ANALYSIS OF THE EFFECT OF TRANSVERSE POWER DISTRIBUTION IN AN INVOLUTE FUEL PLATE WITH AND WITHOUT OXIDE FILM FORMATION[*]

by

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ABSTRACT

Existing thermal hydraulics computer codes can account for variations in power and temperature in the axial and thickness directions but variations across the width of the plate cannot be accounted for. In the case of fuel plates in an annular core this can lead to significant errors which are accentuated by the presence of an oxide layer that builds up on the aluminum cladding with burnup. This paper uses a three dimensional SINDA[1] model to account for the transverse variations in power. The effect of oxide thickness on these differences is studied in detail. Power distribution and fuel conductivity are also considered. The lower temperatures predicted with the SINDA model result in a greater margin to clad and fuel damage.

INTRODUCTION

The PLTEMP[2] (steady state), and PARET[3,4] and RELAP[5] (transient) thermal-hydraulics computer codes can account for variations in power and temperature in the axial direction and through the thickness of a fuel plate. However, variations across the width of the plate are neglected. This is usually justified by the minimal power variations in this direction. However, in the case of an annular core with involute fuel plates extending from inner to outer walls of the vessel, sizable power variations can exist. A fuel plate from the Advanced Test Reactor (ATR) in Idaho was previously analyzed in two and three dimensions and the results show important differences in temperature[6].

Using any of the aforementioned codes to analyze these plates requires an assumption for the transverse power level at a given axial position. The conservative approach is to use the peak value across the width for the hot channel. The temperatures computed are higher than the actual values because power variation and heat conduction are neglected in the transverse direction. This assumption is acceptable for most existing research reactors with MTR-type fuel. However it may be too conservative for new advanced research reactors now being proposed. This study models an involute plate using the SINDA thermal analysis code because it accounts for the transverse power variation and the resulting thermal conduction as well as cooling of the inner and outer side plates. Because assumptions regarding transverse coolant mixing are difficult to justify, and minimal in any case (coolant transit time in the core being analyzed is less than 45 milliseconds), this phenomenon is not included in this analysis.

THE MODEL

The problem under consideration has the following specifications. A 32 MW annular core with 172 involute plates between inner and outer radii of 10.45 cm and 16.55 cm and 80 cm high with a central control rod is modeled. The U_3Si_2 fuel meat has a thickness of 0.76 mm and the aluminum clad has a thickness of 0.38 mm. The coolant channel thickness is 2.2 mm, the coolant inlet temperature is 37°C, and the coolant velocity is 18 meters per second. The cooled side plates promote transverse heat conduction. Because of uncertainty of the actual heat loss at the side plate, several boundary conditions were tried. While the temperature of the unfueled section of the plate was influenced by the condition imposed on the side plate, the results for the fuel temperature were found to be insensitive to this condition.

The analysis also considers the presence of a corrosion layer on the surface of the aluminum clad. This very thin layer consists of boehmite ($\alpha Al_2O_3 \cdot H_2O$) which has a much lower thermal conductivity than the aluminum (2.25 vs. 162 w/(m-°K)). Thus, this thin layer can have a substantial influence on clad and fuel temperatures. When a temperature difference across the oxide layer reaches 130-140°C, spallation of the oxide begins to occur and damage to the clad occurs[7]. This gradient is not approached for the cases in this study. The growth rate of this layer is minimized at a coolant pH of 4.5 to 5. The growth rate also increases with heat flux, interface and oxide temperature, and coolant temperature[8]. Predictions made for growth rate of the oxide layer based on temperatures obtained from a two dimensional(2D) code will be too high.

SINDA is a general thermal analyzer code that accepts a network description of the problem in the form of node dimensions, conductor connections between nodes, etc. Fortran coding can be supplied to compute input factors (eg., heat transfer coefficient) which are dependent on computed quantities (eg., temperature). Figure 1 shows the nodal structure for the SINDA model: Each of 22 axial levels contains 50 diffusion nodes, 13 surface nodes adjacent to the convective media, and a boundary node representing coolant temperature at the outer surfaces of the side plates. Initial runs with the SINDA model were made with a uniform power distribution and no cooling outside the core in order to compare temperatures with those predicted by PLTEMP and PARET. Steady state results show excellent agreement between PLTEMP and the SINDA model, as expected.

STEADY-STATE ANALYSIS

Reactor operation at steady-state power is considered first. The transverse power distribution at five axial locations for the control rod fully inserted is shown in Fig. 2. Figure 3 shows a comparison of the PARET and SINDA results for the transverse temperature distribution in the fuel and the clad for the hot channel with no corrosion. The peak fuel temperature is 7°C lower when transverse heat transfer is considered. The average fuel temperature is almost 30°C lower than the hot channel in PARET. While there is no hot channel per se in an annular core, the only way to account for the transverse peak power in two-dimensional codes like PARET is to use the peak value across the entire width of the fuel element, thus creating an effective hot channel.

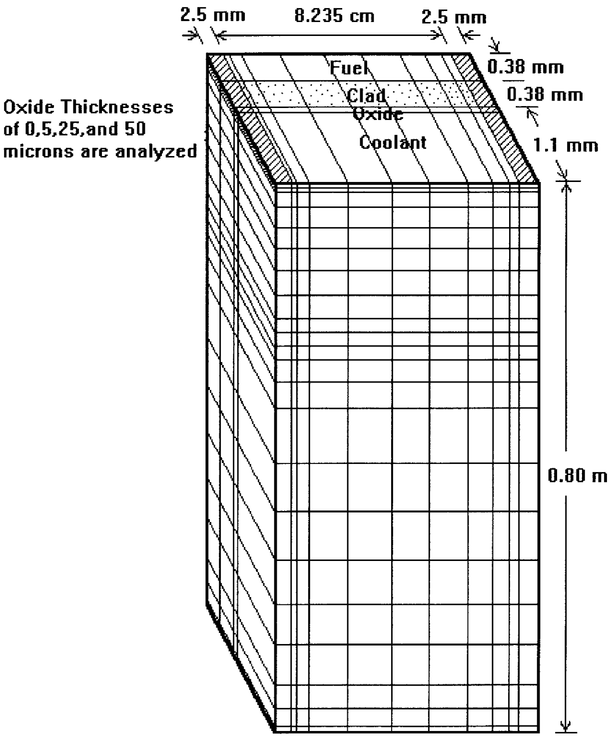

Fig. 1. SINDA Model Nodal Structure

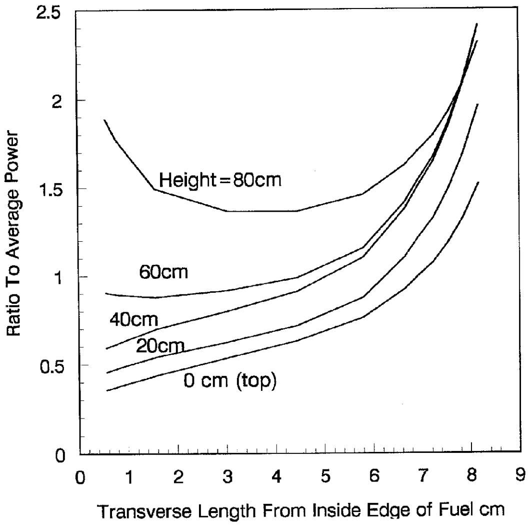

Fig. 2. Transverse Power Distribution (Rod Fully Inserted)

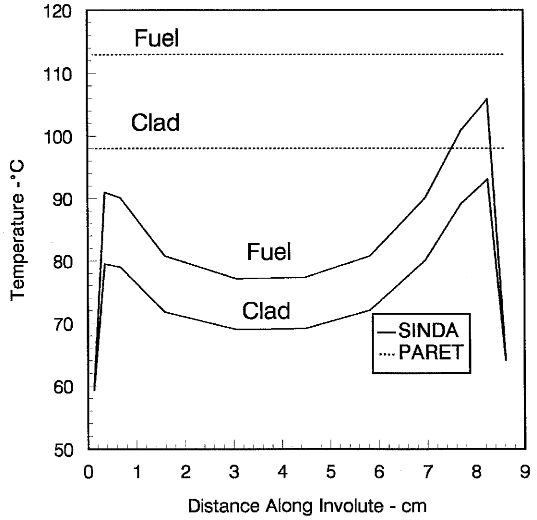

Fig. 3. Comparison of Constant and Varying Power Distribution Along Involute Width

Steady state power cases were run with 0, 5, 25, and 50 micron oxide film thicknesses. Figure 4 gives the transverse temperature distribution in the fuel, clad, oxide center and surface and coolant of a plate with a 25 micron oxide layer located at the core mid-plane. Because there is very little temperature drop across the clad, the separation between the clad and oxide surface temperatures represents the gradient across the corrosion layer. This can also be seen in Fig. 5 where the axial temperature distribution for a clean plate and one with a 50 micron oxide layer is shown. The effect of the oxide layer in increasing the clad and fuel temperature is especially apparent in this figure. The fuel temperature plotted in Figs. 4 and 5 is the peak value across the thickness.

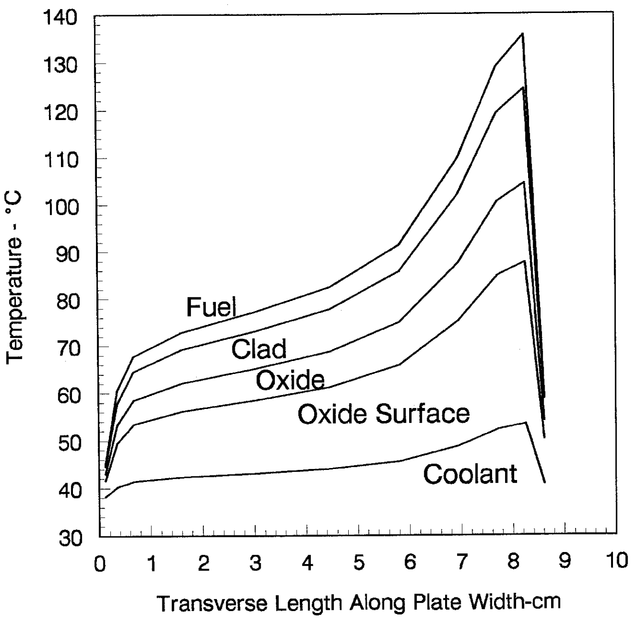

Fig. 4. Transverse Temperature Distribution in Fuel Plate with 25 Micron Oxide Layer (Rod Fully Inserted)

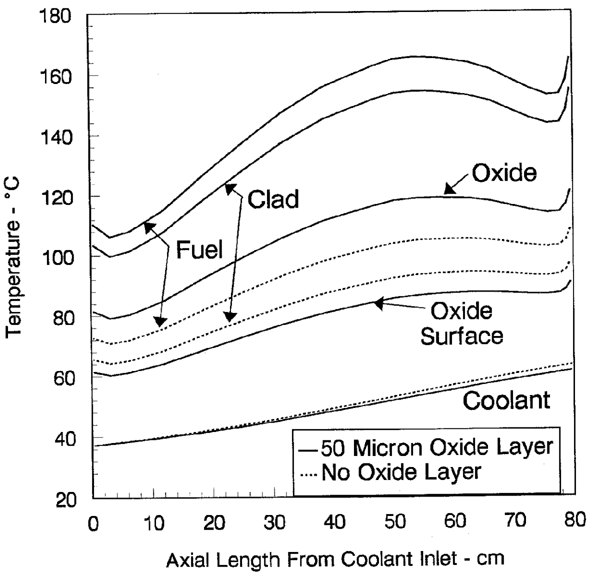

Fig. 5. Axial Temperature Distribution in Fuel Plate (Rod Fully Inserted)

The transverse fuel temperature is shown in Fig. 6 for the four thicknesses of oxide corrosion. Also plotted for comparison is the fuel temperature for a uniform transverse power distribution. Figure 7 shows the effect of the three dimensional(3D) analysis in reducing peak axial temperatures for the four oxide thicknesses.

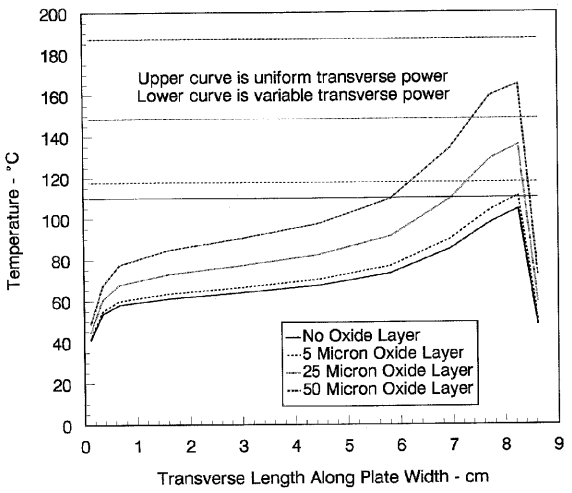

Fig. 6. Transverse Temperature Distribution In Fuel (Rod Fully Inserted)

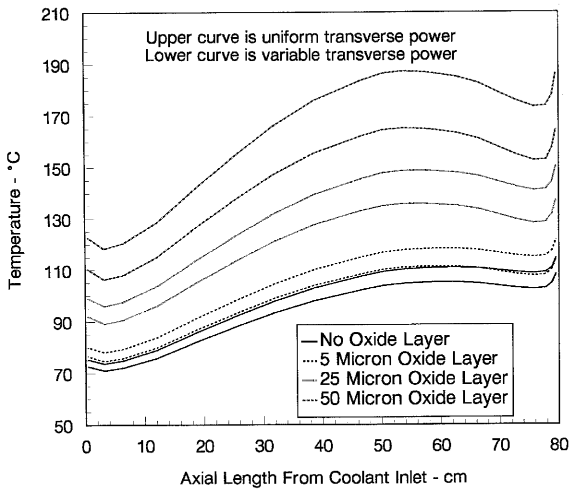

Fig. 7. Peak Axial Temperature Distribution In Fuel (Rod Fully Inserted)

A summary of the fuel, clad, and oxide surface temperatures is given in Fig. 8 as a function of corrosion thickness. While the thicker oxide layer pushes up the fuel and clad temperatures, the oxide surface temperature is quite insensitive to its thickness. A similar plot is shown in Fig. 9 for two different power distributions: Control rod partially withdrawn and control rod fully withdrawn (the latter giving a symmetric power distribution.). These power distributions are less severe than when the control rod is fully inserted.

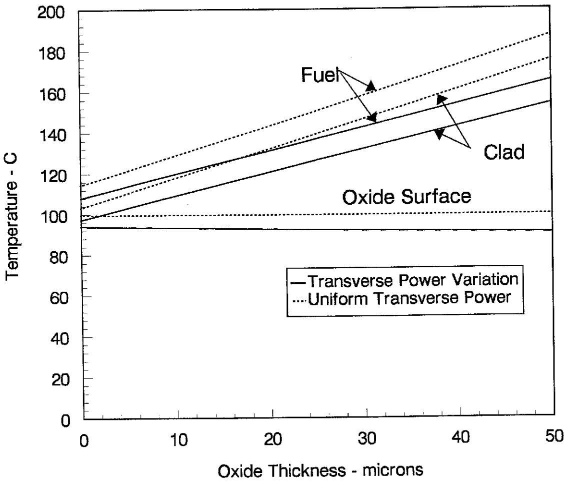

Fig. 8. Variation of Peak Fuel, Clad, and Oxide Surface Temperature with Oxide Thickness (Rod Fully Inserted)

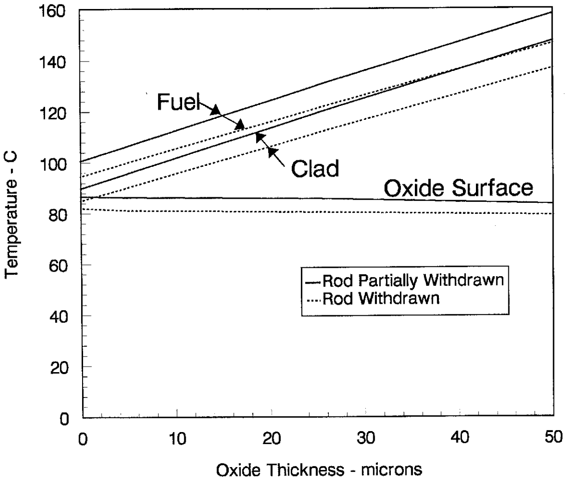

Fig. 9. Variation of Peak Fuel, Clad, and Oxide Surface Temperature with Oxide Thickness

In addition to a much lower average temperature, the peak temperature difference between the two and three dimensional cases increases as the corrosion layer thickness increases as is evident from Fig. 10. The fuel temperature increase for the case of uniform transverse power exceeds 20°C for the thickest corrosion layer considered.

TRANSIENT ANALYSIS

A hypothetical reactivity insertion transient characterized by a linear ramp at a rate of $0.1 per second ending in an overpower trip at 13.5 seconds is analyzed with RELAP. The power history (Fig. 11) computed in RELAP is used in the SINDA model (with a flat transverse power distribution). The temperature histories predicted by the two codes for a fresh fuel element (no oxide layer) showed good agreement. The same non-uniform transverse power distribution used in the steady state case and cooling of the inner and outer vessel is introduced into the SINDA model resulting in a reduction of the peak temperature shown in Fig. 12. The effect of the more exact model is to reduce the peak temperature by about 14°C.

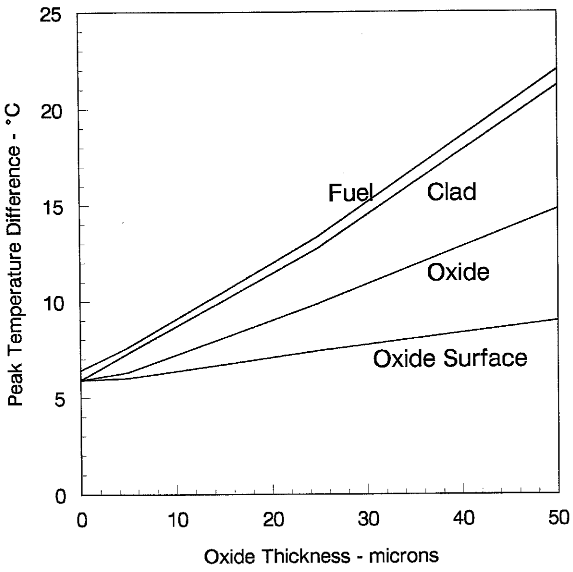

Fig. 10. Temperature Decrement from Uniform Transverse Power Case to Three Dimensional Power Distribution Case (Rod Fully Inserted

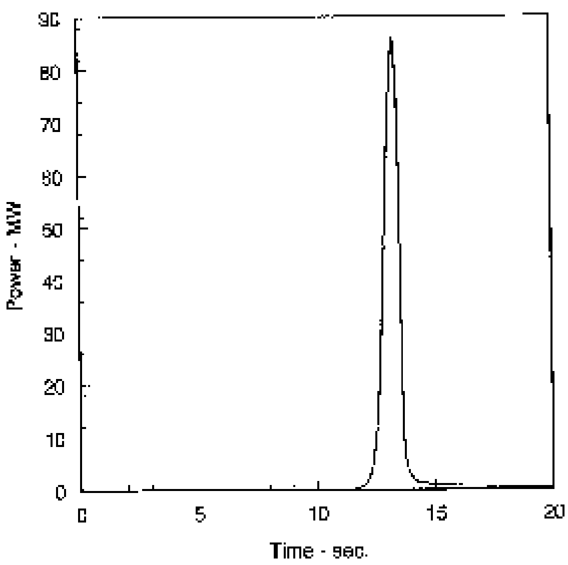

Fig. 11. Power History for Reactivity Insertion at $0.1 Per Second

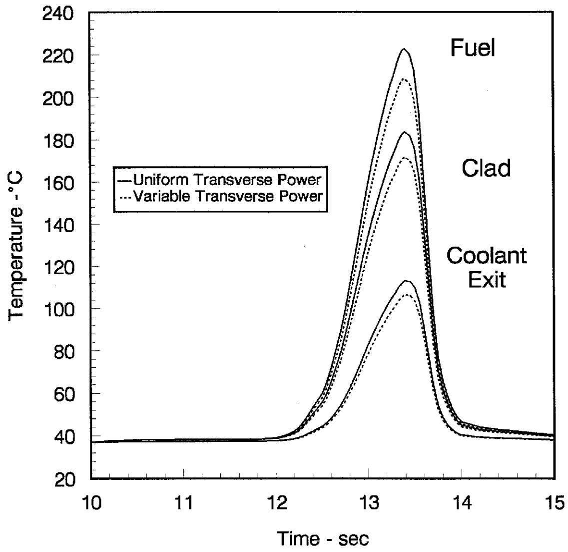

Fig. 12. Peak Fuel, Clad, and Coolant Temperature Response to Reactivity Insertion of $0.1 Per Second

DISCUSSION AND CONCLUSION

The formation of a corrosion layer on aluminum clad fuel plates is critical in high heat flux reactors because it leads to unacceptably high temperatures locally in the fuel and clad that may damage the clad and compromise the fuel plate. The temperatures in the fuel plate - coolant system are central to computations for the rate of growth of the corrosion layer. For instance, according to the Griess correlation[9], the oxide thickness at a given time is proportional to an exponential of the interface temperature: $\exp(-4600/T_i)$. For the control rod fully inserted and no oxide layer, the surface temperatures are 99.6°C for the 2D case and 94.0°C for the 3D case. The 2D results would over-predict the growth rate by 20 percent. For an oxide thickness of 50 microns, the equivalent temperatures are 99.5°C and 90.5°C and the 2D over-prediction of the growth rate is more than 35 percent. Furthermore, the transverse temperature distributions clearly show that the peak temperature occurs only at a local position. Although the oxide layer would be thickest at that point, thinner, adjacent oxide layers would allow transverse heat conduction to dissipate the maximum temperatures as discussed above (Figs. 6 and 10).

Additionally, higher temperatures enhance the reaction between U_3Si_2 and the matrix aluminum, and this interdiffusion process consumes matrix aluminum causing swelling in the fuel meat to develop[10].

This new modeling capability will provide for analysis of high heat flux fuel elements in a more accurate fashion. The more realistic temperature predictions will give confidence in core designs in that a greater margin of safety to element failure will be evident.

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