Kairos Power

KP-NRC-2204-007

April 15, 2022

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US Nuclear Regulatory Commission
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Subject: Kairos Power LLC
Presentation Materials for Kairos Power Briefing to the Advisory Committee on Reactor Safeguards, Kairos Power Subcommittee, on Design Overview for the Hermes Non-Power Reactor

This letter transmits presentation slides for the April 21, 2022, briefing to the Advisory Committee for Reactor Safeguards (ACRS), Kairos Power Subcommittee. At the meeting, Kairos Power will provide an overview of the design of the Hermes non-power test reactor which is currently under NRC staff review for a construction permit. This briefing is intended to provide a high level overview of the Hermes design prior to the ACRS review of the Hermes PSAR.

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If you have any questions or need additional information, please contact Drew Peebles at peebles@kairospower.com or (704) 275-5388, or Darrell Gardner at gardner@kairospower.com or (704) 769-1226.

Sincerely,

Darrell Gardner for

Peter Hastings, PE
Vice President, Regulatory Affairs and Quality

Enclosures:

1) Presentation Slides for the April 21, 2022, ACRS Kairos Power Subcommittee Briefing

xc (w/enclosure):

William Kennedy, Acting Chief, NRR Advanced Reactor Licensing Branch
Benjamin Beasley, Project Manager, NRR Advanced Reactor Licensing Branch
Weidong Wang, Senior Staff Engineer, Advisory Committee for Reactor Safeguards

Enclosure 1

Presentation Slides for the April 21, 2022
ACRS Kairos Power Subcommittee Briefing

Hermes Design Overview

PRESENTATION FOR THE ADVISORY COMMITTEE
ON REACTOR SAFEGUARDS, KAIROS POWER SUBCOMMITTEE

APRIL 21, 2022

Kairos Power's mission is to enable the world's transition to clean energy, with the ultimate goal of dramatically improving people's quality of life while protecting the environment.

In order to achieve this mission, we must prioritize our efforts to focus on a clean energy technology that is *affordable* and *safe*.

Agenda

- Introduction
- Fuel/Core Design
- Reactor Vessel and Internals
- Heat Transport & Pebble Handling and Storage
- Structures
- I&C and Electrical
- Safety Case

Introduction

DREW PEEBLES – LICENSING MANAGER, SAFETY

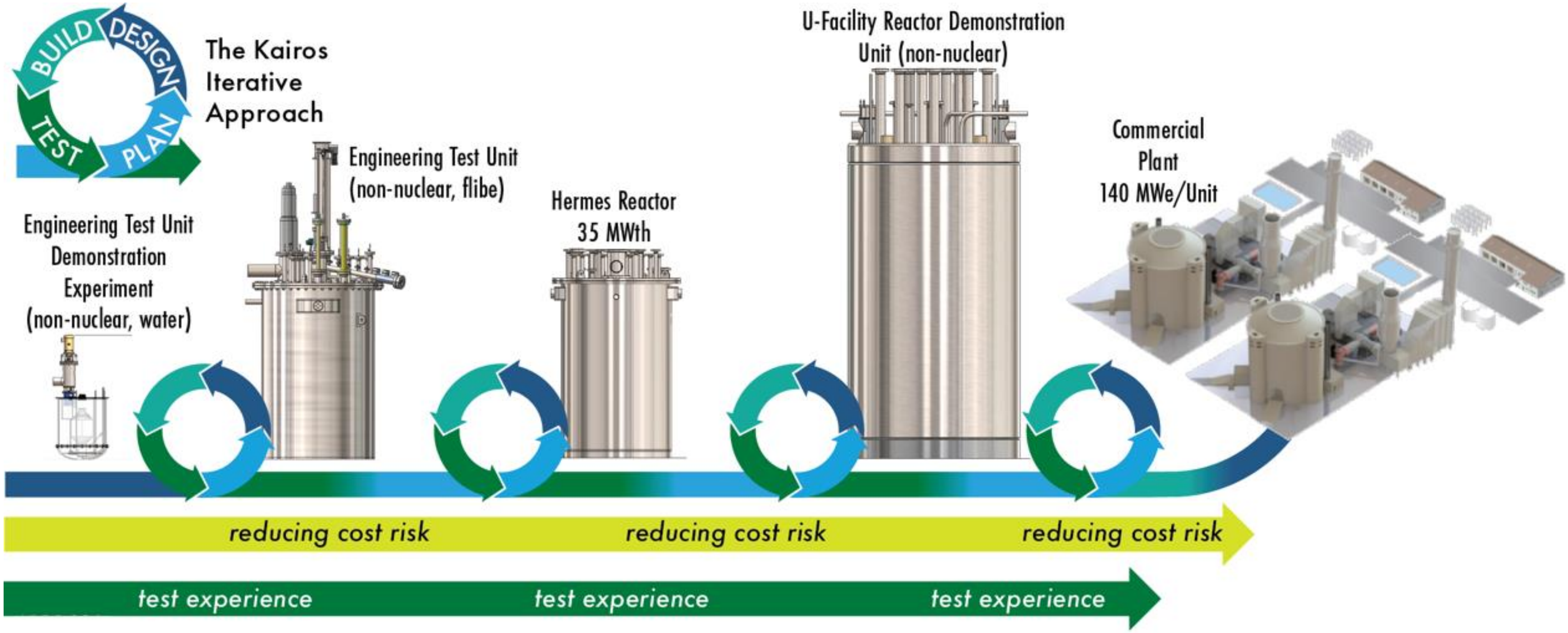
Introducing Kairos Power

- Nuclear energy engineering, design and manufacturing company ***singularly focused*** on the commercialization of the fluoride salt-cooled high-temperature reactor (FHR).
  - Founded in 2016
  - Current Staffing:
    - 269 Employees (***and growing***)
    - ~90% Engineering Staff
- Private funding commitment to engineering design and licensing program and physical demonstration through nuclear and non-nuclear technology development program.
- Schedule driven by the goal for U.S. commercial demonstration by 2030 (or earlier) to enable rapid deployment in 2030s.
- Cost targets set to be competitive with natural gas in the U.S. electricity market.

Kairos Power Headquarters

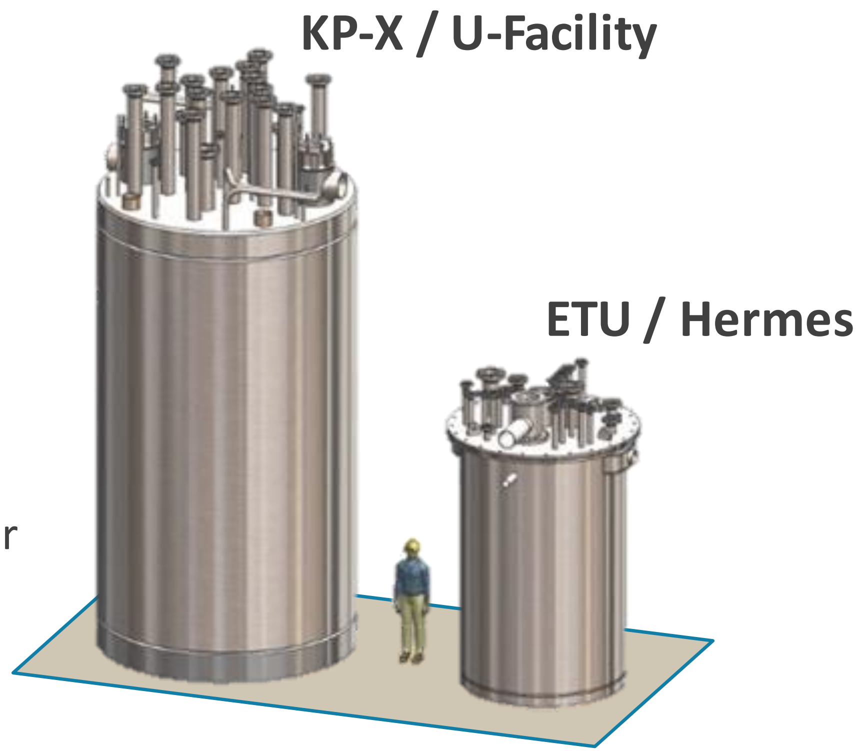
Kairos Power Team

Kairos Power Design Approach



Kairos Power Hermes Reactor Overview

- What?
  - A low power demonstration reactor that will prove Kairos Power's capability to deliver low-cost nuclear heat
- Why?
  - **Cost:** Establish competitive cost through iterative learning cycles
  - **Supply Chain:** Advance the supply chain for KP-FHR specialized components and materials while vertical integrating critical systems
  - **Design / Test:** Deliberate and incremental risk reduction
  - **Licensing Approach:** NRC will license Hermes as a non-power reactor and facilitate licensing certainty for KP-FHR
  - **Operations:** Provide a complete demonstration of nuclear functions including reactor physics, fuel and structural materials irradiation, and radiological controls



Hermes will ultimately demonstrate the U.S. aptitude to license an advanced reactor in a timely manner

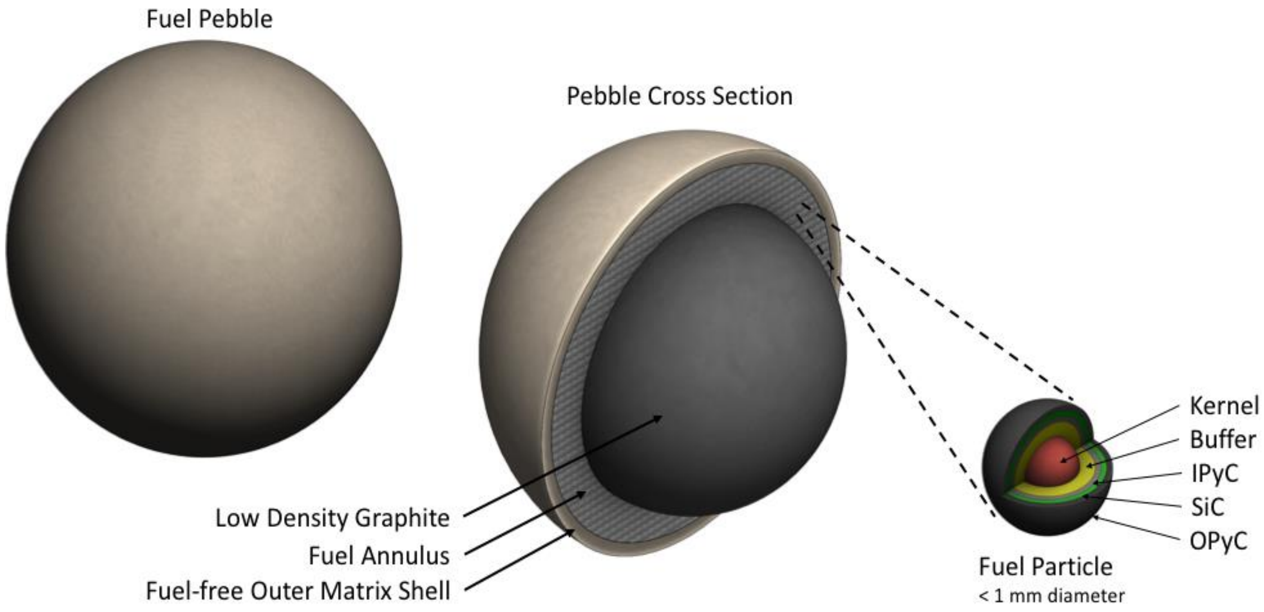
Fuel/Core Design

BRANDON HAUGH – SR. DIRECTOR, MODELING & SIMULATION

NADER SATVAT - MANAGER, REACTOR CORE DESIGN

KP-FHR Uses TRISO Fuel in Pebble Form

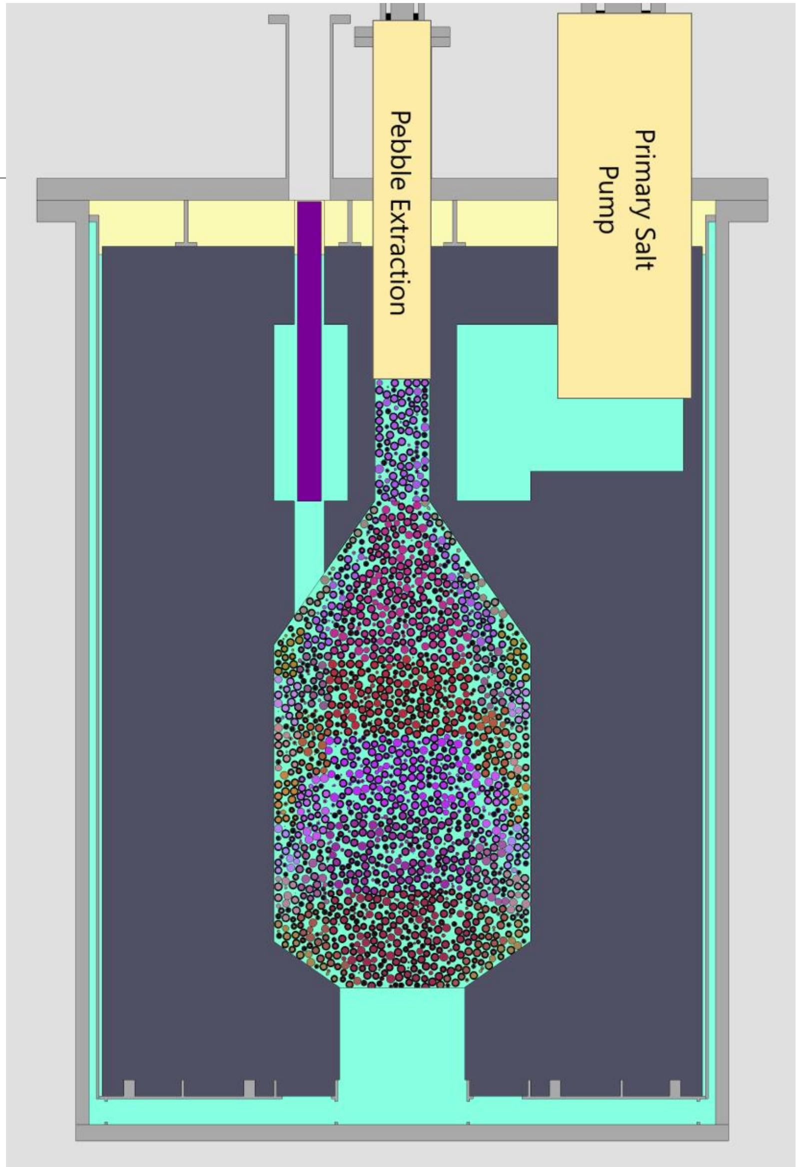
- Fuel Pebble (3 Regions):
  - Innermost portion is a low-density carbon matrix core
  - Fuel annulus - Tri-structural isotropic (TRISO)-coated fuel particles embedded in a carbon matrix
  - Fuel-free carbon matrix shell
- Fuel qualification leverages U.S. DOE Advanced Gas Reactor program
- Core design is a pebble bed concept within a graphite reflector
  - Pebbles are positively buoyant in Flibe
  - Mixture of fuel and moderator pebbles operates with optimal moderation



4.0-cm diameter, annular fuel pebble is the same size as a ping-pong ball

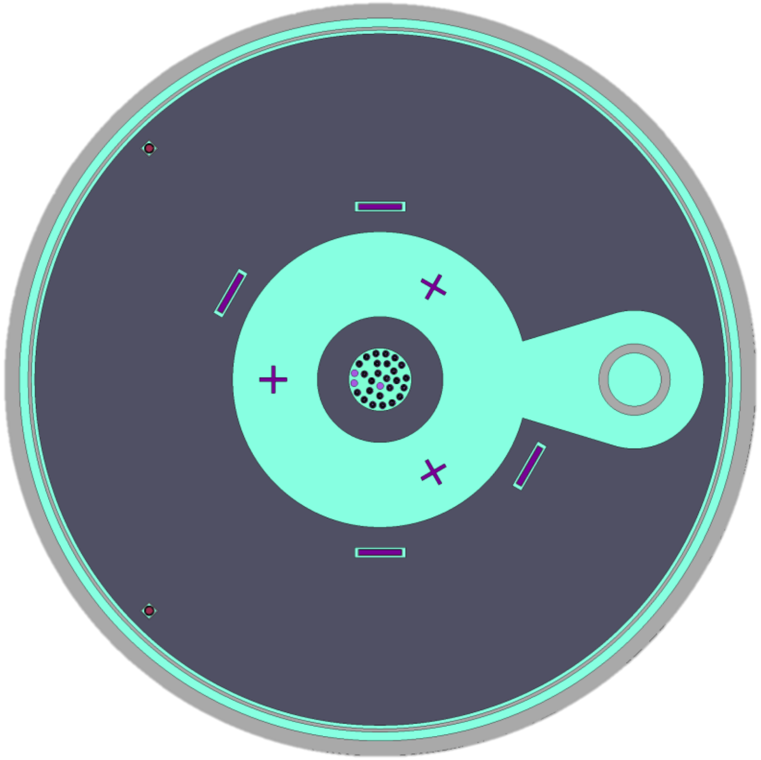
Hermes Core Design

Power:	• 35 MW_{th}
Fuel Cycle:	• 190 days average residence time • 4-6 passes • Discharge burnup 6-8% FIMA
Safety Parameters:	• Overall negative temperature reactivity coefficients • Negative fuel and moderator temperature reactivity coefficients • Negative coolant temperature, and void coefficients
Method for Calculation:	• High-fidelity Serpent 2 and KPACS (Serpent 2/Shuffling)
Power Profile:	• Average Power per pebble = ~1000 W/pebble • Pebble Peaking factor ~2
Coolant:	• Li-7 enrichment level and carbon to heavy metal atom ratio aligned to provide desired temperature reactivity coefficient

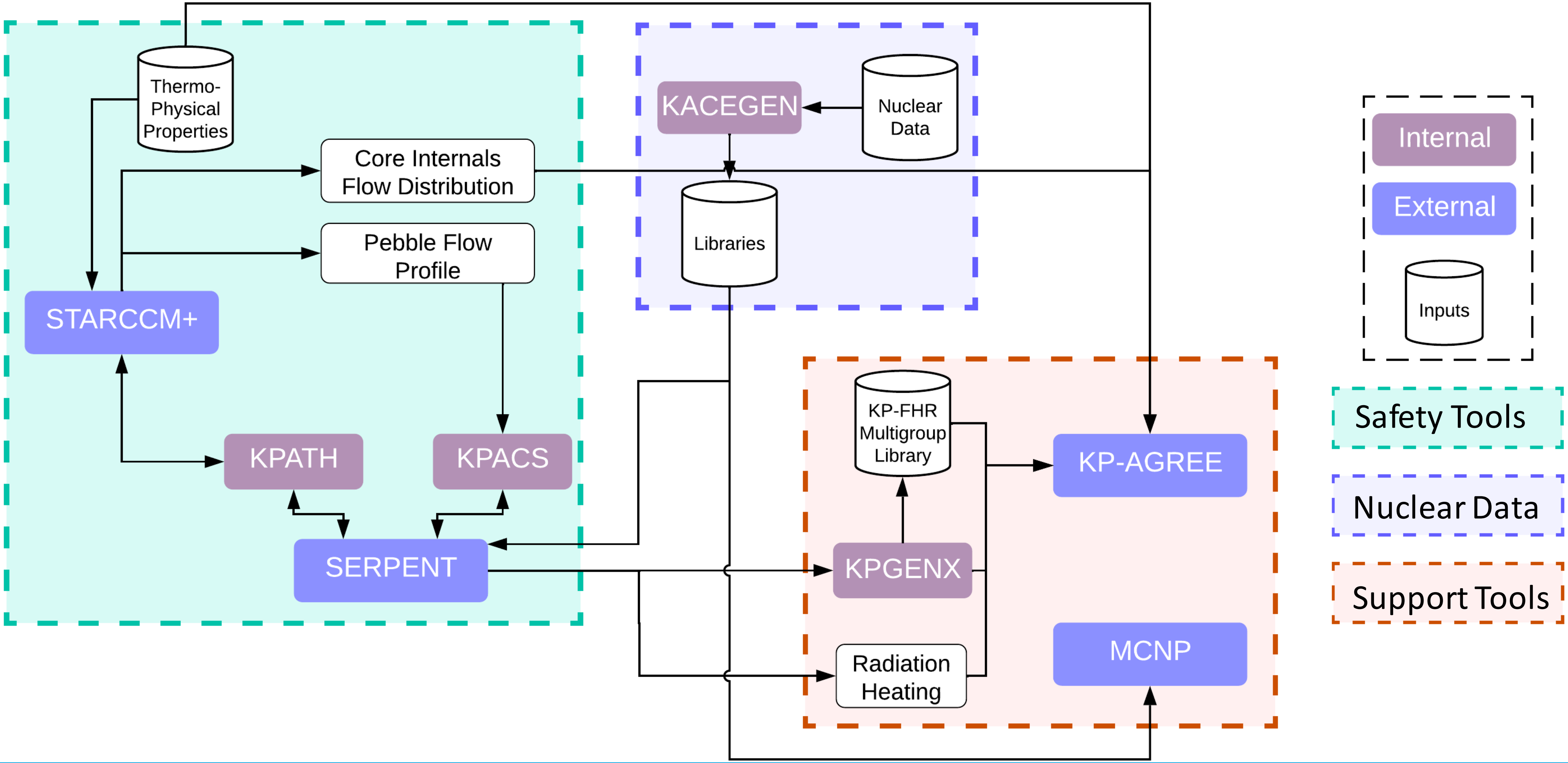


Reactor Control

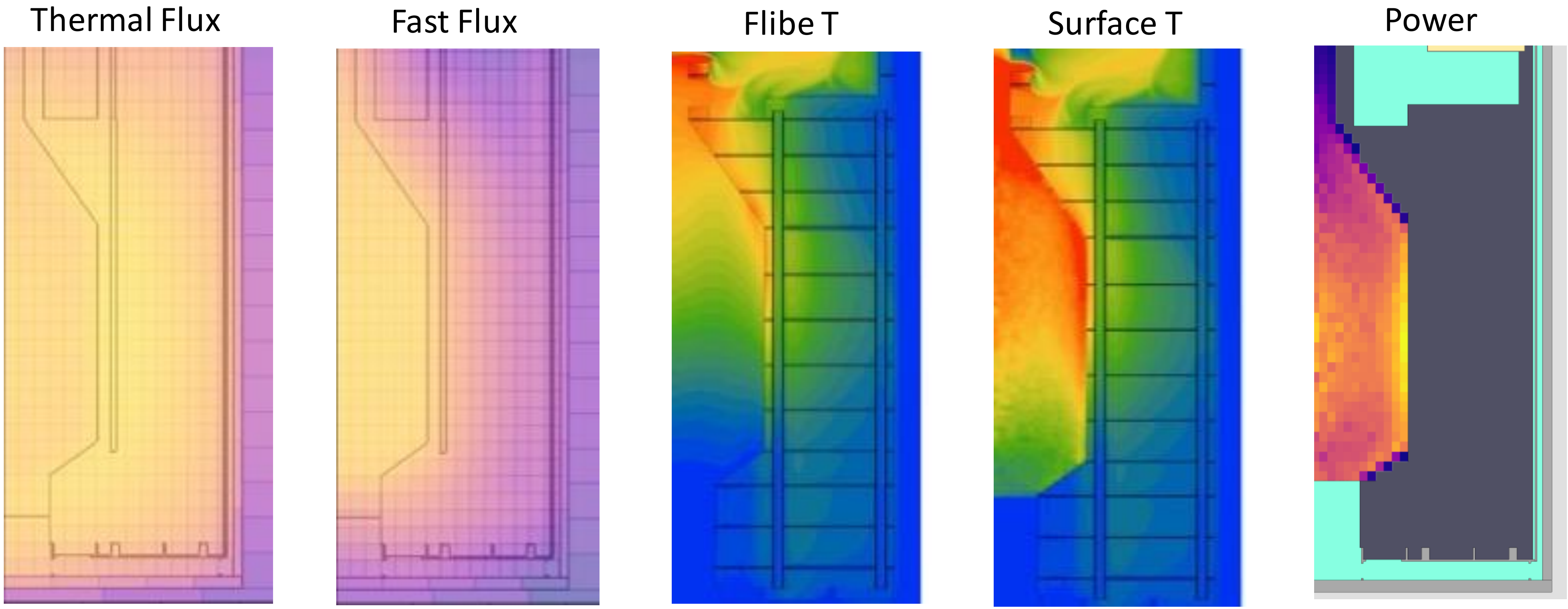
Diversity:	• Reactivity Control System (RCS) • Reactivity Shutdown System (RSS)
Shutdown Margin (SDM) Analysis:	• Compensate power defect, full xenon decay, operational excess reactivity, and B_4C depletion • Single, most reactive rod failure • SDM to k_{eff} of 0.99
Sources of Operational Excess Reactivity:	• Core composition • Compensate change power levels or manage other transients
Method for Calculation:	• High-fidelity coupling tool, KPATH (Serpent 2/Star-CCM+)
Other notes:	• Drive mechanism sets limit on withdrawal rate (rate of reactivity insertion) • KP-FHR has a strong (and prompt) Doppler feedback to reduce regular use of the RCS



Core Design Methodology



Representative Information



$1x10^8$ – $5x10^{14}$ $n/cm^2 \cdot s$

550-700 °C

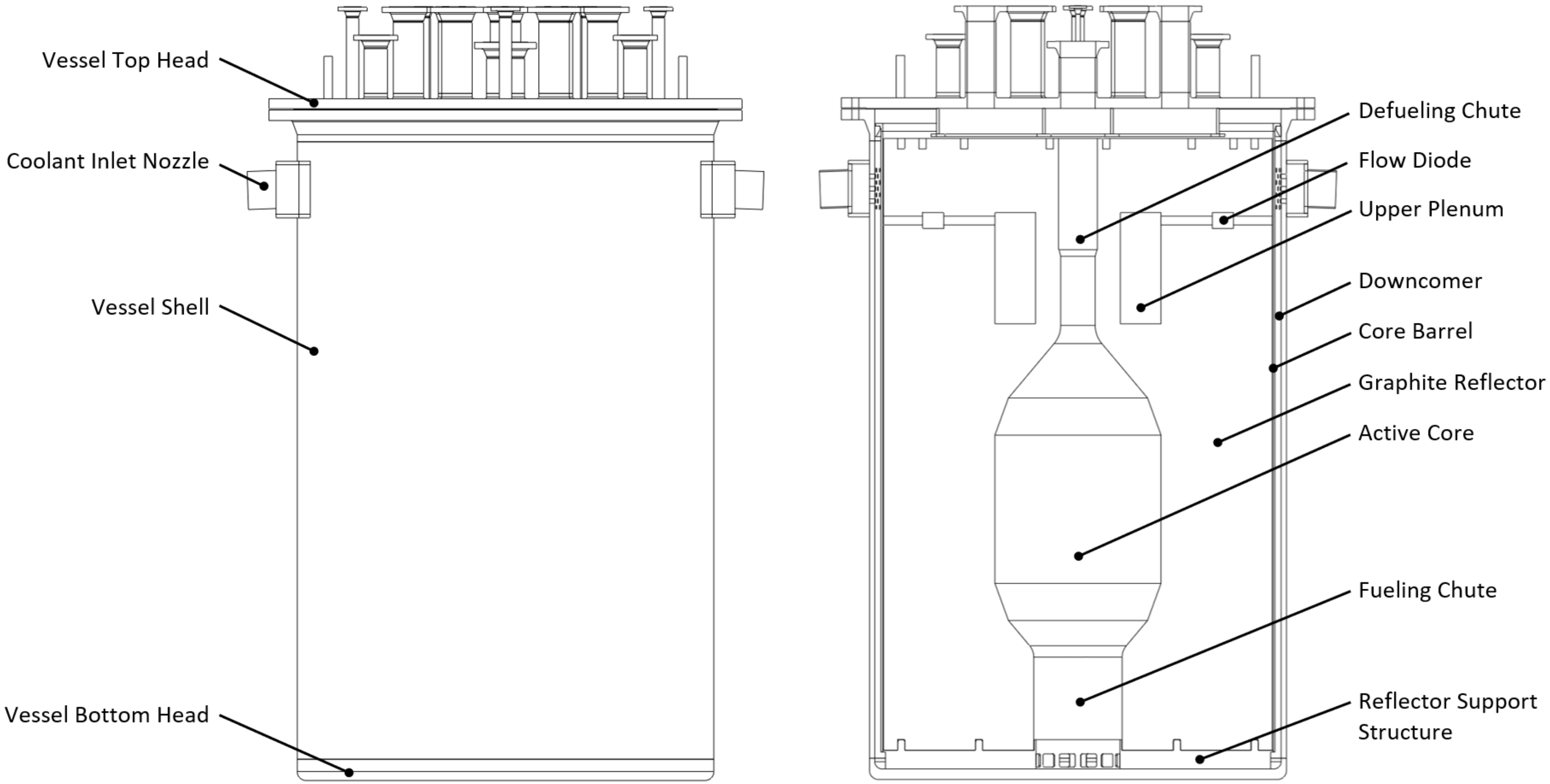
550-700 °C

0 – 26 W/cm^3

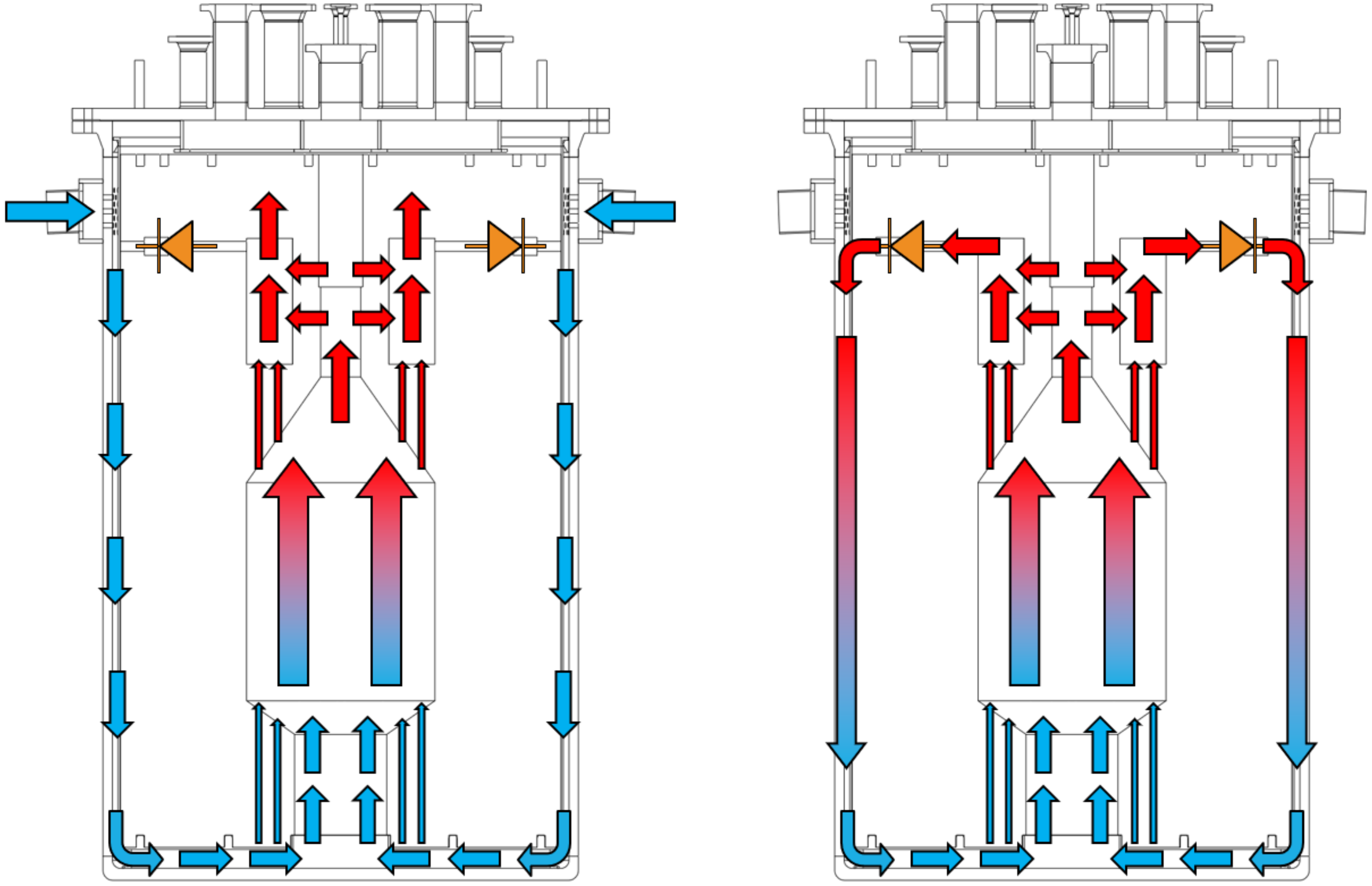
Reactor Vessel and Internals

ODED DORON – SR. DIRECTOR, REACTOR SYSTEM DESIGN

Reactor Vessel and Internals Overview



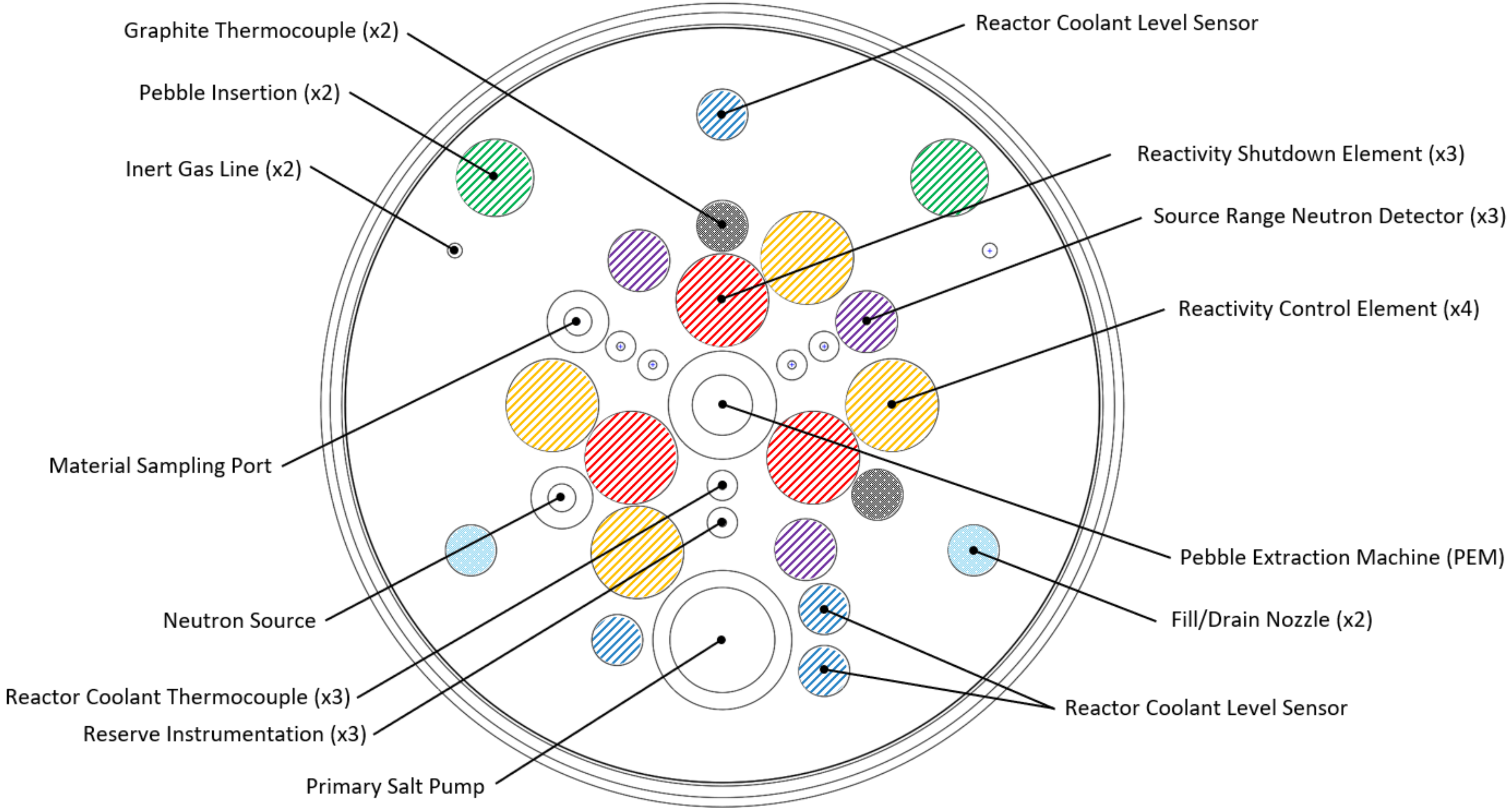
Hermes Coolant Circulation Path Overview



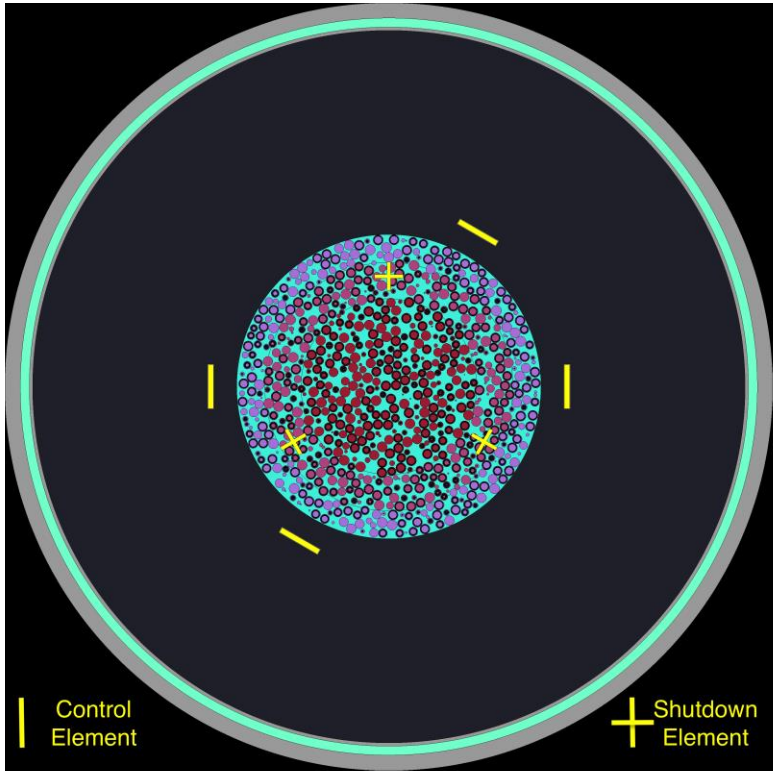
(a) Normal Operation Coolant Flow Path

(b) Natural Circulation Coolant Flow Path

Hermes Head Layout



Hermes Reactivity Control and Shutdown System



Hermes Core Layout

3x inbed shutdown elements

4x excore control elements

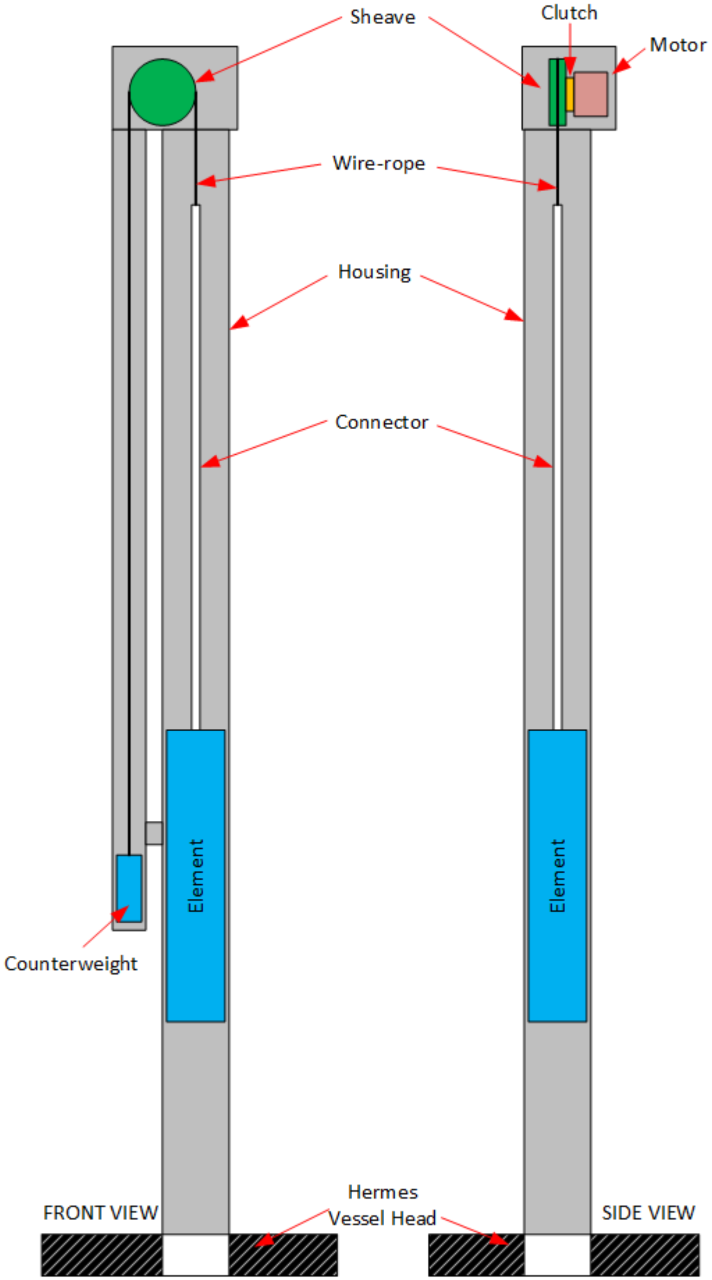
Drive Mechanism

Motor driven sheave to position element

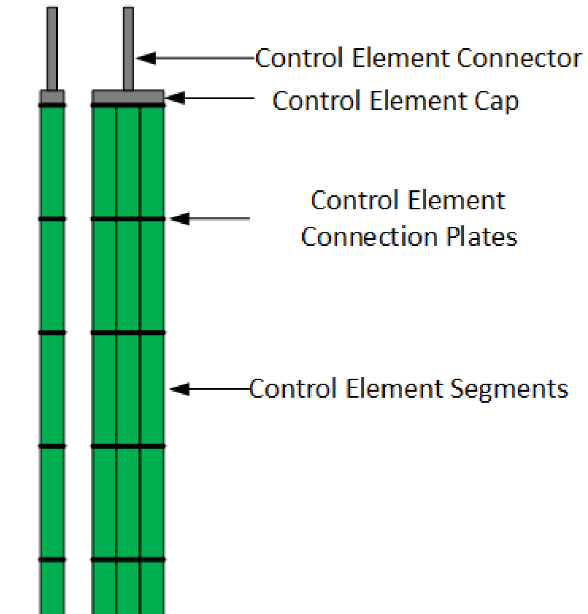
Release Mechanism

#1: Electromagnetic clutch

#2: Motor isolation

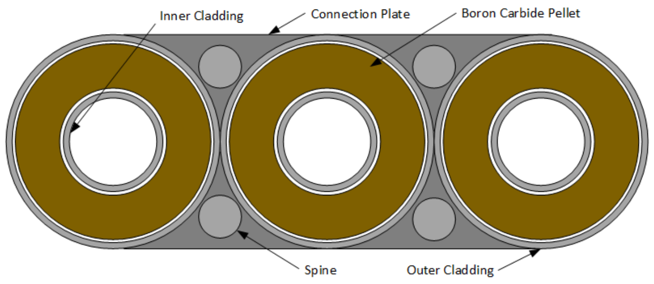


Control Element

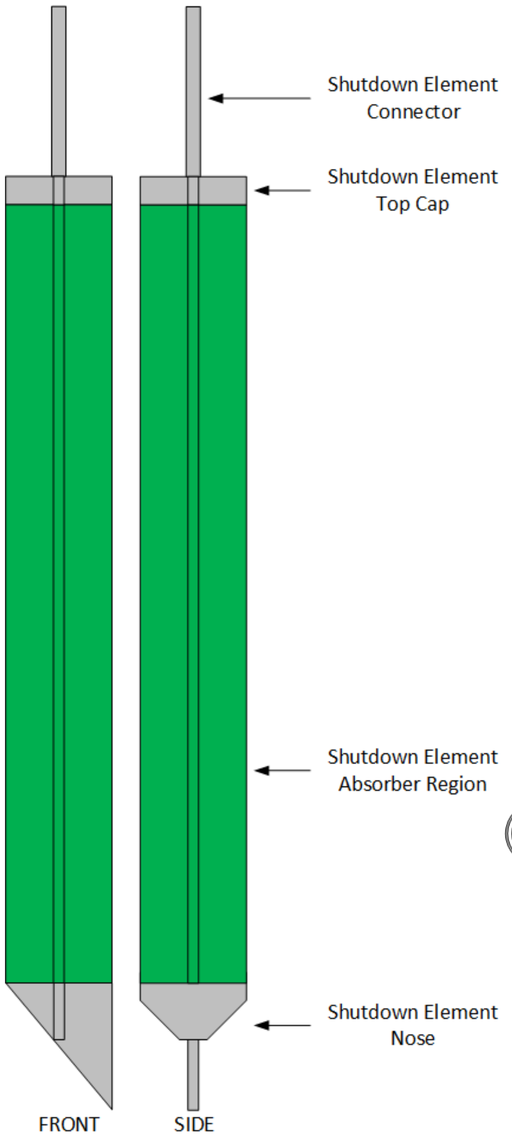


<u>Control Element</u>

Segmented Annular Design
Individual Capsules
Argon fill
Absorber: B4C
Cladding: SS-316H

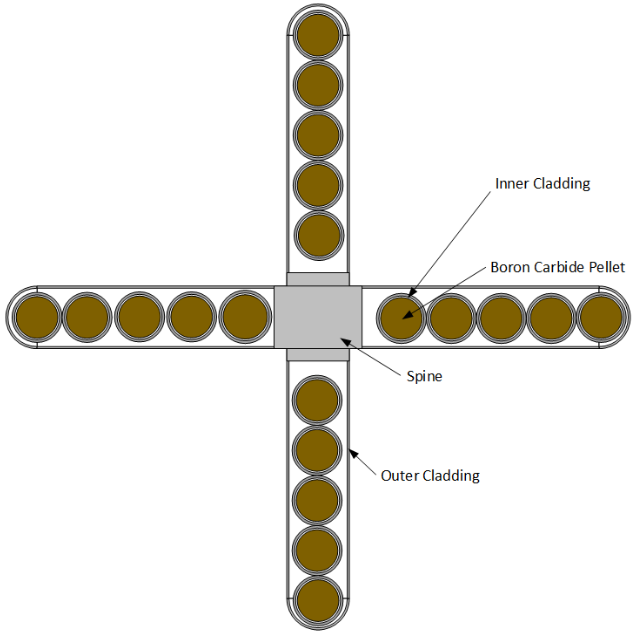


Shutdown Element



<u>Shutdown Element</u>

Cruciform Design
Inner Cladding contains absorber
Argon fill
Absorber: B4C
Cladding: SS-316H



Heat Transport & Pebble Handling and Storage

NICOLAS ZWEIBAUM – DIRECTOR, SALT SYSTEMS DESIGN

Primary Heat Transport System (PHTS) – Overview

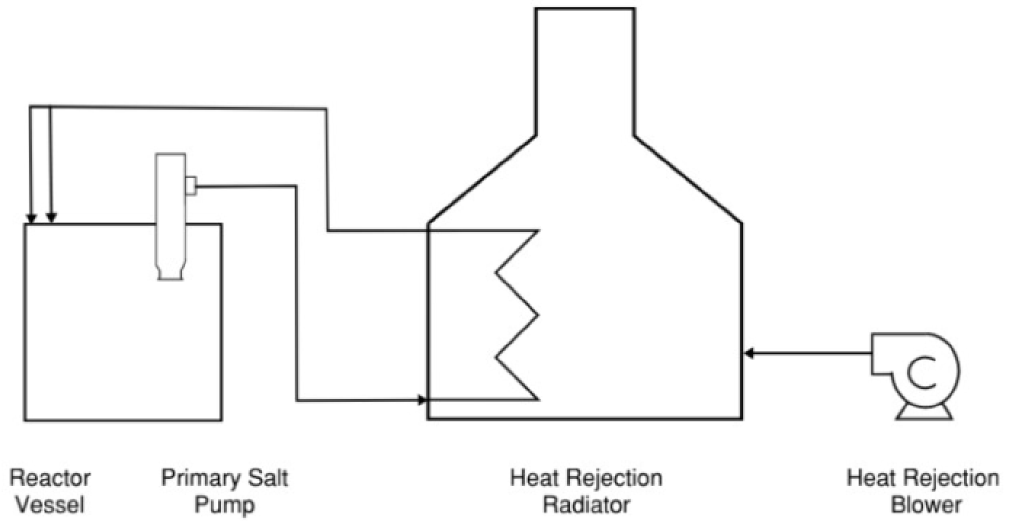
- The Primary Heat Transport System (PHTS) is responsible for transporting heat from the reactor to the ultimate heat sink (environmental air) during power operation and during normal shutdown
- The PHTS operates near atmospheric pressure and does not provide a safety-related heat removal function (see Decay Heat Removal System)
- The safety-related hot leg anti-siphon feature is performed by the Primary Salt Pump downward-facing inlet (the pump being supported in position by the Reactor Vessel upper head)
- Additionally, the PHTS provides for the following functions:
  - Contain and direct the reactor coolant flow between the reactor vessel and the heat rejection subsystem
  - Manage thermal transients (overall thermal balance) occurring as part of normal operations
  - Ensure minimum acceptable temperatures in the PHTS through make-up heating as necessary
  - Provide capability to drain the PHTS to reduce parasitic heat loss during over-cooling transients
  - Provide for in-service inspection, maintenance, and replacement activities

PHTS – System Makeup

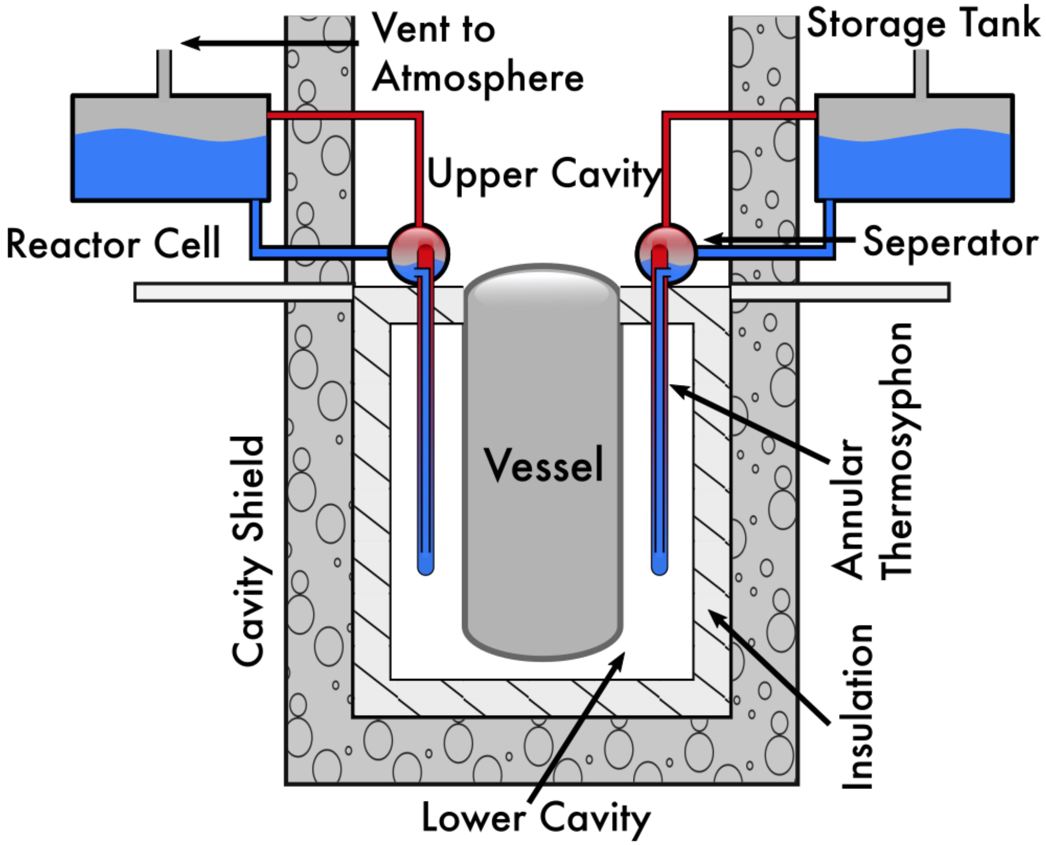
- Reactor Coolant
  - Flibe
- Primary Salt Pump (PSP)
  - Variable speed, cartridge style pump located on the reactor vessel head; inlet extends downwards through the Reactor Coolant free surface
- Heat Rejection Subsystem (HRS)
  - Provides for heat transfer from the reactor coolant to the atmosphere
  - Consists of the heat rejection radiator, heat rejection blower, and associated ducting and thermal management
- Primary Loop Piping
- Primary Loop Thermal Management
  - Provides non-nuclear heating and insulation to the PHTS as needed for various operations

PHTS – High Level Description

Parameter	Value
Thermal duty	35 MWth
Number of HRRs	1
Number of hot legs	1
Number of cold legs	2
Primary loop line size	8-12 in nominal pipe size
HRR inlet coolant temperature	600-650°C
HRR outlet coolant temperature	550°C
Nominal flow rate	210 kg/s
PHTS design pressure	525 kPa(g)



Decay Heat Removal System (DHRS) – Overview



Purpose: Vessel protection during postulated events for which the primary heat transport system (PHTS) is unavailable

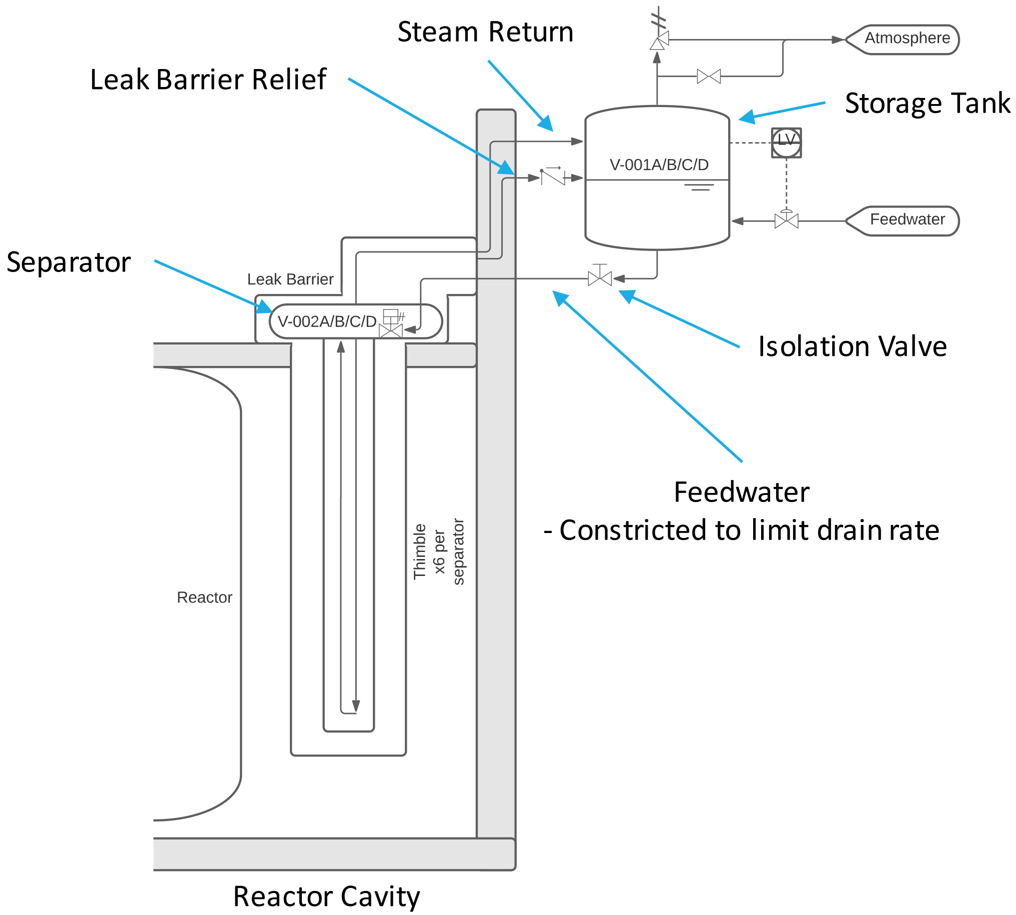
Operation: In-vessel natural circulation coupled to a passive water-based, ex-vessel system via thermal radiation and convection

- Continuous direct boil-off when estimated decay loads exceed parasitic losses
- Shutoff and isolated for low power levels (heat removal via parasitic losses only)
- No change of state on reactor event initiation

Load: Removal rate is a function of vessel temperature

- Due to physics of thermal radiation heat transfer

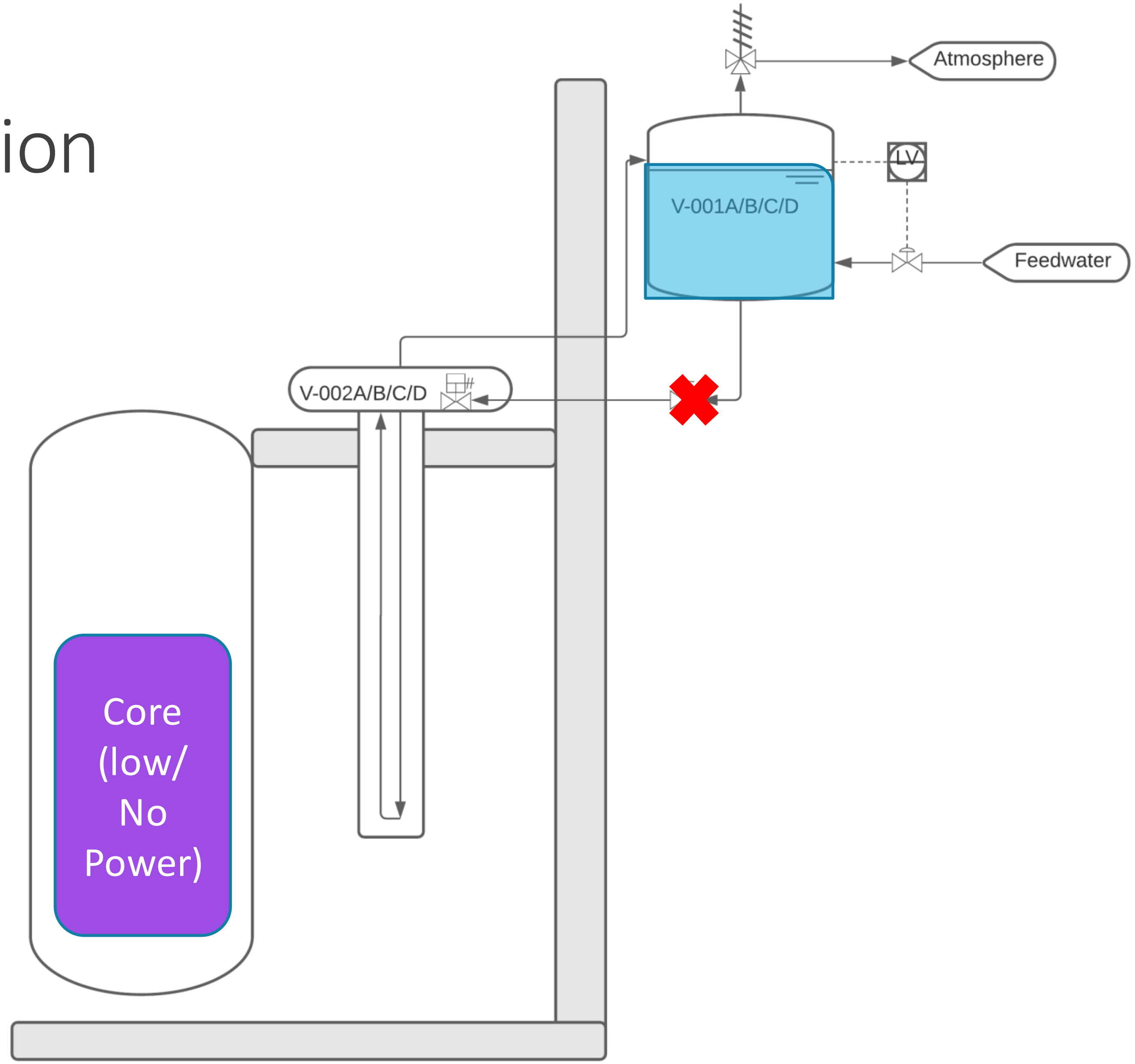
DHRS – Process Flow Diagram



- DHRS does not directly interact with the primary coolant
- No change of state on onset of postulated events
  - Always-on operation for set power levels
- Parallel and independent cooling pathways
  - Four independent cooling loops
  - Only three loops required to meet cooling demand
- Dual-walled for leak prevention and detection
  - Continued heat removal in the presence of a leak
- Active component (isolation valve) failures do not introduce failures in heat removal
  - Isolation valve fails in place (an operating system continues to operate)
  - Float valve nominally fails open

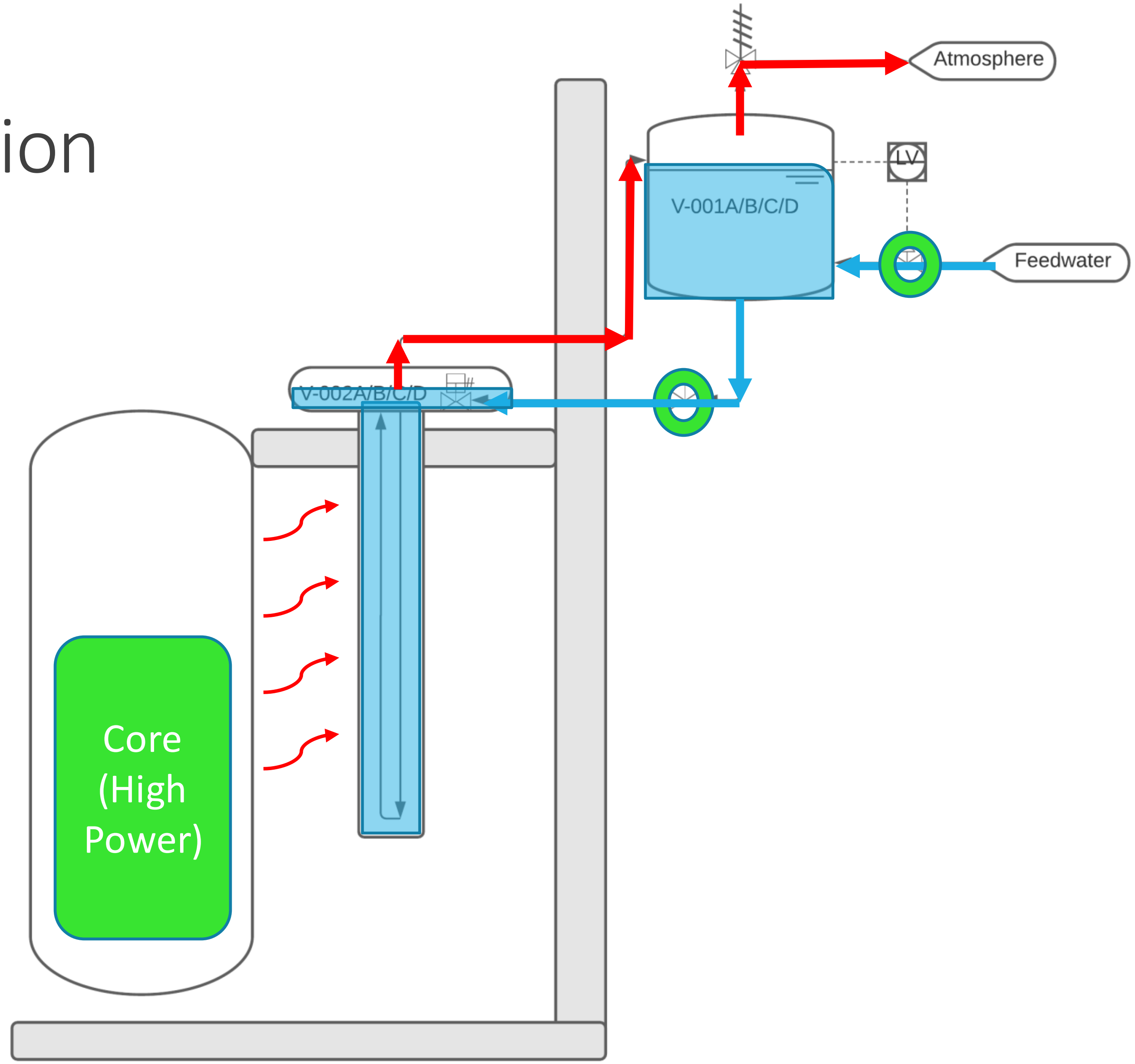
DHRS – Operation

Normal Operation
(DHRS deactivated)



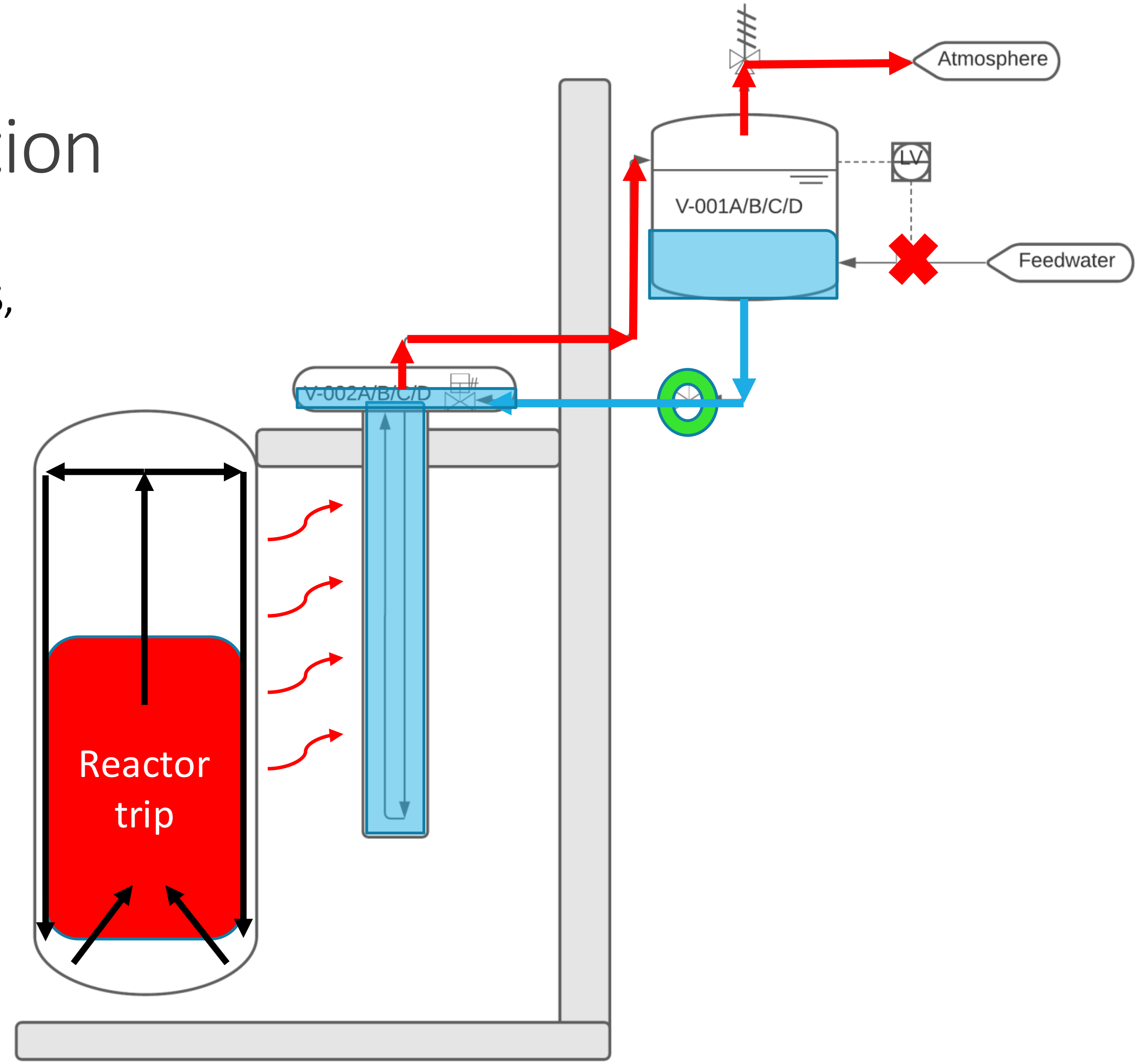
DHRS – Operation

Normal Operation



DHRS – Operation

Transient Event
(unrecoverable loss of PHTS,
loss of electrical power,
loss of feedwater)

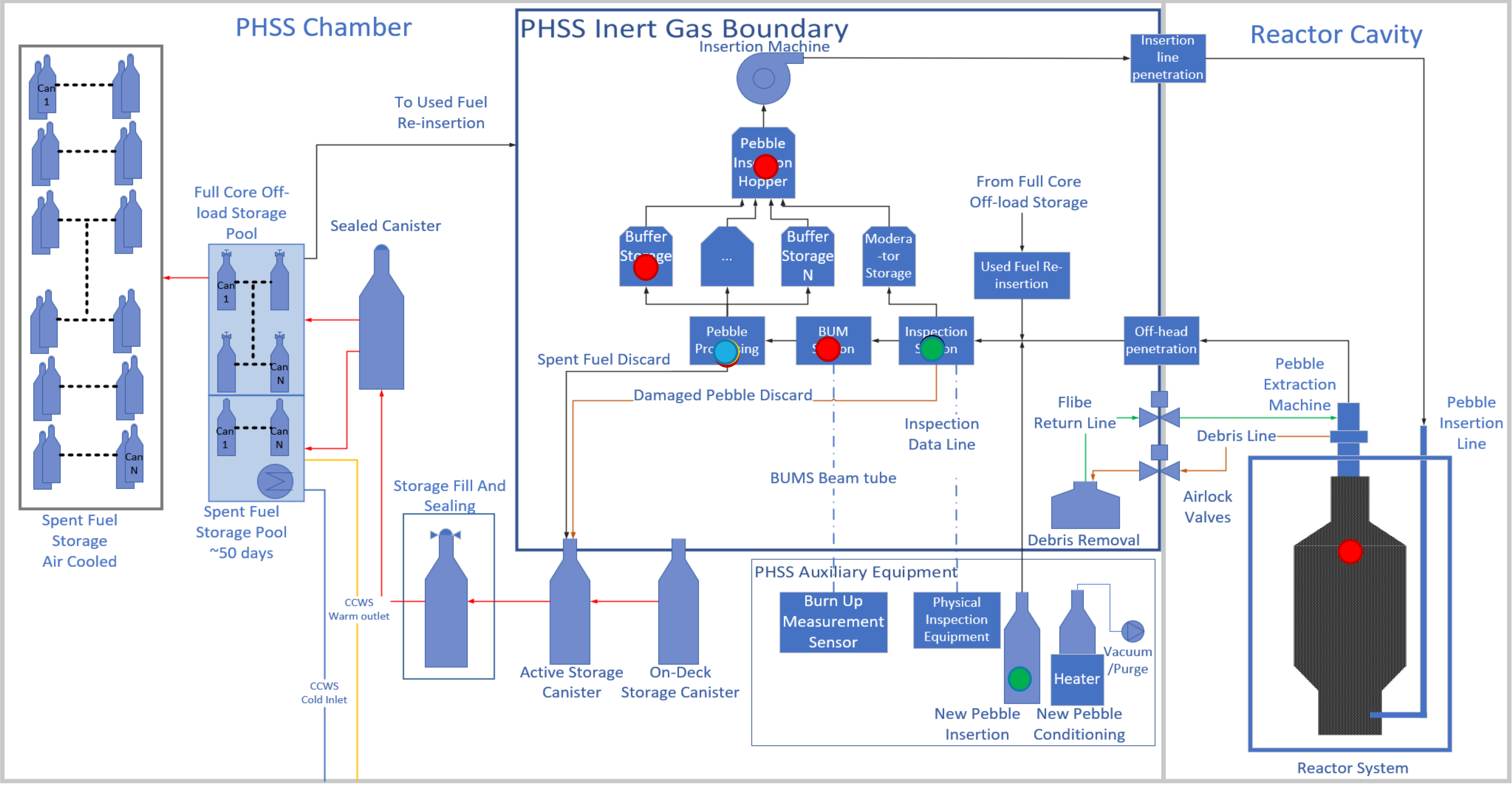


Pebble Handling and Storage System (PHSS) – Overview

- Responsible for handling of fuel in Hermes, from initial on-site receipt, in-process circulation, and final on-site storage
- Major components of the system:
  - Pebble Extraction Machine (PEM): single screw for removing pebbles from molten salt
  - Pebble Inspection System: performs flaw detection and burn-up measurement of removed pebbles
  - Processing System: sorts pebbles into appropriate buffer storage channel based on pebble type
  - Insertion System: stepper wheel feeder mechanism that inserts pebbles into the reactor via an in-vessel insertion line
  - Storage System Canister: stores ~2,000 damaged or spent fuel pebbles in a non-critical configuration
  - Storage Cooling Area: passively cooled, in-building storage area for spent fuel canisters
  - New Pebble System: stores fresh fuel and prepares fuel for circulation via a high-temperature bakeout

PHSS – Layout and Pebble Path

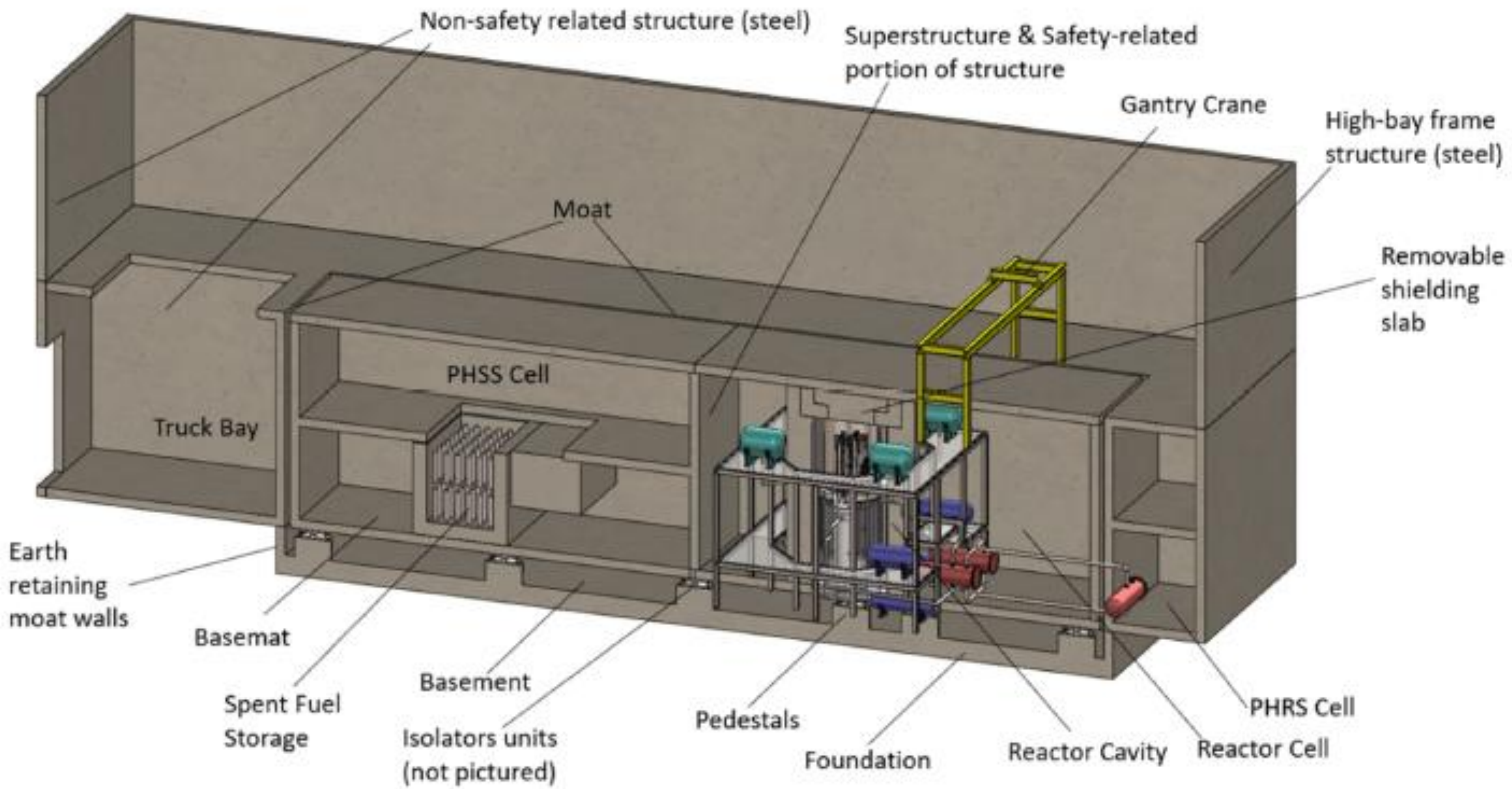
Recirculate Fuel
New Pebble
Other
Spent Fuel
Moderator



Structures

BRIAN SONG – MANAGER, CIVIL STRUCTURES

Reactor Building Layout



Meteorological Loads

- Design considers rain, snow, wind, tornado and wind-borne missiles for site.
- Safety-related reactor building designed without crediting non-safety-related exterior shell for protection from snow, wind, rain, and missile loads.
- Exterior "shell" of safety-related reactor building designed with concrete thickness to protect safety-related structures, systems, and components (SSCs) from high-wind missiles, including debris from potential damage of non-safety-related reactor building.

Flood loads

- Safety-related SSCs will be protected from internal flood (spray and accumulation) with shields, curbs, drains, etc.
- Safety-related Reactor Building protects safety-related SSCs from credible external flood.

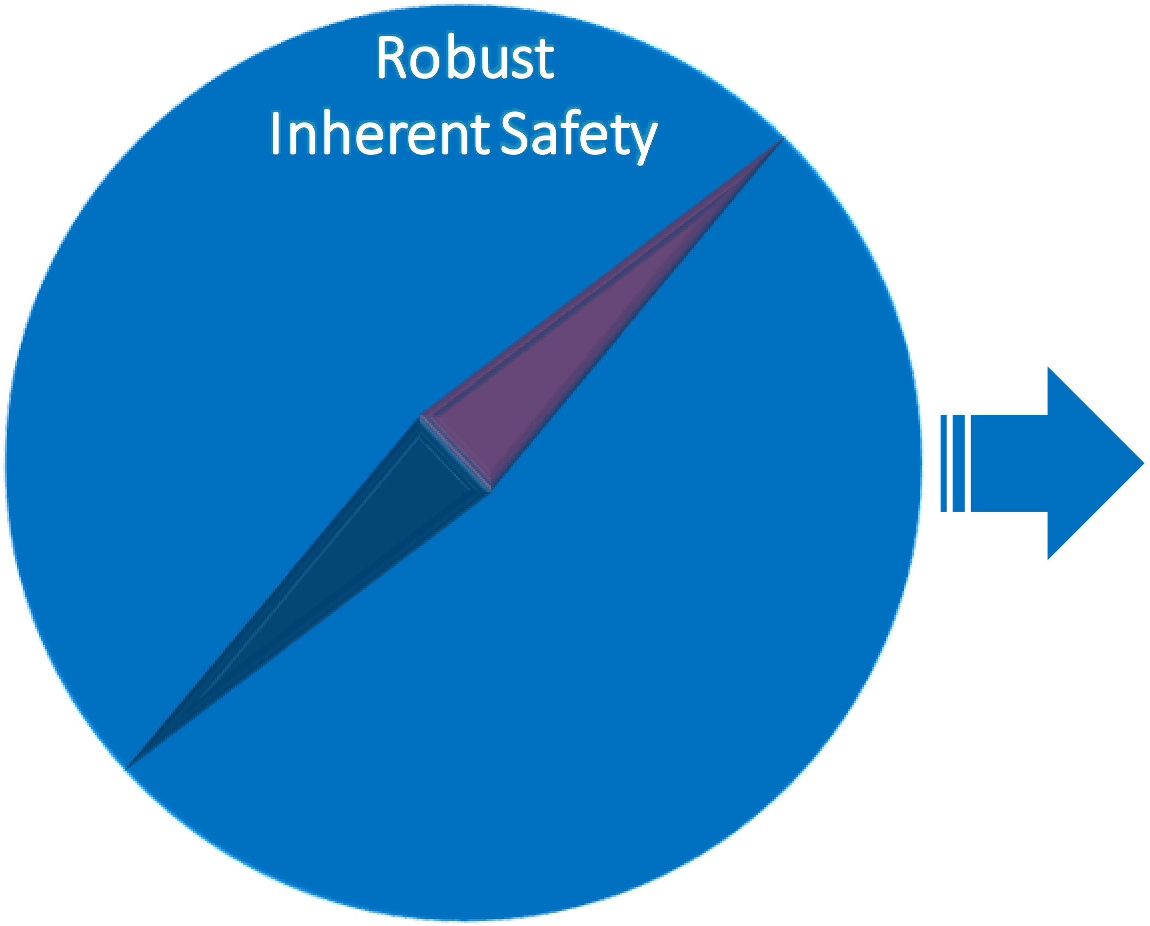
Seismic Loads

- Using risk-informed performance-based insights to define seismic design criteria (i.e. ASCE 43-19, SDC 3)
  - Seismic design basis earthquake based on site-specific seismic hazard considering other recent and nearby seismic hazard analyses and site-specific geotechnical characteristics.
- Safety-related Reactor Building incorporates spring/dashpot seismic isolation system, which lowers seismic demands on safety-related reactor building and safety-related SSCs in both horizontal and vertical directions.
- Moat and flex connections accommodate displacements of isolated safety-related reactor building.
- Safety-related portion of the Reactor Building will be represented by a three-dimensional finite-element model developed in accordance with Chapter 3 of ASCE 4-16.

Instrumentation & Controls and Electrical Systems

ANTHONIE CILLIERS – DIRECTOR, INSTRUMENTATION, CONTROLS AND ELECTRICAL

Instrumentation & Controls and Electrical System Design Relies on the Following Systems



Plant protection and control

- **Reactor Protection System (RPS)**

Safety Hazard Intervention and Event Limiting Defense

- **Plant Control System (PCS)**

System with Operational Reliability and Diagnostics

- **Intelligent Health Monitoring**

Health Evaluation and Analysis in Real-Time

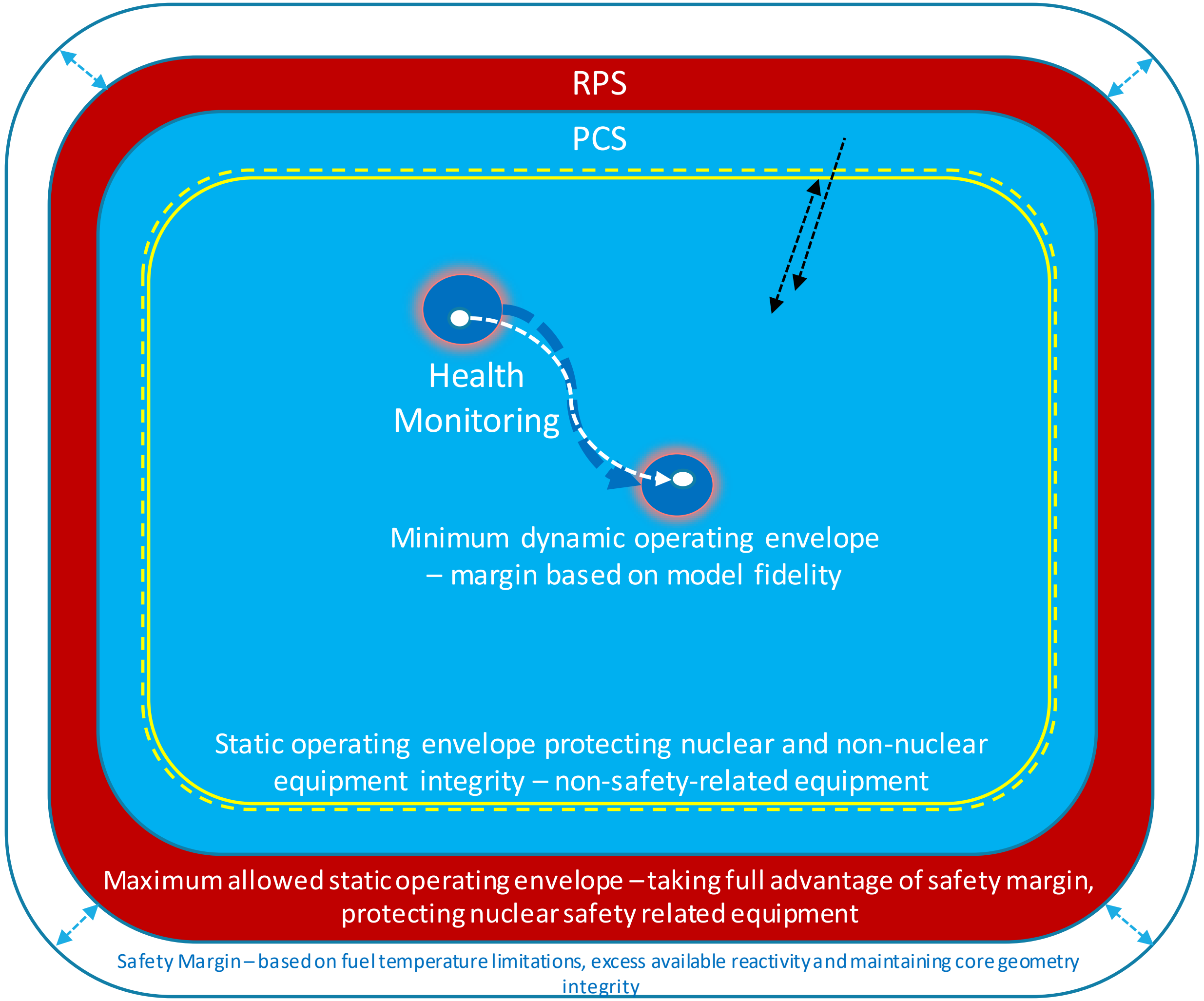
- **Semi-autonomous control room (MCR)**

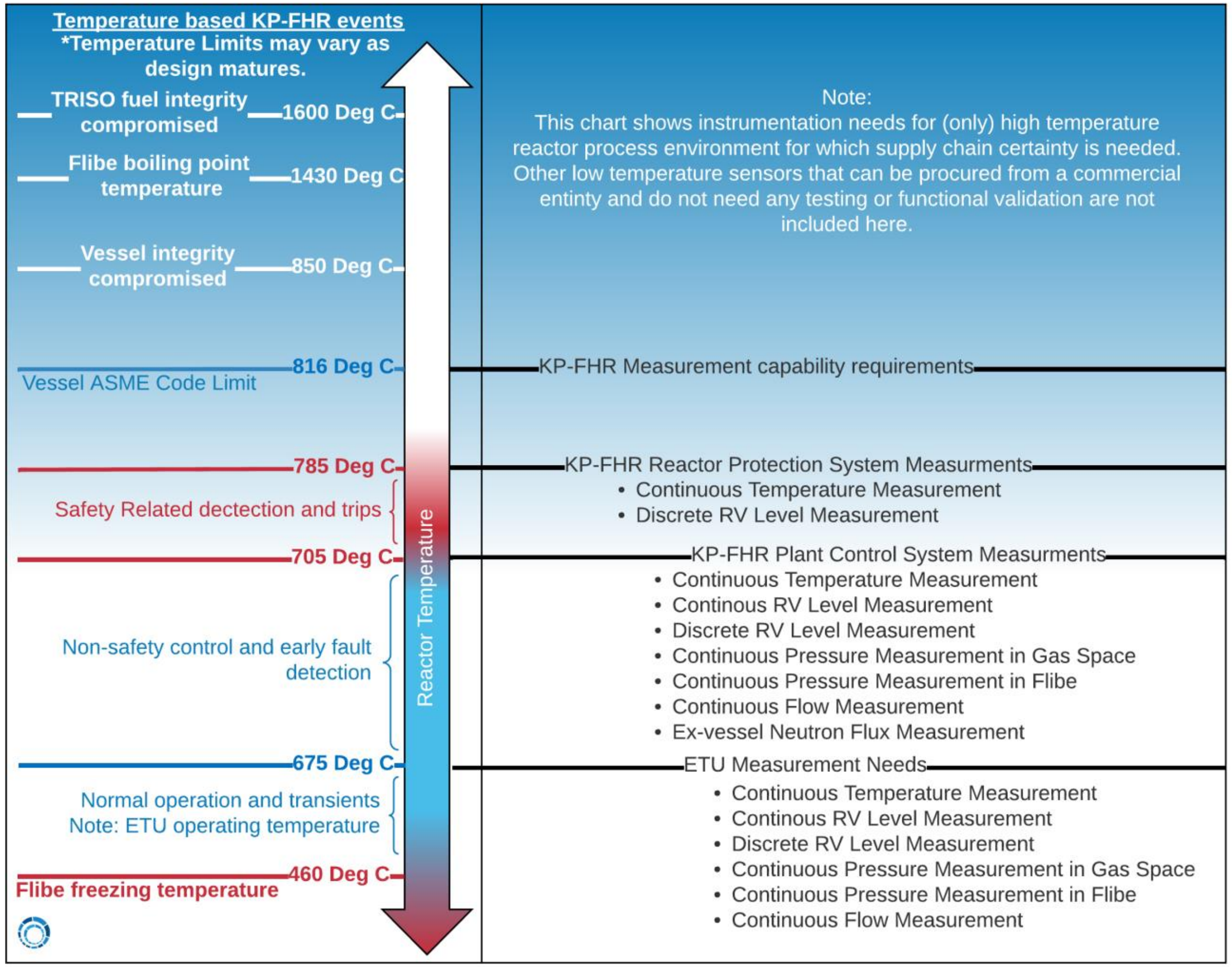
Semi-autonomous Industrial Grade HMI Technology

- **Electrical supply**

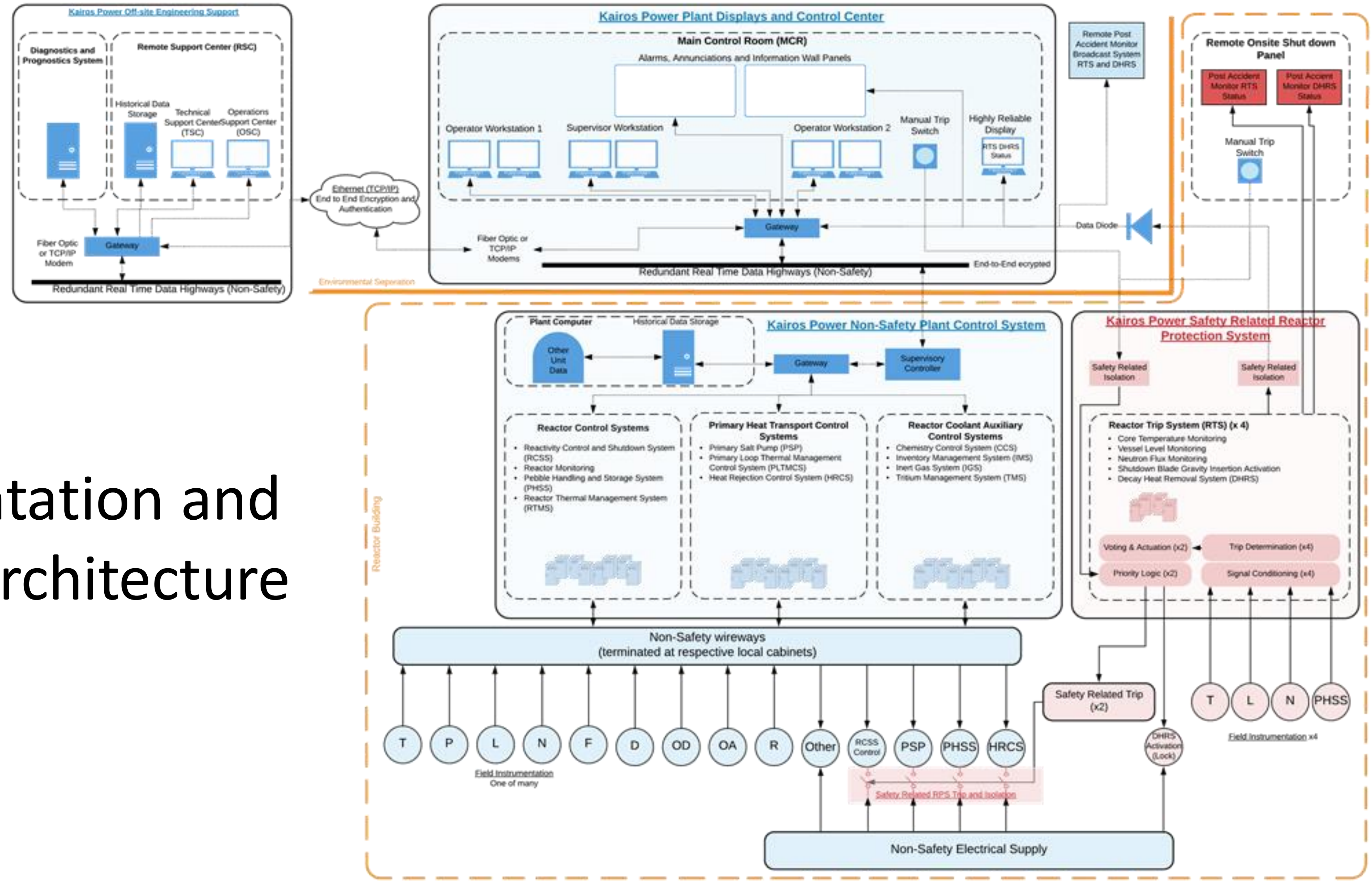
Basic Ohm Law Triangle (V = I.R)

Plant Protection, Control, and Health Monitoring Operating Envelopes

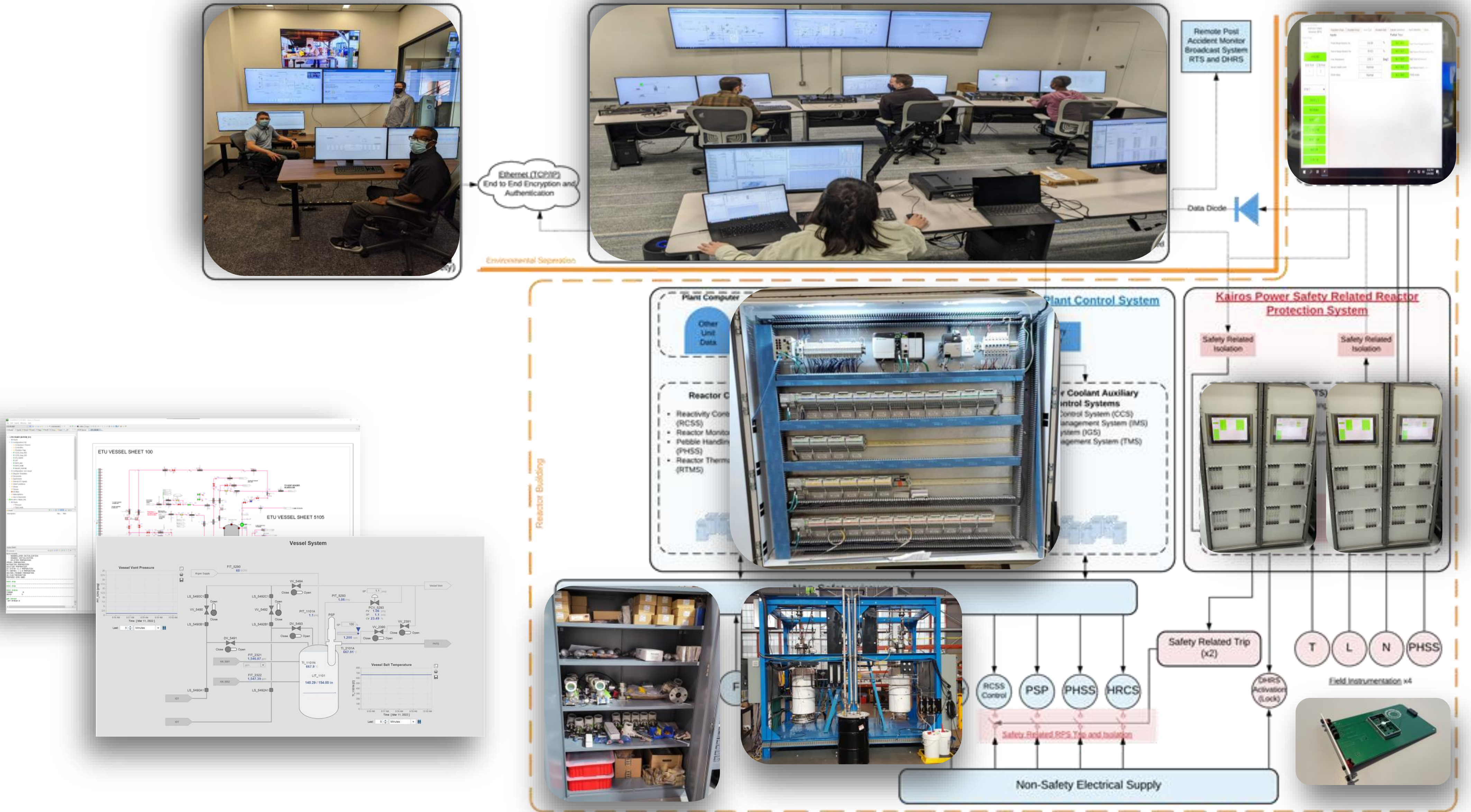




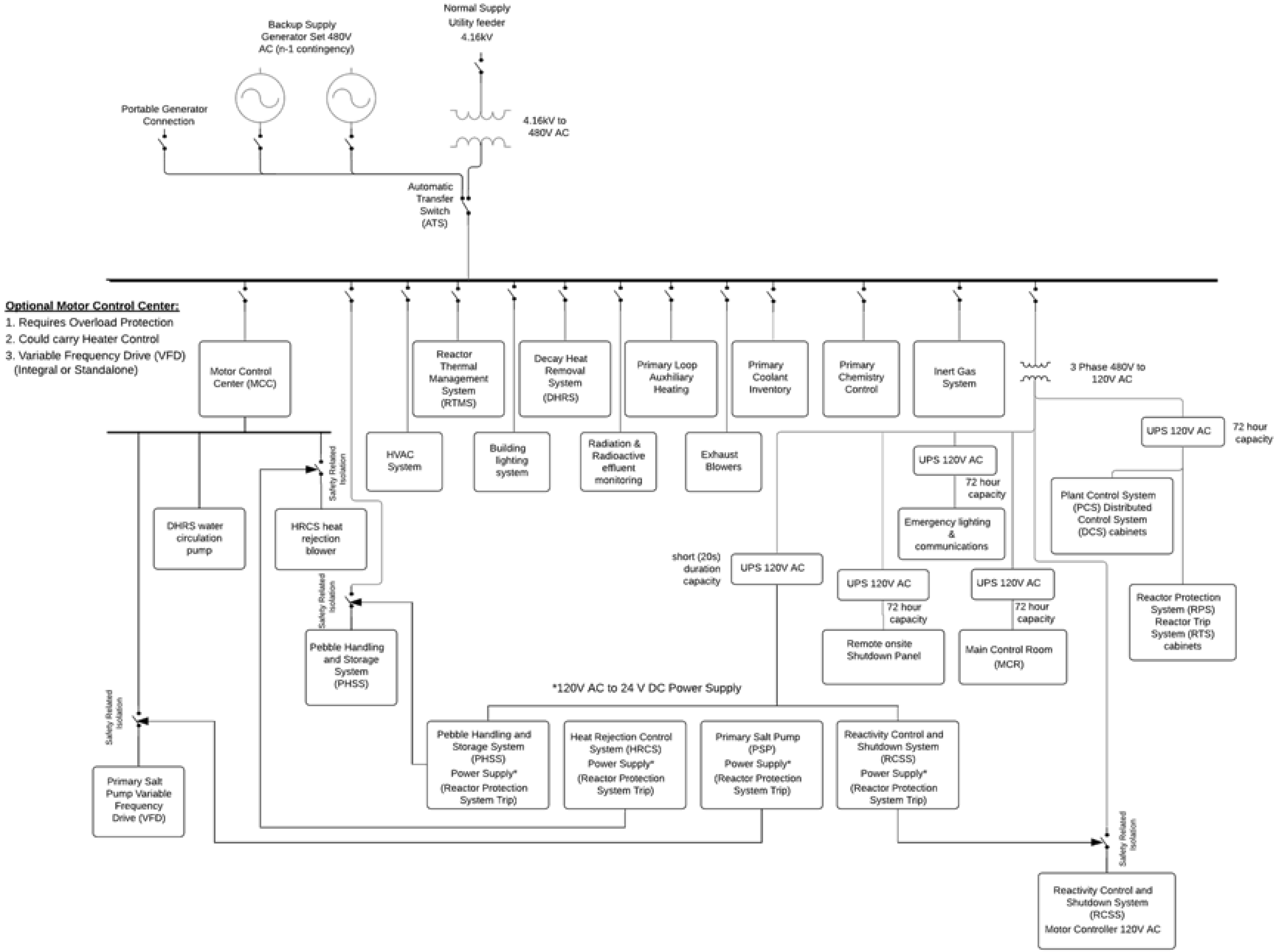
Instrumentation and Controls Architecture



Instrumentation and Controls Architecture



Electrical Architecture



Safety Case

JORDAN HAGAMAN – DIRECTOR, RELIABILITY ENGINEERING

Safety Case Approach

- Deterministic approach consistent with NUREG 1537, Chapter 13
- To demonstrate compliance with regulatory dose limits, a Maximum Hypothetical Accident (MHA) that bounds the Chapter 13 postulated events is analyzed for dose consequences
  - MHA not physical
  - MHA includes conservatisms that maximize source term
  - MHA includes a postulated release of radionuclides
- To ensure that the postulated events are bounded by the MHA:
  - List of postulated events is comprehensive to ensure that any event initiator with the potential for radiological consequences has been considered
  - Initiating events and scenarios are categorized, so that a limiting case for each group can be qualitatively described in CPA (quantitative results will be provided with OLA)
  - Acceptance criteria are provided for the important figures of merit in each postulated event group to ensure the potential consequences of that event group remain bounded by the MHA as the design progresses
  - Prevention of an event initiator is justified in PSAR

List of Events Postulated

- MHA – Hypothetical heat-up with conservative radionuclide transport
- Insertion of Excess Reactivity
- Salt Spills
- Loss of Forced Circulation
- Mishandling or Malfunction of Pebble Handling and Storage Systems
- Radioactive Release from a Subsystem or Component
- General challenges to Normal Operation
- Internal and External Hazard Events

Maximum Hypothetical Accident

- Hypothetical heat-up event with conservative assumptions meant to drive radionuclide release:
  - Pre-transient diffusion of radionuclides from the fuel in the reactor core is neglected
  - Prescribed hypothetical temperature histories are applied to the transient
  - The gas space is not credited for confinement of the radionuclides that release from the Flibe-free surface
  - Conservative, unfiltered, ground level releases
  - Conservative tritium modeling
  - A bounding vessel void fraction is assumed to facilitate the release of low volatility species in the vessel via bubble burst.

Location and Duration	Whole Body Dose (rem)		Thyroid Dose (rem)	
	10 CFR 100 Limit	MHA Result	10 CFR 100 Limit	MHA Result
Exclusion Area Boundary (First 2 hrs at 250m)	25	0.227	300	0.235
Low Population Zone (30 days at 800m)	25	0.059	300	0.081

Postulated Events

- The postulated event methods are provided in KP-TR-018, "Postulated Event Analysis Methodology" (incorporated by reference in PSAR Ch. 13)
- The phenomena for each postulated event group that have the potential to increase dose consequence are identified as figures of merit
- Acceptance criteria are defined for the figures of merit that will ensure that the limiting event in each postulated event group is bounded by the MHA
- Validation and detailed final analyses of the postulated event groups will be performed for the operating license application