P B M R

PBMR OPERATIONAL MODES AND STATES

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Willem Kriel
Manager Module Dynamics and Control Group
(PBMR PTY LTD)

Objective

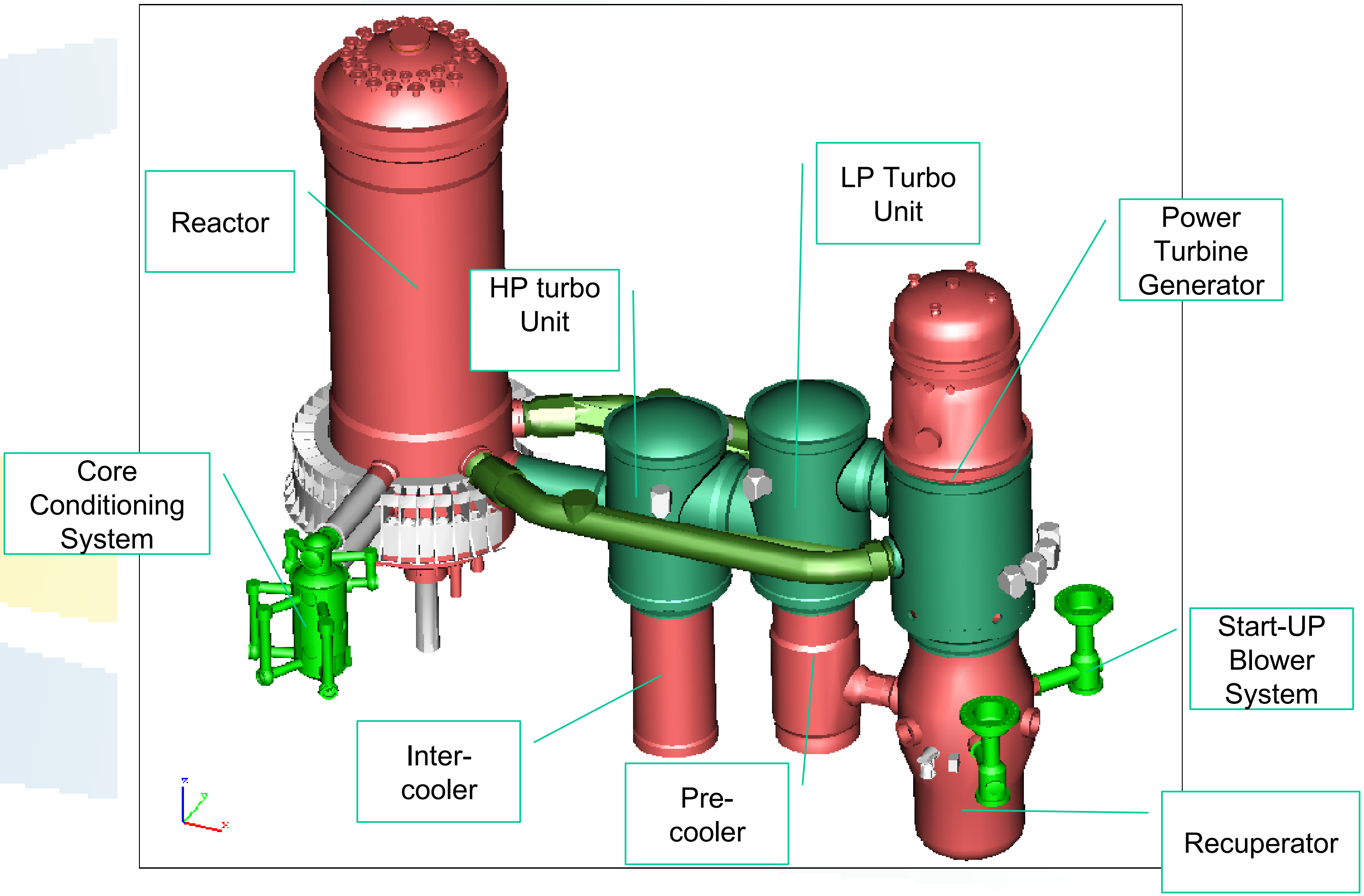
- Inform and educate the NRC regarding the operation of the PBMR

- Demonstrate the application of analytical codes used by PBMR to evaluate plant operation

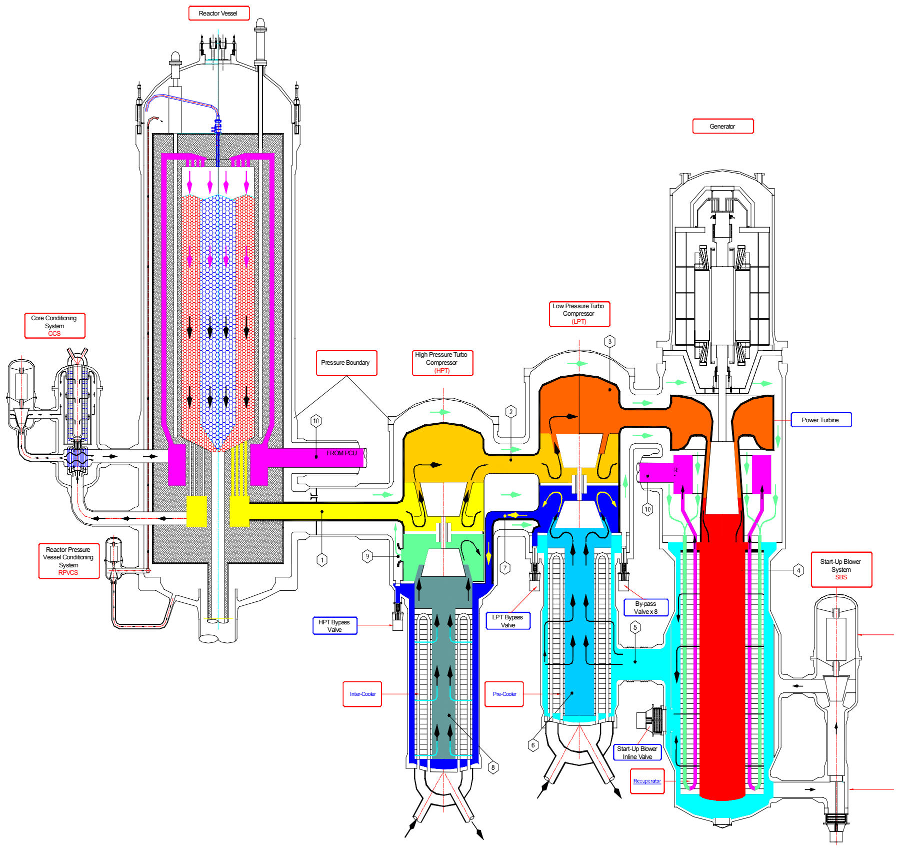
Topics

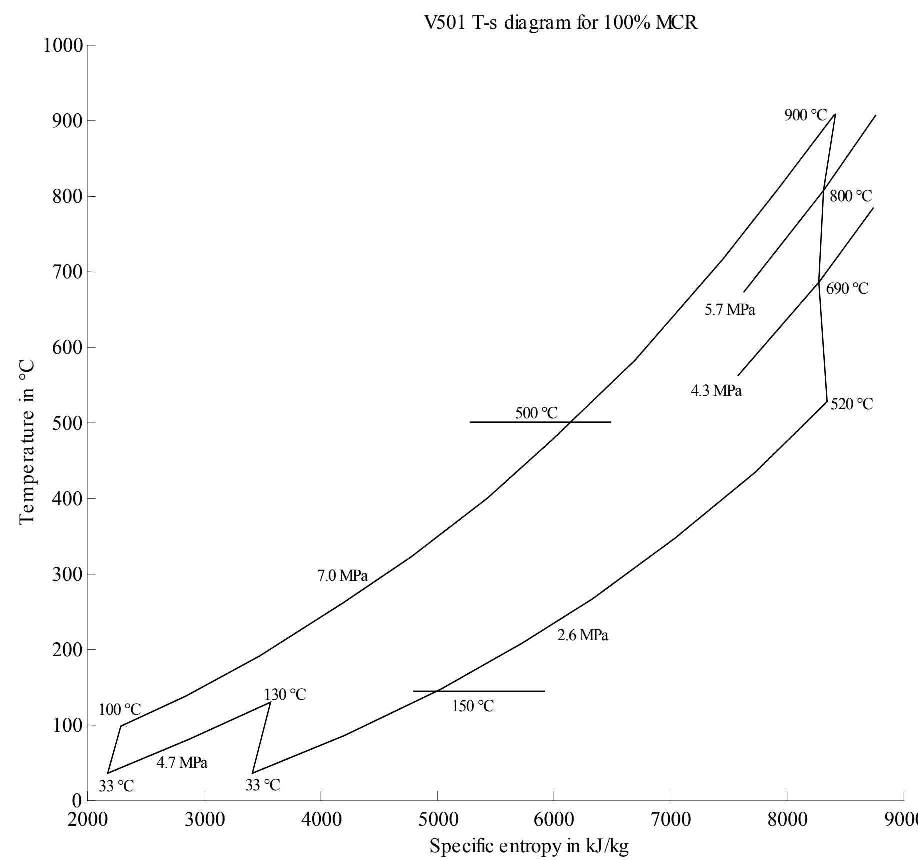
- Quick overview of the PBMR Main Power System (MPS) components and control functions
- Description of Codes used by PBMR to evaluate plant operations
- PBMR Definitions used to describe plant operations
- Description of the Modes, States, Transitions and Transients
- Examples of analyses used to evaluate plant operation

Main Power System (MPS)



Schematic of the PBMR and Temperature – entropy diagram FOR 100% MCR



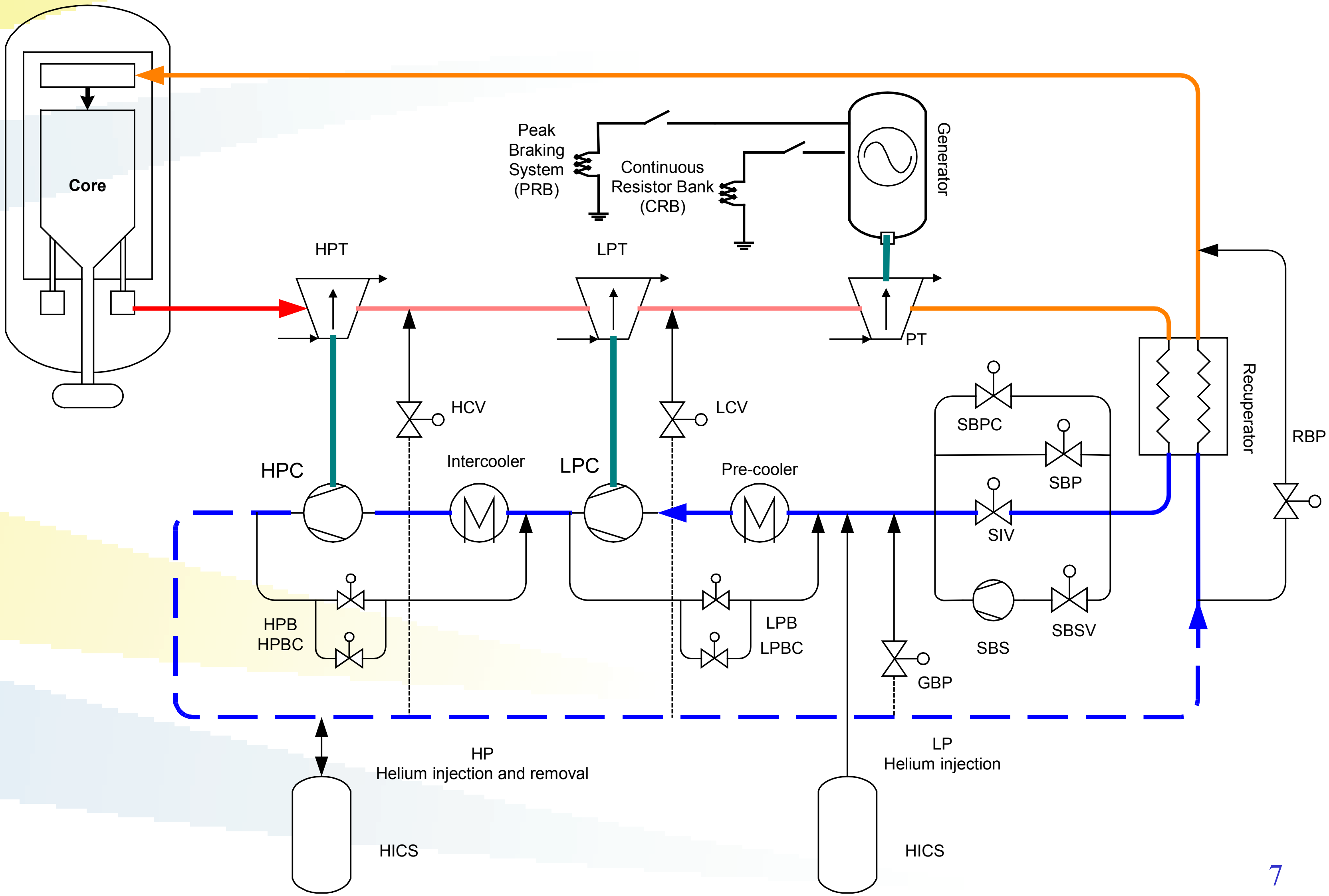


Control Overview

Main control functions:

- Reactor outlet temperature control
- Inventory power control
- Speed control
- Rapid load reduction
- Recuperator inlet temperature control
- Start-up Blower System (SBS) control
- Reactor inlet temperature control

MPS Schematic Showing the Control Elements

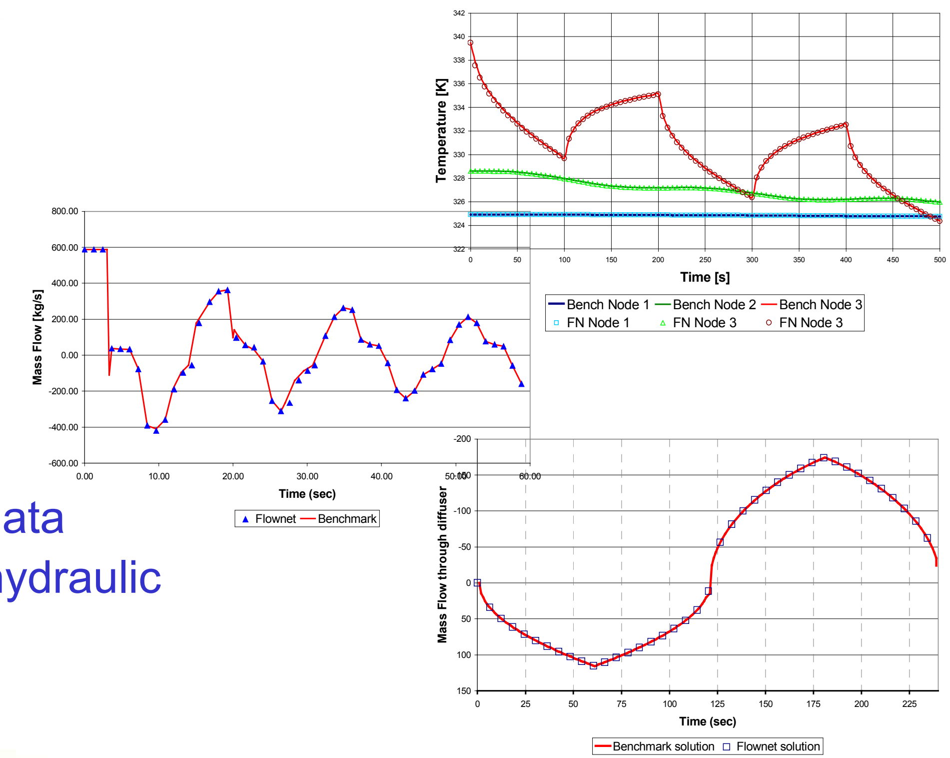


Codes Used To Evaluate PBMR Operation

- Flownet Nuclear
- Simulink
- State Flow

Flownet Verification & Validation

- **QA in accordance to ISO9001 & ANSI/ANS-10.4 & NQA-1**
  - Version control
  - Source code control
  - Discrepancy reports
  - Change requests
  - Design reviews
- Verification and Validation
  - Comparison with Analytical Data
  - Comparison with Experimental Data
  - Comparison with other Thermo-hydraulic codes
    - RELAP 5
    - Flowmaster
    - Explicit code
  - Plant comparisons
    - HTTR Japan: Transients during loss of off-site power
    - Physical model of a three-shaft recuperative Brayton cycle



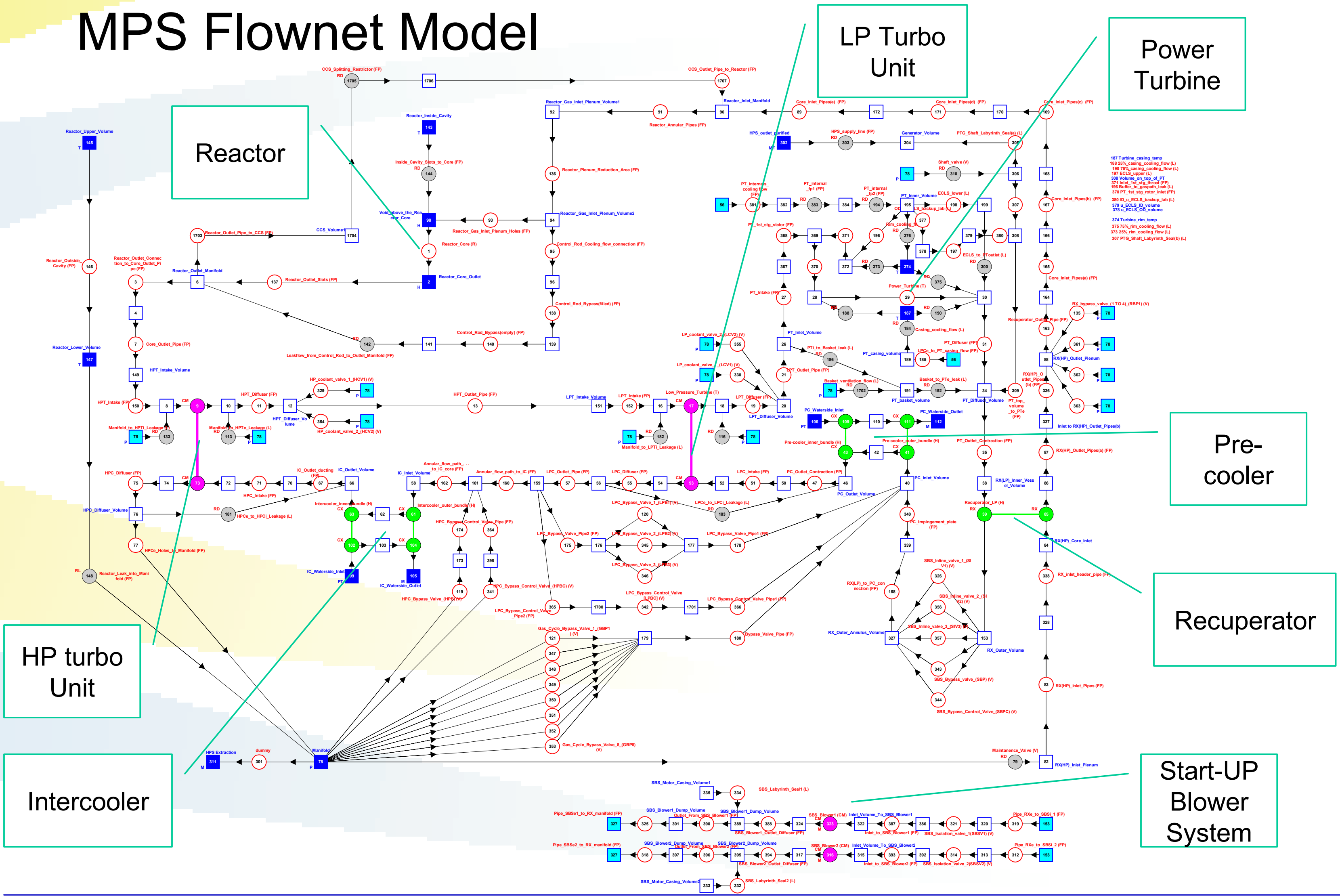
Flownet Nuclear Features and Attributes):

- Flownet Nuclear is PBMR Intellectual Property
- Flownet Nuclear is based on First Principles
- Analysis Tool (Loading Catalogues)
- Simulation Tool (Operator Training)
- Implicit Solving Techniques (Capable of time step variation)
- Industrial Code
- Multi Fluid Capability
- Compressible and Incompressible Fluids
- Gravitational Effects
- Object Orientated Coding
- Relational Data Base

Flownet Nuclear is the "RELAP" for PBMR technology

Flownet Model

MPS Flownet Model



Control System Design

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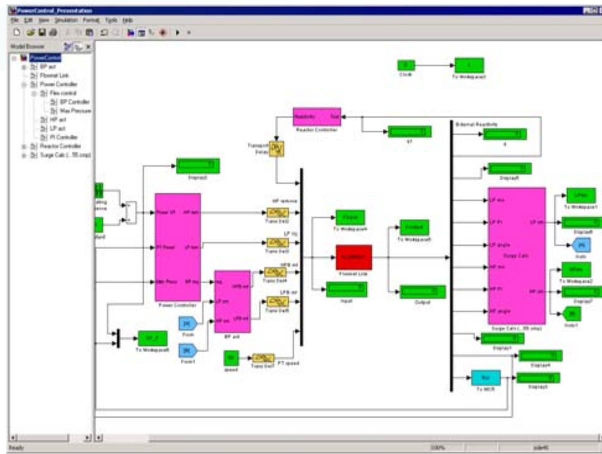
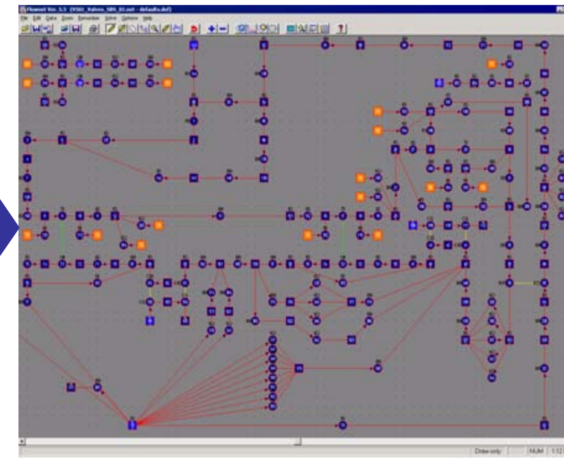
Control System

Process Simulation

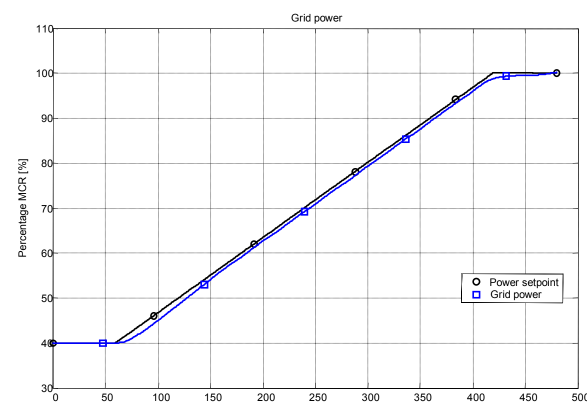
Interactive control system design using the Flownet Nuclear simulator



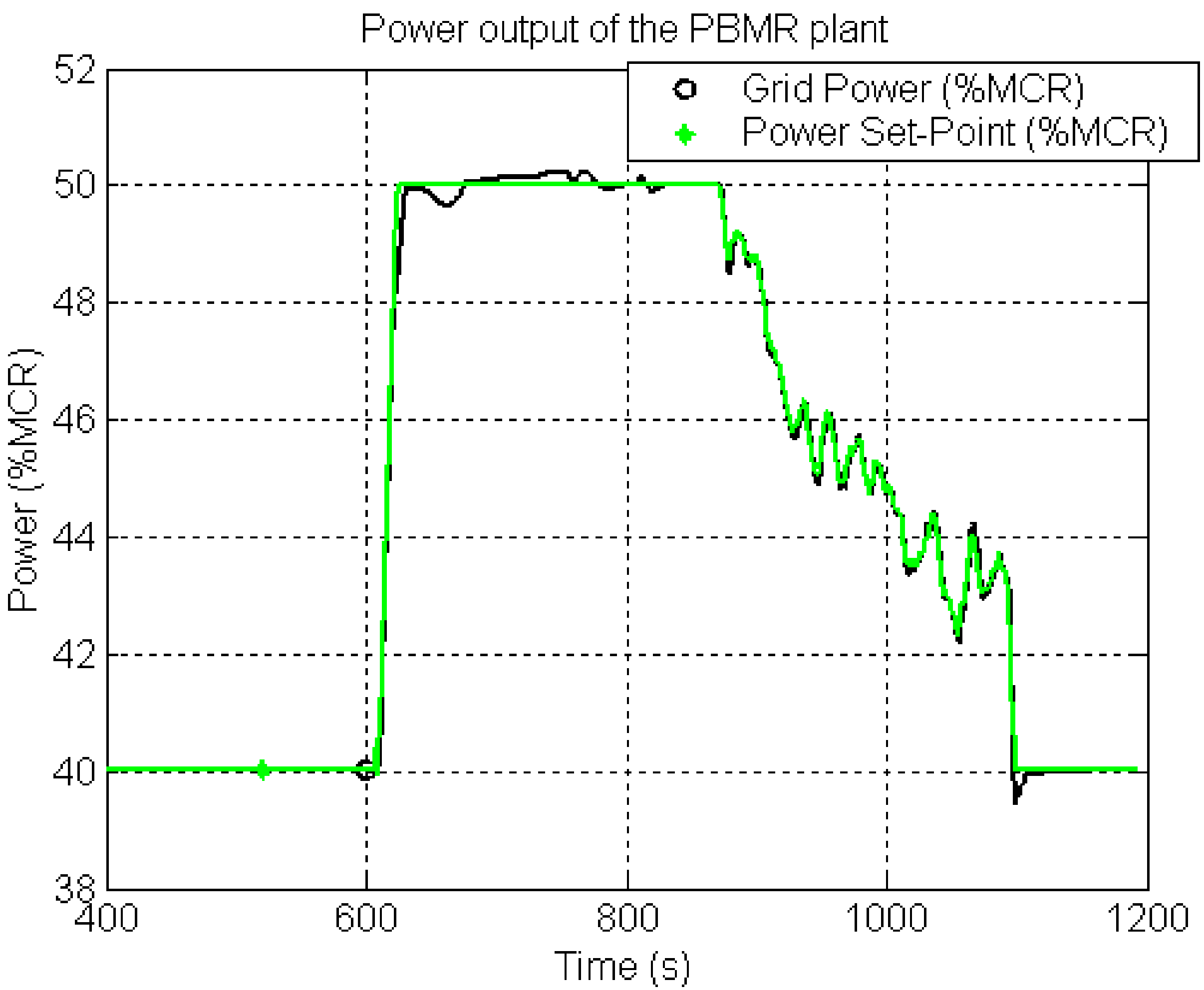


System Identification
- System response tests
- Identification of actuators

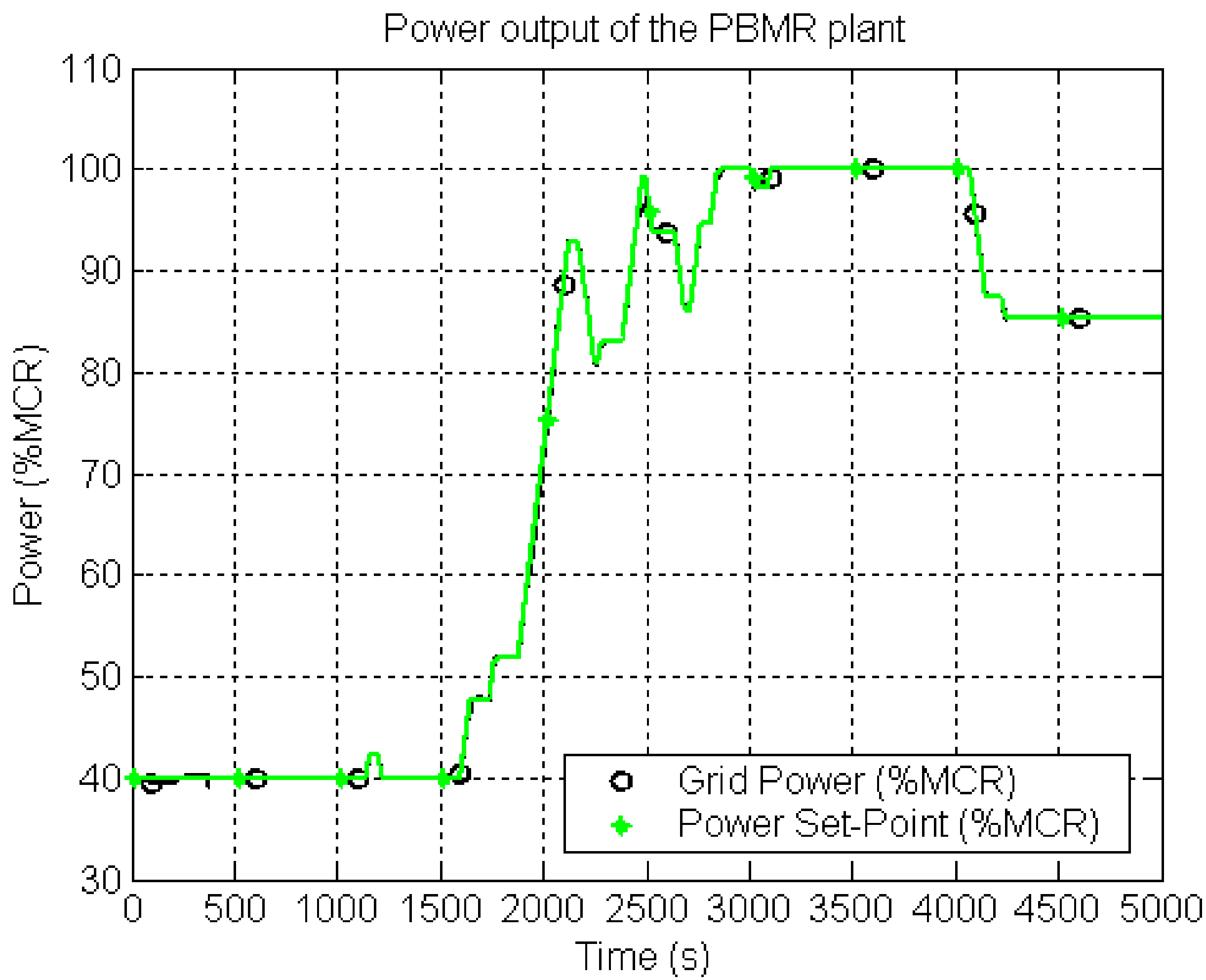
Control System design
- Controller design
- Control interaction
- Controller performance testing



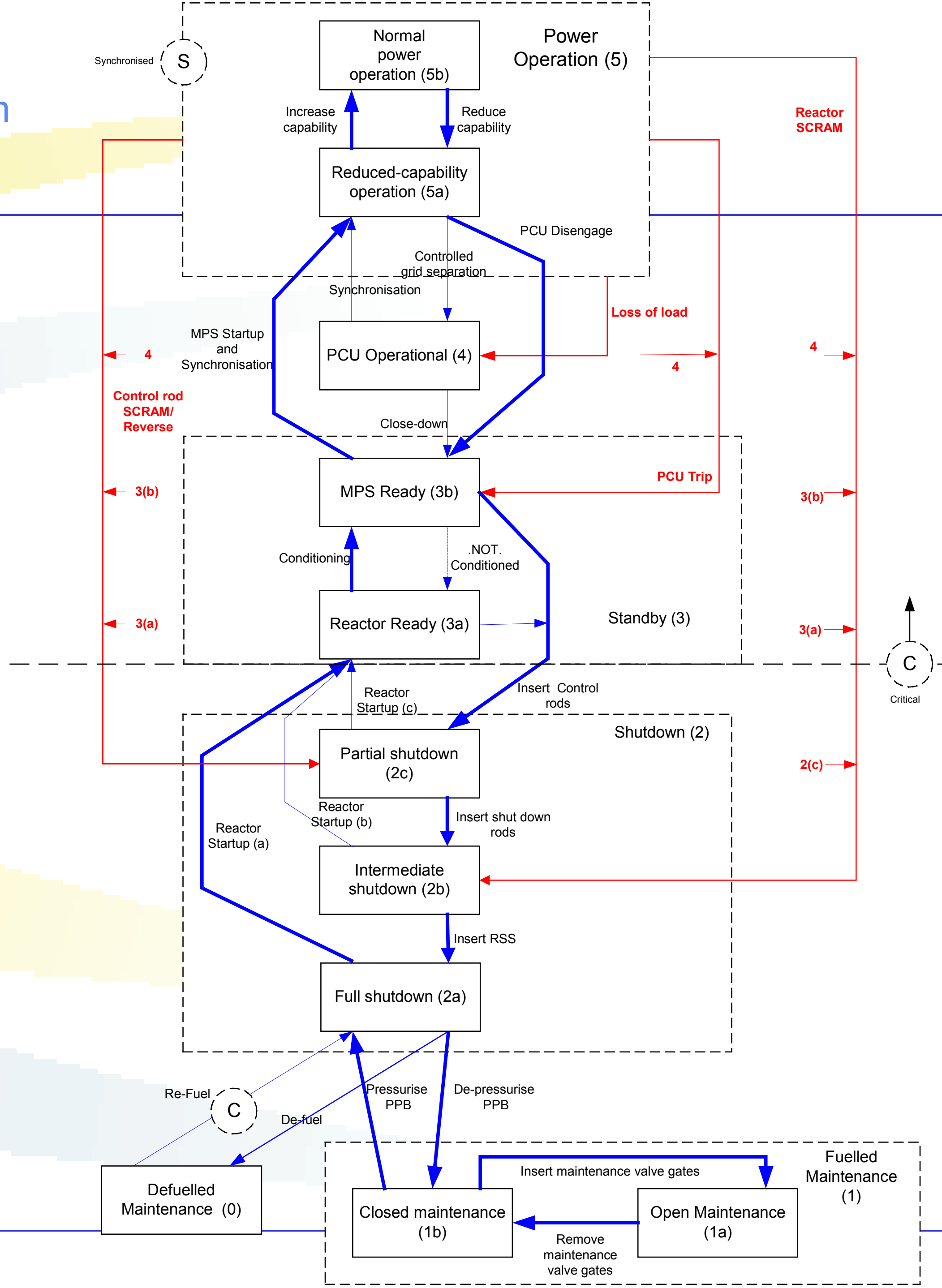
Primary frequency support (PFS)



Automatic generation control (AGC)



Main Mode diagram



PBMR

PBMR Abbreviations

List of abbreviations:

Abbreviation	Description
AGC	Automatic generation control
C	Reactor critical
CCS	Core conditioning system
CRB	Continuous resistor bank
GBP	Gas cycle bypass valve. (Referred to as a single valve although it consists of set of 8 valves)
HCV	High-pressure coolant valve
HICS	Helium inventory control system
HP	High pressure
HPB	High-pressure compressor bypass valve.
HPBC	High-pressure compressor bypass control valve.
HPC	High-pressure compressor
HPT	High pressure turbine
HV	High voltage
ICS	Inventory control system (Part of HICS)
LCV	Low pressure coolant valve
LOEL	Loss of electrical load
LP	Low pressure
LPB	Low-pressure compressor bypass valve. (Referred to as a single valve although it consists of a set of 3 valves)
LPBC	Low-pressure compressor bypass control valves
LPC	Low-pressure compressor
LPT	Low-pressure turbine
MCR	Maximum continuous rating (Usually applicable to power delivered to the grid)
MCRI	Maximum continuous rating inventory

PBMR Abbreviations

List of abbreviations:

Abbreviation	Description
MPS	Main power system
PBMR	Pebble bed modular reactor
PCU	Power conversion unit
PFS	Primary frequency support
PLICS	Primary loop initial clean-up system
PPB	Primary pressure boundary
PRB	Peak Resistor Bank
PT	Power turbine
PTG	Power turbine generator
RBP	Recuperator bypass valve
RCSS	Reactivity control & shutdown system
RCS	Reactivity control system
ROT	Average reactor outlet temperature
RSS	Reserve shutdown system
RU	Reactor unit
S	Synchronized with national grid
SAS	Small absorber spheres
SBP	Start-up blower system bypass valve
SBPC	Start-up blower system bypass control valve
SBS	Start-up blower system
SBSV	Start-up blower system isolation valve
SIV	Start-up blower system inline valve (Referred to as a single valve although it consists of a set of 3 valves)

PBMR :Definitions

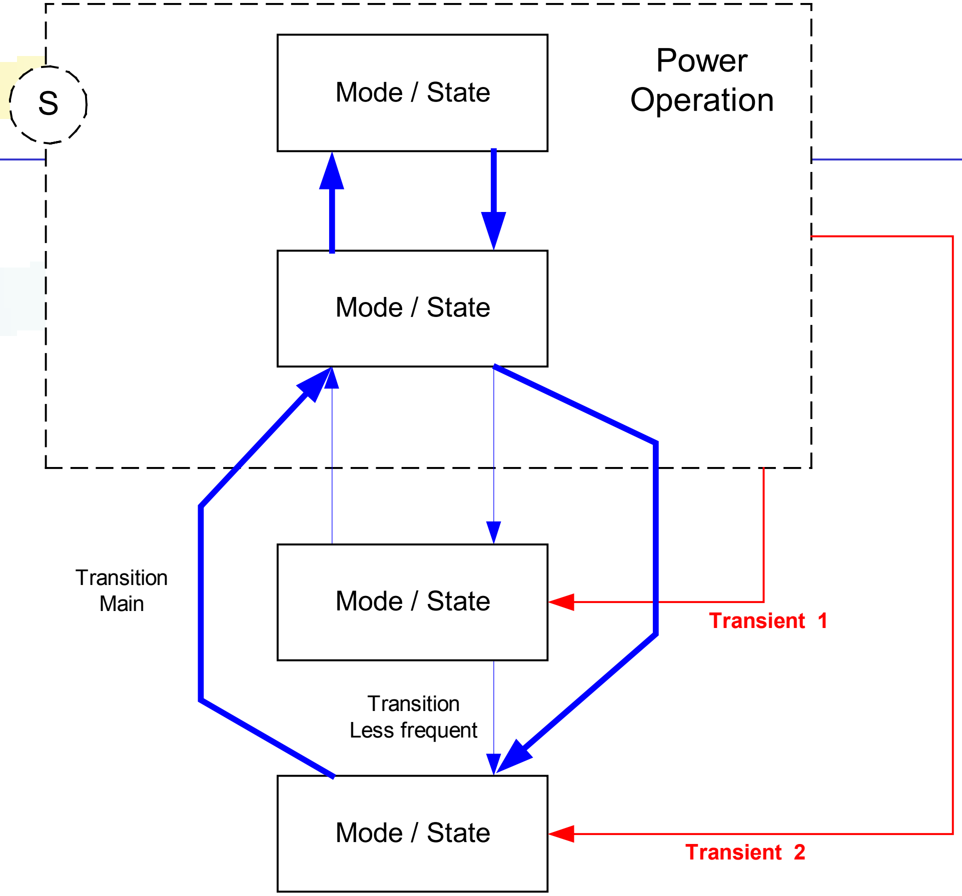
- **Transitions**

  Normal operations taking the plant from one mode or state to the next.

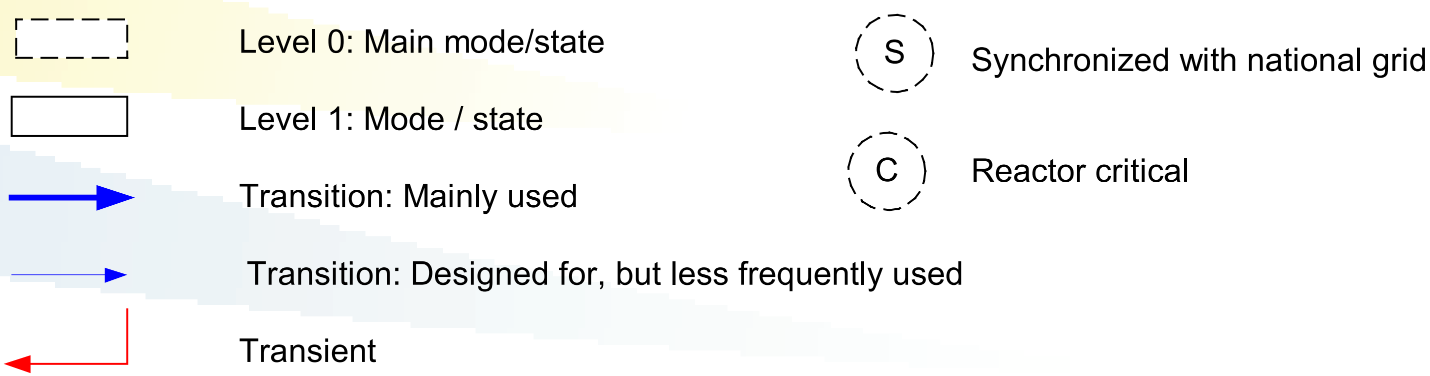
- **Transients**

  Mode or state transitions that should be avoided, but the plant must still be designed to accommodate these transients. The transients result due to faults that arise externally or internally to the plant.

SYMBOLOGY

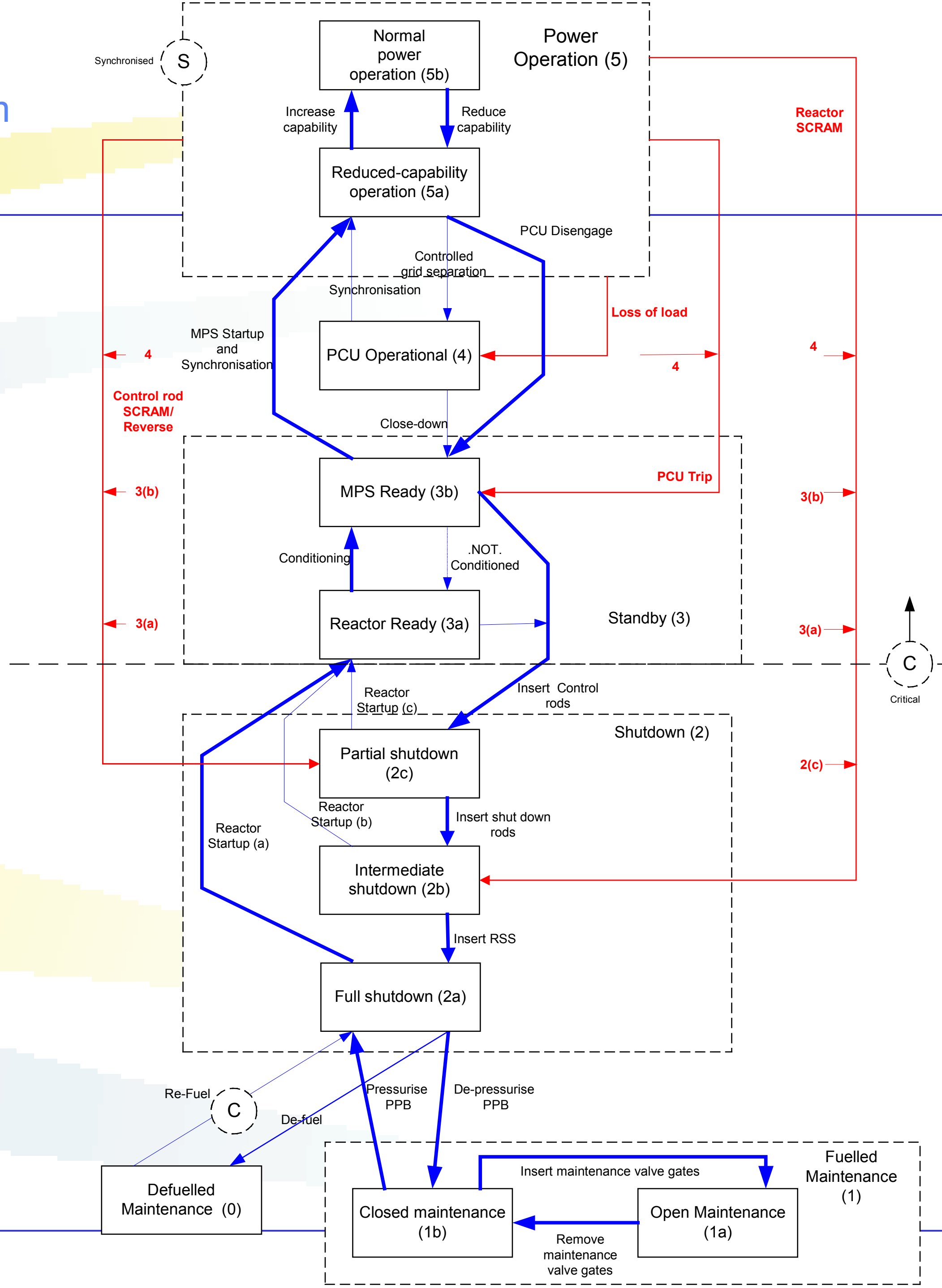


S
Mode / State
Power
Operation
Mode / State
Transition
Main
Mode / State
Transient 1
Transition
Less frequent
Mode / State
Transient 2

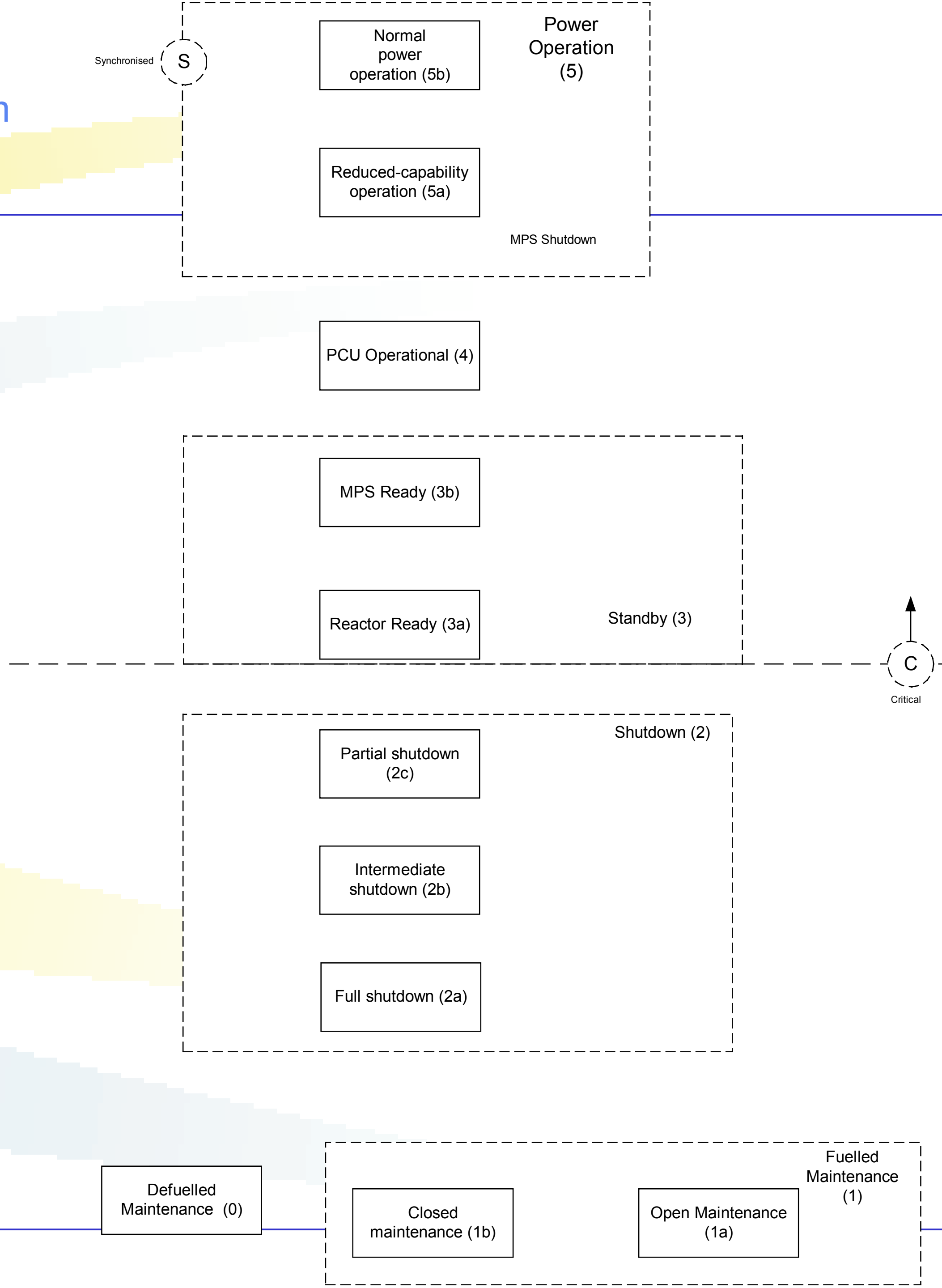


Level 0: Main mode/state
Level 1: Mode / state
Transition: Mainly used
Transition: Designed for, but less frequently used
Transient
S
Synchronized with national grid
C
Reactor critical

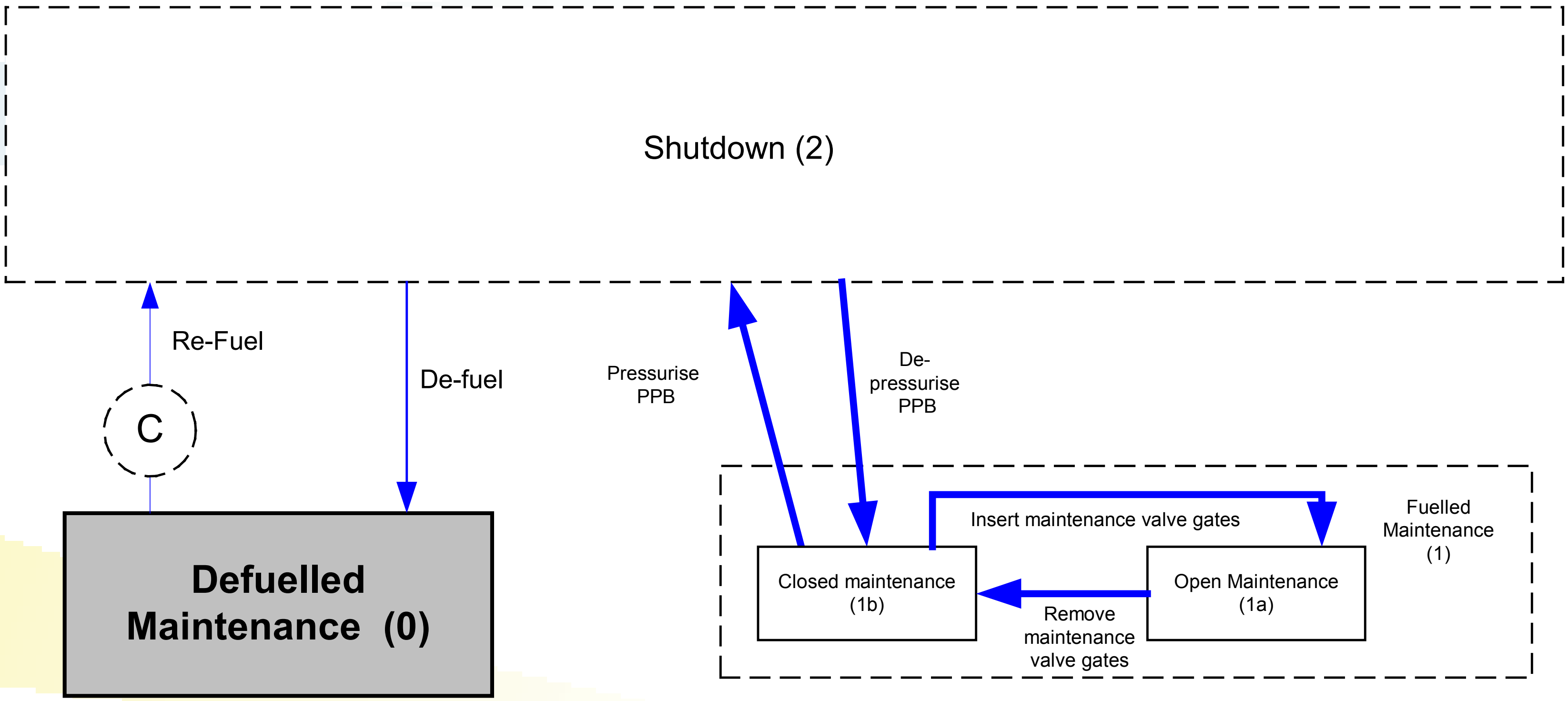
Main Mode diagram



Main Mode diagram



De-fuelled maintenance (0)



De-fuelled maintenance

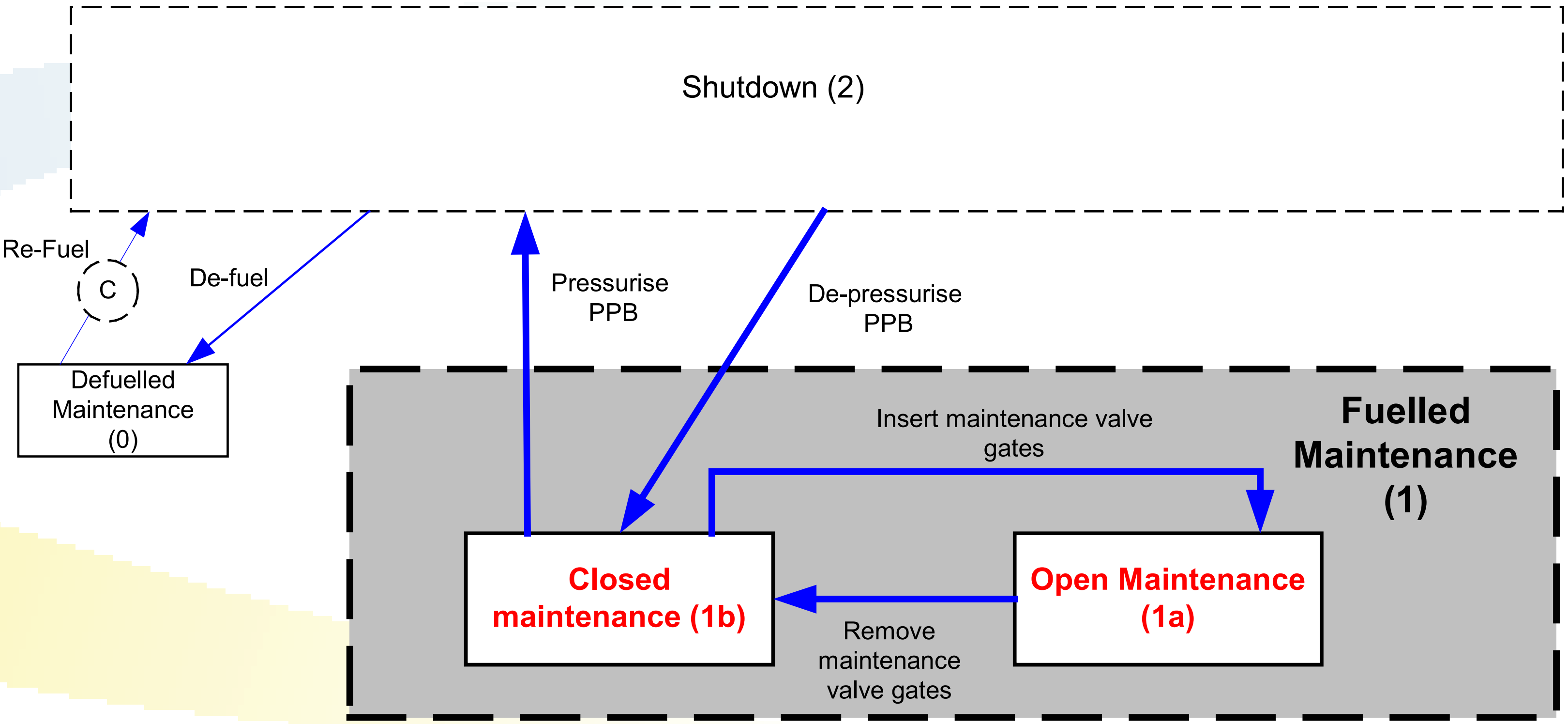
Mode

- Maintenance activities requiring a de-fuelled reactor

States

- The reactor is de-fuelled

Fuelled Maintenance (1)



Fuelled Maintenance

Mode

Maintenance activities performed while the reactor is fuelled

The Core Conditioning System (CCS) is in operation

The Start-up Blower System (SBS) is not operational
(To avoid water ingress, the water pressure in the coolers exceed the helium pressure in the system)

States

- The reactor is sub-critical and CCS operational
- Brayton cycle is not self-sustaining
- The reactor outlet temperature is kept below 400 °C
- PPB pressure is atmospheric (or very close to)

Open maintenance (1a)

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Mode

- Scheduled maintenance done on a six-yearly basis

Air ingress into the PPB is allowed with the exception of core internals

States

- The maintenance valve gates are inserted

Closed maintenance (1b)

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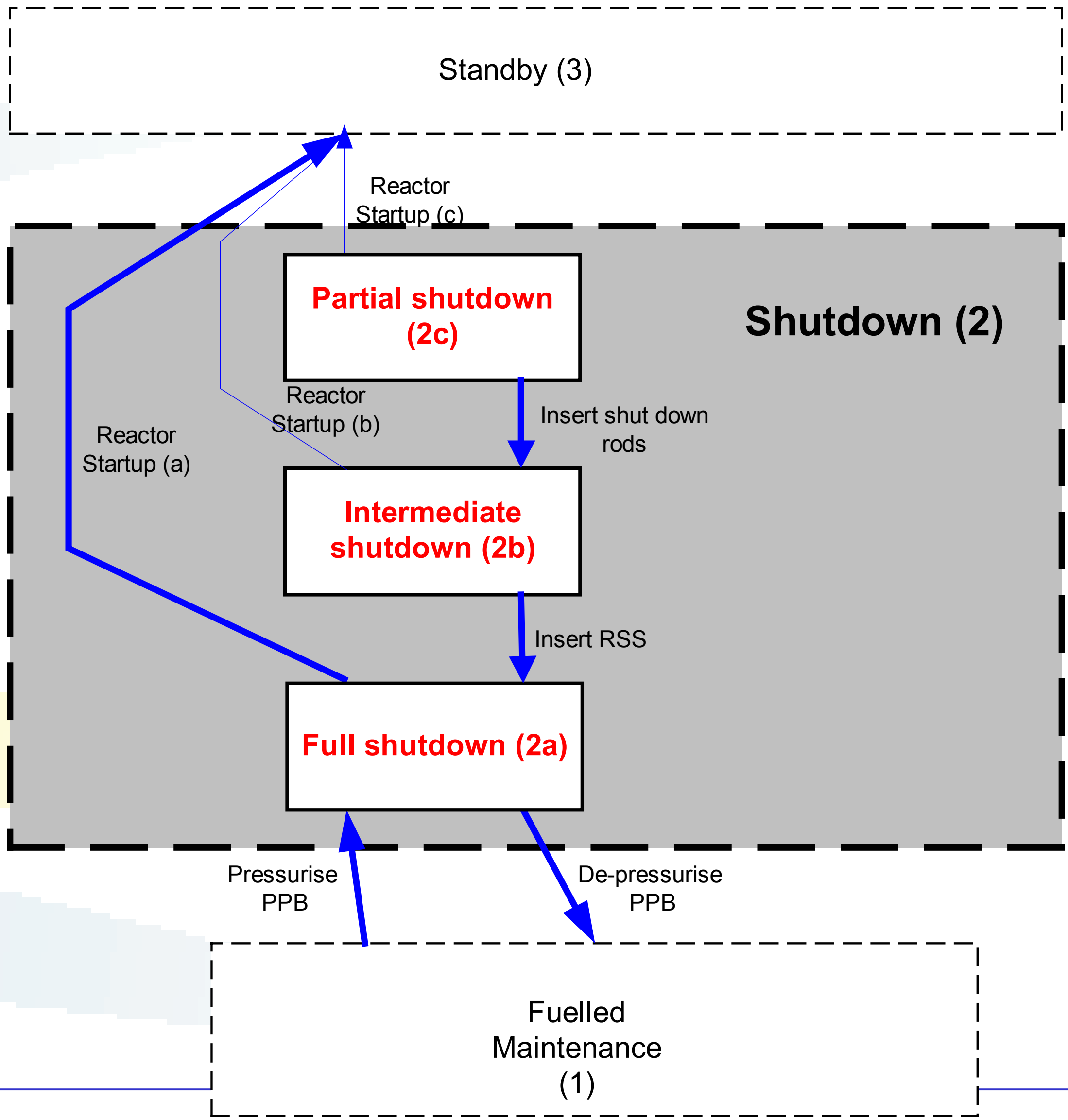
Mode

Unscheduled maintenance is done on a number of specific sub-systems

States

PPB pressure just above atmospheric

Shutdown (2)


Standby (3)
Reactor Startup (c)
Partial shutdown (2c)
Shutdown (2)
Reactor Startup (b)
Insert shut down rods
Reactor Startup (a)
Intermediate shutdown (2b)
Insert RSS
Full shutdown (2a)
Pressurise PPB
De-pressurise PPB
Fuelled Maintenance (1)

Shutdown

Mode

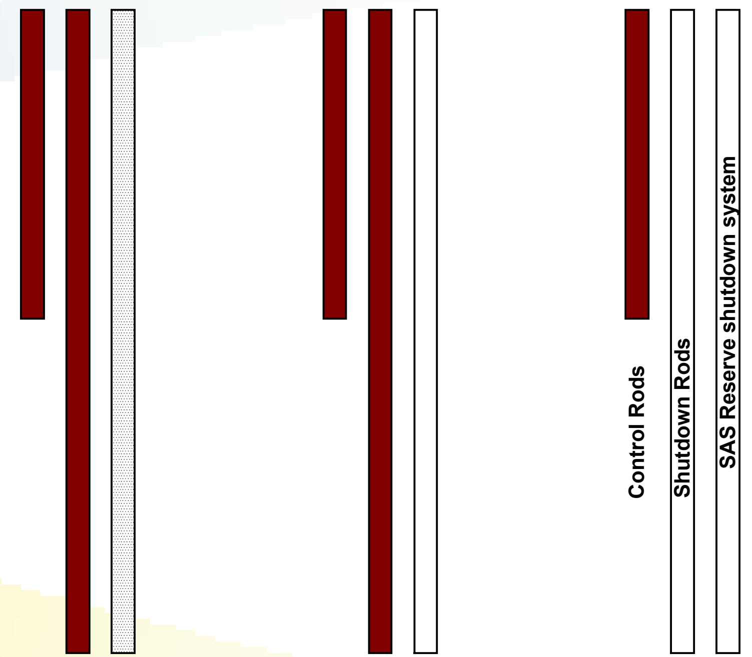
Three reactivity control devices keep the reactor sub-critical

The SBS is operational $\Rightarrow$decay heat removal.

States

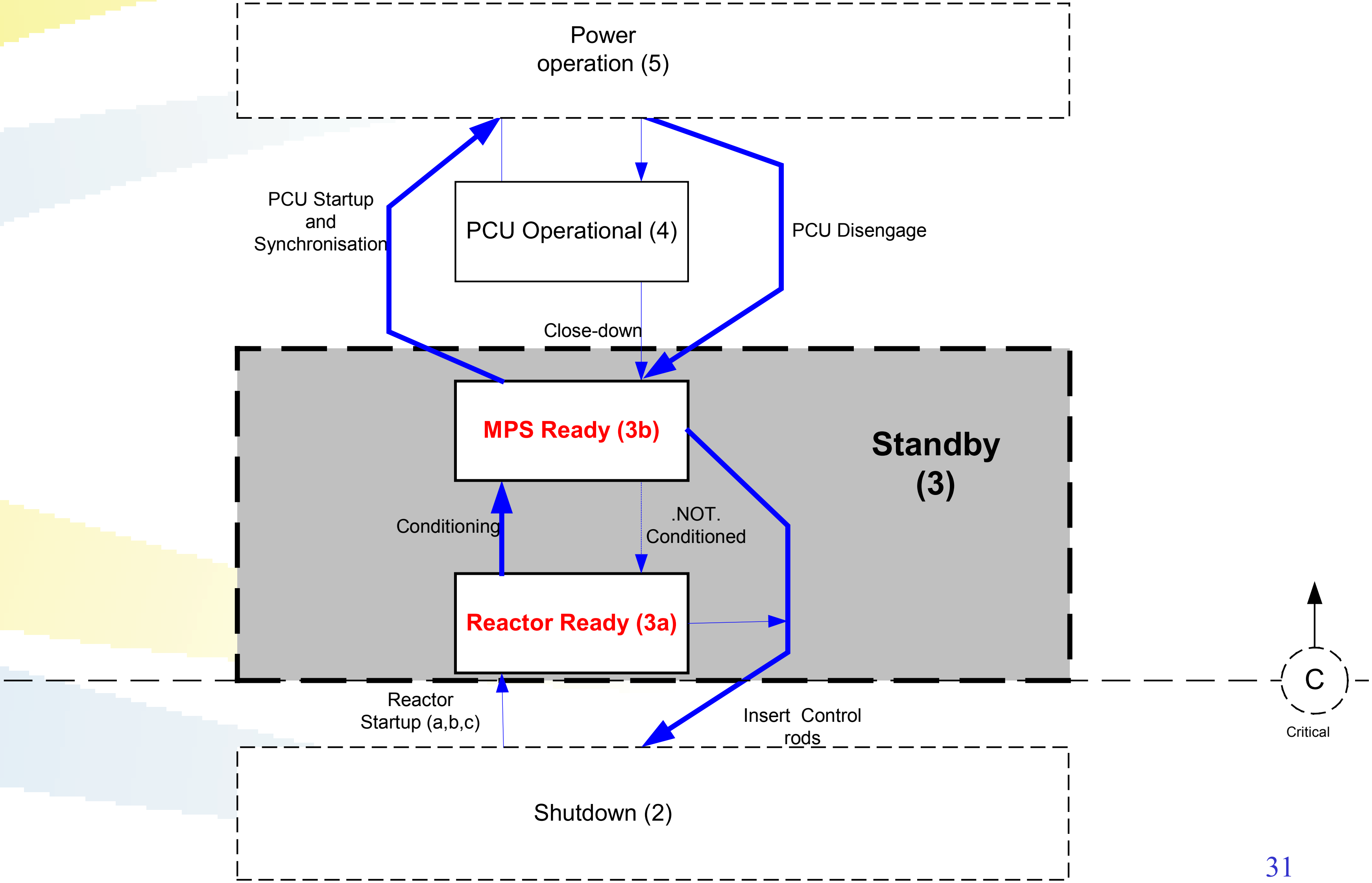
- The reactor is sub-critical and SBS operational
- The Brayton cycle is not self-sustaining
- The PPB is pressurized (no water ingress)

Shutdown Sub-modes (2a,b,c)



	Full Shutdown	Intermediate Shutdown	Partial Shutdown
External Reactivity	(rods as shown)	(rods as shown)	(rods as shown)
+ Reactivity due temperature	<550 °C	>550 °C	>750 °C
+ Reactivity due Xenon	0	0	0
	Sub-critical	Sub-critical	Sub-critical

Standby (3)



Power
operation (5)
PCU Startup
and
Synchronisation
PCU Operational (4)
PCU Disengage
Close-down
MPS Ready (3b)
Standby
(3)
Conditioning
.NOT.
Conditioned
Reactor Ready (3a)
Reactor
Startup (a,b,c)
Insert Control
rods
C
Critical
Shutdown (2)

Standby

Mode

The reactor outlet temperature is controlled with the control rods

Adjustment of the reactor outlet temperature, reactor neutronic and fluidic power and power turbine power will be possible in this mode by using the SBS, the Reactivity Control System (RCS) and gas cycle valves

States

- The reactor is critical
- The Brayton cycle is not self-sustaining

Reactor Ready (3a)

Mode

This mode or state would occur after *reactor start-up transitions* or *not conditioned transition*

States

- The MPS is NOT conditioned as a whole

MPS Ready (3b)

Mode

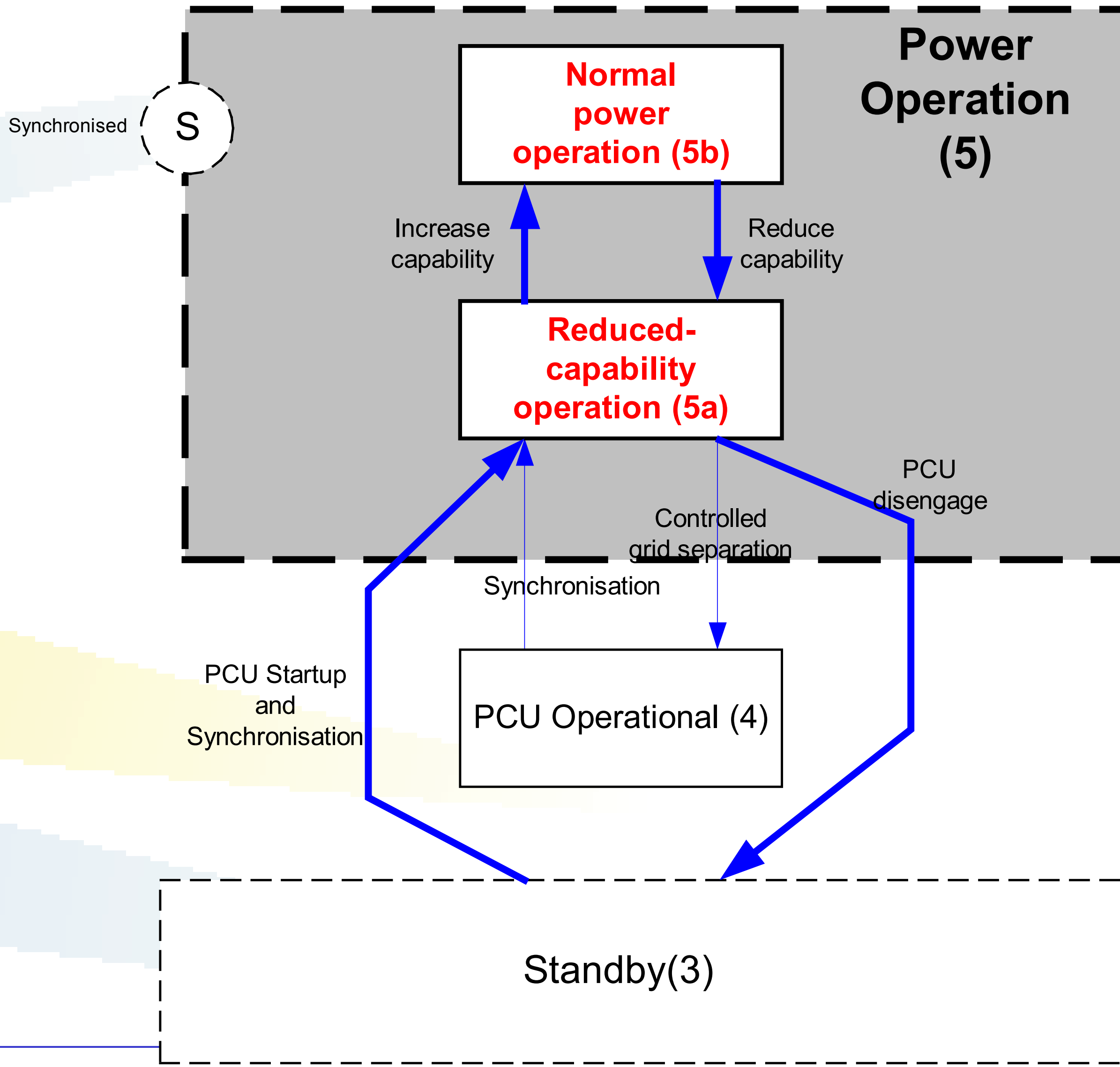
PCU start-up and synchronisation transition can be initiated, since the plant is within the start-up margins ("conditioned")

Entered after a *PCU trip transient* or *Close-down and PCU disengage transitions*.

States

- The reactor is critical
- The MPS is conditioned. If all the plant parameters remain within the “conditioned” margins, the plant will remain in this mode/state.

Power operation (5)



Power operation

Mode

The plant grid power can be automatically adjusted to a power set point

States

- Supplying power and synchronised to grid.
- The Braking System (both the CRB and the PRB) is not in operation.
- Helium PPB inventory level > 40% MCRI

Reduced-capability operation (5a)

Mode

Entered via the *PCU start-up and synchronisation transition* or the *Synchronisation transition*

The base-load power controller will be operational (No AGC)

Reactor outlet temperature controller will operate in one of the following two sub-modes

- Normal reactor outlet temperature controller mode
- Floating reactor outlet temperature controller mode (Xenon effects)

States

- The reactor outlet temperature below or equal to 900 °C .

Normal power operation (5b)

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Mode

Provide power to the grid

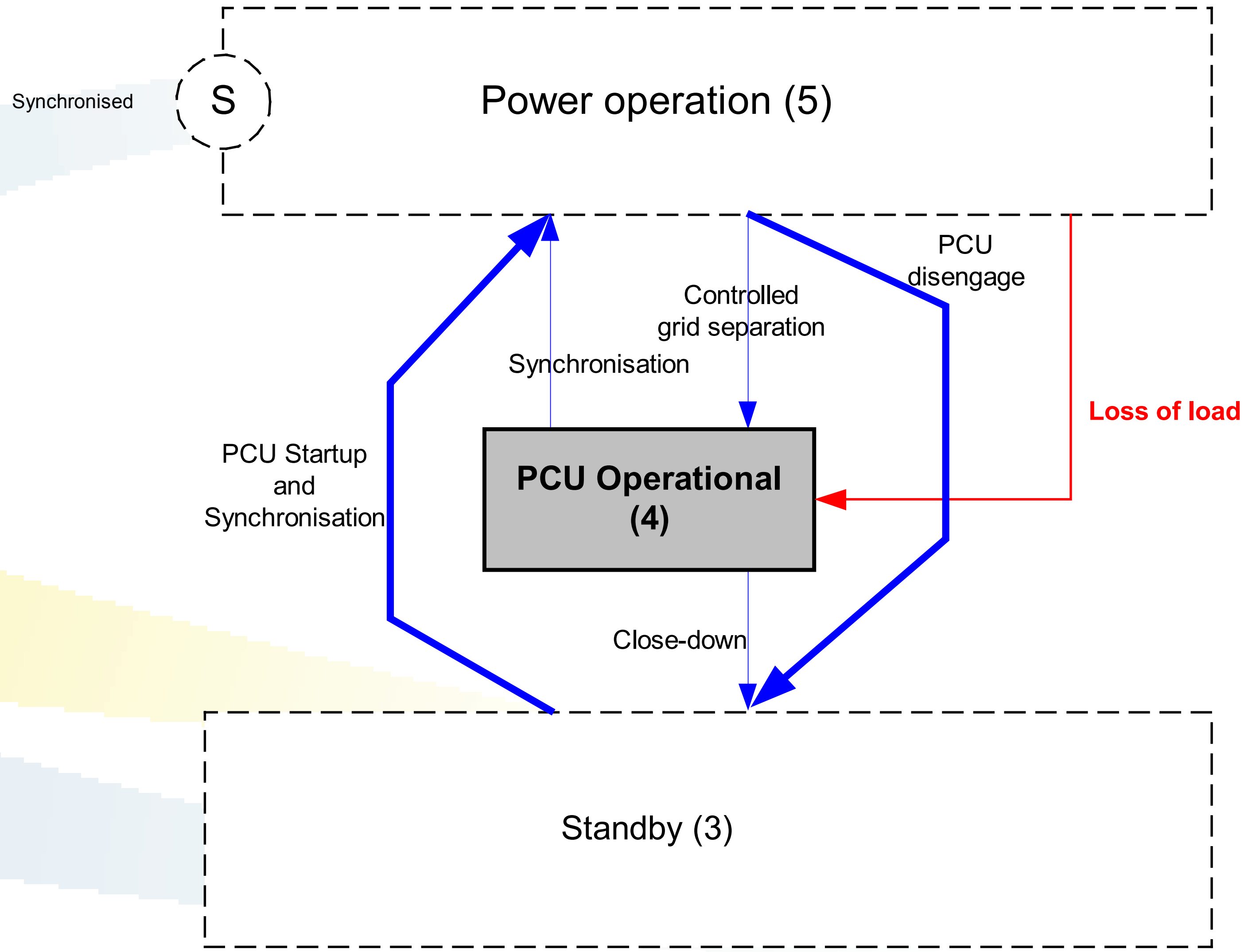
Supporting ancillary services:

- Load following
- Automatic Generation Control (AGC) also known as Regulation or Secondary frequency support. Load “ramping”.
- Primary frequency support, also known as governing

States

- The reactor outlet temperature will be controlled to 900°C
- The power delivered to grid will be between 40% and 100% Maximum Continuous Rating (MCR)

PCU operational (4)



PCU operational

Mode

The mode/state is entered via the *Loss of load transient* or the *Controlled grid separation transition*.

Stable Brayton, low power, high helium inventories, between 40% and 100 % Maximum Continuous Rating Inventory (MCRI).

No power is exported to the grid because the plant is not connected to the grid

PCU operational

States

- Generator breaker closed - house load is supplied by the generator
- Generator breaker open - house load is supplied from an external source
- The reactor temperature outlet temperature between 750°C and 900 °C

MPS State Matrix

MPS State Matrix

Yes/No (above Brayton Self Sustaining) · Yes or No (above Power Generated)

States		Sub-States	No	Reactor	Control Rods	Shut-down Rods	RSS	Brayton Self Sus-taining	SBS	CCS	Power Gene-rated	Synchro-nized	Primary Pressure Boundary	Average Reactor Outlet Temperature	MPS Helium Pressure [kPa]	MPS Helium Inventory [%MCRI]
Power Operation	5	Normal Power Operation	5b	Critical	Operational	Out	Out	Yes	Off	Off	Yes	Yes	Closed	900	NA	>=40
		Reduced-Capability Operation	5a	Critical	Operational	Out	Out	Yes	Off	Off	Yes	Yes	Closed	750 to 900	NA	>=40
PCU Operational	4	PCU Operational	4	Critical	Operational	Out	Out	Yes	Off	Off	Yes	No	Closed	750 to 900	NA	>=40
Standby	3	MPS Ready	3b	Critical	Operational	Out	Out	No	On	Off	Yes	No	Closed	750 to 900	=>2400	>=40
		Reactor Ready	3a	Critical	Operational	Out	Out	No	On	Off	Yes	No	Closed	=<900 ***	=>2400	>=40
Shutdown	2	Partial Shutdown	2c	Sub-Critical	Inserted	Out	Out	No	On	Off	No	No	Closed	750 to 900	=>2400	>=40
		Intermediate Shutdown	2b	Sub-Critical	Inserted	Inserted	Out	No	On	Off	No	No	Closed	550 to 900	=>2400	>=40
		Full Shutdown	2a	Sub-Critical	Inserted	Inserted	Inserted	No	On	Off	No	No	Closed	=<550 **	=>2400	>=40
Fuelled Maintenance	1	Closed Maintenance	1b	Sub-Critical	Inserted	Inserted	Inserted	No	Off	On	No	No	Closed	=<400°C *	Atm.	NA
		Open Maintenance	1a	Sub-Critical	Inserted	Inserted	Inserted	No	Off	On	No	No	Open	=<400°C *	Atm.	NA
Defuelled Maintenance	0	Defuelled Maintenance	0	NA	NA	NA	NA	No	NA	NA	No	No	No	NA	NA	NA

NA=Off/On/Available/Unavailable

Time fraction

Time fraction per mode

Description	Days per year	Time Fraction Prediction % per year for 40 year plant life	
De-fuelled Maintenance (0)	*	*	
Open maintenance (1a)	9	2.5	
Closed maintenance (1b)	3	0.8	
Shutdown (2)	3	0.8	
Reactor ready (3a)	3	0.8	
MPS ready (3b)	2	0.5	
PCU operational (4)	1	0.3	
Reduced-capability operation (5a)	20	5.5	
Normal power operation (5b)	324	88.8	
	365	**100**	**Total**

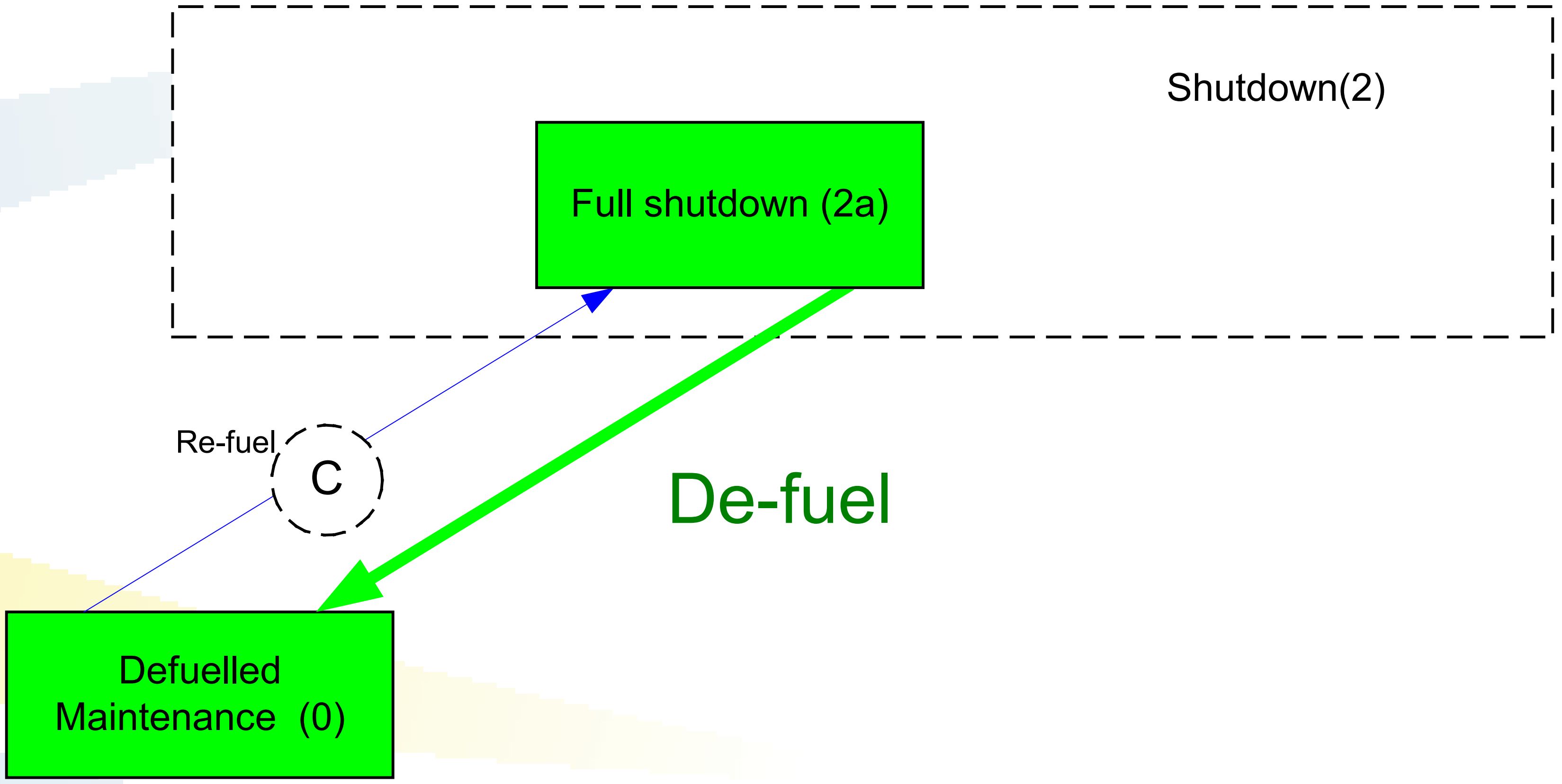
18 Days / year average planned and unplanned

347 Days => 95 % Availability

* The plant will be fuelled and at the beginning and end of the plant lifetime unless special unplanned maintenance requiring a defuelled reactor is encountered.

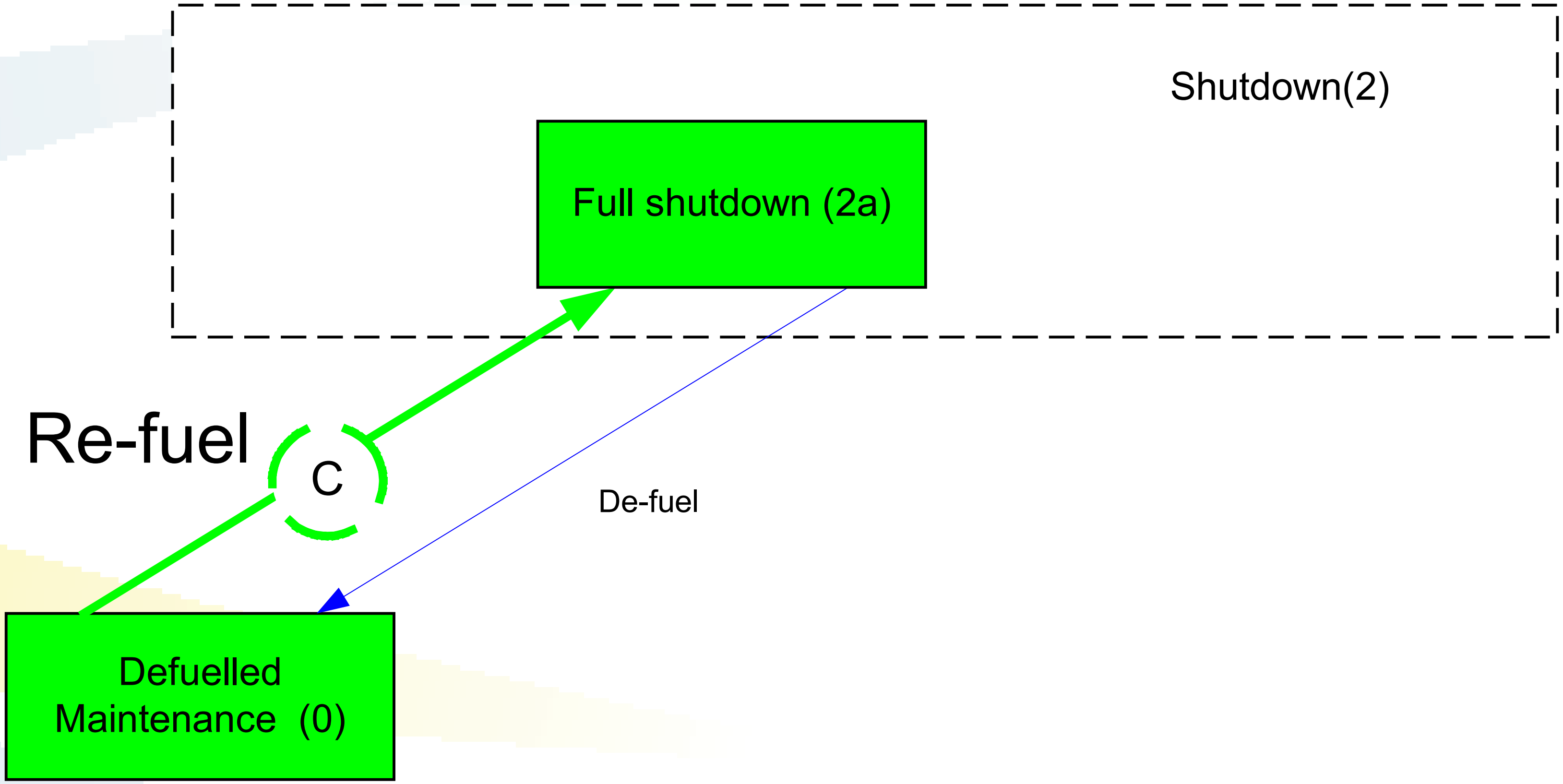
Transitions

De-fuel

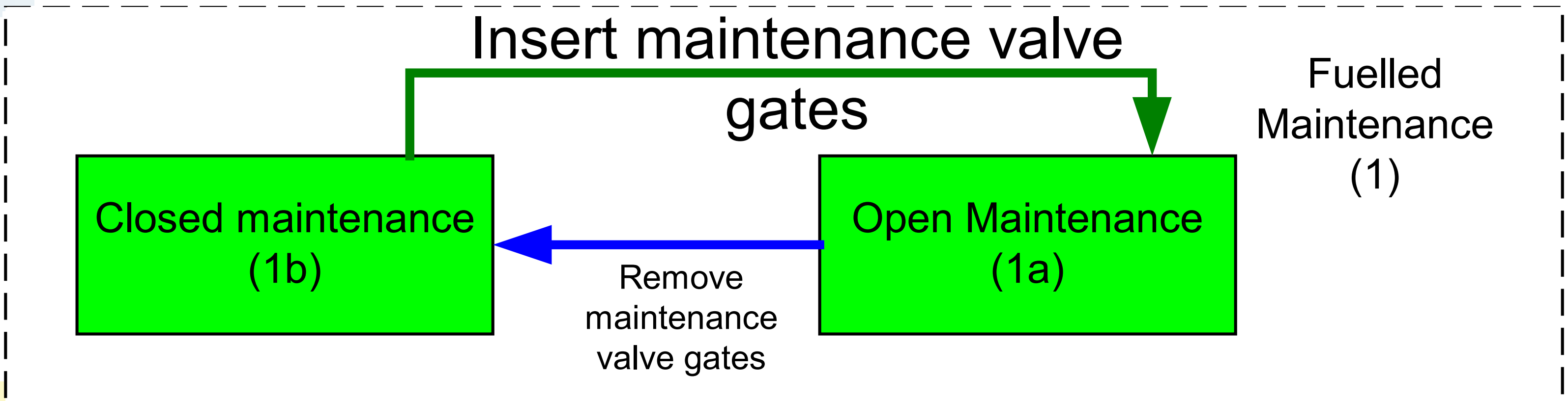


Shutdown(2)
Full shutdown (2a)
Re-fuel
C
De-fuel
Defuelled Maintenance (0)

Re-fuel


Shutdown(2)
Full shutdown (2a)
Re-fuel
C
De-fuel
Defuelled
Maintenance (0)

Insert maintenance valve gates

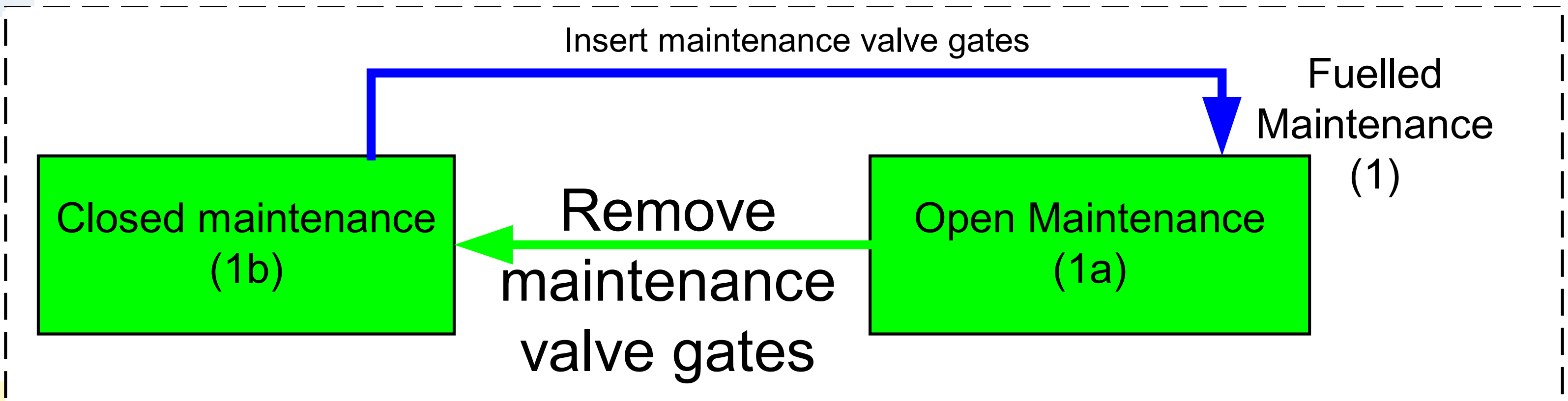


Insert maintenance valve gates

Stepwise procedure

- Maintenance valve gates are positioned in the piping between the PCU and reactor unit (RU).They stop air entering the fuelled reactor
- A temporary tent is erected
- Before lids are opened, the PCU internal pressure (now filled with dry air) is lowered to slightly below atmospheric pressure (30 Pa / 0.3mbar)

Remove maintenance valve gates

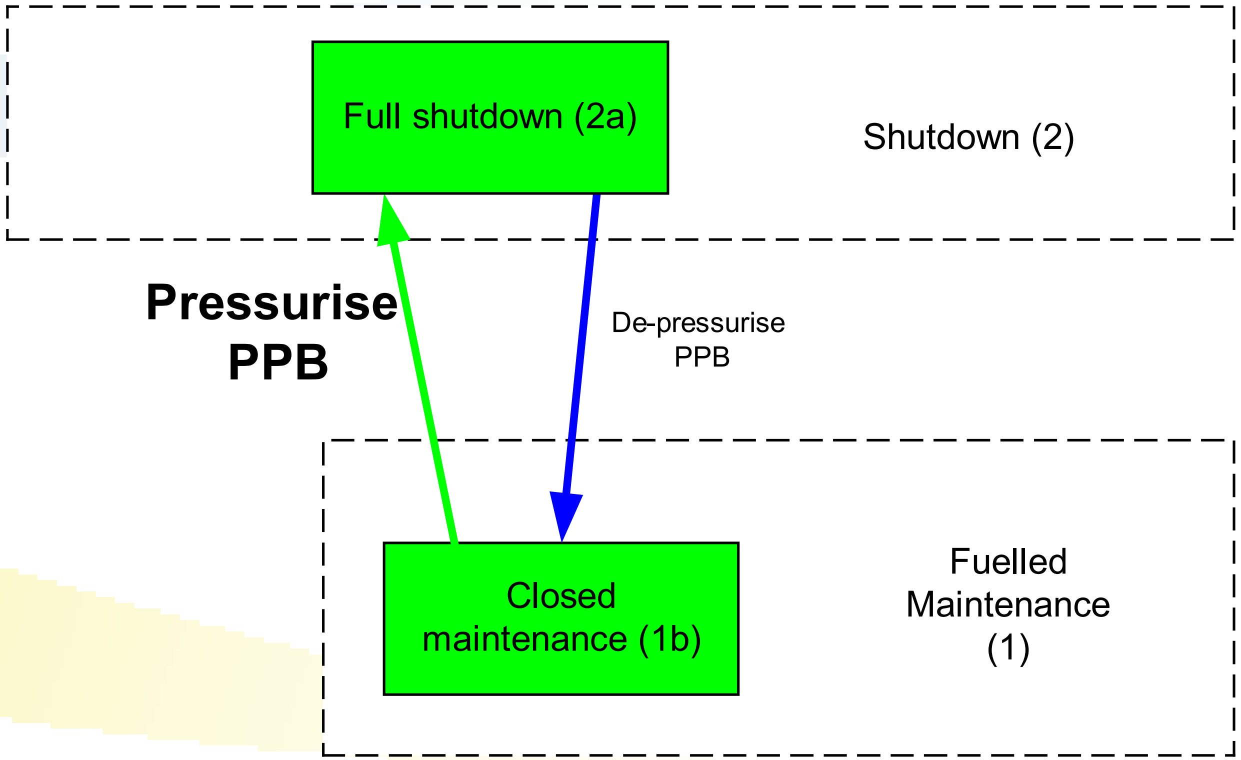


Remove maintenance valves

Stepwise procedure

- Remove the dry air in the PCU by drawing a vacuum in the PCU.
- The extracted air & helium mixture is removed via the Primary Loop Initial Clean Up System (PLICS) filters.
- The helium leaks from the Reactor Unit (RU) into the PCU volume until a vacuum is drawn over both the RU and PCU.
- Once a vacuum has been established, helium is re-introduced into the RU and leaks into the PCU.
- This cycle is repeated until the allowable level of impurities is achieved

Pressurise PPB

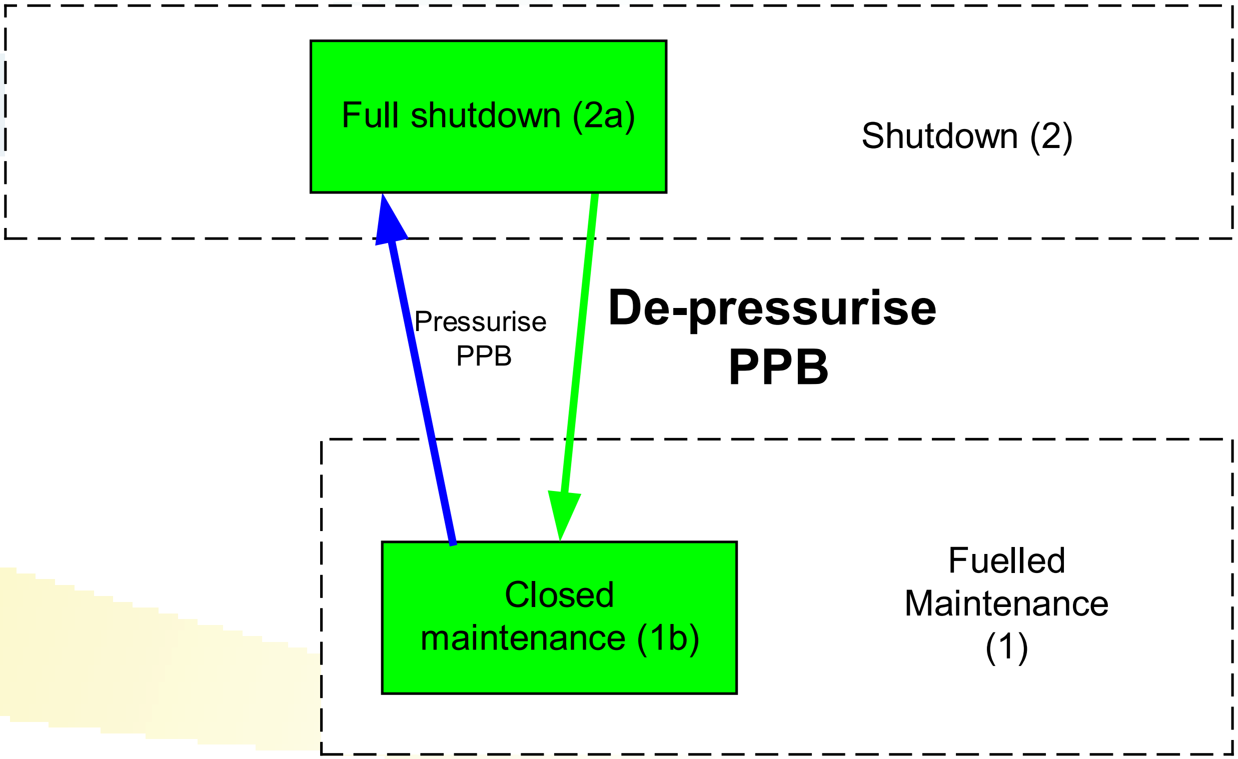


Pressurise PPB

Stepwise procedure

- Fill PPB with helium to 40% MCRI
- Start the main closed circuit pumps that supply cooling water to the inter- and pre-coolers.
- Switch on SBS and decay heat controllers
- Switch off CCS

De-pressurise PPB

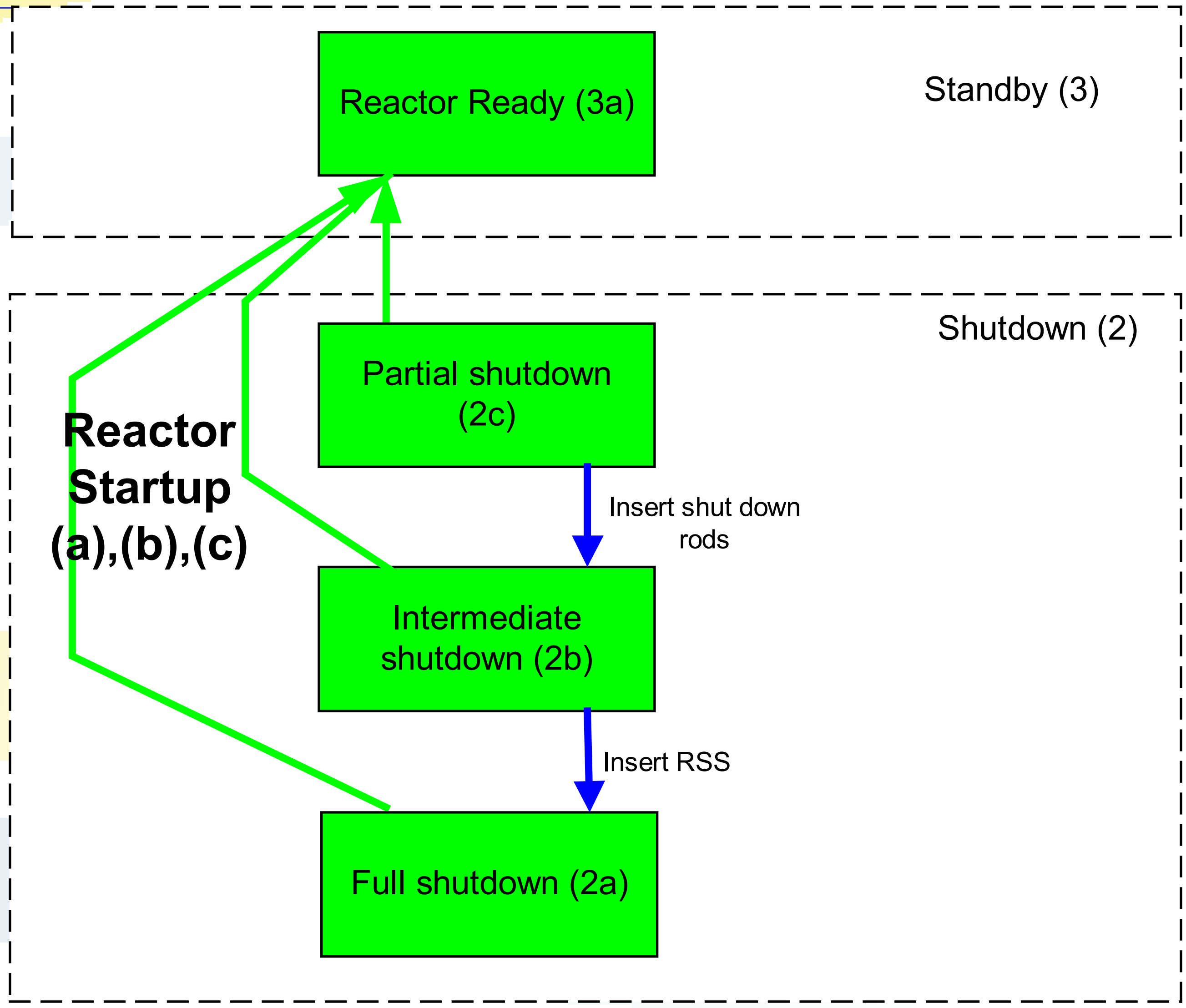


De-pressurise PPB

Stepwise procedure

- Using the SBS reduce reactor outlet temperature (ROT) until 200°C is reached. (2 days)
- Switch the SBS off and the CCS on
- Switch off the main closed circuit pumps that supply cooling water to the inter- and pre-coolers.
- The helium content of the PCU is flushed with dry air.

Reactor start-up (a),(b),(c)



Reactor start-up (a),(b),(c)

PBMR

Stepwise procedure

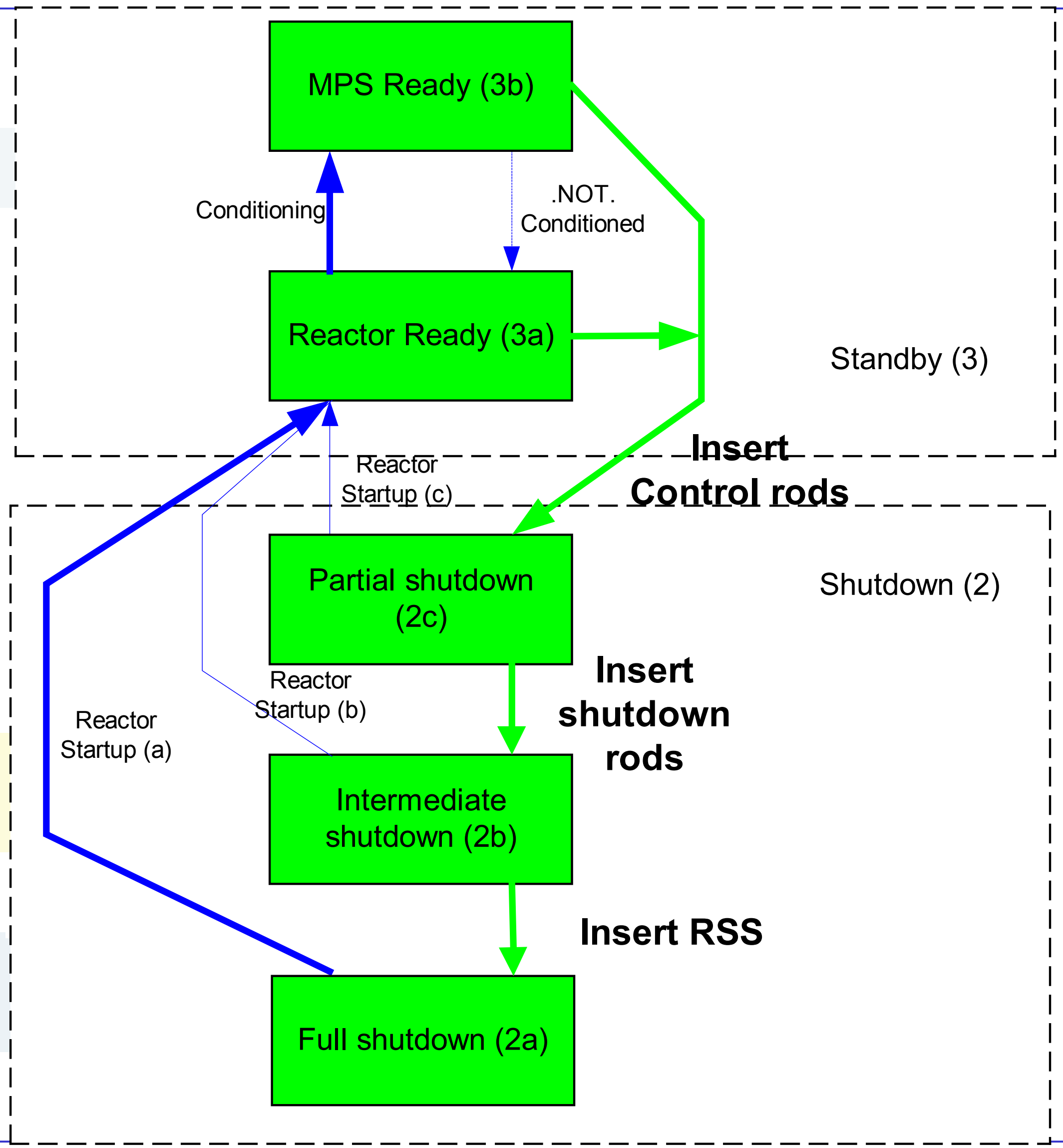
- Confirm that the protection bypass that allows SBS/CCS operations at low Reactor Outlet Temperature (ROT) is activated
- Withdraw the control rods and keep the shutdown rods and the RSS inserted;
- Empty the Small Absorber Spheres (SAS) channels one at a time
- When the neutron count rate takes more than 60 seconds to stabilise, withdraw the control rods slowly to make the reactor critical and switch to the ROT reactivity controller
- The next SAS channel is emptied and the control rods are inserted while keeping the reactor critical (1)
- Repeat (1) until the control rods approach a pre-determined lower limit;

Reactor start-up (a),(b),(c)

Stepwise procedure

- Increase the ROT with nuclear heating using the control rods. The ROT must remain below 550 °C;
- Repeat (1) until all SAS channels have been emptied;
- Remove the shutdown rods while inserting the control rods without exceeding a pre-determined lower limit on the control rods
- Increase the ROT with nuclear heating using the control rods until the shutdown rods are fully withdrawn;
- The protection interlock, which allows SBS/CCS operation for a low ROT temperature is automatically activated when the ROT reaches 755 °C.

Insert ….transitions

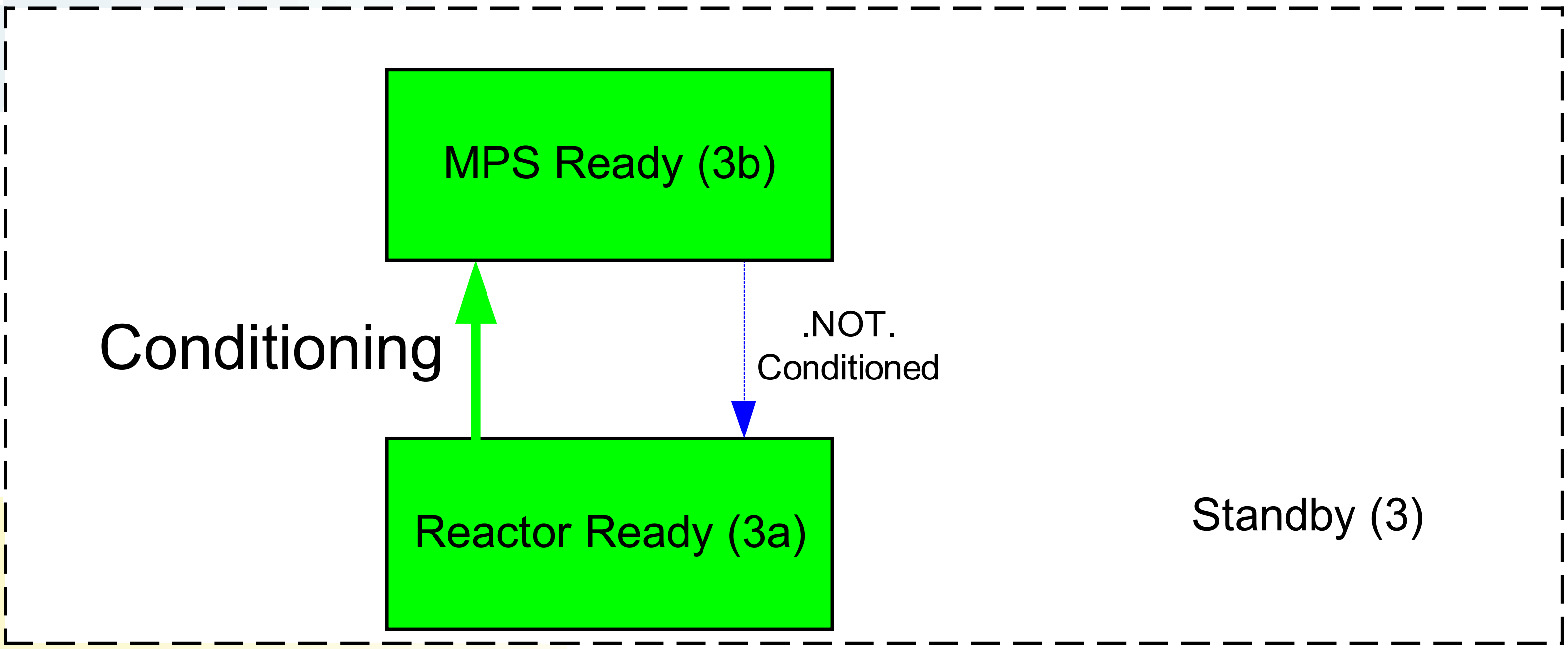


Insert ….transitions

Stepwise procedure

- Insert the rods/SAS in a controlled manner

Conditioning



Conditioning

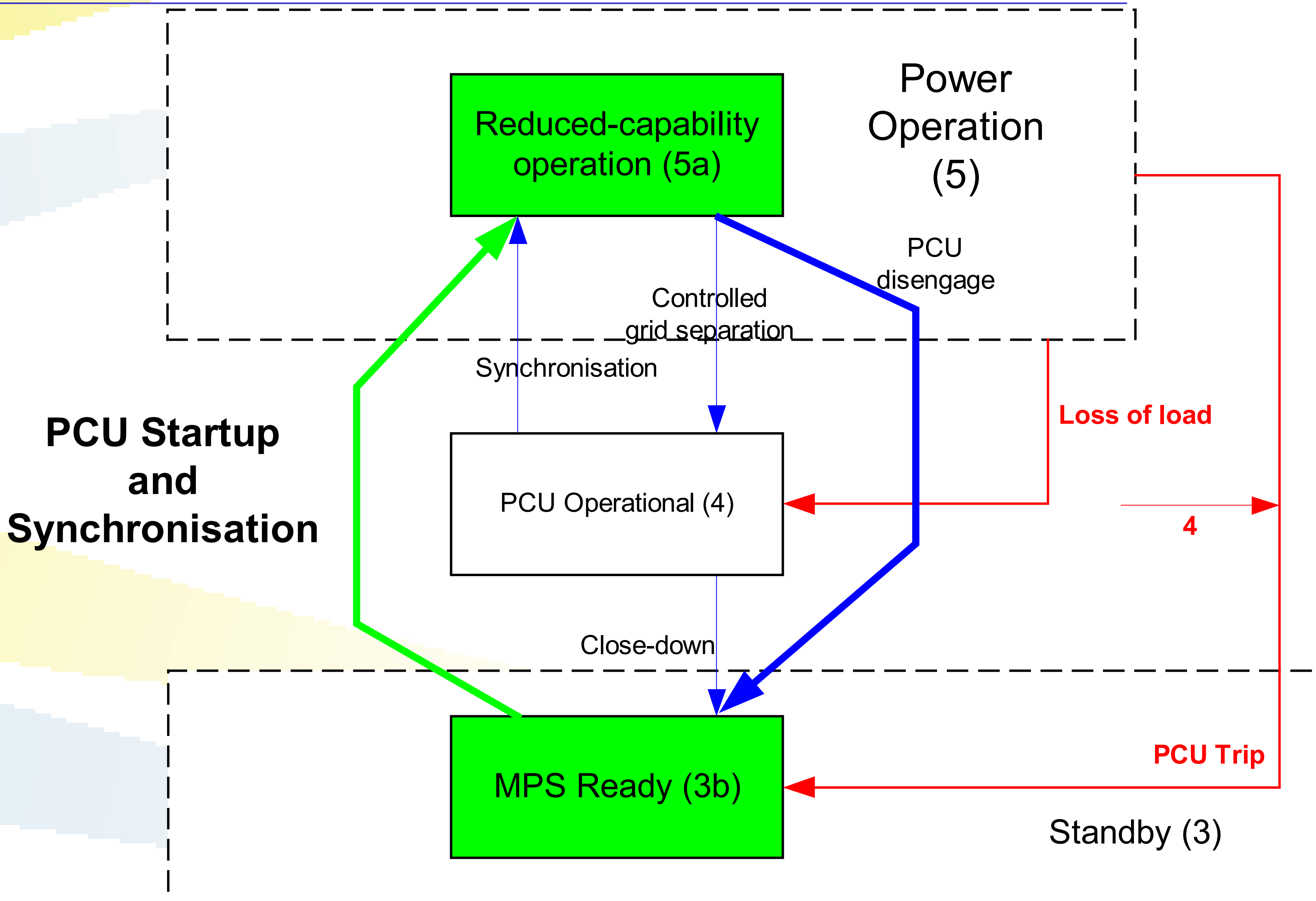
Stepwise procedure

Get the MPS to specified temperature levels (to reduce temperature differentials when the Brayton cycle is started)

Conditioning Controller is activated

Actuator	**Regulated variable**
SBS	Mass flow rate through reactor
Control rods	Reactor outlet temperature
Recuperator bypass valves	Recuperator LP outlet temperature Reactor inlet temperature
HP coolant valve	Recuperator LP inlet temperature
Compressor bypass	Power turbine power
Resistor banks	Power turbine speed

PCU start-up and synchronisation



PCU start-up and synchronisation

Stepwise procedure

• The ROT reactivity controller will control the reactor outlet temperature

• The SBS operates at maximum possible delivery

• The generator excitation is already switched on at a Power Turbine Generator (PTG) shaft speed of 600rpm. The helium pressure and the shaft speed limit the voltage to which the generator is excited.

• A power request of 1 MW for the generator is set together with a speed request of 30 Hz. The LPB and HPB together with the resistor bank will ensure that the generator is stable in this state;

• INITIAL START-UP CONDITION

PCU start-up and synchronisation

Stepwise procedure

• The spin-up sequence: The PTG will pass through the critical frequencies rapidly enough not to exceed undesirable vibration or force limits at the critical frequencies;

Release resistor bank

Control for 1 MW

• The control system will adjust the PTG speed to a value just below the grid frequency;

• The synchronisation sequence is entered

PCU start-up and synchronisation

KEY TO THE GRAPHS THAT FOLLOW

Conditioned MPS and :

Maintain Power Turbine at 1 MW with bypass valves (Power Controller)
Maintain Power Turbine at 30 Hz with Resistor Bank (Speed Controller)

Start-up Process:

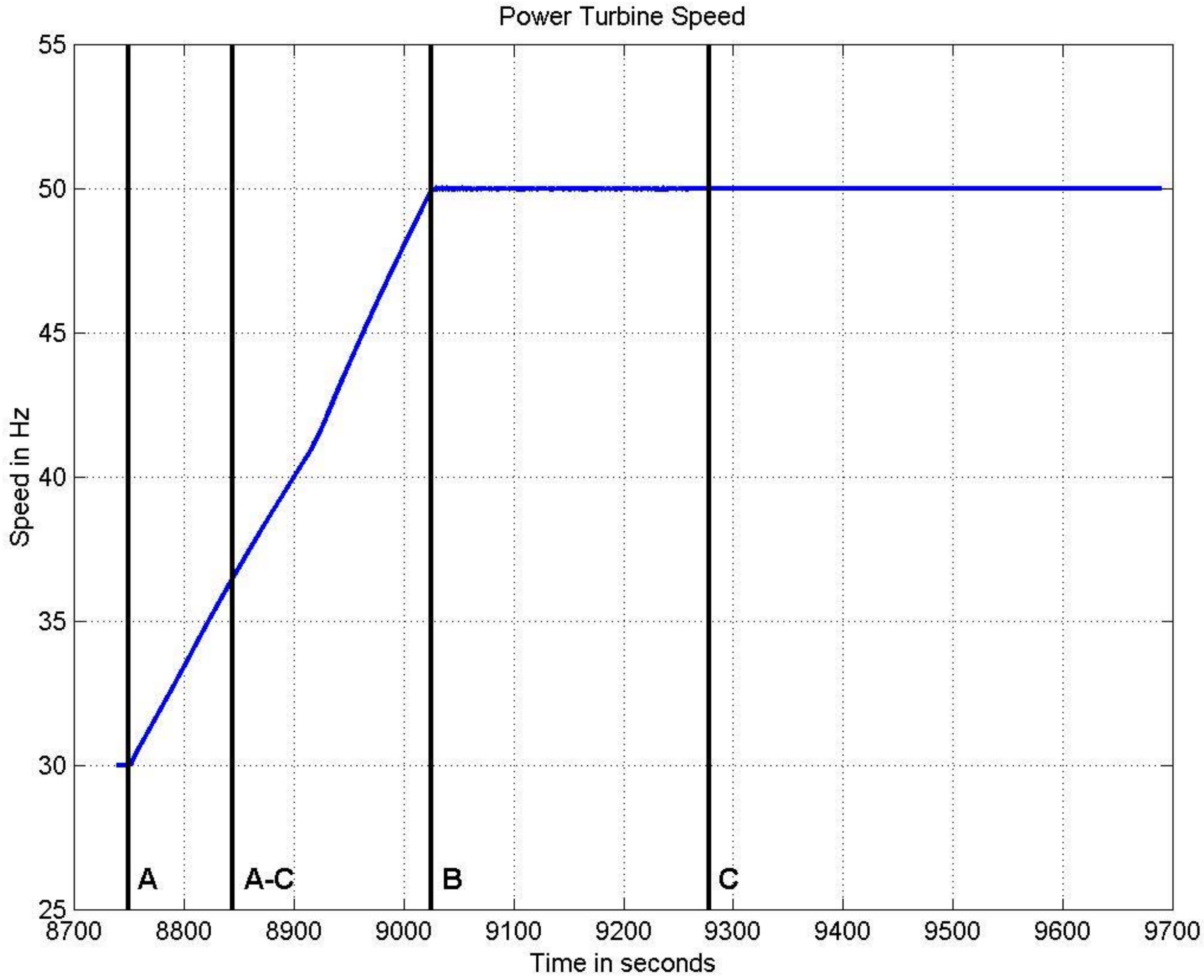
A: Reduce power dissipated by Resistor Bank and allow Power Turbine to speed-up, maintaining Power Turbine fluidic power between 1MW and 1.6 MW with bypass valves (Power Controller)

B: Activate Resistor Bank when Power Turbine reaches 50 Hz (Speed Controller) and commence synchronization

C: Synchronized to Grid and switch over to high cycle efficiency by closing bypass valves

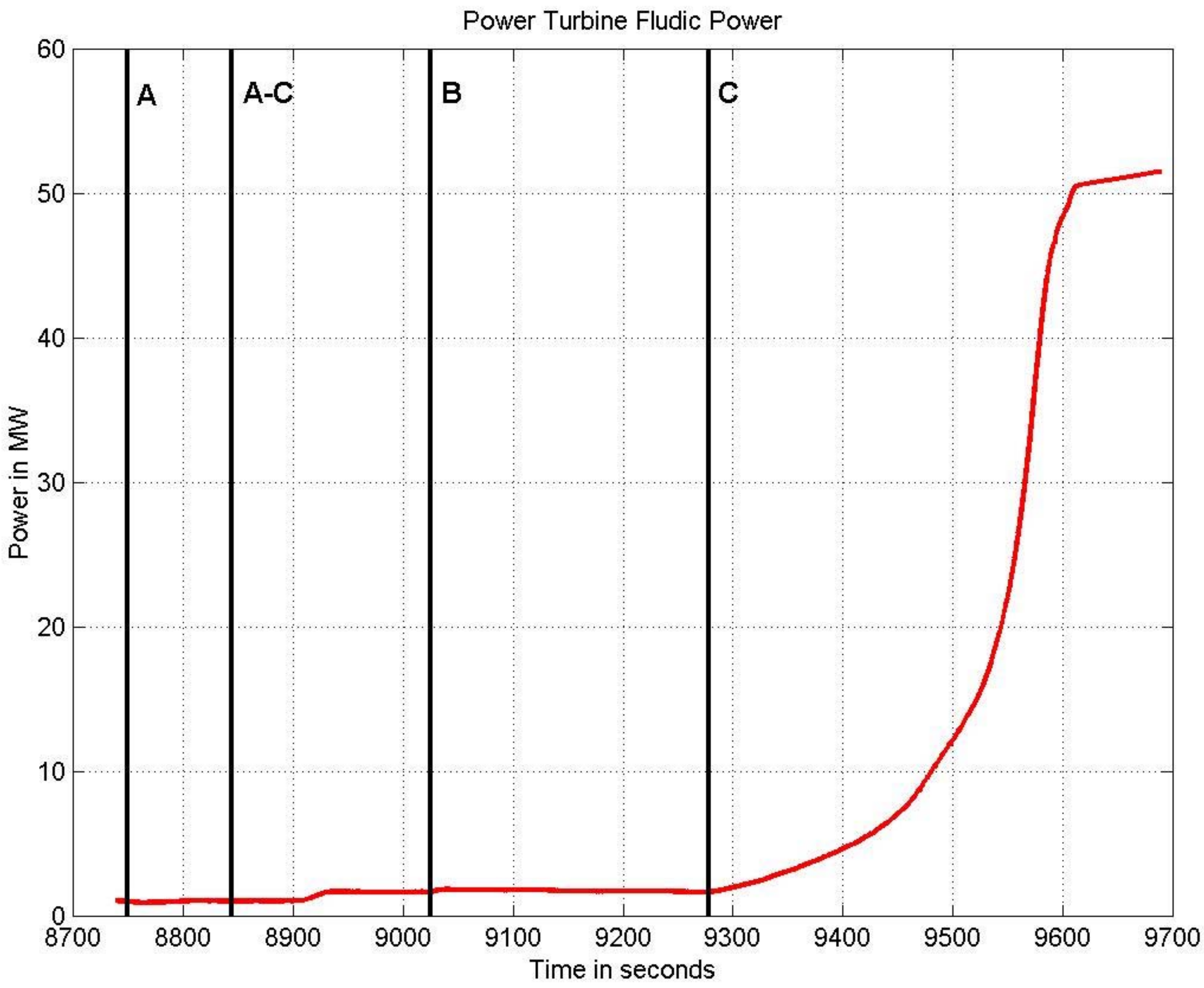
A-C: Brayton cycle self-sustaining - switch off SBS Blowers.

Brayton Cycle Start-Up Graphs (1)

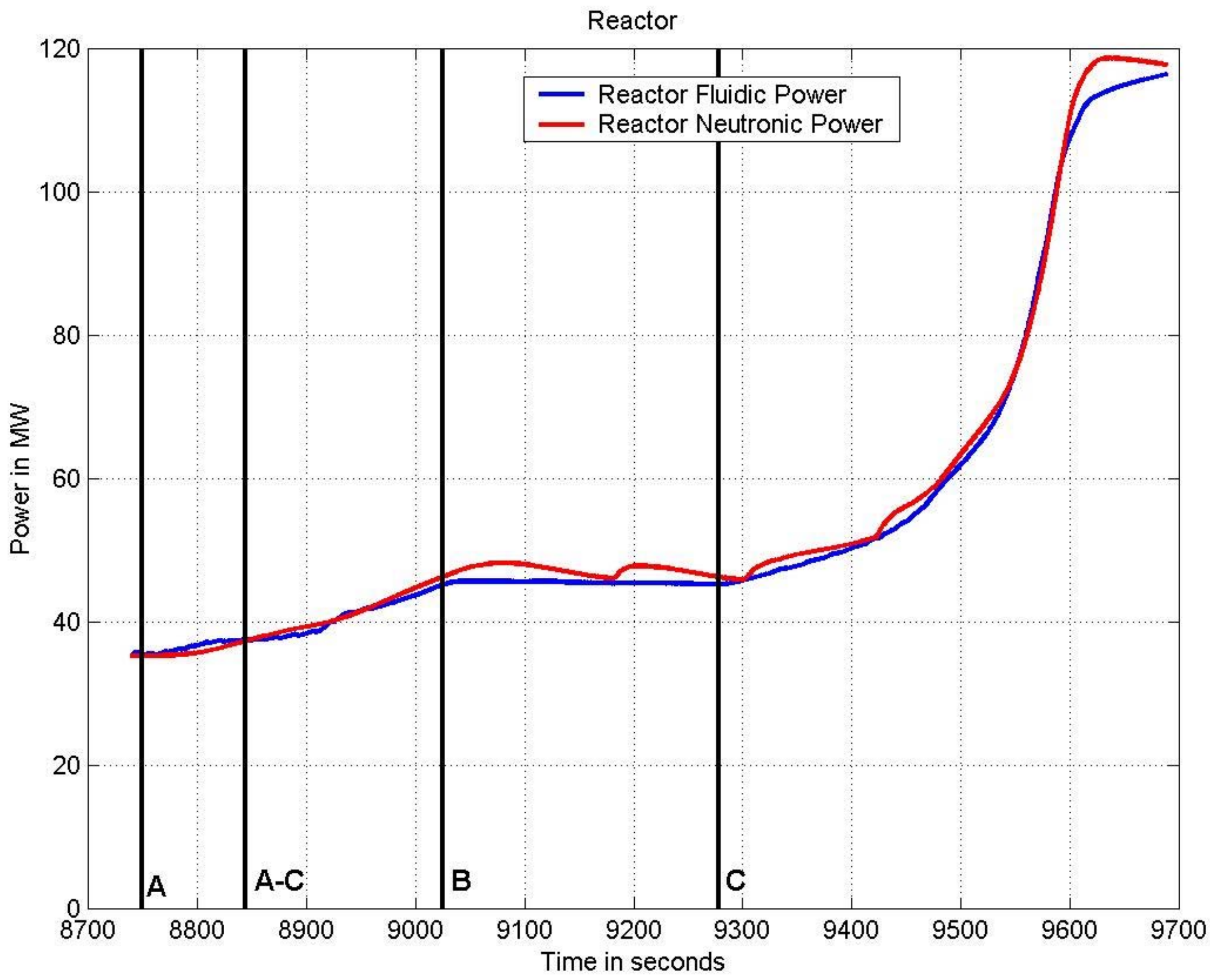


Brayton Cycle Start-Up Graphs (2)

PBMR

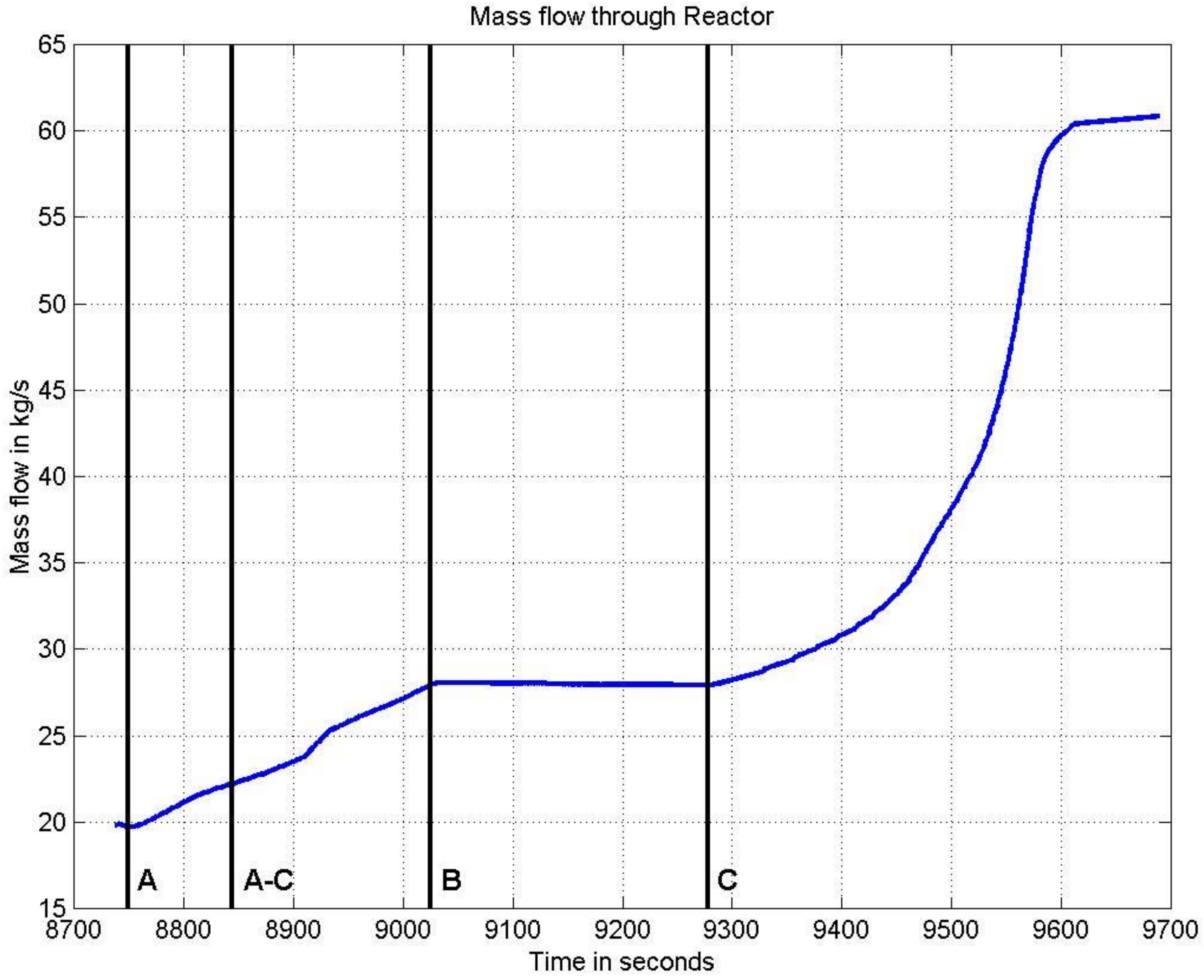


Brayton Cycle Start-Up Graphs (3)

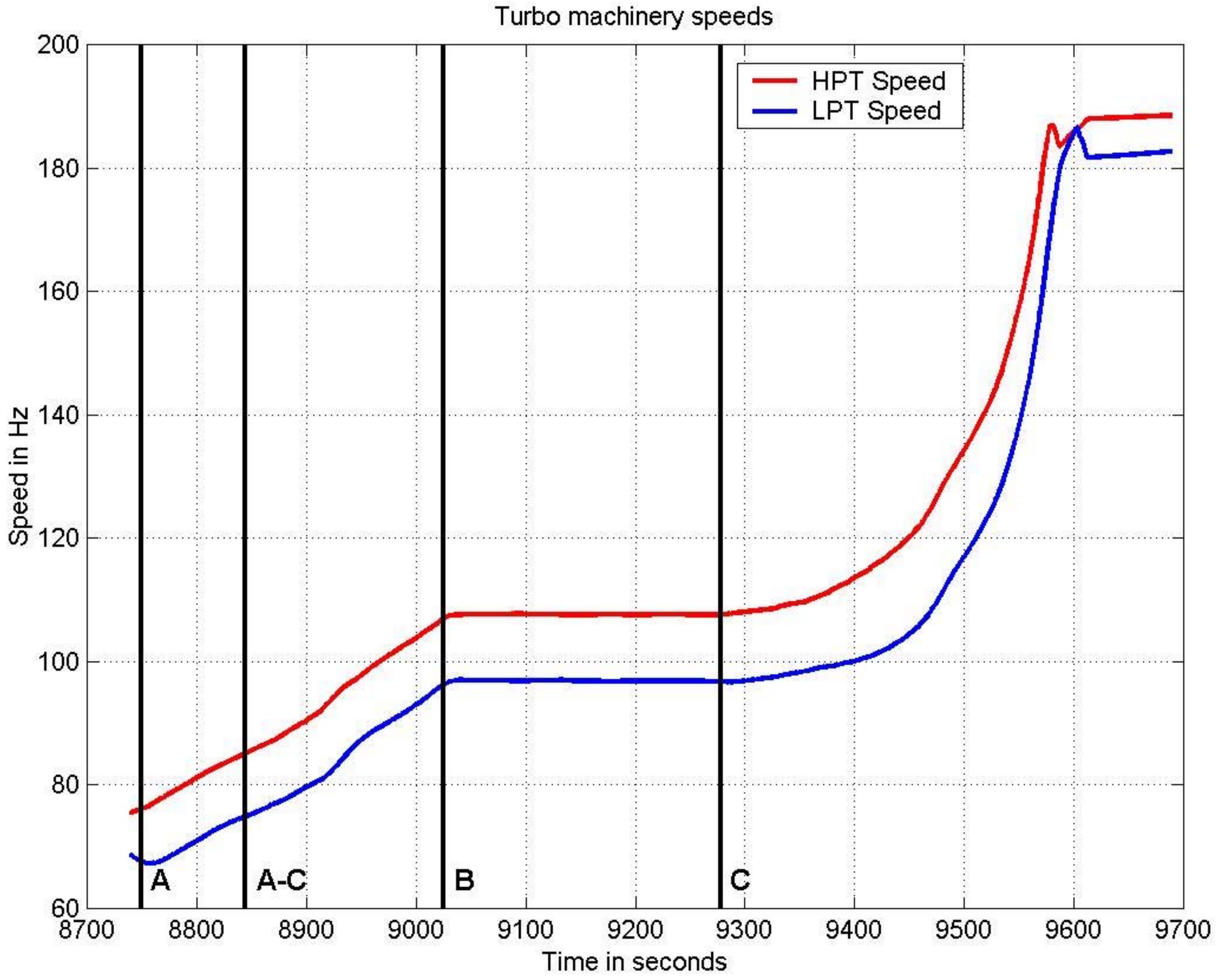


Brayton Cycle Start-Up Graphs (4)

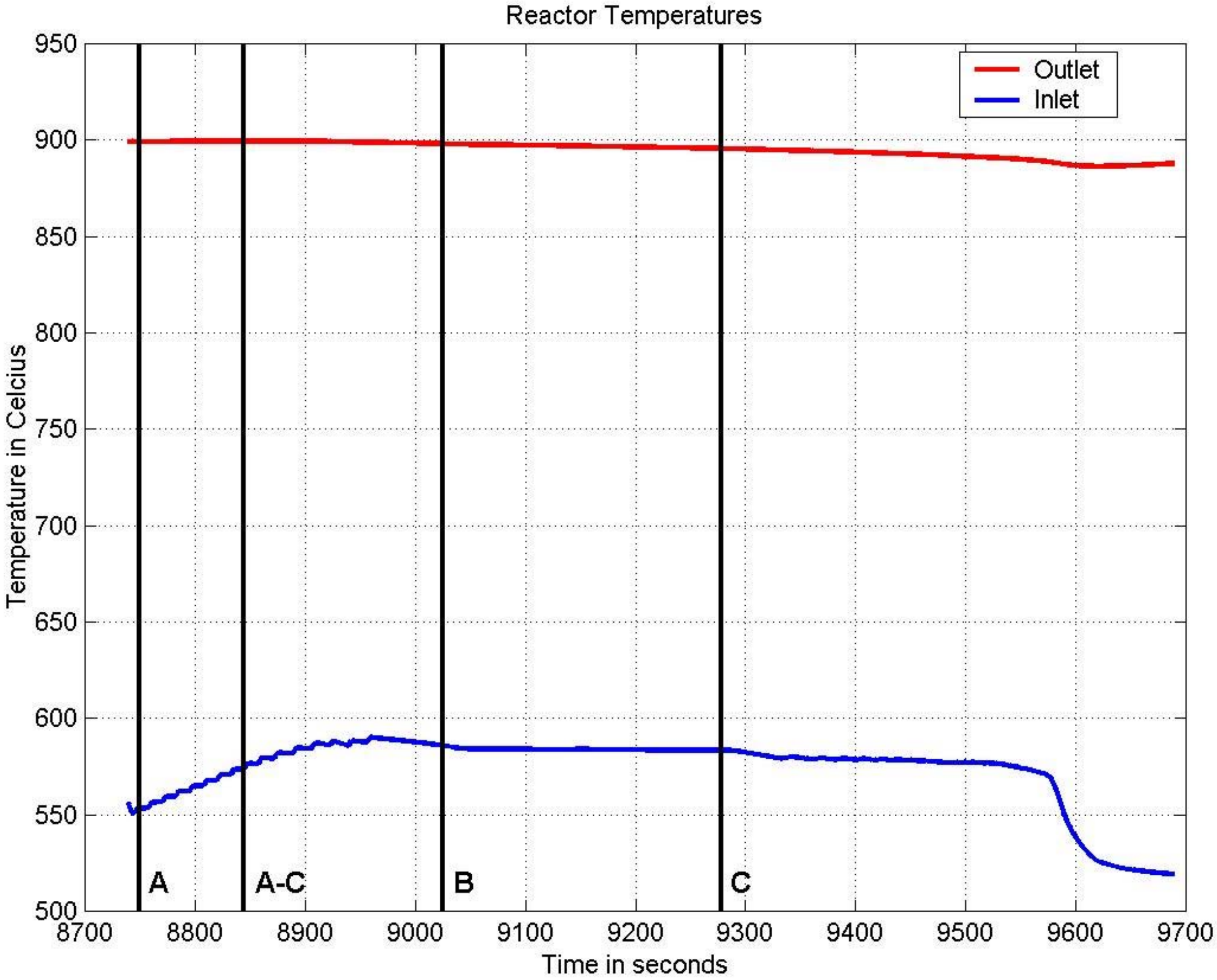
PBMR



Brayton Cycle Start-Up Graphs (5)

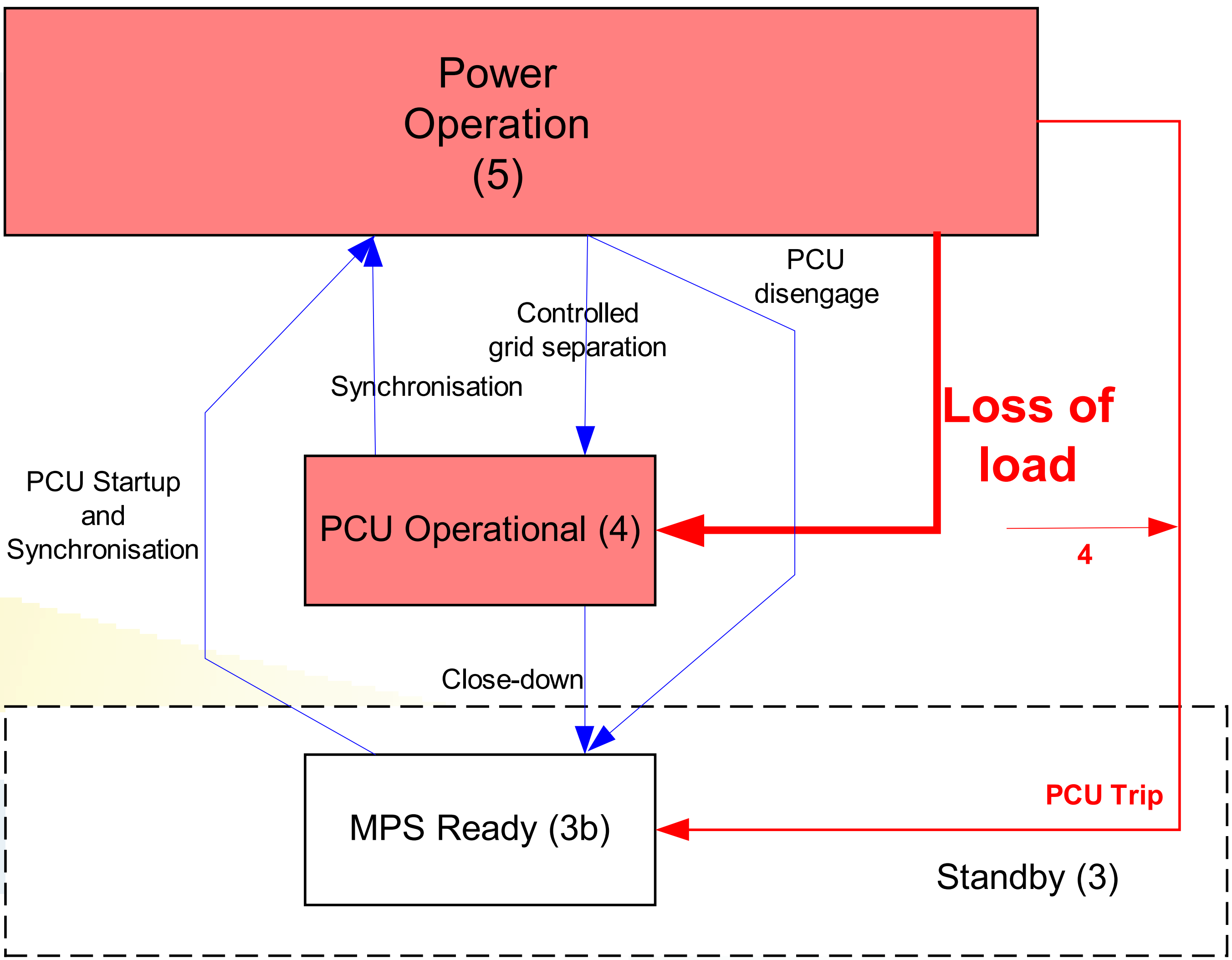


Brayton Cycle Start-Up Graphs (6)



Transients

Loss of load transient



Loss of load transient

Stepwise procedure

- A loss of load condition is detected
- The Gas Cycle Bypass valve (GBP) will open within 0.3 seconds with no feedback control. Opening the valves will ensure the PTG does not over-speed
- The GBP valves will close as soon as the rotational acceleration is negative. This will ensure that the Brayton cycle remains functioning;
- Simultaneously the HPB, LPB and HCV are opened and the resistor bank load is set to maximum.
- The low- and high-pressure bypass valves and resistor bank are used to control the PTG rotational frequency to 50 Hz.
- The HCV will ensure that the recuperator low pressure inlet temperature does not exceed 600 °C;

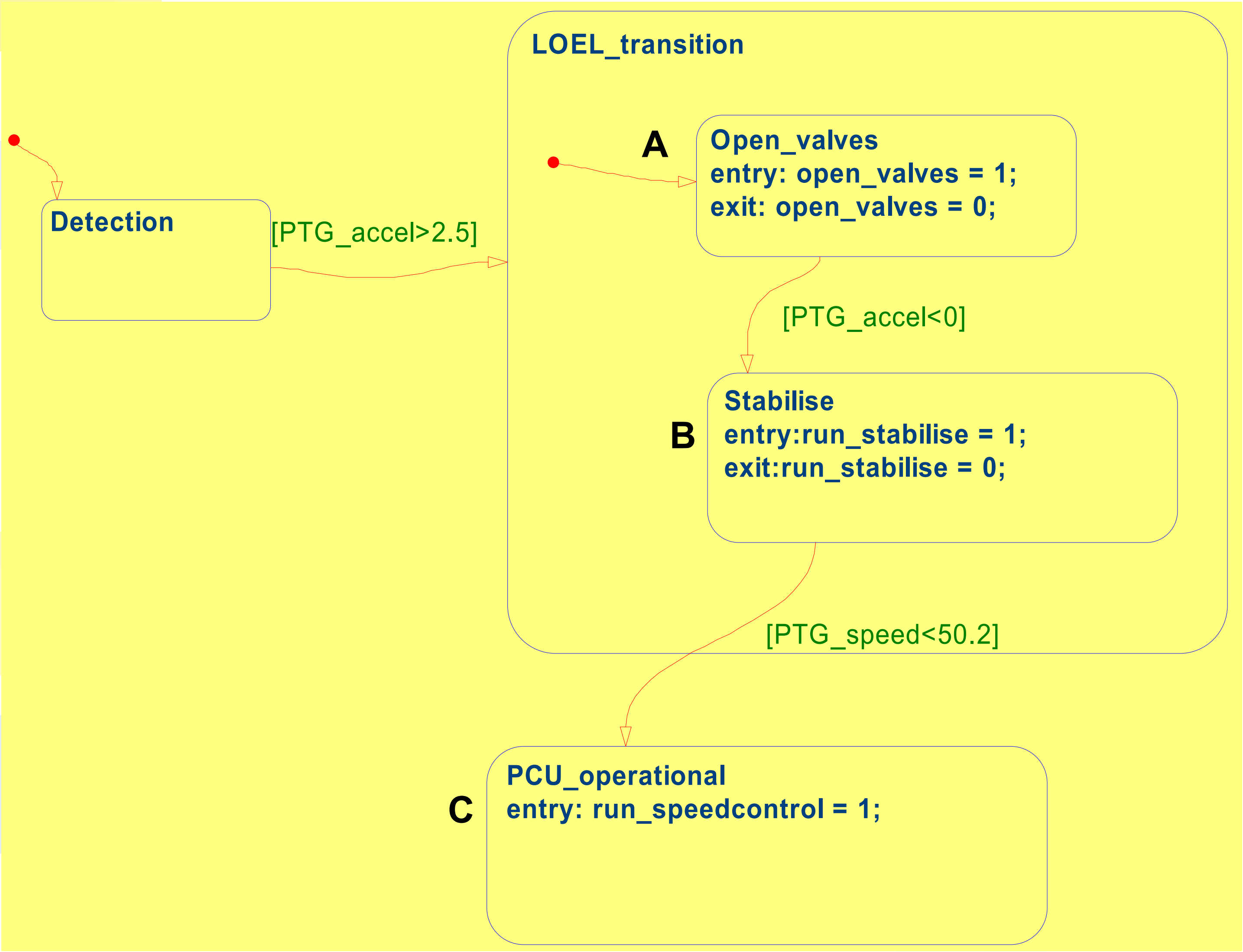
Loss of load transient

Stepwise procedure

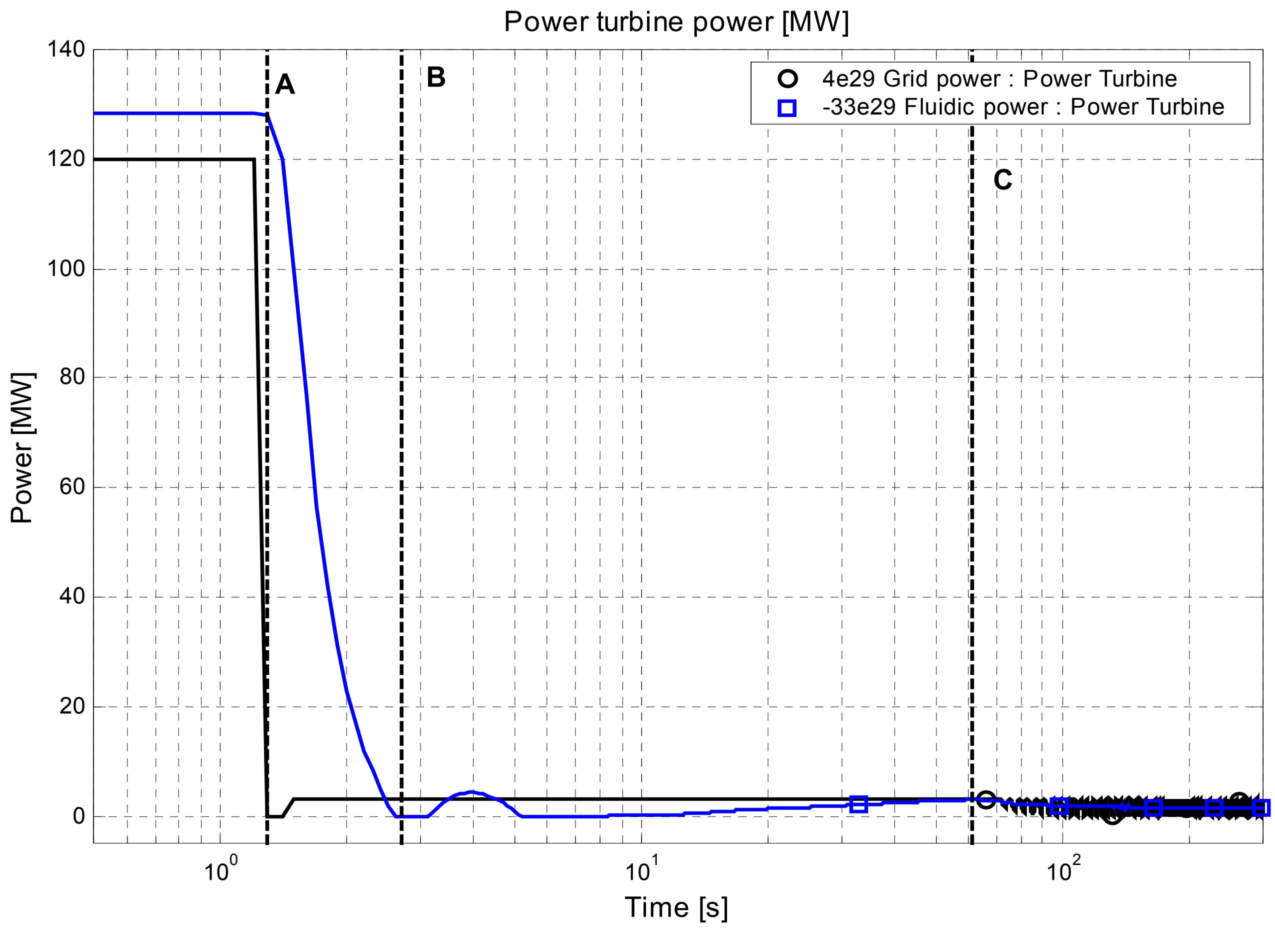
• The electrical protection may operate to trip the generator circuit breaker or the HV breaker, depending on the nature of the initiating event.

• The ROT reactivity controller (control rods) will control the average reactor outlet temperature (ROT).

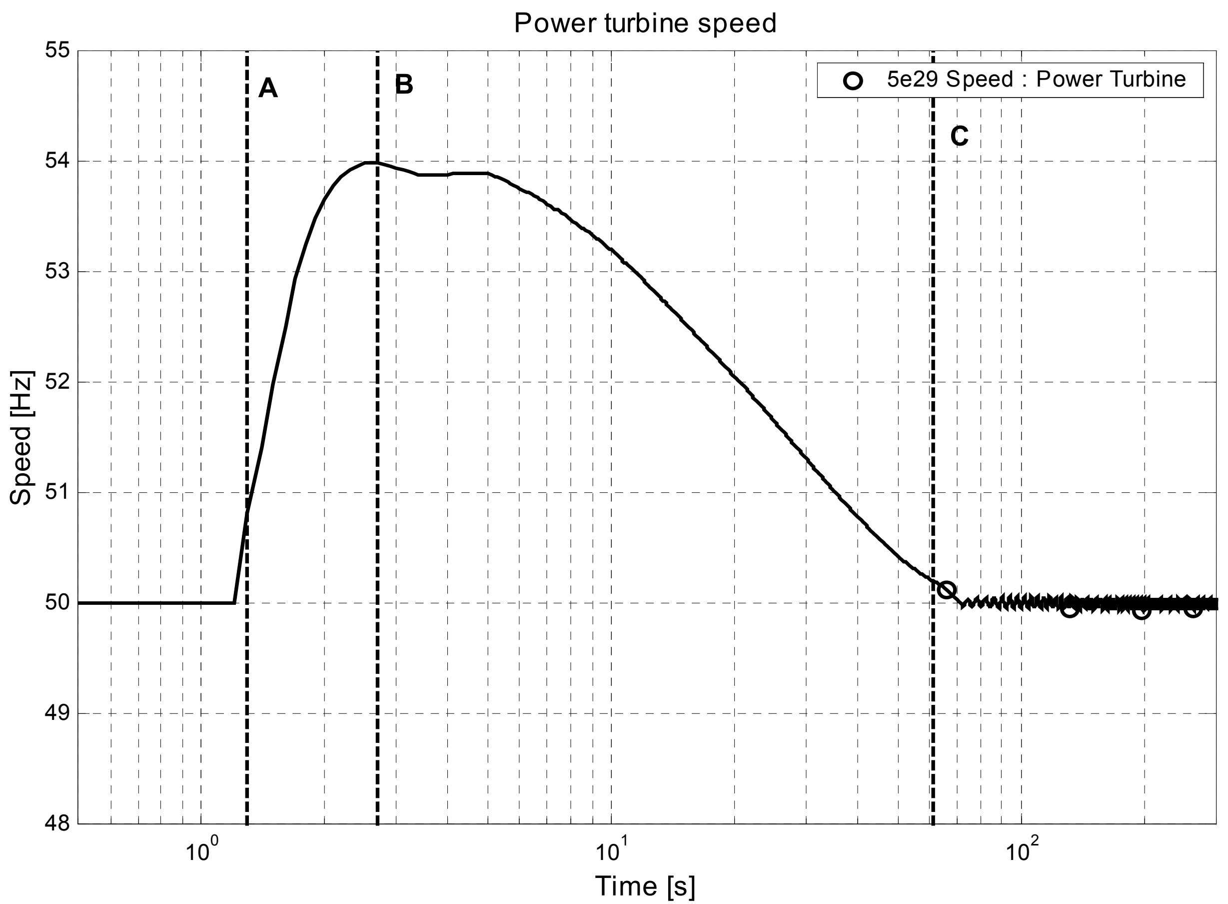
Loss of load transient



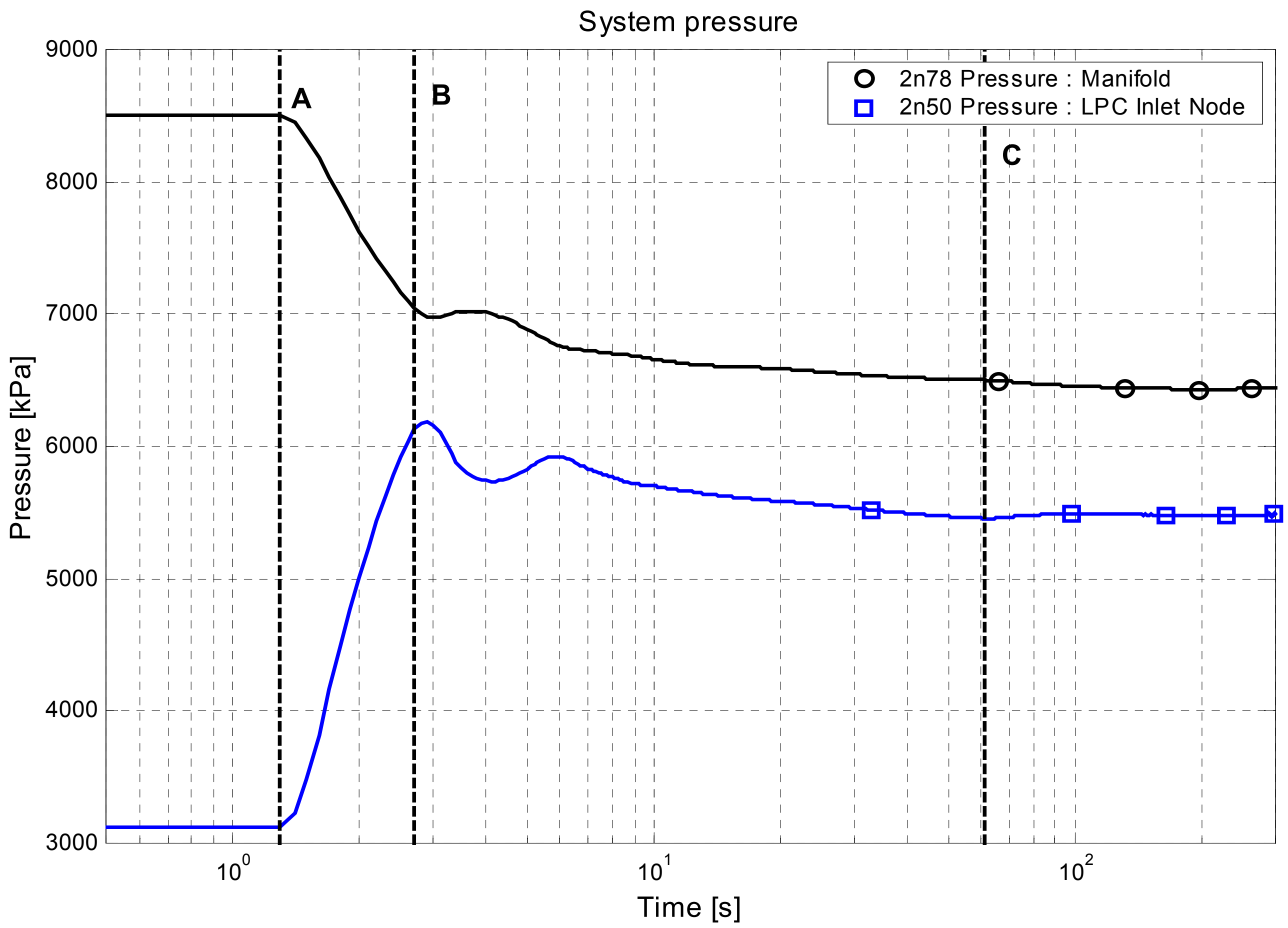
Loss of load transient Graphs (1)



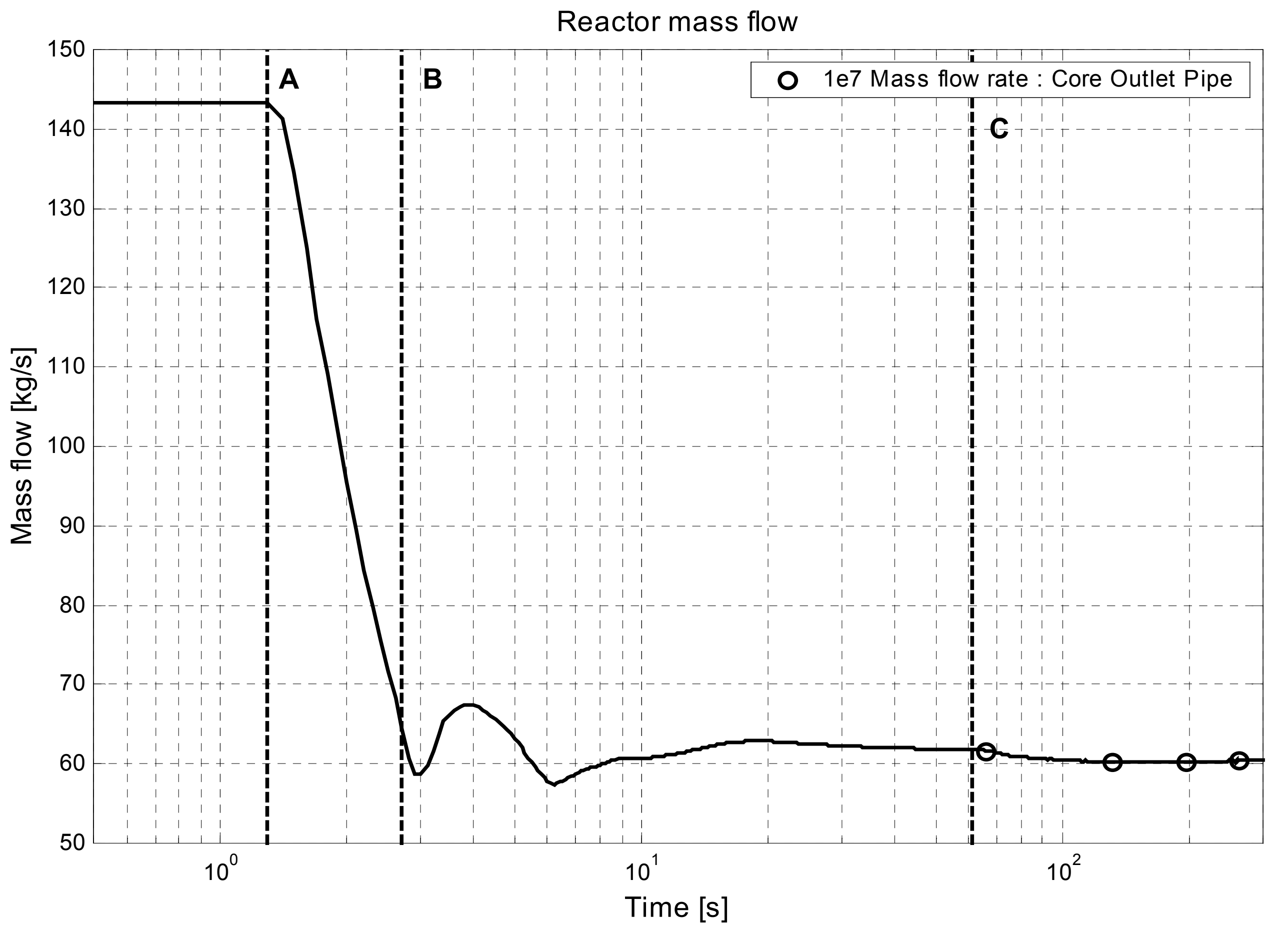
Loss of load transient Graphs (2)



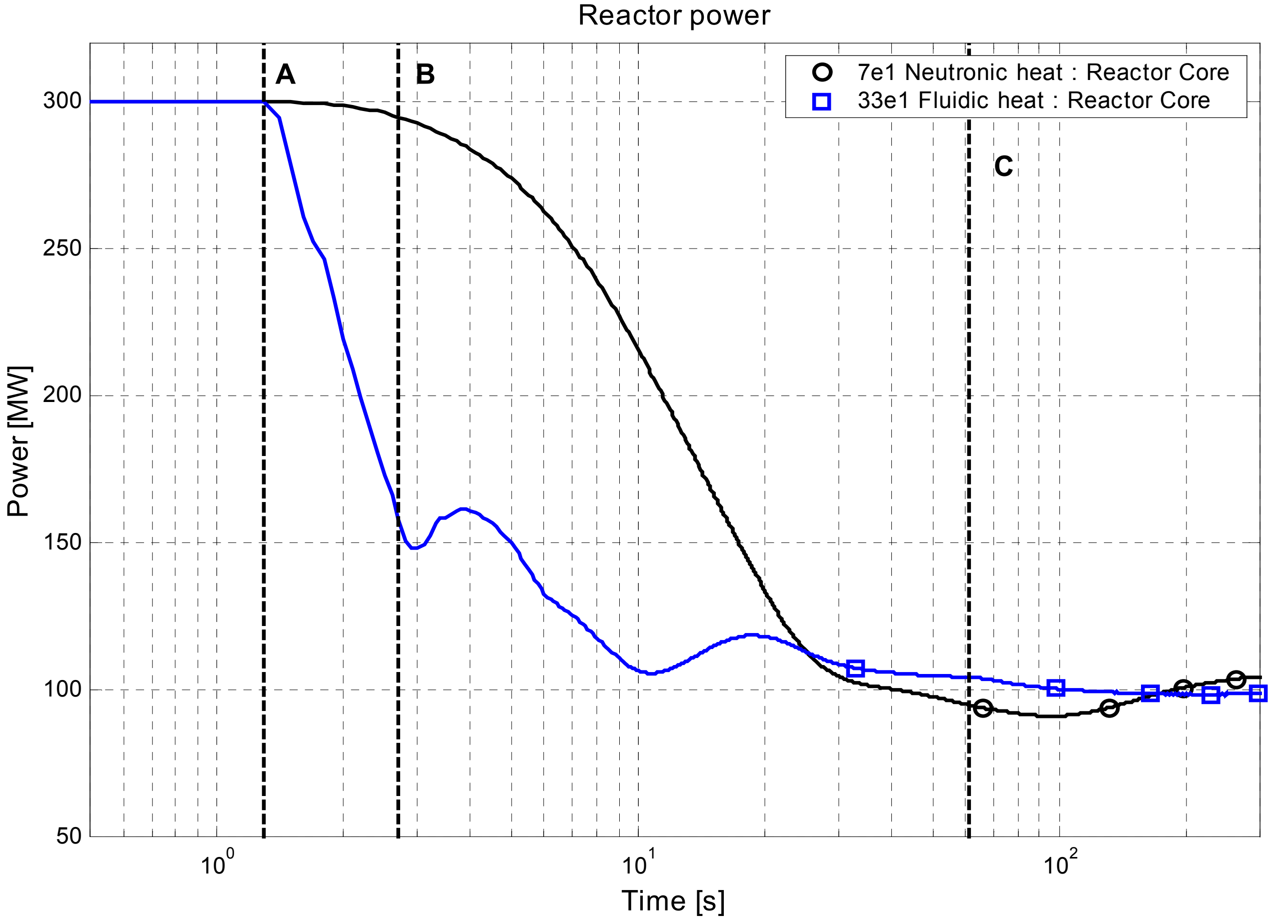
Loss of load transient Graphs (3)



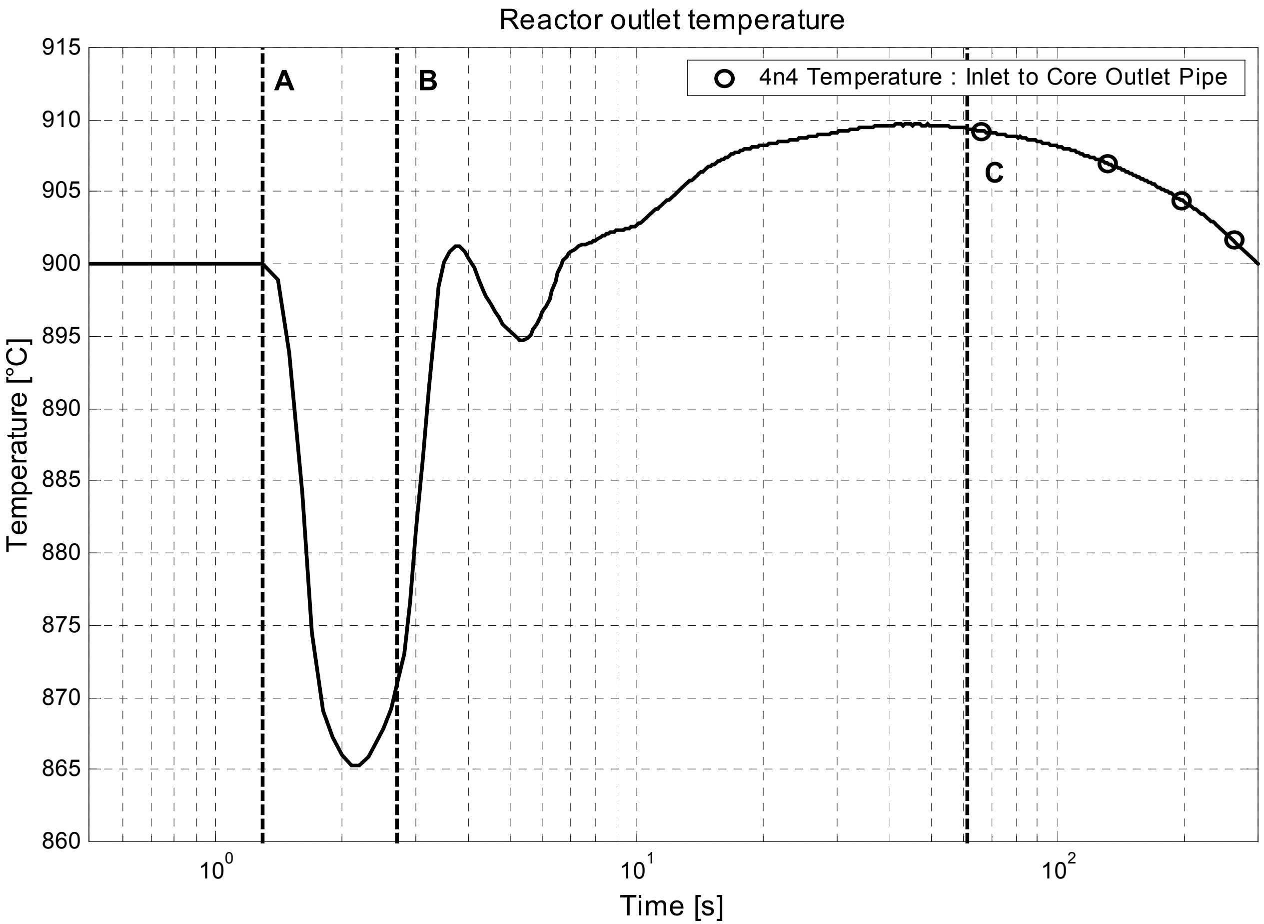
Loss of load transient Graphs (4)



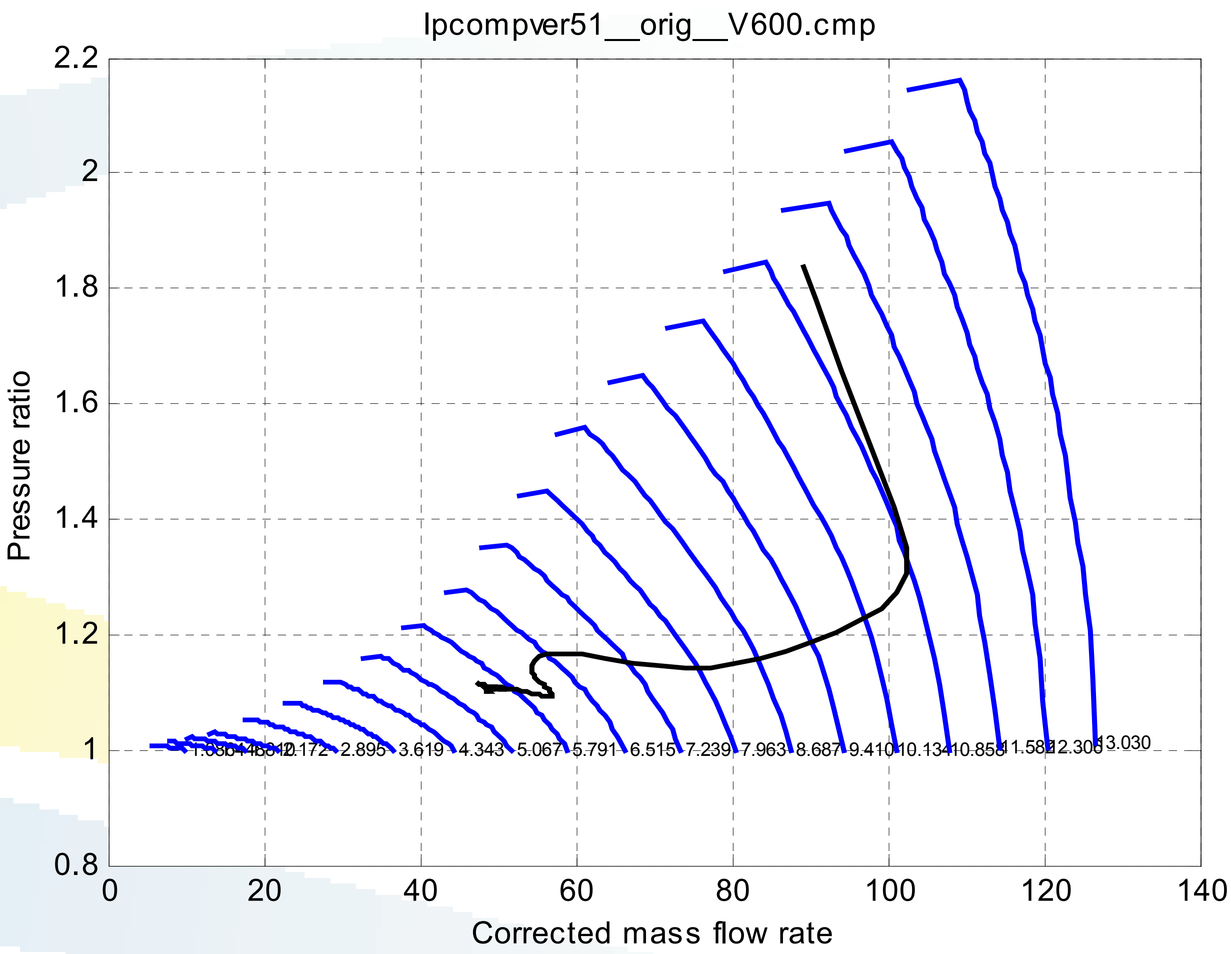
Loss of load transient Graphs (5)



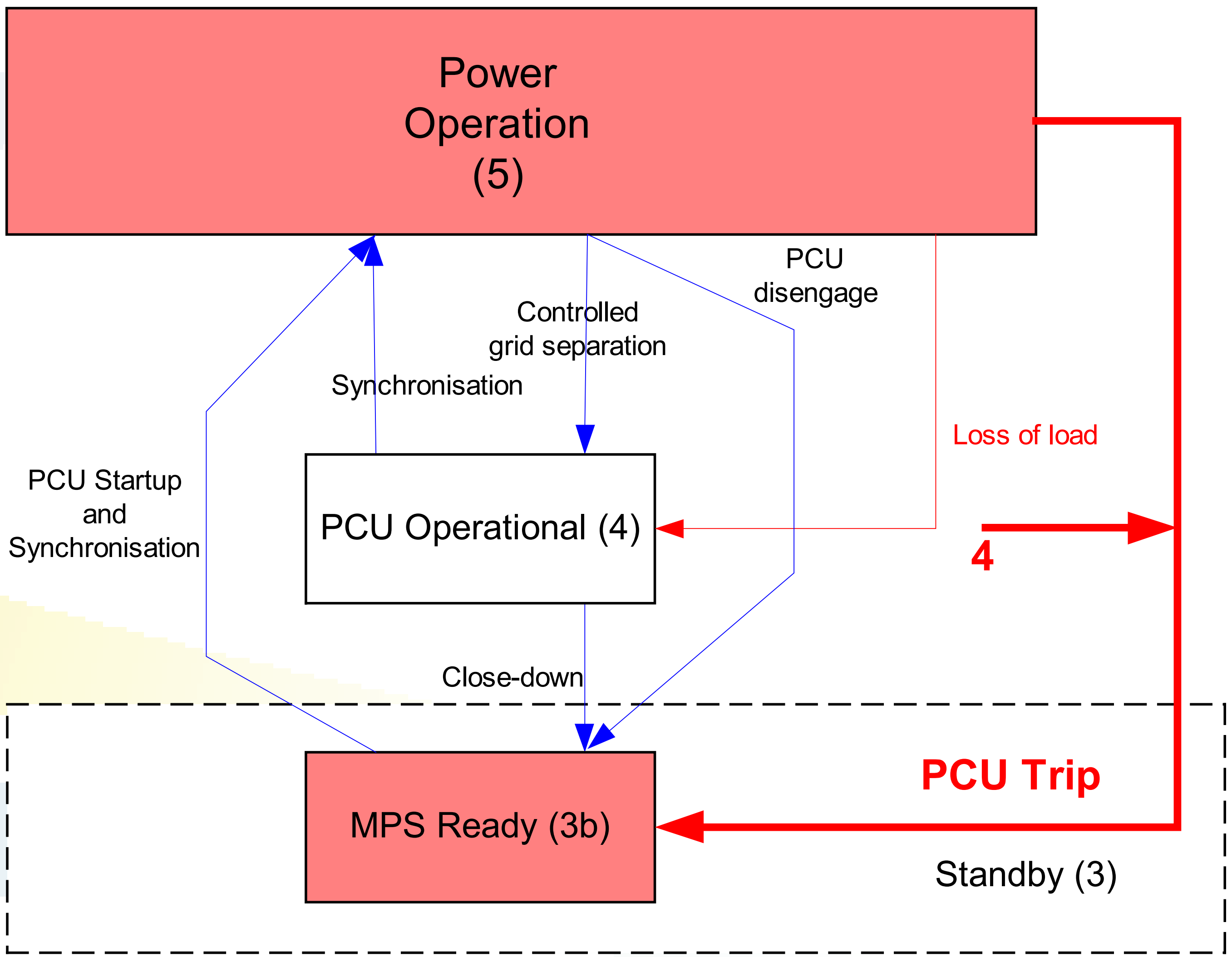
Loss of load transient Graphs (6)



Loss of load transient Graphs (7)



PCU trip transient



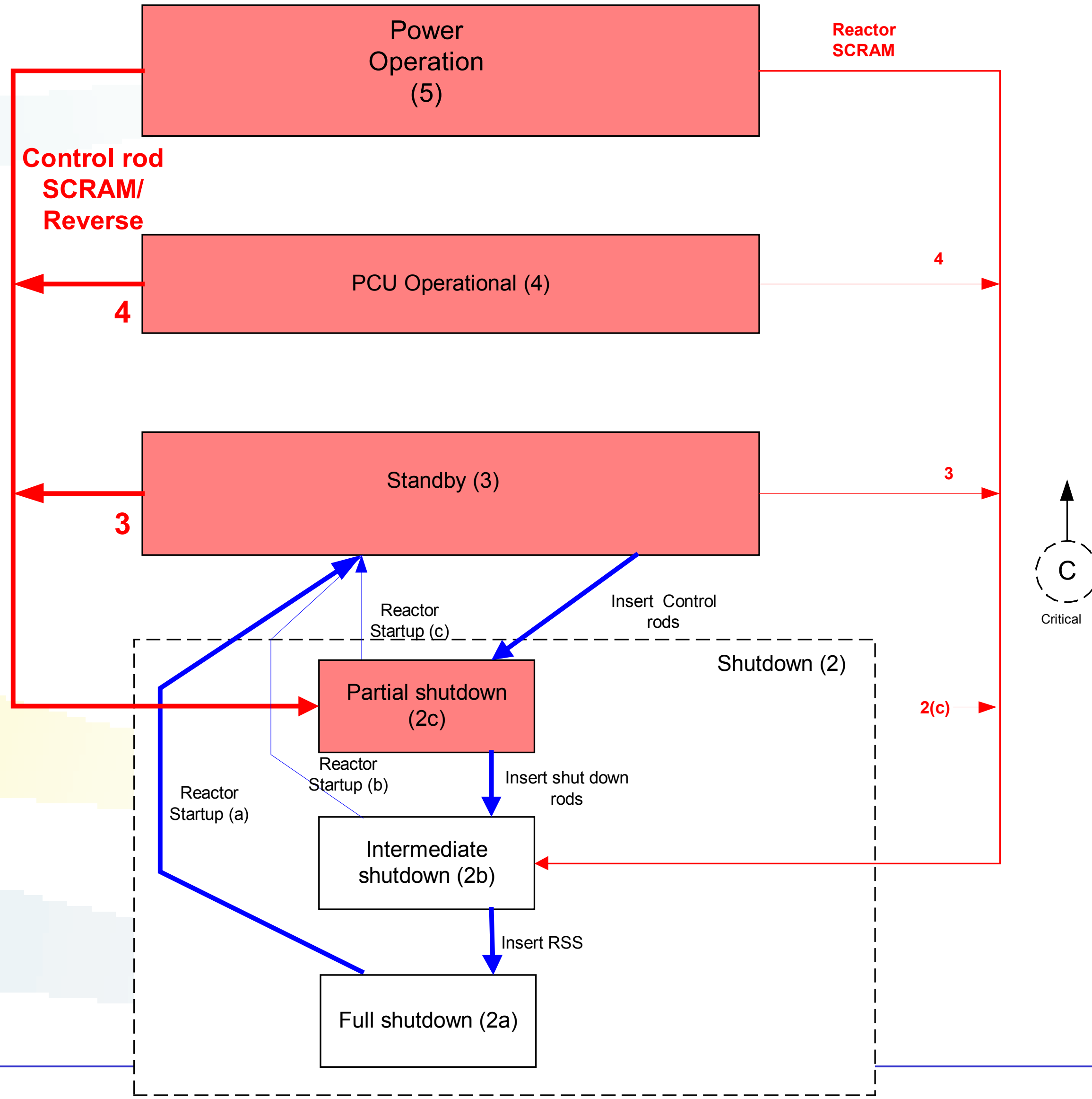
PCU trip transient

This transient occurs when there is a fault within the PCU

Stepwise procedure

- The generator breaker should trip on reverse power conditions;
- The gas cycle bypass valve (GBP) opens and remains open until the Brayton cycle has shut down completely;
- The resistor bank will decelerate the PTG;
- The SBS will be activated to keep flow through the reactor.

Control rod SCRAM / Reverse

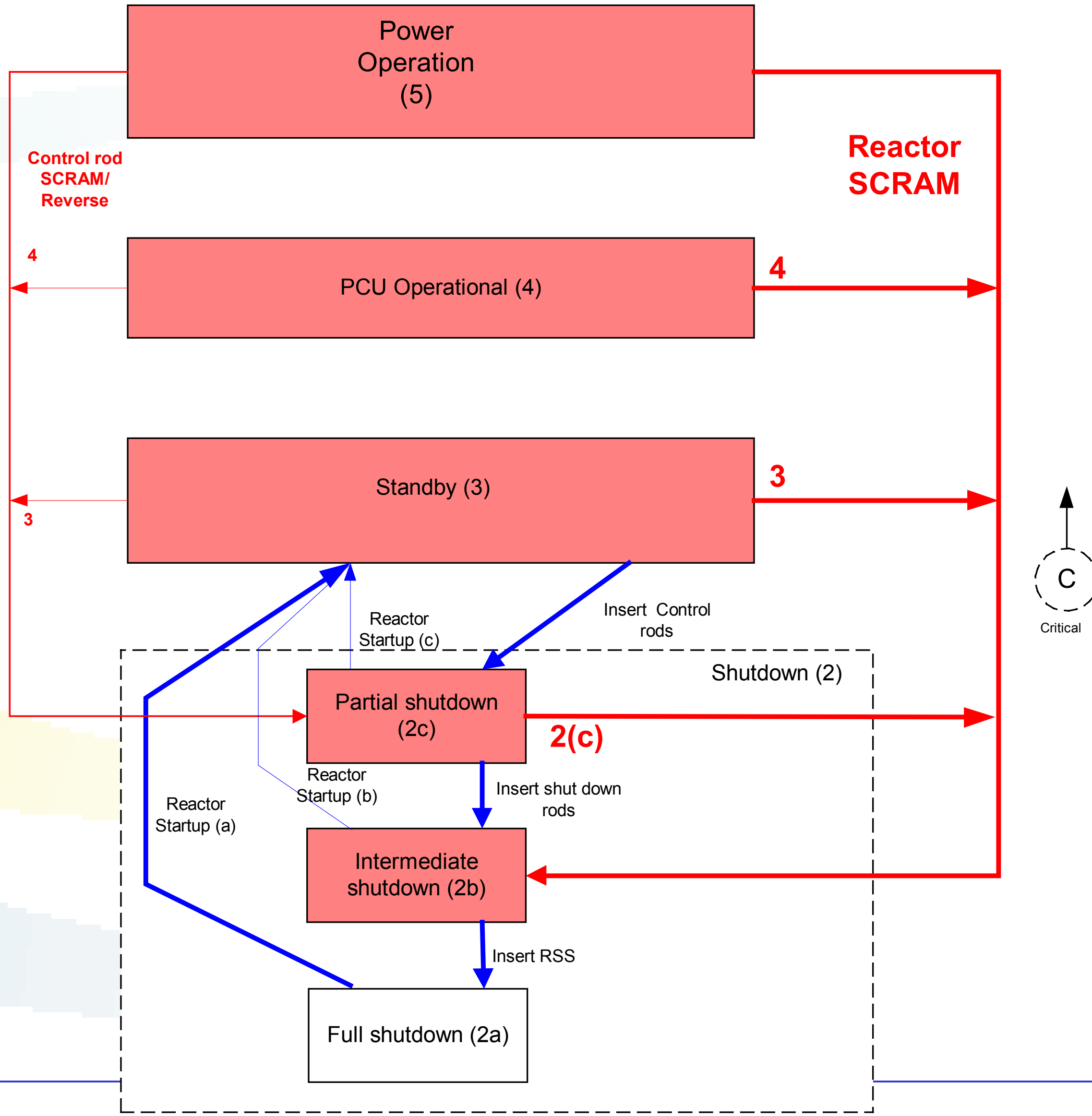


Control rod SCRAM / Reverse

Stepwise procedure

- The SBS/CCS inhibit for low ROT temperatures is activated
- A Control rod SCRAM / Reverse transient is accomplished by gravitationally fully inserting the control rods into the reactor (SCRAM) or fully inserting them in a controlled manner using the motor drives (Reverse);
- A controlled shutdown of the PCU will take place with the operation of the LPB and HPB valves.
- The generator breaker will trip on reverse power conditions
- The resistor bank will decelerate the PTG
- The SBS will be started and the ROT control will be passed from the ROT reactivity controller to the ROT decay heat controller.

Reactor SCRAM



Reactor SCRAM

PBMR

Stepwise procedure

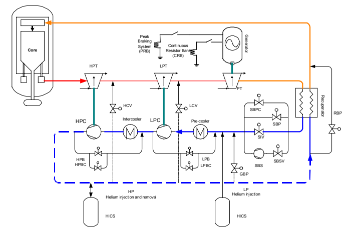
- The SBS/CCS inhibit for low ROT temperatures is activated
- The shutdown and control rods are gravitationally fully inserted into the reactor;
- The gas cycle bypass valve (GBP) will be opened and will remain open until the Brayton cycle has shut down completely.
- The GBP causes the speeds and the power of the turbo units to be reduced.
- The generator breaker will trip on reverse power conditions;
- The resistor bank will decelerate the PTG
- The SBS will be started and the ROT control will be passed from the ROT reactivity controller to the ROT decay heat controller.

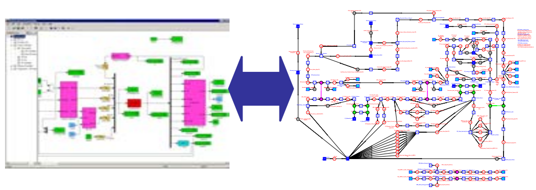
Conclusion

The objective of the presentation was to inform and educate the NRC regarding the operation of the PBMR as well as demonstrate the application of analytical codes used to evaluate plant operation.

Conclusion

Quick overview of the PBMR Main Power System components and control functions

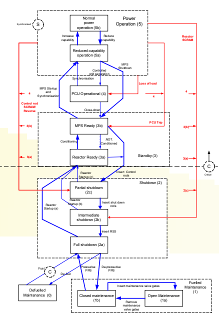




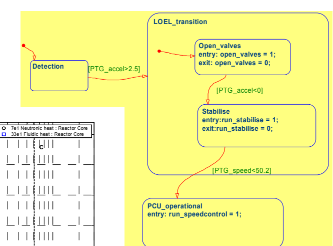
Description of Codes used by PBMR to evaluate plant operations

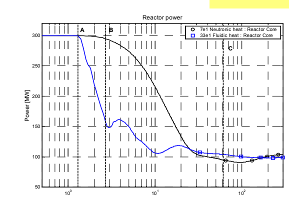
PBMR Definitions used to describe plant operations

SYMBOLOGY



Description of the Modes, States, Transitions and Transients





Examples of analyses used to evaluate plant operation