Our Future is Now

RESEARCH & DEVELOPMENT

Risk Reduction

Development of a Risk-Informed and Performance-Based Safety Case for TerraPower's Molten Chloride Reactor Experiment (MCRE)

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26 January 2024
ANS RP3C Community of Practice

Community of Practice with Pat, Prasad, and Others

= *C3PO*

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RESEARCH & DEVELOPMENT

Agenda

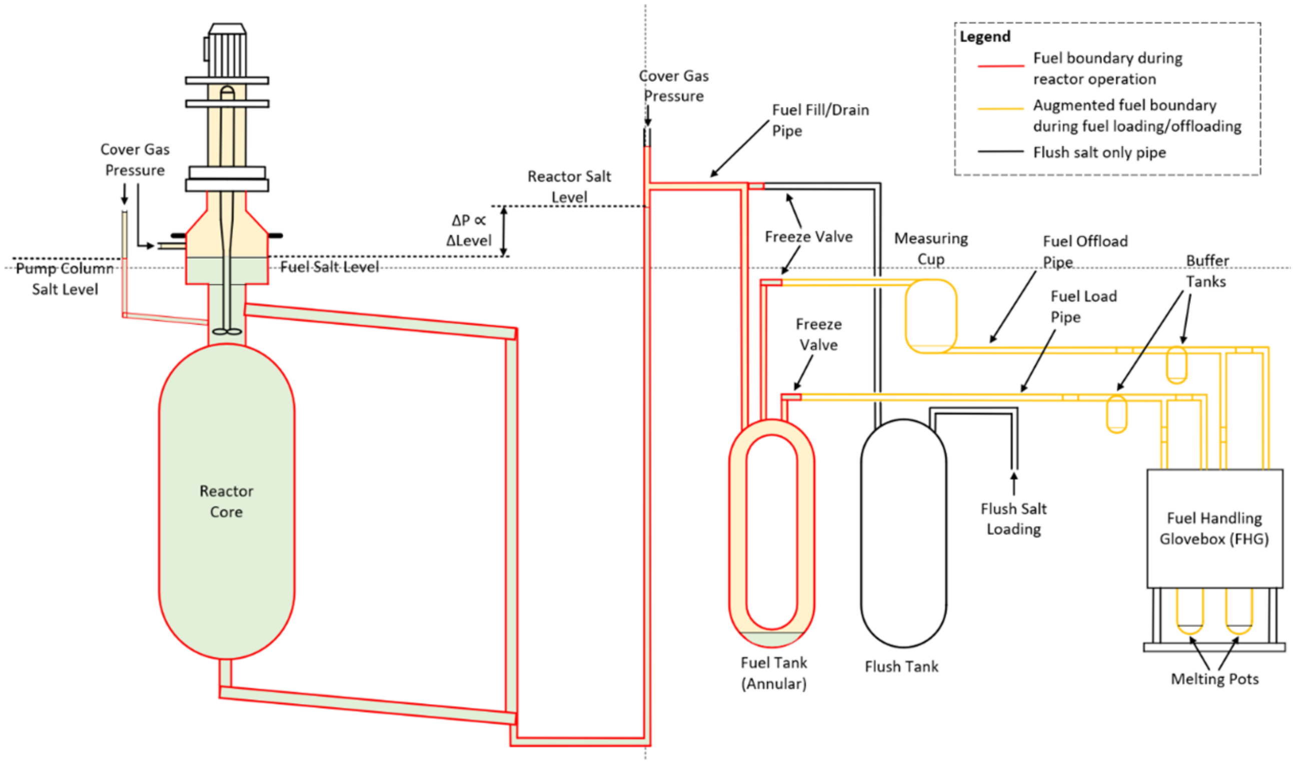
MCRE Mission Statement

To measure key reactor physics phenomena and test hypotheses about Molten Chloride Fast Reactor (MCFR) behavior, to reduce uncertainty and provide foundational knowledge to support the development of the MCFR Demonstration Reactor (MCFR-D).

Objective 1	Safely **achieve criticality** with the first fast spectrum molten salt fueled reactor
Objective 2	Experimentally determine **reactor physics and kinetics parameters** to reduce uncertainty and gather data
Objective 3	Demonstrate the **fuel** loading, fuel salt sampling/analysis, offloading, and general **handling strategy** for chloride fuel salt
Objective 4	Initiate development of industry **supply chain** for key molten salt components operated in a high temperature and radioactive environment
Objective 5	Collect operational/testing data to lay foundation for an operating license for MCFR-D under a risk-informed performance-based **(RIPB) licensing framework**

Reactor Design – Preliminary Design Phase (60%)

Parameter	Value
Rated Thermal Power	150 kW
Design Temperature	700°C
Design Pressure	500 kPa-g
Fuel Salt Mass Flow Rate	25-100 kg/s
Operating Temperature	600-650°C
Fuel Salt Melting Temperature	525°C
Fuel Salt Composition	NaCl-UCl_3 (67-33mol%) 93.2 wt% U-235
Fuel Salt Volume	0.302 m^3
Fuel Salt / HEU Mass	~1000 kg / ~500 kg
Neutron Reflector	82% dense MgO
Reactivity Control	Four rods w/ B_4C 96 wt% B-10
ASME BPVC	Section III Division 5
Material	UNS N06625 Grade 2



MCRE is a relatively simple system designed for <u>experimentation</u>

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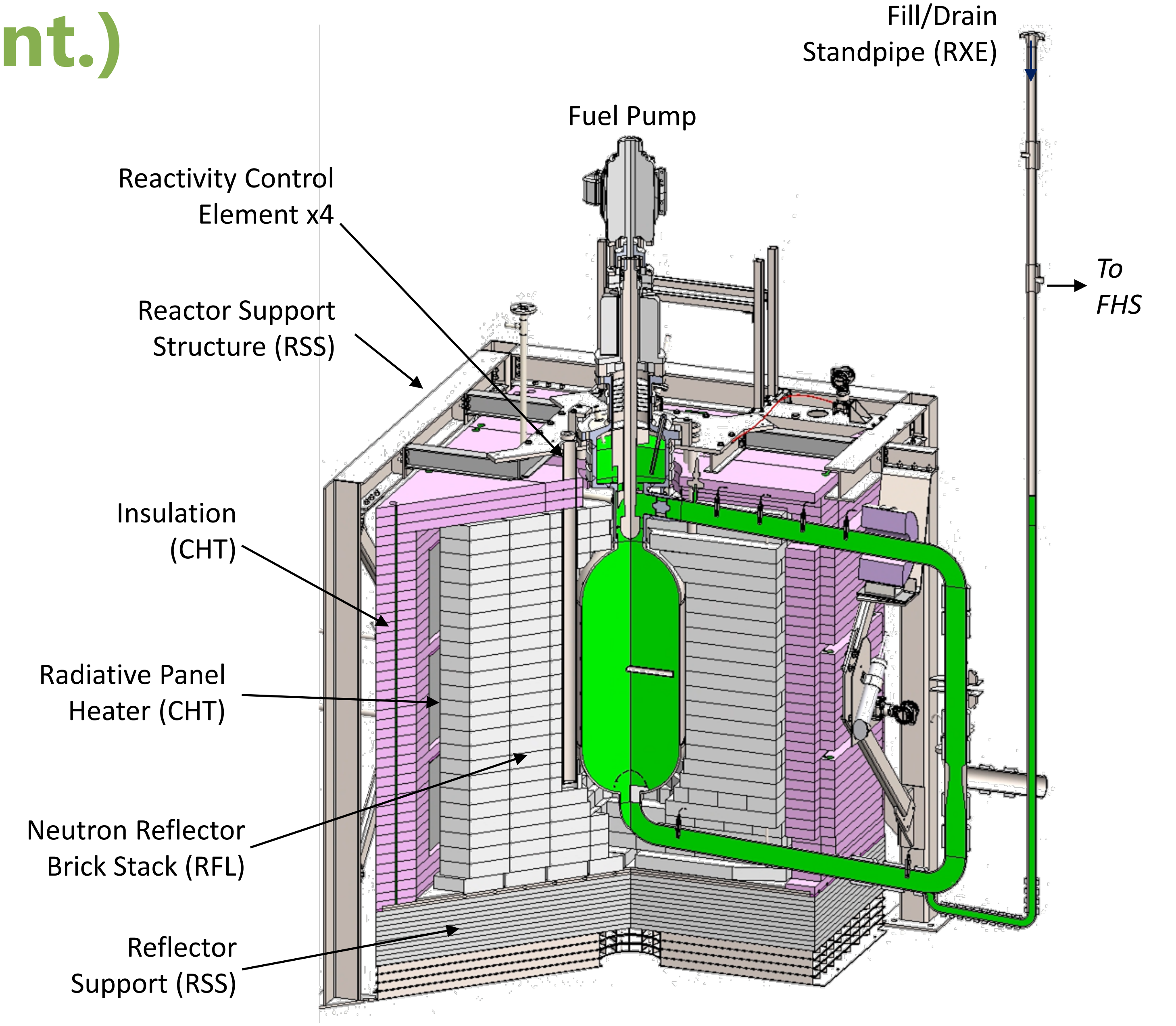
Reactor Design (cont.)

Reactor Core System (RCS)

- Reactor Enclosure System (RXE)
  - Vessel & loop
  - Fill/drain standpipe
- Neutron Reflector System (RFL)
  - High density, high purity MgO bricks
- Reactor Support System (RSS)
  - Reactor support
  - Reflector support
- Core Heating System (CHT)
  - Radiative heater panels
  - Rigid insulation

- Fuel Pump
  - Pump case
  - Rotating assembly
  - Level standpipe



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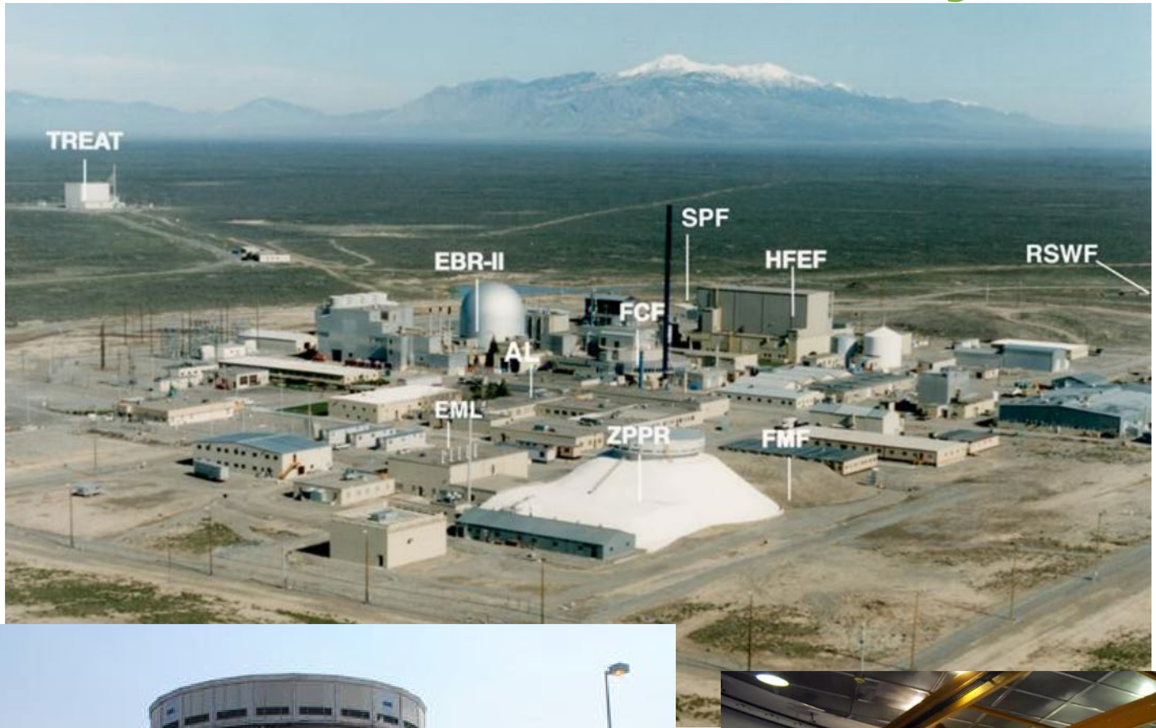
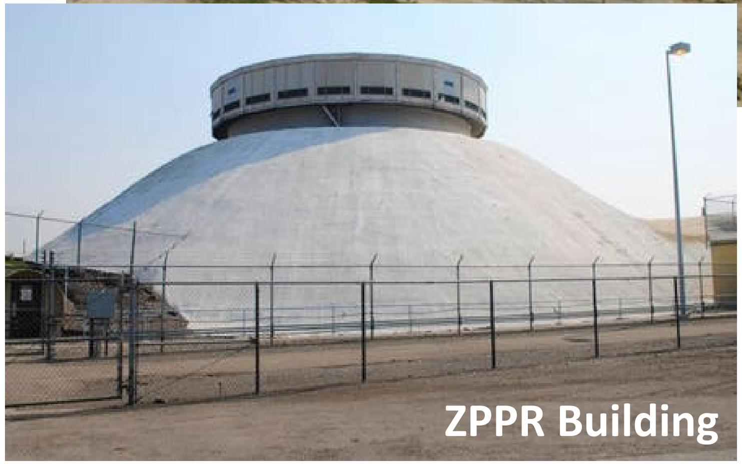
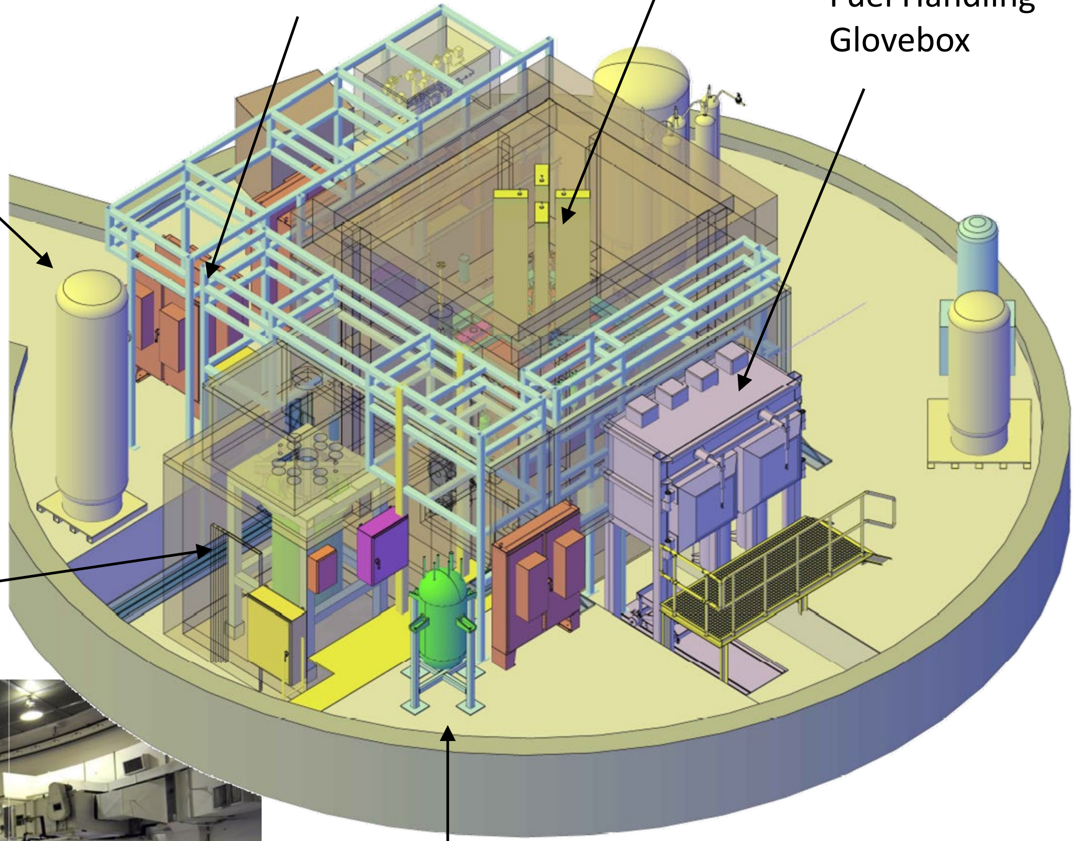
MCRE is planned to be DOE Authorized at INL ZPPR Cell/Facility (LOTUS)



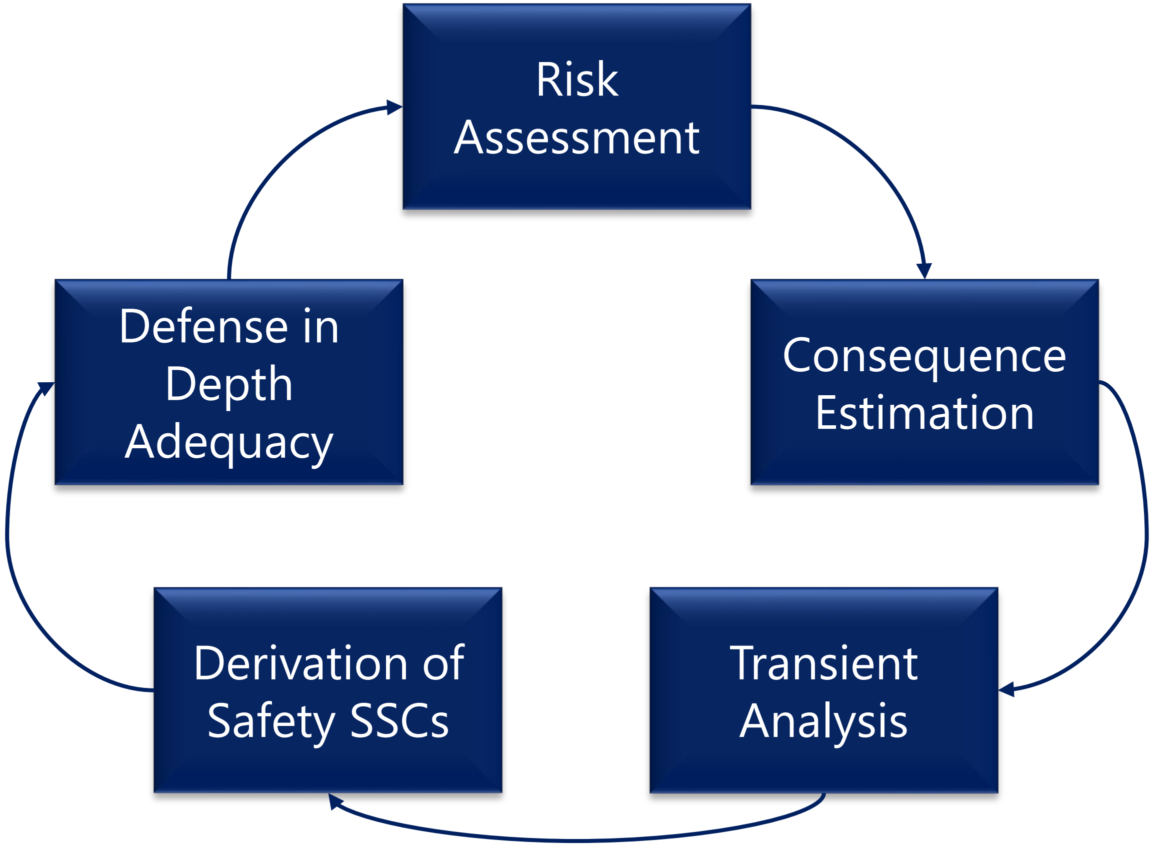




Reactor Safety Philosophy

- Built around satisfying 4 Fundamental Safety Functions
  1. Control of heat generation
  2. Control of heat removal
  3. Retention of radionuclides
  4. Shielding* (project decision to add for worker protection)

- Utilizing the LMP methodology described in NEI 18-04 to develop a RIPB safety case
- Integration of safety in the design
  - Consideration of both safety and experimental requirements
  - Coordination with operations to ensure experiments can be conducted safely



<u>First time for a liquid-fueled MSR</u>

The TP, SCS, INL Safety Team has completed a *full cycle* of the RIPB approach to systematically investigate the safety of MCRE and continuously integrate safety into the design

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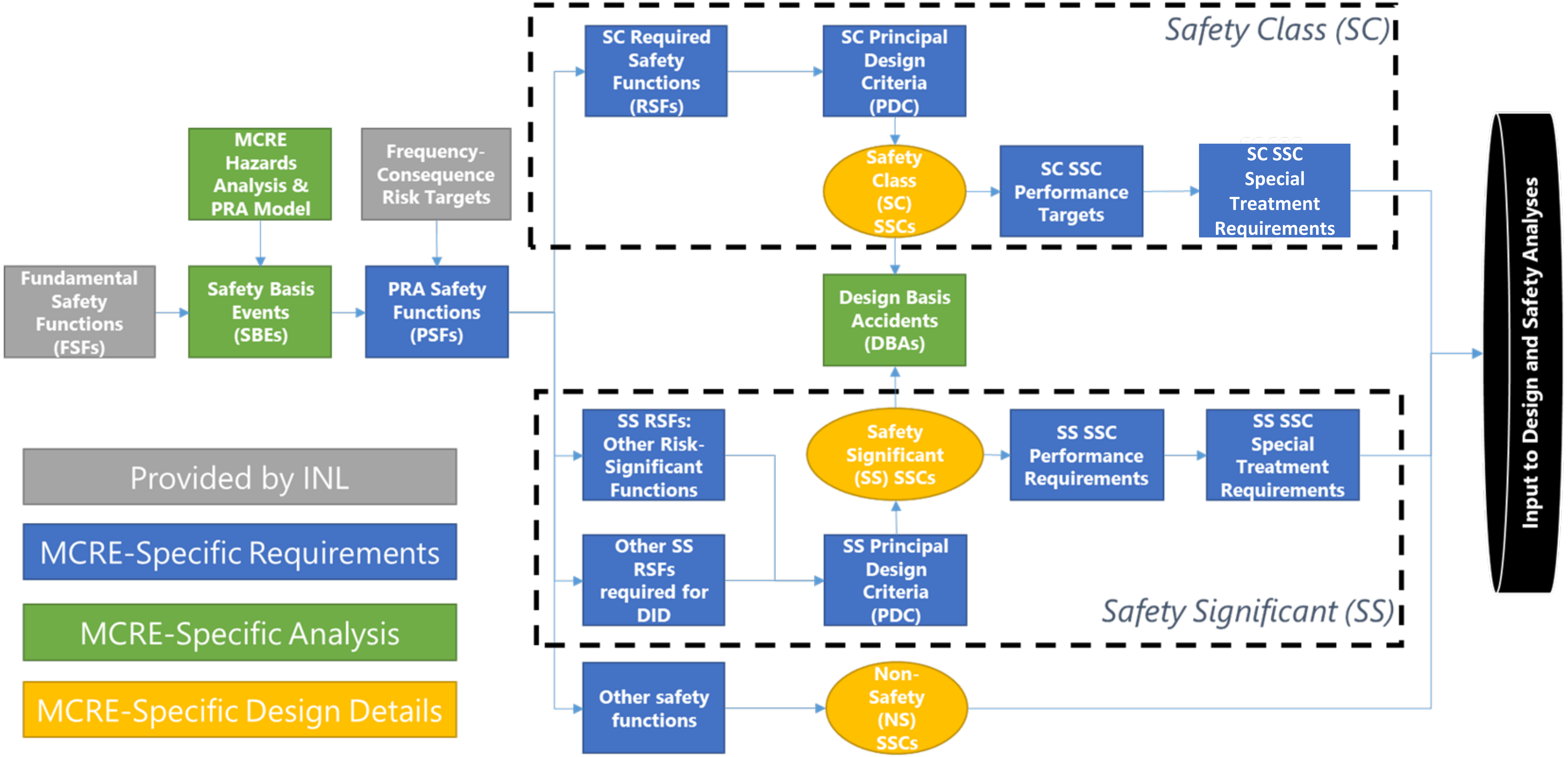
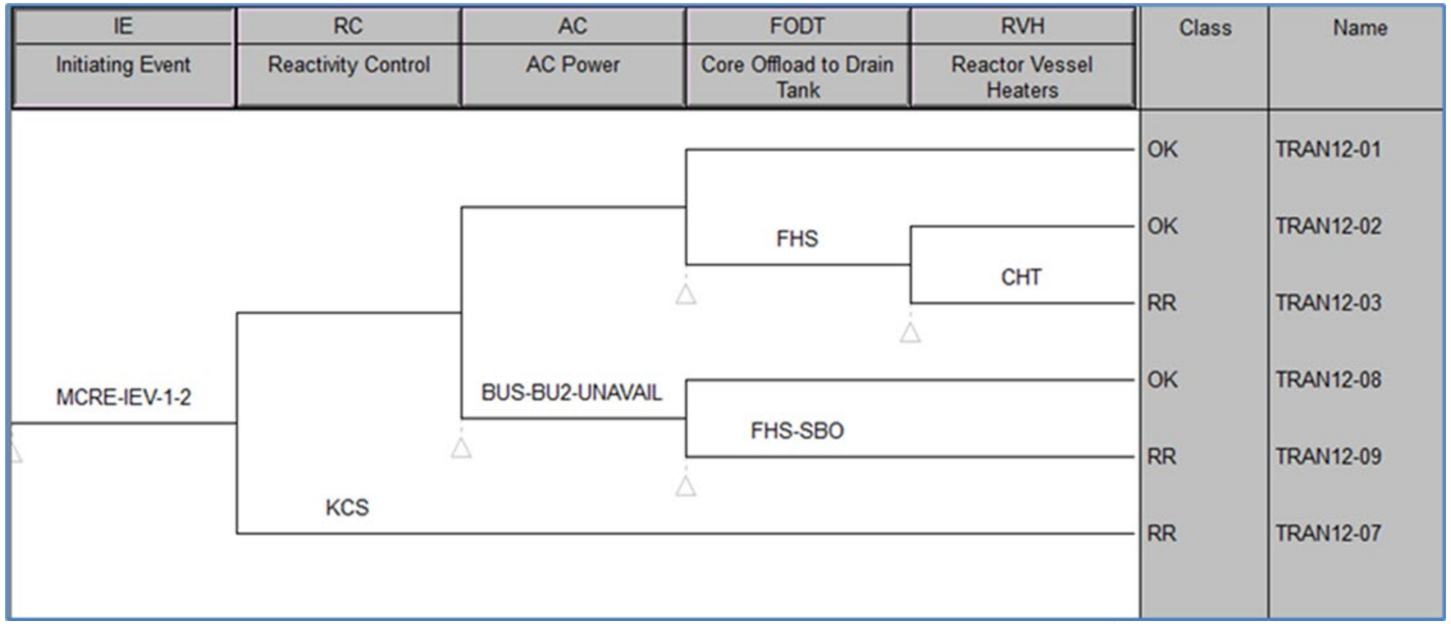
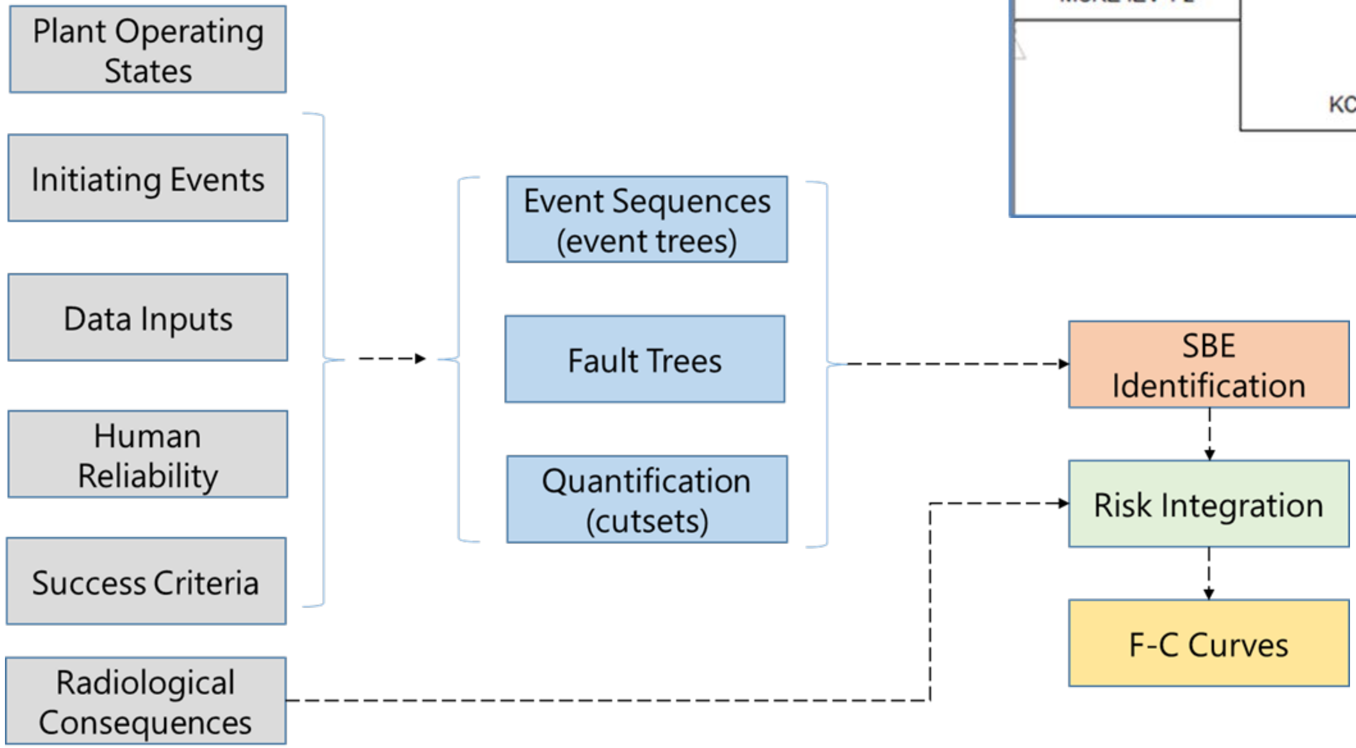
MCRE Safety Case Strategy



MCRE Probabilistic Risk Assessment (PRA)

- PRA used to identify and select Safety Basis Events (SBEs)
- Performed consistent with ASME/ANS RA-S-1.4-2021



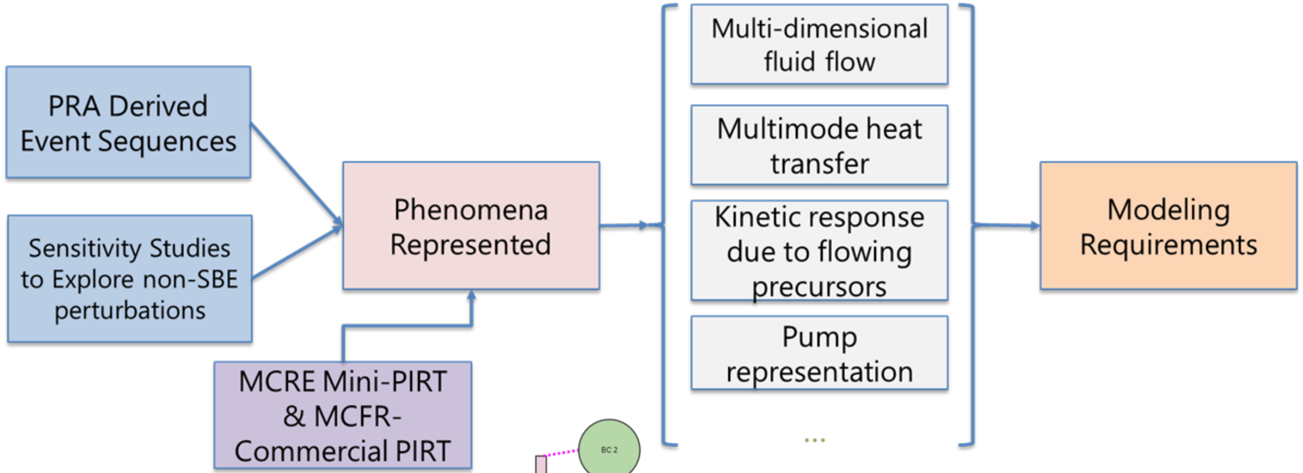


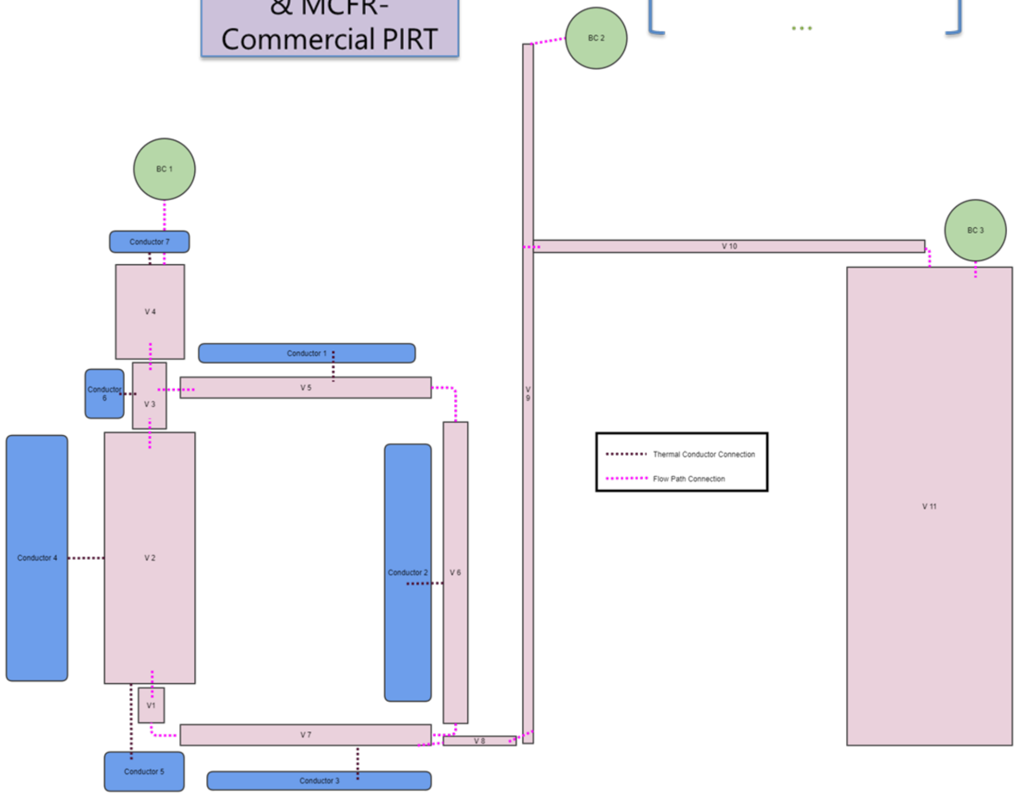
- The MCRE PRA models four distinct PRA safety functions (PSFs)
- A PRA Plan was developed for MCRE, consistent with DOE-STD-1628-2013

Analysis of Safety Basis Events (SBEs)

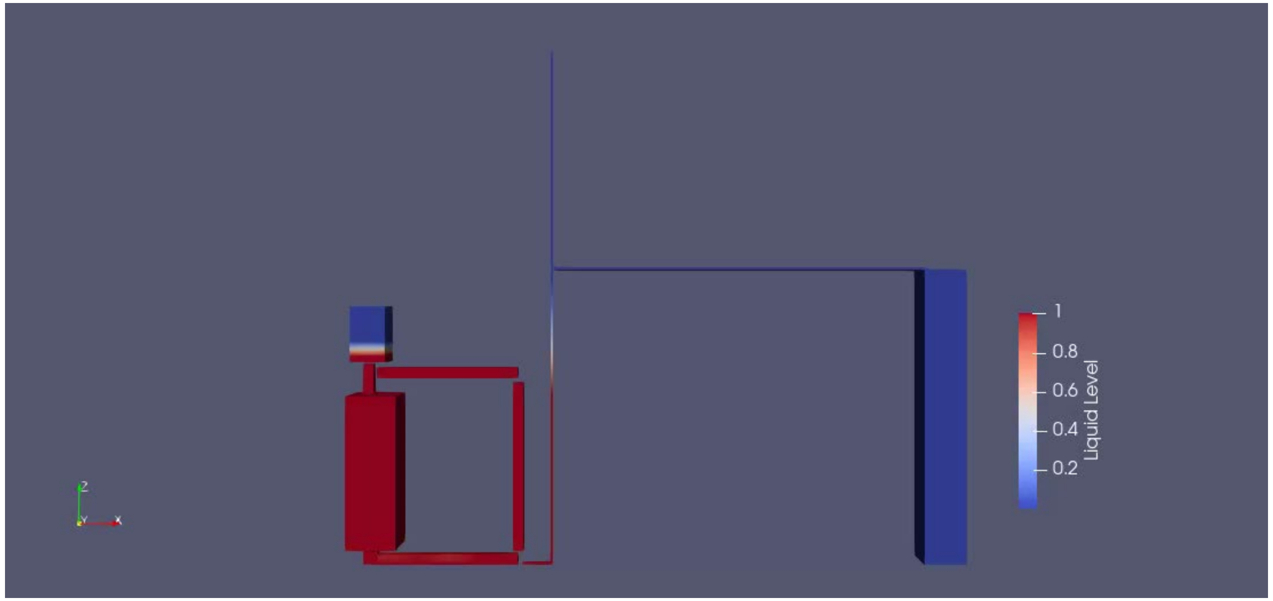
The GOTHIC code was used to develop a "systems level" model of MCRE to consider the coupled thermal-hydraulic and nuclear kinetic response of the system. The MCRE model:

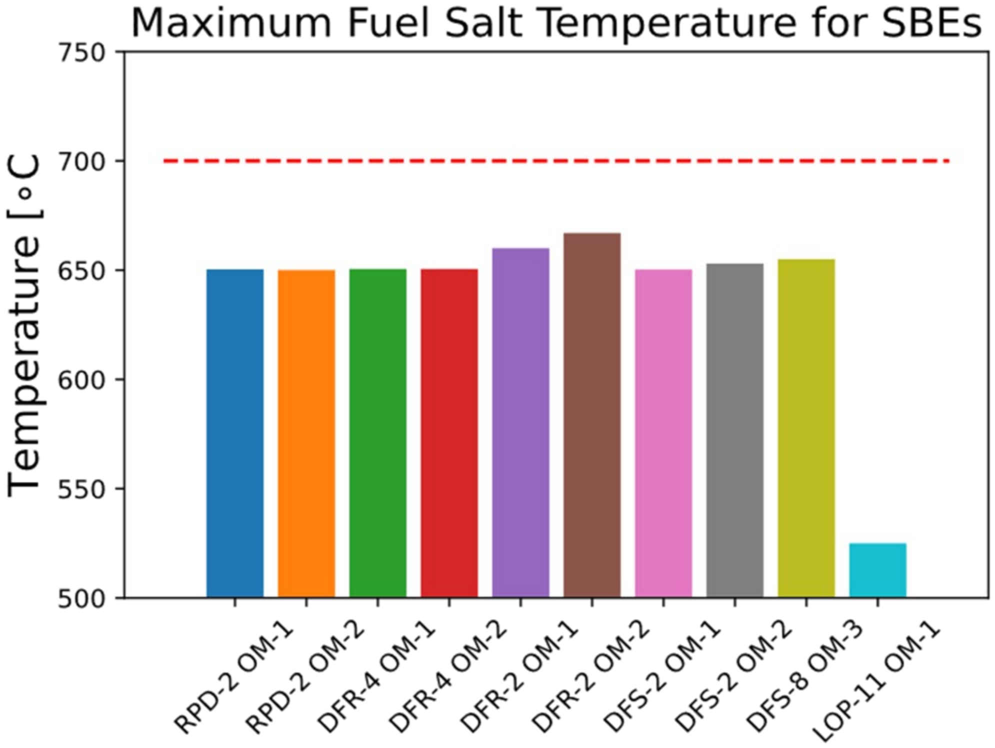
- Consists of lumped and subdivided volumes connected by flow paths
- Considers fluid flow in up to three dimensions (3D)
- Includes multimode heat transfer, radiative, convection, and conduction from fuel to surrounding structures
- Represents plant components (e.g., Pump) and reactor response (SCRAM)
- Utilizes a modified point kinetics scheme to account for reactivity changes due to flow variations
- Tracers track delayed neutron precursors entrained in the flow in up to three dimensions





Safety Basis Events (SBEs) - Results



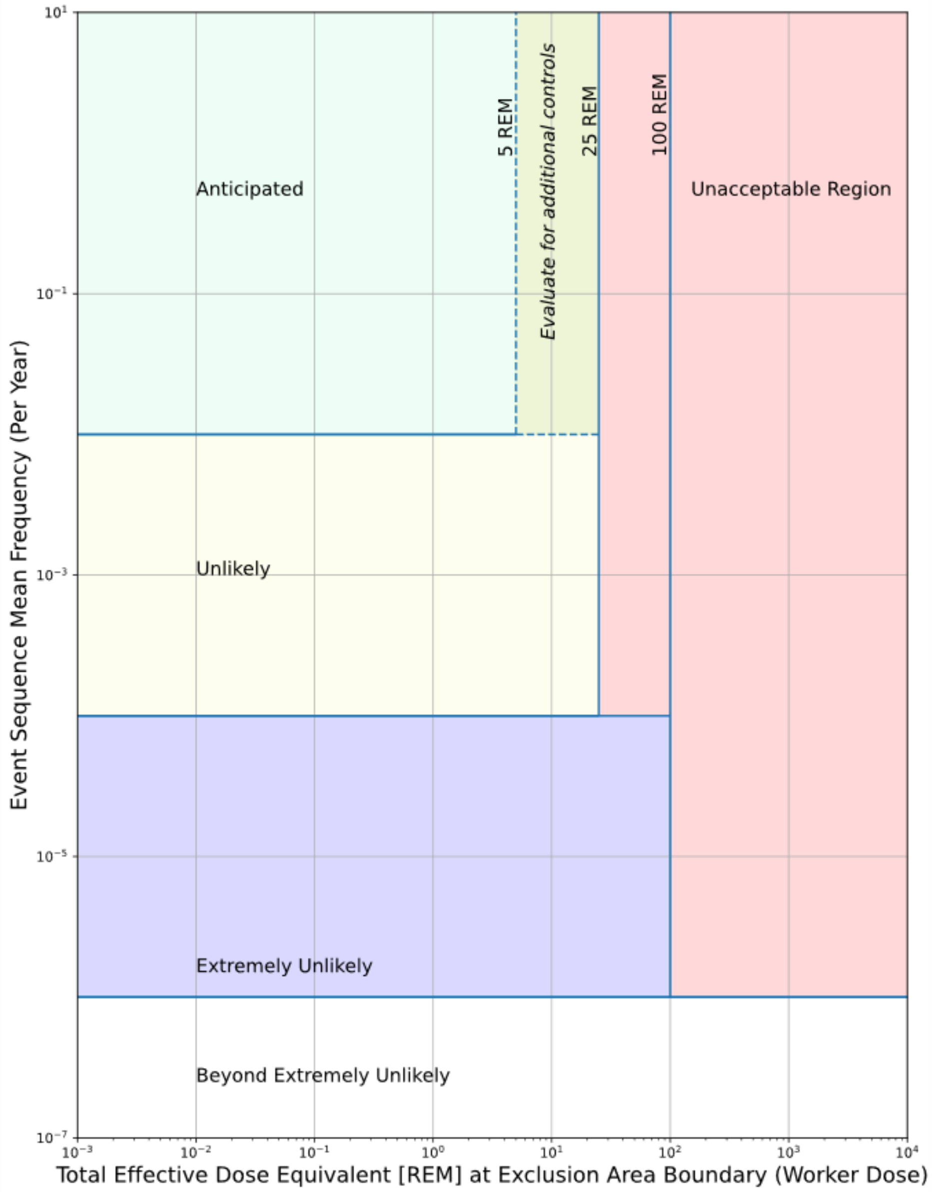


GOTHIC models were used to represent MCRE steady-state conditions, transient behavior representative of the SBEs, and fuel salt pneumatic transfers

Simulations of SBEs showed significant margin to temperatures that could challenge fuel salt barriers

Safety Classification of Systems, Structures, and Components

- A Mechanistic Source Term (MST) was developed to enable assessment of risk in terms of frequency and consequence for the MCRE SBEs
- MCRE structures, systems, and components (SSCs) were categorized as Safety Class, Safety Significant, or Non-Safety based upon DOE-ID guidance
- The safety classification for the MCRE Conceptual Design was conducted at the system level and will be flowed down to individual components as the design matures
- Safety classification included consideration of uncertainties and associated design and safety margins
- Criticality safety considerations play a significant role in MCRE SSC safety classification



Defense-in-Depth (DID) Adequacy

- The MCRE safety case implements the RIPB evaluation of DID process described in NEI 18-04
- ***Margins associated with design maturity*** were incorporated via simplifying and bounding assumptions
- ***Margins associated with adequate DID*** include elevation of certain functions to a Safety Significant classification
- ***Margins associated with parameter uncertainties*** have been handled by a combination of conservative assumptions, sensitivity studies, and quantification of uncertainty. Some of these may be able to be refined as additional data is gathered

Future Work – MCRE Safety Analyses
Uncertainty quantification of SBEs
Estimation of salt freezing time in standpipes
Evaluation of the applicability of underlying correlations in systems models
Characterization of fuel salt leak rates
Development of GOTHIC models for Separate Effects Tests (SETs)
Plant-level Process Hazards Analysis (PHA)
Refinement of system leak response
Salt leak propagation and formation analysis
System overpressure analysis
Seismic two-over-one analyses
Refinement of reliability analyses
Harmonic and voltage drop calculations

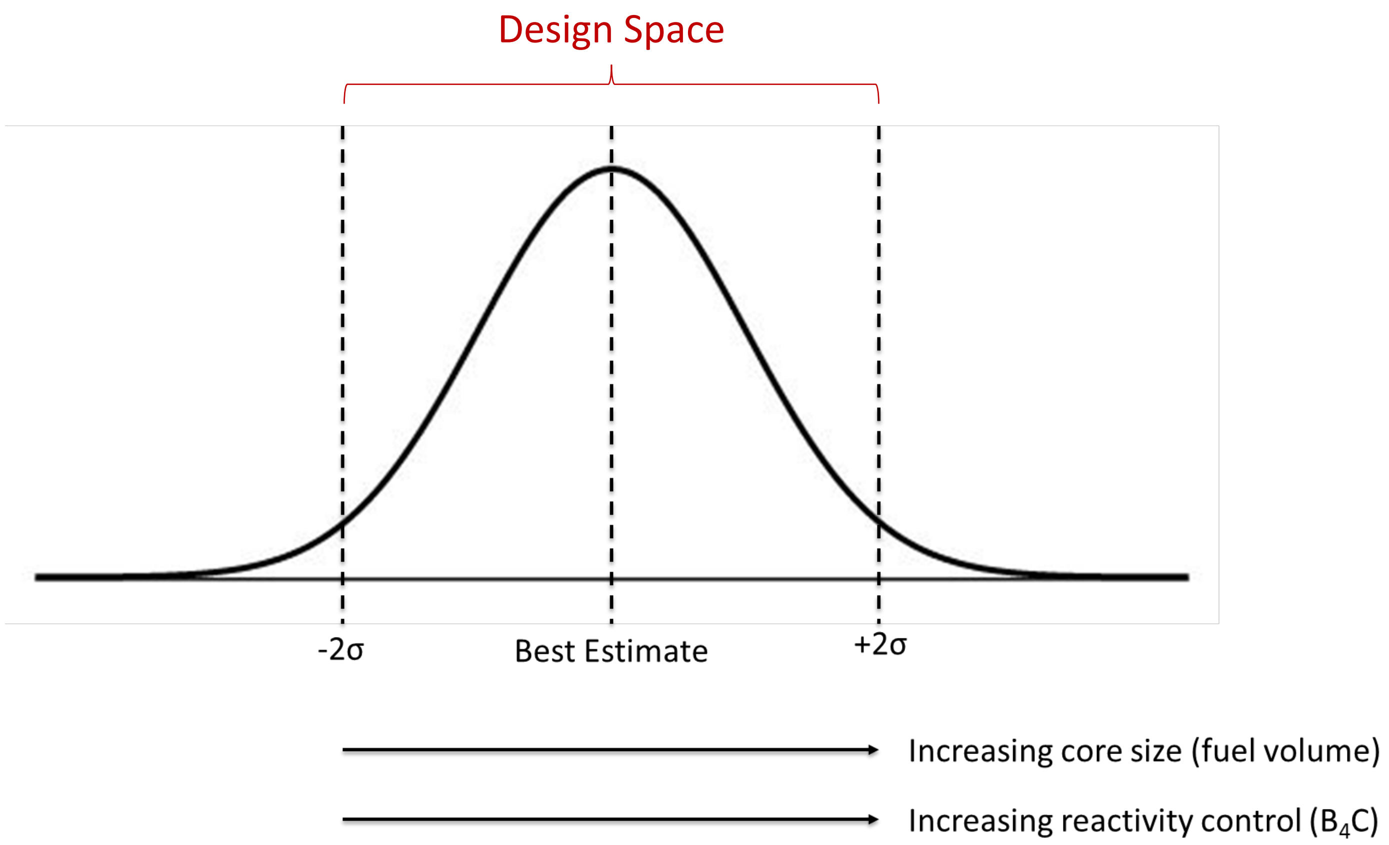
Uncertainty in where MCRE goes critical is quantified and factored into the design

- This is why we are doing MCRE → **find critical point**
- Reactor is oversized
- Reactivity control is oversized

Primary Contributors (35Cl Nuclear Data, Fuel Salt Density, Nuclear Data (all other))

DOE GAIN Voucher – LANL measured ^{35}Cl cross sections in MCRE's energy range (35Cl Nuclear Data)

Components of Uncertainty
^{35}Cl Nuclear Data
Fuel Salt Density
Nuclear Data (all other)
UCl_3 Molecular Composition
Uranium Enrichment
Active Core Diameter
Active Core Height
Vessel Thickness
Alloy 625 Composition
Lower Vessel Head Thickness
Upper Vessel Head Thickness
Monte Carlo Statistics



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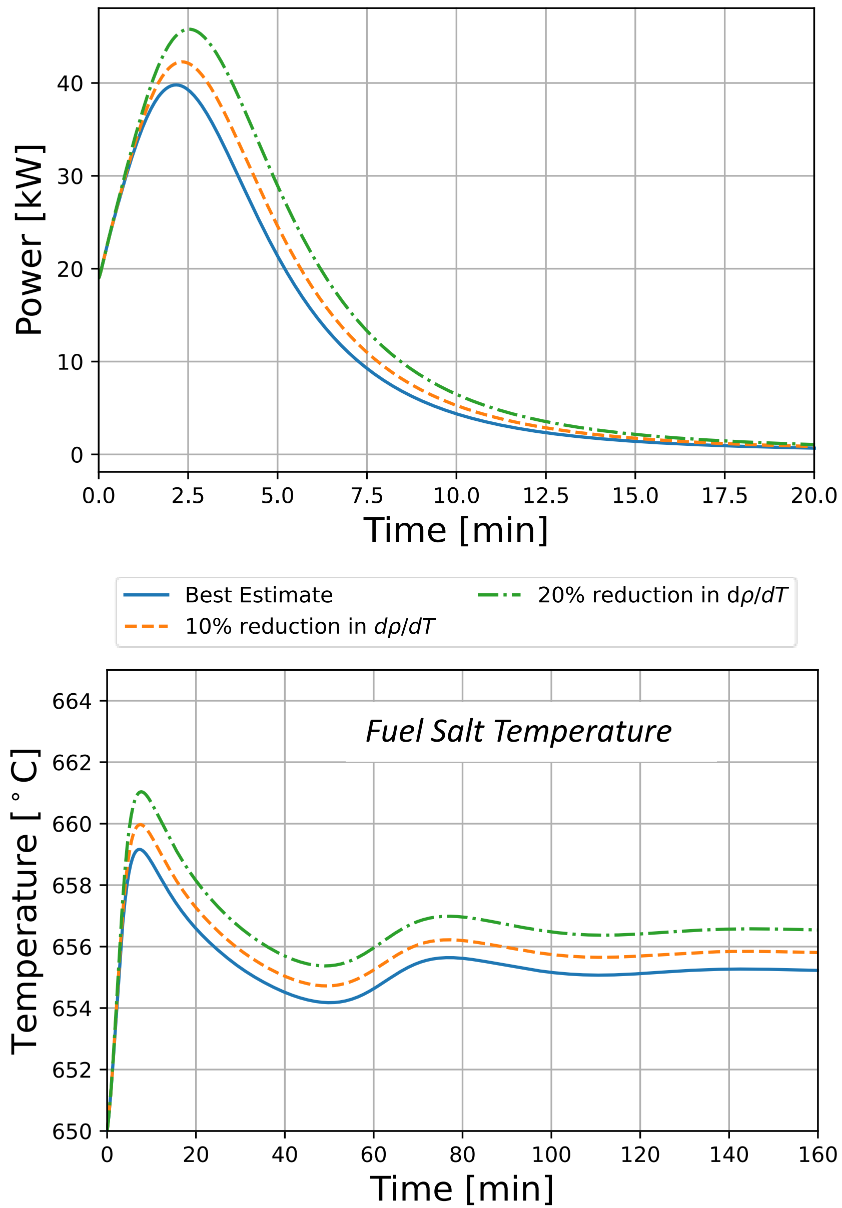
Managing MCRE uncertainties

Uncertainty	*Approach for management*
Component reliability; frequency of SBEs	Uncertainty of failure rate data was explicitly incorporated into MCRE PRA model; 95th percentile frequency estimate was used in evaluating SBE F-C margins.
System behavior (e.g., reactivity balance and timescale of temperature transient) during long-term cooldown of salt following SCRAM without heat addition	SBEs involving failure to drain and lack of ability to add heat from core heaters are assumed to result in release of full inventory of fuel salt; additionally, MCRE mockup and flush salt operations will provide data to support understanding of cooldown timing.
Retention of various radionuclides by fuel salt; volatility of various chemical species	Conservative estimates for isotopic composition of radioactive material released (i.e., burnup calculations) and for radioelement release fractions have been assumed.
Fuel salt behavior outside of an inert atmosphere (e.g., hydration, oxidation of salt)	Conservative assumptions have been made regarding salt composition; experiments being conducted on representative salt samples to understand chemical interactions with air/moisture.
Modeling uncertainty in system-level analyses (e.g., GOTHIC analyses); relative scarcity of relevant benchmarks	Sensitivity studies will be conducted to understand relative importance to a variety of parameters (e.g., fuel salt performance characteristics); analysis will be performed to characterize underlying empirical relationships in software (e.g., GOTHIC) and the applicability to the MCRE flow regime; comparison of simulation to as-built pumped salt loops (e.g., MCRE mockup, flush salt operations in MCRE) will provide opportunities for validation.
Lack of cross section data propagating into reactivity calculations for initial criticality of system	Dedicated analysis and inclusion of significant design margin in KCS.

One full *cycle* of the risk-informed licensing process completed

- Probabilistic Risk Assessment (PRA) derive Safety Basis Events (SBE)
  - 17 SBEs evaluated explicitly – **all remain under the 700°C design temperature**
- Dose consequence compared with likelihood of events
  - To determine Frequency-Consequence plots
- All used to derive Structures, Systems, Components (SSC) Classification and show Defense in Depth (DID) adequacy
- Safety Design Integration Team (INL + SO + TP) convened to agree on SSC Classification proposed
- Conceptual Safety Design Report (CSDR) was submitted to DOE June 2023

Unprotected Loss of Forced Flow (ULOFF)



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MCRE MOLTEN CHLORIDE REACTOR EXPERIMENT

ARDP Risk Reduction

MCRE is in Preliminary Design Phase and focused on construction of a non-nuclear Mockup at TerraPower's Everett, WA Lab

2020 | 2021 | 2022 | 2023 | 2024

Conceptual Design

Preliminary Design

MCRE Mockup

Construction

Salt Ops

Operator Training

Safety Design Strategy (SDS) submitted to DOE

Conceptual Design Safety Report (CSDR) submitted to DOE

Preliminary Document Safety Analysis (PDSA) planned to be submitted to DOE

Mockup Objectives

1. Confirm engineering design
2. Validate thermal-fluid models
3. Inform operational procedures
4. Support INL field operator training
5. Support INL Operational Readiness Review (ORR)

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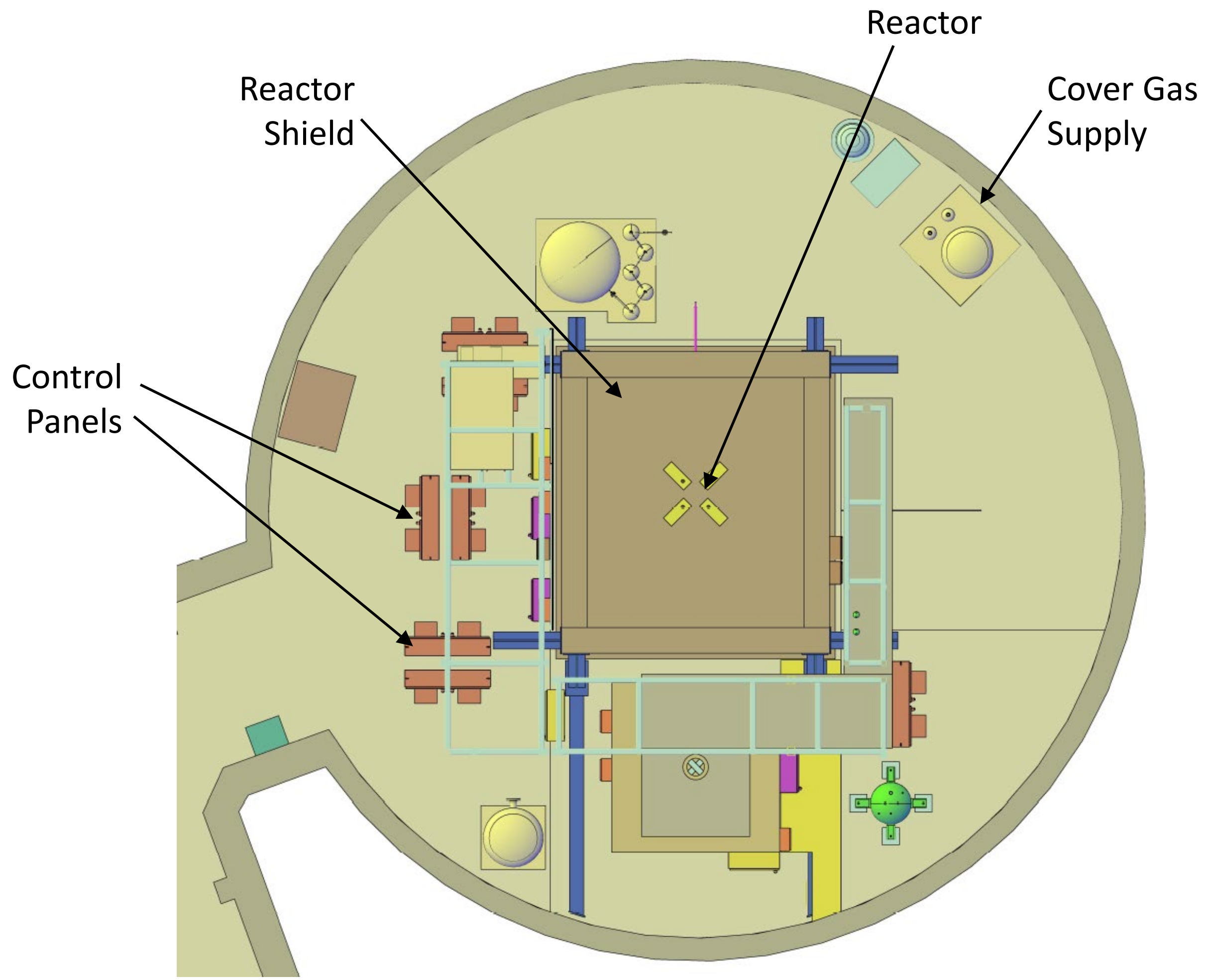
21 Reactor Experiments Planned

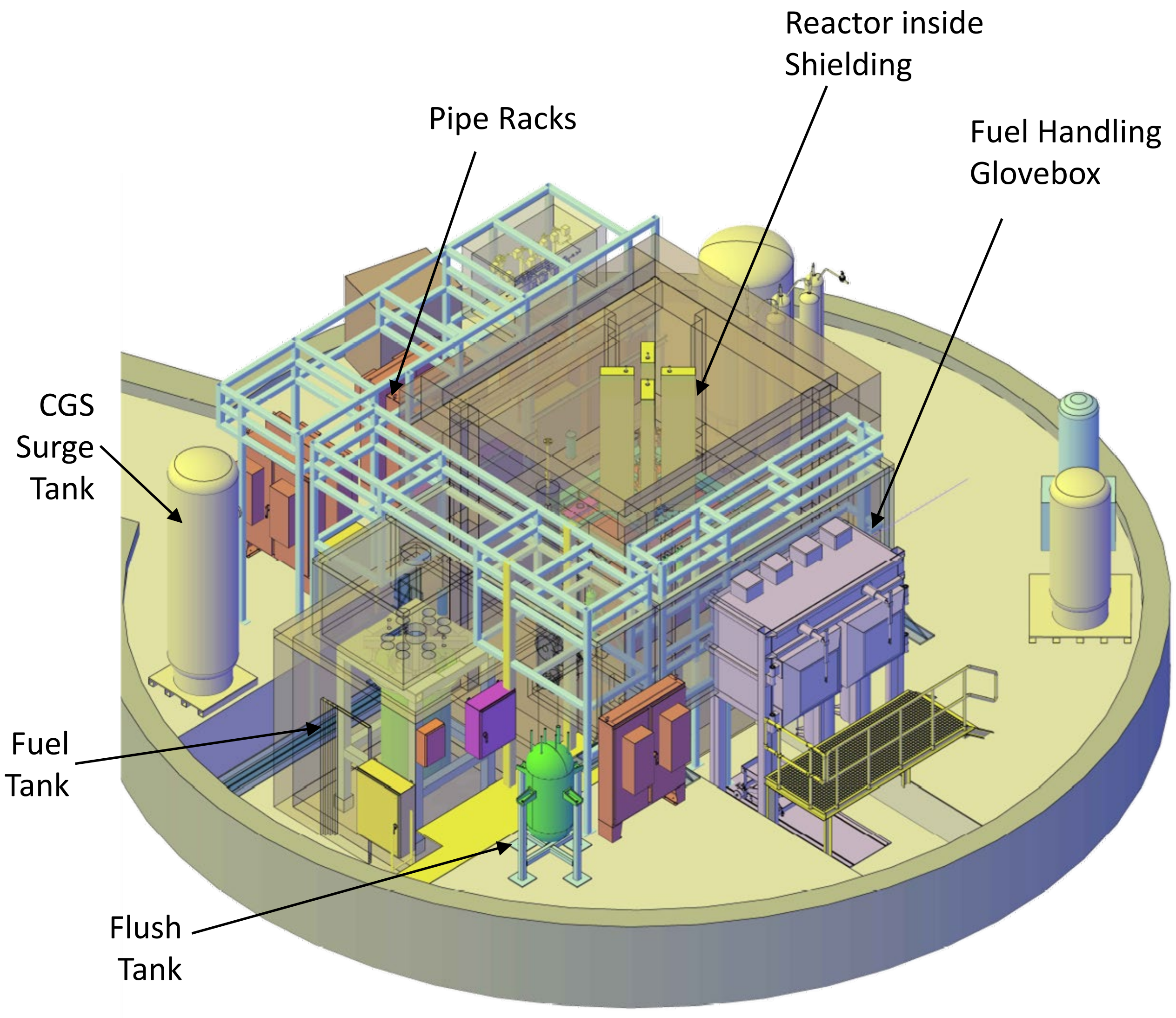
Criticality	**1**	**Approach to Criticality (~650℃)**
Reactor Characterization	2	Determination of Reaction Rates of Fissionable Materials via Wire/Foil Irradiation
	3	Determination of the Neutron Spectrum via Wire/Foil Irradiation
	4	Measurement of the Gamma Flux outside the Neutron Reflector
	5	Differential and Integral Control Rod Worth with no Forced Flow
	6	Differential and Integral Control Rod Worth at Multiple Flowing States
	7	Differential Control Rod Worth at Multiple Fuel Salt Temperatures
	8	Determination of the Dynamic Reactivity Response during Pump Startup
	9	Determination of the Dynamic Reactivity Response during Pump Coastdown
	10	Isothermal Temperature Coefficient
Neutron Kinetics	11	β_{eff} Determination with no Forced Flow
	12	β_{eff} Determination at Multiple Flow Rates
	13	Kinetics Measurements using Alpha (Prompt Neutron Decay Constant) Measurement Techniques
	14	Kinetics Measurements using Noise Analysis
	15	Periodic Perturbations for Stability Analyses
Reactivity Feedback	16	Dynamic Response to Reactivity Insertions
	17	Demonstration of the Load Following Response
	18	Dynamic Reactivity Response during Pump Startup and Coastdown with Thermal Feedback
	19	Dynamic Reactivity Experiments via Rapid Step Control Element Insertions
	20	Unprotected Loss of Forced Flow
	21	Demonstration of the Transition to Low Power Critical

Subject to DOE Cooperative Agreement No. DE-NE0009045

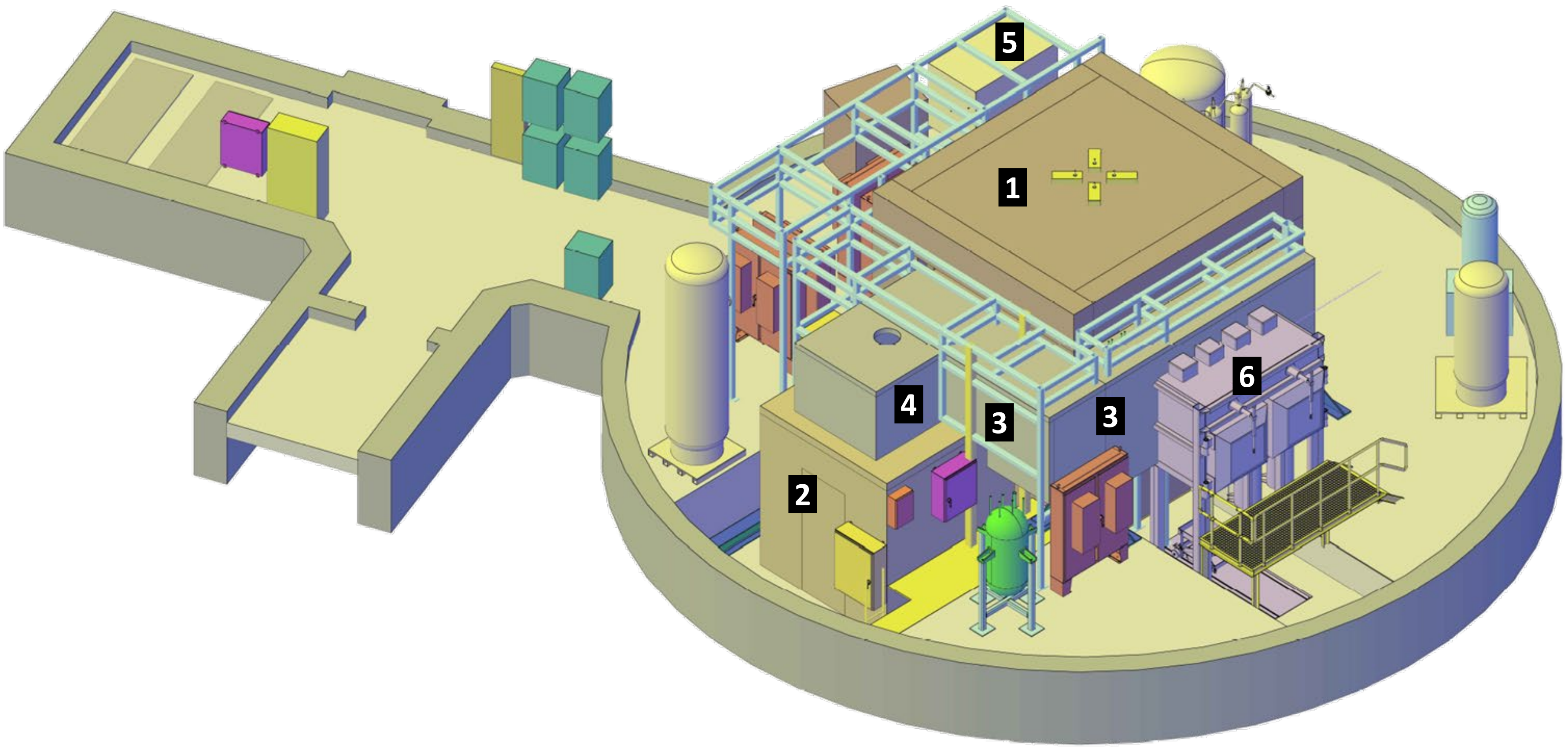
MCRE is in the Preliminary Design Phase (60%)

- LOTUS cell is quickly filling up
  - 90+% of equipment has been located within LOTUS plant model





Shielding located around reactor, fuel tank, fuel piping, CGS condensers, CGS scrubber, and fuel handling glovebox



1 Reactor
2 Fuel Tank
3 Fuel Piping
4 CGS Condenser
5 CGS Scrubber
6 Fuel Handling Glovebox

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