PBMR Event Sequence Framework

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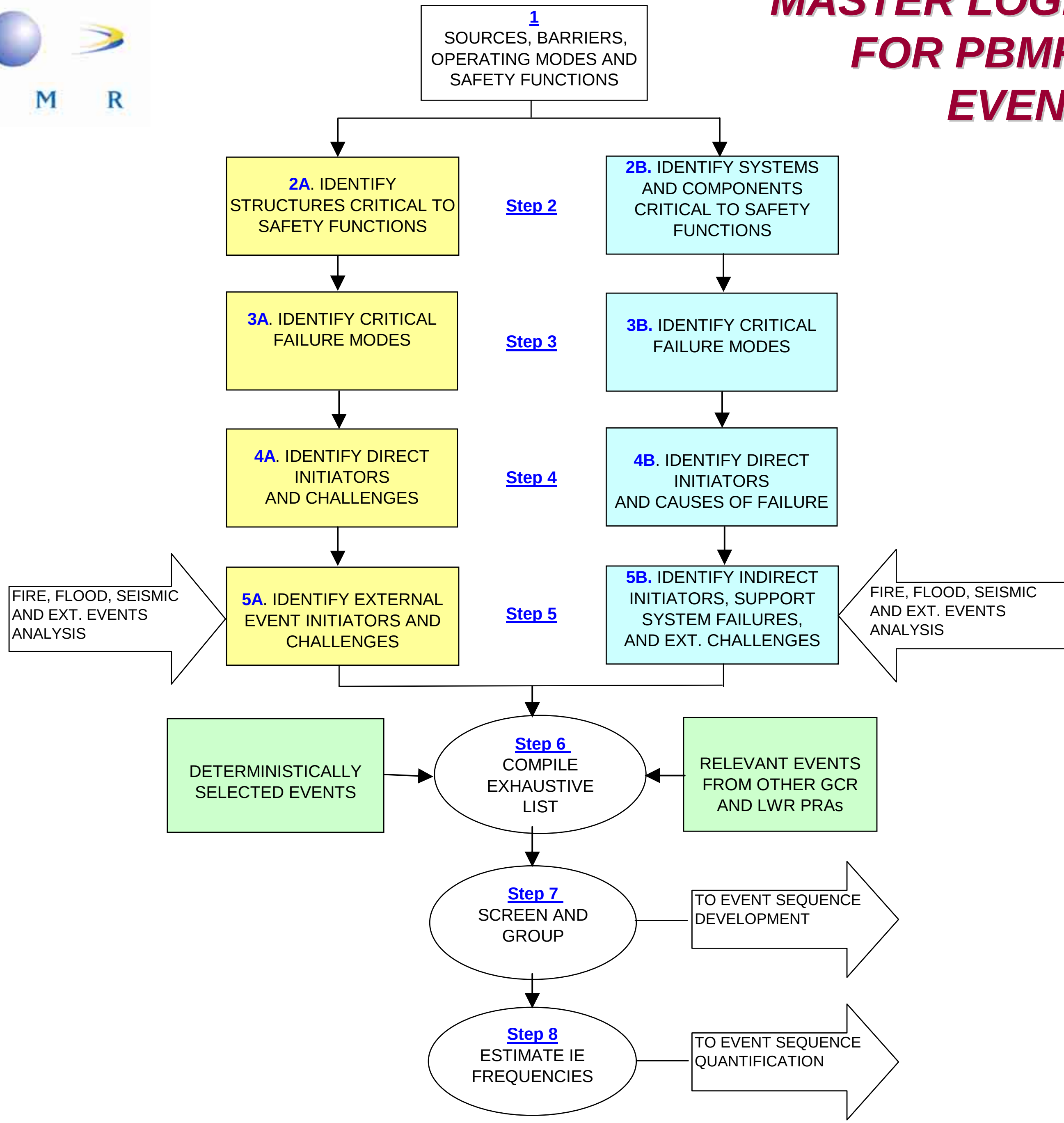
Presentation Objectives

- **Provide framework for describing PBMR event sequences consistent with the safety design philosophy**
  - Initiating events
  - Event sequence framework
  - SSCs available to support safety functions
  - End states
- **Identify similarities and differences with LWR event sequences**
- **Set the stage for presentations on specific event analyses**

Identification of Initiating Events

- **Scope of events included in design**
  - All envisioned operating and shutdown modes
  - Internal events
  - Internal plant hazards, e.g. fires and floods
  - External hazards, e.g. seismic and aircraft crash
- **Methods used to support systematic search**
  - FMEAs and HAZOPs performed to support design
  - Master Logic Diagram method
  - Review of events identified for other HTGRs and LWRs

MASTER LOGIC DIAGRAM FOR PBMR INITIATING EVENT ANALYSIS



Radionuclide Sources and Barriers

Radioactive Material Source	Barriers to Radionuclide Transport
Fuel spheres in the Core	Coated particles, graphite matrix, Helium Pressure Boundary, Citadel, reactor building confinement
Fuel spheres outside Core	Coated particles, graphite matrix, FHSS piping or spent fuel tanks, or used fuel tanks, or new fuel tanks, reactor building confinement
Non-Core sources within the MPS	Helium Pressure Boundary, reactor building confinement
Other sources	Various tanks, piping systems and containers, reactor building confinement

Radionuclide Sources

- **Sources within the MPS HPB**
  - Fuel spheres in core/FHSS
    - *Intact coated particles*
    - *Failed or defective coated particles*
    - *Uranium contamination outside coated particles*
    - *Imbedded/attached to graphite components*
  - Plateout on HPB surfaces and dust
  - Circulating coolant activity
- **Sources outside the MPS HPB**
  - Fuel spheres in storage systems
  - HICS and HPS gas borne activity
  - Solid and liquid radwaste systems

Relative I-131 Inventories

Source	I-131 Inventory (Ci)
Circulating activity	<<1
Plate out on internal HPB surfaces	<1
Uranium contamination outside coated particles	~20
Failed and defective coated particles	~580
Intact coated particles	$\sim 1 \times 10^7$

Functional Initiating Event (IE) Categories

- **Typical PWR IE Categories**
  - Transients (with and without scram)
  - Loss of coolant accidents
  - Steam generator tube ruptures
- **Typical PBMR IE Categories**
  - Transients (with and without scram)
  - Depressurization events
  - Heat exchanger faults

PBMR Functional IE Categories

- **PCU Transients with intact Helium Pressure Boundary (HPB)**
  - Power Conversion Unit (PCU) and Core Conditioning System (CCS) still capable of forced cooling operation
  - PCU failed, CCS still capable of operation
  - CCS failed, PCU still capable of operation
  - PCU and CCS not capable of operation
- **PCU Transients with intact HPB and reactivity addition**
  - Control rod or group withdrawal
  - Removal of RSS small absorber spheres (SAS)
  - Overcooling transients
- **HPB Leaks and Breaks (excl. HPB HX failures)**
  - Small HPB failures resulting in slow depressurization <10mm break size
  - Moderate HPB failures resulting in rapid depressurization with break size >10mm and <230mm
  - Large HPB failures resulting in rapid depressurization with break size >230mm
- **HPB Heat Exchanger Failures**
  - Precooler or Intercooler failures
  - CCS heat exchanger failure
  - CBCS heat exchanger failure

IE Category Characteristics

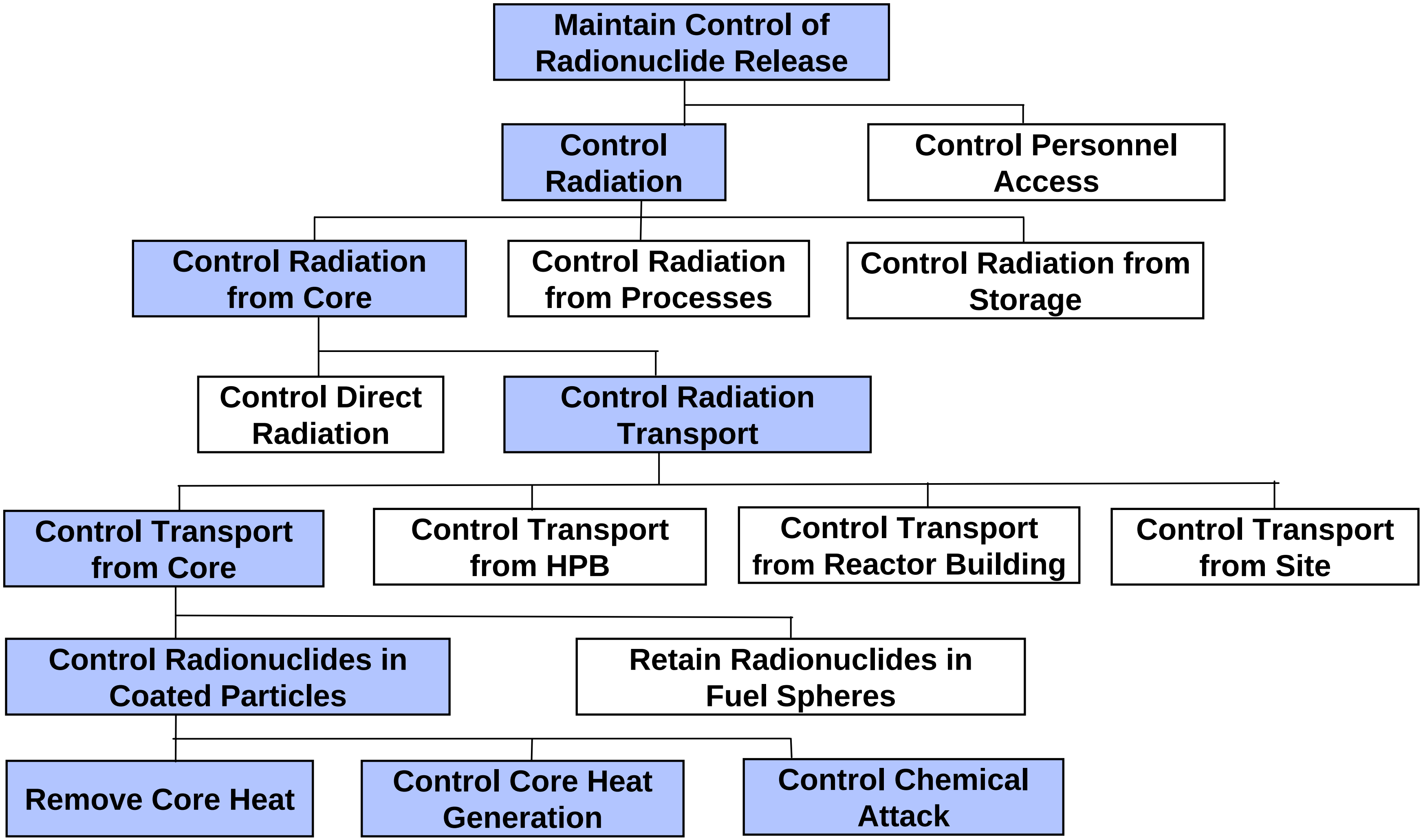
- **PCU Transients with intact helium pressure boundary (HPB)**
  - Captures high frequency causes of loss of Brayton cycle
  - Events where HPB barrier remains effective
  - Includes pressurized forced cooling and loss of forced cooling scenarios
- **PCU Transients with intact pressure boundary and reactivity addition**
  - Captures events with positive reactivity e.g. rod withdrawal and overcooling
  - Events where HPB barrier remains effective
  - Includes pressurized forced cooling and loss of forced cooling scenarios
- **HPB Leaks and Breaks (Excl. Hx failures)**
  - Captures HPB failure modes other than PCU exchangers
  - Events where HPB is breached
  - Includes depressurized forced cooling and loss of forced cooling scenarios
- **PCU Heat Exchanger Failures**
  - Captures HPB failure modes at the PCU heat exchangers
  - Events where HPB is breached and interfacing systems is unavailable
  - Includes depressurized forced cooling and loss of forced cooling scenarios

HPB Failure Size and Locations

Location	Size of HPB Breach		
	Small (<10 mm)	Medium (10 mm to 230 mm)	Large (> 230 mm)
RPV Top	- Instrumentation lines - Small Breaks in medium pipes	- Fuel loading pipes - CBCS outlet - In core delivery system	- None. There are no pipes of this category in this location.
RPV Bottom	- Instrumentation lines - Small Breaks in medium and large pipes	- CBCS inlet - Medium Break in reactor inlet pipe - Medium Break in reactor outlet pipe - Medium Break in de-fuelling chute	- Large break in Reactor inlet pipe - Large break in Reactor outlet pipe - Large break in De-fuelling chute
PCU Cavity	- Instrumentation lines - Small Breaks in medium and large pipes - Small Breaks (cracks) in MPS Heat Exchangers (Pre-cooler, Intercooler, CCS, CBCS)	- Break of any medium pipe - Medium Break in any large pipe - Medium breaks in MPS Heat Exchangers (Pre-cooler, Intercooler, CCS, CBCS)	- Large Break of any large pipe

- **Maintain control of radionuclides**
  - Control heat generation (reactivity)
  - Control heat removal
  - Control chemical attack
    - *Maintain core and reactor vessel geometry*
      - Maintain reactor building structural integrity

PBMR Safety Functions



Approach to Satisfying Safety Functions

- **PBMR safety functions include:**
  - Required Functions to meet the safety requirements
  - Support Functions that provide defense-in-depth by preventing and mitigating challenges to SSCs
  - Both types of functions need to be addressed when defining the event sequences to be considered in the deterministic and probabilistic safety analysis
- **PBMR safety features include:**
  - Inherent characteristics with positive safety attributes
  - Engineered features provided by
    - *Passive SSCs*
    - *Active SSCs*
- **PBMR safety design philosophy is to utilize inherent and passive SSCs to perform the required safety functions**
- **Additional active features provided to:**
  - Meet availability, reliability, and investment protection requirements
  - Provide supplemental prevention and mitigation roles as part of defense-in-depth

SSCs Supporting Control of Radionuclides

- **Passive design selections**
  - Coated particle barrier
  - Graphite matrix
  - Graphite reflectors and other core surfaces
  - HPB barrier
  - Confinement functions of reactor building
  - PRS blowout panels
- **Active systems**
  - PRS dampers
  - HVAC filtration system

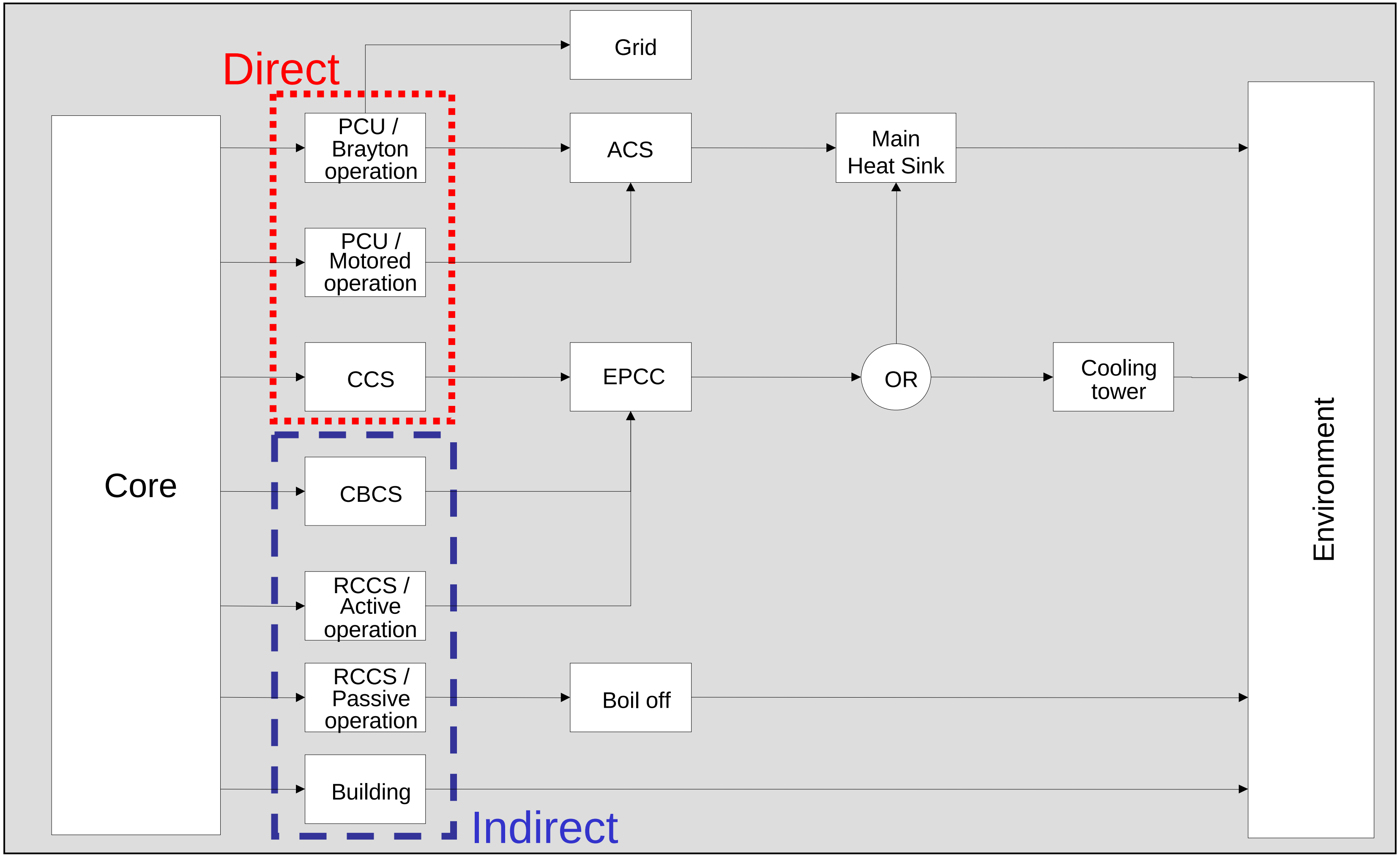
SSCs Supporting Control of Heat Generation

- **Inherent and passive capabilities**
  - Strong negative temperature coefficient of reactivity
  - Less excess reactivity due to on-line refueling
  - Gravity fall of control rods and small absorber spheres (SAS)
- **Active systems**
  - Control and protection systems
    - *Operational Control System (OCS)*
    - *Equipment Protection System (EPS)*
    - *Reactor Protection System (RPS)*
  - Reactivity control systems
    - *Reactivity Control System (RCS) trip release of control rod drives*
    - *Reserve Shutdown System (RSS) release of SAS*

SSCs Supporting Core Heat Removal

- **Inherent and passive capabilities**
  - Large thermal heat capacity
  - Passive core heat removal
    - *Core size, power density, geometry*
    - *Core, uninsulated reactor vessel, and reactor cavity configuration*
  - Passive Reactor Cavity Cooling System (RCCS)
    - *RCCS Tank inventory*
    - *RCCS Tank inventory + DWS (1) or FPS makeup (2)*
    - *RCCS Tank inventory + External tank truck makeup (2)*
    - *RCCS dry*
  - Pressure Relief System (PRS) blowout panels
- **Active systems**
  - Active Reactor Cavity Cooling System (RCCS)
    - *EPCC → MHS*
    - *EPCC → Cooling Tower*
  - Power Conversion Unit (PCU)
    - *Brayton Cycle → ACS → MHS*
    - *Motored PTG → ACS → MHS*
  - Core Conditioning System (CCS)
    - *EPCC → MHS*
    - *EPCC → Cooling Tower*
  - Core Barrel Conditioning System (CBCS)
    - *EPCC → MHS*
    - *EPCC → Cooling Tower*

PBMR Core Heat Removal Pathways



SSCs Supporting Control of Chemical Attack

- **Inherent and passive capabilities**
  - HPB high reliability piping and pressure vessels
  - Minimize penetrations in top of reactor vessel
  - High purity inert helium coolant
  - All interfacing systems at lower pressure than MPS
  - Lack of HPB pressurization mechanisms to open pressure relief system valves
  - ACS rupture discs protect against MPS HX leaks
  - PRS relief blowout panels
- **Active systems**
  - PRS exhaust duct dampers limit air ingress
  - Isolation valves in MPS interfacing systems

Framework for Definition of PBMR Event Sequences

Initiating Event → **Plant Response** → **Reactor Building Response** → **End State**

Initiating Event
- Cause of the Initiating Event
- Initiating Event functional category
- Reactor module impact

Plant Response
- Response of PTG
- Status of the HPB
- Response of reactivity control systems
- Response of core heat removal systems

Reactor Building Response
- Early response
- Long Term Response including mitigating actions
- Pressure relief and isolation response
- HVAC filtration response

End State
- Success criteria achievement
- Fuel integrity status
- Core oxidation status
- Plateout and liftoff status
- Radionuclide transport factors

Event Sequence End State Considerations

- Purpose of end states is to classify event sequences with respect to potential for offsite radiological consequences
- Need to consider events within and outside the design basis
- If there is no HPB failure as part of an initiating event, the HPB remains intact due to absence of challenging core-coolant-pressure boundary interactions
- End state factors defined to process many sequences with small variations in source terms; number of different end states dictated by how finely the consequences need to be resolved.
- End states are similar to Level 3 PRA release categories for LWRs
- Core damage and large early release end states are not appropriate for PBMR

PBMR Event Sequence End States

- **A complete set of event sequence end-states is defined as a combination of factors from four categories of plant states:**
  - Status of HPB Pressure boundary
    - *Intact or HPB failure mode*
    - *Size and location of HPB failure mode*
  - Source term elements
    - *Circulating activity (from depressurization events)*
    - *Lift-off of plateout or dust (from large depressurization events)*
    - *Delayed fuel release (from depressurized loss of forced cooling events)*
  - Response of reactor building
    - *External event challenges*
    - *PRS blow-out panel and damper response*
    - *HVAC filtration response*
  - Source term enhancement factors
    - *Air or water ingress*
    - *Pressure differential across HPB release path*
    - *Core reactivity status*
    - *Core Cooling systems status*