AN IN SITU FEED MONITORING SYSTEM FOR MOLTEN SALT REACTORS

With Fast Neutron Energy Spectrum Molten Salt Reactor Applications

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Molten salt reactors

The Molten Chloride Reactor Experiment was selected as an award winner under the US Department of Energy Advanced Reactor Demonstration Program

https://mfc.inl.gov/SitePages/Zero%20Power%20Physics%20Reactor.aspx

The Zero Power Physics Reactor (ZPRR) facility at Idaho National Laboratory is the intended home of the Molten Chloride Reactor Experiment

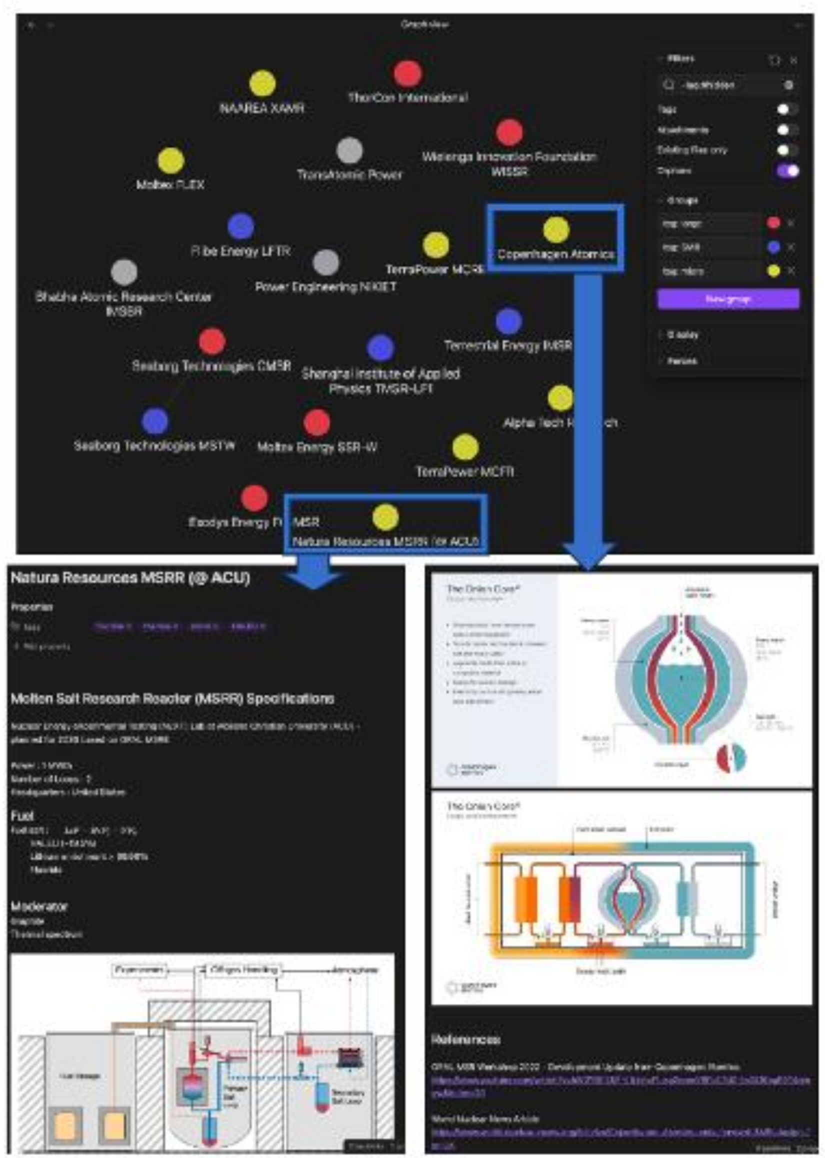
The Nuclear Regulatory Commission (NRC) issued a construction permit for the Natura Resources' MSR-1 at Abilene Christian University in Sept 2024

https://www.naturaresources.com/natura-resources-molten-salt-reactor-at-acu-receives-historic-nrc-construction-permit

The NRC with Natura Resources, ACU, and NEXT Lab leadership

Molten Salt Reactors are Diverse and Need Innovative Safeguards Approaches

- Nuclear material in liquid-fueled molten salt reactors (MSRs) is not in discrete items within the reactor system
- Because they are reactors, safeguards measures applied in other fuel cycle facilities (e.g., UO_2 fuel fabrication facilities) are not directly applicable to liquid-fueled MSRs
    - Material balance evaluations are challenging because of transmutation and depletion of nuclear material



MSR Design Catalog, developed by Oak Ridge National Laboratory

Why MSR feed monitoring?

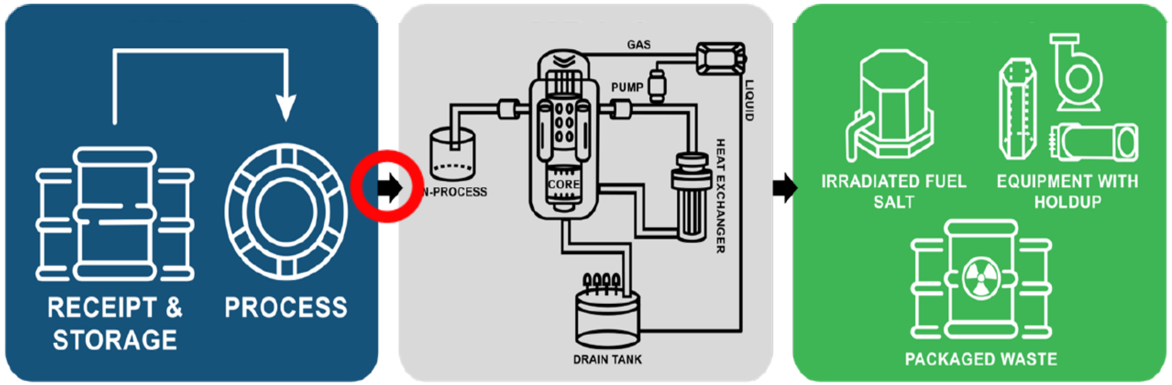
To meet safeguards objectives:

Detect **diversion** of nuclear material in fresh fuel

- Was less feed salt added than reported/declared?
- Has any material been removed from confinement?
- Is the salt composition and enrichment as reported/declared?
- Have there been any changes in quantities or composition of salt to conceal diversion?

Detect **misuse** of MSR facility for undeclared nuclear material production

- Has extra feed salt or fertile material been added?
- Has there been a change in salt composition/isotopics?



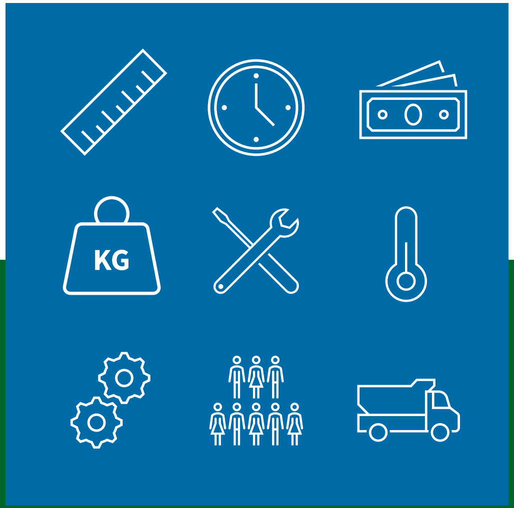
K. Hogue, N. Luciano, et al., Planning for Material Control and Accounting at Liquid-Fueled Molten Salt Reactors, ORNL/SPR-2023/3181, Oak Ridge National Laboratory, 2024.

Reporting requirements for uranium in fresh fuel

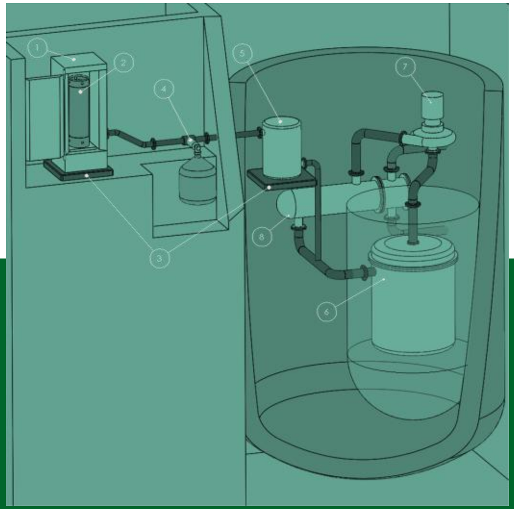
Material	US Nuclear Regulatory Commission	IAEA Safeguards
Total U	whole kg	g (to the mg)
^{235}U	whole kg and isotope wt%	g (to the mg)

Department of Energy, Nuclear Materials Management and Safeguards System (NMMSS) Users Guide–Rev. 2.1, 2022.
International Atomic Energy Agency, Nuclear Material Accounting Handbook, IAEA Services Series No. 15, IAEA, Vienna (2008).

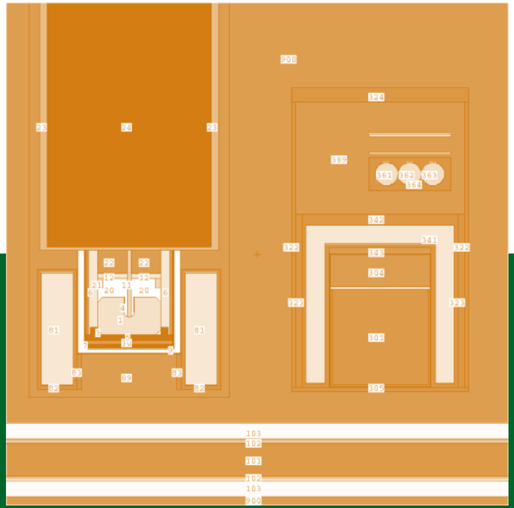
Project scope



Identify figures of merit to survey candidate measurement techniques to achieve a safeguards measurement goal



Down-select measurement techniques to design a MSR feed monitoring system



Perform modeling, simulation, and conduct an experimental campaign to progress the system design

Figures of Merit were identified to compare different candidate measurement techniques.

- Reasonably Achievable Uncertainty
- Time to Achieve Reasonable Uncertainty
- Capital Equipment Cost
- Facility Burden
- Maintenance Intensity
- Technology Readiness Level
- R&D Resources
- Human Capital Requirements for Implementation
- Introduction of Material Removal Path

Measurement time to achieve reasonable uncertainty

The typical measurement times associated with the uncertainties of evaluated techniques, as detailed in open-source literature

When possible, captures the total time required, including aspects such as sample acquisition and preparation, measurement time, interpretation of results, etc.

Result bins:

- < 1 minute
- 1 – 60 minutes
- > 1 hour

Facility burden

Represents the relative burden integrating the measurement technique into existing systems places upon facility designers and operators

Aspects include whether the measurement:

- Adds an appreciable delay time to operations
- Introduces a new ionizing radiation environment
- Requires modification of the reactor system or process equipment
- Requires penetration of the salt-bearing system

High, medium, low

Example: minimally intrusive measurements, such as gamma spectroscopy, would be scored low

Candidate measurement techniques to quantify total U and ^{235}U in molten salt reactor feed

Fissile Mass in Measured Volume

Active neutron / delayed gamma

Active neutron / neutron multiplication

Gamma spectroscopy

Uranium enrichment

Alpha spectrometry

Gamma spectroscopy

Inductively-coupled plasma mass spectrometry (ICP-MS)

Other

Passive n
(^{234}U mass in measured volume)

X-ray fluorescence
(relative elemental abundances)

Bubblers *(total salt volume or mass added & density)*

Flow measurements
(total salt volume or mass added)

Level measurements
(total salt volume added)

Weighing systems
(total salt mass added)

Uranium concentration

Electrochemical sensors

Fourier-transformed infrared spectroscopy (FTIR)

Hybrid K-edge densitometry (HKED)

K-Edge densitometry (KED)

Laser-induced breakdown spectroscopy (LIBS)

Laser-induced fluorescence (LIF)

ICP-MS

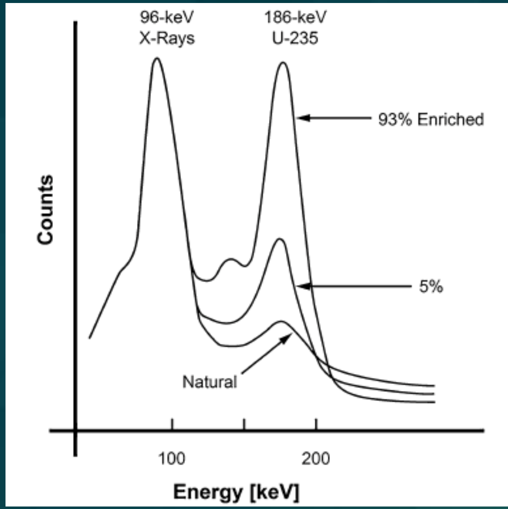
Raman spectroscopy

UV-visible-near-infrared spectroscopy (UV/VIS)

Evaluated Figures of Merit
Example: uranium concentration

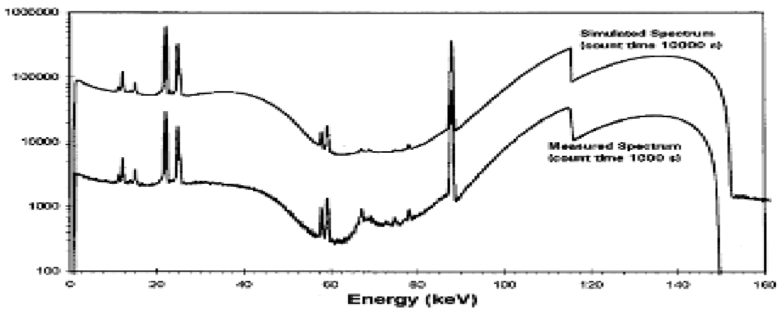
Technique	Electrochemical Sensor	FTIR	HKED	K-Edge densitometry	LIBS	Laser Fluorescence	Mass Spectrometry (ICP-MS)	Raman	UV-VIS and Infrared
In situ?	in situ	in situ	sample	in situ	in situ	in situ	sample	in situ	in situ
Precision	1-4%	N/A	0.5-3%	0.25-5%	2-10%	1-10%	<1%	1-5%	1-6%
Meas. Time	Seconds	1-4 hours	Minutes	Minutes	Seconds	Seconds	>24 hours	Seconds	Seconds
Cost ($K)	< 10	> 100	> 100	> 100	> 100	> 100	> 100	> 100	> 100
Facility burden	High	Medium	High	Medium	Medium	Medium	High	Medium	Medium
Maint. Intensity	Medium	High	Medium	Low	High	High	High	High	High
TRL (other)	5	7	9	9	9	9	9	9	9
TRL (MSR)	5	2	1	1	4	2	3	3	3
R&D for TRL-9	Low	High	Medium	Medium	Medium	High	Medium	Medium	Medium
Human capital	Medium	Medium	Medium	Medium	High	Medium	High	Medium	Medium
Material removal	yes	no	yes	no	no	no	yes	no	no

Down-selected MSR Feed Monitoring System Components



IAEA, An Introduction to Non-destructive Assay Instrumentation, International Atomic Energy Agency, Vienna, 1984

Gamma spectroscopy to monitor and quantify enrichment



S.-T. Hsue, M. Collins, "Simulation of Absorption Edge Densitometry," LA-12874-MS, Los Alamos National Laboratory, Nov. 1994

K-Edge Densitometry to quantify uranium concentration

K. Robb, E. Kappes, "Facility to Alleviate Salt Technology Risks (FASTR): Commissioning Update" ORNL/TM-2023/2846, Oak Ridge National Laboratory, 2023

Weighing systems to quantify and monitor total salt mass added to the reactor system

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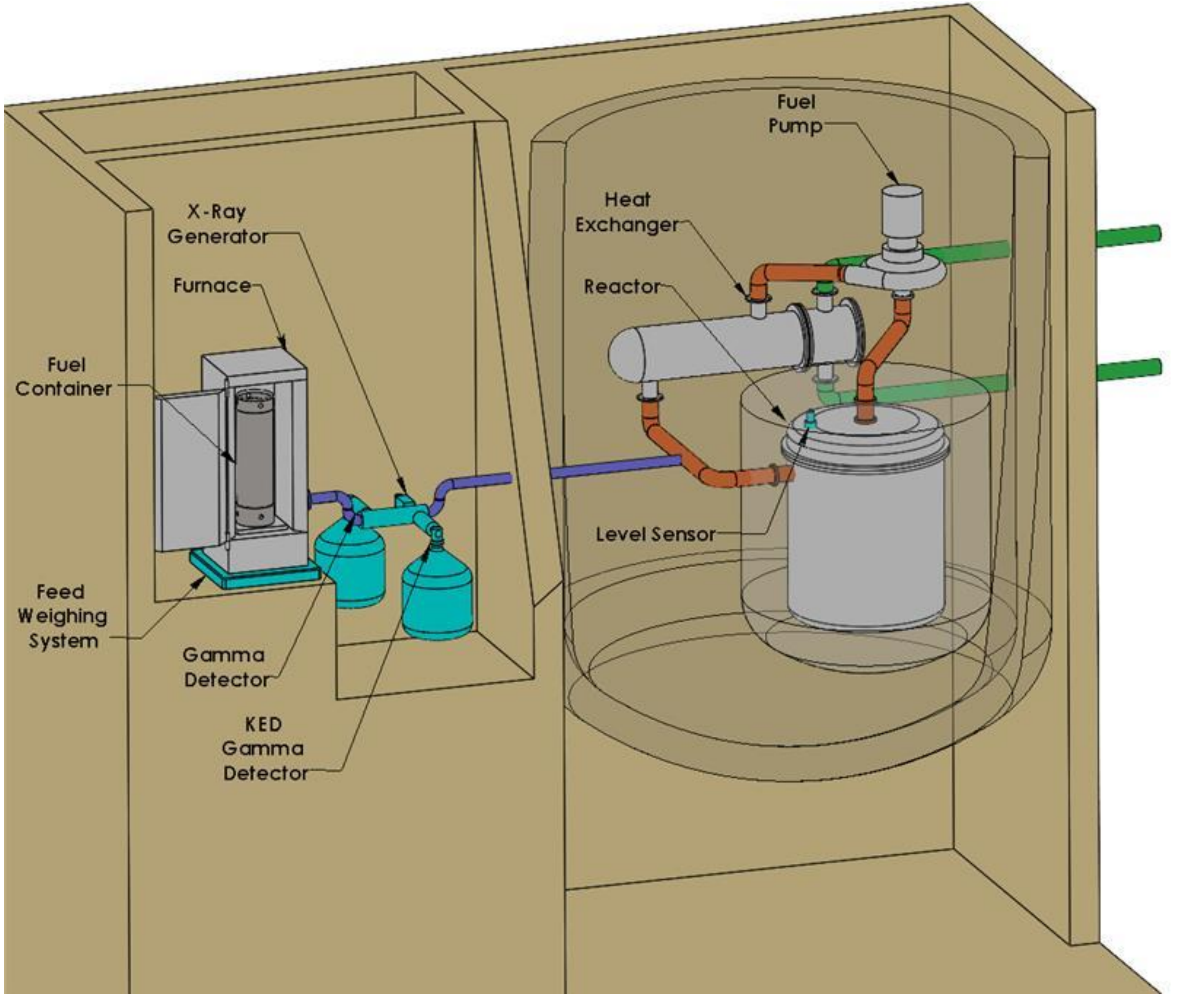
Proposed Feed Monitoring System



Initial design criteria for the MSR Feed Monitoring System

Developed to guide design decisions

Hardware requirements

Components shall not physically touch the salt

Accommodate schedule 40 pipe ranging from 1 to 4” in nominal diameter

Accommodate an outer diameter, including thermal pipe insulation, of up to 10”

Minimize necessary floorspace

Accommodate salt temps up to 750 °C

Performance targets

Related to uncertainty targets, measurement times, and uranium enrichment

Monitoring requirements

Related to detecting diversion of irradiated salt or introduction of undeclared nuclear material through the pipe being monitored

System Component Measurement Campaign: Passive Gamma Spectroscopy

ORNL staff held an experimental campaign at TerraPower, LLC using their depleted uranium salt test loop (NaCl-UCl_3) and gamma detectors

- HPGe, CdZnTe, NaI, LaBr

Goals of the measurement campaign were:

- Demonstrate the use of passive gamma spectroscopy on actinide-bearing molten salt;
- Quantify the uranium enrichment;
- Explore additional research questions related to monitoring and quantification

Measurement campaign was recently completed and data is currently being analyzed relative to these goals

D. Walter, “Molten Chloride Fast Reactor Program Overview ” ORNL MSR Workshop, 2022.

Terrapower, Small Isothermal Molten Salt Pumped Loop Overview, Slides for NSCU, 2024.

Future Work

Analyze data from passive gamma spectroscopy measurement campaign

Complete modeling and simulation analysis on integrated initial system design

Assess MSR design parameters where the monitoring system will be applicable

Salt chemical composition;

Pipe material, diameter, thickness;

Uranium enrichment

Measurement campaign applying K-Edge densitometry to uranium-bearing salt samples

Integrate all system components into an operational uranium-bearing salt test loop

Conclusions

A methodology based on multiple figure of merits to survey candidate measurement techniques to meet a safeguards measurement goal was developed.

The methodology was applied to down select from nineteen measurement techniques to meet the safeguards measurement goal of quantifying total U and ^{235}U in fresh fuel salt feed entering a MSR system.

System components down-selected were:

- K-edge densitometry, gamma spectroscopy, weighing systems (scales).

This work aims toward providing specific, quantitative design recommendations to MSR developers to enable safeguards by design.

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