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Application of a Method to Estimate Risk in Advanced Nuclear Reactors

A Case Study on the MSRE

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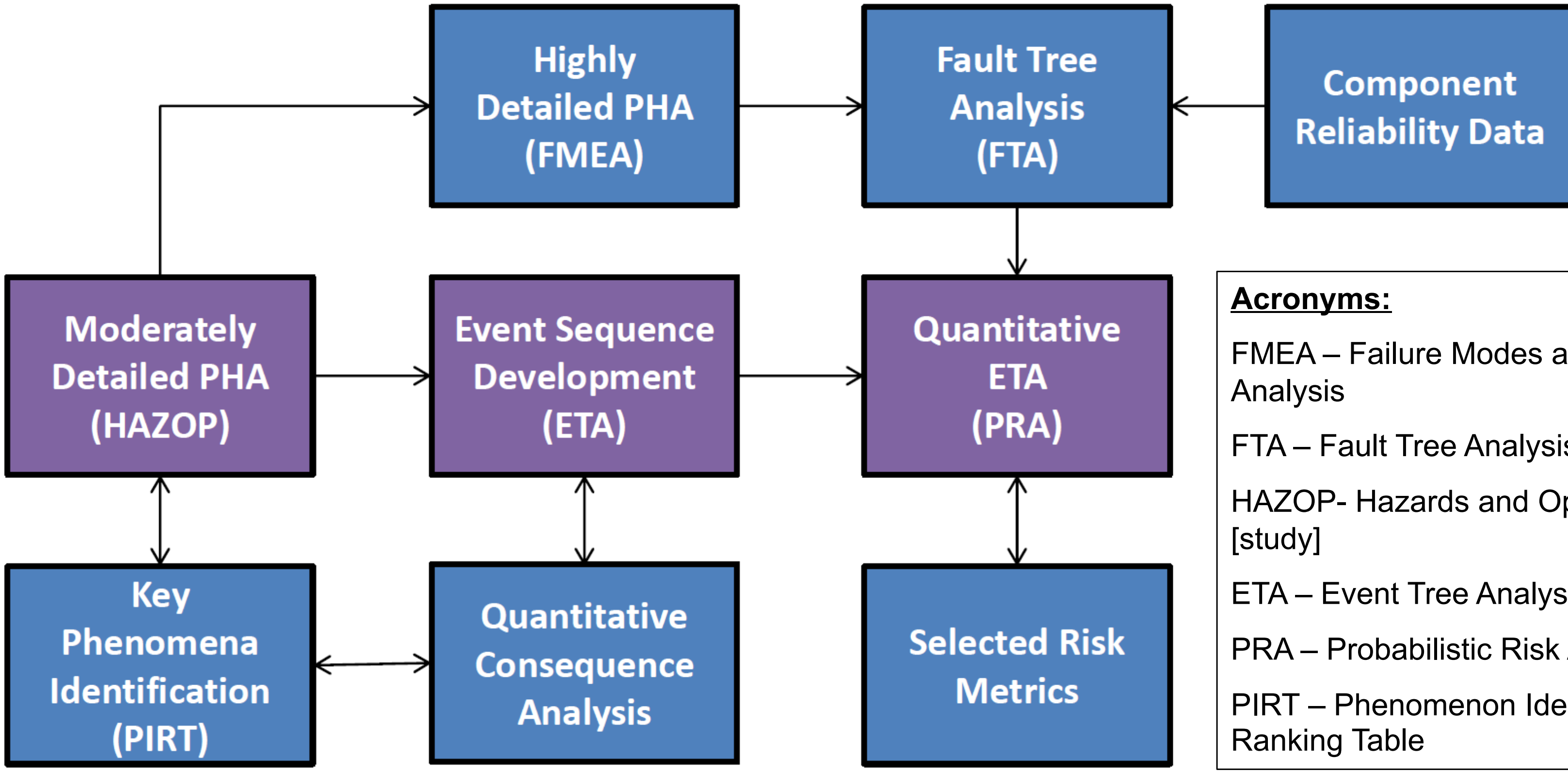
Introduction

- Reactor developers seeking advanced reactor design certification and/or licensing face challenges in efficiently demonstrating their safety case in that the designs:
  - have limited to no commercial operating experience
  - incorporate many novel design elements
  - may have unique radioactive material inventories
- Consistent with a long-stated objective of the industry and the NRC, industry has initiated a number of activities to get NRC endorsement of a risk-informed, performance-based process to help gain this efficiency.
- As part of EPRI's PHA-to-PRA project, a methodology is being developed to shape the PHA process to support developers in executing the proposed industry approach.
  - PHA methods are a technology-neutral and industry-standard tool that allow for an iterative approach to identify hazards in a process or a design
  - The methodology influences and coordinates with other established elements of safety analysis essential for the development of the nuclear safety design and licensing basis
  - Early safety evaluations serve as building blocks for more extensive risk assessments

PHA-to-PRA Methodology



Acronyms:

FMEA – Failure Modes and Effects Analysis

FTA – Fault Tree Analysis

HAZOP- Hazards and Operability [study]

ETA – Event Tree Analysis

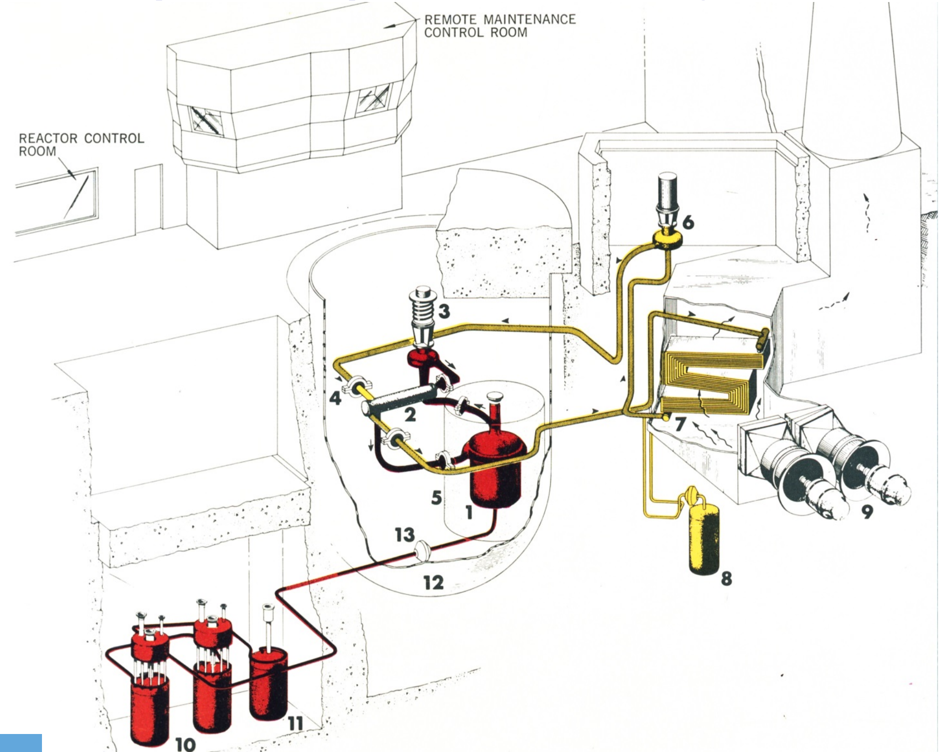
PRA – Probabilistic Risk Assessment

PIRT – Phenomenon Identification and Ranking Table

Molten Salt Reactor Experiment (MSRE) Case Study

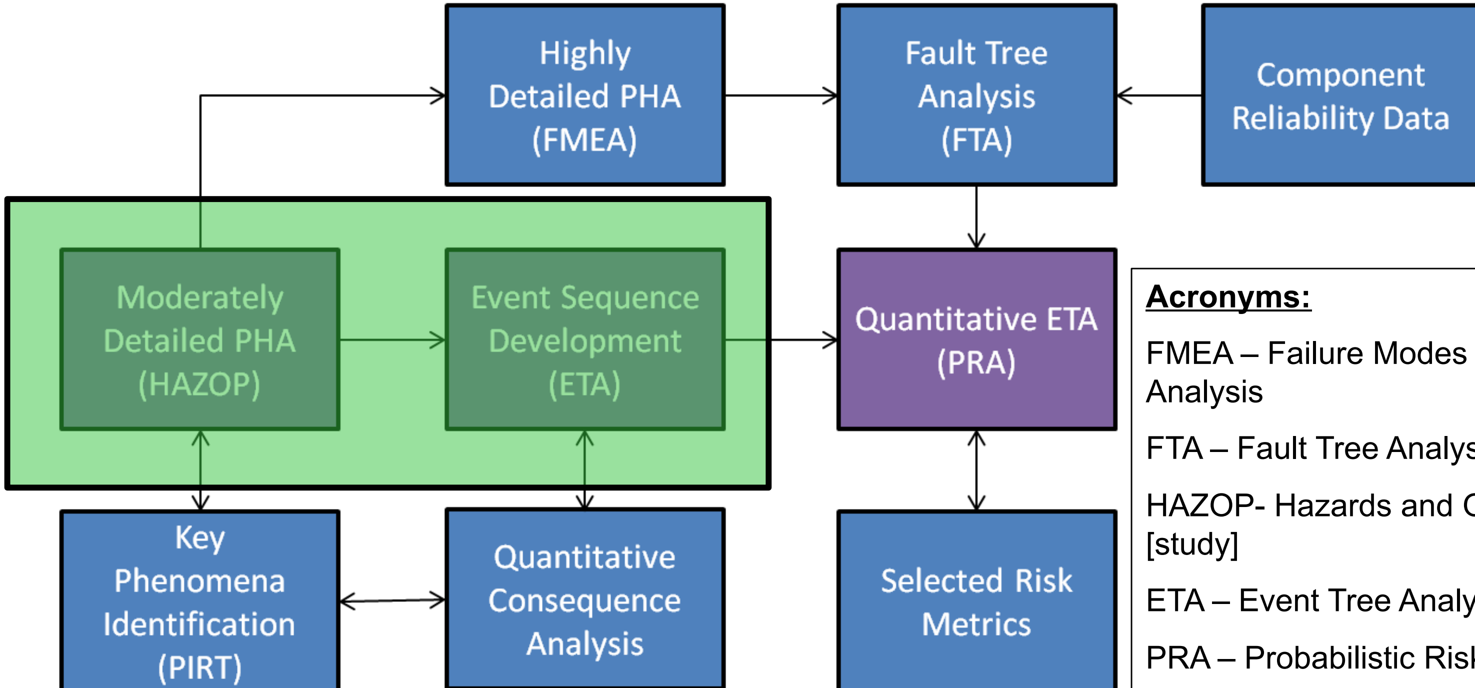
- Phase II of PHA-to-PRA project
- MSRE operated from 1965 to 1969 at ORNL (max power = 8 MW_{th})
  - Liquid (dissolved) fuel design
  - Graphite moderated, thermal-spectrum
  - Fluoride-based (FLiBe) fuel and coolant salts
  - Completed runs using ^{235}U and ^{233}U fuels
- PHA studies completed of each major inventory of radioactive material:
  - **Fuel salt loop**
  - **Off-gas system (handled gaseous fission products)**
  - **Fuel processing system (batch process)**

Extensive design, testing, and operations information available



1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

PHA-to-PRA Methodology: HAZOP to Qualitative ETA



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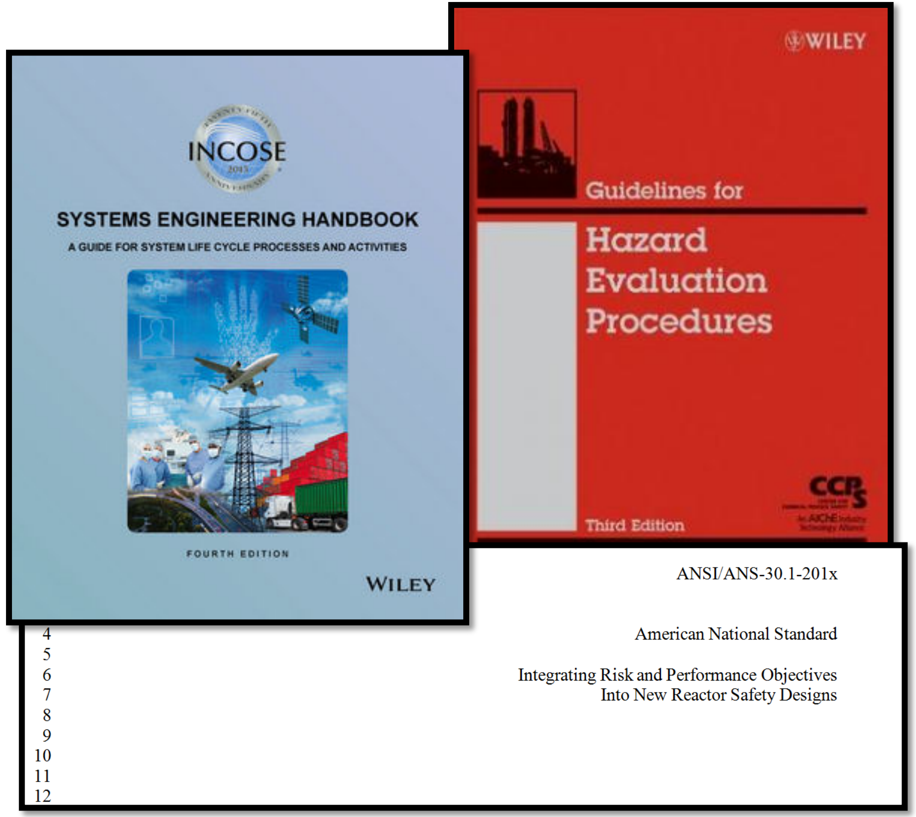
Preparing for PHA: System Characterization

- Identify major hazardous material inventories
  - Hazards could be radiological or chemical in nature
  - Important to understand amount and form of material
  - Can help prioritize first nodes to be analyzed
- Define and understand nodes for PHA studies
  - Functional decomposition is useful
  - Imperative to give adequate attention to interfaces between nodes
- Develop list of important hazards to be considered
  - Goal is to capture phenomena that could challenge barriers to release of hazardous material



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Primary PHA Method: Hazards and Operability (HAZOP) Study

- A HAZOP study is a structured and systematic technique to identify potential hazards and operability problems
  - Guided by assumption that safety-significant incidents represent deviations from normal operating conditions
- Combines available design and operational information with expert input in a structured, documented fashion
- Referenced in draft ASME non-LWR PRA Standard and accepted by NRC and DOE as a method to comprehensively identify system hazards
- Objective is to document specific operational deviations, which each deviation corresponding to a row in HAZOP table
- All meaningful deviations are discussed and recorded within each subsystem or node

NODE: 1.0 DATE REVIEWED: 29-30 Nov 2017

ITEM: Off-Gas Handling
Fig. 5.3 in ORNL-TM-728
Fig. 6.1 in ORNL-TM-728
Fig. 12.1 in ORNL-TM-728
Fig. 8.2 in ORNL-TM-3039

This node handles three different types of gas flow:
1) the continuous flow of helium containing highly radioactive FP gases swept from the fuel salt pump bowl
2) intermittent, relatively large flows of helium containing significant amounts of radioactive gases and particulates associated with salt transfer operations
3) flows of up to 100 cfm of very low activity cell atmosphere gas discharged through the stack filter bank to maintain the reactor and drain tank cells at sub-atmospheric pressure

The first two gas flows are held in piping for about two hours for the short-lived isotopes to decay. Then they pass through activated charcoal to remove all radioactive isotopes except for Kr-85, Xe-131m, and Xe-133. After the charcoal beds, all three gas streams combine and then passes through absolute and roughing filters to remove particulates before being diluted with atmospheric air and discharged through the stack.

Important interfaces for this node include:
a) radioactive gas flows in from the fuel salt pump bowl
b) radioactive gas flows in from the fuel salt drain tank
c) cell atmosphere flows in from the reactor cell
d) heat is removed from the charcoal beds by the cooling water system
e) the effluent gas is exhausted to the atmosphere

Note: Capped and valved off sample and TVC ports were installed in the system and were available for line cleanout

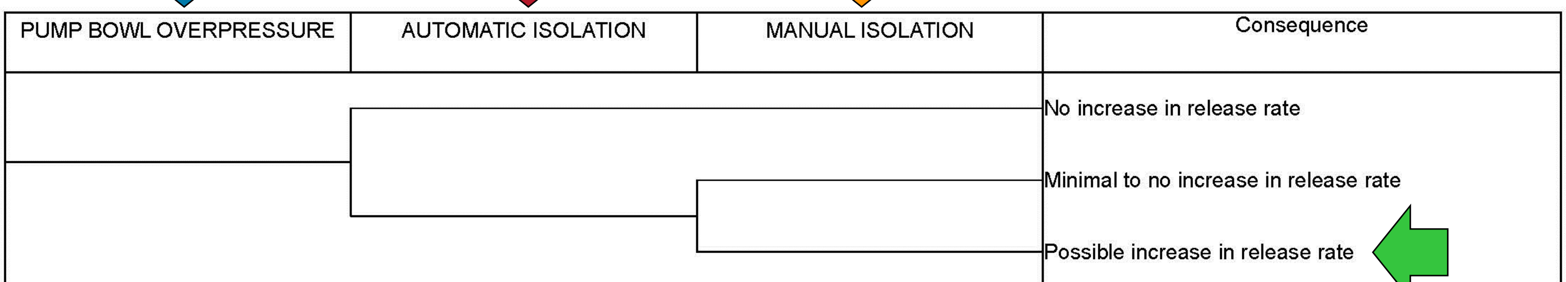
DRAWINGS AND DOCUMENTS
ORNL-TM-728 "MSRE Design and Operations Report Part I: Description of Reactor Design"
ORNL-TM-729B "MSRE Design and Operations Report Part IIB: Nuclear and Process Instrumentation"
ORNL-TM-3039 "MSRE Systems and Components Performance"

DEVIATION	CAUSE	CONSEQUENCE	SAFETY SYSTEMS	ACTION
Temp Increase	Failure of charcoal bed cell cooling water system (holdup volume and main charcoal beds)	Possible damage to beds from overheating Reduction in adsorber effectiveness, increased radioactivity of effluent	Thermocouples are installed at three locations on each of the main charcoal beds (one thermocouple on aux charcoal bed) to measure gas temperature Gas flow can be switched to aux charcoal bed	Investigate cooling of aux charcoal bed

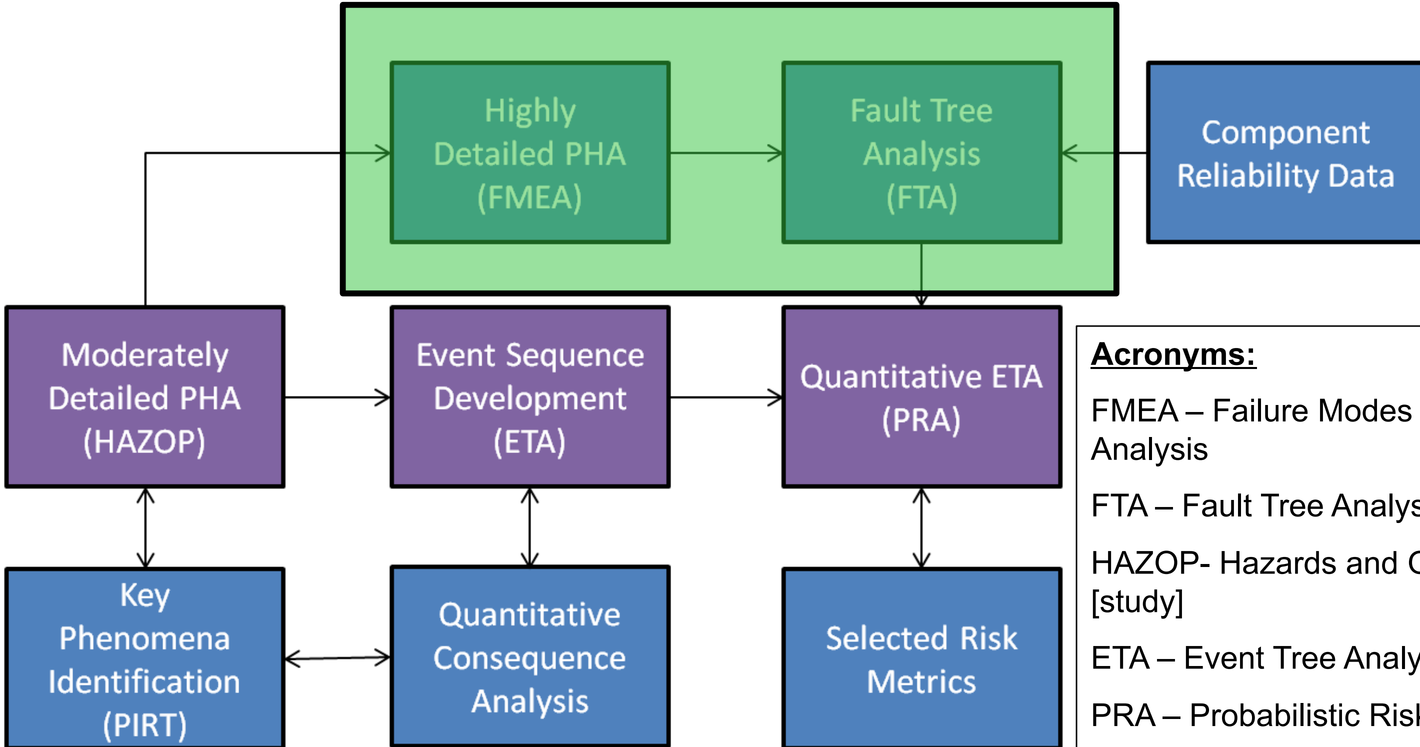
(continued on next page)

Creating Qualitative Event Trees from HAZOP Results

Deviation	Cause	Consequence	Safety System(s)
Pressure Increase	High fuel salt pump bowl cover gas pressure (e.g. flow control valve failure)	• Increased off-gas flow through entire system (VH-1, particle trap, VH-2, charcoal bed) • Increased carryover from fuel salt pump bowl • Decreased residence time in VH-1, VH-2, and charcoal beds	• Pressure indications in fuel salt pump bowl (PT-522/592) • Temperature indications throughout system (TE-522-1, TE-524-1, TE-556-1A) • Radiation monitors downstream of charcoal beds with automatic safety action (RM-557-A/B) • Manual valves available to isolate off-gas flow (V522, V620-627, V557B)



PHA-to-PRA Methodology: FMEA to Qualitative FTA



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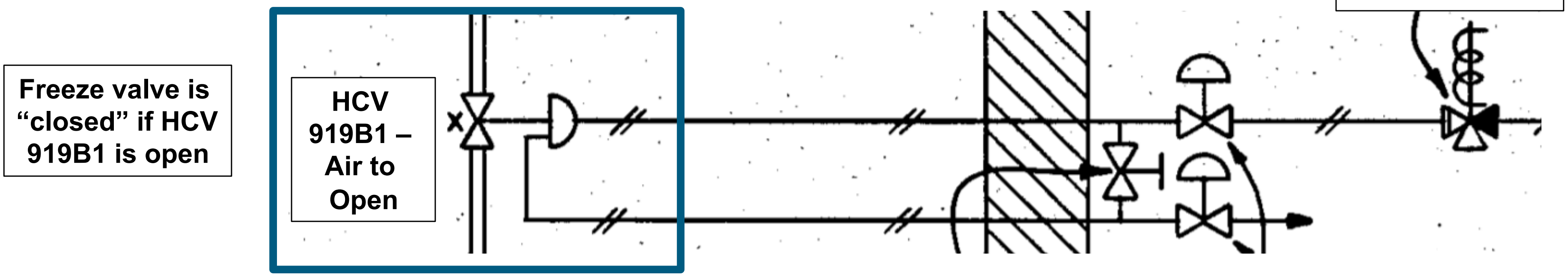
Failure Modes and Effects Analysis

- FMEA evaluates the ways equipment can fail (or be improperly operated) and the effects these failures can have on a system
  - Particularly applicable to systems consisting of mostly mechanical and/or electrical components
- Analysis considers potential consequences and relates them to potential equipment failures
- Each individual failure is considered as an independent occurrence, with no relation to other failures
  - Except for the subsequent effects that it might produce
  - In some circumstances, common cause failures may be considered



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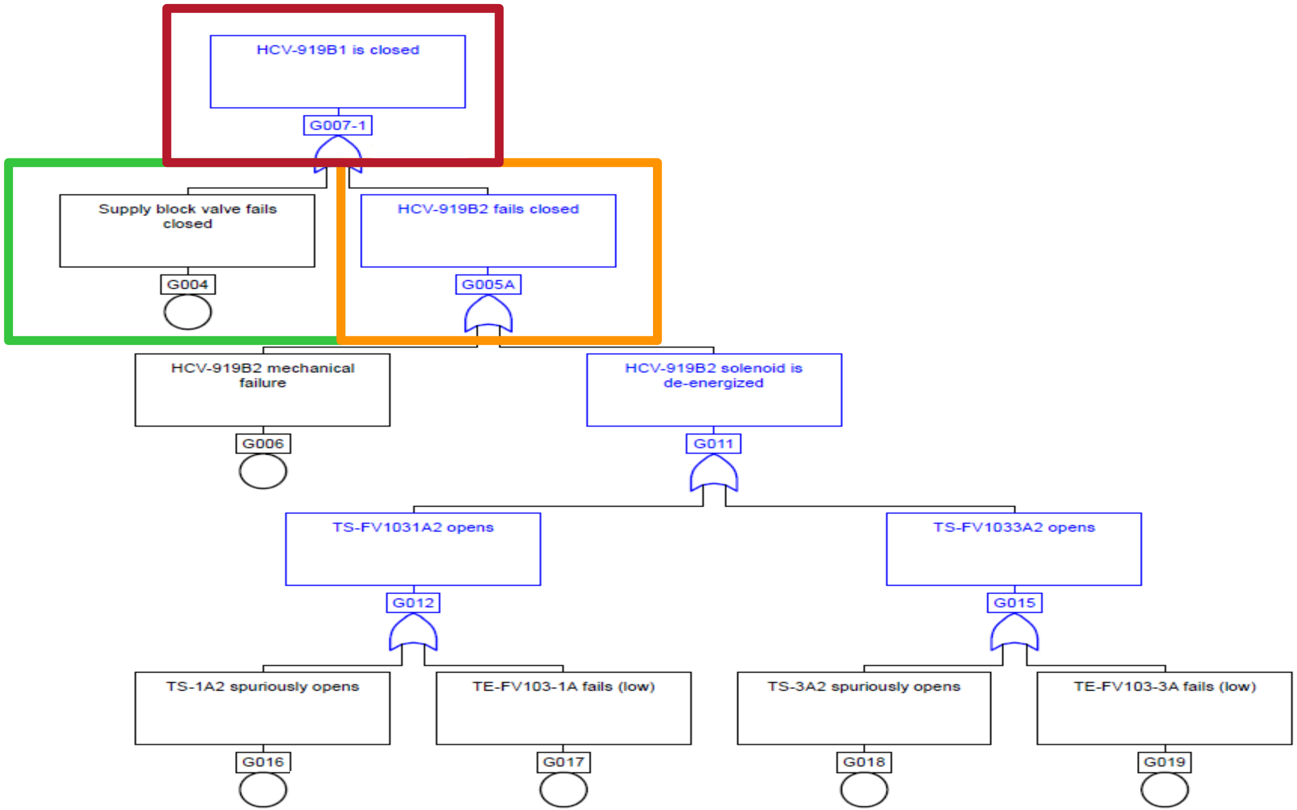
FMEA Results

Identification/ Description	Failure Mode	Effect	Safety Systems
"Supply" block valve for HCV-919B1 (normally open)	Spuriously closes	Closes HCV-919B1, securing 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, securing 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, secures 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	TE-1B and TE-3B are displayed on recorder in aux control room

FTA Model



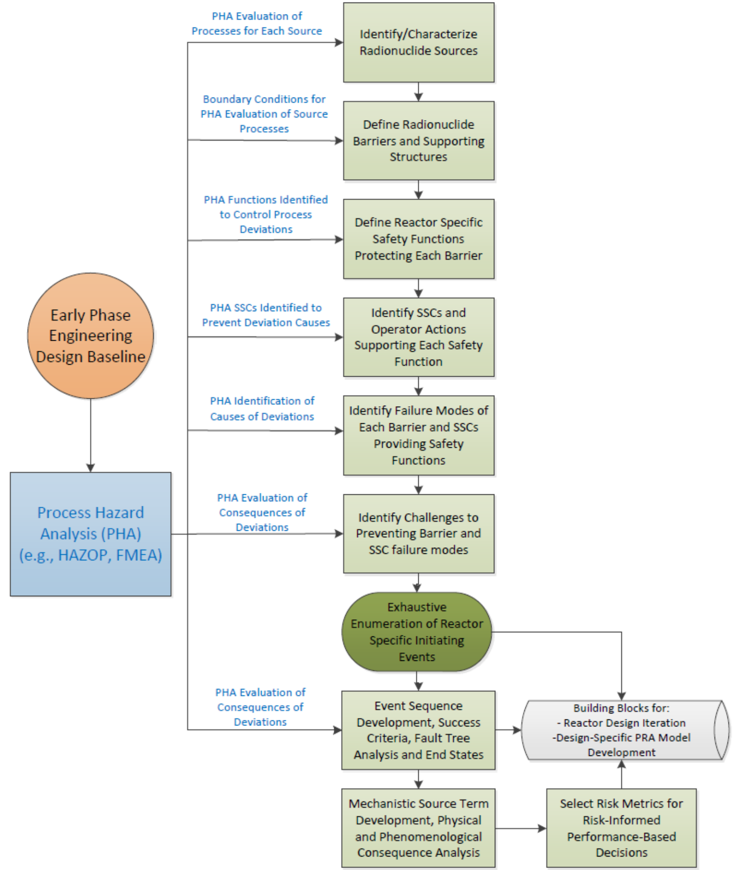
HCV-919B1 is closed
G007-1
Supply block valve fails closed
G004
HCV-919B2 fails closed
G005A
HCV-919B2 mechanical failure
G006
HCV-919B2 solenoid is de-energized
G011
TS-FV1031A2 opens
G012
TS-FV1033A2 opens
G015
TS-1A2 spuriously opens
G016
TE-FV103-1A fails (low)
G017
TS-3A2 spuriously opens
G018
TE-FV103-3A fails (low)
G019

Preliminary Conclusions

- Industry-standard PHA techniques are useful tools to begin investigating the safety and reliability of non-LWR systems early in the design process
  - Moderately detailed methods (such as HAZOP studies) are well-suited for characterizing event sequences of interest
  - Highly detailed methods (such as FMEA) are well-suited for developing fault tree models
- Good systems engineering practices are beneficial in preparing a system design to be analyzed
  - The results of system characterization can also promote a more thorough understanding of the design
- The preliminary methodology being developed produces building blocks that will eventually be used to build a PRA model of an MSR

Relationship to Licensing Modernization Project (LMP)

- Southern Company Services plans to use the MSRE case study results as a basis for LMP table top exercise with NRC
- Envision use of preliminary quantitative assessments as a potential basis to demonstrate:
  - selection of risk metrics
  - evaluation of licensing basis events (AOOs, DBEs, BDBEs)
  - screening selection of safety-related SSCs



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U.S. Department of Energy

Southern Company

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Backup Slides

MSRE Case Study Related Work to Date

- Preliminary Reliability Analysis of Molten Salt Reactor Experiment Freeze Valves – *Accepted for presentation at 2018 Winter ANS Meeting*
- Application of a Method to Estimate Risk in Advanced Nuclear Reactors: A Case Study on the Molten Salt Reactor Experiment – *Accepted for presentation at PSAM14*
- A Technology Neutral Safety Assessment Tool for Advanced Reactors: Preliminary Hazard Assessment and Component Reliability Database for the Molten Salt Reactor Experiment – *Presented at ICAPP 2018*
- Licensing Basis Event Selection Case Study: The Molten Salt Reactor Experiment – *Presented at 2017 ORNL MSR Workshop, ORNL Technical Report to be published*
- Preliminary Risk Assessment of a Generalized Molten Salt Reactor Off-Gas System – *Presented at 2017 Winter ANS Meeting*

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