Licensing Basis Event Selection Case Study: The Molten Salt Reactor Experiment

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Outline

- Introduction
- Radionuclide Sources and Barriers to Release
- Reactor Specific Safety Functions
- Preliminary Initiating Event Grouping
- MSRE Event Sequences
- LBE Identification and Evaluation
- Conclusions

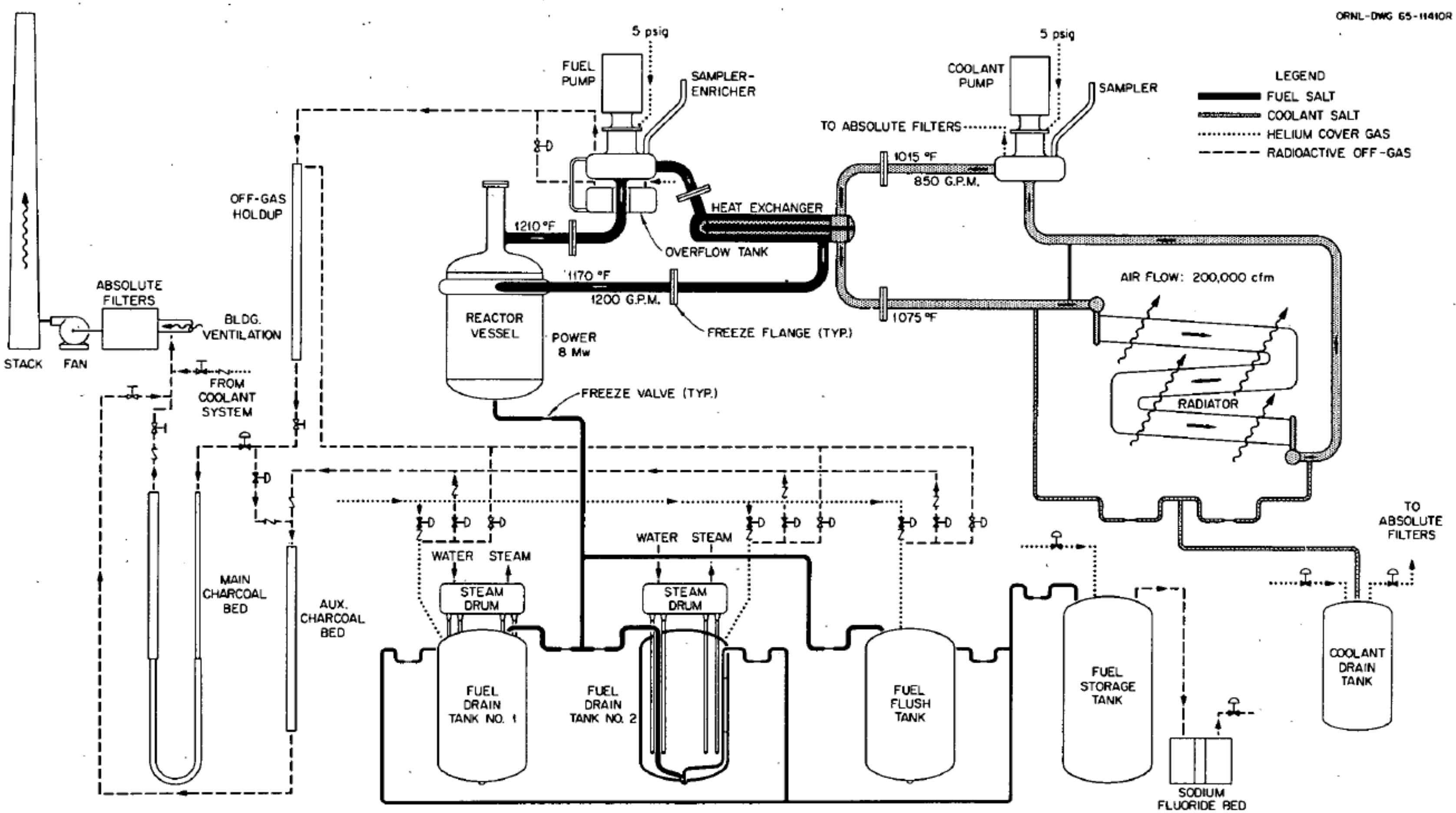
Introduction

Motivation and Background

Licensing Modernization Project

- DOE-Industry cost-shared project to provided end-user perspective on licensing technical requirements
- Technology Inclusive, Risk-Informed, Performance-Based guidance for non-LWRs with an intent to modernize:
  - Selection of Licensing Basis Events (e.g. Anticipated Operating Occurrences, Design Basis Events, Beyond Design Basis Events)
  - System, Subsystem, and Component (SSC) classification
  - Defense in Depth
- 4 discrete white papers to be issued and reviewed by industry and NRC
- Final RIPB guidance to be submitted for NRC endorsement will be compilation of these white papers with revisions from ongoing discussions incorporated

The Molten Salt Reactor Experiment



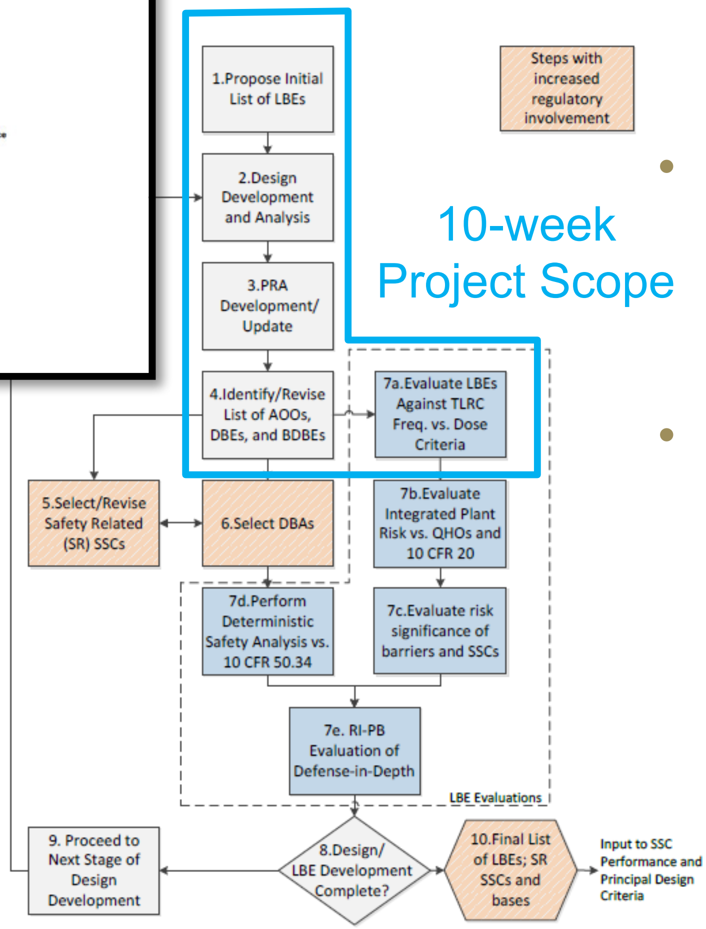
LMP LBE Selection Process


Modernization of Technical Requirements for
Licensing of Advanced Non-Light Water Reactors

Selection of Licensing Basis Events
Draft Report Revision 0

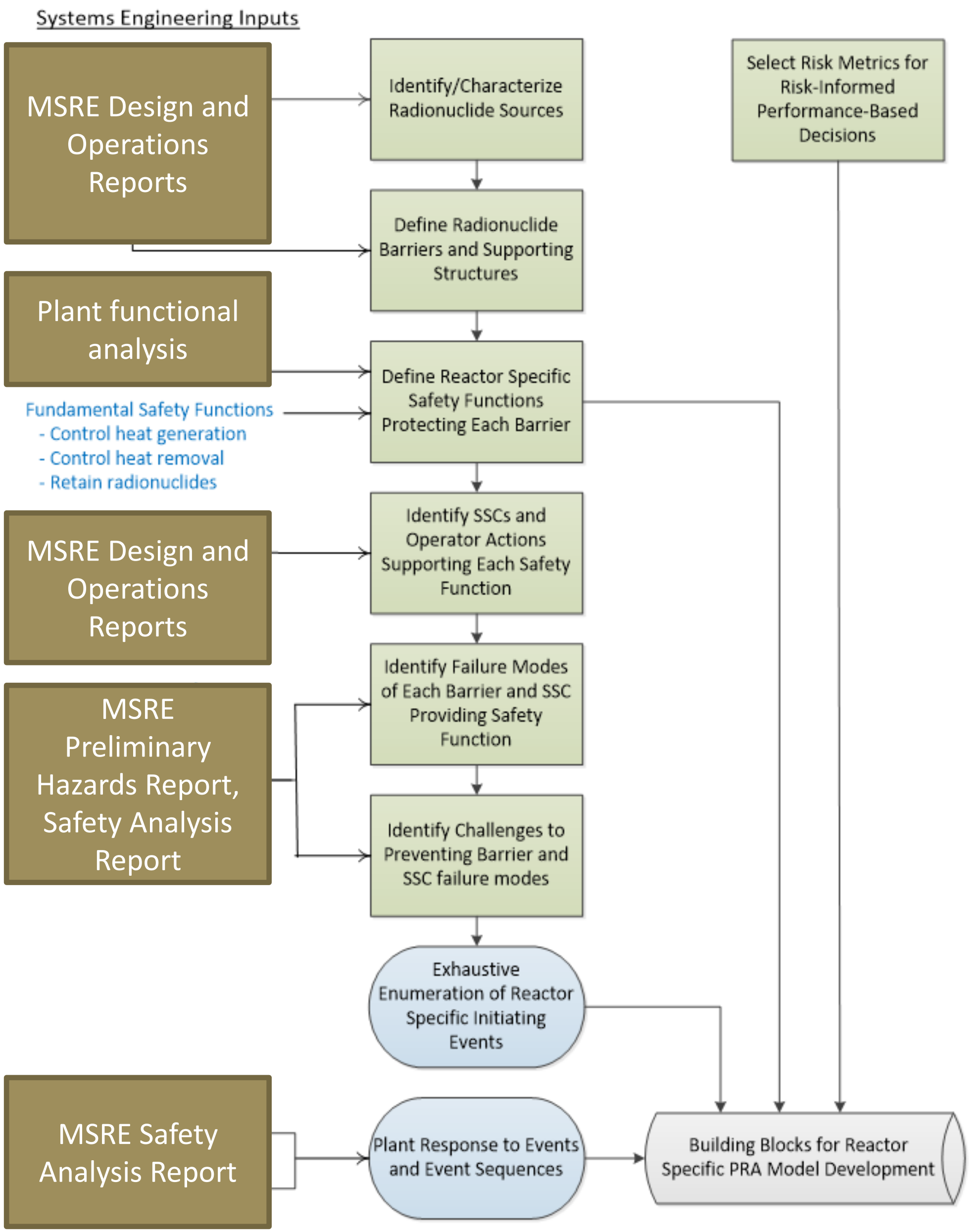
Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

April 2017

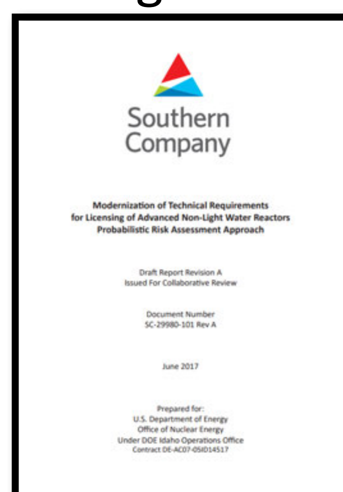


- A Risk-Informed technology-neutral framework for identifying Licensing Basis Events (i.e. AOOs, DBEs, BDBEs) has been suggested by LMP
- Examples can be found in the LBE Selection white paper regarding application to HTGR and SFR
- Project Objective: Investigate applicability of suggested process towards MSRs using MSRE literature, especially:
  - Preliminary Hazards Report
  - Safety Analysis Report
  - Other Design and Operations Reports

Preliminary MSRE PRA Development



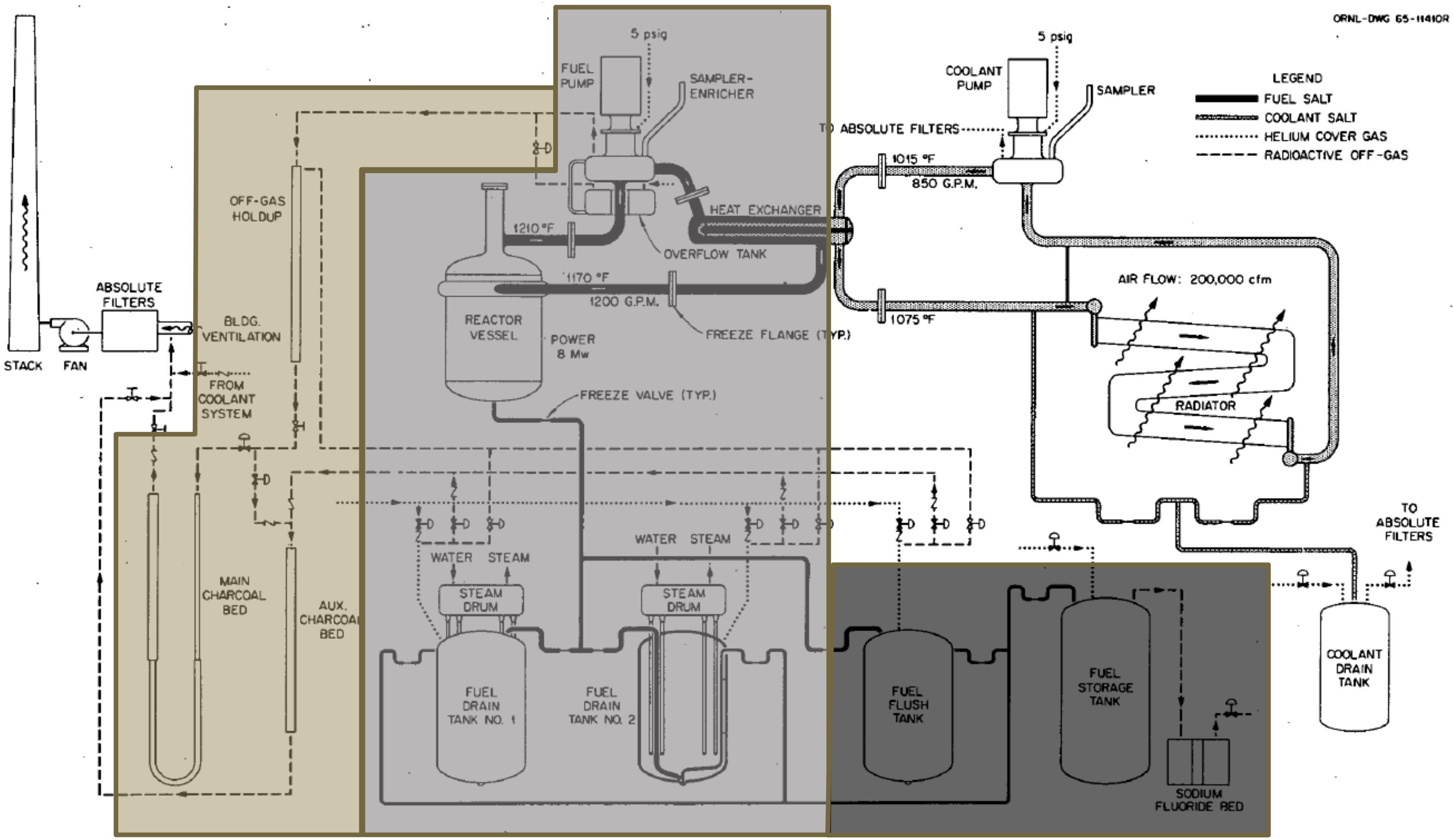
- The approach to developing a preliminary PRA is discussed in a separate LMP white paper
- The systems engineering inputs were identified from the ORNL database of MSRE literature and analyzed/documented to provide insight at each step



Radionuclide Sources in the MSRE

And Barriers to their Release

MSRE Source Term Identification

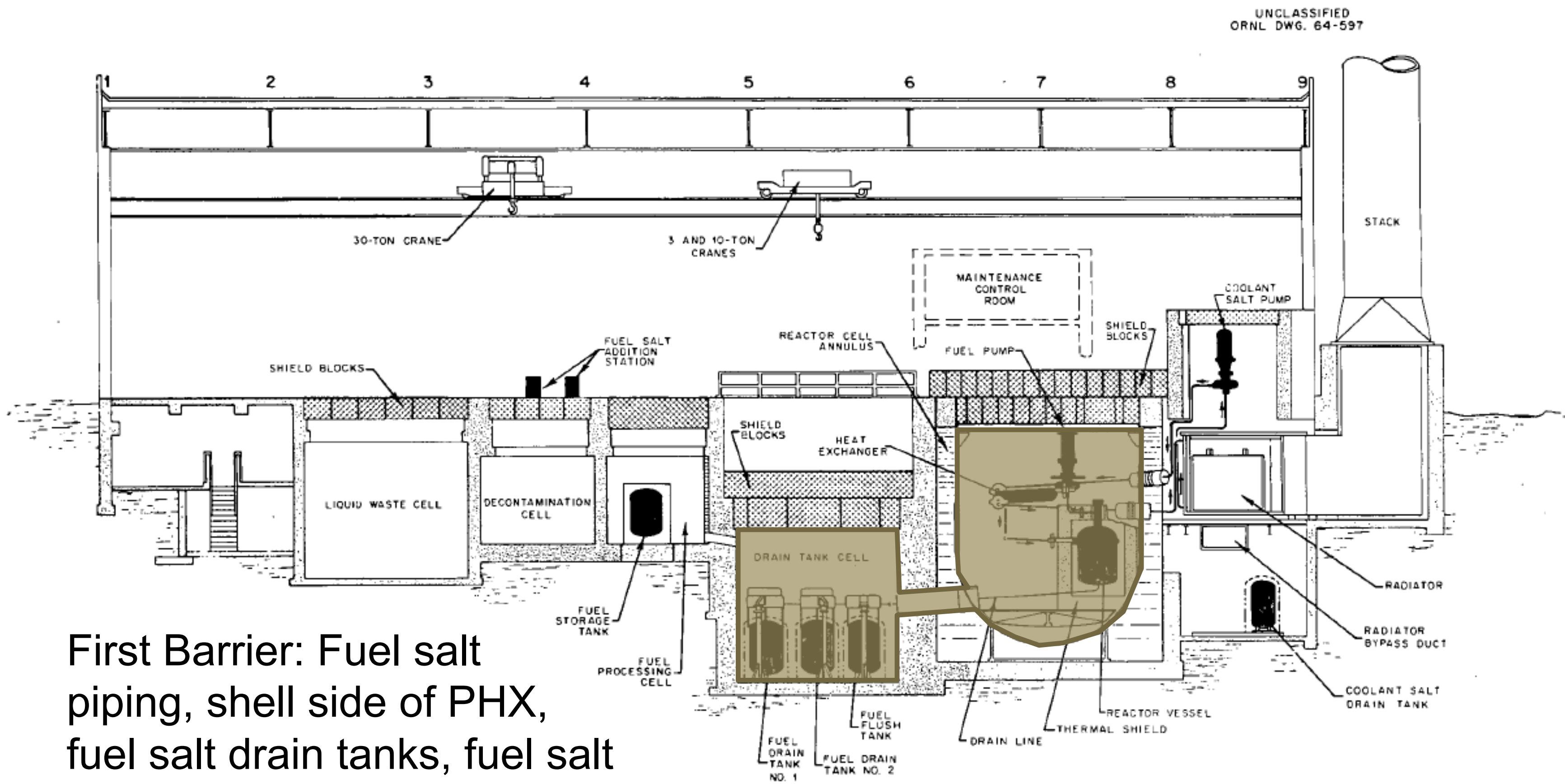


Off-gas System | Fuel Salt System | Salt Processing and Handling

Major MSRE Source Terms

1. Fuel Salt System
   - 10-30 million curies
   - Salt seekers (e.g. Sr, Y, Zr, I, Cs, Ba, Ce) – 59 wt%, soluble
   - Noble metals (e.g. Nb, Mo, Ru, Sb, Te) – 24 wt%, migrate to various surfaces
2. Off-gas System
   - ~280 curies/**<u>sec</u>** from pump bowl into off-gas line
   - Noble gases (Kr and Xe) – 17 wt%, slightly soluble gases
   - Some iodine
   - Decay daughters of noble gases
3. Fuel Processing and Handling Equipment
   - Fuel salt is not processed until xenon has decayed (~1 million curies in total)
   - Fluorination volatilizes H, He, Se, Br, Kr, Nb, Mo, Tc, Ru, Te, I, Xe, U, Np and deposits these downstream of fuel storage tank

Fuel Salt System Barriers



First Barrier: Fuel salt piping, shell side of PHX, fuel salt drain tanks, fuel salt pump

Second Barrier: Seal welded containment structure

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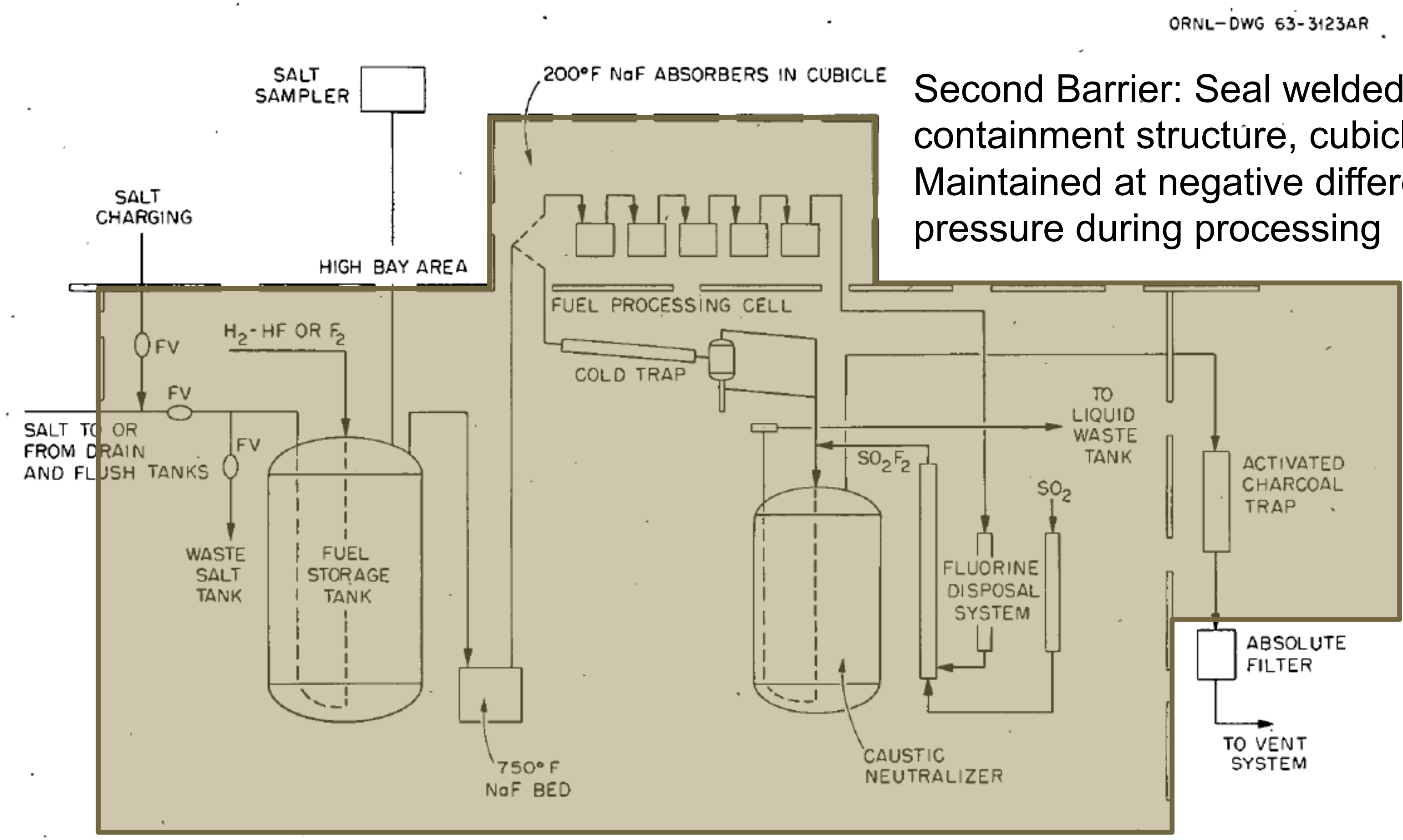
Fuel Processing and Handling Barriers



Second Barrier: Seal welded containment structure, cubicle. Maintained at negative differential pressure during processing

Figure 2.2. MSRE Fuel-Processing System.

Off-gas and Other Barriers

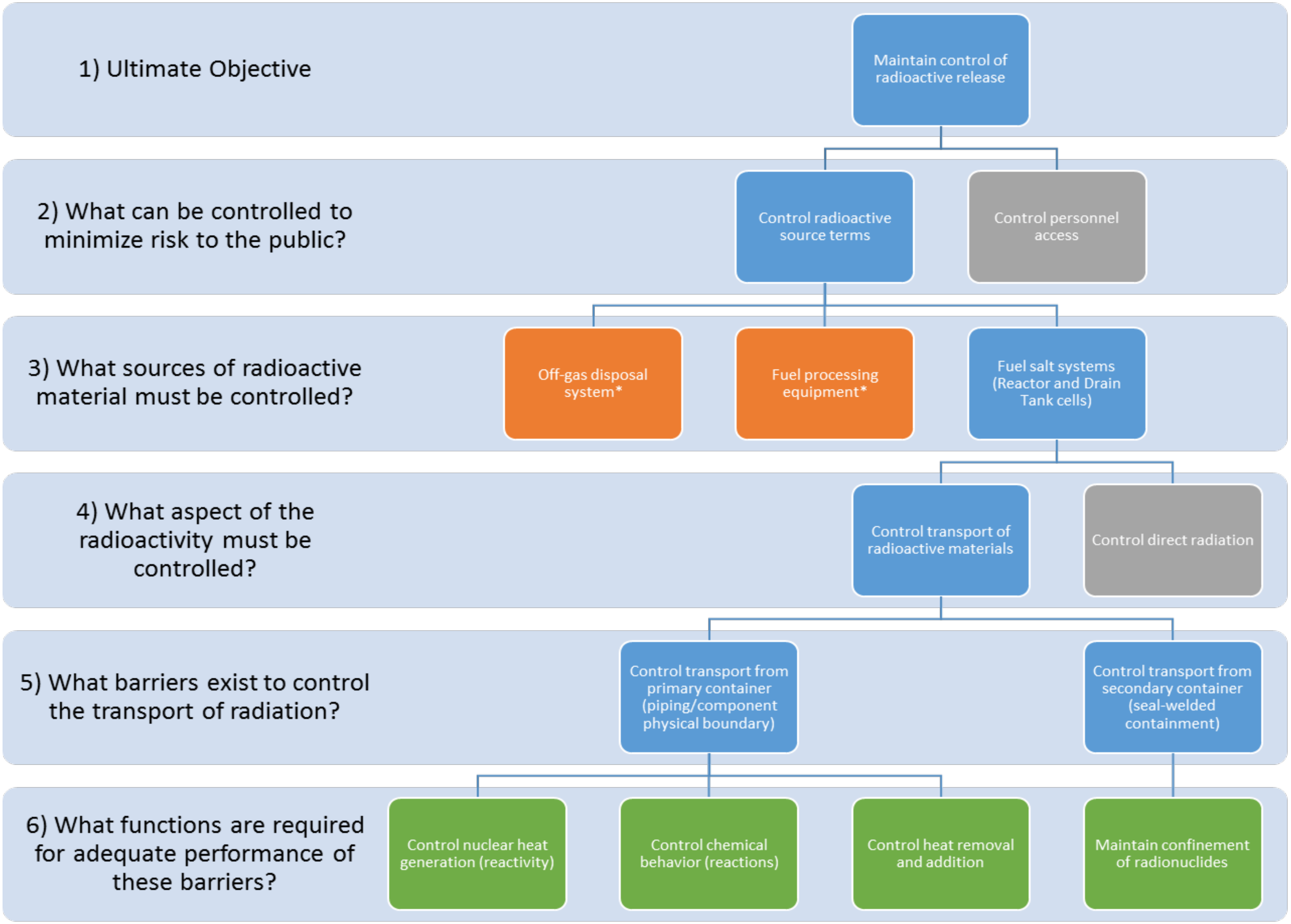
- The second barrier to release for the off-gas system is composed of different structures in different locations around the MSRE building
  - Off-gas line starts in reactor cell
  - Passes through coolant salt areas encased in ¾-inch pipe
  - Passes through valves in pressure tight instrument box in vent house
  - Reaches charcoal bed cell via underground shielded duct
  - **Note:** in the case of high radiation levels at outlet of charcoal bed cell, valves in line are only barrier before stack
- Other barriers to release
  - Vapor condensing system to reduce maximum pressure in reactor cell during Maximum Credible Accident
  - Containment ventilation system mitigates release of solid fission products

MSRE Specific Safety Functions

And the SSCs/Design Features supporting the Safety Functions

Defining MSRE Specific Safety Functions

Plant functional analysis approach similar to that conducted for MHTGR [DOE 1987]



*Note: Levels 4-6 are similar for the other sources, although not all safety functions may be required

MSRE Specific Safety Functions

Including the **3 fundamental functions** according to IAEA [IAEA 2012]:

1. **Control reactivity** – Reduce fission heat generation rate quickly enough to match heat removal capability
2. Control chemical behavior – Reduce and maintain the rate of any undesired chemical reactions (may weaken containment or produce heat) below acceptable rate
3. **Control heat removal** and addition – Provide enough cooling to prevent damage to primary containment in long-term without overcooling fuel salt
4. Control radionuclides within first barrier – maintain structural integrity of boundary
5. **Confine radionuclides** – No more than 1% leakage (1 cm^3 of salt) from secondary container per day

Examples of SSCs and Design Features Supporting the Safety Functions

Total set of SCCs/Design Features for all Safety Functions amounts to 5 pages

SSC/Design Feature Supporting "Control Reactivity" Safety Function	Active/Passive/Design Feature	Applicable Source Term(s)
Negative temperature coefficient (high salt thermal expansion)	Passive (A)	☒ Fuel Salt ☐ Fuel Processing ☐ Off-gas
Drain tank geometry: a concentration increase of fourfold is required for criticality in drain tanks (salt freezing increases concentration by only threefold), flooding drain tank cell does not produce criticality	Design Feature	☒ Fuel Salt ☐ Fuel Processing ☐ Off-gas
Gradual stoppage of pump and exponential decay of neutron precursors limits reactivity effect in core due to loss of fuel salt flow	Passive (C)	☒ Fuel Salt ☐ Fuel Processing ☐ Off-gas
Because MSRE operates in thermal spectrum, additional reflection is needed for criticality outside of the core	Design Feature	☒ Fuel Salt ☒ Fuel Processing ☐ Off-gas
Automatic insertion of poison by control system upon high neutron flux	Active	☒ Fuel Salt ☐ Fuel Processing ☐ Off-gas

Identification of Initiating Events

And Preliminary Grouping

Hazards and Initiating Events Discussed in MSRE Literature

- IEs considered for this work are those that occur during more common operating states (e.g. Operate-Run or Off, not during filling procedures)
- Majority of discussion in MSRE literature focuses on events that occur in fuel salt loop
- Examples:
  - Fuel salt pump failure
  - Coolant salt pump failure
  - Uncontrolled rod withdrawal
  - Concentration of fuel salt in core due to precipitation
  - Leakage from freeze valve or freeze flange

MSRE Preliminary Initiating Event Groups

List based on review of IAEA Level 1 PSA Guidance [IAEA 2010], PRISM and MHTGR examples, and FHR LBE workshop [Berkley 2013]

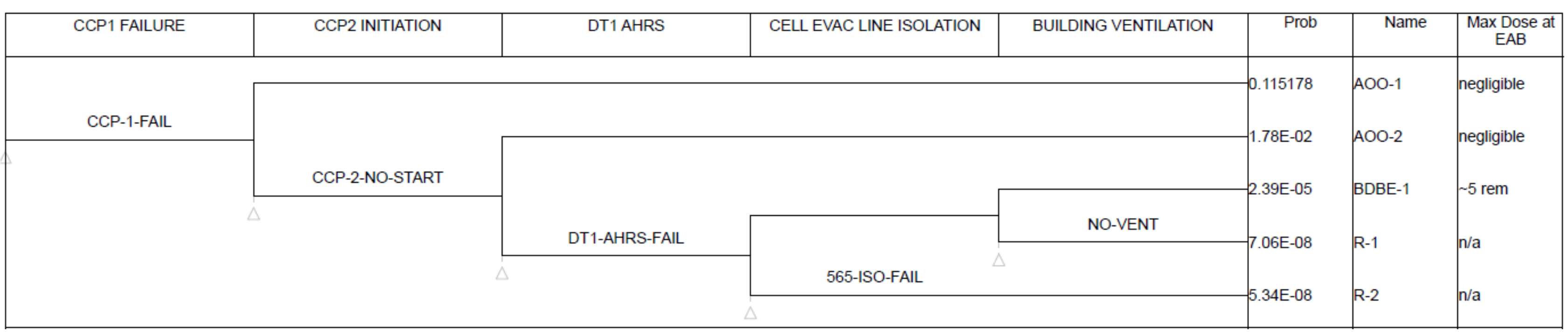
1. Increase in heat removal by coolant system
   - Inadvertent raising of radiator door
   - Radiator blower overspeed
2. Decrease in heat removal from fuel salt (or increased electrical heat addition)
   - Coolant salt pump failure
   - Plugging in coolant salt loop
   - Plugged drain line
   - Failure of drain tank afterheat removal system
   - External heaters over-temperature
   - Inadvertent load scram
3. Decrease in fuel salt flow rate
   - Fuel pump failure
   - Plugging in fuel salt loop
4. Reactivity and power distribution anomalies
   - Unexpected criticality during startup
   - Fuel separation
   - Collection of separated fuel material in reactor core
   - Cold slug upon pump start
   - Uncontrolled rod withdrawal
5. Leakage of substance through the first barrier
   - Heat exchanger leak
   - Heat exchanger tube rupture
   - Leak of drain tank heat removal system
6. Decrease in fuel salt inventory for a given volume
   - Inadvertent melting of freeze valve
7. Radioactive release from a subsystem or component
   - Leaking of freeze valve
   - Leaking/failure of freeze flange
   - Ignition of charcoal beds in off-gas system

LBE Identification

And Evaluation of Consequences

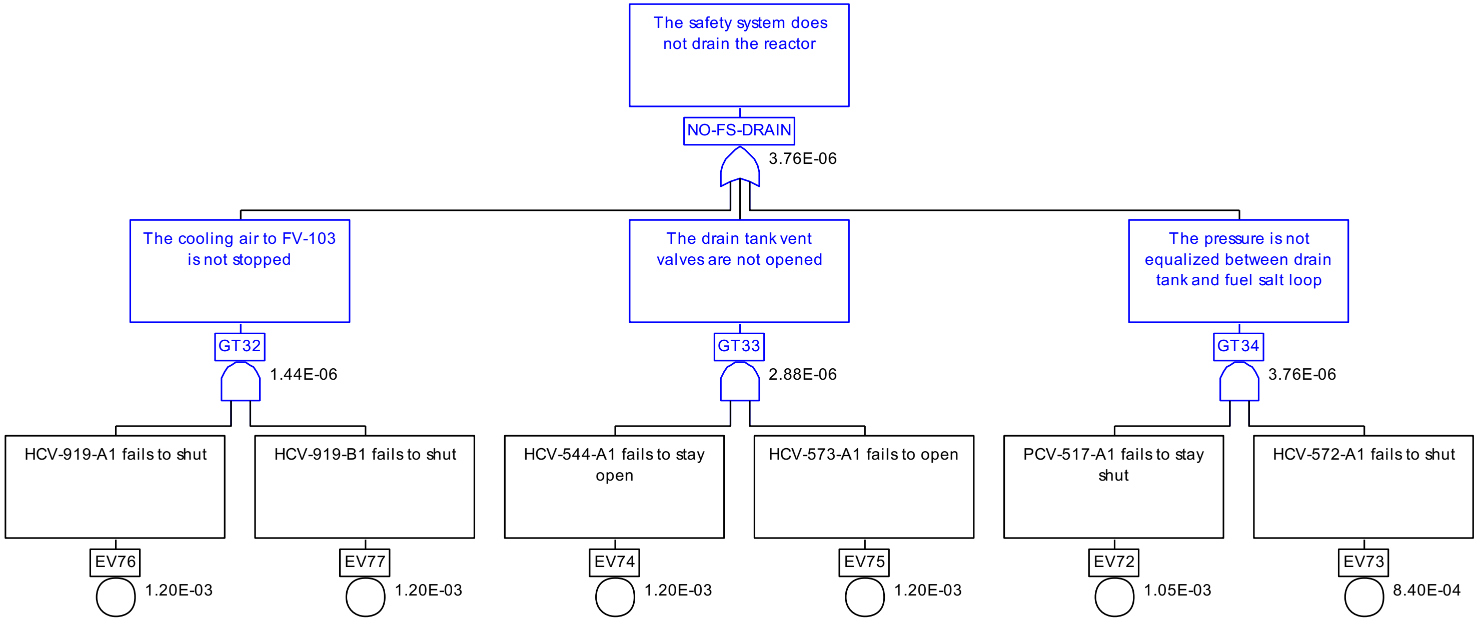
MSRE Event Tree Analysis

- A total of three initiating events were selected:
  - Component Cooling Pump (CCP failure) leading to inadvertent melting of freeze valve between reactor vessel and drain tank
  - Uncontrolled Rod Withdrawal
  - Leak in off-gas line from fuel salt pump
- Event trees and fault trees constructed and evaluated in off-the-shelf commercial software
- Consequences estimated from analysis in MSRE safety analysis report



MSRE Fault Tree Analysis

- Fault trees constructed to estimate probability for event tree gates
- Component reliability estimated from readily available engineering reports
  - Initiated compilation of MSR component reliability database
- Human reliability estimated based on order of magnitude indication in NRC handbook



LBE Selection Results

Sequence	Frequency (year^{-1})	Consequence
AOO-1	0.115	Negligible – no release
AOO-2	1.78E-02	Negligible – no release
DBE-1	1.18E-03	Negligible – no release
DBE-2	9.97E-03	Minimal
BDBE-1	2.39E-05	~5 rem max dose at EAB
BDBE-2	1.56E-06	Negligible – no release
BDBE-3	3.47E-06	Minimal
BDBE-4	2.22E-05	~100 rem max dose at EAB possible*

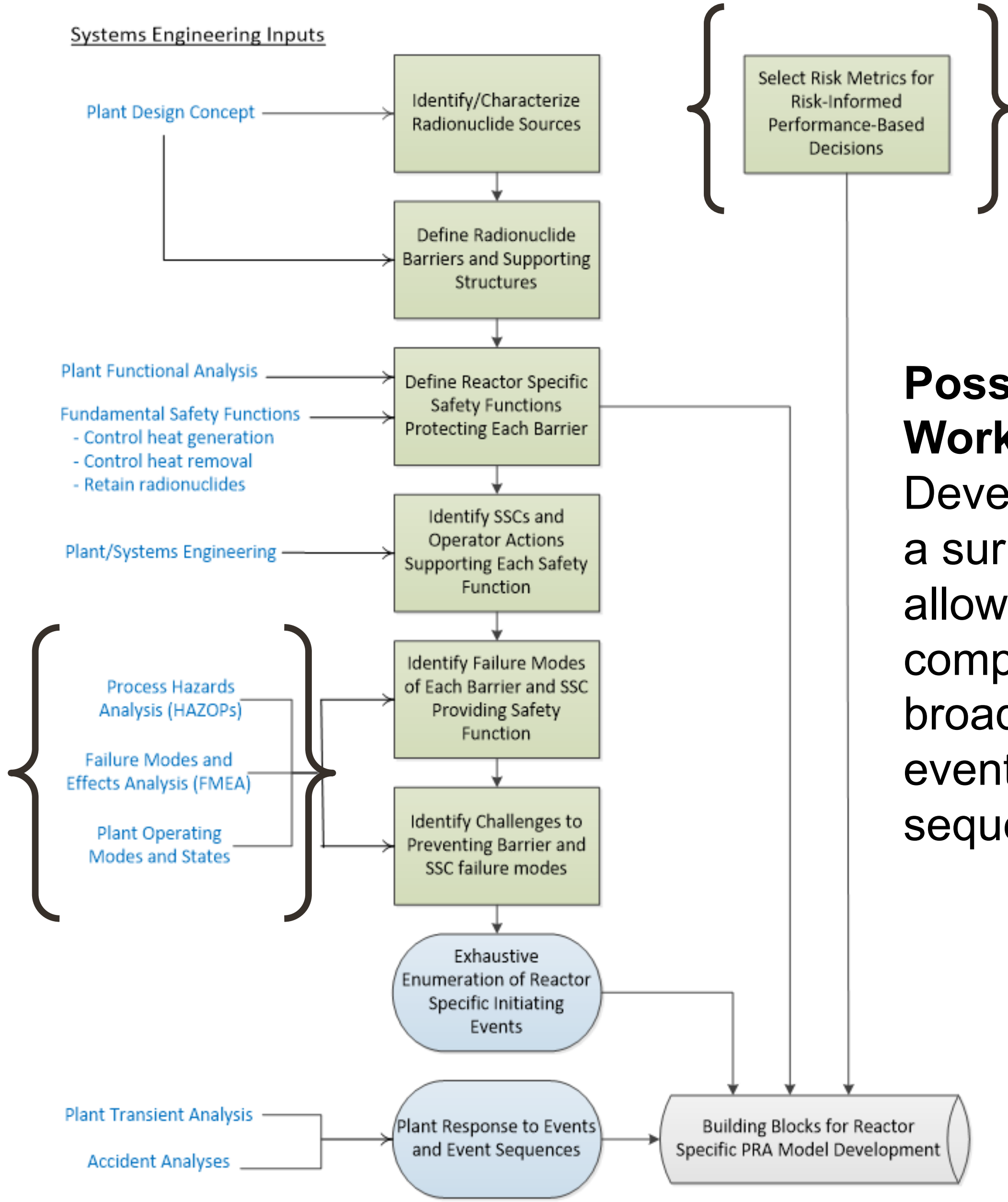
Note: The dose at the EAB due to an unmitigated leak in the off-gas system depends on the leak rate and duration and would likely be less than 100 rem. A dose of 100 rem at the EAB represents what was believed by the MSRE safety analysis to be a bounding scenario, but further analysis is required to more accurately estimate this dose.

Conclusions

LBE Selection for MSRs

Observations from MSRE PRA Development

Possible future work:
Perform industry standard PHA (e.g. HAZOP, FMEA) for MSRE to facilitate development of exhaustive list of IEs



Possible Future Work:
Development of a surrogate to allow for comparison of a broader range of event sequences

Major Conclusions

- 2 of 8 total event sequences have greater than "minimal" consequences
  - Not considered to be a representative sample of entire set of MSRE events
- Design insights
  - Systematic review of auxiliary systems revealed single barrier
  - Design change to avoid corrosion hazard (in drain tank afterheat removal system) added operational risk
- IEs in auxiliary systems can be risk-significant for MSRs
- Source term characterization (and chemistry) important for determining releases in MSR event sequences
  - MSRE was not able to close iodine balance (1/4 to 1/3 of I inventory "unaccounted for"
- Comprehensive PHA (HAZOP) necessary for MSRE
- Configuration management of historical data an issue

Acknowledgements

Oak Ridge National Laboratory

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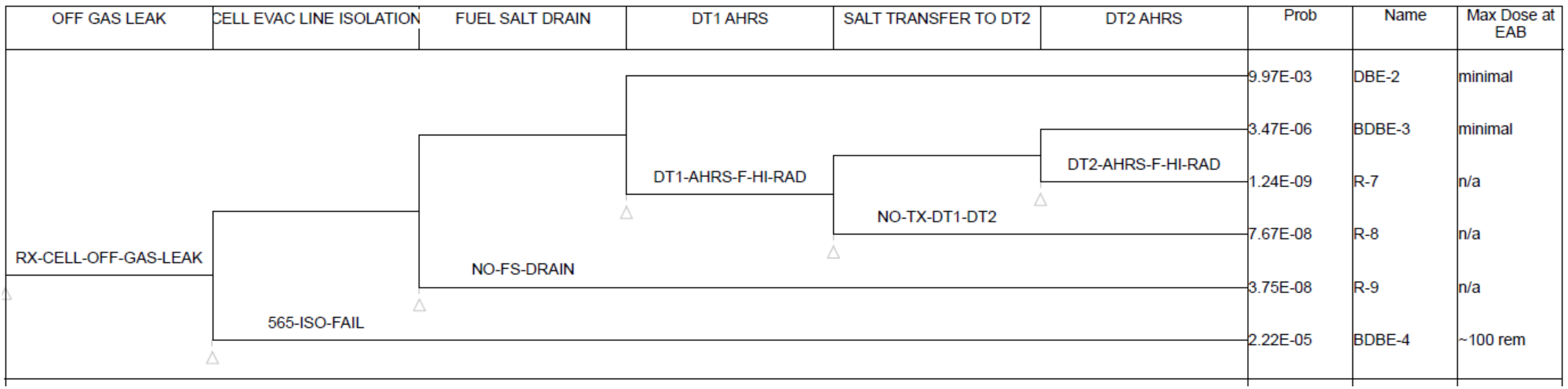
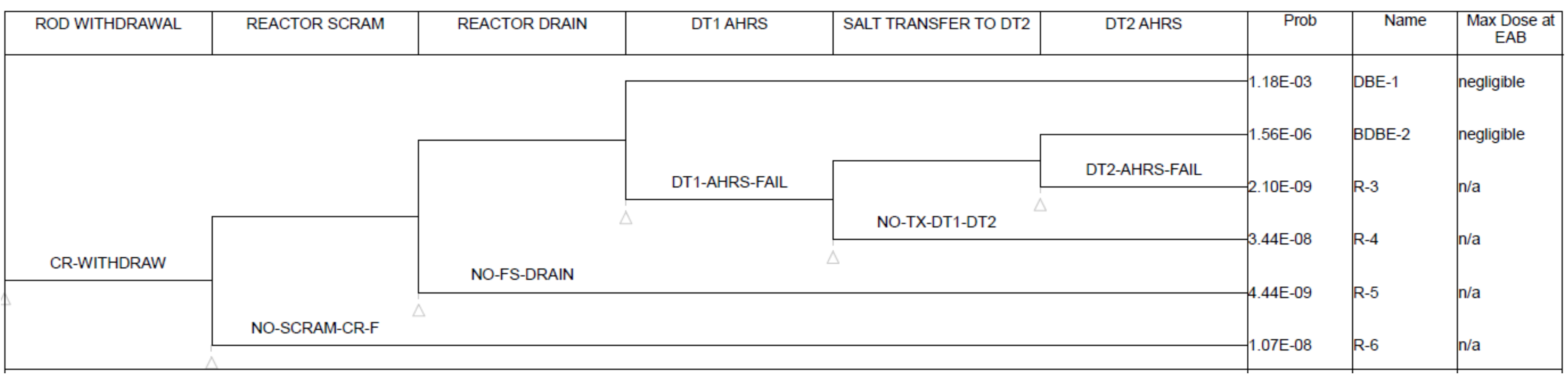
NEUP | Nuclear Energy University Program

U.S. Department of Energy

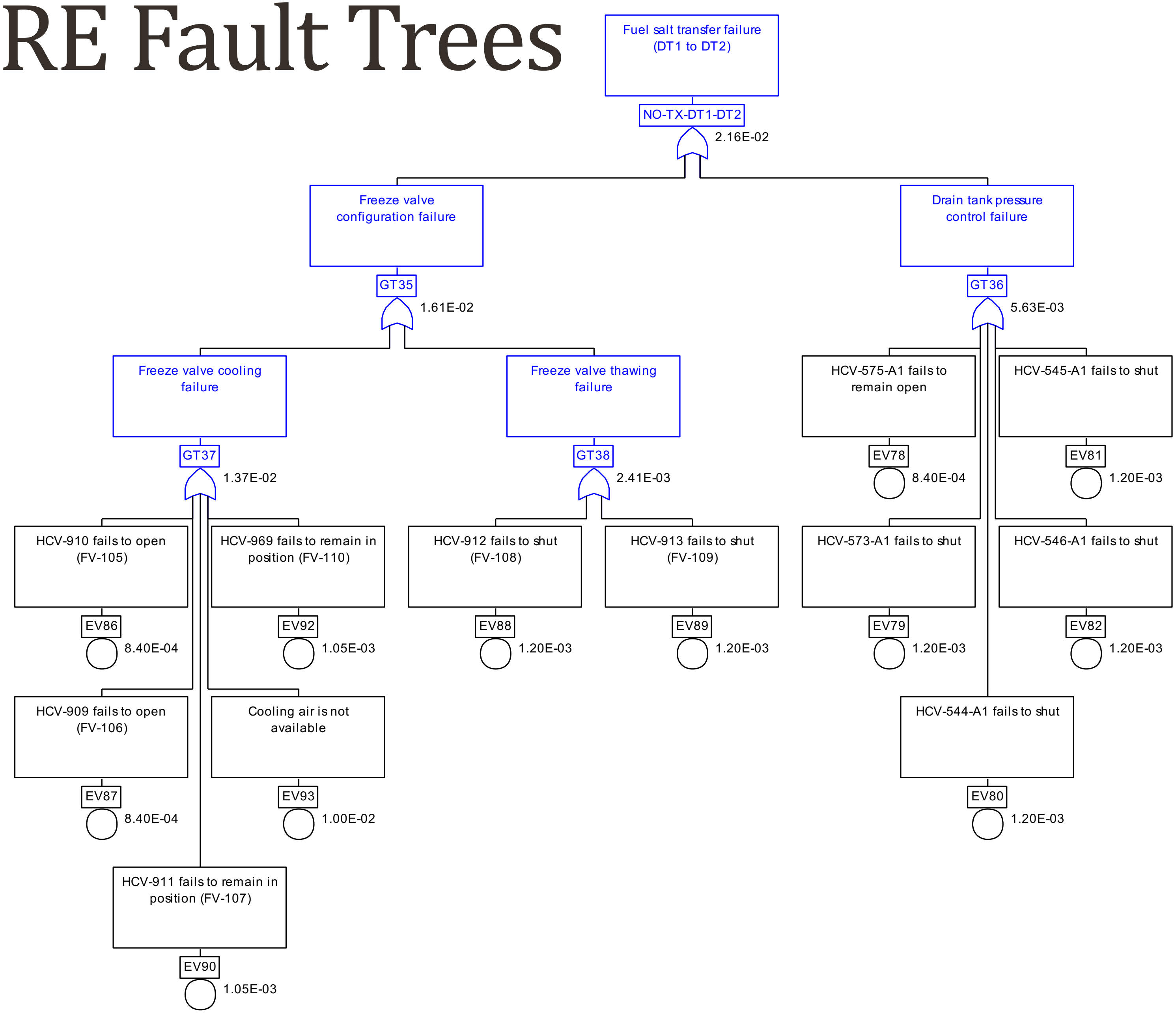
Supplemental Slides & References

MSRE Event Trees

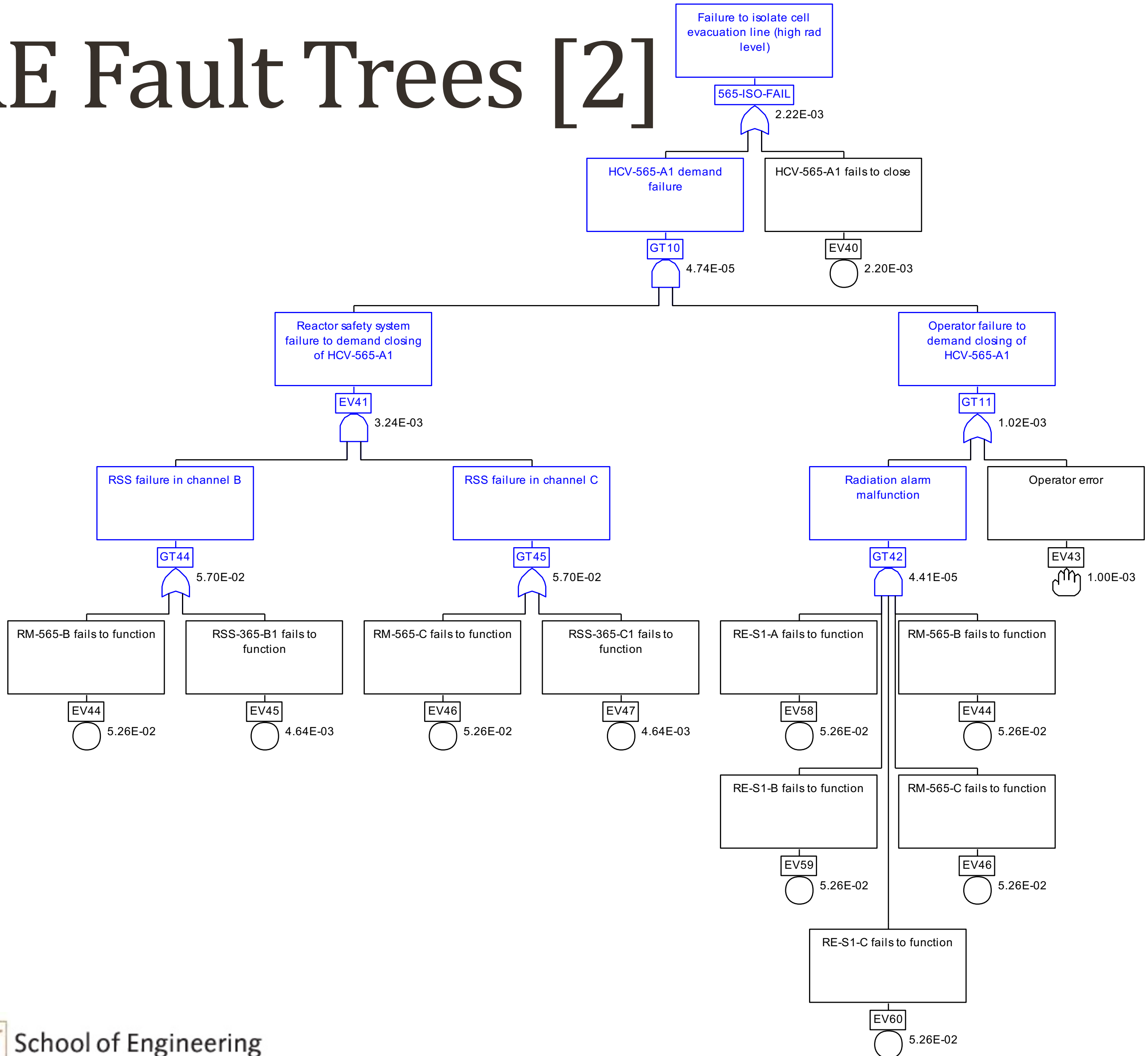




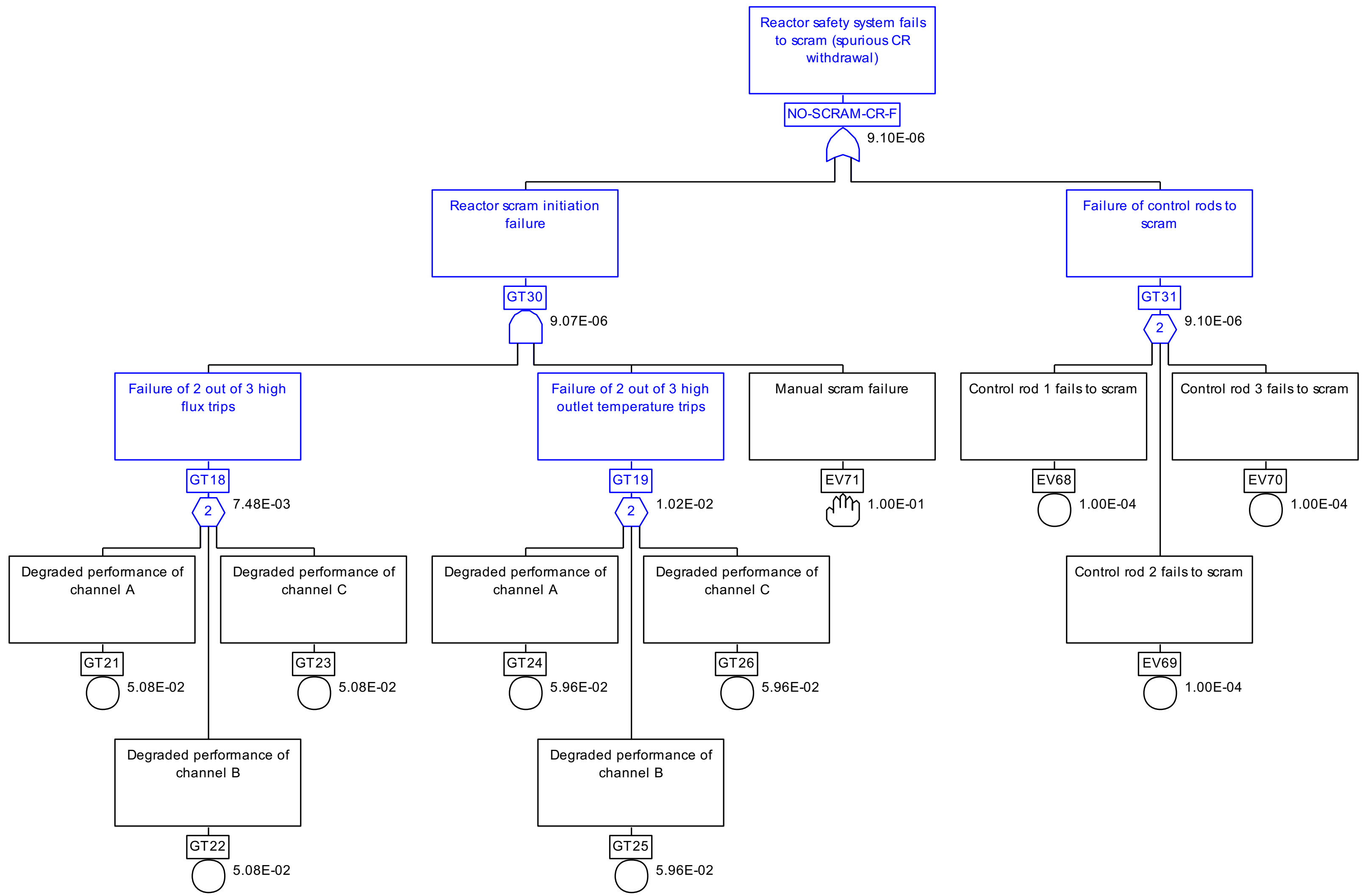
MSRE Fault Trees



MSRE Fault Trees [2]



MSRE Fault Trees [3]



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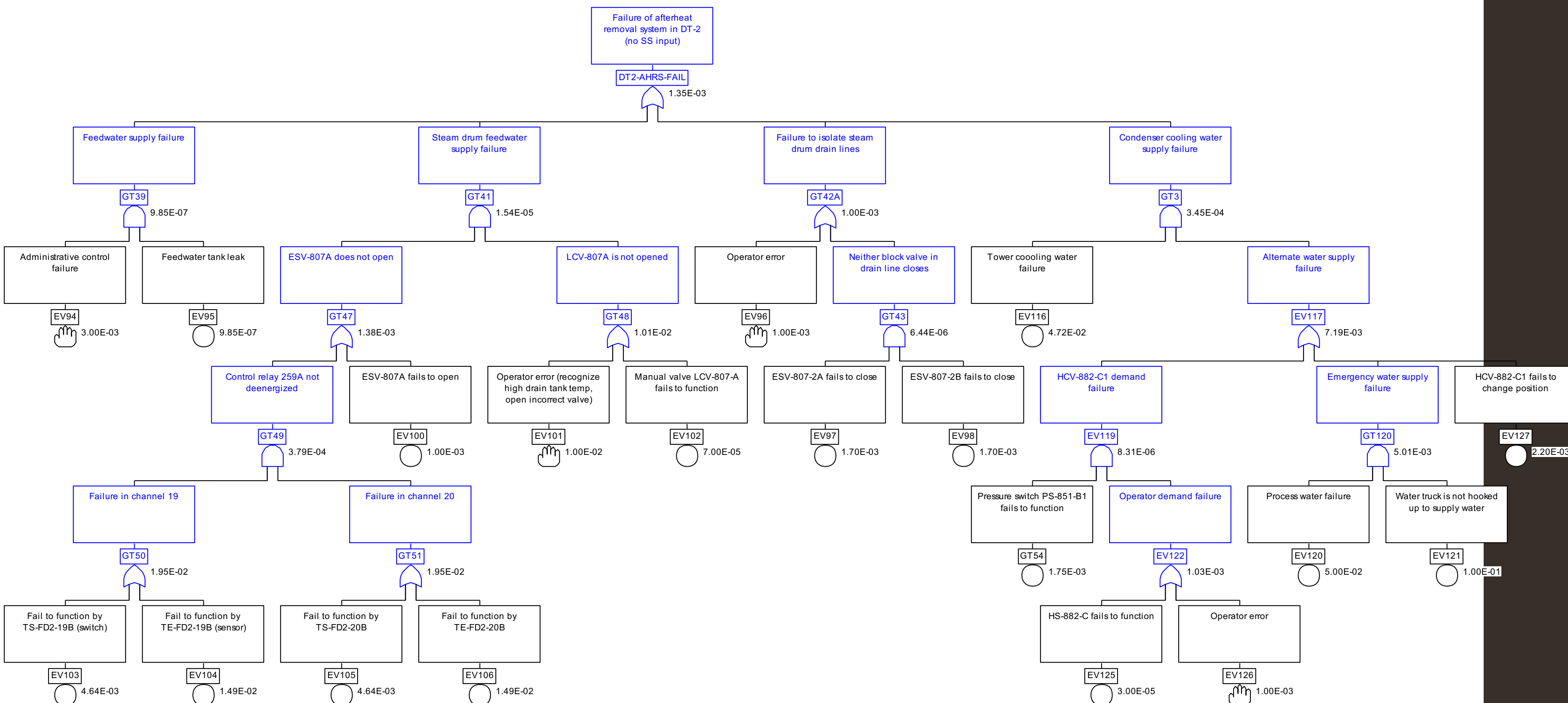
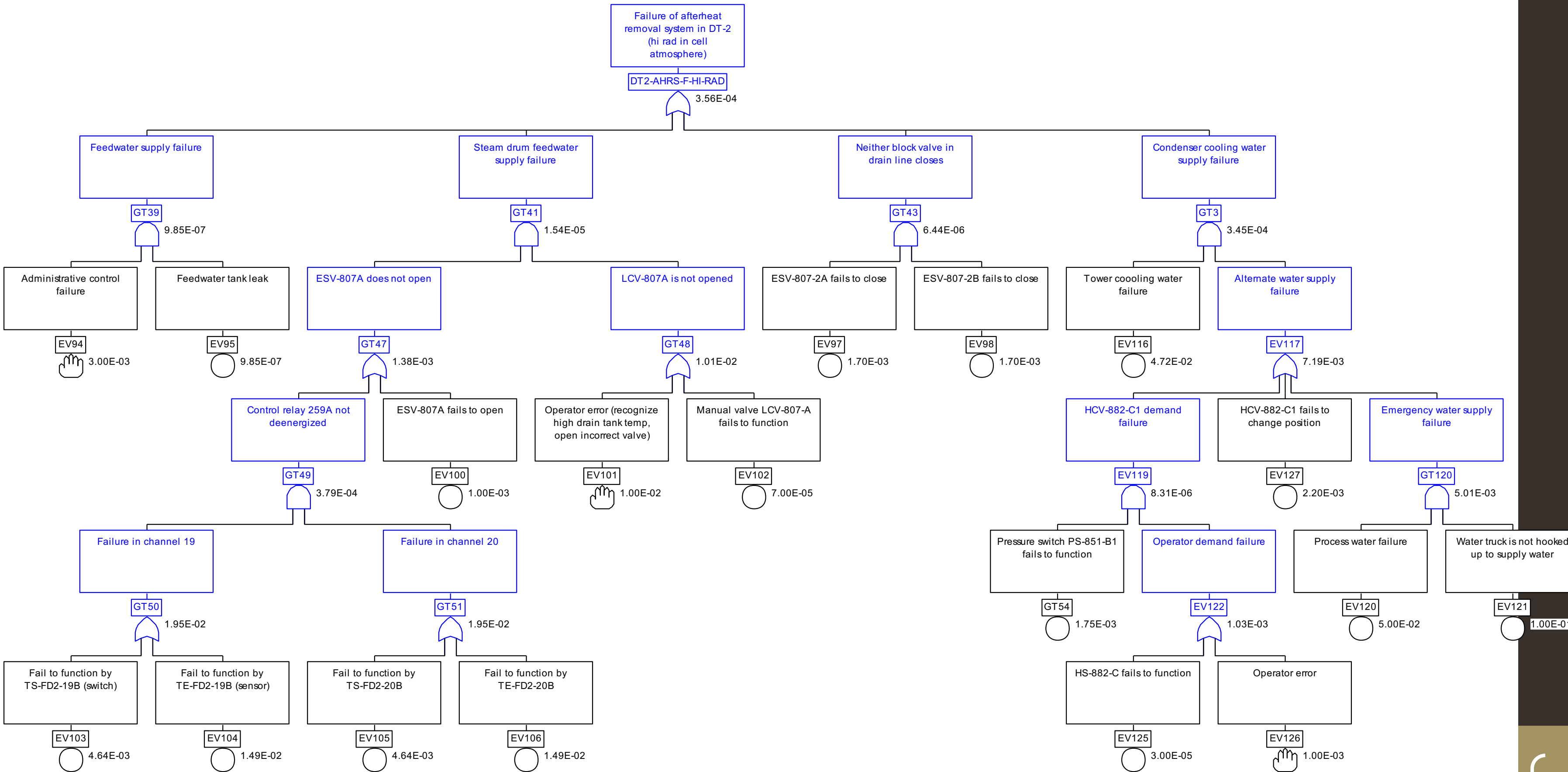
MSRE Fault Trees [4]



MSRE Fault Trees [5]



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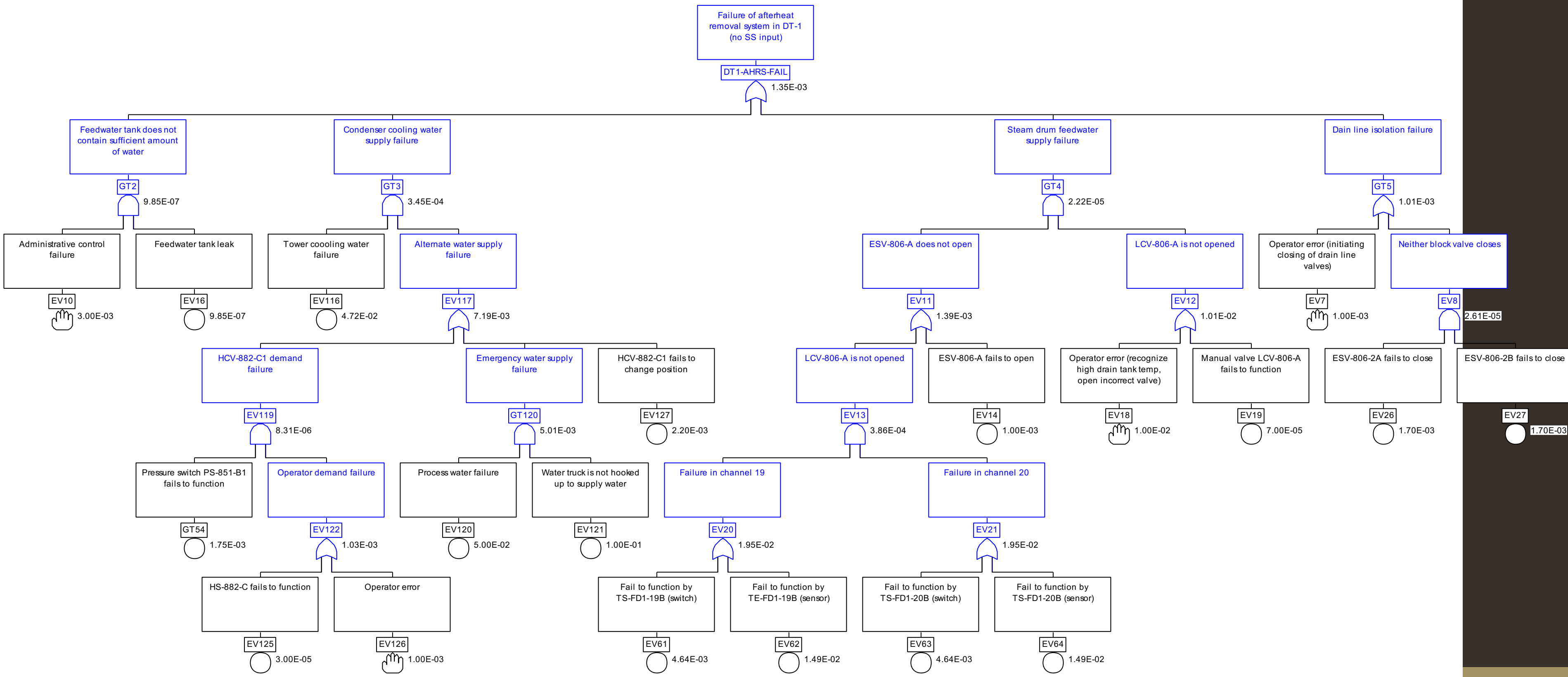
MSRE Fault Trees [6]



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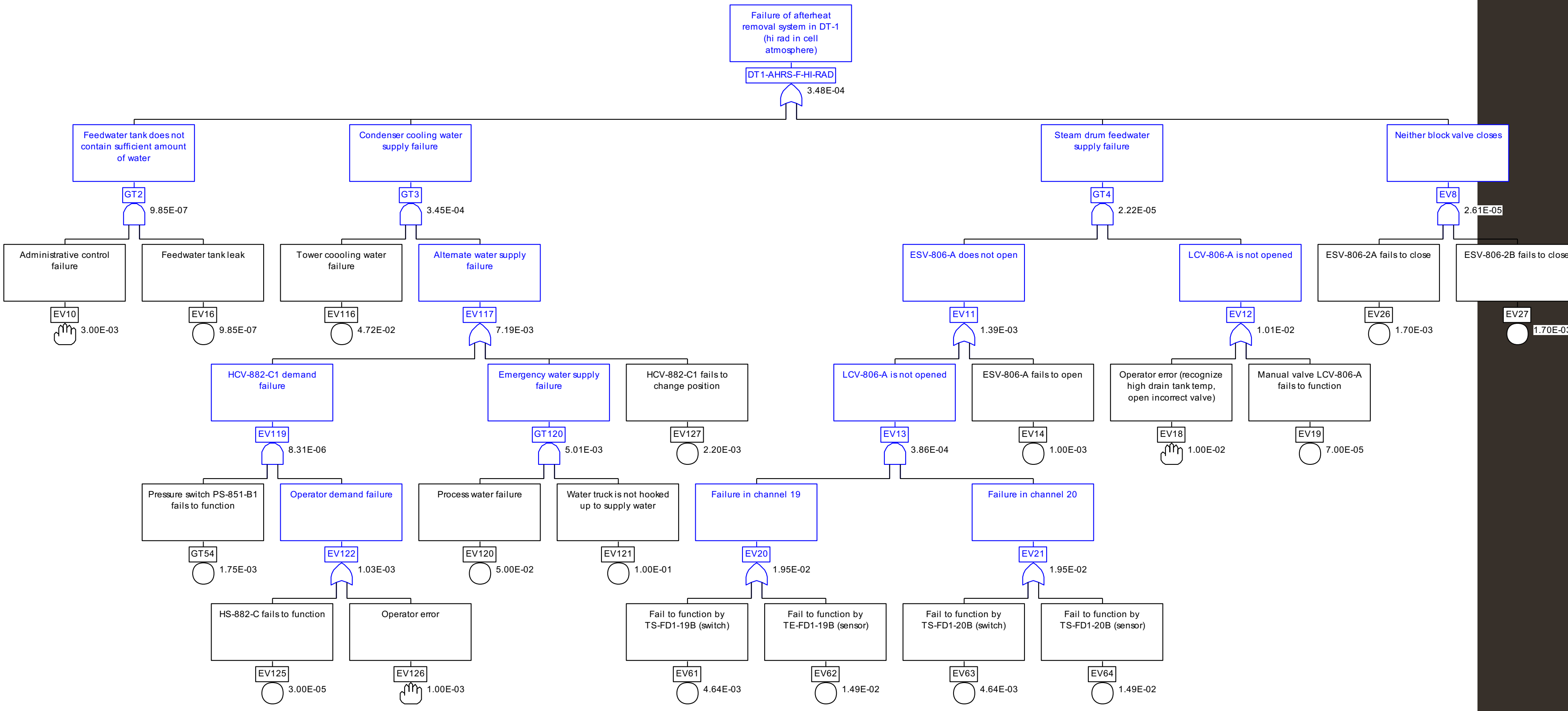
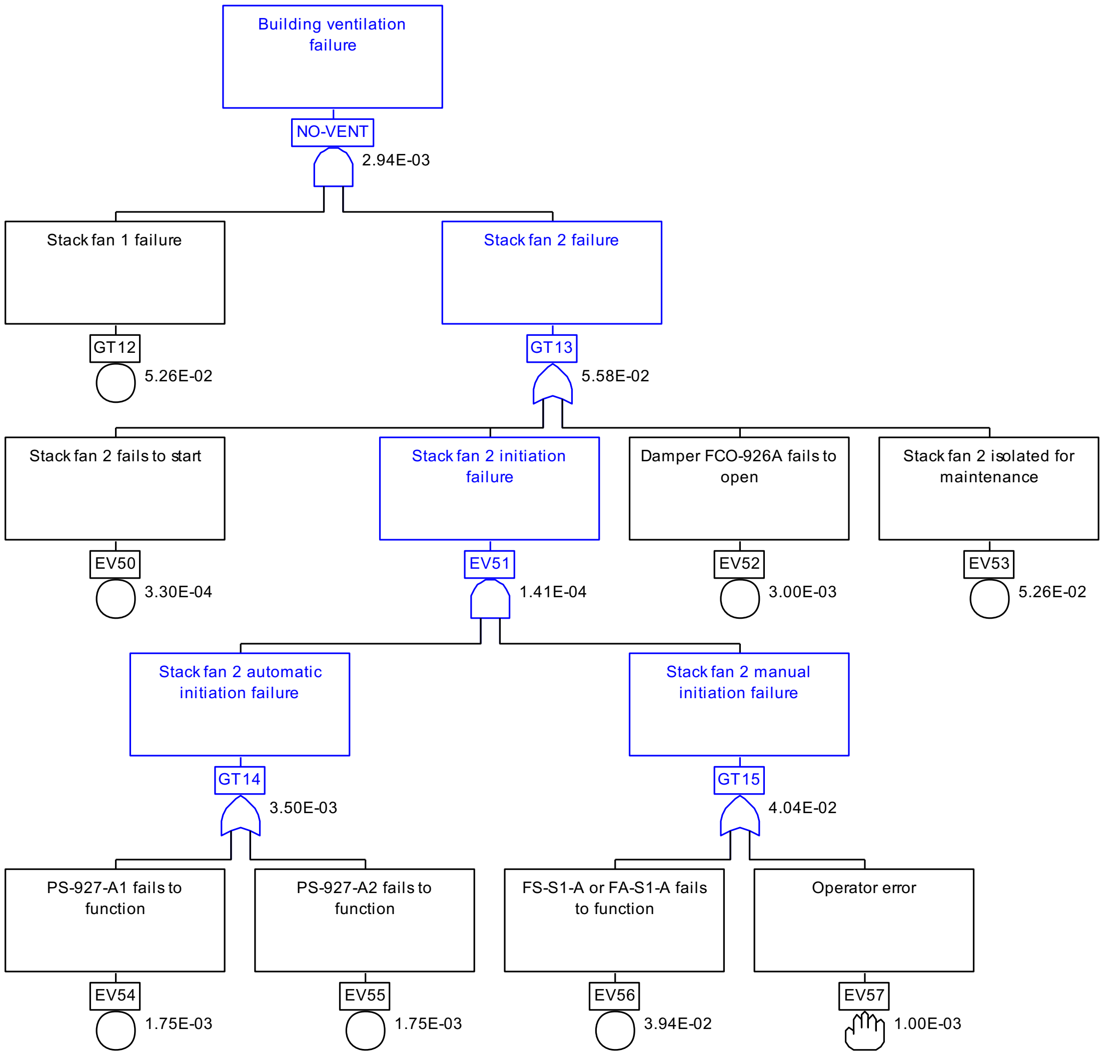
MSRE Fault Trees [7]



MSRE Fault Trees [8]



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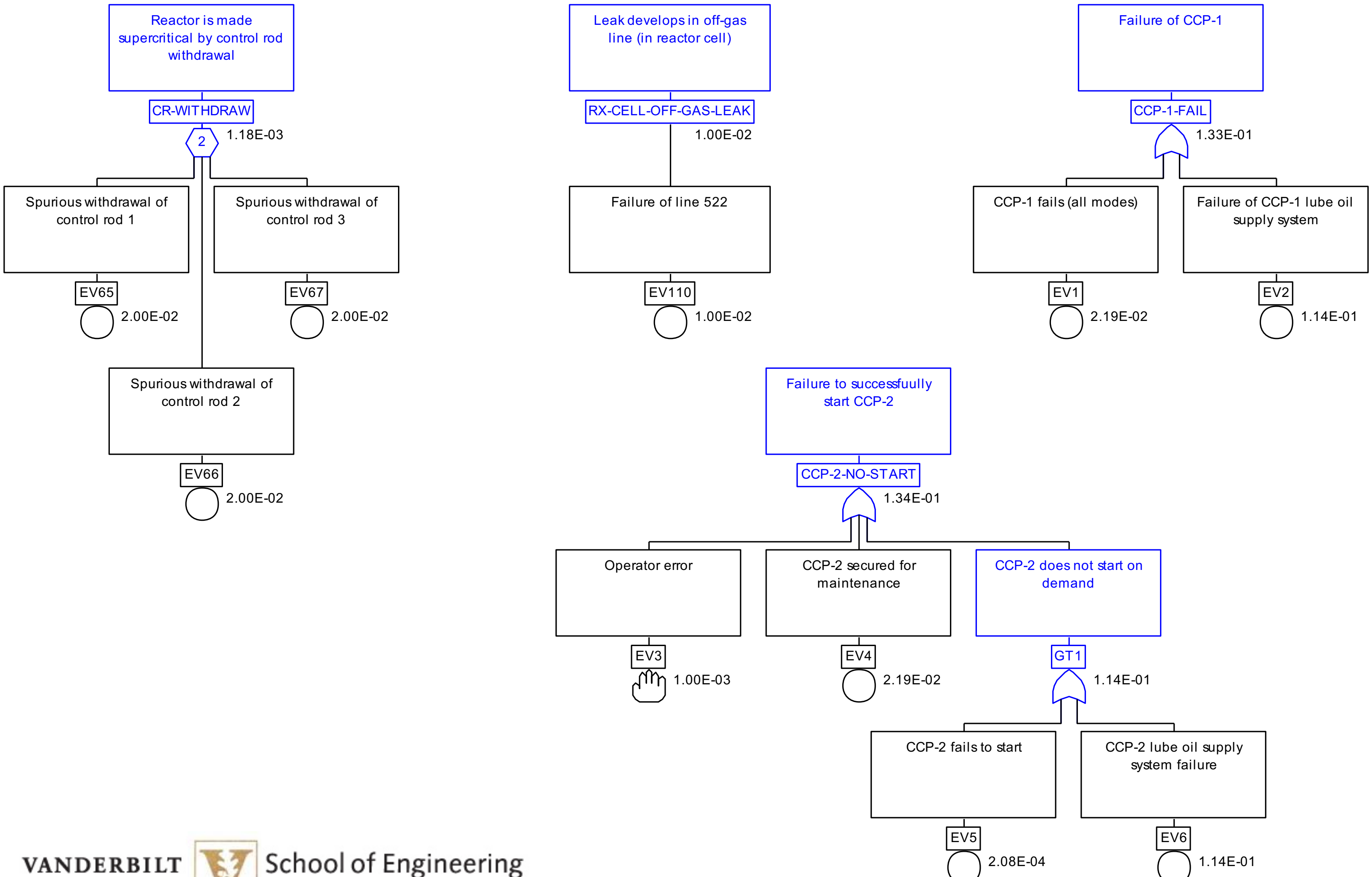
MSRE Fault Trees [9]



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