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Activities in Support of Conversion of the MIT Nuclear Reactor to LEU Fuel

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ABSTRACT

Design and feasibility studies for conversion of the MIT Reactor have shown that the current HEU experimental performance will be maintained with the use of monolithic U-10Mo LEU fuel and an upgrade in operating power from 6 MW to 7 MW. Power peaking for a number of LEU core configurations has been analyzed using the MCNP-ORIGEN coupling code MCODE. This power peaking has been used in steady-state thermal-hydraulic analysis with the result that the limiting safety system setting power based on the onset of nucleate boiling is 7.7 MW.

Because total fuel lifetime may be limited by cladding oxide growth, quantification of the distribution of oxide on the finned aluminum cladding of the MITR HEU fuel elements have been made using a replication process and eddy current measurements. Results of these measurements will be presented.

1. Introduction

The MIT Reactor (MITR-II) core has a hexagonal design that contains twenty-seven fuel positions in three radial rings (A, B, and C), as shown in Figure 1 and is licensed to operate at 6 MW. Typically at least three of these positions (two in the A-ring) are filled with either an in-core experimental facility or a solid aluminum dummy element to reduce power peaking. The remaining positions are filled with standard MITR-II fuel elements. Each rhomboid-shaped fuel element contains fifteen aluminum-clad fuel plates using HEU (93% enriched) in an aluminide cermet matrix with a fuel thickness of 0.76 mm (0.030 in.) and a length of 61 cm (24 inches). The cladding of each fuel plate is machined with 0.25 mm longitudinal fins to increase heat transfer to the coolant. The fuel has an overall density of 3.7 g/cm^3, with a total loading of 506 g ^{235}U in each element.

The core is light water moderated and cooled and is surrounded by a D_2O reflector. Boron impregnated stainless steel control blades are located at the periphery of the core on each of the sides of the hexagon and have a total length of travel of 52 cm. In addition, fixed absorbers can be installed in the upper axial region of the core in a hexagonal configuration between the A and B rings as well as in three radial arms extending to the edge of the core.

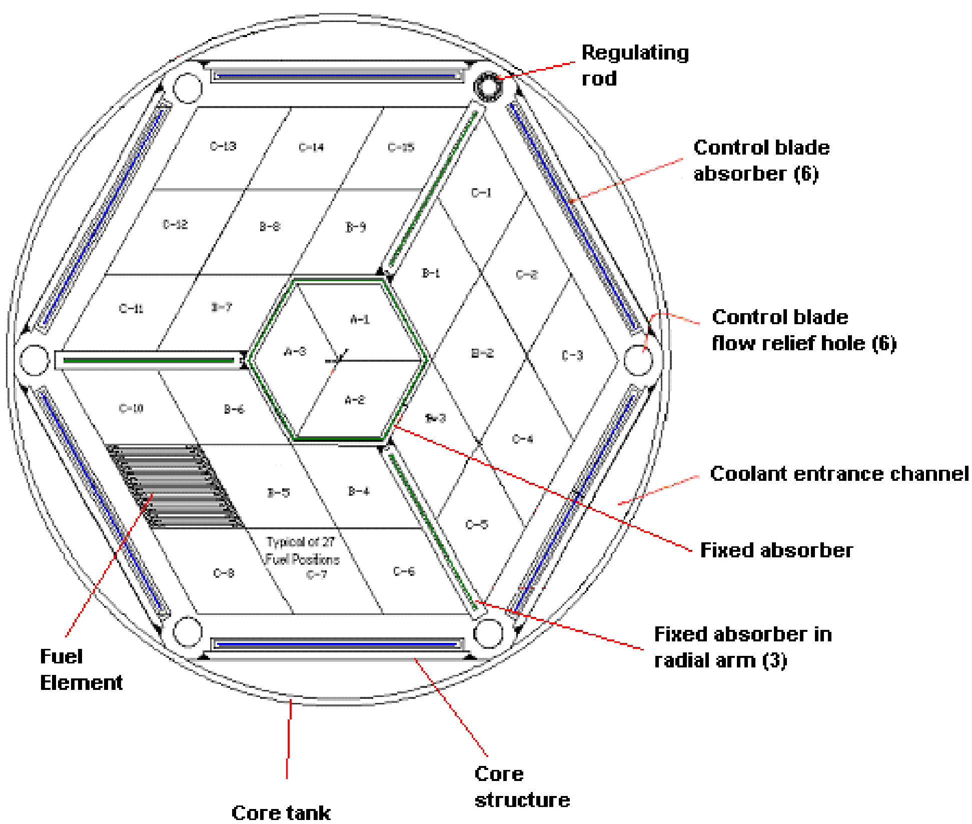

Figure 1. Layout of the MIT Reactor core.

2. LEU Fuel Design

LEU fuel optimization [1] performed for the MIT Reactor has shown that fuels with a density of at least 14 g/cm^3 would be required to reduce the enrichment to 19.75%. Because of this, monolithic U-10Mo LEU fuel with a density of 17.02 g/cm^3 was chosen for the design. This fuel is currently under evaluation by the RERTR program.

A feasibility study recently completed [2] has resulted in a design of a U-10Mo LEU fuel element containing 18 plates with 0.508 mm thick fuel with 0.25 mm cladding below the fins. This analysis shows that an equivalent 6 MW HEU experimental neutron flux can be generated at an LEU reactor power of 7 MW. Sufficient margins to onset of nucleate boiling are also met with the LEU core operating at this power level.

3. Neutronic and Thermal-Hydraulic Modeling

A number of neutronic models have been made for the MIT reactor. The Monte Carlo code MCNP has been used for many evaluations of HEU and LEU core and experiment design studies. The basic reactor design and fuel structure has also been input into the MCNP-ORIGEN linkage code MCODE for fuel management and burnup evaluations. Further discussion of progress in neutronic modelling is discussed in [3].

MCODE has been used to determine power peaking in proposed LEU cores. [4] These power distributions were used to determine the thermal-hydraulic safety limits [5]. In this determination, engineering hot channel factors (EHCFs) were modelled as distributions with both measurement and calculation uncertainties quantified in thermal hydraulics limits analysis using statistical propagation. In addition, the interior coolant channel (full channel) is assumed more limiting than all possible end channel configurations. Uncertainties in the end channel significantly impact whether interior or end channels are limiting, and so further analysis will be required as manufacturing uncertainties in the channel gap become available for the LEU fuel element.

A “hot stripe” approach is adopted to treat for three-dimensional power peaking (i.e., radial power peaking includes both plate peaking and lateral peaking). A “hot stripe” is defined as the most limiting lateral fuel plate section and coolant channel for the thermal hydraulic limits analysis. The power density of the hot stripe is based on a 7 MW depleted LEU core analysis. The hot stripe is assumed to:

- Have no lateral heat conduction within the plate (shown to be a conservative assumption [4])
- Be adjacent to an interior coolant channel, with both sides of the coolant channel having the same heat flux profile.
- Have no coolant mixing (shown to be a conservative assumption [6]).

Safety limits were derived based on the above assumptions and the criterion of avoiding the onset of flow instabilities (OFI). The limiting safety system settings (LSSS) are established to allow a sufficient margin between normal operating conditions and the safety limits. Onset of nucleate boiling (ONB) is chosen as the criterion for the LSSS derivation. This guarantees that boiling will not occur anywhere in the fueled region as long as the limits are not exceeded. Results at limiting conditions (primary flow of 1800 gpm and 10 feet of coolant level above the core) are shown in Figure 2. This gives a maximum LSSS power of 7.7 MW for LEU fuel at the limiting operating temperature (60^{o}C)

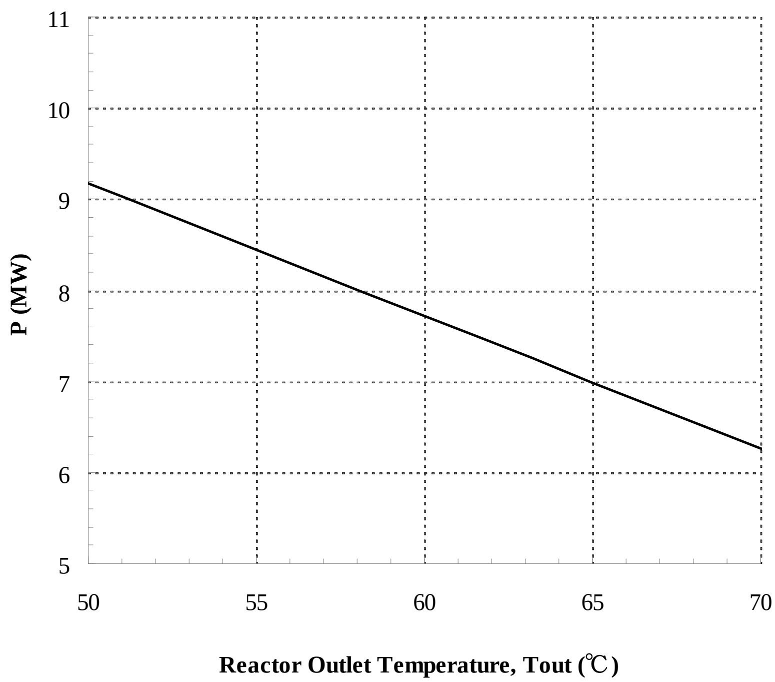

Figure 2. MITR LEU Core Limiting Safety System Settings for Forced-Flow Operation. [5]

4. Thermal hydraulic measurements

In order to better quantify the heat transfer coefficient in rectangular channels as well as determine the point of ONB, a heated thermal-hydraulic loop was constructed at MIT. This loop is being used to study the possibility of using unfinned plates for LEU fuel for the MITR. Details of this design and preliminary results can be found in [7].

5. Determination of oxide growth in finned MITR plates

Currently, burnup of HEU fuel is limited by the assumption of oxide growth on the finned cladding surface. Because there may be no practical burnup limit on monolithic UMo LEU fuel, dimensional examination of the fuel surfaces is needed to provide data on the development of the oxide layer on MITR-II fuel. The oxide thickness affects the heat transfer rate from the fuel to the coolant, and data about the thickness and distribution at the beginning and end of life of the current fuel will be used in the development of burnup specifications and analyses for LEU fuel. It is possible that, as the fuel ages, the oxide layers grow differently on the tops, sides, and bottoms of the grooves, therefore information about the oxide thickness on each of these surfaces is desired.

Two techniques have been used to assess the oxide thicknesses on the fuels surfaces: (1) an eddy current probe used to measure the thickness of the oxide layer on the elements' top surface, and (2) replicas of the fuel surface were made to measure the dimensions of the tops, sides, and bottoms of the fuel's grooved surface to assess the uniformity of the oxide layer thickness.

An assembly, shown in Figure 3, was built to hold a fuel element horizontal and position an eddy current probe or replication fixture in a reproducible location.

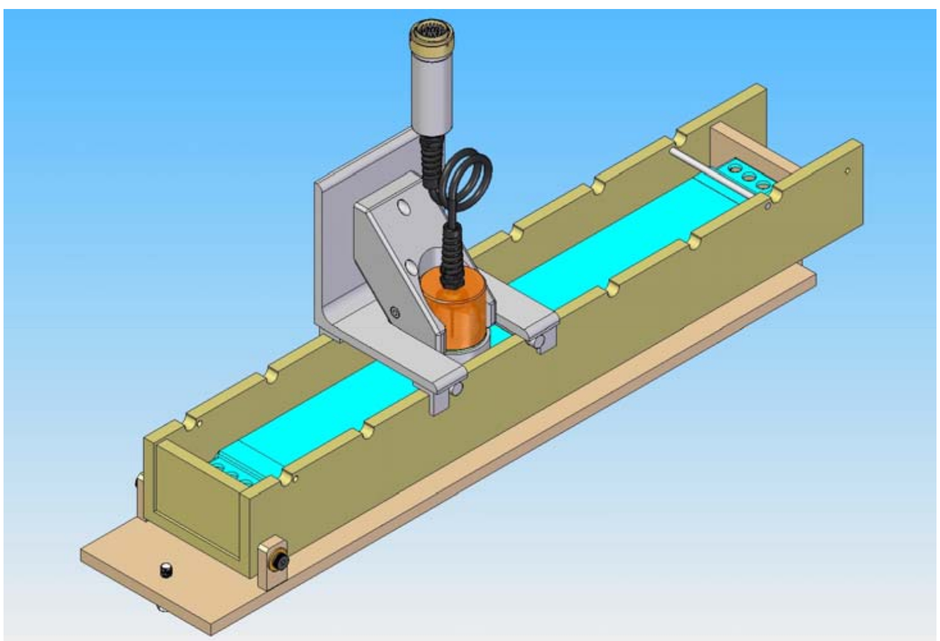

Figure 3. Fixture for eddy current and replication measurements

5.1 Eddy Current measurements

Eddy current measurements were made on a number of fuel elements to determine the extent of oxide growth at the tip of the fins. All of these measurements showed a distribution of oxide proportional to the heat flux and burnup of the elements. A high burnup, low decay (to minimize further oxidation during storage) fuel element was chosen for both eddy current and replication measurements. The eddy current results, seen in Figure 4, show a maximum oxide thickness of about 60 μm.

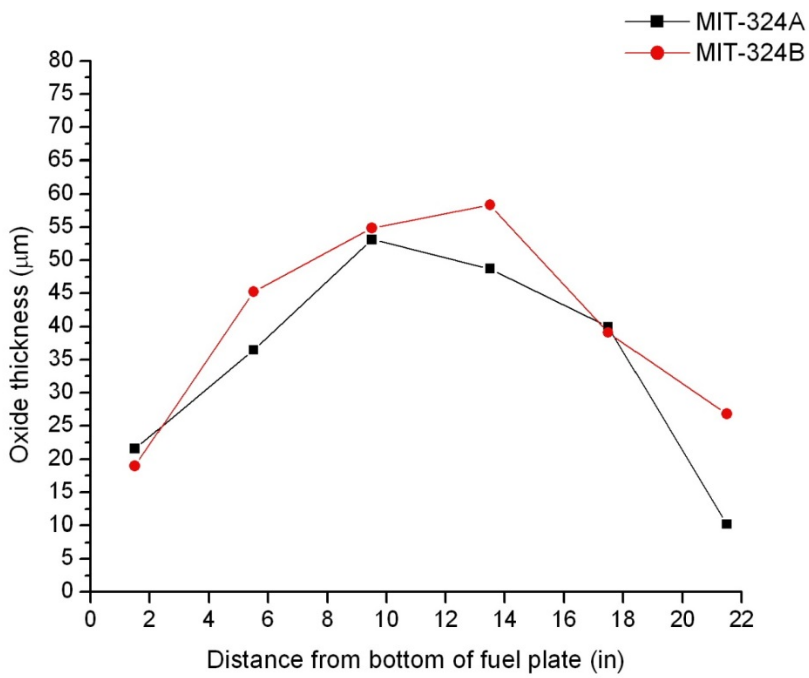

Figure 4. Results of eddy current measurements of oxide thickness on both sides of element MIT-324.

5.2 Replication measurements

The material used to replicate the fuel surface is Reprorubber a two part, quick setting metrological putty, manufactured by Flexbar Machine Corporation. After mixing the two parts, the putty is applied to surface to be replicated, and, after the putty has set (approximately 10 to 15 minutes), it can be removed from the replica surface and examined.

Once the replica is made it is examined using an optical microscope, equipped with an eyepiece reticle to visually measure the width of the tops and bottoms of the replicas' grooves. The width measurements have an uncertainty of roughly ±0.0005". The groove depths were determined by measuring the difference in the height of the microscope's body when the smallest observable features on the ridges and the troughs were in focus. The microscope's body height was determined using a dial micrometer fixed to the microscope's base with the moving indicator pin resting on the body of the microscope. With the microscope at full 7x magnification the uncertainty of the depth measurements was roughly ±0.001".

This technique was first tested on a "dummy" finned fuel plate and replication measurements were compared with actual dimensional measurements. Results from these measurements are shown in Table 1.

Table 1. Measured depths and widths for grooves on a finned and a replica made from this dummy. The grooves are nominally 10 mils (0.25 μm) deep, and the tops and bottoms are both nominally 10 mils wide.

Average and standard deviation of measurements in mils (thousandths of an inch)	Dummy	Replica
Depth	10.0 ± 0.7	9.6 ± 0.5
Dummy top width/ replica bottom width	8.5 ± 0.3	8.8 ± 0.3
Dummy bottom width/ replica top width	9.5 ± 0.4	9.3 ± 0.2

One limitation of these measurements of the groove's top and bottom widths is that the method determines the size of the flat portion of the tops and bottoms, not the width of the bulk of the fin or groove. If the top and bottom surfaces have sharp edges with the groove sides, and the sides are parallel, then an accurate groove or fin width can be measured. However, if the top or bottom surface does not have a sharp edge with the side, or if the sides are not parallel, this method will undermeasure the bulk width of the fin or groove. A laser profilometer is being purchased to obtain a complete 3-D profile of the replicas and eliminate this limitation.

The used MITR-II fuel element #341, which is currently in the reactor's spent fuel storage pool, was placed into the fuel element holder and surface replicas were made at five locations. The measurements for this element's replica are summarized in Table 2.

Table 2. Measured depths and widths for grooves on replicas made at five locations of MITR fuel element 341 along with the replica of the dummy element MIT DUM-22. The grooves are nominally 10 mils deep, and the tops and bottoms are both nominally 10 mils wide.

Average and standard deviation of measurements in mils (thousandths of an inch)	MIT DUM-22	Face up position 3	Face up position 4	Face up position 1	Face down position 3	Face down position 6
Depth	9.6 ± 0.5	9.8 ± 0.4	9.8 ± 0.4	10.0 ± 0.7	9.4 ± 0.5	10.0 ± 0.7
Element top width (replica bottom width)	8.9 ± 0.4	9.0 ±0.4	9.3 ± 0.3	9.1 ± 0.3	8.8 ± 0.2	8.9 ± 0.4
Element bottom width (replica top width)	9.3 ± 0.2	8.2 ±0.5	8.2 ± 0.4	8.8 ± 0.2	7.3 ± 0.3	8.8 ± 0.2

The depth measurements from the element 341 replicas are all close to the depth measurement of the dummy and not very different than the nominal depth of 10 mils (0.25 mm). This indicates that the oxide layer in these areas of the element is not thicker at the bottom of the grooves than at the top. The measurements of the element's groove tops are also very close to the dummy top width although this may be due to the previously mentioned limitation in the measurement technique — unless the oxide layers on the groove sides create a clear edge with a widened flat top (an unlikely scenario), the top widths, as measured using these methods, would not be expected to change over time.

In contrast, the groove bottom widths of element 341 are significantly smaller than those measured on the dummy element indicating oxide growth on the groove sides. Larger decreases in bottom widths (i.e. thicker oxide layers) occurred in the middle of the fuel plate (positions 3 and 4). This difference in oxide thickness along the plate's length is consistent with the eddy current measurements. If the oxide layers on the grooves' sides are uniform from top to bottom, the width changes should be twice as large as the oxide layer thicknesses. Because the width changes measured using the replicas range from 0.5 to 2 mils (12 μm to 50 μm), and the oxide layers measured on the groove tops using the eddy current probe are from 0.5 to 3 mils (12 μm to 75 μm), it may be concluded that the oxide layers on the groove sides are thinner than, or are certainly not greater than, those on the groove tops.

6. Further analyses

The computational fluid dynamics code STAR-CCM+ is being used to analyze the three-dimensional, coupled conduction and convective heat transfer of the LEU fuel design. The goal here is to obtain greater accuracy of modeling the lateral thermal conduction and convective heat transfer, and possibly increasing safety margins.

In addition, alternate fuel designs are being evaluated. Thinning of the edge plates could possibly reduce power peaking, allowing operation at higher power levels.

7. Conclusions

LEU and HEU core analysis models continue to improve the accuracy and reliability of results. Power peaking and thermal-hydraulic analyses show that the monolithic U-Mo LEU fuel design for the MITR has a LSSS power level of 7.7 MW. These models are continually being improved and supplement thermal-hydraulic measurements currently being made.

Eddy current and replication have proved to be a valuable measurement technique in determining oxide thickness and distribution on the finned cladding surface. Results show oxide distribution does not appear to reduce fin effectiveness.

Although alternative designs are still being evaluated, The use of monolithic U-Mo LEU fuel in the MITR continues to be eminently feasible.

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