INL/RPT-24-81994

Nuclear Science and Technology

Natura Resources Molten Salt Research Reactor (MSRR) Fuel Workshop: Summary Report

July 16–18, 2024

SEPTEMBER 2024

Nicholas V. Smith
Senior Technical Advisor, Reactor Systems Design & Analysis

Idaho National Laboratory

Idaho National Laboratory

INL/RPT-24-81994

Natura Resources Molten Salt Research Reactor (MSRR) Fuel Workshop: Summary Report

July 16–18, 2024

Nicholas V. Smith
Idaho National Laboratory

August 2024

Idaho National Laboratory
Reactor Systems Design and Analysis
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

FOREWORD

Idaho National Laboratory (INL) hosted the Natura Resources team in Idaho Falls for a 3-day fuel workshop, July 16-18, 2024. The purpose of this workshop was to understand Natura's fuel requirements, determine the feasibility of producing that fuel at INL, and define the scope of work that would enable fueled operation of the Natura MSR-1 being deployed at Abilene Christian University (ACU).

Page intentionally left blank

CONTENTS

FIGURES

TABLES

ACRONYMS

ACU	Abilene Christian University
CP	Construction Permit
CRADA	Collaborative Research and Development Agreement
DOE	Department of Energy
DOT	Department of Transportation
F&OR	Functional and Operational Requirements
HALEU	High Assay Low Enriched Uranium
INL	Idaho National Laboratory
MSRE	Molten Salt Reactor Experiment
MSRR	Molten Salt Research Reactor
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
UFP	University Fuels Program

Page intentionally left blank

Natura Resources Molten Salt Research Reactor (MSRR) Fuel Workshop: Summary Report

July 16–18, 2024

1. INTRODUCTION

Idaho National Laboratory (INL) hosted the Natura Resources team in Idaho Falls for a 3-day fuel salt workshop, July 16–18, 2024. The purpose of this workshop was to understand Natura's fuel requirements, determine the feasibility of producing the fuel at INL, and define the scope of work that would enable fueled operation of the Natura MSR-1, which is being deployed at Abilene Christian University (ACU).

Figure 1. Natura Resources team touring the Fuels and Applied Sciences building at Idaho National Laboratory's (INL) Materials and Fuels Complex (MFC).

ACU is deploying a Natura Resources 1 megawatt-thermal (MWth) liquid-fueled molten salt reactor (MSR), the Natura MSR-1, on their campus in Abilene, Texas. ACU initiated this reactor project after receiving a Programmatic Letter of Support from the Department of Energy (DOE) in November 2019. Through private funding from Natura Resources, significant progress has been made over the last 4 years to support both the development and deployment of the Natura MSR-1 system at ACU.

1.1. Molten Salt Research Reactor Mission

It is Natura Resources mission to commercially deploy MSRs and in support of this mission they are demonstrating the technology through the deployment of the Natura MSR-1 system at ACU as a molten salt research reactor (MSRR). The MSRR is liquid fuel-salt thermal reactor designed by Natura Resources, LLC. The MSRR will operate at a maximum licensed power of 1 MWth. The MSRR will establish and validate next-generation advanced nuclear reactor technologies, establish reactor operating experience with this reactor type, develop an MSR workforce, and provide a potential testbed for safeguarding tools.

Specialty salts, both uranium bearing and non-uranium bearing, are crucial components required for MSRR operation. ACU has requested support from DOE's Office of Nuclear Energy to meet this need via the University Fuel Services Program. This document defines a path for these materials that includes the provision of high-assay low-enriched uranium (HALEU), conversion of the uranium to UF_4, and the provision of FLiBe salt, enriched in Li-7.

- Conceptual design of the Natura MSR-1 was completed in October 2022.

ACU submitted a construction permit (CP) application to the Nuclear Regulatory Commission (NRC) in August of 2022 for deployment of the Natura MSR-1 as a MSRR) at ACU. The CP application was approved on September 16, 2024.

- The Science and Engineering Research Center (SERC) at ACU, the site of the MSRR, was completed in August 2023.
- Zachry Nuclear Engineering (ZNE) was hired by Natura Resources in July 2023 to complete detailed design engineering of the Natura MSR-1 system.
- Detailed design is expected to be complete by the first quarter of 2025.
- The operating license (OL) application is currently under development and is expected to be submitted to the NRC in the second quarter of 2025.
- Manufacturing, procurement, and construction can begin as early as the first quarter of 2025 with a completed detailed design and approved CP.
- Natura Resources has set a goal of completing reactor construction before the end of 2026.

The fuel required for ACU's MSRR consists of 500 kg of high-assay low-enriched uranium (HALEU) as uranium tetrafluoride (UF_4), enriched to at least 19.5%, and lithium tetrafluoroberyllate (FLiBe) salt enriched in lithium-7 to at least 99.99%.

INL has experience producing a variety of advanced reactor fuels, including UF_4. As part of a separate Advanced Reactor Demonstration Project, INL is currently installing a Fuel Salt Synthesis Line (FSSL) capable of producing metric ton quantities of chloride fuel salt. INL could use existing gloveboxes and fuel salt synthesis furnaces to produce fuel for ACU's MSRR.

1.1.1. Assumptions and Constraints

The following assumptions were captured to support efficient development of an initial plan. The exact technical requirements and schedule details may change as scope is refined and additional detail becomes available.

- The MSRR will be deployed in the already constructed SERC at ACU by the end of 2026.
- INL will synthesize UF_4 from metal HALEU feedstock that will be allocated by DOE.
- 2 years of UF_4 synthesis process development is assumed to produce fuel at relevant scale.
- Once an appropriate UF_4 synthesis process is developed, it is assumed that production of the fuel salt would take at least 1 year.
- INL has infrastructure in place that can be used for UF_4 synthesis. If there are cases where modifications are required, then make, buy, or reuse evaluations will be performed to determine the most efficient path forward.

- Commercial sources of HALEU, UF4, or enriched FLiBe are not available at this time.
- A detailed fuel specification informed by feedstock impurities and synthesis techniques is required to complete detailed design of the MSRR and the OL application.

2. FUEL PRODUCTION PROJECT NEEDS, GOALS, AND OBJECTIVES

This section contains descriptions of the envisioned products and systems to be delivered by the Fuel Production Project.

- ACU needs enough HALEU allocated to the project, enriched in U-235 to approximately 19.75%, by the end of 2024 sufficient to fuel the reactor including process losses and ex-core volume.
    - Rationale: Assumed to be 500 kg HALEU in UF4 form at interface with ACU. HALEU metal is needed as feedstock for the synthesis of UF_4 at INL. This allocation is also needed to deploy private sector funding commitments to construct the reactor.
- ACU needs UF_4 delivered to the MSRR in Abilene, TX in time to support fuel loading and reactor operations.
    - Rationale: This UF_4 material is needed as soon as possible. ACU has set a goal of completing reactor construction before the end of 2026 and fuel would be needed shortly after.
- ACU needs certainty on the exact UF_4-FLiBe composition that will go into the MSRR by the end of 2024.
    - Rationale: The MSRR license application depends on having the exact composition of the fuel defined for safety analyses. Additionally, the MSRR design or supporting infrastructure may change depending on the fuel salt composition.
- ACU needs a documented fuel handing and management plan that covers transportation of the fuel and system interfaces.
    - Rationale: The Apollo Report will define key systems and procedures on the ACU side. This documentation is required to complete detailed design and develop operational procedures.

2.1. Overview of Project Key Elements

2.1.1. Salt specifications

2.1.1.1. Fuel Salt Specification

This fuel specification defines the requirements for UF_4 salt to be produced to support the MSRR. Feedstock, defined as the raw material source of the fuel, and product synthesis requirements, impurity levels, product verification, and storage are included within this section.

This specification lists the desired limits of various impurities deemed acceptable within the UF_4 salt, including the desired physical form of the UF_4, oxygen and water content, desired UF_4:UF_3 ratio, and trace contaminants. This specification also institutes the purification procedures and characterization data that are necessary to support commercial fuel qualification.

Natura would develop a detailed UF_4 fuel salt specification, defining any impurity limits or other requirements that would impact design of an appropriate UF_4 synthesis process and provide this specification to INL. Uranium enrichment requirements will be covered in this specification. It is anticipated that development of this specification would be an iterative process with participation from INL to right-size impurity thresholds and testing requirements that may increase cost or impact schedule.

A third salt specification may be required which defines the critical characteristics of mixed salt containing both UF_4 and FLiBe. Pure UF_4 has a melting point of 1036˚C—adding FLiBe to the salt matrix will reduce the melting point considerably. Mixed salt comes with its own set of challenges; however, it may end up being the best option after considering hardware requirements that result from working with pure UF_4. This salt specification would define the desired ratio of UF_4 to FLiBe salt and any other critical characteristics. An example of the type of information needed is shown in Table 1.

Table 1. Example of fuel salt specification data.

Title	**Requirement**
Isotopic Composition	The isotopic composition of the fuel shall be within the following limits: - U-235: (XXXXX +/- XXXX) wt% - U-234 + U-236 + U-238: <XXXX wt% - U-234 + U-236: <XXXX wt% *(Expressed as relative mass of each U isotope normalized to the cumulative U mass)*
UF_4:UF_3 Ratio	The UF_4:UF_3 ratio shall be within the following limits:
Cumulative Cr, Fe, and Ni Impurities	Cumulative Cr, Fe, and Ni impurities in the fuel salt shall not exceed XXX ppm.
Impurity Content for Multiple Species	Impurities for the broader set of species listed below *should* be below the target value, with a 95% confidence interval.
__	Target and Max

2.1.2. The Apollo Report

The first deliverable produced by INL under this fuel production project is referred to as the Apollo Report. The Apollo Report will include a literature review of UF_4 synthesis techniques and a trade study of synthesis pathways in the context of waste streams, available facilities, uranium feedstock characteristics, hardware requirements, and results of small-scale experiments to validate the trade study. For example, direct fluorination may be an efficient UF_4 synthesis route. However, if it takes 4–5 years to get a glovebox with the surface treatments that prevent extreme corrosion because of fluorine gas exposure, it may be the wrong choice for this project.

The trade study will be conducted in four phases. The task in the first phase is to evaluate salt specification requirements and acceptable tolerances for the composition to produce a synthesis-focused report. This phase will also produce the trade study metrics for the final product. The second phase will be the survey analysis of feasible synthesis options and will include data mining of historical experiences and achievable tolerances. In the third phase, synthesis process options will be developed, leveraging both salt specification requirements (Phase 1) and feasible synthesis pathways (Phase 2) to yield process descriptions that account for final product specifications with attainable tolerances. This phase will conclude with descriptions of feasible synthesis options and their product characteristics with attainable tolerance. The fourth phase will build on the outcome of Phase 3 and it will proceed with trade study evaluations of the characterized synthesis options using metrics developed in Phase 1. The result of the trade study will be a report that documents technically feasible options ranked in order of achievable specifications versus the resources needed. The final report will include the gap evaluation of needs per identified synthesis options versus existing resources and capabilities to support each option. The analysis will allow down-selection of the most feasible synthesis options, costs, schedule, and will provide product specification.

The Apollo Report will evaluate the safeguards and hazard category of facilities as they relate to synthesis options. Uranium feedstock characteristics and pre-treatment options to remove impurities will be evaluated in the Apollo Report. Other topics covered in the Apollo Report will include hardware options, materials compatibility, and hardware requirements resulting from the selection of a given chemical process.

It is envisioned that development of the Apollo Report would be supported by some amount of small-scale experimental work. These experiments would allow for validation of ideas that may seem effective on paper but do not work in practice. Last, the Apollo Report will include a narrative description of the selected fuel synthesis process through shipment, delivery, and fuel loading in the ACU MSRR. This narrative will highlight impacts to MSRR systems and/or processes. It will also be the basis for defining interface requirements and ensuring there are no surprises when the fuel arrives.

2.1.3. Experiments to Inform Nuclear Safety and/or Criticality Safety

Depending on the selected synthesis process and final design of fuel-handling systems in the MSRR, there may be unique off-normal or accident conditions that are not covered by MSRE documentation. There is not a set of planned experiments envisioned here. Rather, this is where experiments to address emergent safety questions would be covered.

2.1.4. UF_4 Synthesis Design

After completing the Apollo Report, INL will develop a UF_4 Synthesis Functional and Operational Requirements Document (F&OR). This F&OR will identify all equipment required to meet the F&OR. Scale-up experiments will be performed with the selected process. A summary report covering the results of selected synthesis route scale-up efforts will be developed. INL will develop a Fuel Salt Sampling and Quality Control Plan.

INL will go through an appropriate UF_4 synthesis design process. One or more design cycles may be required before the Final Design is achieved. INL will follow GDE-987 with appropriate tailoring and hold one or more formal design reviews with project stakeholders. Cost and schedule estimates will be produced commensurate with the design maturity. At Final Design Review of the UF_4 synthesis process the cost estimate for implementing the intended synthesis process should be informed by Request For Proposal (RFP) responses from vendors against a detailed equipment list for procurement.

2.1.5. The Hades Report

The existing UFP provides a fuel take-back service for university research reactors. The systems and capabilities needed to provide an equivalent service for ACU's MSRR need to be developed for their UF_4-FLiBe fuel form. The project team will develop a report, referred to as the "Hades Report," covering existing capabilities, technology development needs, and recommendations. The National Environmental Policy Act (NEPA) and environmental considerations for such a service would be addressed. The report would also survey applicable MC&A techniques for the UF_4-FLiBe fuel. Potential storage locations will be evaluated and compared in this report. The pros and cons of potential fuel processing options would also be covered.

This Hades Report would help DOE make decisions related to how a molten salt fuel take-back program could be implemented. It would also serve as the working interface definition for discussions between ACU and INL related to fuel delivery and take-back systems.

2.1.6. Operating License Approval, Containers Shipped from INL to ACU

The transportation of HALEU poses various technological and regulatory challenges not encountered with uranium enriched below the common 5% limit. To address these issues, a high-capacity HALEU transportation concept for UO_2 transportation was developed at INL. The concept combines an existing transportation package (with a pending U.S. Department of Transportation [DOT] license application), inner canisters filled with HALEU powder, and a novel basket design that includes a borated aluminum flux trap. The investigation concluded that the proposed HALEU transportation concept remains subcritical under all evaluated conditions, provides sufficient radiological protection to the operating personnel and the surrounding environment, is structurally sound, contains and confines the HALEU, and sustains the expected thermal loads. All indicators point toward high potential for successful licensing; however, an evaluation of licensing and permitting requirements is necessary.

2.1.6.1. Container Subtask 1: Container Scoping Study and Existing UF_4 Design Package Evaluation

This subtask begins with an evaluation of licensing requirements and exploration of specific permits required for transportation of HALEU UF_4 from INL to ACU. Previous work provides a starting point for the development of a similar package for the transportation of HALEU in the form of UF_4, which is needed to fuel the MSRR design currently under development. Although the physical form is similar, it is important to note that the fluoride form (UF_4) of the MSRR HALEU fuel is different from the oxide form (UO_2) that was assumed in the development process of the previous transportation concept. The discrepancies caused by the differences in form between HALEU will be identified and addressed through additional analysis and assessment of the UO_2 concept for its suitability to a UF_4 product. This includes analysis of material compatibility between UF_4 and the package components and analysis of identified accident scenarios as well as new accident scenarios that may be identified based on the fluoride form of HALEU. This includes moisture and corrosion issues. In addition, criticality, radiation shielding, and the appropriateness of the criticality benchmarks used for the UO_2 concept will be re-evaluated for UF_4. The number of shipments will also be evaluated from a cost and convenience perspective to make recommendations on sizing of the transportation package.

2.1.6.2. Container Subtask 2: UF_4 Transportation Package Engineering

Beyond the evaluations described in Container Subtask 1, additional work is needed to achieve a licensable design of the transportation package, including basket, flux trap, and powder canisters. Although it is assumed that no major obstacles will be uncovered in the re-evaluation process of the transportation concept for a fluoride HALEU form, significant technical risk remains. It is also assumed that the Type-B packaging license application process has a high chance of being successful and that a license could be extended to cover any necessary modifications identified for UF_4 transportation, or that cask vendors could design similar packaging with an appropriate license. Specific work products from this subtask are UF_4 container technical specifications and drawings.

Efforts in this subtask will focus on addressing deficiencies identified in Subtask 1 and will include preliminary and verified designs, evaluation, and preparation of documents to support a licensing amendment of the existing UO_2 transport packaging. Given the assumptions above, there is high confidence that a certified, transport-ready, high-capacity UF_4 transportation concept could be licensed if priority is given at the NRC and DOT. Close engagement with a selected cask vendor will also be important for increasing the likelihood of successful outcomes for this subtask. After completion and verification of the transportation package design, internal components will be fabricated for the UF_4 loading described in Subtask 3.

2.1.6.3. Container Subtask 3: UF_4 Loading and Unloading Procedures for Developed Transport Package

Procedures for loading and unloading the transportation package with UF_4 will need to be developed. These procedures will depend on the final design of the transportation package. However, if the transportation package design is like the previously developed concept, individual sections could be loaded and the filled canisters subsequently stacked within the packaging. Due to the small, lightweight nature of the individual packages, it is unlikely that heavy or specialized lifting equipment will be necessary during the UF_4 loading process. The unloading of the UF_4 container will depend on the final design of the MSRR fuel-handling system and the final design of the transportation package. Close coordination between Natura/ACU and INL will be necessary during this subtask to ensure containers interface properly and procedures are in place to allow for the removal of the UF_4 from the container. Additionally, close engagement with a cask vendor and input from nuclear fuel producers will increase the likelihood of a successful outcome for this subtask.

2.1.6.4. Container Subtask 4: Container Scoping Study and Evaluation of Existing FLiBe Transport Design Package

This subtask begins with an evaluation of licensing requirements and exploration of specific permits required for transportation of FLiBe. It is likely that an existing container design can be used for the transport of FLiBe. Previous development work provides an excellent starting point for the development of a similar package for the transportation of FLiBe, which is needed to fuel the MSRR design currently under development. This includes analysis of material compatibility between FLiBe and the package components and analysis of identified accident scenarios. Additionally, the number of shipments will be evaluated from a cost and convenience perspective to make recommendations on the transportation package's size.

The FLiBe salt container design will be developed and selected by leveraging existing containers at ORNL capable of meeting transportation mode requirements to deliver FLiBe to ACU. The transportation mode and its requirements will be characterized, focusing on salt shipping-container specifications. Salt receiving capabilities at ACU for receiving and handling the container will be defined. Existing salt containers will be assessed, focusing on their ability to meet transportation requirements for shipping the salt to ACU.

2.2. Interfaces

2.2.1. Contractual Interfaces

For a project of this size, numerous interfaces are required. A contractual interface allowing Battelle Energy Alliance (BEA), Natura, and ACU to enter into a Collaborative Research and Development Agreement (CRADA) is needed. In a CRADA collaboration between Natura, ACU, and INL, ACU Natura would provide to INL a UF_4 fuel salt specification, anticipated schedule and timeline needs, and interface and contact points for the project. Conversely, INL would provide Natura and ACU with an initial scope schedule, completion of an "Apollo" report, eventual samples of UF_4, shipped to Texas A&M for analysis, and details that quantify the final amount of UF_4 to be delivered.

2.2.2. INL Internal Personnel Interfaces

Internally at INL, the engineering change control process will dictate the number of personnel involved with the design, fabrication, installation, and operation of an MSRR fuel-salt synthesis to produce UF_4 salt. These interfaces may depend upon the facility in which the process is to take place. In general, required personnel will include the facility manager, facility operations, criticality safety, nuclear safety, engineering management, system engineering, technical integrator, design engineer, drafting, environmental compliance, industrial health and safety, reliability engineering, special nuclear materials, project management, radiological engineering, training, structural/seismic engineering, cost estimators, procurement and quality engineers, as well as INL upper management support. This list of people will ensure a properly reviewed design. The implementation strategy will collimate into a Concept of Operations document, also known as an Operational Framework, and eventually into the System Design Description (SDD).

2.2.3. INL Equipment Interfaces with ACU

Upon INL's completion of the UF_4 synthesis, INL will be required to ship the final product to ACU. Some equipment interface points must be defined so that ACU may receive the fuel from its shipping configuration and prepare it for reactor operations. Interface points could include storage containers, gloveboxes, reactor loading, and/or sampling equipment.

3. PROJECT LIFE CYCLE PHASES

3.1. Phase One

3.1.1. INL Design of Fuel Synthesis Process

The design of the fuel synthesis process will greatly depend on the uranium source and facilities used to perform the synthesis. Thus, it is important to recognize that certain well-established methods of UF_4 production will not be possible at INL facilities within the required timeframe. It is just as important to preserve the creative problem-solving process so that the fuel synthesis program can achieve its objectives in a timely manner. Thus, any preconceived biases related to a particular technology must be avoided so that all possible synthesis pathways, existing capabilities, and facility limitations can be fully considered.

3.1.2. INL Apollo Report: Trade study looking at synthesis options

As the expected delivery timeline of the specified UF_4 is initially anticipated to be in fiscal year 2027, it is understood that the UF_4 synthesis will need to be immediately actionable—at least in the near term. To better inform the process selection, an initial trade study is needed to gather, evaluate, and provide an initial down-selection of the synthesis processes most likely to succeed from the perspective of facility requirements, as well as those of procurement and chemistry. This trade study should be supported by small scale experiments, where appropriate, to confirm the feasibility of high potential synthesis techniques.

The trade study is intended to provide: (1) a high-level review of the available facilities, and their operating and chemical handling limitations, (2) an assessment of the possible UF_4 synthesis processes without consideration of facility limitations so that all possible options are acknowledged and equally evaluated, and (3) an initial recommendation of the most-likely-to-succeed synthesis pathway, taking into consideration facility requirements and UF_4 synthesis timeline expectations. The Apollo Report has the following Goals:

- Develop methods to convert EBR-II metal U reguli from current form to UF_4
- Consider best available processes available at INL to accomplish the following:
    - Conditioning to convert the 7 kg uranium reguli into the desired morphology and chemical form for UF_4 conversion
    - Selection and implementation of the production process for UF_4
    - Creation of desired UF_4 morphology for shipping (bars, spheres, or other)
- The definition of the UF_4 production process will define the feed requirements for the process, including:
    - Conversion of either metal, oxide, or solution-based feed stock
    - The fuel specification required to define impurity, composition, and morphology constraints
    - Process options such as direct exposure of U metal slugs to gaseous HF, liquid reagents (e.g., BiF_3), and solid reagents (e.g., ammonium bifluoride (ABF)).
- Chemical or mechanical conversion recommendations such as:
    - Conversion to oxide powder by direct oxidation (e.g., voloxidation)
    - Conversion to metal powder (e.g., hydride/dihydride, mechanical pulverization)
    - Dissolution in fluoride salt (e.g., direct fluorination in FLiBe)
    - Dissolution in aqueous solution (e.g., nitric acid, a precursor to oxide powder)
- Evaluation of final UF_4 product form options:
    - Bricks (nominal 6 × 2 × 2 inches)
    - Near-spherical pellets

    - Powder
    - Cast cylinders
    - Other

The top-level design objective is to convert the 7 kg HALEU reguli from EBR-II processing into high-quality UF_4 that shall be shipped to ACU as fuel for the MSRR. The objective of this task is to evaluate processing options and select or implement a rapidly achievable process at INL to enable HALEU UF_4 delivery according to the project schedule.

While many conversion methods are possible given unlimited time, funding, and infrastructure, the project will seek to deploy a timely and efficient UF_4 conversion process leveraging existing INL facilities, equipment, and materials. If the EBR-II HALEU reguli are provided to the MSRR program, INL resources shall be configured for the task. Where possible, the conversion processes will be carried out in existing INL gloveboxes and furnaces.

3.1.3. INL Design of Fuel Salt Container

UF_4 is assumed to be delivered to ACU in 50-100 kg batches. Because of this, the INL-synthesized UF_4 must be stored and shipped in an environment that preserves the fuel's chemistry against environmental contamination. A container with to-be-determined specifications that allows prolonged inert storage and secure transport will be designed for this purpose.

3.1.4. INL – Perform Fuel Synthesis Sale Up Experiments

After a review of the trade study by MSRR stakeholders, concurrence on the best fuel synthesis processes identified in the trade study will be obtained and experiments planned to scale up those processes. Initially, fuel would be produced at the tens of grams scale with the goal of scaling to production of kilograms of fuel per batch. A key aspect of the experimental studies is providing an early indication of relative difficulty among the developed synthesis pathways. Of course, problems may occur at larger scales that were not observed at lower scales, and so observed process difficulties at an early stage should not completely obviate problematic processes from later consideration should the need arise.

After the completion of the initial experiments, a timeline of future experiments optimizing the development lifecycle will be developed. Experimental progress on this timeline will be routinely discussed with MSRR stakeholders for the purpose of communicating differences between expected and observed results and making decisions about the future experimental timeline.

3.1.5. INL – Procure fuel synthesis hardware

Completion of the final design for the fuel synthesis hardware will allow for the procurement of the custom and off-the-shelf hardware necessary for UF_4 synthesis. Depending on the design of equipment, expected long-lead items may be procured at-risk prior to the completion of final design with appropriate engineering, laboratory, and DOE approval. Appropriate quantities of consumable items and spare parts will be procured at this stage to ensure that all hardware necessary for the projected fuel salt synthesis campaign will be on hand at the beginning of the campaign. All equipment will be procured at the quality level appropriate for the intended purpose of the item, as determined by the engineering design, facility management, and relevant nuclear safety and criticality safety reviews.

3.1.6. INL – Fuel synthesis hardware installed and commissioned

Upon receipt of the fuel synthesis hardware, the equipment will be installed in the fuel synthesis facilities as defined in the Apollo report. Commissioning of the fuel synthesis line will require the development of detailed procedures for synthesis, fuel handling, sampling, and processing, as appropriate. The commissioning process may also require readiness reviews at the laboratory management level, and possibly at the DOE level, depending on the extent of modification necessary to existing systems and infrastructure. Demonstration synthesis runs using depleted uranium feedstock may also be performed at this stage to demonstrate competency and process reliability prior to the initiation of synthesis operations with HALEU feedstock.

3.1.7. ACU - Develop receipt and delivery plan

ACU will communicate its readiness to accept Be-containing material, including the existence of a fully developed, reviewed, and approved Be safety plan, in accordance with accepted Be safety standards and Occupational Safety and Health Administration (OSHA) rules. ACU will confirm that it is fully in compliance with this Be safety plan. ACU will develop a plan to accept 2200 kg of FLiBe salt in the specific forms and containers in which the FLiBe will be shipped, including safe transfer from the delivery vehicle to a scale for verification of mass, inspection, and preparation for storage.

3.1.8. Natura & ACU – Preparations to receive UF_4 from INL

ACU will develop the necessary systems, structures, components, programs, and procedures to handle UF_4 subject to applicable NRC requirements. ACU is actively developing these systems and procedures with engineering support from Zachry Nuclear Engineer and university partners. ACU will work with the DOE to define the fuel salt receipt, processing, transport, and end-of-life removal phases.

3.2. Phase Two

3.2.1. INL – Fuel synthesis underway

Upon completion of the commissioning of the fuel synthesis line equipment and authorization to proceed with HALEU UF_4 synthesis, INL will begin production of HALEU UF_4 per the established procedures. It is anticipated that the synthesis campaign will require a relatively large number of batches, as determined by the hardware design and facility mass limitations.

3.2.2. INL – Sampling and analysis of synthesis batches

A statistical sampling plan will be developed to allow for representative sampling of the fuel synthesis batches to allow for confidence that the entire population of batches meets the required fuel specification to minimize project cost. Multiple samples will likely be taken from each batch of fuel salt produced, with a subset of batches receiving full suite analysis at the analytical laboratory for the impurities and properties required by the fuel salt specification. Archive samples of batches not analyzed will be held in reserve in the facility vault to allow for future analysis as necessary.

3.2.3. ACU – MSRR under construction

ACU will contract with Zachry Nuclear Engineering to build, deliver, and install the MSRR. ACU will contract with Natura Resources to receive, house, and operate the MSRR. Natura Resources, Zachry Nuclear Engineering, and ACU will work together to establish acceptance criteria for the reactor and its final assembly on site at ACU.

4. CONCLUSION

Based on the results of this fuel workshop, it would be feasible for INL to produce the ACU MSRR fuel salt, assuming HALEU feedstock can be allocated to this project by DOE. Development of a detailed schedule and budget are still needed before any formal timeline or cost commitments can be made. Production of the UF_4 fuel salt sets the critical path for this project. INL has existing fuel salt synthesis capabilities that could be readily utilized to produce UF_4 for ACU. Once an appropriate UF_4 synthesis process is developed, it is assumed that production of the fuel salt would take at least one year. Other supporting efforts to obtain FLiBe salt and prepare for shipment of fuel to ACU could take place in parallel.

Appendix A

Workshop Participants and Report Contributors

Natura Resources Research Alliance

Jordan Charles Robison - Natura Resources
Jonathan Bernard Scherr - Natura Resources
Jack Wayne Shoemate - Natura Resources
Kimbell Lee Pamplin - Abilene Christian University
Rusty Towell - Abilene Christian University
Steve Biegalski - Georgia Tech
Pavel Tsvetkov - Texas A&M University
Sean McDeavitt - Texas A&M University
Derek Haas - The University of Texas

Zachry Nuclear Engineering

Ramin M Bahai
Matthew James Fallacara

Idaho National Laboratory (INL)

John Baker
Toni Karlsson
James King
Carson McNair
Bill Phillips
Simon Pimblott
Andrew Smith
Nick Smith
David Tolman
Jonathon Wilcox
Jacob Yingling