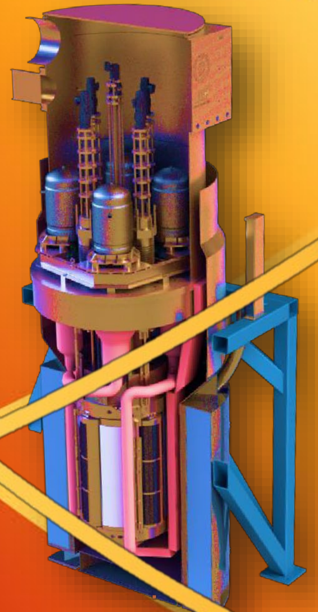
MARVEL Documented Safety Analysis (DSA) Development Strategy and Results



Microreactor Program Review

March 2025

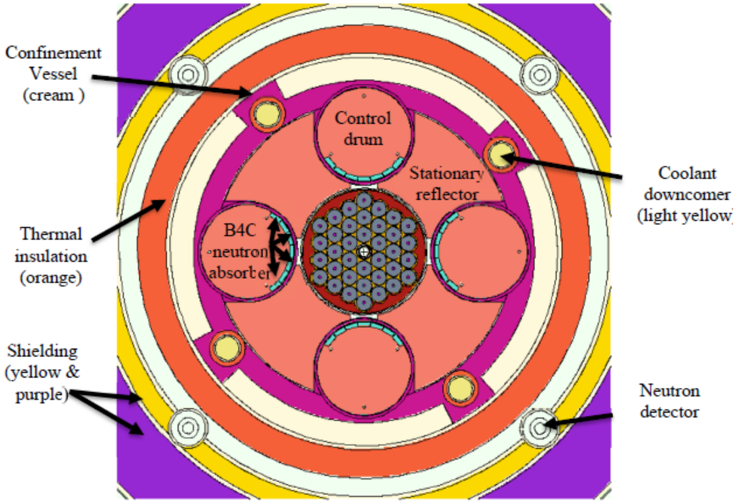
Doug Gerstner
Nuclear Safety Engineer
Idaho National Laboratory

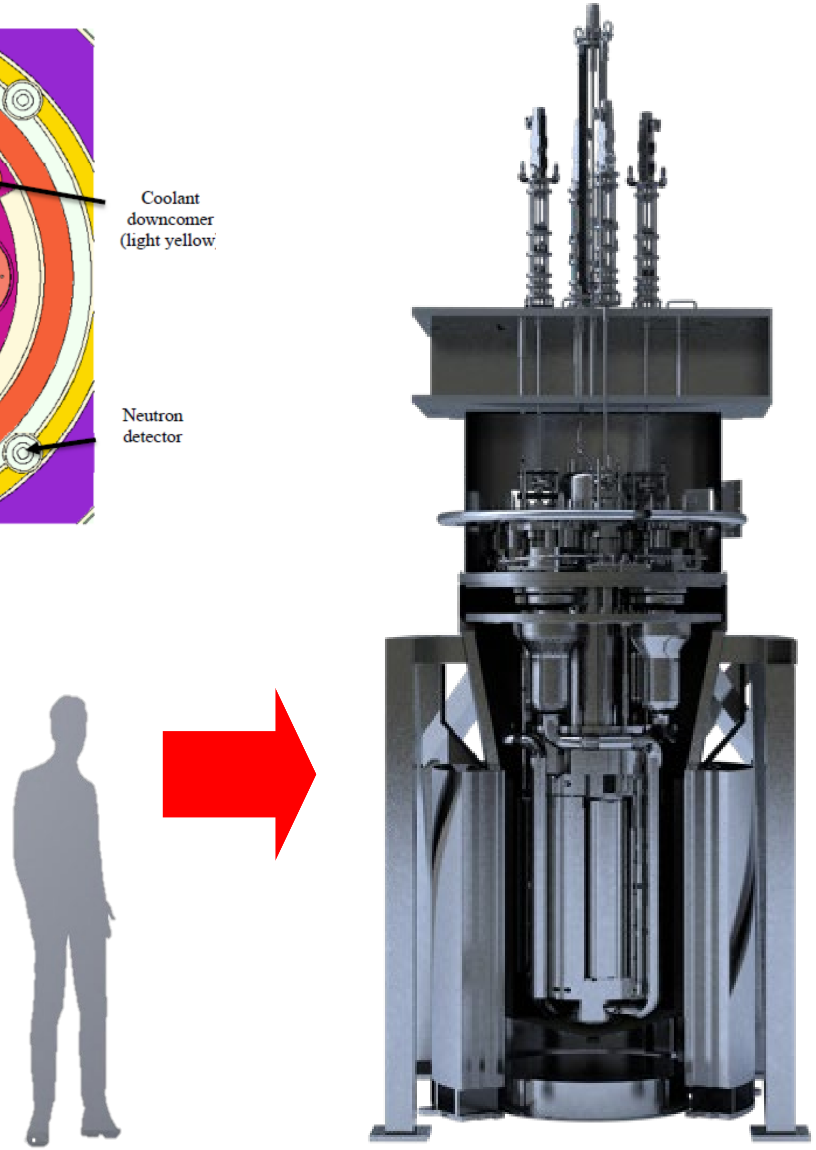
PRESENTATION OVERVIEW

- MARVEL Design Overview
- PDSA Outline and Development Process
- Hazards Analyses Approach and Results
- Design Basis Accident Analysis Results
- Results/Conclusions

MARVEL Design Overview

Key Design Features	
Thermal Power	85 kW nominal
Weight	< 12 US ton
Primary Coolant	Sodium-Potassium eutectic (NaK)
Intermediate Coolant	NaK
Coolant Driver	Natural Convection, single phase
Fuel	TRIGA HALEU (UZrH), 304SS clad, end caps
Moderator	Hydrogen
Neutron Reflector	Graphite, Beryllium (S200), Beryllium oxide
Reactivity Control	Radial Control Drums, Central Absorber
Primary Coolant Boundary	SS316H



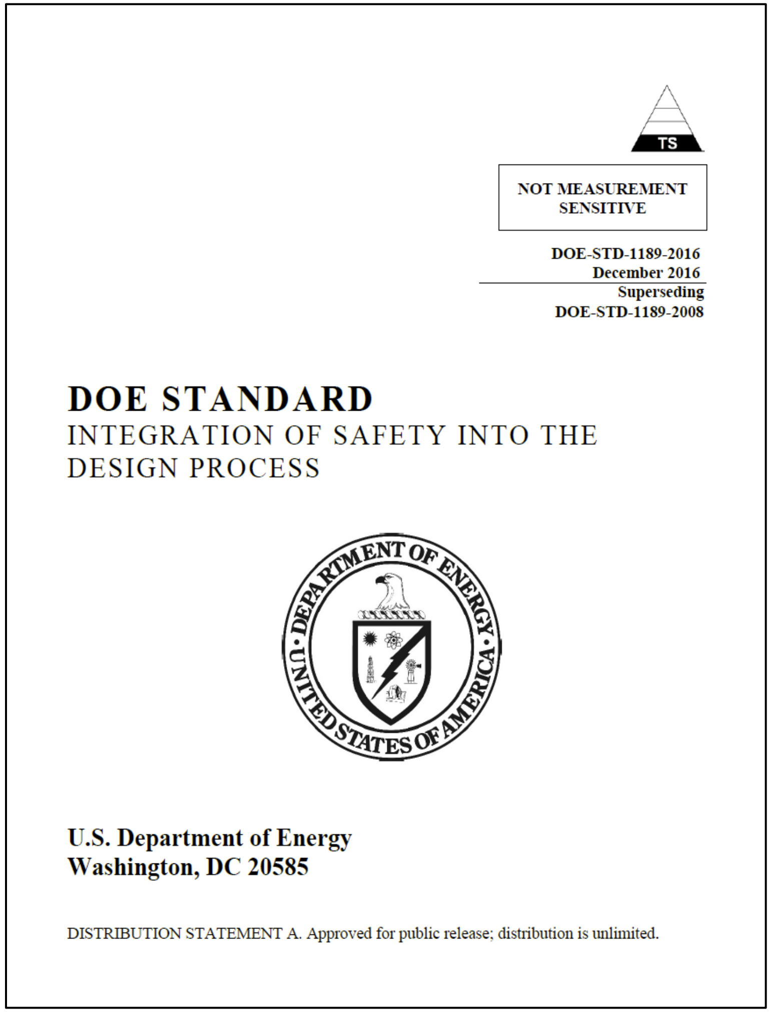


➤ ***Evolution of MARVEL from P-53 to current design. No PRA!***

Safety-in-Design Regulatory Framework

- **10 CFR 830, Subpart B, Nuclear Safety Management**
  - Establishes the safety basis requirements for Department of Energy (DOE) nuclear facilities.
  - Requires the development of a documented safety analysis (DSA) to ensure that hazard controls are established to provide for the adequate protection of workers, the public, and the environment.
- **DOE O 420.1C, Facility Safety**
  - Establishes facility and programmatic requirements for:
    - Nuclear safety design criteria
    - Fire protection
    - Criticality safety
    - Natural phenomena hazards (NPH) mitigation
- **DOE-STD-1189-2016, Integration of Safety into the Design Process**

➢ ***Process outlined in DOE-STD-1189-2016, "Integration of Safety Into the Design Process," provides an opportunity to force a common understanding and agreement at key phases.***


TS

NOT MEASUREMENT SENSITIVE

DOE-STD-1189-2016
December 2016
Superseding
DOE-STD-1189-2008

DOE STANDARD
INTEGRATION OF SAFETY INTO THE DESIGN PROCESS

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA ·

U.S. Department of Energy
Washington, DC 20585

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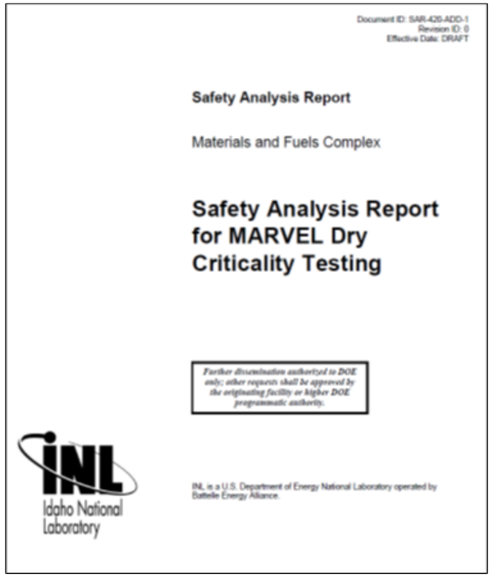
Early Integration of Safety Into the Design Process

- **Safety Design Strategy (SDS)** – Identification of Key Regulatory Requirements and Plant Safety Functions early to aid in guiding design.
  - *Submitted early and approved by DOE-Idaho (DOE-ID) to aid in guiding design.*
  - *SDS covers both dry criticality and full power ops.*
  - *Includes T-REXC.*
- **Preliminary Documented Safety Analysis (PDSA) –** Identification of detailed design parameters necessary to meet plant safety functions and confirmation that design meets general and specific design criteria.
  - *Submitted early and approved by DOE-ID to aid in guiding design.*
  - *Separate PDSA's for dry criticality and full power ops.*
- **Final DSA [Safety Analysis Report (SAR)] and Technical Specifications (TS) –** Documentation of as built configuration and confirmation it meets identified PSAR requirements.
  - *MARVEL PDSA and SAR are in the form of an addendum to the INL Transient Reactor Test (TREAT) safety analysis report (SAR)-420.*
  - *Separate FDSA's and TS's for dry criticality and full power ops*

➢ ***DSA documents for compliance with 10 CFR 830 is progress.***


Document ID: SAR-420-ADD-1
Revision ID: 0
Effective Date: DRAFT

Safety Analysis Report

Materials and Fuels Complex

Safety Analysis Report for MARVEL Dry Criticality Testing

Further dissemination authorized to DOE only; other requests shall be approved by the originating facility or higher DOE programmatic authority.

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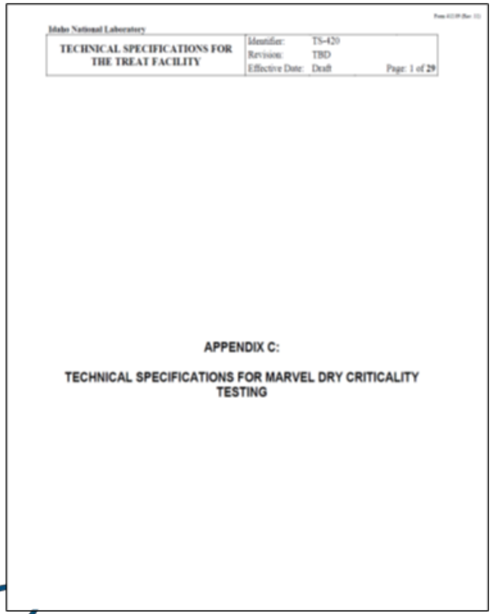
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TECHNICAL SPECIFICATIONS FOR THE TREAT FACILITY	Identifier: TS-420 Revision: TBD Effective Date: Draft	Page: 1 of 29

APPENDIX C:

TECHNICAL SPECIFICATIONS FOR MARVEL DRY CRITICALITY TESTING

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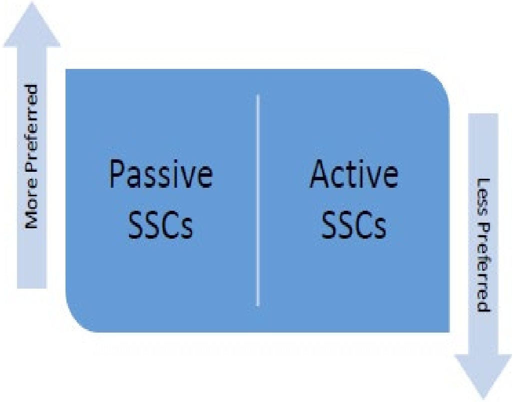
Key Safety Goals in the MARVEL Reactor Design

- **Technology choices drastically affect safety in design:**
  - Low thermal power and low burnup of fuel results in limited available source term.
  - Uranium-zirconium hydride fuel (U-ZrH), sodium-potassium eutectic (NaK) coolant, and structural materials are stable and compatible.
  - Low residual heat.
  - Arrangement of high-conductivity components ensures less stored energy and higher margin to softening or melting of components.
  - Near atmospheric operation of the reactor coolant system limits driving forces for release.
  - Safety functions, including the removal of decay heat, met without reliance on electrical power in response to a postulated event.
  - The reactor structure and other safety-related components are designed to withstand the safe shutdown earthquake.

- **Elements of Passive Safety Design Considered:**
  - Inherent negative reactivity feedback (IRF) ensures reactor power is controlled during overpower or overtemperature events.
  - Decay heat removal during off-nominal events without the need for an emergency core cooling system.
  - Multiple passive confinement barriers result in complicated release paths for fission product release.



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MARVEL PDSA Format and Content

- Follows the existing 17-chapter format of TREAT FSAR as applicable and appropriate.
- Chapter 10 is replaced with a new "Interfacing Systems."
  - ➢ Provides design and safety analysis requirements for End Users
- Content considers the following as guidance as appropriate for a DOE microreactor:
  - RG 1.70 (Used for TREAT FSAR. Being superseded by RG 1.206)
  - NUREG-0800
  - NUREG-1537
  - ANSI/ANS-15.21-2021
  - DOE-STD-1237
  - RG 1.232 (Design Criteria)

➢ ***TREAT SAR and MARVEL PDSA in the form of a 17-chapter RG 1.70 (RG 1.206) SAR***

Form 412.09 (Rev. 11)

Idaho National Laboratory

MARVEL PRELIMINARY DOCUMENTED SAFETY ANALYSIS	Identifier: SAR-420-ADD-1 Revision: 0 Effective Date: DRAFT Page: iv of x

CONTENTS

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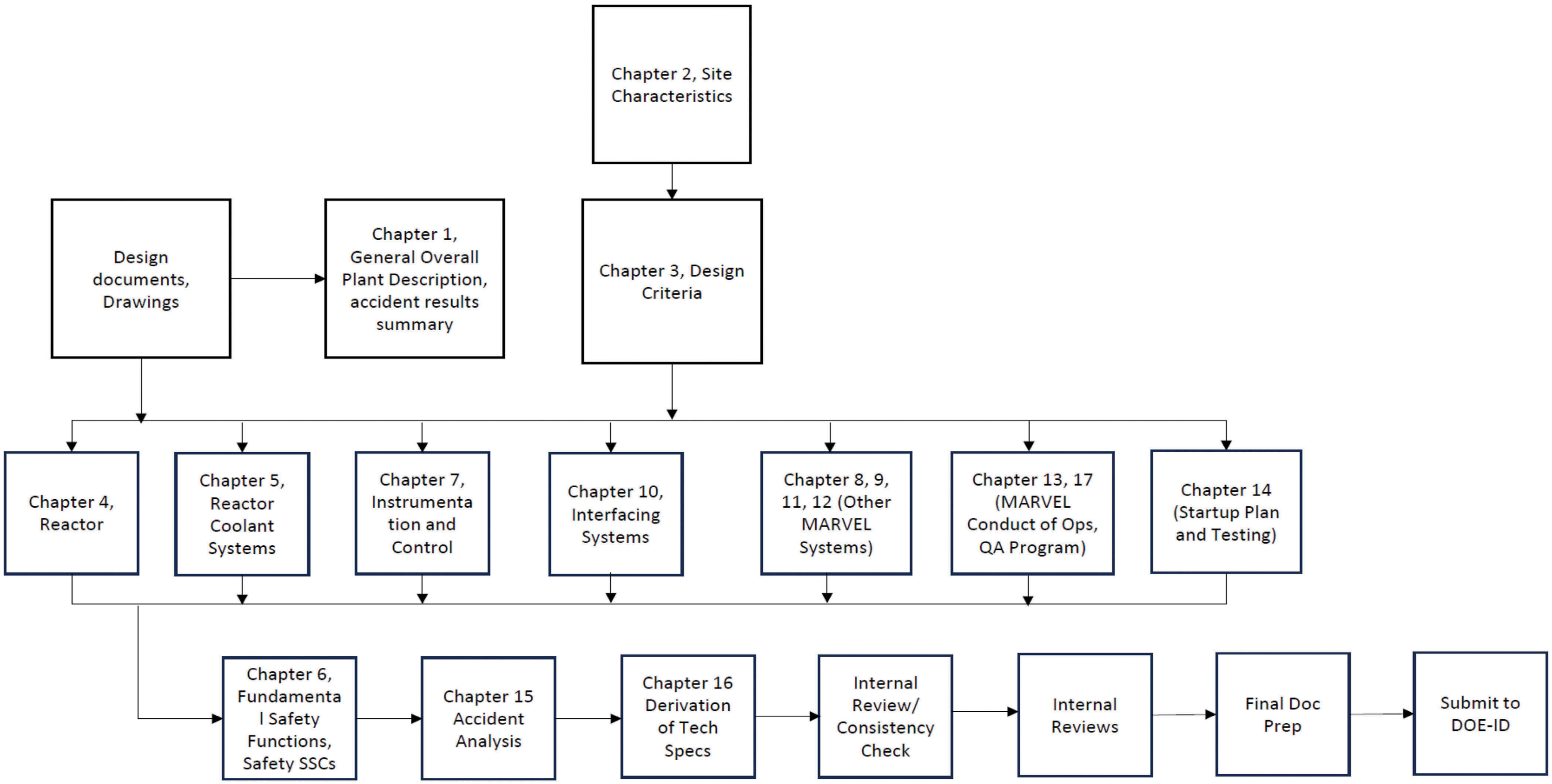
MARVEL PDSA Process



➢ ***Process iterative over the MARVEL Reference, Interim, and final designs.***

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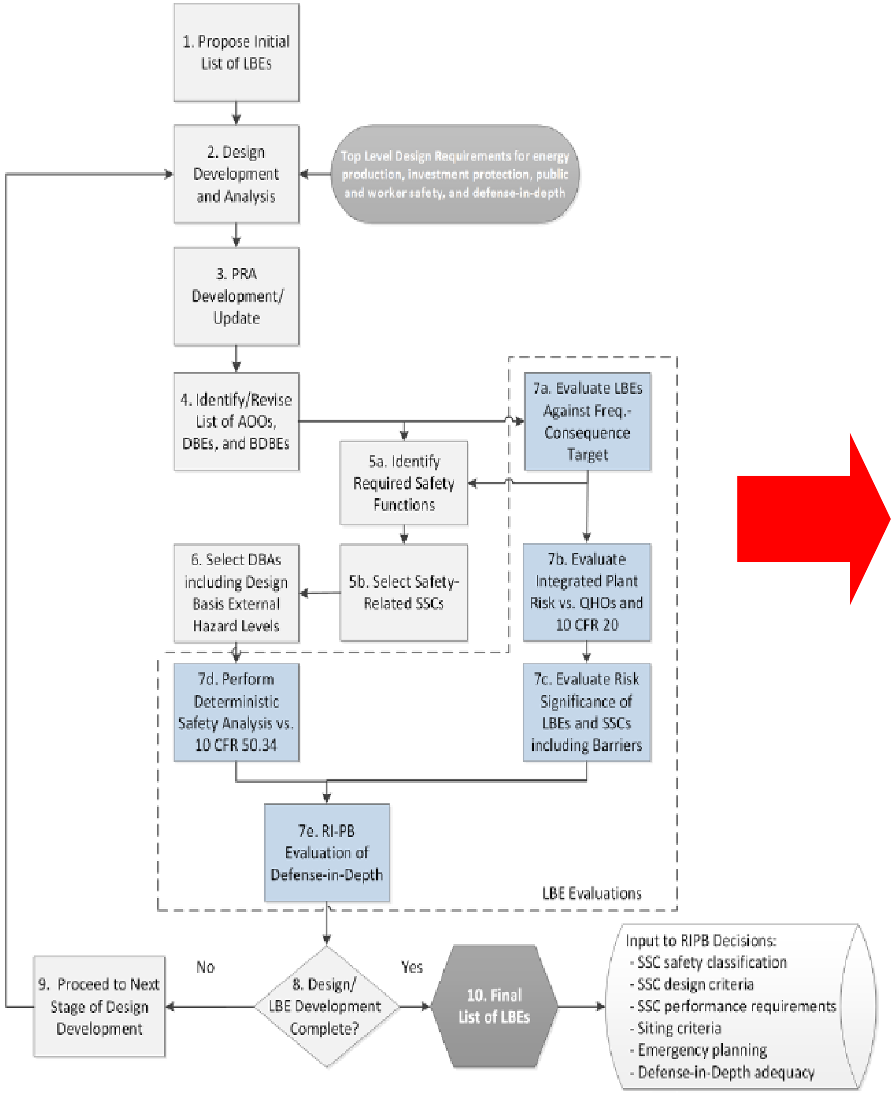
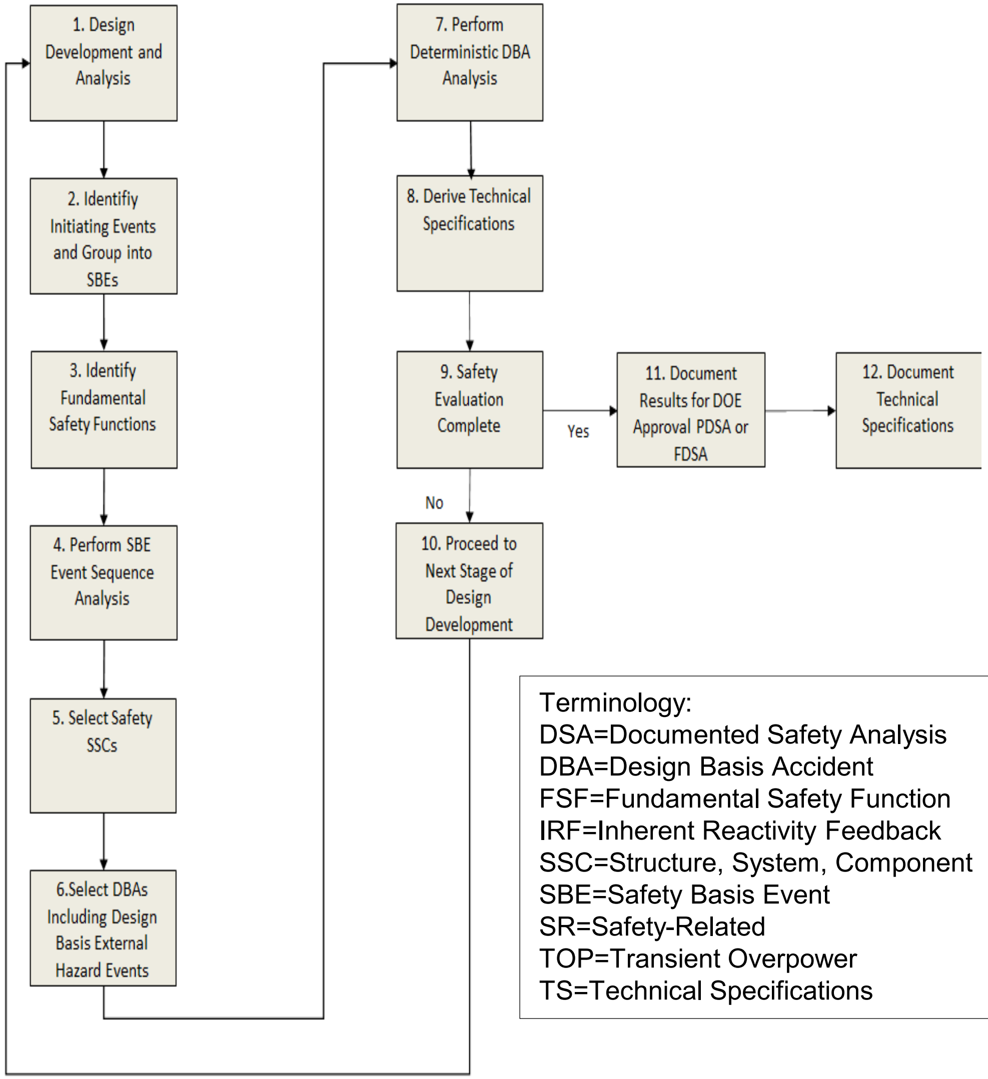
MARVEL ECAR-6440 Hazard Evaluation Methodology

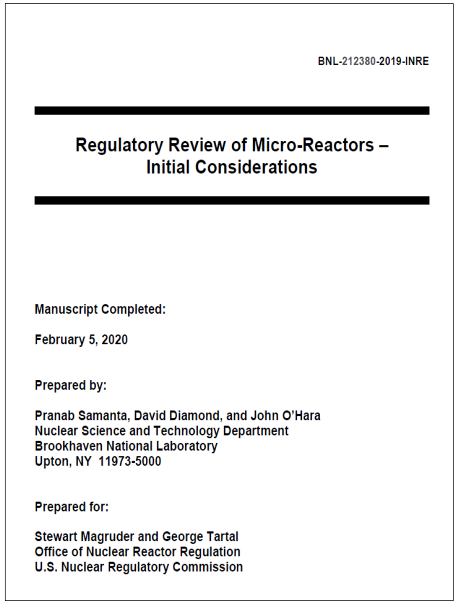
NEI-18-04, Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development

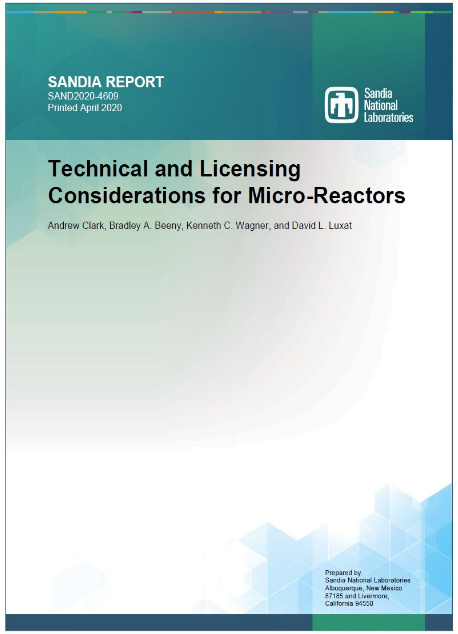


MARVEL



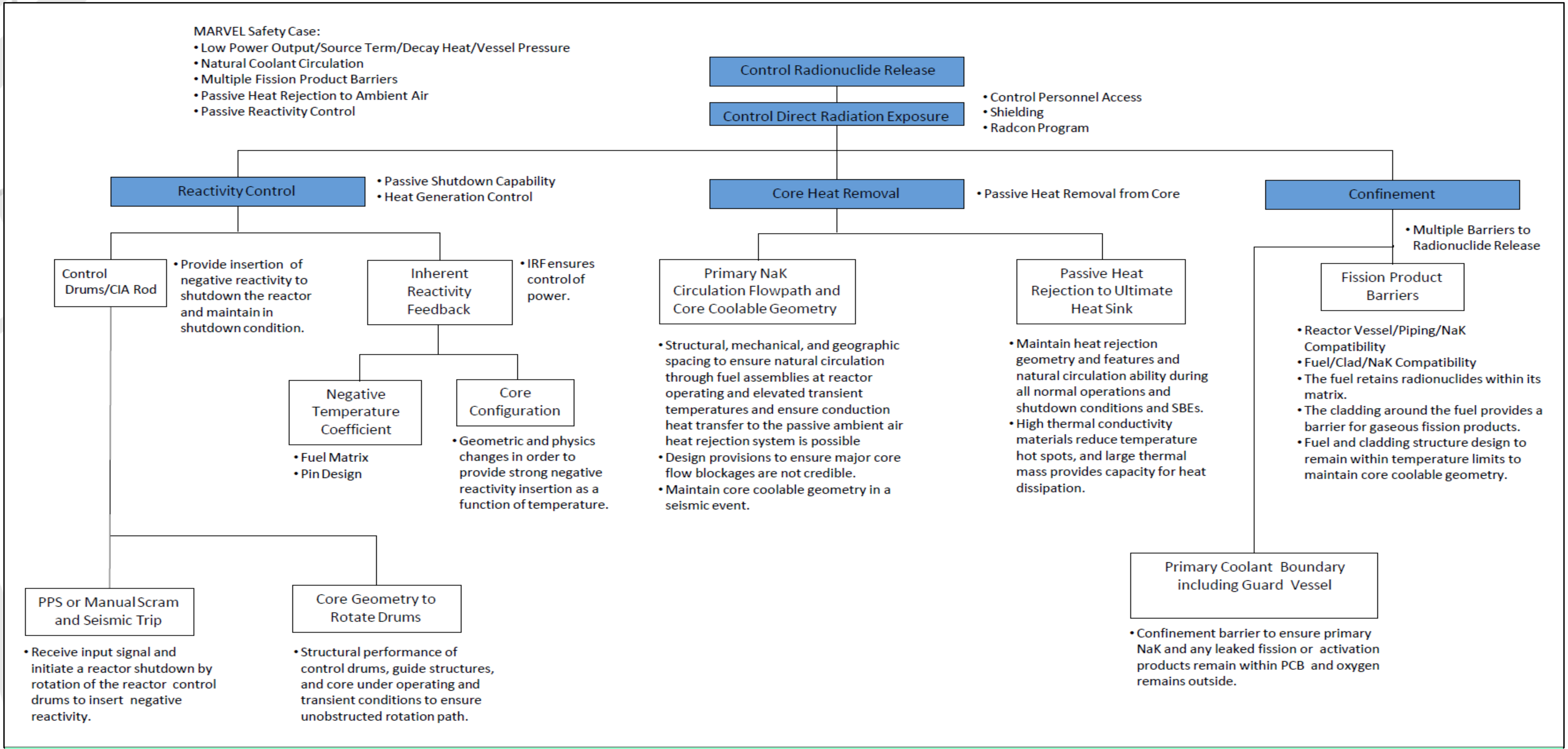
Terminology:
DSA=Documented Safety Analysis
DBA=Design Basis Accident
FSF=Fundamental Safety Function
IRF=Inherent Reactivity Feedback
SSC=Structure, System, Component
SBE=Safety Basis Event
SR=Safety-Related
TOP=Transient Overpower
TS=Technical Specifications





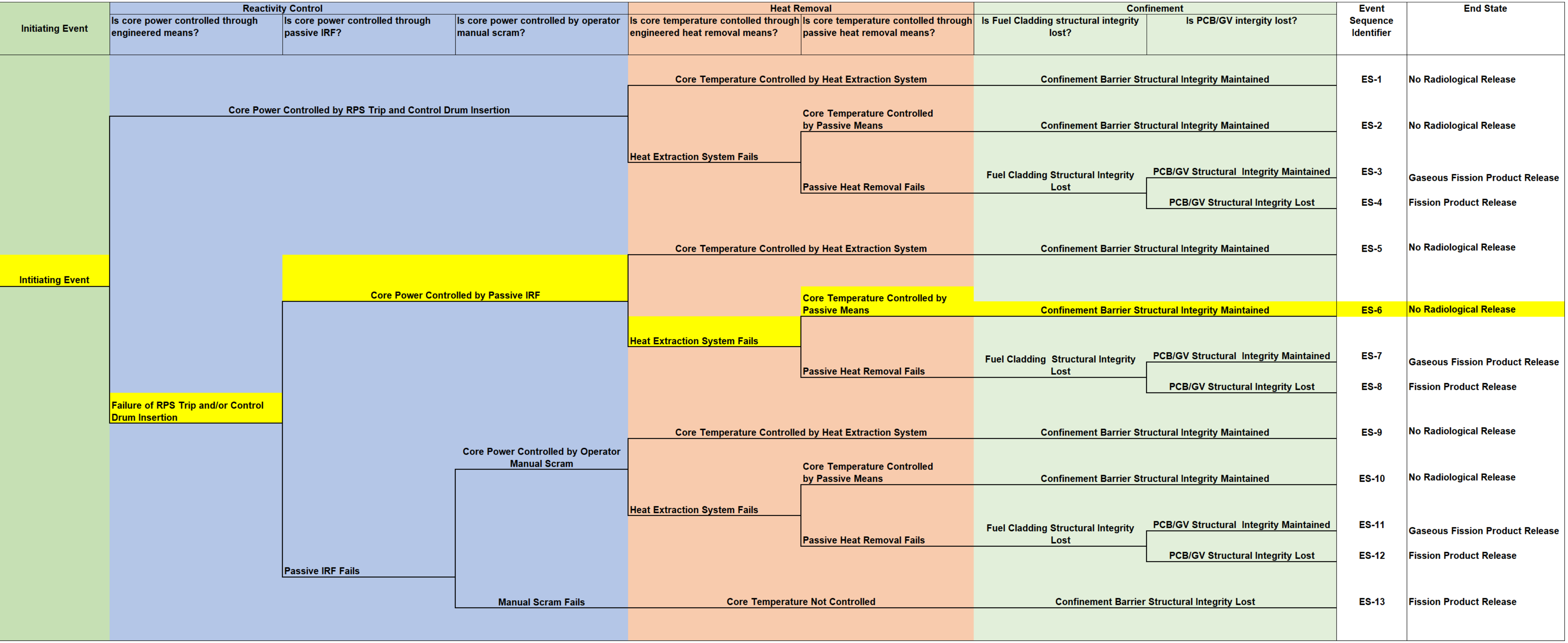
➢ ***PRA not performed – MARVEL Hazard evaluation is largely qualitative.***

MARVEL Fundamental Safety Functions (FSFs)



➢ ***Functions that if fulfilled, keep Initiating Events (IEs) from progressing to end states that could result in core damage and release of radioactive or hazardous material.***

Qualitative Event Sequence Analysis - TOP Example Only

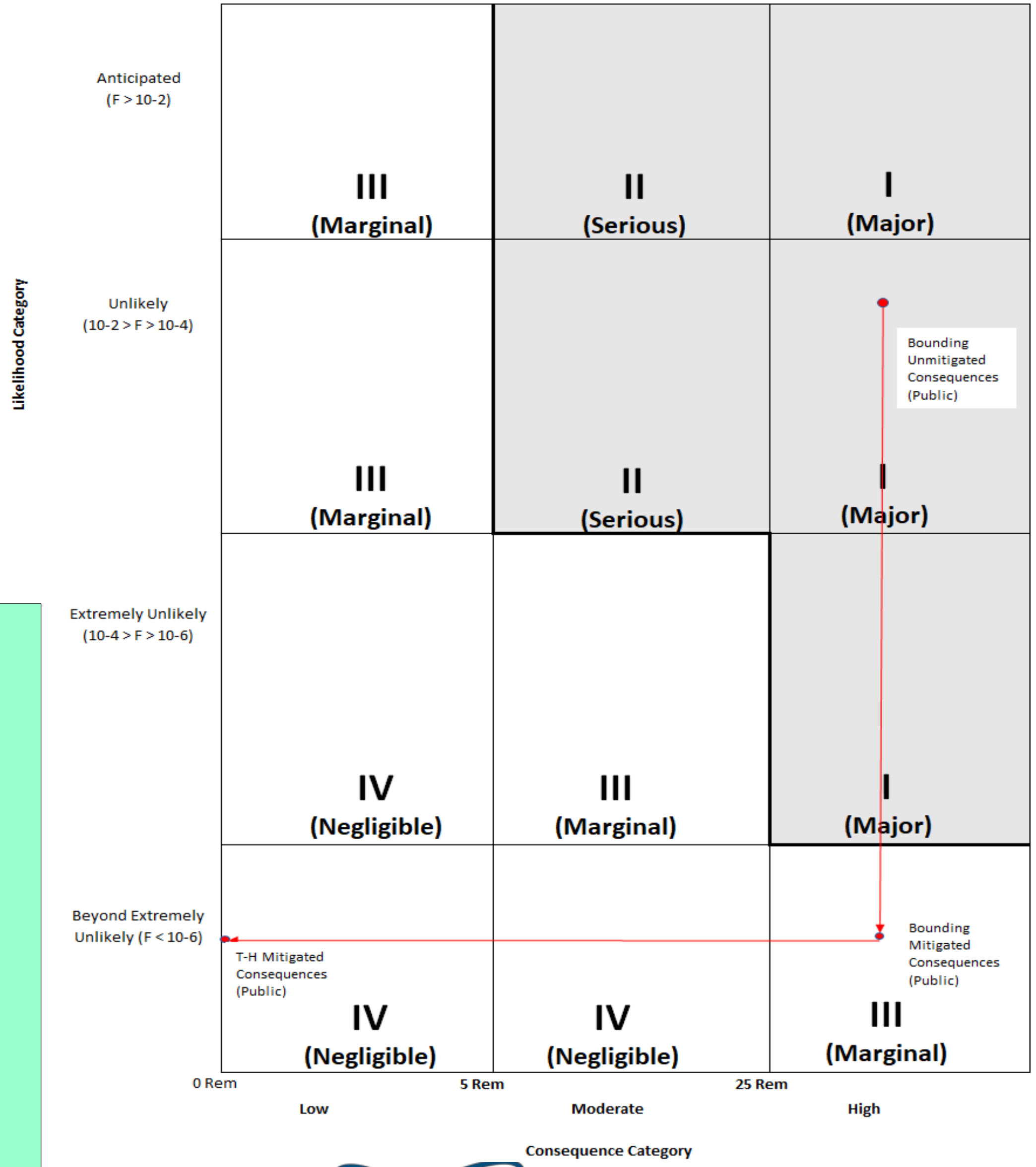


- ***ES-6 relies on passive SSCs alone to perform the FSFs – Result is an end state with no core damage of rad release.***
- ***Passive SSCs performing the Reactivity Control (IRF) and Heat Removal (Core SSCs providing conduction and convection to ultimate heat sink) are therefore designated as Safety-Related (SR).***
- ***"Unprotected" ES-6 Frequency = (IE) x (Failure of Active Reactivity Control) x (Failure of Active Heat Removal)***

Qualitative Risk Analysis

- **Based on DOE guidelines:**
  - Probability of failure of an active FSF SSC is given a one qualitative frequency category frequency reduction (e.g., Anticipated to Unlikely).
  - Probability of failure of a passive FSF SSC is given a two qualitative frequency category frequency reduction (e.g., Anticipated to Extremely Unlikely).

- ***"Unprotected" TOP Frequency = (IE) x (Failure of Active Reactivity Control) x (Failure of Active Heat Removal) = Beyond Extremely Unlikely***
- ***TOP Qualitative evaluation assumes failure of Reactor Protection System trip and control drum insertion AND failure of active heat removal***
- ***TOP Relying solely on passive SR passive IRF and passive decay heat removal to ultimate heat sink***
- ***TOP qualitative risk analysis results in a risk bin IV, or "negligible" risk.***



Selection of Design Basis Accidents (DBAs)

- **Transient Overpower (TOP).** This accident was selected to represent and bound potential events that result from the addition of reactivity events, such as the uncontrolled rotation of one CD to the mechanical stop position resulting in insertion of the total excess reactivity at the highest possible rate.
- **Loss of Heat Sink (LOHS).** This accident was selected to represent and bound potential events that result from the undercooling or decrease in heat removal faults that result in the loss of the capability to remove reactor heat, such as the loss of active heat removal from the reactor core to the ultimate heat sink.
- **Loss of Flow (LOF).** This accident was selected to represent and bound potential events due to the loss of primary flow, such as from IHX failure and leakage of secondary coolant into the PCS.
- **Loss of Power (LOP).** This accident was selected to represent and bound potential events due to the loss of offsite power (LOOP)
- **Seismic Event (g ≤ SSE).** This accident was selected to represent and bound potential events due to a seismic event with a magnitude ≤ the safe shutdown earthquake (SSE).
- **Loss of Coolant Accident (LOCA).** This accident was selected to represent and bound potential events due to a decrease in reactor coolant inventory, such as from a break of the low-elevation components (downcomer, lower plenum).

Quantitative DBA analysis performed assuming only the <u>PASSIVE</u> safety related (SR)-SSCs are available

→

Reactivity Control:

Non-SR (NSR) Reactor Protection System (RPS) and Scram – NOT Available

SR Passive Inherent Reactivity Feedback (IRF) – Available

Heat Removal:

NSR Active Heat Removal – NOT Available

SR Passive Conduction and Convection SSCs – Available

Quantitative DBA Evaluation - TOP Thermal-Hydraulic (T-H) Results

Initiating Event:

- Reactivity insertion ($0.40) due to a single CD movement
- Freq = Unlikely

Available SSCs performing FSFs:

- Active RPS trip of CDs assumed unavailable
- Active heat removal assumed unavailable
- Reactivity control is provided exclusively by IRF.
- Core heat removal is provided exclusively by passive conduction/convection to ultimate heat sink.

Hot spot safety margins for TOP @ hot full power without active heat removal. **(Larger value = more margin)**

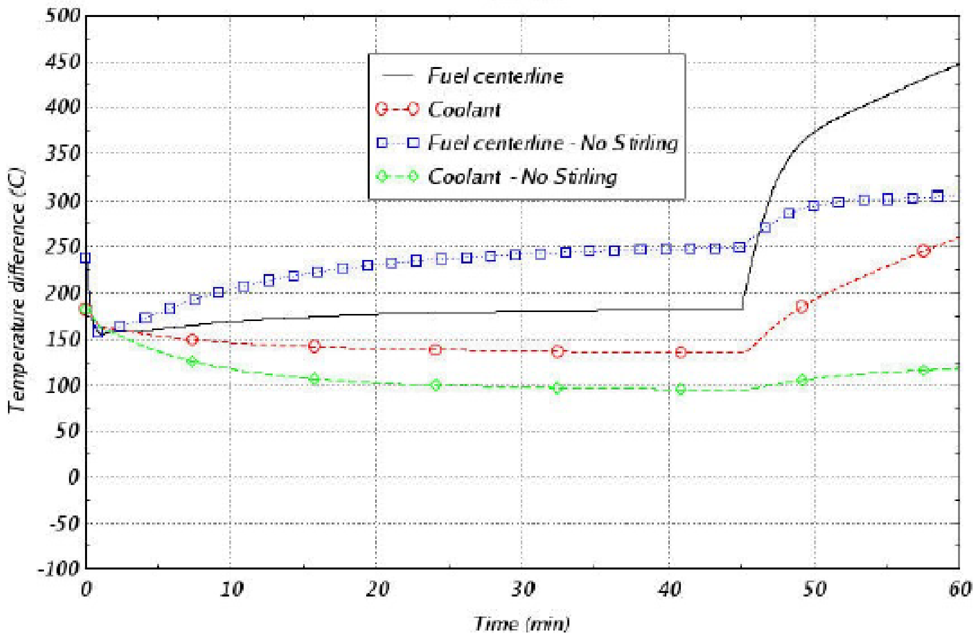


Table 15-2. MARVEL T-H acceptance criteria.

Acceptance Criteria	Design Basis Events			
	Normal Operation	Anticipated Events	Unlikely Events	Extremely Unlikely Events
1	Peak fuel centerline temperature <900°C			
2	Peak clad temperature <764°C			
3	Bulk coolant <530°C			
4		Bulk coolant <650°C		
5			Bulk coolant <704°C	
6	Core remains coolable			

- ***Despite active FSF failures, passive IRF and heat removal ensure T-H acceptance criteria are met, no core damage occurs, and no radiological release occurs.***
- ***Confirms the qualitative hazard evaluation assumptions!***

Conclusions:

As demonstrated in the DSA, the proposed MARVEL design:

- Accommodates various beyond-design-basis accident initiators without producing conditions that might lead to a severe accident.
- The passive inherent negative reactivity feedback, hydraulic, and thermal performance characteristics of the MARVEL design provide margin in many beyond-design-basis sequences to limit accident consequences without activation of active engineered systems or operator actions.
- These same passive characteristics have been shown in the PDSA to provide margin for operational and safety basis events.

The MARVEL hazard evaluation meets the intent of NEI-18-04 as follows:

- ***Risk-Informed*: Although a PRA was not performed, the MARVEL hazard evaluation provides a qualitative approach for risk assessment that provides reasonable assurance of protection of the public and worker. Confirmed by quantitative analysis!!**
- ***Performance-Based*: The MARVEL hazard evaluation provides a simplified analysis of the performance requirements for the passive SSCs performing the FSFs necessary for preventing IEs from progressing into sequences that could result in core damage and radiological or non-radiological releases.**

Thank-you

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Questions?