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Fuel Qualification Methodology Overview

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Introduction

Nuclear Energy eXperimental Testing

- White paper describes ACU's methods for qualifying liquid salt fuel for the ACU Molten Salt Research Reactor (MSRR).
  - Primary objective to provide validated inputs for models used in the MSRR safety analysis.
- MSRR is a 1MWt loop-type, liquid fueled molten salt reactor that will be constructed and operated as a class 104(c) utilization facility.
- Desired fuel source is the EBR II HALEU stock. Fuel design, specification, and subsequent qualification uses this assumption.
- MSRR Fuel Qualification to serve as foundation for future commercial MSRs fuel qualification. *10 CFR 50.43(e)*
- Fuel salt interactions with materials are investigated by separate programs

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Term	Definition
Carrier salt	The salt mixture of LiF and BeF_2 in an approximate 2:1 ratio with enriched ^{7}Li to 99.99 mol % and without the UF_4 fuel.
Coolant salt	The salt mixture of LiF and BeF_2 in an approximate 2:1 ratio used in the MSRR's coolant salt system to remove heat from the reactor loop during normal operation.
Fuel	UF_4 salt enriched in ^{235}U.
Fuel salt	The combination of the carrier salt and fuel, which is the salt mixture of LiF, BeF_2, and UF_4 in a nominal molar ratio of 63:32:5 used in the reactor system.
HALEU	Uranium enriched to between 5% and 20% ^{235}U.
MSRE salt	The salt from the coolant, or secondary, loop system of the MSRE at ORNL.
Test salts	A variety of salt mixtures used in the laboratory testing program which have comparable compositions to salts used in the MSRR.

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Background

- Fuel Salt supports the MSRR fundamental safety features due to its intrinsic thermophysical and chemical properties.
  - Fuel salts provide good heat transfer characteristics, minimal stress on pressure vessels, core homogeneity, fuel structure stability at high burnup, online refueling, and FP retention.
- **MSRR utilizes functional containment** to reduce release of radioactive materials from the facility to below safe levels in accident cases.
  - **Fuel Salt is a barrier for non-gaseous radionuclides** as they remain bound within the salt and salt wetted surfaces.
  - Reactor loop provides the primary boundary to fission product release.
  - Reactor thermal management system catches salt in case of salt leak and provides a barrier to release of non-volatile FPs.
  - Leak tight reactor enclosure provides a final boundary to FP release.

Background: Regulatory Review

- MSRR Fuel Qualification informed by:
  - NUREG/CR-7299 Fuel Qualification for Molten Salt Reactors (2022) and NUREG – 2246 Fuel Qualification for Advanced Reactors (2022).

- Regulations Identified:
  - 10 CFR 50.34(b), 50.34(b)(2), 50.34(b)(3), and 50.34(b)(4)
  - 10 CFR 50.36(c)(4)

- Relevant MSRR Principal Design Criteria
  - PDC 10: Reactor Design
  - PDC 11: Reactor Inherent Protection
  - PDC 16: Containment Design
  - PDC 71: Fuel Salt Compositional Control

Fuel Design Description

- **Nominal Composition:** LiF-BeF_2-UF_4 [molar ratio: 63:32:5]
- **HALEU enrichment:** at least 19.5 wt% U-235
- **Lithium enrichment:** at least 99.99 mol % Li-7
- **Liquidus point** of fuel salt: around 460 °C
- **Typical operating range:** 550°C – 650°C
  - Fuel Salt is maintained above 550°C during operations with Reactor Thermal Management System.
  - Fuel salt reaches up to 750°C briefly during postulated accidents and does not violate steel container temperature safety limits.
- **Fuel Salt composition changes** during operation due to:
  - Fission product buildup, depletion of U-235, UF_4 Addition/Refueling, generation of corrosion products, and contaminants in cover gases
- Specific limits will be defined for impurities after corrosion testing and fuel qualification laboratory testing is complete.

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- Fuel Salt Composition changes are managed to stay within the qualified range.
- MSRR Fuel Salt samples collected and analyzed during operation
  - ICP-MS measures composition
  - Combustion analysis measures oxygen levels
  - Redox potential which indicates corrosivity is measured via electrochemistry techniques
- Fuel salt processed as needed based on data from sample
  - Oxygen/oxidative impurities can be removed via Fuel Salt Purification Vessel H_2-HF treatment
  - Salt can be mechanically filtered
  - Beryllium can be added to adjust redox potential
  - UF_4 can be added to compensate for burnup

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- Thermophysical properties are a function of the salt's chemical composition and temperature.
  - Relevant properties: heat capacity, thermal conductivity, liquidus temperature, density, and viscosity.
- Fuel Qualification will address how these properties respond to changes in chemical composition – corresponding to the MSRR fuel operating envelope.
- MSRR Fuel performance requirements:
  - Fuel salt is maintained in its qualified chemical composition
  - Fuel salt remains a liquid during operation
  - Fuel salt retains non-volatile fission products
  - Fuel salt maintains adequate heat transfer properties.

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- Laboratory tests measure the thermophysical properties of the fuel salt for both normal operation and transient conditions for the entire range of salt compositions relevant to the MSRR.
- Laboratory tests utilize salts that are loaded with fission product surrogates to mimic fuel burnup. Surrogate elements are chosen to represent elements with similar chemical behavior to fission products.
- Ultimate goal of validating salt properties used in analysis which demonstrate the MSRR is safe in normal and transient conditions.
- Uncertainty and accuracy requirements are determined using safety analysis tools.

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- Fuel performance envelope is the bounding set of conditions the fuel salt is qualified for. The laboratory test envelope covers the ranges of temperatures, chemical compositions, and surrogate fission products that are expected in the MSRR.

Table 5: Fuel Salt Performance Envelope & Test Envelope for Thermophysical Properties

Parameter		Fuel Salt Performance Envelope	Test Envelope
Temperature Range (°C)		25 – 750	25 – 750
Fuel Salt Constituents (mol %) $LiF:BeF_2:UF_4$		66:34:0 to 62:31:7 with approximately a 2:1 ratio of $LiF:BeF_2$	See Table 7
FP Concentration Ranges (mol %)	Transition metals	0.0 – 1.08	0.0, 0.2, 1.08
	Alkali metals	0.0 – 0.54	0.0, 0.1, 0.54
	Alkaline-earth metals	0.0 – 1.08	0.0, 0.2, 1.08
	Lanthanides	0.0 – 1.08	0.0, 0.2, 1.08
Note: Table 6 identifies FP surrogates for the laboratory testing.			

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Laboratory Testing

- For the range of compositions and temperatures, the test program will measure:
  - density
  - viscosity
  - thermal conductivity
  - heat capacity
  - heat of fusion
  - liquidus point

Table 7: Compositional Matrix for Test Salts

		UF_4 (mol %)					
		0	**2**	**4**	**5**	**6**	**7**
FP Burnup (mol %)	**0.0 (Fresh)**	0U	2U	4U	5U	6U	7U
	0.7 (Low)	0U-LF	2U-LF	4U-LF	5U-LF	6U-LF	7U-LF
	3.78 (High)	0U-HF	2U-HF	4U-HF	5U-HF	6U-HF	7U-HF

Table 6: Fission Product Surrogate Compositions

Compound	Low Burnup (mol %)	High Burnup (mol %)
ZrF_4	0.1	0.54
Mo		
NdF_3		
CeF_3		
CsF		
BaF_2		
SrF_2		
Total	**0.7**	**3.78**

Notes

1. ZrF_4 and Mo represent transition metals.
2. NdF_3 represents NdF_3, LaF_3, and YF_3.
3. CeF_3 represents CeF_3 and PrF_3.
4. CsF represents alkali metals.
5. BaF_2 and SrF_2 represent alkaline-earth metals.

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Table 8: Thermophysical Property Measurement Test Plan Overview

Property	Test Plan		Standard (if applicable)
	Method	Temperature Range (°C)	
Chemical composition	ICP-MS	n/a	ASTM C1287-18
	Combustion analysis	n/a	n/a
Liquid density	Archimedes bob	LP to 750	n/a
Solid density	Pycnometry	n/a	ASTM B923-22
Viscosity	Rotational rheometry	LP to 750	n/a
Thermal conductivity	Laser flash analysis	25 to 750	ASTM E1461-13
Heat capacity	Differential scanning calorimetry (DSC)	25 to 750	ASTM E1269-11
Enthalpy (heat) of fusion	DSC	25 to 750	ASTM E793-06
Liquidus point (LP)	DSC	n/a	ASTM E794-06

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Conclusions

- ACU will assess the thermophysical properties of the MSRR fuel salt for a range of compositions and temperatures.
- Testing the thermophysical properties will confirm the design basis for MSRR's safety systems and verify that they achieve the fundamental safety functions.
- The results of the Program described in this white paper will be used to establish a fuel salt performance envelope that will be applied through operating limits specified in the MSRR Technical Specifications.