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Special Considerations for the Removal and Disposal of Micro-Reactor Experiments

March 2024

Changing the World's Energy Future

Kristina Diane Yancey Spencer, Evans Damenortey Kitcher, Brett D Welty, Mitchell S Woolf, Andrew J Smith, Jared Harper, James A King, Nicholas Vise Smith

Idaho National Laboratory

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Special Considerations for the Removal and Disposal of Microreactor Experiments – 24540

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ABSTRACT

Idaho National Laboratory (INL) is preparing to host several microreactor experiments through 2030 and beyond. Two new test beds currently under development will operate as microreactor or nuclear system experiment user facilities. Test bed experiments will be performed in series, with each nuclear experiment installed, operated, and removed before installation of the subsequent experiment. The necessarily brief transition period between experiments introduces unique equipment removal and radioactive waste disposal challenges.

This paper evaluates equipment removal and radioactive waste management topics associated with tight sequencing of nuclear experiments and presents some of the solutions and approaches currently planned to meet these special considerations for one such experiment, the Molten Chloride Reactor Experiment (MCRE), slated for operation at INL's Laboratory for Operation and Testing in the United States (LOTUS). The MCRE project is a collaboration between Southern Company Services, TerraPower, and INL, among others, to provide integral nuclear data that will advance molten salt fast reactor technology. MCRE will be the first critical fast-spectrum circulating fuel system ever operated and the first experiment operated in the LOTUS test bed. The experiment will nominally operate at zero power with planned low power excursions, as part of operational planning for MCRE has been to minimize at-power operations to limit fission product formation while still achieving experimental objectives. After the experiment is complete, MCRE will be allowed to radioactively decay for a short period (nominally 90 days) prior to system defueling, flushing, removal, and disposal of all MCRE equipment, readying the test bed for the next nuclear experiment.

Equipment removal and radioactive waste disposal have been integral to MCRE project planning since the Cooperative Research and Development Agreement was formalized in 2021. Due to requirements for future use of the test bed, the MCRE system, of necessity, must be removed in a much shorter time frame than typical for historic reactor decommissioning projects at INL. This results in minimal time for radioactive decay, resulting in not only elevated radiation dose rates but also the presence of short-to-medium-lived isotopes not typically encountered in the reactor decommissioning and radioactive waste management space. Additional unique constraints placed on the project include lack of intrinsic remote-operations capabilities in the test bed, space constraints in the test bed once MCRE has been installed, and contamination minimization requirements to return the test bed to as-found conditions to enable future use.

This paper discusses planned solutions to these challenges. Approaches for implementing remote or semi-remote technologies in a non-hot cell environment with limited space availability are discussed. The paper also summarizes the systems engineering approach for concept development and design of equipment removal systems, which are being implemented concurrent with the MCRE design process, providing feedback to system designers to incorporate features enabling efficient and safe equipment removal approaches.

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The timing of this paper at a relatively early phase of the project is meant to highlight the importance of early planning for nuclear system decommissioning while reactor design is ongoing to allow design feedback on componentry driven from decommissioning system needs. As new, innovative nuclear reactor technologies enter the nuclear market sector, reactor experiments are crucial for providing new integral nuclear data that establish safe operational margins for technology advancement. Microreactor experiments at INL will require safe, effective, and timely decommissioning approaches, which in turn require nuclear systems designed to expedite decommissioning. In addition to the advancement of nuclear reactor technologies, these nuclear experiments provide an opportunity to demonstrate, deploy, and test new removal and disposal capabilities to support the next generation of nuclear reactor technology.

INTRODUCTION

This paper evaluates equipment removal and radioactive waste management topics associated with rapid turnaround of nuclear experimentation. It focuses on the solutions and approaches being planned for one such experiment, the Molten Chloride Reactor Experiment (MCRE). This experiment is funded through the US Department of Energy's (DOE) Advanced Reactor Demonstration (ARD) Program Risk Reduction Pathway award. The MCRE ARD project is a collaboration between Southern Company Services, TerraPower, LLC, and Idaho National Laboratory (INL), among others, to provide integral nuclear data to advance molten salt fast reactor technology. MCRE will be the first critical fast-spectrum circulating fuel system ever operated, and it will be constructed and tested at INL in one of two new test beds for reactor and nuclear system experimentation.

As the principal nuclear energy laboratory, INL's mission is "to discover, demonstrate and secure innovative nuclear energy solutions, other clean energy options and critical infrastructure" [1]. Over the last 70 years, more than 50 unique reactors have been tested and operated on-site, and INL is planning to host multiple microreactor experiments through 2030 and beyond. The laboratory offers unique capabilities to support reactor experiments, including dedicated facilities for nuclear fuel fabrication, examination, and handling, including the new Molten Salt Thermophysical Examination Capability (MSTEC) [2].

MCRE will be the first nuclear experiment operated in the Laboratory for Operation and Testing in the United States (LOTUS) test bed. LOTUS is one of two test beds being established at INL by the National Reactor Innovation Center (NRIC) to host nuclear experiments in support of advanced reactor technology [2]. The other is the Demonstration and Operation of Microreactor Experiments (DOME), which will be built in the facility that housed the Experimental Breeder Reactor II. Experiments will be performed in these test beds in series, with each nuclear experiment being installed, operated, and removed before installation of the subsequent experiment. While this type of serialized experimentation does exist for traditional critical experiments, it does not currently exist in the US for micro-reactors. DOME and LOTUS will help fill a need for more integral nuclear data to support new reactor types.

Removal and disposal activities for micro-reactor systems are different from those for traditional assembly-style critical experiments (such as those funded by the Nuclear Criticality Safety Program) as critical experiments can be reconfigured or replaced on a relatively short time frame due to the lack of fission product buildup. They are also different from decommissioning activities for traditional power or research reactors, which typically radioactively decay for years to decades after the operational period has ended prior to removal and disposal. Given the intended reuse of the facilities, demonstrators and experimentalists have an obligation to return the test beds to as-found condition shortly after the end of experimentation.

The necessarily brief transition period between nuclear system experiments introduces unique equipment removal and radioactive waste disposal challenges. Therefore, the equipment removal and disposal (ERD) of MCRE from the LOTUS test bed is an opportunity to develop new decommissioning techniques for small nuclear experiments and future molten salt systems.

LOTUS TEST BED DESCRIPTION

NRIC was established in August 2019 with the aim of accelerating the demonstration and deployment of advanced nuclear reactor technology. As part of this effort, NRIC is establishing the LOTUS test bed at the Materials and Fuels Complex at INL. LOTUS will be constructed via modifications to the existing Zero Power Physics Reactor (ZPPR) cell, which originally housed the ZPPR critical experiments from 1978 to 1988 [3]. These experiments produced some of the most important integral data for fast burner reactors. In repurposing the ZPPR cell, the LOTUS test bed will continue this legacy, supporting the demonstration of nuclear experiments that operate at less than 500 kW_{th} and that require higher safeguards and security.

The ZPPR cell structure is a 15.24-m [50-foot] inner-diameter cylinder with thick walls of reinforced-concrete. The conceptual design of the LOTUS includes installation of an access door and tunnel on the side of the cell, a new heat removal system, new life safety systems (i.e., fire detection and oxygen monitoring), and new instrumentation and control systems as well as electrical power and necessary security upgrades [2]. Figure 1 shows a picture of the exterior of the existing ZPPR cell, which will become the LOTUS test bed. Figure 2 shows an aerial view of the ZPPR area overlaid with a plan view of the LOTUS facility based on the current LOTUS conceptual design. The overlay shows the cell, tunnel access, support areas, and yard area.

Figure 1. Picture Showing the Outside of the Exterior of the Existing ZPPR Cell Which Will Become the LOTUS Test Bed.

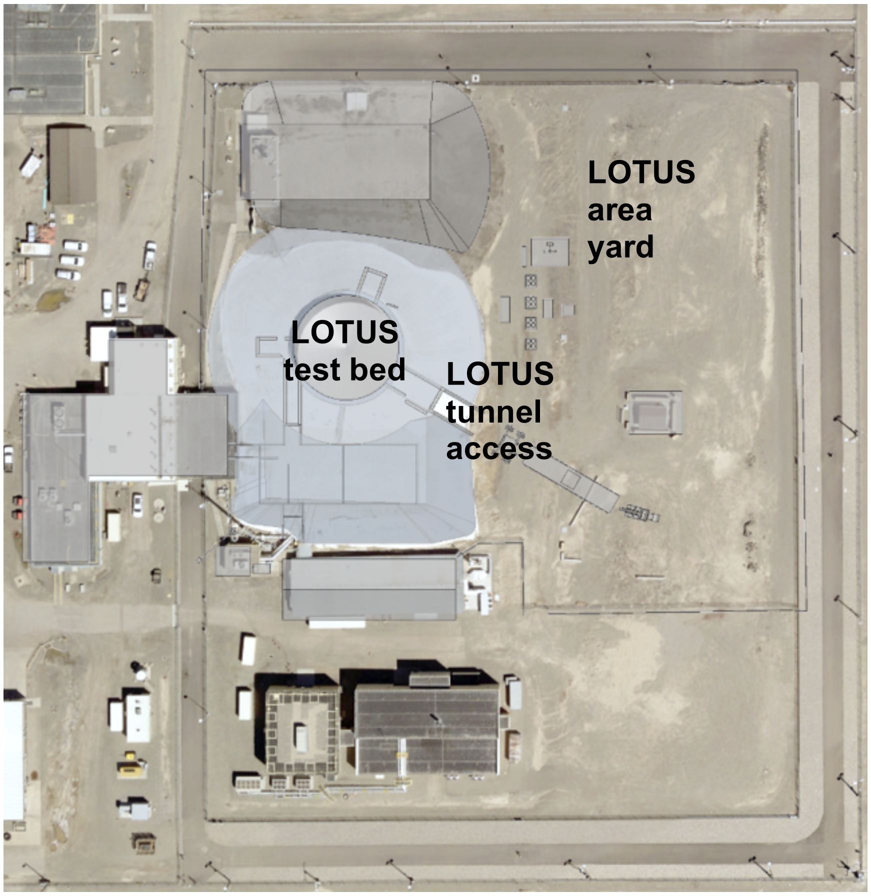

Figure 2. Aerial View of the ZPPR Area Overlaid With the Conceptual LOTUS Facility Layout Showing the Cell, Proposed Tunnel Access, Support Areas, and Yard Area.

The mission of the LOTUS test bed is to accelerate the development and deployment of advanced reactor technologies by providing a test bed where higher security material is needed. To perform this mission, successful removal of a nuclear experiment after completion necessitates the fast turnaround removal of the MCRE. Removal operations must be performed safely, in a timely manner, and without damaging the test bed to prevent extensive decontamination and rehabilitation efforts prior to acceptance of the next nuclear system experiment. Furthermore, ERD of the MCRE in a timely manner demonstrates responsible stewardship of the nation's resources and a commitment to limit future environmental liabilities for DOE.

This rapid turnaround objective provides opportunity for research and development of unique decommissioning technologies and human resources at INL and within the DOE complex. These activities will foster innovation for back-end technologies and techniques that will grow and mature in step with the nuclear system experiments, further accelerating advanced reactor technology development by providing confidence that advanced reactor components and structures can be successfully managed.

MCRE DESCRIPTION

MCRE will be fueled by a $NaCl\text{-}UCl_3$ eutectic mixture (67–33 mol.%) and will operate at a design temperature of 700°C. Table 1 shows key features of the experimental design. The experimental plan for MCRE includes nominal operations at zero power with planned low power excursions. While MCRE will be rated for 150 kW, part of the operational planning effort for MCRE has been to minimize at-power operations to limit fission product formation while still achieving test objectives. After the experiment is complete, MCRE will be allowed to radioactively decay for a relatively short period of time (nominally 90 days) prior to system defueling, flushing, and removal of all MCRE equipment, readying the test bed for the next nuclear experiment.

Figure 3 shows a depiction of the MCRE inside the LOTUS test bed. In the experimental configuration, the fuel salt loop and vessel are suspended from a support structure, and a magnesium oxide reflector is stacked around the vessel. The vessel, loop, and reflector are surrounded by a shielding system, a fuel handling glovebox for loading and unloading of the molten salt fuel, a fuel tank with a dedicated shield for keeping the fuel salt subcritical when the system is defueled, a cover gas system for keeping the fuel salt in an inert atmosphere, and other general plant systems. The figure also shows a tunnel on the right through which parts and packages will be transferred into the facility during installation and out of the facility during ERD.

Table 1. Selected MCRE Characteristics [4].

Parameter	**Value**
Rated Thermal Power	150 kW
Design Temperature	700°C
Design Pressure	500 kPa-g
Fuel Salt Mass Flow Rate	25 to 100 kg/s
Operating Temperature	600 to 650°C
Fuel Salt Melting Temperature	525°C
Fuel Salt Composition	NaCl-Ucl_3 (67–33mol%)
Fuel Salt Volume	0.302 m^3
Fuel Salt Mass	~1000 kg
Neutron Reflector	82% dense MgO
Reactivity Control	Four rods w/ B_4C 80 wt.% B-10

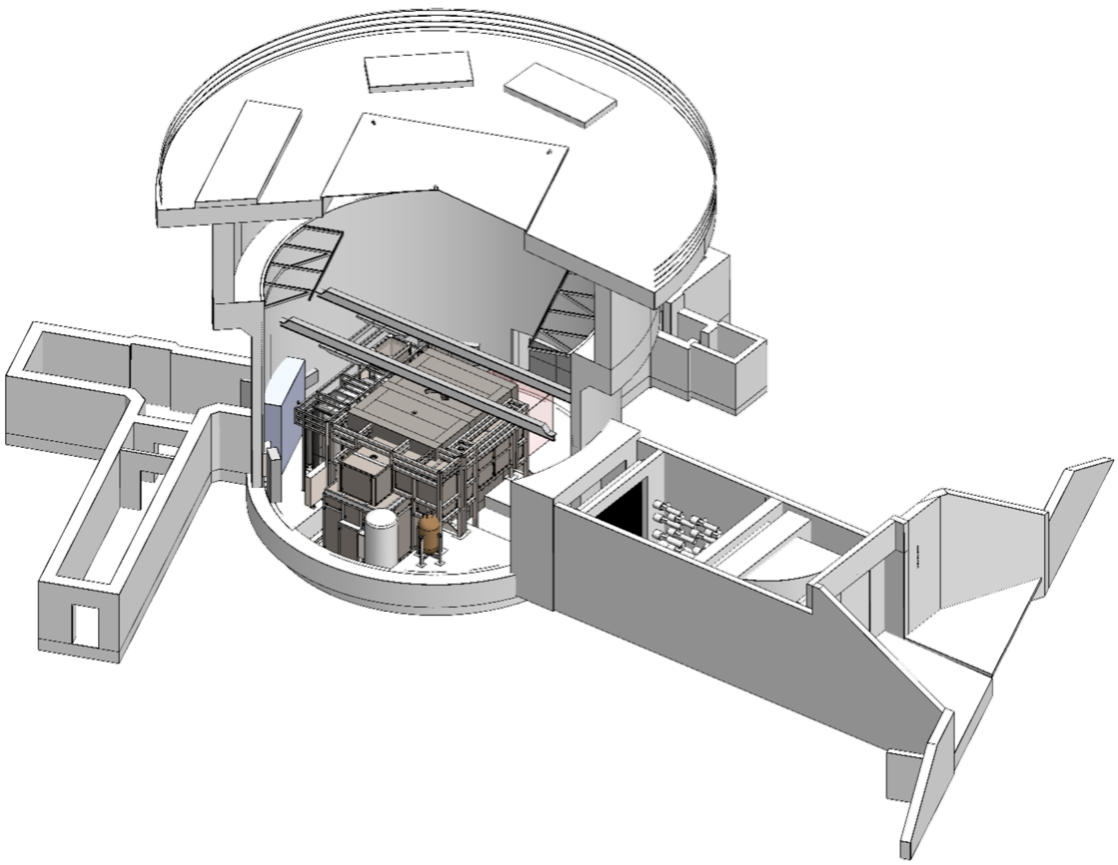

Figure 3. Illustration of the MCRE Inside the LOTUS Test Bed [4].

The MCRE project has completed conceptual design and is currently performing a series of system-level preliminary design reviews. This will culminate in a formal, facility-level preliminary design review in 2024. Concurrently, the design for the LOTUS test bed is progressing, and NRIC received approval for Critical Decision 1 (CD-1) from DOE on June 1, 2023 [5]. ERD planning is at the pre-conceptual level, and both the plan and the functional and operational requirements for ERD are progressing in conjunction with each MCRE system-level preliminary design review. It is expected that ERD plans and systems will complete conceptual design soon after the MCRE design completes preliminary design.

EQUIPMENT REMOVAL AND DISPOSAL CHALLENGES

ERD activities for the MCRE system pose interesting challenges. Some of the key challenges include the complexity and evolving nature of the MCRE design, constraints presented by the LOTUS test bed, the rapid time frame to remove all components from the test bed, the residue remaining after salt removal operations, and the need to take high-quality samples during ERD activities for post-irradiation examination (PIE) to fully maximize the knowledge gained from the experiment. These challenges are summarized here.

MCRE is a complex, evolving fuel salt system, and the project is attempting to achieve several high-level and sometimes competing objectives. Coordination of information and effort is essential between the various parties involved (TerraPower, Southern Company Services, INL, and others), especially to balance experimental design goals with LOTUS test bed constraints and ERD needs.

Space inside the test bed will also be constrained once MCRE has been installed. As the MCRE design has matured, more subsystems have been identified and added to the plant layout, consuming available space in the test bed. This is highlighted in Figure 4, which depicts a NavisWorks® Freedom[a] model with several systems hidden to make the figure more readable. When ERD activities begin, the space inside the test bed will be highly constrained. ERD equipment will have to navigate the area without causing damage to the test bed while maintaining the total weight on the floor below facility limits. Space constraints will ease as ERD progresses, but once space is cleared, then heavier, larger pieces of equipment will need to be removed. These components must fit through the tunnel shown in Figure 3, and they must be movable using either portable remote systems or the overhead LOTUS crane.

The rapid time frame for ERD also leaves minimal time for radioactive decay. This will result in both elevated radiation dose rates (relative to a reactor that had been inactive for an extended period) and the presence of short-to-medium-lived isotopes not typically encountered in normal decommissioning or radioactive waste management space. As a result, some of the components may contain radionuclides that are not covered in typical disposal facility waste acceptance criteria (WAC) or transportation regulations. For example, one comparison of a contaminated subsystem with the limits of an on-site radioactive waste disposal facility found significant contributions to dose from nuclides such as ^{35}S, ^{89}Sr, and ^{91}Y, which had no corollary in the facility's WAC or environmental performance modeling.

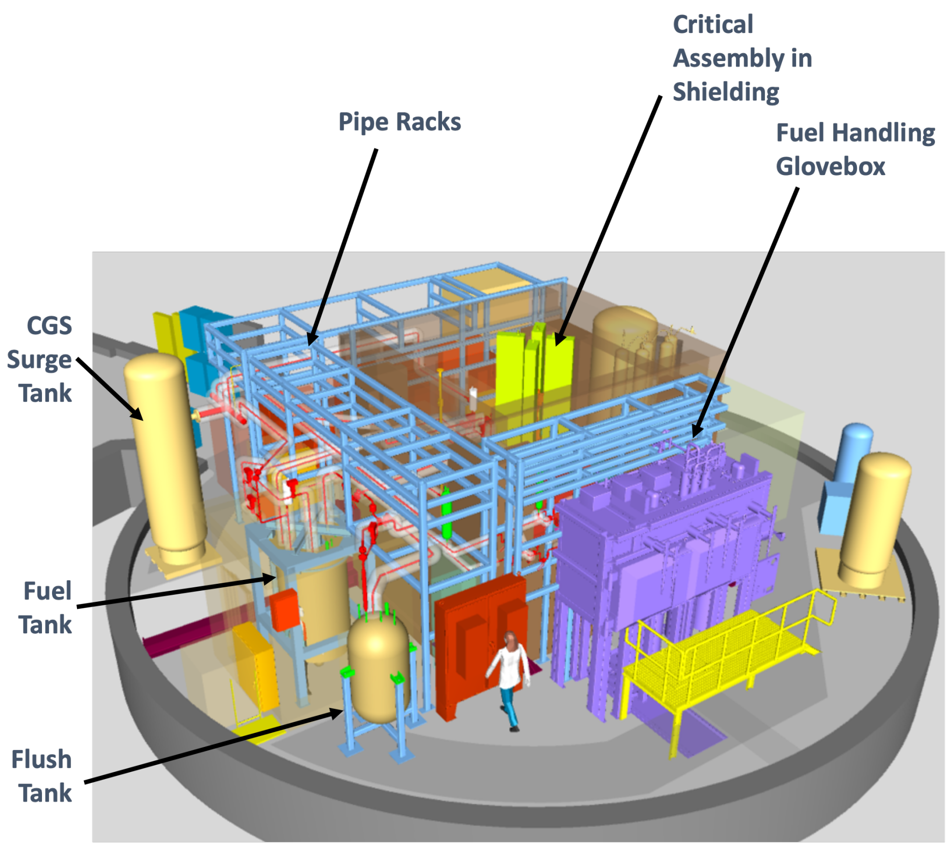

Figure 4. NavisWorks® Freedom Model Showing Some MCRE Subsystems [1].

[a] NavisWorks® is a trademark of Autodesk Inc.in the United States and/or other countries.

One of the unique aspects of MCRE compared to other small nuclear experiments is that the fuel salt will leave residue inside the system. The amount of residue will be mitigated by flush salt operations at the end-of-life, but some residual contaminated flush salt is expected to remain in the piping, the fuel salt freeze valves, the primary vessel, the fuel tank, and any other fuel salt-wetted component. Therefore, ERD capabilities for MCRE must be able to contain and handle any exposed contaminated flush salt, which could be present as a thin film or as small formations of salt in low places.

Additional unique ERD constraints include the need to collect samples for PIE and a lack of intrinsic remote capabilities in the LOTUS test bed. Samples collected for PIE range in size from small coupons to whole components (e.g., the fuel salt pump). To meet analysis requirements, some samples will need almost surgical removal from MCRE to prevent damage, which precludes use of more well-established decommissioning and deactivation approaches. Many of these samples will also require remote manipulation. Any remote capabilities employed to prevent radiation and contamination exposure to workers will have to be provided by the MCRE project.

PLANNED STRATEGIES TO ADDRESS CHALLENGES

The MCRE ARD project has adopted a systems engineering approach to plan, balance, and track strategies for these challenges during ERD to decompose the problem into more digestible chunks. All MCRE systems will need to be removed from the LOTUS test bed during MCRE ERD. As such, equipment removal and radioactive waste disposal has been an integral part of MCRE project planning since the Cooperative Research and Development Agreement was formalized in 2021. The NASA Systems Engineering Handbook is being used by the MCRE project to guide system planning and requirements development [6]. This handbook is the foundation for concept development and design of the ERD system.

The ERD system is currently envisioned as a collection of equipment and tools needed to successfully remove MCRE from LOTUS while protecting workers and maintaining the integrity of the test bed. Figure 5 illustrates the needs, goals, and objectives that were developed for the ERD system. This figure shows how removal of all MCRE equipment from LOTUS can be decomposed into four goals that each address a separate aspect of ERD. Specific metrics, or objectives, are identified for each goal to ensure that success can be quantitatively measured. For example, an "As Low As Reasonably Achievable" (ALARA) optimization process will be used to ensure that absorbed dose is minimized during ERD activities to protect workers. Other process details without specific metrics (e.g., most regulatory requirements) are being incorporated in functional and operational requirements for ERD but not optimized in this initial phase.

The operational framework for MCRE ERD is being developed using Innoslate®[b], a model-based systems engineering tool for cloud-based team collaboration [7]. Figure 6 shows the high-level sequence for the current ERD plan. The general approach is designed to remove non-activated, non-contaminated components first where possible to alleviate space constraints in the test bed when dealing with the more difficult components. Each of the high-level steps shown in Figure 6 are decomposed into more detailed steps, which are broken down further as needed. The Innoslate® environment enables steps to be developed in this manner while keeping track of when resources are consumed and when waste streams are produced. Eventually, the tool is planned to be used for time-motion studies and ALARA optimization.

[b] Innoslate® is a trademark of SPEC Innovations in the United States and/or other countries.

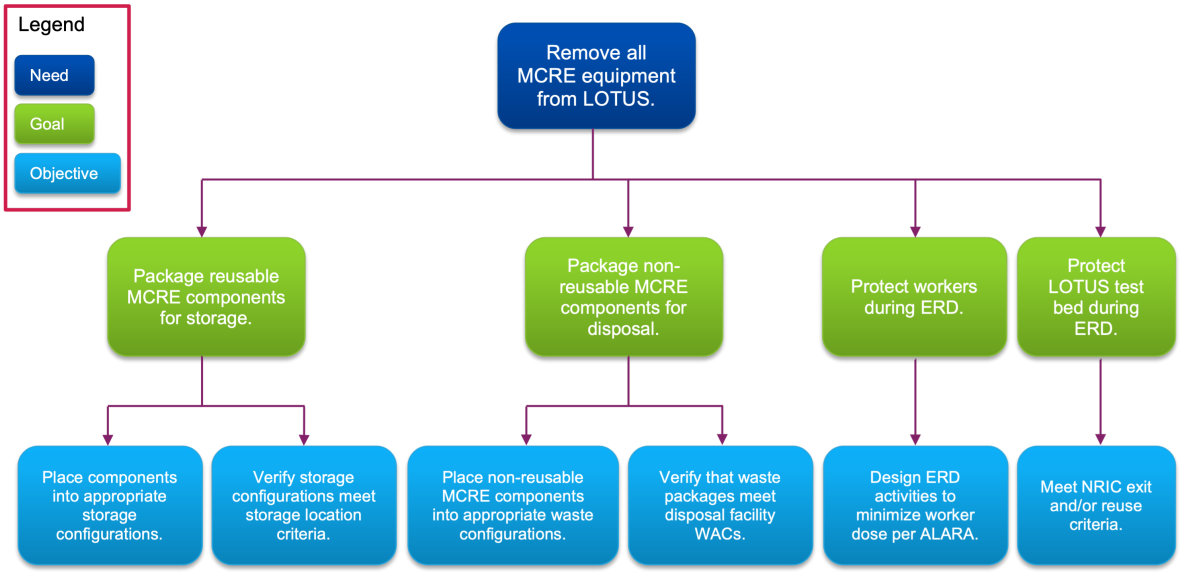

Figure 5. Needs, Goals, and Objectives for the MCRE ERD Operational Sequence.

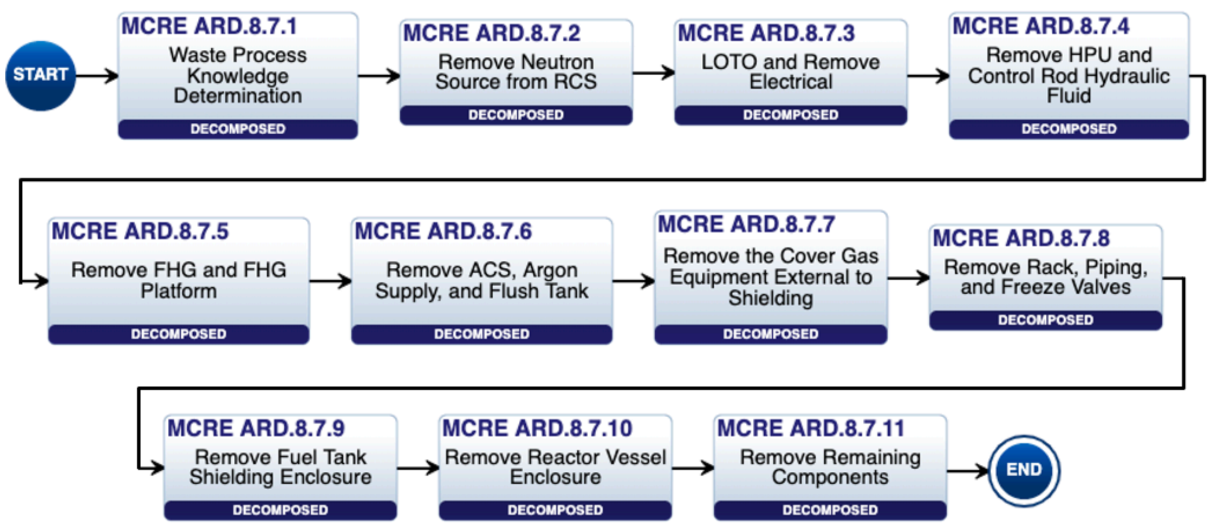

Figure 6. Diagram Showing the Decomposition for MCRE ERD. ERD begins after all fuel salt and contaminated flush salt have been removed from the system.

Design Complexity

At the highest level, the ERD system must be capable of performing several key functions:

- **Characterize the equipment** — For the ERD system, characterization is the determination of all material properties needed for ERD activities. This includes physical properties such as mass, volume, physical dimensions, radiological properties (e.g., dose rates to determine whether the material can be contact-handled or requires remote handling), and isotopic compositions (i.e., masses and/or activity levels for uranium or other fissionable nuclides, activation products, and fission products). This information will be needed for nuclear material accountancy, radiation control, and container packaging, storage, and transportation.

- **Control contamination** — Contamination control will need to be established throughout ERD activities to ensure protection of workers and to minimize impacts to long term use of the LOTUS test bed. Contamination control will range from localized controls, such as glovebags or containment boxes during contact-handled phases of ERD, to larger controls, such as contamination control enclosures or tents to establish contamination boundaries during remote-handled phases of ERD.
- **Perform work remotely** — Some phases of ERD will preclude manned entry based on radiation fields in the LOTUS test bed or within shielded enclosures. During these phases, the other functions required by the ERD system must be performed remotely. This functionality will include the ability for a remote worker to see the equipment and the work being performed.
- **Disconnect or detach the equipment** — Once characterized, each component will have to be disconnected for removal. Disconnection activities include disconnecting equipment from other MCRE equipment, from other LOTUS test bed equipment, and from the LOTUS test bed itself. This will involve tasks such as deenergizing hazard sources, establishing contamination control as necessary, and using manned, semi-remote, or remote tools as necessary to make disconnects or cuts. Disconnecting may also include unbolting items, making guillotine cuts, or making circular cuts.
- **Package the equipment into appropriate containers** — This task will bring empty containers into the LOTUS test bed and mate them to established contamination control so that the inside of the container will be exposed to the contamination area while the outside of the container will be kept clean. Equipment will then be sized and placed into the container. The container will be filled as needed per storage or disposal requirements, grouted if necessary, closed, and moved to the LOTUS exit. These functions will be constrained by the following factors:
    - Size, weight, and form of the material
    - Classification of the material
    - Radiological characteristics of the material
    - Timing of the material being removed from the LOTUS test bed
    - Intended disposal or storage facility.
- **Remove waste packages from the LOTUS test bed** — Once the package is secured, it must be removed from the LOTUS test bed and loaded for disposal or storage. Any man-portable packages will have to meet INL’s standard lifting and handling requirements as well.
- **Transport for container storage or disposal** — Once removed from the test bed and after the necessary holding time, the package will be transported to the appropriate storage or disposal facility.
- **Keep worker dose ALARA** — All ERD activities will be evaluated via the ALARA optimization process and planned accordingly to minimize dose to workers through time, distance, and shielding principles.

The number and variety of items and components for which these functions must be performed results in a complex set of capabilities for the ERD system. While most of these functions fall under well-understood packaging, removal, and decontamination techniques, some are less common. For example, strippable coatings or other contamination barriers may be selected that require installation prior to system startup could be used to prevent contamination of the LOTUS test bed. While the removal of most of the pipes can be handled using standard pipe cutting and crimping technology, the removal of the primary loop will necessitate the ability to make guillotine cuts through an Inconel pipe several inches in diameter.

To be successful, the ERD system will have to meet other functions and requirements that are currently in development. The list below describes additional proposed characteristics:

- **Reliability** – Aggressive timelines have been set for the MCRE project and for the turnaround of the LOTUS test bed for subsequent experiments. To meet this timeline, all components of the ERD system must have a high level of reliability in performing the identified tasks and in surviving the operational environment.
- **Redundancy** – As part of achieving reliability, the ERD system will have redundant capabilities, providing many different options to perform a task should the planned approach prove difficult to implement due to unexpected conditions or changes.
- **Recoverable** – The ERD system will have the ability to recover from upset conditions. This is especially true of remote systems used to handle, package, and transfer radioactive materials. The ERD system should provide a way to mitigate these upset conditions from happening and to recover in case they do happen to complete ERD activities without significant work stoppages.

The planning and sequencing work for ERD is being implemented concurrent with the MCRE design process. This enables the ERD team to provide feedback to system designers to incorporate features enabling efficient and safe equipment removal approaches. An example of how design complexity has driven ERD approaches is the operational need to suspend some fuel handling system components off the cell floor for enhanced cooling air flow and to meet material and structural temperature limits. During the ERD phase, these suspended components will be attached to the crane, disconnected from the structural supports, and lowered to the ground in a controlled manner. This will be performed remotely due to the expected radiation fields in the LOTUS test bed and/or shielded enclosures during the evolution.

Conversely, an example of ERD constraints driving experiment design is the ~4,500 kg (5-ton) load limit of the polar crane in the LOTUS test bed. This drives a strong preference for no single component to exceed this mass limit. Another ERD constraint driving some parts of the experiment design is the package limits associated with existing transport and disposal waste packages and facilities. These represent existing capabilities and resources that will interface with the ERD system, and the design of some components in MCRE have been limited to meet these constraints. For components that exceed these material handling limitations, design efforts have ensured that the components can be readily disassembled or sized.

The MCRE ARD project continues to identify, monitor, and manage the risks and opportunities presented by system interfaces through continued integration with design evolution. The ERD system functional and operational requirements are being concurrently developed with MCRE design maturation, detailing requirements at the lowest level possible as the process progresses.

LOTUS Test Bed Constraints

The key strategy for addressing space constraints in the LOTUS test bed is to remove non-activated, non-contaminated components first (e.g., electrical cable trays and power panels) to clear floor space for removal of more difficult components. These items will be disconnected, moved to the tunnel access, and lifted out of the test bed using the polar crane. Shielding used during operations will be kept in place for as long as possible to allow more radioactive components more time to decay before packaging, handling, and removal. Manned entry is expected to be possible while the shielding is in place, and the early stages focus on making space inside the test bed for remote equipment by removing ancillary equipment first.

Beyond freeing up space in the test bed, floor loading and polar crane limitations place special requirements on the ERD system. For example, the sizing approaches discussed in the previous subsection help address both issues. Other steps to be taken are to upgrade the crane so that it can be remotely operated from outside the test bed and to remove as many heavy components as early as possible, enabling heavy ERD equipment to be brought in while staying within the floor loading limits of the cell.

These approaches and strategies continue to be developed with the operational framework and detailed ERD requirements. They are informed by maturation of the ERD system design with MCRE design. Space-saving strategies also have the potential to inform LOTUS test bed design maturation. Success of this approach depends on demonstrating the necessary removal and sizing techniques, which are planned as part of the conceptual and preliminary design phases for the ERD system.

Short Decay Time Impacts

The short decay time prior to ERD will result in high radiation fields and radiation spectra from isotopes not typically seen during traditional decommissioning activities. To address this challenge, ALARA optimization of the proposed operational framework will be performed to understand the potential dose rate to workers. This will inform where remote or semi-remote systems are necessary and where they can provide the most value for mitigating worker exposure.

Appropriate task sequencing will allow existing shielding to be used for as long as possible and only removed when necessary for ERD. Supplemental shielding will also be employed as needed. As the shielding will be leveraged to reduce dose rates, remote systems must be able to dismantle components through the top of the reactor shield without compromising the steel structure supporting the vessel. This combination will require dexterity in the remote arms.

The MCRE ARD project will work with INL's packaging and transportation organization and waste generator services to identify and address the presence of novel or off-normal radionuclides compared to relevant transportation regulations and disposal facility WAC. The success of this approach will depend on demonstrating any necessary removal equipment, sizing techniques, and vision systems for remote operations.

Contaminated Flush Salt Management

Residual contaminated flush salt in MCRE will be addressed by careful ERD and container limit coordination to ensure that waste can be packaged, transported, and disposed of. Larger salt deposits will be removed by sizing components to facilitate solid salt removal or by other separation processes such as distillation—both of which must be developed and demonstrated. Other options include grouting the material in the waste containers as a means of fixing the contamination as well as providing additional shielding integral to the waste packages.

PIE Planning

One of the primary objectives for the overall MCRE ARD project is to collect operational and testing data that will lay the foundation for an operating license for a subsequent molten salt reactor under a risk-informed performance-based (RIPB) licensing framework. As such, TerraPower drafted an initial list of PIE samples to be retrieved during ERD to be sent for analysis to determine such things as corrosion, embrittlement, and fission product accumulation. This preliminary list is being evaluated under a PIE plan based on needed sample characteristics, difficulty in retrieving the sample, and cost to perform the analysis. This work includes clarification of PIE data needs with TerraPower, identification of analytical facilities at INL where the PIE analysis can be performed, and evaluation of expected sample characteristics against package or facility limits.

Early considerations for PIE sample retrieval requirements have already impacted ERD planning. For example, the primary loop shown in Figure 7 was originally planned to be removed in sections as the remote systems worked inward toward the core. Several PIE samples have been requested along this loop, and the samples need to be taken so the diameter and inner surface of the pipe are not distorted. These parameters resulted in a change to the ERD plan where the side of the steel frame is removed first, then the primary loop is cut as close to the reflector bricks as possible. The loop is then planned to be packaged and transferred to a facility better equipped to cleanly section the loop without deforming the inner surface.

Once the PIE plan is developed, it must be integrated with the ERD operational framework. Any additional requirements that are identified will also need to be incorporated into either the ERD system's functional and operational requirements or the MCRE design, as applicable. The path forward with respect to PIE planning is to complete the PIE plan, develop and demonstrate PIE sample retrieval techniques, and coordinate with internal INL organizations to confirm that existing capabilities are adequate for sample transfer and analysis to meet the PIE data needs.

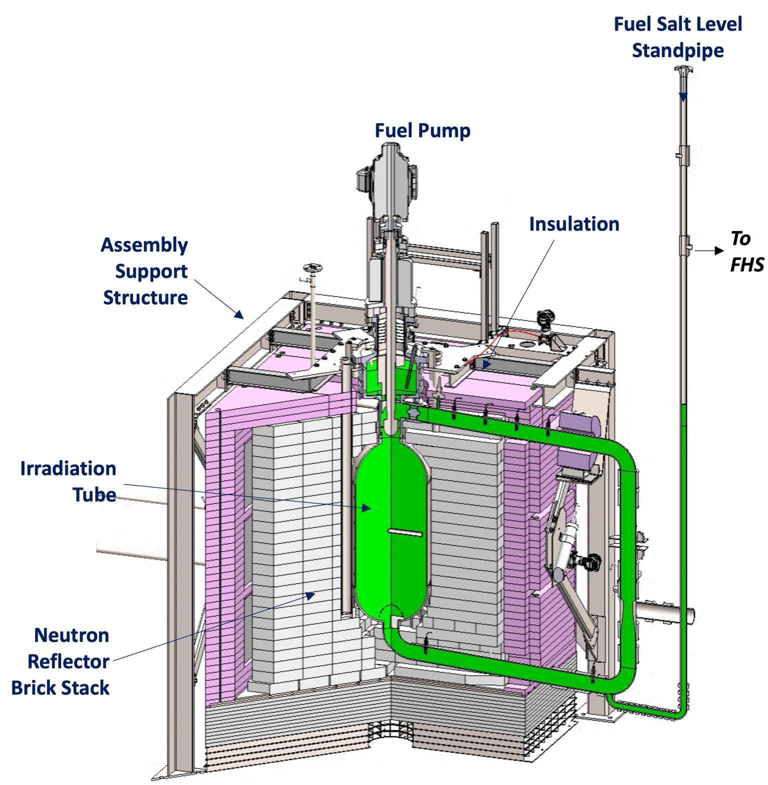

Figure 7. CAD Model Showing the Fuel System Core Surrounded by Reflector Bricks, Insulation, and the Structural Steel Frame [4].

ERD System Technology Validation and Testing

A key component of ERD system planning will be the development and demonstration of the needed capabilities to prove efficacy and proficiency in performing the desired tasks. To do this, several validation experiments are being planned:

- Development and demonstration of remotely operated reflector brick handling techniques.
- Investigation of component sizing techniques to support equipment removal and packaging.
- Development of frozen salt sizing and handling techniques (possibly shredding technology) for frozen heels of contaminated flush salt, followed by demonstration of stability in a solidified grout-flush salt mixture.
- Demonstration of vision system technology, including possible augmented or virtual reality tie-ins with the remote technology.
- Investigation and demonstration of radiation monitoring system.
- Investigation and demonstration of pipe cutting technology, particularly for thick, large diameter pipes.
- Demonstration of containment materials, particularly for surfaces contaminated with flush salt.

While some of these are well-established techniques, their application to a molten salt system may require technological development or modification. For example, shredding metal is not a new application, but shredding Inconel alloy while attempting to control and contain potential flush salt residue adds nuance to the process. Performing these experiments prior to nuclear system installation will provide insight that can be used to update the operational framework for ERD.

CONCLUSIONS

To address the challenges discussed herein, the ERD planning process will continue using systems engineering tools and capabilities to ensure that the operational framework for MCRE ERD can be implemented following experiment execution. Information gained thereby will feed into detailed requirements development and integration of LOTUS, MCRE, and ERD system designs. ERD system technology validation is critical for developing novel techniques and demonstrating efficacy and proficiency in ERD activities.

The timing of this paper at a relatively early phase of the project is to highlight the importance of early planning for nuclear system decommissioning while reactor design is ongoing to allow design feedback on componentry driven from decommissioning system needs. As new, innovative nuclear reactor technologies enter the nuclear market sector, nuclear experiments are crucial to provide new integral nuclear data that establishes safe operational margins for technology advancement. Microreactor experiments at INL will require safe, effective, and timely decommissioning approaches, which in turn require nuclear systems designed to expedite decommissioning. In addition to the advancement of nuclear reactor technologies, these nuclear experiments provide an opportunity to demonstrate, deploy, and test new removal and disposal capabilities to support the next generation of nuclear reactor technology.

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