The Safety-in-Design (SiD) Methodology—As Applied to Advanced Fission Projects & Beyond

Overview for the RIPB Community of Practice

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Outline

- Introduction
- Background on Safety-in-Design (SiD) Methodology
- Using Process Hazards Analysis (PHA) Results to Support Quantitative Risk Estimates—As Demonstrated on a Freeze Valve
- Example Applications of SiD
- Lessons Learned

Introduction

Motivation

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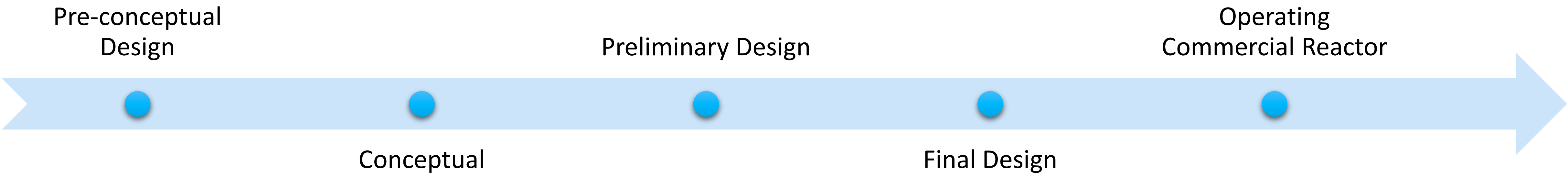
- Interest in advanced (Generation IV) nuclear reactor designs has continued to expand
- Many advanced reactor designs are at an early stage of the design process and differ significantly from Light Water Reactor (LWR) designs
- Previous risk assessment efforts have been largely based LWR design details, experience, and analysis
  - However, benefits of a risk-informed approach have been realized
- The Safety-in-Design (SiD) project[1] was developed in consultation with industry, as represented in the EPRI Advanced Reactor Technical Working Group, to construct a methodology that would use existing risk assessment tools to:
  1. Provide risk-informed insights early in the design process,
  2. Develop the safety case for the design,
  3. Incrementally build that safety case, and
  4. Contribute to the development more quantitative insights, such as Probabilistic Risk Assessment (PRA)—as the reactor design matures.

[1] Originally titled PHA-to-PRA project, see EPRI report No.'s 3002018340, 3002015752, and 3002011917 for further details

EPRI SiD Methodology Benefits

- Early integration of safety assessment into the design process using fit-for-purpose tools and methods can support:
  - Incremental development of the safety case for advanced reactor designs
  - Earlier identification of any needed R&D in time to benefit design
  - Efficient design iteration and improvement
  - Enhanced early regulatory engagement
- Established qualitative and semi-quantitative Process Hazard Analysis (PHA) methods can be used to provide a bridge to quantitative risk assessment.
  - Safety analysis technique not rooted in LWR technology
- Demonstration of a safety assessment approach that can be efficiently integrated with early stages of design and advance with maturing design
  - Recognizes the existence of unknowns for new and varying technologies
- Demonstration of the importance of early integration of SiD for the purpose of identifying and prioritizing risk-significant design issues, technical uncertainty, and targeted needs for additional analysis/R&D/testing
- Demonstration of a SiD methodology that could support a **risk-informed and performance-based** licensing framework



Background on SiD Methodology

Acronyms:
PHA – Process Hazards Analysis
FMEA – Failure Modes and Effects Analysis
MLD – Master Logic Diagram
FTA – Fault Tree Analysis
HAZOP- Hazards and Operability [study]
ETA – Event Tree Analysis
PRA – Probabilistic Risk Assessment
PIRT – Phenomenon Identification and Ranking Table

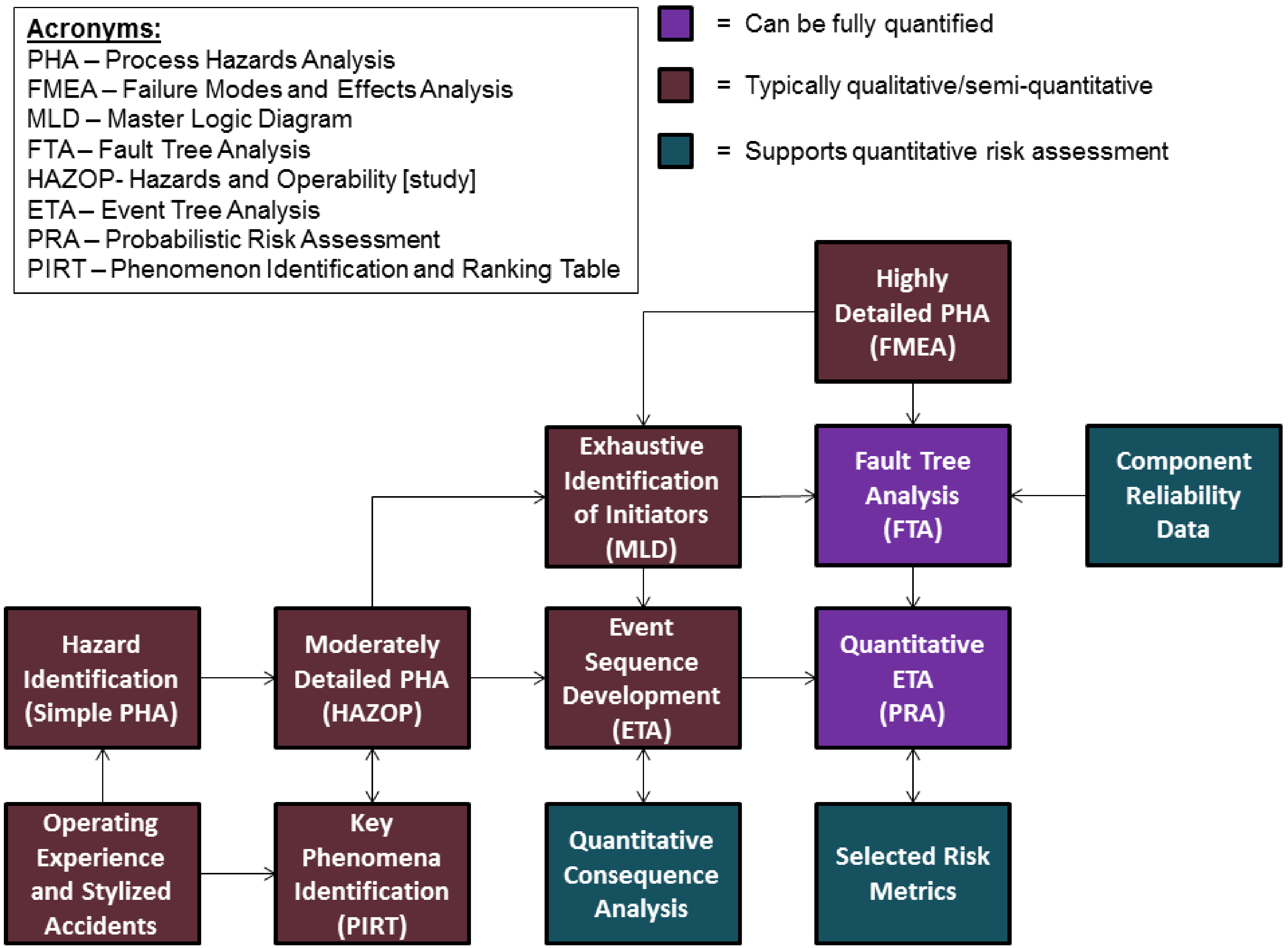


Image credit: EPRI Report 3002015752

Organizing Concept: Process Hazards Analysis (PHA)

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- A PHA is a set of systematic techniques structured to identify potential hazards and operability problems as part of the design process
- Most PHA methods focus on 2 questions from the Risk Triplet (in **bold**)
  - **What can go wrong?**
  - How likely is it?
  - **What are the consequences?**
- Most frequently a qualitative systematic evaluation of process upsets & how event sequences promulgate - can be a starting point for quantitative analysis

- Benefits
  - Powerful tool for early stages of design
    - Pull together design and safety analysts
  - Adaptable, amenable to iteration with increasing detail

- Methods recognized by NRC, DOE & others:
  - ANSI/ASME/ANS RA-S-1.4-2021: Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants
  - NEI 18-04 & NRC Reg. Guide 1.233: Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors
  - DOE-STD-1189-2016: Integration of Safety into the Design Process
  - DOE-STD-1628-2013: Development of Probabilistic Risk Assessments for Nuclear Safety Applications
  - NUREG-1513: Integrated Safety Analysis Guidance Document
  - NUREG-1520: Standard Review Plan for the Review of a License Application for a Fuel Cycle Facility
  - Series of ISO Standards Associated with ISO-31000, Risk Management

NEI 18-04: Preliminary Identification of Hazardous Scenarios

- Early identification can be informed by past experience with other reactor design concepts
  - Informal brainstorming can tend toward familiar scenarios from LWR experience
  - often "core-centric"
- **Such an exercise does not replace a systematic hazards identification and phenomenological study (e.g., HAZOP, FMEA, Phenomenon Identification and Ranking Table [PIRT], etc.)**
  - Stylized scenarios (e.g., LBLOCA, ATWS) can mask other important drivers of risk for advanced reactor designs (e.g., TMI and SBLOCA)

Image credit: EPRI Report 3002015752

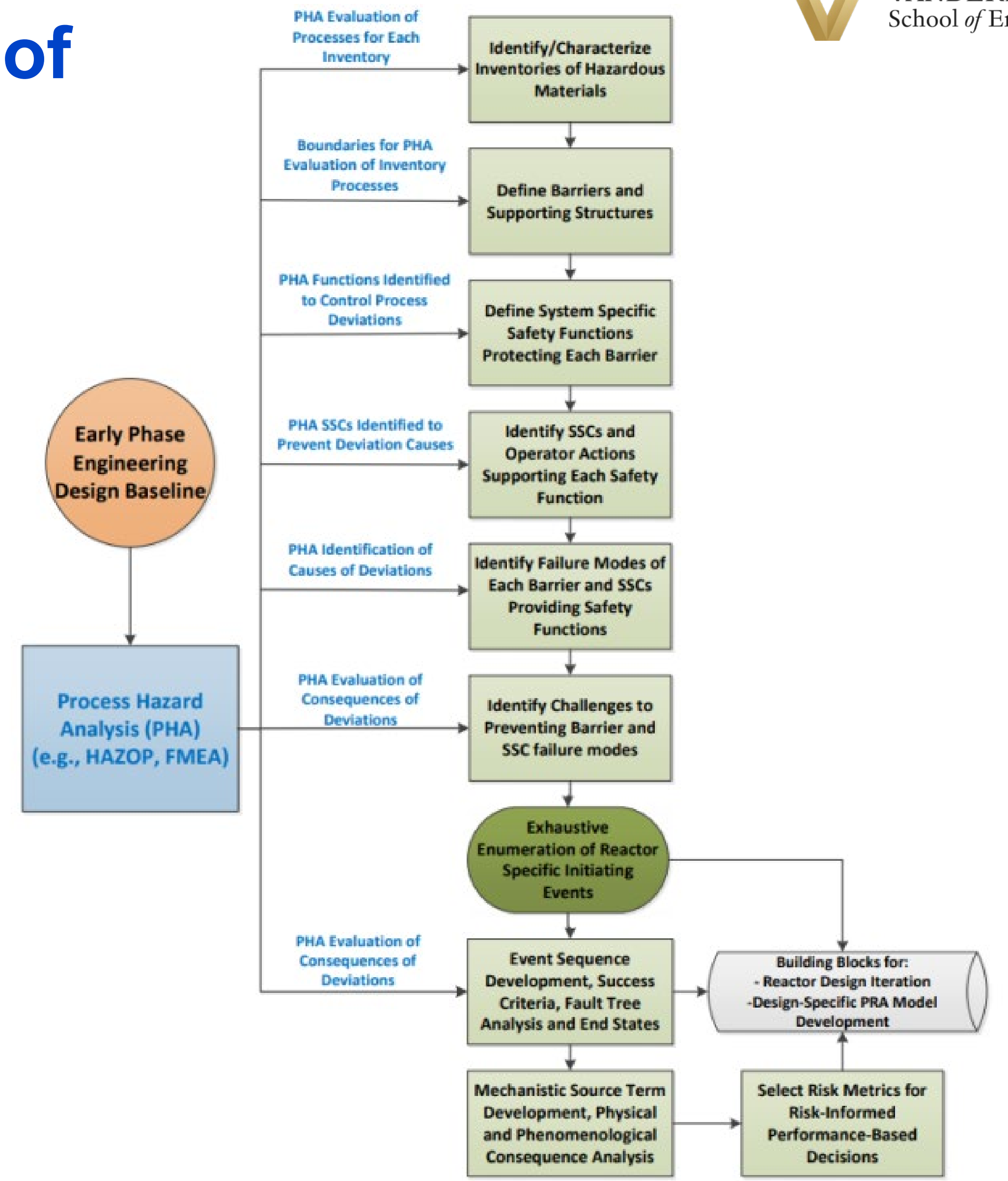

Figure 2-2
Sample iteration of early integration of SiD

Iterative Nature of SiD Methodology

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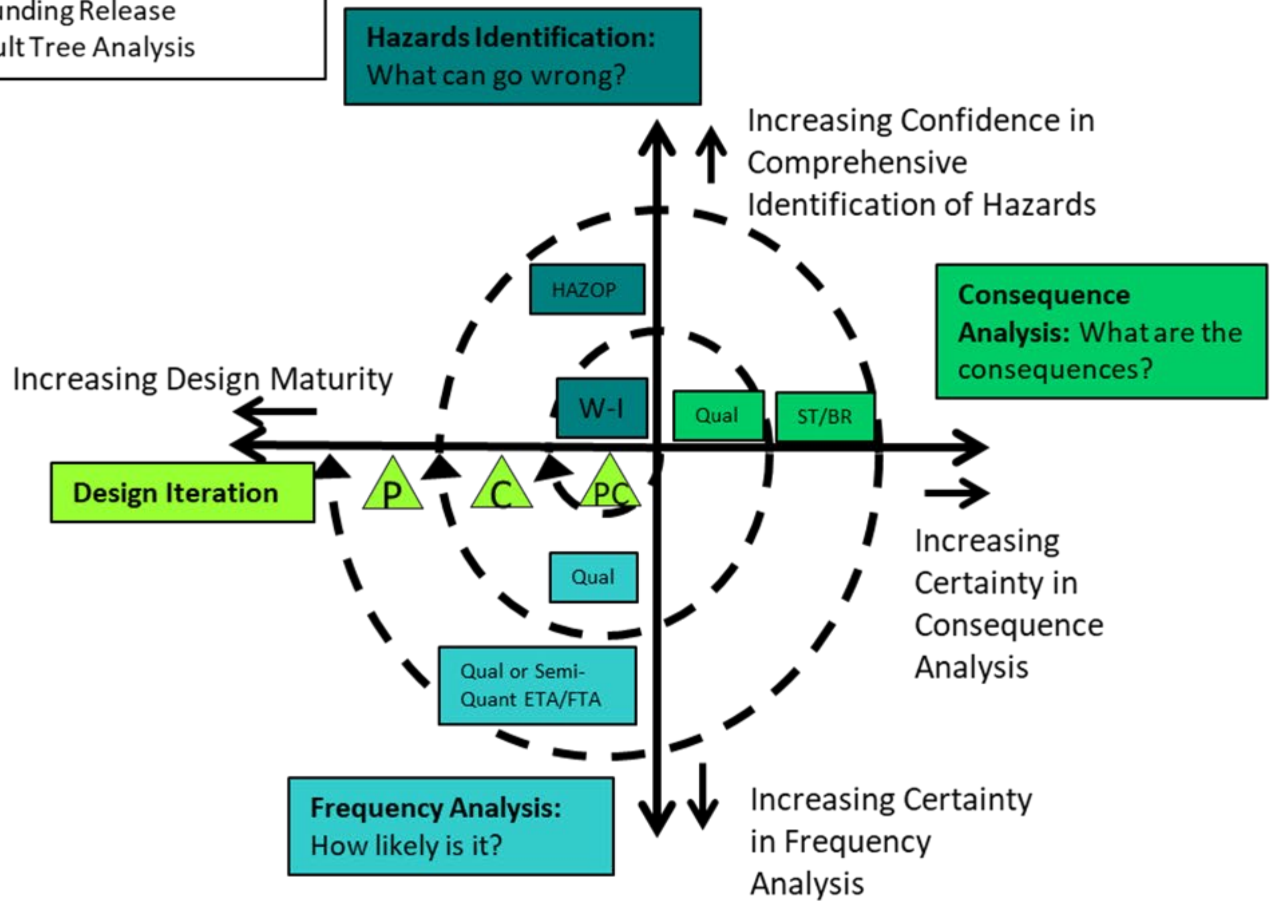
Key:
PC: Pre-conceptual design
C: Conceptual design
P: Preliminary design
W-I: What-If
HAZOP: Hazards and Operability study
Qual/Quant: Qualitative/Quantitative Estimate
ST/BR: Source Term/Bounding Release
ETA/FTA: Event Tree/Fault Tree Analysis



- PHA tool selection depends on, e.g.:
  - Maturity of design
  - Understanding of hazards and phenomena
  - Type of facility
  - Intended use of results

Image credit: EPRI Report 3002015752

Using PHA Results to Support Quantitative Risk Estimates—As Demonstrated on a Freeze Valve

MSRE Case Study: Methodology Application Matrix

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	Operating Experience and Stylized Accidents	Hazard Identification	Key Phenomena Identification	HAZOP Study	Event Sequence Development	Quantitative Consequence Analysis	FMEA	FTA	Component Reliability Data	Quantitative ETA	Risk Metric Selection
Off-Gas System and Component Cooling System	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
Fuel Salt Loop	✓	✓	✓	✓	✓						✓
Freeze Valve	✓						✓	✓	✓		
Fuel Processing System	✓	✓	✓	✓	✓						✓

Refer to EPRI Report No. 3002015752 (Sections 2-3) and EPRI report No. 3002018340 for more information

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Freeze Valves in Molten Salt Reactors (MSRs)

High operating temperatures in MSRs → challenging environment for mechanical valves

Preliminary investigation on the melting behavior of a freeze-valve for the Molten Salt Fast Reactor

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Design improvement

Preliminary Study of the Use of Freeze-Valves for a Passive Shutdown System in Molten Salt Reactors

Qiming Li, Zhongfeng Tang, Yuan Fu, Zhong Li, Naxiu Wang

Check for updates

+ Author Information

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Published Online: February 4, 2019

The use of passive shutdown systems to enhance safety is one element of next-generation reactor design. The Freeze-Valve has been proposed as a key device in the passive system to stop the chain reaction of the Molten Salt

?

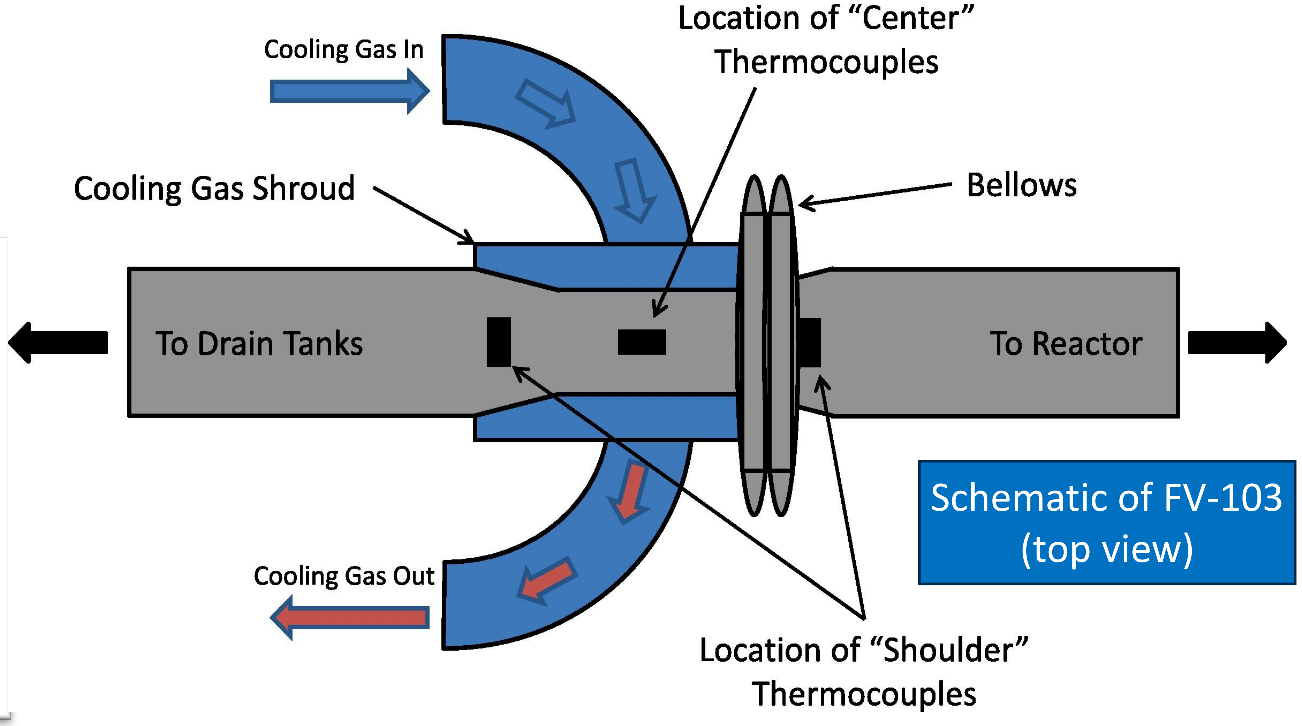
Investigation of Basic Parameters in Developing High-Performance Freeze Valve for Molten Salt Reactor

Tokyo, Japan
July 2020

Indarta Kuncoro Aji

ABSTRACT

Freeze valves are passive safety systems used in MSRs (Molten Salt Reactors). The nuclear fuel of MSRs is a molten salt base. In the freeze valves, salt is frozen by external



Schematic of FV-103 (top view)

Image Credit: Chisholm, B.M., Krahn, S.L., & Sowder, A.G. (2020) and Chisholm, B. (2020)

Research goals:

- Risk insights for design, safety, and/or performance?
- Likelihood (*qualitative*) of failure?
- Reliability/failure rates for quantitative risk assessment?

Evaluations of a Freeze Valve Design

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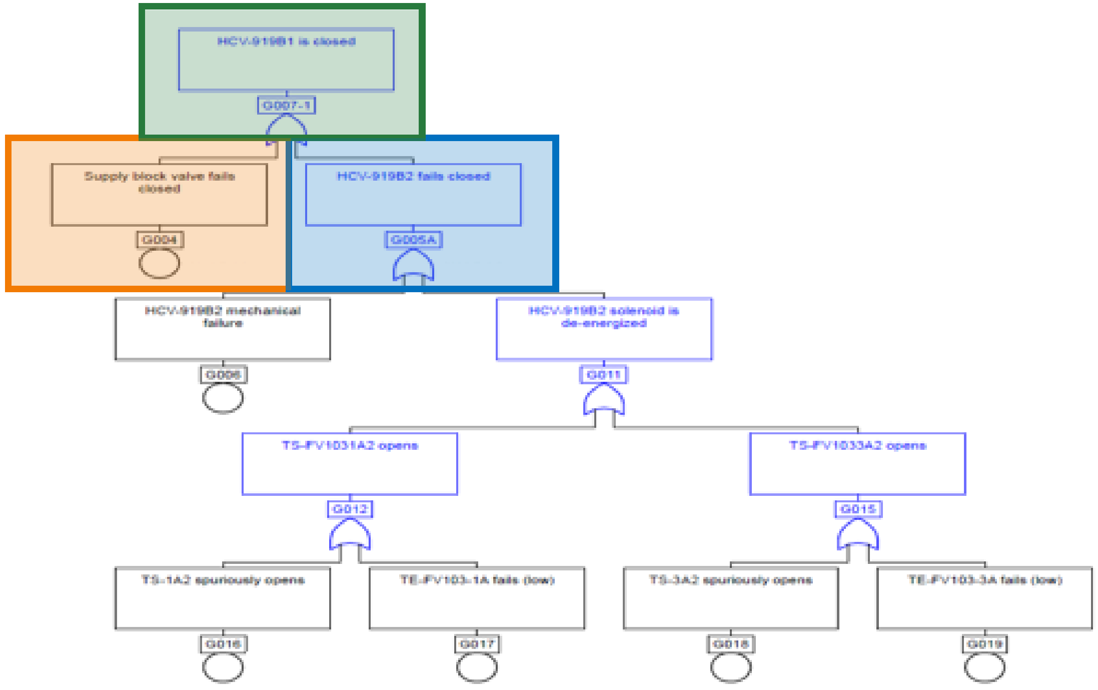
Identification/ Description	Failure Mode	Effect	Safety Systems
"Supply" block valve for HCV-919B1 (normally open)	Spuriously closes	Closes HCV-919B1, isolates cooling gas flow to FV	Operator alarm on high freeze valve temperature, indication of freeze valve condition
Solenoid valve HCV-919B2	Spuriously closes	Closes HCV-919B1, isolates cooling gas flow to FV	Operator alarm on high freeze valve temperature, indication of freeze valve condition
Temperature switch TS-FV103-1A2	Spuriously opens	De-energizes HCV-919B2 and HCV-919A2, isolates cooling gas flow to FV	Operator alarm on high freeze valve temperature, indication of freeze valve condition
Thermocouple TE-FV103-1A	Failure (indicates lower temp than actual)	First, close TS-1A1 Then, open TS-1A2	Redundant temperature indication (TE-FV103-1B) displayed on recorder in aux control room

Example of Failure Modes and Effects Analysis (FMEA) results

Process Hazards Analyses (PHAs) were conducted to provide qualitative insights into FV design and performance



The PHA results were used to structure **fault tree** models to generate preliminary **failure rate** estimates for a specific MSR freeze valve design

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Key Research Results

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Insights from PHA studies

- A **high *qualitative* likelihood** that an operator would be unable to observe, diagnose, and correct a failure in time to prevent **spurious thawing**
  - Many individual component failures result in loss of cooling gas
  - Lack of dedicated instrumentation → sparse information about specific failure
- The specific **safety** function of this freeze valve presented a **trade-off with operability**
  - More redundancy to thaw (drain) upon failure than to remain frozen (not drain)
  - Likelihood of inadvertent thawing (drain) could be reduced by improved I&C design

Insights from Fault Tree Analysis[1]

Failure rate of FV-103 to remain frozen = 0.275/yr
Generic solenoid valve spurious operation = 4.38E-3/yr

Failure rate of FV-103 to thaw when requested = 2.20E-5/d
Generic solenoid valve failure to close = 1.0E-3/d

- The ***quantitative*** failure rate estimates suggest that freeze valve reliability may be **significantly different from mechanical valves**

Key Methodology Takeaway:

Risk is risk! Can be qualitative and/or quantitative…

1) What can go wrong?
2) What are the consequences?
3) How likely is it?

[1] For more detail, see Tables A-1, A-2, and A-3 In EPRI Report No. 3002018340

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Examples of SiD Application

Chronology: SiD Applied to Commercial Systems

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Future: Application of SiD to Fusion Systems

July 2022-Present: General Atomics Fast Modular Reactor (FMR) SiD Strategy

October 2022-Present: TerraPower Molten Chloride Fast Reactor (MCFR) SiD Strategy

February 2021: Hybrid SiD Approach for Commercial Molten Salt Reactor (MSR) Customer

June 2019: Hazard and Operability Study (HAZOP) of Kairos Power Forced Convection Loop (FCL-2)

October 2015: What-If Analysis of FLiBe Energy Liquid Fluoride Thorium Reactor (LFTR)

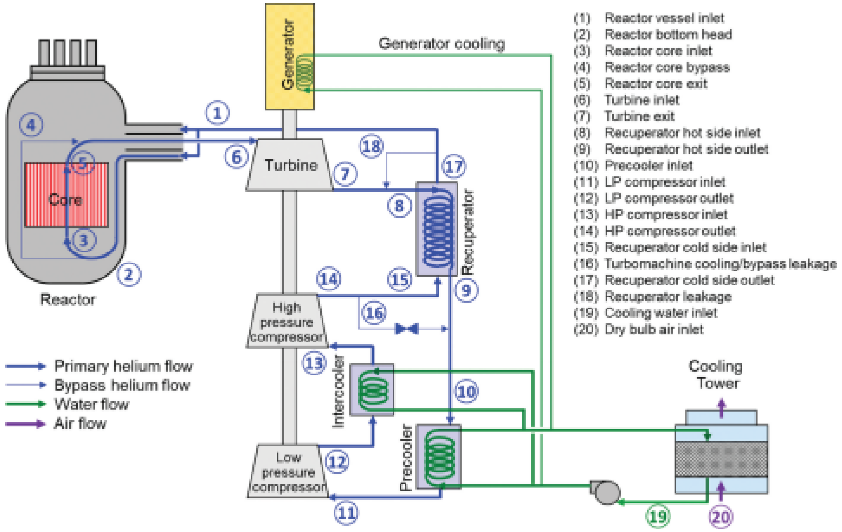

Image Credit: Choi et al., (2024). Progress in Fast Modular Reactor Conceptual Design, Nuclear Technology.

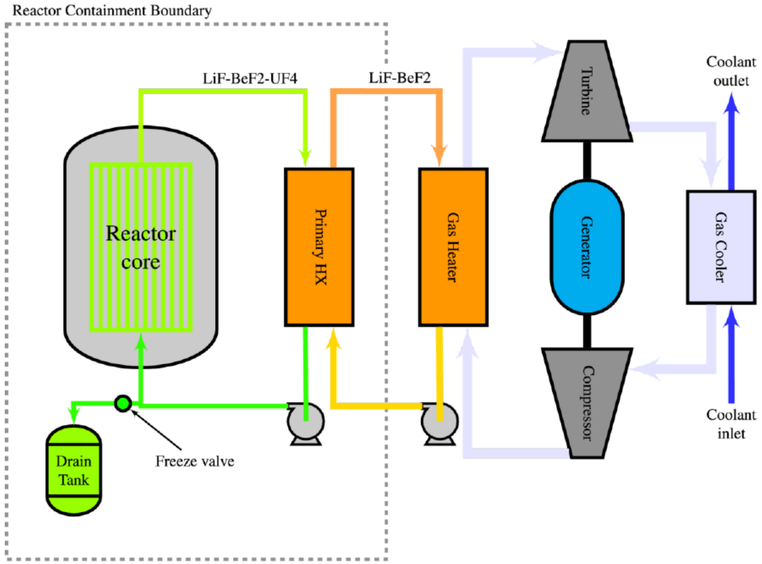

Image Credit: EPRI Report No. 3002005460

Figure 2-1
Reference LFTR design schematic [Flibe Energy, 2015].

What-If Analysis: FLiBe Energy's Liquid Fluoride Thorium Reactor (LFTR)

Summarized in EPRI Report No. 3002005460

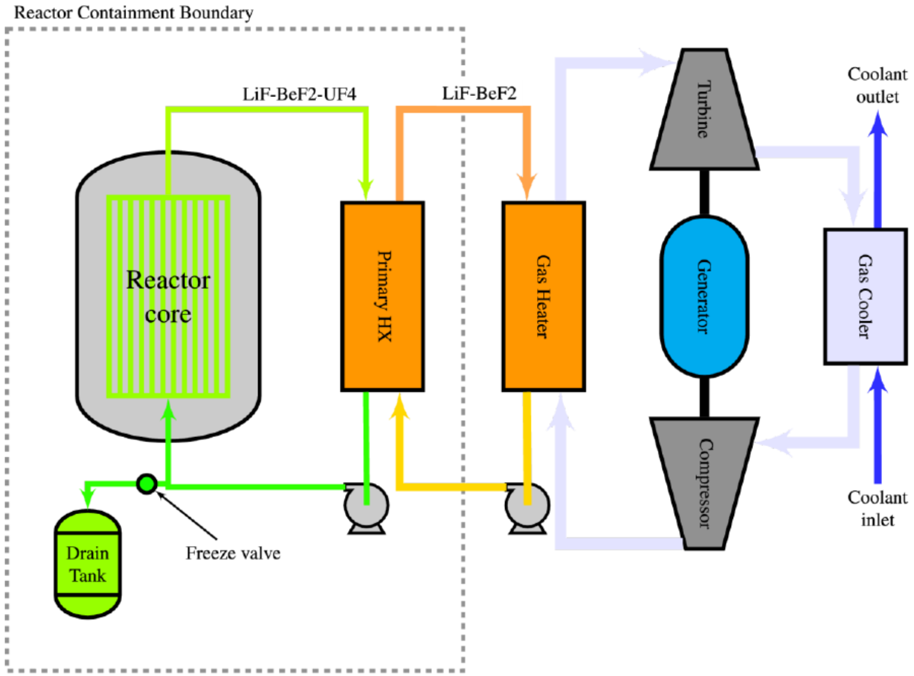

Figure 2-1
Reference LFTR design schematic [Flibe Energy, 2015].

LFTR System or Component	Hazard Scenario
Reactor Vessel/Containment Cell	Unintentional control rod withdrawal
	Loss of blanket salt
	Premature criticality during filling
	Inflow of contaminants or unexpected isotopic ratio in the fuel salt
	Inadvertent release of fission gas from reactor cell and/or containment
Fuel Salt Processing	Hydrogen reacts with fluorine in chemical processing system
	Excess pressure in the helium bubbler
Primary Heat Exchanger	Minor failure in the primary heat exchanger
	Major failure within the primary heat exchanger
	Sealed housing for the electric drive motors for pumps fail
Blanket Salt Processing	Inadequate removal of Pa or U in the blanket salt
	Electrolytic cell is improperly operated
Off-Gas Processing and Treatment	Potassium hydroxide (KOH) is released
Drain Tank	Improper or inadequate cooling of the drained fuel salt
	A partially thawed piece of the salt plug or other solid mass obstructs piping to the drain tank

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Image Credit: EPRI Report No. 3002005460

Interaction Matrix: Kairos Power FCL-2 Loop

Refer to EPRI Report No. 3002015752 (Section 4 & Appendices A-B for more information)

	FLiBe	Air	NaK	Water	Argon
FLiBe					
Air	B1				
NaK	B2	B3			
Water	B7	B4	N		
Argon	Y	B5	B6	N	

Key:
Y= interact during normal operation
BX:
B=potential for interaction if the integrity of a barrier between fluids is compromised,
X=notes number for location in which interaction could take place
N= no potential for interaction based on given schematic

Table 4-1
FCL-2 subsystems and functions

Name	Functional Description	Working Fluid(s)	Major Components
Salt Loop and Drain Tank	Circulate salt around the loop and add heat to salt loop	Molten FliBe	Salt lines, salt pump, heaters, flowmeter, valves, drain tank, primary FliBe-air shell and tube heat exchanger, surge tank
Freeze Valve and Freeze Valve Cooling/Control Valve Work Gas	Supply gas to control of freeze and control valves	Compressed air	Compressed air and compressed air supply lines, control and pressure relief valves
Salt Heat Removal	(1) Remove heat added by heaters in salt loop and transport to ultimate heat sink (2) Provide ancillary cooling to pump jacket, surge tank, and sample removal	Air, water	Secondary air-water gas recirculatory heat exchanger, valves, air and water lines
Cover Gas Supply	Supply argon to control corrosion and set the pressure in the system	Argon	Argon supply and supply lines, control and relief valves, vacuum gauge, 3 relief valves
Vacuum System	Evacuate pockets of gas before filling salt loop (only used during fill stage)	"Used" argon	Vacuum cart, filters, control and freeze valves
Room Ventilation	Provide a flow path for discharge of "used" argon and room atmosphere	Air, "used" argon	Ventilation unit and HEPA filters

Intended uses for Kairos Power FCL-2:

Primary function is to serve as a materials compatibility test loop that facilitates the exposure of coupons of structural materials to circulating molten FLiBe for 1000s of hours

Will also be used as a limited testing ground for the behavior of select components (e.g., valves, pumps, heat exchangers, etc.) exposed to a FLiBe salt environment

Intended Operating Environment for Kairos Power FCL-2:

Working fluid: 20-50 kg (~4 gal) of molten FLiBe

Operating temperature range: 650-700°C

Safety-in-Design (SiD) Approach for GA FMR

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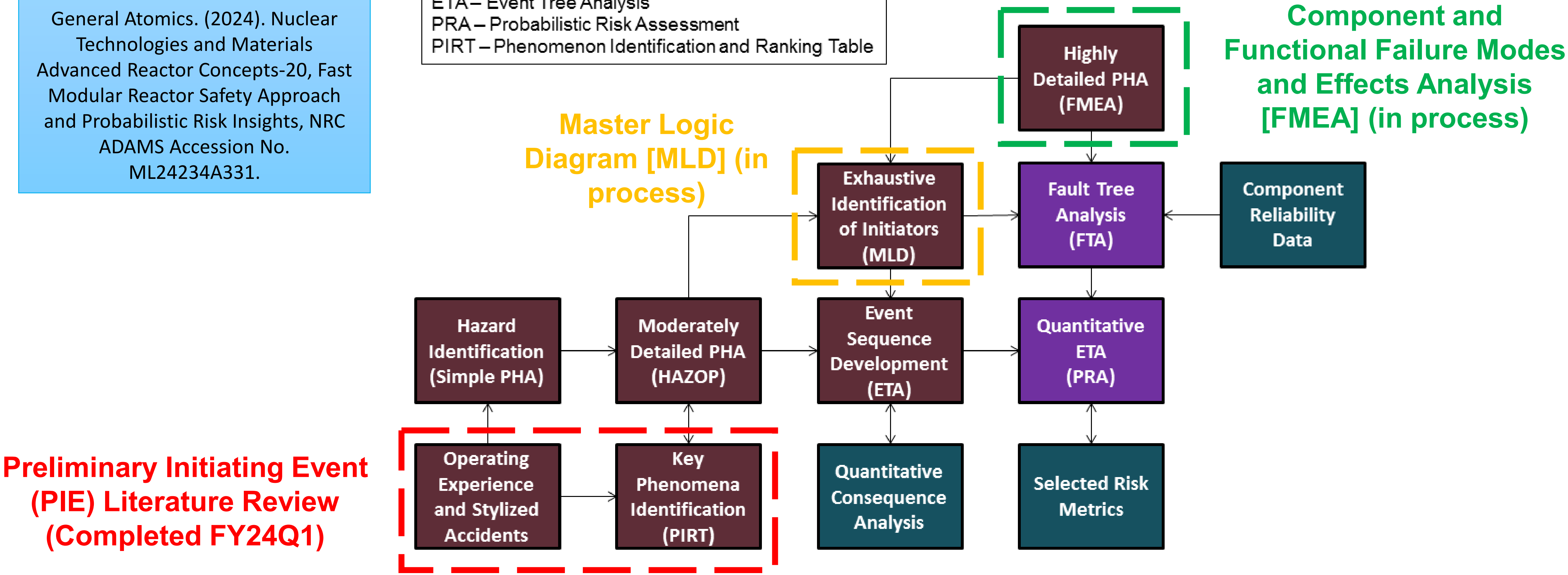
As documented within:

General Atomics. (2024). Nuclear Technologies and Materials Advanced Reactor Concepts-20, Fast Modular Reactor Safety Approach and Probabilistic Risk Insights, NRC ADAMS Accession No. ML24234A331.

Acronyms:
PHA – Process Hazards Analysis
FMEA – Failure Modes and Effects Analysis
MLD – Master Logic Diagram
FTA – Fault Tree Analysis
HAZOP- Hazards and Operability [study]
ETA – Event Tree Analysis
PRA – Probabilistic Risk Assessment
PIRT – Phenomenon Identification and Ranking Table

- [purple] = Can be fully quantified
- [maroon] = Typically qualitative/semi-quantitative
- [teal] = Supports quantitative risk assessment



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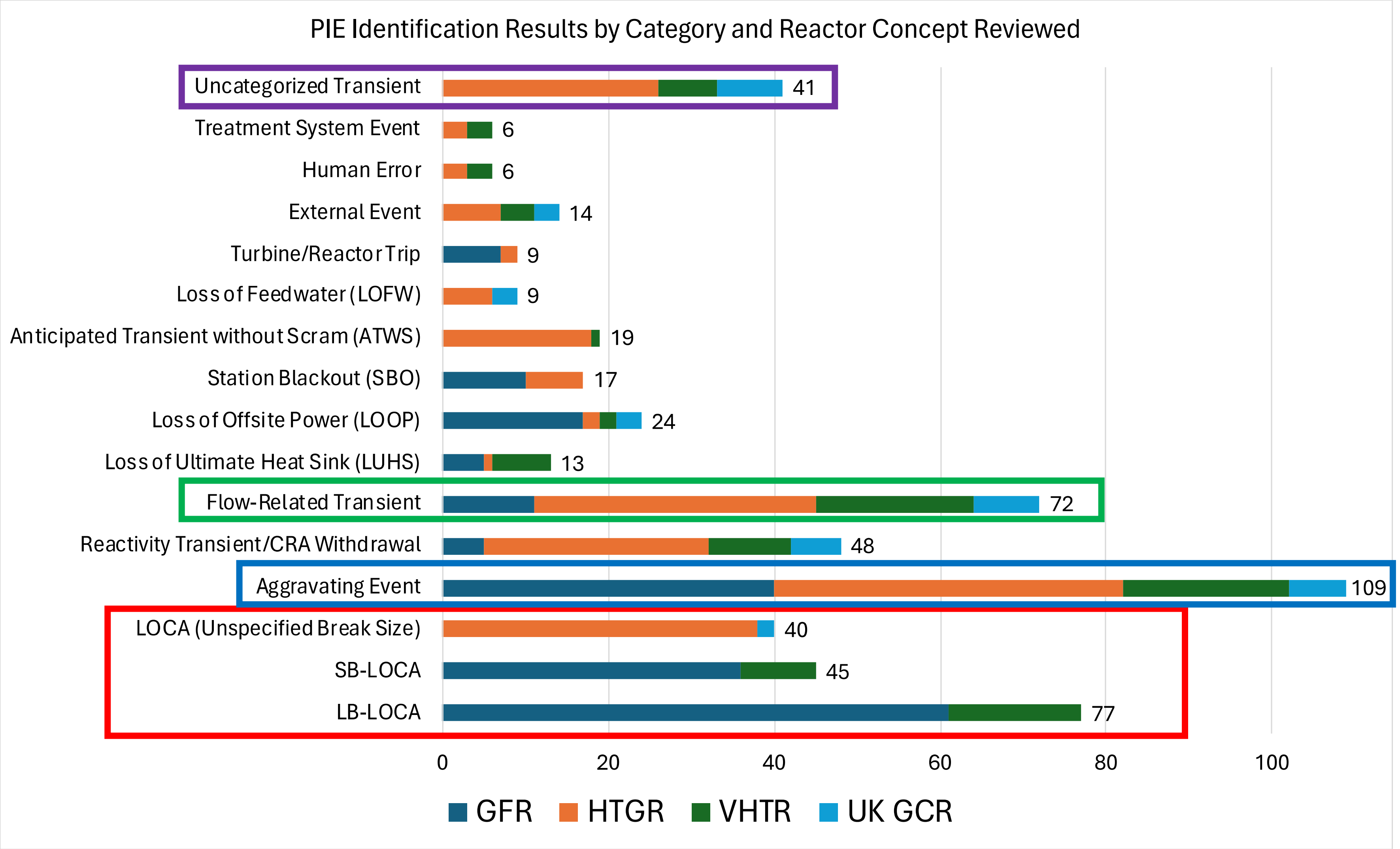
GA FMR Results by Category and Reactor Concept



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

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

Lessons Learned

Methodology Insights (1 of 2)

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- Early SiD methods offer a risk-informed* approach for assessment of early-stage advanced reactor design risk and operability
  - Can be performed incrementally and iteratively
- These qualitative and semi-quantitative hazard/risk assessments can help:
  1. Incorporate safety into the design process
  2. Identify operability issues for design attention
  3. Incrementally build safety case
  4. Identify/prioritize necessary research and development

*The term "risk-informed" used here is consistent with NEI 18-04, *Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development*, and NUREG 1.233, *Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors*

Methodology Insights (2 of 2)

- It will be important to plan for when iterations of safety analyses are to be done throughout the project cycle. Aspects to be considered include:
  - How often?
  - What triggers "for cause" re-appraisals (e.g., design changes)
  - Progression of safety analysis tools as the design matures
  - Alignment of SiD iterations to:
    - Stages in the design process, and/or
    - Technology Readiness Level (TRL) determinations

Thanks to:

- Kairos Power
- Southern Company
- General Atomics
- Flibe Energy
- Oak Ridge National Laboratory
- UCLA (B. John Garrick Institute for the Risk Sciences)

The People Who Helped Us Refine the Methodology (along with others)

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