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EFFECT OF IN-PILE DEGRADATION OF THE MEAT THERMAL CONDUCTIVITY ON THE MAXIMUM TEMPERATURE OF THE PLATE-TYPE U-MO DISPERSION FUELS

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ABSTRACT

Effect of in-pile degradation of the meat thermal conductivity on the maximum temperature of the plate-type research reactor fuels has been assessed using the steady-state heat conduction equation and assuming convection cooling. It was found that due to very low meat thickness, characteristic for this type of fuel, the effect of the meat thermal conductivity degradation on the maximum fuel temperature is minor. For example, the fuel plate featuring 0.635 mm thick meat operating at heat flux of 600 W/cm^2 would experience only a 20^{o}C temperature rise if the meat thermal conductivity degrades from 0.8 W/cm-s to 0.3 W/cm-s.

While degradation of the meat thermal conductivity in dispersion-type U-Mo fuel can be very substantial due to formation of interaction layer between the particles and the matrix, and development of fission gas filled porosity, this simple analysis demonstrates that this phenomenon is unlikely to significantly affect the temperature-based safety margin of the fuel during normal operation.

1. Introduction

RERTR program is currently developing dispersion plate-type fuel for use in research reactors. The fuel plates are comprised of the thin (0.635 mm) rectangular meat surrounded on all sides with aluminum cladding. The meat consists of the spherical U-Mo particles dispersed in the aluminum alloy matrix. It has been established that during fabrication and irradiation, U-Mo particles may react with the matrix forming an intermetallic product with low thermal conductivity. This reaction causes degradation of effective thermal conductivity of the meat. Detailed description of the thermal conductivity degradation mechanisms in U-Mo dispersion fuel meat is given by Hayes et al. [1]. These mechanisms include growth of the intermetallic interaction layer on the interface between U-Mo particles and aluminum alloy matrix, and development of fission gas filled porosity in the U-Mo particle and in the interaction layer.

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It is rightfully thought that the importance of thermal conductivity is paramount in the design and safety of the power reactor fuel and non-plate research reactor fuel. However, as shown in this paper, the fuel plates developed and tested by the RERTR program are a rare exception due to the very thin meat layer and due to efficient heat removal by convection cooling.

The objective of this paper is to demonstrate that during normal operation the plate fuel temperature is insensitive to the significant degradation of the meat thermal conductivity observed in the U-Mo dispersion type fuel plates.

2. Methodology

Equation for steady-state heat conduction in plate type fuel assuming one-dimensional heat flow and symmetry around the center plane is given by Lamarsh [2]. Equation from Lamarsh can be rearranged in more convenient terms:

$$T_m = T_{coolant} + q''\left(\frac{a}{2k_f} + \frac{b}{k_c} + \frac{c}{k_b} + \frac{1}{h}\right)$$

Where,

T_m	maximum fuel temperature,
$T_{coolant}$	coolant temperature,
q''	plate heat flux power,
a	meat half-thickness,
b	cladding thickness,
c	oxide layer thickness,
k_f	meat thermal conductivity,
k_c	cladding thermal conductivity,
k_b	oxide thermal conductivity,
h	heat transfer coefficient,

The assumption of one-dimensional heat transfer ignores heat removal through the edges and the ends of the fuel plate. This assumption is justified for the objectives of this paper, because the thickness of the plate is small compared to the width and length, and because during convection cooling of such plate the heat is removed primarily through the surface of the plate. It is recognized, that during accident conditions the heat transfer regime between the coolant and the cladding may change due to boiling of the coolant, resulting in the drop of the heat transfer coefficient, and possibly causing heat removal through the edges, ends, unfueled zones of the plate, and the hardware that houses the plate during irradiation [3]. Therefore, the findings of this paper apply only when the heat removal occurs primarily through the plate surface, which is typical for the convection cooling regime. It should be noted, that for the peak temperature location, the one-dimensional analysis is more conservative than three-dimensional analysis and will always result in a higher peak temperature values. While the three-dimensional thermal analysis tools are widely available and routinely used by the RERTR program, for the reasons of transparency, the one-dimensional analysis is utilized here.

Using equation (1), fuel temperature can be computed for a given plate geometry, plate power, coolant temperature, thermal conductivity cladding-coolant heat transfer coefficient. The values of the input parameters are given in Table 1.

Table 1. Input parameters for the fuel temperature calculation.

1	Coolant temperature, ^oC	52
2	Plate heat flux, W/cm^2	Up to 621
3	Meat half-thickness, cm	0.03175
4	Cladding thickness, cm	0.03815
5	Oxide layer thickness, cm	0.0005
6	Meat thermal conductivity lower limit, W/cm-s	0.05
7	Meat thermal conductivity upper limit, W/cm-s	0.8
8	Cladding thermal conductivity, W/cm-s	1.75
9	Oxide thermal conductivity, W/cm-s	0.0225
10	Heat transfer coefficient, W/cm^2-K	3.03

In the Table 1 the thermal conductivity upper limit corresponds to the as-fabricated U-Mo dispersion fuel. It is based on the measurements of Lee et al. [4]. The thermal conductivity lower limit is based on the models provided by Hayes et al. [1]. The lower limit corresponds to the thermal conductivity of the reaction product with the fission gas filled porosity of 30%. It signifies the limiting case, when the U-Mo particles have completely reacted with the matrix forming an intermetallic compound. This is a hypothetical situation, as the fuel is not intended to reach such state; however, this corresponds to the lowest known value of meat thermal conductivity for U-Mo dispersion fuels. The analysis presented here does not apply to the dispersion-type plates that feature gross defects such as large internal voids.

3. Results and discussion

3.1. Effect of the meat thermal conductivity degradation on the maximum temperature of the thin fuel plate

Results of fuel temperature calculation using Equation (1) and input data from Table 1 are shown in Figure 1. In Figure 1, plate maximum temperature is plotted for the range of the meat thermal conductivity values from 0.05 to 0.8 W/cm-s for three selected values of heat flux. The key feature of these plots is that the plate maximum temperature does not respond to the thermal conductivity degradation until thermal conductivity falls to approximately 0.2-0.3 W/cm-s. Specifically, for the most demanding case of 600 W/cm^2 the plate would only experience a 20^{o}C temperature rise, when the meat thermal conductivity degrades from 0.8 W/cm-s to 0.3 W/cm-s.

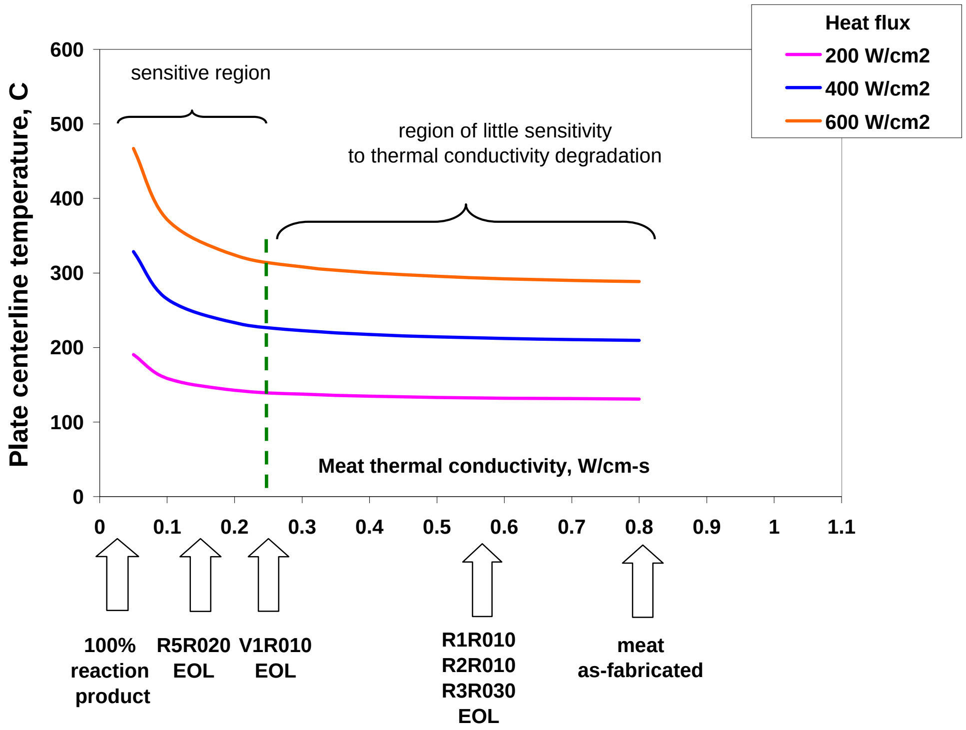

Figure 1. Effect of the meat thermal conductivity degradation on RERTR plate temperature at various heat flux levels. Note that the curves remain nearly flat until thermal conductivity falls to 0.25 W/cm-s (arbitrary threshold is marked with the green dashed line). Thermal conductivities of 100% reaction product (lower limit), as fabricated fuel meat (upper limit), and EOL thermal conductivities of selected plates from RERTR-6 experiment are shown for the reference with arrows on X-axis.

Examination of the Figure 1 suggests that operation of the fuel in the zone where the fuel temperature is highly sensitive to the meat thermal conductivity is less desirable. The temperature limit of the U-Mo dispersion plates has not been formally announced, but it is expected to be somewhere between 500 and 550^{o}C. Even in the most demanding case featuring heat flux of 600 W/cm^2, complete degradation of the meat thermal conductivity will not cause the plate temperature to exceed this tentative limit, assuming typical design and conditions provided in Table 1.

3.2. Meat thermal conductivity degradation in selected plates from RERTR-6 irradiation experiment

It is of interest to examine the extent of thermal conductivity degradation in actual fuel plates from RERTR-6 experiment with respect to the trend presented in Figure 1. It should be noted that the heat flux in these plates did not exceed 200 W/cm^2.

Recent efforts to improve performance of U-Mo dispersion fuel by increase of the silicon content in the matrix and by thermal treatment during fabrication resulted in development of the dispersion fuel forms that feature an interaction layer that does not exceed a few microns at the end of irradiation. This is in contrast with the earlier prototypes whose interaction layer was well in excess of 10 microns. For example, R1R010, R3R030 and R2R010 plates from the RERTR-6 irradiation experiment were reported [5] to have interaction layers of 1.9, 1.5 and 1.7 microns respectively. V1R010 and R5R020 plates representing earlier generation fuel in the same irradiation experiment, featured the interaction layer of 7 microns [6] and 11.3 microns [5] respectively. Results of microscopic examination for these plates were published by Hofman [6].

To estimate the meat thermal conductivity at the end of irradiation in the plates discussed above, the PLATE code was used. Detailed explanation of the PLATE code approach to calculation of thermal conductivity is given elsewhere [1]. Values of the meat thermal conductivity and interaction layer thicknesses calculated using PLATE code are given in Table 1.

Table 1. Values of the meat thermal conductivity at the end of irradiation calculated using PLATE code.

Plate number	PLATE code prediction for the peak burnup location	
	Meat thermal conductivity at the end of irradiation	Interaction layer thickness, microns
R1R010	0.6453	1.59
R2R010	0.5077	1.81
R3R030	0.5082	2.04
V1R010	0.2784	7.14
R5R020	0.1365	11.22

As evident from Table 1 and Figure 1, meat thermal conductivity of the R1R010, R2R010, R3R030 falls in the region of little temperature sensitivity to thermal conductivity degradation. Furthermore, the thermal analysis of these plates could tolerate significant uncertainty in the thermal conductivity determination. Plate R5R020 is located in the sensitive region. Any further degradation of thermal conductivity in this plate will result in a significant temperature increase. Safety-based thermal analysis in this region requires accurate determination of the thermal conductivity of this plate. Plate V1R010 falls on the border of the sensitive region.

4. Conclusion

It has been demonstrated through simple analysis that during normal operation, the effect of in-pile degradation of the meat thermal conductivity on the maximum temperature of the plate-type research reactor fuel is not significant unless meat thermal conductivity drops below 0.2-0.3 W-cm/s. This finding has the following practical significance:

- The existence of desirable operation and design envelope where fuel temperature in insensitive to the meat thermal conductivity degradation has been shown. Latest RERTR fuel plates appear well-positioned in this envelope, while earlier prototypes are on its boundary.
- Thermal analysis of the plates operating in the desired envelope can tolerate significant uncertainty in the meat thermal conductivity determination.
- The effect of the meat thermal conductivity degradation on plate performance should not be overstated during interpretation of the PIE results and fuel design.

These conclusions are based on the calculated meat thermal conductivity values. They will be reassessed if measurements of the thermal conductivity are performed.

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