VANDERBILT
School *of* Engineering

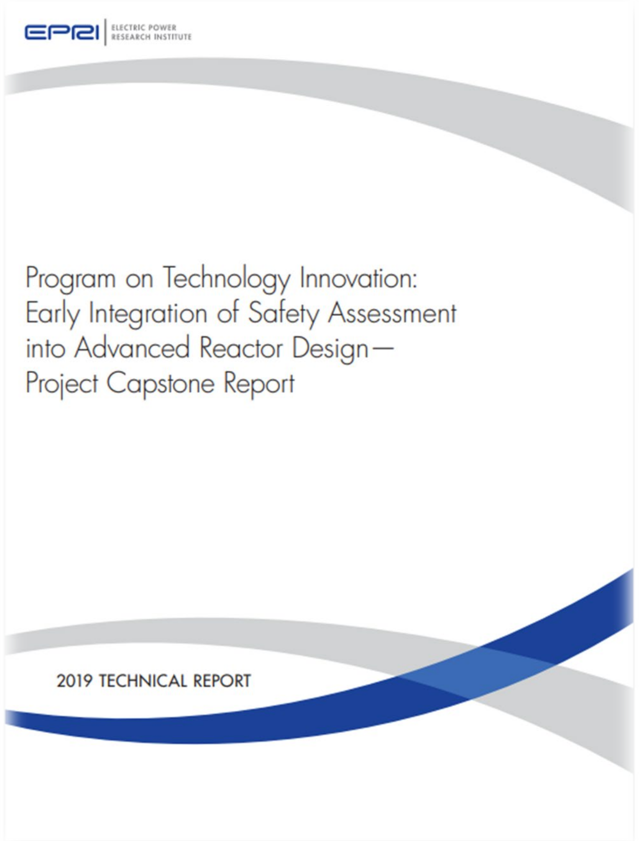
Risk-Informing:
When, Where, and How to Start

Megan Harkema (presenter), Steve Krahn, Irfan Ibrahim

May 30, 2025

Nuclear Environmental Engineering Research Group (NEERG) at Vanderbilt

- Since 2010, the NEERG has performed research for the Electric Power Research Institute (EPRI), the U.S. Department of Energy Office of Nuclear Energy (DOE-NE), and commercial advanced reactor customers.
- Intellectual areas:
  - Nuclear fuel cycle analysis and modeling (LWRs and advanced reactors)
  - **Risk/safety analysis of advanced nuclear reactors**
    - **EPRI/NEERG Safety-in-Design (SiD) methodology**
  - Collaboration-based siting of back-end fuel cycle facilities
  - Public-private partnerships in commercial nuclear development
  - Technology readiness assessment


EPRI ELECTRIC POWER RESEARCH INSTITUTE

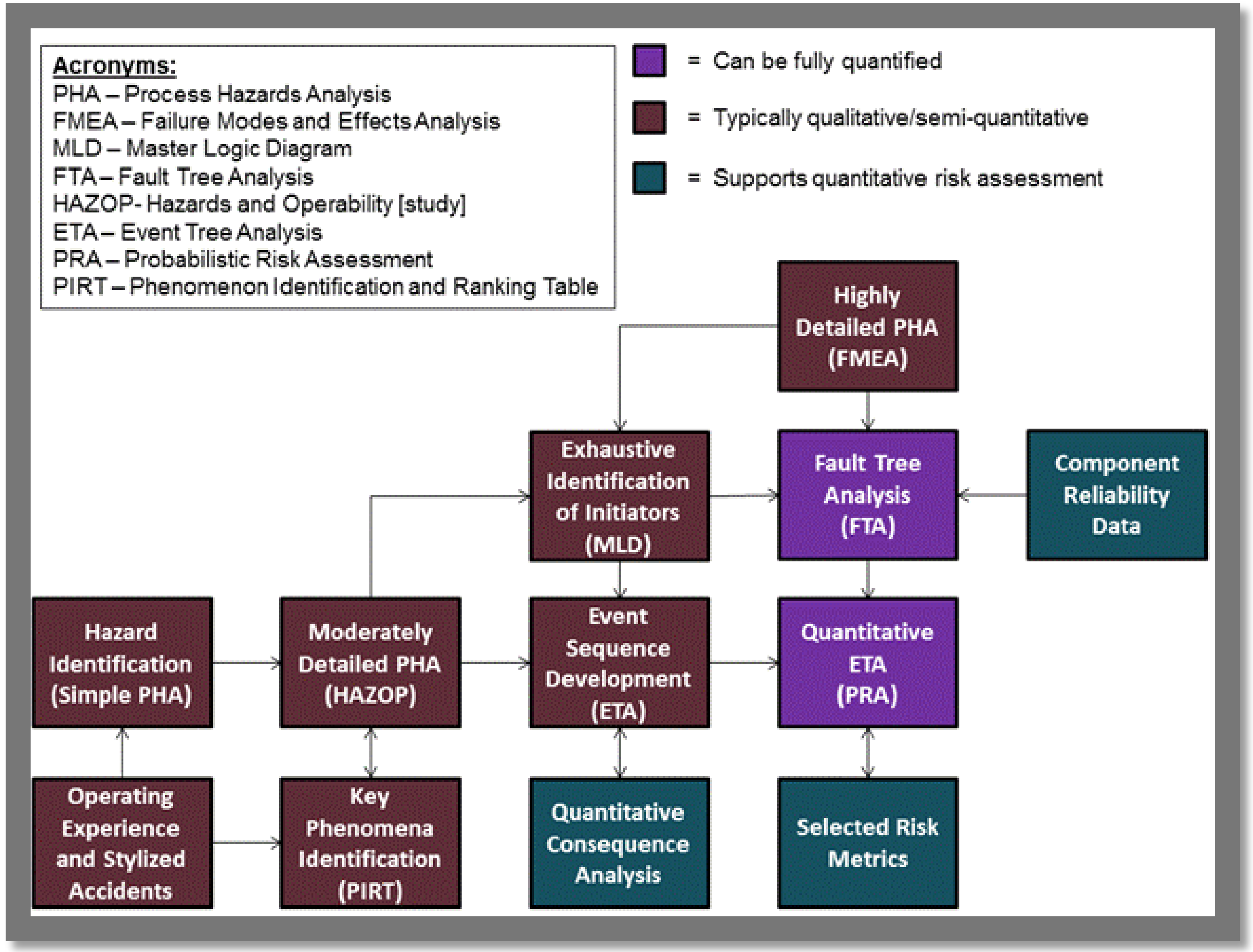
Program on Technology Innovation: Early Integration of Safety Assessment into Advanced Reactor Design—Project Capstone Report

2019 TECHNICAL REPORT

Safety-in-Design Methodology

- Historically, safety analysis of nuclear reactors has been:
  - Deterministic in nature; and
  - Performed after design had largely been completed.
- SiD was developed to help meet advanced reactor safety expectations through **early and iterative incorporation of safety analysis**, using Process Hazards Analysis (PHA) methodologies.
  - Use of SiD allows incremental progression of the safety case—eventually supporting quantitative risk assessment.

Question: When, where, and how do we start using SiD as part of non-LWR design?



Some SiD-related References:

- "Compilation of Molten Salt Reactor Experiment (MSRE) Technical, Hazard, and Risk Analyses: A Retrospective Application of Safety-in-Design Methods," S. Krahn (PI) and B. Chisholm, EPRI, Technical Report 3002018340, September 2020.
- "Early Integration of Safety Assessment into Advanced Reactor Design – Project Capstone Report," S. Krahn, (PI), Program on Technology Innovation, EPRI, Technical Report 3002015752, October 2019.
- "A systematic approach to identify initiating events and its relationship to Probabilistic Risk Assessment: demonstrated on the Molten Salt Reactor Experiment," B. Chisholm, S. Krahn, K. Fleming, Progress in Nuclear Energy, Vol. 129, 103507, November 2020.
- "Literature Review of Preliminary Initiating Events for a Gas-Cooled Fast Reactor Conceptual Design," Ibrahim, I., Harkema, M., Krahn, S., Choi, H., Bolin, J., Thornsbury E., Nuclear Technology (2025).
- "Development and Demonstration of a Prototype Molten Salt Sampling System," M. Harkema, S. Krahn, P. Marotta, A. Burak, X. Sun, P. Sabharwall, in press, Nuclear Technology (2025).

School of Engineering

When to Start?

…as early as possible!

Motivation to Start Early

- PHA methods are flexible. However, all PHA methods are not created equally.
- Choice of PHA for analysis of high hazard systems depends on:

Objectives of analysis team

-Team vs. individual approach

-Documentation needs

-Time required

-Team leader expertise

-Inductive vs deductive hazard identification

-Recognition by a specific industry

Design Maturity

-Breadth of hazards considered

-Preference for qualitative vs. quantitative results

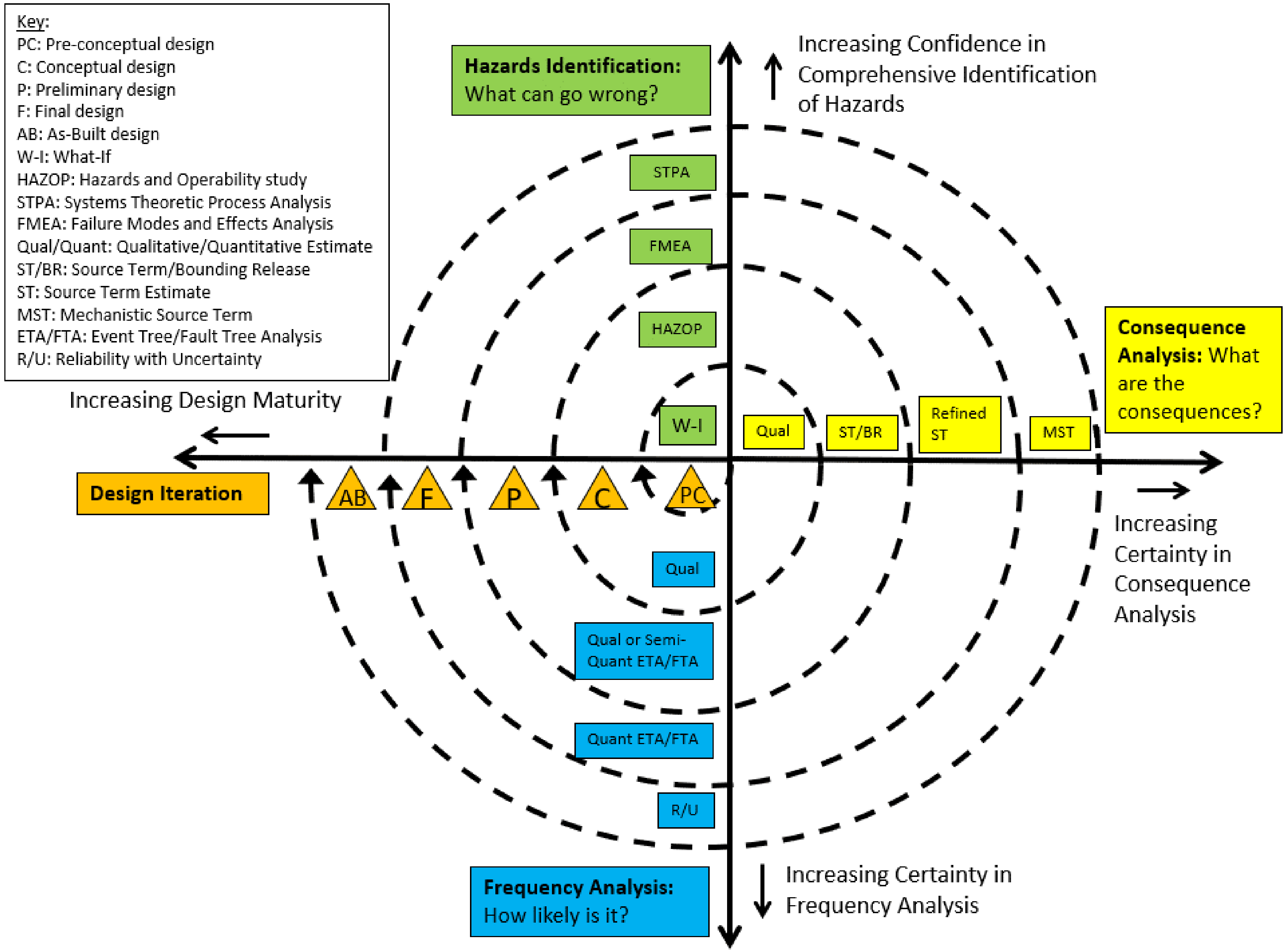
-Preference for identification of single vs. multiple failures

-Identification of gross vs. specific hazards

PHA approach depends on the amount and nature of design & hazard information available

Iterative Nature of SiD

- Safety analysis can begin as early as pre-conceptual design with simple PHA methods like what-if and what-if/checklist analyses.
- However, even simple PHA methods require supporting information.
    - E.g., you need an appropriate checklist to perform a what-if/checklist analysis…



Question: Where do we get the data to build a knowledge base to support performance of a PHA?

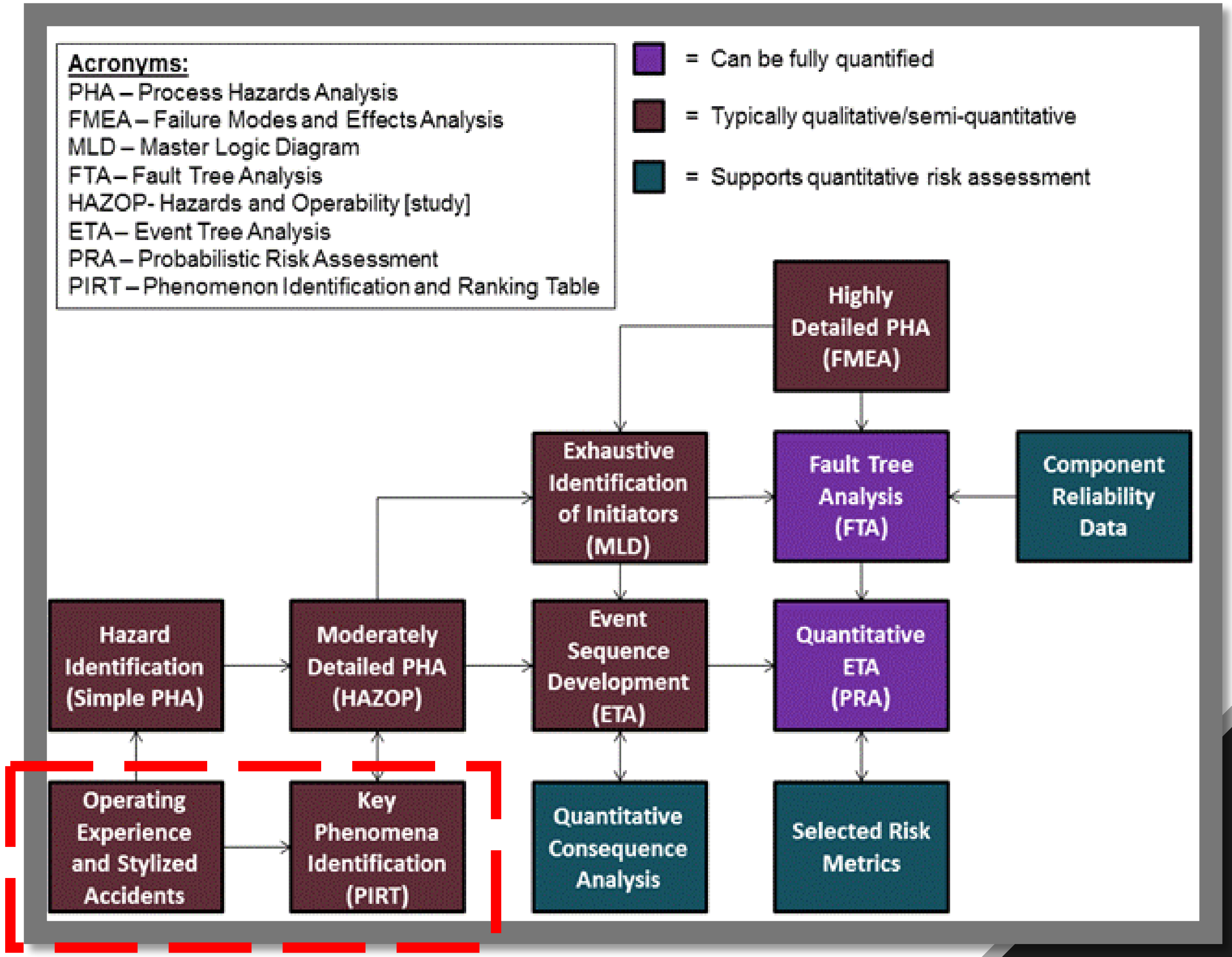
School *of* Engineering

Where to Start?

Do your homework!

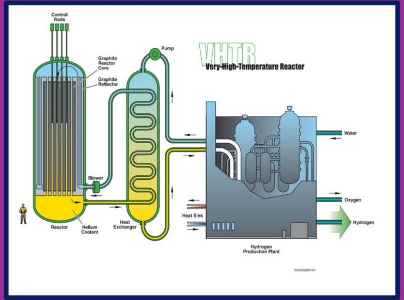
Building a Knowledge Base

- A need exists to build a knowledge base that can be used to support the SiD process throughout the design lifecycle
- At early stages of design, design-specific data to support PHA performance may not be available.
  - That does not mean that that relevant data are not available…just means we need to get creative
- Data sources that can feed into PHAs
  - **Operating experience** from previous operational or similar systems can be a valuable tool to identify hazards & initiators
  - **Stylized accidents** documented in the literature can assist with hazard identification
  - Identifying **relevant phenomena** can help establish a preliminary understanding of the phenomena of interest that could challenge plant safety

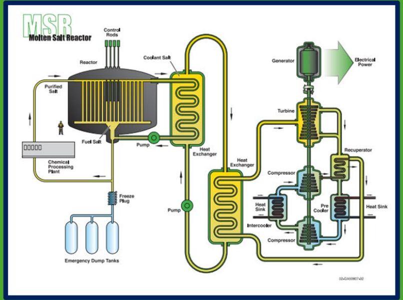


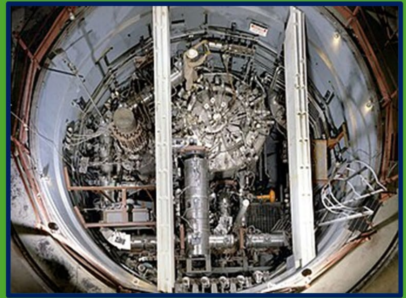
Historical Operating Experience

- Many advanced reactor concepts evolved from technically similar reactors and test facilities that were designed, constructed, and operated during the 1950s-1970s.
  - *Historical reactors and test facilities can represent the most thorough manufacturing, construction, operational, and retirement experience with a given reactor concept.*
- Availability of historical design and operating data relevant to advanced reactor designs can vary based on the reactor concept in question.

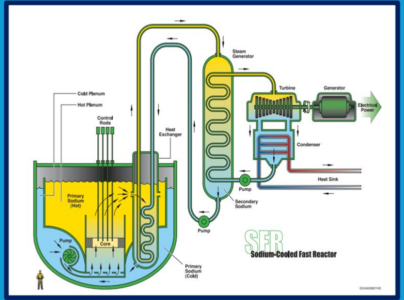


Peach Bottom Unit 1
(1967-1974)





Molten Salt Reactor Experiment (MSRE)
(1965-1969)



Experimental Breeder Reactor-II (EBR-II)
(1964-1994)

Examples of Advanced Reactor Concepts and Historical Analogues

Image Credits: (top) U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems*, GIF-002-00 (2002). (bottom, from left to right) U.S. Nuclear Regulatory Commission, Oak Ridge National Laboratory, Argonne National Laboratory

How to Access Historical Data (Relatively Easily):

- **Web-based keyword searches (Google Scholar, osti.gov)**
- **Component reliability databases (e.g., NaSCoRD, MOSARD)**
- **GAIN Legacy Document Project**
- **Cooperative R&D Agreements (CRADAs) with national laboratories**

Some References:

- "Incorporation of Historical Information into the advanced reactor design process: A case study on the development of a molten salt sampling system," M. Harkema, S. Krahn, P. Marotta, A. Sowder, Transactions of the American Nuclear Society, 127(1): 856-859, 2022.
- M. Harkema, Development and Demonstration of a Risk-Informed Molten Salt Sampling System Design for Molten Salt Reactors, Unpublished Dissertation, Vanderbilt University (2024).
- "Literature Review of Preliminary Initiating Events for a Gas-Cooled Fast Reactor Conceptual Design," Ibrahim, I., Harkema, M., Krahn, S., Choi, H., Bolin, J., Thornsbury E., Nuclear Technology (2025).
- "Populating a Molten Salt Component Reliability Database: Opportunities, Challenges, and Lessons Learned," M. Harkema, S. Krahn, C. Leach, I. Ibrahim, A. Sowder, Transactions of the American Nuclear Society, 124(1): 461-464, 2021.
- "Creating a Molten Salt Component Reliability Database: Initial Efforts and Path Forward," M. Harkema, A. Guler Yigitoglu, S. Krahn, A. Sowder, Transactions of the American Nuclear Society, 123(1):1087-1090, 2020.

Using Historical Data for Design and Safety Analysis

Factors Influencing Designer's Use of Historical Data	Questions for Consideration
Data Access and Availability	*Has the designer comprehensively explored and documented the available data sources for historical parallels and assessed them at a sufficient level of detail?*
Design Novelty	*Has the designer used the historical data in a manner commensurate with the maturity of the historical parallel?*
Uncertainty Reduction	*How is the designer using historical data to support uncertainty reduction for their design?*
Data Quality and Completeness	*Are the data's uses commensurate with the designer's assessment of the completeness of the data and the quality assurance processes implemented?*
Usages for Historical Data	*Has the designer understood and documented any limitations associated with their usage of the historical data?*
Design Methodologies and Thought Processes	*Is the designer using the data in a consistent, systematic fashion?*

Modern Operating Experience

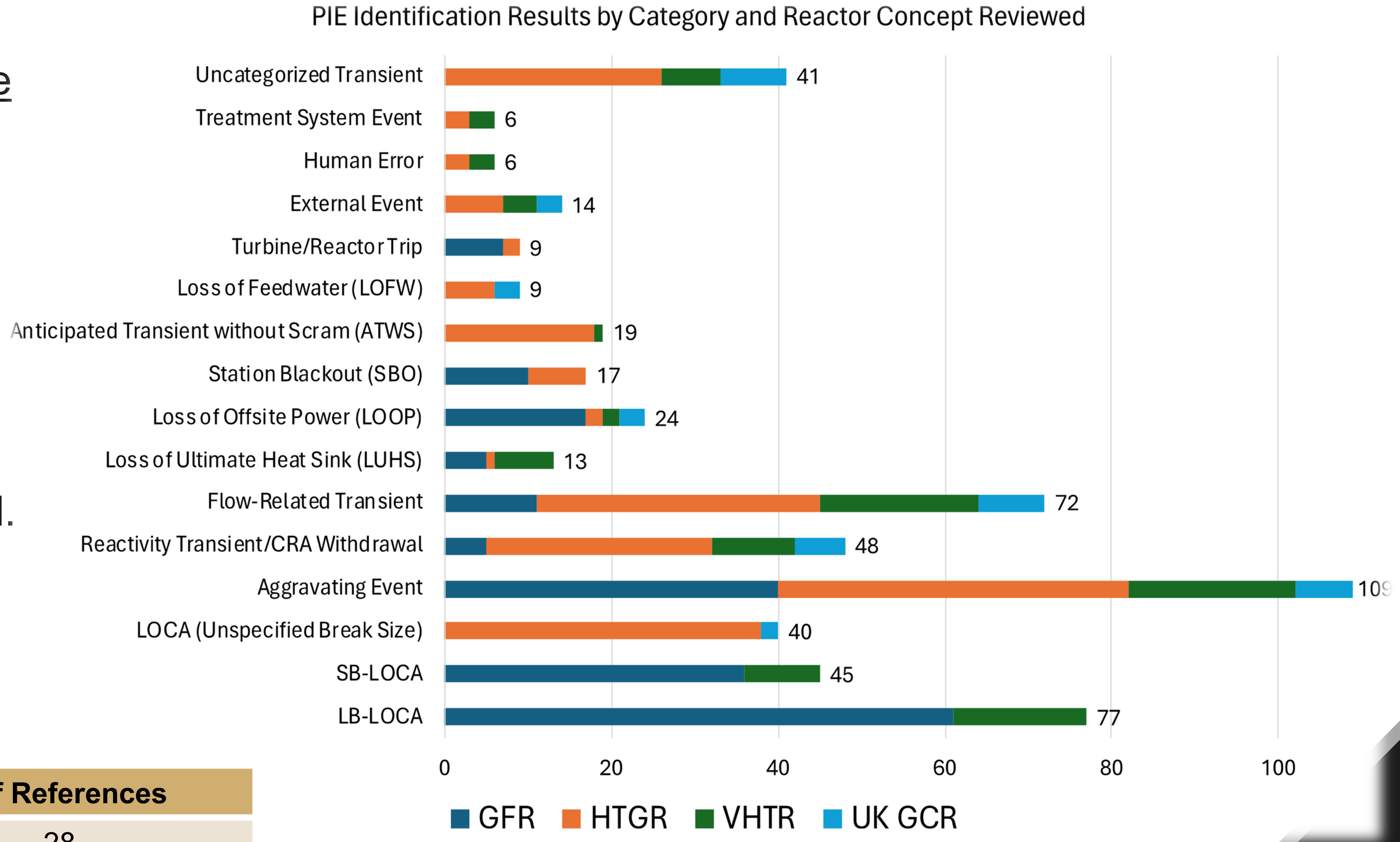
- Operating experience data from existing component reliability databases and systems like T/H test loops, integrated effects test facilities, critical experiments (or even other industries) can be used as input to knowledge base
- Data can be from test system specific to the design in question or from a technically similar system relying on the same components, phenomena, etc.
- Some caveats:
  - Data specific to the design: need to **collect and retain operations and maintenance data** (and associated plans/policies)
  - Data from a technically similar system: **data needs to be screened** for relevancy
    - Expert judgement, delta analysis, etc.

Some Modern Test Facilities…

Example	Location	Concept
Quarter-Scale Reactor Cavity Cooling System (RCCS) Facility	University of Wisconsin Madison	Gas-cooled reactor (GCR)
Molten salt flow loop test bed	Idaho National Laboratory	Molten salt reactor (MSR)
Mechanisms Engineering Test Loop (METL)	Argonne National Laboratory	Sodium fast reactor (SFR)

Stylized Accident Studies

- Although not a substitute for comprehensive initiating event identification, prior safety analyses and transient studies documented in the literature can elicit understanding of undesirable events and event sequences that can challenge the plant's ability to perform its intended function.
- Resources necessary to comprehensively sort through relevant literature are nontrivial.
    - Time
    - Document accessibility



Concept Reviewed	# of Unique PIEs	# of References
GFR	192	28
HTGR	216	48
VHTR	101	20
UK GCR	40	10
Total	**549**	**106**

Key Phenomena Identification

- "…advanced reactors have little to no commercial operating experience; further, the fundamental physical phenomena that govern the performance of non-LWRs can deviate substantially from those in LWRs." (Chisholm et al., 2020)
  - E.g., flow reversal in gas reactor passive decay heat removal systems
- PHAs can help organize phenomenological data into event/accident sequences, but are not necessarily designed for or well suited to phenomena identification

→ **this is where phenomena identification tools (e.g., phenomena identification and ranking table [PIRT]) come in**

- However, a wealth of PIRT literature exists for advanced reactors and may be acceptable for adoption for an early-stage design.

Examples of Recent PIRTs

Concept	Examples of PIRTs Performed
MSR	Diamond et al. (2018). Phenomena Important in Modeling and Simulation of Molten Salt Reactors, BNL-114869-2018-IR.
	Holcomb et al. (2021). Molten Salt Reactor Fundamental Safety Function PIRT, ORNL/TM-2021/2176.
GCR	Lee et al. (2005). Generation of a Preliminary PIRT for Very High Temperature Gas-Cooled Reactors, KAERI/TR-3050/2005 (also INL/EXT-05-00829 and ANL-GenIV-066).
SFR	Aoyagi et al. (2019). Identification of Important Phenomena Through the PIRT Process for Development of Sodium Fire Analysis Codes, Nuclear Engineering and Design, 110240.
	Zhou et al. (2021). Phenomena Identification and Ranking Table of Station Blackout Accidents for China Sodium Cooled Fast Reactor, Annals of Nuclear Energy, 108240.

Chisholm, B., Krahn, S.L., & Fleming, K.N. (2020a). A Systematic Approach to Identify Initiating Events and its Relationship to Probabilistic Risk Assessment: Demonstrated on the Molten Salt Reactor Experiment, Progress in Nuclear Energy, 129, 103507

School *of* Engineering

How to Start

We have all this data…now what do we do with it?

A Tale of Two Case Studies…

For More Information:

"Literature Review of Preliminary Initiating Events for a Gas-Cooled Fast Reactor Conceptual Design," Ibrahim, I., Harkema, M., Krahn, S., Choi, H., Bolin, J., Thornsbury E., Nuclear Technology (2025).

Molten Salt Sampling System (MSSS) Development

Type of Design Project: Subsystem

Historical Context: 2(ish) MSRs have been previously operated; 1 previous iteration of MSSS identified with detailed operating & maintenance records publicly available

Project Goal: Develop & demonstrate a risk-informed MSSS design that outperforms its historical predecessor

Resources: 1 analyst (+reviewers), ~2-3 months part time/PHA

Preliminary Initiating Event (PIE) Identification for the General Atomics Fast Modular Reactor (FMR)

Type of Design Project: Entire Reactor

Historical Context: No GFRs have been operated, but moderate experience exists with gas-cooled concepts in the U.S. & U.K.; similar passive decay heat removal systems being studied for other GCRs and advanced LWRs

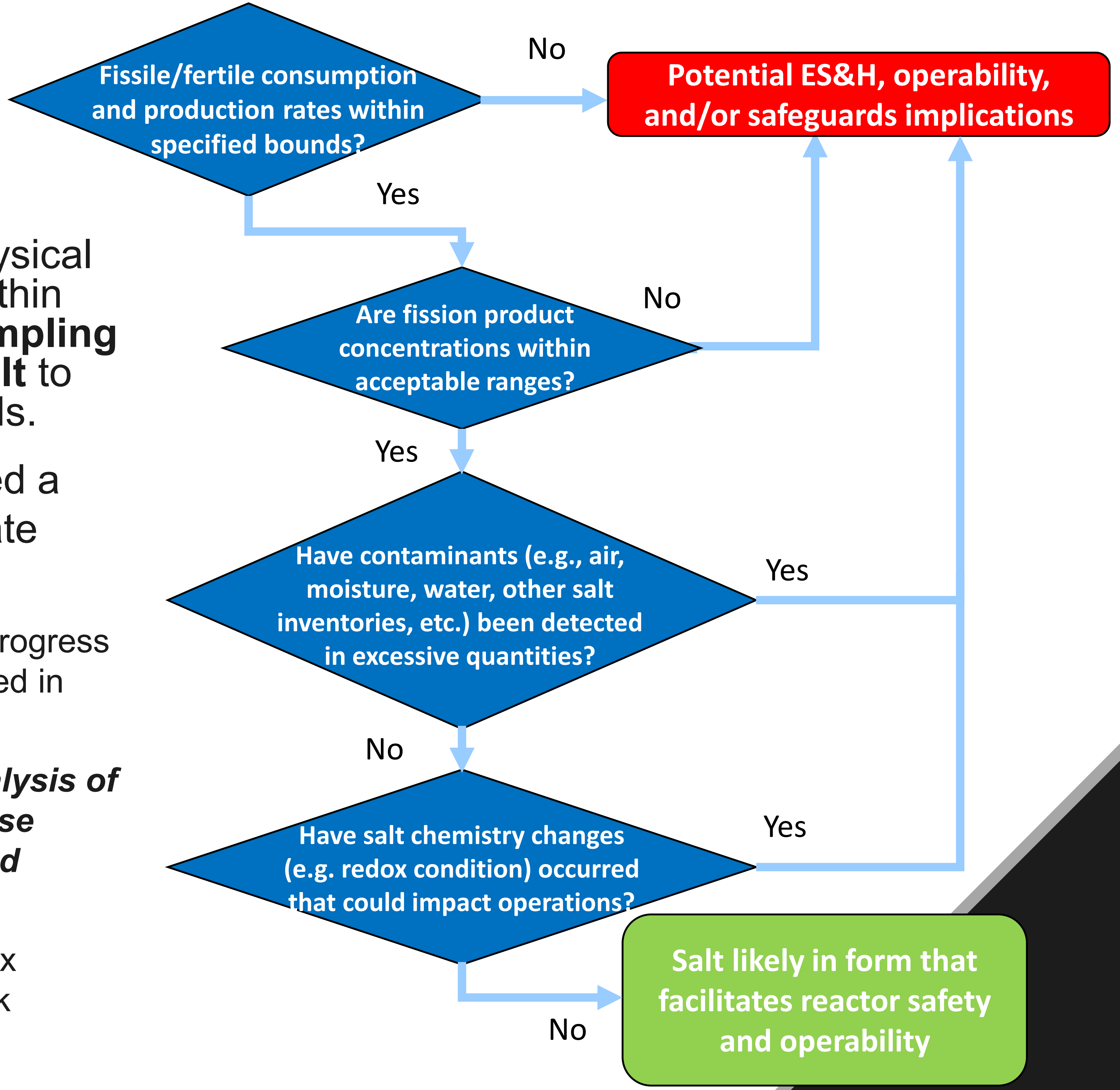
Project goal: Develop initial safety case for GFR design

Resources: 2 analysts (+ reviewers), ~7-8 months part time

STAMP-based Analysis of Historical Parallel → FMEA of Conceptual Design → FTA of As-Built Prototype

MSSS—Background & Historical Context

- Understanding, predicting, and controlling the physical and chemical characteristics of the molten salt within first-generation MSRs requires a **molten salt sampling system (MSSS) for periodic removal of fuel salt** to meet ES&H and safeguardability monitoring needs.
- The Molten Salt Reactor Experiment (MSRE) used a system called the Sampler-Enricher (S-E) to isolate small samples of fuel salt for laboratory testing.
  - S-E's reliability, as documented in MSRE Semiannual Progress Reports, was insufficient for the design to be incorporated in modern MSR designs.
  - ***Lessons can be learned from systematic causal analysis of S-E failure & maintenance data using a fit-for-purpose variant of the Systems-Theoretic Accident Model and Process (STAMP)***
    - STAMP was developed at MIT to account for complex accident contributors (e.g., system/operator feedback mechanisms, flaws in control process, hierarchical communication flaws, etc.).



S-E Performance by the Numbers

- **Operations:** 744 total sampling evolutions over 4 years
  - 592 sampling (removal of fuel salt) operations
  - 152 enriching (addition of fuel salt) operations

- **Maintenance:**
  - Project management description of system operation: "some minor repairs" required (ORNL-TM-3524)
  - However, S-E required corrective maintenance during *every biannual reporting period*
    - 64 (>1/month) occurrences were documented
    - 140 individual corrective actions identified in response
      - Not all of these were successful

(the start of) threshold/criterion development: MSSS should achieve higher degree of reliability than MSRE S-E

An Excerpt from ORNL-4344, MSR Progress Report for Period Ending August 31, 1968

"On the sampling attempt that resulted in the sampler cable becoming tangled, there was no sign of trouble as the cable was unreeled…As it was being rewound, the motor stalled …. A few attempts to unreel and rewind convinced us that the cable was tangled in the isolation chamber as it had been on previous occasions… during repeated attempts to untangle the cable by unreeling and rewinding. In the course of 76 attempts, the drive stalled at various points as the coils of cable were shifted, but in the end there was no net gain.

The isolation valves were left open for the next two weeks, but a slight purge of helium down the tube kept fission products from diffusing back up to the sampler…"

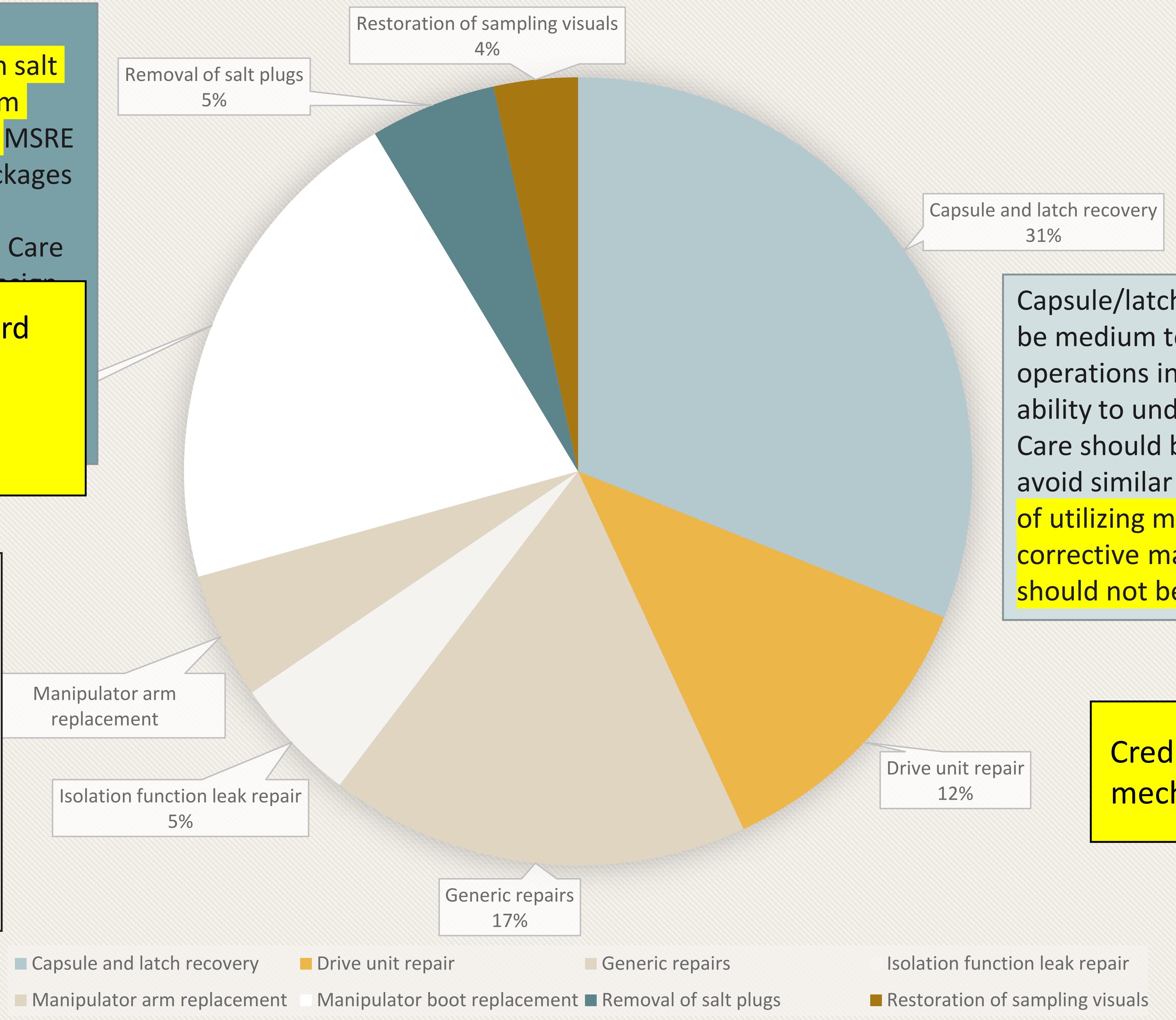
STAMP-Based Causal Analysis

Occurrence	Corrective Action (CA)	Effective CA?	DC, PC, MM, RR, D?	Relevant Hazard	Safety Constraint Violated	Design Insight
66-2-4: An empty sampling capsule was accidentally dropped while operators were attempting to use the manipulator to attach the capsule key to the latch. The capsule fell onto the gate of the operational valve.				Inability to sample or enrich fuel salt	Prevent loss of ability to understand fuel salt makeup; Maintain operability of the reactor	
	66-2-CA-5: A magnet on a cable was used to retrieve the magnetic latch key with capsule attached	Yes	RR			Capsule and latch recovery occurred frequently throughout the duration of MSRE S-E operation...success was achieved using magnets for capsule removal….Care should be given in MSSS design to avoid similar failures; however, the value of utilizing magnets to facilitate similar corrective maintenance evolutions should not be overlooked.
67-1-2: The small particles of salt that cling to the outside of the capsules that get dislodged during handling in 1C and 3A continued to increase the radiation levels inside the sampler-enricher; this has caused contamination spreading into the areas outside of the sampler-enricher…				release of radioactive gas or particulates	prevent release of radioactive gas or particulates	
	67-2-CA-3: A ventilation duct connected to the main building ventilator system was installed near the transport cask position.	Yes	DC			Small salt particles/droplets attached to the externals of the sampling vessel can be difficult to contain. If not properly handled, they can result in contamination spreading outside the system boundary. Novel methods for preventing contamination may be required.

STAMP-Based Causal Analysis: Repeated Instances of Repair & Replacement

Frozen salt can obstruct the sampling tube either from high salt levels in the pump bowl or from drips off of sampling capsules. MSRE staff were able o remove blockages by heating t m without causing u to workers. Care should be gi he MSSS design

Plugging failures brought forward for consideration in FMEA
- Salt & gas lines
- During and after sampling



Manipulators boots are prone to leakage and subject to frequent corrective maintenance. If a MSSS design includes manipulators, care should be taken to ensure that the required barriers to containment are met during sample manipulation.

Capsule/latch recovery operations can be medium to long term maintenance operations in the S-E that impacted ability to understand fuel salt makeup. Care should be given in MSSS design to avoid similar failures; however, the value of utilizing magnets to facilitate similar corrective maintenance evolutions should not be overlooked

Credited as mitigation/recovery mechanism in later-stage FMEA

MSRE S-E Hazards

Hazard	Consequence(s)	Corresponding Safety Constraint	Relevance to MSSS
Release of airborne radiological material (e.g., gas, particulates, etc.)	-Potential for radiation exposure (direct and/or inhalation) to SE operator or other MSRE personnel	Prevent release of radiological material	An MSSS will likely feature a similar radiological inventory to the MSRE S-E (i.e., fuel salt containing SNM and the full spectrum of fission products) with potential radiation exposure consequences that should be considered during design and safety evaluations.
Inability to sample or enrich fuel salt	-Produces reduced understanding of the makeup of the fuel salt, which could lead to **reduced shutdown over a long-term** if ability to sample or enrich was not restored in time. …ability to operate the SE also produced …nability to add fissile material to the …ctor, which could lead to subcriticality … shutdown over a long-term.	Prevent loss of ability to understand fuel salt makeup Maintain operability of the reactor	Because of the similarity in mission for the MSRE S-E and the MSSS, the inability to sample or enrich (if performed by the MSSS) fuel salt within a future MSSS could have similar consequences (potential for inability to understand fuel salt composition) that should be considered during design and safety evaluations.
Electric shock	-Potential for injury to MSRE personnel -Primarily an artifact of timeframe over which the system was designed and operated	Prevent electric shock to workers	Although this hazard is primarily an artifact of the timeframe the MSRE S-E operated, it brings to light a broader category of hazards—standard industrial hazards—that should be considered during MSSS design and safety evaluations.

Risk-informed end point: "Failure to obtain sample" chosen as top level event in later stage FTA

Hazards and safety constraints <u>realized during MSRE S-E operational occurrences</u> were identified as part of the STAMP-based analysis.

FMEA Results by the Numbers

331 total failures evaluated

ID	Failure Mode		Detection	Impact on:			Mitigation/ Recovery	Actions
	Functional Failure	Failure Mechanism		Safety	Operability	Safeguards		
SS1 (salt seal)	Melt too early	Improper fabrication	TI[illegible], no sample obtained	Potential for improper salt analysis/ subsequent reactor control actions	Potential for salt deposits that require cleaning. If melting time becomes frequent issue, downtime may be required to implement design changes	If capsule improper melting time occurs frequently, it could prevent monitoring isotopics on a timeline that supports IAEA diversion timeliness goals	Routine maintenance specifications for capsule housing	Operations/ testing: Develop written procedure for capsule fabrication
SS1 (salt seal)	Melt too late	Low temp in primary salt		Potential for no sample collection, which could result in loss of ability to understand fuel salt composition				Analysis/ safety: investigate potential to model capsule time to melt using COMSOL

58 action items identified.
Resolution of action items can identify:

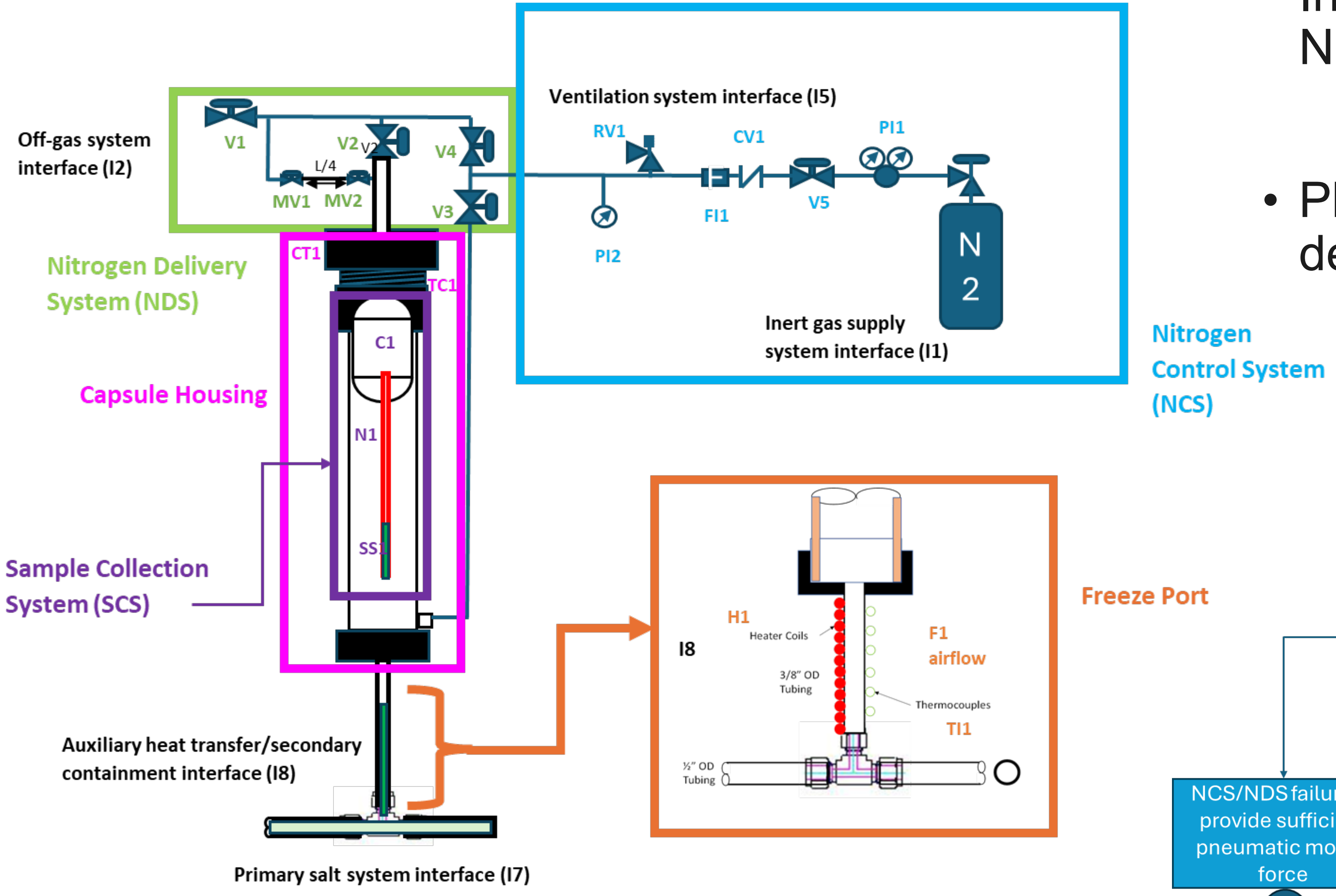
1. Design changes to prevent/mitigate consequences
2. Design elements requiring maturation (e.g., through **safety analysis** or startup testing)

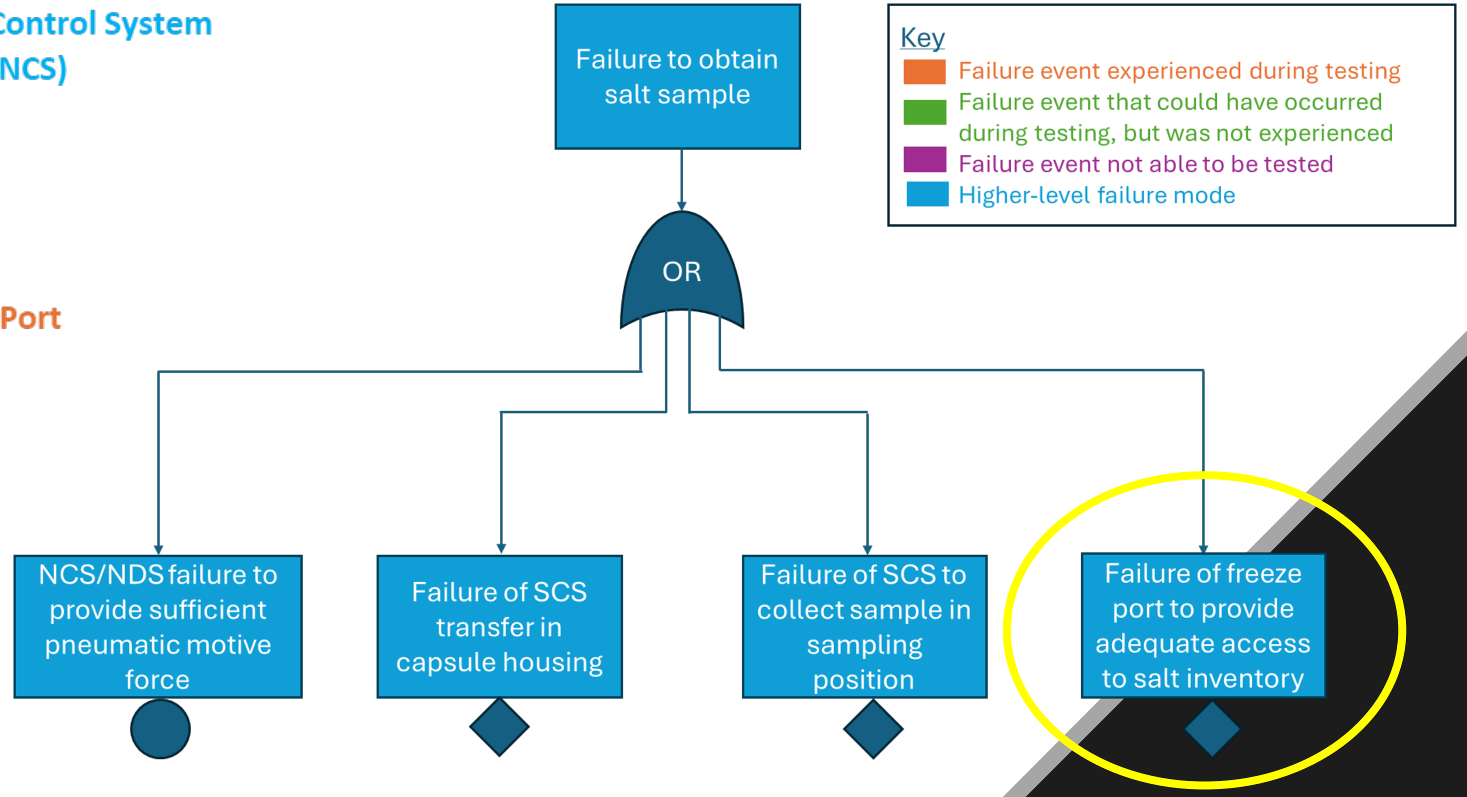
Aggregate examination of 44 total frequently credited detection and mitigation measures can provide important design insights for early-stage designs.

E.g., “no sample obtained” credited 10x as detection mechanism

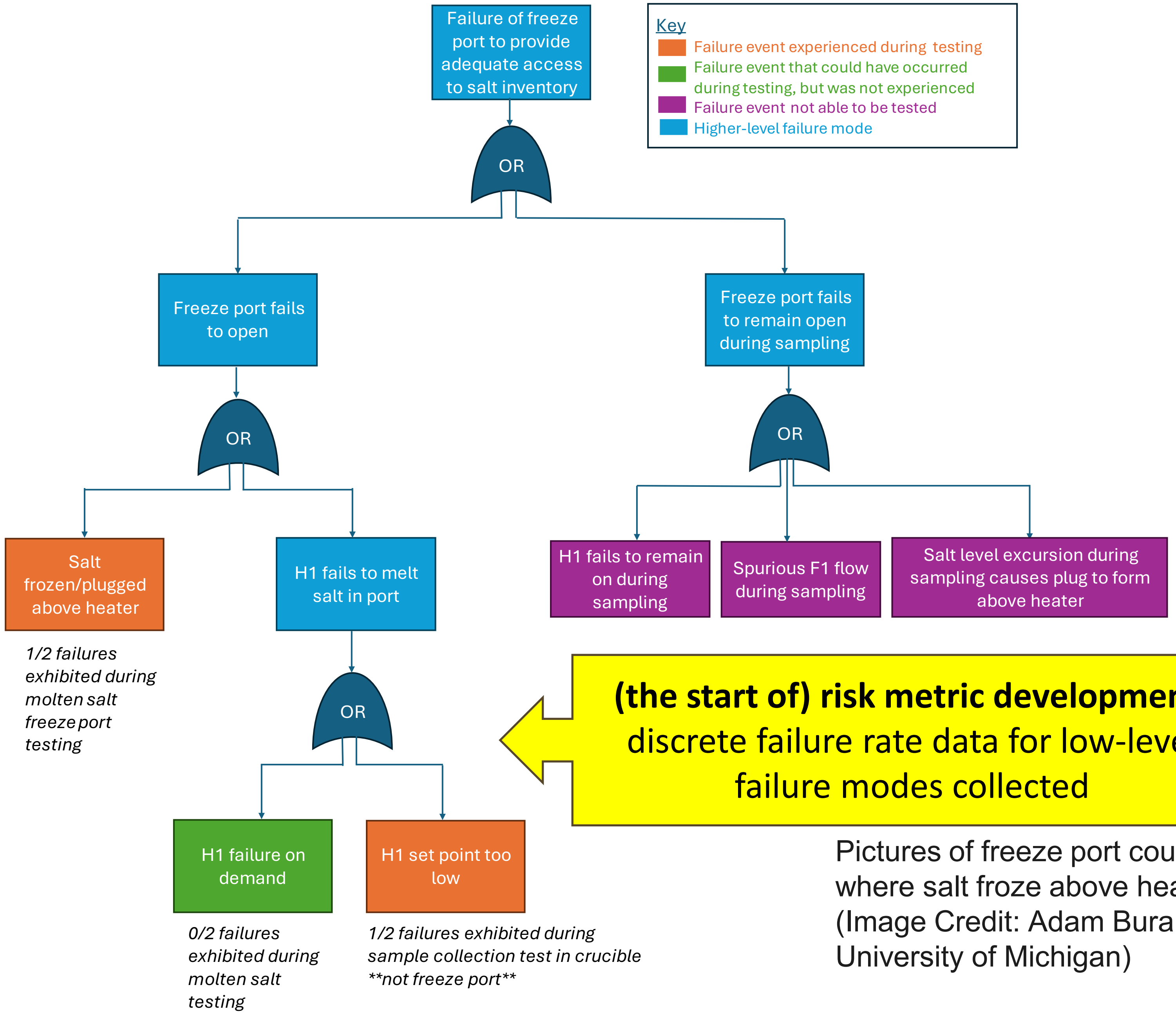
Testing Approach

- Tested key functions at University of Michigan's Molten Salt Facility for Instrumentation Testing (MSFIT), a static NaCl-$CaCl_2$ test facility.
  - Reliability and failure mode data also collected.
- Phased approach to prototype development and testing.

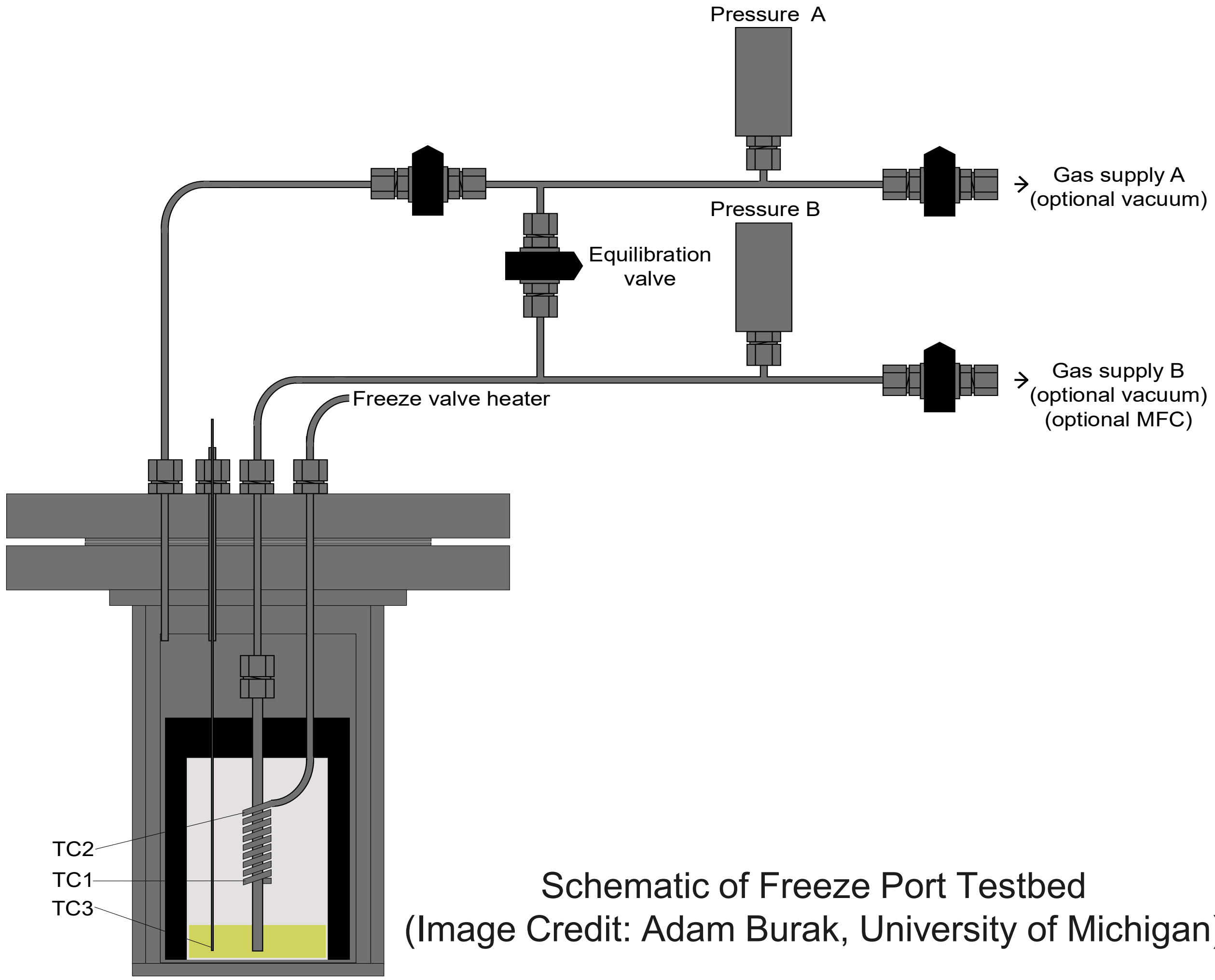




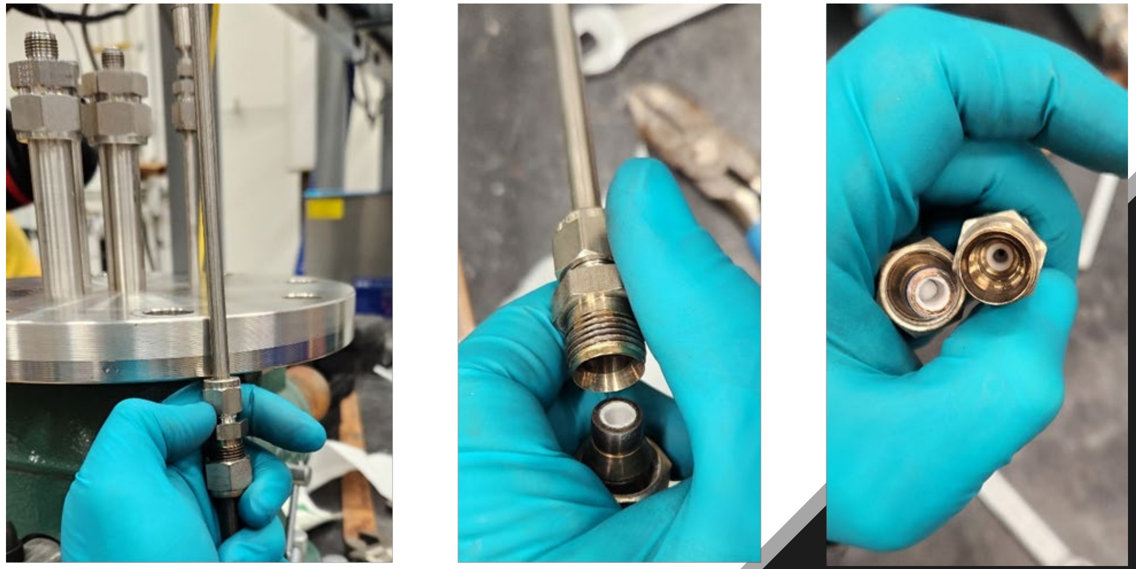
Freeze Port Testing



(the start of) risk metric development:
discrete failure rate data for low-level failure modes collected



Schematic of Freeze Port Testbed
(Image Credit: Adam Burak, University of Michigan)



Pictures of freeze port coupling where salt froze above heater. (Image Credit: Adam Burak, University of Michigan)

Conclusions for Implementing SiD

- **When to start:**
  - As early as preconceptual design, safety & design information can begin to be compiled to support early stage PHAs.
  - In early stages, information does not need to come from design-specific sources, relevant data from technical parallels can be useful in building knowledge base.
- **Where to start:**
  - Build knowledge base by identifying and compiling data on:
    - Operating experience from historical & modern parallels
    - Stylized accident analysis information & results
    - Relevant phenomena
  - As design matures, build in operations & maintenance data collection into test/demonstration programs
- **How to start:**
  - Approach depends on data availability & objectives of design/analysis process
  - Regardless, start with generally applicable data and historical predecessor data (should it exist).
    - Move to using design-specific data as the design matures.

Acknowledgements

VANDERBILT
School *of* Engineering

EPRI

UNIVERSITY OF MICHIGAN

INL
Idaho National Laboratory
70 YEARS OF SCIENCE & INNOVATION

UNLP
University Nuclear Leadership Program

NEUP
Nuclear Energy University Program
U.S. Department of Energy

CRESP
Consortium For Risk Evaluation with Stakeholder Participation

References

- "Compilation of Molten Salt Reactor Experiment (MSRE) Technical, Hazard, and Risk Analyses: A Retrospective Application of Safety-in-Design Methods," S. Krahn (PI) and B. Chisholm, EPRI, Technical Report 3002018340, September 2020.
- "Early Integration of Safety Assessment into Advanced Reactor Design – Project Capstone Report," S. Krahn, (PI), Program on Technology Innovation, EPRI, Technical Report 3002015752, October 2019.
- "A systematic approach to identify initiating events and its relationship to Probabilistic Risk Assessment: demonstrated on the Molten Salt Reactor Experiment," B. Chisholm, S. Krahn, K. Fleming, Progress in Nuclear Energy, Vol. 129, 103507, November 2020.
- "Literature Review of Preliminary Initiating Events for a Gas-Cooled Fast Reactor Conceptual Design," Ibrahim, I., Harkema, M., Krahn, S., Choi, H., Bolin, J., Thornsbury E., Nuclear Technology (2025).
- "Development and Demonstration of a Prototype Molten Salt Sampling System," M. Harkema, S. Krahn, P. Marotta, A. Burak, X. Sun, P. Sabharwall, in press, Nuclear Technology (2025).
- Center for Chemical Process Safety (CCPS). (2008). Guidelines for Hazard Evaluation Procedures, 3rd Ed., New York, NY: John Wiley & Sons, Inc.
- U.S. DOE and the Generation IV International Forum. (2002). A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00, Washington, DC: U.S. Department of Energy.
- Photos
  - Peach Bottom Unit 1: https://www.ans.org/news/article-6207/the-peach-bottom1-htgr/
  - MSRE: Oak Ridge National Laboratory - ORNL Photo 67051-64
  - EBR-II: https://www.ans.org/news/article-5483/the-design-and-legacy-of-experimental-breeder-reactorii/
- "Incorporation of Historical Information into the advanced reactor design process: A case study on the development of a molten salt sampling system," M. Harkema, S. Krahn, P. Marotta, A. Sowder, Transactions of the American Nuclear Society, 127(1): 856-859, 2022.
- M. Harkema, Development and Demonstration of a Risk-Informed Molten Salt Sampling System Design for Molten Salt Reactors, Unpublished Dissertation, Vanderbilt University (2024).

- "Literature Review of Preliminary Initiating Events for a Gas-Cooled Fast Reactor Conceptual Design," Ibrahim, I., Harkema, M., Krahn, S., Choi, H., Bolin, J., Thornsbury E., Nuclear Technology (2025).

- "Populating a Molten Salt Component Reliability Database: Opportunities, Challenges, and Lessons Learned," M. Harkema, S. Krahn, C. Leach, I. Ibrahim, A. Sowder, Transactions of the American Nuclear Society, 124(1): 461-464, 2021.
- "Creating a Molten Salt Component Reliability Database: Initial Efforts and Path Forward," M. Harkema, A. Guler Yigitoglu, S. Krahn, A. Sowder, Transactions of the American Nuclear Society, 123(1):1087-1090, 2020.
- Chisholm, B., Krahn, S.L., & Fleming, K.N. (2020a). A Systematic Approach to Identify Initiating Events and its Relationship to Probabilistic Risk Assessment: Demonstrated on the Molten Salt Reactor Experiment, Progress in Nuclear Energy, 129, 103507

References

- Diamond et al. (2018). Phenomena Important in Modeling and Simulation of Molten Salt Reactors, BNL-114869-2018-IR, Brookhaven National Laboratory,
- Holcomb et al. (2021). Molten Salt Reactor Fundamental Safety Function PIRT, ORNL/TM-2021/2176, Oak Ridge National Laboratory.
- Lee et al. (2005). Generation of a Preliminary PIRT for Very High Temperature Gas-Cooled Reactors, KAERI/TR-3050/2005 (also INL/EXT-05-00829 and ANL-GenIV-066), Idaho National Laboratory/Argonne National Laboratory.
- Aoyagi et al. (2019). Identification of Important Phenomena Through the PIRT Process for Development of Sodium Fire Analysis Codes, Nuclear Engineering and Design, 110240.
- Zhou et al. (2021). Phenomena Identification and Ranking Table of Station Blackout Accidents for China Sodium Cooled Fast Reactor, Annals of Nuclear Energy, 108240.
- Harkema, M., Krahn, S., & Marotta, P. (2019). Evaluating the MSRE Sampler-Enricher: A Fresh Perspective, Transactions of the American Nuclear Society, 121(1), pp. 1193-1196.
- Harkema, M., Krahn, S., & Marotta, P. (2020). Advanced Reactor System Design Insights from STAMP-based Analysis of Historical Parallels, presented at the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference, November 1-5, 2020, Venice Italy.
- Harkema, M., Krahn, S., Marotta, P., & Croff, A. (2020). Development of a Molten Salt Sampling System Design: Progress To-Date and Path Forward, presented at the 2020 Molten Salt Reactor Workshop, October 14-15, 2020 Oak Ridge, TN.
- Harkema, M., Marotta, P., & Krahn, S. (2021). Fuel Salt Sampling and Enriching Technology Design Development—Project Update, Transactions of the American Nuclear Society, 124(1), pp. 465-467.
- Harkema, M., Krahn, S., Marotta, P., & Sowder, A. (2022). Incorporation of Historical Information into the Advanced Reactor Design Process: A Case Study on the Development of a Molten Salt Sampling System, Transactions of the American Nuclear Society, 127(1), pp. 864-867.
- Harkema, M., Krahn, S., & Marotta, P. (2022). Fuel Salt Sampling and Enriching Technology Design Development—Interfacing Systems Analysis and Project Update, Transactions of the American Nuclear Society, 126(1), pp. 688-691.
- Harkema, M., Marotta, P., & Krahn, S. (2022). Model Refinement Studies for Molten Salt Freeze Port Conceptual Design Using COMSOL, Transactions of the American Nuclear Society, 126(1), pp. 87-90.
- Harkema, M., Krahn, S., & Marotta, P. (2023). Expert Elicitation for Collection of Stakeholder Input for a Molten Salt Sampling System Design, Transactions of the American Nuclear Society, 129(1), pp. 796-799.
- Harkema, M., Krahn, S., & Marotta, P. (2023). Fuel Salt Sampling and Enriching Technology Design Development—Failure Modes and Effects Analysis and Safeguardability Checklist Analysis, Transactions of the American Nuclear Society, 128(1), pp. 522-525.
- Harkema, M., Krahn, S., & Moneghan, D. (2024). Achieving Timely Advanced Reactor Deployment—How Can Historical Information Support the Advanced Reactor Design Process Phoenix Project: From Kikuchi to Fastest Path—An International Symposium on Sociotechnical Research on Nuclear Technology, November 7-8, 2024, Ann Arbor, MI.

School *of* Engineering

Backup Slides

STAMP-Based Analysis: Process Overview

1. Functional Decomposition of MSRE S-E

a. Review MSRE S-E design and operating data
b. Identify S-E functions and subfunctions
c. Develop functional decomposition for S-E that reflects results of (b)

2. STAMP-Based Analysis of MSRE S-E Operating Occurrences

a. Create safety control structure (SCS)
b. Parse/discretize events in MSRE S-E operational narratives
c. STAMP-based causal analysis. For each occurrence, identify:
   - System hazard
   - Goal of SCS
   - Safety constraints violated
d. Categorize maintenance events as:
   - Successful or unsuccessful
   - Design change, procedure change, mitigative measure, repair/replacement, diagnostic
e. Evaluate design change and repeated repair/replace occurrences for design insights

3. Collect MSSS Stakeholder Input

a. Identify stakeholders
b. Develop materials to brief stakeholders and collect stakeholder input
c. Brief stakeholders on MSSS design project and requested input
d. Collect stakeholder input on MSSS functionality

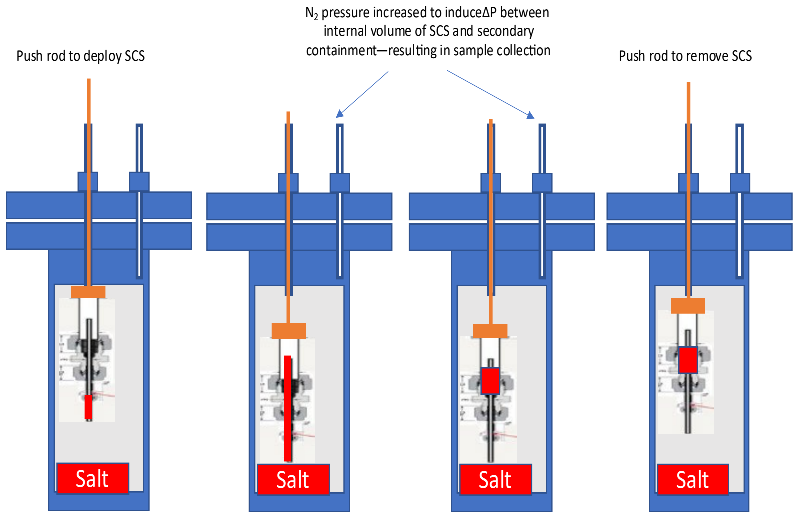
4. Write MSSS Functional Requirements

a. Using MSRE S-E functional decomposition as a framework, integrate insights from STAMP-based analysis and MSSS stakeholder input collection to write MSSS functional requirements.

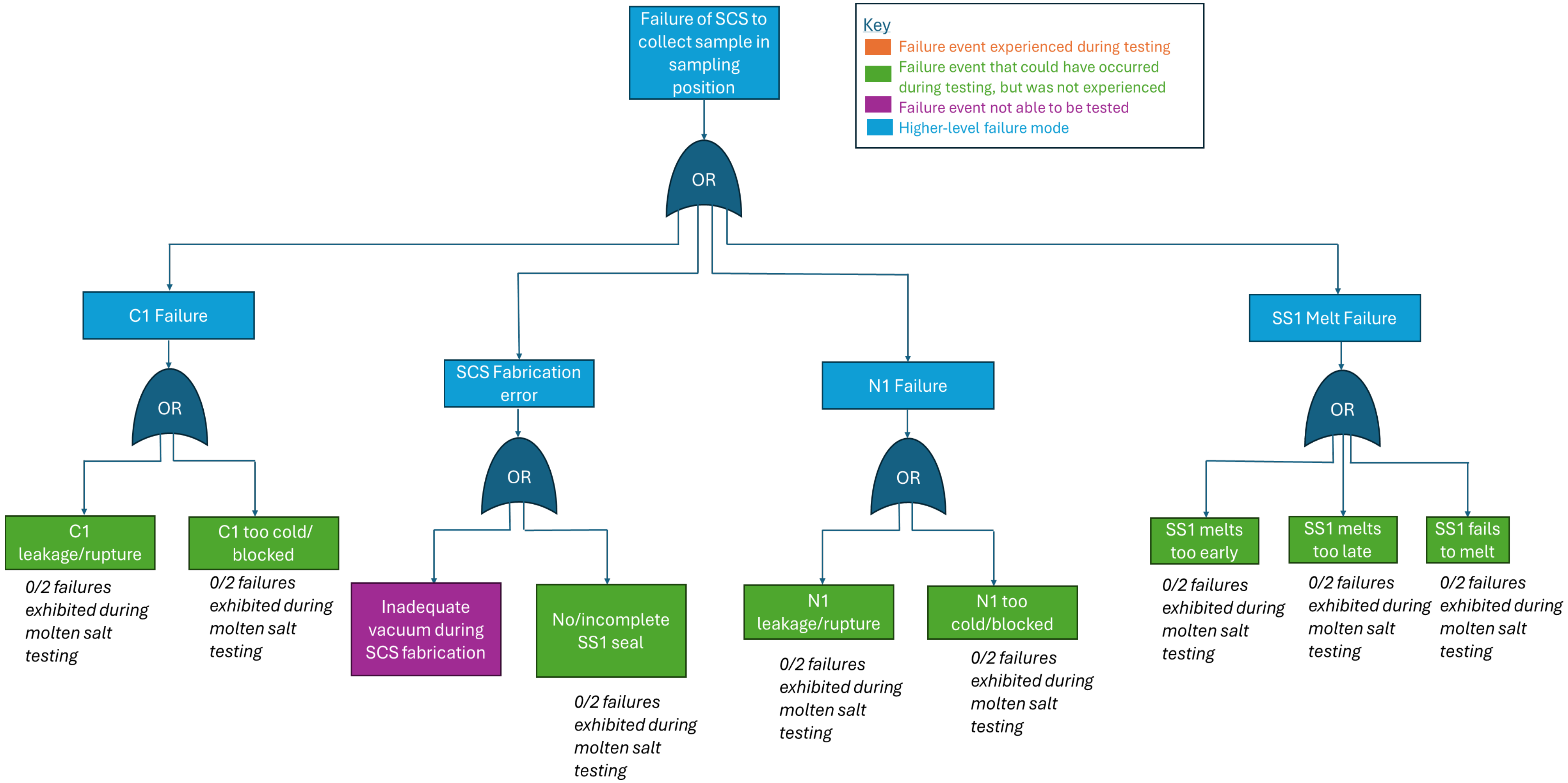
FMEA Selection Matrix

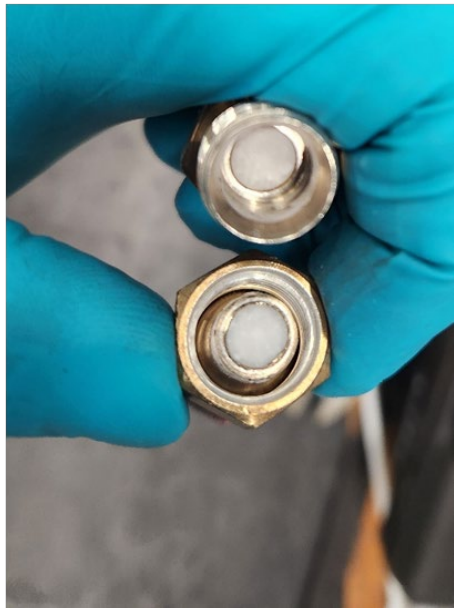
Method	Team vs. Individual Approach	Documentation Needs	Quantitative vs. Qualitative	Breadth of Hazards Considered	Single vs. Multiple Failures
What-if/ Checklist	Team (CCPS, 2008)	Low-Moderate (CCPS, 2008), which may not be appropriate for the level of detail available for the MSSS and the MSRE S-E.	Qualitative (U.S. NRC, 2001)	Loose structure of What-if analysis allows for broad range of hazards to be considered, while inclusion of Checklist can ensure key hazards are not overlooked (CCPS, 2008). However, many What-if/Checklist approaches have a focus on external hazards and well-understood phenomena.	Primarily used for single failures (CCPS, 2008); however, flexibility allows for consideration of multiple failures as well
HAZOP	Team (CCPS, 2008)	Moderate (U.S. NRC, 2001; CCPS, 2008). HAZOP typically relies on the availability of P&IDs or PFDs for a system; these design drawings are available for MSSS, which can allow for broader identification of hazards when considered in conjunction with detailed PHA approach like HAZOP.	Typically qualitative, but quantitative or semiquantitative frequencies and consequences can be assigned as deviations are developed and used as inputs to future quantitative studies (U.S. NRC, 2001)	Can identify broad range of hazards due to parameter-guideword approach (CCPS, 2008); however, HAZOP may struggle to capture deviations due to slow-developing effects (e.g., corrosion) (EPRI, 2019).	Better suited for single failures (CCPS, 2008)
FMEA	Individual or Team (CCPS, 2008)	Moderate-High (U.S. NRC, 2001; CCPS, 2008). FMEA requires design documentation down to the component level to determine failure modes and their effects, which has been developed for many of the critical functions of the MSSS concept.	Qualitative, Semi-Quantitative, or Quantitative (U.S. NRC, 2001)	FMEA can identify broad range of hazards at the component and functions levels of a system (CCPS, 2008), but is not particularly well-suited for identification of external hazards.	Better suited for single failures, unless failures are sequential (CCPS, 2008)

SCS Testing



Freeze port testbed reconfigured to test SCS ability to collect a sample.

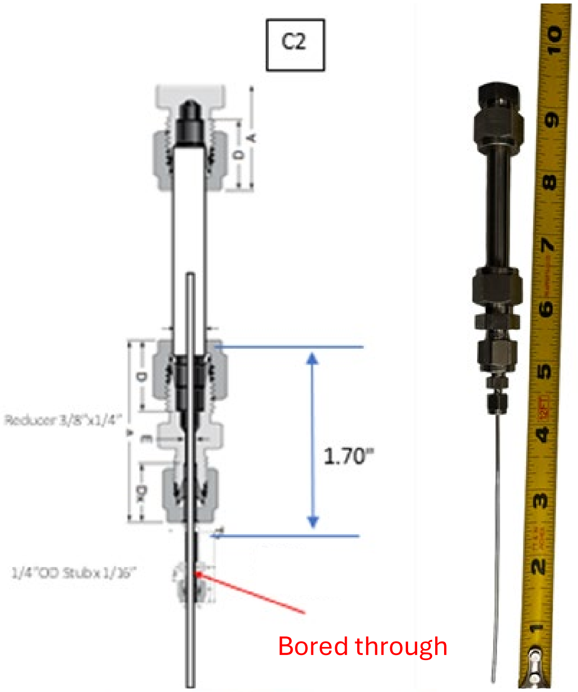


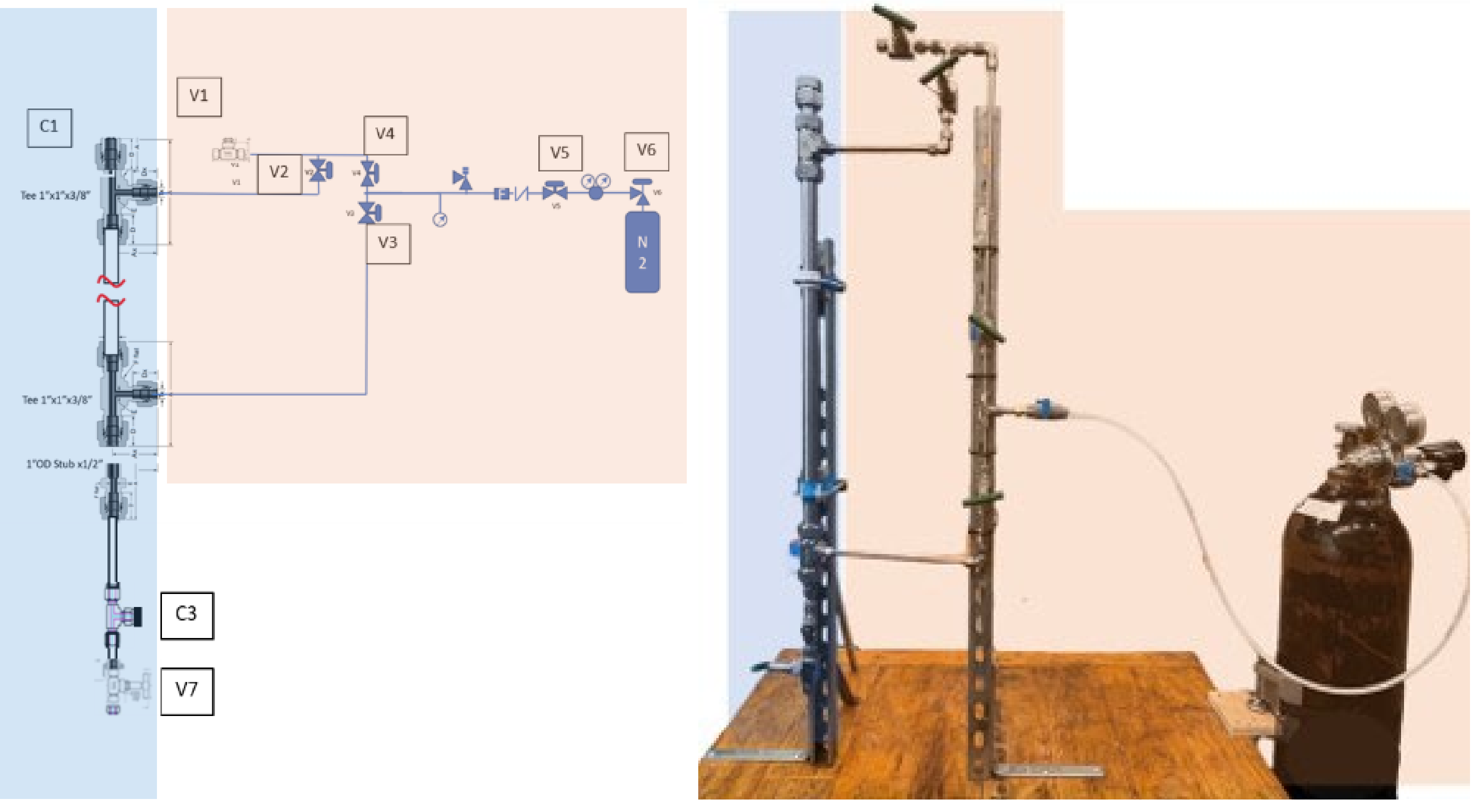


Pictures of the SCS outside (left) and inside (right) after second sample collection test (Image Credit: Adam Burak, University of Michigan)

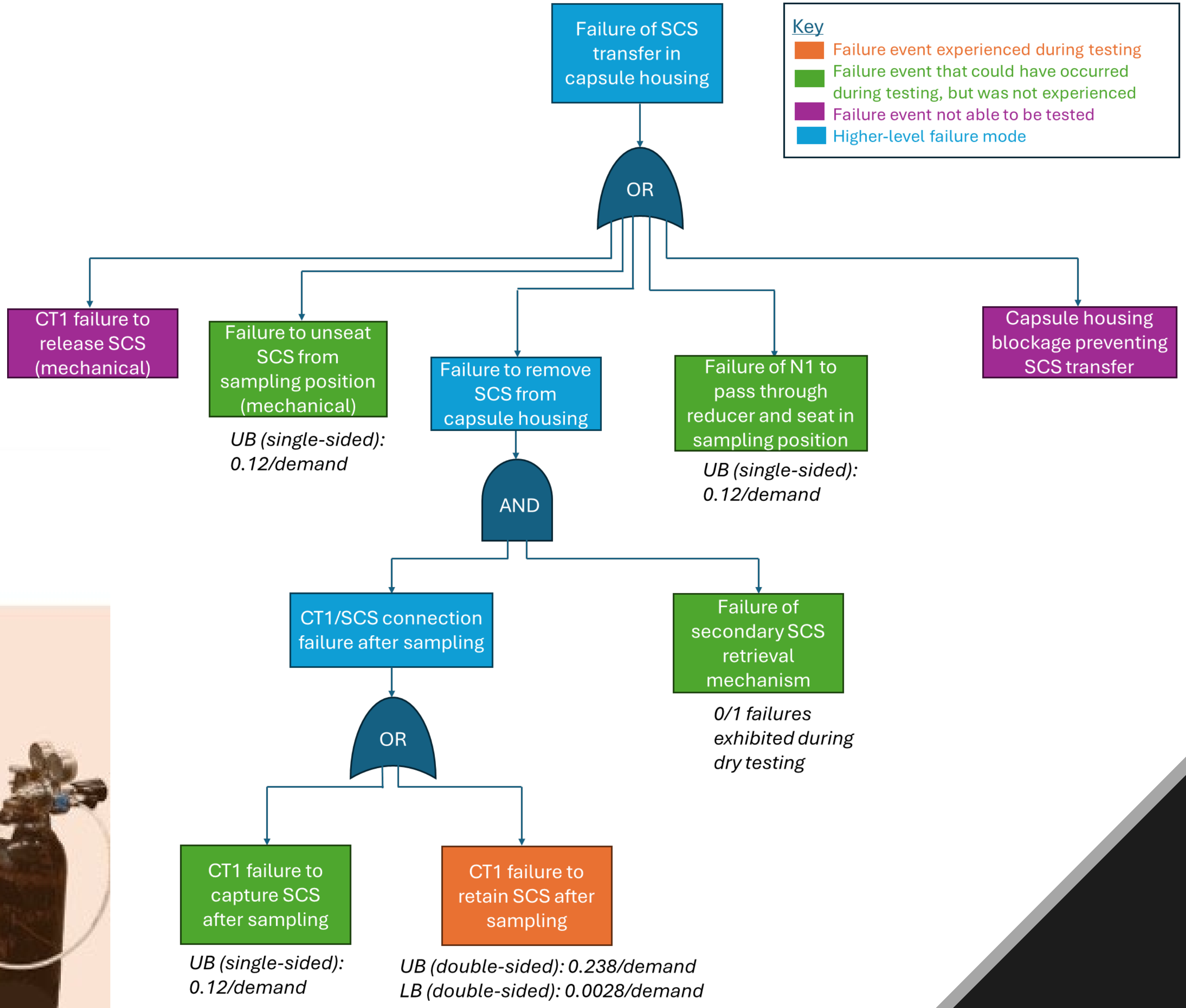
Dry Testing

SCS prototype schematic (left, not to scale) and prototype (right).





Initial dry testing schematic (left) and prototype (right). The capsule housing is shaded in blue and the NCS and NDS are shaded in orange.



General Atomics FMR—Regulatory Basis for PIE Identification

- The need for a **robust** and **thorough** initiating event identification process has been recognized by the ACRS[1].
- Philosophy:
  - ‘Clean sheet of paper’
  - No preconceived set or list of events
  - Develop a spectrum of events from AOOs to very unlikely events
- Draft NRC guidance[2] has also emphasized the importance of ***systematic identification of initiating events***:
  - “Identification of initiating events (IEs) is the starting point for the safety assessment of nuclear power plants. Having a reasonably complete set of IEs is crucial in determining what events could propagate to undesirable consequences and in assessing overall plant risk."

[1]Petti (2023). ”Considerations Related to Licensing First of a Kind Reactors,” *Trans. Am. Nucl, Soc*. 129:712-713.
[2]NRC (n.d.) “Pre-Decisional Draft Regulatory Guide DG-1413: Technology-Inclusive Identification of Licensing Events for Commercial Nuclear Plants.”

General Atomics FMR—Initiating Event Identification Methodology

Approach: perform a comprehensive identification of initiating events from documented operating experience and accident analysis for similar concepts to inform the FMR safety case.

1. Collect and Organize Initiating Events from Relevant Literature

Concepts Reviewed:

- Other GFR conceptual designs
- HTGRs
- VHTRs
- UK CO_2-cooled gas reactors

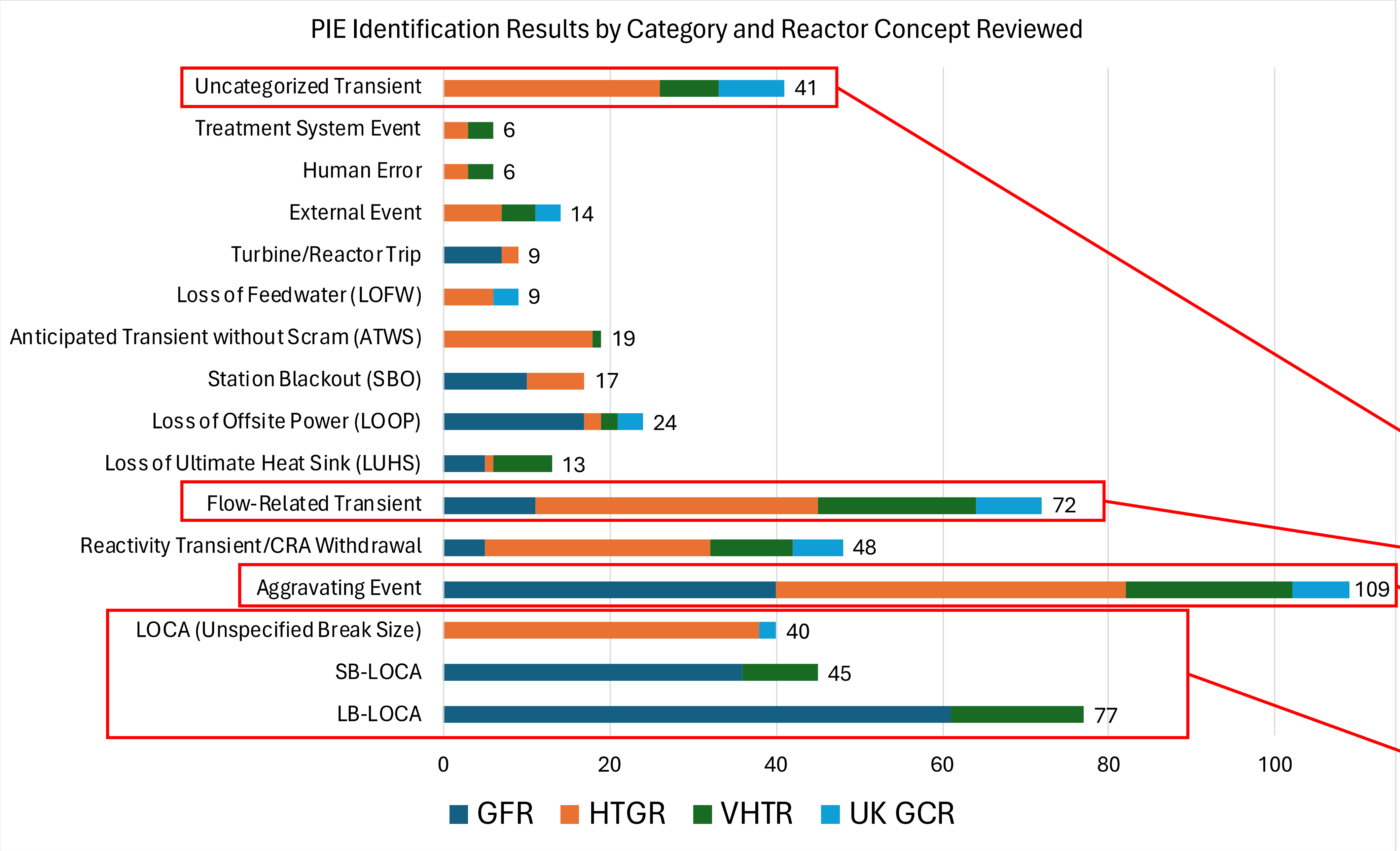
2. Categorization of PIEs

Due to the iterative nature of initiating event identification for the FMR concept (and GFRs in general), the identified IEs were given the label of 'Preliminary Initiating Events' (PIEs).

3. Analysis of PIEs in Relation to GFRs and the FMR concept

Evaluation of the results of the PIE identification effort and discussion of implications for GFR and FMR safety case development.

FMR PIE Review: Results by Category & Concept



Concept Reviewed	# of Unique PIEs	# of References
GFR	192	28
HTGR	216	48
VHTR	101	20
UK GCR	40	10
Total	**549**	**106**

30% of PIEs (remaining PIEs): Events commonly analyzed for general NPP operations

7% of all PIEs: Potentially unique to gas-cooled reactors

13% of all PIEs: PLOFC

20% of all PIEs: Air/Water ingress

30% of all PIEs: DLOFC

FMR PIE Review: Observations & Implications

- Many PIEs included events expected to be analyzed as part of general NPP operations (e.g., LOOP, SBO, External Events).
- There is an emphasis on the evaluation of **DLOFC** and **aggravating events** (e.g., air/water ingress events) – **50%** of all PIEs fell under one of these categories.
  - Prioritization of such event types for detailed analysis for FMR.
- The results revealed a lack of evaluation of several potentially important events for GFRs such as:
  - Helium purification system failures (contain radiological inventory and penetrate reactor pressure boundary)
    - Data needed!
  - External events.
- The FMR features a passive decay heat removal system--which is functionally different than the DHR systems included in the designs reviewed.
  - **Performance of decay heat removal system thus the subject of detailed study via FMEA, functional FMEA, and Master Logic Diagram**