfaces of the clad cause the clad temperatures to approach those of the adjacent fuel. As is well known, uranium forms eutectics with iron and nickel at temperatures near 700° C. Therefore, it is possible that the formation of eutectics between uranium and the constituents of the Type 304 stainless steel clad, which are mostly iron and nickel, could lead to a safety limit in which the maximum fuel surface temperature is 700° C. [1],[2]

2. Analysis

2.1 Sequence of Events for a Hypothetical Partial LOCA

Figure 2 shows the sequence of events, A through D, for a hypothetical partial LOCA. The reactor is assumed to be operating at normal steady-state conditions when a beam tube leak occurs (Sequence A). Normal reactor operation continues except for the gradual decrease in water level, until a reactor scram occurs due to low water level – 19 feet above the core in the UWNR (Sequence B). The power rapidly decreases to decay power levels of about 6% of full power, while good natural circulation cooling remains unabated. This causes the core temperatures to approach that of the reactor coolant inlet. As the water level approaches the tops of the fuel rod (Sequence C) the good natural circulation flow of the reactor coolant is disrupted because the water cannot exit through the top of the reactor and flow to the reactor inlet. Although the good natural convective flow has ended, the heat up of the fuel rods is very slow because the power levels are low and much or all of the fuel is submerged. The water level continues to drop until it reaches the bottom of the leaking beam tube (Sequence D).

2.2 Conceptual Model for Decay Heat Removal from Each Fuel Rod

Since the reactor inlet plenum is always filled with water, it is not possible for air to enter through the inlet plenum and provide natural convective cooling as occurs in a complete LOCA. However, as shown in Figure 1, which represents a fuel rod and its associated adjacent coolant channel, heat is conducted down the rod and into the water, as

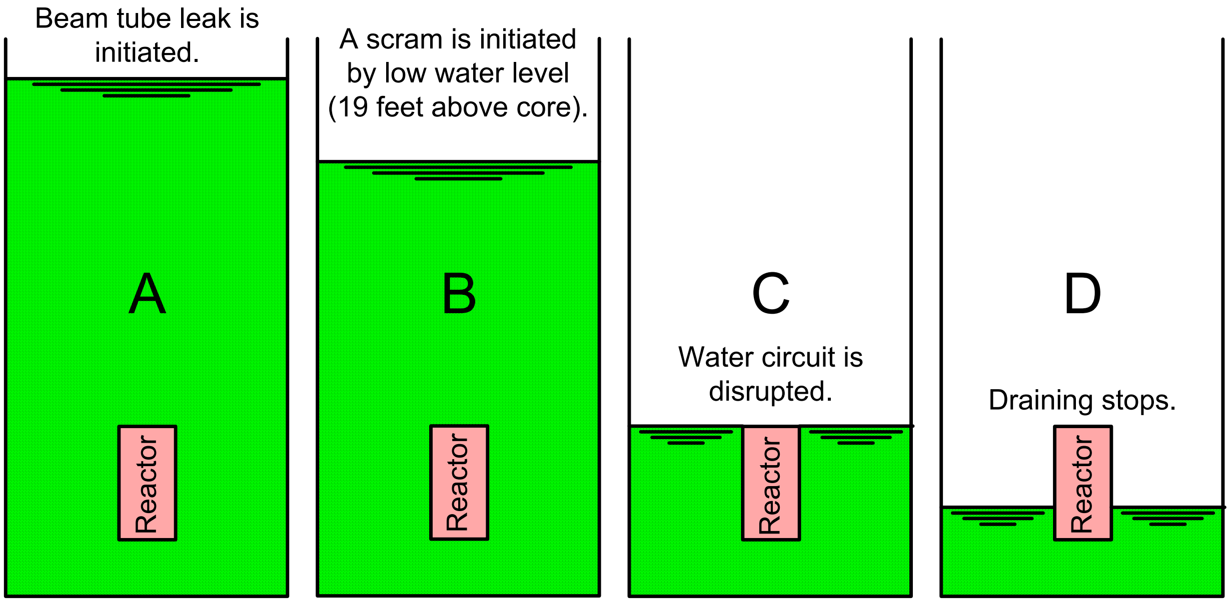

Figure 2 – Sequence for Hypothetical Partial Loss-of-Coolant Accident

indicated by the blue arrows. Boiling on the submerged surface of the rod produces saturated steam, which flows up the surrounding coolant channel. Heat from the fuel rod is also transferred directly to the flowing steam, as indicated by the red arrows, and superheats the flowing steam.

At any instant in time, the amount of steam produced is assumed to be proportional to the power removed from the submerged surface of the rod. This power is determined by integrating the heat flux over the submerged surface of the rod. The pool water is taken to be at 25° C. Seventy-five calories are required to raise 1 gram of water 75° C to the saturation temperature of 100° C. An additional 539 calories are required to convert 1 gram of saturated liquid water to saturated steam. Thus, for every 614 (75 + 539) calories of energy transferred from the submerged surface of the rod 1 gram of saturated steam is assumed to appear at the surface of the water level and flow up the channel.

2.3 Model for Computational Fluid Dynamics (CFD) Analysis

The core cross sectional area was treated as if it were an infinite array of square cells, each with a fuel rod at its center. As a further approximation, the coolant cross sectional area of each cell was modeled as a concentric annulus of the same flow area as the original cell. This allowed a two-dimensional axially-symmetric model of a single cell, Figure 3, to be produced in place of a three-dimensional model.

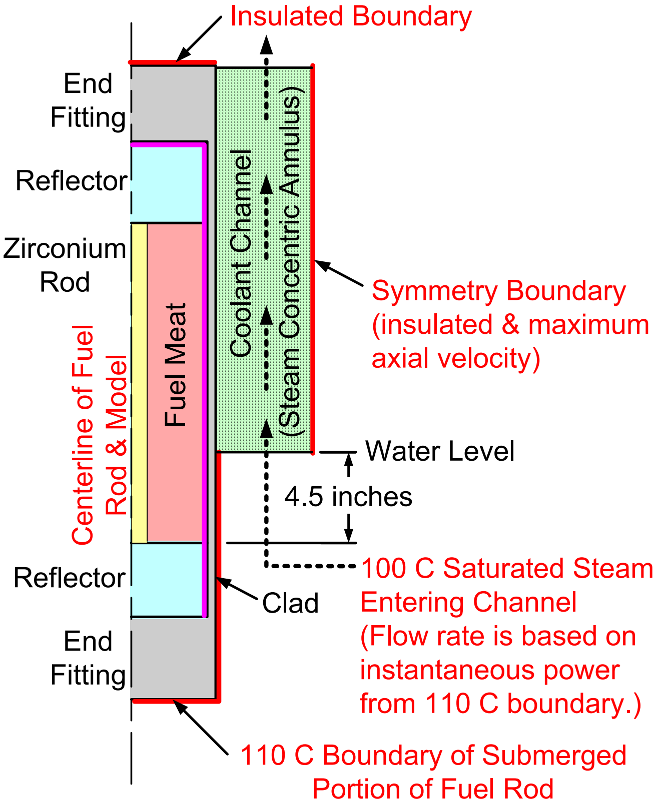

Figure 3 – Model for Computational Fluid Dynamics Analysis

As indicated in the figure, the CFD model includes only the fuel rod and the adjacent steam annulus of the cell. This steam annulus starts at the water level and extends to the top of the rod. The thick red lines in Figure 3 indicate three locations where boundary conditions are specified. The temperature boundary condition at the submerged surface of the fuel rod is 110° C. This temperature is 10° C above the saturation temperature and is intended to correspond to the surface temperature at the onset of nucleate boiling. The top surface of the fuel rod is assumed to be insulated. The centerline of the fuel rod is an axially symmetric boundary. The outer lateral surface of the steam annulus is a symmetry boundary which is adiabatic and where the channel axial component of velocity is at a local maximum and the other velocity components are zero. The initial condition for the model is 100° C everywhere except at the 110° C boundary.

The locations of the gaps included in the model are indicated in Figure 3 by the thick pink line along the inner vertical surface of the clad and the bottom of the upper end fixture. These are the radial gap between the fuel and the clad, the radial gaps between the reflectors and the clad, and the horizontal 1/8th-inch gap between the upper reflector and the upper end fitting. The gap conductance in the radial gap between fuel and the clad was set to 6260 W/m^2-K. This was designed to approximate a 0.0001-inch gap filled with a gas mixture that is 86% xenon and 14% krypton by mole fraction.

The centerlines of the four UWNR beam tubes are aligned with the core mid-plane, which is located 7.5 inches above the bottom of the fuel meat. Since the beam tubes are 6 inches in diameter, the lowest initial water level is 4.5 inches above the bottom of the fuel meat, as indicated in the Figure 3. Saturated steam enters the bottom of the steam annulus at 100° C. For each time interval in the solution the amount of energy transferred to the liquid from the submerged surface of the fuel rod is calculated. For every 614 calories of heat transferred, 1 gram of 100° C saturated steam instantaneously enters the bottom of the annular coolant channel.

The axial power shape along the length of the fuel meat is shown in Figure 4. The decay power fraction as a function of time is shown in Figure 5. The commercial STAR-CD computational fluid dynamics code [3] was used to represent the model and obtain a solution. Time = 0 for the STAR-CD CFD solution starts 15 minutes after the scram, as indicated in Figure 5. At this time the temperature everywhere is assumed to be 100° C, except on the 110° C submerge surface.

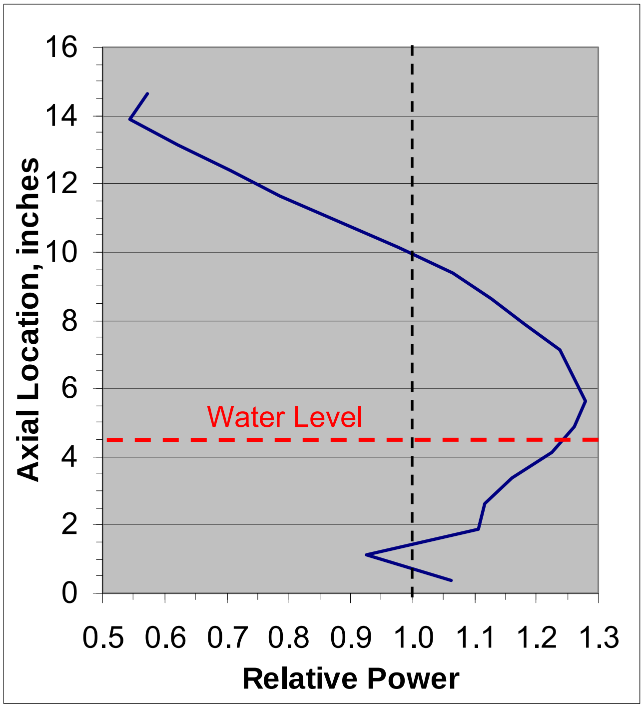

Figure 4 – Axial Power Distribution along Fuel Meat

2.4 Special Computational Issues

Two special computational issues were encountered. First, an on-the-fly method to determine the decay power from the submerged surface to the liquid at each time step as the solution progressed was not found. Instead, a guessed function was used to represent this unknown quantity and obtain an approximate solution. Then the heat flux from the approximate solution was integrated over the submerged surface at each instance of time to obtain a better guess of the unknown function. The better guess was used and the entire transient was solved again. This process was repeated several times until the input guessed function (dashed red "to boil liquid" curve of Figure 6) and the corresponding output function (solid pink "to boil liquid" curve of Figure 6) produced curves that are coincident at all times. As Figure 6 also shows, at each instance in time the total decay power of the hottest rod is partitioned into three parts: 1) to boil liquid, 2) to superheat steam, and 3) is stored in the rod. Initially the power storage is high as the rod is heating up. It

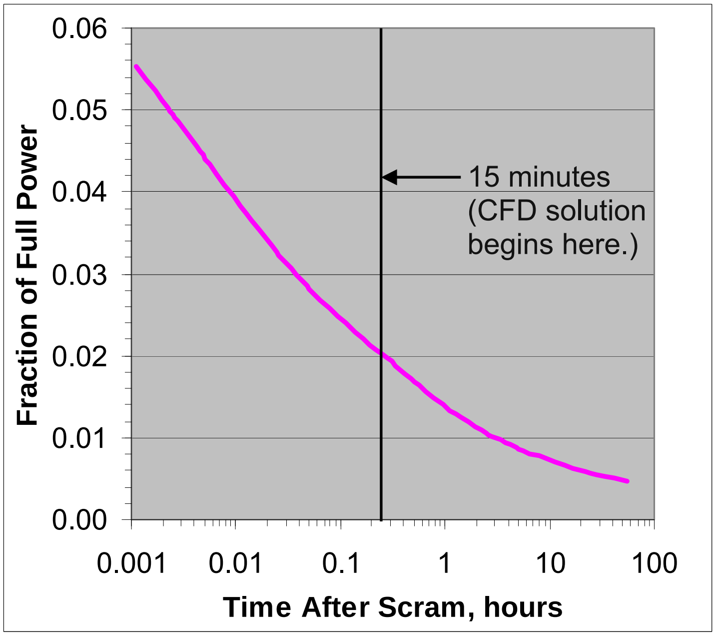

Figure 5 – Reactor Decay Power

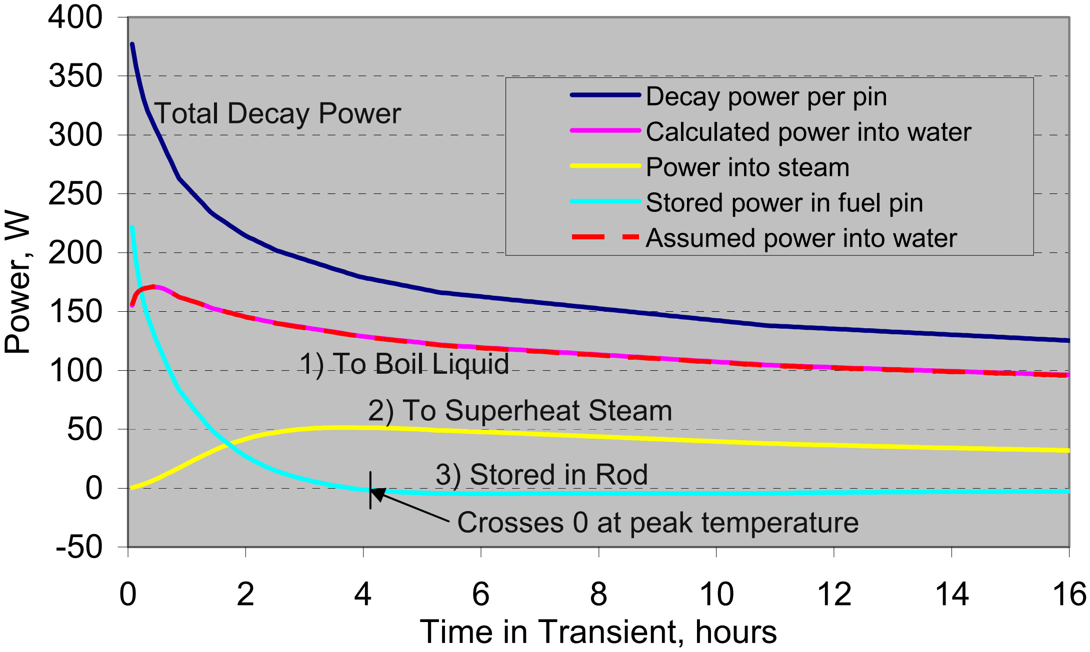

Figure 6 – Partitioning of Total Decay Power into Three Parts

crosses zero as the peak rod temperature is reached and is slightly negative as the rod gradually cools down.

The second issue is the assumption of a fixed water level. As the water is boiled off, the water level gradually drops. As the water level drops the amount of exposed fuel rod increases and if included in the analysis would produce a higher peak fuel temperature then would otherwise be obtained. The reduction in water level depends on the fraction of the total decay power that goes into saturated steam production at each time step. This was estimated from the CFD solution of the hottest rod with the 4.5-inch fixed water level. This fraction increases rapidly from 0 and is 0.63 at 1 hour, 0.68 at 2 hours, and 0.72 at 4 hours, and 0.74 at 8 hours.

As Table 1 shows, at 4.04 hours into the transient solution, which is near the time that the peak fuel temperature is reached (4.07 hours), the water level is 4.25 inches above the bottom of the fuel meat, which is 0.25 inches less than the initial value. The water level drops to 4.00 inches at 7.98 hours and to 3.50 inches at 21.95 hours. A practical way to incorporate the dropping water level directly into a transient CFD solution was not found.

Table 1 – Peak Temperatures Based on Steady-State Solutions

Time, hours	Water Level, in.	Decay Power, W	Decay Power Fraction to Water	Max. Fuel Temp., C
4.04	4.25	178.6	0.7000	577.5
7.98	4.00	152.7	0.7090	560.4
21.95	3.50	115.7	0.7259	528.4

Because near the time that the peak temperature is reached and at times thereafter the temperatures change extremely slowly over time, at each of these instances in time a steady-state solution can be used to approximate the instantaneous transient solution that would be obtained at that time. Thus, a series of steady-state solutions that include the dropping water level can be used to approximate the desire transient solution for times near the peak fuel temperature and beyond.

As in the case of the transient solution, each steady-state solution required several iterations to obtain the correct fraction of decay heat that went into steam production. The results of three steady-state solutions are provided in Table 1, including the decay power level and the fraction of it going to saturated steam production for each solution.

The thesis that in these instances a steady-state solution can be use to approximate individual instances in the transient solution can be tested with the existing transient solution. Table 2 compares the peak fuel temperature for the transient solution at 4.04 hours with that obtained

Table 2 – Comparison of Steady-State with Transient Results

Type of Solution	Time, hours	Water Level, in.	Decay Power, W	Decay Power Fraction to Water	Max. Fuel Temp., C
Transient	4.04	4.50	178.6	0.7205	557.5
Steady State				0.7127	554.7

for a steady-state CFD solution performed for the same water level, 4.5 inches, and the same decay power, that at 4.04 hours into the transient solution (4.29 hours after the scram). The two peak fuel temperatures agree to within 2.8° C, 557.5° C versus 554.7° C.

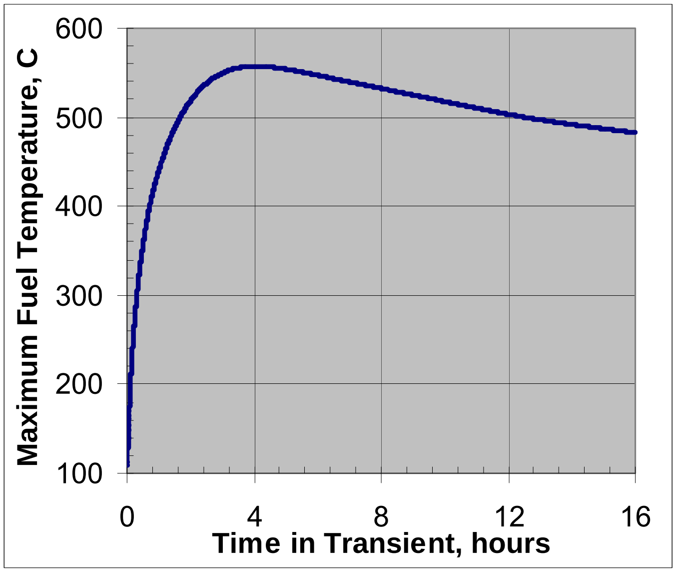

Figure 7 – Maximum Fuel Temperature

3. Solution

Figure 7 shows the peak fuel temperature as a function of time for a fixed water level of 4.5 inches above the bottom of the fuel meat and a peak rod power of 19.7 kW, where the transient solution is initiated 15 minutes after the scram. The peak temperature of 558° C is reached 4.07 hours into the transient. The spatial temperature distribution at this time, Figure 8, shows the steep axial temperature gradient in the fuel, starting near the water level, and the lack of radial temperature gradients throughout much of the computational region.

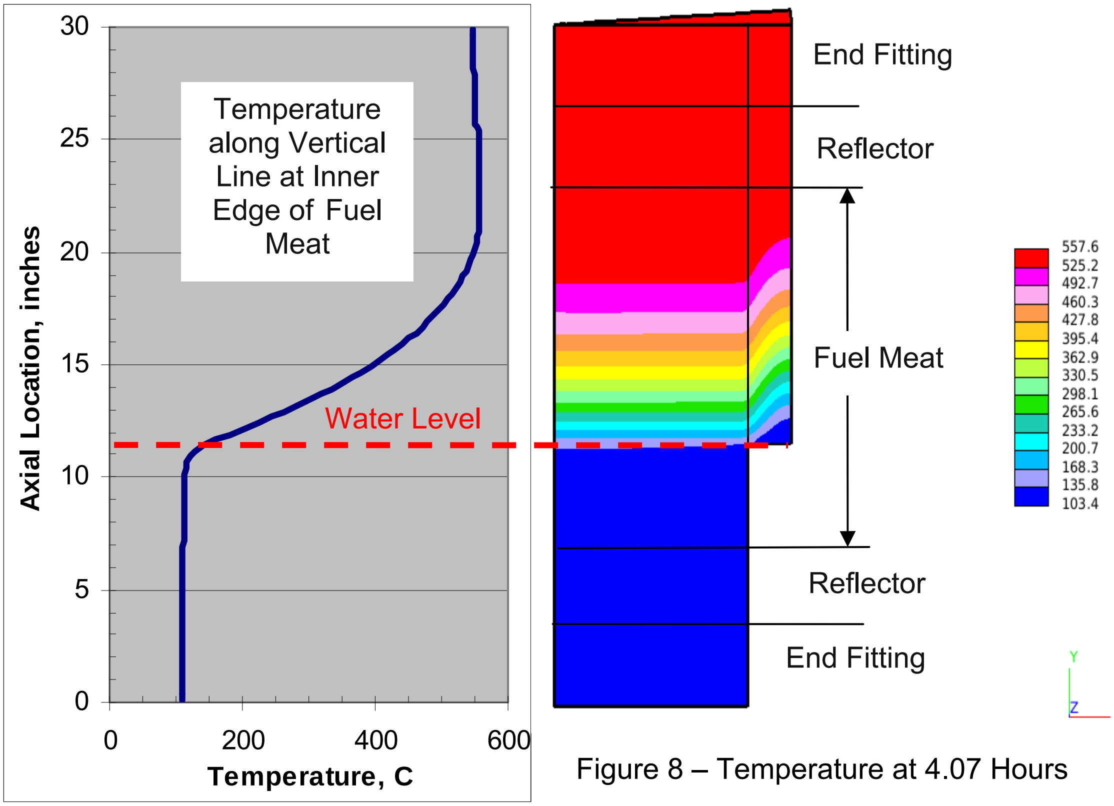

Figure 8 – Temperature at 4.07 Hours

The peak fuel temperature in the Figure 7 transient CFD solution, 558° C, does not include the effects of a dropping water level. This is taken into account via the series of three steady-state solutions whose peaks fuel temperatures are provided in the Table 1. In this table values at 4.04, 7.98, and 21.95 hours, were chosen to correspond to water levels of 4.25, 4.00, and 3.50 inches, respectively. The corresponding peak fuel temperatures are 578, 560, and 528° C, respectively. Based on these results, the maximum fuel temperature including the effects of the dropping water level is reached at about 4 hours into the transient, which is 4.25 hours after the scram, where the peak fuel temperature is 578° C.

4. Model to Demonstrate the Reasonableness of the Results

An approximate model was developed to demonstrate the reasonableness of the peak temperature results. The peak outlet steam temperature during the transient is estimated based on a simple energy balance for steady-state conditions. The results in Figure 8 show that the peak fuel and steam temperatures are about the same. The fraction of the decay power that goes into steam production at the time of the peak temperature, F, is treated as an unknown quantity.

The power going to steam production, F × P, where P is the decay power, must be equal to the product of the rate of steam production, $\dot{m}$, and the energy required to convert one gram of water at 25° C to saturated steam (at 100° C), h, 614 calories. Hence:

$$\dot{m} = \frac{F\,P}{h} \tag{1}$$

The amount of power going to superheat the flowing steam by raising its temperature from the 100° C saturation temperature at the inlet of the channel in the CFD model to the temperature at the outlet is, (1 − F) × P. The steam temperature rise, ΔT, is this power divided by the product of the steam flow rate, $\dot{m}$, and the specific heat capacity of steam at constant pressure, c. Thus:

$$\Delta T = \frac{(1-F)\,P}{\dot{m}\,c} = \frac{(1-F)}{F}\,\frac{h}{c} \tag{2}$$

Since c increases with steam temperature, the average of the steam inlet and outlet temperatures were used in evaluating c. The average steam temperature is the inlet temperature, Tin, plus ΔT/2. The outlet temperature, Tout, is Tin + ΔT.

As Figure 9 shows, if all of the decay power goes to steam production (F = 1), leaving no power to superheat the steam, then the steam outlet temperature is 100° C, which is the steam inlet temperature. As F is reduced, less steam is produced and more of the power goes into superheating the steam. Based on this model and as indicated by the thin vertical line in Figure 9, at least 67.5% of the decay power must go into steam production, if the steam outlet temperature is to remain below 700° C. Since the peak fuel temperature at any instant in time must be greater than the peak steam temperature, steam temperatures above 700°C are to be avoided, if 700° C is the fuel temperature limit.

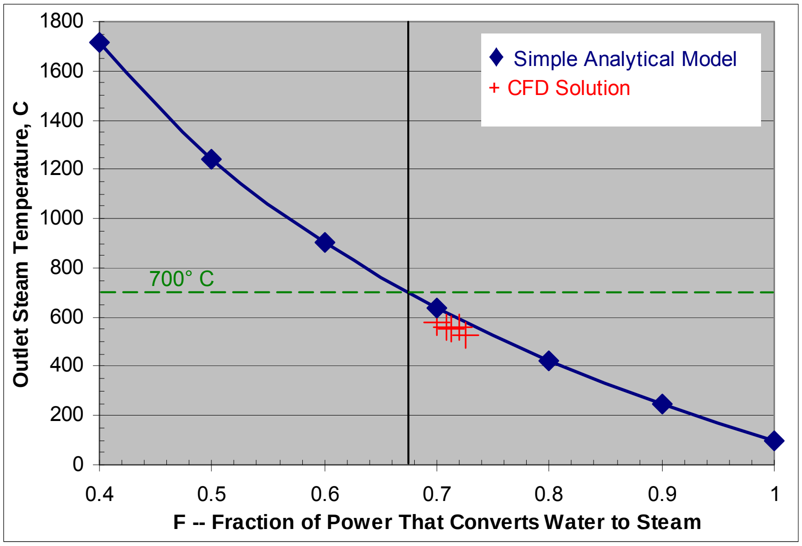

Figure 9 – Simple Analytical Model

All 5 CFD maximum fuel temperature data points provided in Tables 1 and 2 are plotted as red plus signs in Figure 9. As Figure 9 shows, the simple analytical model is very effective at predicting the relationship between the fraction of decay power going to make steam and the peak fuel temperature. However, the fraction of decay power going to make steam could not be predicted with sufficient accuracy without the CFD models.

5.0 Conclusions

The CFD analysis predicts a peak fuel temperature during a partial LOCA in the UWNR of 578° C, which is considerably lower than the temperature of about 700° C that could lead to eutectic formation between the fuel and the cladding. Thus, it is concluded that the UWNR can survive a LOCA initiated by a failure of one of its beam tubes without causing fuel rod failure.

References

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[3] *STAR-CD*, CD-adapco, Plymouth, MI, USA.