# TECHNICAL DESCRIPTION OF THE PBMR DEMONSTRATION POWER PLANT

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## ABSTRACT

Detail technical description of the Pebble Bed Modular Reactor (PBMR) Demonstration Power Plant (DPP).

## CONFIGURATION CONTROL

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## ABBREVIATIONS

This list contains the abbreviations used in this document.

| Abbreviation or Acronym | Definition |
|---|---|
| ac | alternating current |
| ACC | Auxiliary Cooling Circuit |
| ACP | Access Control Point |
| ACS | Active Cooling System |
| AEPS | Auxiliary Electrical Power System |
| AGS | Auxiliary Gas Subsystem |
| AHU | Air Handling Unit |
| ALARA | As Low As Reasonably Achievable |
| AMS | Activity Measurement System |
| AMSL | Above Mean Sea Level |
| ANSI | American National Standards Institute |
| AS | Automation System |
| ASME | American Society of Mechanical Engineers |
| AVR | Arbeitsgemeinschaft Versuchsreaktor (German for Jointly-operated Prototype Reactor) |
| BAC | Burn-up Analysis Computer |
| BACS | Bearing Auxiliary Cooling System |
| BDBA | Beyond Design Basis Accident |
| BISO | Binary Coated Particle (fuel particle with two coatings of PyC) |
| Bq | Becquerel |
| BUMS | Burn-up Measurement System |
| C&I | Control and Instrumentation |
| CAS | Compressed Air System |
| CB | Core Barrel |
| CBCS | Core Barrel Conditioning System |
| CBCSV | Core Barrel Conditioning System Vessel |
| CBSS | Core Barrel Support Structure |
| CCA | Core Ceramic Assembly |
| CCS | Core Conditioning System |
| CCSV | Core Conditioning System Vessel |
| CFR | Code of Federal Regulations |
| CFRC | Carbon Fibre Reinforced Composites |
| CLS | Core Loading Subsystem |
| CRB | Controlled Resistor Bank |
| CRD | Control Rod Drive |
| CRDM | Control Rod Drive Mechanism |
| CRS | Control Rod Scram |
| CS | Core Structures |
| CSC | Core Structure Ceramics |
| CSRS | Core Structure Replacement System |
| CUD | Core Unloading Device |
| CW | Cooling Water |
| CWT | Cooling Water Temperature (Pre-cooler/Intercooler inlet water temperature) |

| Abbreviation or Acronym | Definition |
|---|---|
| DBA | Design Basis Accident |
| dc | direct current |
| DFC | Depressurized Forced Cooling |
| DGBP | Diverse Gas Bypass Control Valve |
| DGS | Dry Gas Seal |
| DiD | Defence in Depth |
| DiD/D | Defence in Depth/Diversity |
| DLOFC | Depressurized Loss of Forced Cooling |
| DPP | Demonstration Power Plant |
| DS | Decontamination System |
| DSIV | Double Seat Isolation Valve |
| DSP | Digital Signal Processor |
| DSRS | Dry Gas Seal Supply and Recovery System |
| DWS | Demineralized Water System |
| ECP | Engineering Change Proposal |
| EHS | Equipment Handling System |
| EIA | Environmental Impact Assessment |
| EMB | Electromagnetic Bearing |
| EMC | Electromagnetic Compatibility |
| EMI | Electromagnetic Interference |
| EMP | Environmental Management Plan |
| EPCC | Equipment Protection Cooling Circuit |
| EPS | Equipment Protection System |
| FCS | Fuel Handling Control Subsystem |
| FHSS | Fuel Handling and Storage System |
| FPS | Fire Protection System |
| FPY | Full Power Years |
| FS | Fuel Sphere |
| FZJ | Forschungszentrum Jülich GmbH (Jülich Research Centre) |
| GBP | Gas Cycle Bypass Valve |
| GBPC | Gas Cycle Bypass Control Valve |
| GCP | Gas Cycle Pipes |
| GCPS | Gas Cycle Pipe System |
| GCS | Gas Conditioning System |
| GCV | Gas Cycle Valves |
| GCVS | Gas Cycle Valves System |
| GRP | Glass Reinforced Polyester |
| GS | Generator System |
| HEPA | High Efficiency Particulate Air Filters |
| HEU | Highly Enriched Uranium |
| HFE | Human Factors Engineering |
| HICS | Helium Inventory Control System |
| HLW | High-level Waste |
| HLWS | High-level Waste System |
| HMS | Helium Make-up System |
| HP | High Pressure |

| Abbreviation or Acronym | Definition |
|---|---|
| HPB | Helium Pressure Boundary |
| HPC | High-pressure Compressor |
| HPGe | High Purity Germanium |
| HPS | Helium Purification System |
| HPTU | High-pressure Turbo-unit |
| HPTV | High-pressure Turbo Vessel |
| HSI | Human-Systems Interface |
| HTR | High-temperature Reactor |
| HVAC | Heating, Ventilation and Air-conditioning |
| IAEA | International Atomic Energy Agency |
| ICC | Intercooler Cooling Circuit |
| ICS | Inventory Control System |
| ID | Internal Diameter |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronics Engineers, Inc. |
| ILTI | Inner Low Temperature Isotropic |
| IP | Internet Protocol |
| ISA | Instrumentation, Systems and Automation Society |
| ISI | In-service Inspection |
| IV | Intercooler Vessel |
| KNPS | Koeberg Nuclear Power Station |
| KTA | Kerntechnische Ausschuss |
| LBE | Licensing Basis Event |
| LCV | Low-pressure Coolant Valve |
| LEU | Low-enriched Uranium |
| LILW | Low- and Intermediate-level Waste |
| LOFC | Loss of Forced Cooling |
| LP | Low Pressure |
| LPB | Low-pressure Compressor Bypass |
| LPC | Low-pressure Compressor |
| LRU | Line-replaceable Unit |
| LV | Low Voltage |
| LWR | Light Water Reactor |
| LWS | Liquid Waste System |
| MCR | Maximum Continuous Rating |
| MCRI | Maximum Continuous Rating Inventory |
| MEPS | Main Electrical Power System |
| MHSS | Main Heat Sink System |
| MM | Multi-module |
| MPS | Main Power System |
| MPS-PB | Main Power System Pressure Boundary |
| MSS | Main Support System |
| MV | Medium Voltage |
| NFPA | National Fire Prevention Association |
| NPP | Nuclear Power Plant |
| NRC | Nuclear Regulatory Commission (USA) |

| Abbreviation or Acronym | Definition |
|---|---|
| NRV | Non-return Valve |
| NSS | Neutron Source System |
| NUREG | Nuclear Regulations (from NRC) |
| OCS | Operational Control System |
| OD | Outside Diameter |
| OEM | Original Equipment Manufacturer |
| OHSA | Occupational Health and Safety Act |
| OLTI | Outer Low Temperature Isotropic |
| p.a. | per annum |
| PB | Pressure Boundary |
| PBMR | Pebble Bed Modular Reactor |
| PCC | Pre-cooler Cooling Circuit |
| PCU | Power Conversion Unit |
| PCUPV | Power Conversion Unit Pressure Vessel |
| PCV | Pre-cooler Vessel |
| PEH | PLICS Electric Heater |
| PEI | Post-event Instrumentation |
| PEMRR | Post-Event Monitoring and Recovery Room |
| PFD | Process Flow Diagram |
| PGA | Peak Ground Acceleration |
| PIDP | PBMR Integrated Design Process |
| PIE | Post-irradiation Evaluation |
| PLC | Programmable Logic Controller |
| PLICS | Primary Loop Initial Clean-up System |
| PLOFC | Pressurized Loss of Forced Cooling |
| PP | Power Plant |
| PPB | Primary Pressure Boundary |
| PPRDMP | Post Pressure Relief Damper |
| PRS | Pressure Relief System |
| PT | Power Turbine |
| PTV | Power Turbine Vessel |
| PVS | PLICS Vacuum Subsystem |
| PWR | Pressurized Water Reactor |
| PWS | Potable Water System |
| QA | Quality Assurance |
| QAP | Quality Assurance Procedure |
| RBP | Recuperator Bypass Valve |
| RC | Reactor Cavity |
| RCCS | Reactor Cavity Cooling System |
| RCS | Reactivity Control System |
| RCSS | Reactivity Control and Shutdown System |
| RCV | Recuperator Vessel |
| ROT | Reactor Outlet Temperature |
| rpm | revolutions per minute |
| RPS | Reactor Protection System |
| RPV | Reactor Pressure Vessel |

| Abbreviation or Acronym | Definition |
|---|---|
| RPVCS | Reactor Pressure Vessel Conditioning System |
| RS | Reactor Scram |
| RSS | Reserve Shutdown System |
| RU | Reactor Unit |
| RUCS | Reactor Unit Conditioning System |
| SABS | South African Bureau of Standards |
| SAR | Safety Analysis Report |
| SAS | Small Absorber Sphere |
| SCS | Sphere Circulation Subsystem |
| SD | Specialized Doorways |
| SDS | Sphere Decommissioning Subsystem |
| SEC | Koeberg Essential Services Water System |
| SFC | Spent Fuel Cooling |
| SFC | Static Frequency Converter |
| SiC | Silicon Carbide |
| SMS | Seismic Monitoring System |
| SRS | Sphere Replenishment Subsystem |
| SS | Sample Sphere |
| SSC | Structures, Systems and Components |
| SSE | Safe Shutdown Earthquake |
| SSS | Sphere Storage Subsystem |
| ST | Special Tools |
| TBD | To be Determined |
| TGS | Turbo-generator Set |
| THTR | Thorium High-temperature Reactor |
| TRISO | Triple Coated Particle |
| U | Uranium |
| u | Atomic Mass Unit |
| UFT | Used Fuel Tank |
| UPS | Uninterruptible Power Supply |
| USA | United States of America |
| WER | Westinghouse Reaktor GmbH |
| WHS | Waste Handling System |
| WHSS | Waste Handling and Storage System |

# 1. SCOPE

This document provides a technical description of the performance and interfaces of the Pebble Bed Modular Reactor (PBMR) Demonstration Power Plant (DPP) up to the interface with the high voltage generator transformer's bushings, from where it forms part of the Client's electrical network.

Off-site waste disposal, the fuel and graphite manufacturing plant and the final spent fuel storage are not covered in this document.

## 1.1 DOCUMENT OVERVIEW

The document covers the following aspects of the PBMR DPP:

- **Power Plant** : Operations, characteristics, layout, maintenance concept and high-level specification.
- **Safety Features** : Safety principles.
- **Fuel** : Fuel design and operating envelope.
- **Plant Description** : Descriptions, functional overviews, operating principles and general characteristics of the major equipment groupings.
- **Maintenance** : Removal and replacement of major components.
- **Site Interfaces** : Interfaces between the DPP on the Koeberg site.

# 2. POWER PLANT

## 2.1 PLANT IDENTIFICATION

The PBMR Demonstration Power Plant (DPP) consists of a single module incorporating all the support and auxiliary systems required for operation and maintenance. As the name implies, it is designed to demonstrate physical conformance to design requirements.

It should be noted that the DPP is NOT a typical module of a multi-module power plant. In a multi-module power plant, some support and auxiliary systems are shared between modules, whereas in the DPP configuration, all systems are incorporated or allocated to the DPP module.

## 2.2 PLANT OVERVIEW

### 2.2.1 System Diagram

Figure 1 indicates the highest level of systems identified in the PBMR DPP.

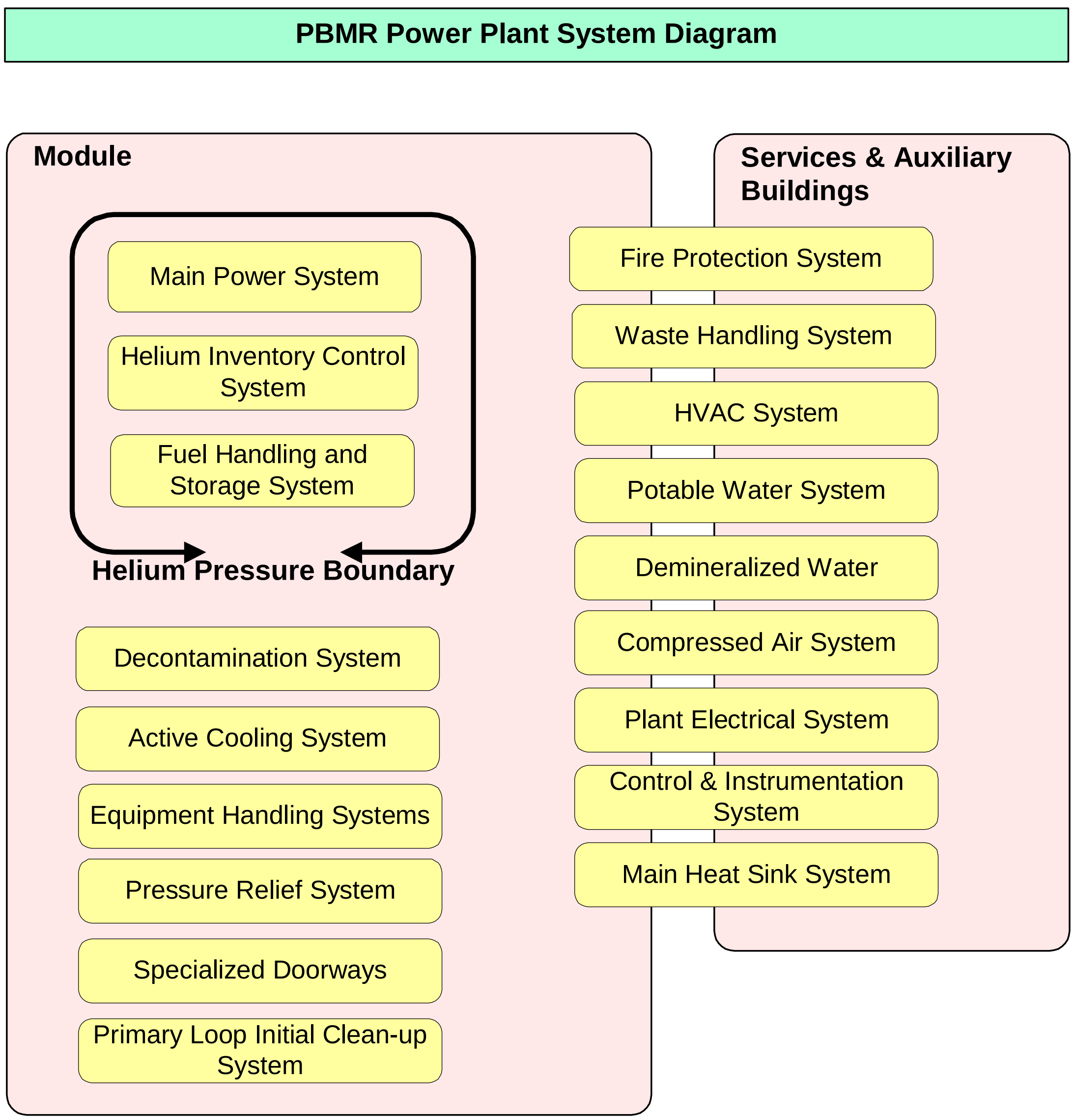



**Figure 1: PBMR Demonstration Power Plant Diagram**

### 2.2.2 Technology Base – Overview

The PBMR module consists of a graphite-moderated, helium-cooled reactor in which the gas is heated by the nuclear fission process, and a direct cycle power conversion unit in which the heat is converted into electrical energy by means of a turbine-driven generator.

The PBMR reactor core is based on the high-temperature gas-cooled reactor technology which was originally developed in Germany. This implies the use of spherical fuel elements, referred to as pebbles, which are in size and physical characteristics the same as the fuel which was developed for the German High-temperature Reactor (HTR) programmes. However, instead of using the German power conversion configuration, which was a gas-to-steam cycle heat exchanger, the PBMR uses a direct cycle power conversion configuration.

### 2.2.3 Brayton Cycle Description

The PBMR Main Power System (MPS) utilizes a recuperative Brayton cycle with helium as the working fluid. A schematic layout of the cycle is shown in Figure 2 while the temperature-entropy diagram of the cycle is shown in Figure 3.

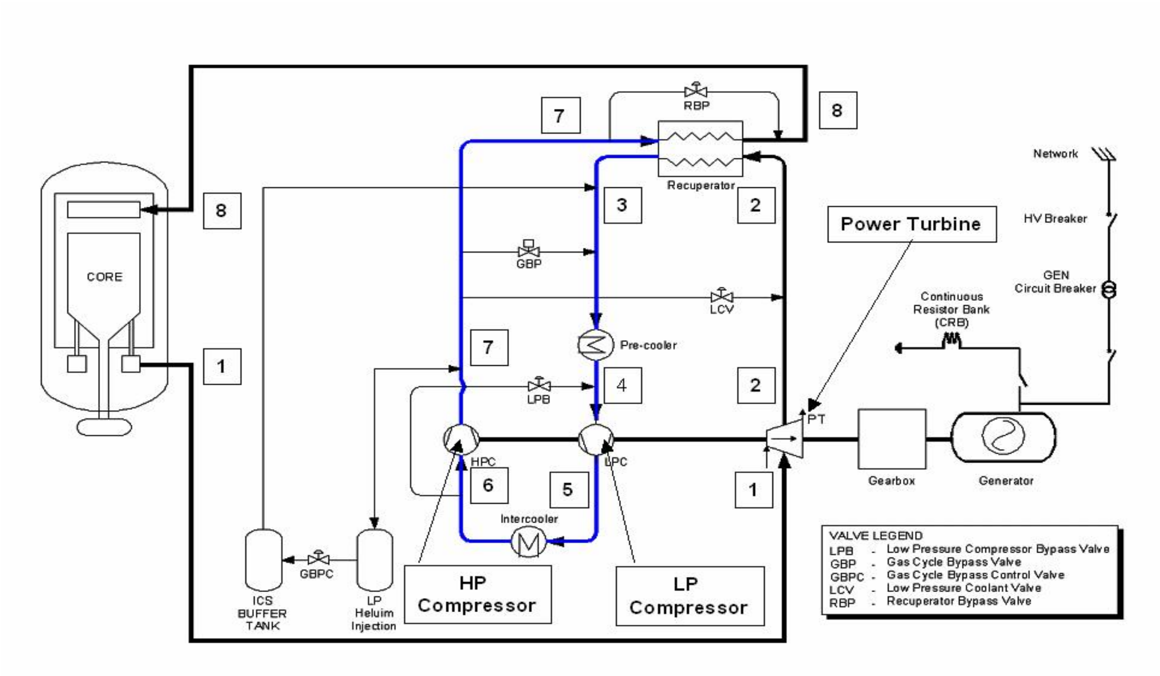



**Figure 2: Layout of the PBMR Recuperative Brayton Cycle**

With reference to Figure 2, starting at state 4, helium at a relatively low pressure and temperature (4) is compressed by a Low-pressure Compressor (LPC) to an intermediate pressure (5), after which it is cooled in an intercooler to state 6. The intercooling between the two multistage compressors improves the overall cycle efficiency. The High-pressure Compressor (HPC) then compresses the helium to state 7. From states 7 to 8, the helium is preheated in the recuperator before entering the reactor that heats the helium to state 1. After the reactor, the hot high-pressure helium is expanded in the Power Turbine (PT), directly driving the LPC and HPC, to state 2. The excess power is used to drive the generator via the gearbox. From states 2 to 3, the still hot helium is cooled in the recuperator, after which it is further cooled in the pre-cooler to state 4. This completes the cycle. The heat rejected from states 2 to 3 is equal to the heat transferred to the helium from states 7 to 8. The recuperator uses heat from the cooling process that would otherwise be lost to the main heat sink to heat the gas before it enters the reactor, thereby reducing the heating demand on the reactor and increasing the overall plant efficiency.

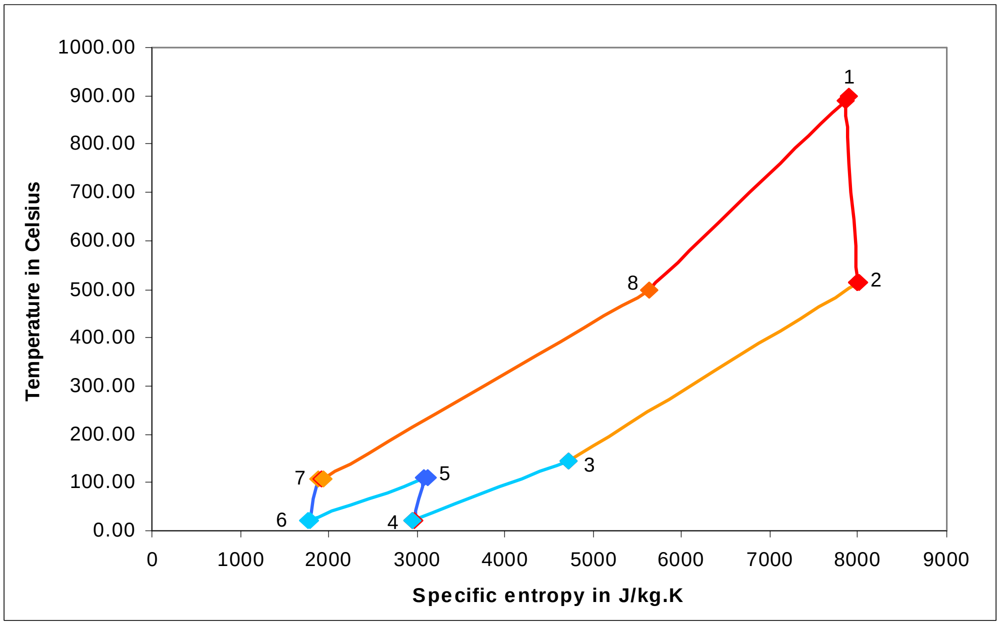



**Figure 3: Temperature-Entropy Diagram of the PBMR Recuperative Brayton Cycle**

### 2.2.4 Plant Design Envelope

The design envelope is a set of enveloping values that design parameters assume or are bounded by, and which define the scope of what is possible or allowed for the plant design.

The design parameters listed in Table 1 define the design envelope:

**Table 1: Plant Parameters Defining the Design Envelope**

| Design Parameters | Enveloping Value(s) | Comment |
|---|---|---|
| **Plant location** | | |
| Location | On Koeberg site | |
| PBMR building size L x W x H | | |
| • Nuclear Island | 74 m x 37 m x 63 m, 41 m above ground | |
| • Conventional Island (L x W) | 37 m x 35.5 m | |
| Site footprint | 37 000 $m^2$ | |
| Site parameters | Seismic, meteorological, hydrological, geological | |
| Emergency planning zone | None, falls inside Koeberg zone | |
| Exclusion area boundary | < 400 m for other sites | |
| **Construction** | | |
| Reactor Building | Robust protective enclosure with controllable radionuclide retention function | Designed to protect the reactor and maintain core geometry, not to retain pressure. Instead, designed to vent internal pressure and reclose. |
| Safe Shutdown Earthquake | 0.4 g PGA horizontal for MPS design<br>0.27 g PGA horizontal for Balance of Plant (BOP) | |

| Design Parameters | Enveloping Value(s) | | | Comment |
|---|---|---|---|---|
| **Main vessels – size, mass** | | | | |
| | ID top & bottom (m) | Overall height (m) | Total mass (t) | |
| Reactor vessel | 6.2 | 30.4 | 1 016 | All dimensions are indication only, since vessels are composite bodies with stepped diameters, welded nozzles, end shells, flanges, etc. |
| **Power** | | | | |
| Total neutronic power (Pn) | 400 MWt | | | |
| Maximum Continuous Rating (MCR) | 175 MWe | | | |
| Continuous stable power range | 40% to 100% of MCR | | | Only during Mode 5(b) normal power operation. |
| | 20% to 100% of MCR | | | Possible steady-state operation. |
| Ramp rate 100 – 40 – 100% | 10% of MCR per minute | | | |
| Load rejection without reactor trip | 100%/75% of MCR | | | With/without resistor bank present. |
| **Power conversion** | | | | |
| Power conversion | Single-shaft Brayton cycle with helium as coolant | | | Shaft is horizontal |
| Generator placement | In conventional island | | | |
| **Core** | | | | |
| Core shape | Annular cylinder around near-solid central graphite reflector | | | |
| Core annulus x average height | [ ][b] | | | |
| **Fuel** | | | | |
| Fuel type | TRISO coated with $UO_2$ particle | | | |
| Fuel enrichment<br>• start up core<br>• normal operation | <br>4.9% to 5.9%<br>9.6% | | | |
| Fuel configuration | Coated particles in 60 mm diameter graphite spheres | | | |
| Uranium content per sphere | 9 g U per sphere | | | |
| Fuel spheres (steady state) | Approx. 450 000 at 60 mm dia | | | |
| Fuel burn-up | Approx. 92 000 MWd/t at 9.6% enrichment | | | |
| Pebble centre temperature<br>• normal operation<br>Fuel loading | 1 130 °C maximum<br><br>Continuous, six passes (average) | | | |
| Fuel entry | Three loading points from Fuel Handling and Storage System (FHSS) | | | |
| **Reactivity control** | | | | |
| Shutdown margin at cold (100 °C) | ≥ 1%Δk | | | |
| **Standby power** | | | | |
| Alternative supply | 11 kV, 10 MW | | | Duyne substation. |
| Main standby diesel generators | 2 x 500 kW, 11 kV | | | |
| Shutdown room standby diesel generators | 2 x 25 kW | | | |

| Design Parameters | Enveloping Value(s) | Comment |
|---|---|---|
| **Primary circuit – MPS Pressure Boundary (MPS-PB)** | | |
| Maximum operating pressure at 100% MCR | 9.0 MPa | |
| Design leak rate of MPS | 0.1%/day of MPS inventory | |
| **Secondary circuit – closed loop cooling** | | |
| Coolant | Demineralized water | Closed circuit. |
| **Tertiary circuit – Main Heat Sink System (MHSS)** | | |
| Coolant | Sea water | |
| Nominal flow rate | 4 000 kg/s | |
| Inlet temperature | < 25 °C | Shares Koeberg Cooling Water (CW) inlet wells. |
| Heat exchange capacity | > 230 MW | |
| Outlet temperature | < 45 °C | |
| Maximum temperature rise in outlet channel | < 1.5 °C | Shares Koeberg outlet channel. |
| **Potable water** | | |
| Storage capacity | 2 270 $m^3$ | Fire protection system reservoirs. |
| Consumption | 200 $m^3$ to 250 $m^3$/month | Used by demin plant, sanitary waste. |
| **Staff** | | |
| During construction | Estimated maximum 800 | |
| Normal operation | Estimated 105 | |
| During outage | Estimated 250 | |
| **Operation and maintenance** | | |
| Plant operating lifetime | 40 years | |
| Availability target | ≥ 95% | |
| General overhauls | 30 to 50 days scheduled per 6 years | |
| **Operational radiological releases to members of the public at 400 m boundary** | | |
| Liquid and gaseous release | < 20 µSv p.a. | Monitored release. |
| **Radiological releases to members of the public under accident conditions** | | |
| Gaseous release | < 50 mSv | |

### 2.2.5 Pebble Bed Modular Reactor Site

#### 2.2.5.1 Layout description

The PBMR Nuclear Island is located [ ][sri] of the Koeberg Nuclear Power Station (KNPS) Nuclear Island. These distances are measured between the centre of the Nuclear Island and the centre line of the Reactor Pressure Vessel (RPV) in the Reactor Building.

The ground floor of the Reactor Building is at an elevation of +13.700 m Above Mean Sea Level (AMSL) while the elevation of the natural ground level at the centre line of the RPV is at an elevation +11.35 m AMSL. The underside of the Reactor Building is founded at a depth of 25.5 m below the ground floor at an elevation of -11.800 m AMSL.

The elevation of the terrace is at level +13.50 m AMSL, and is sloped away from the Reactor Building to prevent any flood waters from entering the Reactor Building.

The roof of the Reactor Building (excluding the parapet walls and lift room) is 41 m above the ground floor.

The primary features of this layout include the following:

- The excavation for the Reactor Building is contained within the boundaries of the emergency road and the inner security fence of the KNPS.
- Minimum upgrading of existing roads is required, none of which are within the KNPS inner security fence.
- Heavy loads are not transported past the KNPS inner security fence.
- Overhead transmission line to Koeberg 132 kV substation is possible.
- Space is available close to the construction site for the Contractor’s yards.
- Changes to the footprints of the Reactor, Services and Auxiliary Buildings can be accommodated.
- The PBMR can easily be incorporated into the KNPS security area prior to fuel loading.

A Generator House supports the generator and allied electrical and auxiliary plant. The Generator House is constructed adjacent to the northern wall of the Reactor Building.

The Services Building comprises a single-storey building located on the site 20 m to the east of the Reactor Building. Some 13 m to the north of the Services Building is the Ancillary Building, also a single-storey building. The Cooling Water (CW) plantroom is located on the north-west corner of the terrace, and the Admin Offices on the south-west corner.

The transformers are situated to the north of the Generator House. These are not enclosed, but are separated by fire walls where required, and provided with suitable bund walls to prevent the spillage of oil and fire retardants outside the bund area.

Heavy-duty, blacktop surface roads are provided on the site with a width of 8.0 m and radii of curves varying between 30 m and 50 m to allow manoeuvring of large transporters. All existing access routes are evaluated for loading, height restrictions and turning radius. Roads on the terrace for traffic related to normal operation of the plant vary between 4 m and 6 m, depending on the access requirements. Loading bays are provided in the Reactor Building and the Generator House. Off-loading and material handling zones are provided at the Services and Auxiliary Buildings. Limited internal parking areas are provided for vehicles adjacent to the Admin Offices.

The clean and dirty stormwater systems are separated on the site. The clean water system diverts the stormwater off the terrace. Dirty water (i.e. water polluted with oils but not contaminated with radioactive material) is routed to a lined holding area to the west of the terrace, where the oils are separated from the water. Waste water from the Waste Handling and Storage System (WHSS) (i.e. water which contains radioactive elements) is routed to the KNPS CW outfall via the Main Heat Sink System (MHSS) ducts.

#### 2.2.5.2 Site requirements

The site layout is required to accommodate access to the PBMR DPP without interfering with the access and day-to-day activities of the KNPS. The level of security applied to the PBMR site shall be at least equal to that applied to the Koeberg Power Plant (PP) once fuel has been delivered to the PBMR site.

The site accommodates the PBMR DPP without affecting the nuclear safety and licensing of the KNPS.

The site layout minimizes the consequent effects of PBMR design basis and beyond design basis external and internal events.

The construction of the earthworks on the site must ensure stability of the plant under the identified design basis and beyond design basis external and internal events. This specifically applies to seismic events.

Environmental Management Plan (EMP). The EMP ensures that the significant environmental issues identified during the Environmental Impact Assessment (EIA) are appropriately addressed.

[Withheld on the basis of it being “Security-Related Information”]

## 2.3 PLANT MAJOR COMPONENT LIST

Table 2 provides a breakdown of the plant hardware in a parent-to-child relationship. The breakdown levels are provided to indicate this relationship.

**Table 2: Demonstration Power Plant Hardware Breakdown Structure**

| Level | Hardware Description |
|---|---|
| 1 | PBMR Demonstration Power Plant |
| 2 | ___PBMR Demonstration Module |
| 3 | ______Main Power System |
| 4 | _________Reactor Unit System |
| 5 | ____________Fuel Core |
| 5 | ____________Reactor Core Structure |
| 5 | ____________Reactivity Control and Shutdown System |
| 4 | _________Power Conversion Unit |
| 4 | _________Core Conditioning System |
| 4 | _________Core Barrel Conditioning System |
| 3 | ______Helium Inventory Control System |

| Level | Hardware Description |
|---|---|
| 3 | ______Fuel Handling and Storage System |
| 3 | ______Active Cooling System |
| 4 | _________Main Cooling Circuit |
| 4 | _________Auxiliary Cooling Circuit |
| 3 | ______Reactor Cavity Cooling System |
| 3 | ______Module Heating, Ventilation and Air-conditioning (HVAC) System |
| 3 | ______Compressed Air System |
| 3 | ______Primary Loop Initial Clean-up |
| 3 | ______Special Tools |
| 3 | ______Equipment Handling System |
| 3 | ______Module Civil and Building System |
| 3 | ______Specialized Doorways |
| 3 | ______Pressure Release System |
| 3 | ______Module Decontamination System |
| 3 | ______Module Waste Handling System |
| 3 | ______Module Fire Protection System |
| 2 | ___Control and Instrumentation Systems |
| 3 | ______Automation System |
| 4 | _________Control Rooms |
| 4 | _________Reactor Protection System |
| 4 | _________Post-event Instrumentation |
| 4 | _________Equipment Protection System |
| 4 | _________Operational Control System |
| 3 | ______Radiation Monitoring System |
| 3 | ______Plant Communication System |
| 3 | ______Seismic Monitoring System |
| 3 | ______KNPS Meteorological Interface |
| 3 | ______Access Control & Security |
| 2 | ___Plant Electrical Systems |
| 3 | ______Main Electrical Power System |
| 3 | ______Auxiliary Electrical Power System |
| 2 | ___Plant High Voltage Yard |
| 2 | ___Main Heat Sink System |
| 2 | ___Site Civil Infrastructure |
| 2 | ___PP Services Facility |
| 2 | ___Plant Auxiliary Buildings |

# 3. MAIN POWER SYSTEM

The Main Power System (MPS) of the PBMR module consists of the following subsystems:

a. Reactor Unit (RU)
   - Core
   - Core Structures (CS)
   - Reactivity Control and Shutdown System (RCSS) (which consists of a control rod system and a Small Absorber Sphere system)

b. Power Conversion Unit (PCU)
   - Turbo-generator Set (TGS)
   - Recuperator
   - Pre-cooler
   - Intercooler
   - Gas Cycle Pipe System (GCPS)
   - Gas Cycle Valves System (GCVS)

c. Pressure Boundary (PB) System
   - Reactor Pressure Vessel (RPV)
   - PCU Pressure Vessel (PCUPV)
   - Reactor Unit Conditioning System (RUCS) Pressure Vessel
   - Pressure Boundary (PB) Support System

d. Main Support Systems (MSS)
   - Core Conditioning System (CCS)
   - Core Barrel Conditioning System (CBCS)
   - Helium Inventory Control System (HICS)

### 3.1 REACTOR UNIT

The Reactor Unit (RU) design is based on the pebble bed high-temperature, gas-cooled reactor technology, which was developed in Germany. Figure 4 shows the general arrangement of the RU integrated into the RPV.

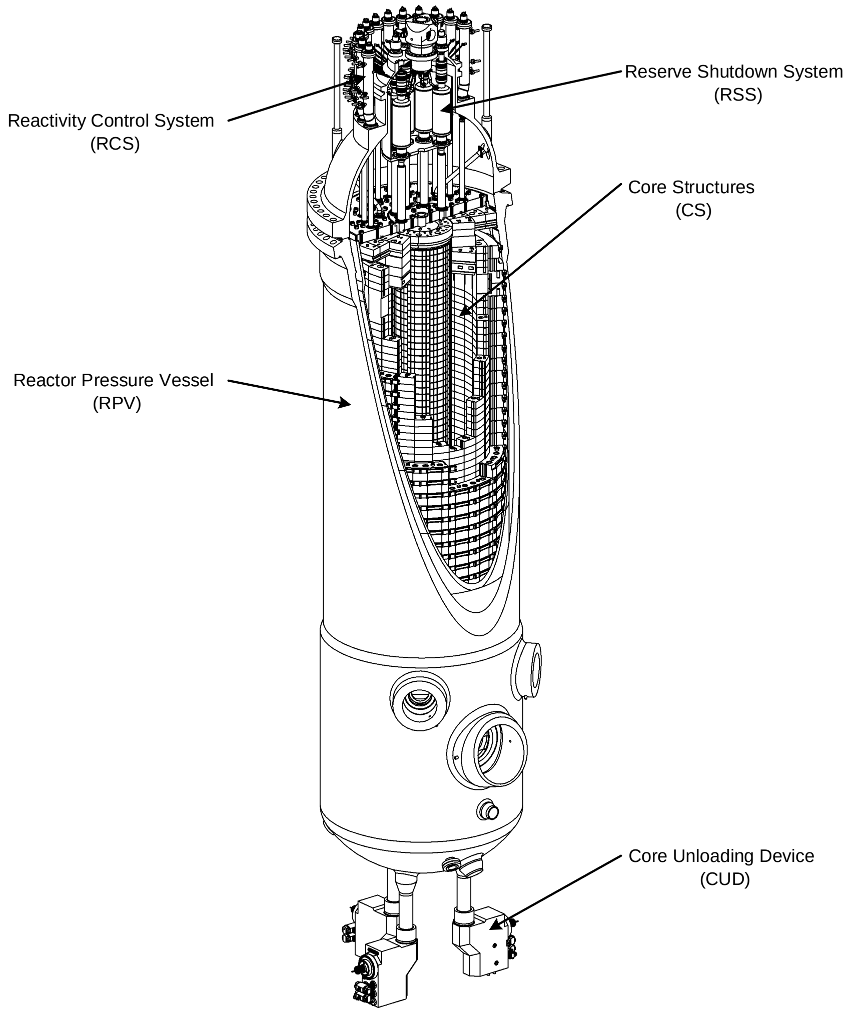



**Figure 4: General Arrangement of the Reactor Unit including the Reactor Pressure Vessel**

### 3.1.1 Core Structures

#### 3.1.1.1 Overview

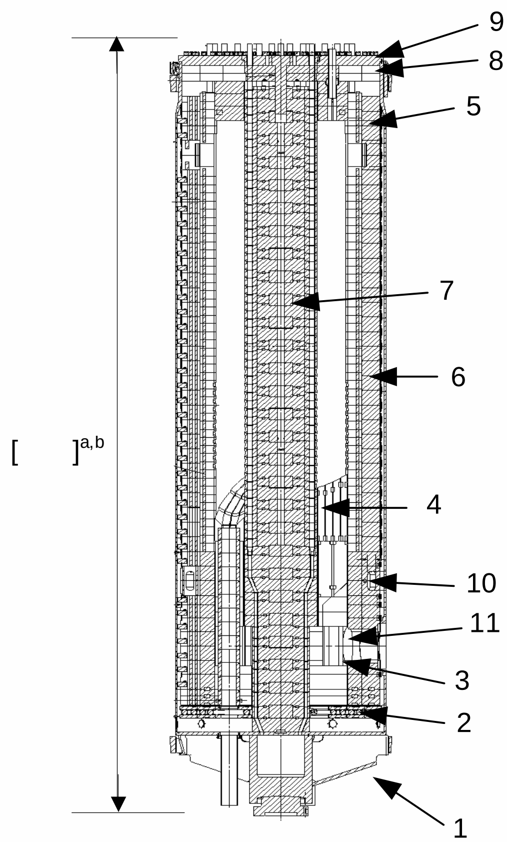
The Core Structures (CS) are also called the core internals, and they have an important role in the core neutronics design and safety analysis. The CS consist of the following:

- Graphite reflectors
- Metallic components such as the Core Barrel (CB)
- Thermal insulation

The CB Assembly consists of the metallic parts surrounding the graphite reflector blocks. The primary function of the CB Assembly is to support the graphite reflector blocks and to bear the external loads that the graphite components cannot withstand. It also acts as a thermal shield to keep the Reactor Pressure Vessel (RPV) at acceptable temperatures. The weight of the core and CS is carried by the Core Support Structure via the single bottom support, through the RPV to the building. The CB Assembly is guided at the top to keep it upright, and it has restraints at the top and the bottom to support it horizontally during a seismic event.

The Core Ceramic Assembly (CCA) consists of the reflector, the reflector restraints and the expansion compensator. The reflector consists of graphite bricks arranged to accommodate thermal and radiation induced deformations throughout the life of the reactor, while maintaining its functions. Graphite keys and dowels connect the bricks together to prevent excessive movement during abnormal events, e.g. seismic, while allowing relative movement due to thermal expansion. This also reduces leak flows.

Refer to Figure 5 for the CS components.




| Number | Component |
|---|---|
| 1 | Core support structure |
| 2 | Expansion compensator |
| 3 | Bottom reflector |
| 4 | Fuel discharge cone |
| 5 | Core barrel sides |
| 6 | Side reflector (inner and outer) |
| 7 | Centre reflector |
| 8 | Top reflector |
| 9 | Core barrel top plate |
| 10 | Main inlet plenum |
| 11 | Main outlet plenum |

**Figure 5: Core Structure Components**

### 3.1.1.2 Functions

The CS:

- Maintain a stable geometry of the core fuel. The graphite reflectors provide neutron reflection.
- Provide access borings for insertion of the control elements of both the Reactivity Control System (RCS) and Reserve Shutdown System (RSS). The requirement is that control rods and/or Small Absorber Spheres (SAS) must be able to be freely inserted or dropped into their channels by gravity. Therefore the deformation of these channels following any event must not hinder the insertion of the control rod elements.
- Ensure continued core cooling by the circulating helium in the coolant circuit. When an accident occurs and none of the Active Cooling Systems (ACS) are available, the residual heat is transferred by natural processes from the core in such a way that the maximum core fuel temperature does not exceed the allowable limit.
- Assure fuel flow.
- Limit the temperatures and the fast neutron fluence in the metallic CB and the RPV.
- Protect the RPV from the high-temperature gas in the core.
- Provide for the insertion of instrumentation and sensors on the Demonstration Power Plant (DPP).

### 3.1.1.3 Design codes

The design of the CS is based on the experience and techniques developed in the German High-temperature Reactor (HTR) programme (AVR, THTR, HTR-Modul). Therefore PBMR use Westinghouse Reaktor (WER) (former BBC) and FZJ for knowledge transfer to the PBMR design team. The PBMR design is done in accordance with internationally recognized design codes for the different components. The metallic Core Support Structures are designed in accordance with the ASME III Subsection NG and Code Case N-201-4 design codes. The graphite structures are designed in accordance with the limits in KTA 3232 (draft) ‘Regulation for the Design of the Internals of the High Temperature Reactor’. This is a design code specifically developed for graphite components during the German HTR programme.

### 3.1.1.4 Design description

Figure 6 shows the size comparison between the PBMR 400 MW CS and the CS of the HTR-Modul and the Thorium High-temperature Reactor (THTR). (A typical Light Water Reactor [LWR] CS is also added for core size comparison.) The volume of the PBMR core is large to have a low power density, and it is designed to have a large surface-to volume ratio for efficient heat transport to the heat sink external to the RPV.

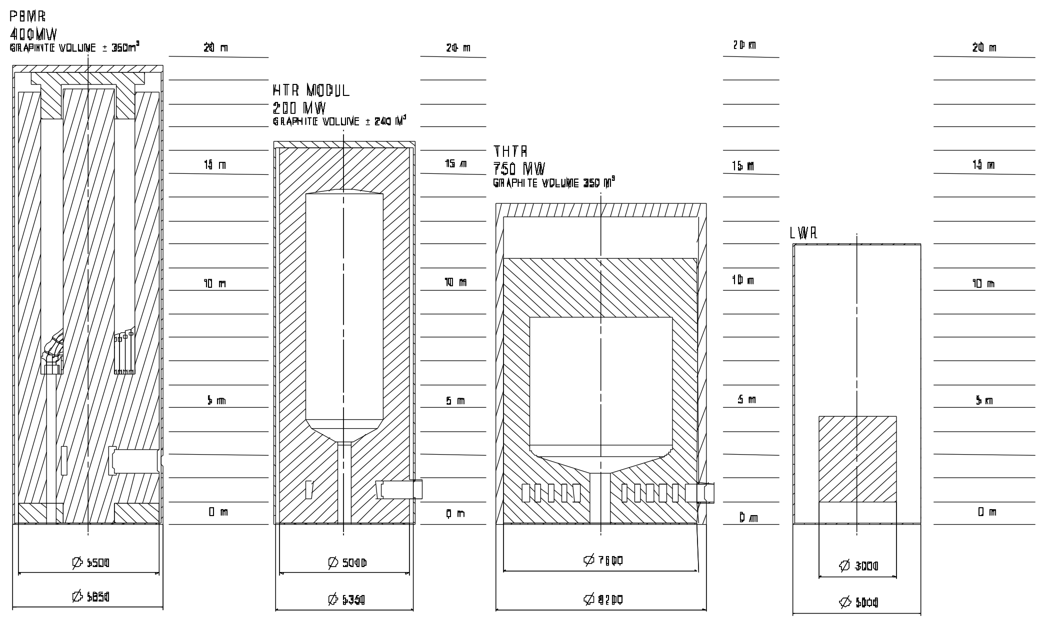



**Figure 6: Size Comparison between PBMR, HTR-Modul and THTR Core Structure Design**

#### 3.1.1.4.1 Description of ceramic components

a. Bottom reflector structure

a,b

b. Side reflector structure

a,b

Figure 7 shows the side reflector design.

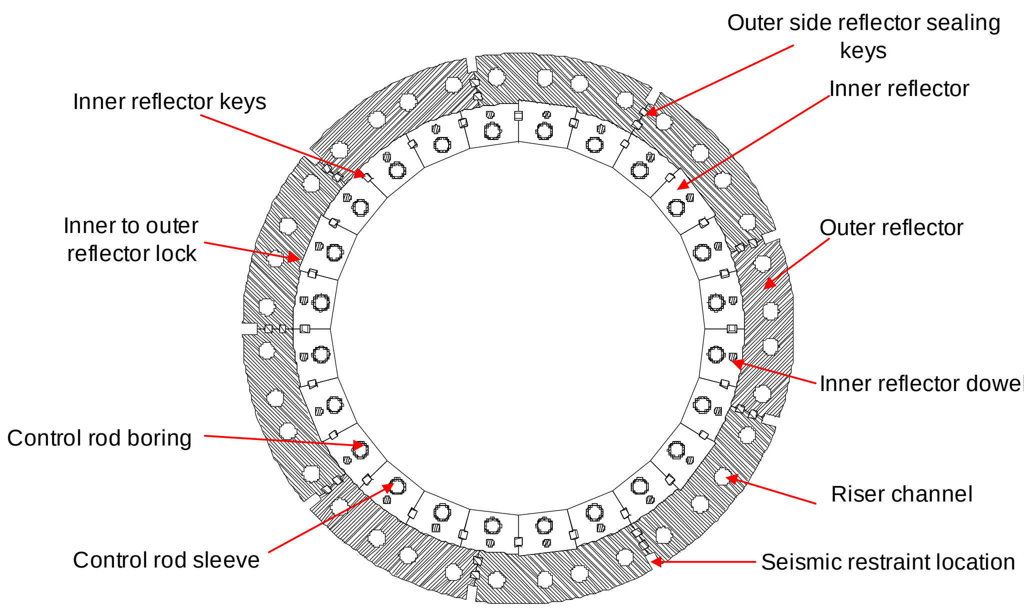



**Figure 7: Side Reflector**

c. Top reflector structure

The function of the top reflector is to provide neutron reflection and radiation shielding to the area above the top plate, as well as to thermally insulate the CB top plate from the core.

The top reflector blocks are suspended from the CB top plate by means of Carbon Fibre Reinforced Composites (CFRC) tie rods.

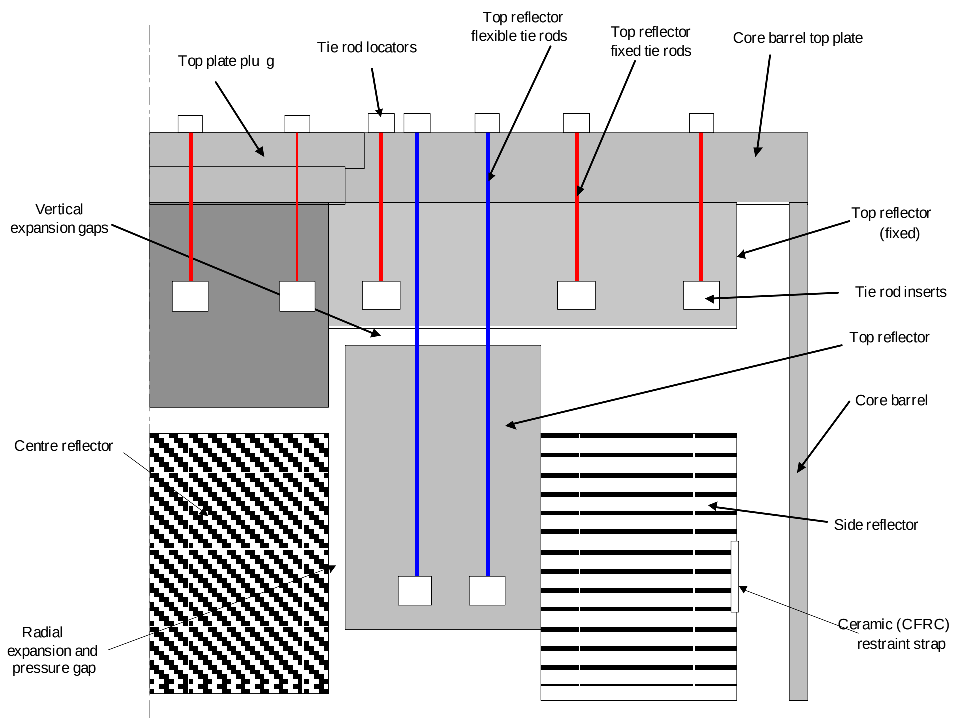



**Figure 8: Top Reflector Design**

d. Central reflector structure

The central reflector is split into the inner and outer sections. Because the outer 400 mm of the reflector is affected most by radiation-induced damage, the inner section is used as the load-bearing structure.

Figure 9 shows the arrangement of the blocks to form the central reflector.

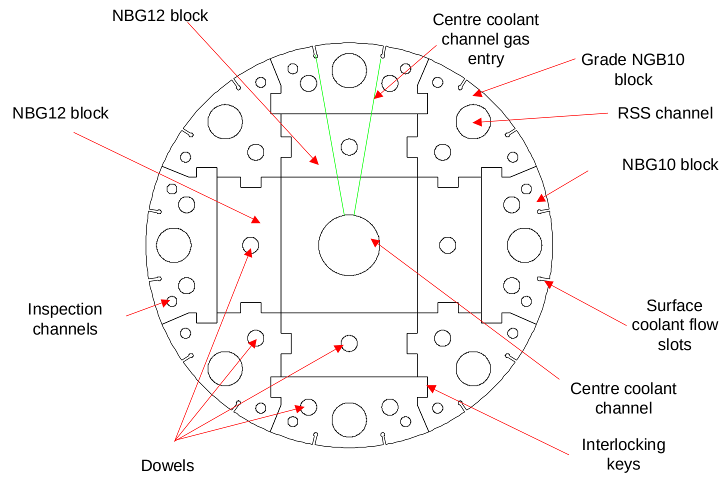



**Figure 9: Section through the Central Reflector**

### 3.1.1.4.2 Description of metallic components

The CB Assembly consists of all the metallic parts of the CS. Its primary function is to support the Core Structures Ceramics (CSC) during normal operation and postulated events. The CB also forms a thermal shield to assist the cooling systems to control the RPV temperature.

The main components of the CB Assembly are listed below, and the layout is shown in Figure 10.

a. Core Barrel

The CB comprises the CB side and the Core Barrel Support Structure (CBSS). [

]$^{a,b}$ Three defuelling chutes extending from the bottom of the CBSS, guide the fuel spheres out of the core to the Core Unloading Devices (CUDs) outside the RPV.

b. Core Barrel Top Plate Assembly

The CB Top Plate Assembly is actually the lid of the CB. The Top Reflector is suspended from the Top Plate. The Top Plate allows access for the Fuel Handling and Storage System (FHSS), RCS and RSS.

c. Core Barrel Bottom Support

The CB Bottom Support structure supports the CB to the RPV in the vertical direction.

d. Lower Support Ring

The Lower Support Ring supports the CB horizontally at the bottom, during a seismic event.

e. Upper Support Ring

The Upper Support Ring supports the CB horizontally at the top, during a seismic event.

f. Core Barrel Lateral Guides

The CB Lateral Guides keep the CB Assembly upright during normal operation.

During normal operating conditions, the weight of the core and the CSC is carried by the CB Assembly via the single Bottom Support, through the RPV to the building. The CB Assembly is guided at the top to keep it upright during normal operation. Additionally it has strong restraints at the top and the bottom to support it horizontally during a seismic event. The CB Assembly will fit in a cylinder with a diameter of [ ][b] and a length of [ ][b] The total mass of the CB Assembly is approximately 324 t.

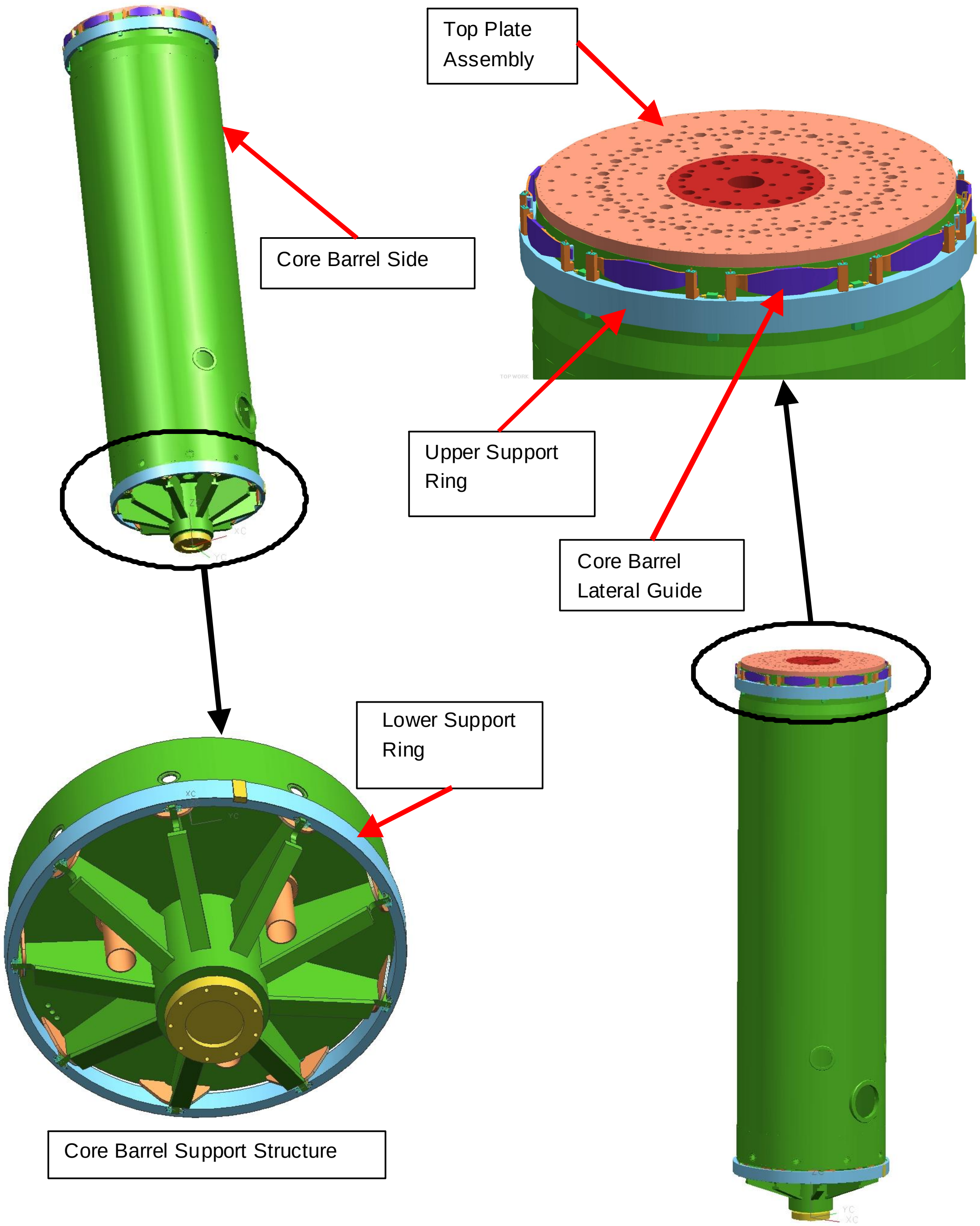



**Figure 10: Core Barrel Assembly Layout**

### 3.1.2 Core Conditioning System

#### 3.1.2.1 Functional overview

The function of the Core Conditioning System (CCS) is to remove core decay heat from the reactor when the Brayton cycle is not operational or when the motored Turbo-generator Set (TGS) is not functional. This is done in the following modes of operation:

- In modes that will allow maintenance operations to take place.
- When the motored TGS is unable to remove decay heat, the CCS acts as a back-up to the motored TGS decay heat removal function.
- During Main Power System (MPS) commissioning, the CCS circulates heated nitrogen for the Primary Loop Initial Clean-up System (PLICS). This clean-up system removes moisture from the core graphite structures.
- During maintenance, the CCS provides cooling flow to the reactor defuel chute in order to cool the fuel spheres entering the CUD.

The operation of the CCS is as follows:

- Hot core outlet gas is extracted from the core outlet pipe and transported to the inlet of the CCS water-cooled heat exchanger. Heat is extracted from the system through the use of the CCS water cooler. Cooled helium leaving the CCS heat exchanger is then directed back to the core inlet pipe via the CCS blower. The blower controls the required mass flow rate through the system. Figure 11 is a simplified process flow diagram depicting the CCS.
- When the CCS is used during MPS commissioning, an electric heater which is part of the PLICS is attached to the CCS. Flow is directed through the PLICS electric heater on its way back to the core inlet plenum in order to heat the core and graphite structures.
- It is necessary to cool fuel spheres before they enter the FHSS CUD. During normal and motored TGS operation, this flow is provided through a line connecting the PCU to the reactor defuel chute. When the Brayton cycle or the motored TGS is unable to provide this flow, the CCS shall direct a small portion of flow to this connection point on the reactor defuel chute.

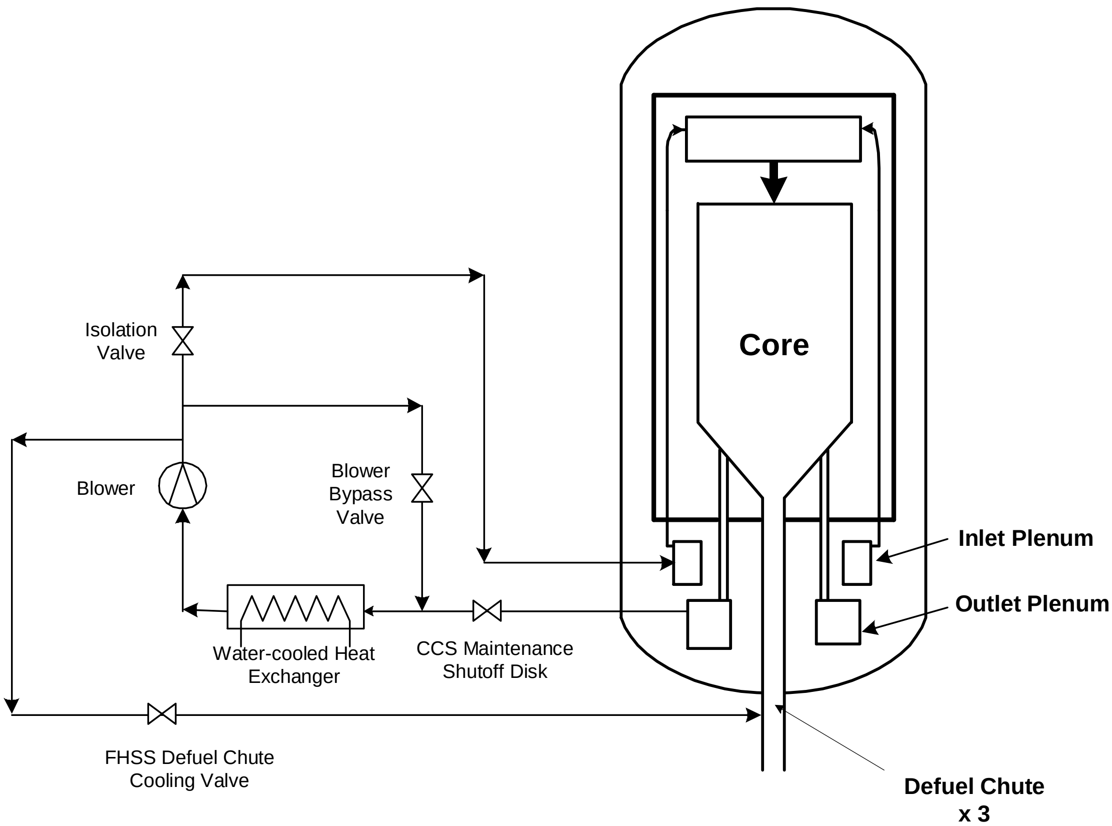



**Figure 11: Simplified Core Conditioning System Process Flow Diagram**

### 3.1.2.2 Components

The CCS consists of the following components:

- Blower
- Water-cooled heat exchanger
- Blower bypass valve
- Isolation valve
- Maintenance shut-off disc
- Piping

### 3.1.2.3 Operating conditions and modes

Refer to Table 3.

**Table 3: Core Conditioning System Operating Conditions and Modes**

| Condition | Unit | Value |
|---|---|---|
| Depressurized Forced Cooling (DFC) | | |
| • Heat removed (at 100 kPa) | MW | b |
| • CCS flow rate | kg/s | |
| Motored TGS transition | | |
| • Heat removed | MW | |
| • CCS flow rate | kg/s | |

Table 4 is a map of CCS operation with respect to the MPS Modes and States.

**Table 4: PBMR Plant Operating Modes and States – Core Conditioning System**

| PBMR Plant Operating Modes and States | | CCS Operation |
|---|---|---|
| (5) Power Operation | (5b) Normal Power Operation | a,b |
| | (5a) Reduced-capability Operation | |
| (4) Operational Standby | (4b) PCU Operational Islanded | |
| | (4a) Synchronized Standby | |
| (3) Standby | (3b) MPS Ready | |
| | (3a) Reactor Ready | |
| (2) Shutdown | (2c) Partial Shutdown | |
| | (2b) Intermediate Shutdown | |
| | (2a) Full Shutdown | |
| (1) Fuelled Maintenance | (1b) Closed Maintenance | |
| | (1a) Open Maintenance | |
| (0) Defuelled Maintenance | | |

### 3.1.3 Core Barrel Conditioning System

#### 3.1.3.1 Functional overview

The function of the Core Barrel Conditioning System (CBCS) is the following:

a,b

The operation of the CBCS is as follows:

- Hot helium is collected in the upper volume of the RPV and directed to the CBCS, which is situated in the bottom volume of the PCU citadel area.
- Within the CBCS vessel, helium is directed through a water-cooled heat exchanger where heat is removed from the system. Helium then flows through a centrifugal blower into the bottom volume of the RPV. Helium is distributed evenly into the gap between the CB and RPV. The helium flows up in the annulus between the RPV and the CB. This

helium flow cools the CB and maintains the CB within temperature limits. This flow also maintains the RPV belt line within specific temperature limits. Figure 12 shows a simplified process flow diagram of the CBCS.

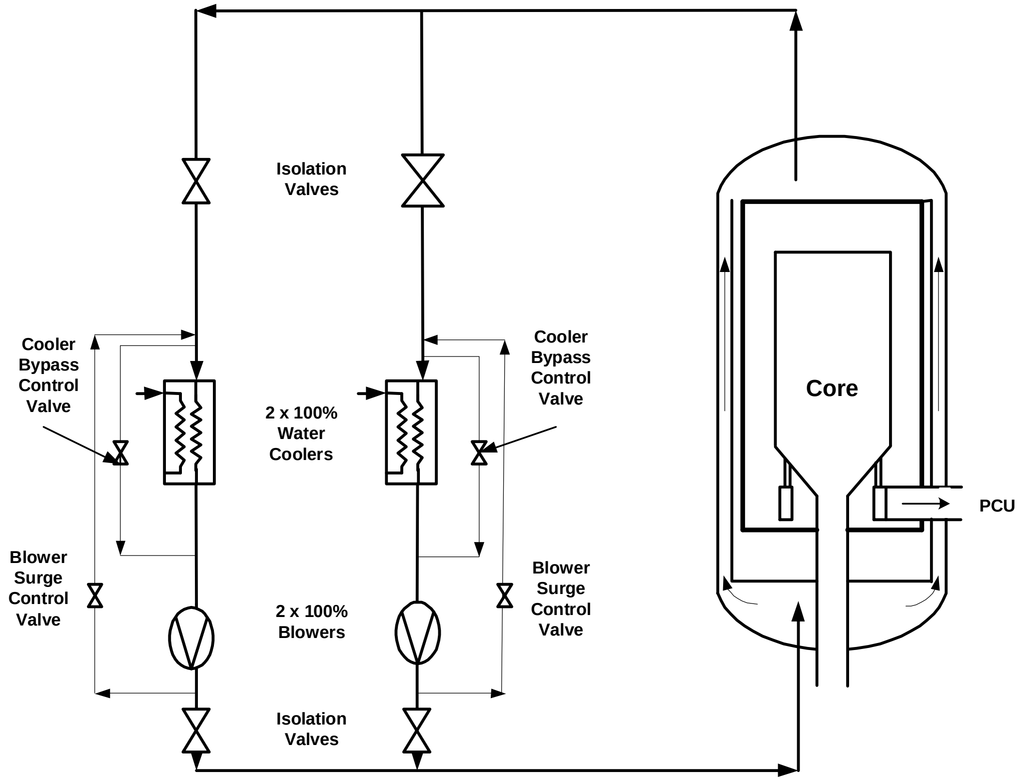



**Figure 12: Simplified Process Flow Diagram of the Core Barrel Conditioning System**

### 3.1.3.2 Components

The CBCS consists of the following components:

- Blowers (x 2)
- Heat exchangers (x 2)
- Blower bypass valves (x 2)
- Isolation valves (x 4)
- Pressure boundary piping
- Distribution plenum

### 3.1.3.3 Operating conditions and modes

Refer to Table 5.

**Table 5: Core Barrel Conditioning System Operating Conditions and Modes**

| Condition | Unit | Value |
|---|---|---|
| 100% MCR, 100% Maximum Continuous Rating Inventory (MCRI) | | |
| • Heat removed | MW | b |
| • CBCS flow rate | kg/s | |
| 40% MCR, 40% MCRI | | |
| • Heat removed | MW | |
| • CBCS flow rate | kg/s | |

Table 6 maps CBCS operation with respect to the MPS Modes and States.

**Table 6: PBMR Plant Operating Modes and States – Core Barrel Conditioning System**

| PBMR Plant Operating Modes and States | | CBCS Operation |
|---|---|---|
| (5) Power Operation | (5b) Normal Power Operation | a,b |
| | (5a) Reduced-capability Operation | |
| (4) Operational Standby | (4b) PCU Operational Islanded | |
| | (4a) Synchronized Standby | |
| (3) Standby | (3b) MPS Ready | |
| | (3a) Reactor Ready | |
| (2) Shutdown | (2c) Partial Shutdown | |
| | (2b) Intermediate Shutdown | |
| | (2a) Full Shutdown | |
| (1) Fuelled Maintenance | (1b) Closed Maintenance | |
| | (1a) Open Maintenance | |
| (0) Defuelled Maintenance | | |

### 3.1.4 Reactivity Control and Shutdown System

The Reactivity Control and Shutdown System (RCSS) consists of three systems:

- Reactivity Control System (RCS)
- Reserve Shutdown System (RSS)
- Neutron Source System (NSS)

#### 3.1.4.1 Reactivity control system

##### 3.1.4.1.1 Functional overview

The RCS is used to control the reactivity in the core, to quickly shut the reactor down and to keep it in a shutdown state. The RCS consists of 24 identical units, which consist of one group of 12 control rods and another group of 12 shutdown rods. The control system moves each group alternatively to have the rods inserted to an equal depth into the side reflector. Following a scram or shutdown signal, the control rods are inserted into the top part of the reflector and the shutdown rods are inserted into the bottom part of the reflector.

The RCS units are raised and lowered mechanically inside the borings in the side reflector. The system will also hold them steady in any position in their entire range of travel. Insertion of the rods is by gravity when power is cut to the drive motors (scram activation). The Reactor Protection System (RPS) will first initiate the drop of the control rods, and later the shutdown rods, should the need arise. During this event, the drop velocity of the RCS units is limited to a pre-determined value.

##### 3.1.4.1.2 Modes of operation

During the anticipated operating modes of the PBMR, the RCS is required to raise and lower the control rods or to insert them, and hold them steady in any position over their entire range of travel.

The control rod and shutdown rod positioning is commanded by the Operational Control System (OCS). Control- or shutdown rod insertion (scram) action is initiated by the RPS, which overrides the OCS.

The states of the RCS during Plant Operational Modes with the associated control rod and shutdown positions are provided in Table 7. The table also shows the state of the RSS in relation to the control rod and shutdown rods.

##### 3.1.4.1.3 Major component list

The RCS consists of the following major subsystems/components:

a. RCS Control Rod Drive Mechanism

   The Control Rod Drive Mechanism (CRDM) consists of the chain drive, chain container and scram shock absorber. The main function of the CRDM is to translate rotational movement into linear movement. Refer to the layout in Figure 13.

b. Rod and chain

   The function of the control rods is to absorb neutrons. The chain connects the chain drive to the control rod.

c. RCS secondary shock absorber

   The function of the secondary shock absorber is to prevent damage to the control rod and the core structures graphite following a chain failure.

d. RCS drive motor

The function of the RCS drive motor is to keep the control rod in position, to move the control rod up and down, and to insert the control rod during a power failure.

e. RCS control rod guide tube

The function of the RCS Control Rod Guide Tube is to connect the CRDM housing to the CS and to serve as a guide for the Control Rod.

f. RCS maintenance equipment

The function of the maintenance equipment is to allow for removal and replacement of RCS parts, with minimal air ingress.

g. RCS Control and Instrumentation

The RCS Control and Instrumentation (C&I) has electrical equipment that relays power from the Auxiliary Electrical Power System (AEPS) to the electrical terminals in the RCS, and translates signals from and to the C&I system.

**Table 7: Reactor Cavity Cooling System States Associated with Plant Modes from Operation to Defuelled**

| **Modes** | | **Sub-modes** | |
|---|---|---|---|
| Power Operation | 5 | Normal Power Operation | 5b |
| | | Reduced-capability Operation | 5a |
| Operational Standby | 4 | Synchronized Standby | 4a |
| | | PCU Operational Islanded | 4b |
| Standby | 3 | MPS Ready | 3b |
| | | Reactor Ready | 3a |
| Shutdown | 2 | Partial Shutdown | 2c |
| | | Intermediate Shutdown | 2b |
| | | Full Shutdown | 2a |
| Fuelled Maintenance | 1 | Closed Maintenance | 1b |
| | | Open Maintenance | 1a |
| Defuelled Maintenance | 0 | Defuelled Maintenance | 0 |

a,b

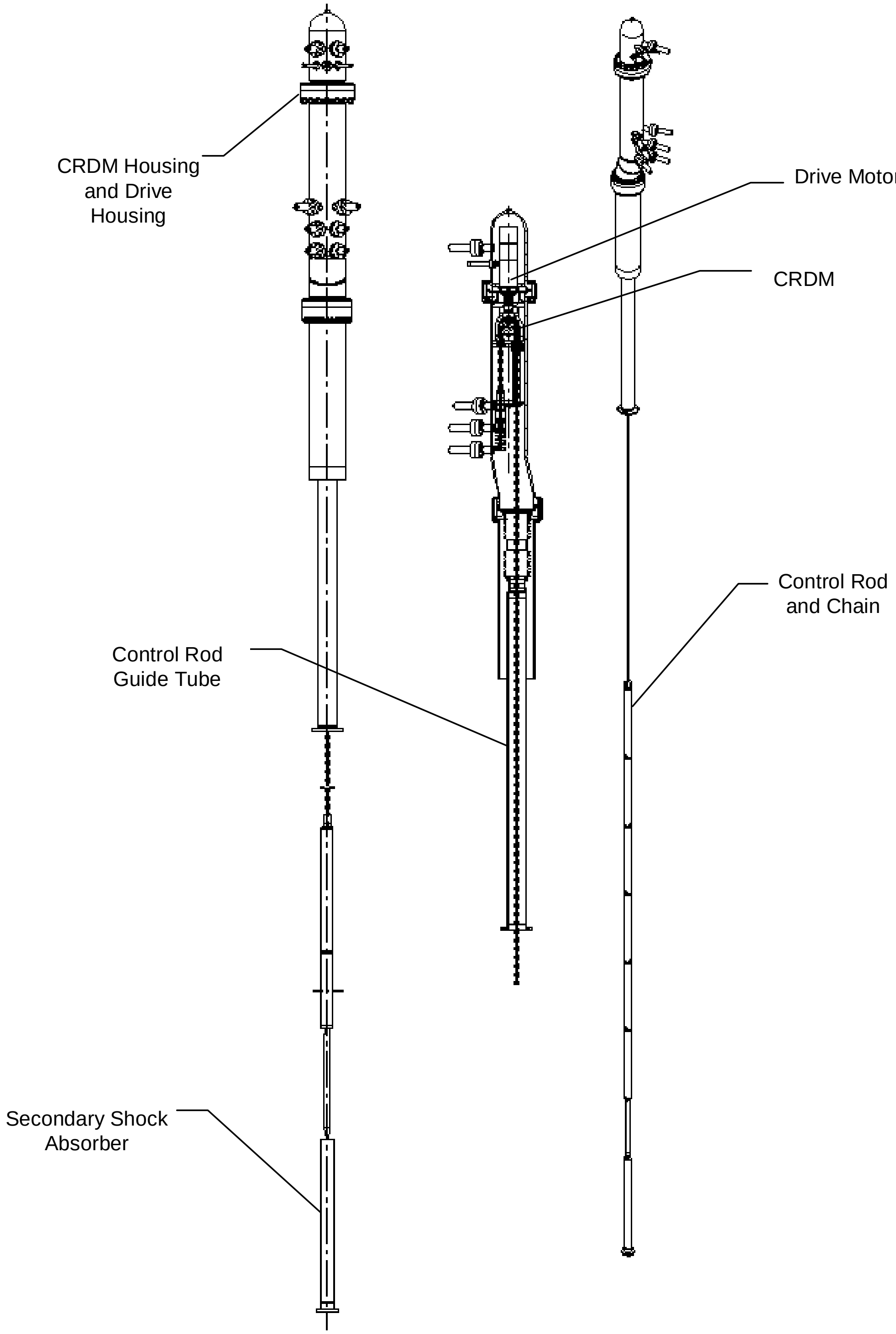



**Figure 13: Reactivity Control System Layout**

#### 3.1.4.2 Reserve shutdown system

##### 3.1.4.2.1 Functional overview

The Reserve Shutdown System (RSS) consists of eight units that can insert Small Absorber Spheres (SAS) into the eight borings of the central reflector. SAS are typically inserted to shut the reactor down to 'cold' conditions for maintenance operations. When inserted, the RSS keeps the reactor subcritical to an average core temperature of at least 100 °C.

The SAS contain natural $B_4C$. The $^{10}B$ in the natural $B_4C$ is the neutron absorber.

When shutdown is required, the valves of the SAS storage units are merely opened, to allow the SAS to flow under gravity into the central reflector borings.

The SAS are removed from the channels (all eight channels are removed at the same time), and transported back via the sphere return pipe to the feeder bin by means of a gas transport system. The feeder bin distributes the SAS to the eight SAS storage containers. Gas flow from the FHSS blower fluidizes and moves the SAS. During SAS transport, the FHSS does not transport fuel. The FHSS is isolated from the reactor and the RSS switches to SAS transport mode.

The handling and transportation of the SAS back to the eight storage units is done at gas temperatures that will not cause damage to the valves in the valve block, or to other components that might be sensitive to high-temperature gas. Figure 14 provides a schematic diagram of the RSS.

The RSS mechanical functions are the following:

- To load SAS into the RSS
- To store SAS
- To insert SAS into the borings of the central reflector
- To remove the SAS from the central reflector and to transport them back to the feeder bin from where they are distributed to the eight storage containers of the RSS

The SAS units, interfacing with the RPV and CB, operate under the same pressure and temperature as the reactor, and therefore SAS can only be transported at gas temperatures amenable to the valves and other components wetted by gas flow.

##### 3.1.4.2.2 Reserve shutdown system major components

a. Storage container

   The storage container stores the SAS and allows the release of the spheres into the borings in the central reflector of the reactor. Refer to Figure 14.

b. Storage container connection pipe

   The storage container connection pipe directs the SAS from the storage container to the borings in the central reflector. It can also compensate for relative movement due to thermal expansion between the core structures and installation point of the storage containers.

c. Storage container support structure

   The storage container support structure houses and supports the eight storage containers. The RPV in turn supports the storage container support structure.

d. Sphere discharge pipe

   The sphere discharge pipe conveys (gravity feed) the SAS from the borings in the central reflector to the bottom valve bank. The sphere discharge pipe provides for cooling of the SAS by gas from the FHSS blower during the transport of hot SAS.

e. Bottom valve bank

The bottom valve bank directs the spheres from the sphere discharge pipe to the discharge vessel. It is further used to direct the conveying gas to the discharge vessel of the SAS (during transport of the SAS) or to bypass the discharge vessel transport point of the SAS (during conditioning of the transport line before transport of the spheres). The bottom valve bank houses the isolation valves that are used to isolate the reactor from the SAS return- and the gas transport pipes when required.

f. Discharge vessel

The SAS are fluidized in the discharge vessel in a controlled manner to allow transport of the SAS to the storage container feeder bin.

g. SAS return pipe

The SAS return pipe conveys the SAS from the discharge vessel to the feeder bin.

h. Top valve bank

The top valve bank houses the SAS isolation valves and the gas return valves. It directs the SAS to the storage container feeder bin and the return gas to the blower gas return pipe. It isolates the reactor from the sphere return pipe and the blower gas return pipe when required.

i. Feeder bin

The feeder bin receives SAS and directs the spheres to the various storage containers during SAS transport.

j. Transport gas supply system

The transport gas feed pipe supplies the transport gas from the FHSS blower outlet manifold to the bottom valve bank. It will further return the transport gas to the FHSS blower inlet manifold.

k. SAS cooling system

The SAS cooling system uses the gas from the FHSS system blower to cool the SAS before the spheres enter the valve bank (bottom) during transport operations.

l. SAS

The SAS absorb neutrons. The spheres are released into the SAS borings by actuation of a valve mechanism in the storage containers.

#### 3.1.4.2.3 Reserve shutdown system architectural layout

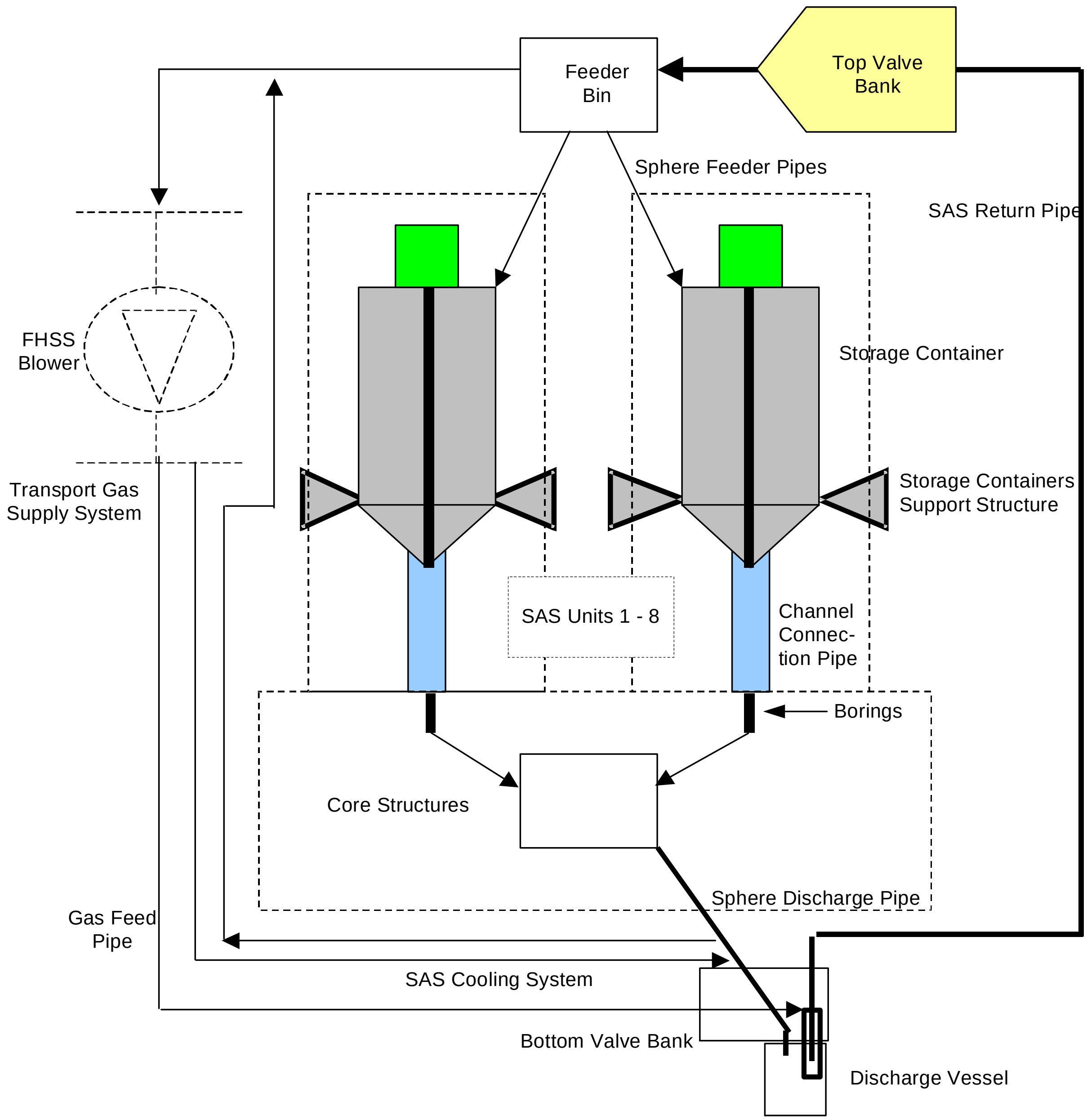



**Figure 14: Reserve Shutdown System Schematic Layout**

### 3.1.5 Neutron Source System

To start the neutron multiplication in the core, a removable isotopic neutron source is inserted into one of the instrumentation channels until sufficient fission product neutrons are available to provide a statistically reliable neutron background for start-up.

## 3.2 POWER CONVERSION UNIT

### 3.2.1 System Overview

The Power Conversion Unit (PCU) utilizes a direct gas cycle in which the hot helium exiting the core is used to drive a gas turbo-generator directly.

The MPS operates on a Brayton thermodynamic cycle, the T-S diagram of which is shown in Figure 15.

The flow diagram of the system is shown in Figure 16. The layout of the MPS is shown in Figure 17.

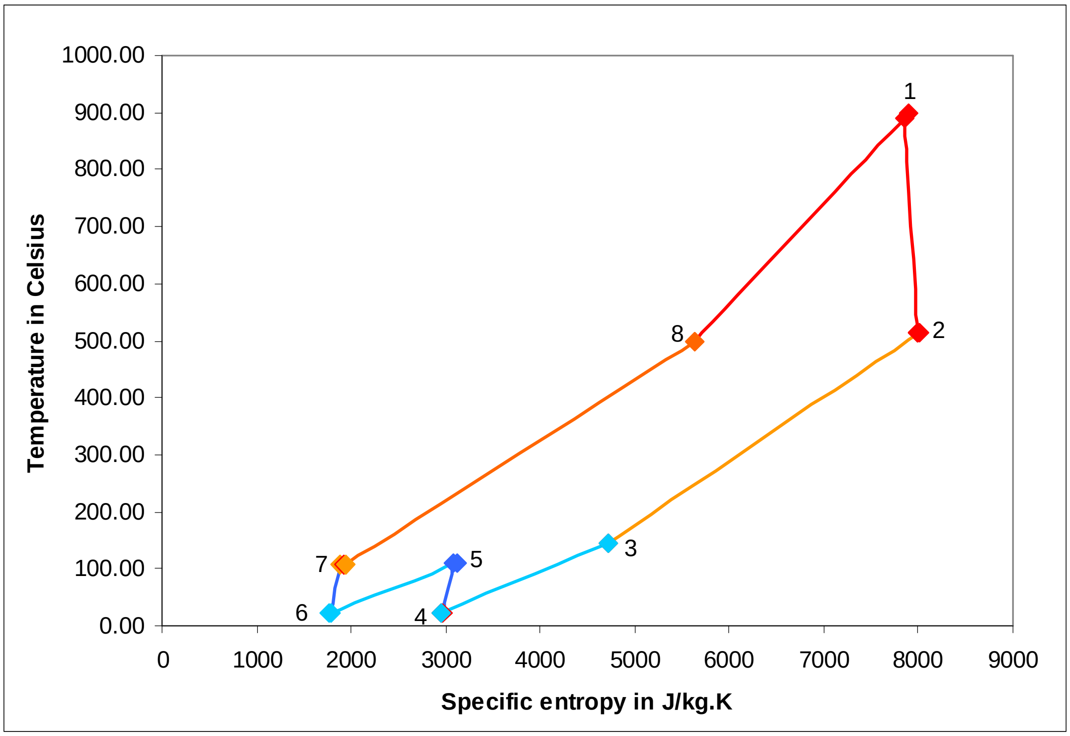



**Figure 15: Brayton Cycle T-S Diagram**

**Legend:**

1 to 2: Turbine

2 to 3: Recuperator

3 to 4: Pre-cooler

4 to 5: LP Compressor

5 to 6: Intercooler

6 to 7: HP Compressor

7 to 8: Recuperator

8 to 1: Reactor

a,b

**Figure 16: Conceptual Flow Diagram of the Power Conversion Unit**

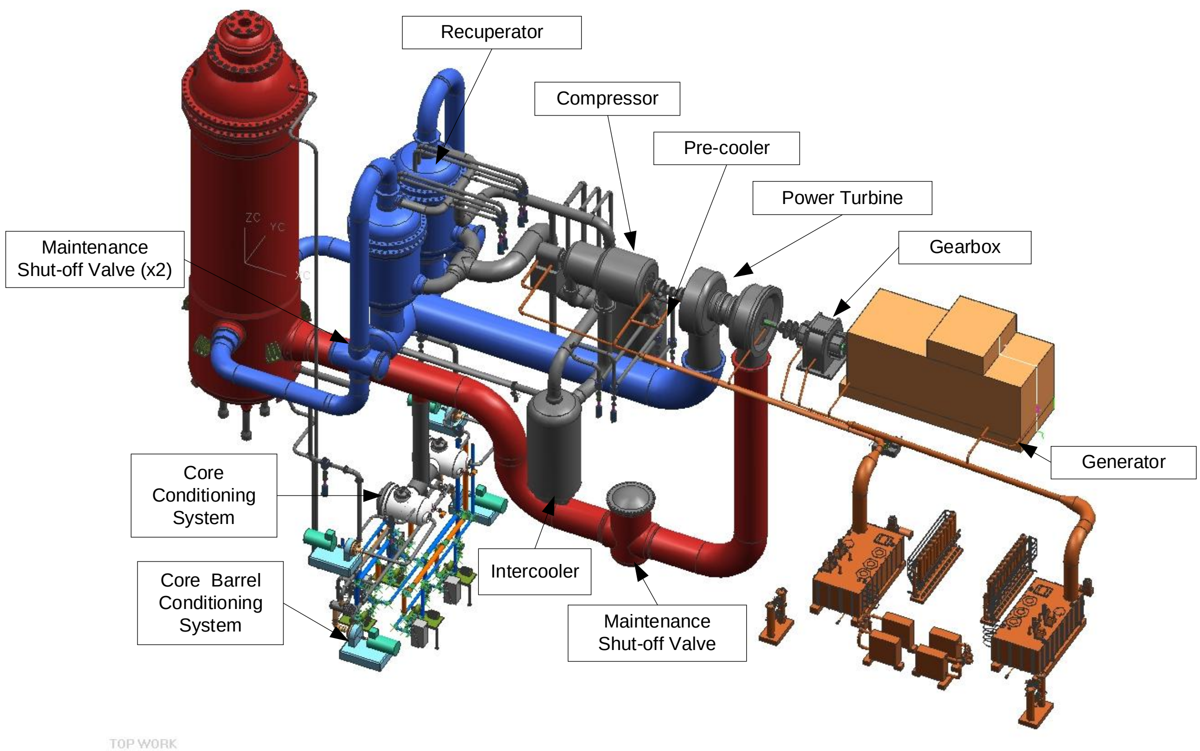



**Figure 17: Main Power System Layout**

### 3.2.2 Turbo-generator Set

#### 3.2.2.1 System Overview

The prime function of the Turbo-generator Set (TGS) is to convert the energy of the circulating hot high-pressure helium, from the reactor outlet, into electrical energy. A secondary function is to compress and circulate the helium in the Brayton cycle.

Other requirements are that these functions are to be performed with the highest possible efficiency, and the system must be controllable during all specified operating conditions and transients.

The system consists of one turbine driving the compressor on the one shaft end, and the generator on the other. Synchronous speed of the generator is 3 000 rpm. The turbine and compressor operate at 6 000 rpm to increase the efficiency of these units. A gearbox facilitates this speed ratio.

The compressor is intercooled and is split into a low- and a high-pressure stage.

Shaft sealing against atmosphere is by means of hydrodynamic gas seals referred to as Dry Gas Seals (DGSs).

The turbine outlet gas passes through a recuperator where the temperature is further reduced.

The recuperator outlet gas passes through a water-cooled pre-cooler before entering the Low-pressure Compressor (LPC).

The LPC outlet gas passes through an intercooler before entering the High-pressure Compressor (HPC).

The HPC outlet gas passes through the recuperator to increase the temperature before returning to the reactor.

#### 3.2.2.2 Design Description

Figure 18 shows the overall concept layout of the TGS.

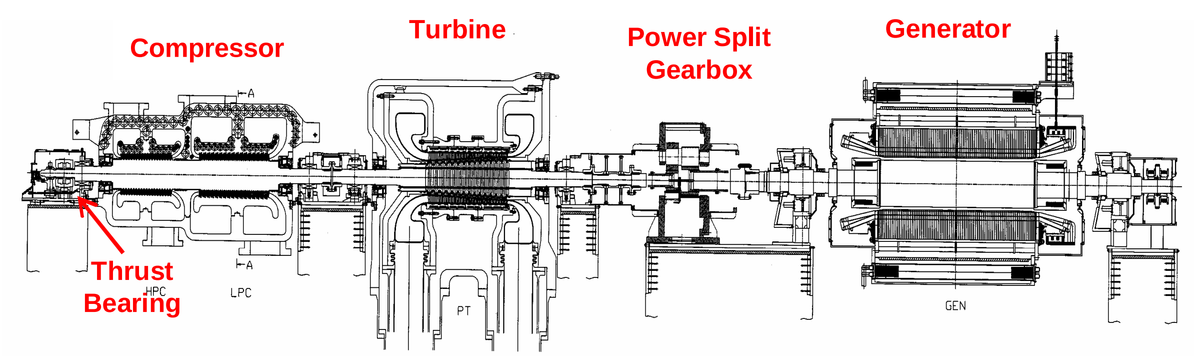



**Figure 18: Turbo-generator Set Concept Layout**

The LPC and HPC share a common casing with a journal bearing on either side of this.

The turbine and generator shafts are also supported on journal bearings on either side of the casings.

The thrust bearing is located on the High-pressure (HP) shaft end of the compressor. This ensures easy access and reduced size/losses. Rotordynamically it was also found to be the most suitable location for the thrust bearing.

All bearings are oil lubricated and operate under atmospheric conditions. The bearings are supported by independent foundations. The compressor and turbine casings, in turn, are supported from the bearing casings.

The shaft penetrations are sealed at four locations by DGSs:

- HP compressor casing
- LP compressor casing
- Turbine casing inlet side
- Turbine casing outlet side

A 180 MW gearbox with a speed ratio of approximately 2:1 is located between the turbine and generator.

This gearbox forms the separation between the controlled turbine house and the uncontrolled generator house. The gearbox casing will be sealed with the separating wall.

The generator is a standard horizontal, air-cooled unit. It will be equipped with a Static Frequency Converter (SFC) by means of which the TGS can be operated as a motor during start-up. (The so-called motored TGS.)

Flexible shaft couplings are used between:

- Compressor and turbine
- Turbine and gearbox
- Gearbox and generator

#### 3.2.2.3 Technical Specification (Design Point Conditions)

Refer to Table 8.

a,b

**Table 8: Technical Specification (Concept Design)**

### 3.2.3 Turbine

The conceptual 14-stage axial flow turbine is shown in Figure 19.

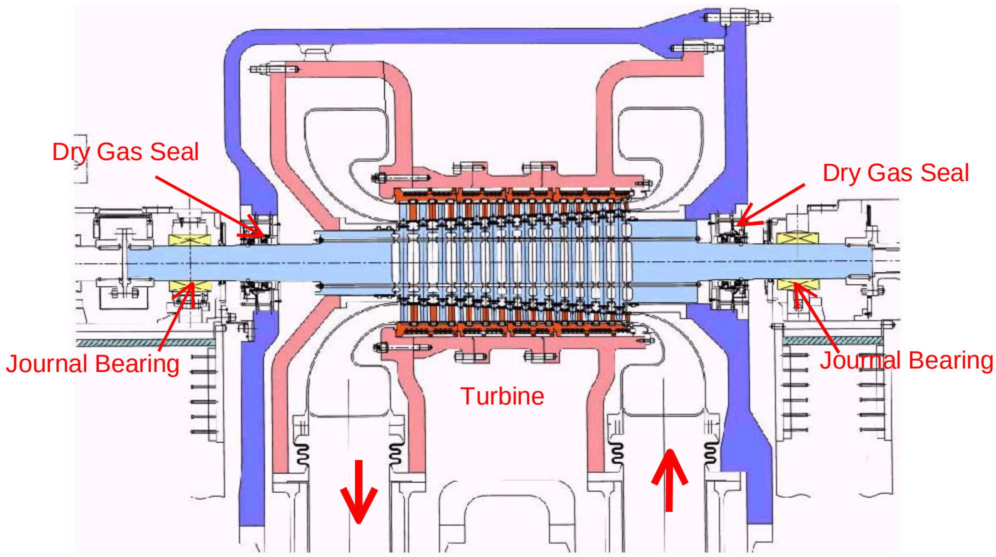



**Figure 19: Turbine Conceptual Layout**

The basic operating conditions specifications are given in Table 8.

Bottom inlet and outlet by means of a coaxial pipe is shown.

The bearing span is [ ][b]

The turbine has a double casing. A bleed flow of the HP compressor outlet feeds into the volume between the casings, which in turn enters the outer volume of the concentric hot pipes. In this way it is ensured that the outer pressure boundary is kept at a temperature below the code temperature limit of 371 °C of the ferritic material. Finally, this cooling flow enters the recuperator.

The casing forms part of the pressure boundary and is designed according to ASME III, Division 1, Subsection NC. In addition it is designed to contain any internally generated missiles.

The casing is supported on the bearing pedestals.

Pipe forces and moments on the turbine casing are minimized by adequate pipe supports and flexible support of the recuperator.

The positions of the DGSs are shown. The spaces between the DGSs and the oil lubricated journal bearings are open to atmosphere. This is to prevent any ingress of oil into the system.

Any helium leakage from the DGSs is collected in a pipe and can be treated as required.

### 3.2.3.1 Compressor

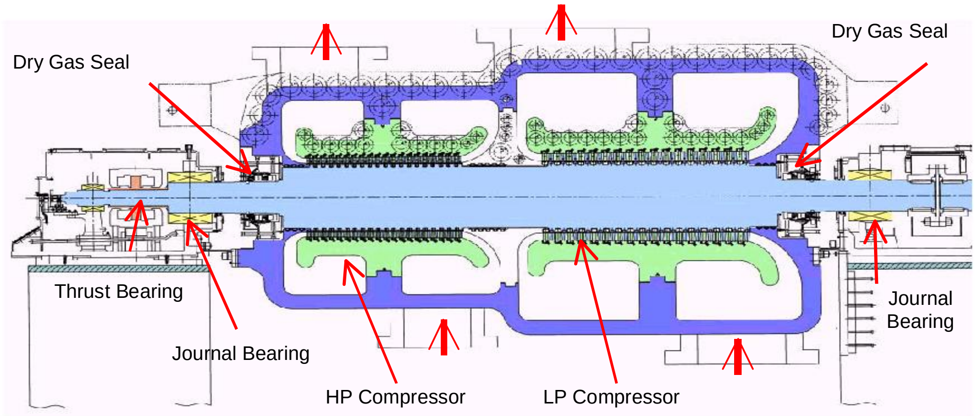



**Figure 20: Compressor Conceptual Layout**

The conceptual LP and HP compressor stages are shown in Figure 20.

The top half of the drawing is a horizontal section and the lower half is a vertical section.

Thus, both inlet and outlet nozzles are located in the lower casing.

The basic operating conditions and specifications are given in Table 8.

The LP and HP stages have a common casing with a journal bearing at either end.

The casing forms part of the pressure boundary and is designed according to ASME III, Division 1, Subsection NC. In addition, it is designed to contain any internally generated missiles.

The casing is supported on the bearing pedestals.

Pipe forces and moments on the compressor casing are minimized by adequate pipe supports and flexible support of the pre- and intercoolers.

The bearing span is [ ][b]

Due to the low operating temperatures, a horizontally split single casing is adopted.

For the same reason, the inlet and outlet pipes have a single wall. Cooling is not required.

The positions of the DGSs are shown. The spaces between the DGSs and the oil lubricated journal bearings are open to atmosphere. This is to prevent any ingress of oil into the system.

Any helium leakage from the DGSs is collected in a pipe and can be treated as required.

### 3.2.3.2 Gearbox

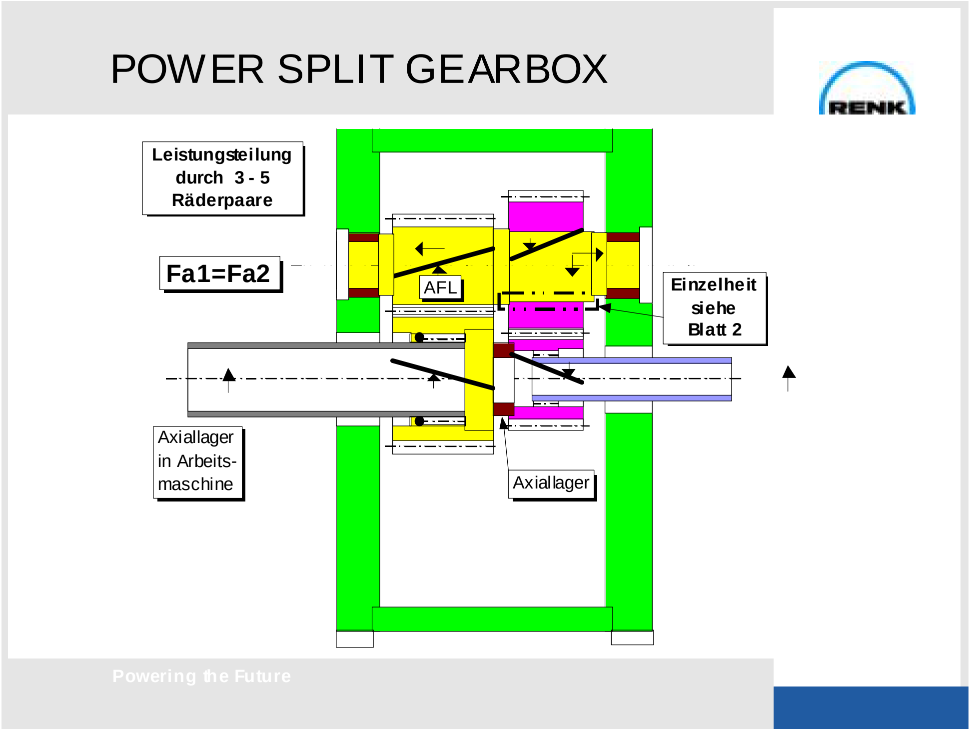



**Figure 21: Gearbox Conceptual Layout**

A gearbox is introduced between the turbine and generator with a speed ratio of approximately 2:1. The generator synchronous speed is fixed at 3 000 rpm. Turbomachines are more efficient, smaller and cost effective at higher speeds, but have limits with regard to material properties at high temperatures. At 900 °C gas inlet temperature and proven materials, 6 000 rpm is an optimum speed for the turbine. This justifies the gearbox.

The turbine transmits 180 MW. With the conventional spur type gearbox the gear sizes, forging sizes, pitch line velocities and a number of other design criteria are beyond the limits of proven technology in this power range.

To circumvent this, the layout shown in Figure 21 is adopted. The input power from the turbine (from the right in Figure 21) drives a sun gear. This drives a number of planet shafts around its circumference (five in this case), which in turn drive a sun output gear. In this way the gear loading, pitch line velocities and gear sizes are reduced. All designs and components are within the range of proven technology.

To reduce windage losses in the gearbox, a vacuum is drawn inside the casing with a small pump. Due to this vacuum, the gearbox is suitable to form the drive train seal between the controlled turbine house and the uncontrolled generator house.

The gearbox is a low-risk item with the added advantage that the system can be adopted for 50 Hz and 60 Hz by simply changing the gear ratios.

### 3.2.3.3 Generator system

The generator is an air-cooled machine. The rotor is directly cooled and the stator is indirectly cooled. The machine is mounted horizontally in a clean and easily accessible environment.

The main characteristics of the generator are summarized in Table 9:

**Table 9: Main Characteristics of Generator**

| Parameter | Value |
|---|---|
| Rated active power | 180 MW |
| Rated power factor | 0.85 lagging |
| Rated voltage | 13.2 kV |
| Rated frequency | 50 Hz ±2% |
| Rated speed | 3 000 rpm ±2% |
| Excitation | Static (brushes) |
| Design standard | International Electrotechnical Commission (IEC) |

### 3.2.3.4 Bearing system

Conventional oil lubricated bearings are used at either end of the compressor and turbine casings as well as the generator stator.

A thrust bearing is located at the high-pressure end of the compressor. [

][a,b]

Journal and thrust bearings are of the tilting pad type.

The bearing casings are sealed and purged on the shaft and atmospheric pressure is maintained by venting to atmosphere. In this way every effort is made to avoid contamination of the oil system.

Despite the above precautions, two separate oil systems are installed.

- The first serves the turbine and compressor bearings.
- The second serves the gearbox and generator.

The systems are housed separately to ensure that the gearbox and generator systems are contamination free, even in case of contamination of the first system.

Each oil system has a flow of [ ][b] and comprises the following components:

- Main oil tank of approximately [ ][b] capacity
- Main ac oil pump
- Auxiliary ac oil pump
- Emergency dc oil pump
- Jacking ac oil pump
- Emergency dc jacking oil pump
- Duplex filters

- Two water-cooled plate type oil coolers
- Piping, valves, power supply panels and full control and instrumentation

All piping within the building is coaxial, with the pressurized supply lines running inside the atmospheric oil return line. The latter is run in a trench to contain any spillage in the improbable event of a failure. This trench terminates in a sump of sufficient capacity for the full oil inventory.

A fire protection system is provided.

### 3.2.3.5 Dry gas seal

The TGS has four DGSs where the shaft penetrates the casing. Two are located in the turbine casing and two in the compressor casing.

Figure 22 shows a typical tandem type DGS. The red rings are Tungsten Carbide (or equivalent) hard material rotating with the shaft. The blue rings are the stationary graphite rings forming the mating sealing surface.

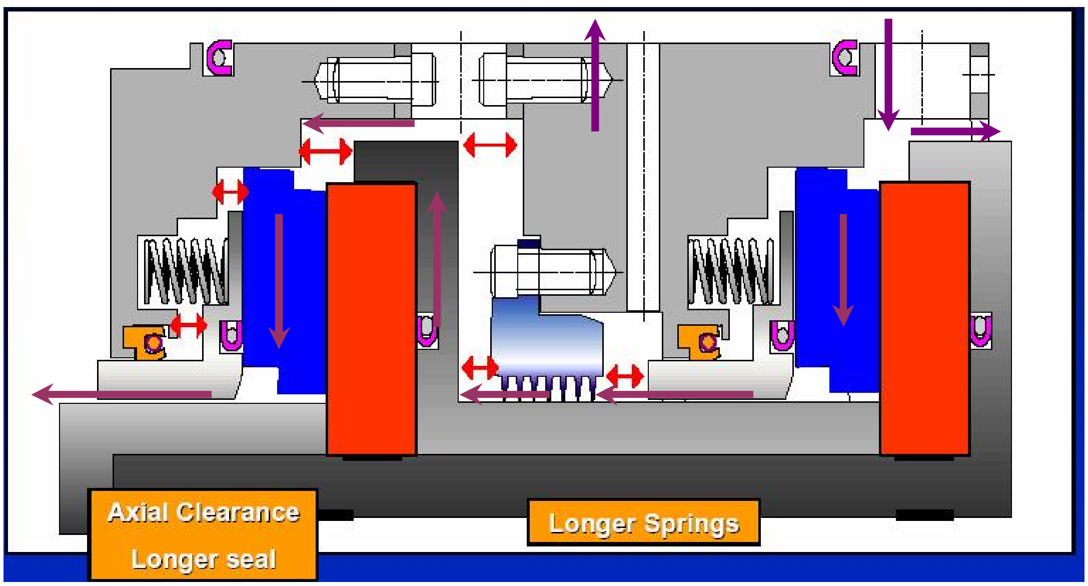



**Figure 22: Sealing Gas Flow Path (Purple Arrows) and Relative Movement between Shaft and Housing (Red Arrows)**

a,b

a,b

**A typical PBMR Dry Gas Seal System**

Figure 23 illustrates the flow of a typical tandem type DGS used, complete with the sealing gas system.

**Note:** Figure 23 is based upon the previous vertical shaft arrangement. This is a vertical 450 mm diameter shaft operating at 3 000 rpm and 35 bar pressure. The horizontal, single shaft arrangement, with four DGSs, has shaft diameters from 200 mm to 350 mm diameters operating at 6 000 rpm and pressures varying from 90 bar to 30 bar. **The values in this diagram are indicative only and will not apply to the present single shaft configuration.**

Actual values for the single shaft arrangement are still to be determined. Tests are planned under actual operating conditions to verify the calculated figures.

Figure 23 illustrates the seal arrangement that comprises the following main elements:

- Labyrinth seal on the process (helium) side.
- A chamber for injecting filtered helium.
- The inboard DGS with a large pressure difference.
- A chamber from where leaked helium is withdrawn and recovered to the system.
- The outboard DGS with a small pressure difference to minimize helium leakage.
- A chamber from where leaked helium, mixed with clean air, is discharged to atmosphere through the Heating, Ventilation and Air-conditioning (HVAC) system.
- A split labyrinth on the generator side where filtered air is injected, part of which leaks inboard and mixes with the helium leaked through the outboard DGS, and the rest leaks outboard into atmosphere. The purpose of filtering the air is to prevent damaging foreign matter from entering the DGS.

The sealing helium is extracted from the system, filtered and introduced to the seal through a control valve. Under steady state conditions, the system pressures provide the required pressure differences. During standstill and pressure equalization in the system, sealing helium is still required to prevent damaging unfiltered helium entering the DGS. A blower (with back-up blower) provides the required pressure differences under these circumstances.

The largest portion (98%) of the sealing helium escapes through the inboard labyrinth into the Power Turbine (PT). The remaining 2% escapes through the inboard DGS. This is compressed and returned to the system at the point of lowest pressure (LPC inlet). A positive displacement compressor (with back-up) is provided for this.

Only a very small proportion of the sealing helium [ ][b] escapes through the outboard DGS into atmosphere.

In the event of a DGS failure, the following back-up safety measures still apply:

- An inboard labyrinth throttles the total possible flow in case of a total failure of the DGS.
- Two DGSs are arranged in series. If one fails, the other restricts leakage.
- Condition monitoring (differential pressure measurements) alarms an impending DGS failure.
- An outboard labyrinth with sealing air will finally restrict gas flow to atmosphere.

The DGSs are industrially proven subsystems. More than 15 000 seals with more than 150 000 000 operating hours are in use. DGSs operate at pressures of up to 400 bar. The sizes and speeds applicable to the single shaft system are only slightly above standard applications. Tests will be conducted to prove the suitability and actual leak rates of the proposed seals.

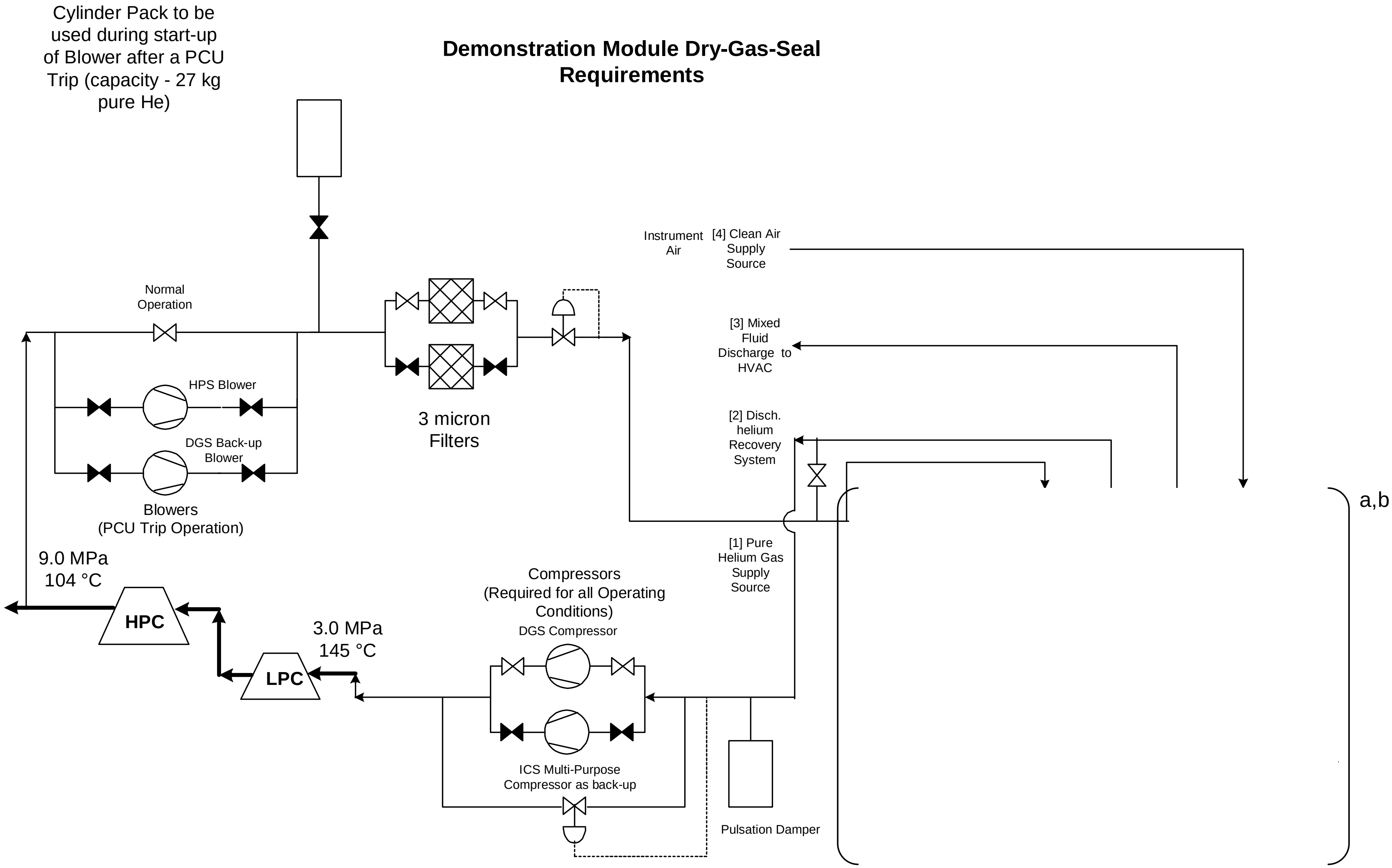



**Figure 23: Dry Gas Seal System**

### 3.2.4 Main Power System Heat Exchangers

The Main Power System (MPS) has the following three heat exchangers:

- Recuperator : gas-to-gas plate fin heat exchanger.
- Pre-cooler : plate-fin and tube gas-to-water heat exchanger.
- Intercooler : plate-fin and tube gas-to-water heat exchanger.

#### 3.2.4.1 Recuperator

The recuperator is used to pre-heat high-pressure helium returning to the reactor with the hot low-pressure gas leaving the PT. This greatly increases the cycle efficiency by preventing a total loss of energy from the pre-cooler. Two recuperators are used in parallel. Each recuperator consists of eight cores, each piped within the recuperator vessel to single inlet and outlet connections for the primary and secondary sections. The heat exchanger cores are counter-flow units, small chemically etched grooves to increase the heat transfer surface. The grooves are etched in a wavy pattern to enhance heat transfer and reduce cost.

The principle of the technology is indicated in Figure 24. There is a printed circuit plate pattern for the primary and secondary side, which are stacked and diffusion bonded to form an integrated block. The secondary plate is shown, with groove width 1 mm. The port region at the right is divided between the primary side port in the plane of the paper and the secondary side port flowing in the direction perpendicular to the paper. A distributor connects the ports to a matrix, where counterflow heat transfer between primary and secondary flow takes place. The distributor at the left connects to the left port region.

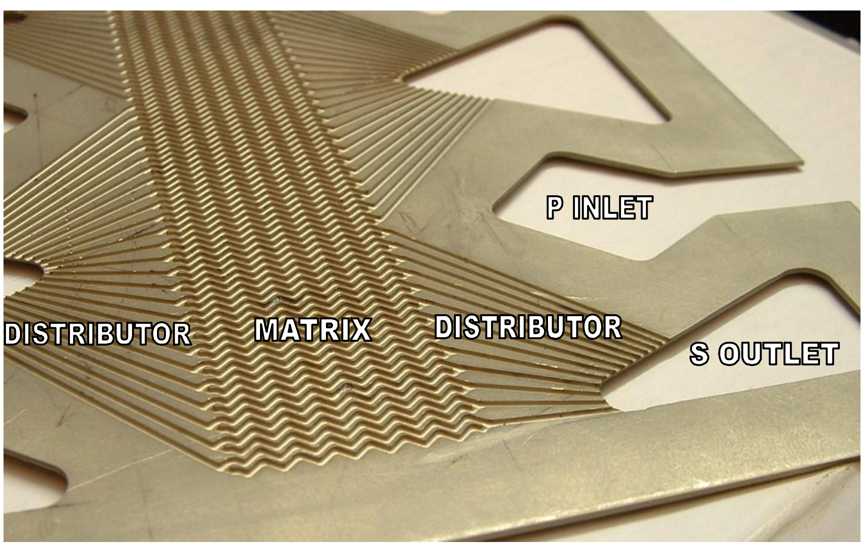



**Figure 24: Printed Circuit Plate**

The stacked block is fitted with welded-on manifolds and constitutes a core. The flow pattern through the core is shown in Figure 25.

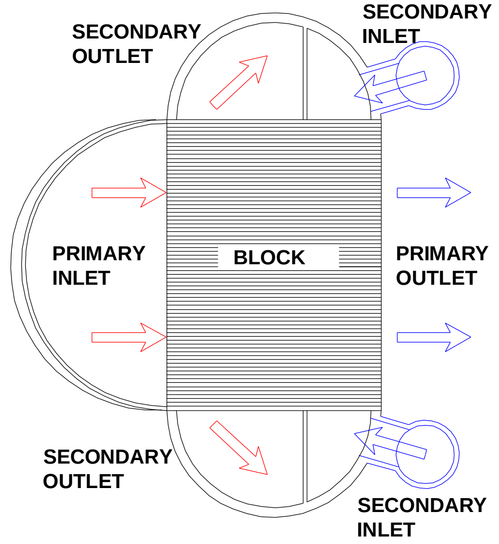



**Figure 25: Flow Pattern through the Core**

Inside the recuperator vessel, the cores are connected as shown in Figure 26

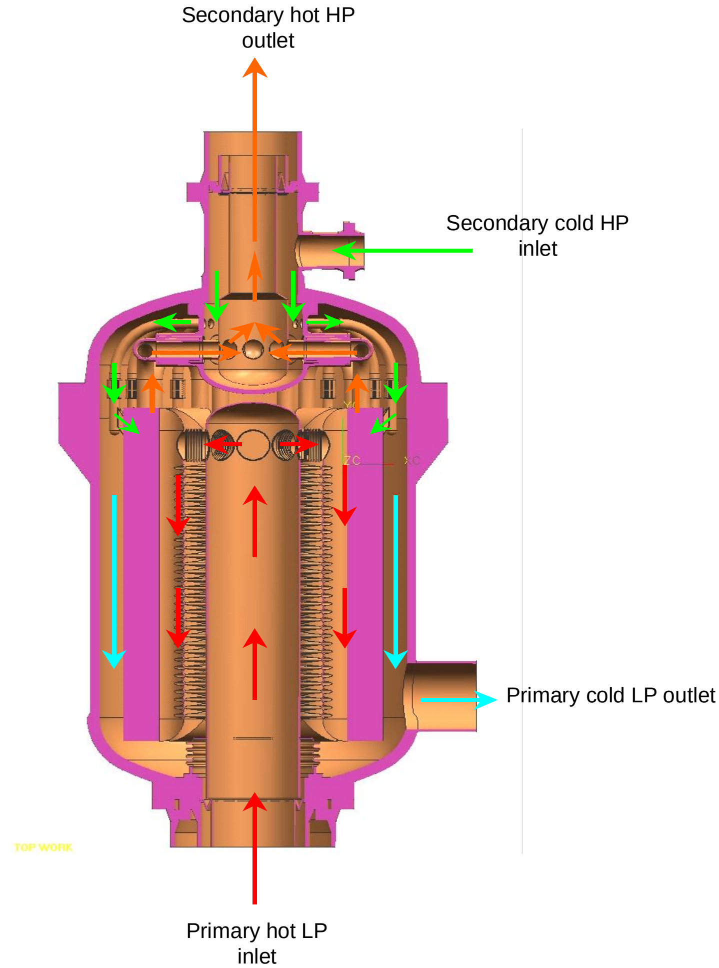



**Figure 26: Flow through Recuperator**

#### 3.2.4.2 Pre-cooler and intercooler

The pre- and intercoolers are of exactly the same design, with slight differences in operating points. The coolers use a four-water-pass arrangement with plate fins used as the extended surface. The cooler is modular, consisting of two bundles of 10 rectangular fin-tube modules arranged in an annulus around the centre line of the unit. Suitable baffles are used for sealing between modules and at the top of the cooler. On the water side, water is supplied by the Active Cooling System (ACS) to the inner part, and then flows up and down through the first bundle of u-tubes. The water then gathers in a section of the water box before going up and down through the second bundle of u-tubes, and then out to the ACS. Treated demineralized water is used to prevent scale, corrosion and erosion.

Helium enters from the outside and flows radially inward through the cooler. Once through, the gas flows through the large cylindrical plenum in the centre to the outlet. Figure 27 and Figure 28 show cross-sections through the pre-cooler.

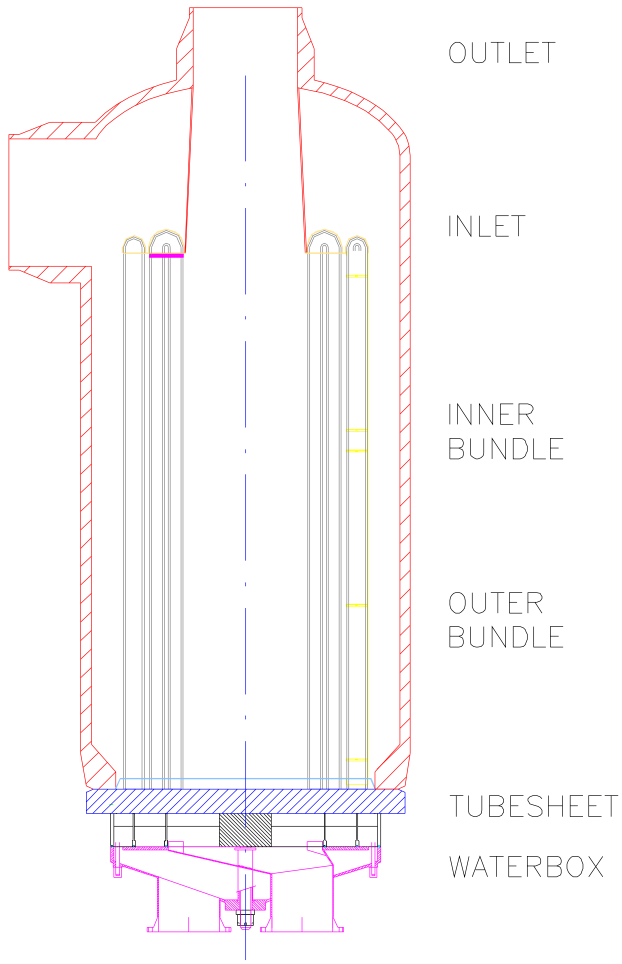



**Figure 27: Pre-cooler Construction**

a,b

**Figure 28: Top View of Fin-Tube Modules**

### 3.2.4.3 Operating conditions of the main power system heat exchangers

Table 10 gives the performance of the heat exchangers in the S100 Flownex model results.

**Table 10: Performance of Heat Exchangers**

| Parameter | Temp. In (°C) | Temp. Out (°C) | Pressure (kPa) | Mass Flow (kg/s) |
|---|---|---|---|---|
| Recuperator high-pressure side | | | | b |
| Recuperator low-pressure side | | | | |
| Pre-cooler helium side | | | | |
| Pre-cooler water side | | | | |
| Intercooler helium side | | | | |
| Intercooler water side | | | | |

## 3.2.5 Helium Inventory Control System

### 3.2.5.1 Overview

The Helium Inventory Control System (HICS) consists of the following subsystems:

- Inventory Control System (ICS)
- Helium Purification System (HPS)
- Helium Make-up System (HMS)
- Dry Gas Seal Supply and Recovery System (DSRS)

Table 11 provides an overview of the HICS functions during the different modes and states.

**Table 11: PBMR Plant Operating Modes and States – Helium Inventory Control System**

| HICS Operating Modes | Power Plant Operating Modes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Defuelled Maintenance | Fuelled Maintenance | | Shut-down | | | Standby | Operational Standby | Power Operation |
| | | MPS Open | MPS Closed | Full | Intermediate | Partial | | | |
| **Inventory Control System** | | | | | | | | | |
| Pressure differential injection/ extraction | | | | | | | | | |
| Rapid injection (booster operation) | | | | | | | | | |
| Extraction using compressors | | | | | | | | | |
| Tank level adjustment (compressor) | | | | | | | | | |
| Helium storage (MPS and FHSS) | | | | | | | | | |
| Overpressure of CS (maintenance) | | | | | | | | | |
| **Helium Purification System** | | | | | | | | | |
| Purify helium | | | | | | | | | |
| **Helium Make-up System** | | | | | | | | | |
| Provide fresh helium | | | | | | | | | |
| **DGS Supply and Recovery System** | | | | | | | | | |
| Provide dust-free helium to DGS | | | | | | | | | |
| Provide dust-free helium to DSRS | | | | | | | | | |

a,b

#### 3.2.5.2 Inventory control system

The MPS inventory is controlled by using the pressure differential between the MPS and six storage vessels. The control of pressure within the MPS is a means of controlling the power output of the PBMR Demonstration Power Plant (DPP); by controlling the pressure within the system, the mass flow rate is controlled.

The pressure in the respective vessels cascades from a high pressure to a lower pressure. Helium is transferred by extracting helium from the part of the MPS that is under the highest pressure, and transferring it into storage vessels (transferring into the highest pressure vessel first, and then the second highest vessel, and so on), or injecting helium from higher pressure vessels into a part of the MPS that is under lower pressure (starting with the lowest pressure vessel, and then the second lowest pressure vessel, and so on). The MPS compressors do most of the work required to increase the pressure of the helium in order to store it in the storage vessels. A flow diagram of the Inventory Control System (ICS) is shown in Figure 29.

The primary functions of the ICS are:

- Control of the helium mass within the MPS
- Storage of the helium of the MPS and FHSS during a maintenance outage

##### 3.2.5.2.1 Components of the inventory control system

The components of the ICS are the following:

- Inventory Control Storage Vessels
- Control Valves
- Capacitance Mass
- Isolation Valves
- Pressure Relief Valves
- Bursting Discs
- Main Compressor
- Multi-purpose Compressor
- Piping
- Buffer Tanks

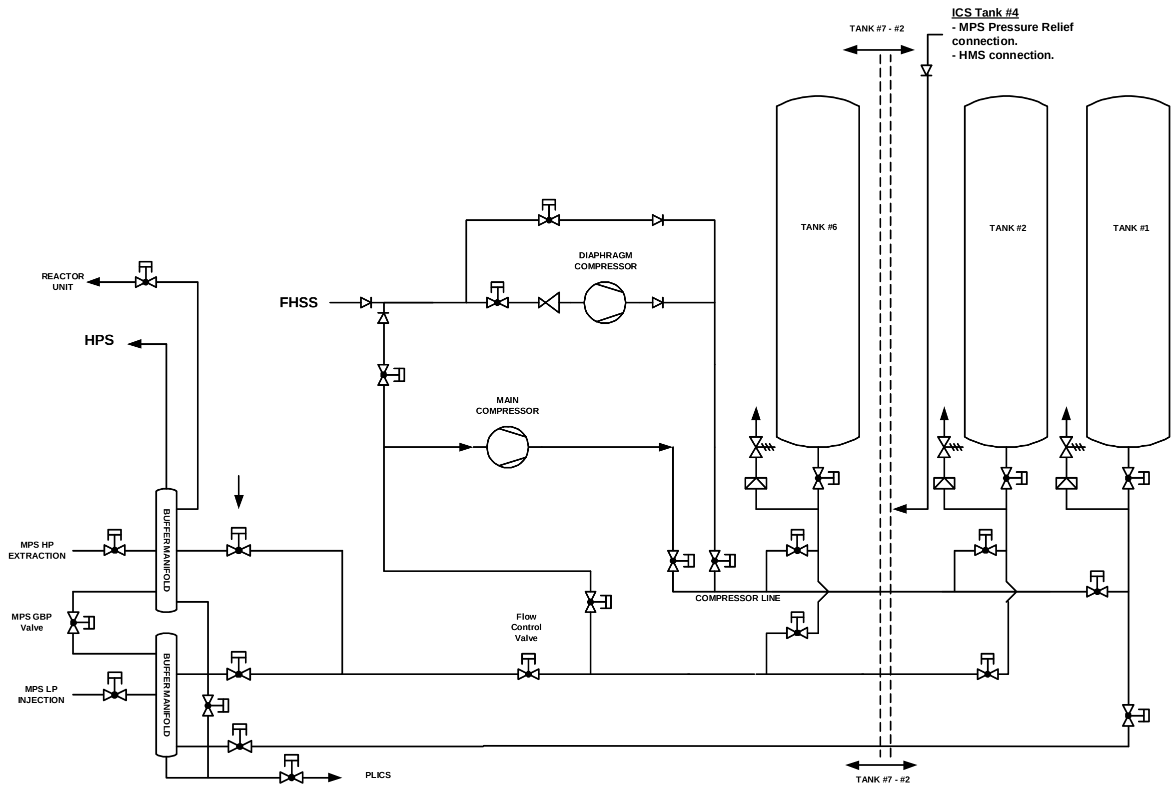



**Figure 29: Simplified Inventory Control System Process Flow Diagram**

### 3.2.5.2.2 Operating characteristics of the inventory control system

Refer to Table 12.

**Table 12: Operating Characteristics of the Inventory Control System (V701)**

| Condition | Value |
|---|---|
| Load following during normal operation – range | b |
| Load following during normal operation – rate | |
| Extraction from MPS from 40% MCRI to 1 bar | |
| Capacitance mass in each storage tank | |

### 3.2.5.3 Helium purification system

The Helium Purification System (HPS) provides the required degree of helium purity. High purity coolant is required in order to minimize corrosion and contamination in the MPS. This is done by bleeding off a partial flow of helium from the MPS. The extraction point is from the manifold of the MPS, i.e. the highest pressure point within the MPS. This shall be done through a connection point on the ICS buffer tanks. This flow is tapped off constantly during operation of the plant. The HPS removes chemical gaseous contaminants from the primary coolant within the MPS by the use of, catalysts, adsorbers and the manipulation of helium temperature extracted from the MPS. A flow diagram of the HPS is shown in Figure 30.

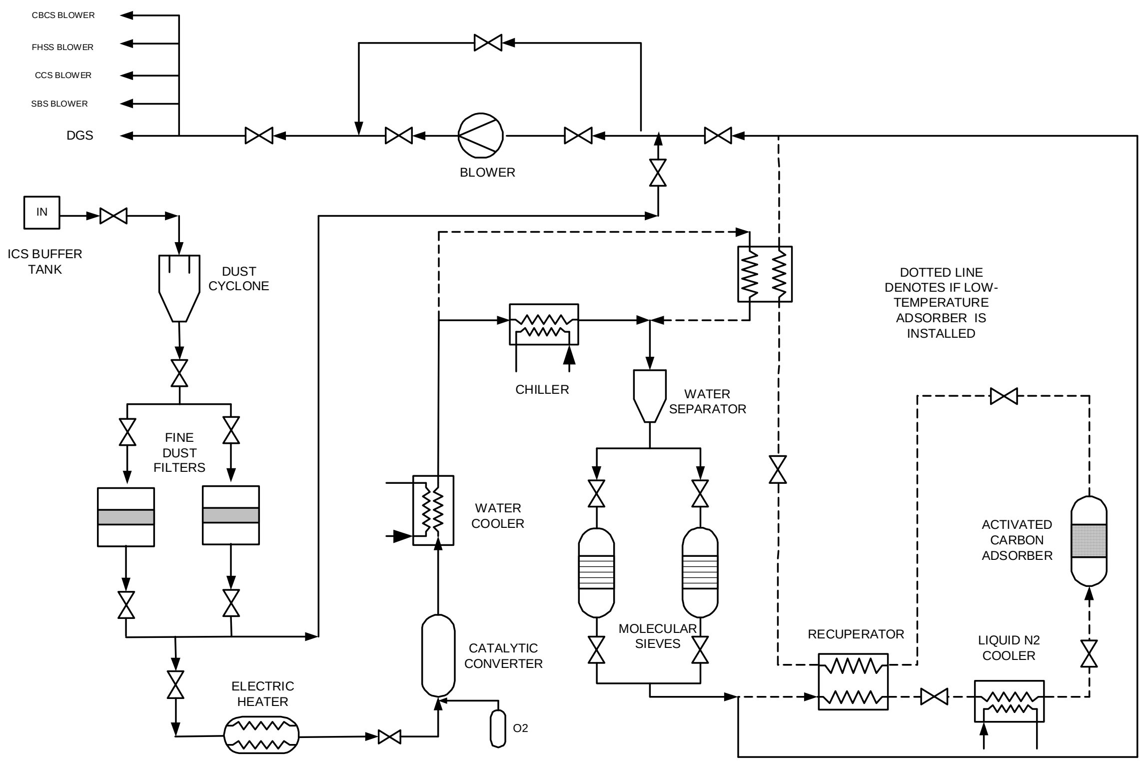



**Figure 30: Simplified Helium Purification System Process Flow Diagram**

The primary functions of the HPS are:

- To remove the following gaseous contaminants –
  - $H_2O$ (water)
  - $O_2$ (oxygen)
  - CO (carbon monoxide)
  - $CO_2$ (carbon dioxide)
  - $H_2$ (hydrogen)
  - $N_2$ (nitrogen)
  - $CH_4$ (methane)
  - HTO (tritiated water)
  - HT (tritiated hydrogen
  - $^{14}C$ (carbon 14)
  - T tritium
- To purify the primary system before initial Brayton cycle start-up and after inspections and maintenance.

### 3.2.5.3.1 Components of the helium purification system

The components of the HPS are as follows:

- Heater
- Catalytic Converter – converts CO to $CO_2$ and $H_2$ to $H_2O$
- Oxygen Cylinder – regenerates catalytic converter
- Water Cooler (200 °C)
- Water Cooler (10 °C)
- Chiller – provides 5 °C water
- Water Separator – removes condensate
- Water Collection Tank
- Recuperator
- Molecular Sieve – removes $CO_2$ and $H_2O$
- Low-temperature Recuperator
- Cryogenic/Liquid Nitrogen Cooler (optional)
- Activated Carbon Filter – removes $N_2$ (optional) and $CH_4$
- Liquid Nitrogen Storage Tank (optional)
- Liquid Nitrogen Pump (optional)
- Blower – provides necessary flow rate
- Regeneration Heater
- Regeneration Water Cooler
- Regeneration Blower
- Regeneration Water Separator
- Piping
- Control Valves
- Isolation Valves
- Pressure Relief Valves
- Bursting Discs

### 3.2.5.3.2 Operating characteristics of the helium purification system

Refer to Table 13.

**Table 13: Operating Characteristics of the Helium Purification System**

| Condition | Value |
|---|---|
| Low-temperature adsorber unit to remove nitrogen<br><br>HPS flow rate at 100% MCRI | a,b |
| HPS flow rate at 40% MCRI | |

### 3.2.5.4 Helium make-up system

The Helium Make-up System (HMS) replenishes the small leakages from the MPS as quantified in Table 14. This is done by transferring purified helium from commercially available helium storage containers into a storage vessel within the ICS. A limited supply of these containers is stored on site and replaced on an ongoing basis when necessary. The MPS is initially filled using external liquid helium containers connected via the HMS to the ICS storage vessels. The primary functions of the HMS are:

- To replenish the MPS daily helium leakages
- To initially fill the MPS with the required amount of helium

#### 3.2.5.4.1 Components of the helium make-up system

The components of the HMS are as follows:

- Compressor – transfers fresh helium when there is no pressure differential
- Control Valves
- Isolation Valves
- Pressure Relief Valves
- Piping
- Cylinder Banks – Fresh Purified Helium
- Initial Fill Liquid Helium Container
- Initial Fill Pump

#### 3.2.5.4.2 Operating characteristics of the helium make-up system

Refer to Table 14.

**Table 14: Operating Characteristics of the Helium Make-up System**

| Condition | Value |
|---|---|
| Daily leakage from MPS (to be made-up per day) | a,b |
| Helium purity | |
| Storage capacity of HMS | |

### 3.2.5.5 Dry gas seal supply and recovery system

The Dry Gas Seal Supply and Recovery System (DSRS) provides dust-free helium to the DGS of the Turbo Machines. This dust-free helium is used to prevent dust ingress into the DGS sealing faces. Purified helium from the DSRS is transferred to the DGS, where a large portion of the flow returns to the MPS through labyrinths. A small portion of the flow, leaking through the inner DGS seal face that does not return within the seal to the MPS (through the labyrinths), is recovered and externally compressed and returned to the MPS using an external compressor, thus minimizing the amount of helium lost. A flow diagram of the DSRS is shown in Figure 31. The primary functions of the DSRS are:

- To supply dust-free helium to the DGS of the Turbo Machines
- To recover helium from the DGS of the Turbo Machines
- To supply dust-free helium to the blowers of the CCS, the FHSS and the DSRS

#### 3.2.5.5.1 Components of the dry gas seal supply and recovery system

The components of the DSRS are as follows:

- Blower – provides for the necessary flow rate
- Compressor – returns a small portion of supply flow back to the MPS
- Control Valve
- Isolation Valve
- Piping
- Cylinder Pack – provides helium during start-up of back-up blower
- Cyclone Filter – removal of dust
- Fine Dust Filter – removal of dust

a,b

**Figure 31: Dry Gas Seal and Recovery System Process Flow Diagram**

#### 3.2.5.5.2 Operating characteristics of the dry gas seal supply and recovery system

Refer to Table 15.

**Table 15: Operating Characteristics of the Dry Gas Seal Supply and Recovery System**

| Condition | Value | |
|---|---|---|
| Supply flow rate per seal – normal operation (100% MCRI) | | |
| Supply pressure – normal operation (100% MCRI) | | a,b |
| Supply flow rate – PCU trip | | |
| Supply pressure – PCU trip | | |
| Recovery flow rate – normal operation (100% MCRI) | | |
| Recovery pressure – normal operation (100% MCRI) | | |
| Recovery flow rate – PCU trip | | |
| Recovery pressure – PCU trip | | |
| Compressor delivery pressure – inlet of MPS pre-cooler | | |
| Dust filter requirement | | |
| Redundant blower | | |
| Redundant compressor | | |
| Redundant dust filter | | |
| Flow rate through HPS dust filters (DSRS function) | | |
| Cyclone filter | | |
| Fine dust filter | | |
| Dust-free helium to helium blowers | | |

### 3.2.6 Turbo-generator Set

#### 3.2.6.1 Overview

The functions of the TGS are as follows:

- To provide flow during Brayton cycle start-up
- To provide flow for conditioning of MPS Component.
- To provide flow for the removal of core decay heat (Brayton cycle not operational)
- To provide flow to maintain the MPS at operating temperature after a PCU trip

##### 3.2.6.1.1 Brayton cycle start-up

The primary function of the TGS is to create the necessary flow rate within the MPS circuit for Brayton cycle start-up.

##### 3.2.6.1.2 Conditioning

The TGS is also used to condition the MPS components in order to minimize thermal stresses on MPS components during the start-up transient. This is done by simultaneously allowing the core to heat up to operating temperatures while creating a flow in the MPS circuit.

#### 3.2.6.1.3 Core decay heat removal

Motoring the TGS is also used to reduce the temperature of the MPS in order to go down to a maintenance condition, i.e. when the core is subcritical. This is done by reducing the Reactor Outlet Temperature (ROT) through the removal of core decay heat. This temperature reduction is done by creating a flow in the MPS and by manipulating the recuperator bypass valves in order to reduce the return temperature to the core. The pre- and intercoolers are thus used to extract heat from the system.

#### 3.2.6.1.4 Maintaining a constant reactor outlet temperature

In the event of a PCU trip, the aim is to initially maintain the MPS at operating temperatures in order to be able to restart the Brayton cycle.

This is done by motoring the TGS to create a flow in the MPS, and by manipulating the recuperator bypass valves in order to extract as much core decay heat as is being generated. Thus the ROT is maintained at a constant temperature.

### 3.2.6.2 Components and function

Refer to paragraph 10.2.4.

### 3.2.6.3 Operating conditions and modes

#### 3.2.6.3.1 Start-up characteristics

| Condition | Unit | Value |
|---|---|---|
| 40% MCRI start-up | | ( )b |
| • Inlet pressure | kPa | |
| • Flow rate | kg/s | |

#### 3.2.6.3.2 Decay heat removal characteristics

| Condition | Unit | Value |
|---|---|---|
| Decay heat removal down to maintenance conditions | | ( )b |
| • Inlet pressure | kPa | |
| • Flow rate | kg/s | |
| Maintaining reactor outlet temperature | | |
| • Inlet pressure | kPa | |
| • Flow rate | kg/s | |
| Transition from motored TGS to CCS | | |
| • Inlet pressure | kPa | |
| • Flow rate | kg/s | |

Table 16 maps operation with a motored TGS with respect to the MPS modes and states.

**Table 16: Operation with a motored Turbo-generator Set with respect to the Main Power System Modes and States**

| Plant Operating Modes and States | | Motored TGS Operation |
|---|---|---|
| (5) Power operation | (5b) Normal Power Operation<br>(5a) Reduced-capability Operation | a,b |
| (4) Operational Standby | (4b) PCU Operational | |
| (3) Standby | (3b) MPS Ready<br>(3a) Reactor Ready | |
| (2) Shutdown | (2c) Partial Shutdown<br>(2b) Intermediate Shutdown | |
| | (2a) Full Shutdown | |
| (1) Fuelled Maintenance | (1b) Closed Maintenance<br>(1a) Open Maintenance | |
| (0) Defuelled Maintenance | | |

### 3.2.7 Gas Cycle Valves

#### 3.2.7.1 System description

The Gas Cycle Valves (GCV) are situated on the PB. The main purpose of the valves is for control and equipment protection. The GCV consist of:

- Gas Cycle Bypass (GBP) Valves
- Low-pressure Compressor Bypass (LPB) Valves
- Low-pressure Coolant Valves (LCV)
- Recuperator Bypass Valves (RBP)
- Diverse Gas Bypass Control Valve (DGBP)
- GBP Control Valve (GBPC)

Figure 32 and Figure 33 show the position of the valves on the MPS.

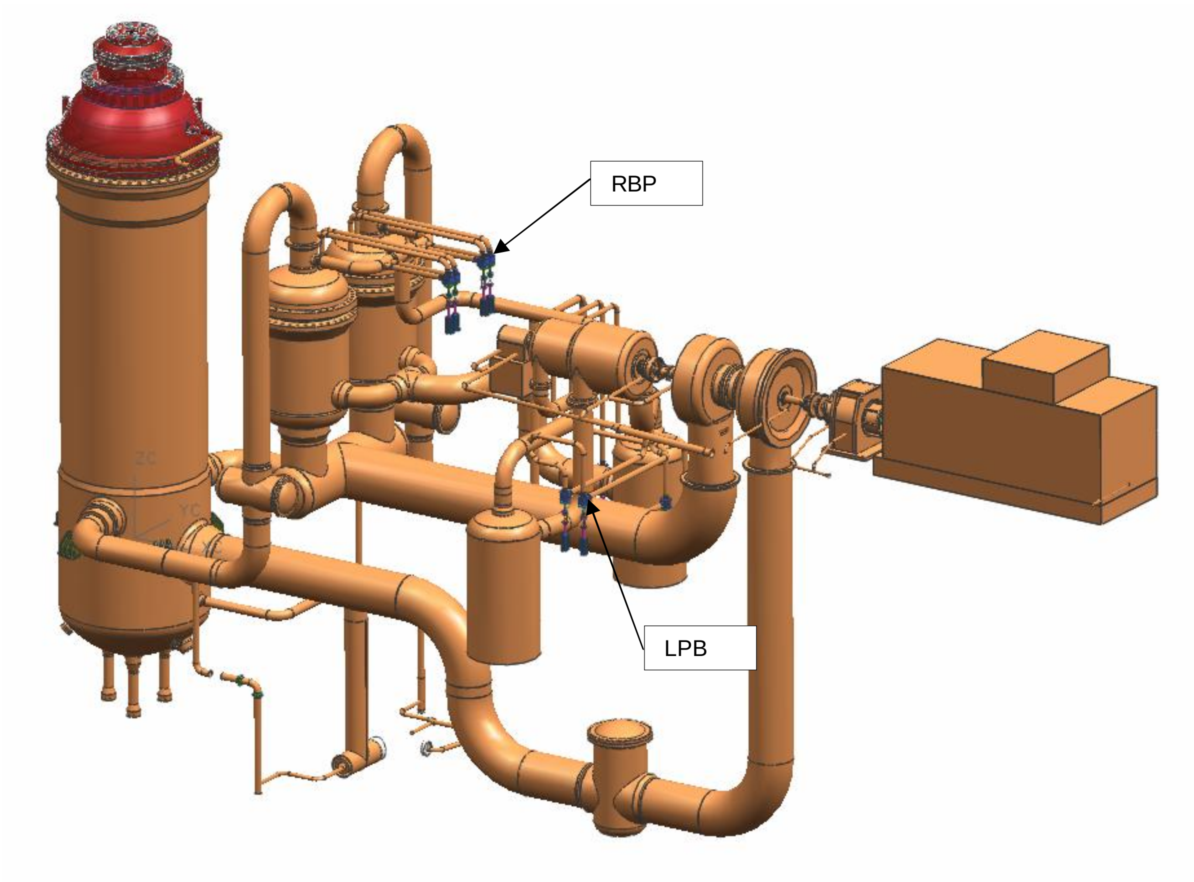



**Figure 32: Position of Gas Cycle Valves on the Main Power System**

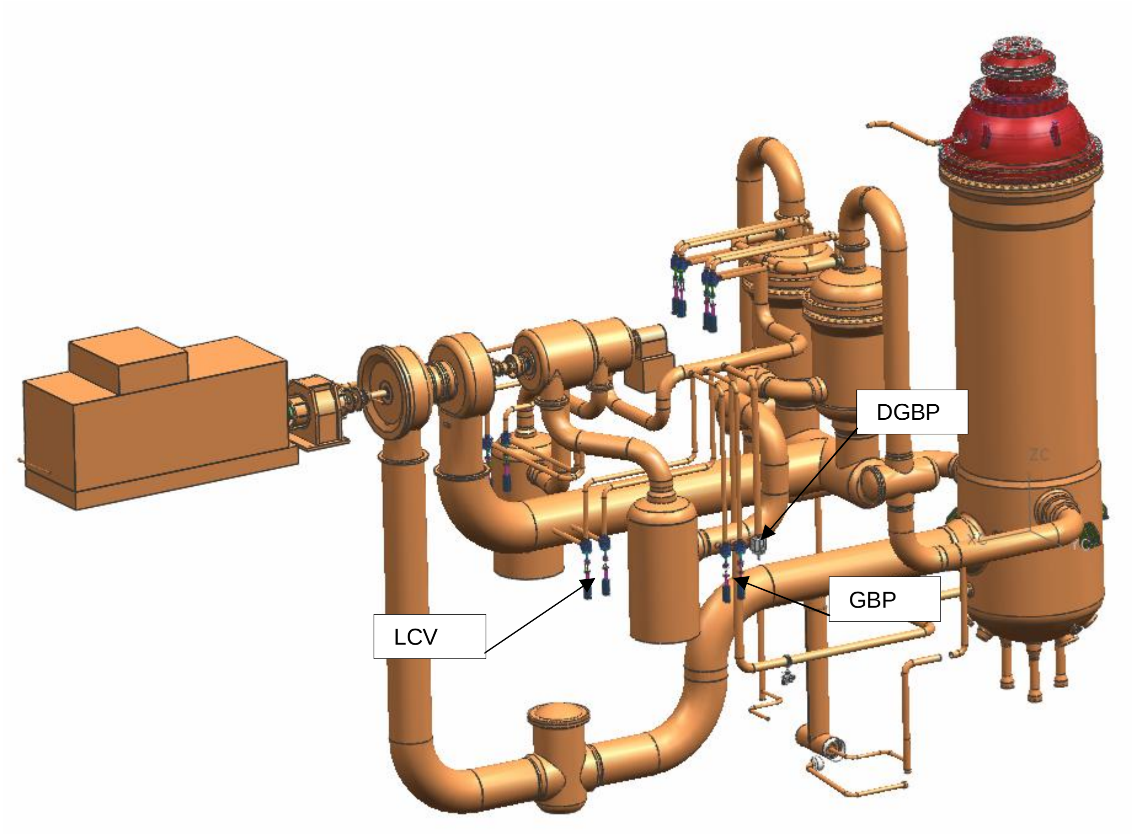



**Figure 33: Position of Gas Cycle Valves on the Main Power System**

The schematic diagram in Figure 34 shows the positions of GCV in the MPS.

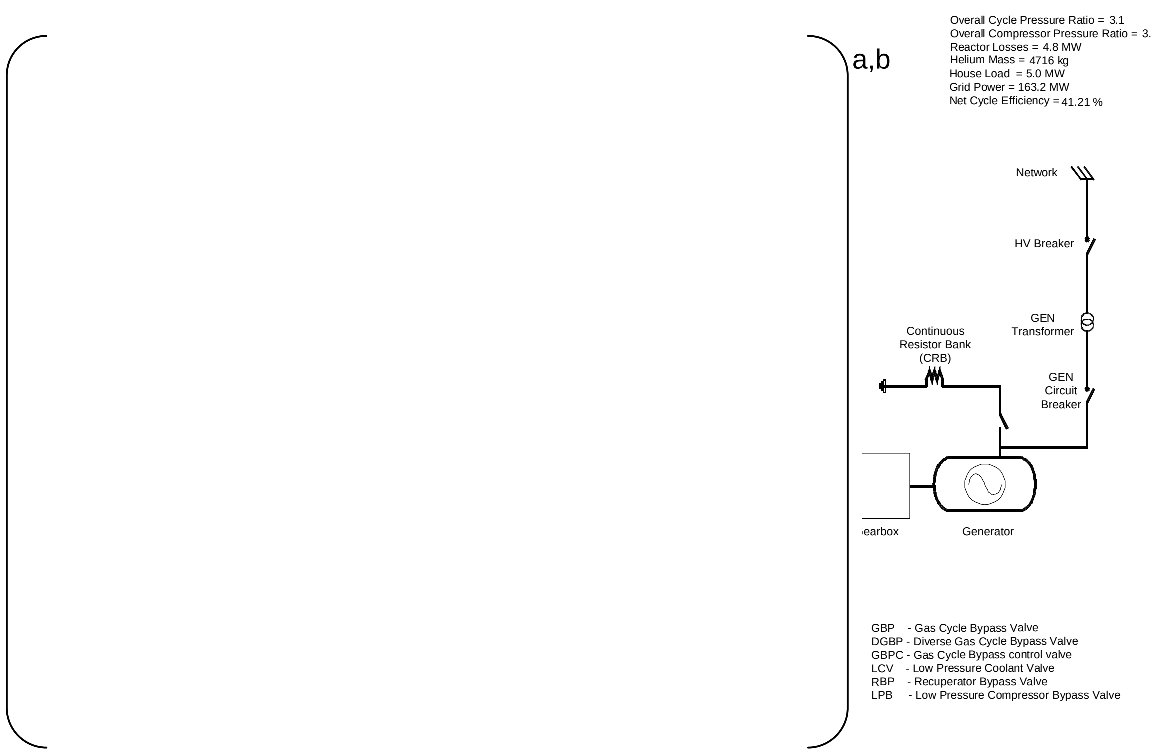



**Figure 34: Schematic Diagram Showing Positions of Gas Cycle Valves in Main Power System**

### 3.2.7.2 Functional description

#### 3.2.7.2.1 Gas cycle bypass valves

The GBP are used during the PCU trip and Loss of Load transients. The function of the valves is to ensure that PT over-speed does not occur during a PCU trip. The valves open and stay open until the Brayton cycle stops. During a Loss of Load, the valves have to close to keep the Brayton cycle in operation. The primary purpose of the valves is equipment protection.

The successful operation of these valves is critical to prevent over-speed of the PT.

These valves are fast-acting Isolation Valves and consist of [ ][b] valves. Figure 35 shows the location of the valves.

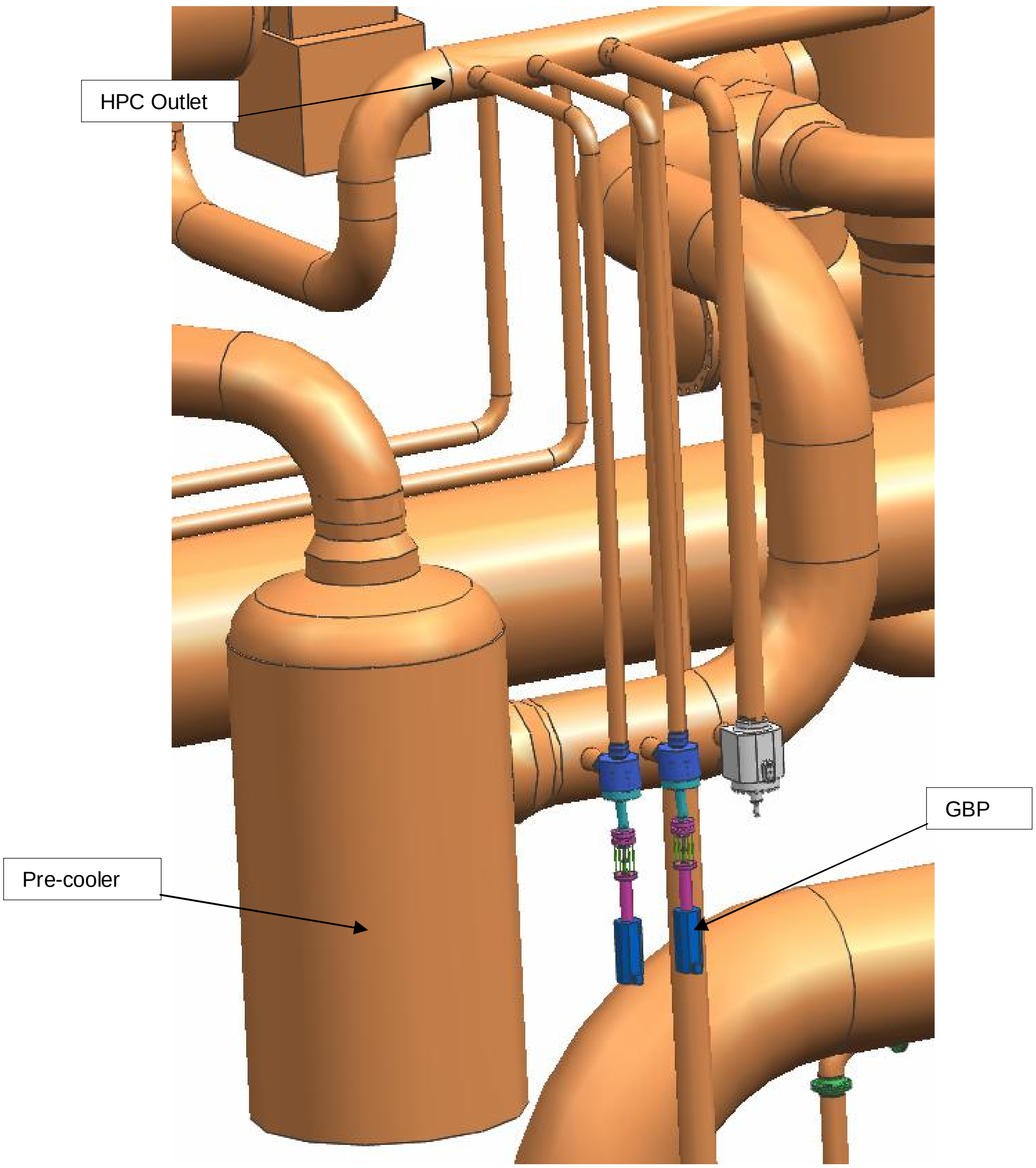



**Figure 35: Gas Cycle Bypass Valves**

#### 3.2.7.2.2 Low-pressure compressor bypass valves

The LPBs ensure that the MPS can operate at low power levels, but with a high helium inventory, typically 100% MCRI

The LPBs are Control Valves and consist of [ ][b] valves. Figure 36 shows the location of these valves.

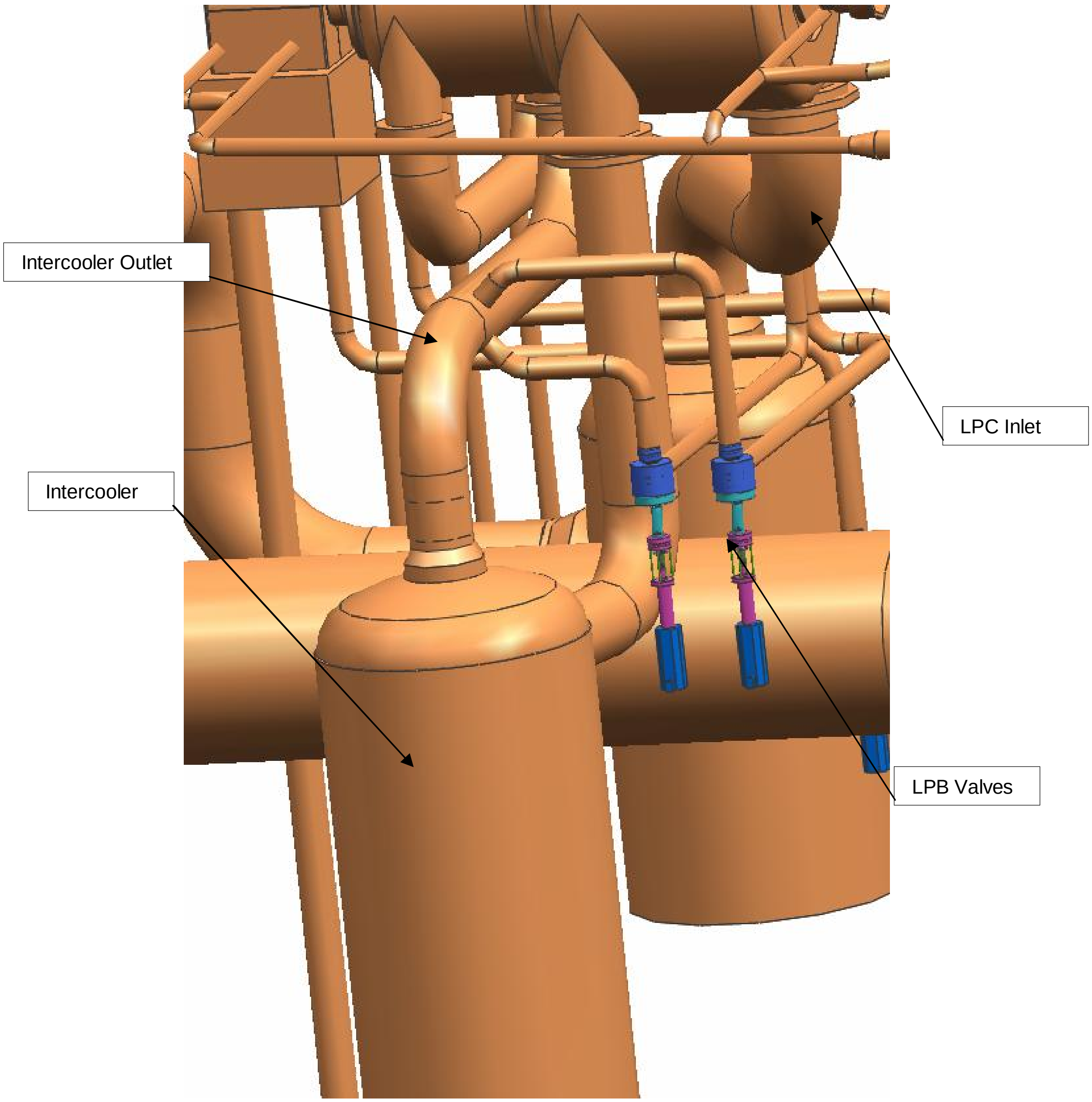



**Figure 36: Low-pressure Compressor Bypass Valves**

#### 3.2.7.2.3 Low-pressure coolant valves

The LCVs ensure that the temperature of the gas entering the recuperator does not exceed the specified limits. By opening the valves, cold gas from the HPC outlet mixes with the hot helium leaving the PT, thus decreasing the temperature of the helium that enters the recuperator. This occurs during transients.

The coolant valves are Control Valves and consist of [ ][b] valves. Figure 37 shows the location of these valves.

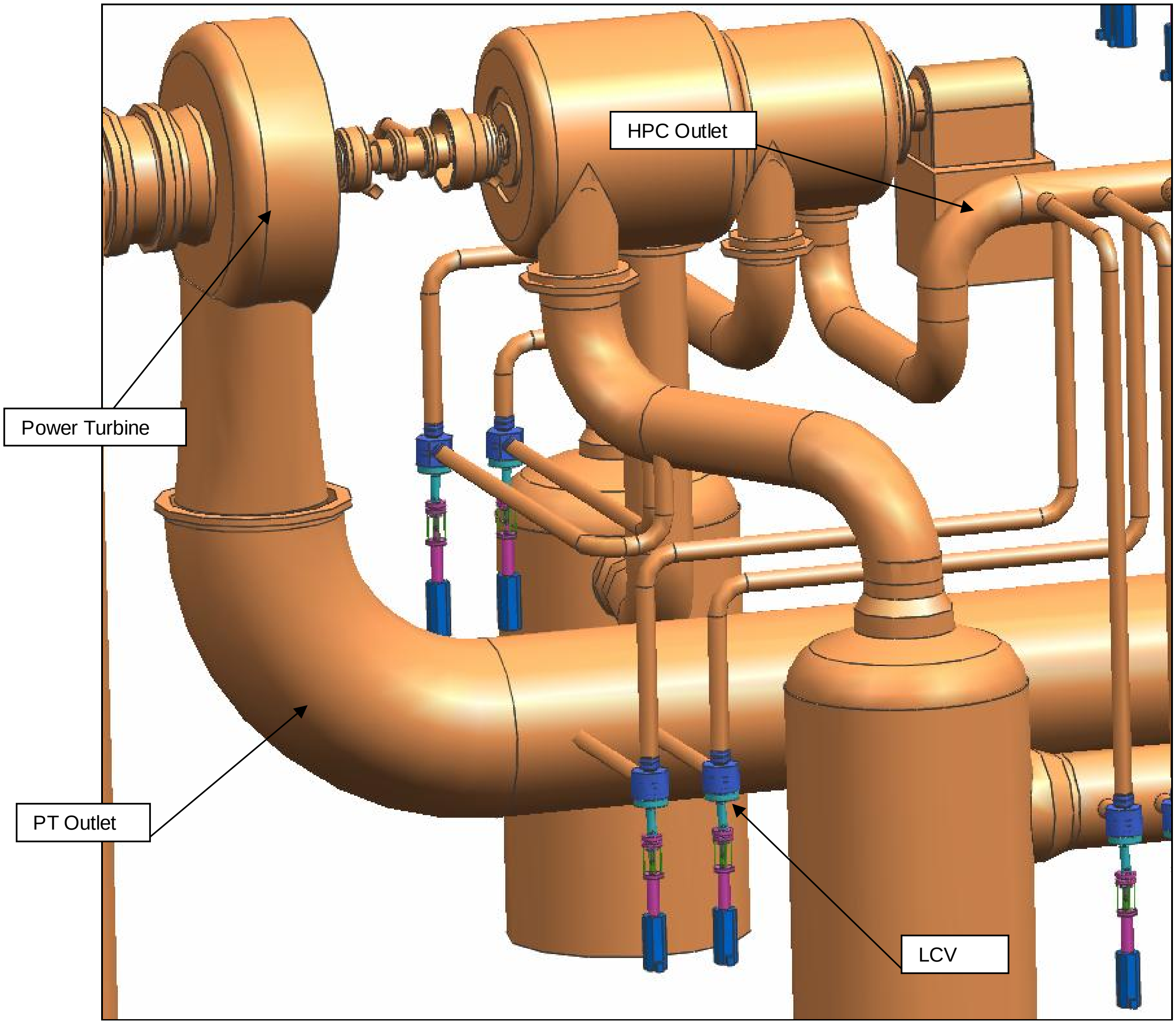



**Figure 37: Low-pressure Coolant Valves**

#### 3.2.7.2.4 Recuperator bypass valves

The RBPs are used when heat is being removed from the reactor. This valve is opened to ensure that helium returning to the reactor does not absorb all the heat coming from the reactor. Thus, the removal of heat in the pre-cooler is increased, and in this manner the heat generated in the reactor can be removed.

The RBPs are Control Valves and consist of [ ][b] valves. Figure 38 shows the location of these valves.

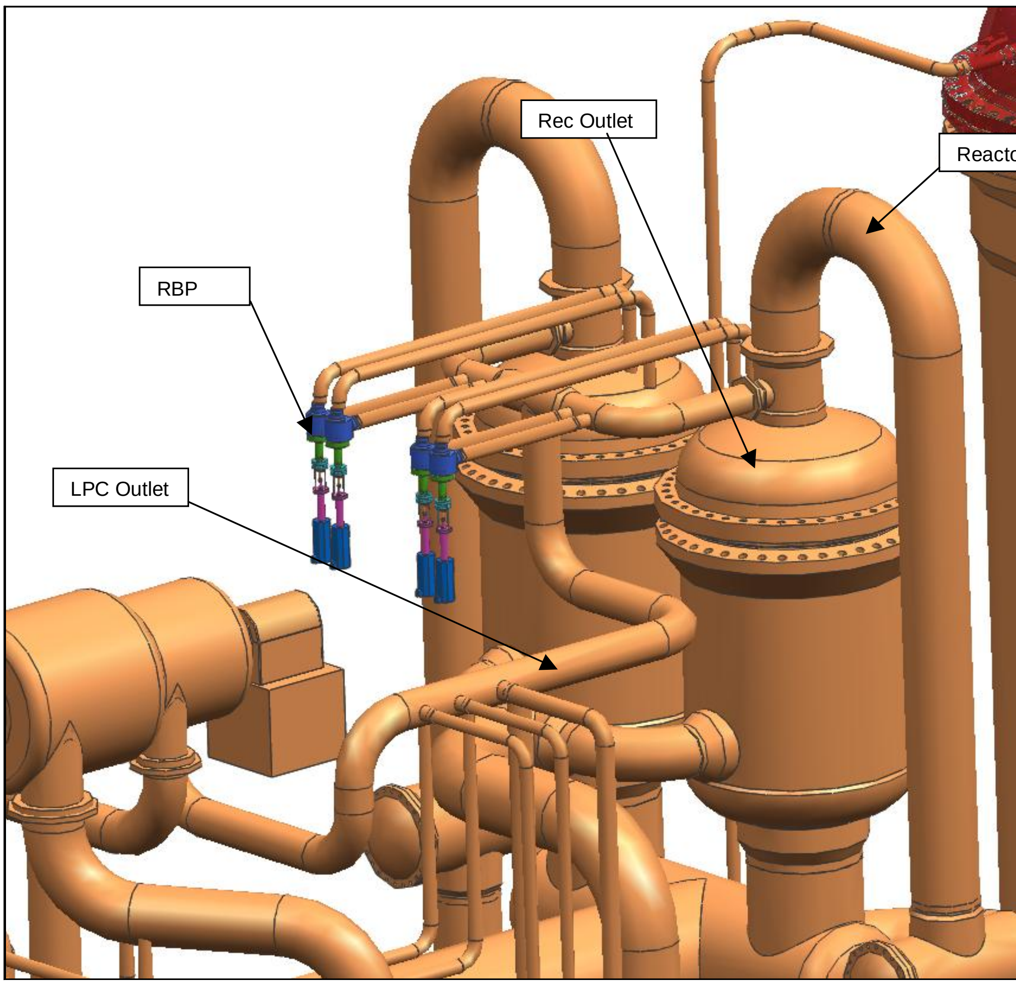



**Figure 38: Recuperator Bypass Valves**

### 3.2.7.2.5 Diverse gas bypass control valve

The DGBP serves as a diverse back-up for the GBP valves. This valve will use the process helium for actuation.

This is a quick-opening Isolation valve and the size will be equivalent to all the GBP valves.

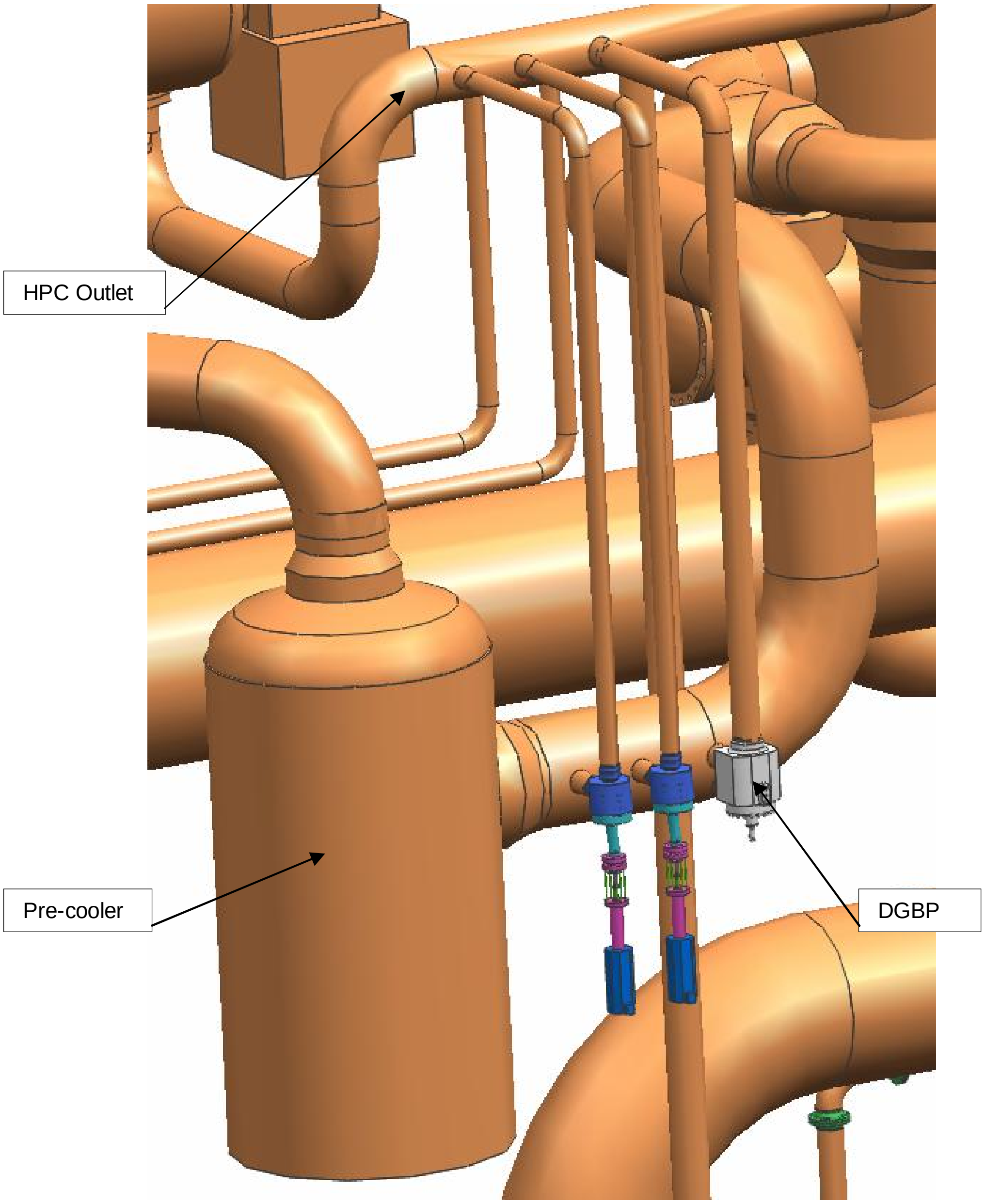



**Figure 39: Diverse Gas Cycle Bypass Valve Location**

#### 3.2.7.2.6 Gas cycle bypass control valve

The GBPC valve is used primarily in the normal power operation mode, and specifically to control power when in automatic generation control or primary frequency support.

The valves are opened to achieve a 'bypass reserve'. When the valves are closed, the power increases and vice versa. The adjustment of the valves, therefore, occurs frequently, but the mass flow rates through the valves are significantly less than those of the LPB valves.

The GBPC is a Control Valve and consists of [ ][b] valve. The GBPC is situated in the HICS between the HP- and LP Buffer Tanks.

### 3.2.8 Gas Cycle Pipe System

#### 3.2.8.1 System definition

The Gas Cycle Pipe System (GCPS) is a passive structure inside the PCU. This system conveys the helium gas between the CS and the PCU, as well as between the various components of the PCU. The GCPS consists of insulated pipes for the transport of hot gas (gas temperatures above [ ][b]). The insulated hot gas pipes include the pipe connections between the CS and the PT, the PT and the recuperator, and the pipes between the recuperator and the CS.

( ) a,b

For a representation of a typical hot gas pipe, refer to Figure 40 and Figure 40.

#### 3.2.8.2 System functions

The functions of the GCPS are:

- To transport hot helium ([ ][b]) between the various components of the MPS.
- To limit the heat loss from the hot gas to the rest of the system.

#### 3.2.8.3 Design description

##### 3.2.8.3.1 Layout

Refer to Figure 41 for the GCPS layout. Internally thermal insulated pipes are used to transport hot gas from one component of the MPS to another, inside a cooling environment. For this type of insulation, the temperature of the pressure-loaded pipe is significantly less than that of the hot gas. The advantages of having a low pipe temperature are that a high allowable stress in the pressure loaded pipe material can be allowed, a relatively small thermal expansion needs to be allowed for, and a small amount of heat loss.

a,b

##### 3.2.8.3.2 Main components

The GCPS consists of the following pipe sections:

a. Core outlet pipe

   The core outlet pipe connects the core internals with the PT. This pipe can be disconnected from the core internals to allow the core internals to be removed. Provision is made for sensors to measure temperature and pressure of the helium gas.

b. Turbine outlet pipe

   The turbine outlet pipe connects the PT to the recuperator.

c. Core inlet pipe – front

   The core inlet pipe – front connects the recuperator to the core internals. Provision is made for the installation of sensors to measure flow rate, temperature and pressure of the helium.

d. Core inlet pipe – back

   The core inlet pipe – back connects the recuperator to the core internals. Provision is made for the installation of sensors to measure flow rate, temperature and pressure of the helium.

e. CCS pipes

   The CCS pipes connect the CCS to the reactor inlet and outlet pipes. They consist of one CCS inlet pipe and one CCS outlet pipe. Provision is made for the installation of sensors to measure temperature of the helium.

a,b

**Figure 40: Core Outlet Pipe**

a,b

**Figure 40: Construction of Gas Cycle Pipe Insulation**

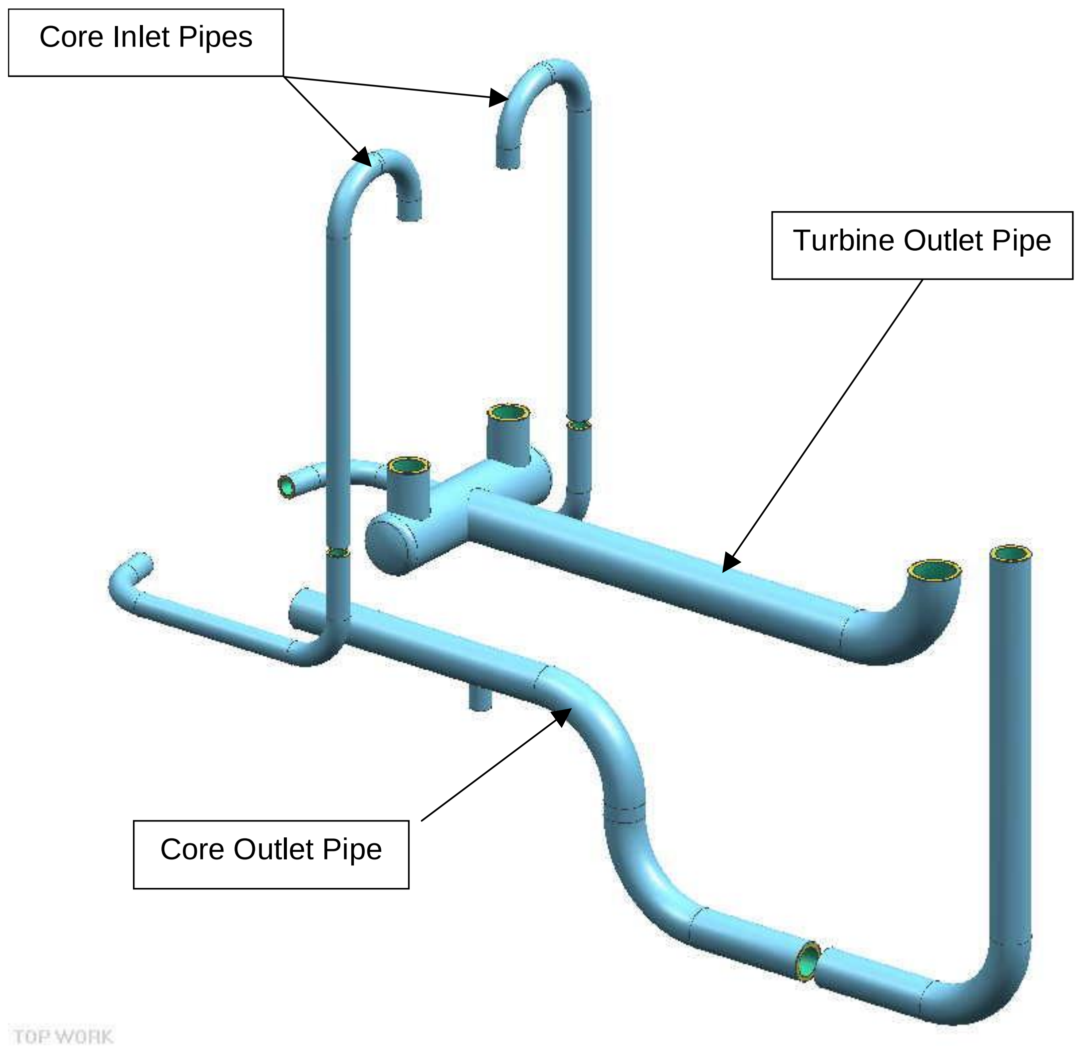



**Figure 41: Gas Cycle Pipe System Layout**

#### 3.2.8.3.3 Control and instrumentation

The temperature and pressures of the gas are monitored at various positions within the GCPS.

### 3.2.8.4 Performance

The GCPS is exposed to the internal conditions of the PCU, and is designed to guide the transport of the hot helium over the life of the plant without the need for maintenance or replacement. Pipe sections and expansion joints are welded together to form leak-tight pipe assemblies. The pipe ends are also welded to ensure the required leak-tightness. The GCP connections to the CB are bolted and are designed for a bypass leak rate of < 0.2 g/s. All the GCPs are subjected to external pressure. Table 17 gives an indication of the typical nominal conditions to which the GCPS is subjected.

**Table 17: Gas Cycle Pipe System Nominal Operating Conditions**

| Pipe | Differential Pressure (kPa) [(1)] | Temperature (°C) | Helium Flow Velocity (m/s) |
|---|---|---|---|
| Core Outlet Pipe | | | b |
| Turbine Outlet Pipe | | | |
| Core Inlet Pipe – Front | | | |
| Core Inlet Pipe – Back | | | |
| CCS – Cold Pipe | | | |
| CCS – Hot Pipe | | | |

**Note 1:** Highest pressure is external to the pipes.

#### 3.2.8.4.1 Operation

The GCPS is a passive system, its only function being to provide a flow duct for the main gas stream. The gas mass flow characteristics are determined by the operation of the PCU.

#### 3.2.8.4.2 Loads

All normal operating steady-state and transient loads, as well as all abnormal operating conditions, are considered in the design of the GCPS. In addition, all loads induced by the relevant Licensing Basis Events (LBEs) are considered.

#### 3.2.8.4.3 Materials

Materials for the manufacture of the GCPS are selected from those for which data are available. The materials used in the design can be summarized as follows:

- Pressure pipe : a,b
- Liner :
- Insulation outer shell :
- Insulation mats :
- Insulation wool :

#### 3.2.8.4.4 Codes

Where applicable, internationally accepted codes and standards are used for the design of the components of the GCPS. Where no such codes and standards exist, evidence of past references shall be provided to show that the design process meets the requirements of safety and reliability. Where this is not possible, the designs shall be proven by acceptable validation tests on prototype components or systems. The design is based on ASME B31.1.

#### 3.2.8.4.5 Mechanical failure of pressure pipe

The Gas Cycle Pipes (GCPs) are subjected to external pressure, and rupture of these pipes is not expected. The most likely failure mechanism is a crack that will result in an in-leakage of the cold higher-pressure helium into the pipe. This will result in an immediate reduction of cycle efficiency, but nuclear safety is not compromised. In the extreme case, a collapse of the GCP can be postulated. This will result in a Pressurized Loss of Forced Cooling (PLOFC). Large pressure oscillations are not expected, because these pipes connect relatively large volumes in the MPS, and these volumes will damp any oscillations.

### 3.2.9 Main Power System Pressure Boundary

### 3.2.9.1 Design basis

#### 3.2.9.1.1 Functions

The functions of the Main Power System Pressure Boundary (MPS-PB) are:

- Containment of the helium coolant inventory at operating pressure
- Acting as a barrier to the release of circulating fission products to the environment
- Provision of structural support and alignment for the PCU components
- Transfer of the decay heat from the reactor core via the RPV as part of the PB to the Reactor Cavity Cooling System (RCCS) during loss of forced cooling events (ensure adequate core heat removal)
- Maintenance of the geometry of the core within acceptable geometrical limits under all normal and abnormal events
- Provision of structural support and alignment for the RU components.

### 3.2.9.2 Operating principles

#### 3.2.9.2.1 Performance criteria

The MPS-PB is designed to withstand all the normal operating conditions over a lifetime of 35 Full Power Years (FPY), and all the abnormal conditions for the specified number of occurrences, without any degradation of its ability to perform its nuclear and non-nuclear safety-related functions. The MPS-PB is designed for a maximum working pressure of 9.0 MPa, and a design pressure of 9.7 MPa.

#### 3.2.9.2.2 Normal operation

The highest operational pressure to which the MPS-PB will be subjected is 9.0 MPa, which is the highest possible pressure that can be achieved by the two turbo-compressors during normal operation at 100% Maximum Continuous Rating (MCR), i.e. at full helium inventory with all bypass valves closed. The internal surface of the PCU pipes and vessels is maintained at 100 °C by the helium stream leaving the HPC, which is at this temperature. During normal operation, the recuperator and pre-cooler vessels, and connecting pipe are exposed to helium gas temperatures of 150 °C, and the intercooler vessel and connecting pipes to 130 °C. The pressures of these vessels are 3.0 MPa (recuperator and pre-cooler vessels) and 5.2 MPa (intercooler vessel) respectively. The RPV is operated at higher temperatures of 280 °C to 300 °C to ensure that it is maintained within the temperature envelope of established neutron fluence data.

Following a PCU trip, the pressure inside the MPS-PB rapidly equalizes at 6.8 MPa, thus the pressure of the RPV and PCU pipes and vessels will decrease, and that of the recuperator, the pre-cooler and intercooler vessels will increase.

The CCS vessel is subjected to the same conditions as the RPV.

#### 3.2.9.2.3 Abnormal operation

In a Depressurized Loss of Forced Cooling (DLOFC) event, the pressure will rapidly decrease to atmospheric, and the RPV wall temperature will increase to [ ][b]. During a Pressurized Loss of Forced Cooling (PLOFC) event, the pressure will rapidly decrease to 6.8 MPa, and the RPV wall temperature will increase to [ ][b].

### 3.2.9.3 Description

#### 3.2.9.3.1 Reactor pressure vessel description

The RPV consists of a main cylindrical section with torispherical upper and lower heads. The upper head is bolted to the cylindrical section and incorporates penetrations for the mechanisms of the FHSS, RCS, RSS, CBCS, and for the in-core instrumentation. An opening is provided in the centre of the upper head to allow access to the CS for reflector replacement.

The lower head is welded to the main cylindrical section, and will have openings for fuel discharge, the RSS discharge, the CBCS, and an access opening intended for use only during initial installation operations.

The nozzle forgings of the PCUPV and the vessel supports are attached to the lower reinforced part of the cylindrical section. This part is reinforced to withstand reactor vessel support loads and manifold nozzle loads. The RPV supports provide vertical as well as bottom horizontal support.

The shell flange at the top of the vessel accommodates the studs for bolting down the pressure vessel closure head. The studs are of the scant shank type, screwed into blind tapped holes in the flange ring.

The RPV has an internal diameter of 6.2 m and a nominal thickness of 180 mm. The top and reinforced parts have a thickness of 285 mm. The vessel head has an internal radius of 3.75 m and a nominal thickness of 165 mm, and for the bottom dome, these measurements are 3.75 m and 165 mm respectively. The maximum external diameter of the RPV is approximately 7.3 m (over vessel head flange) and its total length is approximately 30.17 m. The mass of the RPV with the vessel head is estimated at 1 250 t.

Localized shielding may be attached to structures inside the RPV top part to reduce activation of the RPV head.

The nuts and washers have convex mating surfaces in order to ensure favourable load distribution. Welded-lip seals provide leak tightness. Additional reinforcement is provided at the level of the upper attachment points for the upper seismic restraints. The CS is vertically supported at the bottom by a foot support that is part of the bottom dome.

A separation structure isolates the RPV and PCU volumes, but allows equalization of pressure.

#### 3.2.9.3.2 Power conversion unit pressure boundary description

The Power Conversion Unit Pressure Boundary (PCUPB) consists of:

- Power Turbine Vessel
- High Pressure Compressor Vessel
- Low Pressure Compressor Vessel
- Recuperator Vessels
- Pre-cooler Vessel
- Intercooler Vessel

These vessels are interconnected by means of:

- Reactor Pressure Vessel – Power Turbine Connection Pipe
- Power Turbine – Recuperator Vessels Connection Pipe
- Recuperator Vessels – Pre-cooler Vessel Connection Pipe
- Pre-cooler Vessel – Low-pressure Compressor Casing Vessel Connection Pipe
- Low-pressure Compressor Casing Vessel – Intercooler Vessel Connection Pipe
- Intercooler Vessel – High-pressure Compressor Casing Vessel Connection Pipe
- High-pressure Compressor Casing Vessel – Recuperator Vessel Connection Pipe
- Recuperator Vessel – Reactor Pressure Vessel Connection Pipes.

The Recuperator Vessels (RCVs) have an internal diameter of [ ][b] and a nominal thickness of [ ][b].

The Pre-cooler Vessel (PCV) has an internal diameter of [ ][b] and a nominal wall thickness of [ ][b].

The Intercooler Vessel (IV) has an internal diameter of [ ][b] and a nominal wall thickness of [ ][b].

The PCUPB is connected to the RPV by means of three cylindrical sections, i.e. the Reactor Pressure Vessel – Power Turbine Connection Pipe (Core Outlet) and the two Recuperator Vessel – Reactor Pressure Vessel Connection Pipes (Core Inlet) sections. The Reactor Pressure Vessel – Power Turbine Connection Pipe (Core Outlet) has an internal diameter of [ ][b] and a nominal wall thickness of [ ][b], and the two Power Turbine Vessel (PTV)-RPV connection pipes have internal diameters of [ ][b] and a nominal wall thickness of [ ][b].

The Power Turbine – Recuperator Vessels Connection Pipe has an internal diameter of [ ][b] and a nominal wall thickness of [ ][b].

The MPS-PB is designed such that all the major components can be installed and removed from the top. The MPS-PB is provided with reinforced openings for access, inspection and cable and instrumentation penetrations. The mass of the PCUPB is estimated at approximately 850 t.

All components of the MPS are mounted on support structures attached to the inside of the RPV and PCUPV.

### 3.2.9.3.3 Support arrangement

( )[a,b]

The supports for the RPV are designed to maintain the concrete structures at acceptable temperatures.

### 3.2.9.3.4 Thermal insulation

The complete MPS-PB is externally insulated, except for the part of the RPV that corresponds to the height of the active core. This is to passively transmit core heat from the reactor to the RCCS. The purpose of this external insulation is to limit heat loss from the system, and insulation of a conventional design is foreseen.

### 3.2.9.3.5 Materials

The RPV is manufactured from carbon steel SA 533 Type B Class 1 for plates, SA 508 Type 3 Class 1 for forgings and SA 540 Grade B24 Class 3 for bolts.

The PCUPV is manufactured from carbon steel SA 533 Grade B Class 2 for plates, SA 508 Grade 3 Class 2 for forgings and SA 540 Grade B24 Class 3 for bolts.

Embrittlement of the RPV material due to fast neutron irradiation damage cannot be excluded, but preliminary analysis indicates it is less severe than that in the currently operating Pressurized Water Reactors (PWRs). Since the PBMR RPV is operated at the same wall temperatures as the PWR, the existing worldwide materials database on neutron embrittlement is expected to be applicable.

### 3.2.9.3.6 Design code

The RPV shall be designed and constructed to ASME III, Division I, Subsection NB and Code Case N-499-2. The PCUPV shall be designed and constructed to ASME III, Division I, Subsection NC. An N-Stamp will not be required, but the quality is demonstrated to be at least equal to that of ASME III.

#### 3.2.9.3.7 Major equipment

The MPS-PB System consists of the following components:

a. Reactor Pressure Vessel (RPV)

   The RPV contains the RU components, i.e. the Core Support Structures, the RCSS components, and the parts of the Fuel Handling, CCS and CBCS.

b. Power Conversion Unit (PCU)

   The PCU portion of the MPS-PB comprises the following:

   - Reactor Pressure Vessel – Power Turbine Connection Pipe
   - Core Outlet Pipe Maintenance Shut-off Disk Vessel
   - Power Turbine Casing Vessel (contains the Power Turbine)
   - Power Turbine – Recuperator Vessels Connection Pipe
   - Recuperator Vessels (containing the Recuperator cores)
   - Recuperator Vessels – Pre-cooler Vessel Connection Pipe
   - Pre-cooler Vessel (contains the Pre-cooler)
   - Pre-cooler Vessel – Low-pressure Compressor Casing Vessel Connection Pipe
   - Low-pressure Compressor Casing Vessel (contains the Low-pressure compressor)
   - Low-pressure Compressor Casing Vessel – Intercooler Vessel Connection Pipe
   - Intercooler Vessel (contains the Intercooler)
   - Intercooler Vessel – High-pressure Compressor Casing Vessel Connection Pipe
   - High-pressure Compressor Casing Vessel (contains the High-pressure compressor)
   - High-pressure Compressor Casing Vessel – Recuperator Vessel Connection Pipe
   - Recuperator Vessel – Reactor Pressure Vessel Connection Pipes
   - Core Inlet Pipe Maintenance Shut-off Disk Vessels
   - Core Outlet Pipe – Core Conditioning System Vessel Connection Pipes
   - Core Conditioning System Vessel – Core Inlet Pipe Connection Pipes

c. Core Conditioning System (CCS)

   The CCS is connected to the reactor outlet and inlet pipes by two pipes.

d. Core Barrel Conditioning System Vessel (CBCSV)

   The CBCSV contains the CBCS blowers. This vessel is connected to the RPV by two pipes.

e. Vessel Support System

   The Vessel Support System transfers the weight of the MPS-Pressure Boundary System to the building and maintains its orientation under all postulated abnormal conditions. The Vessel Support System consists of:

   - Reactor Pressure Vessel Support System, which provides the vertical and horizontal support for the RPV. It constrains the RPV in a seismic event.
   - Power Conversion Vessel Support System, which provides the vertical and horizontal support for the Power Conversion Vessel, and also provides the necessary seismic constraints.

f. MPS-Pressure Relief System

   The MPS-PRS provides the over pressure protection of the MPS-PB System.

g. Vessel External Insulation System

   The External Insulation System limits parasitic heat losses from the MPS-PB System.

#### 3.2.9.3.8 Instrumentation and controls

Instrumentation for surveillance and monitoring is provided.

#### 3.2.9.3.9 Loads

All normal operating steady-state and transient loads, as well as all abnormal operating conditions, are considered in the design of the MPS-PB. In addition, all loads induced by the relevant Design Basis Accidents (DBAs) are considered in the design basis. These include PLOFC, DLOFC and other enveloping events. Design pressures and temperatures are given in Table 18.

The nominal performance characteristics of the MPS-PB are summarized in Table 17.

**Table 18: Design Pressures and Temperatures**

| Vessels | Pressure (kPa) | Temperature (°C) |
|---|---|---|
| RPV, CCSV | 9 700 | 350 |
| PCU PB | 9 700 | 250 |

#### 3.2.9.3.10 Special protective measures or equipment

The MPS-PB shall be protected against over pressurization by pressure relief devices as required by ASME III. This shall consist of two pressure relief devices. The set point of one device is 9.7 MPa and the other is 10.67 MPa (110% of the design pressure).

#### 3.2.9.3.11 High reactor pressure vessel wall temperatures

( )a,b

In a DLOFC event, the RPV wall temperature will, over time, increase to 527 °C, but the pressure will rapidly decrease to atmospheric. As in the previous case, this temperature is limited primarily by the RCCS.

#### 3.2.9.3.12 Pipe breaks

The MPS-PB is designed to handle a design basis pipe break, the equivalent diameter of which is currently being investigated, but it could be as large as 230 mm. Such a break will not cause gross deformations, loss of dimensional stability, damage to safety classified SSC, or damage to non-replaceable Structures, Systems and Components (SSC) of the MPS. The MPS-PB may, however, require localized inspections and repair before it is returned to service.

#### 3.2.9.4 Test and inspection

##### 3.2.9.4.1 Pre-operational testing

The MPS-PB shall be subjected to all pre-operational integrity tests as required by the design and construction code. It shall also satisfy all statutory requirements with regard to pressure testing.

##### 3.2.9.4.2 Surveillance testing

A detailed analysis has not yet been performed to determine the end of life neutron fluence. Final calculations can only be performed during the detail design phase. However, if this analysis shows that the fluence at the end of design life will exceed 1 x $10^{17}$ n/$cm^2$ of E > 1 MeV neutrons, an RPV material surveillance programme is implemented. Fracture toughness requirements are established from internationally accepted practice.

##### 3.2.9.4.3 In-service inspection

The design of the MPS-PB System makes provision for all probable In-service Inspection (ISI) that may be required by the design code and inspection authorities. The MPS-PB is designed to allow inspection of all welds externally. The RPV is provided with the necessary features, rails, etc. to allow for external remote inspection.

a,b

**Figure 42: Main Power System Schematic**

# 4. FUEL

## 4.1 FUEL SPECIFICATION

Nominal characteristics for a PBMR fuel sphere are shown in Table 19.

**Table 19: Nominal Characteristics for PBMR Fuel Sphere**

| Characteristic | Unit | Nominal Value |
|---|---|---|
| **Fuel Sphere:** | | |
| Geometry | - | Spherical |
| Fuel sphere diameter | mm | 60 |
| Fuel region diameter | mm | 50 |
| Fuel-free region thickness | mm | 5 |
| Heavy metal loading | g/FS | 9 |
| Uranium enrichment | % U-235 | 9.6 (equilibrium core) |
| **Coated Particle:** | | |
| Kernel diameter | μm | 500 |
| Buffer layer thickness | μm | 95 |
| Inner Low Temperature Isotropic (ILTI) layer thickness | μm | 40 |
| SiC layer thickness | μm | 35 |
| Outer Low Temperature Isotropic (OLTI) thickness | μm | 40 |

The spherical PBMR fuel sphere is cold pressed from matrix graphite, which is a mixture of natural graphite, electrographite, and a phenolic resin that acts as binder. It consists of an inner region that contains fuel in the form of spherical coated particles embedded in the matrix graphite. A shell of matrix graphite that does not contain any fuel surrounds the inner region.

A coated particle consists of a spherical uranium dioxide kernel surrounded by four concentric coating layers. The first layer surrounding the kernel is a porous pyrocarbon layer, known as the buffer layer. An inner high-density pyrocarbon layer, a silicon carbide layer, and an outer high-density pyrocarbon layer follow this layer. The layers are deposited sequentially by dissociation of gaseous chemical compounds in a continuous process in a fluidized bed.

Figure 43 shows the design of the PBMR fuel sphere.

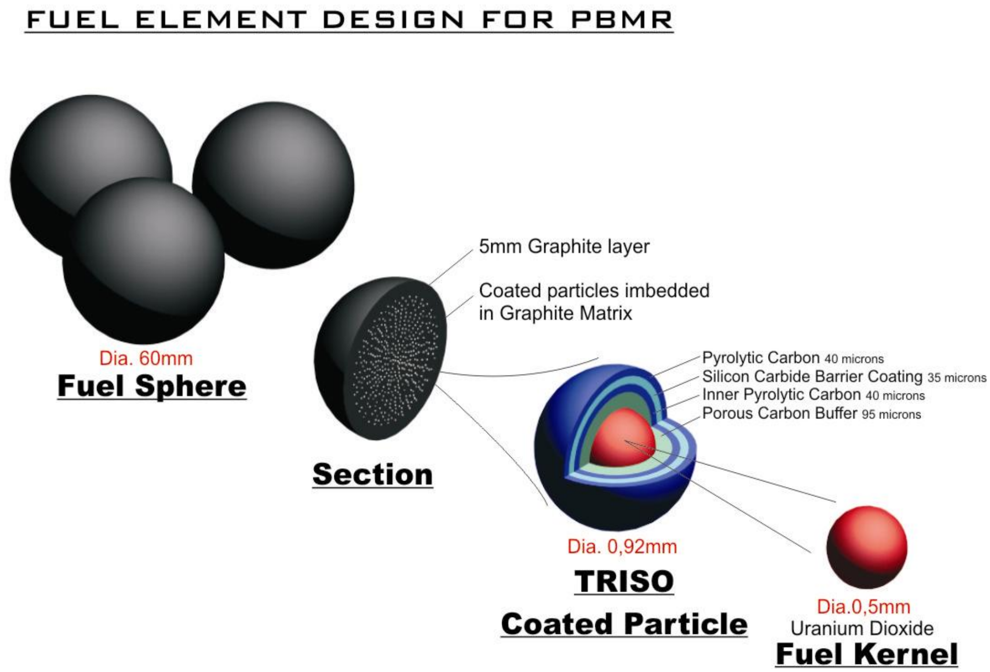



**Figure 43: PBMR Fuel Sphere Design**

## 4.2 COATED PARTICLE

The properties of LEU-TRISO coated particles are among the most important factors determining the radiological safety of the PBMR. This is because the fission product retention in the fuel spheres, and the maximum fuel temperature that can be tolerated in the reactor core, are determined by the coated particle properties.

### 4.2.1 Kernel

Nuclear fission reactions in the kernel produce a mixture of radioactive fission products. Among these there are some gaseous as well as some volatile (mainly metallic) chemical elements, which cause stress in the coatings surrounding the kernel because of the pressure they exert. Therefore wet chemical processes that produce highly spherical kernels are used during the initial stages of kernel manufacture. This ensures that stress concentrations leading to crack formation in coating layers during irradiation in the reactor are prevented.

The spherical fuel kernel consists of stochiometric uranium dioxide ($UO_2$). The basic manufacturing steps for the kernel are as follows. $U_3O_8$ powder is dissolved in nitric acid to form uranyl nitrate. The solution is neutralized with ammonia and allowed to flow through an oscillating nozzle to produce spherical droplets. As the droplets fall through a gaseous ammonia atmosphere, the spherical outer surface of the droplet gels. The particles fall into an aqueous ammonia solution where they solidify into ammonium uranate. They are then aged and washed to remove ammonium nitrate and organic additives, dried, and calcined. The dry kernels are reduced to $UO_2$ in hydrogen and sintered, and are then ready to be coated.

### 4.2.2 Buffer Layer

The first layer in contact with the kernel is known as the buffer layer, and it is deposited at a temperature of approximately [ ][b] from acetylene ($C_2H_2$). The temperature and other conditions in the fluidized bed are adjusted to produce a porous pyrocarbon layer that has approximately 50% of the theoretical density of pyrocarbon.

The purpose of the buffer layer is to provide void volume for gaseous fission products in order to limit pressure build-up within the coated particle. It also serves to decouple the kernel from the inner pyrocarbon layer to accommodate kernel swelling, thereby reducing the build-up of stress in the outer coating layers during irradiation.

### 4.2.3 Inner Pyrocarbon Layer

The inner high-density, isotropic layer of pyrolytic carbon is also referred to as the Inner Low Temperature Isotropic (ILTI) pyrocarbon layer. It is deposited from a mixture of acetylene and propylene at a temperature of approximately [ ][b] in a fluidized bed, and has an average density of approximately [ ][b]

The ILTI layer forms the first load-bearing barrier against the pressure exerted by fission products within the fuel kernel and buffer layer, thereby reducing the pressure on the next layer, which consists of silicon carbide (SiC). During irradiation, the ILTI and Outer Low Temperature Isotropic (OLTI) layers shrink at first, expanding again as higher fast neutron dose levels are reached. The interaction between the ILTI and OLTI high-density pyrocarbon layers and the SiC layer sandwiched between them plays an important part in keeping the SiC layer under compressive stress as long as possible during irradiation.

Although an intact ILTI layer forms a practically impenetrable barrier for fission gases and iodine, it becomes increasingly pervious to caesium, silver and strontium at higher temperatures.

### 4.2.4 Silicon Carbide Layer

When SiC is deposited from methyltrichlorsilane at approximately [ ][b] under the correct conditions, a layer of nearly 100% theoretical density is obtained.

At high temperatures, the ILTI and OLTI layers partially lose their ability to contain caesium, silver and strontium. The purpose of the SiC layer is to prevent the release of these fission products into the graphite matrix, and thence into the reactor coolant stream. The SiC thus acts as the principal pressure and fission product retention barrier in the coated particle. The coated particle structure results in the SiC layer being kept under compression as long as possible by its interaction with the ILTI and OLTI pyrocarbon layers as described above.

The production of fuel elements having coated particles with intact SiC layers, and the guarantee that these layers will remain intact under all foreseeable reactor core conditions, form the most fundamental basis for the safe operation of the PBMR.

### 4.2.5 Outer Pyrocarbon Layer

The OLTI pyrolytic carbon layer is deposited in exactly the same way as the ILTI layer. The function of this layer is to protect the SiC layer against damage in the fuel manufacturing processes following on the coating process. It also provides prestress on the outside of the SiC layer, due to its interaction with the ILTI layer under fast neutron irradiation during the fuel lifetime in the reactor core, thereby reducing the tensile stress in the SiC layer.

Experience has shown that coated particle failure in fuel elements can be greatly reduced through a sorting process, by removing particles that show an unacceptable deviation from a spherical shape. During isostatic pressing, unround coated particles show a much greater tendency to crack, than spherical particles.

## 4.3 FUEL SPHERE

### 4.3.1 Overcoating

Before the final pressing of a fuel sphere, a coating of finely ground matrix graphite is applied to the outer surface of each coated particle in a rotating drum. This coating is known as the 'overcoat', and its purpose is to prevent coated particles from coming into contact with each other, thereby damaging their coatings during pressing of the fuel elements.

### 4.3.2 Matrix Graphite

Coated particles are embedded in matrix graphite. Highly graphitized materials are used for fuel manufacture for the following reasons:

- Highly graphitized material ensures dimensional stability during irradiation with fast neutrons, as partially graphitized material will undergo further graphitization under fast neutron irradiation, with accompanying dimensional changes.
- Once a fuel element has been pressed, it is no longer possible to change the degree of graphitization of the materials contained in the fuel element. Graphitization takes place in the temperature range 2 700 °C to 3 000 °C, at which temperatures SiC is dissociated and the fission product retention capability is destroyed. Therefore, after pressing and machining, the final heat-treatment of pressed fuel spheres is done at a temperature of [ ] . Thus each fuel element will contain some ungraphitized material originating from coking of the resinous binder material at [ ][b].
- Highly graphitized material also has the desirable property that it can be relatively easily pressed to the required density.

The function of the matrix graphite is to contain and protect the coated particles in a fuel sphere from mechanical damage and to provide a heat conduction path between the coated particles and the reactor coolant. The carbon in the matrix also acts as the moderator for neutrons in the PBMR core.

### 4.3.3 Pressing

Fuel spheres are pressed at high pressure, without the application of external heat, to obtain the required density that ensures adequate stability and heat conduction. This also provides the correct amount of carbon in the reactor core to determine heat capacity and moderation.

PBMR fuel elements are pressed in two steps:

- In the first step, coated particles and matrix material are mixed and pressed to form a fuel containing an inner sphere of 50 mm in diameter. Fuel particles are distributed evenly in the inner fuel-containing zone to prevent the development of hot spots in a fuel element.
- In the second step, matrix material is added to the mould and pressed to form a 5 mm thick fuel-free region around the fuel-containing region. The purpose of this region is to protect the inner zone from mechanical and chemical damage during handling and operation.

# 5. FUEL HANDLING AND STORAGE SYSTEM

## 5.1 OVERVIEW

The function of the Fuel Handling and Storage System (FHSS) is to perform all the required fuel manipulations required during the entire life cycle of the PBMR. These include:

- Initial loading of the core of the reactor with graphite spheres
- Replacing the graphite spheres with fresh fuel spheres intermixed with graphite spheres during initial start-up
- Gradually changing the start-up core composition of graphite and fuel to a fuel only composition, and then to a core consisting of fuel to be used in the equilibrium state
- Loading and unloading the fuel into and from the reactor core while the reactor is operating at power
- Spent fuel discharge to spent fuel tanks
- Loading of fresh fuel to compensate for spent fuel discharges

The fuel spheres are circulated by means of a combination of gravitational flow and pneumatic conveying processes using helium at Main Power System (MPS) operating pressure, as the transporting gas. The design of the FHSS is based partly on that of the THTR 300, which used an on-line fuelling scheme with a multipass capability. Fuel spheres circulate through the core several times (the present design caters for six passes) before reaching their maximum burn-up, upon which they are discharged to the spent fuel storage tanks.

## 5.2 COMPONENTS AND FUNCTION

The FHSS consists of the following subsystems:

- Core Loading Subsystem CLS
- Sphere Storage Subsystem SSS
- Sphere Circulation Subsystem SCS
- Sphere Replenishment Subsystem SRS
- Fuel Handling Control Subsystem FCS
- Circulating Gas Subsystems GCS
- Sphere Decommissioning Subsystem SDS
- Auxiliary Gas Subsystem AGS
- High-level Waste Handling Subsystem HLWHS

(The High-Level Waste [HLW] consists of the broken or damaged spheres, or spheres worn down to minimum diameter.)

Table 20 lists the main functions performed by the FHSS Subsystems.

**Table 20: Functional Requirement Allocation Sheet**

| No. | Function | SCS | GCS | AGS | FCS | SSS | SRS | CLS | SDS | HLWHS |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | Operate FHSS | X | X | X | X | X | X | | | X |
| 1.1 | Standby for Operation | | X | X | X | | | | | |
| 1.2 | Circulate Fuel and Graphite Spheres | X | X | X | X | | | | | |
| 1.3 | Store Spent Fuel Spheres | | X | X | X | X | | | | |
| 1.4 | Store Damaged Spheres | X | X | X | X | | | | | X |
| 1.5 | Sample Spheres | X | X | X | X | X | | | | X |
| 1.6 | Provide Fresh Fuel Spheres | X | X | X | X | | X | | | |
| 2.0 | Maintain FHSS | | | | | | | | | X |
| 3.0 | Commission FHSS | X | X | X | X | X | X | X | | X |
| 4.0 | Decommission FHSS | | X | X | X | X | | | X | X |

The physical layout of the FHSS occupies the following building spaces:

- A space below the Reactor Pressure Vessel (RPV) where the three Core Unloading Devices (CUDs) are situated.
- A vertical shaft where the pneumatic sphere lifting lines are situated.
- A sloping floor above the RPV where the helix, sphere management stations and burn-up measurement stations are situated.
- A room adjacent to the reactor cavity where the spent fuel, used fuel and graphite tanks are situated.
- The space above the helix where the fuel and graphite replenishment equipment are situated and where the Activity Measurement System (AMS) is situated. (Refer to Figure 44.)

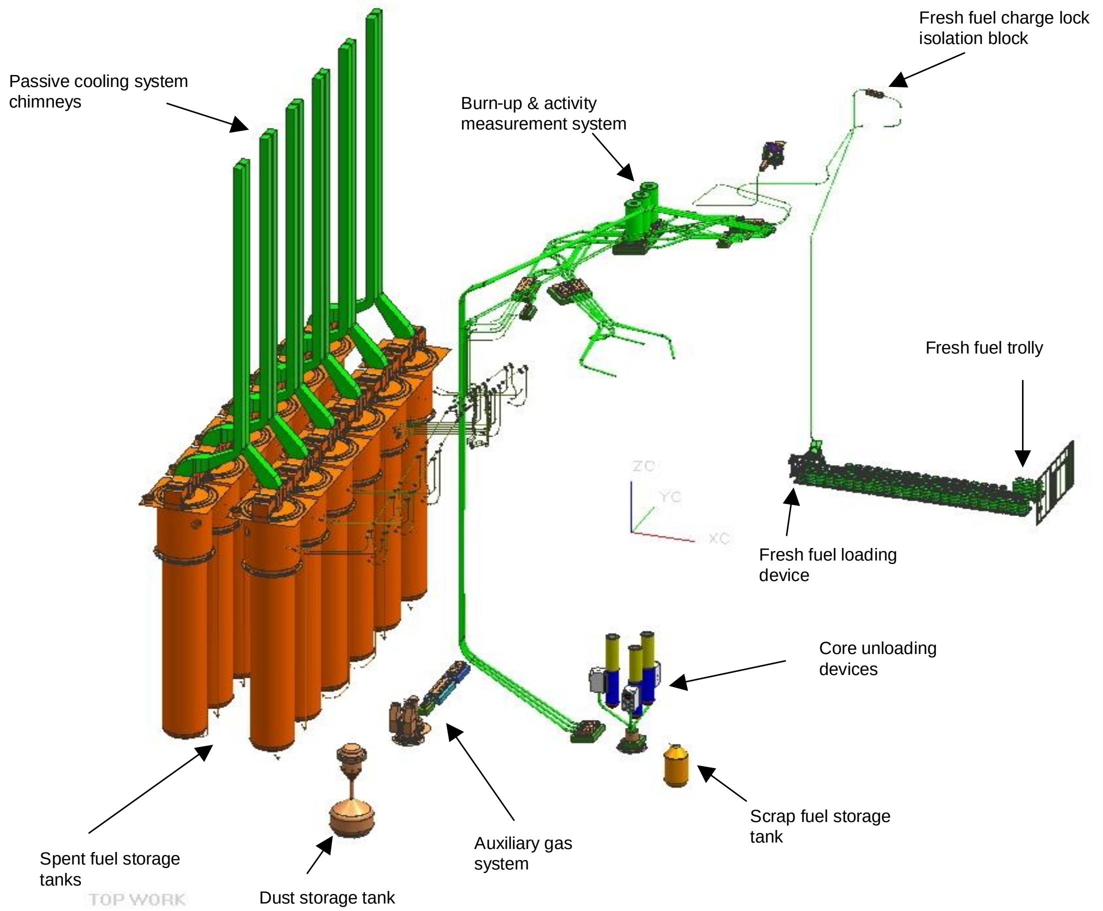



**Figure 44: Isometric Layout of the Fuel Handling and Storage System inside the Reactor Building**

## 5.3 CORE LOADING DURING COMMISSIONING AND START-UP

During commissioning of the reactor, the CLS is used to initially load the complete core of the reactor with graphite spheres fed into the fresh fuel charge lock. The CLS prevents the graphite spheres from being dropped through an unacceptable height onto the core graphite structures and causing damage. This loading operation takes place with the reactor vessel open to atmospheric pressure. The initial loading of graphite spheres into the core prior to the first loading of fuel is shown in Figure 45.

The start-up core, consisting of a mixture of start-up fuel and graphite, is loaded under helium pressure on top of the graphite core while graphite spheres are simultaneously removed from the bottom of the core on a one sphere to one sphere basis Figure 46. The CLS makes provision for the loading and circulation of the start-up core with different ratios of fuel spheres to graphite spheres, for fuel spheres with different enrichment levels (start-up enrichment), and for a specific loading sequence of these spheres.

## 5.4 SPHERE STORAGE

Sufficient storage space is available in the sphere storage system for:

- The storage of a full core load of graphite spheres as used during the initial core loading to criticality, and to be reused for subsequent outages that require defuelling and refuelling.
- The on-site storage of a six-month supply of fresh fuel. The fresh fuel is stored in canisters containing 1 000 fresh fuel spheres each.
- The on-site storage of used fuel in a tank, which can accommodate the fuel in a core when the entire core needs to be unloaded.
- The on-site storage of all the spent fuel generated by the module during its operating life of 35 Full Power Years (FPY), and then for a further 40 years after the module is shut down. Each spent fuel tank is fitted with an extraction point for the removal of spheres to transportation containers during decommissioning.

The destination of a sphere at any stage of the plant operation is dependent on the **mode and state** of operation, the **type of sphere** (fuel/graphite) and the **burn-up** achieved in the case of a fuel sphere. All the possible destinations for fuel/graphite spheres are as follows:

- Used fuel storage tank (used fuel spheres)
- Graphite storage tank (graphite spheres)
- Spent fuel storage tanks (spent fuel spheres)
- Reactor core (fresh/used fuel spheres and graphite spheres during the start-up phase)
- Sphere sampling block (spheres identified for removal from the system)
- Damaged sphere container (damaged fuel/graphite spheres or sphere fragments)

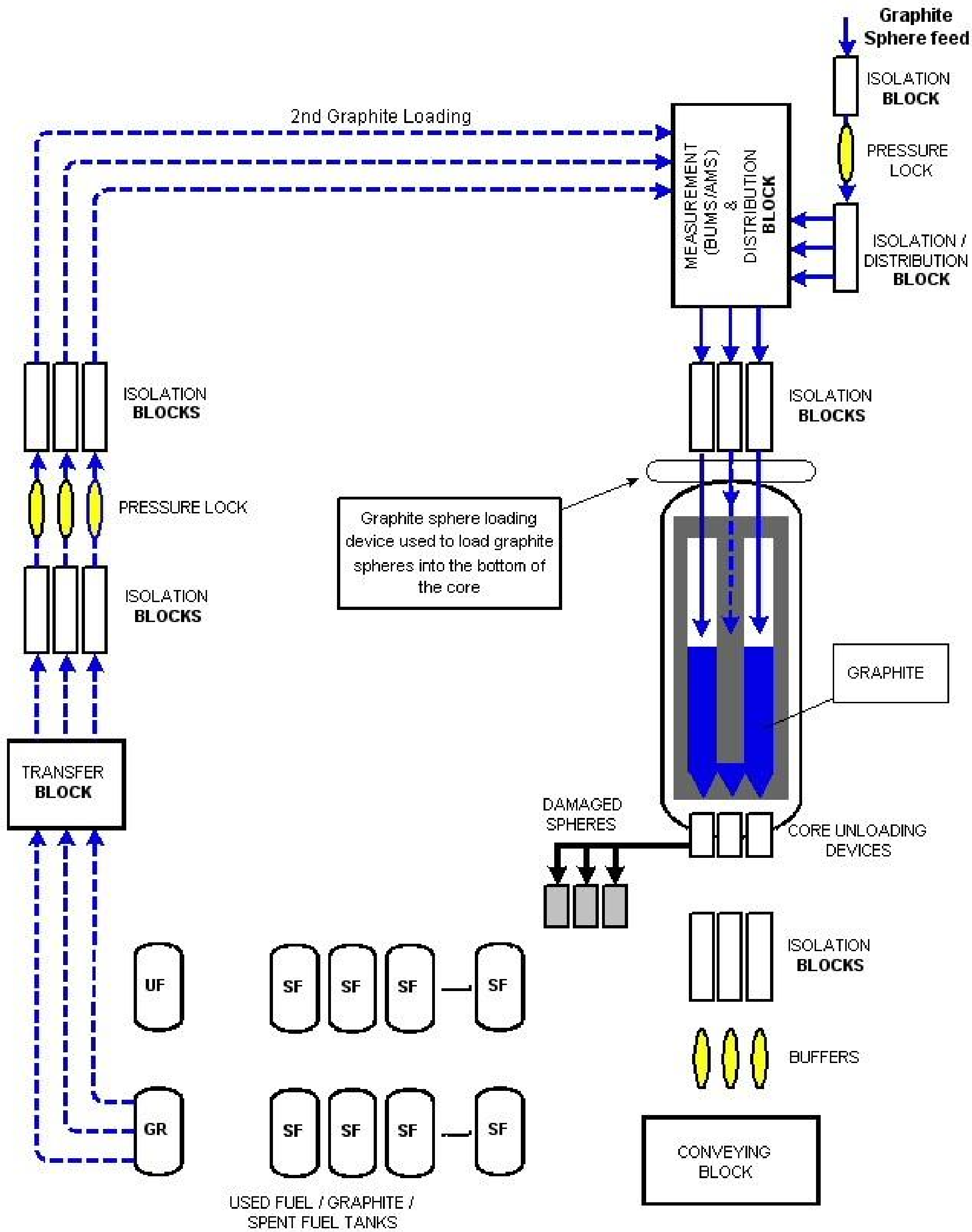



**Figure 45: Initial Loading of Graphite Spheres into Core**

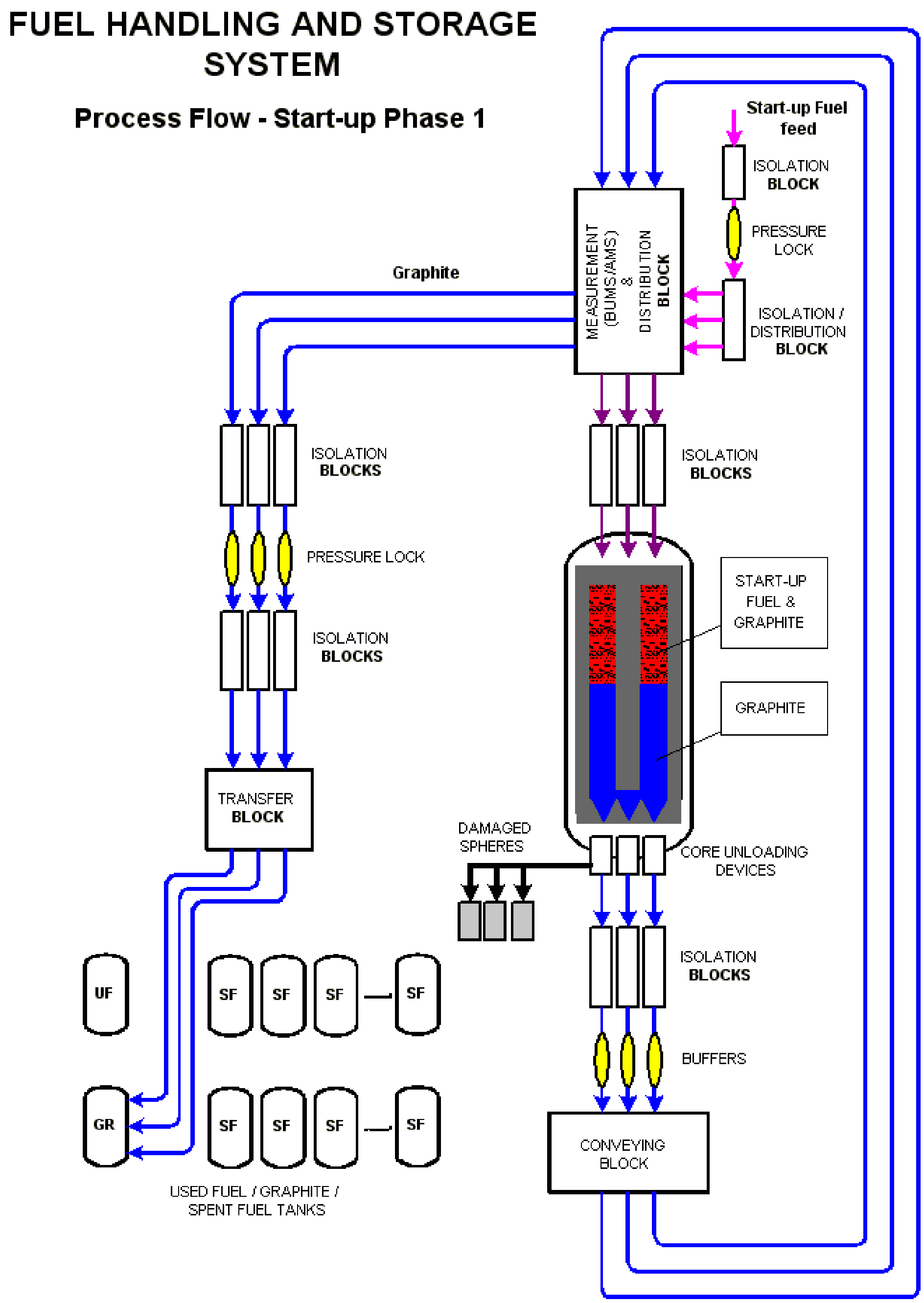



**Figure 46: Start-up Core Circulation**

## 5.5 SPHERE CIRCULATION

During normal operation, the SCS circulates the fuel and graphite spheres through the reactor core. The fuel and graphite spheres, or only the fuel spheres, depending on whether the reactor operates in the initial start-up mode or whether it is in the equilibrium mode, are circulated by means of a combination of gravitational flow and pneumatic conveying using helium gas at MPS operating pressure, as the transporting medium. Under normal operating conditions, fuel spheres inside the conveying systems are exposed to a nominal maximum operating pressure of 9 MPa, and a temperature of 250 °C.

Spheres are removed via three discharge chutes at the bottom of the core by means of three CUDs. The CUD has a facility that can separate damaged or under-size spheres from the system. The spheres are pneumatically lifted to the top of the reactor, and after passing through the AMS to distinguish fuel from graphite, the burn-up is measured by means of the Burn-up Measurement System (BUMS). Spheres that do not exceed the permissible burn-up are returned to the reactor core. This process is shown in Figure 47.

Fuel spheres are recycled through the core nominally six times before the specified fuel burn-up is achieved. The FHSS is designed to be capable of increasing the nominal number of passes through the core to 10 times for the same specified burn-up, should the need arise.

Once the spheres have reached their maximum burn-up, the SCS directs/discharges fuel to the SSS and accepts fresh fuel from the SRS to replace the discharged spent fuel. Worn and damaged fuel and graphite spheres can also be replaced if and when necessary.

An extraction point is provided for the removal of fuel or graphite spheres for Post-irradiation Examination (PIE) purposes. The extraction process does not influence the normal operation of the MPS, and is able to take place whenever on-line circulation is active, using a discharge lock and sample sphere container.

The FHSS has the capability for separating and removing damaged spheres, sphere fragments and under-sized spheres from the circulation system. A facility is designed into the CUD where these are collected, and from where they will be removed to an HLW storage vault for long-term storage. The removal process does not influence the normal operation of the MPS, and is able to take place whenever on-line circulation is active.

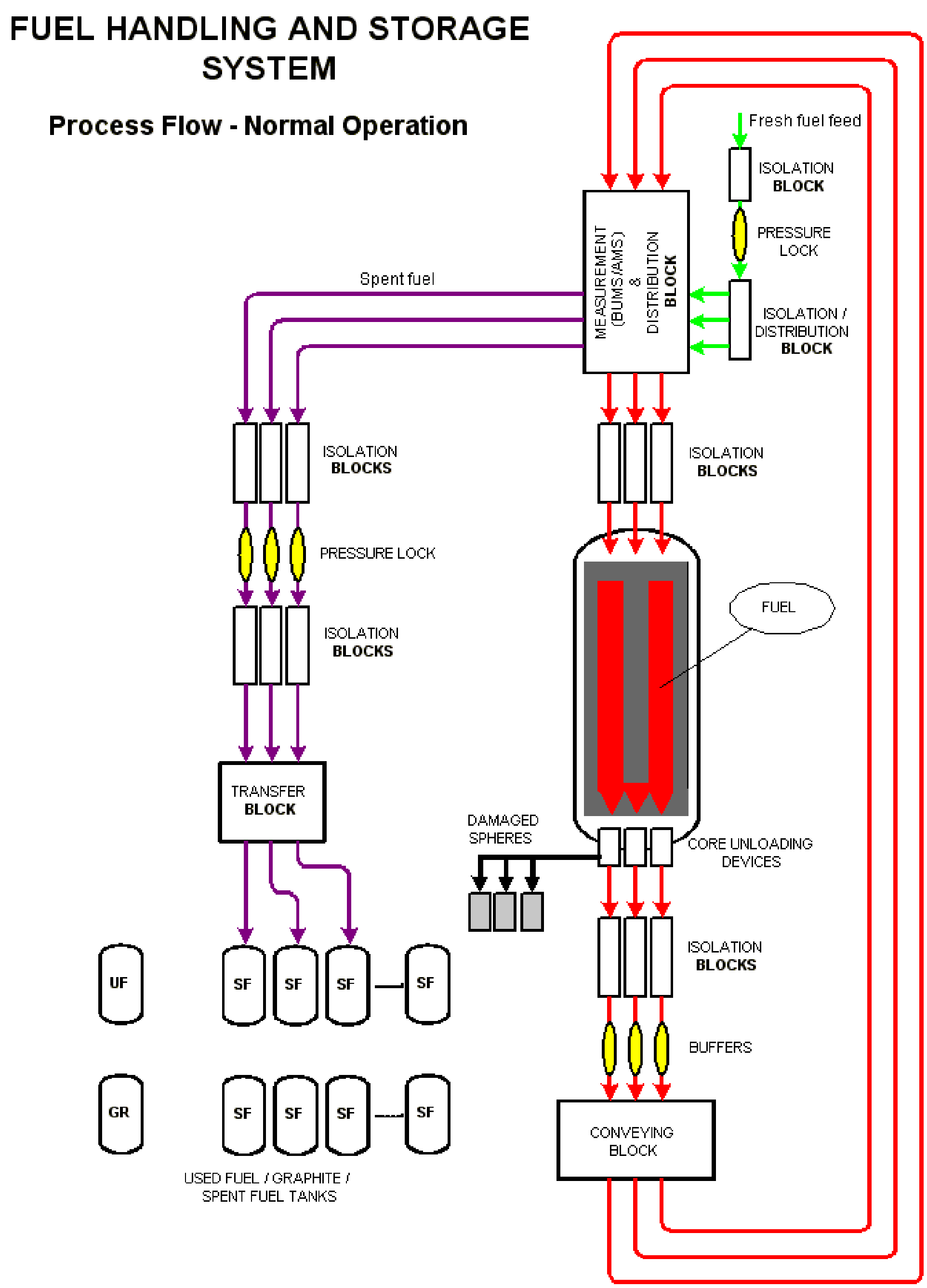



**Figure 47: Simplified Process Flow Diagram for Normal Operation**

## 5.6 DEFUELLING, UNLOADING AND REFUELLING

During an unscheduled maintenance shutdown, which requires the fuel to be removed from the reactor core, the SCS is used to unload fuel spheres from the core and load graphite spheres into the top of the core in place of the fuel spheres – called defuelling. Defuelling is not a planned operation for the scheduled maintenance shutdowns. This process can be reversed and the used fuel spheres from the Used Fuel Tank (UFT) replace the graphite spheres in the core – called refuelling. (This activity is carried out in conjunction with a loading to criticality procedure.)

a,b

### 5.6.1 Defuelling

During this transition sequence, the fuel spheres in the reactor core are removed, and stored in the used fuel storage tank.

Two distinct modes of operation are envisaged: Unload and Defuel.

#### 5.6.1.1 Unload

The core is emptied of fuel. The fuel is stored in the UFT. It is not necessary to do measurements on the fuel during this transition. The number of fuel spheres removed is monitored.

#### 5.6.1.2 Defuel

The core is emptied of fuel, and for each fuel sphere removed from the core, a graphite sphere is fed into the core. The fuel is removed to the UFT. The sequence is as follows:

a,b

### 5.6.2 Refuelling

During this activity, the reactor is refuelled with fuel spheres after a defuelling activity. Prior to refuelling, the system must be cleaned by the Primary Loop Initial Clean-up System (PLICS) if the reactor core was exposed to significant amounts of air and moisture during the maintenance period.

During this activity, the graphite spheres are removed from the core and replaced by fuel spheres. The fuel spheres are removed from the UFT and the graphite spheres are returned to the graphite storage tank.

The sequence is as follows:

a,b

(**Note:** This activity is carried out in conjunction with a loading to criticality procedure.)

a,b

### 5.7 END OF PLANT LIFE

At the end of life of the PBMR module, the SCS is used to remove the used fuel spheres of the last core from the reactor and discharge these into the UFT.

During final decommissioning, the spent fuel spheres are removed from the SFTs and conveyed to a point where they can be loaded into the Spent Fuel Transport Casks suitable for final disposal at a designated site. This pneumatic conveying is achieved by means of clean, dry air at atmospheric pressure as the transporting medium. The used fuel and graphite spheres, stored in the Used Fuel Storage Tank and Graphite Storage Tank respectively, are removed and transported to the Spent Fuel Transport casks in the same manner.

Damaged fuel spheres and dust extracted from the FHSS are stored as HLW in canisters in a vault in the Demonstration Reactor Building for the duration of the expected plant life. It is possible to store this HLW for another 40 years after final shutdown.

## 5.8 PLANT OPERATING MODES

The plant operating modes of the FHSS as mapped to the power plant operating modes are listed in Table 21.

**Table 21: Power Plant/Fuel Handling Storage System Operating Modes Matrix**

| FHSS Operating Modes | Power Plant Operating Modes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Defuelled Maintenance | Fuelled Maintenance | | Shutdown | | | Standby | Opera-tional Standby | Power Operation |
| | | MPS Open | MPS Closed | Full | Inter-mediate | Partial | | | |
| Standby | | | | X | X | X | X | X | X |
| Load Start-up Core | | | | X | X | X | X | X | |
| Circulate Start-up Core | | | | X | X | X | X | X | X |
| Circulate Equilibrium Core | | | | X | X | X | X | X | X |
| Defuel Core | | | | X | | | | | |
| Refuel Core | | | | X | | | | | |
| Unload Core | | | | X | | | | | |
| Maintenance | X | X | X | X | X | X | X | X | X |
| Commission | | X | X | | | | | | |
| Load First Core Graphite | | X | | | | | | | |
| Decommission | | X | X | | | | | | |

# 6. PLANT LAYOUT AND EQUIPMENT ARRANGEMENTS

## 6.1 PLANT LAYOUT

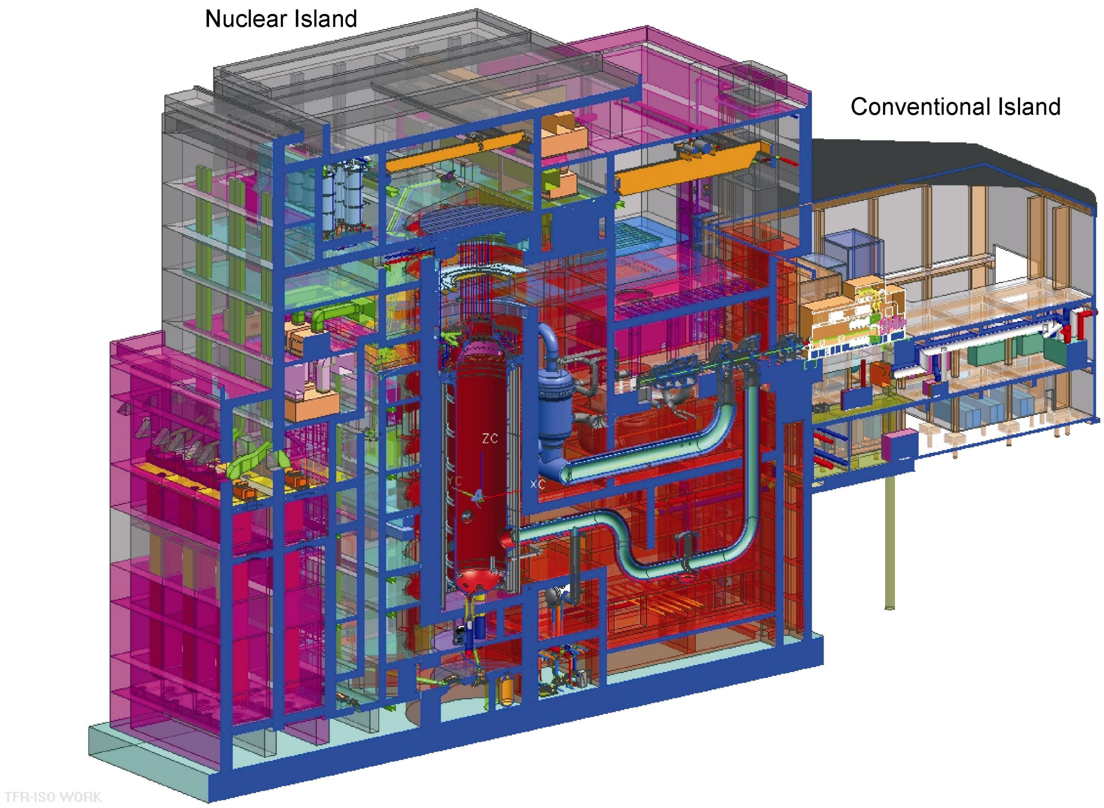



**Figure 48: Plant Layout**

**Nuclear Island**

| | | |
|---|---|---|
| Height total | : | 63 m |
| Height above ground | : | 41 m |
| Depth below ground | : | 22 m |
| Width | : | 37 m |
| Length | : | 74 m |
| Levels (floors) | : | 11 |
| Material | : | 40 MPa concrete |
| Seismic acceleration | : | 0.4 g |
| Aircraft crash | : | < 2.7 ton no penetration |
| | | B777 penetration of outside shell; nuclear safety not compromised |

**Conventional Island**

| | | |
|---|---|---|
| Height total | : | ~ 25 m |
| Height above ground | : | ~ 19 m |
| Width | : | 35.5 m |
| Length | : | 37.0 m |

## 6.2 EQUIPMENT LAYOUT

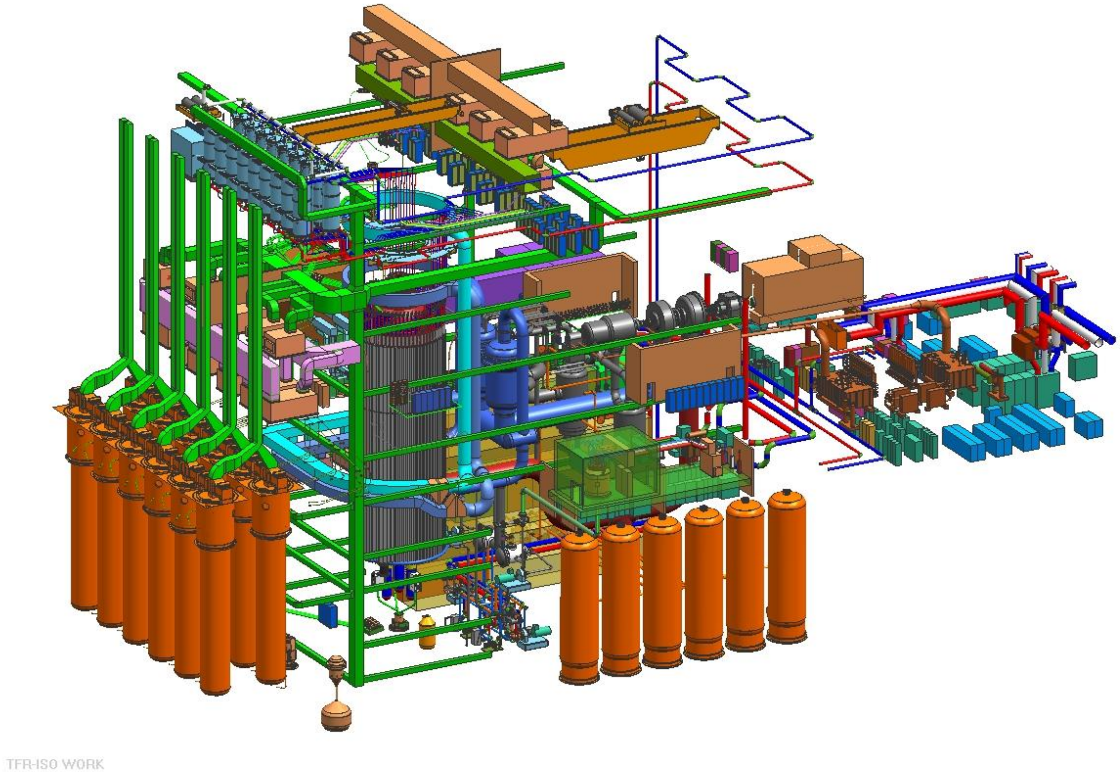



**Figure 49: Equipment Layout**

## 6.3 MAIN POWER SYSTEM LAYOUT

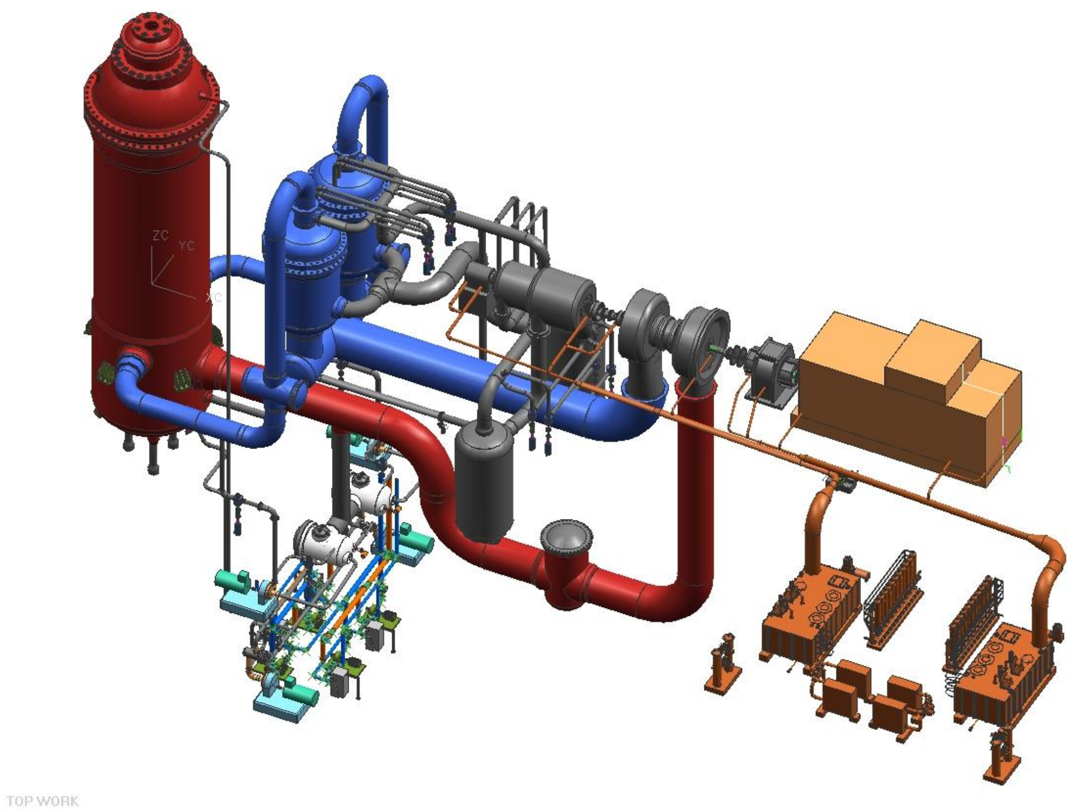



**Figure 50: Main Power System**

| | | |
|---|---|---|
| Power output | : | 400 MWt (design) |
| | | 165 MWe (design) |
| Coolant | : | Helium |
| Coolant pressure | : | 9 MPa |
| Outlet temperature | : | 900 °C |
| Total mass | : | ~4 000 t |
| Helium mass | : | ~6 000 kg |
| Net cycle efficiency | : | 42% |

## 6.4 FUEL HANDLING AND STORAGE SYSTEM

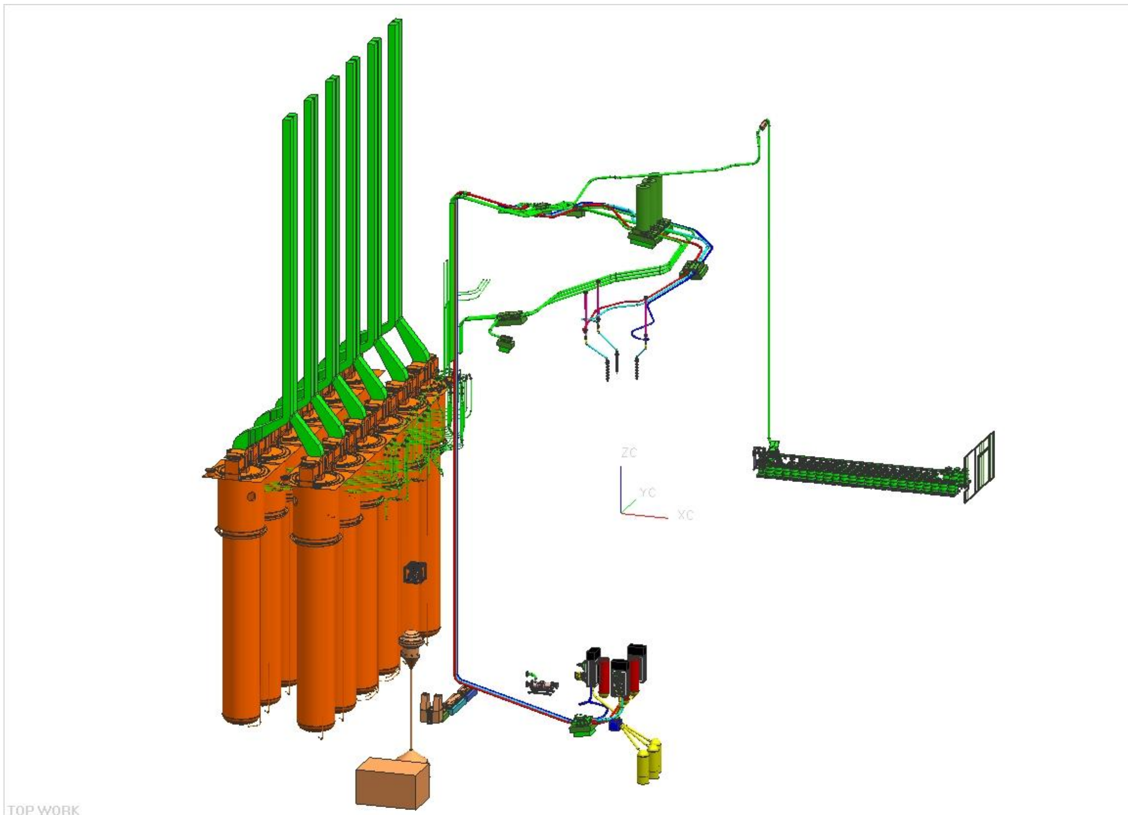



**Figure 51: Fuel Handling and Storage System**

| | |
|---|---|
| Hourly sphere circulation rate | : 500 to 1 100 |
| Daily operating time | : 8 h to 12 h |
| Operating pressure | : 1 MPa to 9 MPa |
| Fuel sphere feeding points | : 3 |
| Core defuelling points | : 3 |
| Fresh fuel storage capacity | : 70 000 spheres |
| Spent fuel storage capacity | : 6 000 000 spheres |
| Number of tanks | : 10 spent fuel tanks |
| | : 1 graphite storage tank |
| | : 1 used fuel storage tank |
| Spent fuel period | : Up to 80 years |

## 6.5 HELIUM INVENTORY CONTROL SYSTEM

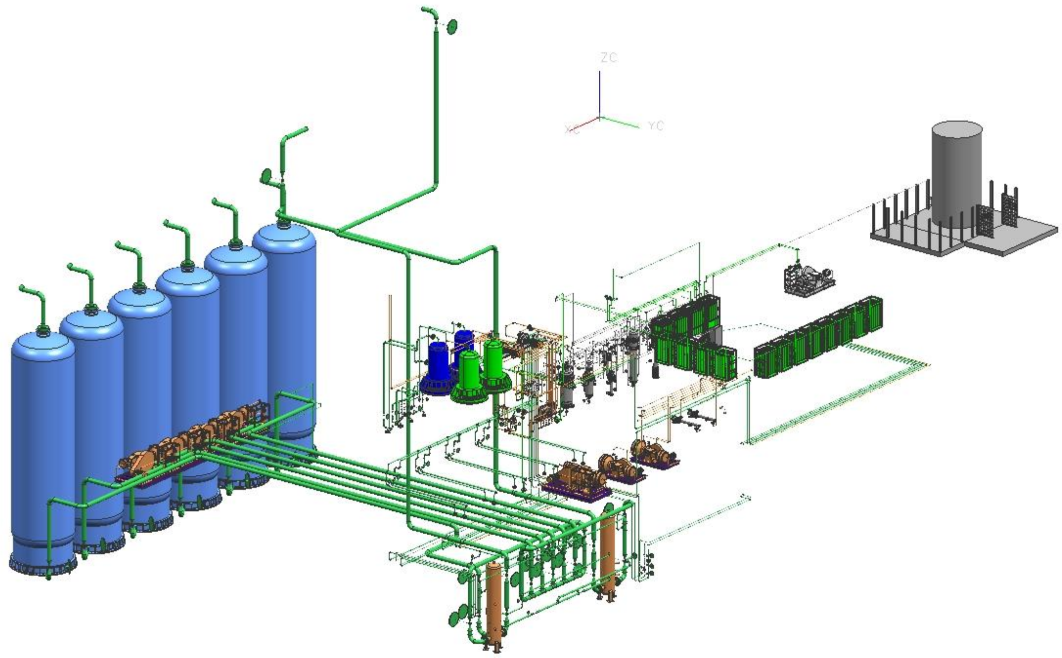


**Figure 52: Helium Inventory Control System**

**Inventory Control System**

Storage capacity :
Storage pressure :
Flow rate at 10% inventory :
High-pressure compressor flow rate :
Multi-purpose compressor flow rate :
Mass of tanks :

b

**Purification System**

b

**Make-up System**

Storage capacity :

Cylinder capacity :

b

# 7. PLANT AND MAJOR COMPONENT MAINTENANCE CONCEPT

The maintenance philosophy for the major Line-replaceable Unit (LRU) replacement and maintenance actions on the Main Power System (MPS), Fuel Handling and Storage System (FHSS) and the main subsystems of the Demonstration Power Plant (DPP) are presented in this chapter.

## 7.1 MAINTENANCE CONCEPT AND LEVELS OF REPAIR

A four-level maintenance concept is established for the Multi-module (MM) plants. Initially only levels 1, 2 and 4 will exist, but level 3 (regional maintenance facility) will be developed as the number of modules in a particular area (country or subcontinent) justifies the cost thereof.

The levels of support are defined as follows:

- 1st line: Operator maintenance;
- 2nd line: On-site maintenance facilities;
- 3rd line: Regional maintenance facilities (limited for DPP) owned and managed by PBMR; and
- 4th line: Supplier maintenance and support.

For the DPP, limited maintenance infrastructure is available. Maintenance on first-of-a-kind Structures, Systems and Components (SSCs) is done in close cooperation with the Original Equipment Manufacturer (OEM). Decontamination of large equipment, e.g. the Power Turbine (PT), is done within the DPP.

It is a design requirement on the plant that the repair work that can be performed inside the module is limited. The activities are limited to replacement of LRUs, which can then be either repaired or discarded outside the module in a suitable facility. Limited external facilities are available for the DPP. Repair activities inside the DPP module are more comprehensive than for the MM plant.

A significant amount of inspection and test equipment is required because of the testing and operation of a first-of-a-kind design. Standardized maintenance will be implemented on the MM plant design.

## 7.2 PLANT OUTAGES

The plant is being designed with low-level, easy maintenance in mind. The planned outages are scheduled at six-year intervals.

The duration and scope of these planned outages are as follows:

### 7.2.1 After 6 Years of Operation

A 30-day outage takes place, with the following major activities:

- Replacement of the PT. For the MM, the PT will be replaced with a replacement unit. The removed unit will then be reworked and prepared at a 3rd line (regional) facility for installation in another module. For the DPP, the same units will be repaired and worn components be replaced for as long as no complete spare units are available.
- Inspection of the generator.
- Inspection and maintenance on the blowers inside the Pressure Boundary (PB).
- Inspection and maintenance on the Reactivity Control and Shutdown System (RCSS).

### 7.2.2 After 12 Years of Operation

A 30-day outage takes place, during which the same activities as for the 6th-year outage are performed, as well as inspection of the compressor to verify the condition of the equipment. Since there is uncertainty regarding the durability of the turbine and the required maintenance activities, the duration of the outage may increase to 50 days.

### 7.2.3 After 18 Years of Operation

A 30-day outage takes place, repeating the activities of the 6th-year outage, with the provision that if the PT had shown any deterioration during the previous inspection, it may be repeated, increasing the outage to a total of 50 days.

### 7.2.4 After 24 Years of Operation

Core reflector replacement takes place. This process will take approximately 180 days. The activities of a 12th-year outage are repeated during this period, and the PT and/or generator may require replacement.

### 7.2.5 After 30 Years of Operation

As for the 18th-year outage.

### 7.2.6 After 36 Years of Operation

As for the 12th-year outage.

## 7.3 MAINTENANCE – BASIC PRINCIPLES

The following principles were used when the maintenance concepts were developed:

- The maintenance concepts should limit air ingress into the reactor core. Air in the MPS requires clean-up and has the potential to cause corrosion of graphite structures. The limited air that could possibly enter the MPS should be dry and dust-free.
- Limit (preferably prevent) the release of contaminated dust-borne helium into the building environment. When opening the citadel above the Power Conversion Unit (PCU), the laydown area becomes a controlled area.
- The duration of the 6- and 12-year outages shall not exceed the respectively specified 30 and 50 days.
- Minimum use of remotely operated tools or robotics due to potential high cost of this type of equipment. However, consideration is given to the ALARA (As Low As Reasonably Achievable) principle for human exposure and loss of production time against ease of maintenance.
- Direct line of sight or remote visual aids are used for positioning tools, removing components and realigning components during re-installation.
- ALARA is applied to limit the exposure of plant personnel to contamination or radiation during all modes of maintenance.
- No personnel access into the PCU manifold with the reactor fuelled.

# 8. AUXILIARY SYSTEMS

## 8.1 ACTIVE COOLING SYSTEM

### 8.1.1 Overview

The Active Cooling System (ACS) consists of a number of independent closed circuits that are filled with inhibited demineralized water to prevent the formation of scale and sludge in the heat exchangers. The closed circuits transfer their heat via plate type water-to-water heat exchangers, to the sea via the Main Heat Sink System (MHSS). Refer to Figure 53 and Figure 54.

Sea water is drawn from the existing Koeberg pump station sea water inlets, and pumped through a common header to the Cooling Water (CW) plant room. The discharge from the CW plant room is again collected in a common header, which returns the water to the sea.

The closed circuit cooling systems feature a dedicated water make-up system, which is interconnected with a chemical dosing system that allows monitoring of the inhibitor concentration of the demineralized water.

Each closed circuit features a maintenance drainage facility.

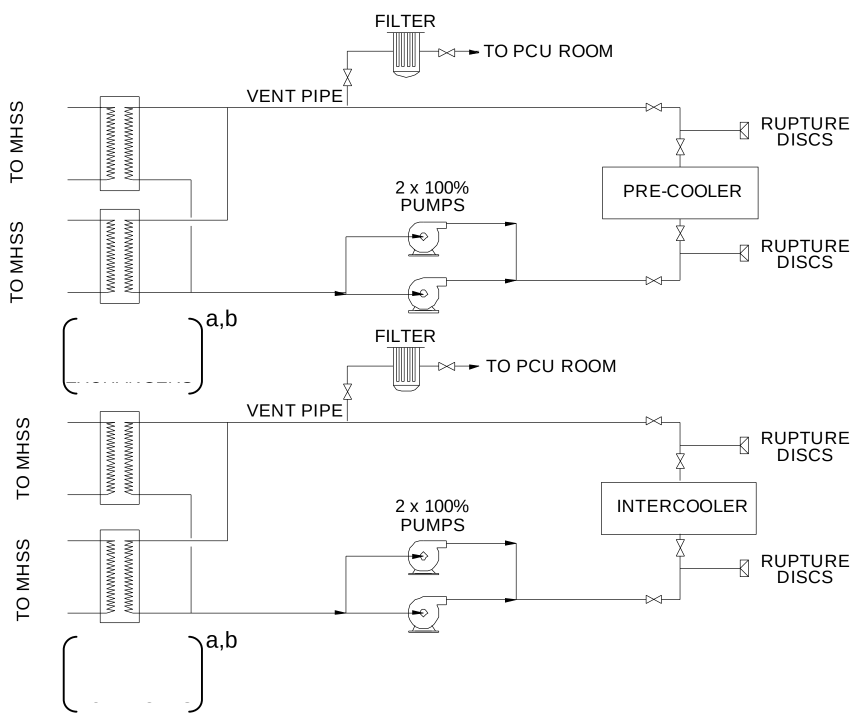



**Figure 53: Schematic Layout of the Pre-cooler and Intercooler Loops of the Active Cooling System Main Closed Circuit**

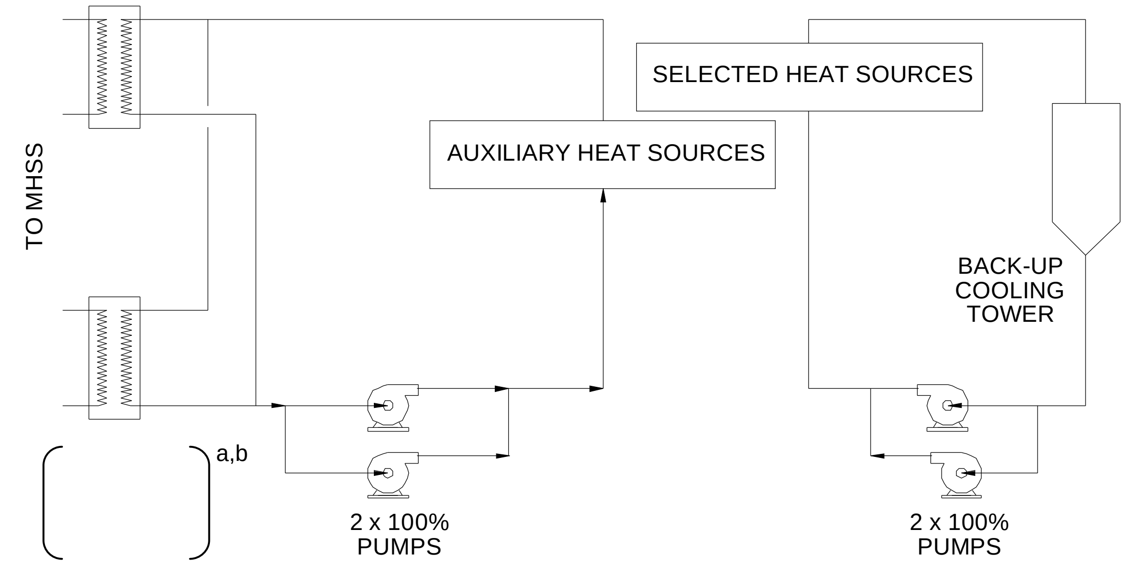



**Figure 54: Schematic Arrangement of the Active Cooling System Auxiliary Closed Circuits**

### 8.1.2 Components and Functions

The ACS comprises three circuits:

- The Pre-cooler and Intercooler Cooling Circuits (PCC and ICC) transfer approximately [ ][b] respectively, of waste heat to the MHSS. The pre-cooler and intercooler circuits are independent of each other, each being linked directly to the MHSS. (Refer to Figure 53.)
- The Auxiliary Closed Circuit removes a total of approximately [ ][b] of waste heat from the following auxiliary systems:
  - Compressed Air System (CAS)
  - Fuel Handling and Storage System (FHSS)
  - Generator air coolers
  - Heating, Ventilation and Air-conditioning (HVAC) system
  - Helium Purification System (HPS)
  - Helium Inventory Control System (HICS)
  - Primary Loop Initial Clean-up System (PLICS)
  - Static Frequency Converter (SFC)
- In each of the auxiliary subsystems, heat is transferred from the heat source into the closed water circuit, and from the closed circuit, into the MHSS (refer to Figure 54). A cooling tower is provided to act as back-up for selected auxiliary systems, i.e. those required for safe shutdown in the event of a unit trip.

The ACS is, as far as practicable, made up of standard, proven pumps, valves, heat exchangers, etc. The pre-cooler, intercooler and auxiliary circuits are each provided with [ ][b] heat exchangers, and 2 x 100% pumps. The pumps are provided with diesel generator electrical back-up

From the CW plant room, cold demineralized water is pumped to the module. Within the module, the water is distributed to all the heat sources before returning to the heat exchangers in the CW plant room.

### 8.1.3 Layout

#### 8.1.3.1 Cooling water plant room

All the pumps and heat exchangers of the ACS and Equipment Protection Cooling Circuit (EPCC), which feeds the RCCS active circuit, are located in the CW plant room, which is designed as a restricted area because of the possibility of entrained and dissolved gases being carried through from the module by the ACS, and also because of the possibility of water from the RCCS being activated. During maintenance of the plant room equipment, any water spilled is collected in bunded areas and drained by gravity into the module sump, from where it will be treated as contaminated waste. These same drains cater for more severe spillages resulting from ruptures in any of the closed circuit pipes.

Water from a rupture in the sea water lines in the plant room is collected in a separate trench and can be pumped back into the sea.

Personnel entering and leaving the plant room have to pass through a controlled change room equipped with showers and storage bins for contaminated clothing.

#### 8.1.3.2 Back-up cooling tower

The Auxiliary Cooling Circuit (ACC) back-up cooling tower is sized to take over the cooling duties of the HICS and FHSS, CAS, HVAC system, and the static converter. It is required:

- During plant maintenance, to allow these systems to continue operating if so required, e.g. HVAC, and air compressors.
- During a plant trip when heat must continue to be removed for a period of time after the trip.
- During the loss of the auxiliary cooling system for any reason, in which case the selected sources are needed for safe shutdown of the plant.

Pipework from the tower runs directly into the CW plant room where the cooling tower main pumps are located. From the pumps, the tower feed and return lines attach directly onto the adjacent Auxiliary Closed Circuit lines through three-way valves, making it simple to isolate the auxiliary system and divert the water to the tower. Those auxiliary heat sources which are not served by the cooling tower, will automatically be isolated when the tower switches on.

The tower pumps and fan(s) receive electric power from the diesel generators. Redundant pumps are provided.

#### 8.1.3.3 Pipework

A network of uncoated (internally) steel pipes connects the heat exchangers to the many heat sources in the module and on the site. Pipes range in diameter from 25 mm up to 600 mm, and are externally corrosion protected.

#### 8.1.3.4 Radiation detectors and rupture discs

Radiation detectors are fitted at the inlets and outlets of the pre-cooler and intercooler waterboxes to give early warning of a gas leak. The inlet and outlet pipes are also fitted with rupture discs and pressure control valves to protect the Active Cooling System (ACS) from over-pressure damage in the event of a high-pressure gas leak from the pre-cooler or intercooler, into the water circuit. Drain valves are fitted between the pre-cooler and intercooler units and their respective isolating valves, to enable these units to be isolated and drained.

### 8.1.3.5 Gas vent pipes

The hot water outlet pipes from the heat sources are connected to vent pipes designed to extract gases from the water, and to release such gases via particulate filters, into the module, from where the gases are filtered and released to atmosphere via the HVAC system. The vent particulate filters allow air to pass back and forth to balance the pressures in the ACS with that in the module, but prevent dust and other impurities from entering and contaminating the demineralized water. From the base of the vent pipes, the hot water leaves the module and passes through the heat exchangers in the CW plant room. The water level in the vent pipes is monitored, and a drop in level automatically activates the water make-up system.

### 8.1.3.6 Demineralized water supplies

Inhibited demineralized water for make-up purposes is supplied from the existing KNPS storage tanks to a smaller ([ ][b]) storage tank situated in the CW plant room. The first fill of demineralized water is tanked in, as will be the case for subsequent fills if the systems are drained. From the local storage tank, make-up water is released under pressure to all the closed circuits by an automatic make-up system, which will also monitor the make-up water flow rate.

Each closed circuit has its own sampling and drainage facilities.

## 8.1.4 Plant Operating Modes

### 8.1.4.1 Plant normal, reduced capacity and standby modes

The ACS group will follow the requirements of the higher-level (e.g. MPS) systems. During normal and reduced capacity operation of the plant, and during plant standby, the pre-cooler, intercooler and auxiliary circuits will run at their maximum rated capacity.

### 8.1.4.2 Plant shutdown mode

During plant shutdown, the heat being released from the core is due to decay, and is dissipated by the RCCS. Some decay heat will also be released by the pre-cooler and intercooler, and this heat will be carried away by the respective cooling circuits, which will continue operating at rated capacity until shut down by the operator.

Those auxiliary heat sources which need cooling water flow during plant shutdown, will be connected to the back-up cooling tower.

### 8.1.4.3 Plant maintenance mode

During maintenance of the power plant, the PCC and ICC pumps will normally be stopped, but will be under the control of the operator. Those auxiliary heat sources which need cooling water flow during plant maintenance, will be connected to the back-up cooling tower.

### 8.1.4.4 Pre-cooler and intercooler cooling circuits

The PCC and ICC will remove waste heat from the Power Conversion Unit (PCU) pre-cooler and intercooler respectively, and transfer this waste heat via plate heat exchangers to the MHSS. The pre-cooler and intercooler circuits will be independent of each other, each being linked directly to the MHSS. Pipes carrying water at temperatures above 60 °C will be lagged.

Both circuits will be fitted with rupture discs and pressure control valves located immediately below the respective cooler waterboxes. The controlled area where the waterboxes are located in the module, prevent entry for normal regular maintenance of the control valves, so the rupture discs are retained to act as a back-up protection should the valves malfunction. With the valves operating correctly, gas pressure will be kept at approximately 1 MPa, thereby allowing the CCS to continue operating to shut the unit down safely.

For a larger gas leak, one in which the gas cannot be released quickly enough via the vent pipe, the increased pressure will force the pressure control valve to open. The gas (and some water) will be released into the general area below the cooler until the gas system pressure drops to approximately 1 MPa, which is the design pressure of the cooler water box and cooling water system. At this pressure, systems such as the Core Conditioning System (CCS) can continue to operate. Spilled water will be drained to the module sump for analysis and disposal.

Should the pressure control valves fail, the rupture discs will open, releasing the gas until atmospheric pressure is reached.

#### 8.1.4.5 Helium leaks into the water circuit

At Maximum Continuous Rating (MCR), the PCU helium cycle will operate, at the pre-cooler and intercooler waterbox flanges, at pressures of at least 2 MPa higher than the pressure in the water circuits. This pressure difference is necessary to minimize the possibility of water entering the PCU helium circuit.

The inlet and outlet water pipes connected to the pre-cooler and intercooler waterboxes are fitted with isolating valves, pressure relief valves and instruments which can detect the presence of helium in water. Pressure and temperature transmitters are also fitted to the pre-cooler and intercooler inlets and outlets, while water level transmitters are fitted to monitor the water level in the vent pipes.

In the event of a slow leak of helium and other gases into the PCC or ICC, the helium detectors will trigger an alarm. Most of the entrained gases will collect in the vent pipes, and will be released back into the module, to be filtered and removed by the HVAC system. Some gases may remain entrained or dissolved in the closed circuit water, and will be carried to the CW plant room. To make provision for such an event, the CW plant room will be a controlled entry facility.

#### 8.1.4.6 Water leaks

Closed circuit leaks are detected by measuring an increase in make-up water flow and by level detectors in the vent pipes as well as by subsequent pressure drops at the pump suction flanges, all of which are monitored from the control room. All leakages from the closed circuits in the module will flow to the module sump on the -22 m level. Within the CW plant room, leakage of sea water is separated from leakage of demineralized water, the former being collected in a local sump, and the latter being collected in the module sump.

### 8.1.5 Control and Instrumentation

The purpose of the ACS control system is:

- To interpret signals from the process monitoring instruments and to use these signals to initiate alarms, readouts or automatic actions, or to prepare the systems for manual intervention.
- To interpret signals derived from operator actions, and to initiate or alter plant operational modes accordingly.

All systems are run either by the operator initiating a system start command, or by another system within the automation control system generating a start request based on process conditions.

The automation control system software logic monitors the status of inputs relevant to the circuit components, process conditions and the functional criteria.

In any circuit, should any operating pump fail, the next available pump will automatically start. The control logic monitors the status of the valves in each circuit to ensure a flow path for the water before a pump is started.

The water levels in the vent pipes are monitored by level transmitters, and any abnormal drop in the water level is alarmed. Should the water level continue to drop, the operator will decide on whether or not to decrease module power. Should no operator actions follow, and should the water level continue to drop, the pumps of the affected closed circuit will trip at a preset water level.

## 8.2 REACTOR CAVITY COOLING SYSTEM

### 8.2.1 Overview

The Reactor Cavity Cooling System (RCCS) receives cooling water from the Equipment Protection Cooling Circuit (EPCC). The closed circuits of the EPCC are filled with inhibited demineralized water to prevent the formation of scale and sludge in the heat exchangers. The closed circuits transfer their heat via plate type water-to-water heat exchangers, to the sea via the MHSS.

The RCCS is safety classified, and due to the fact that active contaminants could make their way from the cavity to the CW plant room via the RCCS pipework, the plant room is a controlled area.

### 8.2.2 Components and Functions

#### 8.2.2.1 Functional definition

The RCCS components are safety classified to SC2 level, and will be seismically designed to be capable of functioning after a Safe Shutdown Earthquake (SSE). (Official safety and seismic classifications to be confirmed when relevant procedures have been finalized.)

Basic functions and requirements of the RCCS:

- To provide investment protection by preventing thermal radiation from impinging directly onto the concrete walls of the reactor cavity.
- To remove all waste heat from the reactor cavity during normal operation, thereby maintaining the concrete surfaces of the cavity below their design temperature limits. (A nominal 65 °C under normal operating conditions.) Back-up cooling of the RCCS will be provided for this function, in the form of the EPCC cooling tower.
- To remove all decay and residual heat transferred to the reactor cavity during a pressurized and depressurized loss of forced helium cooling event.
- In the event of the loss of active pumping capacity of the EPCC, to remove heat from the reactor cavity passively, and to release this heat to atmosphere in the form of steam. Passive operation must continue for a minimum period of 72 hours.

- Switching from active to passive operation must take place without any mechanical, electrical or human intervention.
- It is not a primary function of the RCCS to ensure that the fuel does not exceed its maximum allowable temperature, but together with the design of the heat transfer path from the fuel to the outer surface of the Reactor Pressure Vessel (RPV), the RCCS is required to assist the gas cooling systems in controlling the RPV temperature during normal operation, and in a postulated loss of forced gas cooling event. The RCCS has minimal effect on the fuel temperature.

### 8.2.2.2 Loads

Under normal operating conditions, the heat load to which the RCCS standpipes will be exposed, is [ ][b], while for a Depressurized Loss of Forced Cooling (DLOFC) the heat load increases to approximately [ ][b].

### 8.2.2.3 Back-up cooling tower

The cooling tower is a closed circuit modular unit with its own fan(s) and 2 x 100% circulating pumps. The hot water will pass through stainless steel coils from which the heat is transferred to the air. With the ambient design dry bulb temperature being 34 °C, and a re-cooled water temperature requirement of [ ][b], the tower is spray assisted, and thus provided with 2 x 100% on-board spray pumps.

The cooling tower will come into operation automatically if the EPCC circuit cannot provide power to the RCCS.

### 8.2.2.4 Vents and filters

The RCCS is a closed system maintained at atmospheric pressure. To achieve this, the header tanks are open to atmosphere via a particulate filter that prevents dust and other impurities from entering the system, but allows air transfer to balance the internal and external pressures.

During passive operation, steam is released to the atmosphere via this same route.

### 8.2.2.5 Demineralized water supplies

Demineralized water for make-up purposes is supplied by the ACS.

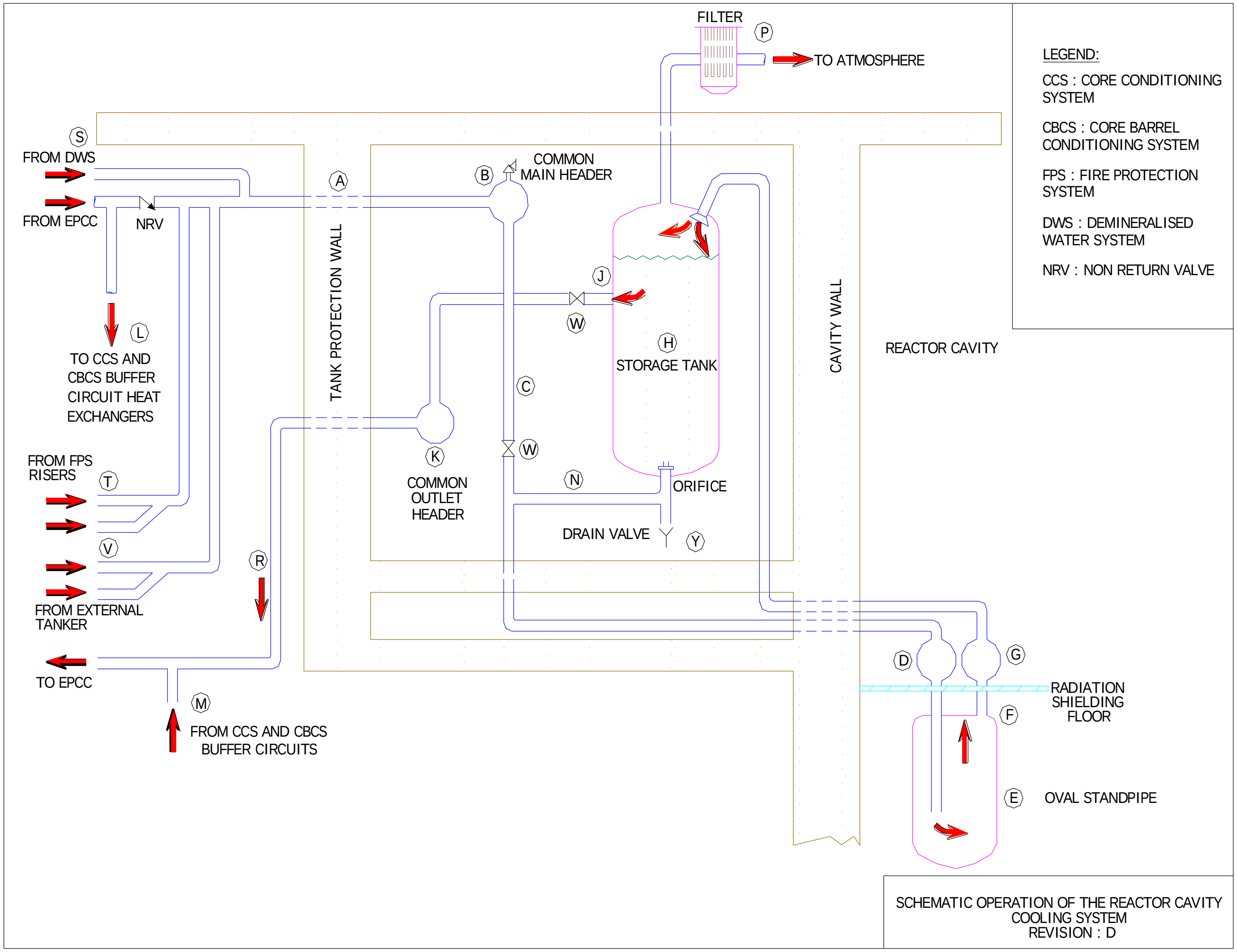



**Figure 55: Schematic Layout of the Reactor Cavity Cooling System in the Reactor Cavity**

### 8.2.3 General Description

Referring to Figure 55:

During active operation, [ ][b] of cold water is pumped from the EPCC heat exchanger, through the tank protection wall (A) to the main cold water header (B) above the water storage tanks (H). The water in the main cold water header flows into 18 branch pipes (C). Each of the 18 branch pipes enters an intermediate header (D) to which four outlets are welded, giving a total of 72 cold water inlet pipes, each connected to an individual standpipe (E). Each of these 72 cold water inlet pipes supplies approximately [ ][b] of cooling water at a nominal duty point temperature of [ ][b], to one standpipe.

On being released at the bottom of the oval standpipes, the water flows slowly upwards, increasing in temperature. After leaving at the top of the standpipes (F), the heated water from four standpipes recombines in the intermediate header (G), flows into the storage tank (H), then exits the tank at (J) and flows to the EPCC heat exchanger via the common main outlet header (K) and common return pipe (R).

Each tank will have a manually operated drainage point (Y) and manually operated isolation valves (W) for isolating the train for maintenance and inspection. (A train being one tank, four standpipes and associated pipework.)

A small bore pipe (N) containing an orifice plate, will connect each tank to its corresponding cold water inlet pipe (C). During normal active operation, an insignificant amount of cold water will pass from the inlet pipe, via the orifice, into the tank, thereby bypassing the standpipes. Should the active system be lost, and the water in the standpipes heat up and then start to boil, water from the tank will gravitate through the orifice into the cold water inlet pipe, and hence into the standpipe, to replace water lost by evaporation. During this passive operating mode, steam will be collected above the water in the tanks, and will be released to atmosphere via a common steam heater and particulate filter (P).

When not in passive mode, the filter will prevent contaminants from outside the Reactor Building entering the tanks via the steam header. These filters will allow clean air to pass through so that the pressure in the tanks is in balance with the ambient air pressure.

Topping up of the water storage tanks to account for normal system losses, will be an automatic action by the Demineralized Water System (DWS) (S). After larger water losses, e.g. due to passive operation, refilling will be a manually activated operation, drawing water from the DWS if time permits, or from the Fire Protection System (FPS) if fast replacement is required (refer to PBMR document number 017550). Emergency make-up lines (T) from the FPS risers in the module, and (V) from a tanker, tie in upstream of the Non-return Valve (NRV)

Tap off points to and from the CCS and Core Barrel Conditioning System (CBCS) buffer circuits are located outside the cavity at (L) and (M).

The 18 water storage tanks will be located adjacent to the cavity, on level 27.9 m. Feeder pipes to the standpipes will penetrate the floor, running under this floor up to the cavity penetration points.

The RCCS will operate in parallel with the CCS and CBCS buffer circuits, all three being cooled by the EPCC pumps and heat exchangers.

### 8.2.4 Operation

#### 8.2.4.1 General

The RCCS is a constant flow, water-based cooling system, which removes heat from the reactor cavity. Heat collected by the RCCS during normal operation, will be transferred to the (EPCC, which in turn will transfer the heat to the Main Heat Sink System (MHSS) for release into the environment. Loss of the EPCC will result in the RCCS being automatically connected to the back-up cooling tower. Loss of the EPCC as well as the cooling tower will result in the RCCS converting automatically to passive operation, a mode which can continue unassisted for up to 72 hours. Water from the DWS and/or FPS can be used to replace that lost by evaporation, and in this way, passive operating times can be extended indefinitely.

After use of the FPS, which contains potable water, the RCCS tanks will be drained and refilled with demineralized water, followed by a blowdown/make-up programme to restore the water chemistry.

Start-up of the EPCC will allow active operation of the RCCS to be restored at any time during passive operation, provided that the water level in the tanks is still above the outlet pipes.

**Flow Balancing**

The low flow rate in the standpipes means that small resistance differences may cause imbalances in the 18 circuits. To balance the flows, each outlet pipe, where it enters the water storage tank, will be fitted with a slot weir. The weirs will be located just above the water level in the tanks. Together with the common inlet and outlet headers, automatic balancing of the circuits will be achieved.

### 8.2.5 Operating Modes

#### 8.2.5.1 Plant normal, reduced capacity and standby modes

During normal and reduced capacity operation of the plant, and during plant standby, the RCCS will run at full active flow.

#### 8.2.5.2 Plant shutdown and fuelled maintenance modes

During plant shutdown, the heat from the core will be due to decay only, and the RCCS will continue operating at full flow. During plant maintenance, as long as there is fuel in the reactor, the RCCS will be in operation.

#### 8.2.5.3 Power plant defuelled maintenance mode

During defuelled maintenance of the power plant, the RCCS flow can be stopped.

#### 8.2.5.4 Power plant trip conditions

In the event of a power plant trip (operational fault, Loss of Forced Cooling [LOFC]) without loss of grid power, the RCCS will continue to run at full active flow. If grid power is lost, the RCCS will run at full flow on the EPCC back-up cooling tower, whose pumps and fan motors will be supplied with electrical power from diesel generators.

#### 8.2.5.5 System leaks

Any water leakage from the RCCS into the reactor cavity will generally evaporate, but should the RPV be cold, the water will also gravitate via local drains to the module sump. Should the header tank level controllers fail at the same time as a system leak occurs, the make-up system valves will not open, but the drop in pump suction head is detected by the pump suction side pressure transmitter. The suction pressure is monitored from the control room, and provides an independent means of detecting water losses.

### 8.2.6 Control and Instrumentation

The purpose of the RCCS control system is:

- To interpret signals from the process monitoring instruments and to use these signals to initiate alarms, readouts or automatic actions, or to prepare the systems for manual intervention.
- To interpret signals derived from operator actions, and to initiate or alter plant operational modes accordingly

#### 8.2.6.1 Control system characteristics

The automation control system software logic will monitor the status of inputs relevant to the circuit components, and process conditions and the functional criteria.

Each of the tanks is fitted with a vent pipe through which air or steam can pass unaided to atmosphere.

The water level in the header tanks is monitored by level transmitters, and any abnormal drop in the water level is alarmed. Should the water level continue to drop, the operator will decide on whether or not to decrease module power, or activate additional tank filling procedures. Should no operator actions follow, and should the water level continue to drop, the pumps will trip at a pre-set water level, the system will automatically convert to passive operation, and the cooling tower will take over the cooling duty of the buffer circuits.

## 8.3 MAIN HEAT SINK SYSTEM

### 8.3.1 Overview

The Main Heat Sink System (MHSS) is a standard open circuit pumping and piping system. Pump and valve components in contact with sea water are of stainless steel, while piping is Glass Reinforced Polyester (GRP).

The system circulates sea water from the existing KNPS pump house to the PBMR CW plant room, and back to the existing KNPS outlet structure.

### 8.3.2 Components and Functions

#### 8.3.2.1 General

The MHSS is, as far as practicable, made up of standard, proven components. The MHSS is not deemed to be a nuclear safety system, and no reliance is to be placed on it to prevent the reactor or fuel system from releasing radiation to the environment.

The function of the MHSS is to remove waste heat from the following circuits:

- The ACS Pre-cooler Cooling Circuit
- The ACS Intercooler Cooling Circuit
- The ACS Auxiliary Closed Circuit
- The EPCC Closed Circuits

Waste heat transfer is achieved via plate heat exchangers located in the CW plant room, adjacent to the Reactor Building.

#### 8.3.2.2 Loads

The MHSS is designed to achieve a total heat transfer of approximately 240 MW from the module complex to the sea. This is done with a sea water flow rate of [ ][b], giving a sea water outlet temperature from the PBMR, of approximately [ ][b]. With the addition, at the KNPS outlet structure, of a minimum of [ ][b] of water from the KNPS condensers (one unit), the temperature of the water released to the Atlantic remains within environmentally acceptable limits, i.e. an increase of no more than 1 °C above the normal KNPS release temperature.

### 8.3.3 Layout

The MHSS pumps a continuous flow of CW from the sea to the CW plant room, where the water passes through particle filters before reaching the ACS and EPCC heat exchangers. Marine debris from the filters is fed into the hot return line and is discharged back into the sea.

The 4 x 50% MHSS pumps are installed in the existing KNPS service water pumphouse. The sea water is drawn into six inlet bays, passes through existing raking screens, is chlorinated, passes through drum screens, and enters the interconnecting pipe linking the two Koeberg pump houses.

This interconnecting pipe runs underground between the two pump houses and is branched just before entering the services pump house, one branch forming an emergency back-up feed to the services pumps if their sea water intakes are unavailable, the other feeding the MHSS pumps.

The MHSS pumps have no back-up sea water supply, and loss of this supply will result in a module trip. Nuclear safety is not at risk.

The pumps are grouped into two sets of two pumps each, each set being supplied from an independent electrical board.

The CW pipes between the services pump house and the CW plant room are buried.

### 8.3.4 Operation

#### 8.3.4.1 Plant normal, reduced capacity and standby modes

During normal and reduced capacity operation of the plant, and during plant standby, the MHSS will run at full flow.

#### 8.3.4.2 Plant shutdown and maintenance modes

During plant shutdown, the core decay heat transferred from the RPV is removed by the RCCS and transferred to the EPCC. Some heat will also be generated by various auxiliaries, and transferred to the MHSS by the ACS.

### 8.3.5 Control and Instrumentation

The purpose of the MHSS control system is:

- To interpret signals from the process monitoring instruments and to use these signals to initiate alarms, readouts or automatic actions, or to prepare the systems for manual intervention.
- To interpret signals derived from operator actions, and to initiate or alter plant operational modes accordingly.

The control system automatically switches between pump sets in the event of pump failures or running hour limits. Diesel generators are available if grid power is lost.

## 8.4 FIRE PROTECTION SYSTEM

### 8.4.1 Overview

The primary focus of the Fire Protection System (FPS) is to protect Systems, Structures and Components (SSC) from the effects of internal fires by means of passive measures, and where applicable, fixed fire suppression systems. The building is divided into a number of fire areas, and the use of active fire protection measures matches the safety requirements for the safety-related functions and systems in the area. This includes functions such as core heat removal, reactivity control and confinement of radionuclides. Initiating events caused by internal fires are evaluated by deterministic and probabilistic analyses.

### 8.4.2 Design Bases and Philosophy

SSC important to safety are designed and located to minimize the probability and effect of fires and depressurization events. Non-combustible and heat-resistant materials are used wherever practical throughout the unit, particularly in locations such as the containment and control room. Fire detection and fire-fighting systems of appropriate capacity and capability are provided and designed to minimize the adverse effects of fire on SSC important to safety. Fire-fighting systems are designed to assure that their rupture or inadvertent operation does not significantly impair the safety capability of these SSC.

For each fire hazard, a suitable combination of fire prevention, fire detection and suppression capability, and ability to withstand safely the effects of a fire, is provided. Both equipment and procedural aspects of each are considered.

Property investment areas have been established based on National Fire Prevention Association (NFPA) codes as well as South African Building Codes (SABS 0400) and other International Guidelines for the Fire Protection of Nuclear Power Plants to mitigate the consequences of fire, and to reduce the potential of loss of power generation capability. In some instances, engineering judgment, based on industry practices, has been utilized to balance a potential loss due to fire versus the benefit of providing any passive or active fire protection feature. For example, installing fire-rated seals for penetrations between floor elevations in each electrical cable chase to mitigate the spread of a fire vertically, or providing curbing around large pumps to contain any lube oil leaks is implemented. A fire detection system to allow for an early warning of a fire is implemented throughout the plant, and appropriate detectors are selected for the specific risks associated with the respective areas.

### 8.4.3 Safety

The fire detection and protection measures extend into controlled areas. Water released into these areas is collected and processed by the Waste Handling System (WHS).

Life Safety areas based on NFPA codes (e.g. NFPA 101) as well as South African Building Codes (SABS 0400) and other guidelines are used to provide an egress path from all areas of the plant, buildings, or structures (stairwells).

#### 8.4.3.1 Safe shutdown equipment

Equipment required to support safe shutdown is kept free from fire damage, smoke, and hot gases. In addition, fire suppression systems when activated will not migrate into other fire areas such that it would have an adverse affect on safe shutdown, e.g. fire suppression water leaking into other area and causing an electrical fault or flooding concern.

#### 8.4.3.2 Special hazards

Due to radiological or combustible loading hazards, some areas have multiple design functions (i.e. radiation shielding, pressure, thermal expansion, and fire). While the design basis of the structure considers these features, penetrations through these areas maintain the same multiple design conditions, as applicable.

### 8.4.4 Layout

#### 8.4.4.1 General

The PBMR design features fire-resistant barriers/enclosures, fire doors and dampers (passive fire protection), fire-retardant cable insulation, and non-combustible construction in general. Automatic fire detection and automatic/manual fire suppression features (i.e. fire hose stations and portable fire extinguishers) are provided for the early warning and subsequent suppression of fires that may occur. In addition, passive features in the design of the PBMR for the removal of the decay heat from the reactor core allow the PBMR to withstand the effects of fires.

The detection system is sited to provide early warning of fire conditions in all risk areas. This system is interlocked with the HVAC system to automatically shut the dampers or provide a facility to remotely shut down dampers on supply and extract air routes.

2 x 100% reservoirs, and 2 x 100% pumps (one electric and one diesel) are provided. Water is fed into ring mains around the buildings, and hence into risers within the buildings. From the risers, the water is distributed to each fire zone. Quick-acting valves will release water into the areas in which it is needed in the event of a fire. Portable equipment and safety gear such as face protection, tunics and extinguishers are sited in and around the facility at accessible points.

Generally, the PBMR is subdivided into separate fire areas as determined by the fire risk assessment for the purpose of limiting the spread of fire, protecting personnel, and limiting the resultant consequential damage to the plant. Fire areas are separated from each other by fire barriers, and all penetrations through the fire barriers are sealed with fire rated materials appropriate to the fire barrier breeched.

Due to the unique nature of the PBMR design, there are no specific regulatory document(s) that prescribe the fire protection requirements. Due to the similarity of functions of various areas to those of existing Nuclear Power Plants (NPPs), the NFPA codes are applied to most of the fire areas. Further guidance from NUREG 800 and 10CFR50 was also used.

#### 8.4.4.2 Reactor Building

Confinement areas encompass the radiation classification zones during normal operation. Fire areas were established within the PBMR based on life safety, property loss, code, or regulatory requirements/guidance.

#### 8.4.4.3 Services building

The Services Building contains the following three sections. Fire barriers are provided for life safety, equipment protection, as well as regulatory requirements, as necessary.

a. Waste Handling is an engineered building (i.e. poured concrete type structure) comprised of various rooms associated with radiological waste processing and storage, as well as electrical equipment and battery rooms. These rooms are typically provided with two-hour fire-rated barriers, while the radiological storage areas will have three-hour fire-rated barriers.
b. The Services Building is a design built structure (i.e. steel frame, Butler-type building on a poured concrete floor) where the Main Control Room, as well as offices and workspace for supporting site staff and services, are located. The control room within this building has two-hour fire-rated barriers, while the remaining walls have fire ratings commensurate with life safety egress requirements and/or by room function and use.
c. The Workshop/Office Area is an extension of the Services Building and provides additional workshops, laboratories, lockers, and offices. Similarly, walls within this area have fire ratings commensurate with life safety egress requirements and/or by room function and use.

#### 8.4.4.4 Transformers

An automatic deluge system is installed for the transformers. This is coupled with a pilot line actuation system. This line runs parallel to the water spray piping, but utilizes a fusible sprinkler to detect a fire. During a fire, the heat fuses the sprinkler(s) that releases the air, and the deluge valve opens.

#### 8.4.4.5 Cable tunnels

Cable tunnels are provided with firewater suppression systems and include hose stations or wet pipe sprinklers.

#### 8.4.4.6 Diesel generator building

A fixed fire suppression system is used to protect both the diesel generator and day storage tanks.

#### 8.4.4.7 Diesel fuel oil storage tank

The main diesel storage tank is buried, and therefore no fire systems are required to protect this plant.

#### 8.4.4.8 Lube oil storage tank

Lube oil storage tanks, pumps and motors are protected by fixed fire suppression systems. Foam/water systems are used where the fire potential dictates a higher knockdown capability is required for fire extinguishment.

#### 8.4.4.9 Cooling water plant room

Due to the electrical motors, fire detection is provided for this building, in addition to hose reels and hand-held extinguishers.

#### 8.4.4.10 Fire pumphouse building

Fire detection is provided for this building, in addition to hose reels and hand-held extinguishers. In addition, a fire suppression system is provided for the diesel fire pump.

#### 8.4.4.11 Firewater systems

Fire areas/zones have been established along with major equipment associated with systems in each area. The largest combustible loading requiring suppression protection is the main transformer with [ ][b] of oil, which typically requires a volume of firewater of the order of [ ][b]. The pump capacities calculated assume a firewater deluge system for the transformer.

While a fire is not required to be considered coincident with a seismic event, by regulatory guidance recommendations, provision is made to supply water to standpipes and hose connections for manual fire-fighting in areas containing equipment required for safe plant shutdown in the event of an SSE.

The fire main loop is designed and installed in accordance with NFPA 24, which includes the system yard hydrants that provide manual firewater suppression capability for the entire site, while also serving as a back-up protection for areas not otherwise protected with an automatic water suppression system. The hydrants are spaced around the perimeter of the site and are strategically located to optimize coverage. Each hydrant is provided with a hose house containing hoses and other related equipment for fire brigade use.

The fire main loop is supplied with water from two 100% fire pumps. Each pump is capable of supplying firewater to the largest fixed water sprinkler system, plus approximately 2 000 l/min for hose streams. A pressure maintenance jockey pump maintains the pressure in the fire protection water distribution system.

### 8.4.5 Operation

The fire detection systems include audible and visual alarms in the Main Control Room. These systems are designed in accordance with applicable codes and standards (NFPA 72 and British Standard EN 54). Alarms include local control panels associated with fixed extinguishing systems, local panels associated with area detection systems, and local panels supervising the monitor switches on the interior sectional control valves. Control Room operators as well as site personnel utilize the plant communication system to provide notification of fire emergencies. Site-wide notification of fire or other emergencies is per public address system.

In addition to the fire detection system being used to actuate a fire suppression system as discussed above, detection systems are utilized to provide prompt early warning of a fire in the incipient stages, to preclude fire damage.

The communication system design provides effective communication between plant personnel in all vital areas during fire conditions under maximum potential noise levels. Two-way voice communications are vital to safe shutdown and emergency response in the event of fire. Suitable communication devices are provided as follows:

- Fixed emergency communications independent of the normal plant communication system, installed at pre-selected stations.
- A portable radio communications system provided for use by the fire brigade and other operations personnel, required to achieve safe plant shutdown. This system does not interfere with the communications capabilities of the plant security force.

Water is taken from the municipal mains, and is used to fill the two storage tanks. Each tank is sized to allow for [ ][b] full operation of the FPS.

#### 8.4.5.1 Pumps

The electric pump is normally used, with the diesel pump being kept in reserve. The installation of two 100% capacity fire pumps (i.e. one electric motor driven and one diesel driven) ensures that system pressure or flow requirements are available in the event of a failure of the one pump or loss of off-site power.

#### 8.4.5.2 Storage tanks

The tanks are interconnected such that fire pumps can take suction from either or both. A failure in one tank or its piping will not cause both tanks to drain. Either tank can be refilled in 8 h. The potable water system is the supply source to refill the tanks.

#### 8.4.5.3 Control and instrumentation

The alarm contacts from each fire pump controller are monitored at the Main Fire Control Panel located in the Main Control Room of the Services Building. In addition, the firewater tank level is monitored.

## 8.5 HEATING, VENTILATION AND AIR-CONDITIONING SYSTEM

This paragraph covers only the HVAC of the Reactor Building. The HVAC systems of the Services and Auxiliary Buildings are not described in this document.

### 8.5.1 Functional Requirements

The module HVAC has the following functions:

- To supply fresh air to the building
- To maintain specified environmental parameters, temperature and where required, humidity
- To maintain sub-atmospheric pressure and direction of flow in the zones
- To remove heat from mechanical and electrical equipment
- To remove airborne radioactive gases, aerosols and dust particles from within the Reactor Building by purging, filtering, recirculation and local extract air
- To minimize environmental impact by filtering exhaust air
- To extract smoke during a fire and after it has been extinguished

### 8.5.2 Building Pressure Zones

In order to direct air leakage between rooms from less or more contaminated rooms, the rooms are kept at static pressure differential with the more contaminated room at a lower static pressure. This zoning includes three pressure zones, namely:

- Static pressure 3 : All controlled zones containing vessels with radioactive gases and particles.
- Static pressure 2 : All controlled areas which are not Zone 3.
- Static pressure 1 : All uncontrolled zones with no nuclear radiation exposure.

The pressure zones are controlled at the following static pressures irrespective of filter condition:

- Static pressure Zone 3 : -90 Pa to -110 Pa gauge pressure.
- Static pressure Zone 2 : -40 Pa to -60 Pa gauge pressure.
- Static pressure Zone 1 : Atmospheric pressure or above.

### 8.5.3 General System Description

The HVAC for the Reactor Building consists of a water-cooled chilled water system supplying chilled water to fan coil units throughout the building, as well as to once-through fresh air supply Air Handling Units (AHUs) serving three pressure zones. Extract air systems extract air from the three pressure zones to maintain the set pressures in the three zones. Two separate self-contained split-package unit installations provide controlled conditions to the module shutdown room, Reactor Protection System (RPS) rooms and Post-event Instrumentation (PEI) rooms. A mechanical ventilation extract system is provided for the PEI battery rooms.

#### 8.5.3.1 Centralized chilled water system

The centralized chilled water system provides chilled water via a distribution supply and return chilled water piping system to the outside air supply AHUs and room fan-coil cooling units. The chillers consist of two suitable commercially available, standard liquid chiller units, each with a primary chilled water circulating pump. Each chiller provides approximately 100% of the total calculated cooling capacity. The chiller pump combinations shall be connected into a primary closed-loop chilled water circuit to provide constant water flow through each chiller during all load conditions. The condenser water systems are connected to the ACS. The chilled water is supplied to the AHUs by means of secondary chilled water pumps connected into the primary chilled water closed loop. Four sets of secondary chilled water pumps (consisting of one duty and one standby unit) shall supply chilled water to the AHUs and fan coil units.

#### 8.5.3.2 Centralized air-handling system

The three centralized air-handling systems shall each consist of the following elements:

- Outside air intake AHUs, each with 100% redundant air-handling capacity
- Supply air duct work systems
- Control systems
- Extract air duct work systems
- Exhaust air fan/filter units (carbon filtration only for Zone 3 extract), each unit with 100% redundant capacity

The outside air intake AHUs shall each consist of a prefabricated air-handling plenum section or housing (complete with inter alia, thermally insulated wall, roof and floor panels, access doors, airflow control dampers, mounting frames, light fittings, water condensate collection and removal facilities and electrical distribution), air filters, a chilled water cooling coil, an electric re-heater, a supply air fan and associated control system.

The exhaust air AHUs extracting air from Pressure Zone 3 shall each consist of a prefabricated plenum or housing (complete with wall, roof and floor panels, access doors, airflow control dampers, mounting frames, light fittings and electric distribution) primary filters, secondary filters, high-efficiency particulate air filters, electric heater, activated carbon filters, an exhaust air fan and associated control system. The exhaust AHUs serving the pressure Zones 1 and 2 shall not be provided with any air filters. High Efficiency Particular Air Filters (HEPA) shall be installed into the room supply and extract air intakes of the Pressure Zone 3 system to prevent contamination into duct work. All exhaust air systems shall also provide a smoke extract function during fire conditions

#### 8.5.3.3 Localized fan-coil type air-handling systems

The constant air volume fan-coil cooling units shall be located within rooms and provide sensible cooling in these rooms. The units shall each consist of housing, integral control system, supply air fan, coarse air filter and chilled water cooling coil. Unit sizes shall be standardized to simplify spares provision. Piping and duct work connections shall be provided to facilitate quick replacement by spare units so that maintenance or repairs can be performed in workshops. Cooling units shall be selected from standard, commercially available units to provide reliable operation by the use of suitable, quality components and simplified operation. Fan-coil units shall be connected to commercially available, low-pressure, galvanized sheet metal supply air duct work and suitable air outlets where air distribution is required. Standby units shall be installed in Zone 3. A number of spare units shall be kept in stock to facilitate quick replacement of installed units. Additional chilled water supply and return connections shall be provided in all building rooms to facilitate future possible addition of room fan-coil units due to changed cooling loads.

#### 8.5.3.4 Air handling of the post-event monitoring and recovery room

Two 100% capacity systems independent of each other and of any other module air-conditioning systems shall be provided for the Post-event Monitoring and Recovery Room (PEMRR). Purified outside air, filtered by means of HEPA and activated carbon filters, shall be supplied into the PEMRR. Room dry bulb temperature and relative humidity shall be controlled for all rooms. AHUs shall consist of locally installed, direct expansion type, split system AHUs with interconnecting refrigerant piping. The AHUs and condensing units shall be supplied with power from dedicated standby generator systems. Control systems shall be provided to close the outside air intakes automatically and start recirculating the air when the air intake downstream of the air filters contains harmful gas products or particles. The equipment shall be selected from available high-quality commercial products. System components shall be designed, mounted and protected to withstand seismic events

#### 8.5.3.5 Battery room ventilation extract systems

The battery rooms are maintained at 25 °C dry bulb, and the ventilation system is designed to limit the concentration of hydrogen gas to below 1% of room volume. The supply air is supplied from the centralized AHUs and the exhaust air is extracted through dedicated, corrosion resistant duct work and fans to outside. Two 100% capacity fans are provided and each is supplied from the standby power system.

### 8.5.4 Process Flow and Schematic Diagrams

Refer to Figure 56, Figure 57 and Figure 58.

#### 8.5.4.1 Air handling of reactor protection system rooms and post-event instrumentation rooms

Two 100% capacity systems independent of each other and of any other module air-conditioning system shall be provided for the RPS and PEI Rooms. The AHUs will recirculate, filter and cool the air prior to supplying the air to the three rooms. Room dry bulb temperature shall be controlled. AHUs shall consist of locally installed, direct expansion type, split AHUs with interconnecting refrigeration piping. The AHUs and condensing units shall be supplied with power from the dedicated standby generator systems. The equipment shall be selected from availably high-quality commercial products. System components shall be designed, mounted and protected to withstand seismic events

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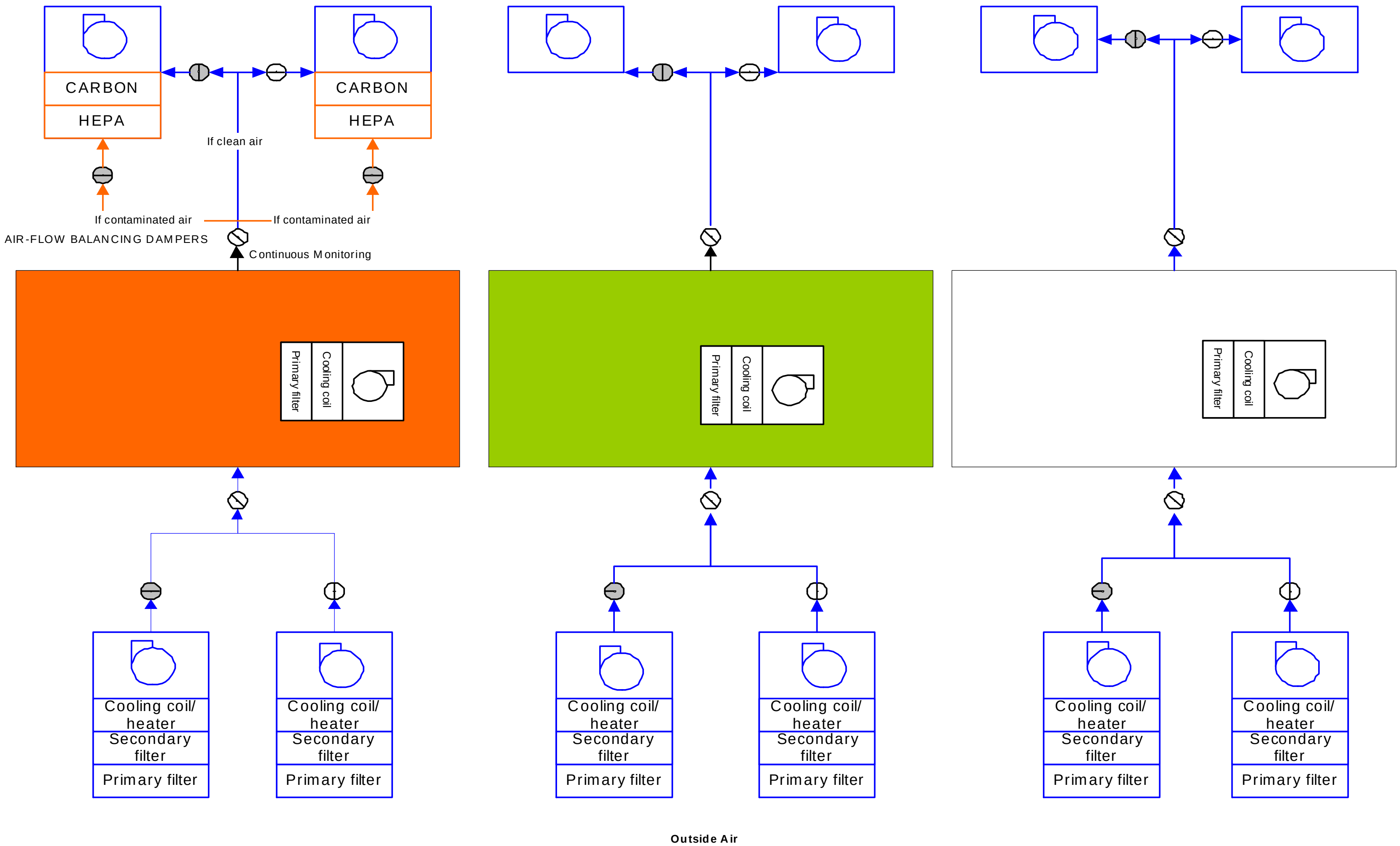



**Figure 56: Pressure Zone and Fan-Coil Air-handling System**

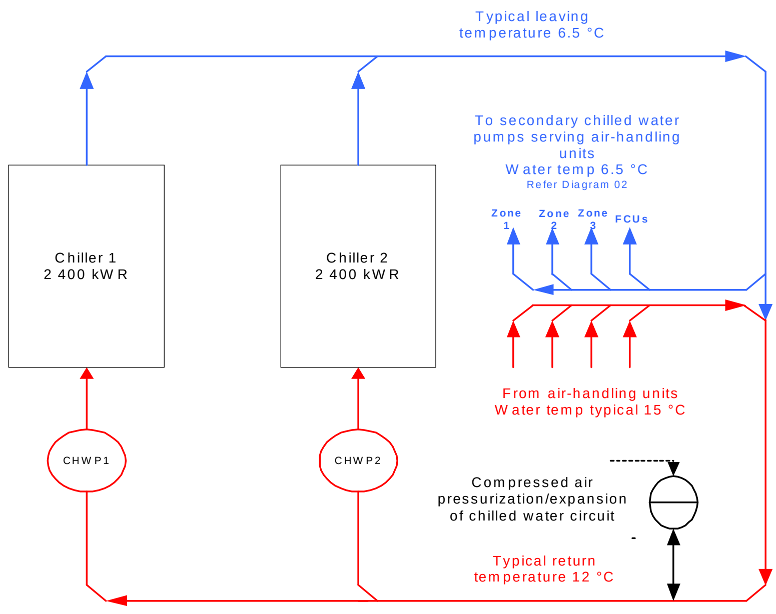



**Figure 57: Central Chilled Water Generation System**

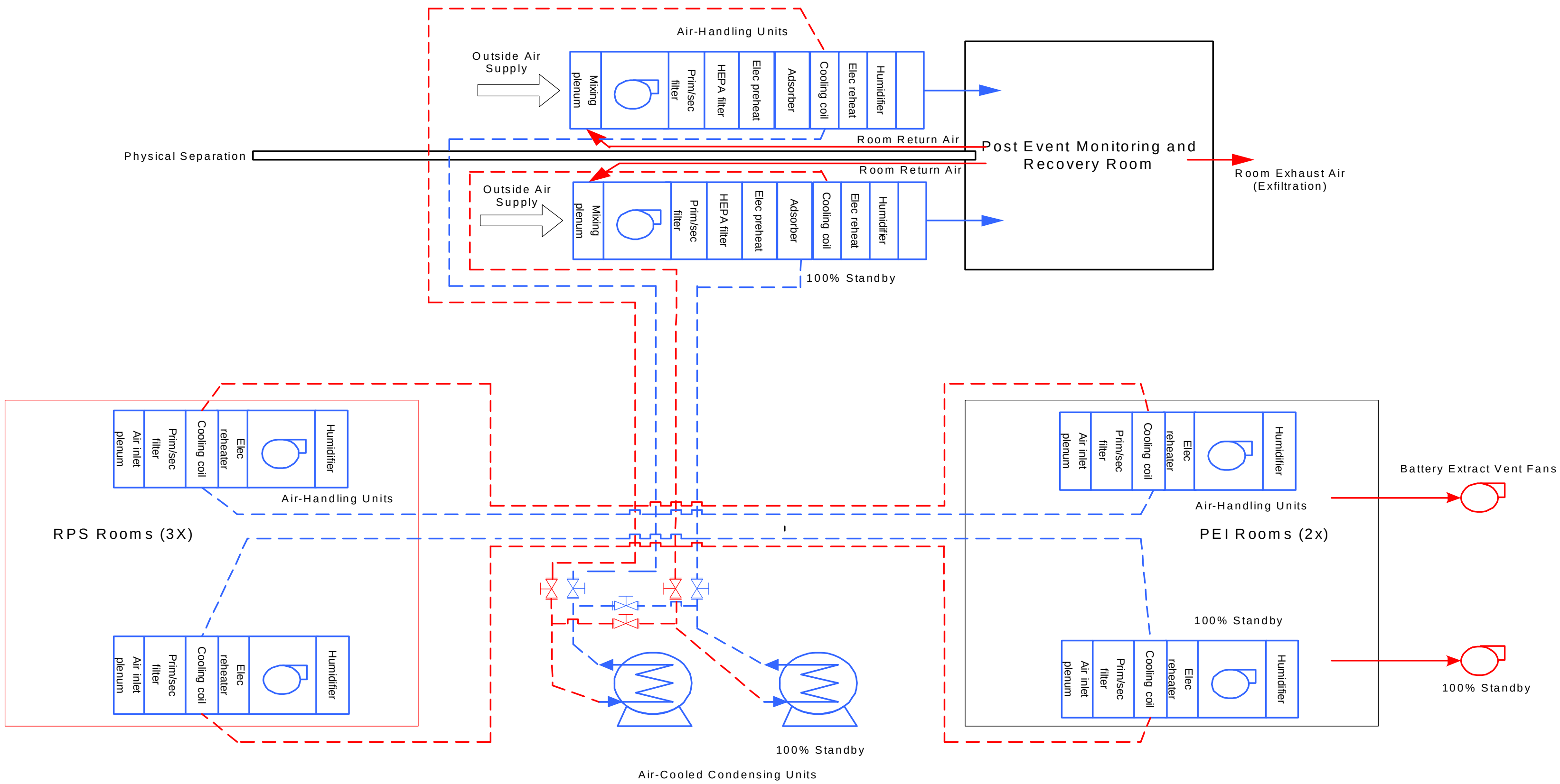



**Figure 58: Post-event Monitoring and Recovery Room, Reactor Protection System Rooms and Post-event Instrumentation Rooms Heating, Ventilation and Air-conditioning System**

## 8.6 PRIMARY LOOP INITIAL CLEAN-UP SYSTEM

### 8.6.1 Function

The PLICS is used to remove water vapour and other absorbed gases from vessels and systems that will eventually be containing helium that will come into contact with the core, to prevent graphite corrosion and build-up of Carbon 14 (C-14). Clean-up is achieved by pre-drying and evacuation stages.

The clean-up process is required after:

- First installation of the core structures
- Core reflector replacement
- Open maintenance on the PCU

The following systems are cleaned by the PLICS:

- Main Power System (MPS) (including the first load of graphite spheres)
- HICS
- FHSS

### 8.6.2 System Breakdown

The PLICS consists of three systems:

- PLICS Electric Heater (PEH)
- PLICS Vacuum Subsystem (PVS)
- PLICS Electric Heater Power Supply

Refer to Figure 59 for the layout of the PLICS in the Reactor Building.

### 8.6.3 Clean-up Operation

a. Pre-drying stage

Gaseous nitrogen is introduced into the reactor from the mobile nitrogen source. The pressure in the reactor shall be controlled at [ ][a,b]. During this operation, the maintenance valves are closed.

The PEH heats the nitrogen that is being circulated by the CCS blower system, which will in turn heat up the reactor, the FHSS and its internals to a temperature of between [ ][a,b].

The moisture content of the nitrogen is monitored, and a percentage of the nitrogen is vented to atmosphere when a predetermined moisture content level has been reached.

Gaseous nitrogen will once again be introduced into the MPS, and the above procedure is repeated. This procedure is repeated until the point is reached where effective removal of moisture is no longer possible by means of purging the system.

b. Evacuation stage

The PVS is used to evacuate nitrogen and other absorbed gas from the MPS, FHSS and the HICS to the required allowable levels during the first commissioning, after open maintenance on the PCU and after core reflector replacement. Evacuation is done to a pressure of [ ][b] absolute.

### 8.6.4 PLICS General Performance

The PLICS cleans the MPS, FHSS and HICS to the following levels:

- The amount of nitrogen, after the initial clean-up of the core (after installation) and purging with helium, is [ ][b].
- The amount of nitrogen in the PCU, after open maintenance on the PCU and purging with helium, is [ ][b].

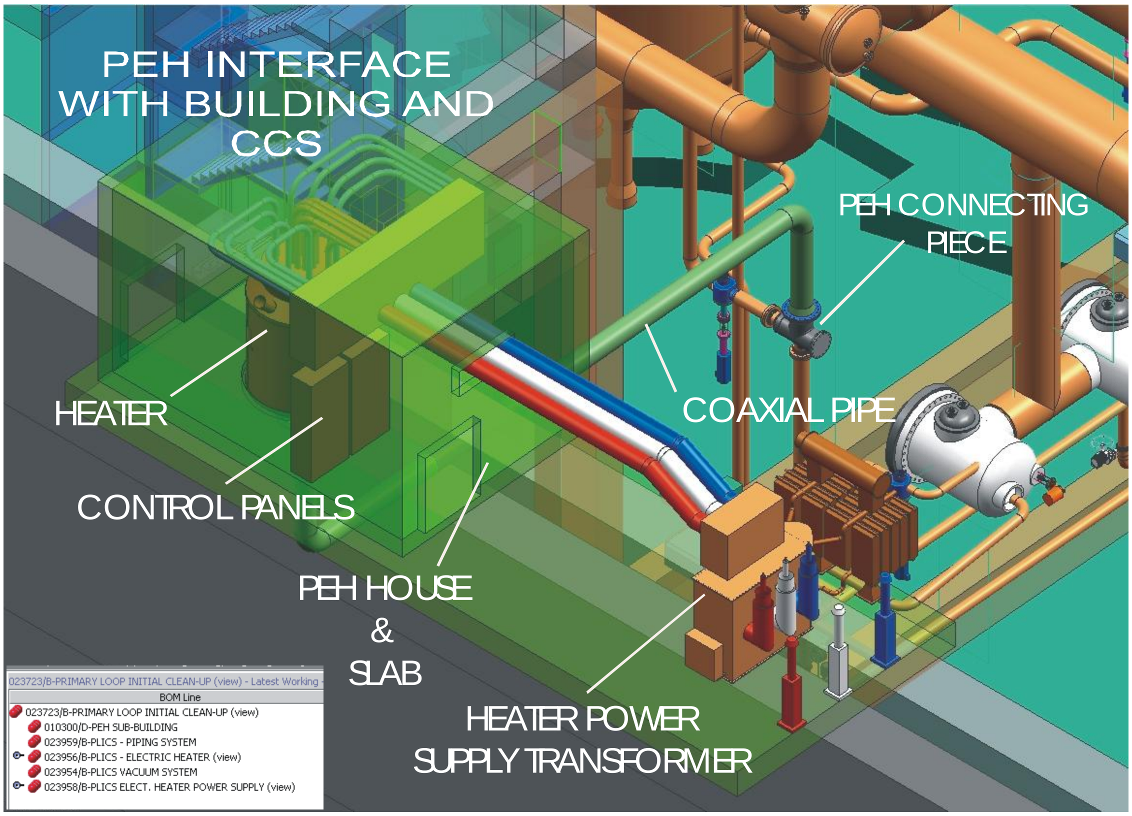



**Figure 59: General Layout of Primary Loop Initial Clean-up System in the Reactor Building**

## 8.7 COMPRESSED AIR SYSTEM

### 8.7.1 General System Description

The CAS consists of a Low-pressure (LP) air system and a High-pressure (HP) air system, which are housed in the Ancillary Building. The air is supplied to the module through a single pipe per system.

#### 8.7.1.1 Low-pressure air system

The LP system consists of two compressor sets with independent electrical supply. Each set consists of two screw compressors rated at [ ][b]. Each set can supply the full plant requirement, resulting in 100% redundancy. During normal operation, the compressor in each set will switch on as required to supply the required duty.

The air is treated to a dew point of [ ][b] and conditioned to the quality required by user systems.

The LP system is mainly used by the FHSS, HICS and Dry Gas Seal (DGS) systems, and for maintenance, decontamination and transferring collected effluent.

#### 8.7.1.2 High-pressure air system

The HP air system consists of [ ][b] water-cooled HP reciprocating compressors, complete with water-cooled after-cooler, desiccant dryer, filtration and a single air receiver. Each compressor supplies [ ][b] dew point to the HICS valves.

### 8.7.2 Availability of Equipment

The compressors, after coolers, filters, refrigerated driers, desiccant driers and all air receivers will all be off-the-shelf items. Apart from the redundancy provided by installing standby compressors for each of the HP and LP systems, connection points on each of the pipe reticulation systems at ground level are supplied outside the building to connect mobile compressor sets if required.

### 8.7.3 Control

The air compressors on both LP and HP systems are provided with a local selection switch for local (manual) start/stop control. The air compressors are enabled from the Automation System (AS) when the remote control mode has been selected. If enabled, compressors will cycle on or off by means of their integral control system, depending on compressed air demand. The air dryers are controlled from each associated air compressor by means of electrical interlocking, but are provided with a local override switch for maintenance purposes.

## 8.8 PRESSURE RELIEF SYSTEM

### 8.8.1 Overview

The Pressure Relief System (PRS) ensures that pressure build-up in the Reactor Building remains within the structural design margin of the building during depressurization events.

### 8.8.2 Functions

The prime functions of the PRS are to:

- Preserve the structural integrity of the Reactor Building during an emergency depressurization event (defined as a break in the Pressure Boundary (PB) equivalent to a double-ended guillotine break of a pipe with inside diameter [ ][a,b]).
- Preserve the structural integrity of the Reactor Cavity (RC) during faulted depressurization events (defined as a break in the PB equivalent to a double-ended guillotine break of a pipe [ ][a.b] inside diameter).
- Limit delayed release of helium to atmosphere subsequent to any depressurization event.

### 8.8.3 Layout

A relief route consists of a rupture panel and a duct. The rupture panels and ducts ensure that the pressure in the room where the break occurs does not exceed the safe loading of the structure.

A ventilation shaft is provided to direct escaping gas to atmosphere. The opening of the shaft is provided with a dust cover to prevent ingress of dust under normal operation, and with two independent closing mechanisms to cover the opening once the gas has been relieved.

### 8.8.4 Operation

Five PRS modes of operation are distinguished. The modes correspond with the load categories as defined in the PBMR Integrated Design Process (PIDP) and are associated with the PBMR event classes as defined in the same document.

- During normal operating conditions (load category A), the PRS is in mode A. (Standby with status of components being monitored in order to provide early warning, should a component of the PRS malfunction.)
- In the event of a small pipe break, which results in an abnormal operating condition (load category B), PRS mode B is activated. Should the capacity of the HVAC system in the room where the break develops be insufficient to contain the consequences of the break within the room, helium is vented via PRS Route B for small pipe breaks to the PCU area, where the ventilation capacity of the HVAC system ([ ][b]) should be sufficient to ensure filtered release to the environment.
- In the event of a medium pipe break, which result in an emergency condition (load category C), PRS mode C is activated. Helium is vented to atmosphere via PRS Route C for medium pipe breaks, and the route is closed by means of the Post Pressure Relief Damper (PPRDMP) upon completion of depressurization.
- In the event of a large pipe break, which results in a faulted condition (load category D), PRS mode D is activated. Helium is vented to atmosphere via PRS Route D for large pipe breaks, and the route is closed by means of the PPRDMP upon completion of depressurization.
- During Inspection and Testing conditions (load category P), the PRS is in mode P. (PRS system also under inspection and test to confirm/ensure availability and dependability.)

The PRS routes are schematically portrayed in Figure 60. The route numbers correspond with the prevailing load categories.

a,b

**Figure 60: Pressure Relief System Functional Flow Diagram**

## 8.9 SPECIALIZED DOORWAYS

Specialized Doorways (SD) is a system of barriers used to control access while maintaining zone integrity in the Reactor and Services Buildings during normal operation and design basis accidents.

### 8.9.1 Functions

The prime functions of the SD are to:

- Facilitate access to, and egress from, the various areas/rooms of the Reactor Building
- Enhance safety
- Facilitate control of access/egress

The access/egress function provides for (distinguishes between) personnel and equipment. As far as equipment is concerned, the requirement (need) for access during construction is separated from the maintenance requirement for access. The maintenance requirement is in turn subdivided into SSC specific requirements where possible. The enhanced safety function is composed of the following sub-functions:

- Facilitate emergency egress
- Prevent injury/damage because of accidental access to lift and hoist shafts
- Limit the distribution of combustion products should there be a fire in the building
- Limit airborne contamination
- Resist the consequences of a depressurization event
- Limit spread of radioactive contamination

The functional breakdown is depicted in **Error! Reference source not found.**.

### 8.9.2 Layout

Personnel can only gain access to a controlled zone through the Radiation Protection dressing room in the Services Building. Access to the different areas is obtained via stairways and lifts.

### 8.9.3 Operation

Separate stairways and lifts for the controlled and uncontrolled areas are provided throughout the Reactor Building.

The turbine and compressor can be moved in or out of the Reactor Building through the loading bay and the equipment hatch on the lay down floor. Small items of equipment and fresh fuel enter and leave the building's controlled area through the SD on ground level.

## 8.10 DECONTAMINATION SYSTEM

### 8.10.1 Overview

The Decontamination System (DS) addresses all aspects of decontamination during the plant's operational life. Only limited facilities are required because of the following plant properties:

- The maintenance concept is based on Line-replaceable Units (LRUs). Parts are replaced rather than repaired, to reduce downtime. This removes the need for a facility that is able to handle peak loads, since time is available to decontaminate between maintenance intervals.
- Because the surface activity of most maintenance parts is low, removal of plated activity before maintenance is not essential. This applies to parts such as valves and blowers that constitute the bulk of the parts to be handled, but not necessarily to the turbines.
- The demonstration module is constructed on the KNPS site, and the KNPS decontamination facility is available, but not on demand.

The main requirement for the decontamination facility is therefore to ensure that loose surface contamination is removed to provide a safe environment to work and prevent spreading of activity.

The DS provides the following processes:

- Vacuum cleaning. Limited vacuum-cleaning before, during and after removal of components from the plant is used to limit spreading of activity by removing the worst collections.
- Dry ice cleaning is used in glove boxes and wet abrasive blasting is used to remove graphite dust and other loose contamination.
- Hand-wipe cleaning of parts is provided where necessary.

### 8.10.2 Functions and Components

#### 8.10.2.1 Functions

a. The main function of the DS is to remove loose surface contamination and ensure that the dose rate to maintenance personnel is acceptable.
   i. Because of the line-replaceable concept, this function allows only the disassembly and reassembly of components and subsystems.
   ii. This function is achieved by applying de-dusting techniques such as vacuum cleaning, dry ice cleaning and wet blasting.

b. Recover replaceable parts for reuse
   i. Decontaminate parts to allow repair in a licensed facility.
   ii. Decontaminate to allow release of parts for repair in an unlicensed facility.
c. Decontaminate scrapped components to the extent required by ALARA (As Low As Reasonably Achievable) principles.

The system does not handle components that are significantly activated by neutron exposure. The system is not intended to decontaminate material for release.

#### 8.10.2.2 Components and equipment

In order to provide for these functions, the following processes and equipment were selected:

##### 8.10.2.2.1 Vacuum cleaning

Industrial vacuum cleaners equipped with HEPA filters are used.

##### 8.10.2.2.2 Dry ice ($CO_2$) cleaning

Dry ice cleaning machines are commercially available. A range of nozzles is supplied to fulfil the various requirements. The operation shall be conducted in permanent or temporary enclosures, each fitted with an extraction fan and HEPA filter.

Smaller permanent enclosed working areas are supplied in the Decontamination area where components such as valves can be cleaned and disassembled in glove boxes. These enclosures shall be fitted with working surfaces and materials handling equipment such as jigs and hoists. Each enclosure shall be connected to the extraction system.

Temporary enclosures shall be constructed where necessary to enable cleaning of assemblies that are too large to be moved into the permanent enclosure. These enclosures will incorporate an extraction fan and filter.

##### 8.10.2.2.3 Wet blasting chemical decontamination

$CO_2$ blasting is supplemented by a wet abrasive blasting process such as glass beads. The water will help to contain the removed dust, and may achieve some decontamination of plating by abrasion and leaching. Effluent from the wet processes is collected and transferred to the Liquid Waste System (LWS) for treatment.

### 8.10.3 Operation

#### 8.10.3.1 Primary cleaning operations

When components are removed from the plant, the exposed surfaces are vacuumed to prevent spreading of activity.

Graphite dust will accumulate in all crevices and on surfaces exposed to the coolant gas. The first action after an area is exposed is to vacuum the exposed surfaces. This operation is repeated throughout all maintenance actions. The accumulated dust and filters are disposed of through the WHS.

Dry ice cleaning is used to remove loosely bound contamination. It is foreseen that most of the exposed graphite can be removed in this way, leaving a clear metal finish. Airflow and ice feed can be adjusted to suit different conditions.

Large assemblies will be moved to a maintenance area fitted with suitable equipment and space to disassemble and decontaminate components as they are removed.

Hand-wipe decontamination will make use of commercially available decontamination solutions. It is used selectively on surfaces where additional cleaning or decontamination is required. An example is the sealing faces of pressure vessel lids. This method will be used on the fixed end of the plant.

#### 8.10.3.2 Wet chemical decontamination

The KNPS facility can be used where their existing processes are suitable. This will only be done in exceptional circumstances.

## 8.11 WASTE HANDLING SYSTEM

The WHS is designed to handle, store and discharge low- and medium-level liquid and solid radioactive waste generated during normal operation, maintenance activities, and upset conditions of the PBMR.

### 8.11.1 Gaseous Waste

Under normal operational conditions where conservative MPS leakage of [ ][b] per day is assumed, the consequences to members of the public have been determined to be well within acceptable discharge levels. No other scenarios are anticipated under normal operation where significant quantities of radiological effluent are generated as acute releases, and therefore no provision has been made for a gaseous radioactive waste processing system.

### 8.11.2 Liquid Waste

#### 8.11.2.1 Overview

Liquid waste is generated at the hot laundry, hot laboratory, decontamination facility, controlled area washroom, from leaks of the CW circuits inside the Reactor Building, and from general cleaning and fire suppression operations. The data in Table 22 was derived by scaling from similar gas-cooled reactors that included steam turbines. These figures are therefore considered to be enveloping values.

**Table 22: PBMR Liquid Effluent Generation**

| Source | Average Qty ($m^3$/d) | Max. Qty ($m^3$/d) | Average qty ($m^3$ p.a.) | Specific Activity (Bq/$m^3$) |
|---|---|---|---|---|
| Liquid waste from decontamination and laboratory | | | | a,b |
| Liquid waste from laundry | | | | |
| Liquid waste from building drains and sumps | | | | |
| Liquid waste from showers and washrooms | | | | |

This effluent adds to approximately 2 000 m³ p.a., and will lead to an additional public dose of < 4 µSv p.a.

In the HPS, water is collected from the gas cycle containing tritium as well as other nuclides. Because the tritium is already in a concentrated form, it may be immobilized as solid waste rather than being diluted into the liquid waste.

The liquid waste system consist of three main subsystems, namely the ion exchanger, precipitation and release subsystems:

- The ion exchanger system receives and treats effluent from the hot laboratory, module drains and decontamination facility.
- The precipitation system treats the effluent containing soap from the hot laboratory and washroom.
- The release system facilitates and monitors the release of effluent from the plant.

Continuous sources of uncontaminated effluent from the HVAC condensate is drained to the industrial effluent that is monitored before release.

A simplified Process Flow Diagram (PFD) of the system is shown in Figure 62..

#### 8.11.2.2 Layout

A 200 m³ module sump is placed below the turbo machine in the Reactor Building. All areas are connected via gravity drain lines to the sump, except on level -22 where pumps are used to transfer liquid into the sump.

The liquid waste processing plant is located in the Services Building, while the collection tanks for both systems are in the Services Building. Effluent is transferred by the LWS. The sumps for the washroom and hot laboratory are next to the Services Building.

#### 8.11.2.3 Operation

##### 8.11.2.3.1 Ion exchange system

This effluent is collected in the module or hot laboratory sumps. Effluent from the module sump is transferred in batches to the ion exchanger system in the Services Building. The sump is normally kept empty, except when a large volume of effluent may collect that will take some time to process.

A gross gamma analysis is done on each batch of effluent received. If the measured activity exceeds a value close to the licensed maximum value, it is deionized. The effluent is collected separately to allow for post-treatment. If the activity is low enough, the ion exchanger is bypassed.

Effluent from the hot laboratory is treated in the same way. Even if the activity is not limiting, the pH and other necessary measurements are done to ensure compliance with the water permit.

##### 8.11.2.3.2 Precipitation system

A batched process is used where activity is measured to determine if processing is necessary. If it is, a flocculent is added, and after settling, the sediment and overflow are separated. Both the sources are analysed to ensure that the allowable release limits have been reached. If not, the effluent is reprocessed or evaporated.

##### 8.11.2.3.3 Release system

Effluent from the processes described in paragraphs **Error! Reference source not found.** and **Error! Reference source not found.** is collected in separate tanks that are isolated and analysed through full spectrum analysis. If the effluent complies with the required standard and authorization is received, the effluent is released into the MHSS. If the effluent does not comply with the acceptable limits, it is reprocessed.

Effluent is monitored during the release. If a set maximum value is exceeded, the release is terminated and the effluent is reprocessed.

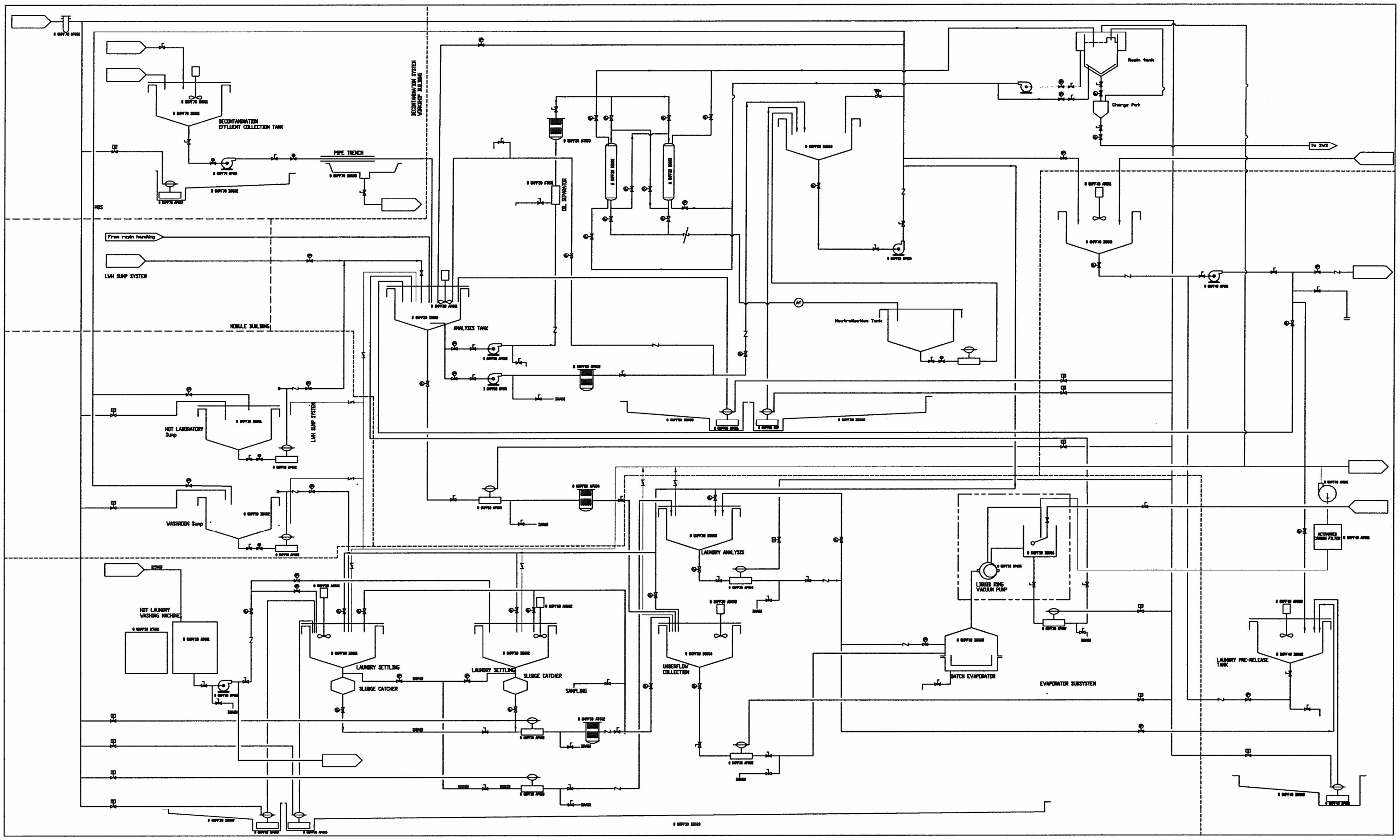


**Figure 62: Liquid Waste System Process Flow Diagram**

### 8.11.3 Solid Waste

#### 8.11.2.4 Overview

The solid waste system handles all radioactive waste from the plant except spent and used fuel, which are part of the FHSS.

The solid waste system consists of three subsystems, namely:

- Compactable waste
- Non-compactable waste
- Waste storage

All Low- and Intermediate-level Waste (LILW) (short lived) is conditioned for disposal at Vaalputs, a near surface depository. All other waste is stored until decommissioning of the plant, at which stage a suitable repository would have been developed.

**Table 23: Solid Waste Origin and Expected Volume**

| Waste Type | Source | Volume Drums p.a. | Expected Activity (Bq/g) |
|---|---|---|---|
| Filters | HVAC Filters (HEPA) | 8 | 0.35 |
| | Helium filters (sintered SS) | | |
| | Vacuum cleaner filters (cloth and HEPA) | | |
| | FHSS vacuum cleaner filter | | |
| | Dried filters from the liquid waste system | | |
| Compactable solid waste | Cloth (paper, overalls, etc.) | 100 | 0.35 |
| | Sweepings from floors (vacuum cleaner filters) | | |
| Non-compactable solid waste | Ion exchanger resins (dried) | 6 | Dependent on the point of origin |
| | Gaskets (metal and polymer) | | |
| | Discarded parts (bearings, parts, valve parts, etc.) | | |
| | Electrical motors, heaters elements | | |
| | Bolts, nuts, washers | | |
| | Dust from cyclones, etc. | | |
| Evaporator | Effluent from evaporator (sludge) | | $1 \times 10^5$ |

#### 8.11.2.5 Components

The solid waste system comprises the following major equipment:

- In-drum waste compactor
- Resin and graphite dust immobilization plant
- Liquid solidification plant
- Waste storage areas

#### 8.11.2.6 Layout

The compactable waste plant is inside the Reactor Building. The solidification and immobilization plants shall be in the Services Building, next to the liquid waste plant.

Compactable waste is stored in the Reactor Building with the in-drum compactor. The same area provides storage space for the pre-compacted waste.

Additional controlled storage areas are provided for storage of components that will later be reused or that cannot be classified as LILW. This area will also provide storage for removed graphite blocks, control rods, etc.

#### 8.11.2.7 Operation

Dry compactable waste is collected in 200 l drums and compacted. The drums are kept in an intermediate store at the compactor.

Dry non-compactable waste is immobilized by adding mortar to the drums. If necessary, concrete containers shall be used to provide shielding. Solidified resin, dust or liquid are prepared in similar containers.

Small quantities of low contaminated oil are expected from compressors and equipment. These are immobilized using commercial processes complying with the Vaalputs Waste Acceptance Criteria.

Short-lived high-level waste is stored on site in suitable containers in controlled areas until such time as it can be reclassified.

## 8.12 EQUIPMENT PROTECTION COOLING CIRCUIT

### 8.12.1 System Operation

The Equipment Protection Cooling Circuit (EPCC) is a constant flow, water-based cooling system. Heat collected will be transferred to the MHSS for release into the environment. Loss of the EPCC pumps due to mechanical failure will result in the RCCS, CCS and CBCS being automatically connected to the back-up cooling tower. Loss of the EPCC due to an electrical supply failure will result in the activation of the diesel generator, which backs up the cooling tower as well. Loss of all the above will result in the CCS and CBCS buffer circuits being tripped and the RCCS converting automatically to passive operation.

### 8.12.2 Operating Modes

#### 8.12.2.1 Power plant normal, reduced capacity and standby modes

During normal and reduced capacity operation of the MPS, and during MPS standby, the EPCC will run at full active flow. Water flow rates to the RCCS, and CCS and CBCS buffer circuits will remain at their design values.

#### 8.12.2.2 Power plant shutdown and fuelled maintenance modes

During MPS shutdown, the EPCC will be responsible for the transfer of core decay heat to the MHSS, and will thus continue operating at full flow. During plant maintenance, as long as there is fuel in the reactor, the EPCC, or the cooling tower, will be running.

#### 8.12.2.3 Power plant defuelled maintenance mode

During defuelled maintenance of the MPS, the EPCC flow will be stopped.

#### 8.12.2.4 Power plant trip conditions

The sequence of events after a plant trip, is as follows:

- In the event of a power plant trip due to an operational fault, loss of forced gas cooling, etc. without loss of grid power, the EPCC will continue to run at full active flow. An operational problem with the EPCC plant at this time will result in the cooling tower being automatically brought into service.
- Loss of grid power under the above circumstances will result in the EPCC or the cooling tower receiving electrical power from the diesel generator.
- Loss of the diesel generator at this point will result in the loss of the EPCC and the cooling tower, and conversion of the RCCS to passive operation.

### 8.12.3 Requirements

#### 8.12.3.1 System definition

a. Functional definition

The EPCC pumps, heat exchangers and main valves will be installed in the CW plant room, with pipework running in closed channels to the Reactor Building, then into a second closed channel in the module, from where branch lines will feed cold water to the CCS buffer circuit, CBCS buffer circuit, and the RCCS. The EPCC is safety classified to SC-3, and will be seismically designed to be available during and after an operating basis earthquake.

Basic functions and requirements of the EPCC:

- To provide a constant supply of cold demineralized water at approximately 3 °C above the current sea water temperature.
- To transfer heat collected in the module to the MHSS.
- To provide a back-up cooling facility in the form of a cooling tower, to which hot water will automatically be diverted in the event of a loss of the EPCC pumps and/or heat exchangers.

b. Defence-in-depth measures

- The EPCC, and cooling tower pumps, fans and selected critical valves, will receive electrical power from the diesel generators in the event of a loss of grid power.
- The EPCC will have a redundant 100% capacity heat exchanger.
- All pumps will have 100% back-up.
- Buffer circuits will protect the EPCC in the event of a high-pressure helium leak from the CCS or CBCS.
- The buffer circuits will have redundant pumps and heat exchangers.

#### 8.12.3.2 General description

a. In the CW plant room

The [ ][b] heat exchangers and 2 x 100% pump sets, will be installed in the CW plant room. Cold water will be pumped to the main inlet header in the module, the returning hot water being fed into the primary side of the operating EPCC heat exchanger to complete the closed circuit loop. Feeder lines to the buffer circuits will branch off from the main EPCC-RCCS line.

b. Interfaces

The spatial coordinates of all interfaces with the EPCC will be detailed in the drawings forming part of this system specification. The physical interfaces between the EPCC and the MHSS will be at the flanges of the secondary sides of the heat exchanges, while for the RCCS, the interfaces will be the points at which the feed pipes attach to the tank headers. Interfacing flow rates will be fixed, but temperatures will vary as the sea water temperature varies.

Interfaces of the CCS and CBCS buffer circuits with their respective units will be at the flanges of these units.

Interfaces with the buildings will be the support and penetration points.

c. Cooling tower

The EPCC cooling tower will consist of three cells, each cell being a closed circuit, induced draught, modular unit with its own 2 x 50% fans, and 2 x 100% on-board spray pumps. 2 x 100% main circulating pumps will supply water to the three cells via a common header. The hot water will pass through stainless steel coils from which the heat will be transferred to the air. Since a dry tower cannot achieve close approach temperatures without becoming excessively large, the re-cooled water temperature will be approximately 5 °C above the ambient dry bulb temperature, which at the system design point, is 34 °C. Under these conditions, the EPCC would have a water temperature of approximately 39 °C. With an 8 °C temperature rise over the buffer circuit heat exchangers, the CCS and CBCS units will see an inlet water temperature of 47 °C. During hot ambient conditions, therefore, water will be sprayed over the coils to reduce the re-cooled (i.e. EPCC) water temperature to approximately 27 °C, thus allowing water to be fed to the CCS and CBCS at 35 °C.

These temperatures will be monitored constantly during tower operation. The tower can be activated manually for test purposes.

The tower will have non-flooding basins and covered spray water reservoirs which will remain full at all times. Spray water will be potable, but after usage, the cooling tubes must be rinsed with demineralized water to minimise the build-up of scale.

During use of the spray system, approximately 3.6 kg/s will be lost due to evaporation. Automatic topping up of the spray water reservoir will be done by the Potable Water System (PWS). The DWS rinsing facility will be manually operated, one cell being rinsed at a time.

The cooling tower will be erected adjacent to the CW plant room, and will receive electrical power from the diesel generators in the event of a loss of grid power. It will come into operation automatically if the main EPCC circuit is lost for any reason.

d. Leakage and spillage

Where possible, pipework in the CW plant room will run in trenches. Drains in the trenches will allow for quick transfer of water to the module sump in the case of demineralized water, or the site drains in the case of sea water. Leakage from an open heat exchanger will be a mixture of demineralized and sea water, and in this instance the sea water will also be drained to the module sump.

Removable covers over the trenches will facilitate personnel movement in the plant room. Bund walls, drip trays and splash walls will be installed as needed under and around pumps and heat exchangers, including those of the buffer circuits, to catch spillage.

The pipe trench between the CW plant room and the module will also act as a sump in the event of leakage in any of the pipes running between the two buildings. A manually actuated valve in this trench will allow water collected in the trench to be released into the ACS shaft in the module, this shaft acting as a transfer sump between the trench and the module sump.

Water levels in the trenches will be monitored and alarmed.

Leakages from the buffer circuits will be carried to the module sump by gravity.

e. Control and Instrumentation

The purpose of the EPCC and buffer circuit control system will be:

- to interpret signals from the process monitoring instruments and to use these signals to initiate alarms, readouts or automatic actions, or to prepare the systems for manual intervention;
- to interpret signals derived from operator actions, and to initiate or alter plant operational modes accordingly.

f. Control system characteristics

All systems will be run either by the operator initiating a system start/stop command, or by another system within the automation control system generating a start/stop request based on process conditions.

The automation control system software logic will monitor the status of inputs relevant to the circuit components, process conditions and functional criteria.

g. Common pump control characteristics

There will be two modes of pump operation, namely operational and manual. Operational mode will be fully automatic, while manual mode will be used only during maintenance, or in the event of a failure of the automation control system.

Pump activation will be based on pump availability, with the pump having the lowest operating hours becoming the one with the highest priority. Pumps will run on a cycle of approximately [ ][b]. (Engineering norm.)

In any circuit, should any operating pump fail, the next available pump will automatically start.

i. Manual mode

In manual mode, the operator will decide which pumps are to be started. The operator will start each pump individually from the module control room, unless otherwise dictated.

ii. Operational mode

In operational mode, systems will be started either by the operator initiating a system start command, or by another system within the automation control system generating a start request based on process conditions.

The automation control system software logic will monitor the status of inputs relevant to the circuit components, process conditions and the functional criteria.

On a start request, the logic will determine whether the circuit through the heat exchangers is open, and if so, the pump with the highest priority will be started.

h. Common valve control characteristics

All valves for isolating the pumps and heat exchangers will be electrically actuated and manually operated from the control room, with feedback of the open and closed status of the valve. The control logic will monitor the status of the valves in each circuit to ensure a flow path for the water before a pump is started.

In a changeover to the back-up cooling tower, the control system will switch the three way valves to allow tower flow to enter the RCCS and the buffer circuit heat exchangers.

i. General alarm and trip conditions

If a pump trips, a pump trip alarm will be generated.

If any of the valves on the primary sides of the heat exchangers is closed, or if the water temperature in the circuit increases while the required number of pumps is running, an alarm will be generated. If any of the valves on the secondary sides of the heat exchangers is closed, an alarm will be generated.

If a pump is running and the pump inlet and/or discharge isolating valves are closed, the pump will trip and an alarm will be generated.

Alarms will be activated and pump start-up curtailed, if any one of the heat exchangers is isolated. The inlet and outlet water temperatures and pressures of each heat exchanger will be monitored.

j. Pump start sequence

All pumps will be interlocked with the module nuclear power plant start sequence, and a power plant start permit will not be obtained if the EPCC and buffer circuits are not available.

When a ‘pump start’ request is received, the following steps will take place:

- The logic will determine whether the circuits through the required heat exchangers, are open.
- The EPCC and buffer circuit pumps with the highest priority will be started automatically. A ‘pump off’ command, a ‘pump trip’ signal or a pump cycle rotation command will initiate a start command for the standby pump, then stop the operating pump. The logic will adhere to the criteria that in each circuit, one pump must operate under Main Power System (MPS) full, part load or standby conditions

k. Starting of cooling tower

When the control system initiates a signal calling for back-up flows, the following steps will be taken:

- The three-way valves will isolate the heat exchangers while opening the lines to the cooling tower.
- The highest priority pump of the cooling tower will start, together with the tower fans, thereby transferring the circuit cooling duties to the cooling tower. Alarms will alert operators to the fact that this flow change has been initiated.
- If the ambient air temperature is above the set point, the highest priority spray pump will be started. (The set point will be determined during the detailed design phase.)
- Should a tower pump trip during any of the above sequences, the control system will start the standby pump.

The pumps and fans of the cooling tower will automatically switch to the diesel generators if the grid power is lost

# 9. AUTOMATION SYSTEM

## 9.1 GENERAL

The Automation System (AS) comprises safety and non-safety-related Control and Instrumentation (C&I) systems for automated plant protection, control, monitoring, and for operator-to-plant interaction (Human-System Interfaces [HSIs]). The AS ensures that the plant is operated within its defined operating envelope. The AS subsystems are integrated via digital data communication media to enhance across-system data flow.

The main AS subsystems are defined in Table 24.

**Table 24: Automation System Subsystems**

| Subsystem | Definition |
|---|---|
| Human-System Interface (HSI) | The system that enables plant operators to interact with the plant through the automation system. HSIs are provided in two control rooms, namely the Main Control Room and the Post-Event Monitoring and Recovery Room (PEMRR). |
| Reactor Protection System (RPS) | The system that ensures that reactor heat production is maintained within safety limits by automatically shutting the reactor down under Design Basis Accidents (DBAs). |
| Post-event Instrumentation (PEI) | The system that provides information displays to operators during normal operation, during and following DBAs, to enable them to assess the safety status of the plant. |
| Equipment Protection System (EPS) | The system that protects systems and equipment identified as significant owner investment. |
| Operational Control System (OCS) | The system that performs non-safety plant protection, control monitoring and data recording. |
| Reactor Manual Shutdown System | The system comprising manual controls for control rod and small absorber sphere insertion respectively. |

Figure 62 provides a high-level architecture representation of the AS.

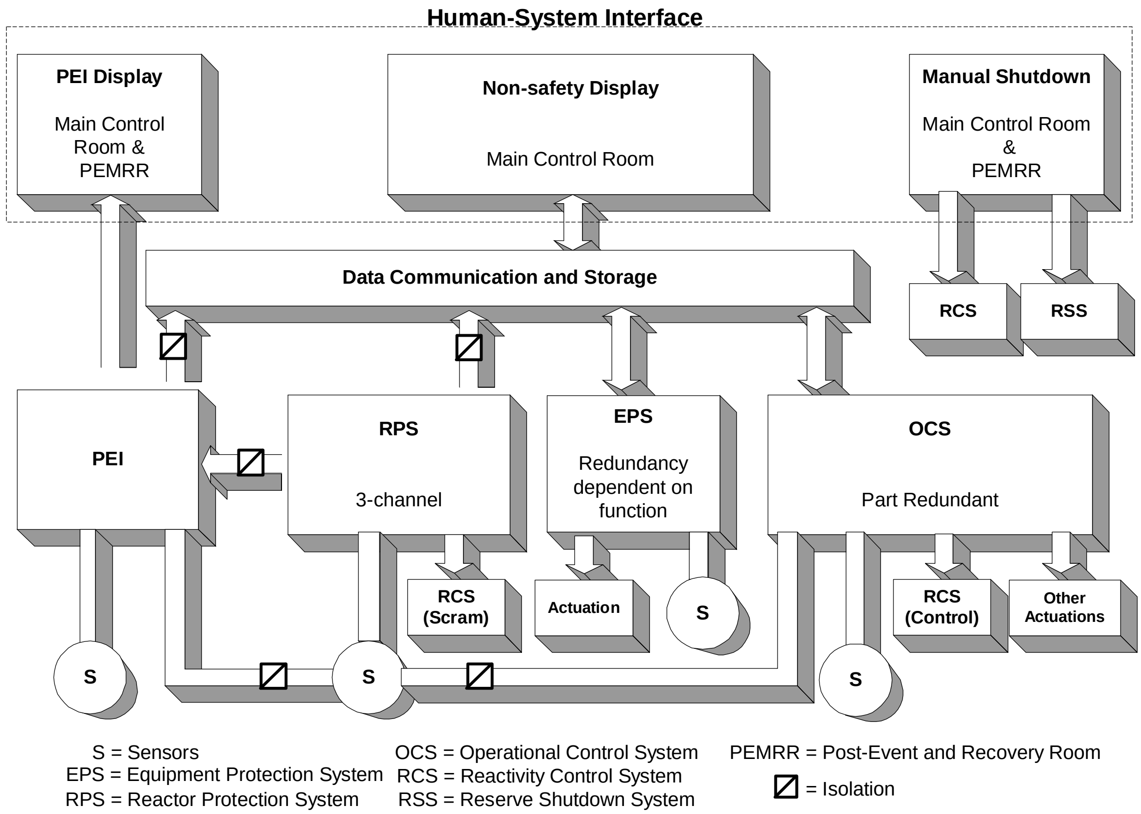



**Figure 62: Automation System Architecture**

The principle of Defence in Depth (DiD) is applied in the AS design to ensure that reactor shutdown can be initiated.

The OCS controls the plant automatically, and reactivity control is accomplished by adjusting setpoints on the control rod drive motors.

The RPS also monitors reactor variables and automatically initiates control rod scram when the variables exceed setpoint values. Power to the control rod drive motors is switched off, causing the control rods to drop under gravity. The RPS and OCS use diverse hardware and software platforms to reduce possibility of common mode failures.

The operator can also manually initiate control rod insertion and Reserve Shutdown System (RSS) activation through a set of independent hardwired controls. These controls are duplicated in the non-seismic Main Control Room, and the seismically designed PEMRR. The plant safety characteristics are such that operators have sufficient time to take manual action.

Table 25 describes the DiD concept.

**Table 25: Defence-in-depth Principle – Reactor Shutdown**

| System | Operational Control System | Reactor Protection System | Reactor Manual Shutdown System | |
|---|---|---|---|---|
| Actuation | Automatic runback of control rods | Automatically actuates control rod scram | Operator initiated control rod insertion | Operator initiated small absorber sphere insertion |
| Mechanism | OCS provides new setpoints to Control Rod Drive (CRD) to lower the control rods | Disconnecting power by opening of scram breakers | Disconnects power to system | Disconnects power to system |
| Information Display | Non-safety | Safety | Non-safety | |
| Platform | Non-safety Industrial | Safety platform | Diverse | |
| Sensors | Share RPS safety sensors | Safety sensors | | |

The AS design goals and design solutions are indicated in Table 26.

**Table 26: Automation System Design Goals**

| Key Design Requirement | Design Solution |
|---|---|
| Plant shall be controlled within its defined and safe operating envelope. | The OCS automatically controls the plant within operating design parameters, and responds to all anticipated operational occurrences. The RPS is designed to respond to inputs showing higher than allowed process parameters. |
| Design shall comply with regulatory requirements. | Apply the principles of Defence in Depth/Diversity (DiD/D) to ensure that the reactor can be shut down. Three levels of DiD and diverse systems are employed to shut the reactor down. Safety systems comply with US Nuclear Regulatory Commission (NRC) requirements where applicable to pebble bed plant design. Fail-safe design principles such as de-energize to trip are employed. |
| Number of operators shall be minimized. | The level of automation and HSI design employs Human Factors Engineering (HFE) principles to minimize the number of operators required. |
| Modern control system technology shall be applied to ensure longer operating life cycle and design for system upgrading as technology develops. | Digital programmable control system technology with remote input/output modules. |
| System must be of integrated and modular design. | Subsystems are integrated through data communication networks. |
| Plant reliability and availability shall be enhanced to ensure a single failure does not cause plant shutdown. | Redundancy is applied in the RPS, PEI, EPS and parts of the OCS.<br>Continuous self-diagnostics are performed and detected failures are alarmed to operators.<br>Electrical isolation is provided between segments of the system to prevent electrical fault propagation.<br>Physical separation is provided between redundant channels, and between subsystems.<br>Equipment is environmentally qualified commensurate with safety classification and intended usage. |
| Effective levels of plant investment protection shall be provided. | Plant protection functions are evaluated to determine required availability of actuation, and those that require significant reliability are implemented in the EPS to simplify maintenance and testing. |

## 9.2 HUMAN-SYSTEM INTERFACE

### 9.2.1 Description

Two control areas are provided:

- The Main Control Room, where the operator can interact with the AS during normal and abnormal plant conditions.
- The Post-Event Monitoring and Recovery Room (PEMRR), an alternative shutdown area where the operator can interact with the AS to perform functions necessary during and after an upset event when the Main Control Room is not available.

The physical design of the control areas is such that the entire environment supports the task of the operator.

The control areas employ multi-functional displays and control features that create an integral, compact workstation with a consistent interface for all plant operating conditions and operator tasks. Input devices are standard keyboards and mice.

In addition, hard controls (push-buttons) are employed for reactor scram.

Control areas are ergonomically designed and conform to all relevant Human Factors guidance.

#### 9.2.1.1 Main control room

The Main Control Room provides control desks for the plant operator and supervisor and wide display panels for the display of Power Plant (PP) overview information:

- The wide display panels consist of three individually definable displays.
- The operator control desk consists of visual display units that display all operational information, redundant PEI/RPS display panels, standard computer keyboards and mice, hard controls with diverse displays, and plant-wide communication devices. In addition, printers are used to produce reports and screen prints of displays.
- The supervisor control desk consists of visual display units that display all operational information, standard computer keyboards and mice.

Figure 63 shows the Main Control Room.

**Figure 63: Main Control Room Concept**

### 9.2.1.2 Post-event monitoring and recovery room

The PEMRR provides a control desk for emergency operations, and facilities to house all necessary procedures and information to support the operator's task during and after an upset event.

The control desk consists of visual display units that display all operational information, redundant PEI/RPS display panels, keyboard, hard controls with diverse displays and plant-wide communication facilities.

The procedures and information provided for task support are contained in hardcopy in bookcases in close proximity to the control desk.

The control area is designed to support a habitable environment in which the operator can monitor the plant and recover from upset events.

Figure 64 shows the physical layout of the PEMRR.


**Figure 64: Post-event Monitoring and Recovery Room Concept**

### 9.2.2 Functions

The HSI enhances safe, efficient and reliable operation of the PP by control room staff. It provides an integrated and modular architecture for use by control room operators, supervisors and engineering staff.

The overall control function of the plant is simplified by:

- Reducing system complexity through application of sound HFE principles and techniques.
- Providing facilities to ensure optimal situation awareness and operator vigilance.
- Reducing mental workload.
- Minimizing or eliminating the probability of operator error.
- Providing integrated task and procedural support, which includes efficient access to an integrated computer-based procedure and reference facility.

### 9.2.3 Key Requirements

The design of both control rooms is guided by ergonomic requirements as outlined in NUREG-0700, SABS 0400-1990 and OHSACT (Act 85 of 1993).

a. The HSI shall enable the operator to perform control, monitoring and diagnostic tasks with efficiency, effectiveness, safety and satisfaction, where:
   i. *Effectiveness* means the accuracy and completeness with which operators achieve specified goals.
   ii. *Efficiency* means the resources expended in relation to the accuracy and completeness with which operators achieve goals.
   iii. *Satisfaction* means the freedom from discomfort, and positive attitudes towards the use of the HSI.
   iv. *Safety* means preventing the operator from committing such errors of commission or omission that will compromise the safety of plant, humans or environment.
b. HFE shall be an integral part of all development and integration activities.
c. The design of the HSI shall support human-centred automation to ensure:
   i. Resolving issues related to the degradation of basic skills with the associated performance implications should the automation fail.
   ii. Overcoming the hesitancy of human operators to take over from an automated system even when there is compelling evidence of a problem.
   iii. Keeping the operator in the loop and situationally aware of system performance.
   iv. Designing HSIs appropriate for an advanced system; balancing operator workload (high and low) associated with automated systems.

## 9.3 REACTOR PROTECTION SYSTEM

The Reactor Protection System (RPS) ensures that heat generation is limited to a predetermined level by making the reactor subcritical, and assuring long-term subcriticality following a DBA.

### 9.3.1 Description

The RPS is a digital programmable safety system. A system block diagram is provided in Figure 65. The system is comprised of three redundant channels. The commands from the redundant channels are combined in two-out-of-three coincidence voting logic. RPS information displays are combined with those of the PEI and provided in the Main Control Room and PEMRR. The reactor shutdown panels comprise manual controls in both control rooms and are hardwired to the scram breakers and to the RSS actuators for diverse reactor shutdown initiation.

The RPS will be designed to make the reactor subcritical, and to assure long-term subcriticality under all DBAs.

The RPS is designed and qualified for the full range of environmental conditions from DBAs, to the Safe Shutdown Earthquake (SSE). The system is electrically powered from an Uninterruptible Power Supply (UPS).

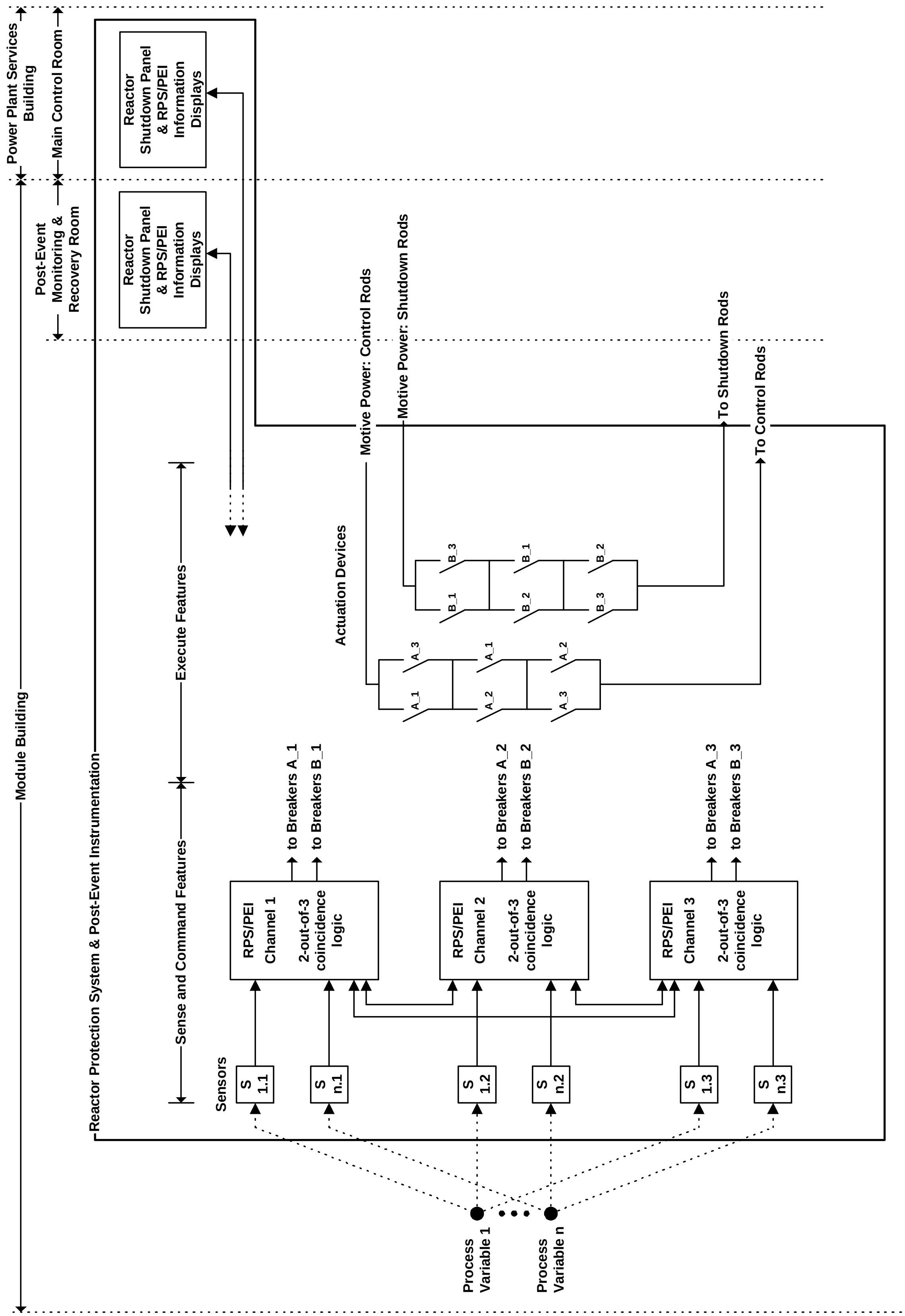



**Figure 65: Reactor Protection System Block Diagram**

### 9.3.2 Functions

#### 9.3.2.1 Execute functions

The system initiates three different protective actions, namely a Control Rod Scram (CRS) and a Reactor Scram (RS, and small absorber sphere insertion):

- CRS is defined as the gravitational full insertion of the 12 control rods into the reactor's side reflector.
- RS is defined as the gravitational full insertion of all the control rods (i.e. the 12 control rods and the 12 shutdown rods) into the reactor's side reflector.

#### 9.3.2.2 Sense and command functions

The RPS senses process conditions as indicated in Table 27, and commands the appropriate protective action (i.e. CRS or RS) accordingly.

**Table 27: Reactor Protection System Functions**

| Plant Condition | Description |
|---|---|
| Reactor overpower | The RPS monitors reactor power with ex-core neutron detectors that are thermally corrected (through off-line calibration against fluidic power). The RPS initiates a CRS when the neutron flux reaches 105%, and an RS when it reaches 110%. Additionally, a CRS is initiated when the integrated power for eight consecutive hours exceeds 103%. |
| Primary coolant over-temperature | The RPS monitors reactor coolant outlet temperature with a matrix of thermocouples that are located in the reactor outlet pipe, upstream of the high-pressure turbine. The RPS initiates a CRS when the average temperature reaches 925 °C, and an RS when it reaches 935 °C. |
| Excessive reactor power increase | The RPS calculates reactor period from the ex-core neutron detectors' outputs. The RPS initiates a CRS when reactor period gets too short. |
| Loss of forced cooling | The RPS monitors flow status of primary coolant through the reactor with a differential pressure measurement across the reactor. The RPS initiates a CRS after a predetermined time delay when loss of flow is detected. The time delay is long enough that no operational interference is caused, but short enough that no uncontrolled re-criticality will occur after the reactor has gone subcritical as a result of its negative temperature coefficient. |
| Loss of primary coolant | The RPS monitors loss of primary coolant status through a primary coolant pressure measurement in the reactor. The RPS initiates a small absorber sphere insertion after a predetermined time delay when loss of coolant is detected. The time delay is long enough that no operational interference is caused, but short enough that no uncontrolled re-criticality will occur after the reactor has gone subcritical as a result of its negative temperature coefficient. |
| Earthquake detected | The RPS initiates an RS and small absorber sphere insertion when the safe shutdown earthquake occurs. |

### 9.3.3 Key Requirements

The RPS meets the requirements of IEEE Std. 603, and its computers and software meet the requirements of IEEE Std. 7-4.3.2. RPS hardware is Class 1E quality.

## 9.4 POST-EVENT INSTRUMENTATION

### 9.4.1 Description

The Post-event Instrumentation (PEI) is a safety monitoring, recording and display system in addition to the normal operational displays provided. It displays information in the Main Control Room and PEMRR to operators during normal operation, as well as during and following DBAs, to enable them to assess the safety status of the plant. The system is electrically powered from a UPS for 24 h.

The PEI is designed and qualified for the full range of environmental conditions from PBMR DBAs, including the SSE.

### 9.4.2 Functions

The functions of the PEI system are listed in Table 28.

**Table 28: Post-event Instrumentation Functions**

| Function | Variables |
|---|---|
| Provide information to operators in support of manual RS and RSS actuation. | |
| Provide safety-related system inoperability status indication | RPS status. |
| Provide safety-related system bypassed indication | Battery-powered system supply:<br>• RPS, including its execute features; and<br>• any other auxiliary or supporting system that effectively renders inoperative the safety functions of the RPS. |
| Provide information about plant status during and after DBAs | • Reactor Cavity Cooling System (RCCS) water level status.<br>• Pressure relief shaft damper status.<br>• Variables to indicate reactor shutdown status.<br>• Variables to indicate the effectiveness of residual heat removal.<br>• Variables to indicate the status of primary coolant pressure retention.<br>• Variables to indicate the status of radioactivity containment.<br>• Variables to indicate the conditions inside the reactor cavity and other areas.<br>• Variables to indicate the radiological release to the environment. |

### 9.4.3 Key Requirements

The PEI meets the applicable guidance from the US NRC Regulatory Guide 1.97.

## 9.5 EQUIPMENT PROTECTION SYSTEM

### 9.5.1 Description

The Equipment Protection System (EPS) is a high-reliability, non-safety-classified, diverse system that monitors critical parameters that provide an indication of potential equipment damage, and initiates protective action when set limits are exceeded. It is designed to stringent standards with a high level of internal diagnostics.

### 9.5.2 Functions

The EPS protects high-value major plant equipment such as the turbo-machine against over-speed, vibration and compressor surge. Typical protective action is the opening of the Gas Cycle Bypass Valves (GBPs) to terminate the Brayton cycle.

### 9.5.3 Key Requirement

International Standard IEC 61508 and ISA Standard S84 are used as a guideline for allocating integrity level to each function.

## 9.6 OPERATIONAL CONTROL SYSTEM

### 9.6.1 Description

The Operational Control System (OCS) is a commercially available distributed control system that supports an open architecture, field bus, distributed input/output modules, and intelligent field devices that perform automated plant control, the monitoring of plant and process variables, and data storage. Redundant networks and controllers are provided to prevent plant shutdown due to single sensor or component failure. Table 29 indicates the plant area and allocation and redundancy of automation units (hardware unit that operates independently regarding measurements, control and actuation).

**Table 29: Allocation of Operational Control System Automation Units**

| Automation Unit | Plant Area |
|---|---|
| Main Helium Loop | Redundant controllers to control Brayton cycle start-up and continuous plant operation. It includes the control of the reactor, compressors, main turbine-alternator set, start-up blower system, and Active Cooling System (ACS). |
| Fuel Handling and Storage System (FHSS) | Non-redundant controller to control all functions related to the fuel handling. |
| Helium Inventory Control System (HICS) | Redundant controllers to control all functions related to the helium inventory control. |
| Compressor and turbine control | Fast-acting redundant controllers to perform compressor anti-surge control on the turbo-unit compressors and helium blowers. |
| Analytical instrumentation interfaces | Handles the special interfaces to analysers and analytical instrumentation. No redundancy is provided. |
| Test and Evaluation | Non-redundant automation unit for the once-off test and evaluation measurements. |

The design takes cognizance of the possible need for successive hardware and software upgrades during the productive life of the plant in order to take advantage of new technology, or to ensure continuous support when the existing control system becomes obsolete.

A video display system provides video camera monitoring of selected plant areas, with recording and playback capability.

An engineering workstation is used to prepare, document, and download software configurations to controllers.

Table 30 lists the estimated system size in terms of input/output quantities.

**Table 30: Estimated Operational Control System Input/Output Quantities**

| Input/Output Type | Quantity |
|---|---|
| Binary inputs | a,b |
| Binary outputs | |
| Analogue inputs | |
| Analogue outputs | |
| Total | |

### 9.6.2 Functions

The highest practical level of automation is implemented in order to minimize the number of operators and optimize operator interaction. Major functions include:

- Diverse platform for the shutdown of the reactor
- Closed loop control of plant variables
- Process interlocking
- Display of process and plant information to operators for plant supervision and control
- Execution of operator commands
- Data storage

### 9.6.3 Key Requirements

Table 31 lists the key performance requirements.

**Table 31: Operational Control System Key Requirements**

| Parameter | Requirement |
|---|---|
| | a,b |

## 9.7 SEISMIC MONITORING SYSTEM

### 9.7.1 Description

The Seismic Monitoring System (SMS) provides indication of the strong motion seismic activity in the Reactor Building as well as in the free field of the plant site. The system will not trigger automatic responses.

Figure 66 is a schematic presentation of the SMS.

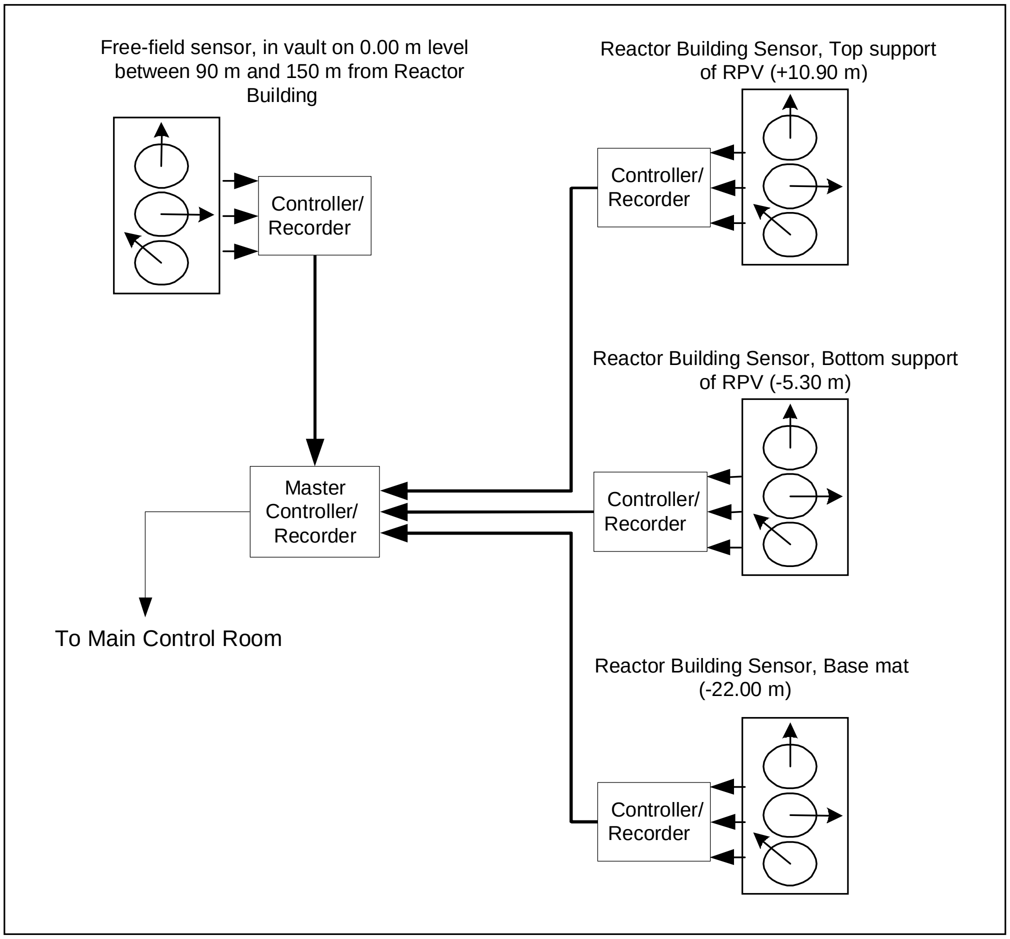



**Figure 66: Seismic Monitoring System Schematic Description**

The major components of the SMS are:

- Four triaxial sensors with local recording and control equipment (i.e. three mutually orthogonal directions, one of which is the vertical acceleration).
- Internal battery back-up power supply.
- Central controller with remote recording facilities.

The architecture for the SMS incorporates redundancy principles as well as ease of installation and maintenance. The triaxial acceleration sensors are placed in their respective positions in the Reactor Building and the free field. The Reactor Building recording equipment is placed in close proximity to the sensors to offer a single installation and maintenance point. The free-field sensor is placed in a vault just below the terrace level of the plant site. The recorder for the free-field sensor is placed in the Reactor Building. All four recording devices are linked to the central recording facilities via network communication cables. The use of expensive sensor signal cables is minimized, and the signal cables are reduced from three to one for each sensor.

The recording facilities for the seismic instrumentation systems are redundant. Local recording and remote recording are used. The local recording will take place at the position of the sensor or a convenient position in the immediate vicinity of the sensor. The remote recording will take place at the central controller/recorder for the whole system. The central recorder is located in the PEMRR. No redundant sensors are envisaged.

The local controller/recorder of the triaxial sensors is linked to a central or remote controller/recorder, and this is linked to the PBMR OCS. The links between the local controller/recorders and the central controller/recorder are digital network communication links, while the sensors are linked to the local controller/recorders as digital hardwired input channels.

Each of the sensor/controller systems is supplied with a UPS as well as a battery back-up. The battery back-up is sized to provide at least 24 h of full power operation as required in US NRC Regulatory guide 1.12.

The local recording facility is in the form of a hard disk drive. The hard disk has more than 4 GB storage capacity. The local recording is duplicated in the central recorder, thus the local recording is a back-up for the central recording in the event that the communication or central recorder fails, and thus the data of strong motion seismic events will not be lost. The hard disk is removable and can be removed and data accessed at a different location if the need arises.

The position of the sensors in the Reactor Building was chosen to represent positions as indicated in US NRC Regulatory guide 1.12, and also to represent specific mass points as used in the seismic analysis of the Reactor Building structure. The positions correspond to a foundation measurement and two measurements for the reactor (the reactor structure and the top of the reactor).

### 9.7.2 Functions

The functions of the SMS are the following:

- Monitoring, display and alarming of strong motion seismic activity in and around the plant site, triggered or continuously.
- Recording of the ground motion for historical analysis.

### 9.7.3 Key Requirements

The key requirements for the SMS are contained in the documents listed in Table 32.

**Table 32: Seismic Monitoring System Key Requirement References**

| Document Title | Document Number |
|---|---|
| American Nuclear Society: Earthquake instrumentation criteria for nuclear PPs | ANSI/ANS – 2.2 – 1988 |
| Nuclear PP instrumentation for earthquakes | US NRC Regulatory guide 1.12 Rev. 2 – 1997 |
| Earthquake engineering criteria for nuclear PPs | Appendix S to 10 CFR Part 50 |

## 9.8 KOEBERG NUCLEAR POWER STATION METEOROLOGICAL INSTRUMENTATION INTERFACE

### 9.8.1 Description

The Demonstration Power Plant (DPP) is not equipped with its own meteorological facility. It is linked to the existing meteorological station at Koeberg Nuclear Power Station (KNPS). The system provides data on the meteorological conditions via the OCS for information and archiving purposes.

### 9.8.2 Functions

The KNPS meteorological interface provides the DPP with the following information as requested by the DPP operator:

- Wind speed
- Wind direction
- Relative humidity
- Air temperature
- Pressure
- Precipitation
- Solar radiation

### 9.8.3 Key Requirements

The key requirements applicable to the meteorological data are listed in the American Nuclear Society standard for determining meteorological information at nuclear power sites (ANSI/ANS-2.5-1984).

## 9.9 BURN-UP MEASUREMENT SYSTEM

### 9.9.1 Description

The Burn-up Measurement System (BUMS) is an instrument designed to measure the burn-up of PBMR fuel spheres by means of spectroscopic evaluation. Based on the spectroscopic evaluation, the BUMS classifies spheres as graphite, used fuel (fuel with burn-up less than target burn-up) or spent fuel (fuel with burn-up greater than target burn-up).

The BUMS includes three major components: a High Purity Germanium (HPGe) detector assembly with positioning table and cryogenic refrigeration system, a Digital Signal Processor (DSP) based burn-up analysis system, and a photon collimator.

[

][a,b] These components (excluding the compressor) are all housed inside the shielded aluminium detector enclosure. A three-dimensional drawing of the BUMS detector assembly, with the aluminium covers removed, is provided in Figure 67.

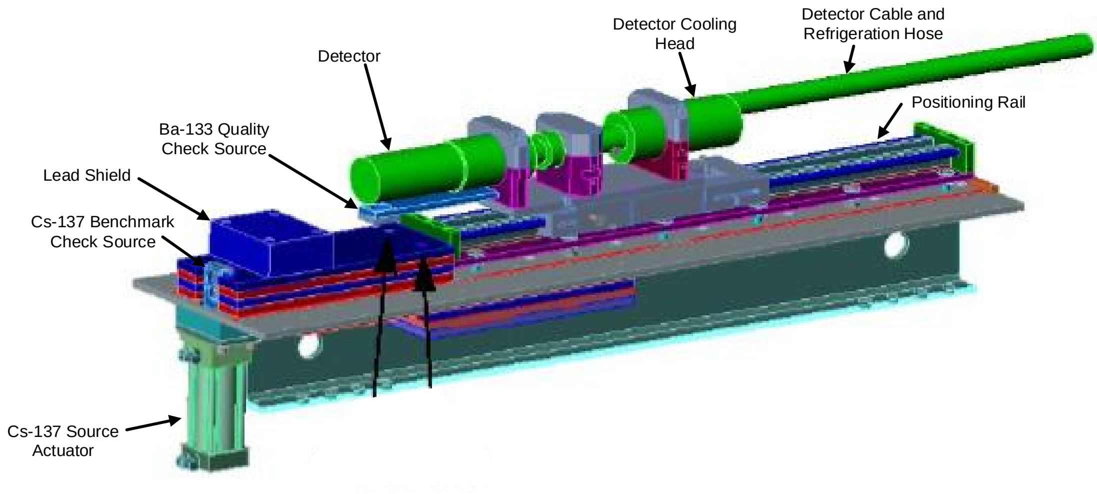



**Figure 67: Burn-up Measurement System Detector Assembly Three-dimensional Drawing**

a,b

### 9.9.2 Functions

The BUMS will perform several different types of analyses, including graphite/fuel discrimination, the discrimination between low burn-up and high burn-up fuel, and the categorization of higher burn-up fuels as either used fuel or spent fuel. [

a,b

a,b

## 9.10 ACTIVITY MEASUREMENT SYSTEM

The Activity Measurement System (AMS) is designed to measure the dose rate emitted by PBMR spheres, and to categorize the spheres as either fuel or graphite. Measurement results are communicated to an operator interface display/keyboard and the FHSS. The FHSS performs the physical routing of the spheres based on this information.

The two major components of the AMS are:

- The detector with cable conduit assembly
- The amplifier/signal processing assembly

a,b

The amplifier/signal processor assembly is housed in a stainless steel enclosure. It is composed of a power filter, low and high voltage power supplies, current amplifier, operator interface, terminal blocks, calibration/self-diagnostics circuitry, and a PLC.

## 9.11 TRAINING SIMULATOR

### 9.11.1 Description

The training simulator is primarily intended for use in the training and licensing of plant operators.

Real time simulation is possible. Malfunctions can be introduced by means of the instructor station, to evaluate the resulting process and operator behaviour. The steady state accuracy of the simulator data is comparable to both full and intermediate power levels of the reference unit. Values of critical parameters agree within [ ][b] of the measured reference unit parameters. (Values of non-critical parameters agree within [ ][b] of the measured reference unit parameters.)

The training simulator system consists of the elements depicted in Figure 68.

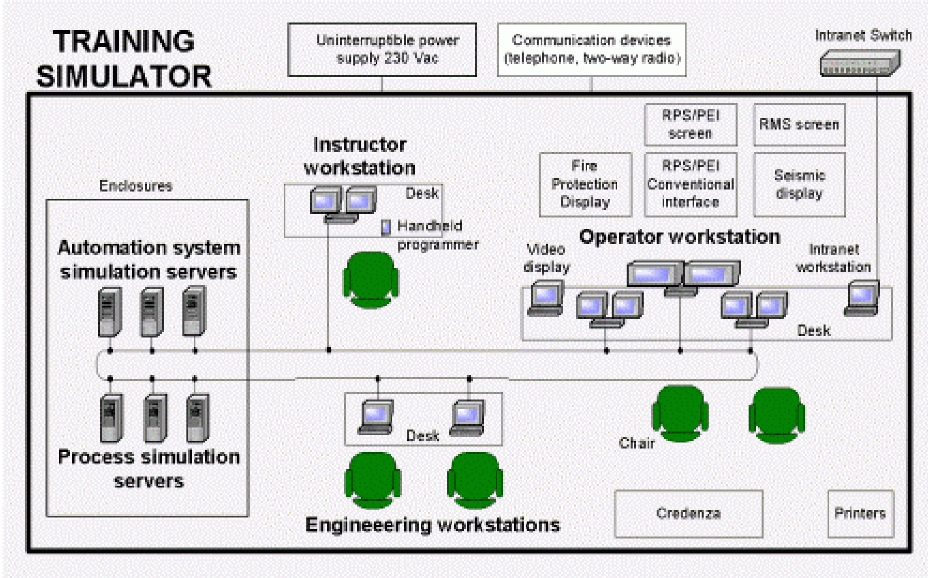



**Figure 68: Training Simulator Concept**

### 9.11.2 Functions

The training simulator supports the following tasks:

- Training, assessment and certification of operators
- Validation of operator interfaces as well as control and automation designs
- Development and validation of operating procedures

### 9.11.3 Key Requirements

Table 33 lists key requirements for the training simulator.

**Table 33: Training System Key Requirements**

| Component | Requirement |
|---|---|
| System | Real-time simulation shall be possible. Malfunctions can be introduced by means of the instructor station, to evaluate the resulting process and operator behaviour.<br>The instructor shall be alerted when certain simulator operating parameters approach values indicative of events beyond the implemented model or known plant behaviour. |
| Human-System Interface | The HSI for the training simulator shall be an exact replica of the HSI in the Main Control Room, including the Task Support System. It shall be able to perform simulations in selectable speeds. It shall also support pause functionality, scenario capturing, and start-off from a retrieved scenario. |
| Hardware Simulator | The hardware simulator system shall be able to perform simulations in selectable speeds. It shall also support pause functionality, scenario capturing, and start off from a retrieved scenario.<br>The hardware simulator shall provide an exact replica of the OCS and its behaviour. In real-time operation, control system hardware shall be simulated to the extent that operators will not be able to detect a difference. |

| Component | Requirement |
|---|---|
| Steady State Operation | The simulator-computed values of critical parameters shall agree within [ ][b] of the measured reference unit parameter.<br>The simulator-computed values of non-critical parameters shall agree within [ ][b] of the measured reference unit parameter. |
| Maintainability | State-of-the-art, yet proven, off-the-shelf products (except for in-house developed software) shall be used, in an effort to have a maintainable system for as long as possible. |

# 10. ELECTRICAL SYSTEM

## 10.1 GENERAL

### 10.1.1 Functional Description

The PBMR Electrical System consists of the Main Electrical Power System (MEPS) and the Auxiliary Electrical Power System (AEPS). The main functions of these are as follows:

a. MEPS
   - i. Converts the generator output to the network voltage and transmits the power to the network.
   - ii. Accelerates the power turbine generator to synchronous speed during plant starting.
   - iii. Protects the main power generator and the components of the electrical system by disconnecting these components in the event of an electrical fault.
   - iv. Measures the electrical power flowing into and out of the generator and the Power Plant (PP).

b. AEPS
   - i. Provides and distributes electrical power to plant subsystem electrical loads (house load).
   - ii. Controls the power to the electrical loads in conjunction with the Control and Instrumentation (C&I) System.
   - iii. Provides back-up power in case of the loss of off-site power.
   - iv. Protects auxiliary electrical and mechanical equipment against damage due to electrical faults, mechanical overload conditions and lightning strikes.

### 10.1.2 Network Connections

Figure 69 is a schematic of a portion of Eskom's 400 kV network near the proposed PBMR Demonstration Power Plant (DPP). Two coupling transformers connect the 400 kV substation at Koeberg Nuclear Power Station (KNPS) to the 132 kV Koeberg substation, as shown in Figure 70. The main connection of the PBMR DPP is to the Koeberg 132 kV substation. The power produced by the PBMR DPP will therefore be delivered across this connection. The alternative supply connection is to Duyne substation.

[Withheld on the basis of it being “Security-Related Information”]

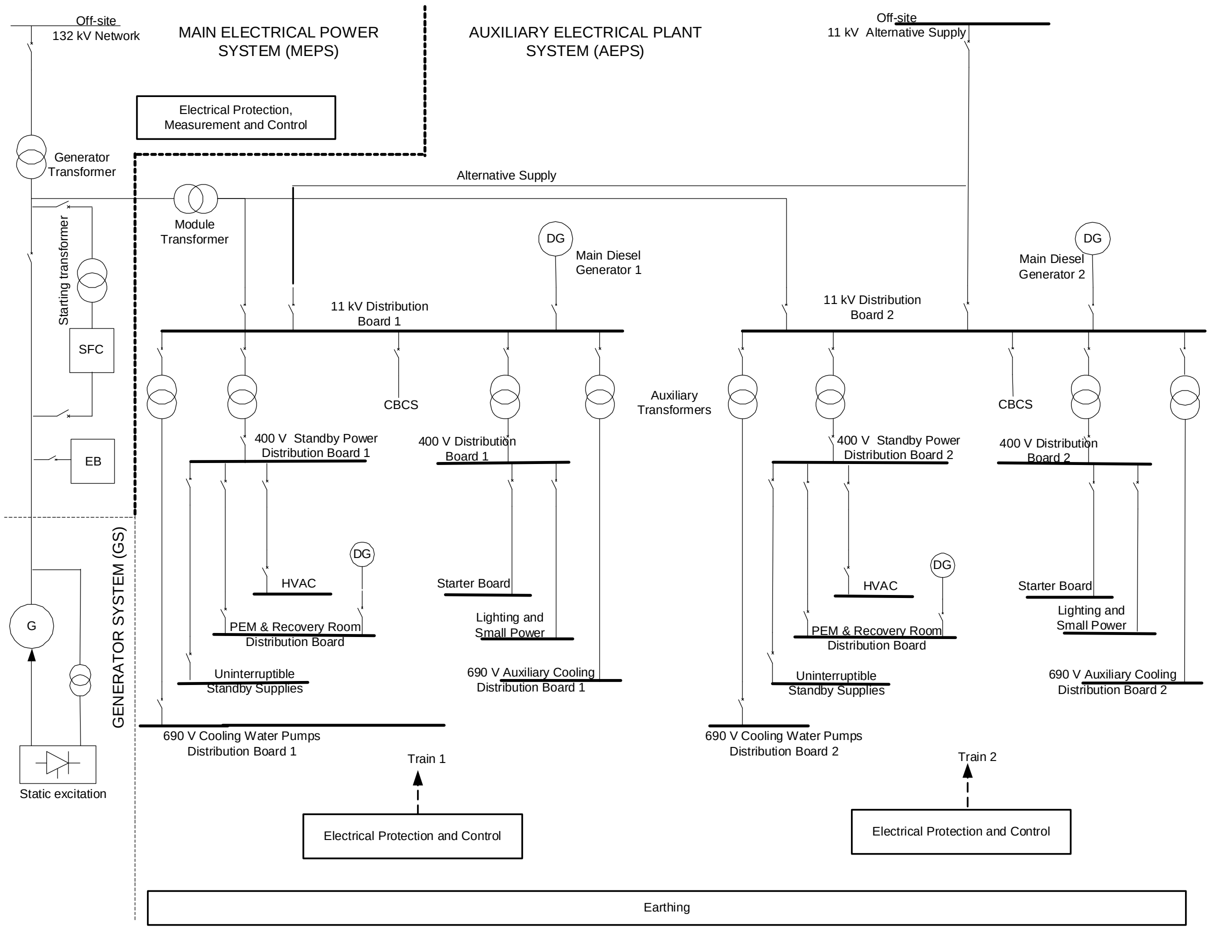
**Figure 69: 400 kV Network Near the PBMR Demonstration Power Plant**

[Withheld on the basis of it being "Security-Related Information"]

**Figure 70: Main and Alternative Connection of PBMR Demonstration Power Plant to Eskom Network**

### 10.1.3 Layout

Figure 71 is a high-level single-line diagram that shows the design layout of both the MEPS and the AEPS.




Legend:

G: Generator
GS: Generator System
DG: Diesel generator
SFC: Static frequency converter
EB: Electrical brake
CBCS: Core barrel conditioning system
PEM: Post-event monitoring

**Figure 71: Layout of Electrical System**

## 10.2 MAIN ELECTRICAL POWER SYSTEM

**Note:** The interface to the external network is described as part of paragraph 10.3, Auxiliary Electrical Power System.

### 10.2.1 Busbar System

The busbars connect the main power generator to the generator transformer via the generator circuit-breaker. They also connect the module transformer, starting transformer, static frequency converter and electrical brake as shown in Figure 71.

The busbar system includes the current transformers as well as the earthing circuit at the star point of the main power generator.

The busbars are air-insulated.

### 10.2.2 Generator Circuit-breaker

The generator circuit-breaker connects the main power generator electrically to the network via the generator transformer. It is tripped by the electrical protection in the event of a failure of the main power generator, generator transformer or module transformer.

The generator circuit-breaker includes current transformers, voltage transformers, and an isolator for the connection of the static frequency converter.

### 10.2.3 Generator Transformer

The generator transformer provides the power interface between the high-voltage network and the main power generator. It transforms the power from 13.2 kV to 132 kV. When the plant is disconnected from the network, power to the auxiliaries is obtained from the high-voltage network via the generator transformer.

The generator transformer is provided with an on-load tap changer for network voltage regulation purposes. It is rated at [ ][b].

### 10.2.4 Static Frequency Converter

The Static Frequency Converter (SFC) is used to provide power to the plant's generator during starting. It is also used to balance the shaft of the Turbo-generator Set (TGS) after installation and major maintenance have been performed on the TGS. The shafts of the generator and the Power Turbine (PT) are balanced separately prior to the installation, but trim-balancing of the coupled shaft is performed using the SFC. The SFC is rated at [ ][b].

### 10.2.5 Controlled Resistor Bank

The Controlled Resistor Bank (CRB) provides an electrical load to the generator during plant start-up. The CRB is used to achieve fine speed control of the generator during synchronization to the external electrical network. The power dissipated by the CRB is continuously controllable in the range [ ][b]

**Note:** It may be decided to use the SFC to achieve fine speed control during synchronizing. In that case the CRB is no longer required.

### 10.2.6 Electrical Protection

The functions are grouped into the Main protection and the Back-up protection. The protection covers the Generator System (GS) (i.e. the main generator and the excitation system) as well as all the components of the MEPS.

The MEPS includes a redundant automatic synchronizer that is used to synchronize the generator to the external electrical network prior to the closing of the relevant circuit-breaker.

### 10.2.7 Electrical Measurement

The measurement equipment measures electrical parameters (power, voltage, electrical energy, etc.) at the terminals of the following components:

- Alternative supply to AEPS
- 132 kV network
- Generator
- Generator transformer
- Module transformer (the main supply transformer for the AEPS)
- CRB
- SFC transformer
- Excitation transformer

### 10.2.8 Summary of Ratings

**Table 34: Main Component Characteristics of Main Electrical Power System**

| Component | Type or Rating |
|---|---|
| Generator transformer type | a,b |
| Generator transformer rating | |
| Busbar type | |
| Generator circuit-breaker rated withstand current (1 s)<br>Generator circuit-breaker braking rated short-circuit current | |
| SFC rated power | |
| Connection of generator transformer to electrical network | Overhead transmission line to 132 kV substation |

## 10.3 AUXILIARY ELECTRICAL POWER SYSTEM

### 10.3.1 General

The Auxiliary Electrical Power System (AEPS) consists of two power trains (refer to Figure 71). Most electrical loads are redundant, and one load of each redundant pair is supplied from each power train. Due to the passive safety features of the plant design, the AEPS is not safety related.

The main characteristics of the AEPS are indicated in Table 35:

**Table 35: Main Characteristics of Auxiliary Electrical Power System**

| Characteristic | Description |
|---|---|
| House load | 7.1 MVA |
| Power quality | Normal voltage regulation: ± 5% of nominal voltage<br>Short time voltage regulation: ± 10% of nominal voltage (1 h)<br>Power frequency regulation: ± 2% of 50 Hz<br>Short-time frequency regulation: -5%, +3% of 50 Hz (1 h)<br>Voltage unbalance: negative phase sequence ± 1% of positive phase sequence |
| Motor starting technology | Intelligent motor control with communication bus to control system |
| Distribution voltages | 11 kV, 690 V, 400 V and 230 V |
| Electromagnetic Compatibility (EMC) | Complies with US Reg. Guide 1.180, EPRI Guideline TR-102323 Rev. 2 and relevant sections of IEC 61000 |
| Main Diesel Generators | Redundant sets – 1.5 MW each<br>Two local fuel tanks of 3 600 l for 12 h runtime<br>Common fuel tank of 9 600 l |
| Post-Event Monitoring and Recovery Room (PEMRR) diesel generators | Redundant sets – 100 kVA each<br>Two local fuel tanks of 1 000 l for 24 h runtime |

The power distribution redundancy is required to ensure reliable power supply to the Reactor Cavity Cooling System (RCCS) for investment protection. The redundant power trains are separated in the building to prevent common failure due to external events.

### 10.3.2 Off-site Power Supplies

Off-site power is derived from the following sources (refer to paragraph 10.1.2):

- Koeberg 132 kV high-voltage yard
- Duyne 132 kV distribution substation

When the plant is not producing power, the AEPS can be supplied with power from the Koeberg 132 kV yard through the Generator transformer and the Module transformer (refer to Figure 71). Alternatively, if this supply is not available, power to the plant's auxiliaries can be obtained from Duyne substation.

Power to the auxiliaries can also be supplied from Duyne substation whilst the plant is producing power and delivering it to Koeberg 132 kV substation.

### 10.3.3 On-site Power Supplies

On-site power sources consist of the main plant generator, the standby diesel generators and UPS. The standby generators and UPS are described in more detail in the following paragraphs.

#### 10.3.3.1 Standby diesel generators

Two 1.5 MW, 11 kV diesel generators are provided, one on each power train. The functions of the standby diesel generators are to provide:

- controlled shutdown power; and
- power for standby supplies during a station blackout.

Two 50 kW, 400 V diesel generators are provided to provide back-up power to the PEMRR and the UPS of the Reactor Protection System (RPS) and Post-event Monitoring System. These diesel generators and associated switchgear are seismic qualified.

#### 10.3.3.2 Uninterruptible power supplies

| UPS | Loads | Rating | Standby Time |
|---|---|---|---|
| 440 V Battery set | Electromagnetic Bearing (EMB) supply (1 h)<br>Oil pump motor supply (1 h)<br>Standby lighting supply (1 h)<br>Reactivity Control System (RCS) and Reserve Shutdown System (RSS) (4 h)<br>Reactor Building access control and radiation monitoring (1 h) | TBD | See ‘Loads’ column |
| 220 V Battery set | Lubrication oil system | TBD kW | TBD |
| 110 V Battery set | Electrical protection and control<br>(Circuit-breakers, electrical protection panels, electrical measurement panel, SFC, etc.) | 15 kW | 4 h |
| 50 V Battery set | Tele-control and communication | 15 kW | 4 h |
| C&I UPS | C&I | 50 kVA | 1 h |
| Services Building Access Control and Radiation monitoring | Access control and radiation monitoring | 20 kVA | 1 h |
| Services Building Standby Lights UPS | Standby lighting in control room and radiation monitoring area | 5 kVA | 1 h |
| RPS and PEI UPS | Reactor protection and post-event monitoring | 10 kVA | 24 h |
| PEMRR UPS | Lighting for PEMRR and its diesel generators | 5 kVA | 1 h |
| Cooling Water C&I UPS | C&I in the Cooling Water (CW) substation | 5 kVA | 30 min |

### 10.3.4 Component Functions

The functions of the AEPS components are summarized in Table 36.

**Table 36: Functions of Auxiliary Electrical Power System Components**

| Component | Main Function |
|---|---|
| Module Transformer | Transforms the generator output or the power derived from the network via the generator transformer to the AEPS Distribution System and limits sub-transient fault level |
| Auxiliary Transformers | Transfer power at suitable voltage levels to the Distribution Boards |
| Medium Voltage (MV) Switchgear | Switch medium voltage electrical power and control electrical power to motors and auxiliary transformers |
| Low Voltage (LV) Switchgear | Switch low voltage electrical power and control electrical power to motors and other loads |
| Electrical Cabling | Power connections of the MV and LV distribution boards and loads<br>Communication bus connections on the MV and LV switchgear electrical protection and control relays |
| Earthing System | Connection of all equipment to the earth bonding tags that are connected to the building reinforced structure |
| Lighting, Small and Maintenance Power | Provide environmental lighting at all levels inside the Reactor Building and outside<br>Provide small and maintenance power at all levels inside the Reactor Building |
| UPS (ac and dc) | Provide standby power in case of a complete loss of off-site power |
| Main Diesel Generators System | Provides standby power during a station blackout for controlled shutdown power |
| PEMRR diesel generators | Provide standby power during a loss of off-site to the shutdown room distribution system |

# 11. CIVIL STRUCTURES

## 11.1 REACTOR BUILDING

### 11.1.1 Layout Description

The Nuclear Island is that part of the power plant which supports and protects the Primary Pressure Boundary (PPB) and supporting systems. It comprises the Reactor Building, the footprint of which is 73.89 m by 37.0 m. The length of the footprint reduces to 67.39 m above building elevation 15.5 m. The height of the Reactor Building as measured from the top of the raft foundation to the top of the roof slab is 62.3 m (excluding the parapet walls and lift motor rooms on the roof).

The functions of various sections of the Nuclear Island are categorized below. (Refer to Figure 48.)

- The Reactor Building is defined as the entire structure that houses the PPB and its ancillary systems. The Reactor Building is designed to withstand loads and missile impacts due to events induced either by man-made or natural sources external to the building. These sources typically include for earthquakes, aircraft impact, tornadoes, loads induced by accidents at nearby industrial facilities or transportation routes, extreme winds and environmental temperatures, and flooding. However, these sources specifically exclude sabotage, terrorist attacks and the effects of war. The Reactor Building is operated at a pressure less than atmosphere so that leaks occur into the Reactor Building and not visa versa.
- Within the Reactor Building, the citadel surrounds and supports the Reactor Pressure Vessel (RPV) and Power Conversion Unit (PCU). That part of the citadel, which houses the RPV and Reactor Cavity Cooling System (RCCS), is referred to as the Reactor Cavity (RC). The primary function of the citadel is to form a second barrier to externally generated Design Basis Accidents (DBAs). In the case of internally generated DBAs, the RC constitutes the primary barrier to the RPV. The RC also provides the seismically qualified base for the support of the RPV and the RCCS.

An additional function of the citadel is to enclose the high radiation area around the RPV and the PCU, and provide radiation protection for the plant personnel.

In the event of a break in the PPB or a high-energy line, a containment system is designed to ensure that the release of fission products to the environment is kept well below regulatory limits. This system is designed such that the initial pressure transient is dissipated to atmosphere. As the quantity of fission product in the escaping helium is low, the radioactive releases calculated at the site boundary are well below limits. In the event that small pipes, having an equivalent diameter less than [ ][a,b] are ruptured, the pressure transient is vented through the Heating, Ventilation and Air-conditioning (HVAC) system. Larger pipe breaks are vented through the Pressure Relief System (PRS).

Thereafter, the PRS is sealed to ensure that any later releases are kept within the containment system until a filtration system can be activated to filter out the main biologically active isotopes. The building containment, together with the PRS and filtration system, is called the Containment System.

The design of the PRS is such that for large breaks, a quick-acting valve in the HVAC system closes to protect the HVAC system, and a rupture panel in the depressurization route opens at a predetermined pressure, allowing the gas to escape to atmosphere. After release of the excess pressure, the depressurization shaft is closed automatically by a damper mechanism. A manual back-up closure mechanism is provided should this damper fail to operate. After closure of the pressure relief shaft, the building integrity is restored and the HVAC is allowed to resume the conditioning of the environment inside the containment.

The Reactor Building interfaces with the majority of the plant systems housed within, and the various features of these interfaces, such as the space requirements, the installation procedures and maintenance access, are considered in the layout of the plant. The loads imposed by the various systems on the module are summarized in the PBMR plant-loading catalogue.

### 11.1.2 Functional Description

The structural integrity of the Reactor Building is to be ensured under a series of extreme load events which have been stipulated in the Regulatory Guides, and which have been shown through past experience in the nuclear industry to have the potential to cause damage to the nuclear plant. In addition, the probabilistic risk assessment and safety analysis of the PP within the Reactor Building may require the analysis of further extreme load events. These extreme events include both natural and man-induced scenarios, initiated either external or internal to the Reactor Building.

All the extreme load events create the potential for the release of radioactive material to the environment.

A fundamental principle in the development of the Reactor Building design is for the building to survive all the postulated extreme load events, and continue to provide support to the nuclear safety-related plant systems after these events. Furthermore, the Reactor Building must continue to provide a containment, which will both restrict the release of radioactive material to the environment and limit the ingress of air into the citadel.

The Reactor Building is therefore designed to withstand the extreme load events with minimal damage to the structure, whilst ensuring overall stability to the RPV, PCU and other nuclear safety-related plant, as well as the ability to confine and minimize releases from these plant systems.

Where site-specific data is available, this is used in the definition of the Reactor Building design bases. In certain instances such data may not be available, and investigation programmes are developed. Where these programmes extend over many years, the design bases are established on relevant data from other sites throughout the world. The data collection programmes are then to be used to reconfirm these design bases, as data becomes available.

The functional requirements to which the Reactor Building is designed, include:

- Radiation zoning
- Shielding
- Access control
- Decontamination ability
- Nuclear and industrial safety
- Fire protection and compartmentalization of plant
- Equipment lifting capability
- Mitigation of flooding hazards
- Waste treatment, handling and storage capability
- Provision of barriers against the ingress of ground water
- Compliance with the leak tightness requirement to minimize uncontrolled releases of radioactive material
- Application of Defence in Depth (DiD) and ALARA (As Low As Reasonably Achievable)

- Resistance to internal and external DBAs
- Provision of a vented containment system
- Facilitation of the installation, maintenance and decommissioning of the plant
- Storage of radioactive waste, new and spent fuel
- Compliance with the environmental impact requirements
- Constructability of the building

### 11.1.3 Summarized Detail

The primary construction material is reinforced concrete. Due consideration is given to the durability requirements of the site.

The codes of practice used in the design are ACI-349 for reinforced concrete and ANSI AISC N690 for structural steelwork.

The construction standards primarily follow the rules set out in SABS 1200.

### 11.1.4 Interfaces

The Reactor Building interfaces with all the plant items housed in the building. Interface specifications are compiled by each of the various systems and the detailed interface with the building described.

## 11.2 CONVENTIONAL ISLAND

### 11.2.1 Layout Description

The Conventional Island is defined as that part of the power plant which supports the non nuclear part of the PCU, namely the generator. It comprises the Generator House, the footprint of which is 35.50 m by 37.0 m. The Generator House comprises a basement founded 5.80 m below ground level (elevation 13.4 m AMSL), a ground floor which is accessed via a loading bay, and the laydown floor for the generator 6.8 m above ground. A crane is currently located at 11.0 m above the laydown floor.

### 11.2.2 Functional Description

The Generator House performs the following primary functions:

- Provides access to the generator during operation and maintenance
- Houses the ancillary plant serving the generator e.g. breaker, SFC
- Houses the generator transformer and unit transformer busbars
- Houses the two redundant trains of electrical systems interfacing with the Nuclear Island
- Houses the two lube oil systems serving the turbine, compressors and generator in the controlled and non-controlled areas

### 11.2.3 Summarized Detail

The structure is constructed using reinforced concrete to a level 3.0 m above the laydown floor, and structural steel with cladding above this level. Due consideration is given to the durability requirements of the site.

The codes of practice used in the design are ACI-349 for reinforced concrete and ANSI AISC N690 for structural steelwork.

The construction standards primarily follow the rules set out in SABS 1200.

### 11.2.4 Interfaces

The Generator House interfaces with all the plant items housed in the building. Interface specifications are compiled by each of the various systems, and the detailed interface with the building is described.

## 11.3 AUXILIARY BUILDINGS

### 11.3.1 Layout Description

The Auxiliary Buildings are located on the site in such a manner to ensure access by road. The Auxiliary Buildings house various plant systems and do not interact directly with either the Reactor Building or the Services Building. The particular buildings comprising this group are:

- The Diesel Generator Building that houses the two back-up diesel generators
- The Diesel Fuel Building that contains the fuel oil storage tank for the diesel generators
- The Lube Oil Storage Building that houses the lube oil storage tank for the Turbo-generator Set (TGS) bearings
- The Cooling Water (CW) Plant Room that houses heat exchangers, pumps and associated equipment for the Active Cooling System (ACS), Reactor Cavity Cooling System (RCCS) and the heat exchangers of the Main Heat Sink System (MHSS)
- The Fire Pump House that accommodates the fire pumps and associated equipment required for supplying the fire-fighting water to the site (including the Reactor Building, the Services Building and the various Auxiliary Buildings)
- The Fire Protection System (FPS) Water Storage Tanks

In addition to the buildings identified above, the following features are also considered as part of the Auxiliary Buildings:

- The Transformer areas on which the various transformers are located
- The tunnels and services ducts that provide a means of transferring services between the various buildings on the site

### 11.3.2 Functional Description

The specific functional requirements and features for a particular Auxiliary Building are determined by the plant system that it houses, and these are summarized below:

a. The Diesel Generator Building, the Diesel Fuel Building and the Lube Oil Storage Building
    - All spilled fuel oil must be contained and collected. Under no circumstances must the fuel be allowed to leak into the surrounding soil.
    - Fire and blast protection must be provided.
    - Spilled oil and fire-fighting water must be managed.

b. The CW Plant Room

All spilled water in the controlled area must be contained, collected and subsequently drained into the Waste Handling System (WHS).

c. The Fire Pump House

The Fire Pump House has redundant systems for plant protection. The pump house and water storage tanks should be designed to resist the design basis earthquake to be able to deal with fires resulting from a seismic event.

d. Transformer areas

- Fire and blast barriers must be provided to contain fires, thus preventing a fire at a particular transformer from spreading to adjacent transformers and/or items of the plant.
- All spilled oil and fire-fighting water must be contained and collected.

e. Tunnels and services ducts

- The tunnels and services ducts are designed to resist the effects of seismic motions.
- Provision must be made to accommodate relative movement between tunnels and the buildings that they connect to.
- Fire protection measures must be provided.
- Provision must be made to drain water spilled during the suppression of a fire or following a leak in a pipe. Provision must also be made to prevent leakage of ground water into below grade tunnels and ducts.
- Access must be provided into tunnels and services ducts. The extent of the access is dictated by the requirements of the items housed by the particular tunnel or duct, as well as the general layout and configuration of the tunnel or duct.
- Emergency exits and lighting must be provided.

### 11.3.3 Summarized Detail

The primary construction material is reinforced concrete. Due consideration is given to the durability requirements of the site.

The codes of practice used in the design are ACI-349 for reinforced concrete and ANSI AISC N690 for structural steelwork.

The construction standards will generally follow the rules set out in SABS 1200.

### 11.3.4 Interfaces

The Auxiliary Buildings interface with all the plant items housed in the buildings/structures. Interface specifications are compiled by each of the various systems and the detailed interface with the building is described.

# 12. POWER PLANT OPERATIONS

## 12.1 GENERAL CONTROL DESCRIPTION

The control strategy and transient behaviour of the PBMR is determined by the dynamic of the Reactor Unit (RU) and the Power Conversion Unit (PCU). To understand the dynamic response of the PBMR, the effect of the following system characteristics on the dynamics should be well understood:

a,b

The difference in speed of response of the RU and PCU has a certain advantage, but at the same time also creates a demanding coordination requirement.

The advantage is that the large thermal capacity of the core allows relatively fast load changes of the system without requiring fast response from the reactivity control of the core. In principle, the energy stored in the core can be withdrawn or stored with minimum core temperature changes. The reactor has a negative temperature coefficient, which results in the reactivity, and consequently the neutronic power, changing to counteract temperature changes. The reactor is, therefore, nearly self-regulating, and the minimum of control interaction is required to maintain the reactor outlet temperature at a given value.

A full loss or partial loss of electrical load will result in the acceleration of the Turbo-generator Set (TGS) to potentially unacceptable rotational speeds. Thus the power turbine requires active speed control when the generator is not connected to a stable grid.

Thus, in principle, the PBMR consists of an inherently stable and slow acting heat source coupled to fast acting power conversion machines (in terms of temperature). The PCU will require active control to remain stable under all anticipated operating scenarios.

## 12.2 PLANT OPERATING ENVIRONMENT

### 12.2.1 Cooling Water Temperature

a,b

The minimum cycle temperature in the PBMR plant is one of the critical parameters for achieving the highest possible cycle efficiency. This temperature is the minimum gas temperature directly after the pre- and intercoolers, which in turn is determined by the efficiency with which heat can be exchanged between the helium gas and the primary cooling water. Although this cooling water is currently supplied via an intermediate heat exchanger between the sea water as secondary coolant and the intermediate cooling loop, it can also be supplied from a number of other secondary sources. Secondary coolant options for obtaining the required cooling water may include wet or dry cooling towers, or even water from dams, rivers and lakes. The different cooling methods will, however, have different thermal characteristics for the primary cooling water. In the current design, the main heat sink temperature is the sea water temperature.

a,b

The CWT determines the helium inlet temperature of the Low-pressure Compressor (LPC) and the High-pressure Compressor (HPC), which has a large effect on the performance of the PBMR Brayton cycle. The PBMR design is optimized to deliver the maximum grid power for a given CWT by adjusting the size of the turbo machines. The maximum grid power decreases with an increase in CWT, as can be seen in Figure 72. The design curve in Figure 72 represents points for which the maximum reactor power (400 MW) is produced and the manifold is at its maximum working pressure (9 MPa). The reactor power and the manifold pressure are the limiting characteristics when optimizing the plant (it is assumed throughout that the reactor outlet temperature is 900 °C).

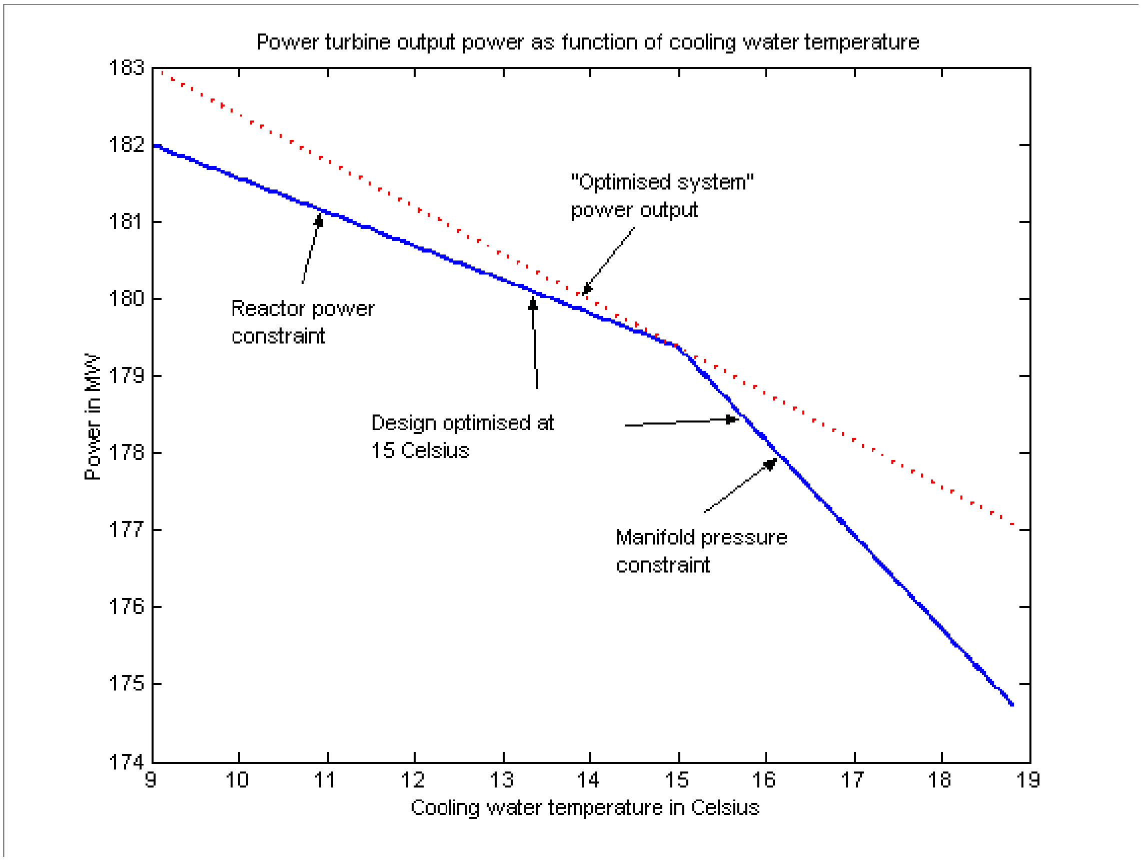



**Figure 72: Cooling Water Temperature Design Curve**

a,b

For the Koeberg site location, it is then possible to calculate the total power production based on past temperatures of the site location. The historic data for the temperatures was taken and the produced grid power is calculated assuming that the plant was optimized for a specific temperature. Figure 73 shows the normalized total grid power for a PBMR module located at Koeberg with different CWT design points.

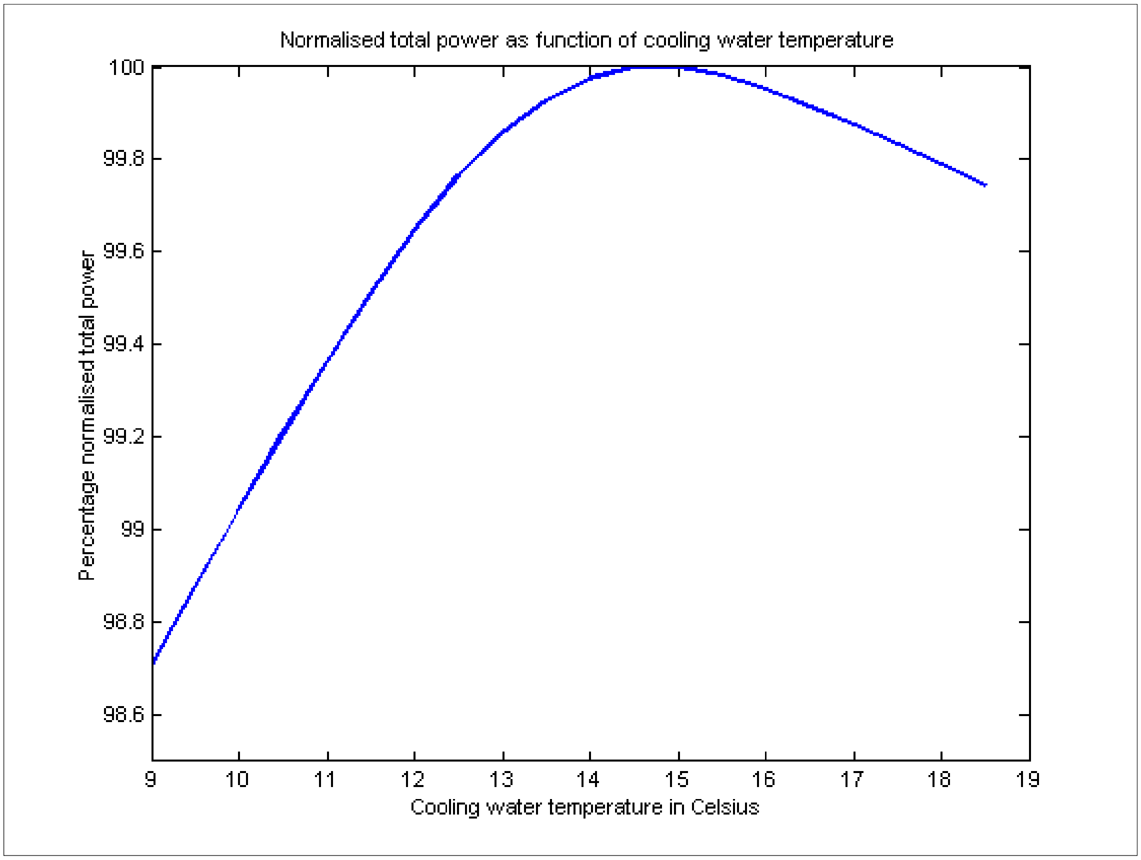



**Figure 73: Total Annual Power for Koeberg**

### 12.2.2 Abnormal Conditions

The following Main Power System (MPS) abnormal environmental conditions resulting from natural and system generated upset events are considered in the design of the plant:

#### 12.2.2.1 Load conditions generated by the plant

These refer to loads on the plant as generated by events internal to the pressure boundaries of the Fuel Handling and Storage System (FHSS), Helium Inventory Control System (HICS) and MPS.

- **Missiles generated by rotary machinery:** Missiles generated by rotary machine components inside the pressure boundaries will be contained inside the pressure boundaries. Missiles generated by other rotary machines will be contained by their structural supports, covers or immediate civil structures.
- **Loads generated by a sudden depressurization of the pressure boundaries due to a small non-isolatable pipe break:** Continued operation may be resumed after closure or isolation of the break, provided that no safety requirements are violated.
- **Loads generated by a sudden depressurization of the pressure boundaries due to a medium pipe break:** It is acceptable that limited replacement or repair of subsystems or components may be necessary before operation can resume.
- **Loads generated by a sudden catastrophic failure of a large non-isolatable pipe:** It is possible to keep the reactor within acceptable safe conditions following such an event. The system is designed to take into consideration the local shock wave effects due to the sudden blow-down.
- **Flooding:** Flooding due to the rupture/failure of an internal system.

- **Fire**.
- Any other transients leading to a fast change in operating conditions.

#### 12.2.2.2 Externally generated load conditions

These loads are typical of those analysed in the design of the civil and structural works of Nuclear Power Plants (NPPs) and generally follow the recommendations made by the US Nuclear Regulatory Commission (NRC) and the International Atomic Energy Agency (IAEA).

These loads are site-specific, and although an attempt was made to encompass most sites around the world in the licence basis, these loads shall be re-evaluated and confirmed for the DPP site.

The following external loads are considered in the plant design:

- Wind Loads
- Tornado Loads
- Atmospheric Temperature Loads
- Precipitation Loads (rainfall and snow)
- External Flood Loads
- Internal Flood Loads
- Missile Loads
- Aircraft Crash Loads
- Seismic Loads (Safe Shutdown Earthquake [SSE] = 0.4 g Peak Ground Acceleration (PGA) horizontal and 0.27 g PGA vertical)

## 12.3 POWER PLANT CONSTRAINTS AND OPERATIONAL ENVELOPE

### 12.3.1 Operating Restriction on Compressors

a,b

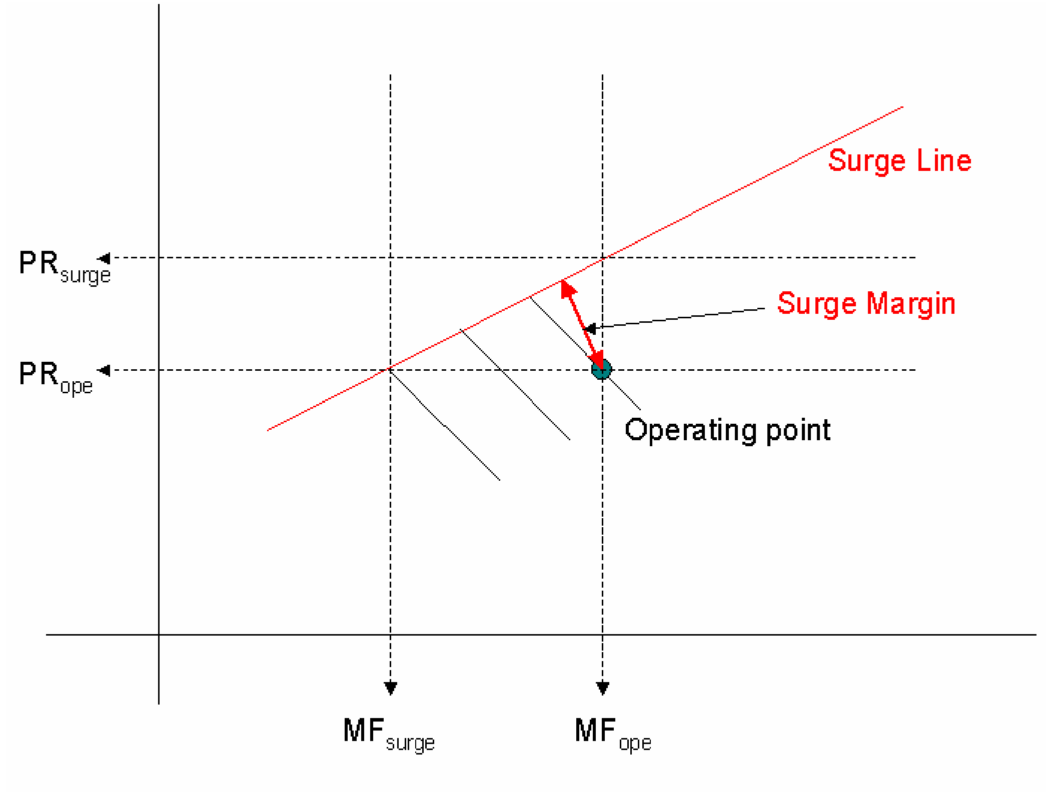



**Figure 74: Compressor Map**

a,b

### 12.3.2 Inventory Limitations

a,b

[ ]a,b

### 12.3.3 Reactor Limitations

The reactor maximum average helium outlet temperature is 900 °C. The maximum rate of change of the ROT is [

]a,b

The reactor constraints are summarized in Table 37.

**Table 37: Reactor Constraints**

| Process Variable | Process Analytical Limit | Control Range |
|---|---|---|
| ROT | | |
| ΔT across reactor | | |
| d/dt (ROT) | | |
| Control rod speed | | |
| SAS removal | | |

a,b

.

### 12.3.4 Inventory Adjustment Limitations

The maximum rate at which helium can be injected or removed from the MPS-PB is [ ]b The resulting change in power is 10% MCR/min.

### 12.3.5 Total Plant Inventory Limitations

The control system will prompt the operator if the total helium inventory is not within [ ]b of the nominal plant inventory.

### 12.3.6 Start-up Margins

The MPS ready mode and state are defined by the MPS being within the start-up margins. The MPS start-up and synchronization transition sequence can be initiated whenever the MPS is within the start-up margins.

The start-up margins are given in Table 38.

**Table 38: Start-up Margins**

| Process Variable | Start-up Margin |
|---|---|
| ROT | [ ]a,b |
| Manifold pressure | |
| Surge margin | |
| Turbo-generator Set (TGS) speed | |

## 12.4 MAIN POWER SYSTEM CONTROL FUNCTIONS

The following paragraphs give a general control description of the Main Power System (MPS) of the PBMR. Different control objectives are described, together with the control actuators and the measurement devices that are used. The following definitions are given to clarify some of the concepts used to describe the control functions:

- **Cooling Water Temperature (CWT)** is the water inlet temperature of the pre-cooler and the intercooler. The CWT is a function of the site location and the type of main heat sink used. The CWT also varies during the year as the site temperature changes.
- **Reactor Outlet Temperature (ROT)** is the average helium outlet temperature exiting the reactor. Under normal power operation, this temperature is 900 °C.
- **Maximum Continuous Rating (MCR)** is defined as the maximum grid power produced by a PBMR unit at the design CWT of 28 °C and an ROT of 900 °C. The reactor power at 100% MCR is limited to 400 MWt, and the manifold pressure is limited to a maximum value of 9 MPa.
- **Maximum Continuous Rating Inventory (MCRI)** is defined as the mass of helium in the Main Power System Pressure Boundary (MPS-PB) corresponding to the same percentage MCR at a CWT of [ ][b.] Thus, 40% MCRI is the mass of helium in the MPS-PB when 40% MCR is produced and 100% MCRI is the mass of helium in the MPS-PB when 100% MCR is produced (assuming that the CWT is [ ][b] and all bypass valves are closed). It must be noted that the helium mass corresponding to 50% MCRI is **NOT** half the mass of helium corresponding to 100% MCRI. (It is not a linear relationship.)

### 12.4.1 Reactor Outlet Temperature Control

In order to achieve stable Brayton operation and for component integrity, the ROT is controlled. The ROT is usually controlled to a specific value, and during certain transition sequences and modes of operation, the outlet temperature can be ramped at a given rate of temperature increase or decrease. The ROT can be controlled when the reactor is critical or when the reactor is subcritical. The control differs in these two cases.

When the reactor is critical, the ROT is controlled using the control rods. The ROT is measured together with the reactor neutronic power and the reactor fluidic power. The neutronic power is derived from the neutron flux measurement. The reactor fluidic power is calculated using the reactor inlet and outlet temperature and the helium mass flow rate through the reactor. This is known as ROT reactivity control.

When the reactor is subcritical, the ROT is controlled using the speed of the motored TGS. Only the ROT is measured. By changing the speed of the motored TGS, the mass flow rate through the reactor can be adjusted, which in turn determines the heat removed from the reactor, thereby controlling the ROT. This mode of ROT control is known as ROT decay heat control.

The control and shutdown rods are not used to regulate the temperature directly. They are used to compensate for the reactivity fluctuations resulting from load following, for a reactor scram and when the plant is shut down to maintenance conditions. The Reserve Shutdown System (RSS), consisting of the Small Absorber Spheres (SAS), is only used during the maintenance modes, and transition sequences to and from maintenance modes. During the maintenance mode, the ROT is kept below 400 °C.

During maintenance, the maintenance valves are used to isolate the reactor from the PCU. The Core Conditioning System (CCS) is used to cool the reactor during PCU maintenance.

### 12.4.2 Power Control

Refer to Figure 75. By adding to the gas inventory of the cycle, the heat absorbed in the core and the electrical power generated by the Power Turbine (PT) will be increased, and vice versa. This is the primary method of controlling power. The Inventory Control System (ICS) is used to adjust the inventory in the MPS-PB. Helium is normally injected into the MPS-PB at the inlet of the pre-cooler and removed at the manifold. When the helium mass in the MPS-PB is changed, the pressure ratios and temperatures within the circuit remain constant, and only the gas density and power levels are changed. High efficiency can be maintained at all power levels above 40% MCR with helium inventory adjustment.

a,b

**Figure 75: Main Power System Schematic**

The difference between the required power set point and the actual electrical power generated determines whether helium should be injected or removed from the MPS-PB. The pressure in the manifold is measured to ensure that the MPS-PB is not over pressurized. The total inventory in the MPS-PB is estimated to ensure that the minimum and maximum MCRI limits are not exceeded for a given cooling water temperature.

Opening the Gas Cycle Bypass Control Valves (GBPCs) will reduce the generated electrical power, and closing them will increase the power. By opening the GBPCs, some of the helium that would normally pass through the reactor and turbines is recirculated through the compressors. The PT power is reduced owing to the decrease in mass flow rate and the compressors using proportionately more of the available thermal energy.

Under normal load ramping between 40% MCR and 100% MCR, the GBPCs can be used in addition to the ICS. This enables the plant to ramp up and down at 10% MCR per minute without the non-minimum phase effect resulting from injecting helium at the pre-cooler inlet (The non-minimum phase effect results in the power decreasing before increasing due to the helium injection.)

### 12.4.3 Total Inventory Control

The total plant inventory in the MPS-PB and the HICS changes over time due to leakage of helium. It is undesirable to have large variations in the total plant inventory, since it leads to reduced plant capabilities, both when the inventory is higher or lower than the nominal inventory. The Helium Make-up System (HMS) is used to inject helium into the inventory control system when required.

### 12.4.4 Speed Control

Speed control of the TGS is performed when the generator is not synchronized to the grid. The TGS is then free to change speed, and active control is needed to maintain the speed at a specified set point. Speed control is also used during the synchronization process when the generator is synchronized to the grid. The regulation accuracy for speed control is 50 Hz $\pm$ 0.05 Hz.

The speed controller measures the speed of the TGS and uses the Low-pressure Compressor Bypass (LPB) Valve, Low-pressure Coolant Valve (LCV) and the variable resistor bank (Continuous Resistor Bank [CRB]) to control the speed. The LPB and LCV change the power turbine fluidic power, which acts as driving force to the TGS. The CRB absorbs electrical power produced by the generator and therefore has a braking effect on the TGS.

### 12.4.5 Rapid Load Reduction

Refer to Figure 75. When the electrical load is lost, the electrical power removed from the generator will decrease accordingly (loss of load transient). However, the fluidic power supplied to the power turbine still remains the same, and to ensure that the PT does not rapidly accelerate, the fluidic power needs to be reduced quickly.

The GBP is used to do this. The GBP, connecting the highest system pressure (HPC outlet) to the lowest system pressure (LPC inlet), will instantaneously reduce the speed of all turbines. This is triggered by the speed indication of the generator backed up by independent electronic and mechanical trip mechanisms of the PT.

a,b

### 12.4.6 Recuperator Inlet Temperature Control

Refer to Figure 75. The recuperator is designed for a maximum working temperature of 600 °C. During operation at low power levels < 40% MCR, the LPB and LCV are used. This operation results in temperature changes in the system. The low-pressure inlet gas temperature to the recuperator can then in certain cases increase above the 600 °C limit.

A recuperator temperature controller measures the recuperator low-pressure side inlet temperature. The temperature is controlled using the LCV valves. The coolant valves allow cool helium from the manifold to be introduced into hot gas before it reaches the recuperator.

### 12.4.7 Static Frequency Converter Control

Refer to Figure 75. The SFC causes a mass flow through the MPS. It is used for starting up the Brayton cycle and to remove heat from the reactor during the conditioning of the MPS. The speed of the SFC is controlled, as this determines the mass flow rate through the MPS.

### 12.4.8 Reactor Inlet Temperature Control

Refer to Figure 75. The reactor inlet temperature needs to be controlled. The inlet temperature control must satisfy the following three requirements:

- Certain reactor components (such as the core barrel) affected by the inlet temperature must be kept below a specified temperature.
- The temperature difference between the reactor outlet and the reactor inlet causes stresses in core structure components, thus the inlet temperature should be controlled to above a specified temperature.
- The heat removed from the reactor is a function of the temperature difference across the reactor and the mass flow rate. Changing the mass flow rate through the reactor is accomplished by adjusting the SFC speed. Currently the design is that control is a function of the SFC mass flow rate only, and the temperature difference across the reactor is kept constant.

The inlet temperature of the reactor is measured and controlled using the Recuperator Bypass Valve (RBP). The RBP causes some of the helium to bypass the high-pressure side of the recuperator. This results in a decrease of the reactor inlet temperature and an increase in the pre-cooler inlet temperatures.

## 12.5 POWER PLANT OPERATIONS

### 12.5.1 Modes and State Diagram

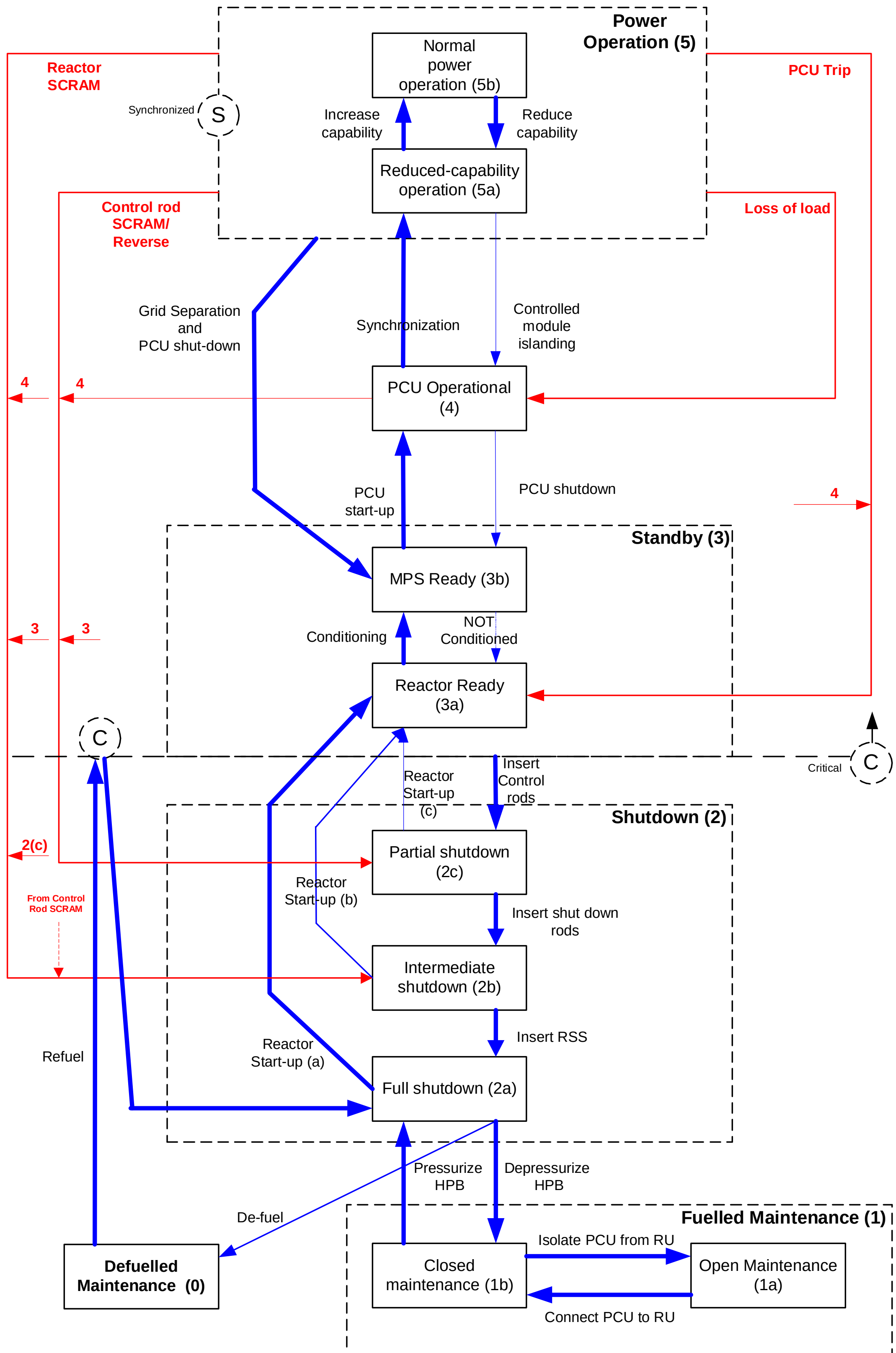



**Figure 76: Modes and State Diagram**

### 12.5.2 Load Control

Load ramping under normal operating conditions includes all cases for which the maximum rate of load change does not exceed 10% of MCR per minute. This translates to 16 MWe/min or 0.267 MWe/s.

Base load and load following operations are achieved through the use of the Inventory Control System (ICS). The ICS is designed to either add or remove helium from the cycle, so as to increase or decrease the average pressure level in the system. As the pressure level changes, the average density of the gas in the cycle also changes, and with it the mass flow rates through the reactor, turbo-machines and heat exchangers. By increasing or decreasing the mass flow rate, the power level can be increased or decreased with minimal change in cycle temperatures. This ensures maximum efficiency at power levels for which the helium inventory level of the MPS exceeds the minimum MCRI.

By making use of only the ICS, the plant is capable of load changes of 10% MCR in 15 min within the range of minimum and the maximum MCRI. Accurate load ramping (tracking a changing set point) is not possible in this mode of operation.

The load ramping makes use of the ICS together with the GBPCs. The GBPC is kept partially open and is closed while helium is injected at the pre-cooler inlet.

The compressor bypass valves LPB, and GBPC shown in Figure 75 are used for load changes. The figure shows single valves, but in practice the bypass configurations consist of multiple valves. Opening any number of these valves results in some fraction of the total mass flow bypassing the reactor and turbines, thereby reducing the generator power output. By varying the number of valves that are opened simultaneously, the rate of change in power output can be controlled. As opposed to inventory control, opening the bypass valves results in changes in the cycle temperatures.

Table 39 gives a breakdown of the plant load change capability at the design CWT of 28 °C.

**Table 39: Load Change Capability**

| Actuator | Operating Range | Ramp Rate | Set Point Tracking | Efficiency | Frequency of Operation |
|---|---|---|---|---|---|
| ICS | 40% MCR to 100% MCR | 10% MCR in 15 min | No | Maximum | Normal |
| | | | | | |

a,b

| Frequency of Operation | Net Cycle Efficiency Range |
|---|---|
| Normal: 1% to 100% of time spent in power operation | Maximum: 38% to 41% |
| Limited: 0.1% to 1% of time spent in power operation | Medium: TBD |
| Rare: < 0.1% of time spent in power operation | Low: TBD |

### 12.5.3 Loss of Electrical Load

The loss of load transient is defined as loss of electrical load on the generator, which leads to acceleration of the TGS. Moreover, the conditions at every position in the cycle must remain within safe operating limits during the transient, and the plant must not trip.

The Brayton cycle can remain self-sustaining after the total loss of electrical load from any power level at any CWT. This includes both the case where the house load remains connected, and the case where the house load is disconnected from the generator. The plant can operate for an indefinite time separated from the grid.

a,b

### 12.5.4 Start-up

a,b

### 12.5.5 Conditioning

Conditioning is a two-way operation and includes heat-up and cool-down to raise the temperature of MPS Structures, Systems and Components (SSC) to the temperature range at which they will operate.

### 12.5.6 Reactor Heat Removal

a. Temperature constraints

**Table 40: Main Power System Temperature Constraints**

| System | Allowable Temperature (°C) |
|---|---|
| Recuperator LP inlet | [ ]b |
| Recuperator LP outlet | |
| Reactor inlet temperature | |
| Reactor temperature differential | |
| ROT | |

b. Temperature rate limits

[ ]b

# 13. SPECIAL TOOLS AND EQUIPMENT HANDLING SYSTEMS

The Special Tools (ST) and Equipment Handling Systems (EHSs) are identified either according to the location of the Structures, Systems and Components (SSC) within the plant, or equipment type, or a combination of these. This provides optimal use between various support requirements and strategies.

## 13.1 EQUIPMENT HANDLING SYSTEMS

### 13.1.1 Equipment Handling Systems for Construction

The ST and EHSs are not applicable to the construction phase, unless otherwise specifically stipulated.

The exceptions to date are as follows:

- The Reactor crane and Power Conversion Unit (PCU) overhead crane are installed during construction, and used to assist with the assembly of the Main Power System (MPS) thereafter, within the safe working load limits of the cranes.

### 13.1.2 Reactor Crane

The crane services the area above the Reactor Pressure Vessel (RPV). Refer to Figure 77. In this area the following activities take place:

- Control rod replacements and maintenance
- Reserve Shutdown System (RSS) assembly removal and replacement
- Core Structure (CS) replacement
- Reactor Cavity Cooling System (RCSS) maintenance tasks
- In-service Inspection (ISI) tasks on the reactor assembly

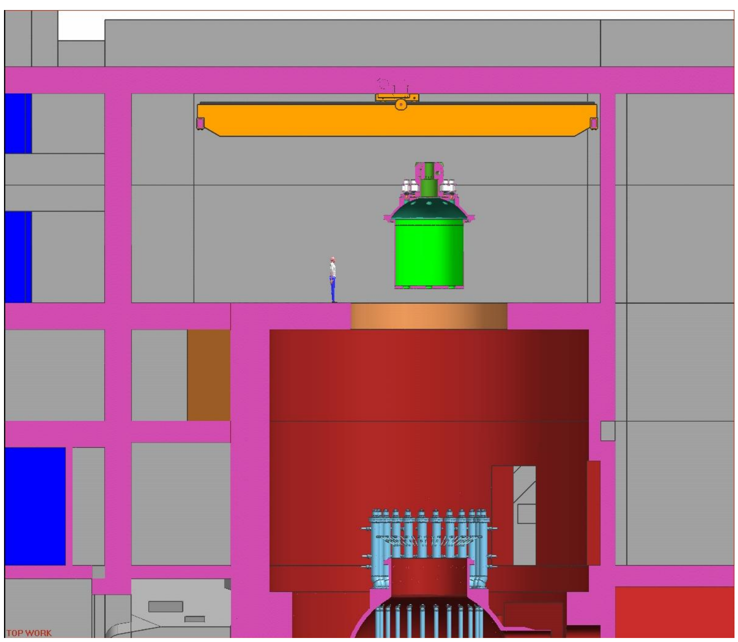


**Figure 77: Reactor Crane**

### 13.1.3 Reactivity Control and Shutdown System Maintenance Carriage Gantry

The RCSS gantry provides the interface for the RCSS special maintenance carriage to service the RCSS system.

Figure 78 shows a concept for the RCSS maintenance gantry and support platform.

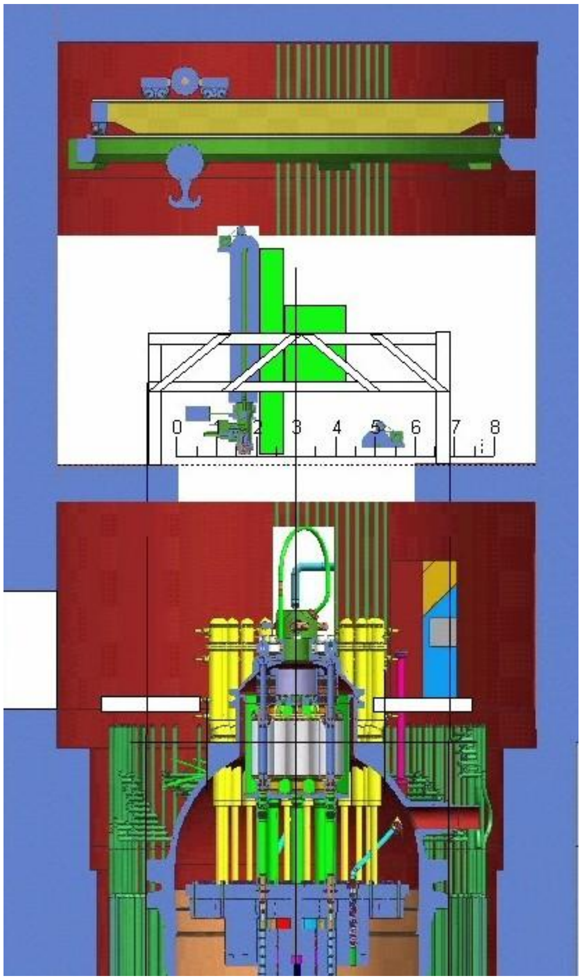


**Figure 78: Reactivity Control System Maintenance Carriage Gantry**

### 13.1.4 Power Conversion Unit Crane

This crane services the following SSC: Refer to Figure 79.

- Power turbine and compressor
- Minor components such as valves

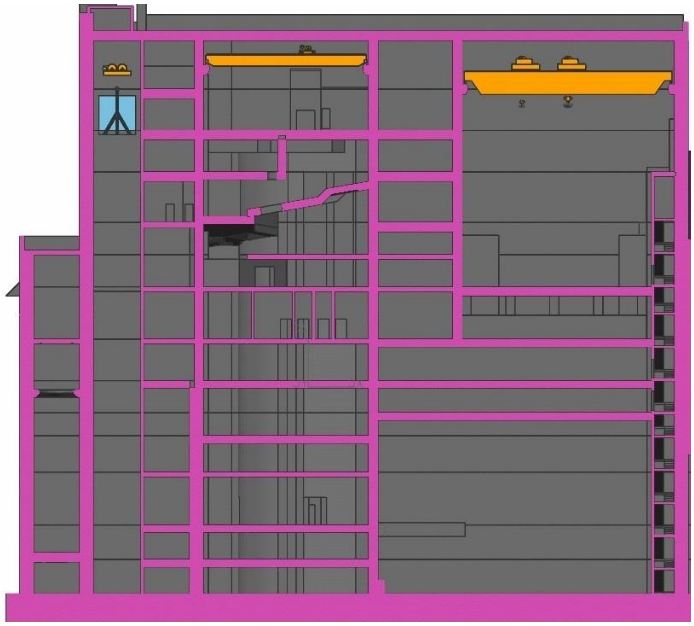


**Figure 79: Power Conversion Unit and Reactor Cranes**

### 13.1.5 Strand Jack Gantry

Figure 80 shows a strand jack gantry system that can remove the power turbine.

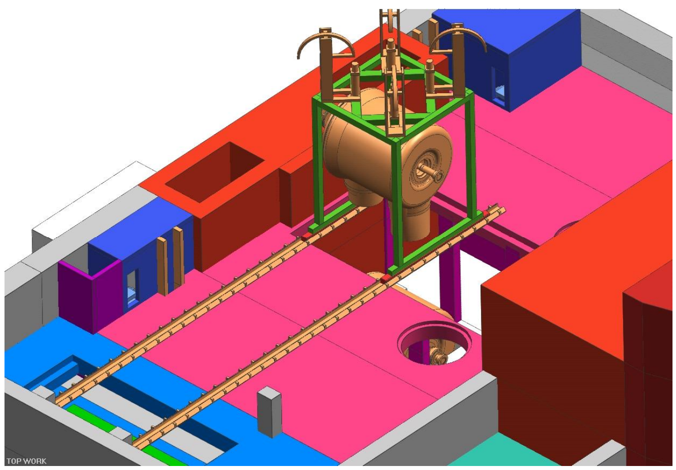


**Figure 80: Strand Jack Gantry**

### 13.1.6 Generator Crane

An overhead crane will be required to support maintenance on the generator rotor, and peripheral equipment in the generator hall.

### 13.1.7 Equipment Hoist

The hoist is required to move the scrap fuel High-level Waste (HLW) trolley and cask from where it is used to service the Fuel Handling and Storage System (FHSS) valves blocks above the reactor, down to the HLW handling area in the bottom of the building.

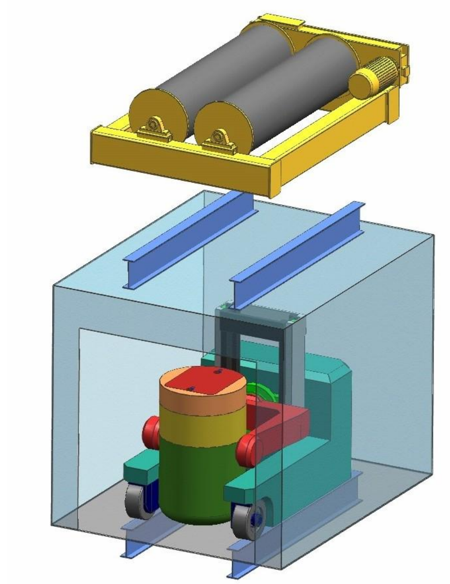


**Figure 81: Equipment Hoist**

## 13.2 SPECIAL TOOLS

The ST are identified either according to the location of the SSC within the plant, or equipment type, or a combination of these. This provides optimal use between various support requirements and strategies.

The ST are discussed per subsystem.

### 13.2.1 Reactor

#### 13.2.1.1 Reactor internal inspection and maintenance

The ST that are required to access the reactor include bolting equipment, seal welding equipment, lip seal cutting equipment, shielding, casks, and enclosures. Access is required primarily for the core reflector replacement.

Inspection and replacement requirements are being developed, and concepts are developed as the requirements become clearer.

#### 13.2.1.2 Core structure replacement system

A preliminary concept for the Core Structure Replacement System (CSRS) is shown in Figure 82.

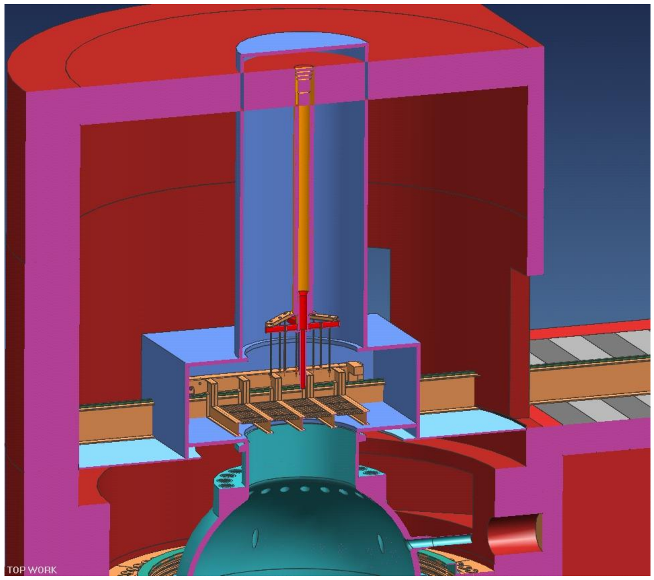


**Figure 82: Inner Reflector Replacement Concept**

The initial core structure installation and commissioning process is in a 'clean' (non-nuclear) environment, and personnel access is not a significant limitation. The core structure assembly tools will then later undergo further development for use in a radiologically contaminated environment to perform the core structure refit. The initial installation activities would help to evaluate and validate the midlife replacement concept.

A system is being conceptualized to be able to perform a core structure refit during the midlife outage. This entails dismantling the top end of the reactor (such as removing the RSS assemblies), and removing the centre column. The transport and storage of the core structure's used graphite blocks are accommodated within the site infrastructure.

#### 13.2.1.3 Reactivity control and shutdown system

A suite of associated specialized tools and equipment is provided to remove and replace the Reactivity Control and Shutdown System (RCSS). The Reactivity Control System (RCS) and Reserve Shutdown System (RSS) each have unique special tools, as well as certain common equipment.

The transport and storage of the core structure's used control rods are accommodated within the site infrastructure.

Figure 83 depicts the concept for the control rod removal tool.

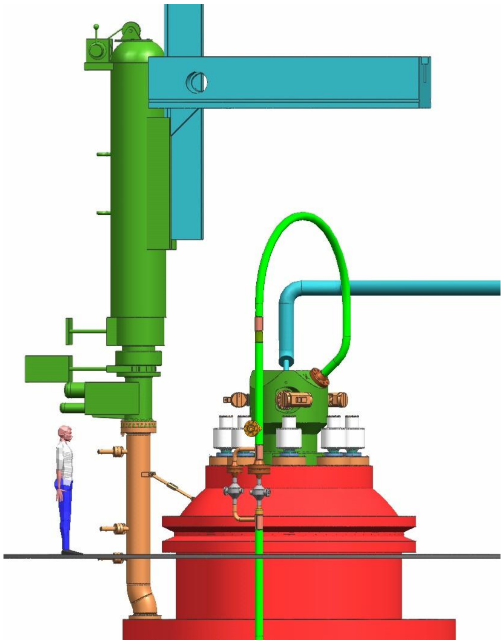


**Figure 83: Control Rod Removal Tool Concept**

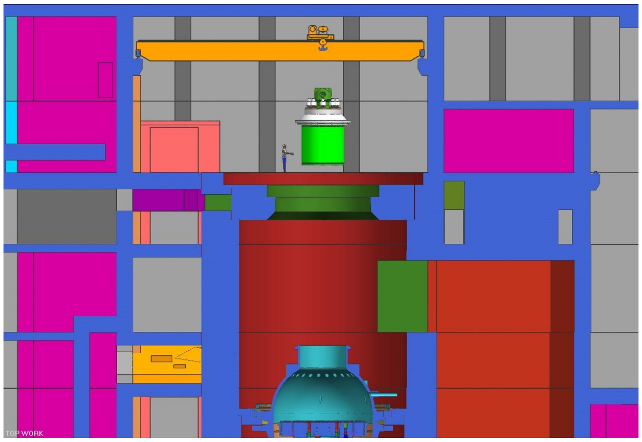


**Figure 84: Reserve Shutdown System Assembly Removal Concept**

### 13.2.2 Fuel Handling and Storage System and High-level Waste Storage

Many of the ST for the FHSS are based on the Thorium High Temperature Reactor (THTR) designs and lessons learned.

The HLW storage facility in the bottom of the module stores the scrap or damaged fuel as extracted by the Core Unloading Devices (CUDs). The ST include scrap fuel collection, transfer and transport machines. Figure 85 shows a high-level waste transport trolley.

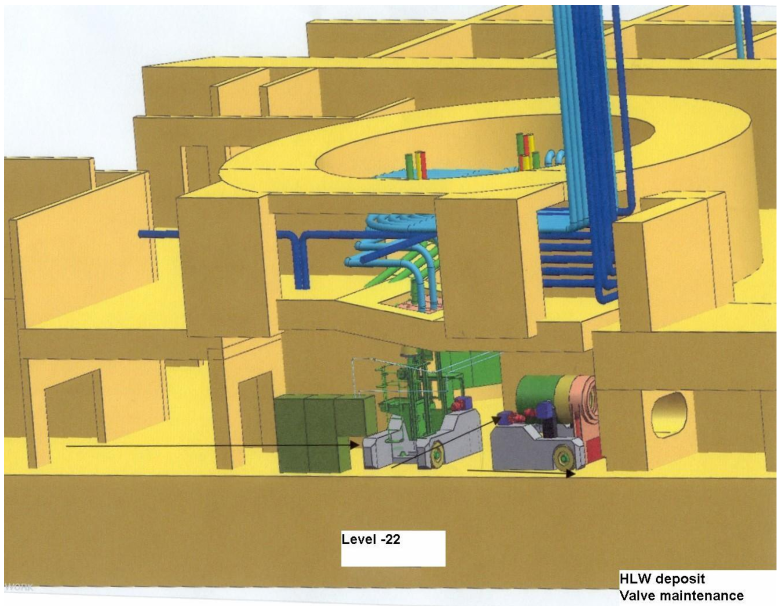



**Figure 85: High-level Waste Handling Equipment**

### 13.2.3 Reactor Cavity Cooling System

The RCCS is designed for life of the plant, thus no scheduled maintenance other than ISI is envisaged. Provision is made in the design for 'as required' inspection and repair of the RCCS. ST will be developed up to the point of having a basic design in place, so that should a repair become necessary, the required equipment can be procured at short notice. As far as possible, 'off-the-shelf' equipment is used.

### 13.2.4 Power Turbine and Compressor

It is anticipated that MHI will supply the necessary special tools required for performing maintenance on the MHI machines (3rd and 4th line). The ST provided on site for the maintenance and removal of the turbo machinery includes stands and cradles for placement, storage of the machines on the laydown floor. Equipment handling infrastructure to install and remove the turbo-machinery is included.

A heavy equipment-handling specialist provides the strand jack gantries as turnkey projects to install and remove the power turbine.

The strand jack equipment-handling gantry is required for initial installation, as well as any removal and replacement of the power turbine during operation.

### 13.2.5 Generator

Tools for the generator (brush replacements, water leak detectors, condensation detectors, coil temperature sensors, rotor lifting attachments, stator lifting attachments) are supplied by MHI.

### 13.2.6 Gas Systems

#### 13.2.6.1 Helium inventory control system

Special Tools (ST) and Equipment Handling Systems (EHSs) are provided for the removal and replacement of the filters, blowers and valves of the Helium Inventory Control System (HICS) and Gas Conditioning Systems (GCSs).

#### 13.2.6.2 Primary loop initial clean-up system

The Primary Loop Initial Clean-up System (PLICS) is situated outside the module, and is not initially exposed to contaminated graphite dust. Thus no ST are envisaged for this SSC. Should contamination of the PLICS heating elements occur during later use, the ST(s) could then be procured at short notice. The possibility of using some of the existing gas system's ST for the PLICS maintenance is being studied.

#### 13.2.6.3 Main power system pressure boundary and gas cycle pipes

Operational ST and EHSs are not provided for construction and installation. PBMR will, however, closely observe the methods and equipment used by the construction specialists.

#### 13.2.6.4 Valves: gas cycle and gas system valves

Specialized casks, trolleys, bagging and removal and replacement equipment are required for the larger valves. Figure 86 shows a typical arrangement for the removal of a large valve situated on the Main Power System Pressure Boundary (MPS-PB).

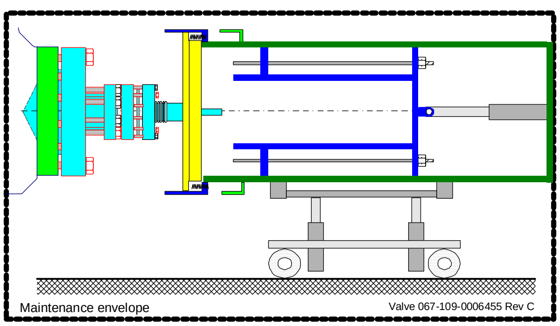



**Figure 86: Typical Valve Extraction Device**

### 13.2.7 Heat Exchangers (Pre-cooler, Intercooler, Recuperator)

The design of the heat exchangers accommodates inspection and repair requirements, such as required for plugging tubes.

It is not planned to replace the heat exchangers during the life of the plant. Should it be necessary for any of the exchangers to be replaced, certain of the civil structure may need to be removed. No provision is made for ST or EHS for heat exchanger replacements.

# 14. MAINTENANCE ON MAJOR EQUIPMENT

The plant's compact layout and the direct cycle configuration imply a unique environment for the removal and replacement of major components. This chapter describes the step-wise preparation and approach to these activities.

## 14.1 POWER CONVERSION UNIT MAINTENANCE

### 14.1.1 Power Conversion Unit Specific Maintenance Preparation

The following preparation is done to ensure that the plant is in such a condition that specific maintenance can be done on the Power Conversion Unit (PCU) internals:

a,b

### 14.1.2 Major Maintenance Tasks on the Power Conversion Unit

#### 14.1.2.1 Remove and replace power turbine

a. Removal and replacement

The removal and replacement procedure is as follows.

**Note:** This is a very preliminary description, as the design of these components has not been done in any form of detail for PBMR to be able to evaluate the feasibility of this removal technique. This document will be updated as soon as this information has been confirmed.

- After the three maintenance valves have been installed and dry clean air has been introduced into the PCU, the two pipes at the bottom of the turbine are uncoupled. This could include the undoing of the seal weld and unbolting of the flanges, and the removal of the sliding section of the pipe, or any other pre-planned means. As this is a double pipe, the inner pipe also needs to be uncoupled, either in a similar fashion, or as it is designed to be removed.

- This removal procedure needs to take into account that no spreading of any contamination inside the building is allowed. Therefore the necessary bagging and shielding technique will be employed during this process.
- Next the oil system is uncoupled, the bearings caps are removed, the rotating components are secured, and the couplings are disconnected. Because there is no coupling to the helium side, this is a conventional action and requires little extra precaution, barring the possible damage to the gas seals which need special attention.
- The turbine is now coupled to the Heavy Lifting Device, which could be a Strand Jack Mechanism or (possibly, but unlikely) a crane.
- The turbine is lifted from its position and as it is lifted the two pipes at the bottom of the turbine are separated in an organized manner, to ensure that there is no release of any contamination products into the surrounding atmosphere.

b. Re-installation

Re-installation of turbo machinery is the reverse of the above. Because the dust was removed from the components, it is easier to replace the turbine. When the coupling to the pipe work is done, care should be taken to prevent any dust inside the pressure boundary from escaping.

After the turbine has been replaced, bolted down and seal welded, the dry air in the PCU is removed by drawing a vacuum in the PCU. The extracted air and helium mixture is removed via the PLICS filters. During this activity, the helium feeding into the RU is shut off and the maintenance valves remain in position. The helium can be allowed to leak from the RU into the PCU volume until a vacuum is drawn over the total volume of both the RU and PCU. The vacuum that is developed is a very low level vacuum, since the maintenance valves cannot withstand a serious vacuum. Once a vacuum has been established, helium is re-introduced into the RU, and a controlled leak of helium into the PCU is again established. This cycle of drawing a vacuum in the PCU and re-introducing helium into the RU is repeated until the allowable level of impurities is achieved in the PCU. It is expected that no more than two cycles will be required.

#### 14.1.2.2 Replacing the generator

The replacement of the generator is a standard procedure which does not call for any special arrangement other than the conventional requirements for the removal and maintenance.

#### 14.1.2.3 Replacing the compressors

The replacement of the compressor set is very similar to the replacement of the turbo-unit. A separate description is not called for, unless the information that forms part of the further development of the compressors proves to be different. It is therefore not described in any detail.

#### 14.1.2.4 Replacing the pre-cooler and intercooler

**Note:** It is not expected to replace the coolers during the life of the plant. They are, however, designed to be replaceable should the need arise. The initial installation of the coolers will verify the requirements for equipment handling and measures to manage the contaminated dust and plate-out of the coolers. Since the pre-cooler and intercooler are identical, the replacement is expected to be similar.

The replacement procedure is as follows:

- The bottom header of the cooler is removed to expose the waterside of the cooler.
- The bolting system, which works on the same principle as the turbine, is removed from the bottom of the cooler.
- This will release the cooler, which can then be removed from the cavity via the top of the HPTU cavity into a double-walled plastic bag, to contain the contaminated dust. If the plate-out on the cooler is significant, it may be required to be placed in a shielding cask.
- The cooler can then be removed to the maintenance area where it can be decontaminated from all loose radioactive dust. This facility can be made into a temporary decontamination plant with the required safety features included in the design.
- The fitting of a new cooler is the reverse of the removal.

#### 14.1.2.5 Replacing the recuperator

**Note 1:** It is not expected to replace the recuperator during the life of the plant. It is, however, designed to be replaceable should the need arise. The initial installation of the recuperator will verify the requirements for equipment handling and measures to manage the contaminated dust and plate-out of the recuperator.

**Note 2:** Because the design of the recuperator has not been finalized, the detail of the replacement has to be verified once the information has become available.

The replacement procedure is as follows:

- The recuperator is opened from the top with a shielding cask in attendance. Many precautions must be taken to prevent any contamination from spreading to any part of the plant, since the recuperators are considered to be the sieve of the plant, with considerable amounts of dust stored. The recuperators are expected to have a very high level of plate-out, making it very difficult to get close to the components. Because the recuperators do not have any moving parts, it is not expected that any maintenance will be conducted on the equipment, and the requirement will probably be that it has to be stored safely inside a cask for safe disposal at a later stage.
- The recuperator assembly ([ ][b]) is removed to the maintenance area where it can be decontaminated from all loose radioactive dust, or where the loose contamination can be solidified, to prevent the spreading of contamination to the air at any point during its lifetime.
- The procedure for the fitting of a new recuperator is the reverse of the removal procedure.

#### 14.1.2.6 Balancing the turbo-units, the power turbine and generator

The Power Turbine (PT) and generator are balanced separately after any work has been done that could significantly disturb the balancing accuracy. Trim balance is done in situ with the use of a Static Frequency Converter (SFC) driving the generator. The trim balancing plane of the assembled unit is close to/on the coupling between the turbine and generator.

## 14.2 GAS CYCLE VALVE MAINTENANCE

Maintenance operations on the Gas Cycle Valves (GCV) are done with the MPS pressure approximately [ ][b] below atmospheric pressure. The procedure is as follows:

- Isolate the valve from the rest of the MPS-PB if possible, and reduce the pressure on the valve to [ ][b] below atmospheric. This is done to prevent a release of contaminated helium to the building atmosphere. As a precaution, the maintenance valves in the gas cycle piping can be closed as described above, depending on the location of the valve that requires replacement. The temperatures of the gas and the surrounding material are to be below [ ][b] before work in the area may commence. The valve body and seat are removed as a unit.
- An enclosure/bag is fitted around the external housing of the valve prior to removal and re-installation. The mass of the valves is such that support is required (a crane and/or a stand) during the removal and installation tasks.
- After re-installation of the valve, it is not expected that the PCU will require flushing/purging prior to helium pressure increase. If there has been a breach in the container or bag whilst removing the valve, and a large quantity of air has entered the PCU, flushing/purging will be required. Otherwise it is considered that the Helium Purification System (HPS) will be able to clean up any air from the system.

## 14.3 REACTIVITY CONTROL AND SHUTDOWN SYSTEM MAINTENANCE

### 14.3.1 Reactivity Control System Maintenance

The maintenance on all the Reactivity Control System (RCS) components inside the RU is done with the reactor at [ ][b] or more below atmospheric pressure. All special tools are designed to allow the minimum air ingress into the reactor. The motor drives (Control Rod Drive Mechanism [CRDM]) are replaced with the pressure inside the reactor at [ ][b] below atmosphere. A special seal has been designed to prevent any leakage of air into the reactor at this pressure.

This paragraph describes the replacement of the following equipment after a failure:

- The chain and/or chain wheel
- The control rod drive motor
- The valve actuator
- The control rod
- The secondary shock absorber

The maintenance on the Control Rod System is done after the reactor has been completely shut down, the pressure of the helium has been lowered to slightly under atmospheric pressure, and the reactor is cooled to a temperature of [ ][b] by using the motored TGS. The CCS is then started to maintain acceptable core temperatures.

Due to shutdown considerations, only one control rod can be maintained at a time.

The following sequence is required for the total removal of a control rod and drive assembly, which is regarded as the most complicated task on the RCS. All other tasks are subsets of these.

- Determine the radiation levels in the area for shielding purposes.
- Ensure that the control rod is in the bottom position.
- Disconnect the electrical and control couplings from the RCS.

- Remove the drive motor housing manually. (Outside the Pressure Boundary [PB]; not activated.)
- Remove the electrical motor manually. (Outside the PB; not activated.)
- Connect the special handling tool to the RCS top structure.
- Connect the interface mechanism to the CRDM housing.
- Place the RCS container that will house the control rod and its assemblies, on the container transport trolley, and connect it to the interface mechanism on the RU top.
- Remove all personnel to a safe platform.
- Use remote control and handling equipment to hoist the CRDM, control rod, chain and/or chain wheel and put this equipment into the container.
- Remove the filled RCS container from the area. Use another container to install the new equipment in the reverse order of removal.
- Special caution is required during the removal of the equipment, due to the potential of streaming of neutrons from the core. A floor especially designed for this purpose is installed over the top of the reactor.
- The RCSS components are removed in a helium environment to ensure minimal ingress of air into the RU.

### 14.3.2 Reserve Shutdown System Maintenance

**Note:** This task description needs to be verified and updated when the information has proved to be stable enough for verification.

The maintenance on all the Reserve Shutdown System (RSS) components inside the RU is done with the reactor at [ ][b] or more below atmospheric pressure. The holding magnet and position indicator coil are replaced with the pressure inside the reactor at [ ][b] below atmospheric pressure.

The maintenance on the RSS is done with the MPS in closed maintenance mode. The pressure of the helium inside the PB is lowered to slightly under atmospheric pressure, and the reactor is cooled and maintained at a temperature of [ ][b], via the motored TGS or the CCS.

Due to shutdown considerations, only one RSS channel can be maintained at any one time.

The following sequence is required for the most complicated task on the RSS. All other tasks are subsets of these.

It is accepted that the Small Absorber Spheres (SAS) have been dropped into the core reflector for major maintenance activities on the plant. If the SAS cannot be inserted due to the failure of the RSS release valve, the actuator vessel will have to be removed with the SAS inside the vessel. Although the probability is extremely low, it can be done, but this will mean that the core may have to be defuelled.

Task description: removal of the RSS valve

- Remove the electrical or control connections.
- Remove the RSS Return Double Seat Isolation Valve (DSIV) actuator and the holding magnet coils. This can be done without breaching the PB.
- Install the RSS Interface Tool, which is similar to the one used for the RCS, but adapted for use on the RSS.
- Loosen the valve actuator assembly bolts.
- Install the valve and valve actuator assembly tool and flush this tool with helium.
- Replace the defective valve and/or the valve actuator.

- Special caution is required during the removal of the equipment, due to the potential of streaming of neutrons from the core. A purpose-designed floor or tool is installed over the top of the reactor.
- Fasten the valve and valve actuator assembly bolts.
- Remove the interface tool.
- Re-install the DSIV valve actuator vessel and holding magnet coils.
- Reconnect the electrical/control connections to the RSS.
- Leak test the system to ensure good sealing of the PB.
- As with the RCS, the RSS components are removed in a helium environment. Minimal air ingress is expected into the RU. It is possible to remove the remaining air from the system via the HPS.

## 14.4 HELIUM INVENTORY CONTROL SYSTEM MAINTENANCE

The Helium Inventory Control System (HICS) is divided into three subsystems:

### 14.4.1 Helium Make-up System

- Replacement of empty bottles. This is an operational task with no radiation risk.
- Replacement and servicing of the compressor. Standard-type compressor with limited radiation risk.

### 14.4.2 Helium Purification System

The HPS is isolated from the PCU during any maintenance activity on the HPS. After the maintenance has been completed, the system is flushed with helium.

a. Replacement of controller

   Standard task with limited radiation risk.

b. Replacement/emptying of large particle size dust cyclone

   Adequate shielding is provided to do this task.

c. Replacement of fine dust filter

   Similar to the above.

d. Replacement of molecular sieve

   The molecular sieve consists of a number of elements, which are regenerated at a regular interval to enable molecular impurities to be removed from the working fluid. The molecular sieve can only be regenerated a limited number of times before it reaches its saturation limit. The individual elements of the sieve must then be replaced. These elements measure 270 mm diameter x 1.5 m long. The removal is into a cask.

e. Replacement of a valve

   The valves that are used in the HPS are standard valves. The maintenance concept is the same as the others.

f. Replacement of blower

   The blower replacement is done in the same manner as the removal of the valves. The motor and blower are removed as a unit for further work in another facility.

### 14.4.3 Inventory Control System

As with the HPS, the Inventory Control System (ICS) can be isolated from the MPS for maintenance purposes. After the maintenance is completed, the system is flushed with helium.

a. Repair of a helium inventory storage tank

   These tanks are designed for life and are not expected to fail. The tanks are inspected in accordance with the requirement of the Occupational Health and Safety Act (OHSA) and applicable code. The OHSA specifies a 36-monthly hydrostatic test at 1.25 times the working pressure or at 1.1 times the working pressure if the medium is a non-flammable gas (such as helium). Small defects on the vessel are repaired in situ. In the event of a tank replacement due to the size of the failure, this can be done, although cumbersome.

b. Replacement of rupture disc

   If a disk has ruptured, the gas escapes to atmosphere via the designated pressure relief routes. Replacement of the rupture disc is done with the tank at sub-atmospheric pressure. Portable shielding is positioned as required.

c. Maintenance of the compressors

   Scheduled tasks on the compressor include replacement of oil, filters (oil and helium), stem seals, valve adjustment, etc. The compressor is isolated from the rest of the system and is repaired with normal commercially available equipment. Most of these maintenance tasks do not breach the Helium Pressure Boundary (HPB) and therefore have a limited risk of contamination of the surrounding area.

d. Maintenance of cooling system

   The system has five coolers as part of the compressor system, each one cooling a particular stage of the compressed helium. The coolers use demineralized water from the Active Cooling System (ACS). Maintenance on these components consists of the exchange of the coolers and plugging of the cooling tubes. A cooler is isolated from the rest of the system and can be replaced using standard tools and equipment.

## 14.5 FUEL HANDLING AND STORAGE SYSTEM MAINTENANCE

The Fuel Handling and Storage System (FHSS) is subdivided into nine subsystems. Many components are common between these subsystems, and the tasks are not considered to be different, except that the working conditions vary between these subsystems. The generic maintenance tasks per type of component are described. Since the FHSS can be isolated from the reactor, all tasks (except for the defuelling machine's maintenance tasks) can be performed under full power conditions.

a. FHSS valve replacement

   Types of valves include double seat isolation valves, gas shut-off valves, flow restrictors, counters, indexers and diverters. These valves all consist of three elements, of which only the configuration of the active part varies. The shaft penetration and the valve drives are identical in all cases.

   A valve is removed using a specially designed valve removal tool that is mounted on a forklift.

b. Defuelling machine

   i. Scrap fuel removal

      **Note:** This task has not been confirmed yet. The maintenance philosophy on this task needs to be confirmed before agreement is reached about the maintenance requirements.

      Undersize and damaged fuel is stored in the scrap collection can of the defuelling machine. This is emptied as soon as the fuel spheres have reached the predetermined level in the can. A vacuum system sucks the spheres from the collection cans and places them in a scrap fuel container. The scrap fuel spheres are removed with a tool similar in layout and working to the one developed for the Thorium High-temperature Reactor (THTR). The broken and damaged spheres are moved to the damaged fuel sphere storage.

ii. Drive mechanism

Replacement of the drive mechanism, the shaft penetration and the complete defuelling machine is possible and uses the design of the THTR's Special Tools (ST).

c. Helium blower system (transportation gas)

The blower is pulled into a cask and transported to the maintenance facility.

As far as preventive maintenance on the blower is concerned, the blower is running on Electromagnetic Bearings (EMBs), and very little preventive maintenance is anticipated.

d. Gas evacuation system (vacuum system)

The vacuum pump is replaced upon failure.

e. Cyclone filter

Servicing consists of tasks such as the removal of the dust cask, when it is full. This task is done with the same tool that removes the scrap fuel spheres from the defuelling machine. The dust is transported in the container and stored in the scrap fuel storage in the building.

## 14.6 REACTOR CORE STRUCTURES MAINTENANCE

The reactor core structure is designed not to require any maintenance or access during normal operation. The only maintenance that will occur during the midlife of the plant is when the side and central reflectors are replaced. Refer to Chapter 13 for a description of the replacement sequence.

# 15. SAFETY FEATURES

The fundamental safety design philosophy as embedded in the PBMR Safety Case, details a number of basic safety philosophies to which the PBMR is designed. It is not always apparent how these principles are applied in the design, and why systems that are available to prevent or mitigate Design Basis Accidents (DBAs) are not necessarily graded and regarded as non-safety-grade defence-in-depth systems. The following paragraphs provide the background to the safety design and logic of the design requirements.

## 15.1 BASIC SAFETY

A basic principle in the design is that the probability is extremely low that during operation the PBMR will require members of the public living at or beyond the exclusion zone to be evacuated, or the implementation of other integration actions, or other mitigating actions. A second principle is that this must be achievable without the need for active systems to take preventive or mitigating action within [ ][a,b] after the event.

These principles are fulfilled by:

- Fuel design
- Heat production
- Heat removal
- Limiting chemical attack on fuel and core structures

### 15.1.1 Safety Interaction

The fuel that forms the basis of the PBMR design has been shown to have excellent fission product retaining properties up to temperatures well above 1 600 °C. The basic function of the design of the PBMR shall be to ensure that this temperature range is not exceeded by a significant fraction of the fuel during any DBA or Beyond Design Basis Accident (BDBA), using deterministic analysis with conservative assumptions for the determination of this fuel temperature.

a. Design characteristics

   The following design characteristics form the basis for complying with this demand:

   Decay heat resulting from the operation of the Power Plant (PP) must be transferred by simple natural means that do not require the operation of any active components needing a power supply or the movement of pneumatically or otherwise operated valves. This is accomplished as follows:

   i. The core is designed to have a large surface-to-volume ratio for efficient heat transport to the heat sink external to the Reactor Pressure Vessel (RPV).
   ii. The materials in the heat transport path are safety classified. A high confidence level in the validation of the heat transfer analysis can therefore be assumed.
   iii. The heat sink of the Reactor Cavity Cooling System (RCCS) provides a large passive heat sink with sufficient capacity to remove all residual heat for a number of days without any active operator intervention.
   iv. The absence of water in the RCCS shall not lead to excessive fuel or RPV temperatures.
   v. The decay heat source is limited by limiting the reactor power level.
   vi. Active cooling of the core by available systems will always be the primary goal during normal operation and in upset conditions, but there shall be no need for any active systems to ensure that the fuel temperatures are kept within the proven safe range.

vii. Any increase in fuel temperature, whether intentional or unintentional, that exceeds the safe operating regime, shall be limited by the inherent negative feedback of the core and the rest of the core such that no significant power excursions can result.

b. Systems are safety graded

The systems that assist in the passive safety of the reactor are as follows:

i. The materials of the core and core structures that play a significant role in the heat transport during upset conditions.

ii. The core structures and the RPV properties that ensure the maintenance of core geometry shall be safety graded to the effect that they may not deform for any identifiable event such that core geometry is disturbed enough to cause a significant rearrangement of the fuel spheres, leading to a reactivity increase exceeding the specified limits.

iii. The RCCS (except the active components) shall be safety graded mainly to protect the civil structures from overheating. The consequence is that the system shall be redundant and that the reactor power shall be reduced to a predetermined level if a part of the RCCS is unavailable. (Note that it may be safer to keep operating normally in a low power mode than to stop the reactor and rely on auxiliary cooling systems.)

iv. Despite the fact that any reactivity addition leading to an overpower condition is automatically countered by the core negative reactivity feedback, the Reactor Protection System (RPS) and the associated control rods are to be safety graded to ensure prompt insertion of the control rods should an overpower condition be detected.

### 15.1.2 Fuel

Although maximum fuel temperatures for excursions without active cooling will not exceed the design limits, it is obvious that the operating system should endeavour to keep the core at normal operating temperatures at all times, including upset conditions. Should normal cooling by Brayton cycle be lost, alternative systems, in particular the motoring of the Turbo-generator Set (TGS) and the Core Conditioning System (CCS), can be brought into operation. This is regarded as a defence-in-depth measure to ensure that there is no unnecessary challenge to the safety-graded heat removal path. It is thus not regarded as necessary to classify the systems used to actively remove core heat in the shutdown condition as safety related.

The design philosophy expressed above is valid as long as the fuel behaves in line with previous experience. This is to be ensured by rigorous Quality Assurance (QA) to be applied in manufacturing, and a supporting fuel qualification programme to test fuel under expected operating and maximum upset events conditions. Such tests were performed in Germany and the USA on a range of different fuels (High Enriched Uranium [HEU], Low Enriched Uranium [LEU], $ThO_2$, UC, $UO_2$) for BISO and TRISO fuels. These tests showed excellent fission product retention properties to well beyond 1 600 °C. Serious degradation of the retention capabilities only starts to appear for temperatures exceeding 2 000 °C, showing that there is no sudden transition temperature (cliff edge) where the fuel will fail disastrously.

The maximum fuel temperature in a Depressurized Loss of Forced Cooling (DLOFC) event with only the RCCS operating is influenced by the following factors:

a. The operating power level for the 6 h prior to the event.

b. The power distribution in the core, as the hottest fuel elements will be nearly fresh fuel at the position of the power peak. These fuel elements also contain the least amount of fission product, and therefore have a low level of internal stress from gaseous fission products. Only particles with defects are expected to release part of the fission product inventory.

c. The heat conducting properties of the core and core structures play an important role. The main contributors are the pebble bed and the graphite reflector thermal conductivity. The reflector thermal conductivity reduces under the influence of fast neutron radiation. The thermal conductivity quickly reaches an intermediate stable value after a few years of irradiation. Later on there is another sudden decrease in thermal conductivity. The end of life value is defined at the onset of this decrease. The expected end of life value is used in the analysis. Any change in this value will affect the conducting property and the maximum fuel temperature. Lesser effects are due to the emissivity of the core barrel and RPV.

d. The temperature of the centre reflector has a noticeable effect on the fuel temperature, because a cold centre reflector with a high heat capacity helps to absorb the initially high decay heat production, and thus depresses the final maximum temperature reached.

The maximum fuel temperatures follow roughly the power distribution before the event, and there is thus a distribution of fuel temperatures with only a small percentage attaining the maximum predicted temperature. Only fuel spheres whose maximum temperature exceed 1 200 °C for any length of time contribute measurably to the total additional release of fission products in a heat-up event[1]. Analysis has shown that for all High-temperature Reactors (HTR), this type of event provides the dominant source term for public exposure, and the main safety emphasis in the design is thus geared towards ensuring that the fuel temperatures remain within tolerable limits for Design Basis Accidents (DBAs), and credible Beyond Design Basis Accidents (BDBAs).

### 15.1.3 Heat Production

From the foregoing discussion, it is clear that fuel temperatures can be kept within limits by ensuring that heat production is regulated and limited, and that the heat removal path can transport the heat in a guaranteed manner. The heat production in upset situations is dependent on the residual heat in the core (decay heat as well as stored heat), which in turn is dependent on the operating power level. A second effect could be the addition of reactivity leading to a power excursion, but tests have shown that the coated particle fuel stays intact up to an energy deposition rate far exceeding anything the PBMR could induce by reactivity insertion exceeding the design base. Thus the decay heat resulting from power operation is the only energy source to be considered in the safety design analysis of the PBMR Demonstration Power Plant (DPP).

The maximum power level for the PBMR is to a large extent determined by the level of decay heat that can be tolerated in the case of a DLOFC. The power level is controlled by the Operational Control System (OCS) based on the neutron count rate in the RPS power range channels, and is set not to exceed 105% of maximum rated power. If this power level is exceeded, the RPS will scram the reactor. Additionally, there is a power integrator that monitors the cumulative power output for the previous 6 h and generates an alarm, and thereafter a scram, if that average exceeds the equivalent of 103% of full power. These limitations are included to ensure that in the case of a depressurization event, the decay heat will not exceed the levels used in the safety analysis. *It is to be noted that failure of the system to scram will not, by itself, constitute an event of any consequence, as any danger to personnel or public can only result if it is followed by a loss of coolant event without active core cooling.*

1 **Note:** [

]a

It is thus clear that control of heat production is in actual effect a defence-in-depth measure that serves to prevent the occurrence of initial conditions which, in the case of a DBA, could lead to consequences in excess of those postulated in the Safety Analysis Report (SAR).

### 15.1.4 Heat Removal

The heat removal process is as follows:

- Heat removal during normal operation is provided by the Brayton cycle, whereby nuclear heat is transported away from the core and converted to electricity and waste heat.
- In the case where the Brayton cycle is halted by design or through a fault, the cooling is automatically taken over by motoring the TGS using the same circuit as the Brayton cycle.
- The motoring of the TGS is put into operation by the OCS in response to signals that the Brayton cycle has collapsed, or is stopped by the OCS itself in response to the detection of fault conditions.
- The OCS will automatically reduce the reactor power to a level commensurate with the heat removal capability of the motored TGS.
- A specific failure to be expected is a leak in either the pre-cooler or intercooler, and the system layout is such that the faulty cooler can be isolated and cooling with the motored TGS can continue with the remaining cooler, provided the helium inventory left allows sufficient pressure to be attained.
- It is expected that isolation valves in the water circuit will not be perfectly gas tight, and that continued leakage through these valves will slowly depressurize the Main Power System (MPS).
- However, with the reactor shut down, the decay heat produced will steadily decline, and even if no further cooling by motoring the TGS or by the Core Barrel Conditioning System (CBCS) or the CCS is possible, the ultimate core heat up will be considerably less than if the leak was not isolated.
- In the event where the motoring of the TGS is also unavailable because of the nature of the initial fault, the CCS will be brought into operation by the OCS or the reactor operator.
- The CBCS will continue to operate and remove heat from the reactor by cooling the core barrel, independent of the operation of the motored TGS or CCS.
- The CCS circulates helium through the core and removes it through a separate circuit that can be coupled to the cooling towers and be driven by power from the diesel generators.
- Again, as in the case for the motoring of the TGS, the main purpose is to prevent the system from reverting to a cooling mode by the RCCS alone, and so prevent any heat-up of fuel and core structures. This enables a relatively fast return to normal conditions, provided the Power Conversion Unit (PCU) is available.
- The CCS is able to remove core heat at atmospheric pressure, and even if helium continues to be lost from the system through an unisolatable leak, cooling can continue with the remaining coolant that can be augmented from the helium inventory through a slow-feed system allowing a slight overpressure to be maintained.
- It is estimated that under these conditions, the cooling can be maintained for several days before the helium supply is exhausted.

- Such cooling will only be stopped if there is a real danger that air can enter the core through the breech in the helium pressure boundary.
- Analyses will be performed to estimate the resulting core heat-up should CCS cooling be lost after a certain elapsed time, but it is certain to be less than the design base analysis, where only RCCS cooling is assumed.
- In this case as well, the use of the CCS is a proactive measure to prevent the condition where cooling through passive means is the only remaining means left for cooling the core.

The only passive systems that are relied upon to limit fuel and RPV temperatures to within the allowable limits and are to be regarded as safety relevant, are those that form part of the passive heat transport system from the core to the environment. These are:

a. The fuel itself
b. The core structures
c. The RPV
d. The RCCS, including the components that allow boil-off if active cooling is unavailable within the first heat-up period. Note that the main function of the RCCS is to protect the concrete from excessive temperatures (investment protection).

## 15.2 SAFETY DESIGN SPECIFICATION

### 15.2.1 Fuel

The fuel for the PBMR will be supplied by a third party supplier. In order that fuel of a high quality is produced, the supplier has to show that established manufacturing methods that consistently produce high quality fuel are used. In effect, this means that the fuel shall be manufactured according to the prescriptions used in manufacturing the fuel used for the proof tests for the HTR-Modul. In order to show that the fuel matches the specifications for quality and burn-up, a fuel test qualification programme will be performed. The PBMR design assumes that the fuel will meet the set targets, and the design and safety analysis is based on that presumption.

### 15.2.2 Heat Production

Heat production is a function of core design and operation. The core performance requirements and design parameters for safety design are given in Table 41 and Table 42.

**Table 41: Core Performance Requirements**

| Description | Unit | Value |
|---|---|---|
| Core thermal power – design goal | MWt | 400 |
| Maximum fuel temperature under normal operating conditions (bypass flows included) | °C | 1 130 |
| Load follow capability (xenon override) | % power | 100 – 40 – 100 |
| Maximum power production per fuel sphere (pebble) | kW | 4.5 |
| Reactivity shutdown margin at 100 °C (only Reserve Shutdown System (RSS) | %Δk | ≥ 1 |
| Average fuel residence time | days | 927.9 |
| Target burn-up per fuel sphere (pebble) | GWd/t | ~92 |

**Table 42: General Design Parameters**

| Design Parameters | Unit | Value |
|---|---|---|
| Fuelling regime | | Multiple pass > (6x) |
| Fuel (equilibrium core) | | LEU (9.6% U-235) |
| Number of fuelling points | | 3 |
| Number of defuelling points | | 3 |
| Pebble bed packing fraction | | 0.61 (average)* |

**Note*:** This value will be verified for the PBMR core geometry by the use of test facilities

Within these given values, the core design is such that the following mandated parameters are not exceeded:

1. At any point in the operating life of the plant, the reactor must be able to be shut down fast, using the control rods followed by the shutdown rods.
2. At any given time in the history of operation, it must be shown that the reactor can be brought to a cold shutdown condition (100 °C) using the RSS only.
3. During normal operation, no fuel spheres may exceed a power level of 4.5 kW (based on analysis).
4. For a postulated event with loss of coolant and cooling only by the RCCS, the maximum fuel temperature must be passively limited to a level that will ensure that the release of radioactivity at the site boundary is within the allowable limits.
5. For a postulated event without active core cooling, the core barrel and the RPV temperatures may not exceed values that can lead to plastic deformation and the possible loss of guaranteed core geometry.
6. In order to keep the releases of fission products during normal operation in line with ALARA (As Low As Reasonably Achievable) principles, the maximum normal operating temperature of the fuel shall not exceed 1 130 °C.
7. The excess reactivity available in either the control system or from plausible upset events must be such that any addition of this reactivity may not lead to short-term fuel temperatures outside the experimentally documented maximum allowable values.
8. Enough excess reactivity must be available during normal operation to allow load following manoeuvres to take place from 100% Maximum Continuous Rating (MCR) to 40% MCR and back without having to change coolant outlet temperatures.

### 15.2.3 Heat Removal

#### 15.2.3.1 Core structures design

The core structures design is such that:

a. During normal operation, the heat produced by the reactor core can is removed by forced cooling without exceeding the temperature limit of 1 130 °C.
b. In the case of an event that results in loss of active core cooling, the maximum fuel temperature is passively limited to a level that will ensure that the release of radioactivity at the site boundary is within the allowable limits.
c. In the case of a pressurized loss of forced cooling, the natural circulation is able to limit core temperatures to values whereby the maximum fuel temperature is kept < 1 300 °C.

d. In the depressurized case, the heat transport path is from the fuel in the core to the reactor cavity, and this heat path is guaranteed by an appropriate choice of materials and dimensions to prevent any fuel exceeding the temperatures as defined previously.

e. As a defence-in-depth measure, the availability of active cooling, even in depressurized conditions, has a high probability of being available and effective.

#### 15.2.3.2 Reactor cavity cooling system

The function of the RCCS is to receive the waste heat from the RPV and transport it away from the Reactor Cavity (RC). Only the passive mode of operation of the RCCS is a safety-classified function. The active mode is considered a defence-in-depth measure. The following requirements are made of the RCCS:

a. The RCCS is able to receive the full amount of decay heat present in the reactor to a value averaged over the first 10 h after shutdown.

b. The RCCS remains operable in the active or passive mode for at least three days after any event without operator action.

c. In the passive mode, the RCCS rejects the heat to the environment by boiling off water contained in the system. There is sufficient water in the system to allow boil-off to proceed to a level in the tanks corresponding to the top of the active core.

d. The primary function of the active operation of the RCCS is to prevent degradation of the concrete walls of the RC by limiting the wall temperature to < 65 °C.

### 15.2.4 Protection against Chemical Attack

The MPS as well as other systems that can provide a path for air to enter the core shall be designed with the following in mind:

a. Where possible, there shall be isolation valves between the reactor core and other systems, so that a leak in the MPS and auxiliary systems can be isolated to prevent air ingress and keep helium in the core.

b. Where it is not possible to use isolation valves, alternative means shall be used to isolate the core from the rest of the system after a depressurization event.

c. The number of penetrations of the RPV above the lower level of the core is limited by design to a minimum.

### 15.2.5 Containment of Radioactive Materials

#### 15.2.5.1 Conservative design

As all the gaseous coolant will be contaminated by the inclusion of atomic or dust-bound fission and activation products, the design of systems containing coolant needs to be such that there is a low probability of leaks appearing in these systems. The design of coolant containing systems is thus conservative, and possible pathways for leaks are minimized. The coolant system acts as a barrier to the release of fission products released from the fuel.

#### 15.2.5.2 Breach of containment

a. In the event of a breach of the Helium Pressure Boundary (HPB), the building acts as a tertiary barrier to the release of radioactive material to the environment.

b. The building includes a containment system that will be able to withstand a pressure pulse caused by a defined size pressure boundary breach, and shall be able to filter small leaks to remove fission products.

c. In the event of a medium break, the containment system vents the pressure pulse and it can reclose the containment system possible filtration of any further radioactive material releases.

d. The vent path for design base breaks is above the roof height to ensure proper dispersion of the radioactive material released.

### 15.2.6 Personnel Protection

In order to prevent undue exposure of plant personnel, the design provides for adequate shielding of and around Structures, Systems and Components (SSC) that need to be maintained during operation. No components that need to be maintained with the reactor at power are placed in the RC. All maintenance tasks will be identified before the design is finalized, so that the ALARA principle can be applied in the design for ease of maintenance and identification of special tools that may be needed.

# 16. INTERFACES OF THE DEMONSTRATION POWER PLANT ON THE KOEBERG SITE

The following interfaces have an influence on the design and configuration of the PBMR Demonstration Power Plant (DPP).

## 16.1 [WITHHELD ON THE BASIS OF IT BEING "SECURITY-RELATED INFORMATION"]

## 16.2 [WITHHELD ON THE BASIS OF IT BEING "SECURITY-RELATED INFORMATION"]

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## 16.3 [WITHHELD ON THE BASIS OF IT BEING "SECURITY-RELATED INFORMATION"]

## 16.4 [WITHHELD ON THE BASIS OF IT BEING "SECURITY-RELATED INFORMATION"]

## 16.5 LIGHTING OF THE SITE

Lighting needed to illuminate access routes into and out of the Reactor, Services and Auxiliary Buildings is attached to the buildings.

## 16.6 VISITORS' CENTRE

The Services Building boardroom is equipped for the purposes of marketing the PBMR to potential clients and the handling of other VIPs. The existing Visitors' Centre for the KNPS is also capable of hosting visitors.

## 16.7 TRAINING SIMULATOR

Control room simulator training is performed in a facility separate from the Services Building and demonstration plant control room. The actual location of a training simulator has not yet been decided.

## 16.8 [WITHHELD ON THE BASIS OF IT BEING "SECURITY-RELATED INFORMATION"]

## 16.9 [WITHHELD ON THE BASIS OF IT BEING "SECURITY-RELATED INFORMATION"]

## 16.10 [WITHHELD ON THE BASIS OF IT BEING "SECURITY-RELATED INFORMATION"]

## 16.11 [WITHHELD ON THE BASIS OF IT BEING "SECURITY-RELATED INFORMATION"]

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## 16.12 SEWAGE

The sewage system for the PBMR is designed to cater for the PBMR Demonstration Power Plant (DPP) requirements as defined during the construction, operating and maintenance periods. The system flows into the existing KNPS sewer network at the pump station located to the south west of the KNPS.

The KNPS has indicated that the existing sewer system will have to be upgraded to handle the additional flow.

## 16.13 MONITORING BOREHOLES

In accordance with the recommendations of the Environmental Management Plan (EMP), boreholes for monitoring of ground water quality should be installed before construction of the PBMR DPP commences. The locality of the boreholes is determined by the site-specific geological and geohydrological information.

## 16.14 HEALTH PHYSICS/RADIATION MEDICINE SERVICES

The use of the KNPS services for the management of radiation exposure has been agreed in principle. These services specifically refer to Whole Body dose measurement and the provision of on-site emergency radiation treatment.

## 16.15 EMERGENCY PLAN

The emergency plan for the PBMR DPP, during both the construction and operation phases, will include for an appropriate level of integration with the licensed emergency plan at the KNPS site.