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Final Report for CRADA/NFE-18-07194 with TerraPower LLC

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June 2020

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OAK RIDGE NATIONAL LABORATORY
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Nuclear Nonproliferation Division

FINAL REPORT FOR THE COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT (CRADA) NFE-18-07194 WITH TERRAPOWER LLC

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CONTENTS

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Del
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ABSTRACT

Because of the potential economic and safety benefits of the molten salt reactor (MSR) concept, development of several designs has been initiated around the world over the past decade. New international nuclear safeguards needs and verification challenges are likely to arise because of the commercial interests in MSRs and the number of MSR design variants. As a result, work was undertaken to explore the cross-cutting issues specific to the application of international nuclear safeguards (i.e., safeguards) to liquid-fueled molten salt reactors (LFMSRs). Through a public-private partnership, a report was developed that focuses on the TerraPower Molten Chloride Fast Reactor (MCFR) design that has received a funding award from the US Department of Energy (DOE), Office of Nuclear Energy[1] [1].

The report is intended to provide a preliminary analysis for a safeguards-by-design (SBD) effort to inform designers about how safeguards could be applied to LFMSRs by the International Atomic Energy Agency (IAEA).Although the report specifically focuses on the TerraPower design, the conclusions are applicable to the main design features of LFMSRs and can be used to extrapolate how existing IAEA safeguards measures for other fuel cycle facilities can be appropriately applied or modified. The report evaluates the appropriate safeguards approaches for LFMSRs, presents existing safeguards inspection technologies are still valid for LFMSRs, and identifies new challenges that will require novel measurement instruments to meet verification standards of the IAEA and the international safeguards regime.

This document summarizes the results of the work performed under the full report developed as part of the Cooperative Research and Development Agreement (CRADA). This summary does not contain any protected CRADA information and is intended for public release.

[1] In January 2016, the US Department of Energy awarded a 5-year, $40 million cost share award for continued research and development into TerraPower's MCFR project. This award includes TerraPower, the Southern Company, ORNL, the Electric Power Research Institute, and Vanderbilt University.

1. STATEMENT OF OBJECTIVES

This is the final report for CRADA NFE-18-07194 with TerraPower LLC. This document summarizes the results of the work documented in the Oak Ridge National Laboratory (ORNL) sponsor-controlled report, "Cross-cutting Safeguards Issues for Liquid-Fueled Molten Salt Reactors, ORNL/SPR-2019/1184." The sponsor-controlled report contains protected CRADA information, is export controlled, and is marked as Official Use Only. This final CRADA report does not contain any protected CRADA information and is intended for public release.

The work performed under this CRADA explores the cross-cutting issues specific to the application of international nuclear safeguards to LFMSR designs, specifically using the TerraPower MCFR design that has received a funding award from the US Department of Energy (DOE), Office of Nuclear Energy as a basis for investigation. The report is intended to provide a preliminary analysis for a SBD effort to inform designers about how safeguards could be applied to generally to LFMSRs by the International Atomic Energy Agency (IAEA).

The report evaluates the following questions:

- What are the appropriate safeguards approaches, and what existing safeguards inspection technologies and practices are valid?
- What may be the new challenges for safeguards inspectors?
- Are there measurement technologies and instruments that could be used in applying safeguards to LFMSRs? If not, what technologies may need to be modified or developed?
- What new safeguards technologies will be required to meet verification challenges, and what steps should be taken to prepare the IAEA and international safeguards regime to be ready?

To answer these questions, the report identifies the main process flows for LFMSRs and the main points in the system where safeguards could be applied. A major focus is extrapolating how existing IAEA safeguards measures implemented in current fuel cycle facilities, including nuclear reactors and spent fuel reprocessing plants, can be applied. If no current methodology or safeguards measure is applicable to LFMSRs, a gap analysis based on the issues identified and the current level of safeguards technology and approaches available is provided. These concepts are then applied directly to the proposed TerraPower MCFR design, but those portions have been removed from this document because of the restrictions imposed by nondisclosure agreements.

2. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

ORNL was funded by the Office of International Nuclear Safeguards within the National Nuclear Security Administration (NNSA). TerraPower provided in-kind funding by developing, assembling, and providing design information. ORNL and TerraPower conducted a collaborative approach in developing the subject ORNL sponsor-controlled report.

The Office of International Nuclear Safeguards works to strengthen the effectiveness and efficiency of the international safeguards system. It provides technical expertise to develop and inform US safeguards policy positions. It also develops concepts and technologies to address current and future nuclear fuel-cycle safeguards challenges.

The work performed under this CRADA provides the following benefits:

- The analyses performed will help to develop and refine advanced concepts for and approaches to international safeguards for LFMSRs that could result in more effective and efficient IAEA verification at declared safeguarded nuclear facilities.

- This effort will provide implementable ideas for new or improved safeguards concepts and approaches.

- The work done addresses real-world safeguards challenges for this class of advanced reactors. It offers improvements in safeguards effectiveness and/or efficiency by identifying gaps in the current safeguards regime with respect to emerging technologies.

- This work is crucial to developing advanced reactor designs. It isolates the measures that must be present in concept and prototype designs that ensure all material within the facility is safeguarded from misuse or diversion. Having a thorough understanding of the needed SBD elements for LFMSRs directly contributes to the nation’s energy, environmental, and national security interests.

- This work provides viable recommendations for safeguarding liquid fuel within an advanced reactor design, such as TerraPower’s MCFR.

3. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

International nuclear safeguards are activities through which the IAEA can verify that a State is fulfilling its international commitments not to use nuclear programs for nuclear-weapons purposes and promoting the broader scope of nuclear nonproliferation. The goal of nuclear nonproliferation is to prevent the spread of nuclear technology and materials that could be used to develop nuclear explosive devices by non-nuclear weapons states, as defined in the Treaty on the Non-Proliferation of Nuclear Weapons [2]. Once a country signs the treaty, it is obligated to enter into a comprehensive safeguards agreement with the IAEA, which allows the IAEA to apply safeguards that determine whether all declared nuclear material is accounted for and no undeclared nuclear material or activities exist. Under a comprehensive safeguards agreement, the three generic safeguards objectives are applied, with most nuclear facilities focusing on addressing the first two objectives.

1. To detect any diversion of declared nuclear material at declared facilities or locations outside facilities;

2. To detect any undeclared production or processing of nuclear material at declared facilities or locations outside facilities; and

3. To detect any undeclared nuclear material or activities in the State as a whole.

In general, safeguards activities are designed to verify the State's declarations about nuclear material quantities, locations, and movements, and to detect indications of undeclared nuclear material or activities. The IAEA uses the following techniques and measurements [3]:

- On-site inspections by IAEA inspectors including short notice random and unannounced inspections

- Nuclear material accountancy, such as the review of facility records and supporting documentation

- Measurements of nuclear material (e.g., weight, gamma, neutron)

- Unique identifiers for nuclear material items

- Surveillance (e.g., cameras), containment (e.g., seals), and monitoring (e.g., monitoring nuclear material flows using unattended radiation measurements, monitoring of facility operational data such as pressure, temperature or power levels)

- Collection and analysis of environmental and nuclear material samples

- Verification of facility design for features relevant to safeguards

To establish current practices for safeguards, current practices for power reactors, reprocessing facilities, and fuel fabrication facilities were considered. Because the fuel can only be measured in a bulk form as a moderator-fuel matrix, LFMSRs will share some safeguards and material accounting components of each of these facilities. The full report detailed each of these facility components, as well as the misuse and diversion scenarios associated with each facility. As such, safeguards for a LFMSR may contain elements of safeguards from

- nuclear reactors (because fissile material [i.e., plutonium] can be created in the core of reactors and fission and transmutation changes the isotopic properties of the fuel salt),

- SNF reprocessing facilities (because the fissile material exists in liquid form, is transported throughout the system, and changes chemical and physical properties), and

- fuel fabrication plants (because the fuel salt may be manufactured on-site from fissile material delivered in bulk form to the facility).

3.1 POTENTIAL DIVERSION SCENARIOS, UNDECLARED PRODUCTION, AND CONCEALMENT METHODS

Based on the general design characteristics of an MCFR, this section discusses potential diversion scenarios, undeclared production pathways, and concealment methods for LFMSRs.

These scenarios assume that a facility is conducting its activities with full knowledge of and support from its national authorities. The main concern regarding the diversion scenarios related to reactors is the removal of fresh fissile material (^{235}U) or the production and removal of undeclared fissile material (plutonium); therefore, the correlation of diversion scenarios to LFMSRs involves:

- Removal of unirradiated fuel salt from the fuel salt production area

- Removal of irradiated fuel salt from the reactor primary loop

- Irradiation of undeclared fuel salt in the primary loop

- Removal of unirradiated and irradiated fuel salt from fuel holding areas outside the primary loop

- Removal of irradiated material from cleanup/off-gas/polishing/flush/cover gas systems

- Removal of irradiated fuel salt from consignment when it leaves the facility

- Diversion from waste streams (i.e., fuel production, cleanup systems, and final fuel exiting core)

An analysis of the potential diversion scenarios for an MCFR was provided in Appendix B of [1].

3.2 POTENTIAL SAFEGUARDS TECHNOLOGIES AND MEASUREMENTS

Based on information provided for a MCFR, reactor physics and fuel cycle analyses were performed including the modeling of the addition and removal rates in the online processing systems. This determined the isotopic content of the irradiated fuel salt in the core and throughout the energy system. This was provided in Appendix A of [1]. This section summarizes the challenges and recommendations based on these analyses as well as the material balance areas (MBAs) and key measurement points (KMPs) identified in Appendix B of [1] and the potential international safeguards measures and nuclear material accounting and control features. This CRADA summary does not contain any proprietary or protected information and applies generally to LFMSRs that have provisions for the removal of fission products and the input and withdrawal of nuclear material.

3.2.1 Fresh fuel receipt (unirradiated)

If fresh fuel salt is delivered to the LFMSR, when it arrives at the reactor it will be in sealed containers, and existing IAEA safeguards measures could be applied.

It is unlikely that the safeguards approach will require opening of containers; therefore, nondestructive analysis (NDA) measurements will dominate. However, it is likely that an IAEA inspector may be required to attend the measurements at the time of fuel receipt. It is assumed that the nuclear material will be well-characterized before receipt, and therefore the measurements will be for purposes of continuity of knowledge. It is also assumed that the nuclear material is stored under normal (dry and inert environment) storage conditions at ambient temperatures. The following metrics could be measured for fresh fuel:

- Weight measurement using calibrated load cells (scales) to weigh the containers
- Enrichment measurements using a high-purity germanium detector
- The (alpha, n) signature of the bulk quantity of nuclear material obtained by gross neutron counting using a neutron slab detector or small array of neutron slab detectors. The (alpha, n) signature should be reproducible and predictable.

3.2.2 Fuel salt manufacturing

Note, this process is similar to a fuel fabrication facility, and the safeguards applied by the IAEA are likely to be closer to the safeguards applied to a fuel fabrication facility rather than a reactor facility.

If the fresh fuel salt is to be manufactured at the reactor site, the safeguards measures below could be applied.

- Containment and surveillance (C/S) of fuel salt storage area.
- Seals applied to material storage containers after verification.
- Measurements through NDA or destructive analysis (DA) to verify that nuclear material isotopic content in fuel salt product matches raw material receipts. This could be done prior to processing and then again after processing to account for losses.
- Calculation of material unaccounted for (MUF) values and monitoring of cumulative MUF (CUMUF)
- Weight or volume measurements for mass.
- Verify identity of containers and integrity of tamper-indicating devices.
- Surveillance of the fuel salt storage area could be implemented by storing containers on a pad to ensure they are not moved without an alert being recorded.

3.2.3 Transfer of fresh (unirradiated) fuel salt to fresh fuel storage area

Whether the fuel salt is manufactured or received, it will be placed in a storage area before introduction into the reactor systems. Existing safeguards measures could be adapted and applied to fresh/unirradiated molten salt transfers. For example, measurements could be performed both before and after the transfer to verify that the same type and amount of nuclear material was transferred. Alternative methods to monitor the transfer pipe using a flow meter could be explored (i.e., alternatives to performing a live measurement during the transfer using an in-line flow meter). It is not known if an IAEA inspector would be required to attend the transfer of fresh fuel to the storage area.

If the fuel salt is solid, the following verification measurements and methods could be applied:

- Repeat NDA measurements could be performed at fresh fuel receipt to quantify enrichment and weight since movement.

- Existing NDA techniques would have to be modified for the solid fuel salt form.

If the fuel salt is liquid, the following verification measurements and methods are proposed:

- Assuming liquid fuel salt transfer between two tanks, quantify the difference in tank volumes using load cells (if possible) and a fill height measurement using a gauge or bubbler.

- Perform enrichment measurement using a high-purity germanium detector for each tank before and after the transfer.

- Provide the difference in neutron count rates as a result of the transfer using neutron slab detectors adjacent to each of the tanks.

- Take samples from both tanks to monitor concentration. Concentration measurements could be nondestructive using a hybrid K-edge technique or DA. (DA is likely to be preferable.)

- Sample isotopic composition could be measured using isotope dilution mass spectrometry, Thermal Ionization Mass Spectrometry, or an equivalent technique.

- For liquid fuel salt, no existing standard NDA instrument exists.

3.2.4 Fuel salt storage (unirradiated)

Fuel salt will be held in a storage area before introduction into the reactor systems. Existing safeguards measures could be adapted and applied to fresh/unirradiated molten salt transfers. NDA or DA could be used to determine isotopic content of unirradiated, or fresh, fuel salt, as well as possible weight or volume measurements for mass. NDA or DA methods could also be used to determine isotopic content of irradiated fuel salt. Seals on fuel salt containers and C/S of fuel salt storage systems may be necessary. A novel C/S approach may be to store the containers on a pad that indicated if and when containers are moved. This may be recorded for future IAEA verification.

3.2.5 Transfer of fresh fuel salt (unirradiated) to primary loop

After initial operations begin, fresh fuel salt will be periodically input into the primary loop based on the desired reactor operating parameters. The following steps could also be taken:

- Measure flow rates and total flows, either periodically or continuously—Existing safeguards measures could be adapted and applied to fresh/unirradiated molten salt transfers.

- Process monitoring of reactor dynamics—The addition and removal of nuclear material will likely change reactor core power dynamics and may be able to be measured and correlated.

3.2.6 Reactor primary loop

During operations, there will be a continuous flow from the core to the fuel salt and noble gas cleanup systems. There will also be continuous input of irradiated fuel salt from the fuel salt cleanup systems consisting of fuel salt that has been withdrawn from the primary loop and conditioned as well as fresh fuel salt containing nuclear material. During flushing operations, there will be either flush salt in the reactor core and primary loop, or the reactor core will be empty except for residual amounts of fuel salt remaining after the flushing operations are complete.

The following existing safeguards measures could be applied:

- C/S of reactor containment.
- NDA or DA samples to verify isotopic content of the primary loop. (The fuel salt must be homogeneous.)
- After flushing operations, holdup material will be in the primary loop, and the flush salt will contain residual fuel salt.
- A mass balance is theoretically possible only during reactor shutdown.
- Reactor core instrumentation that can be joint-use for both system operation and IAEA inspections should be considered.
- Safeguards approaches such as mailbox declarations, which involves communicating certain operator actions to the IAEA using remote, secure data transmission, and the IAEA can then perform random unannounced inspections to verify declared plant operations can be considered.

3.2.7 Transfer of fuel salt to/from the core—fuel salt polishing/cleanup systems, and noble gas processing systems

LFMSRs will have systems that process the liquid fuel and remove fission products and noble gasses from the primary loop. These systems may consist of fuel salt filters, degassing, and separations vessels. These systems are connected to the irradiated fuel salt from the reactor vessel systems. The following main design features need to be considered from a safeguards perspective:

- Removal of fission products will likely change reactor core power dynamics and may be able to be measured and correlated.
- This will likely be a continuous process during reactor operation.

The following verification measurements and methods should be considered:

- NDA/DA measurements of the fuel salt filters and noble gas filters to determine uranium and plutonium content
- Flow rates and flow monitoring using in-line measurements
- Concentration measurements
- Sampling is proposed for the measurement of isotopic composition. A standoff gamma-ray spectrum is unlikely to be useful because Compton effects will be large and likely to mask useful signatures, particularly at low energies (<500 eV); saturation of detector electronics (dead-time effects) because of the high intensity and thus high-count rate of short-lived fission product gamma rays; and (alpha, n) reactions in light materials are likely to dominate the background for passive neutron measurements.

The following research and development needs are associated with these measurement activities:

- Develop NDA instruments to measure irradiated fuel salt, which has not been done before in an NDA context.
- Develop a flow meter for the continuous removal process. Flow rate measurement would require prior knowledge of the pipe diameter, which could perhaps be included in the design information verification.
- Investigate short-lived fission products and flow between two sensors on standard-diameter pipe.
- Position two detectors at the start and end points of each transfer to monitor changes in the count rates caused by the transfer.
- Evaluate what high-energy (>3 MeV), short-lived gamma lines are viable and can be correlated to an actinide composition of the fuel salt. Investigate signal-to-noise ratio and viability. These measurements will need to be combined with a transmission measurement (e.g., x-ray system).
- Investigate the use of neutron emission at short times just out of the core. This has never been done before in an NDA context. The absolute neutron count rate will be tied to curium.
- Consider what is being used for the reactor core instrumentation in case it can be joint-use (i.e., operational and inspection).
- Consider development of an in-line transmission system to get concentrations.
- Radiation-hardened electronics and sensors may be a requirement for in-line flow monitoring.
- Sampling strategy needs to be developed (i.e., physical/engineering method).
- Identify the key environmental and radiological measurement characteristics of the noble gas system
- Investigate the use of active neutron measurements.
- Delayed neutron measurements will have to consider a continually changing source term.
- Active neutron measurements built into a flow monitor concept could be used to determine total fissile mass.
- Investigate whether dual-energy neutron interrogation sources can be used for the determination of both uranium and plutonium content.
- Investigate whether delayed gamma rays could provide uranium/plutonium ratio.

3.2.8 Flush salt systems

Periodically, the entire contents of the reactor core will be drained, and the flush salt will be used to "flush" the irradiated fuel salt to reduce its presence in the core. There will be nuclear material left in the holdup in the primary loop, and the nuclear material content in the flush salt will increase with each use until it is cleaned or replaced. It is assumed that initially the flush salt does not contain nuclear material. If the flush salt contains unirradiated nuclear material during its first use, then separate KMPs should be established for the introduction of the fuel salt.

NDA or DA may be used to measure isotopic content of unirradiated and irradiated flush salt (i.e., after first use) containing nuclear material. Some of the same approaches and discussions from the previous section on fuel salt cleanup systems are applicable, including possible weight or volume measurements for mass. The flush salt mixture must be homogeneous.

3.2.9 Fuel salt storage (irradiated)

Some fuel salt may be removed from the primary loop (irradiated) and held in storage tanks. Quantities of irradiated material in irradiated fuel storage tanks can be compared with the amount that are measured/reported as transfers to and from the storage area. Some of the same challenges already discussed will apply regarding measurements through NDA or DA to determine isotopic content of unirradiated (i.e., fresh) fuel salt. The following safeguards techniques may be used:

- Weight or volume measurements for mass
- Application of seals to irradiated fuel salt containers
- C/S measures

3.2.10 Shipment of irradiated fuel

Irradiated fuel may need to be shipped off-site. Packaging and shipping of irradiated fuel will require safeguards measures, and it can be assumed that suitable containers would be developed that could be sealed and treated as an item. Volume/weight measurements could be used for mass, and shipping containers may contain seals. The used fuel must be characterized as completely as possible before it is transferred out of the MBA.

The following verification measurements and methods could be applied:

- Isotopic composition through high-resolution gamma-ray spectrometry using high-purity germanium detectors.
- Reactivity measurements using passive neutron counting.

3.2.11 Nuclear material in waste streams

Nuclear material in waste streams will need to be verified through NDA, DA, or samples of both. Volume/weight measurements should be used for mass, and waste storage containers may be sealed. Note that termination of safeguards on waste material is possible if nuclear material is sufficiently diluted or practically irrecoverable.

3.3 SAFEGUARDS CHALLENGES

The facility safeguards approaches that will be implemented at an LFMSR will be based partly on the potential diversion strategies, misuse of the facility, safeguards measures that can be realistically applied, and the results of examining design information. This section discusses some of the challenges for applying safeguards at LFMSRs.

3.3.1 Online processing and the addition of fertile and fissionable/fissile material

One of the significant features of LFMSRs is the potential for online processing of the fuel salt and the option for adding fertile and fissionable/fissile material. This can be done on a batch or continuous basis. This feature generally affects the way safeguards approaches could be applied to LFMSRs. The ability to add nuclear material will change the core dynamics, fission rates, and the production of plutonium. The ability to process the fuel salt will remove nuclear material from the primary loop for the purpose of removing undesirable constituents (e.g., fission products that act as reactor poisons). This complicates the application of safeguards from multiple perspectives, as delineated in the discussions below.

3.3.2 Nuclear material accounting and obtaining material balances

Nuclear material accounting is a fundamental tool for IAEA verification activities. Nuclear material accounting is based on the MBAs and KMPs that are selected as well as the operator's MBA and KMP structure, and a facility's item control and monitoring areas. The types of measurements needed, the accuracy and uncertainties associated with those measurements, and how those measurements can be reliably obtained must be determined. It is currently not known how a nuclear material accounting system could be set up in an LFMSR. An LFMSR cannot be safeguarded as an item facility, as power reactors currently are, but would likely be considered a bulk facility for the purposes of safeguards. Existing accountancy measures on unirradiated fuel salt shipped to an LFMSR could be employed as described above. Measuring the input of the nuclear material into the reactor would also be relatively straightforward. However, once it is introduced into the reactor, it does not resemble a typical light water reactor or even a Canada Deuterium-Uranium reactor with online fueled reactors [4]. A light water reactor can be considered an item during operation because it is sealed. For a Canada Deuterium-Uranium Reactor, the fuel bundles transferred into and out of the reactor core are tracked and monitored as items. However, an LFMSR reactor vessel would likely not be considered an item during operation because of the continual input and removal of nuclear material. Because the reactor cannot be sealed during operation and the amount of uranium and plutonium is constantly changing, it would be very challenging to establish a material balance at a given point in time. Compounding this situation is the fact that measurements and access by inspectors would be difficult because of the extreme radiation fields and high temperatures associated with irradiated fuel salt with little or no cooling time (see discussion below).

One possibility is considering near-real-time accounting techniques that have been developed for high-throughput bulk handling facilities such as reprocessing plants. It is not known how near-real-time accounting might be implemented in an LFMSR. Although LFMSRs would be considered low-throughput facilities, the difficulty in establishing a material balance at any time may make the application of near-real-time accounting appealing, especially if it was automated, carried out remotely, or both.

3.3.3 Difficulty in conducting physical inventories

Because of the continuous nature of LFMSRs operations, it is not realistic to periodically shut down the reactor to take a physical inventory. In this case, it is impossible to "freeze" the nuclear material movements into and out of the reactor core because this activity is an integral part of operations. Additionally, any irradiated fuel salt or contaminated equipment will not be accessible to inspectors, and all verification will have to be done remotely.

3.3.4 Maintaining continuity of knowledge for bulk materials

Together with performing physical inventories, nuclear material at an LFMSR must be tracked, measured, and recorded. As the fuel salt and associated materials are transferred between control areas, the volumes, masses, and compositions of these materials should be known, if not for international safeguards then potentially for domestic safeguards/security to prevent theft by insiders. Challenges specific to LFMSR operations that will affect tracking of bulk materials and maintaining continuity of knowledge include

- tracking and identifying raw material or unirradiated fuel salt as it is delivered to the facility,
- introducing fuel into the reactor with minimal expected shutdowns, and
- continually removing and introducing fertile and fissile material from the primary loop and other processing aspects.

These challenges will be especially present where access to material and their containers may be difficult or impossible.

3.3.5 Modeling and isotopics to predict inventories of nuclear material

LFMSRs present unique challenges beyond the capabilities of modeling and simulation tools typically addressing reactor physics (i.e., characterizing neutron behavior and time-dependent changes within the molten salt resulting from irradiation), fuel cycle (i.e., characterizing mass flow rates of materials in and out of the molten salt), and systems (i.e., characterizing the transport of material throughout the system and its impact on the behavior and safety of the reactor system) [5]. These challenges primarily result from

- the movement of fuel-bearing molten salt and
- the potential for continuous feeds (i.e., fissile and fertile material) and removals (e.g., fission products, noble metals) to and from the molten salt.

For common reactors in operation today, fuel is designed to contain all fission products and transmutation chain isotopes; this is often an assumption within typical reactor modeling and simulation tools that prevents the application to characterize the behavior of liquid-fueled nuclear reactor systems. Furthermore, the feed and, in particular, the removal rates can vary for different elements because of the passive or chemical means by which the elements are processed and managed. This results in the need to not only predict the isotopic composition of the salt at each time step but also to be able to model the continual feed and removal of specific elements at different rates, keeping track of where they go in the system and what they become as they decay. For example, removal rates are specified using an element-specific *cycle time*, which is defined as the amount of time it takes to completely remove an element from the salt. Cycle times vary from seconds for volatile gases and noble metals to tens, hundreds, or thousands of days for semi-noble metals and rare earth elements, and the inventory calculation tools must be able to deal with this level of complication.

3.3.6 Reactor startup versus equilibrium and potentially significant change in operating parameters

One fundamental aspect of LFMSRs is that fissile material loading can be changed at any time during operations. The actinide isotopic makeup will be different during startup through the equilibrium point of the system. Reactor operations could also change significantly during the lifetime of the reactor; for example, the reactor may change its breeding or burn ratios or the types of fissile and fertile material introduced into the core. This, of course, would be limited by the design of the reactor and its operating license. The regulatory authority would presumably strictly specify how the reactor would be allowed to operate, principally for safety and environmental reasons. Nevertheless, if a safeguards system were to be designed based on the operating characteristics during startup and equilibrium, and then those operating characteristics changed significantly during the reactor's lifetime, the safeguards approach would need to be reevaluated and the facility attachment revised.

3.3.7 Extreme physical and radiation environments

Access by inspectors and the survivability of instruments will be challenging in LFMSRs because of extreme radiation fields, high temperatures, and the highly corrosive environment, let alone the challenge of designing measurement techniques that can be effective at these radiation fields. A fraction of the fuel salt resides outside the core at any given time, which implies that a fraction of the delayed neutrons is born outside the core. However, only two-thirds of a percent of neutrons are delayed. Nevertheless, the presence of delayed neutrons born outside the core implies that there is a nonzero neutron flux, and thus radiation damage and neutron activation will occur. The primary loop piping and heat exchangers will likely receive radiation doses (on the order of 300× lower than the peak values in the core), and the primary coolant system will likely become slightly activated. These effects need to be considered in the design of instruments.

This environment will make it challenging to measure irradiated materials at the KMPs. Therefore, knowledge of the radiation environments that exist at various points in the system will be an important factor in determining what points can be measured and how. This requires additional modeling and analysis. The following questions remain to be answered:

- Will the IAEA be limited in its ability to install C/S systems if the systems are not be able to withstand the harsh environments?
- Will the IAEA be able to independently measure inventories of MBAs?
- Will the IAEA be able to collect samples for DA?
- Will the inspectors be able to conduct Design Information Verification (DIV) after operation has started?
- Will inspectors be able to compare piping diagrams with actual installation?
- What assurances will inspectors have that piping will not change after verification?

3.3.8 Lack of access by IAEA inspectors

One of the key IAEA verification activities is access to the facility by IAEA inspectors. Because of the high-radiation and high-temperature environments, access may be very limited. This challenge can be mitigated by other safeguards approaches including remote monitoring, shared use of operator equipment, and C/S. This will be highly dependent on how the LFMSR design addresses physical spaces including facility layout, area access, equipment configuration, barriers, and shielding.

3.3.9 Applying the appropriate NDA and DA techniques and measurement uncertainties

Very limited NDA and DA measurement techniques exist for use with irradiated fuel salt. The closest technology is pyroprocessing for metallic fuel–containing nuclear material and fission products. No known measurement techniques are available for use with fuel salt with short or no cooling time. Appendix A in [1] includes an analysis of potential methods for measuring the spectra from short half-life fission products that could provide a unique way to correlate the signatures with the production, consumption, and content of nuclear material.

Since the measurement techniques have not yet been determined, it is not known what effect uncertainties will have on the accuracy on which material balances are determined. One positive note is that LFMSRs do not have high throughput with respect to other kinds of bulk facilities (e.g., reprocessing or fuel fabrication facilities). Once an initial load of fuel salt is placed in a reactor, relatively small amounts of fuel enter and exit the facility relative to other bulk facilities, where thousands of kilograms of material are processed on a continual basis. LFMSRs can therefore be considered low-throughput facilities. The measurements must be precise and reproduceable with an emphasis on change detection. The accuracy needs to be appropriate for the measurement application and based on measurement targets. Further studies of how measurements related to MCFR safeguards can be performed with such high radioactivity will likely be needed.

3.3.10 Holdup of nuclear material in systems and equipment

Based on operational experience from ORNL's Molten Salt Reactor Experiment, nuclear material will plate-out on surfaces within the process, both purposefully and accidentally. When coupled with the high-radiation environment, it will be more difficult to establish material balances, identify MUF, and pinpoint the part of the system where the material may exist. Additionally, LFMSR designs might account for replacement of major components, such as pumps and valves, that were part of the primary loop. When these are replaced, there will be holdup-containing nuclear material in the equipment, which may have to be quantified.

3.3.11 Frozen versus liquid fuel salt and homogeneity

Because solid and liquid fuel salt will exist in the facility, both irradiated and unirradiated, they will likely require completely different approaches for accounting and measurement. Frozen salt may be easier to account for if the fissile concentration and content from a homogeneous mixture can be determined using NDA or DA; then the container might be weighed to establish an inventory and then sealed. Liquid salt by its nature will have a high temperature, in addition to the high radiation field if irradiated. Homogeneity will be important in both cases if samples are to be representative of the material being measured.

3.3.12 Fuel salt chemistry and isotopic effects on fissile material production

Both the chemistry and isotopic makeup of the fuel salt molecules may influence the fissile material production in the system. For example, enriching the fuel salt in ^{37}Cl will affect the neutron economy and the rates at which fissile material is created. Additionally, the chemical properties of the fuel salt will affect the types of materials and the rate at which they will plate-out, which will influence reactor dynamics and, subsequently, the isotopics of the actinides in the fuel salt.

3.4 DESIGN REQUIREMENTS FOR LFMSR SAFEGUARDS

The goal of SBD is to facilitate the application of IAEA safeguards to a specific facility. SBD helps to minimize risk that certain designs will be difficult for the agency to apply safeguards, which in turn increases cost and affects operations. Because applying safeguards is a fundamental international requirement that all States and facilities must meet, this could be interpreted as a negative feature of the design. A designer can keep general design requirements in mind [3].

- Performing all relevant IAEA activities (e.g., DIV) before permanently closing process areas to make access difficult. Because many areas in an LFMSR will not be accessible after operations begin, this is particularly important.

- Reducing opportunities for undeclared removal of nuclear material. In many ways, the high-radiation and high-temperature environments in an LFMSR will both hinder and help safeguards application. The environment will hinder safeguards application because of inspectors' lack of access for verification purposes. However, many areas will be permanently off limits to personnel, and access will be blocked. This includes the irradiated fuel that may be stored on-site. This may limit potential diversion pathways.

- Reducing the potential for human error. This is a generic safeguards design requirement because designing the nuclear material accountancy system to modularize or automate the processes that facilitate safeguards activities can improve effectiveness.

- Reducing the potential for loss of safeguards data (e.g., during off-normal events). Care should be taken to ensure that nuclear material that is transferred within the system during off-normal events must be accounted for before re-start of normal operations. If not, a complex and time-consuming re-inventory may be needed.

- Including features that minimize or eliminate inventory remaining outside easy-to-measure locations. This will be particularly challenging for LFMSRs because of the high-radiation and temperature environments. There may not be any easy-to-measure locations for parts of the LFMSR system.

- Making recommendations for how safeguards equipment can be made reliable and low maintenance. Any recommendations that the designer can make that would ensure IAEA equipment is reliable will improve safeguards implementation and reduce operator burden. Suggestions may include location, shielding, temperature/humidity, fault tolerance, backup power, and redundancy. Providing reliable power and data transmission is the backbone for safeguards systems.

- Allocating space for safeguards cabinets and inspector office space. Generic safeguards design requirements call for cabinet space to hold IAEA equipment and information kept under IAEA seal in between inspections, as well as for an area from which IAEA inspectors can perform work and communicate among themselves and with management.

When choosing design options, the designer should consider how those options may affect the application of safeguards [6]. Considerations should include:

- Will the design option create additional or alter existing diversion paths, undermining confidence that the safeguards approach can detect covert removal of nuclear material?

- Will the design option increase the difficulty of design information examination and verification activities, decreasing the IAEA's assurance that established inspection activities will provide sufficient information to verify that there has been no indication of diversion of declared nuclear material and no indication of undeclared nuclear material or activities in the State?

- Will the design option impede the IAEA's capability to verify that diversion has not taken place (i.e., all nuclear material is in declared areas)?

- Will the design option create new potential, or alter an existing potential, for the facility to be misused for undeclared activities or make the detection of such misuse more difficult?

For an LFMSR, the potential diversion scenarios are repeated below with possible design considerations:

- **Removal of unirradiated fuel salt from the fresh fuel salt receipt—**Design considerations should include ensuring that continuity of knowledge from the shipper of the raw material or the fuel salt is maintained. Joint use of IAEA seals could minimize requirements for inspectors to be present. The IAEA will likely require installation of surveillance C/S equipment to detect unauthorized movement or processing. Minimizing ingress and egress for personnel as well as minimizing pathways for the fuel salt could simplify the safeguards approach.

- **Removal of irradiated fuel salt from the reactor primary loop**—It will be difficult to establish material balances during LFMSR operations. Therefore, designers should consider minimizing the pathways for removal of fuel salt from the reactor primary loop. Because most MBAs will be highly radioactive, designers should consider how IAEA monitoring equipment may be installed on existing pathways and whether joint IAEA–operator equipment could be recommended.

- **Irradiation of undeclared fuel salt in the primary loop—**Designers should minimize the pathways for introducing fuel salt into the primary loop. For existing pathways, this fuel salt could be irradiated or unirradiated. If irradiated, the suggestions regarding removal of irradiated fuel salt from the primary loop could be applied. If unirradiated, designers should consider how IAEA monitoring equipment may be installed.

- **Removal of unirradiated and irradiated fuel salt from fuel holding areas outside the primary loop—**This diversion pathway is of somewhat greater concern, especially where storage is in multiple locations and material can be removed during reactor operations. Minimizing storage areas outside the primary loop would be beneficial. Nuclear material accountancy should be designed with a high level of confidence that such diversion would be detected and must consider measurement errors, biases, and uncertainties that could result in MUF.

- **Removal of irradiated material from cleanup/flush systems**—The designers must properly consider that significant amounts of nuclear material that may exist in cleanup and flush systems, including those for off-gases and cover gases. The fact the volatile gases and metals have a high affinity for plating out in filters and other parts of the system, and for otherwise exiting the fuel salt mixture, must be accounted for. Therefore, strategies, systems, measurements, and other approaches that address this reality should be considered.

- **Removal of irradiated fuel salt from consignment when it leaves the facility or subsequently—** This generic safeguards issue may not be part of the initial considerations for plant startup and operations; however, proper container designs, handling of the fuel salt, and accounting for the irradiated fuel salt should be considered.

- **Diversion from waste streams (fuel production, cleanup systems, and final fuel exiting core)—** Issues of how to measure, contain, and account for nuclear material that has accumulated from waste streams must be considered. This is true for the irradiated fuel processing as well as fresh fuel production, if it is included in the design of the facility.

A more detailed analysis should be performed regarding specific LFMSR design features that may hinder (or facilitate) the application of current and future safeguards technologies and approaches.

4. SUBJECT INVENTIONS (AS DEFINED IN THE CRADA)

There are no subject inventions as a result of this research.

5. COMMERCIALIZATION POSSIBILITIES

The report focused primarily on applying existing safeguards measures from other fuel cycle facilities to LFMSRs and identifying gaps and needs for SBD practices for LFMSR developers. Many of the challenges that LFMSRs present from a safeguards perspective could be commercialized on their own merits. This section will detail what elements indicated in Section 3 could provide pathways for novel opportunities for research and development and result in the commercialization of applicable technologies.

Some of these findings were used to generate reactor physics and fuel cycle models for the addition and removal rates of online processing systems with on information provided for a MCFR. However, the specifics of these analyses were removed from this report, pursuant with applicable nondisclosure agreements. To generalize the analysis from such simulations for LFMSRs, this section summarizes the challenges and recommendations based on these analyses, as well as similar MBAs and KMPs identified Section 3 of this report. This summary does not contain any proprietary or protected information and applies generally to LFMSRs that have provisions for the removal of fission products and the input and withdrawal of nuclear material.

5.1 RESEARCH AND DEVELOPMENT NEEDS FOR SAFEGUARDS VERIFICATION MEASUREMENTS AND INSTRUMENTATION

The discussion above indicates a variety of research and development needs with respect to instruments and measurement systems. To properly define instrumentation design requirements, specific design details for facility layouts will also need to be considered (e.g., physical space for access to the pipes/tanks/items being measured). As such, accuracies and uncertainties of proposed measurement techniques and instruments are difficult to determine at this early stage in the assessment process.

What is known is that it will likely not be possible to directly measure the actinides in irradiated fuel salt, so their quantities and concentrations will have to be inferred from correlations of radiation signatures from fission products, including very short-lived fission products. The LFMSR is unique in that it offers the possibility to measure very short-lived fission products on a continuing basis during reactor operations. Not only is this not like any other reactor design, but the existence of these short-lived fission products would be very difficult for an operator to spoof or mask. Consequently, this offers an exciting possibility for safeguards applications—if they can be measured!

Joint IAEA use of instrumentation—Consider whether instrumentation can be joint-use during both normal operations and IAEA inspections.

- Operational status/parameters—Because of the dynamic nature of the consumption, production, and transmutation of nuclear material, a reactor’s operational modes need to be thoroughly documented and available for IAEA verification.

- Process monitoring—The flow of fuel salt will need to be monitored as it is withdrawn and fed back into the primary loop by the various processing and cleanup systems that remove noble metals, gases, and cover gases to allow IAEA verification.

- Salt solution monitoring—This could be considered a subset of process monitoring dealing specifically with the form of the fuel salt, including its chemistry, isotopics, and other physical characteristics.

- In-core monitoring—Consider the system the operator is using and whether joint (i.e., operator and inspector) measurement can be performed.

Unattended monitoring and remote monitoring—Consider where unattended measurements will be required, how authenticated/automated sampling systems would be installed, and how unattended and remote monitoring may be employed by the IAEA.

- Consider the point at which unattended measurements will be required, as well as the practicalities of performing unattended measurements (e.g., calibrations for unattended measurements, data transfer).

- Consider the role of robotics and automation for unattended measurements.

Flow meters—To implement some of the nuclear material accountancy, process monitoring, and joint use of instrumentation, the development of a flow meter for transfers of irradiated salt should be investigated.

Radiation hardened electronics—Because of the high-radiation environments in LFMSRs, evaluate what radiation hardened electronics and sensors could be developed/applied.

Active neutron measurements—Investigate whether active neutron measurements can play a useful role for NDA of fissile isotopes within irradiated fuel salt.

- Understand any potential issues with the use of active neutron interrogation sources within the nuclear facility.

- Evaluate the potential role of neutron source replacements (e.g., neutron generators) for performing active neutron interrogation measurements for this application.

- Assess the feasibility of self-interrogation methods.

- Investigate whether dual-energy neutron interrogation sources can be used for the determination of uranium and plutonium content.

- Investigate whether delayed gamma rays could provide uranium/plutonium ratio.

6. PLANS FOR FUTURE COLLABORATION

Based on the work performed under this CRADA, TerraPower received significant benefit from the safeguards analysis in considering possible future design options. Future collaboration may be undertaken regarding reviewing design changes to the MCFR as well as other options such as experimental or proof-of-concept designs. This is yet to be determined.

7. CONCLUSIONS

The IAEA could employ existing safeguards technologies and approaches for LFMSRs. This is especially true for the fuel salt and components that are not yet irradiated. However, once irradiated, existing measurement technologies and techniques will likely not be sufficient. For example, there are no known methods for directly measuring the fissile content of irradiated fuel salt. Even traditional safeguards approaches such as C/S would likely need to be modified because of multiple pathways and process features of LFMSRs and the attendant extremely high radiation fields.

From an international safeguards and material accounting perspective, LFMSRs will likely be considered bulk and not item facilities because, unlike conventional reactors, the fuel is not contained in discrete fuel assemblies that can be counted as items. This will provide a fundamental basis for how technical measures are selected for IAEA safeguards approaches. Additionally, there will be continuous feed and withdrawal of nuclear material as well as online processing of the fuel salt. Another characteristic of LFMSRs is the continually changing isotopics in the fuel salt, even during equilibrium reactor operations. And even the fuel salt chemistry will influence the type and quantity of actinides and the rates of fissile material production. All these attributes will make it challenging to establish material balances, MBA structure, and KMPs.

Based on the information provided, a preliminary assessment of the potential diversion scenarios was performed and suggestions were provided about what safeguards measure might be employed to detect any diversion of nuclear material. To determine what technologies should be developed, a comprehensive diversion pathway analysis should be performed to determine credible diversion and misuse scenarios and to identify points in the system that must be measured and the corresponding timeliness goals. This will require more precise modeling of the system to characterize the fuel salt and other material and its associated radiation and physical properties at specific points in the system. Based on this, specific safeguards technologies and methodologies can be suggested.

Establishing material balances, performing physical inventories, and maintaining continuity of knowledge will be challenging given existing safeguards approaches and technologies. The high radiation fields and temperature will both hinder and help the application of safeguards. They will hinder them because many areas of an LFMSR will be inaccessible to inspectors. However, the limited access, ingress, and egress and the movement of nuclear material may simplify the application of safeguards. Holdup of nuclear material in the systems, piping, and equipment will also likely play a significant role for MUF. The fuel will be in both its frozen and liquid forms in various parts of the reactor, which will require different safeguards techniques. An LMCFR is not a high-throughput facility; consequently, the inventory can be tightly controlled so that measurement uncertainties will be greatly reduced compared to other high-throughput facilities. This factor is important for measurement of the nuclear material, as it reduces the challenges of closing material balances given that the volume of nuclear material entering and exiting the facility during normal operations is significantly smaller.

The report documents the new modeling and simulation tools that have been developed to determine isotopics for a homogeneous reactor as well as throughout the entire system. These tools consider the complexity of the continuous flow and feed and removal of material from the fuel salt. They are essential to identifying the characteristics of the fuel salt at specific points in the system. This should also be extended to look at the life cycle of the fuel salt from startup to equilibrium and other operational modes.

This analysis acknowledged that the MCFR design evaluated will not separate pure fissile material from the fission products. However, because of the fast spectrum, the plutonium that is being bred in the system is of significantly higher fissile content throughout the life of the system compared with the plutonium produced during normal operations in a light water reactor. However, in an MCFR a quasiequilibrium is reached where the fissile content remains constant. Comparatively, the total Pu in a light water reactor will increase linearly over the life of the plant and may result in higher Pu content than in an MCFR. Although safeguards are applied equally to any material that contains ^{239}Pu (i.e., it does not take into consideration the isotopics of the plutonium), it is considered by the IAEA during the design of the safeguards approach, including the negotiation of the facility attachment. The design of the MCFR should identify ways to limit access to the fuel salt, to correctly measure the plutonium content and isotopics, and to allow adequate verification methods by the IAEA.

The report identifies possible radiation signatures of fission products based on the isotopics provided by the modeling and suggests correlations that may be used for nondestructive measurement purposes. This will also include an indication of the expected doses throughout the building to consider potential access for IAEA inspectors. Since high radiation fields will make it challenging to conduct measurements, a detailed understanding of the radiation field will help determine what areas can be accessed by inspectors and the survivability of instruments needed for remote measurements at key points in the system.

Some suggestions made in the report include joint IAEA use of facility operated equipment and instruments, such as operational status of the reactor, process monitoring, and in-core monitoring. Additionally, the expanded use of unattended and remote monitoring will likely be needed because of the limited access and the high-radiation and high-temperature environments present. Also, it should be determined how closely coupled the reactor operations are with the isotopics to see if the measured values of isotopes present in the fuel salt can be an indicator of reactor operational history and if this information can be used for safeguards purposes. All these topics should be considered for an SBD approach as part of an integrated approach including security, safety, and other design considerations.

Based on the analysis in the report, existing safeguards methods and technologies will likely not be sufficient to meet all the verification challenges posed by LFMSRs and their associated fuel cycles. This will require consideration of how existing safeguards technologies and inspection methodologies can be modified and employed and what technologies and methodologies must be developed.

8. REFERENCES

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