PBMR

Plant Operations and Maintenance Overview

Hans-Wolfgang Chi

Objectives

- **Introduction to PBMR plant operations and maintenance**
- **Overview of plant behavior during normal operations**

Content

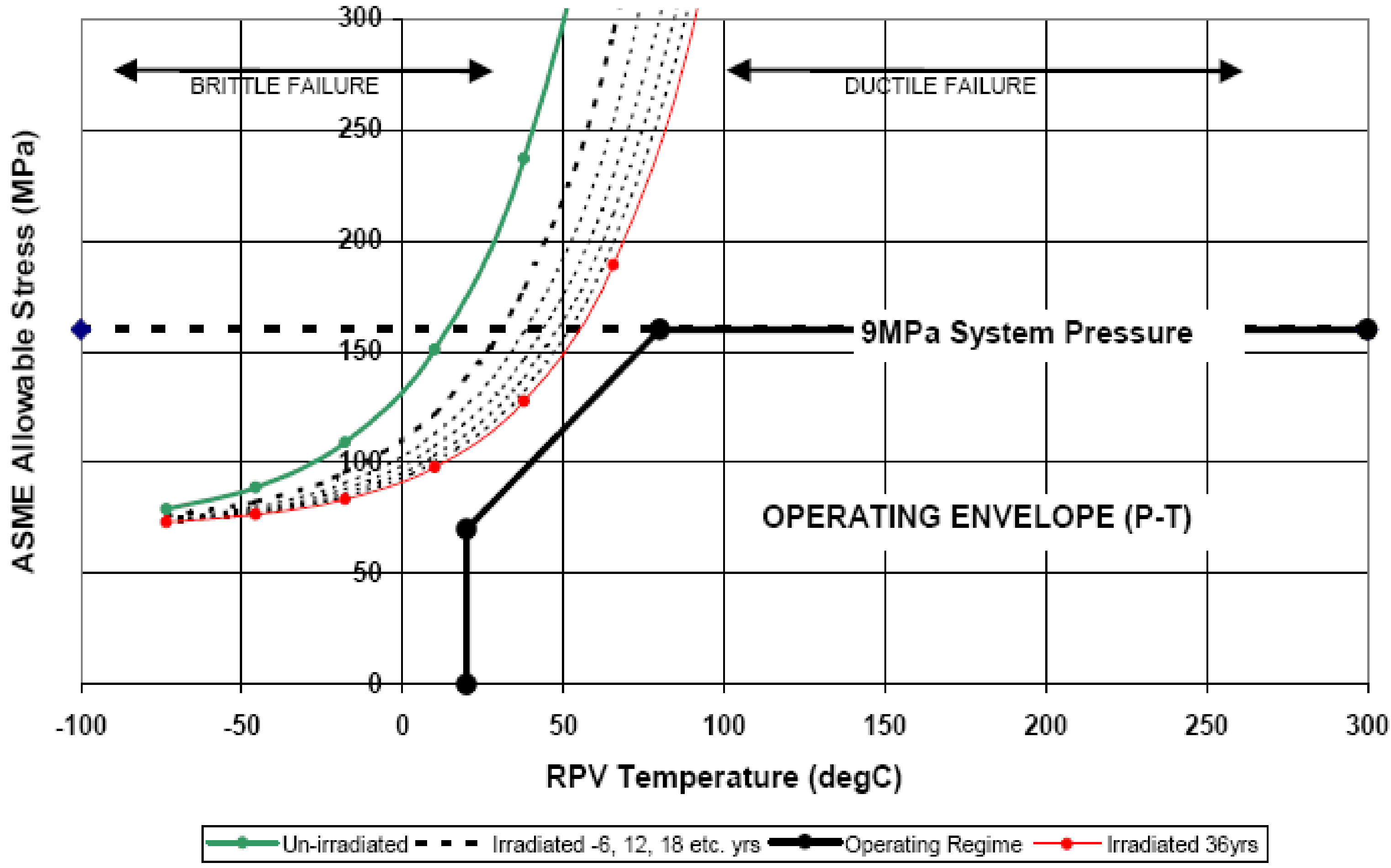
- Plant operating parameters
- Operating modes and states
- Description of key transitions
- Plant behavior during transitions
- Initial criticality and rise to power
- Maintenance approach

Nominal Plant Parameters

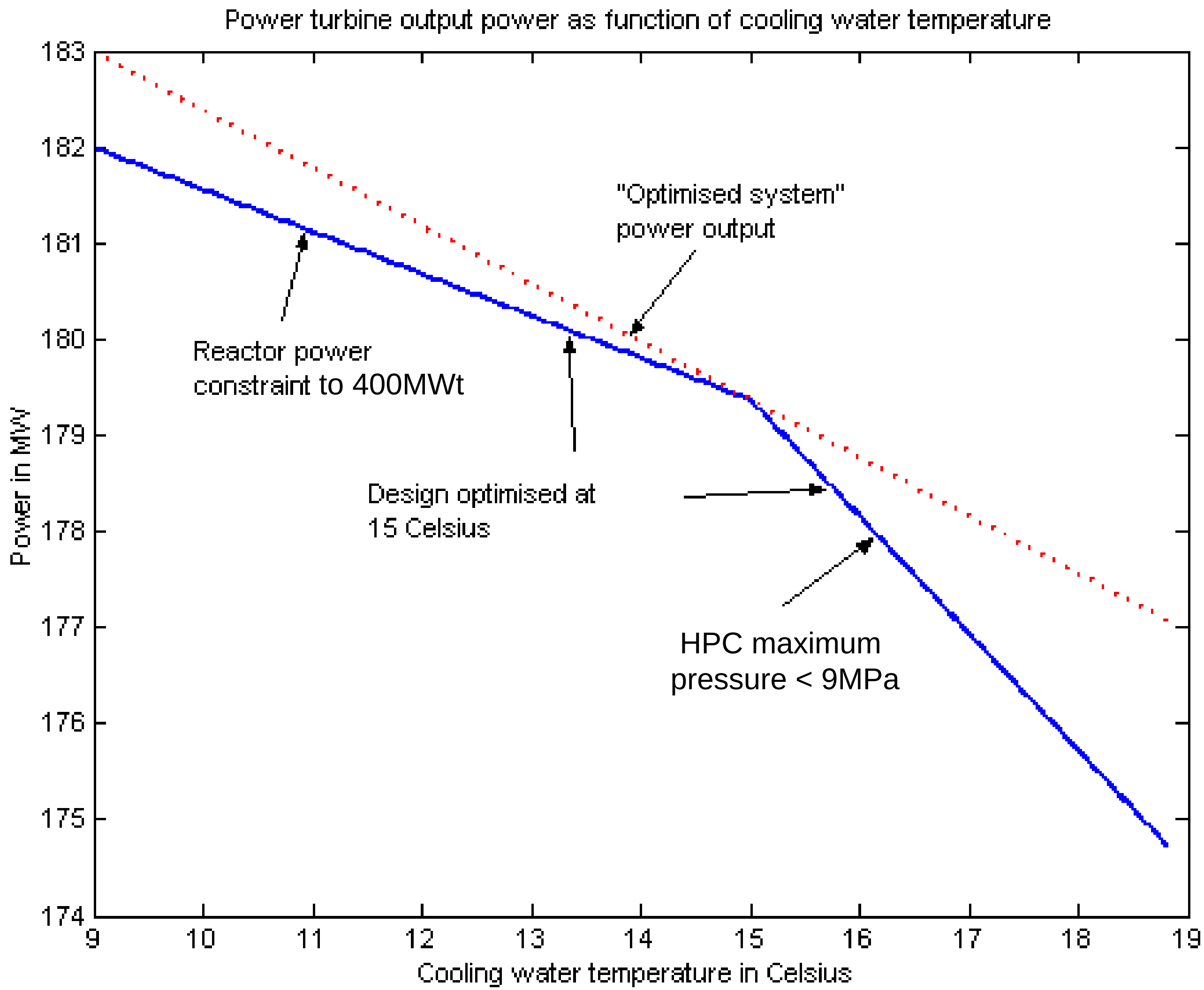
Thermal power	≤ 400 MWt
Core outlet temperature	≤ 900ºC
Core inlet temperature	~ 500ºC
Core temperature rise	≤ 450ºC
Helium Pressure	< 9 MPa
Compressor surge margin	> 10%

- **RPV pressure-temperature envelope**

RPV Pressure-Temperature Envelope



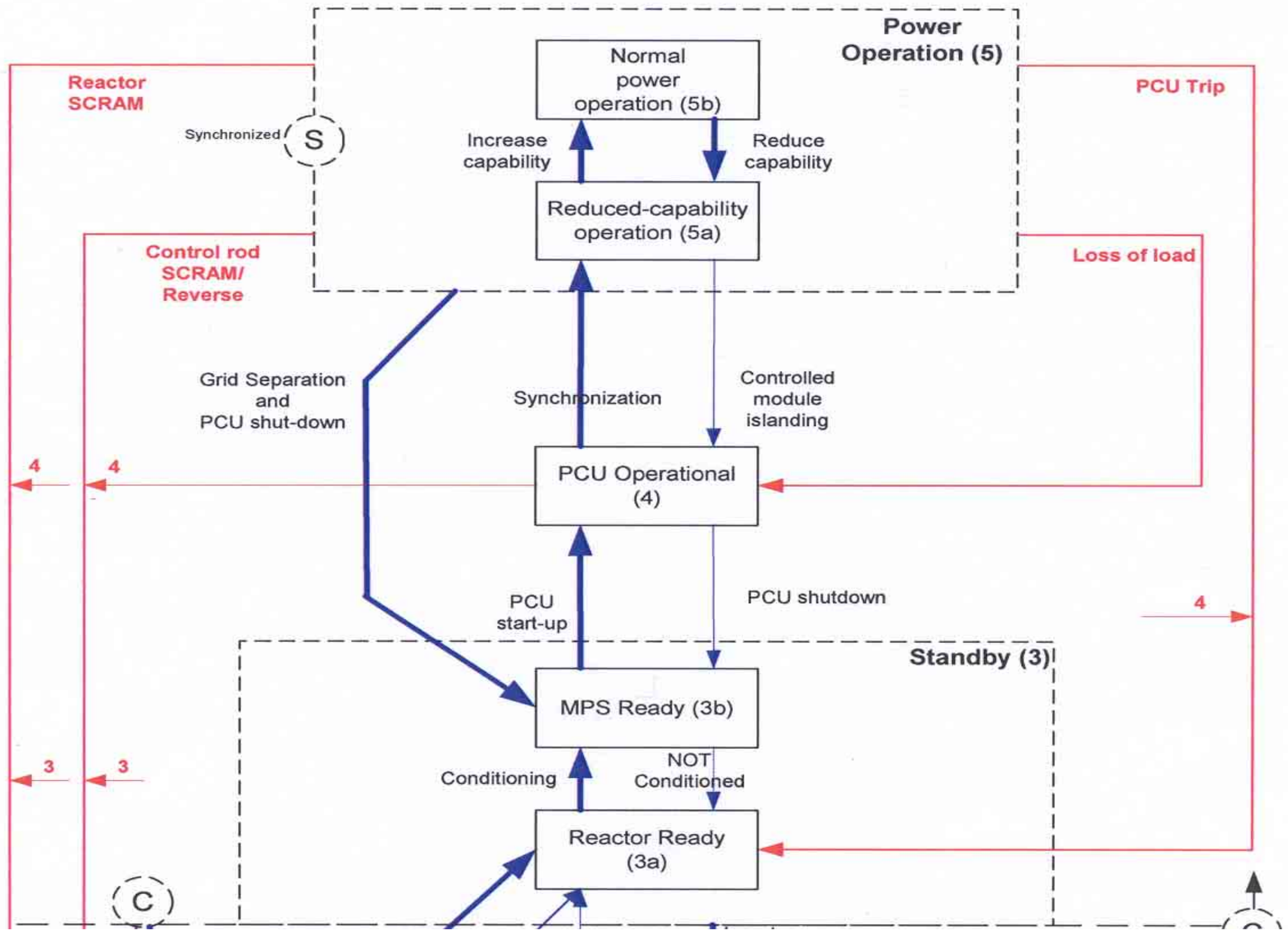
Electrical Power as Function of Site Cooling Water Temperature



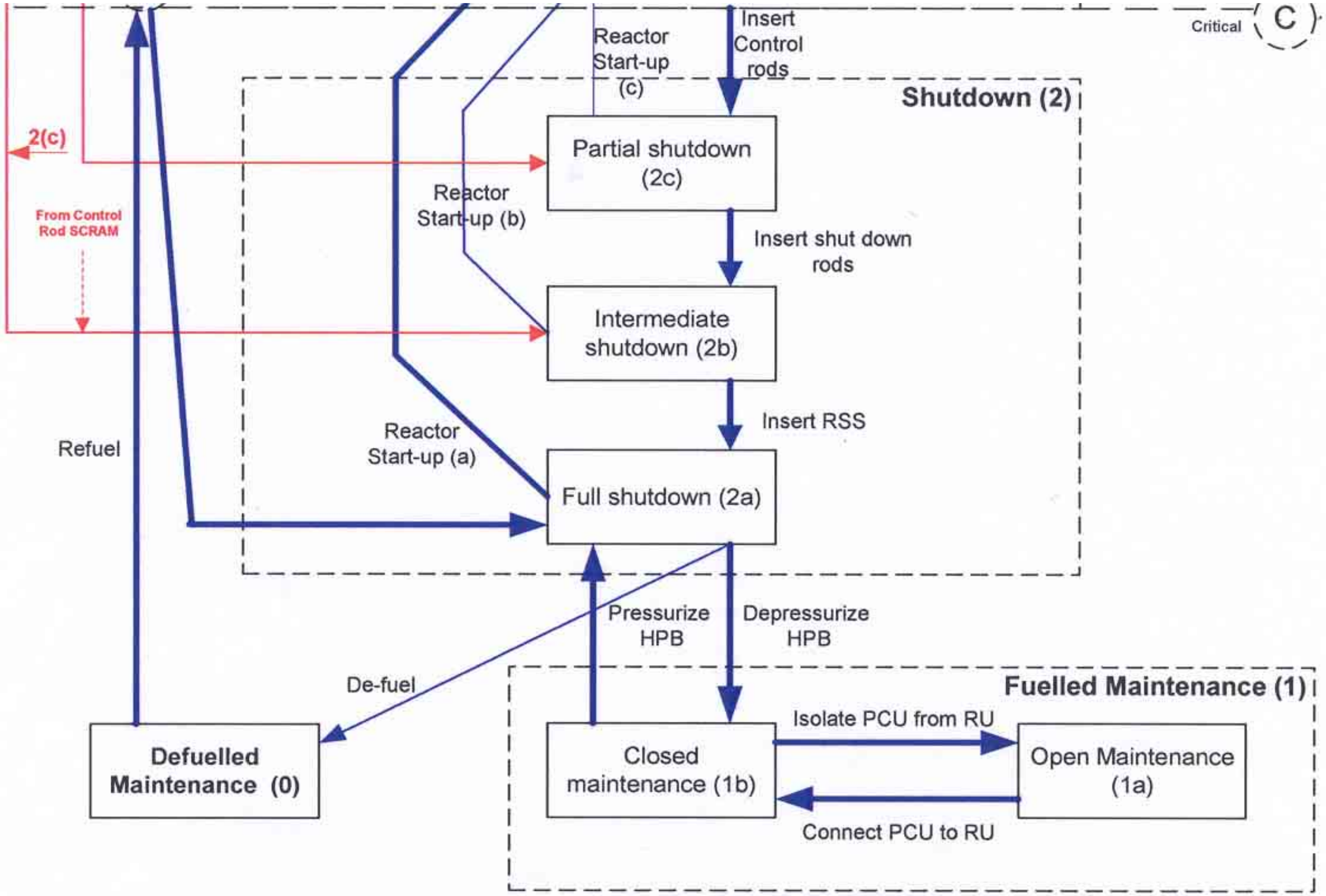
Plant Steady States

- **Power Operation (Mode 5)**
  - 100% MCR Load
  - 40% MCR load
- **PCU Operational (Controlled Island Operation) (Mode 4)**
- **Standby (Mode 3)**
  - MPS ready
  - Reactor ready
- **Shutdown (Mode 2)**
  - Partial (Control Rods inserted only)
  - Intermediate (Control Rods and Shutdown Rods inserted)
  - Full (All Rods and Small Absorber Spheres inserted)
- **Fueled Maintenance (Mode 1)**
  - HPB Closed
  - Open PCU
- **Defueled Maintenance (Mode 0)**

Operating Modes and States



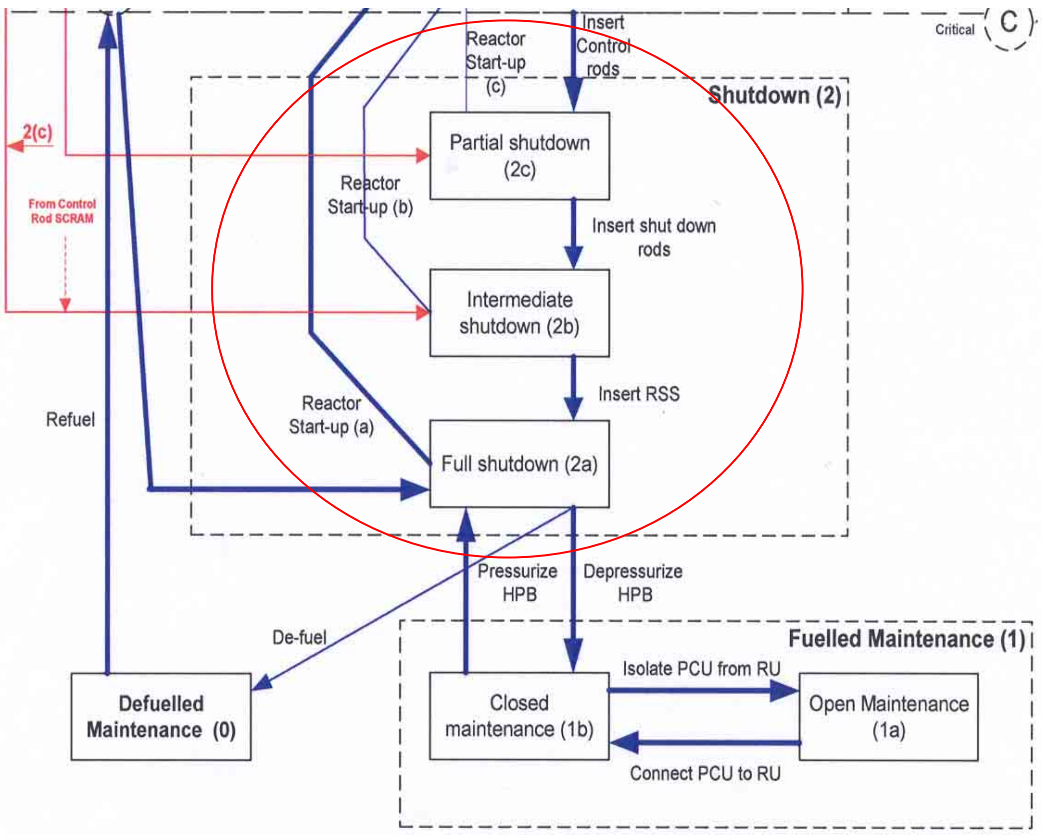
Operating Modes and States



Description of Key Transitions and Transients

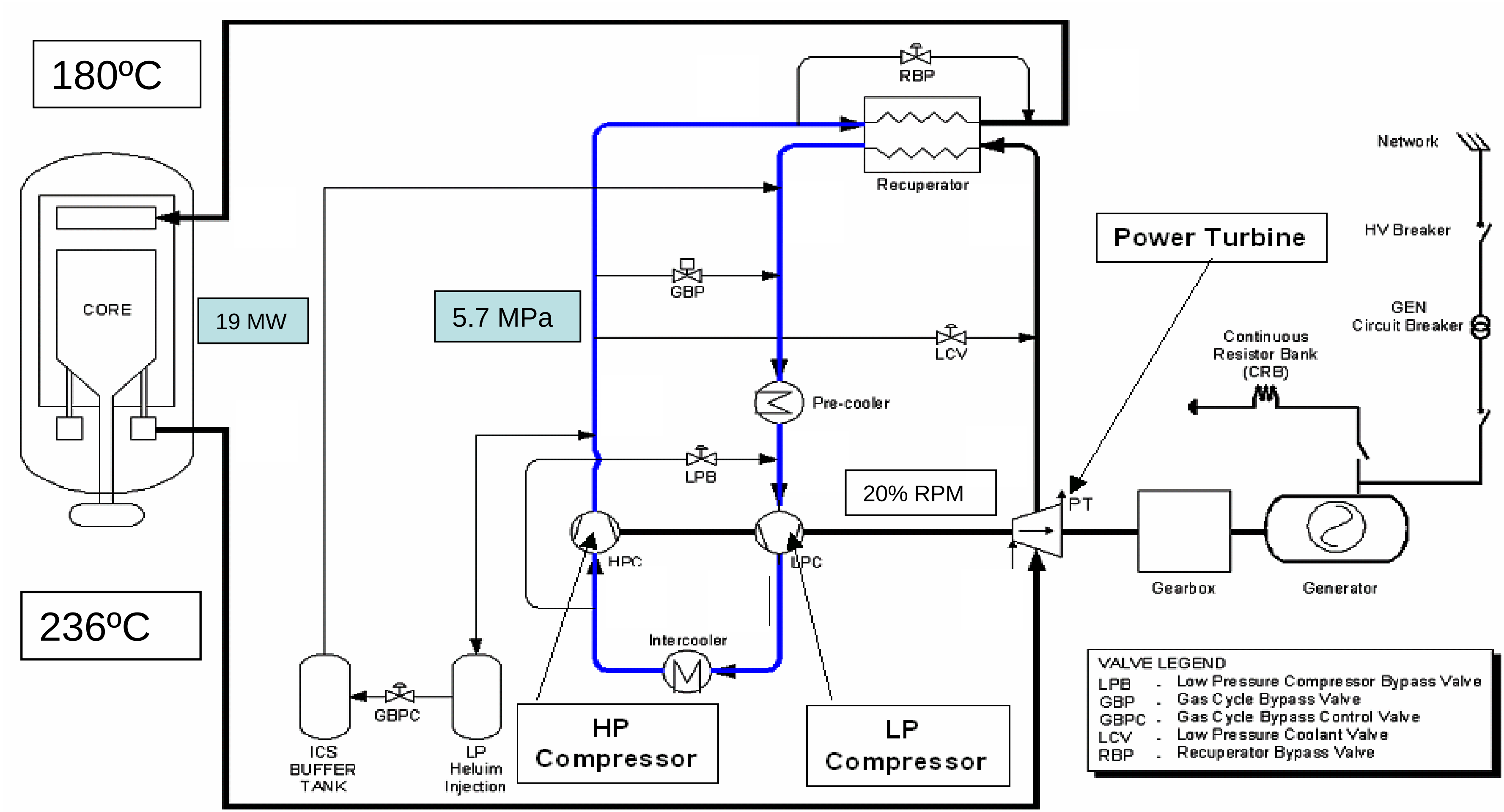
- Reactor start up
- PCU start up
- 100-40-100 load change
- Reactor rundown with PCU trip
- Loss of load

Reactor Start-up Transition

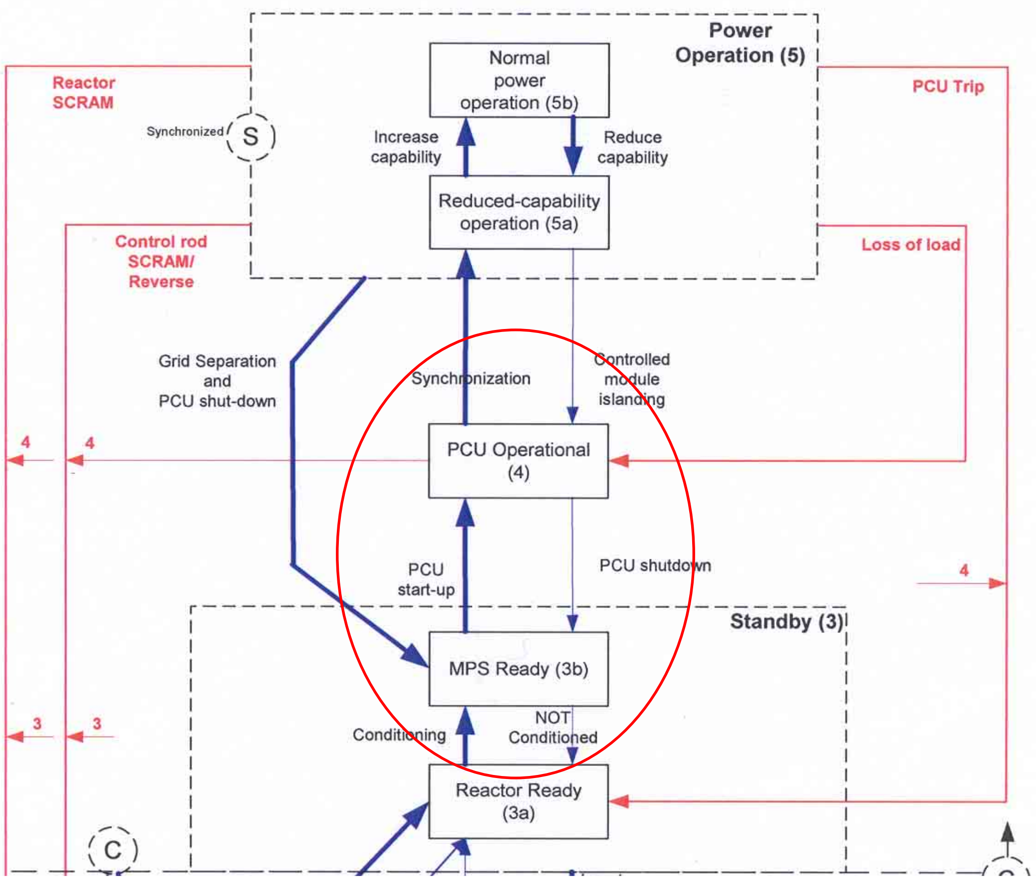


- **The HPB is closed and filled with helium.**
- **The CCS or PCU is used for circulation.**
- **The reactor is heated up on Primary Loop Initial Clean-up System (PLICS) or PCU to about 300ºC before taken critical.**
- **The exact sequence of reactivity withdrawal will depend on the xenon and the temperature of the core.**

MPS Ready (Mode 3b)

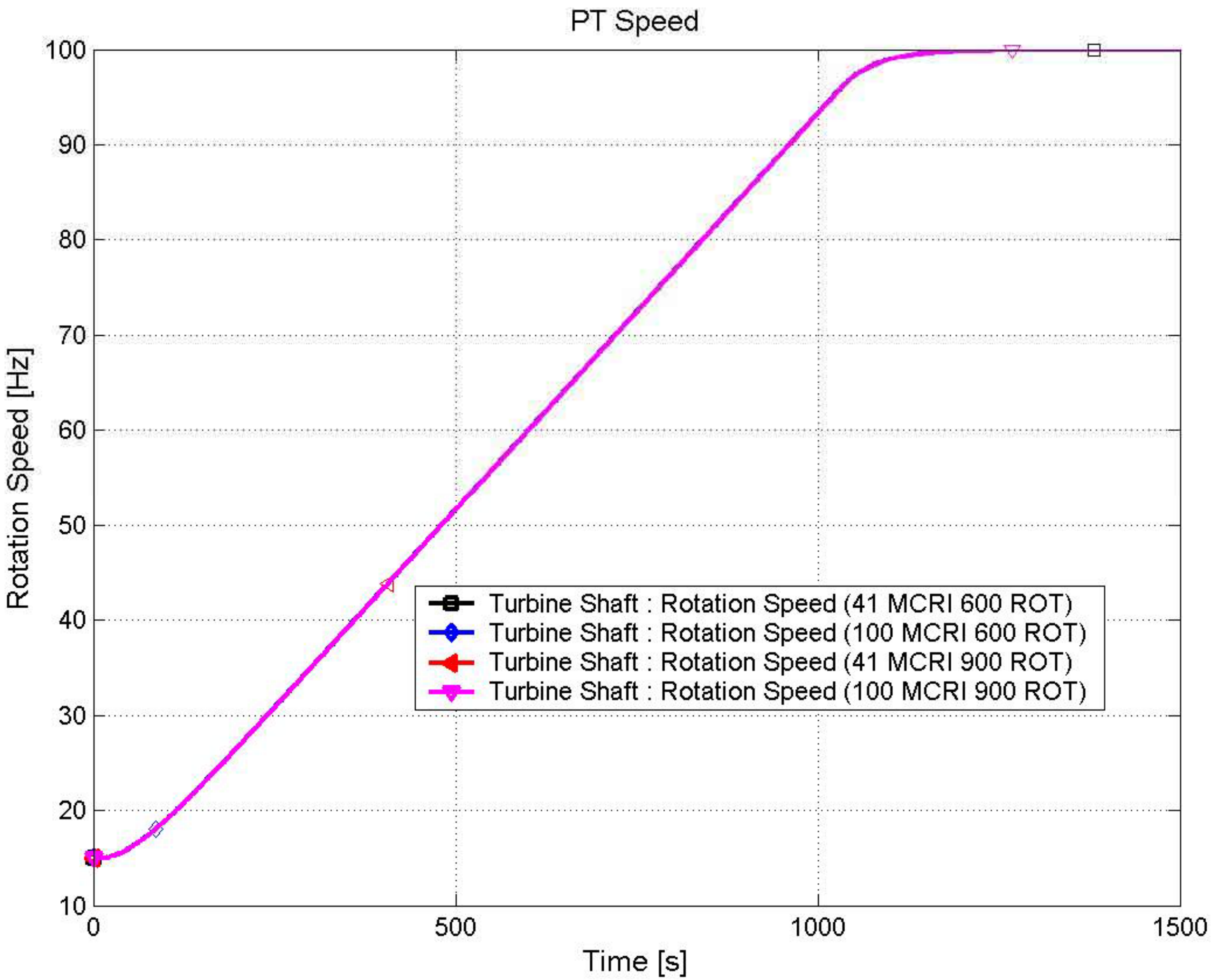


PCU Start-up Transition

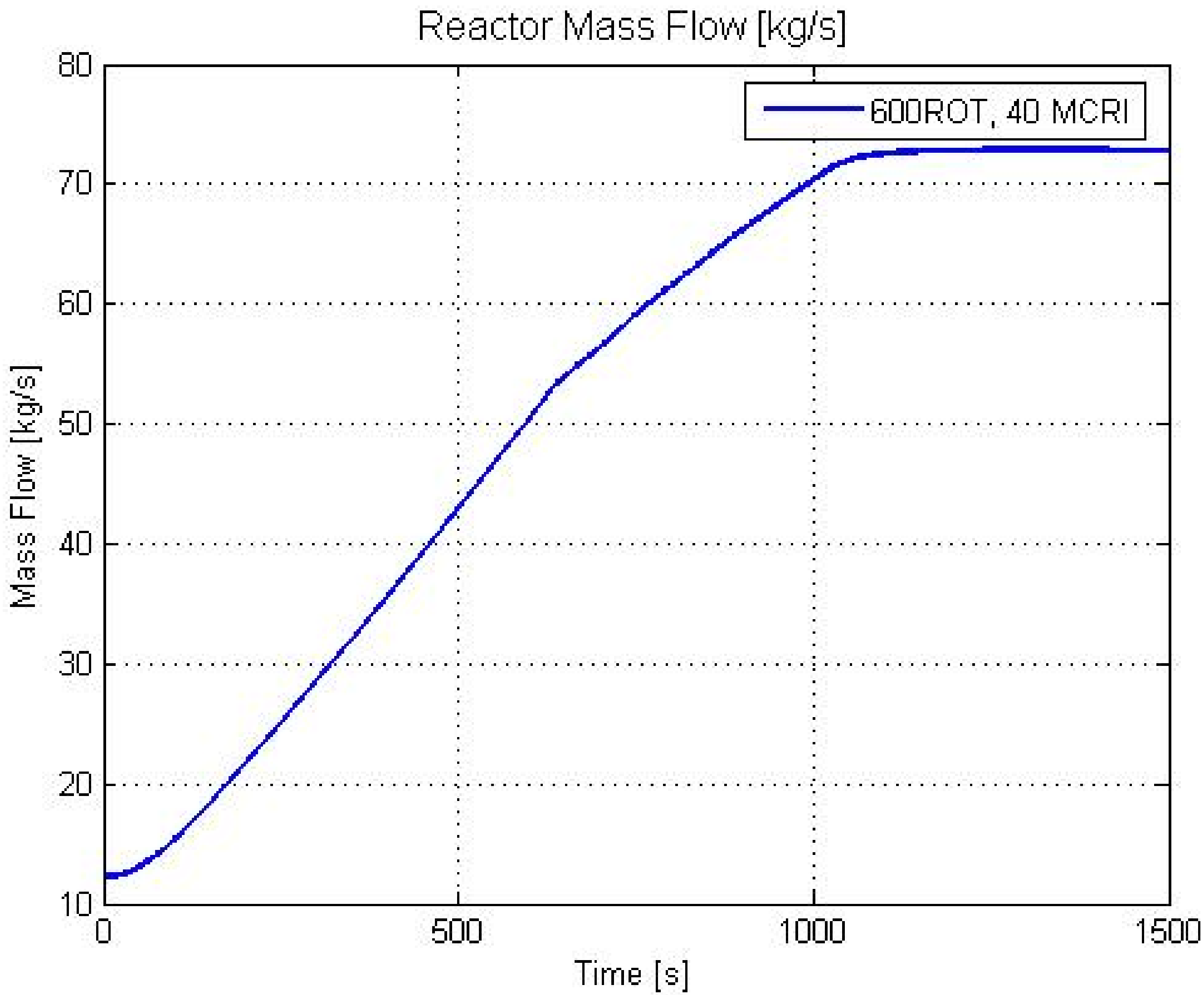


- **Plant initially at MPS ready state**
  - Reactor is critical.
  - PCU has been conditioned and is operating on SFC.
- **There are different transitions depending on initial reactor conditions:**
  - From ROT at 600ºC (40% MCRI or 100% MCRI)
  - From ROT at 900ºC (40% MCRI or 100% MCRI)

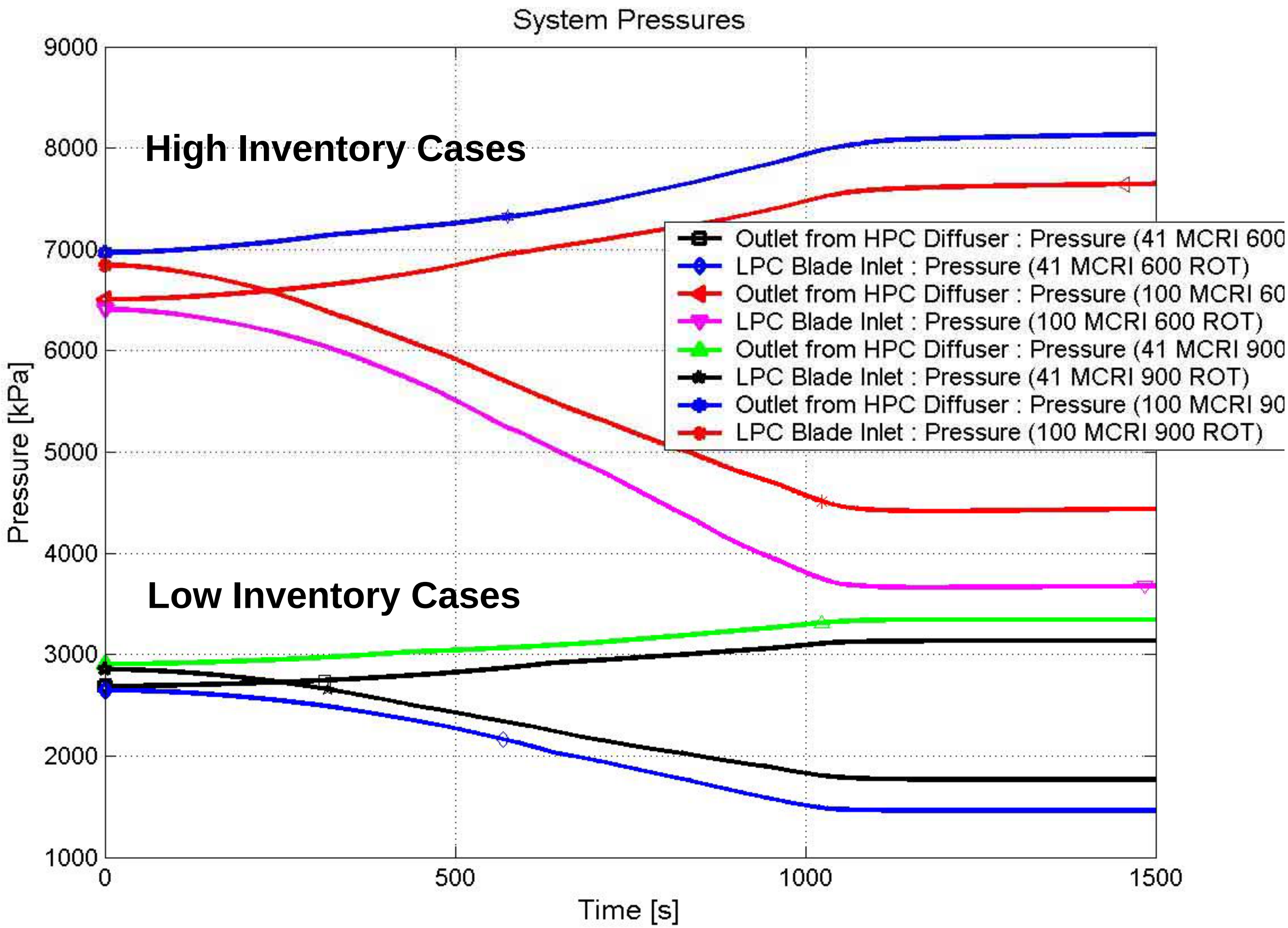
PCU Start-up
Turbine Speed



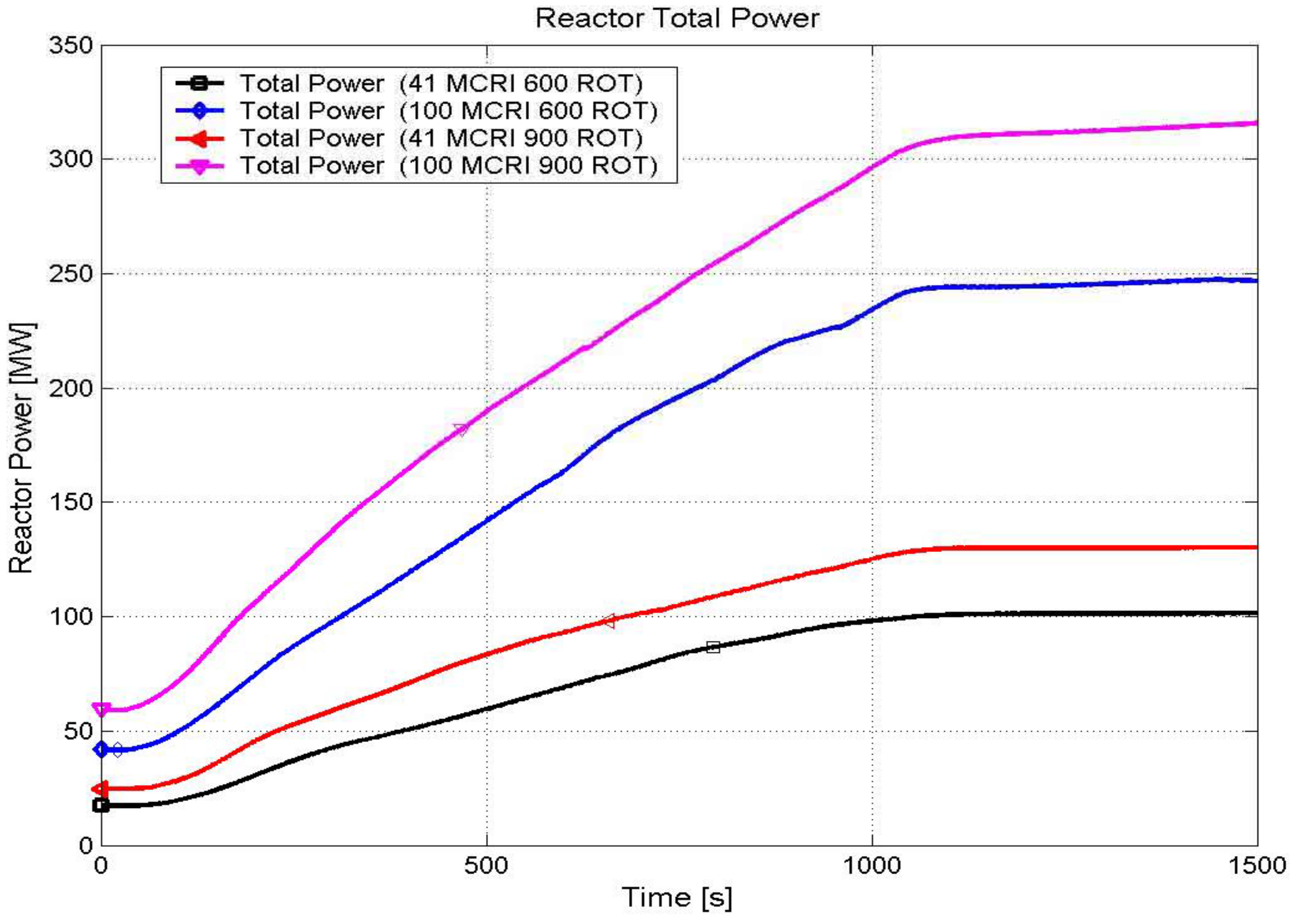
PCU Start-up
Reactor Mass Flow Rate



PCU Start-up
Cycle Pressure Ratio

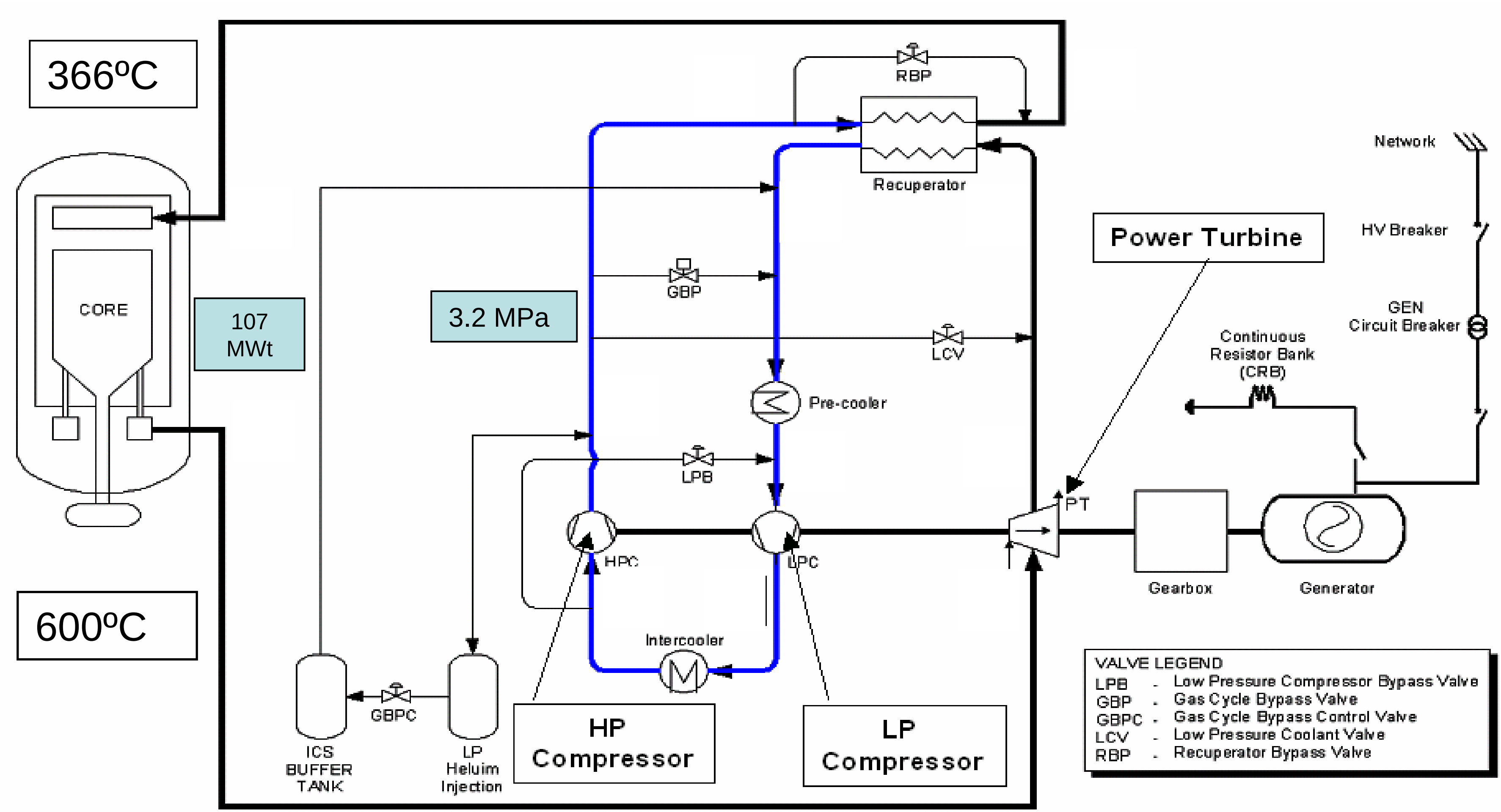


PCU Start-up
Reactor Power



Example Calculation [to be developed]

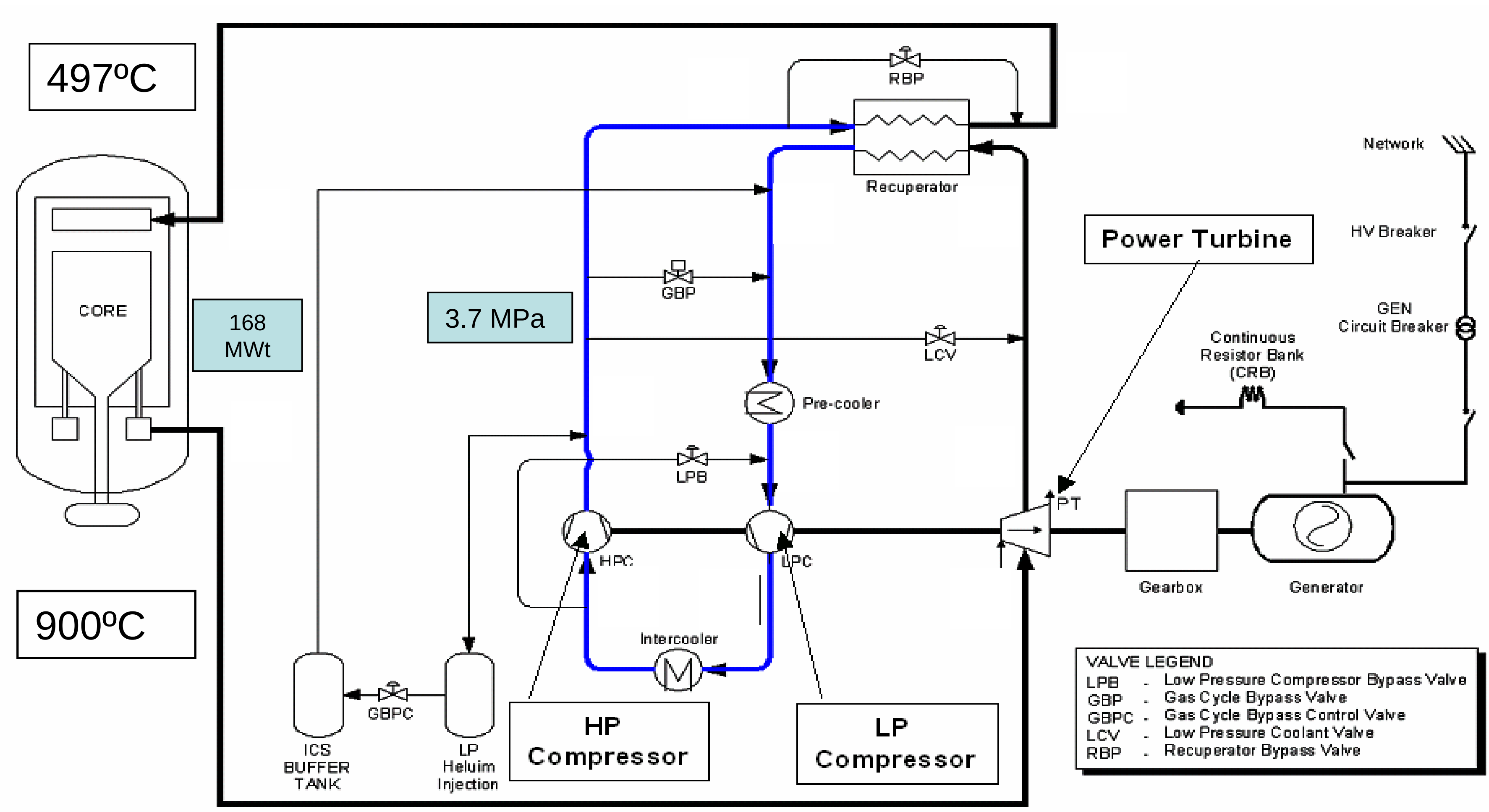
PCU Operational (Mode 4)



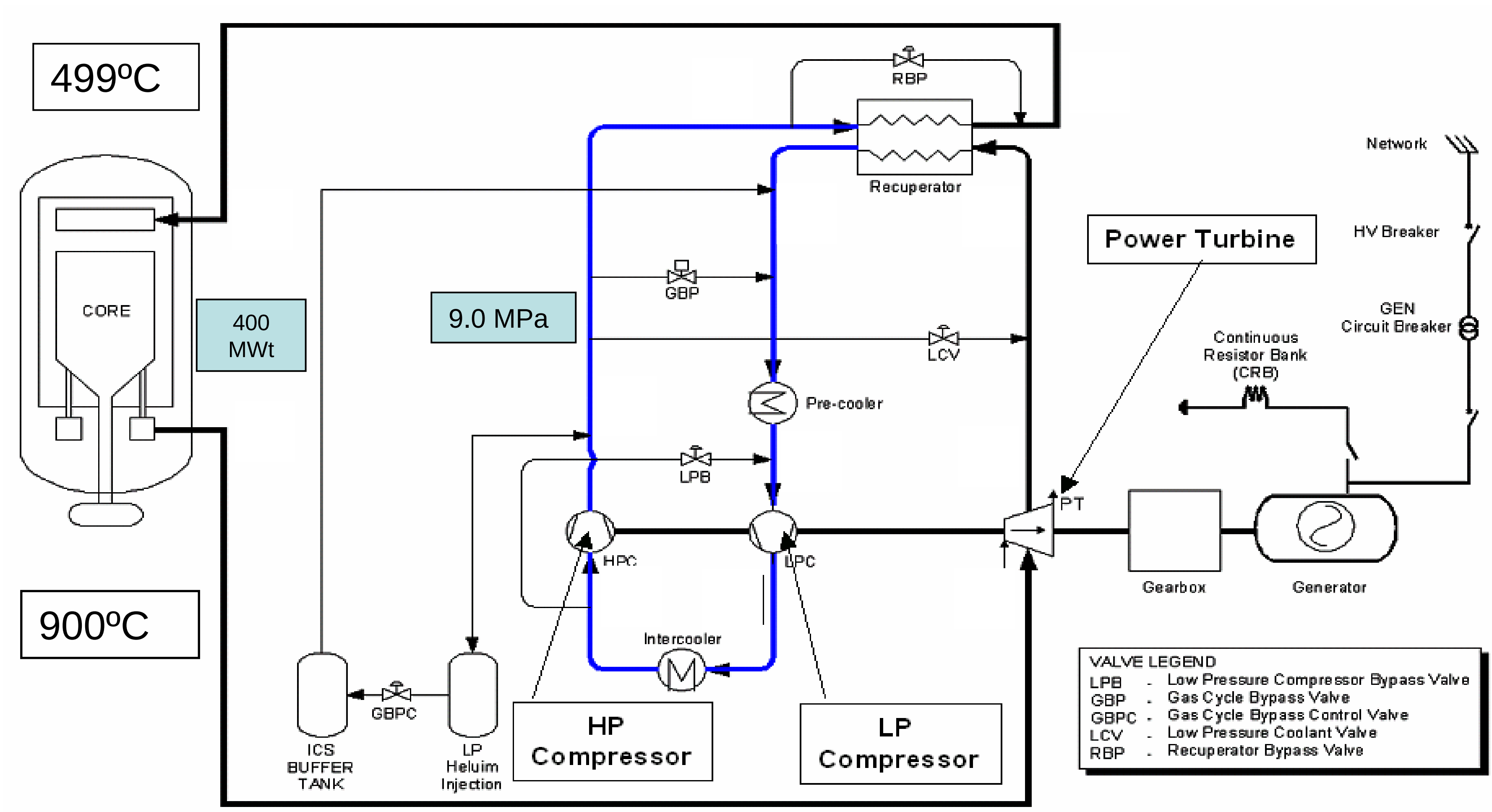
Transition Time Scales

- **Fill primary coolant to 40% inventory: ~40 hrs**
- **Depressurize primary coolant from 40 MCRI to atmospheric condition: ~40 hrs**
- **PCU start up from turning gear speed to 100% MCR load: ~6 hrs**
- **PCU rundown from 100% MCR load to turning gear: ~5 min**
- **Primary coolant clean up from open maintenance to reactor ready to go critical: 24-96 hrs**

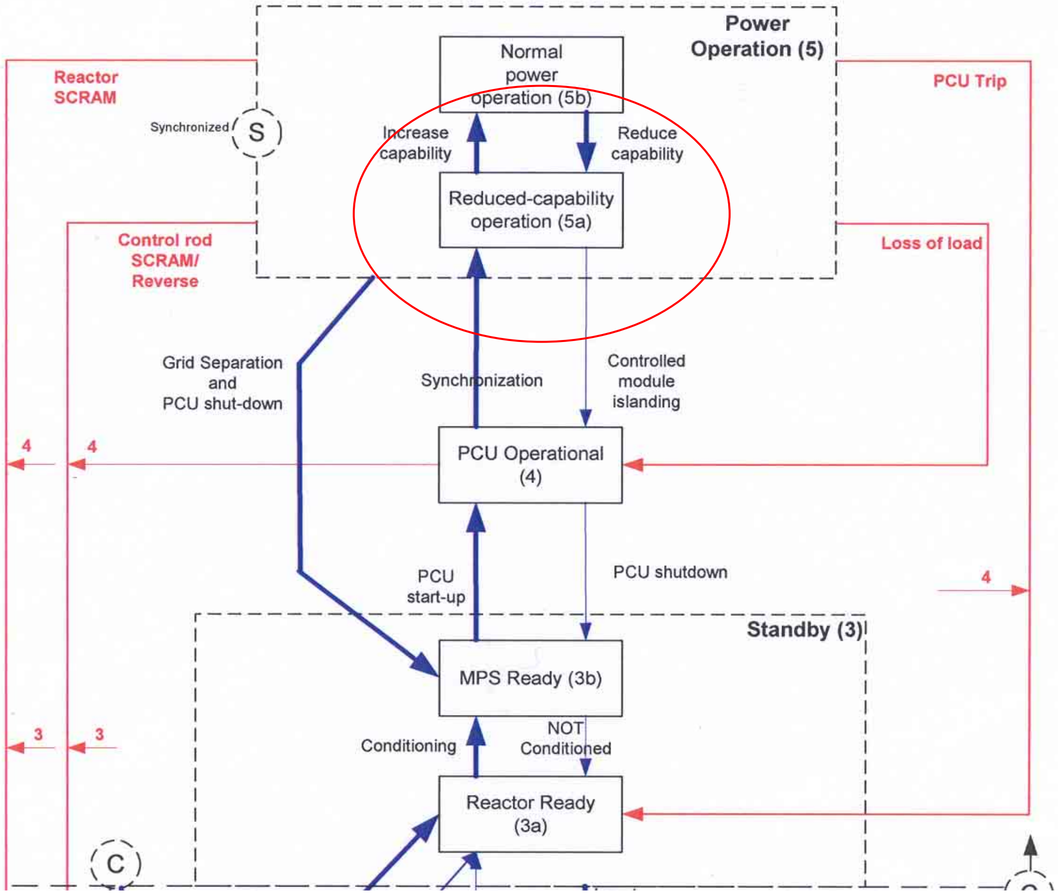
Power Operation
40% MCR Load (Mode 5)



Power Operation
100% MCR Load (Mode 5)

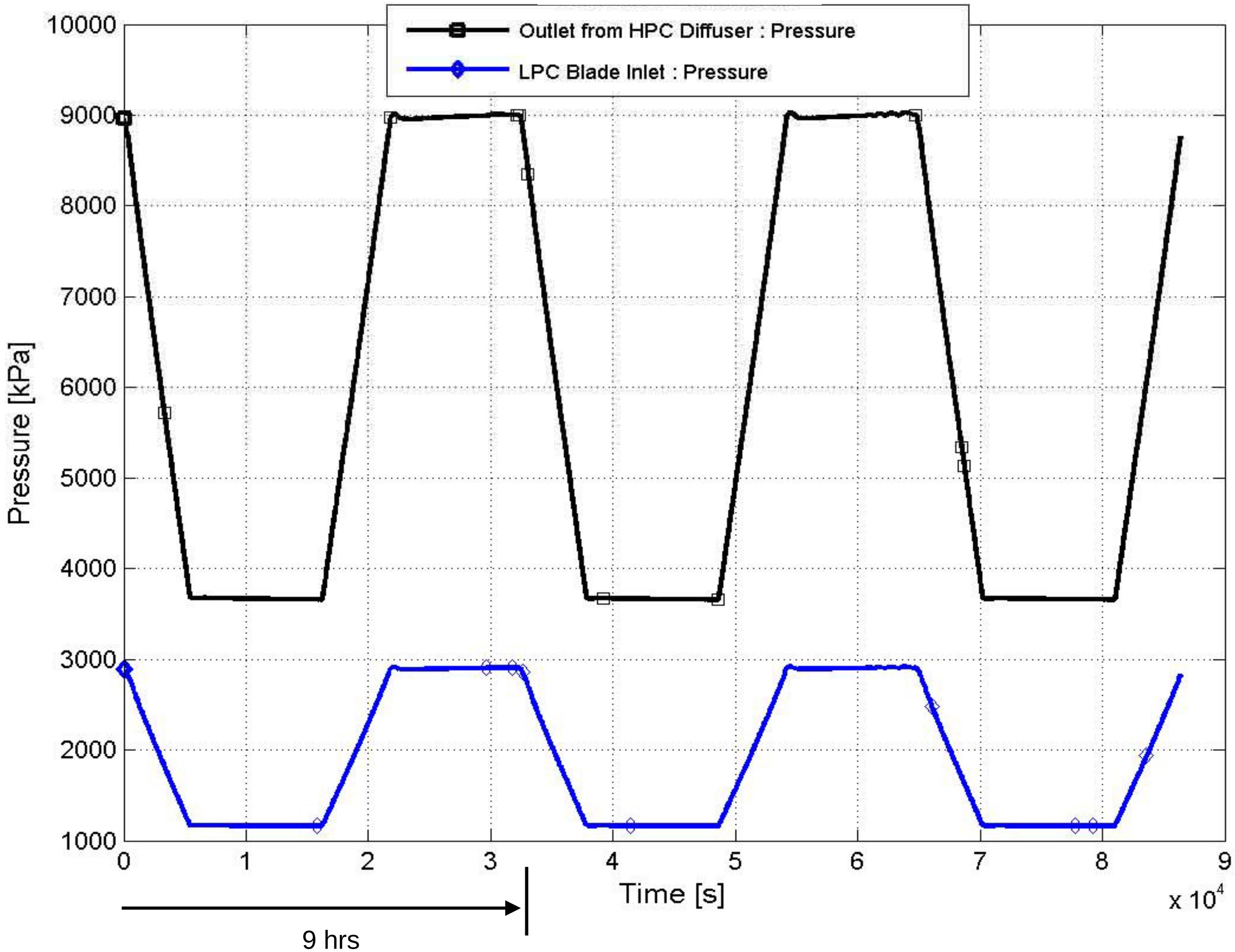


Power Operation 100%-40%-100% Load Change

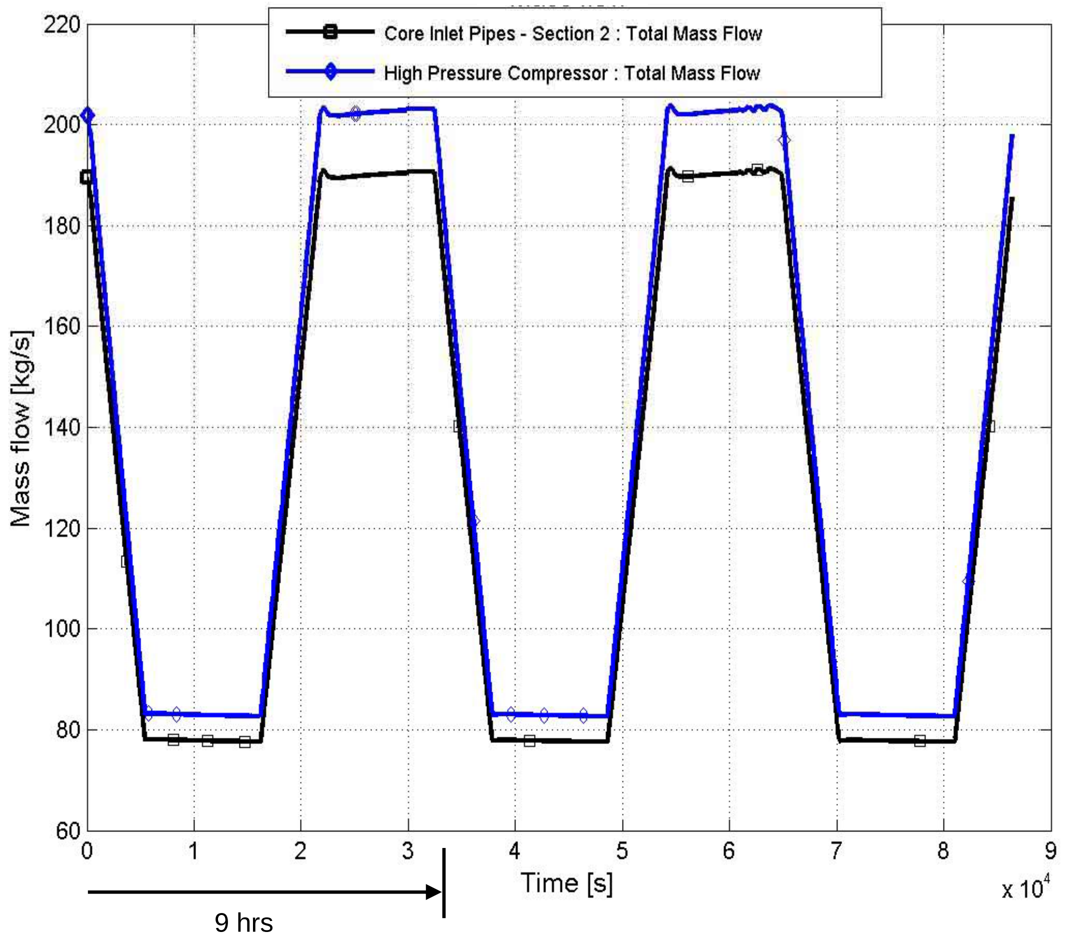


- Normal load swing between 100%-40%-100% over a period of ~9 hrs
- Based on inventory control alone
- Reactivity control based on maintaining reactor outlet temperature constant
- Ramp rate used: 10%/15 min

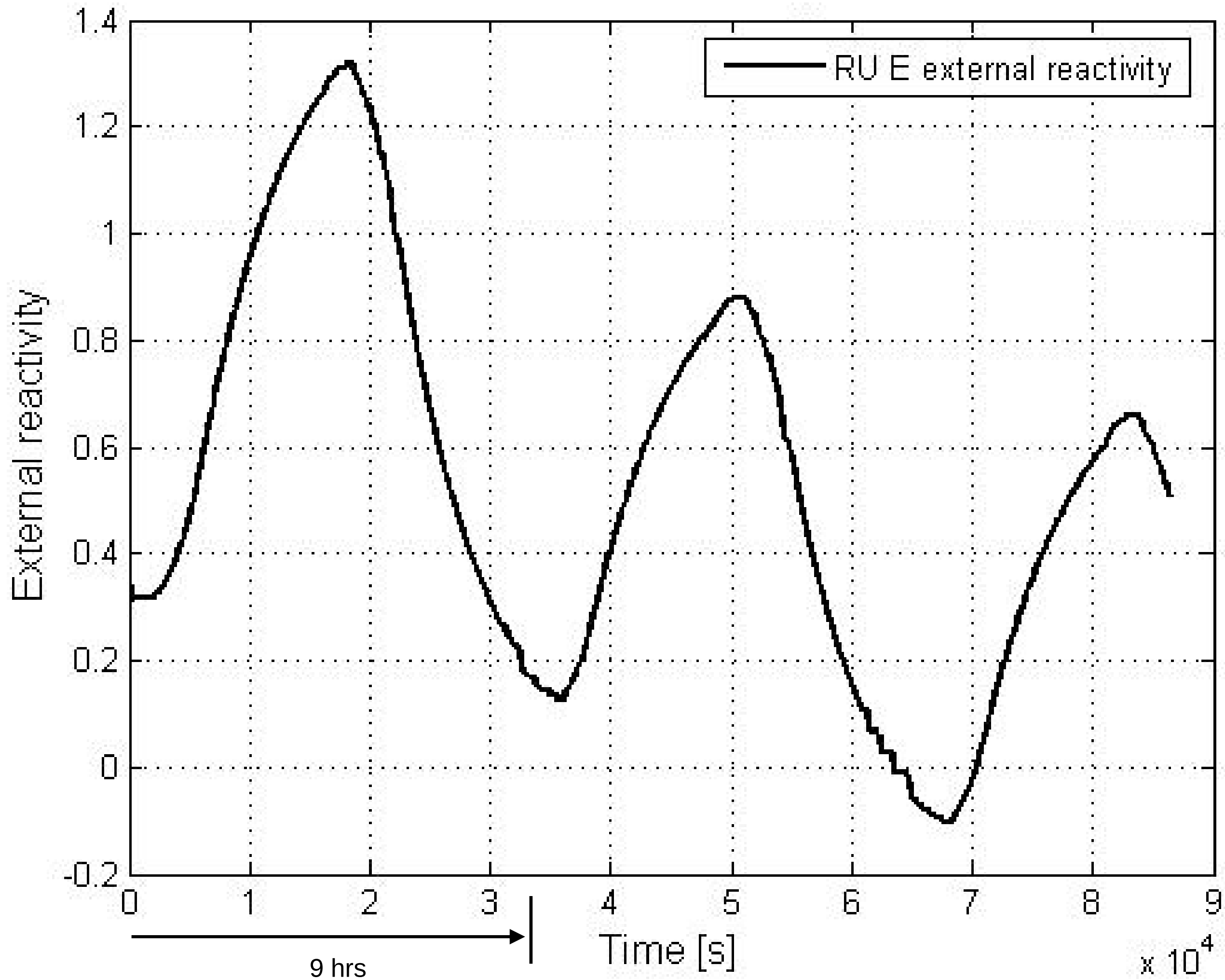
100%-40%-100% Load Change System Pressures



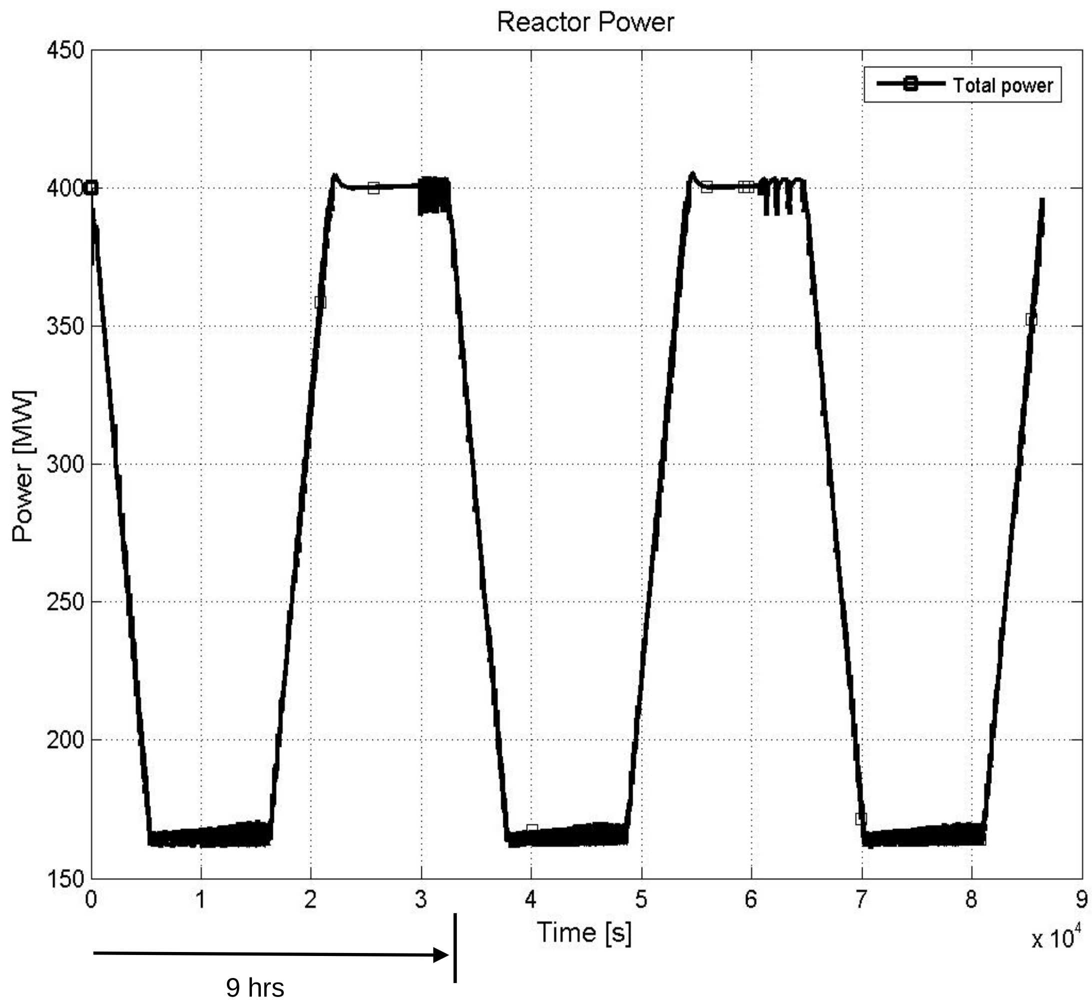
100%-40%-100% Load Change
Mass Flow Rates



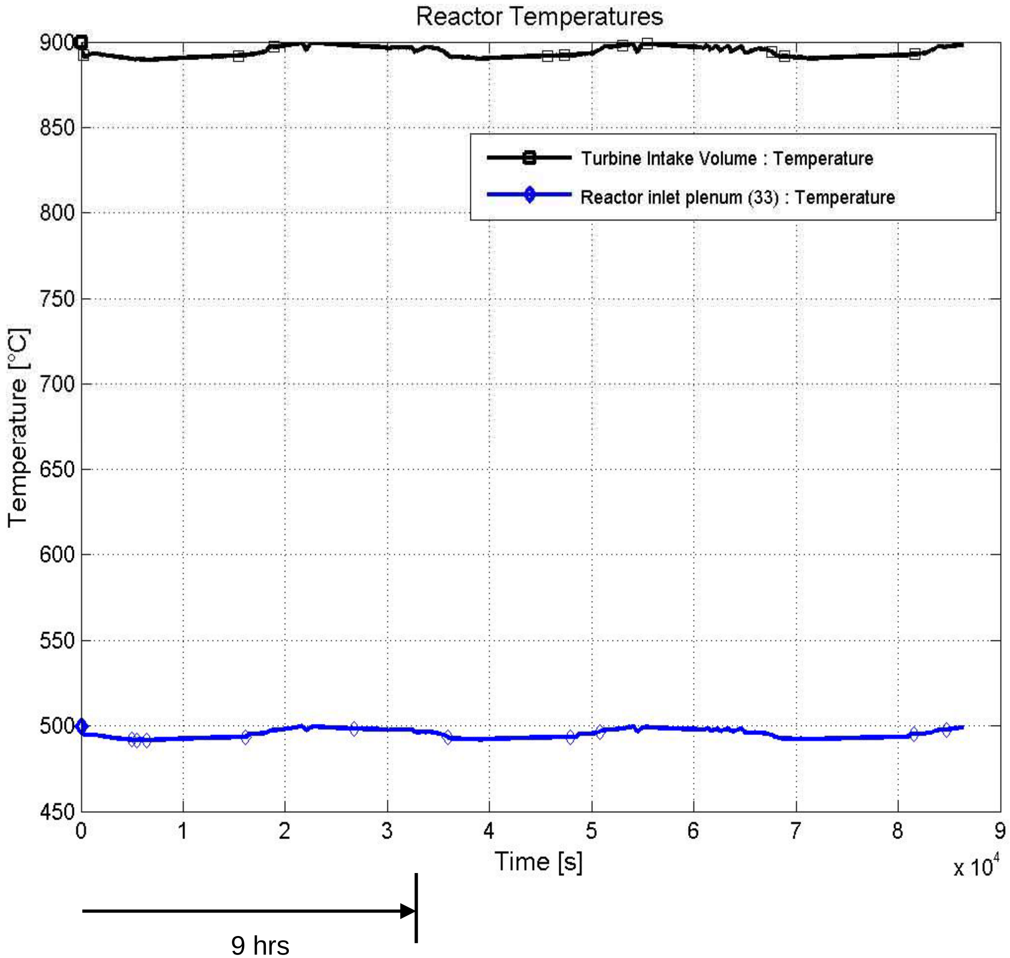
100%-40%-100% Load Change Control Rod Reactivity



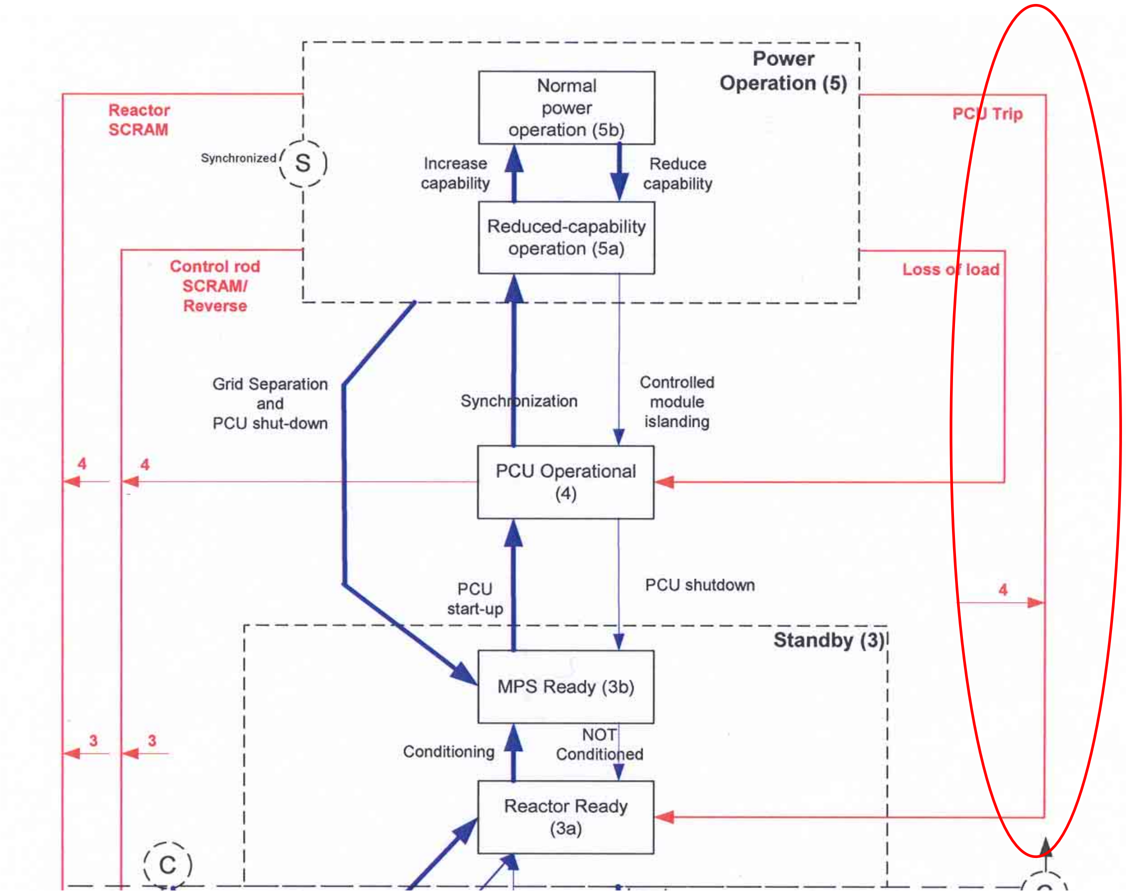
100%-40%-100% Load Change Reactor Power



100%-40%-100% Load Change Core Temperatures

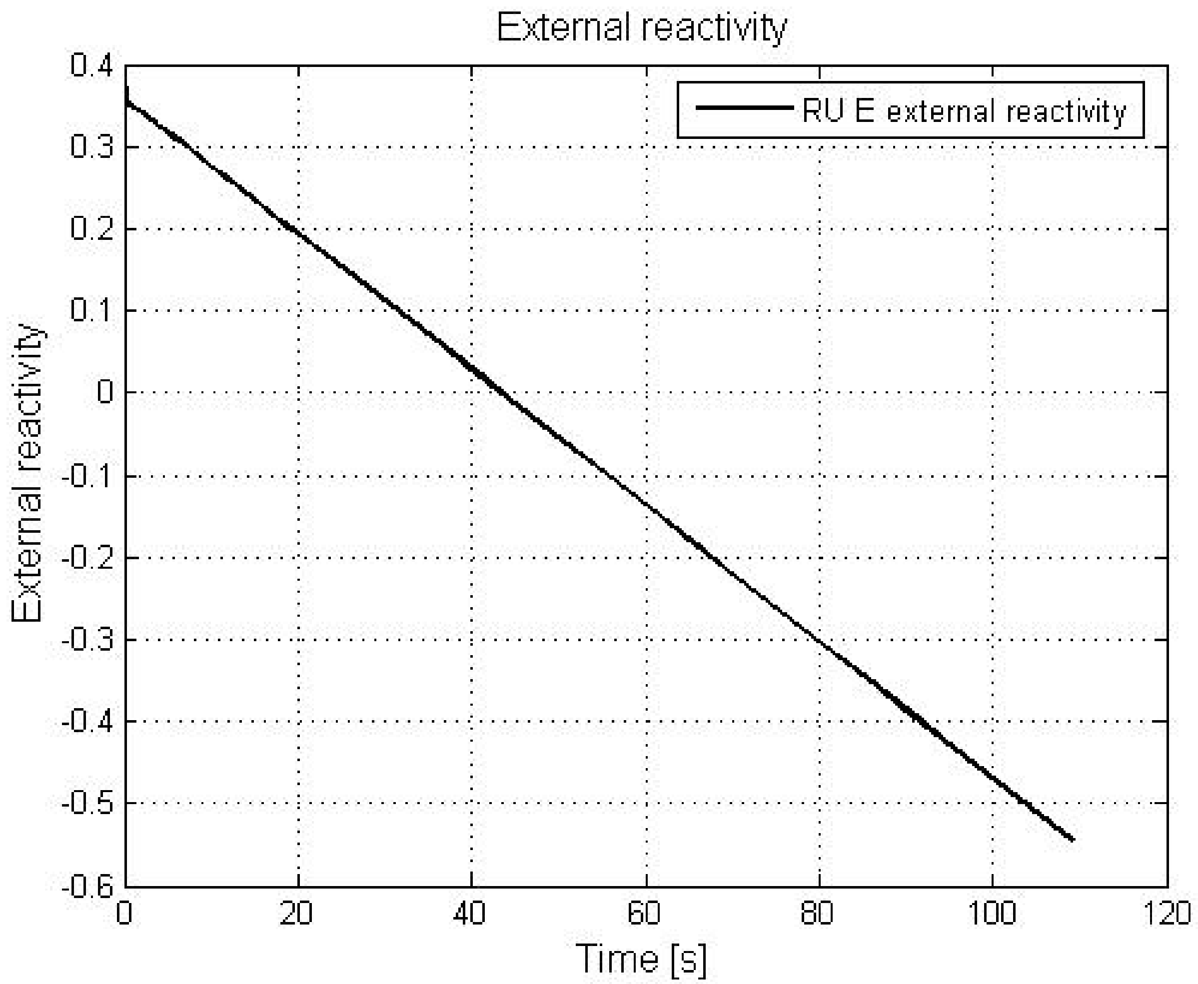


Reactor Rundown With PCU Trip

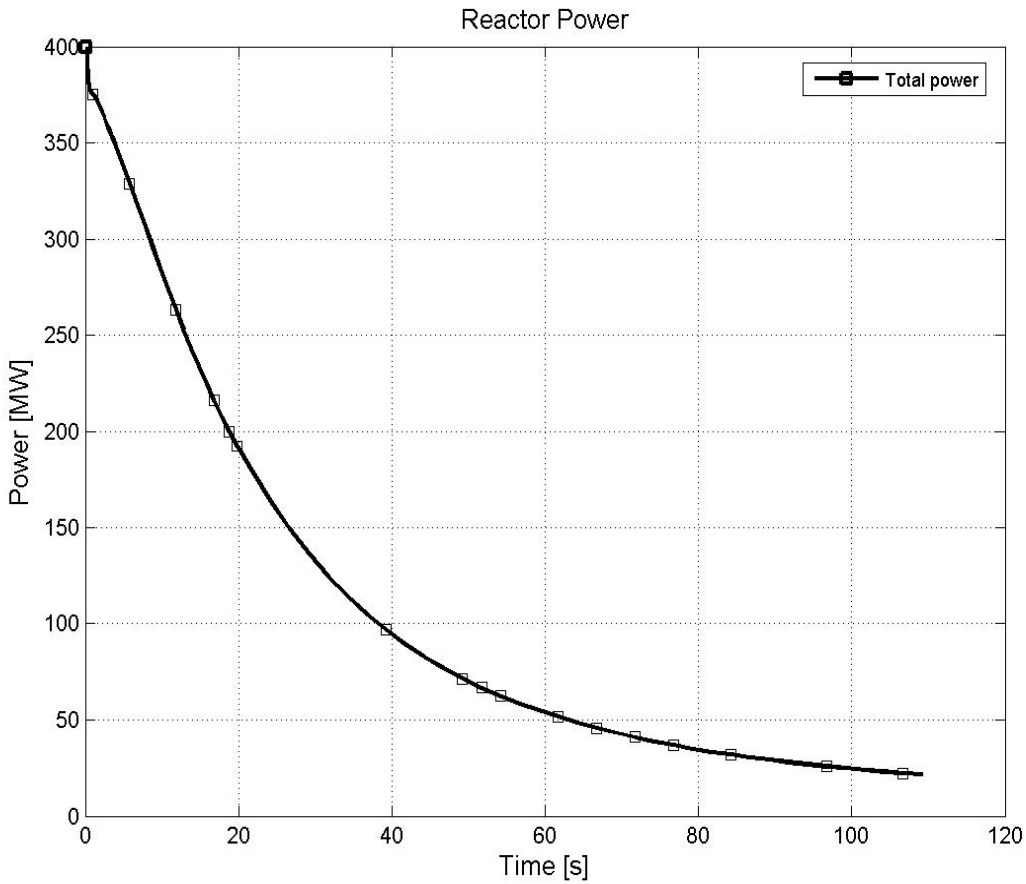


- Control rods drive the reactor power down.
- It is assumed that the PCU is tripped by opening the Gas Cycle Bypass Valves and coasts down.
- After the PCU speed drops below ~ 10%, cooling is initiated on CCS.

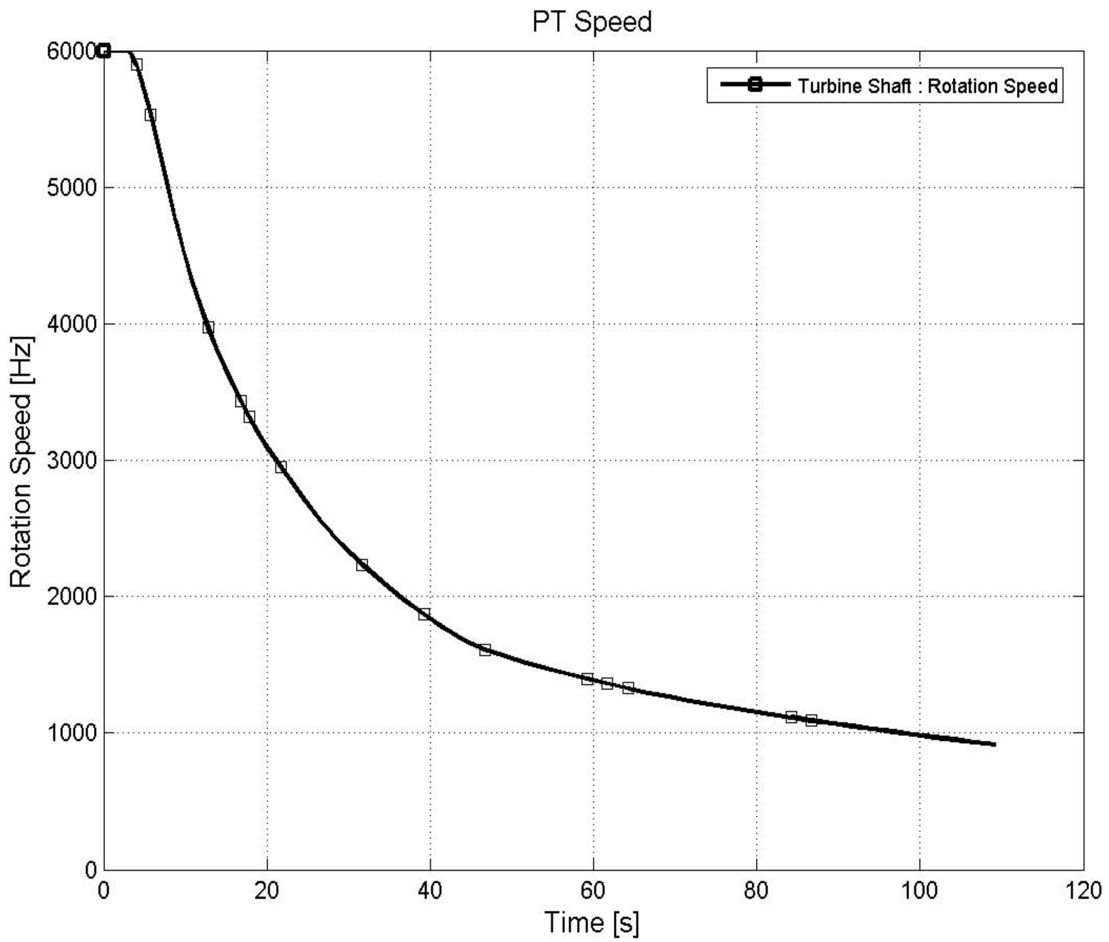
Reactor Rundown With PCU Trip Reactivity Insertion



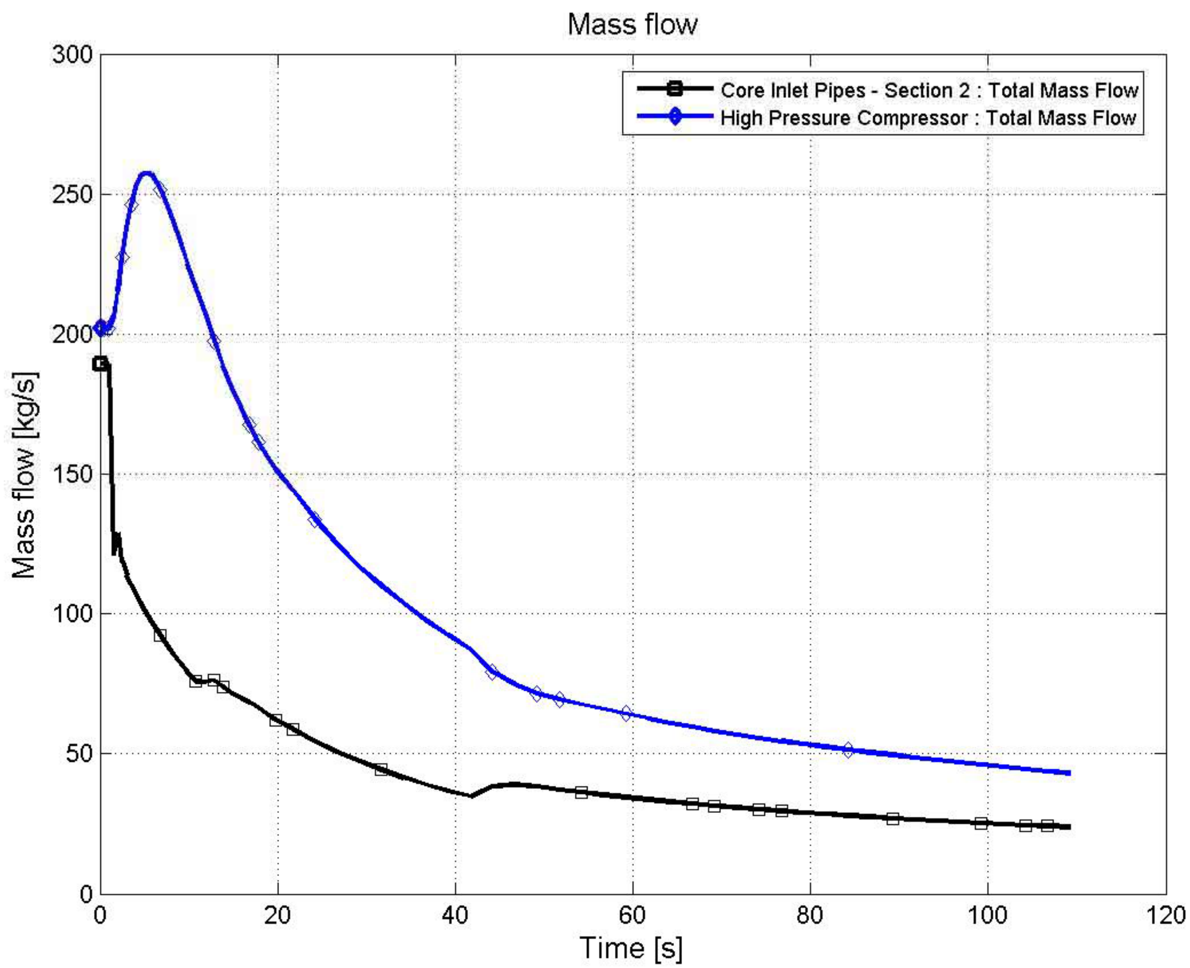
Reactor Rundown With PCU Trip
Reactor Power



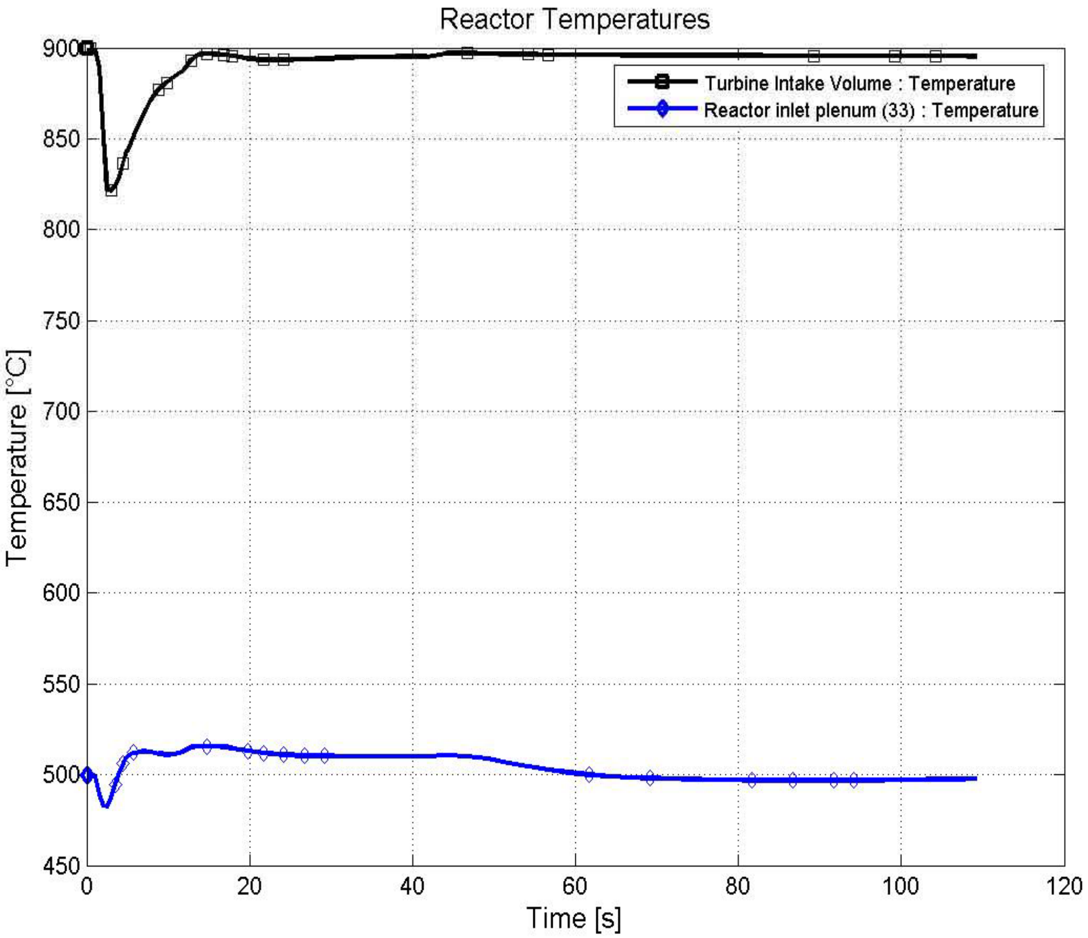
Reactor Rundown With PCU Trip Turbine Speed



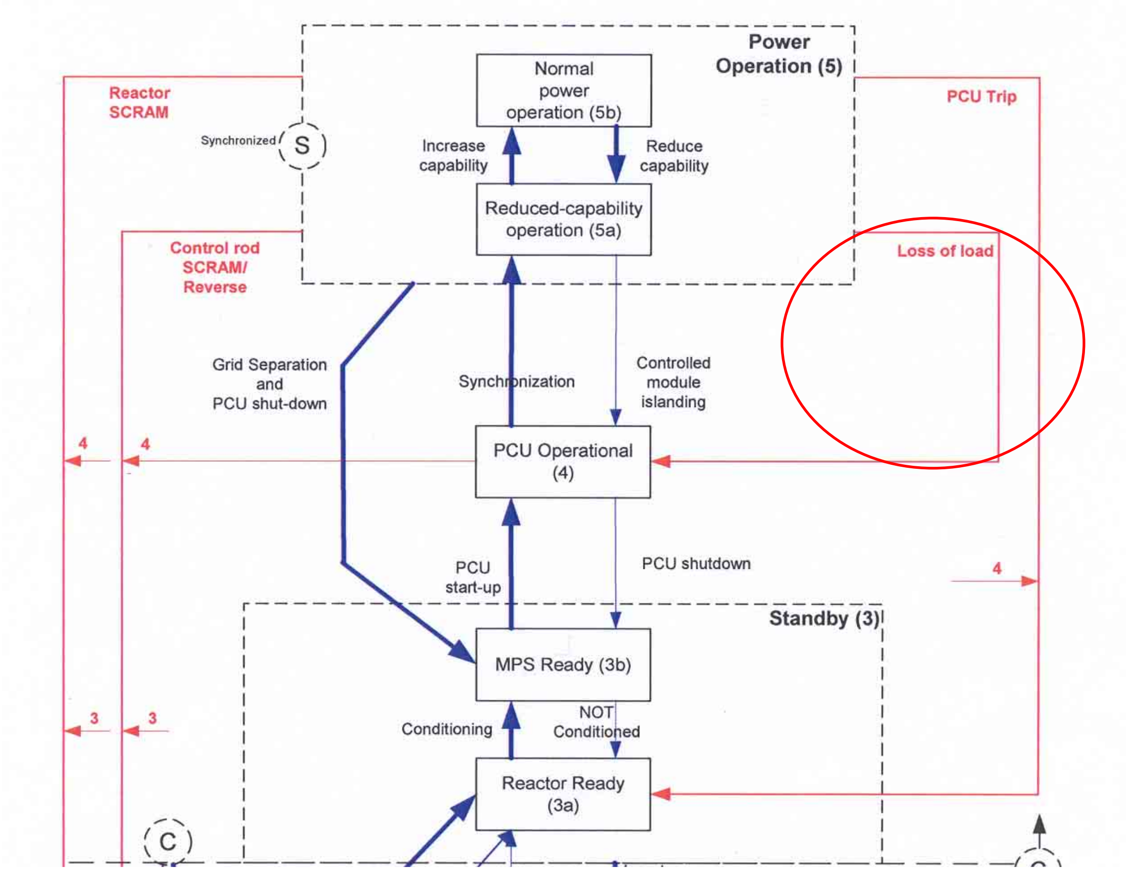
Reactor Rundown With PCU Trip Mass Flow Rates



Reactor Rundown With PCU Trip
Core Temperatures

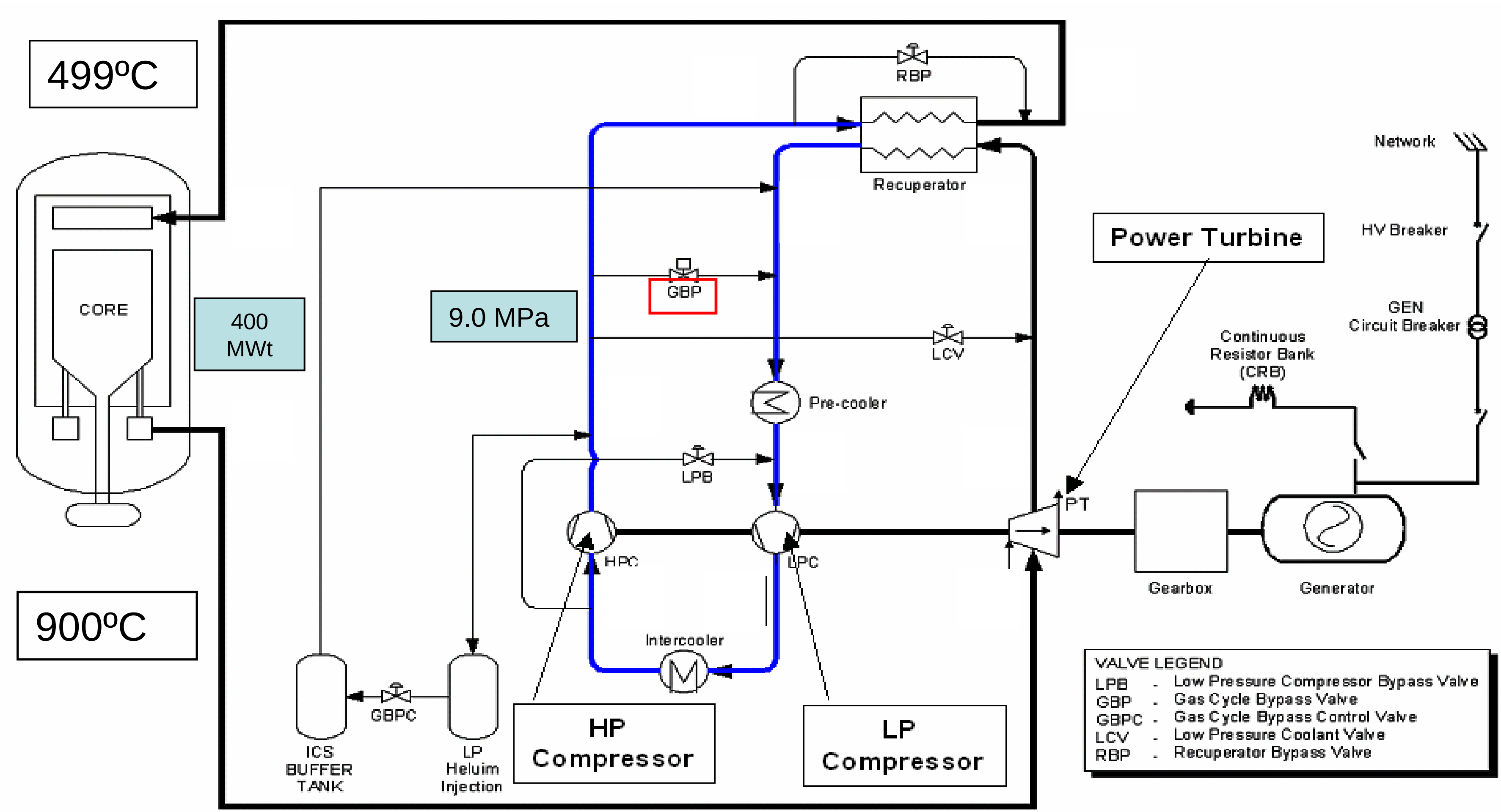


Loss of Load Transient

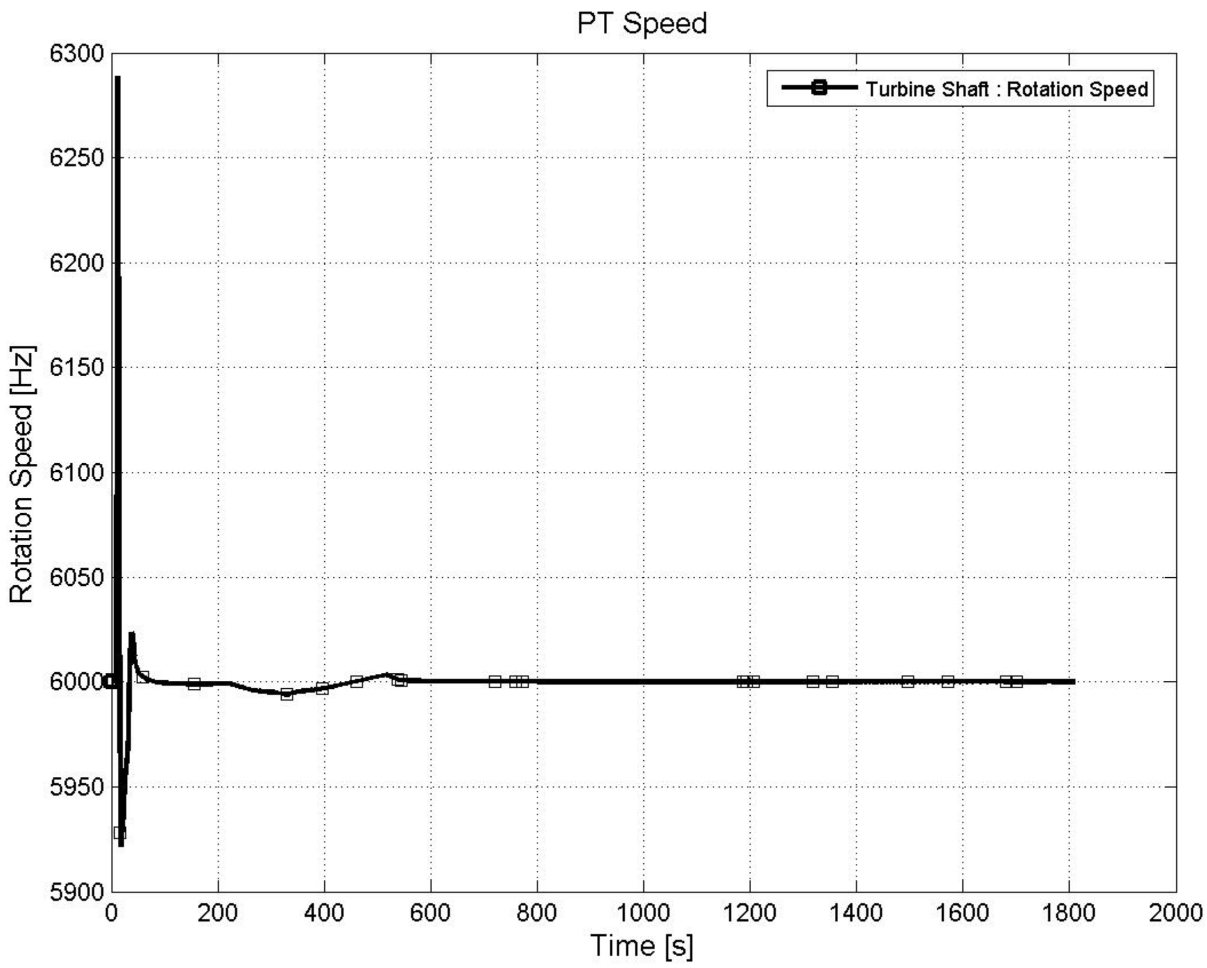


- **Loss of off-site grid**
- **As Turbine Generator speeds up the GBP valves open to limit the speed increase**
- **PCU transitions to Island operation on house load**

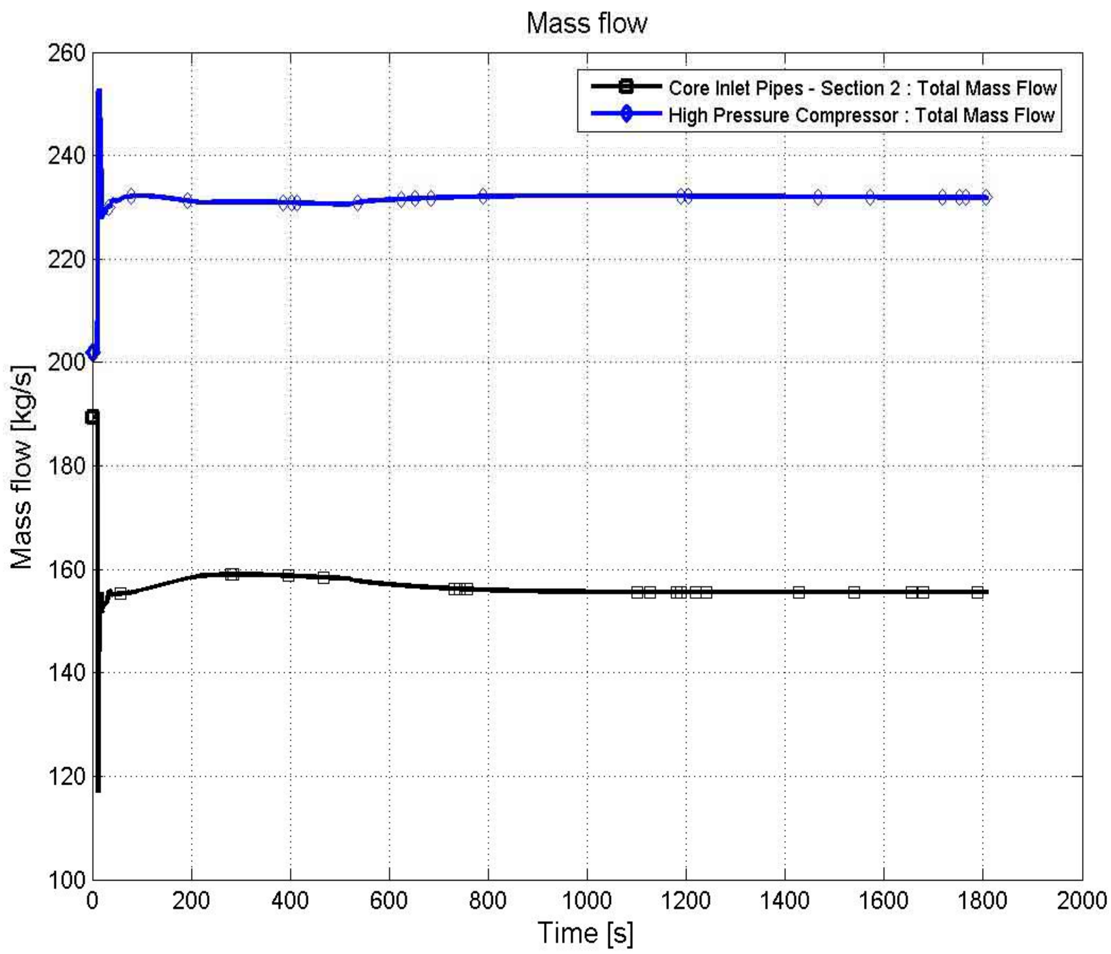
100% MCR Load (Mode 5)



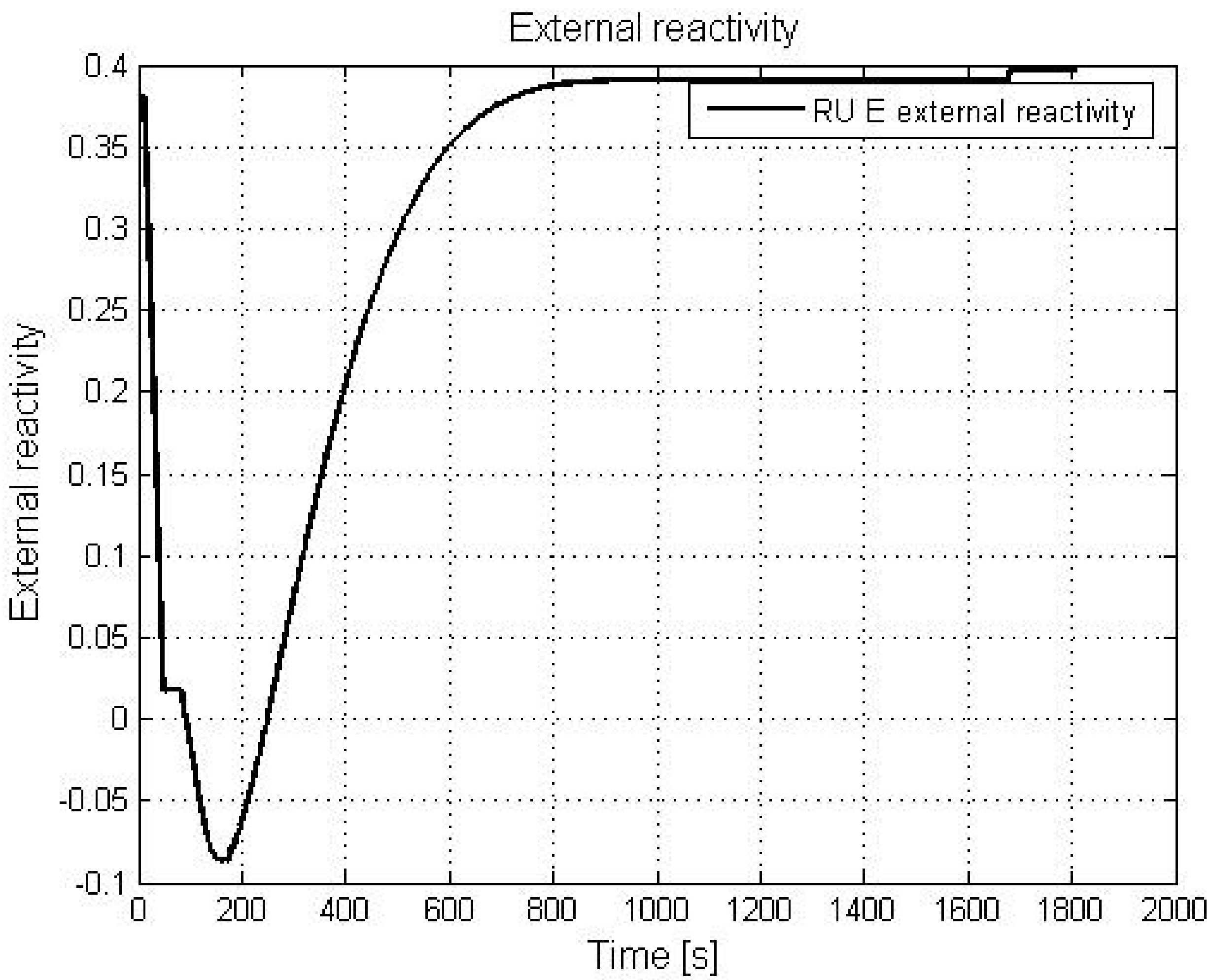
Loss of Load
Turbine Speed



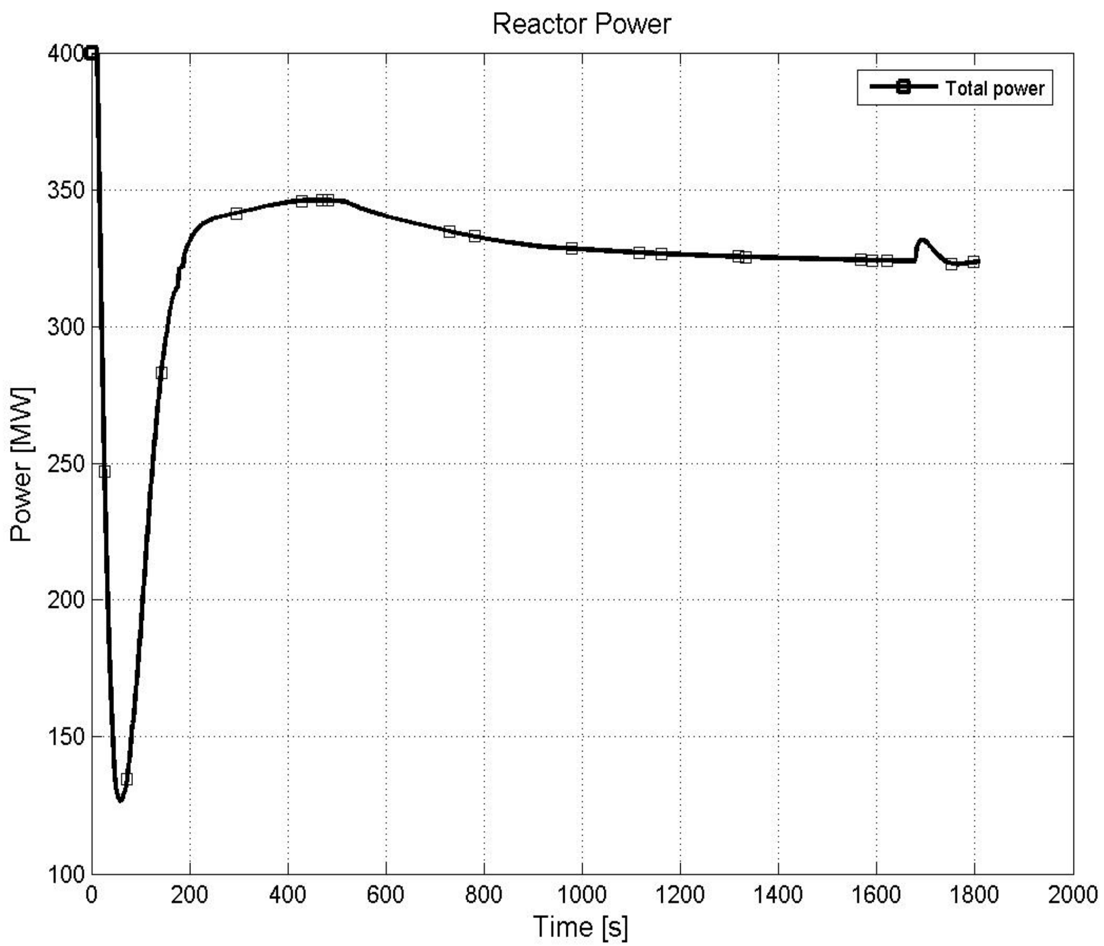
Loss of Load
Mass Flow Rates



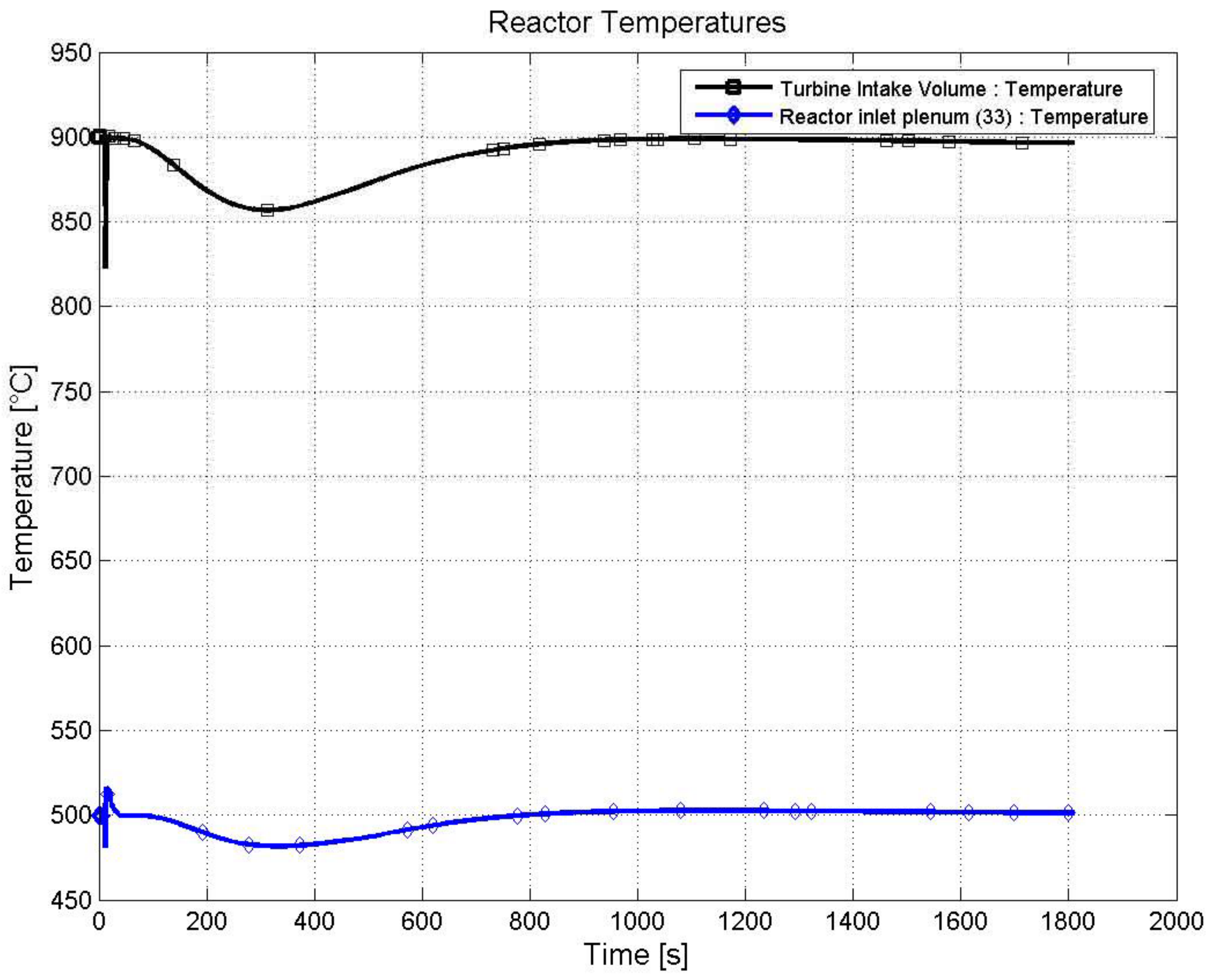
Loss of Load Reactivity



Loss of Load
Reactor Power



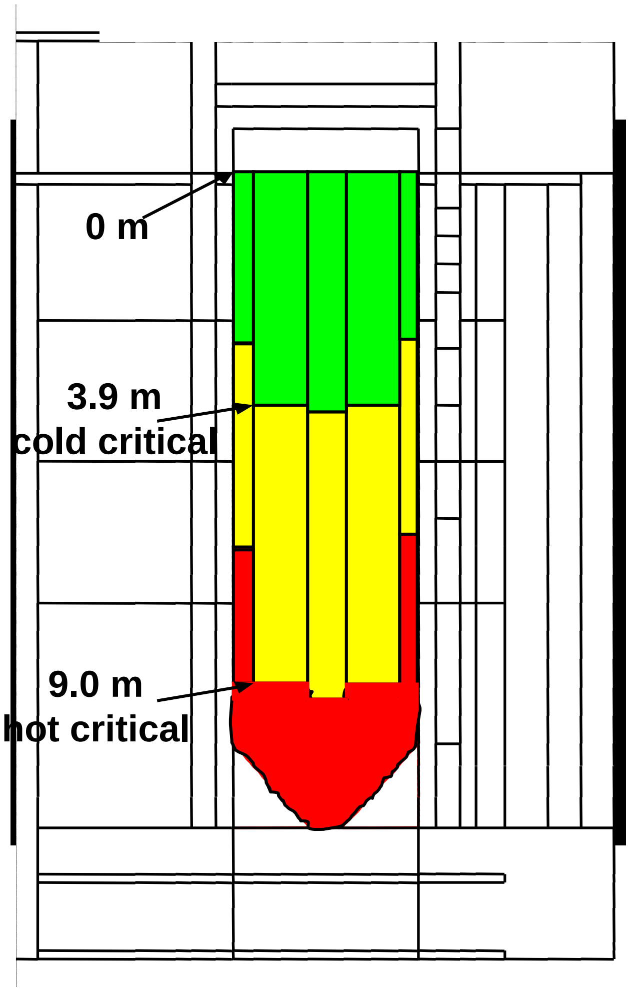
Loss of Load
Reactor Temperature

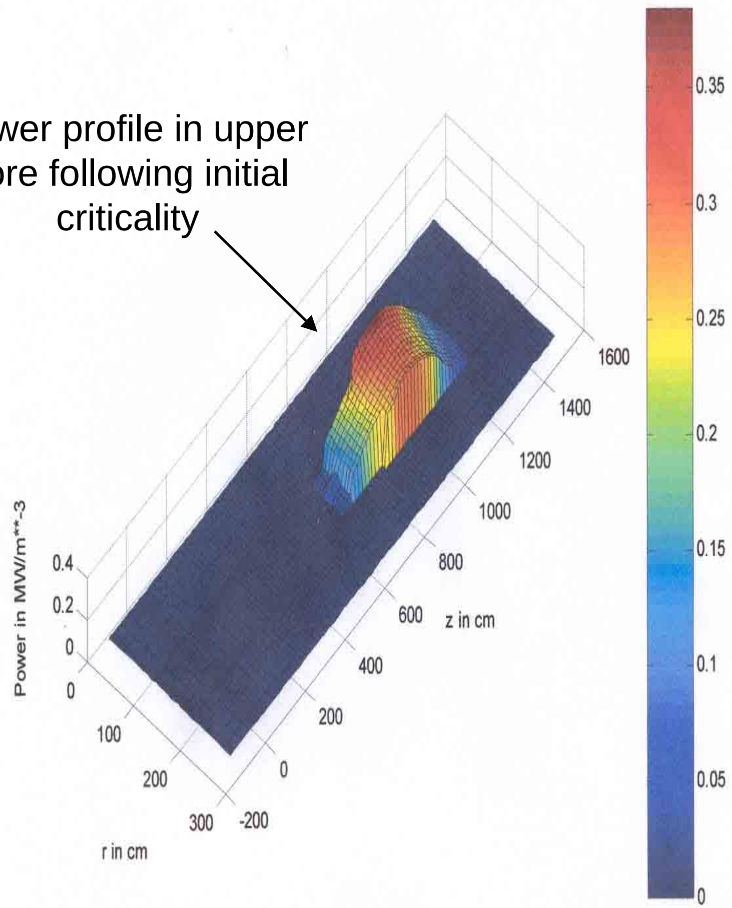


Initial Core Loading Requirements

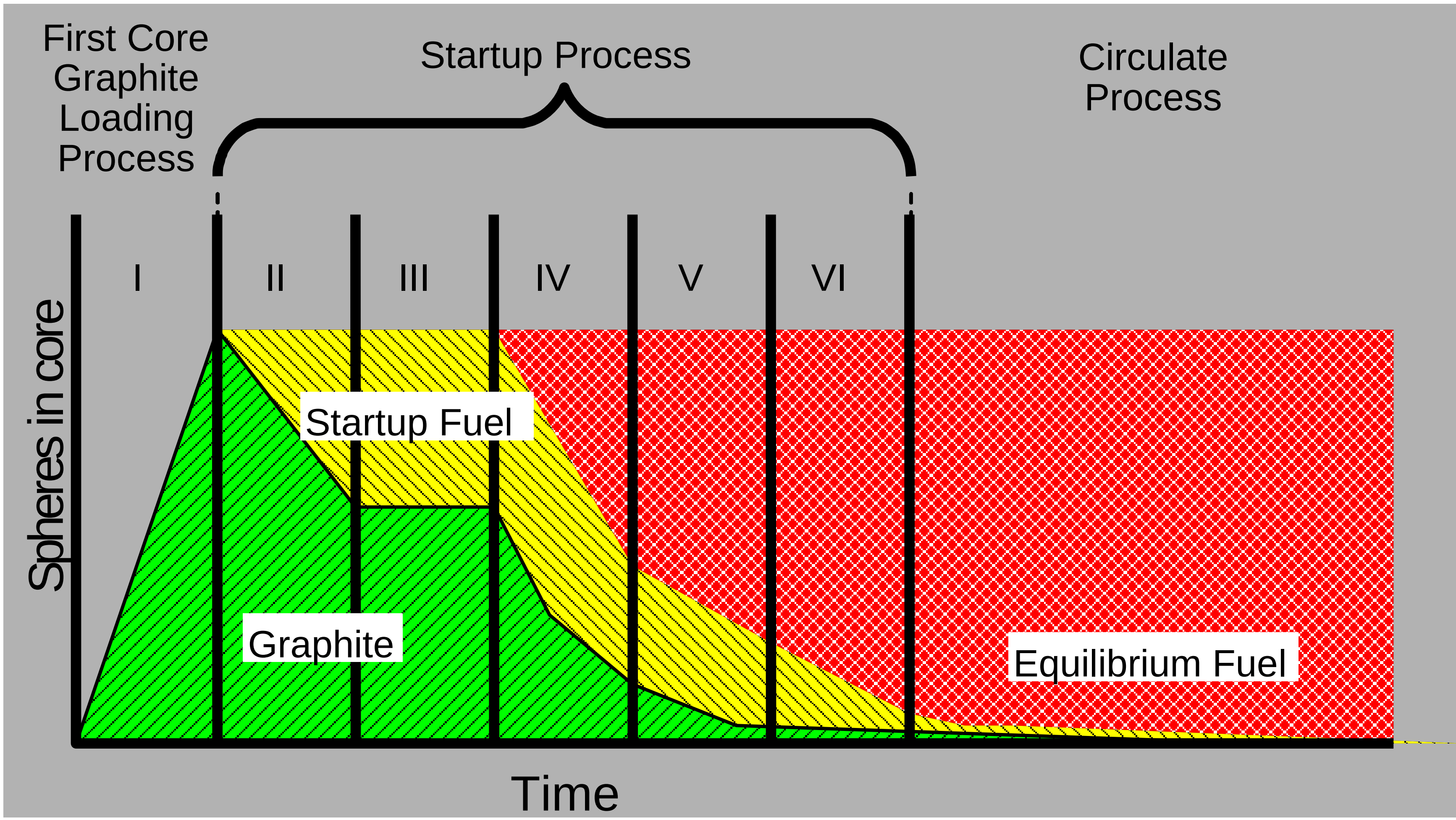
- **The reactor is initially filled with graphite spheres only.**
- **To achieve initial criticality, a mix of initial enrichment fuel spheres and graphite spheres is then added to the top of the core.**
  - The mix is selected to achieve criticality with fuel spheres flowing down to at least 4m from the top of the core.
  - The first full operating temperature is reached prior to the fuel spheres filling no more than ~9m down from the top of the core.
- **Other limitations:**
  - Limit peak fuel temperature to 1130ºC
  - Limit maximum power to 4.5 KW/fuel sphere
  - Utilize no more than two enrichments (initial and equilibrium)
  - Achieve shortest time to full power

Initial Core Loading





Transition from Startup to Equilibrium Core



Maintenance Elements

- Maintenance principles and guidelines
- Level of maintenance
- Scheduled major maintenance intervals
- Maintenance during plant at power
- Maintenance requiring plant at shutdown states
- Mid-life maintenance

MAINTENANCE PRINCIPLES AND GUIDELINES

- Apply ALARA principle
- Minimize major planned outage durations to 30 to 50 days
- Minimum use of remotely operated tools or robotics due to potential high cost
- Provide for visual contact for maintenance activities
- Minimize air ingress into the reactor core to reduce production of C14 and to reduce restart time
- Minimize the release of contaminated dust-borne helium into the building environment

Level of Maintenance

- **On-line maintenance/repair**
  - Exchange of equipment
  - In-situ repair (rare)
- **Off-line maintenance/repair**
  - Removal of equipment
  - Repair at
    - *On-site*
    - *Off-site at central facility*
    - *Off-site at vendor*

Major Scheduled Maintenance Intervals

- **Every 6 full power years**
  - Replace turbine components
  - Inspect generator
  - Inspect & maintain PCU compressors
  - Inspect & maintain RCSS
  - Duration: ~30 days
- **Every 12 full power years**
  - Same as 6 full power years
  - Duration: 30 to 50 days (due to uncertainty of durability of turbine for DPP)
- **After 18 or 24 full power years**
  - Same as 6 full power years. Additionally, possible replacement of core reflector elements
  - Duration: 150 -180 days

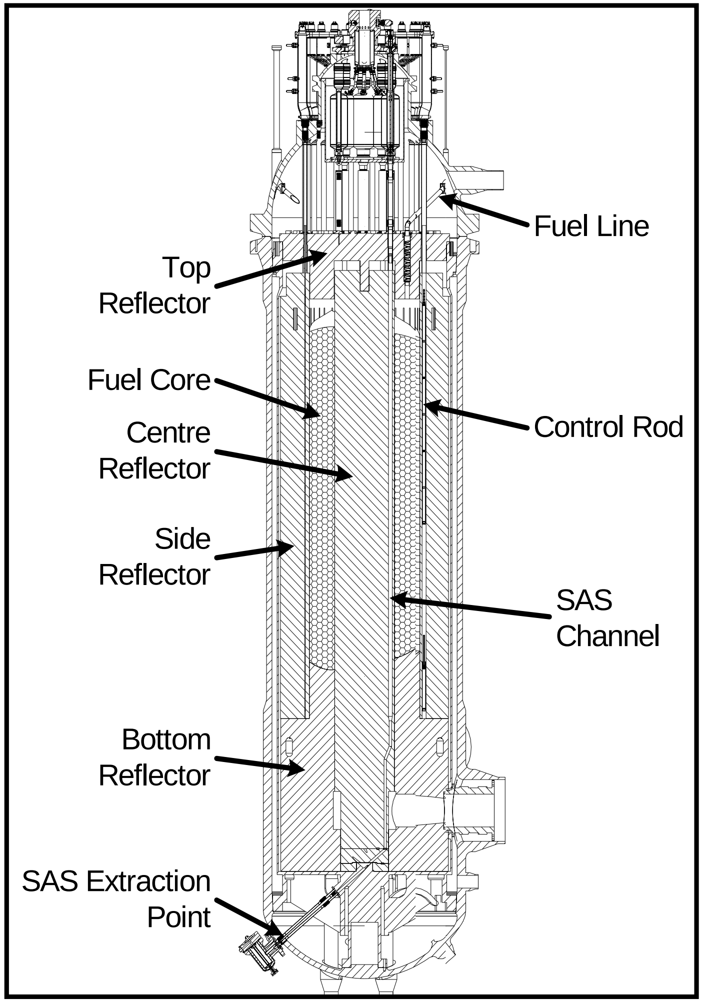
Maintenance During Power Operation

- **Following systems can be maintained while the plant is at Mode 4 – 5**
  - Most components of the FHSS
  - Some components of the CBCS, CCS and RCCS
  - Components of the cooling water systems and HVAC
  - Some components of the HICS

Maintenance Requiring Plant To Be At or Below Shutdown Modes

- **Maintenance at Mode 1b**
  - Inspection and service of PCU components (except possibly the Recuperator)
  - Inspection and service of Reactor Unit systems and components such as control rod drives, etc.
- **Maintenance at Mode 0**
  - Possibly the Recuperator
  - Mid-life core internals replacement, should it become necessary after 18 to 24 full power years (requires core unloading) (special case)

Mid-Life Maintenance



- **Possible replacement of central and outside reflectors**
  - Defuel and empty the core
  - Remove the top head opening
  - Expected to take about 3 months

Answers to Previous Questions

- Core power determination
- Key PBMR time constants
- Shutdown temperature margins

Reactor Core Thermal Power Level Determination

$$P_{Thermal} = P_{PCU} + P_{CBCS} + P_{RCCS} + P_{HVAC}$$

- **P_{PCU} = Heat transferred to PCU**
  - (Core outlet temperature- core inlet temperature) x Core outlet flow x Helium specific heat
- **P_{CBCS} = Heat loss to CBCS**
  - (CBCS inlet temperature – CBCS outlet temperature) x CBCS flow rate x Helium specific heat
- **P_{RCCS} = Heat loss to RCCS**
  - (RCCS inlet temperature – RCCS outlet temperature) X RCCS flow rate x Water specific heat
- **P_{HVAC} = Heat loss to HVAC in the Citadel**

Key Time Constants

- **Reactor core adiabatic thermal inertia:**
  - Fuel only: ~7×10^{7} J/K or ~1K/min/MW
  - Fuel & Reflector: ~4.8×10^{8} J/K or ~0.1 K/min/MW
- **MPS coolant transit time: ~30 sec**
- **Primary coolant purification time constant: ~1.1%/h**

Shutdown Temperature Margin

- 12 control rods at mid core (about 3.6% or down to ~100ºC, without xenon decay)
- 12 additional shutdown rods to core bottom (about 8% or down to < 100ºC, xenon fully decayed)
- 8 reserve shutdown absorber channels filled without control rods inserted (about 12% or down to < 20ºC, xenon fully decayed)