DEVELOPMENT OF A MOLTEN SALT SAMPLING SYSTEM DESIGN

Progress To-Date and Path Forward

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INTRODUCTION

- MSRs require the ability to sample the hot, highly-radioactive fuel salt (or primary coolant salt) and to introduce additional (e.g. fuel or redox control) materials to monitor and control:
  - progress of corrosion
  - fissile material consumption and isotope distribution
  - fuel salt redox condition
  - in-leakage of coolant salt or other contaminants
- The Molten Salt Reactor Experiment (MSRE) employed a “Sampler-Enricher” (S-E) to access and remove fuel salt for analysis. However, the system’s operation was marginal.
  - Vanderbilt University, the University of Michigan, and Idaho National Laboratory are leading a NEUP-funded project to develop and demonstrate, in a non-radioactive environment, a modern equivalent to the S-E with improved reliability and the potential to serve as a technology model for future MSRs.

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MSRE SAMPLER-ENRICHER PERFORMANCE

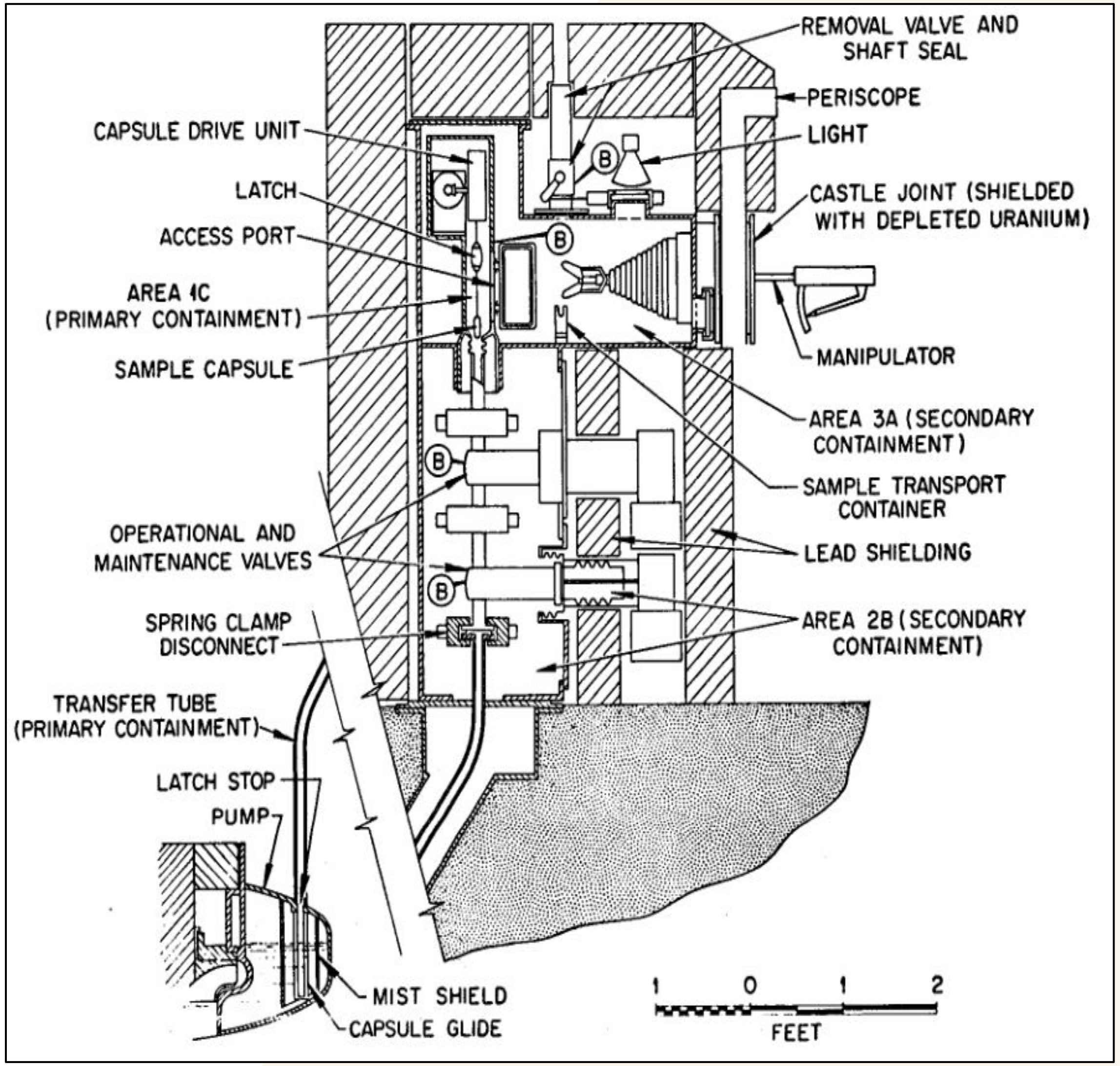

Image Credit: R.C. ROBERTSON, "MSRE Design and Operations Report, Part I: Description of Reactor Design," ORNL-TM-0728, Oak Ridge National Laboratory (1965).

- The MSRE S-E was used to:
  - Remove salt samples from the MSRE fuel salt loop for subsequent laboratory analysis.
  - Enrich salt or add chemistry control materials to the MSRE fuel salt loop.
- The MSRE S-E exhibited operability and reliability issues that make it a candidate for redevelopment for use in future MSRs. Frequent issues included:
  - Loss of control of sampling capsules (temporary and permanent)
  - Manipulator boot ruptures
  - Radionuclide leakage from salt-fouled valves

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MOTIVATION FOR MOLTEN SALT SAMPLING SYSTEM

- **Online monitoring has been suggested for measuring and tracking operational characteristics in advanced reactors, including MSRs; however…**
  - Prediction of physical and chemical properties of molten salts with online monitoring technologies utilizes models/correlations still in development
    - Model refinement will likely benefit from or require measurements only made possibly by molten salt sampling within an operating MSR
  - Fuel qualification
    - Predictive models used to fully understand fission and corrosion product behavior require extensive MSR experimental databases that do not yet exist
    - Shortcomings in predictive models has led ORNL to suggest that MSR fuel qualification will be done within the first reactors and require primary salt sampling (ORNL/LTR-2018/1045)
  - A molten salt sampling system may also be used as a means of controlling salt composition and reactivity
    - Could be used to insert fissile/fertile material or chemistry control additives into the reactor

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PROJECT SCOPE

ongoing

Task 1
- Investigate historical molten salt system technical documentation to fully characterize molten salt sampling system **interfacing systems** and **functional requirements**.

Task 2
- **Develop initial conceptual design** that incorporates modern-day technological advances, design standards, previous molten salt sampling system experience, and stakeholder input.

Task 3
- **Perform hazard evaluation/reliability modeling** concurrently with the design development process.

future

Task 4
- Create **initial physical prototype** of conceptual molten salt sampling system design.

Task 5
- Perform **prototype testing** in water-based environment (time permitting) and in molten salt environment (at University of Michigan FLUoride Salt Test Facility [FLUSTFA])

Task 6
- Make design changes and **develop and test second iteration** physical prototype (if necessary).

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STAMP-BASED ANALYSIS OF THE MSRE S-E

- The Systems Theoretic Accident Model and Process (STAMP) is an accident analysis methodology that uses systems engineering insights to model accidents as inadequate enforcements of "constraints"
  - Constraints: limits placed on design and operation that a system must adhere to for safe operation
- STAMP can help account for accident contributors that may be overlooked in traditional accident analysis methods

Occurrence No.	Description of Occurrence	Corrective Action Nos.	Description of Corrective Action	Hazard	Goal of SCS	Related System Function	Design Insight
65-2-1.2	Maintenance gate valve leak through the upper seat of the maintenance valve, causing difficulty with proper operation of the interlock that used buffer pressure to indicated whether the valve was fully closed.	3039-65-2-CA-3	Cleanup would have been difficult and valve replacement was not warranted so a mechanical method of assuring the valve was closed was substituted for the pneumatic method.	1- release of radioactive gas or particulates	prevent release of radioactive gas or particulates	1.5.1: Prevent contaminant ingress into system. **1.5.2: Minimize fission product egress from system.**	Removing molten salt from the fuel salt loop can result in liquid salt sticking to the externals of the sampling vessel. This salt can drip onto (or break off if it freezes) and contaminate system internals and potentially interfere with valve performance. Care should be taken to minimize the possibility of internal system contamination from solid or liquid salt droplets, possibly by incorporating a dedicated cleaning system or by facilitating modular component replacement.
65-2-8.1	Failure of manipulator boot from boot overpressure	66-1-CA-1.2	A new safety-grade circuit was added to close valve in the exhaust line to the vacuum pump to prevent the development of excessive differential pressure across the boot during sampler evacuation operation	1- release of radioactive gas or particulates	prevent release of radioactive gas or particulates	1.7.4.2: Prevent system operation in the event of unsafe conditions.	Manipulators are useful tools for remote handling of highly radioactive materials. To this day, manipulators boots are prone to rupture and subject to frequent corrective maintenance. If a molten salt sampling system design includes the use of manipulators to handle radioactive salt, care should be taken to ensure that the required barriers to containment are met during sample manipulation. Preferably, these barriers would not consist of the manipulator boots themselves. Design alternatives such as modern three-dimensional robots may also be substituted for manipulators.
66-1-2	Capsule hang up upon sample withdrawal (the capsule or latch had hung on the gate of the operational or maintenance valve). Cable backed up into the drive unit box and caught in the motor gears.	66-1-CA-10	The open limit switches for the operational and maintenance valves were reset to open the valves wider.	2- inability to sample or enrich fuel salt	prevent loss of ability to understand makeup of fuel salt/maintain operability of the reactor	1.3.1: Transport collection device from fuel salt system to system boundary. 1.3.2: Transport collection device from system boundary to fuel salt system.	Regardless of transport mechanism, the travel of the sampling vessel can be easily impeded by small projections into the internals of the system. The system should be designed with sufficient clearance between the sampling vessel and the vessel confinement mechanism to minimize the possibility of the vessel's travel being impeded by any protusions.

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REQUEST FOR STAKEHOLDER INPUT

- In order to ensure that the molten salt sampling system design meets expectations and exhibits the appropriate functionality, *the project team is requesting MSR vendor input on the items below (discussed in the following slides)*.
  - The high-level functions identified for the molten salt sampling system
  - The completeness of the list of molten salt sampling system interfacing systems
  - The molten salt sampling system freeze port design concept

<u>We plan to follow-up (via email) with those present after the workshop to provide a summary of the systems engineering work performed on the design to-date and request your formal input via a short questionnaire</u>

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MOLTEN SALT SAMPLING SYSTEM FUNCTIONAL HIERARCHY (AS PERCEIVED BY PROJECT TEAM)

Decreasing importance for a modern molten salt sampling system

1. Salt sampling: remove salt samples from a molten salt stream to determine salt characteristics
2. Controlling fluorine potential (redox): inserting reducing materials to counteract the oxidizing effects of fission
3. Gas sampling: removing cover gas samples (containing fission gases) from a molten salt stream's expansion volume to determine cover gas characteristics
4. Enriching: adding fissile or fertile material to a salt stream
5. Managing bulk fuel salt fission product concentrations: removing bulk fuel salt to maintain acceptable concentrations of fission products
6. Miscellaneous testing (e.g., inserting materials coupons into the fuel salt and/or cover gas)

Functions performed by MSRE S-E

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MOLTEN SALT SAMPLING SYSTEM INTERFACING SYSTEMS

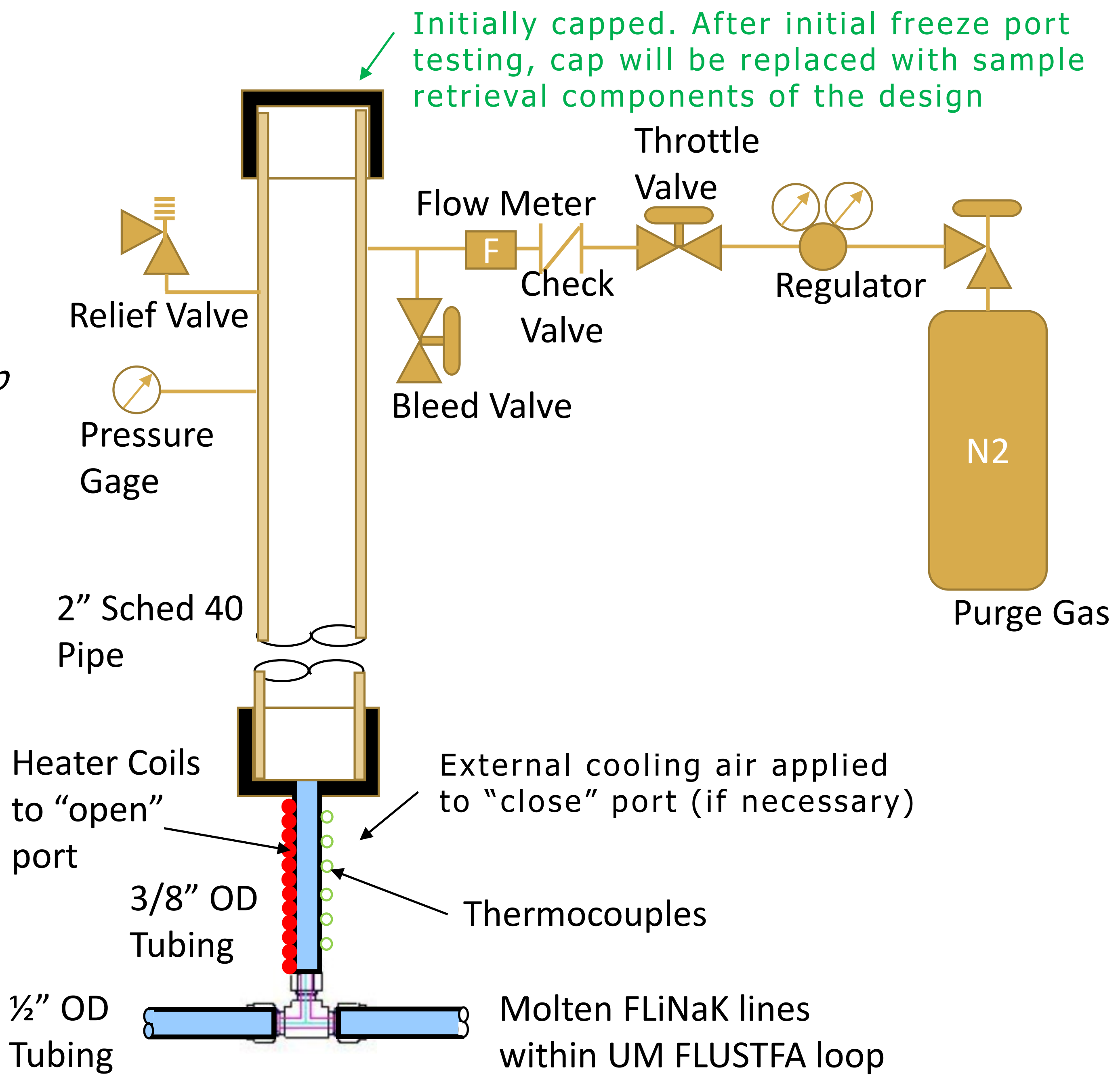
MSRE System	Equivalent Modern System
Fuel Circulating System	Primary Salt Circulating System
Cover Gas System	Inert Gas Supply System
Off-gas System	Off-gas System
Electrical Services System	Power Supply System
Radioactive Materials Analytical Laboratory	Salt Analysis System
Sample Transport System	Salt Analysis System
Component Cooling System	Auxiliary Heat Transfer System/Secondary Containment
Instrumentation and Control System	Reactor I&C/Monitoring System
Data Logger	Reactor I&C/Monitoring System
Containment Ventilation System	Cell Air System
MSRE Operator	System Operator

FREEZE PORT CONCEPT

Concept for prototype system being designed to fit the University of Michigan FLUSTFA loop

UM FLUSTFA Conditions

Parameter	Value
Primary Structural Material	SS 316-H
Operating Temperature	550-700 ˚C
Molten Salt Composition	Eutectic LiF-NaF-KF (46.5-11.5-52 mol%)
Cover Gas	Nitrogen



FREEZE PORT OPERATION

- **Open port**
  - Open bleed valve to purge existing gas
  - Increase N2 purge gas pressure to match salt system pressure
  - Secure cooling air, energize port heaters
    - Monitor port thermocouples and possible level sensors
  - Monitor N2 flow
    - Flow initiates
    - Port temperatures drop
    - Port is open

- **Close port**
  - Shut off port heaters
  - Start cooling air flow
  - Shut off N2 flow
  - Monitor port temperatures
  - Open bleed valve slowly
  - Port temperatures indicate frozen salt in port
  - Shut bleed valve

Initial Conditions

- Freeze port installed with nitrogen in headspace and frozen salt in port tubing
- Cooling air provided to port tubing
- Salt system heated and flow established through main salt system piping

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PATH FORWARD

Task 3

- **Perform hazard identification/reliability modeling** concurrently with the design development process.

– After collection and incorporation of stakeholder input into molten salt sampling system design, a hazard evaluation of the new design will be performed.

  – *A hazard evaluation of the MSRE S-E has already been completed.*

– Choice of hazard evaluation is design-specific. It depends on:

  – Availability of design information

  – Resources available

  – Breadth of hazards considered

Task 4

- Create **initial physical prototype** of conceptual molten salt sampling system design.

– After hazard evaluation insights are incorporated into design, a design prototype will be fabricated and prepared for testing.

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SPECIAL THANKS TO OUR PARTNERS AND SPONSORS

UNIVERSITY OF MICHIGAN

Dr. Xiaodong Sun

INL Idaho National Laboratory

70 YEARS OF SCIENCE & INNOVATION

Dr. Piyush Sabharwall

OAK RIDGE National Laboratory

NEUP Nuclear Energy University Program

U.S. Department of Energy

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QUESTIONS OR COMMENTS?

REFERENCES

1. G.F. Flanagan, D.E. Holcomb, W.P. Poore III, Molten Salt Reactor Fuel Qualification Considerations and Challenges, Oak Ridge National Laboratory, ORNL/LTR-2018/1045 (2018).N.G. LEVESON, "New Accident Model for Engineering Safer Systems," *Safety Science*, 42, *4*, 237 (2004).
2. N.G. LEVESON, *Engineering a Safer World*, The MIT Press, Cambridge, Massachusetts (2011).
3. M. Harkema, S. Krahn, P. Marotta, Evaluating the MSRE sampler-enricher: a fresh perspective, Transactions of the American Nuclear Society, 121(1):1193-1196, 2019.
4. R.C. ROBERTSON, "MSRE Design and Operations Report, Part I: Description of Reactor Design," ORNL-TM-0728, Oak Ridge National Laboratory (1965).
5. M.W. ROSENTHAL, et al., "Molten-Salt Reactor Program Semiannual Progress Report for Period Ending February 28, 1970," ORNL-4548, Oak Ridge National Laboratory (1970).
6. R.B. GALLAGHER, "Operation of the S-E in the Molten Salt Reactor Experiment," ORNL-TM-3524, Oak Ridge National Laboratory (1971).
7. M.W. ROSENTHAL, et al., "Molten-Salt Reactor Program Semiannual Progress Report for Period Ending August 31, 1967," ORNL-4191, Oak Ridge National Laboratory (1967).
8. M.W. ROSENTHAL, et al., "Molten-Salt Reactor Program Semiannual Progress Report for Period Ending August 31, 1968," ORNL-4344, Oak Ridge National Laboratory (1969).
9. R.H. GUYMON, et al., "MSRE Systems and Components Performance," ORNL-TM-3039, Oak Ridge National Laboratory (1973).

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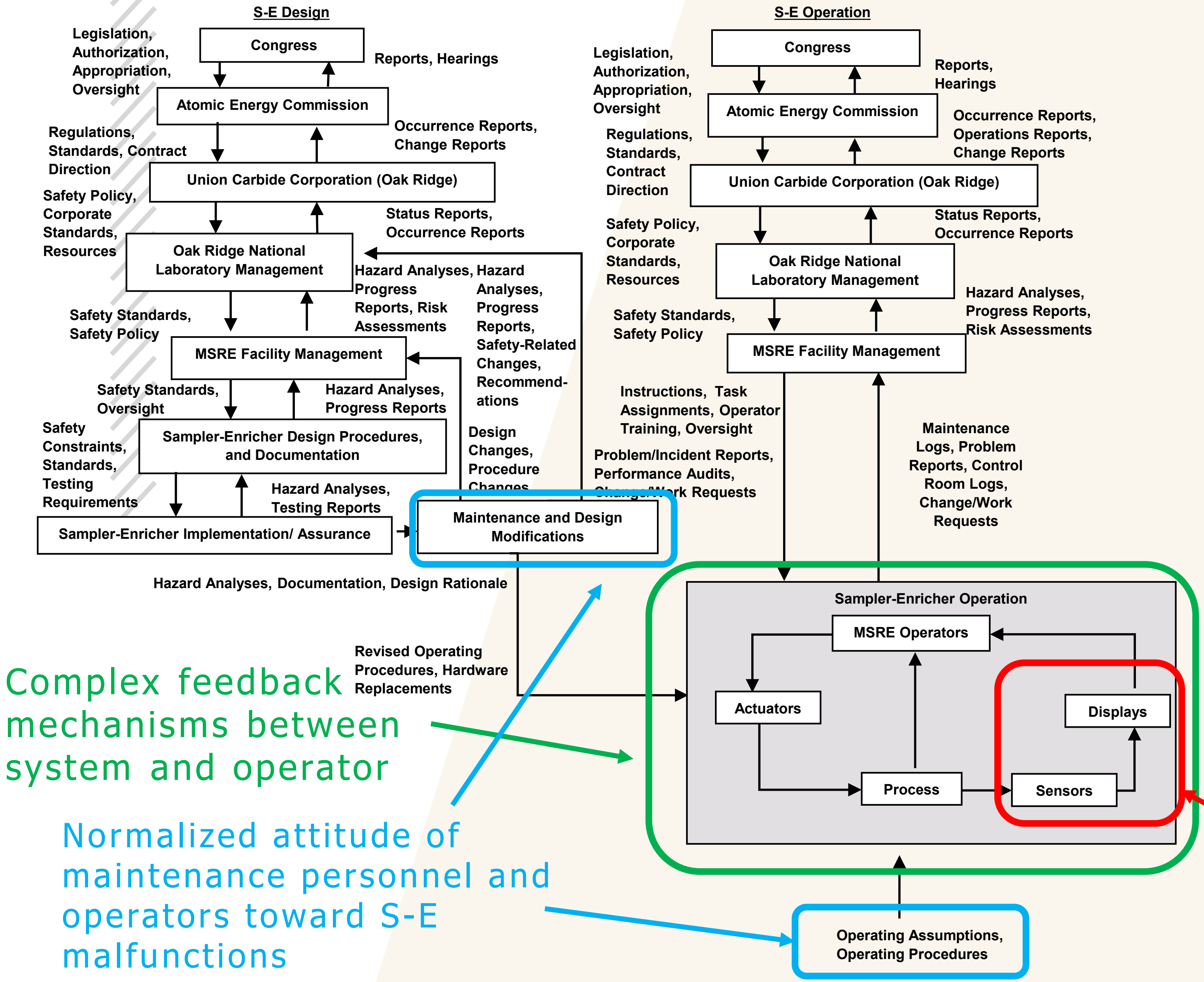
BACK-UP SLIDES

STAMP-BASED ANALYSIS OF THE MSRE S-E



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Inadequate capsule position feedback mechanism

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MSRE S-E FUNCTIONAL DECOMPOSITION