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Thermal Model for Horizontal In-Water and In-Air Mini-Plate Experiments in the Advanced Test Reactor

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INTRODUCTION

Mini-plate (MP) irradiation tests are fueled experiments designed for irradiation testing of plate type fuel in multiple test locations in the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL). These MP experiments are non-instrumented drop-in tests where small aluminum-clad fuel plate samples are cooled directly by the ATR Primary Coolant System (PCS) water. These fueled experiments contain aluminum-clad fuel mini-plates consisting of monolithic U-10Mo. Previous thermal analyses have been documented concerning oxide growth [1] and thermal safety margins [2] for the MP-2 experiment. A thermal analysis was performed on the MP-2 experiment using a new technique for calculating the necessary time after the experiment has been irradiated and reactor shutdown necessary to not exceed the 95% lower bound blister threshold temperature for the fuel in a horizontal in-air configuration. Also discussed is a horizontal in-water model analysis.

After the experiment is irradiated in the ATR, the fuel-meat temperatures are calculated at 12 hours after shutdown. This ensures fission products will not be released at the 12-hour mark if this experiment is removed from the reactor and accidentally dropped onto the working tray. Horizontal is the most severe geometrical configuration (minimum heat transfer) since the blister threshold temperature is considered its safety limit. The horizontal in-air analysis is also performed considering the experiment is horizontal in a drained canal with natural convection heat transfer and outside air.

The purpose of the initial mini-plate testing campaign's irradiation, known as MP-1 [3], was to form the base fuel specimens. MP-1 has been irradiated and its purpose was to test fuel performance at bounding conditions using fuel specimens fabricated by a commercial fabricator. MP-2 will populate a comprehensive fuel performance data set. The MP-2 experiment will be irradiated in several locations of the ATR as shown in Figure 1. The fuel plate thickness and geometry are similar to the MP-1 experiment [3], with the only variable being the fuel meat thickness. This model of the B-12 position is treated as encompassing the I-21, I-24, and B-9 positions since it has more fuel and higher total heat than the other positions.

Since the blister threshold temperature is a function of fission density, a series of fission densities is calculated for the B-12 position to cover the other three positions. The B-12 position specifically uses fuel meat that is 0.016-in. thick by 3.25-in. long and 0.75-in. tall. The total plate thickness is 0.050-in. Aluminum cladding forms the barrier between the PCS and the fuel meat. This paper will demonstrate the newly developed technique for calculating necessary decay time after shutdown for a series of fission densities using the ABAQUS [4] finite element and heat transfer code.

Model Description

The MP-2 experiment in the B-12 position has 32 possible fuel-plate positions as shown in Figure 2. Fifteen of these positions are taken with fuel plates, while the rest are positioned with dummy plates. A total of five water channels exist, with three between the four plates and two on the outsides. The entire length of the finite element model is 33.5-in. This experiment as shown in Figure 3 has hafnium rings within the capsule to help shape the neutron flux profile near the ends of the fuel plates, shown with green/blue color in Figure 4.

Shown in Figure 5 is the finite element mesh of one of the capsules with fuel plates depicted in brown. Water finite elements are not shown. Hexagonal eight-noded brick finite elements are used. Eight finite elements span across the fuel meat with four finite elements through the aluminum cladding on each side for a total of 16 across the fuel plate. The entire model consists of approximately 1.5 million finite elements. The fuel meat zone has 40 elements along its length and 20 across the width.

For the horizontal in-water model, all the water channels are replaced with steam. Air finite elements are placed in the water channels for the horizontal in-air model. For both models, solid diffusion/continuum finite elements with no advection are used for the steam and air. This is a conservative assumption since natural convection inside the water channels will enhance the heat transfer. For the air model, no surface-to-surface radiation is included. Exterior black-body radiation is included to an infinite sink at room temperature.

The 95% lower bound blister threshold temperature [5] varying with fission density (FD) is defined as:

- For fission density (FD) $\leq 1.5 \times 10^{21}$ fissions/cm^3, Tb (lower 95% prediction bound) = 478°C
- For FD $\geq 1.5 \times 10^{21}$ fissions/cm^3, Tb = (lower 95% prediction bound) = $3.25\text{x}10^{7} \cdot \text{FD}^{-0.2282}$ (°C).

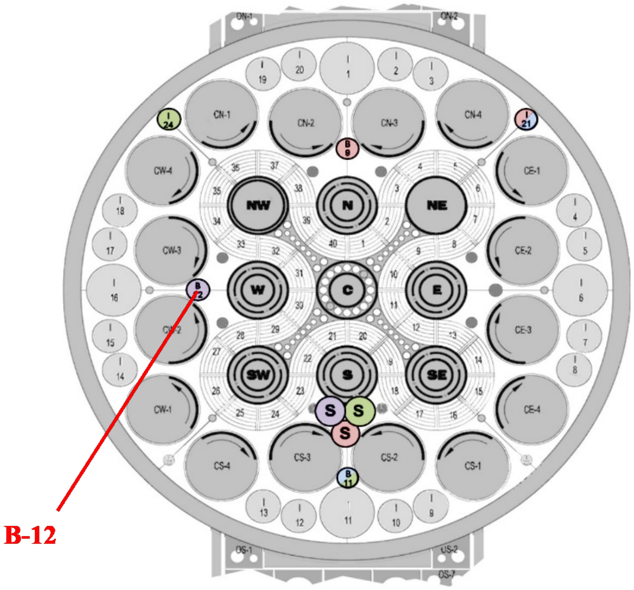

Figure 1. ATR core cross section for MP-2 experiments.

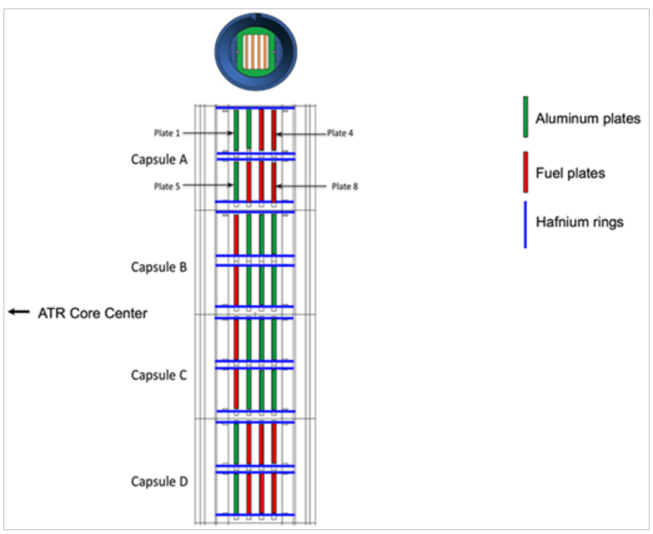

Figure 2. Fuel plate loading by geometry (dummy plates shown in green).

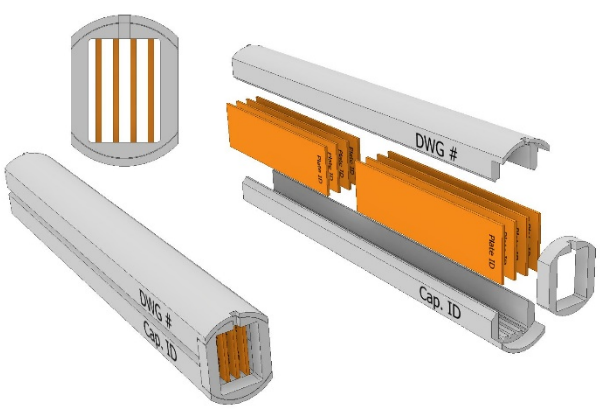

Figure 3. MP-2 capsule configuration.

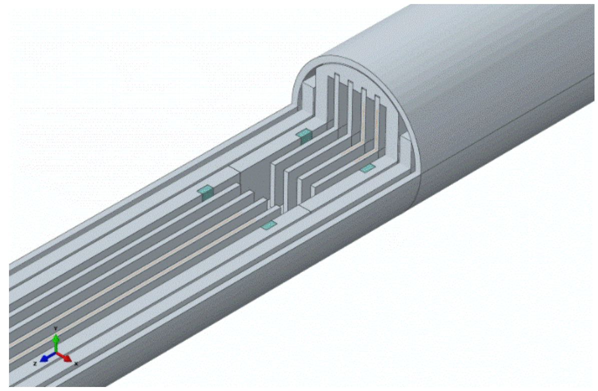

Figure 4. Zoomed in cutaway view of model without PCS water with hafnium rings shown in blue.

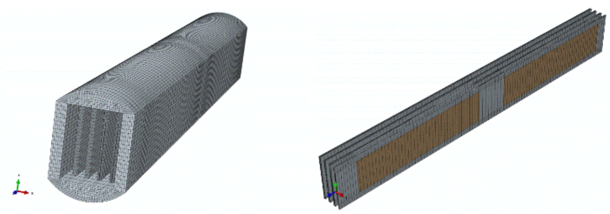

Figure 5. Finite element mesh of one capsule with fuel plates.

Natural convection heat transfer is modeled with a temperature-varying heat-transfer coefficient on the outside of the aluminum basket that contains the experiment described in [7]. The following set of equations show the heat-transfer coefficient used for air and water:

$$T_{wall\_air_i} := 2 \cdot T_{film\_air_i} - T_{inf} \tag{1}$$

$$\beta_i := \frac{1}{T_{film\_air_i}} \tag{2}$$

$$Ra_{Dair_i} := \frac{(\rho_i)^2 g \beta_i c_{p_i} \left(T_{wall\_air_i} - T_{inf}\right) \cdot Diam^3}{\mu_i k_i} \tag{3}$$

$$Pr_{air_i} := \mu_i \frac{c_{p_i}}{k_i} \tag{4}$$

$$Nu_{Dair_i} := \left[0.60 + 0.387 \cdot \frac{\left(Ra_{Dair_i}\right)^{\left(\frac{1}{6}\right)}}{\left[1 + \left(\frac{0.559}{Pr_{air_i}}\right)^{\left(\frac{9}{16}\right)}\right]^{\left(\frac{8}{27}\right)}} \right]^2 \tag{5}$$

$$h_{air_i} := \frac{Nu_{Dair_i} \cdot k_i}{Diam} \quad (6)$$

$$h_{rad_i} := \sigma \cdot \varepsilon_{Al} \left[\left(T_{wall\_air_i}\right)^2 + \left(T_{inf}\right)^2 \right] \cdot \left(T_{wall\_air_i} + T_{inf}\right) \quad (7)$$

Where the aluminum emissivity is assumed to be 0.1.

$$h_{tot_i} := h_{air_i} + h_{rad_i} \quad (8)$$

Decay heat was calculated from [6] with the following equations:

$$Decay(\tau, T) := \sum_{i=0}^{22} \left[\frac{\alpha_i}{\lambda_i} \cdot e^{-\lambda_i \cdot \tau} \cdot \left(1 - e^{-\lambda_i \cdot T}\right) \right] \quad (9)$$

$$Pow\_fact := \frac{Decay(\tau, T_{inf}) - Decay(\tau + T\_op, T_{inf})}{200} \quad (10)$$

Where τ is the time since shutdown, T_op is the operating time and assumed to be 360 days of irradiation. This Pow_fact is the multiplier used to find the heat rates for the water and air model. For the water model at 12 hours, the multiplier is about 0.005. At 29 days after shutdown the multiplier is about 0.0013. If the irradiation time is shorter than 360 days, then these decay heat multipliers will be lower according to equations 9 and 10, but 360 days is used to be conservative. A series of blister threshold temperatures were calculated ranging from (1.5 to 6.0) 10^{21} fissions/cm^3.

Fission heat rates for the fuel meat and gamma heat rates for the water, aluminum, and hafnium were calculated separately from the MCNP physics and neutronics code [8] and input into ABAQUS.

RESULTS

The results are shown in Figure 6 through Figure 10 and Table 1. Shown in Figure 6 is the fission density in the fuel meat, imported from the physics calculations, at the end of the 6th and final cycle of irradiation in B-12. The top of the model is on the bottom left of the figure with capsule A on the left and capsule D on the right. Capsules A, B, and C have fresh fuel for ATR cycle 1, then new fuel for cycle 2 and remain for the third cycle, then new fuel for cycle 4 and then remain for cycles 5 and 6. Capsule D has the same fuel irradiated for all six cycles and hence the highest fission density in Figure 6. Figure 7 shows the irradiation schedule of B-12. Figure 8 shows the fuel meat centerline temperature for the horizontal in-water model at 12 hours after shutdown. Temperatures are well below the blister threshold temperature. Figure 9 shows the number of days necessary for the horizontal in-air model to be exactly at the lower 95% blister threshold temperature limit varying with fission density. For a higher blister threshold temperature at a fission density of 1.5×10^{21} fissions/cm^3 or less, it requires fewer days (12 days) since the decay heat is higher. For a fission density of 5.0×10^{21} fissions/cm^3 the number of days is about 28 since the blister threshold temperature is lower and it requires more time for the decay heat to become lower.

Figure 10 shows the temperature contours of the fuel meat centerline at 28.55 days for a fission density of 5.01×10^{21} fissions/cm^3. The peak temperature is right at the lower 95% blister threshold limit.

Table 1 shows the iteration history to arrive at the values in Figure 9.

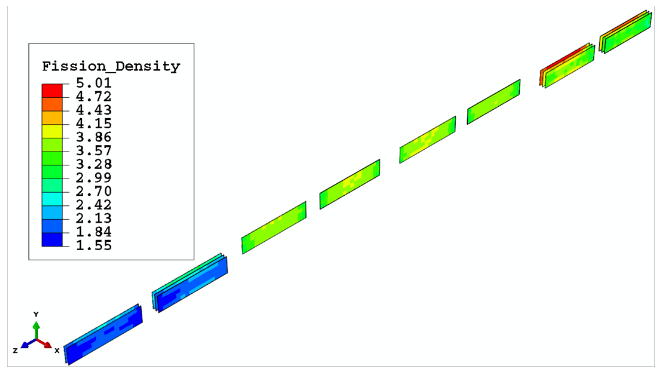

Figure 6. Fission density (10^{21} fissions/cm^3) at end of irradiation.

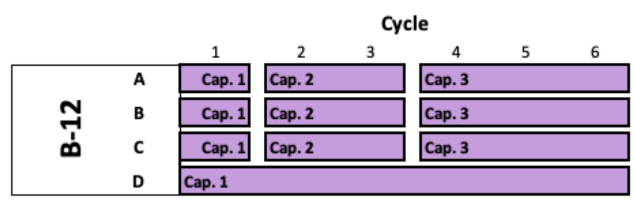

Figure 7. Irradiation schedule for B-12 for six cycles.

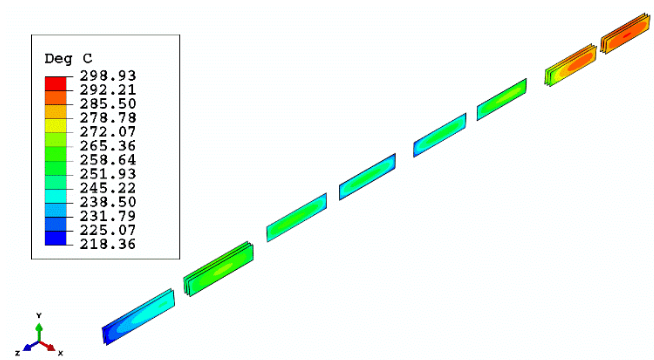

Figure 8. Temperature contours (°C) of fuel meat at end of irradiation for horizontal in water, 12 hours after shutdown.

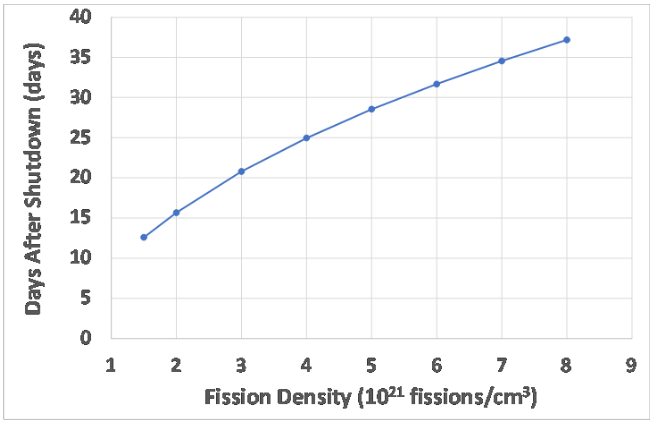

Figure 9. Horizontal in-air days after shutdown versus fission density to be at 95% lower blister threshold temperature.

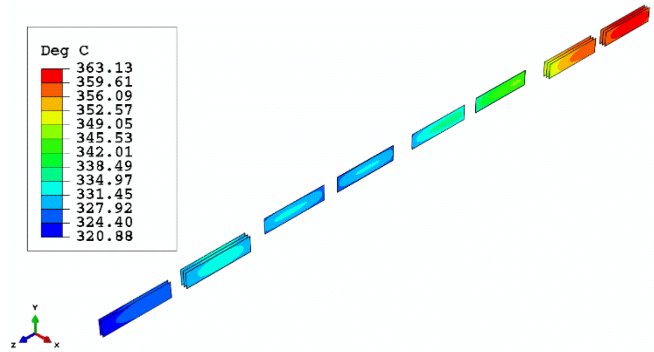

Figure 10. Temperature contours of fuel meat at 28.55 days after shutdown for horizontal in air (FD=5.01× 10^{21} fissions/cm^3).

Table 1. Iteration progress for horizontal in air.

			Horizontal in Air											
Fission Density	95% Blister Temp	95% Blister Temp	Iteration # 1		Iteration # 2		Iteration # 3		Iteration # 4		Iteration # 5		Iteration # 6	
(10^{21} fiss/cm^3)	(°C)	(°F)	Days	Max Fuel (°F)	Days	Max Fuel (°F)	Days	Max Fuel (°F)	Days	Max Fuel (°F)	Days	Max Fuel (°F)	Days	Max Fuel (°F)
1.5	478.00	892.40	30	673.00	20	776.37	8.78	979.95	13.60	873.60	12.75	889.32	12.58	892.76
2	447.70	837.86	35	634.09	25	719.30	11.09	923.68	16.93	818.58	15.86	834.88	15.66	838.12
3	408.14	766.64	40	601.31	30	673.01	16.94	818.26	21.58	757.03	20.85	765.89	20.79	766.57
4	382.20	719.96	45	573.12	35	634.10	20.92	764.88	25.76	711.93	25.02	719.32	24.96	719.67
5	363.23	685.81	50	548.23	40	601.33	24.09	728.77	29.45	677.73	28.60	685.28	28.55	685.64
6	348.42	659.16	55	526.79	45	573.14	26.44	705.25	32.91	649.69	31.81	658.14	31.68	659.23
7	336.38	637.49	60	508.30	50	548.25	27.66	693.54	36.28	625.55	34.77	636.01	34.55	637.50
8	326.29	619.31	65	492.70	55	526.81	27.88	691.77	39.79	602.52	37.55	616.93	37.18	619.19

NOMENCLATURE

c_p	specific heat	(J/kg-K)
g	gravity	(m/s^2)
h	heat transfer coefficient	(W/m^2/K)
k	thermal conductivity	(W/m/K)
Nu	Nusselt number	( )
Pr	Prandtl number	( )
Ra	Rayleigh Number	( )
T	temperature	(K)

Subscripts

conv convection
D diameter
inf infinity
wall wall

Greek

ρ density (kg/m^3)
μ viscosity (kg/m-s)
ε emissivity
σ radiation const

CONCLUSIONS

This paper shows a method for several experiment test trains to be conservatively covered by one thermal analysis concerning how many days after shutdown an experiment needs to cool for varying amounts of burnup.

ACKNOWLEDGMENTS

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