DEFUELING THE MITR-II FOR LEAK REPAIR

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On December 12, 2022, the MIT Research Reactor (MITR-II) was shut down after the operator noticed a reduction in nuclear safety channel power indication [1]. Investigation into the vertical port which houses the detector revealed that primary water had leaked from the core tank and/or system piping and flooded the port well, causing the decrease in neutron signal. It quickly became clear that intensive investigation efforts would be needed, but were limited by the high dose from the irradiated fuel in the core tank. Defueling the entire core tank, including the wet storage ring, was necessary in order to mitigate the dose to reactor staff during leak location and repair efforts. To support complete defueling, supplemental criticality analyses were performed for the fuel storage location. It took a total of 10 working days to remove all the fuel from the core tank. Additional Helium-3 detectors were installed in a reactor vertical port to monitor neutron count rates as fuel was moved out of the core, and to establish a reference for the data readings that would be expected during future refueling. January 31, 2023, was the first instance since initial core loading in 1975 that the core tank had held no fuel [2].

1. Introduction

1.1. Overview of Reactor Design

The MITR-II is a 6 MW thermal, tank type research reactor that is light water moderated and cooled, with a heavy water and graphite reflector. Nominal operation of the reactor follows a quarterly cycle, with continuous operation at 5.7MW for approximately 11 weeks followed by an outage period of 2 weeks for refueling, experiment removal and installation, equipment maintenance, and surveillance testing and calibration. The reactor can accommodate up to 3 in-core experiments, and has many auxiliary irradiation facilities including a vertical thimble, horizontal beam ports, pneumatic tubes, and a thermal neutron beam (TNB) room [3].

The reactor core sits at the bottom of the light-water-filled core tank and holds 24 fuel elements. Around the periphery of the interior wall of the core tank sits a cadmium-lined wet storage ring with 27 available positions for storage of partially spent fuel elements, solid dummies, and experiment dummies or apparatus. An interim storage location exists on site to hold discharged fuel elements until such time as they can be transferred offsite for long term storage. Typically, the spent fuel storage pool (SFP) contains up to a dozen fuel elements awaiting shipment. There are three cadmium lined storage racks in the pool, consisting of a 5x5 grid theoretically capable of storing a total of 75 elements.

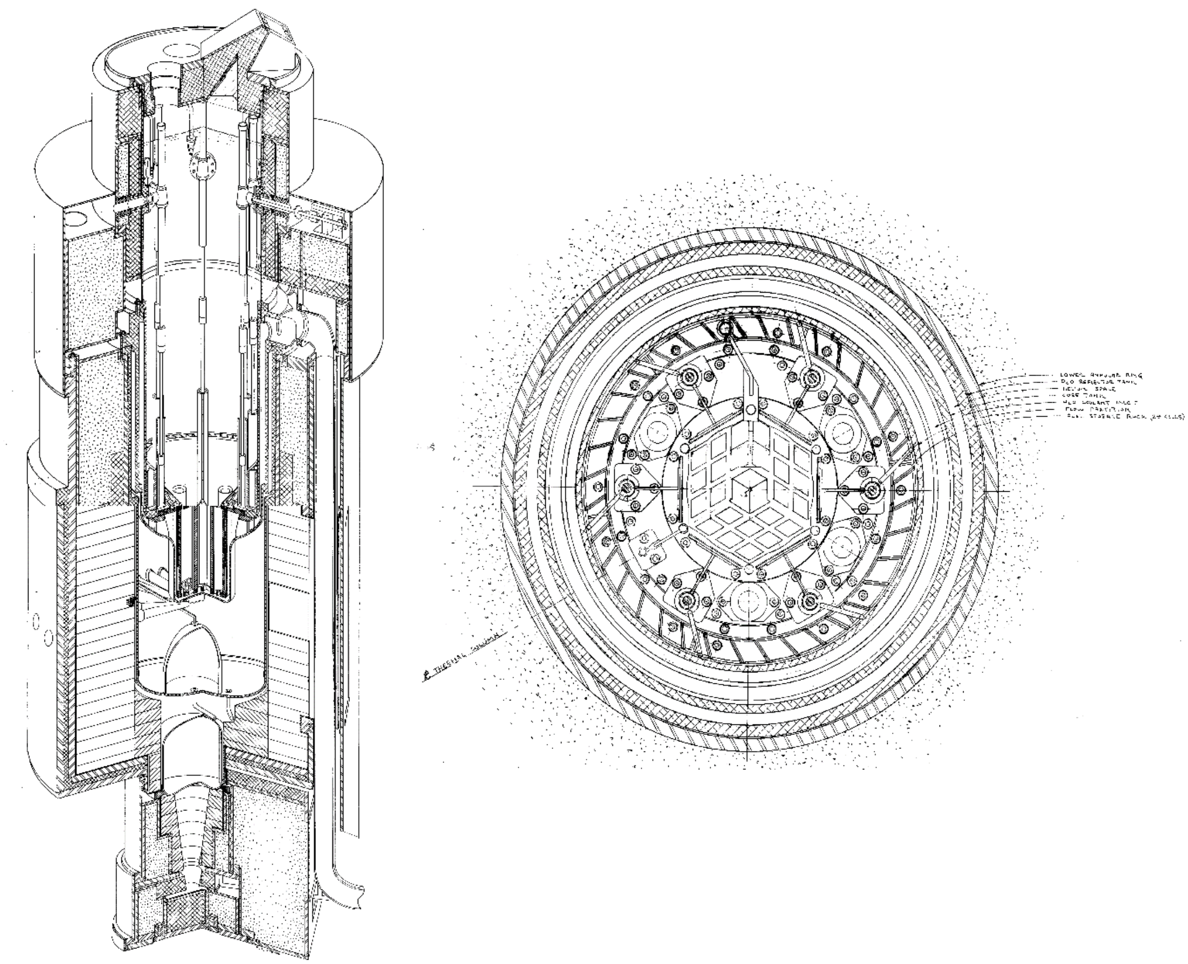

Figure 1: Engineering drawing cross section of core structure: Vertical slice showing core tank, reflector tank, graphite region, and upper shielding blocks on left; horizontal slice showing core tank, wet storage ring on right [4,5].

1.2. Description of Events

On the morning of December 12, 2022, the console operator observed on the 0900 hourly logs that the signal from nuclear safety channels #2 had decreased more than was expected from typical instrument fluctuations. After informing the on-shift Supervisor and briefly investigating for other potential causes, the operator immediately shut down the reactor, as the signal loss was continuing and a leak was suspected. Operations staff inspected the reactor top, TNB room, and equipment room for any signs of a leak. At 1829 a shutdown checklist was initiated to secure reactor systems from full power operating alignment [1]. Further investigation was performed the following day on the pneumatic tube system and nuclear instrumentation with no abnormal conditions found. After sufficient decay time had passed, on December 14, staff opened up the port plug for the graphite region vertical thimble that houses the fission chamber for channel #2 and discovered the entire volume was filled with water. The fission chamber was removed and placed in dry storage. Attempts were made to drain the water but were quickly halted by the reactor radiation protection (RRP) officer present, due to radiation levels from contaminated sediment. Gross activity sampling of the water confirmed it had to come from the primary system due to the levels of detected Na-24 that result from a high energy (n, alpha) reaction with the Al6061 structural materials of the core tank. Work was postponed and an operations planning meeting held to discuss next steps [6].

1.3. Decision to Defuel

There was a limited list of likely points of failure that could be allowing primary water to leak into the graphite region and pool in the 3GV2 thimble. Attempts to drain the water were unsuccessful and the region continued to fill and overflow, indicating the leak was continuing. Measurements of the volume drained and time to refill allowed an estimation of the leak rate to be made, approximately 7.5 gallons of water each day. The leaking water was dripping down the pipe chase tunnel into the basement equipment room where it was possible to collect it into 55-gallon drums and monitor the level.

Attempts to lower the core tank level to determine the height of the leak and potentially halt it were also unsuccessful. The decay heat from the core and wet storage ring placed limits on how far the water level could be lowered and how long low levels could be maintained. If the leak could not be observed from outside the reactor shielding or easily located by core tank level manipulation, the only remaining option was to remove large shielding blocks from around the core tank to search for visual indications of moisture. The heat removal requirements and dose limits indicated that it was necessary to remove all fuel from the core tank, in order to protect personnel and safeguard against the possibility that the leak may worsen and sufficient water levels might not be maintained.

2. Defueling Process

2.1. Space and Logistics

Defueling the core tank in its entirety was a time-consuming process due to the space constraints and resulting limits on fuel movements. To discharge elements from the core tank, the fuel cask must be placed on top of the reactor lid and fuel elements winched up inside the cask via a port plug in the lid. This configuration allows access to only four positions of the wet storage ring plus the element lifting basket where an additional pre-loaded element may sit. Therefore, a maximum of 5 elements can be removed from the core tank before the transition shielding pieces must be disassembled and the lid removed in order to position the next batch of elements. Only one maintenance crew at the NRL is sufficiently trained and experienced to perform these evolutions. It took four full work days to empty the wet storage ring, another day to move all 24 active core elements from their in-core positions into the wet storage ring, and then five more days to empty the ring into the storage pool again.

The storage pool racks were designed with 75 total positions. At the end of all defueling procedures they held a total of 63 partially irradiated elements. Other non-fuel components stored in positions, including experimental dummies and capsules, were moved elsewhere in the storage pool to free up the cadmium-lined positions.

2.2. Procedure Guidelines

All core tank fuel movements and changes to core configurations are controlled by a set of written procedures that ensure movements are properly documented, safety calculations are performed, and all necessary approvals have been given. Nominal evolutions include shuffling fuel within the core tank, movements between core positions and wet storage ring, and movement of fuel from the storage ring out of the core tank into the SFP [7].

Several new questions had to be addressed throughout this maintenance process: how to satisfy instrumentation and monitoring requirements using the remaining detectors during fuel movements when most of the fissile material has been removed, how to document and verify safety requirements are met for subcritical core configurations outside the experience of operations staff, and preparing a written procedure for eventually moving fuel back from the SFP into the core tank.

Much of the planning relied on the documentation from the initial MITR-II Startup Report from 1975 [2]. It provided reasonable justification for normalizing element counts on a 1/M plot to a critical mass loading, a qualitative comparison of the measurements for a <22 element core loading, and guidelines for stabilizing fuel elements in the grid plates while so many positions are empty.

3. Criticality Analysis

The necessary number of storage positions needed far exceeded the usual number of elements in the SFP. In 2016, in response to NRC concerns about cadmium degradation in wet storage systems, a Criticality Study was performed for several fuel storage locations at the NRL including the SFP and the in-core wet storage ring [8]. The report made three recommendations concerning the storage pool, depending on the number of fuel elements to be stored, a summary of which is given in Table 1.

Table I: Criticality Study Conclusions

# Elements	Storage Limits
0-9	None, no credit for Cd.
10-20	Use only one rack, do not use centermost position or its four neighboring positions (8, 12, 13, 14, 18). No credit for Cd.
20-60	Maximum of 20 fuel elements per rack, same restrictions as above. Racks should be mechanically fixed or a spacer installed to maintain distance. No credit for Cd.
61+	Taking credit for cadmium content required, no specific configuration guidelines listed.

A new procedure was also written to measure the presence of cadmium in the storage box liners by removing the side plate of a single box and taking weight measurements to estimate cadmium mass. An acceptance criterion of 10% of original mass was implemented with a surveillance frequency of 5 years [9].

3.1. Storage of >60 Elements

There was not any reason to suspect complete loss of cadmium liners. However, due to the way the most recent analysis was reported and the abnormal number of elements requiring storage, additional calculations were run to study configurations with full racks. The analysis preserved most of the initial conditions and model assumptions used in the full 2016 report, including geometry, fuel specification, and data libraries. The problems were run in MCNP5 v1.60 with new starting random seeds, an increased number of neutron histories, and twice as many active cycles [10]. The available data for cadmium content was sourced from the original fabrication drawings and records of the most recently performed PM 7.4.6.4 SFP Fuel Storage Rack Cadmium Degradation Monitoring. The last performance of the procedure in February 2021 measured a satisfactory weight of 280 g [9]. It is assumed the weighed liner is representative of every box side as there is not data for other inserts. The minimum 81 g value was used in the analysis as a conservative boundary condition for every storage box in the model. The aluminum structural materials were again neglected in this analysis and the modelled cadmium density was reduced to preserve the liner volume for the assumed mass; see Fig. 2.

Three rack spacing positions were modelled and are shown in Fig. 3; a nominal case (A) with the center of each rack 66 cm from the central point, a minimum[1] triangular case (B) with a rack spacing of 44 cm from the central point, and a physically unlikely linear stacked case (C). In all cases the pitch between elements was set to 11.0 cm as the most conservative value in the previous parametric study [8]. Each rack is filled with 25 identical lattice units of the fresh HEU fuel element inside a cadmium liner box shown in Fig. 3. In every case the pool was modelled with pure 20 C light water at a density of 0.997 g/cc.

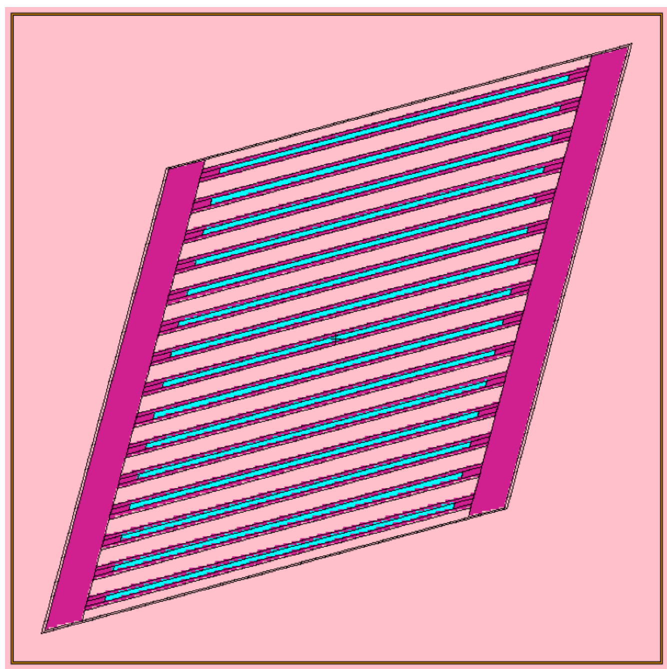

Figure 2: Modelled HEU element inside cadmium box liners. Element Al6061 cladding (magenta), UAl_x fuel meat (cyan), light water (pink) and cadmium (yellow) are shown.

The values of k_{eff} and associated standard deviations are given in Table 2 for all three cases. Under conservative assumption, every case was well below the margin for subcriticality and TS limit of 0.9 for fuel storage [11]. The full storage racks appear to remain sufficiently neutronically isolated from each other in all configurations, allowing for the use of all 25 positions. Provided there is no reason to suspect the cadmium liners have been removed or degraded, a mechanical spacer will also not be required to fix the racks at a predetermined location in order to store fuel elements in all three racks. Under conservative

[1] The minimum spacing of case B was increased from 42 cm used by K. Sun [8] to 44 cm to accommodate the geometry of the cadmium box liners.

assumptions of 75 fresh fuel elements, cold 20 C water, and only 10wt% cadmium content remaining in the box liners, subcriticality will be maintained with a sufficient margin.

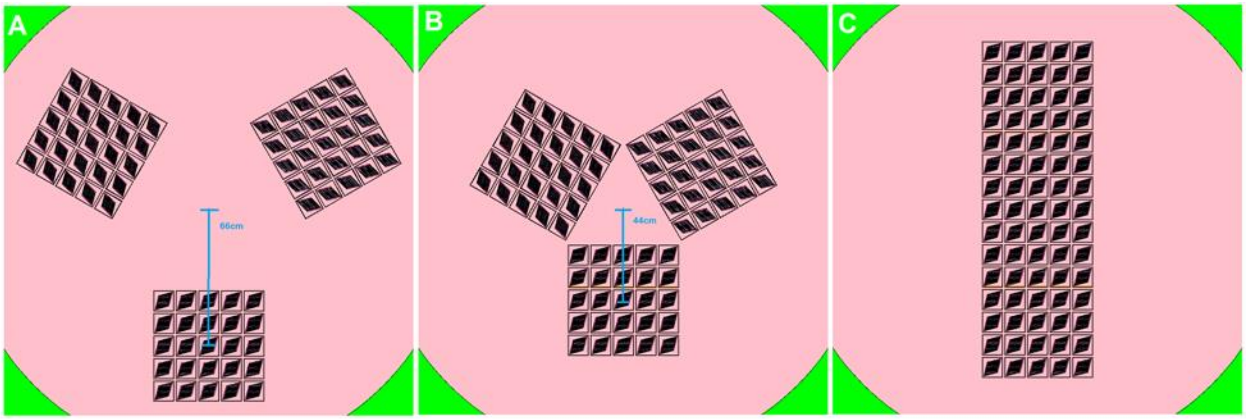

Figure 3: Three cases of rack spacing configurations. Case A (left) has a nominal 66 cm distance from the pool center, Case B (center) with a minimum distance of 44 cm, and Case C (right) with an unlikely linear stacking of the racks.

Table II: Eigenvalue results for three cases of rack configurations in the SFP.

Case	**k_{eff}**	**1 σ uncertainty**
A - Nominal (66 cm)	0.52860	0.00019
B - Minimum (44 cm)	0.52983	0.00013
C - Stacked	0.55994	0.00013

3.2. Temporary Storage Rack

It was discovered, during the fit testing of the SFP racks using a non-fueled dummy, that more positions had warped or swelled than were previously assumed and could not be used to hold partially irradiated fuel. At least 63 positions were needed to store all of the fuel elements removed from the core tank in addition to the existing SFP inventory. A request was made for analysis to determine whether a temporary storage rack could be made to provide six extra appropriate storage locations for elements. The rack was planned to be simply constructed of 6” OD Al6061 tube, with ¼” thick walls. This material was selected because it was already available on site and could quickly be assembled into a serviceable rack. The tube was cut into approximately 18” tall segments and welded together into a packed triangle shape; see Fig. 4. The edges of the tubing were de-burred to prevent scratches or damage to the elements. There was no cadmium or other neutron-absorbing material in the temporary rack storage structure.

The same calculations as in Section 3.1 were repeated with the temporary storage rack in the center of the pool and fully filled. Each of the three permanent racks were again filled with fresh HEU elements, surrounded by cold 20 C pure light water, and the rack liners wee assumed to contain only 10% cadmium mass. The racks were spaced 49 cm from the center of the pool, slightly further apart than the minimum distance analyzed previously but allowing for the addition of the temporary rack; see Fig 4. This model had a total of 81 fresh elements, 18 more than the maximum planned for storage. With the full temporary rack, the resulting k_{eff} of the system was 0.61020 ± 0.00014, well below the margin for subcriticality and the limit specified in TS 5.4.4 “Fuel Element Storage” [11].

Figure 4: Temporary storage rack after component welding but before final de-burring and cleaning for install into SFP (left). Full SFP racks under most conservative conditions, with temporary Al6061 storage rack in the center. 81 total HEU elements modelled, 10% cadmium mass assumed in permanent rack liners (right).

4. Refueling the Core Tank

A primary concern for refueling is measurement of source counts as elements are placed in core positions. The instrumentation used for full power operation is located quite far from the core and source neutrons must traverse the core tank, heavy water reflector, and graphite reflector region to reach the detectors. Additionally, MITR-II has predominantly relied upon photoneutrons as a startup source, utilizing the reaction between the deuterium in the reflector tank and the MeV range photons given off by decaying fission products to achieve a measurable count rate without having to install an external neutron source. As a result, the neutron sources the NRL maintains on site are fairly weak, the strongest only producing on the order of 10^7 nps. Initial refueling is expected to be monitored in a similar manner as the core defueling evolution, using several Helium-3 detectors temporarily installed in a vertical thimble until the signal is strong enough to be measured by the less-sensitive fission chambers of the nuclear safety system.

The discovery of the primary leak delayed many important irradiations, training evolutions, licensing exams, and other scheduled maintenance. However, the process of locating and correcting the leak provided NRL staff with many valuable lessons with respect to equipment, documentation procedures, reactor design, and job planning. Many of the shielding blocks removed and auxiliary system components that were exposed have not been seen since original installation in the mid-1970s. Defueling the entire core tank was a serious undertaking, but it allowed for dose exposure minimization and the concurrent performance of other potential high-dose projects near the core tank. When the location of the leak was found in a primary system pressure sensor line, it validated the decision to defuel as repairing that pipe and connection would then have required removing the upper shield access ring and draining the core tank to the level of the anti-siphon valves. Making the decision early on allowed us to avoid the extra exposure and heat removal concerns during the investigation.

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