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Fuel Management and Safety Analysis for LEU Conversion of the MIT Nuclear Reactor

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ABSTRACT

As part of the LEU conversion program at the MIT Nuclear Reactor Laboratory, the ORIGEN-MCNP coupling code MCODE has been benchmarked and used to develop a fuel management system to optimize the introduction of LEU fuel and subsequent management of fuel movements to minimize power peaking. These results are then used for subsequent thermal-hydraulic analyses and verification of operating safety limits. Additionally, the distribution and buildup of oxide on the finned aluminum cladding is being evaluated to determine the impact on heat transfer and possible burnup limits for LEU fuel. Finally, analyses were made to compare the radiation release consequences between HEU and LEU fuel of the design basis accident of the melting of four or five fuel plates.

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

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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.

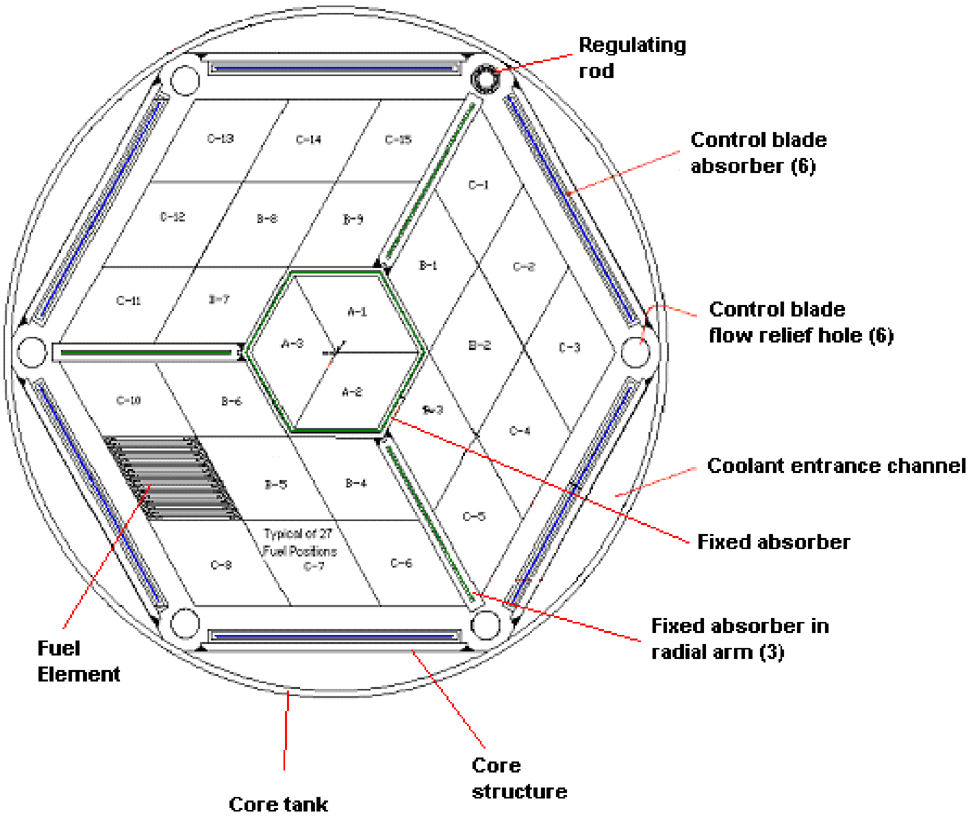

Figure 1. Layout of the MIT Reactor core.

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 and is expected to be qualified for use within the next four years.

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 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. A graphical user interface (GUI) has been designed and built into the MCODE model in a version called MCODE-FM [3], which includes the ability to model all aspects of fuel management at the MIT reactor, including fuel flipping, rotating and storage for later use. The latter capability includes an ORIGEN calculation of decay and tracking of relevant radioisotopes, including actinides. A criticality search algorithm can also be utilized so that the control blade motion can be modelled. The number of axial burnup nodes as well as fuel plate grouping can also be varied, depending on resolution and computational time needed. The output of MCODE-FM includes the ability to track and plot power peaking or number densities of any relevant isotope on a per node, per plate, or per assembly basis.

The MCODE model was benchmarked by comparing measured values in initial HEU cores from 1975-76 as well as more recent cores through 2009 [4]. The K_{eff} at critical blade heights for three fresh core configurations were seen to match within 0.4% $\Delta K/K$. In addition calculated blade worth curves were seen to match measured values within approximately the same value. The critical blade heights were calculated for a series of twelve cores operated in 2008 and 2009. The beginning- and end-of-cycle blade heights were calculated to be within 1% $\Delta K/K$ for all cores.

MCODE is now being used for routine MITR fuel management calculations. Power peaking values for each node are input into a spreadsheet and safety limit calculations are made, taking into account flow disparities and other reactor conditions to verify an adequate margin to onset of nucleate boiling, given for the limiting safety system settings.

4. LEU Analysis and Code Optimization

A steady-state neutronics analysis of a fresh LEU core using monolithic U-Mo fuel was also made using the MCODE model, comparing physics parameters with a fresh HEU core. The results are detailed in [5]. Blade worths, reactivity coefficients, and the reactivity effect of fuel and reflector changes were found to be close to the HEU values. In addition, the delayed neutron fraction for LEU fuel was calculated and found to be within 3% of the HEU core. The prompt neutron lifetime for the LEU core was calculated using the 1/v absorption method and found to be 60 μs, as compared with the HEU value of 77 μs, not including photoneutrons.

In order to determine LEU fuel cycle length, core depletion calculations were made on the LEU-fuelled core operating at 7 MW for twelve cycles with fuel management analogous to the depletion of the 2008-2009 HEU cores mentioned above. These results are shown in Figure 2. This shows that, because of the lower thermal flux present in the LEU fuel, the reactivity change for LEU is less than that for HEU, resulting in a total number of full power days of 607 for LEU, compared with 388 for HEU. This reduces the number of fuel elements required annually by about 30%.

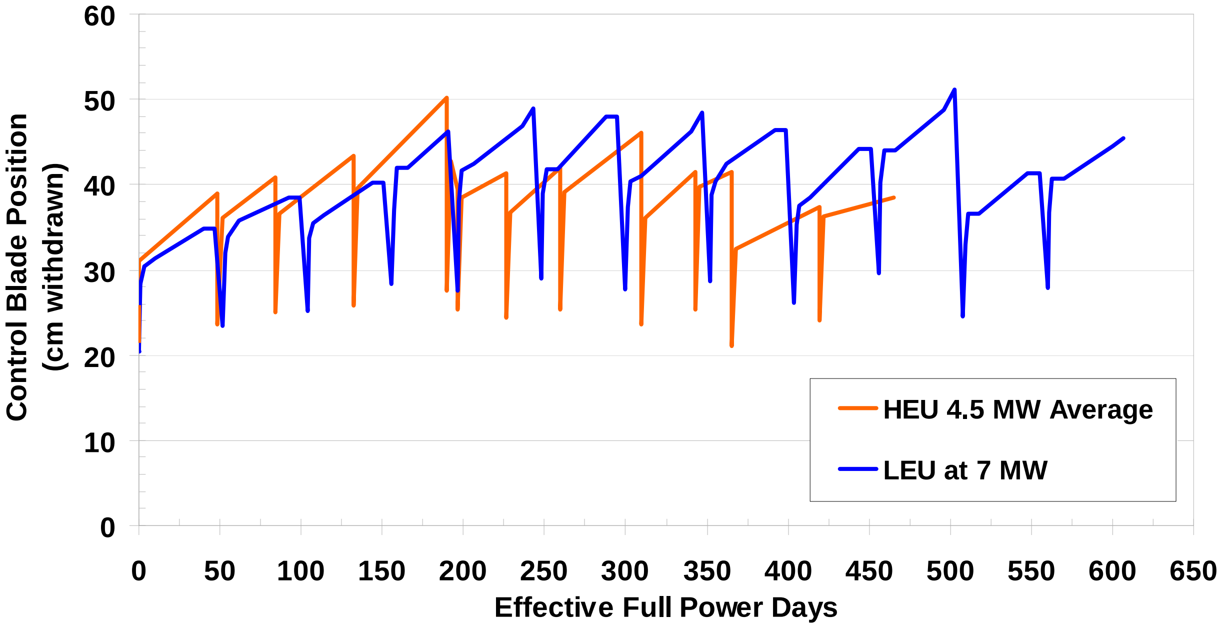

Figure 2. Control blade position for twelve HEU and LEU cores

Optimization of the MCODE model was studied, taking into account run times while varying the number of plates (radial zones) per element, axial nodes, and azimuthal "striping" in a depletion zone, as well as considering the number of particles modeled in MCNP. Although run times get significantly longer for the overall number of nodes, a model of a single radial zone per element, sixteen axial nodes and a single azimuthal stripe was considered adequate for use in routine MITR fuel management. These numbers can be easily varied for more specific analysis needs, and finer meshes should be periodically used to avoid compounding of errors [6].

There is also an effort underway to make an automated preliminary assessment of fuel management options prior to running MCODE. This will eliminate unnecessary runs and provide refueling options that are more optimized than the ad hoc method currently used.

5. Mixed core results

In addition to optimization of current cores, efforts have been made to optimize fuel management during the transition to LEU fuel. Because MIT will likely be the first reactor to begin using monolithic U-Mo fuel, we plan to gradually introduce LEU fuel into the HEU core over a number of refueling cycles. MCODE has been used to develop a refueling scheme while minimizing power peaking. Initial results, shown in Figure 3, indicate that LEU peaking is generally higher than HEU elements and that HEU peaking drops considerably as more LEU elements are added, thus making power higher in LEU elements, particularly newer ones. Peaking is also generally higher at the end of the fuel cycle. Thus, it may be necessary to keep a reserve of fresher HEU elements on hand during the transition period.

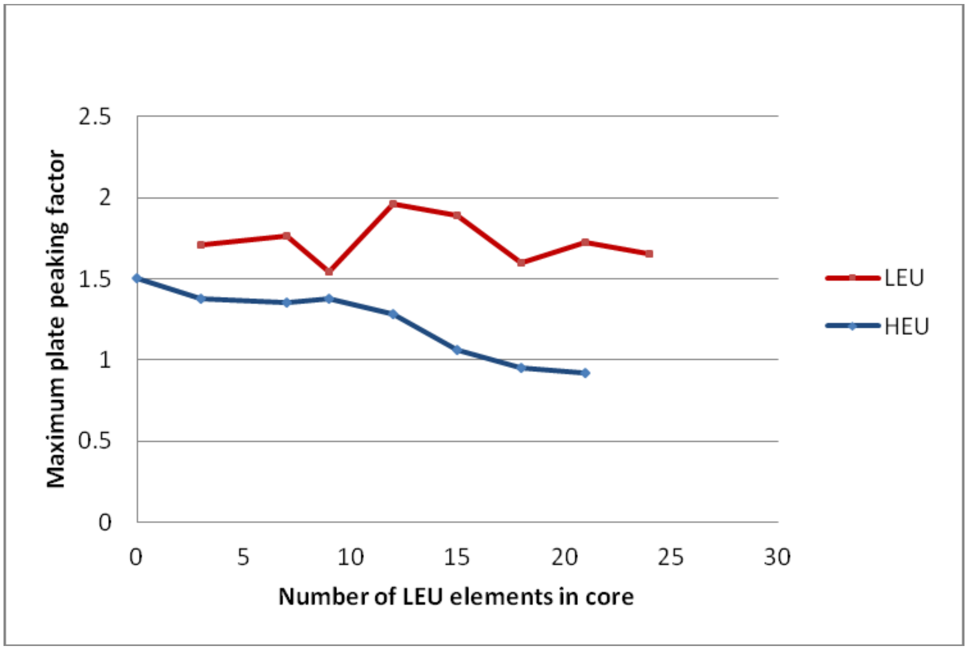

Figure 3. Maximum power peaking in transition cores

6. Distribution of Oxide on the Cladding Surface

Although initial testing on monolithic UMo fuel shows that there may not need to be a burnup limit, there is concern about the buildup of oxide on the aluminum cladding, in particular the distribution of oxide on the finned surface of MITR fuel. This can also change the effectiveness of the fins in heat transfer, particularly in transient conditions.

In order to quantify this, a series of measurements using an eddy current probe were made on the surface of spent HEU fuel and compared with fuel parameters such as pH, heat flux, and operating history. Unfortunately, because of the nature of eddy current measurements, only the oxide thickness on the tip of the fin can be quantified, so further measurements using a replication technique are being planned. In addition, a series of irradiation tests using plates prefilmed with a boehmite coating are being planned.

7. Maximum Hypothetical Accident Analyses

A preliminary analysis of the doses from radiation release of the maximum hypothetical accident (MHA) was made [7]. The MHA is a scenario in which a flow blockage occurs in a fuel element, completely obstructing flow to a number of channels. For the HEU fuel design, four plates are assumed to have melted, whereas in the LEU case five plates are assumed melted because of the larger number of plates in an LEU element. All plates are assumed to be at the maximum calculated peak power, with a peaking factor of 2.0 assumed for HEU operating at 6 MW and 1.76 assumed for LEU operating at 7 MW.

Because of the absence of release fraction data for UMo fuels, both HEU and LEU fuels are assumed to have identical release fractions for fission products and actinides. The release fractions were based on NRC regulatory guides 1.195 and 1.183 and assumed 100% of noble gases and 90% of I and Br were released to the coolant, with the coolant-to-containment releases based on evaporation.

A summary of offsite dose results at 8 and 21 meters from the reactor containment building (points of closest public occupancy) are shown in Table 1. These indicate that the LEU doses are slightly larger, due mostly to a larger number of plates melting. The doses are dominated by noble gases and iodine, with the actinide contributions being negligible, even with the significantly larger mass of U-238 in the LEU fuel.

Table 1. Offsite dose consequences from the maximum hypothetical accident

	HEU	**LEU**
Power (MW)	6.0	7.0
Number of plates melted	4	5
Total thyroid dose (rem)	0.179	0.233
Total dose at 8 m (rem)	0.398	0.486
Total dose at 21 m (rem)	0.529	0.640

8. Further analyses

A number of efforts are ongoing in analyses and determination of heating effects. A heated out-of-pile loop is being built to verify correlations for onset of nucleate boiling for finned channels. Analyses of thermal “striping” on a fuel plate with two dimensional heat transfer have been performed. In addition, a statistical treatment of thermal-hydraulic safety limits has been studied. These results will be presented in a separate paper at this conference [8].

A preliminary assessment of requirements for the Safety Analysis Report for the conversion of MITR from HEU to LEU Fuel was also made, including proposed fuel specifications and tolerances, assumed fission product release fractions, as well as identification of methodologies and requirements for LEU safety analyses [9].

9. Conclusions

LEU conversion analyses of the MITR have proceeded with improvements to neutronic models for HEU, LEU and mixed cores. MCODE has been updated for use in routine fuel management and analysis of LEU fuel needs have shown that about 30% less LEU fuel will be needed to maintain operations at 7 MW, as compared with current HEU operations at 6 MW.

Neutronic, thermal-hydraulic and radiation release analyses continue to show that conversion of the MIT Reactor to monolithic U-Mo LEU fuel is feasible and show some advantages over the current HEU fuel. Conversion of the MITR awaits successful qualification and demonstration of UMo fuel.

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