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Safeguards Considerations for Fuel Salt Fabrication

Strategic Security Sciences

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Safeguards Considerations for Fuel Salt Fabrication

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Executive Summary

Molten salt reactors (MSR) with liquid fuel present a unique safeguards challenge whereby the current verification techniques have not been evaluated for effectiveness and applicability. While MSR operations have been the subject of prior studies, the front-end liquid fuel preparation activities have not been extensively evaluated. Reviewing the existing resources on fuel fabrication and evaluating the range of fuel fabrication process options available will allow safeguards analysts to identify the applicability of existing safeguards practices, identify gaps in capability, and identify opportunities where safeguards may be applied.

There is no existing supplier of fuel salt for MSRs. In an extensive review of MSR technology, the International Atomic Energy Agency's (IAEA's) Nuclear Power Technology Development Section acknowledges the gap in existing capabilities for fuel salt fabrication, noting, simply, "if demand exists, supply will appear."[1] Salt reactor fuel has not been previously produced on an industrial scale in a non-nuclear weapon state. These characteristics of MSR fuel fabrication present high levels of uncertainty, but they also represent an opportunity to mature safeguards techniques alongside liquid fuel preparation technologies.

This study focuses on the fabrication of uranium tetrafluoride (UF_4) based fuels, as this type of fuel is common among advanced reactor designs and closely relates to existing fuel cycle infrastructure. Through the evaluations performed within this project, the authors conclude that while front-end processes to support fuel salt fabrication are not yet well-developed, they are closely aligned with legacy processes for which the IAEA has applied safeguards. Fuel salt fabrication steps are exceedingly similar to intermediate steps in the uranium conversion process used to produce UF_6 and the deconversion process used to convert UF_6 to UF_4. This includes the use of feedstocks—UO_2 and UF_6—for which IAEA has extensive experience in applying safeguards and established methods. Additionally, many of the safeguards-by-design best practices applicable to uranium conversion and fuel fabrication facilities will be applicable to fuel salt synthesis. However, the IAEA has comparatively less experience with applying safeguards to UF_4 as a final product than for UO_2, UF_6, and finished solid fuel.

This work provides a conceptual discussion of how to implement safeguards for a notional process flow based on one of the identified synthesis process options. From this analysis, the authors conclude that safeguards implementation is conceptually straightforward for fuel salt synthesis and can be accomplished primarily with well-established and simple techniques. The conclusion that safeguards can be implemented with simple techniques is partly contingent on the qualification of nuclear material measurement equipment deployed for measuring uranium content in UF_4 and UF_4 mixtures. Future work to demonstrate the ability of equipment developed and deployed for measuring uranium in other chemical forms to accurately measure UF_4 content in containers would confirm the availability of a mass verification technique and the usability of existing IAEA tools. This includes developing international target values for the application of IAEA tools to the measurement of uranium in UF_4.

The analysis in this report identified considerable uncertainty in how the fuel salt supply will be developed. This is due to both the lack of established plans by MSR developers and nuclear fuel companies and the considerable variability in MSR fuel specifications. Detailed safeguards by design

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[1] IAEA, "Status of Molten Salt Reactor Technology," Technical Reports Series No. 489, 2021, https://inis.iaea.org/collection/NCLCollectionStore/_Public/52/090/52090830.pdf?r=1.

work to support the front end of the MSR fuel cycle will not be possible until these plans mature. Additionally, based on an evaluation of current industry plans, the authors suggest that MSRs will rely heavily on established fuel suppliers and uranium conversion infrastructure to meet their fuel supply needs. If this comes to fruition, safeguards implementation for fuel salt fabrication will need to be integrated with existing plant safeguards practices, potentially complicating the ability to implement safeguards by design. Development work to verify cross-applicability of uranium measurement equipment and any limitations for use with UF_4 can proceed before many other process variables for fuel salt synthesis are confirmed.

1. Introduction

Molten salt reactors (MSR) with liquid fuel present a unique safeguards challenge whereby the current verification techniques have not been evaluated for effectiveness and applicability. While MSR operations have been the subject of prior studies, the front-end liquid fuel preparation activities have not been extensively evaluated. Reviewing the existing resources on fuel fabrication and evaluating the range of fuel fabrication process options available will allow safeguards analysts to identify the applicability of existing safeguards practices, identify gaps in capability, and identify opportunities where safeguards may be applied.

There is no existing supplier of fuel salt for MSR. In an extensive review of MSR technology, the International Atomic Energy Agency's (IAEA's) Nuclear Power Technology Development Section acknowledges the gap in existing capabilities for fuel salt fabrication, noting, simply, "if demand exists, supply will appear."[2] Fuel salt preparation for an MSR with liquid fuel combines chemical processes similar to those performed at uranium conversion, fuel fabrication, and reprocessing facilities. While many safeguards techniques applied to existing fuel cycle facilities will have applicability for fluoride salt liquid fuel preparation, there is no direct analogue. The processes for liquid fuel fabrication are performed in chemically or physically harsh environments. Where existing safeguards technology and techniques may be applicable, they will need to be validated for use in this environment. Additionally, salt reactor fuel has not been previously produced on an industrial scale in a non-nuclear weapon state. These characteristics of fuel salt fabrication present high levels of uncertainty, but they also represent an opportunity to mature safeguards techniques alongside liquid fuel preparation technologies.

Numerous MSR designs are under development in the United States (and several other internationally) with a diverse set of design features. The degree to which techniques for liquid fuel fabrication safeguards will be transferrable across design variations is unknown. This study focuses on fabrication of uranium tetrafluoride (UF_4) based fuels, as this type of fuel is common among advanced reactor designs and closely relates to existing fuel cycle infrastructure.

The project includes a review of the literature on liquid fuel salt fabrication processes and of U.S. vendors and reactor developers' stated place. Through this review, the project identifies the range of liquid fuel fabrication processes being considered and a range of fuel supply scenarios (i.e., centralized fabrication facility or distributed fabrication). The most likely processes are further evaluated to assess how international safeguards could be applied to fuel salt fabrication. This evaluation is performed at both the process-step level and the integrated-system level. Since there is a high level of uncertainty about fuel salt fabrication in the industry, the paper evaluates the tradeoffs between various options, emphasizing how design decisions will impact the ability to implement international safeguards.

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[2] IAEA, "Status of Molten Salt Reactor Technology," Technical Reports Series No. 489, 2021, https://inis.iaea.org/collection/NCLCollectionStore/_Public/52/090/52090830.pdf?r=1.

2. Background

2.1. Fuel Salt Options

Molten salt reactors (MSRs) are a class of reactor distinguished by the use of liquid salts as coolant in low pressure, either as a solid fuel core cooled by liquid salt or as a combination of fuel dissolved in the carrier salt. The characteristics of the MSR design present many desirable qualities including high temperatures that allow for high efficiency heat production and electricity generation, low pressure operations, and favorable neutron economy. MSRs are designed with large negative temperature and void reactivity coefficients that shut down when salt temperatures increase beyond design limits. The passive safety features reduce the likelihood of criticality accidents and contribute to the overall appeal of MSRs as alternatives to traditional light water reactors. Research into MSRs began in the 1960s and culminated into the two experimental programs at Oak Ridge National Laboratory (ORNL): the Aircraft Reactor Experiment and the Molten Salt Reactor Experiment (MSRE). The latter achieved the first self-sustaining nuclear reaction with a liquid fuel in 1960.[3] No major developments were made in the MSR space from 1975 to the 2010s, although experimental work was conducted on a large-scale lead-cooled fast spectrum MSR (MSFR) from 1968 to 1973 in the United Kingdom until funding ceased.

In recent decades, there has been renewed interest in MSR concepts with varied designs. Countries currently developing MSRs include Canada, China, Denmark, France, Japan, Russia, and the USA. A variety of coolant and carrier salt concepts have been proposed (and pursued), including LiF, BeF_2, NaF, RbF, ZrF_4, KCl, amongst other proprietary chloride and fluoride salts. FLiBe has continued to emerge as a popular salt for MSR development, given the salt's optimal thermal and neutronic properties as well as the extensive knowledge base established by ORNL in the 1960s. A non-exhaustive list of candidate salts for commercial and research MSR concepts with dissolved fuel is included in Table 1. This list is based on vendor documentation, information provided to the IAEA, and academic sources. Seven of the concepts identified on this list include fissile or fissionable fluoride salts within their fuel mixture. Given the popularity of fluoride salts and their extensive history, this report will focus on fluoride fuel salt synthesis.

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[3] "Time Warp: Molten Salt Reactor Experiment—Alvin Weinberg's magnum opus," https://www.ornl.gov/molten-salt-reactor/history#:~:text=Oak%20Ridge%20National%20Laboratory's%20Molten,during%20its%20four%2Dyear%20run.

Table 1: Proposed Molten Salt Reactor Concepts[4]

Designer	Country	Reactor	Fuel Form	Fuel Type	Primary Salt
International Thorium Molten Salt Forum	Japan	MSR-FUJI	Dissolved	U, Th	FliBe, ThF_4, UF_4
Flibe-Energy	USA	LFTR	Dissolved	U, Th	FliBe, UF_4 (Driver) FliBe, ThF_4 (Blanket)
SINAP	China	TMSR-LF/ smTMSR-400	Dissolved	U, Th	FliBe, ThF_4, UF_4, ZrF_4
CNRS EURATOM, ROSATOM	France, Russia	MARS/ MOSART	Dissolved	U, Th, TRU	FliBe-$TRUF_3$ (Driver), FliBe-ThF_4-UF_4 (Blanket)
CNRS EURATOM, ROSATOM	France, Russia	MSFR/EVOL	Dissolved	U, Th, TRU	LiF-$TRUF_3$-UF_4 (Driver), LiF-ThF_4 (Blanket)
Terrestrial Energy	Canada, USA, UK	IMSR-400	Dissolved	U	Proprietary mix, containing Na, LiF, BeF_2
Transatomic	USA	TAP	Dissolved	U, Th, TRU	LiF
Copenhagen Atomics	Denmark	Atomic Waste Burner v0.2.5	Dissolved	U,Th, TRU	LiF-ThF_4-PuF_4
BARC	India	IMSBR	Dissolved	U, Th	Unspecified (Driver) LiF-ThF_4 (Blanket)
Seaborg Technologies	Denmark	MSTW/CMSR	Dissolved	Th, TRU	NaF-RbF-$TRUF_4$, NaF-ZrF_4-$TRUF_4$
Martingale	USA	ThorCon	Dissolved	U,Th	NaF-BeF_2
TerraPower	USA	MCFR	Dissolved	U	Chloride salt
Elysium	USA, Canada	MCSFR	Dissolved	U, TRU	Chloride salt
MOLTEX	UK, Canada	SSR-U/SSR-W	Dissolved, encapsulated	U (SSR-U), U, TRU (SSR—W)	NaF-RbF-UF_4 (SSR-U), KCl-$TRUCl_3$-UCl_3 (SSR-W)
Thorenco	USA	Thorenco	Molten	U, Th	UF_4 (Driver) ThF_4 (Blanket)
Institute for Solid-State Nuclear Physics	Germany	Dual-Fluid Reactor	Molten	U, Pu	UCl_3, $PuCl_3$

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[4] Beauvais, Z., Breshears, A., Heilman, B., Argonne National Laboratory, unpublished information, 2021.

References: **5,6,7,8,9,10,11,12,13,14,15**

2.2. Commercial Fuel Salt Fabrication Plans

Current MSR developers do not have direct access to industrial-scale suppliers of pure UF_4, LiF, and other constituents of fuel salt. These supply chains are emerging to support the needs of reactor designers but are not established today. At the time of this study, liquid fuel fabrication is limited to the development of prototype MSRs or the research and development (R&D) stage and has not progressed to large-scale production. Therefore, standardization of systems and practices have yet to be established, and most MSR designers have not publicly released their fuel supply plans.

The most detailed plan observed was a press release announcing an agreement between Terrestrial Energy (Canada) and Orano for the Integral Molten Salt Reactor (IMSR). This agreement will include uranium enrichment, chemical conversion of IMSR fuel form, production, transportation, packaging, and logistics, in addition to analysis for full-scale commercial production and supply of IMSR fuel to major market deployment to the United States, Canada, Japan, and the United Kingdom.[16] While it does not

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[5] International Atomic Energy Agency, "Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System," September 2020, Accessed: 15 September 2020, https://aris.iaea.org/Publications/SMR_Book_2020.pdf.

[6] United States Nuclear Regulatory Commission, "Advanced Reactors (non-LWR designs)," 15 September 2020, Accessed: 15 September 2020, https://www.nrc.gov/reactors/new-reactors/advanced.html.

[7] Canadian Nuclear Safety Commission, "Pre-Licensing Vendor Design Review," 20 August 2020, Accessed: 11 September 2020, https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm.

[8] Kadak, A.C., "A Comparison of Advanced Nuclear Technologies," Columbia University Center on Global Energy Policy, March 2017, Accessed: 15 September 2020, https://energypolicy.columbia.edu/sites/default/files/A%20Comparison%20of%20Nuclear%20Technologies%20033017.pdf.

[9] Electric Power Research Institute, "Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design -- The Liquid Fluoride Thorium Reactor (LFTR)," 22 October 2015, Accessed: 9 June 2020, https://www.epri.com/research/products/000000003002005460.

[10] Zeng, Y., *et al.*, "Tritium Transport Analysis in a 2-MW Liquid-Fueled Molten Salt Experimental Reactor with the Code TMSR-TTAC," Nuclear Technology, 2019, 205:4, 582-591, DOI: 10.1080/00295450.2018.1507200.

[11] Ignatiev, V., *et al.*, "MARS: Story on Molten Salt Actinide Recycler and Transmuter Development by Rosatom in Co-operation with Euratom," NEA/NSC/R(2015)2, 2015, https://inis.iaea.org/collection/NCLCollectionStore/_Public/47/093/47093722.pdf?r=1.

[12] Brovchenko, M., *et al.*, "Neutronic benchmark of the molten salt fast reactor in the frame of the EVOL and MARS collaborative projects," EPJ Nuclear Science and Technologies, Volume 5, 2019, Accessed: 17 July 2020, https://doi.org/10.1051/epjn/2018052.

[13] Vijayan, P.K., *et al.*, "Conceptual Design of Indian Molten Salt Breeder Reactor," Pramana—Journal of Physics, Vol 85. No. 3, September 2015, DOI: 10.1007/s12043-015-1070-0.

[14] Holden, C.S., "Thorenco Process Heat Reactor," Presentation to Thorium Energy Alliance, 2012, https://thoriumenergyalliance.com/resource/charles-s-holden-thorenco-llc-thorenco-process-heat-reactor/.

[15] Huke, A., *et al.*, "The Dual Fluid Reactor – A Novel concept for a fast nuclear reactor of high efficiency," Annals of Nuclear Energy, Vol. 80, 25 February 2015, http://dx.doi.org/10.1016/j.anucene.2015.02.016.

[16] Terrestrial Energy, "Terrestrial Energy and Orano Sign Comprehensive Agreement for Nuclear Fuel Supply for IMSR Power Plant," 29 September 2021, https://www.terrestrialenergy.com/2021/09/29/terrestrial-energy-and-orano-sign-comprehensive-agreement-for-nuclear-fuel-supply-for-imsr-power-plant/.

involve the supply of uranium fuel salt, a similar agreement has been made between Kairos and beryllium supplier Materion to assist in developing Kairos' coolant salt.[17]

Outside of the reactor vendor community, Molten Salt Solutions plans to synthesize metal chloride and fluoride salts for MSR use.[18] While little is publicly posted about their synthesis methods, they are the result of technology transfer from Los Alamos National Laboratory, and their process is described as "selective metal fluoride salt synthesis."

Researchers have also investigated novel UF_4 production options other than those previously used for industrial-scale production (see Section 2.3). Dides, Hernández and Olivares demonstrated the pilot-scale synthesis of UF_4 from UF_6, using an electrochemical mercury cell.[19] This process produced UF_4 with greater than 98% purity. While the direct technique is not scalable to industrial production levels due to the toxicity of mercury, it is promising for research quantities and may indicate other electrochemical techniques are possible. Joly *et al*. have demonstrated direct conversion of UO_2 to UF_4 under ionothermal reaction conditions using PF_6.[20] They propose this technique as an alternative to established industrial processes that use HF.[21] Other alternative processes using NF_3[22,23] and NH_4HF_2[24] have been reported in the literature, as well.

In evaluating the public literature of MSR designers, the authors did not identify any instances of reactor vendors expressing plans to perform their own fuel salt synthesis. Given the overall consolidation in the nuclear fuel industry, the difficulty of licensing and operating a facility capable of performing uranium chemical conversions, and the early plans laid out by Terrestrial Energy and Kairos, industry appears to trend towards development of uranium salt production capabilities within the existing uranium conversion infrastructure. In this case, it is likely that UF_4 meeting a reactor designer's specifications would be developed at an existing uranium conversion or fuel fabrication plant. The material could either be mixed with carrier salt at the fuel supplier's facility or the reactor site.

2.3. Historical Production for Molten Salt Reactors

Methods for preparing fluoride mixtures at ORNL were originally developed to support the Aircraft Nuclear Propulsion Program and continued during the MSRE and subsequent research programs.

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[17] "Kairos Power and Materion commission fluoride salt purification plant," Nuclear News, 20 July 2022, https://www.ans.org/news/article-4143/kairos-power-and-materion-commission-fluoride-salt-purification-plant/.

[18] Molten Salt Solutions, https://www.moltensaltsolutions.com/copy-of-separations.

[19] Dides, M., Hernández, J., and L. Olivares, "Uranium tetrafluoride production at pilot scale using a mercury electrode cell," *Nuclear Engineering and Technology*, September 2021, https://doi.org/10.1016/j.net.2021.11.013.

[20] Joly, F., *et al*., "Direct conversion of uranium dioxide UO_2 to uranium tetrafluoride UF_4 using the fluorinated ionic liquid [Bmim][PF6]," *Dalton Transactions*, 2020, DOI: 10.1039/c9dt04327f.

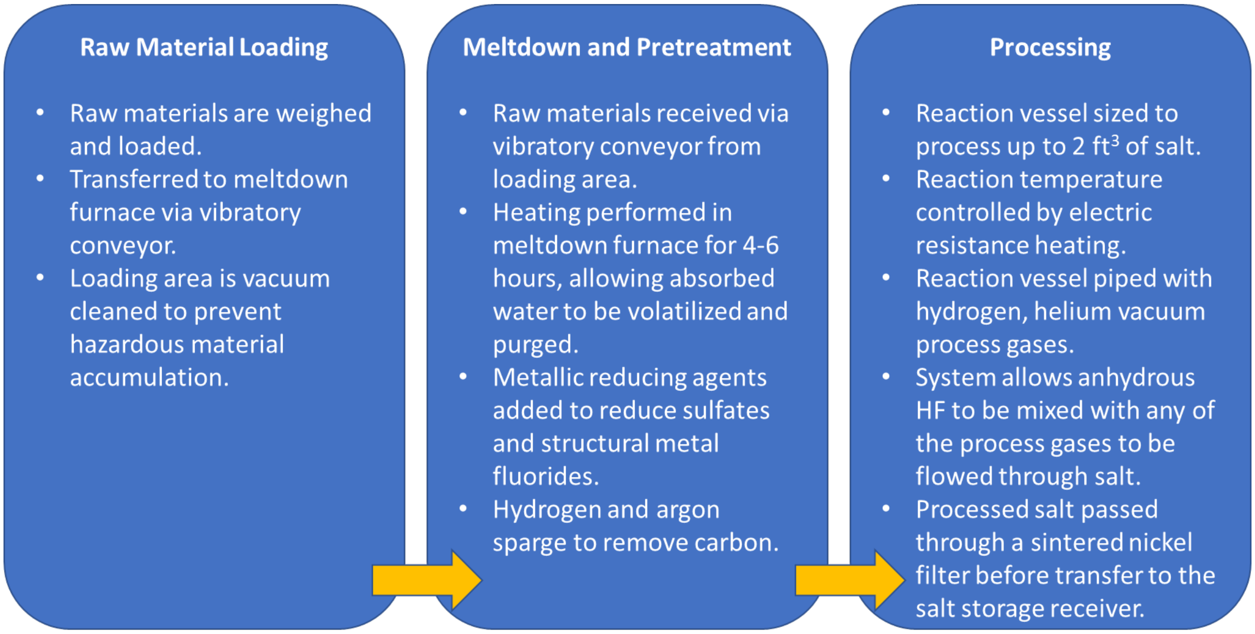
[21] *Ibid.*

[22] Casella A.M., R.D. Scheele, and B.K. McNamara, "Characterization of the Kinetics of NF3-Fluorination of NpO_2," *AIP Advances*, 2015, DOI:10.1063/1.4939143.

[23] Niu, Y., *et al*., "Study on the fluorination reaction of uranium tetrafluoride by nitrogen trifluoride," *Journal of Fluorine Chemistry*, 2020, https://doi.org/10.1016/j.jfluchem.2019.109436.

[24] Silva Neto, J.B., *et al*., "Production of uranium tetrafluoride from the effluent generated in the reconversion via ammonium uranyl carbonate," *Nuclear Engineering and Technology*, 2017, https://doi.org/10.1016/j.net.2017.07.019.

Detailed information on the ORNL process can be found in external references.[25,26] The MSRE program resulted in extensive research on salt synthesis and purification; however, their work in this area was greatly simplified by the availability of salt feedstocks from existing enrichment, defense, and commercial suppliers. The MSRE fuel form consisted of a mixture containing $LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$ (65-29.1-5.0-0.9 mole %). MSRE was able to obtain pure UF_4 directly from the U.S. Atomic Energy Commission (predecessor to Department of Energy, DOE), pure LiF directly from the Y-12 site, and BeF_2 and ZrF_4 from commercial sources.[27] Few details on the U.S. Atomic Energy Commission's UF_4 production process are publicly available, but natural UF_4 was produced from UO_2 via the wet hydrofluorination process and enriched UF_4 was reduced from UF_6 (both processes described further in Section 2.4).[28]



Raw Material Loading

- Raw materials are weighed and loaded.
- Transferred to meltdown furnace via vibratory conveyor.
- Loading area is vacuum cleaned to prevent hazardous material accumulation.

Meltdown and Pretreatment

- Raw materials received via vibratory conveyor from loading area.
- Heating performed in meltdown furnace for 4-6 hours, allowing absorbed water to be volatilized and purged.
- Metallic reducing agents added to reduce sulfates and structural metal fluorides.
- Hydrogen and argon sparge to remove carbon.

Processing

- Reaction vessel sized to process up to 2 ft^3 of salt.
- Reaction temperature controlled by electric resistance heating.
- Reaction vessel piped with hydrogen, helium vacuum process gases.
- System allows anhydrous HF to be mixed with any of the process gases to be flowed through salt.
- Processed salt passed through a sintered nickel filter before transfer to the salt storage receiver.

Figure 1: ORNL MSRE Salt Processing Steps

The remaining synthesis steps consisted of charging the raw materials, pretreatment, melting, and hydrofluorination to remove impurities. A basic description of these processes is presented in Figure 1, based on historical process descriptions.[29] The MSRE processing steps were necessary to purify materials to a level acceptable for MSRE use. Impurities were removed from the fluoride melts with a variety of reducing agents and volatized in the gas effluent stream or filtered out. Oxides, sulfur, and structural metallics were also removed from the salt mixture to prevent deposition of solid oxide particles (or scale) and prevent corrosion at high temperatures in the reactor vessel. Solvent salt (alternately referred to as carrier salt), $LiF\text{-}BeF_2\text{-}ZrF$, was synthesized separately from fuel concentrate

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[25] ORNL, "Molten-Salt Reactor Program semiannual progress report for period ending July 31, 1964," 1964.

[26] Shaffer, J.H., "Preparation and Handling of Salt Mixtures for the Molten Salt Reactor Experiment," ORNL-4616, January 1971.

[27] *Ibid.*

[28] U.S. Department of Energy Office of Environmental Management, "Linking Legacies: Connecting the Cold War Nuclear Weapons Production Processes to Their Environmental Consequences," January 1997, https://www.energy.gov/sites/default/files/2014/03/f8/Linking_Legacies.pdf.

[29] *Ibid.*

salt, UF_4-LiF, and fuel enriching capsules. Batches of uranium-bearing salt were capped at 15 kg of ^{235}U due to criticality safety concerns. Purified fuel salt was then transferred to a storage vessel. While salt containers can be sealed against atmospheric contamination, the ORNL MSRE connected their salt containers to a live helium line to ensure an inert atmosphere in the container and ensure against possible leaks.

MSRE-era ORNL programs researched numerous unit processes beyond those used in the production of salt for MSRE. Frederickson *et al*. present a thorough review of this work.[30] This work included evaluation of all basic processes necessary to operate the salt processing portion of a two-fluid molten salt breeder reactor. In addition to hydrofluorination and reduction (described elsewhere in this report), ORNL researched an electrochemical process to oxidize uranium in liquid bismuth to form UF_4 salt.

2.4. Commercial Uranium Fluoride Processes

UF_4 is routinely encountered in the nuclear fuel cycle. It is an intermediate chemical form of uranium in processes for the production of UF_6 from uranium oxide and an intermediate chemical form in the production of uranium metal from UF_6. Commercial uranium conversion plants produce UF_4 as an intermediate product, typically following the hydrofluorination of UO_2, as described in the equation below. Conversion plants operating in both nuclear weapon states and non-nuclear weapon states (i.e., Argentina and Canada[31]) produce UF_4 as an intermediate product. Laboratory and pilot-scale operations with UF_4 have been conducted in Japan. The milling and conversion pilot plant at Ningyo Toge performed UF_4 synthesis processes in the 1980s.[32] The plant implemented a process for purification of uranium ore that involved the dissolution of the ore in sulfuric acid, chemical stripping steps to remove impurities, electrolytic reduction to form tetravalent uranium, and ultimately the precipitation of UF_4 following the addition of hydrofluoric acid.[33] In this case too, the UF_4 was produced as an intermediate product for subsequent fluorination to produce UF_6. The process can also be applied to yellowcake.[34]

There are two widely-used flowsheets for hydrofluorination: a "wet" process and a "dry" process. Wet hydrofluorination uses aqueous hydrofluoric acid and precipitates the UF_4 from solution. Dry hydrofluorination uses anhydrous hydrogen fluoride gas at elevated temperatures within fluidized or moving bed reactors.[35] Both dry and wet hydrofluorination processes are likely suitable for fuel salt preparation from UO_2 feedstock; however, UF_4 produced from dry hydrofluorination is generally regarded as producing a higher purity product.[36] Additionally, using the wet hydrofluorination process requires an additional UF_4 drying step before it is ready for containerization. Different types of heated

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[30] Fredrickson, G., *et al*., "Molten Salt Reactor Processing – Technology Status," INL/EXT-18-51033, August 2018.
[31] Kwong, A.K., and S.M. Kuchurean, "Ceramic UO_2 Powder production at Cameco Corporation," Proceedings of the fifth international conference on CANDU fuel, 1997, https://inis.iaea.org/collection/NCLCollectionStore/_Public/31/006/31006093.pdf?r=1.
[32] Hirono, S., and I. Yasuda, "A Milling and Conversion Pilot Plant at Ningyo Toge, Japan," IAEA-TC-453.5/7, *Development of Projects for the Production of Uranium Concentrates*, November 1985, https://inis.iaea.org/collection/NCLCollectionStore/_Public/19/016/19016743.pdf?r=1.
[33] *Ibid.*
[34] *Ibid.*
[35] Figueroa, J., and M. Williamson, "Uranium Dioxide Conversion," ANL/CSE-13/25, 30 August 2008, https://publications.anl.gov/anlpubs/2014/09/106366.pdf.
[36] Edwards, C.R., and A.J. Oliver, "Uranium Processing: A Review of Current Methods and Technology," JOM, September 2000, https://doi.org/10.1007/s11837-000-0181-2.

vessels, such as screw reactors, rotary calciners, fluidized beds, stirred beds, or vibrating-tray-type beds, are used in the hydrofluorination process.[37]

Uranium Dioxide Hydrofluorination to Uranium Tetrafluoride

$$UO_2(s)+4HF(g)\rightarrow UF_4(salt)+2H_2O(g)$$

UF_4 is seldom produced as a final product in existing commercial uranium conversion facilities. There are currently three operational plants that perform uranium conversion to UF_4 within the civil nuclear fuel cycle: Comurhex II Malvesi Plant in France, Chepetski Machine Plant in Russia,[38] and the Springfields Main Line Chemical Plant in the United Kingdom.[39] An additional UF_4 conversion plant was operated at Fernald, OH, in the United States until 1956.[40] It is important to note that none of these plants are in non-nuclear weapon states, and thus not subject to full-scope IAEA safeguards.[41]

UF_4 is a precursor for uranium metal production, including the production of depleted uranium metal for non-nuclear applications, such as radiation shielding and munitions. Commercial plants have produced depleted UF_4 for this purpose either as a byproduct of UF_6 conversion, as described above, or through reduction of UF_6. The reduction of UF_6 through the reaction described in the equation below generally produces higher purity UF_4 than produced through hydrofluorination. The reaction between UF_6 and H_2 is extremely exothermic and can be carried out by concurrent flow of UF_6 and H_2 in a heated shaft reactor or in a kiln.[42]

Uranium Hexafluoride Reduction to Uranium Tetrafluoride

$$UF_6(g) + H_2(g)\rightarrow UF_4(s) + 2HF(g)$$

A large-scale plant for the deconversion of UF_6 to UF_4, and ultimately UO_2, was licensed by the Nuclear Regulatory Commission in 2012 to be built and operated in New Mexico, but has not yet begun construction.[43] The plant is designed to operate using the same reduction process described previously.[44] It is also designed to complete the reaction in a large reaction vessel with UF_4 powder removed via a cooling screw to a hopper for interim storage prior to subsequent processing. The cooling screw, hoppers, and other parts in the solids handling system are equipped with a dust collection system to collect UF_4 dust generated through the process. The plant was also designed to synthesize non-nuclear fluoride products for sale.

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[37] Raffo-Caiado, A.C., *et al*., "Model of a Generic Natural Uranium Conversion Plant—Suggested Measures to Strengthen International Safeguards," ORNL/TM-2008/195, November 2009, https://doi.org/10.2172/969659.
[38] Nuclear Threat Initiative, "Chepetsky Mechanical Plant (ChMZ)," October 2021, https://www.nti.org/education-center/facilities/chepetsky-mechanical-plant-chmz/.
[39] IAEA, Nuclear Fuel Cycle Facilities Database, https://infcis.iaea.org/NFCIS/Facilities.
[40] *Ibid.*
[41] Comurhex II in France is subject to EURATOM safeguards. In 2021, the most recent year for which IAEA published an annual report, the nuclear material at Comurhex II was not under IAEA safeguards.
[42] Edwards, C.R., and A.J. Oliver, "Uranium Processing: A Review of Current Methods and Technology," JOM, September 2000, https://doi.org/10.1007/s11837-000-0181-2.
[43] US NRC, "IIFP Fluorine Extraction an Depleted Uranium Deconversion Plant Licensing," 2 December 2020, https://www.nrc.gov/materials/fuel-cycle-fac/inisfacility.html#milestones.
[44] International Isotopes Fluorine Products, "Fluorine Extraction Process & Depleted Uranium De-Conversion (FEP/DUP) Plant: License Application," 29 December 2011, https://www.nrc.gov/docs/ML1212/ML12123A674.pdf.

Each of the plants discussed above performs UF_4 conversion of natural or depleted uranium prior to subsequent UF_6 conversion and enrichment or to convert depleted UF_6 to less volatile chemical forms. Outside of facilities supporting a nuclear weapons program (e.g., the Y-12 National Security Complex), the authors could not identify industrial production capabilities for enriched UF_4 as an end product.

Industrial facilities for the production of thorium tetrafluoride (ThF_4) have not been constructed or operated. ThF_4 can be produced through similar reactions to those described for uranium.[45,46] Given the difference in safeguards requirements for thorium and enriched uranium, this report did not further evaluate thorium production processes. Similarly, uranium and thorium chloride production processes lack the maturity of those that can be applied to fluorides.[47] UO_2 can be chlorinated to synthesize uranium trichloride (UCl_3) using various chlorinating agents, including CCl_4, $COCl_2$, Cl_2-CCl_4, NH_4Cl, or Cl_2 gas.[48] In partnership with an advanced reactor developer, Argonne National Laboratory has investigated the conversion of UO_2 to UCl_3 in salt solution.[49] The research resulted in a fundamental understanding of the chloride fuel salt synthesis process but has not yet been demonstrated as an option that can be scaled for industrial production.[50] Additional research is needed on the corrosion of materials in chloride salts and the control of fuel impurities before an industrial chloride fuel salt synthesis process can be demonstrated.[51]

2.5. International Safeguards Implementation at Uranium Conversion Plants

While many uranium fuel cycle processes involve the production and handling of UF_4, the IAEA experience with applying international safeguards to UF_4 is relatively recent. In 2003, the IAEA revised its policy on the “so-called” starting point of safeguards on uranium conversion facilities. The policy changed the starting point from only the final products of conversion plants, considered suitable for fuel fabrication or enrichment, to uranyl nitrate solutions prepared early in the conversion process.[52] This policy change extended the scope of international safeguards to include detailed material accounting and control of UF_4 prepared as an intermediary step for UF_6 production. As encountered in the existing civil nuclear fuel cycle, UF_4 is typically unenriched or depleted in ^{235}U. Diversion of this material for use in nuclear weapons would require subsequent processing through one of the following routes followed by conversion to a weapons-usable chemical form:

- Fluorination to UF_6 followed by enrichment in a centrifuge or gaseous diffusion plant,
- Reduction to metal followed by enrichment in an atomic vapor laser isotope separation system,
- Irradiation as a solid target, with subsequent reprocessing to extract Pu.

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[45] Frederickson, G., *et al*., “Molten Salt Reactor Processing – Technology Status,” INL/EXT-18-51033, August 2018.

[46] Souček, P., *et al*., “Synthesis of UF_4 and ThF4 by HF gas fluorination and redetermination of the UF_4 melting point,” Journal of Fluorine Chemistry, 2017, http://dx.doi.org/10.1016/j.jfluchem.2017.05.011.

[47] Frederickson, G., *et al*., “Molten Salt Reactor Processing – Technology Status,” INL/EXT-18-51033, August 2018.

[48] *Ibid.*

[49] Williamson, M.A., and J. Willit, “Synthesis of Molten Chloride Salt Fast Reactor Fuel Salt from Spent Nuclear Fuel,” ANL/CFCT-C2017-17170, December 2019.

[50] *Ibid.*

[51] Frederickson, G., *et al*., “Molten Salt Reactor Processing – Technology Status,” INL/EXT-18-51033, August 2018.

[52] Raffo-Caiado, A.C., *et al*., “Model of a Generic Natural Uranium Conversion Plant—Suggested Measures to Strengthen International Safeguards,” ORNL/TM-2008/195, November 2009, https://doi.org/10.2172/969659.

Low enriched UF_4 for MSR fuel salt is considered an indirect use nuclear material by the IAEA, with a significant quantity of 75 kg ^{235}U and a timeliness detection goal of 1 year.[53] Subsequent enrichment is still necessary for UF_4 used in molten salt reactors to become weapons usable; however, the likely required enrichments (i.e., high-assay low enriched uranium or HALEU, uranium with enrichment nominally between 5 and 20%) reduce the required separative work units (SWU) necessary. While UF_4 is readily convertible to metal or UF_6 for further enrichment, the estimated time needed to convert this material to a form usable in a nuclear explosive device is on the order of 3 to 12 months.[54]

There is a body of experience in performing material control and accounting measurements on UF_4 for U.S. domestic safeguards that may be applicable to safeguarding fuel salt fabrication facilities. In 1972, the American National Standards Institute (ANSI) published "Analytical Standards for Accountability of Uranium Tetrafluoride." This was endorsed for use by the U.S. Atomic Energy Commission in their Regulatory Guide, "Standard Analytical Methods for the Measurement of Uranium Tetrafluoride (UF_4) and Uranium Hexafluoride (UF_6)."[55] The standard included detailed methods for subsampling, gravimetric analysis, and isotope determination by mass spectrometry, among others, but does not address non-destructive assay (NDA) methods.[56] The standard and regulatory guide have been subsequently withdrawn but could be reconstituted and updated with modern methods. Additionally, use of UF_4 within defense fuel cycles has likely resulted in a body of work on UF_4 NDA outside of the open literature.

The most recent set of IAEA International Target Values (ITV) (2010) do not directly address the measurement of uranium content in UF_4.[57] ITVs are provided for various measurement techniques applicable to uranium oxide, hexafluoride, metals and alloys, and nitrate solutions, but are not directly identified for UF_4. Some methods that are applicable to pure uranium compounds could potentially be applied to UF_4, but further work will be needed to verify if the target values are applicable. These methods are listed in Table 2 along with the parameters for which they may be useful. Additionally, various measurement methods in use for UO_2 and UF_6 could conceptually be adapted for use with UF_4. However, this will require demonstration of the applicability and identification of performance limits. This is discussed further in subsequent sections of the report. Systems and equipment for performing bulk measurements that are independent of chemical form, such as load cells and electronic balances, should not require additional demonstration for use with UF_4.

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[53] IAEA, "IAEA Safeguards Glossary: 2022 Edition," International Nuclear Verification Series, No. 3, October 2022, https://www-pub.iaea.org/MTCD/Publications/PDF/PUB2003_web.pdf.

[54] *Ibid.* Definition 3.13, Conversion Time.

[55] U.S. Atomic Energy Commission, "Standard Analytical Methods for the Measurement of Uranium Tetrafluoride (UF_4) and Uranium Hexafluoride (UF_6)," Regulatory Guide 5.4, 2 February 1973, https://www.nrc.gov/docs/ML1922/ML19221B364.pdf.

[56] ANSI, "Analytical Procedures for Accountability of Uranium Tetrafluoride," N15.6-1972, American National Standards Institute: New York, NY, 1972.

[57] IAEA, "International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials," STR-368, https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/057/49057994.pdf.

Table 2: Measurement Methods Applicable to Pure Uranium Compounds[58]

Measurement Method	Parameter
Gravimetry	Uranium element concentration
Titration	Uranium element concentration
Combined product uranium concentration and enrichment assay	Uranium element concentration
Inspector Multichannel Analyzer-NaI	^{235}U abundance measurement
Mini Multichannel Analyzer-NaI	^{235}U abundance measurement

The IAEA has published safeguards-by-design (SBD) guidance for uranium conversion facilities that would generally apply to fuel salt fabrication plants.[59,60] In this guidance, the IAEA identifies two principal safeguards objectives for uranium conversion plants: to detect the possible diversion of pure material for further processing elsewhere and to detect the processing of undeclared feed to produce undeclared product. Both of these objectives translate to fuel salt fabrication facilities as well. Specific concealment methods and safeguards-by-design considerations to simplify their detection by ensuring safeguardability are listed in Table 3. As with any chemical processing plant using fluorides, salt fabrication plants will involve acute chemical hazards. The reactions involved in producing UF_4 occur at high temperatures and may require thermal shielding or physical standoffs for operator safety. Due to these likely barriers, safeguards-by-design considerations addressed early in the design of these facilities will prevent unnecessary risks to IAEA inspectors and/or costly retrofits.

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[58] *Ibid.*

[59] IAEA, “International Safeguards in the Design of Uranium Conversion Plants,” IAEA Nuclear Energy Series, No. NF-T-4.8, October 2017, https://www-pub.iaea.org/MTCD/Publications/PDF/P1766_web.pdf.

[60] IAEA, “International Safeguards in the Design of Fuel Fabrication Plants,” IAEA Nuclear Energy Series, No. NF-T-4.7, May 2017, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1699_web.pdf.

Table 3: Applicable Diversion Concealment Methods and Safeguards-by-Design Measures[61]

Potential Concealment Methods	**Safeguards-By-Design Considerations**
• Understating the feed • Reporting a false material loss incident • Overstating a loss in a waste stream • Tampering with IAEA surveillance, monitoring or tamper indicating devices • Replacing diverted nuclear material with nuclear material of lower strategic value	• Easy to read, unique identifiers for nuclear material items • A minimum number of penetrations in the containment structures • Visible pipes, ductwork, and processing equipment • Provisions for seals and other tamper indicating devices • The use of near real time accounting and process monitoring • Layout of the plant to facilitate the segregation of material and to make mixing, substitution and inappropriate transfers more difficult • Accurate measurement of in-process material and measured discards • Controlled access to locations for receipts, storage and the measurement of nuclear material

The guidance document indicates that the IAEA typically designates a uranium conversion plant as a single material balance area (MBA) with multiple key measurement points (KMP).[62] The example KMP structure for a conversion facility includes measurement points upstream and downstream of the hydrofluorination process step, with measurement points for the oxide feed and UF_6 product, respectively. While this is an example provided to indicate attributes of SBD applicable to a conversion plant, it suggests that existing approaches for uranium conversion may bypass direct measurement of UF_4.

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[61] IAEA, "International Safeguards in the Design of Uranium Conversion Plants," IAEA Nuclear Energy Series, No. NF-T-4.8, October 2017, https://www-pub.iaea.org/MTCD/Publications/PDF/P1766_web.pdf.

[62] IAEA, "International Safeguards in the Design of Uranium Conversion Plants," IAEA Nuclear Energy Series, No. NF-T-4.8, October 2017, https://www-pub.iaea.org/MTCD/Publications/PDF/P1766_web.pdf.

3. Process Options

There is a wide range of options available to future fuel salt producers on how to configure their production processes. This includes different options for basic chemical processes, operational layout, and integration with other fuel cycle steps. This section evaluates how different process choices impact the implementation of international safeguards for fuel salt synthesis activities. The evaluation is based on the fuel cycle subject matter expertise of the Argonne team, historical precedence for uranium conversion activities, and other basic considerations. Some of the information is speculative but allows discussion of how a process may be designed to simplify the implementation of safeguards.

3.1. UF_4 Synthesis

3.1.1. Process Overview

There are two basic methods for UF_4 salt synthesis, depending on the starting form of uranium: hydrofluorination or reduction. The hydrofluorination process converts UO_2 to UF_4 by reaction with hydrogen fluoride gas. The reduction process converts UF_6 to UF_4 by reaction with hydrogen gas. The chemical equations describing these processes are presented below (repeated from Section 2.4).

Uranium Dioxide Hydrofluorination to Uranium Tetrafluoride

$$UO_2(s)+4HF(g)\rightarrow UF_4(salt)+2H_2O(g)$$

Uranium Hexafluoride Reduction to Uranium Tetrafluoride

$$UF_6(g) + H_2(g)\rightarrow UF_4(s) + 2HF(g)$$

As discussed in Section 2.4, both wet and dry hydrofluorination processes have been developed for producing UF_4. The wet process is typically used when UF_4 is subsequently fluoridated to produce UF_6 and is not typically used to produce a final product. The dry process is typically used when the UF_4 is subsequently reduced to produce metal and is regarded as producing a higher purity product. For that reason, the analysis presented here focuses on the dry process. The dry hydrofluorination process involves a solid-gas reaction between UO_2 and HF. It is typically completed in a fluidized-bed reactor at temperatures in the range of 300°C to 500°C, with complete conversion of UO_2 typical when performed at an industrial scale. Researchers at the European Commission Joint Research Centre in Karlsruhe published a literature review on lab-scale uranium fluoride synthesis.[63] They identified alternate methods including hydrofluorination of UO_2 in a LiF-BeF_2 melt, though it was shown to be less effective than the gas-solid reaction.

Reduction of UF_6 by hydrogen gas has a high activation energy, requiring a very high reaction temperature of 1200°C to 1700°C.[64] The reaction is exothermic, allowing self-sustainment. In the design of the proposed UF_6 deconversion facility, the reaction vessel is equipped with external cooling and electrical heating to allow process control.[65] Unreacted UF_6 will be removed with the off-gas and can be

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[63] Souček, P., *et al*., "Synthesis of UF_4 and Th_4 by HF gas fluorination and redetermination of the UF_4 melting point," Journal of Fluorine Chemistry, 2017, http://dx.doi.org/10.1016/j.jfluchem.2017.05.011.

[64] Aleksandrov, B.P., *et al*., "Reduction of uranium hexafluoride to tetrafluoride by using the hydrogen atoms," J. Phys.: Conf. Ser. 751 012012, 2016, doi:10.1088/1742-6596/751/1/012012.

[65] International Isotopes Fluorine Products, "Fluorine Extraction Process & Depleted Uranium De-conversion (FEP/DUP) Plant: License Application, Chapter 1," December 2011, https://www.nrc.gov/docs/ML1212/ML12123A674.pdf.

captured on filters and carbon-bed traps for recovery or disposal.[66] The ORNL MSRE program also investigated a wet variant of the process where UF_4 was reduced in solution with $LiF-BeF_2$.

The primary factor for consideration in determining which process will likely be pursued for fuel salt fabrication is the available forms of the feedstock. Many MSRs will require enriched uranium fuel, typically at HALEU enrichments. If reactor vendors secure HALEU supplies from down-blended highly enriched uranium (HEU), it is possible that UO_2 would be favored.[67] On the other hand, if HALEU were obtained through enrichment, it is likely that enriched UF_6 would be the feedstock for subsequent fuel salt fabrication as gaseous UF_6 is required for centrifuge enrichment. In this case, the reduction process would be favored as it starts with UF_6 and would avoid unnecessary intermediate conversion steps.

Both available UF_4 synthesis processes require operations with hazardous gases. HF, present as a reagent in hydrofluorination and a product of reduction, presents an acute inhalation toxicity hazard and is highly corrosive. HF corrodes most substances and readily reacts with metals to produce hydrogen, presenting a potential explosion hazard. Similarly, the reduction process requires hydrogen gas which presents a potential explosive hazard.[68] Designing and operating either process will require implementing extensive process safety, chemical safety, and explosive safety measures. Where enriched uranium is involved, criticality safety will need to be considered as well.

As with the choice of synthesis process, external factors may drive the choice of where to site a fuel salt fabrication facility. For MSR demonstration plants constructed before a market has emerged for fuel salt or designs requiring non-standard chemical forms (i.e., not UF_4 or UCl_3), fuel is more likely to be fabricated in a laboratory setting or a one-off production line at an existing nuclear facility. However, as demand emerges for salt fabrication, established fuel suppliers are likely to enter the market. These suppliers would be incentivized to incorporate fuel salt fabrication lines within their existing fuel fabrication and uranium conversion plants. This approach would take advantage of cost efficiencies associated with existing site programs, licensing, and existing infrastructure. Reactor vendors have initiated discussions with established fuel suppliers, indicating that this model is likely. The authors did not identify any significant advantage to fabricating fuel at the reactor site as opposed to a dedicated production facility. However, for reactor designs where extensive salt processing using HF or F_2 gas is required, the added burden of onsite fuel fabrication may be minimal.

3.1.2. Safeguards Implementation

Basic models of the unit operations for uranium synthesis by the hydrofluorination method and reduction method are presented in Figure 2 and Figure 3, respectively. Safeguards implementation for uranium hydrofluorination and uranium reduction processes will be conceptually similar. Both processes involve receiving well-characterized feedstocks from a supplier (UF_6 from an enrichment plant, UO_2 from a down-blending process or fuel supplier, or either from prior operational steps in the plant), reacting

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[66] *Ibid.*

[67] In the United States, excess HEU is stored at the Y-12 National Security Complex. As part of their normal production processes for NNSA Defense Programs, Y-12 routinely handles uranium in UF_4 form. If this supply of uranium was used to produce down-blended UF_4 for MSR fuel, it could bypass either of the proposed processes.

[68] U.S. NRC Technical Training Center, “Fuel Cycle Processes: Uranium Conversion,” March 2010, https://www.nrc.gov/docs/ML1204/ML12045A005.pdf.

the material with process gases to produce a new chemical form, filtering off-gases to remove entrained solid uranium compounds, and eventual containerization and handling of the UF_4 product.

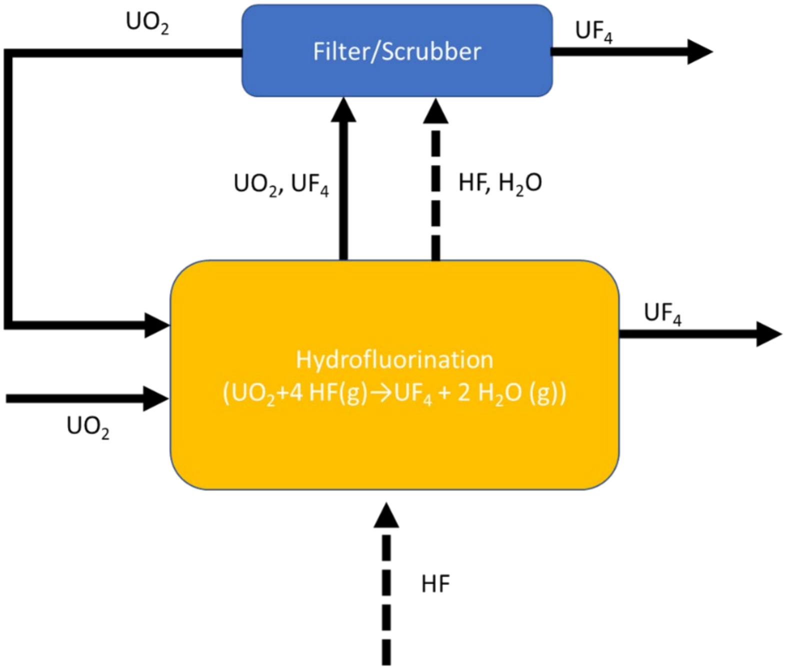

Figure 2: Basic Hydrofluorination Process Depiction

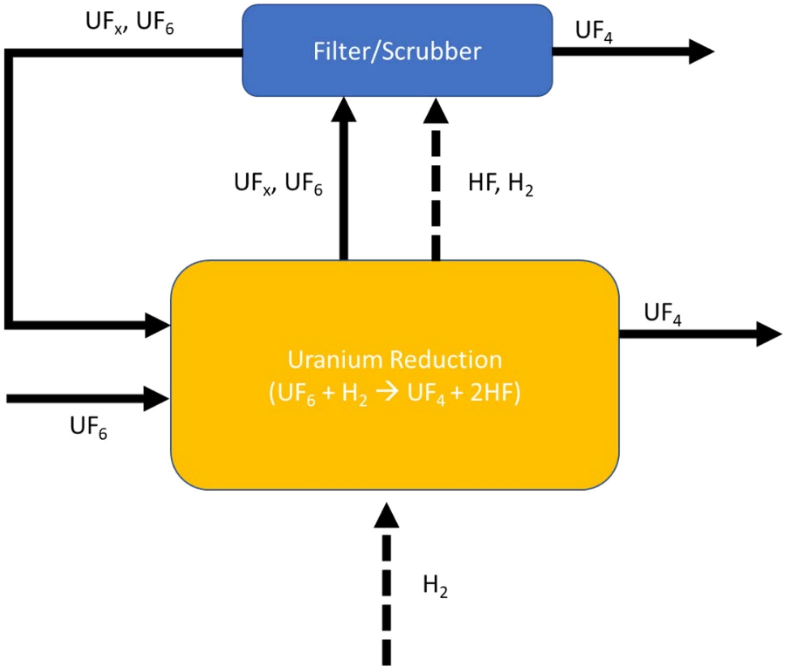

Figure 3: Basic Reduction Process Depiction

A facility operator will first need to confirm the uranium mass and enrichment of received feedstock. For both UF_6 and UO_2 feeds, the mass confirmation can be performed by weighing received canisters. The mass of the uranium in received containers can be calculated based on the chemical form of the material, assuming operators can demonstrate a high level of uniformity in their product. This can be verified with sampling records from the supplier or, if needed, sampling performed upon receipt. This may be necessary for product quality reasons as well.

Measurement of the ^{235}U 186 keV gamma ray with NaI scintillator detectors can be used to rapidly and accurately determine the feedstock enrichment. The MMCN system used by the IAEA—a NaI scintillator coupled with a miniature multichannel analyzer in a standardized counting geometry—can determine the enrichment of UO_2 powder in a matter of minutes. A higher resolution method using a high-purity germanium detector has also been used by the IAEA and is compatible with performing enrichment measurements on UF_6 in shipping containers with 1-2% accuracy.[69] There are no physical limitations to applying this measurement technique to UF_4 too, if a separate verification of the product enrichment is required (for example, at a later receipt stage). Unattended monitoring equipment developed for measuring UF_6 enrichment at enrichment plants, such as the online enrichment monitor (OLEM), could be adapted for use with the UF_6 feed to the reduction process.

Using load cells to measure the mass of UF_4 product requires confirming the uniformity of the product stream. Raman spectroscopy has been demonstrated to produce unambiguous spectra for UF_4, allowing Raman spectroscopy measurements to be proposed as "straightforward characterization techniques for …nuclear safeguards."[70] Due to its capability to evaluate chemical speciation, Raman spectroscopy could be useful for confirming UF_4 product uniformity, allowing homogeneity to be assumed for safeguards measurements. X-ray photoelectron spectroscopy has been demonstrated to identify impurities in UF_4 powder and could, conceptually, be used in this manner.[71] Other laboratory-based, chemical methods are available as well. Use of any of these techniques will require product sampling and will be subject to the applicable uncertainties.

Based on reported process efficiencies from similar industrial capabilities, the quantities of uranium entrained in process gases should be minimal. From one reference describing design assumptions for a depleted uranium hydrofluorination facility, 0.002% of input uranium mass is entrained in the process gases.[72] Of this, 90% is directly recoverable through use of filters, leading to overall uranium process losses of 0.0002% of input mass.[73] The remainder of this mass would likely remain attached to HEPA filters that would be collected as facility waste. This remaining material could likely be accounted for.

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[69] IAEA, "Safeguards Techniques and Equipment: 2011 Edition," International Verification Series No. 1 (rev. 2)., 2011, https://www-pub.iaea.org/MTCD/Publications/PDF/nvs1_web.pdf.

[70] Villa-Aleman, E., and M. S. Wellons, "Characterization of uranium tetrafluoride with Raman spectroscopy," *Journal of Raman Spectroscopy*, 22 March 2016, DOI 10.1002/jrs.4909.

[71] Feng, X., D'Souza, B., and J. Zhang, "Uranium tetrafluoride (UF_4) powder analyzed by XPS," *Surface Science Spectra,* 12 July 2019, https://doi.org/10.1116/1.5119805.

[72] Figueroa, J., and M.A. Williamson, "Uranium Dioxide Conversion," ANL/CSE-13/25, 30 August 2008, https://publications.anl.gov/anlpubs/2014/09/106366.pdf.

[73] *Ibid.*

3.2. Carrier Salt Mixing and Containerization

3.2.1. Process Overview

For nearly all MSR concepts, the fuel salt (e.g., UF_4 or UCl_3) is mixed with a carrier salt for use in the reactor. There is substantial variation between commercial concepts in the choice of carrier salt and the concentration of uranium in the salt mixture. Additionally, the operational needs of individual reactor facilities will likely vary for whether they intend to load mixed fuel and carrier salt directly in their reactor or add the two components separately. For these reasons, there is a high level of uncertainty as to whether this step will be performed by a fuel supplier (which would ship mixed fuel and carrier salt as a final product) or by the reactor operators.

In its most basic implementation, this process involves (1) melting the fuel salt and adding it to a previously molten carrier salt, (2) adding melted carrier salt to previously molten fuel salt, or (3) melting a mixture of solid UF_4 and carrier salt powder. The mixture will likely be agitated to ensure consistency. If the mixture is to be shipped offsite, the mixture will be allowed to cool, crushed to form a powder, and packaged. If the mixture is prepared at the reactor site, it may be mixed in the reactor vessel, mixed in a holding tank and immediately transferred to the reactor vessel, or mixed and containerized similar to offsite preparation. This simple processing step is depicted in Figure 4.

If high purity feedstocks are unavailable or there is reason to believe that impurities may have been introduced to the feedstocks during handling or improper storage, then chemical purification may be performed at this step as well.[74] This was performed at MSRE, as described in Section 2.3, and involved H/HF sparging the molten salt mixture.

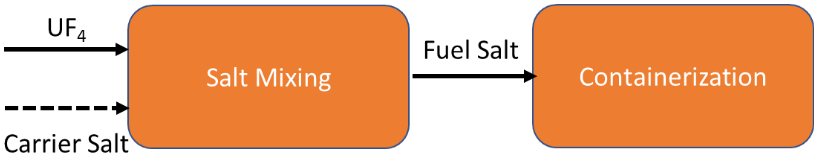

Figure 4: Salt Mixing and Containerization Process Depiction

Fuel fabricators will containerize fuel salt for transfer to reactor operators. Depending on the needs of a given reactor facility, this could be done with containers of UF_4 or containers of mixed fuel and carrier salt. There is not currently an industry standard container for enriched UF_4. The ES-3100 container, a DOE-designed and engineered double containment vessel, is certified by the DOE for transporting up to 24 kg of highly enriched uranium in UF_4 (18 kg ^{235}U).[75] This container is NRC certified for transport of highly enriched uranium in many other material forms but is not certified for use with UF_4.[76] This is a likely option for future commercial shipments of UF_4 and fuel salt mixtures. From a review of U.S. regulatory documents, the authors identified a single approved container for over-the-road transportation of enriched UF_4—a modified version of a container originally designed for transporting

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[74] Shaffer, J.H., "Preparation and Handling of Salt Mixtures for the Molten Salt Reactor Experiment," ORNL-4616, January 1971.

[75] Memorandum for Robbins, T., from J. Shenk, "DOE Certificate of Compliance Number 9315 Revision 19," 22 November 2022, DOE Certificate of Compliance Number 9315 Revision 19.

[76] Certificate of Compliance for Radioactive Material Packages, Certificate 9315, Rev. 15, ML16210A012, 3 August 2016.

research reactor fuel.[77] The fissile material limit for that container was set at 5 kg of low enriched uranium— impractically low for initial reactor fueling. MSRE set their enriched uranium salt storage container limit to a similarly low 15 kg ^{235}U.[78] Reactor and fuel vendors will need to develop and qualify a container to handle much larger shipments of enriched UF_4 or mixed fuel and carrier salt. Recent press announcements from an MSR vendor and commercial nuclear fuel supplier indicate that they have received regulatory approval in the United States, Canada, and the United Kingdom to use light water reactor fuel transport containers for over-the-road shipment of standard assay LEU MSR fuel.[79] Technical details on the design of the container were not available, but the information indicated that this container is not yet approved for the transfer of HALEU fuel salt. Cursory searches identified a Chinese patent for a UF_4 over-the-road container, but the details on its suitability for higher enrichments and level of testing were not identified.[80]

Given fissile material content, an over-the-road transport container would need to meet Department of Transportation Type B package designation for use in the United States. This is recommended internationally as well.[81] UF_4 is chemically stable for short-term storage and compatible with many structural metals. UF_4 reacts slowly with water vapor in air to form UO_2 and HF, which would corrosively attack container structural metals, so fuel salt containers will likely be filled in an inert atmosphere and purged, back-filled, and hermetically sealed.[82] Past analyses of UF_4 as a chemical form for long term storage and disposal of depleted uranium assumed standard 30-gallon or 55-gallon drums. Enriched uranium may require different configurations to meet criticality safety constraints.

3.2.2. Safeguards Implementation

In mixed fuel and carrier salt, uranium mass cannot be as easily determined from the direct mass measurement of the drum. Knowledge of the carrier salt mass in the drum is needed. This does not pose a problem for a facility operator implementing material accounting as long as the UF_4 mass entering the mixing step is well controlled. However, for IAEA inspectors, a separate measurement capability is needed to independently verify the uranium mass in a mixed drum. This can be accomplished through sampling and laboratory analysis or, preferably, through use of an NDA system that can be used in situ. Sampling for laboratory analysis is operationally difficult, as it requires opening drums, taking samples, and sending them to an analytical laboratory for analysis. It is also subject to statistical uncertainty introduced by the sampling approach.

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[77] U.S. NRC, "Revalidation of the French Certificate of Approval No. F/313/B(U)F-96 For the Model No. TN-BGC1 Package," 26 December 2012, https://www.nrc.gov/docs/ML1236/ML12362A412.pdf.

[78] Shaffer, J.H., "Preparation and Handling of Salt Mixtures for the Molten Salt Reactor Experiment," ORNL-4616, January 1971.

[79] "Terrestrial Energy and Orano Complete Successful IMSR Fuel Packaging And Transportation Evaluation," 1 November 2022, https://www.terrestrialenergy.com/2022/11/01/terrestrial-energy-and-orano-complete-successful-imsr-fuel-packaging-and-transportation-evaluation/.

[80] China Nuclear Seventh Research And Design Institute Co., Ltd., "Packaging shell for containing uranium tetrafluoride container," Patent #CN114550959, November 2020, https://patents.google.com/patent/CN114550959A/en?oq=CN114550959.

[81] IAEA, "Regulations for Safe Transport of Radioactive Material," Specific Safety Requirements No. SSR-6, Rev. 1, 2018, https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1798_web.pdf.

[82] Folga, S.M., and P.H. Kier, "Engineering Analysis for Disposal of Depleted Uranium Tetrafluoride," ANL/EAD/TM-106, June 2001.

As described in their most recent listing of safeguards equipment and techniques, the IAEA does not deploy NDA systems specifically configured for the measurement of uranium content in UF_4 or salt mixtures.[83] Both neutron and gamma techniques for NDA may be possible with UF_4. In its cooled, containerized form, UF_4 is a crystalline powder. With some uranium compounds with higher density, self-attenuation can prevent the use of gamma-ray NDA techniques for mass determination in bulk configurations. Attenuation by container walls also contributes to the error of gamma measurements for uranium compounds.[84] The theoretical density of UF_4 is 6.70 g/cc, and, in its powder form, the bulk density ranges from 2.0 to 4.5 g/cc.[85] This is lower than UO_2 or uranium metal, reducing the detrimental effect of gamma ray self-attenuation that occurs in measurements of those materials.

Uranium has a low spontaneous fission term, preventing passive neutron NDA techniques for measuring uranium mass in some chemical forms. Uranium tetrafluoride has an $^{19}F(\alpha,n)^{22}Na$ production term that may allow the container to be self-interrogating.[86] Otherwise, active neutron interrogation can be used. An active well coincidence counter (AWCC) is suggested as one method to measure the uranium content in mixed fuel salt samples directly. Use of an AWCC provides a high accuracy[87] assay of the ^{235}U content in small containers, but an AWCC is not configured to accommodate a 30- or 55-gallon drum. AWCCs should be able to accommodate a variety of fuel salt mixtures, but specific mixtures will need to be validated for use with this instrument. Mixtures that contain Beryllium (Be) may prove difficult, as Be is also a multiplying medium and could skew neutron coincidence measurements. This would be mitigated by performing a thermal neutron measurement, as (n,2n) is a threshold reaction, but could still be triggered by fission neutrons. The AWCC would need to be qualified for specific salt mixtures prior to use in a safeguards approach. Active neutron interrogation using a shuffler may be possible to accommodate larger volumes of UF_4 (up to a 55-gallon drum),[88] but equipment to perform this is not listed in the most recent version of the IAEA's "Safeguards Techniques and Equipment."[89]

For offsite preparation and mixing, there is the potential for uranium holdup in processing equipment. Quantification of this material may be subject to large uncertainties. The total mass of mixed-salt holdup can be determined by the mass difference between fuel salt and carrier salt going into the mixing vessel and the mass of mixed salt contained in drums following the mixing step. However, the exact quantities of uranium in that holdup can only be inferred from direct mass difference and are subject to

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[83] IAEA, "Safeguards Techniques and Equipment: 2011 Edition," International Verification Series No. 1 (rev. 2)., 2011, https://www-pub.iaea.org/MTCD/Publications/PDF/nvs1_web.pdf.

[84] Miller, K.A., *et al.*, "A New Technique for Uranium Cylinder Assay Using Passive Neutron Self-Interrogation," IAE-CN-184/131, https://media.nti.org/pdfs/Miller_A_New_Technique_for_Uranium_Cylinder_Assay_using_Passive_Neutron_Self-Interrogation.pdf.

[85] "Depleted UF_6 Management Information Network," https://web.evs.anl.gov/uranium/guide/ucompound/propertiesu/tetrafluoride.cfm#:~:text=The%20bulk%20density%20of%20UF,of%20the%20starting%20uranium%20compounds..

[86] Peters, W.A., *et al.*, "A kinematically complete, interdisciplinary, and co-institutional measurement of the $^{19}F(\alpha,n)$ cross section for nuclear safeguards science," INL/EXT-16-38791, May 2016, https://doi.org/10.2172/1263500.

[87] IAEA, "International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials," STR-368, https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/057/49057994.pdf.

[88] Hurd, J.R., Hsue, F., and P.M. Rinard, "Shuffler Measurements of Previously Unverified and Unconfirmed Inventory Items," LA-UR-96-2373, 1996, https://www.osti.gov/servlets/purl/394436.

[89] IAEA, "Safeguards Techniques and Equipment: 2011 Edition," International Verification Series No. 1 (rev. 2)., 2011, https://www-pub.iaea.org/MTCD/Publications/PDF/nvs1_web.pdf.

assumptions on homogenization of the mixture. These assumptions would need to be confirmed with swipes.

Containers will need to be hermetically sealed for product quality considerations. This provides an opportunity to also apply a tamper indicating seal for safeguards. Once sealed, if they are uniquely numbered and associated with a traceable weight measurement, fuel salt containers may be treated as items while in storage, awaiting shipment to a reactor facility. Containment and surveillance measures that would apply to any storage of nuclear material containers can be applied.

3.3. Flowsheet Options

As a general reactor category, MSRs are an extremely flexible platform. The IAEA identified a taxonomy of MSR technology that consisted of 20 different reactor types categorized by coolant salt, operating spectrum, fuel salt, and other attributes.[90] The range of fuels and fuel cycle options to supply this wide range of reactors is correspondingly complicated. Independent of the fuel selection, the Argonne team identified a variety of parameters that characterize the likely fuel fabrication options to supply an MSR. These are described in Table 4.

Table 4: Salt Synthesis Process Options

Parameter	**Options**
Fuel synthesis/fabrication location	• At the reactor site • At an existing/traditional fuel cycle facility (e.g., conversion facility) • At a standalone salt fabrication plant
Operation Schedule	• Batch operations • Continuous production
Input feed and chemical process	• UF_6 feed with reduction • UO_2 feed with hydrofluorination • Alternate feed and process
Form in transport	• Mixed fuel and carrier salt • Fuel salt and carrier salt shipped independently, mixed at the reactor site • Fuel salt mixed with used, loaded carrier salt at the reactor site
Reactor Design	• Chemical form (e.g., chloride or fluoride) • Single enrichment • Multiple enrichments • Reuse of irradiated carrier salt • Fertile target salt

Considered together, the available process options could lead to dozens of different fuel fabrication arrangements. For example, a reactor requiring a single enrichment fuel salt could be produced offsite via a process line at a uranium conversion plant, produced at the reactor site through any of the previously described processes, or a combination thereof (e.g., UF_4 from a conversion plant could be shipped to the reactor to be mixed with an inert carrier salt supplied separately). These processes could

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[90] IAEA, "Status of Molten Salt Reactor Technology," Technical Reports Series No. 489, 2021, https://inis.iaea.org/collection/NCLCollectionStore/_Public/52/090/52090830.pdf?r=1.

be conducted on an as-needed, periodic basis depending on reactor demand, or they could be performed continuously allowing a slow accumulation of fuel salt stored awaiting use. Independent evaluation of safeguards implementation for each option was outside the scope of this evaluation. However, options that presented a clear advantage through simplifying safeguards implementation or a clear disadvantage by complicating safeguards implementation are identified. Otherwise, this analysis evaluates options that can be considered with discussion on how alternate fabrication routes would impact safeguards implementation.

4. Process Safeguards Analysis

The goal of performing this process safeguards analysis is to identify likely measures for implementing international safeguards at a fuel salt fabrication facility and identify possible barriers to doing so. This consists of steps to identify the material balance area (MBA) structure and key measurement point (KMP) locations for likely process flowsheets, discuss factors that could influence the MBA definitions and KMP selections, identify possible safeguards upsets, and identify mechanisms to address them. This analysis builds upon the concepts identified at the unit process level in the prior section. This information is presented in a manner to allow discussion and comparison, as there is no absolute answer for how to apply safeguards to a fuel salt fabrication facility.

IAEA guidance suggests defining an MBA as an area in or outside a facility where:

- The quantity of nuclear material in each transfer into or out of each MBA can be determined;
- The physical inventory of nuclear material in each MBA can be determined when necessary, in accordance with specified procedures in order that the material balance for IAEA safeguards purposes can be established;
- Inventory and flow KMPs must be able to be defined such that it is possible to measure the complete inventory of the MBA; and
- Options for containment and surveillance are available for implementation.[91]

All nuclear material transfers in and out of an MBA must be reported to the IAEA, but nuclear material movement within an MBA does not require reporting. Defining a large MBA encompassing multiple process segments may reduce the required reporting but may, ultimately, make efforts to complete a material balance more complicated. Defining an MBA structure at too fine a level of detail will potentially constrain operations and could lead to unnecessary and cumbersome reporting to the IAEA.

The IAEA typically designates uranium conversion facilities as a single MBA. This is appropriate for unenriched uranium product but may not offer the level of specificity necessary to meet nuclear material accounting and control (NMAC) goals for enriched material. The IAEA commonly uses a three MBA model for fuel fabrications plants, consisting of a feed storage MBA, a process MBA, and a product storage MBA. This allows materials of a given type to be segregated, simplifying measurements, and allows chemical transformations of the nuclear material to all occur within a single MBA. The three MBA structure for fuel fabrication facilities was used as the basis for the proposed approaches to the processes analyzed below.

4.1. Basic Process Flowsheets

Two basic process flowsheets were analyzed. Based on the review of vendors' stated plans and subject matter expertise of the Argonne team, these were deemed the most likely options for preparing UF_4-based fuel salt mixtures. Many of the principles applied to these flowsheets are applicable to other process options as well.

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[91] IAEA, "Nuclear Material Accounting Handbook," Services Series 15, May 2008, https://www-pub.iaea.org/MTCD/Publications/PDF/svs_015_web.pdf.

4.1.1. Factory Synthesis of UF_4

A simplified process flow is presented in Figure 5 for production of UF_4 from UF_6 without supplemental mixing with an inert carrier salt. The process flow is divided into three MBAs: a feedstock storage area, a processing area, and a product storage area. The structure and basic concepts are applicable to facilities utilizing a separate chemical process but producing a similar product. Implementing safeguards at this facility can be accomplished with five flow KMPs and four inventory KMPs, described in Table 5.

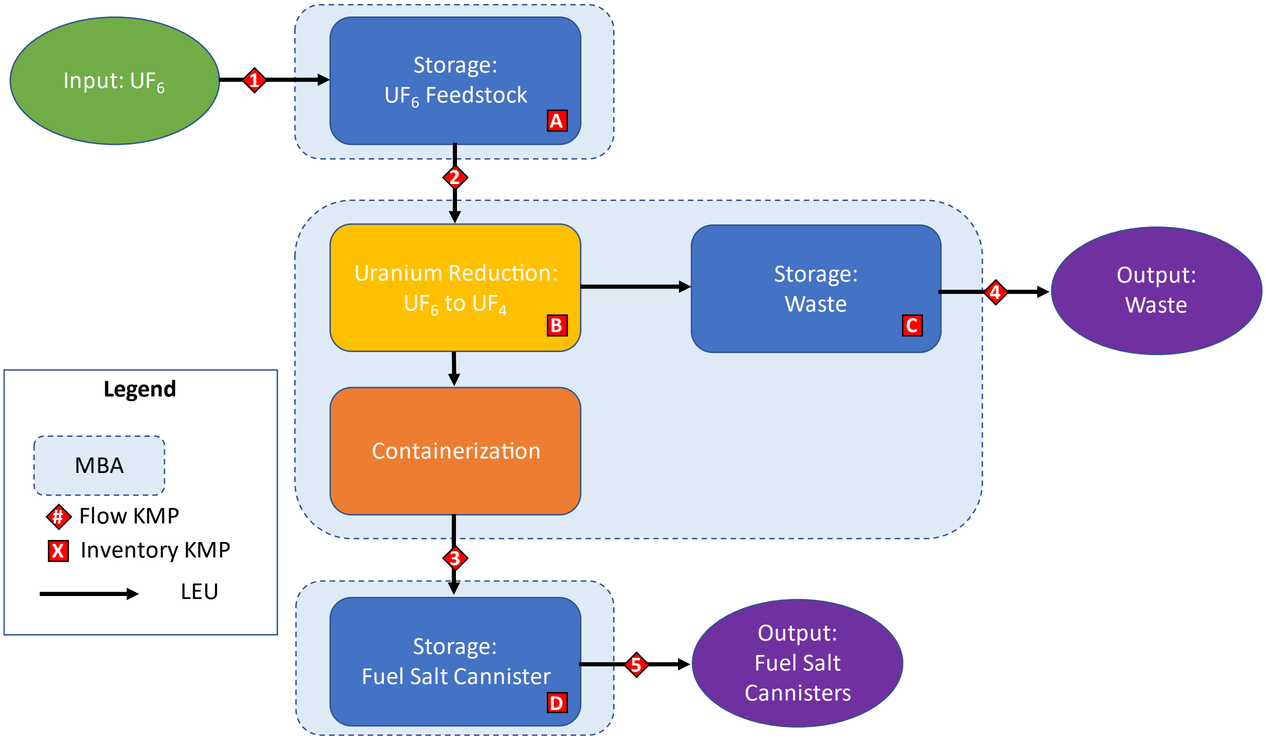

Figure 5: Simplified UF_4 Synthesis Process Flow

Table 5: MBA and KMP Description for Simplified UF_4 Synthesis Process

Measurement Point	**Description**	**Measurement Method**
Flow KMP #1	UF_6 container receipt	Weight, Enrichment by NDA
Flow KMP #2	In-process UF_6 container transfer to processing MBA	Weight
Flow KMP #3	UF_4 container transfer to product storage MBA	Weight, Chemical Assay
Flow KMP #4	Waste container offsite transfer	Various
Flow KMP #5	UF_4 container transfer out of product storage MBA	Weight, NDA
Inventory KMP A	UF_6 container storage inventory	Weight
Inventory KMP B	In-process inventory	Various
Inventory KMP C	Waste material inventory	Various
Inventory KMP D	UF_4 container product inventory	Weight, NDA

Feedstock is initially received from an outside supplier. Where fuel salt fabrication facilities are sited separate from existing uranium conversion facilities, this material will be in standard sized containers (e.g., 30B or 48Y for different enrichments of UF_6) and is likely well-characterized.[92] Operators can confirm container masses upon receipt using established techniques. Once received into plant storage, the presence of UF_6 containers can be maintained using visual surveillance. Tags can be applied to individual cylinders in storage to demonstrate that they have not been tampered with.

UF_6 containers will be connected to process piping. The in-process cylinder can either be located in the processing MBA or the storage MBA. Safeguards implementation is simplified if the in-process cylinder is moved to the processing MBA, as transfers between the MBAs would be in terms of full cylinders only. In this case, flow KMP #2 would only monitor movement of discrete cylinders (and possibly a confirmation radiological measurement to ensure no residual fissile material remains). Alternately, if the interface between the MBAs is located along the internal UF_6 piping line, with the in-process cylinder located in the storage area, flow KMP #2 would require flow monitoring of gas evolved from the in-process cylinder. This could be accomplished with flow monitors, load cells weighing the in-process cylinder, or both. While not technically challenging, this introduces unnecessary complexity to the approach.

If fuel salt is fabricated in a production line within an existing uranium conversion or deconversion facility, the feedstock may be delivered via internal process piping. In that case, the safeguards approach for the fuel salt process line will be integrated with broader safeguards implementation at the plant.

Within the processing MBA, the UF_6 is converted to UF_4 through the reduction process. Material accounting through this step requires accurate monitoring of the UF_6 gas introduced to the reaction vessel, accurate determination of the UF_4 removed and containerized, and a method to account for uranium-bearing compounds entrained in the process gases. The material balance for this area is given by the following equations.

Contributions to Process MUF

$$MUF_{Process} = M_{In} - M_{Out} - M_{Inventory},$$

$$\begin{aligned} MUF_{Process} = {} & M(U\ in\ from\ storage) - M(U\ in\ product\ out) - M(U\ in\ waste) \\ & - M(U\ in\ UF_6\ container) - M(U\ in\ holdup) \end{aligned}$$

The mass of uranium introduced to the process area from storage is known from inventory KMP A. The remaining mass of uranium in the in-process UF_6 container can be determined through weighing (i.e., by placing the container on a load cell), flow monitoring, or both. The mass of uranium in containerized UF_4 product can be determined at flow KMP #3. Good quality assurance practices will require evaluation of the chemical purity and uniformity of the product. Once the process is well-established and the chemical purity of the UF_4 is known and demonstrated to be consistent and predictable, the product mass can be obtained from mass measurements. Until that is established, a combination of mass measurements and chemical assay (destructive or non-destructive) may be necessary. Uranium will become entrained in the off-gas from the reduction process and will predominantly consist of UF_6, UF_5, and UF_4. UF_4 solids can be filtered out of the off-gas where they will either be removed as waste or returned to the process as

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[92] There is not currently an approved container for over-the-road transportation of UF_6 with HALEU enrichments. This report assumes that one will be developed and standardized.

product. Any uranium collected as process waste will need to be accounted for. Lastly, including a method to directly measure UF_4 holdup in the reduction vessel could serve to reduce the MUF for this MBA. Process efficiency, criticality safety considerations, and the inherent economic value of uranium will incentivize operators to reduce the holdup in the vessel. This is emphasized if HALEU is used as feedstock. However, it is likely that there will still be residual holdup regardless of whether these measures are implemented.

The product containers are received from the processing MBA into the product storage MBA. These containers should be sealed prior to delivery into this MBA, with unique item identifiers tied to known container material masses. Within the MBA, containment and surveillance measures will be implemented to verify containers remain sealed and unperturbed. Container weights may be verified as the product containers are shipped out of the MBA at flow KMP #5.

4.1.2. Factory Synthesis of UF_4 and Mixing of Fuel Salt

Safeguards implementation at a facility that both synthesizes UF_4 and mixes the UF_4 with inert carrier salt is conceptually similar to that described in Section 4.1.1. The major difference is that the product is a mixture, subject to variations in uranium content, as opposed to a uniform salt. This difference complicates the measurement of the final salt product, disallowing direct measurement by mass without making assumptions on the homogeneity of the mixture.

To address this, an intermediate step of collecting and containing the UF_4 in interim storage can be implemented, followed by mixing fuel and carrier salt in batches, where the overall U mass in each batch is known from the UF_4 mass added. This approach is described in Figure 6. If the batch size is limited to a single container of mixed salt product, measurements at flow KMP #3 can be implemented with low uncertainty. Otherwise, the UF_4 may divide disproportionately between containers and will need to be verified. Alternately, directly measuring the mass of the carrier salt added to the mixture could reduce this uncertainty.

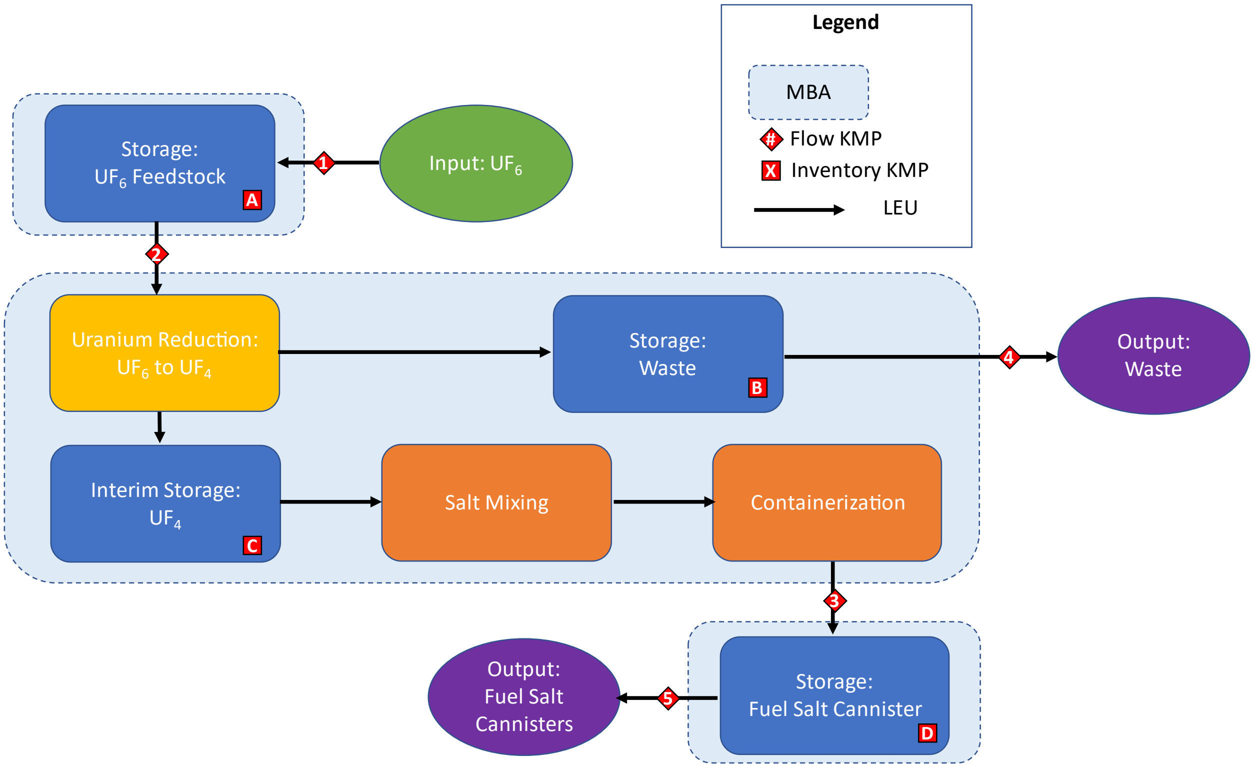

Figure 6: Simplified UF$_4$ Synthesis and Fuel Salt Mixing Process Flow

5. Conclusion and Recommendations

Through the evaluations performed within this project, the authors conclude that while front-end processes to support fuel salt fabrication are not yet well-developed, they are closely aligned with legacy processes for which the IAEA has applied safeguards. Fuel salt fabrication steps are exceedingly similar to intermediate steps in the uranium conversion process used to produce UF_6 and the deconversion process used to convert UF_6 to UF_4. Existing techniques will need to be modified and confirmed as implementation details emerge regarding which processes are favored by industry, fuel salt shipping configurations, and level of process infrastructure present at the reactor site. However, the authors conclude that the fabrication of UF_4-based fuel salts does not present any fundamental challenges for safeguards implementation.

While industrial capacity for MSR fuel salt synthesis has not yet been established, past experience in the nuclear industry with UF_4 allows the development of a safeguards implementation strategy for salt synthesis facilities. This includes considerable overlap between safeguards by design practices for uranium conversion facilities and future fuel salt synthesis facilities. The authors identified two legacy chemical processes that are likely to be utilized for UF_4 fuel synthesis: hydrofluorination from UO_2 and reduction from UF_6. This work provides a conceptual discussion of how to implement safeguards for a notional process flow based on the reduction process. From this analysis, the authors conclude that safeguards implementation is conceptually straightforward for both of these processes and can be accomplished primarily with well-established and simple techniques.

The conclusion that safeguards can be implemented with simple techniques is partly contingent on the qualification of nuclear material measurement equipment deployed for measuring uranium content in UF_4 and UF_4 mixtures. Future work to demonstrate the ability of equipment such as active well coincidence counters to accurately measure UF_4 content in containers would confirm the availability of a mass verification technique and confirm the usability of existing IAEA tools.

The analysis in this report identified considerable uncertainty in how the fuel salt supply will be developed. This is due to both the lack of established plans by MSR developers and nuclear fuel companies and the considerable variability in MSR fuel specifications. Detailed safeguards by design work to support the front end of the MSR fuel cycle will not be possible until these plans mature. From an evaluation of current industry plans, the authors suggest that MSRs will rely heavily on established fuel suppliers and uranium conversion infrastructure to meet their fuel supply needs. If this comes to fruition, safeguards implementation for fuel salt fabrication will need to be integrated with existing plant safeguards practices, potentially complicating the ability to implement safeguards by design.

6. Acknowledgements

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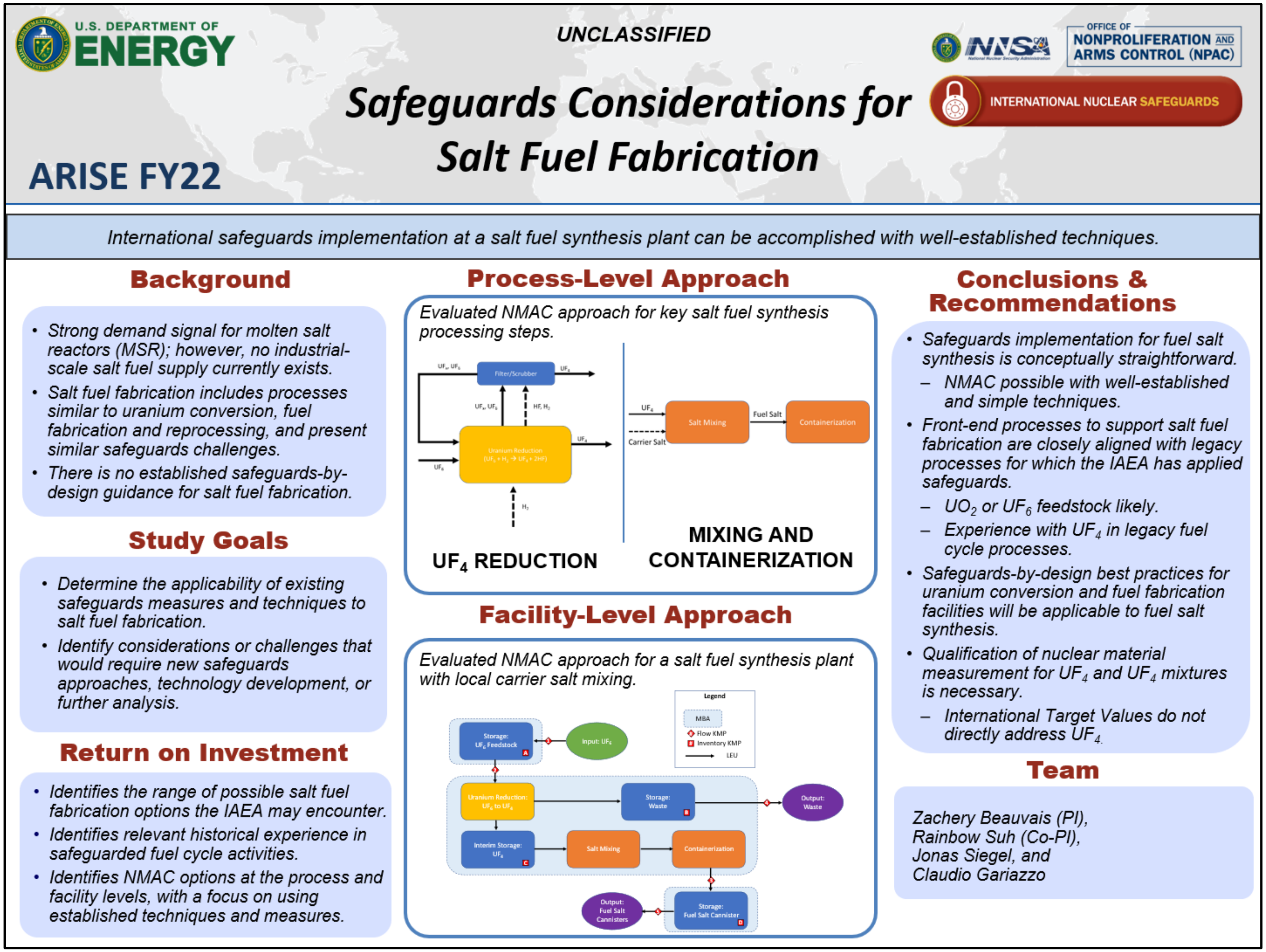
Appendix: Project Overview



U.S. DEPARTMENT OF ENERGY

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NNSA

OFFICE OF NONPROLIFERATION AND ARMS CONTROL (NPAC)

INTERNATIONAL NUCLEAR SAFEGUARDS

Safeguards Considerations for Salt Fuel Fabrication

ARISE FY22

International safeguards implementation at a salt fuel synthesis plant can be accomplished with well-established techniques.

Background

- *Strong demand signal for molten salt reactors (MSR); however, no industrial-scale salt fuel supply currently exists.*
- *Salt fuel fabrication includes processes similar to uranium conversion, fuel fabrication and reprocessing, and present similar safeguards challenges.*
- *There is no established safeguards-by-design guidance for salt fuel fabrication.*

Study Goals

- *Determine the applicability of existing safeguards measures and techniques to salt fuel fabrication.*
- *Identify considerations or challenges that would require new safeguards approaches, technology development, or further analysis.*

Return on Investment

- *Identifies the range of possible salt fuel fabrication options the IAEA may encounter.*
- *Identifies relevant historical experience in safeguarded fuel cycle activities.*
- *Identifies NMAC options at the process and facility levels, with a focus on using established techniques and measures.*

Process-Level Approach

Evaluated NMAC approach for key salt fuel synthesis processing steps.

UF_4 REDUCTION

MIXING AND CONTAINERIZATION

Facility-Level Approach

Evaluated NMAC approach for a salt fuel synthesis plant with local carrier salt mixing.

Conclusions & Recommendations

- *Safeguards implementation for fuel salt synthesis is conceptually straightforward.*
  - *NMAC possible with well-established and simple techniques.*
- *Front-end processes to support salt fuel fabrication are closely aligned with legacy processes for which the IAEA has applied safeguards.*
  - *UO_2 or UF_6 feedstock likely.*
  - *Experience with UF_4 in legacy fuel cycle processes.*
- *Safeguards-by-design best practices for uranium conversion and fuel fabrication facilities will be applicable to fuel salt synthesis.*
- *Qualification of nuclear material measurement for UF_4 and UF_4 mixtures is necessary.*
  - *International Target Values do not directly address UF_4.*

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