18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18- S02-2

PBMR REACTOR DESIGN AND DEVELOPMENT

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ABSTRACT

The PBMR reactor is the first pebble bed reactor that will be utilised in a high temperature direct Brayton cycle. This leads to a number of unique challenges. The impact of these challenges on the structural design of the reactor and its subsystems are discussed. The reactor design and especially the design of the Core Structures are described. This design description covers the functional requirements, structural arrangement and features of these subsystems and their components. The design of the reactor results in components utilizing design codes and materials that are currently available.

Keywords: PBMR, Core Structures, graphite, pebble bed

1. INTRODUCTION

A 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. This conversion takes place in the Main Power System, and utilizes a recuperative Brayton cycle with helium as the working fluid. A schematic layout of the cycle is shown in Figure 1.

The primary function of the reactor is to generate heat. This is performed by sustaining a fission chain reaction in the core. This fission chain reaction results in the production of fission products in the fuel. The safety functions of the reactor are all centred on keeping the release of these fission products from the fuel as low as possible. In the PBMR reactor this is achieved through protecting the fuel by ensuring safe shutdown of the reactor and the ability to remove the decay heat during all normal operating and accident conditions. The PBMR reactor is able to meet these requirements in a natural and passive way by relying only on gravity, conduction, convection and thermal radiation.

The PBMR reactor is based on the high-temperature gas-cooled reactor technology which was originally developed in Germany. This includes 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.

The rest of this paper will give an overview of the components and systems in the reactor followed by more detailed discussions of the most important structural components such as the Core Structures, Reactivity Control System, Reserve Shutdown System and the Reactor Pressure Vessel.

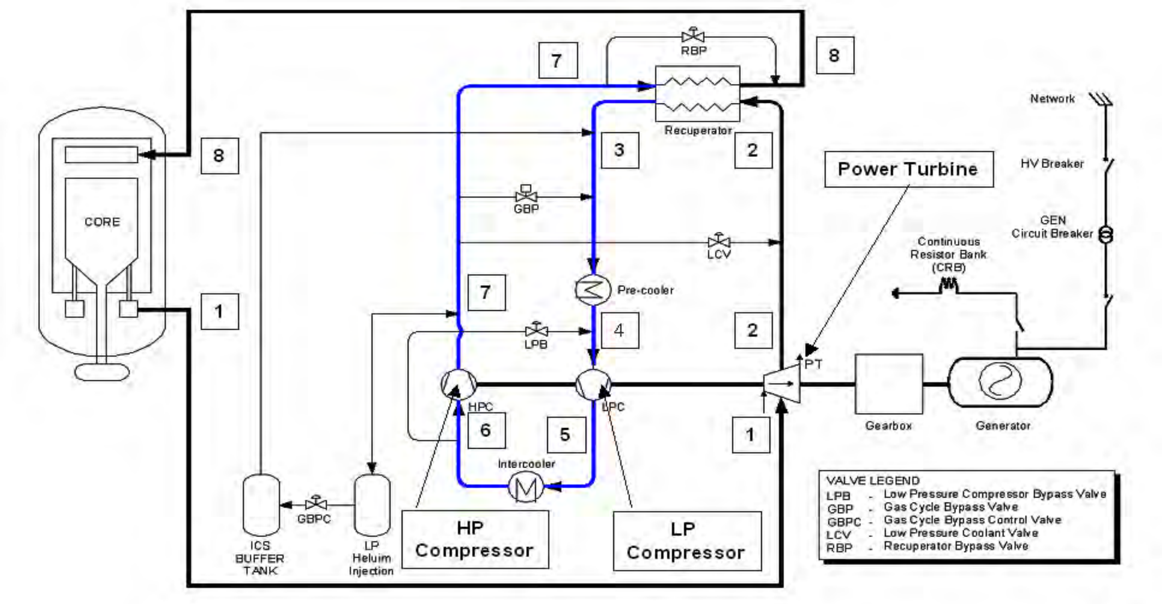

Figure 1: Layout of the PBMR Recuperative Brayton Cycle

2. REACTOR DESCRIPTION

The Reactor Unit (RU) (Figure 2) consists of the fuel, the Core Structures (CS), the Reactivity Control System (RCS) and the Reserve Shutdown System (RSS), all contained inside the Reactor Pressure Vessel (RPV). The core of the RU consists of an annulus filled with 60 mm fuel spheres. The volume of the annulus is large enough to ensure a low power density (~5MW/m^3), and combined with the large heat capacitance of the RU results in the ability to survive a depressurized loss of forced cooling accident. The aspect ratio of the RU resembles a tall and slender cylinder to optimise the heat transfer area to pebble bed width to enhance the passive heat transfer path whilst keeping the fuel and component temperatures within limits. The passive heat transfer path transports heat away from the fuel to the environment beyond the RPV. The efficiency of this heat transfer path allows the RU to survive a depressurized loss of forced cooling without exceeding any of the component temperature limits, resulting in a design that does not require coolant to remove decay heat from the fuel.

The fuel spheres are continuously recycled through the core and discarded when they have reached their burnup target. This results in constant power and temperature profiles in the core once an equilibrium core has been established. This equilibrium core represents the conditions that the reactor will experience for the majority of the design life. Under this scheme, each fuel sphere is recycled through the core an average of six times. The parameters of the reactor are given in Table 1.

Table 1: Reactor Unit Parameters

Parameter	PBMR
Reactor thermal power	400 MW
Coolant	Helium
Reactor inlet temperature	500 °C
Reactor outlet temperature	900 °C

Parameter	PBMR
Mass flow rate	192 kg/s
System operating pressure	9 MPa
Pressure Vessel	Steel
Reactivity Control System	24 control rods in the side reflector
Reserve Shutdown System	8 channels in the centre reflector filled with absorber spheres
Coolant flow direction	Downwards
Pebble bed inner diameter	2.0 m
Pebble bed outer diameter	3.7 m
Pebble bed height	11.0 m
Volume of pebble bed	~84 m^3
Number of fuel spheres	~452 000
Design life	35 Full Power Years
Fuel Burnup Target	92 000 MWd/tU

The fuel is based on proven TRISO-coated fuel particles with Low Enriched Uranium (LEU) dioxide as developed for the HTR-Modul reactor (Reutler, 1982). TRISO fuel was extensively used in the AVR reactor (Bäumer, 1990) as well as many other test facilities over a large range of temperatures, neutron fluences and burnups. The overall coated particle is approximately 1 mm in diameter. The fuel particles are moulded into 50 mm diameter graphite spheres, each containing approximately 14 500 coated particles. This 50 mm graphite sphere is then surrounded in a further 5 mm thick, fuel free, graphite layer resulting in a overall fuel sphere of 60 mm diameter. The fuel spheres are contained in an annular core volume shaped and supported by the graphite reflectors of the CS.

The main components of the CS are the metallic Core Barrel Assembly (CBA) and the Core Structure Ceramics (CSC). The CSC includes the reflectors that are grouped into the top-, centre-, side- and bottom reflectors. The basic structural material of the reflectors is purified graphite machined in the form of wedge shaped blocks. The graphite blocks are stacked in vertical columns and supported by the CBA. The CBA is a steel cylindrical shell that is located and supported within the steel RPV. The inlet and outlet pipes to and from the RU connect through core connections to the CSC from where the gas flows through the pebble bed from the top to the bottom.

The flow scheme in the RU receives gas from the compressor via the two Core Inlet Pipes where it flows into an inlet plenum. The gas then gets distributed in riser channels in the side reflector that transports it up to the top of the pebble bed. The gas then flows down through the pebble bed where it is heated and through the bottom reflector until it gets collected in the outlet plenum and transported back to the turbine through the Core Outlet Pipe. This flow scheme keeps the hot gas inside the graphite at all time, thereby protecting the metallic components of the CBA and RPV from the high temperature gas.

Reactivity control and shutdown of the core is accomplished by the RCS, with the RSS providing a diverse backup system for long term shutdown of the core. The RCS consists of 24 rods containing B_4C as neutron absorber that can be raised or lowered in channels in the Side Reflector. The RSS can insert small graphite spheres containing B_4C in to channels in the Centre Reflector, adding enough neutron absorption to keep the reactor subcritical at cold conditions (100°C and Xenon free core). Both the RCS and RSS are designed to be fail to safe systems, by inserting their respective neutron absorbers into the core under gravity alone, even if all the power falls away.

A schematic horizontal and vertical cross-section through the reactor unit is shown in Figure 3 and Figure 4 respectively.

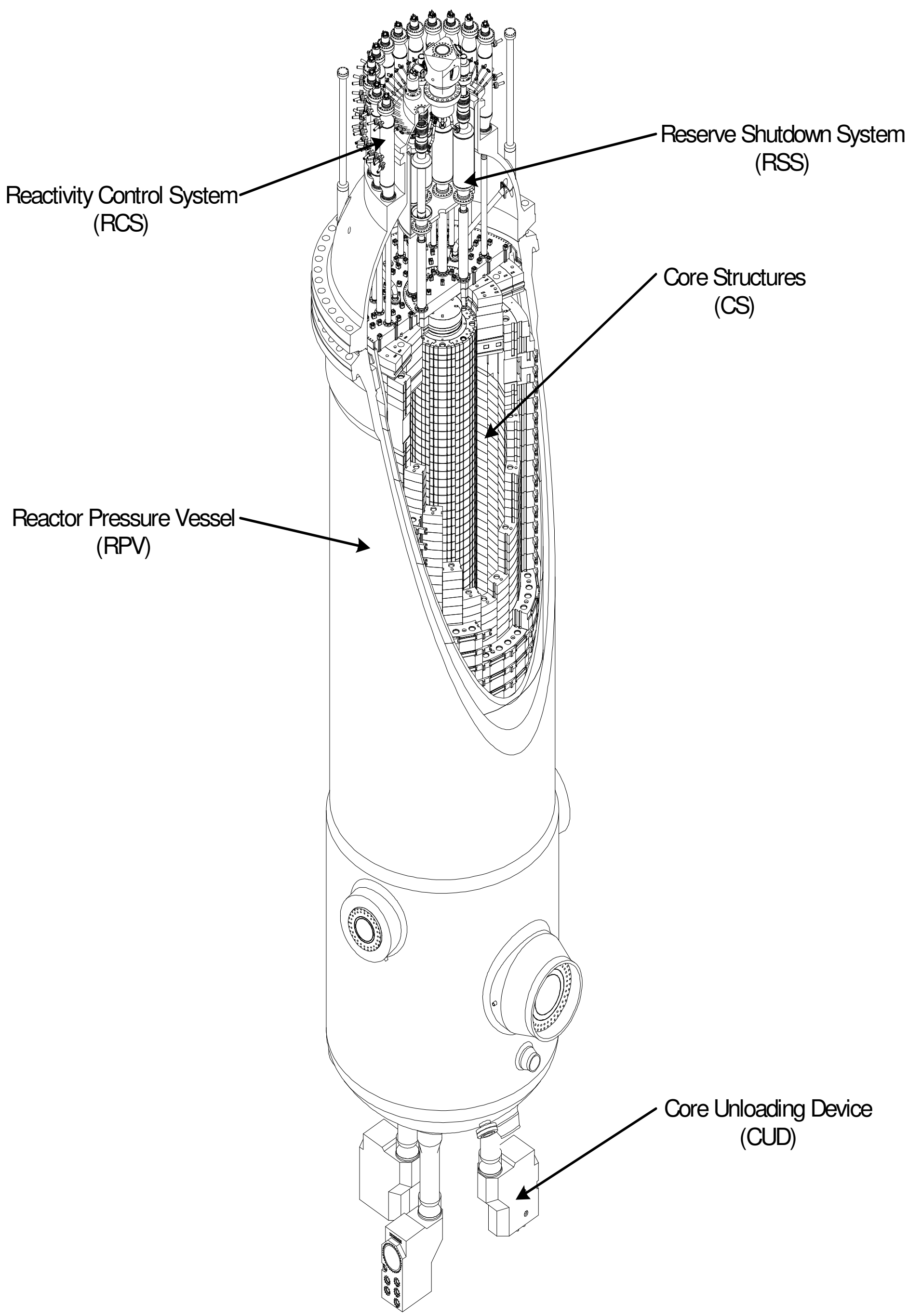

Figure 2: General Arrangement of the Reactor Unit inside the Reactor Pressure Vessel

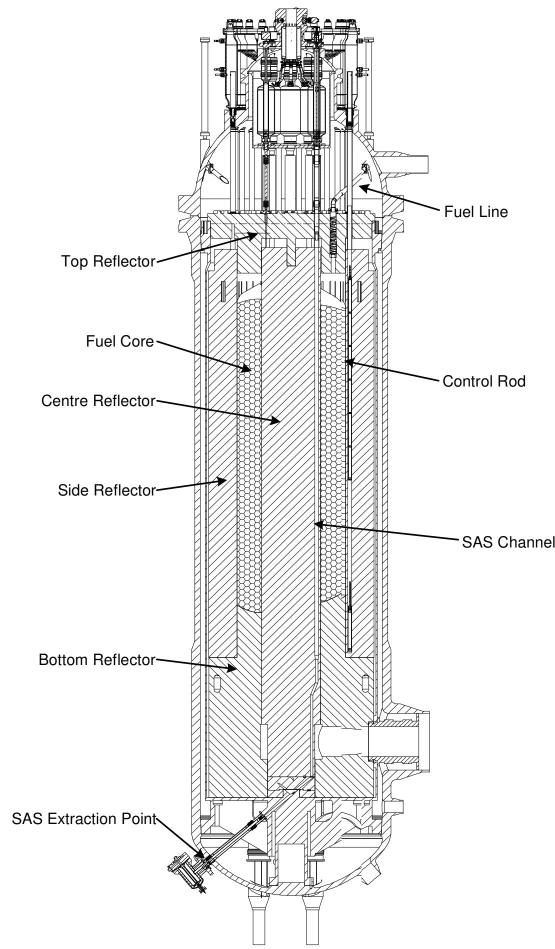

Figure 3: Vertical Schematic Section through the Reactor Unit

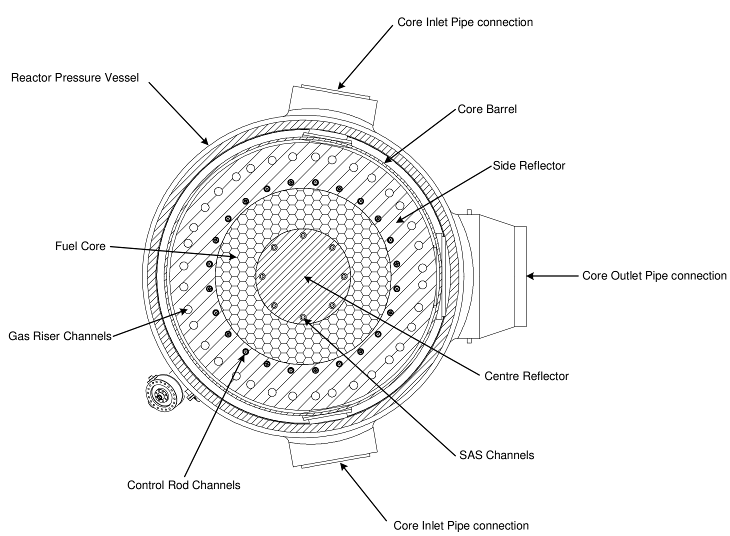

Figure 4: Horizontal Schematic Section through the Reactor Unit

3. CORE STRUCTURES DESCRIPTION

The Core Structures (CS) are the structural components within the RU that define and maintains a stable pebble bed geometry. The CS consists of two major assemblies – the Core Structure Ceramics (CSC) and the Core Barrel Assembly (CBA). All of the major components are shown on the layout drawing in Figure 5 and a summary of the key parameters of the CS design is described in Table 2.

Table 2: Geometric Specifications for the Core Structures

Description	Unit	Value
Side Reflector outer diameter	m	5.5
Side Reflector inner diameter (pebble bed outer diameter)	m	3.7
Centre Reflector diameter (pebble bed inner diameter)	m	2.0
Angle of defuel cones in bottom reflector	degrees	45
Number of fuel loading positions		3
Number of fuel discharge tubes		3
Discharge tubes inner diameter	m	0.51
Approximate overall height of core barrel	m	23.1
Inner diameter of the core barrel sides	m	5.75
Wall thickness of the core barrel sides	m	0.05

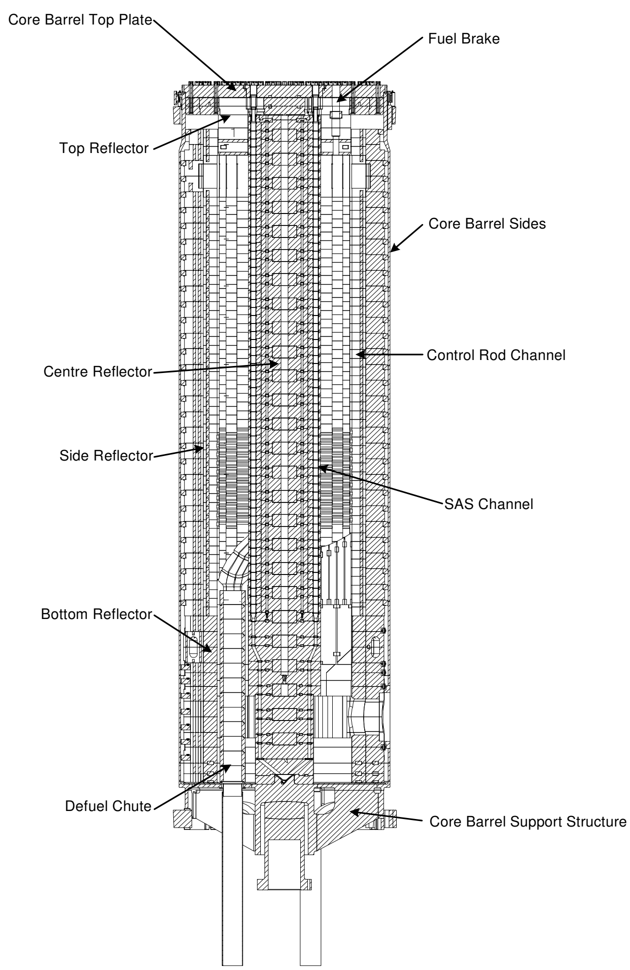

Figure 5: General Arrangement of the Core Structures

3.1 Core Structure Ceramics Description

The CSC is manufactured from individual graphite blocks. These blocks are arranged and interconnected so that they perform the required structural functions. The CSC is divided into the Bottom Reflector (BR), the Side Reflector (SR), the Centre Reflector (CR) and the Top Reflector (TR). The general arrangement and design principles that form the basis for the design of the CSC are based on the German designs for the THTR (HRB, 1985) and later reactors. The graphite structures are designed in accordance with the limits in the draft KTA 3232 '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.

The main functions of the CSC are to:

- Form and support the annular pebble bed through the reflectors (SR, BR, CR). The mechanical loads due to dead weight, lateral loading due to the pebble bed, seismic loadings and the pressure drops established in the core are borne by the CSC and transmitted to the CBA.
- Permit the circulation of fuel through the core by providing sphere inlets in the TR, the geometry of the top surface of the BR and the provision of three defuel chutes.
- Provide neutron reflection while protecting the metallic components from exposure to high neutron fluence levels with the BR, SR and TR.
- Provide a passive heat transfer path between the fuel and the Core Barrel.
- Allow the insertion of the neutron absorbers from the RCS and RSS into the core by providing channels in the SR and CR.

The Bottom reflector is constructed on the Core Barrel Base Plate. The bottom reflector is supported by the thermal expansion compensator manufactured from CFRC to compensate for the difference in thermal expansion between the steel and graphite components. This construction forms the base of the CS by supporting both the side and centre reflectors as well as the fuel core. The stability and the exact location of the bottom reflector are essential for this requirement. The two outermost columns of BR blocks are provided with sealing keys, manufactured to tight tolerances, to ensure that the leak flow between the inlet and outlet in the core is limited.

The first layer of blocks in the BR is manufactured from a solid insulation material. This is required to protect the Core Barrel Support Structure from the high temperature of the core outlet gas. Above this layer, there are the layers of graphite blocks that form the floor of the core outlet plenum. The core outlet plenum is provided to ensure that the outlet gas is collected and channelled to the outlet duct. The BR above the outlet plenum has slots between the blocks. These slots are required to provide for the flow of the outlet gas from the core to the outlet plenum.

The top layer of the BR blocks is shaped to provide the required outlet geometry for sphere flow (see Figure 6). The geometry selected is based on three cones with an angle of 45^{o}, centred on the three defuel chutes with steps between the blocks to avoid capturing spheres. The blocks forming the entrance to the defuel chute are provided with an additional blend to improve the movement of spheres through the core. This geometry ensures that the flow of spheres through the core is reliable, and that the residence time of the spheres within the core is within acceptable limits. The 510 mm diameter defuel chutes are located in the centre of the fuel annulus and equi-spaced circumferentially at a pitch of 120° whilst the diameter of the chutes is selected to ensure that no sphere blockage will occur. The defuel chute further isolates the spheres from loading within the BR by lining each chute with a graphite liner. This separates the movement of the bottom reflector from the expansion of the fuel in the chutes.

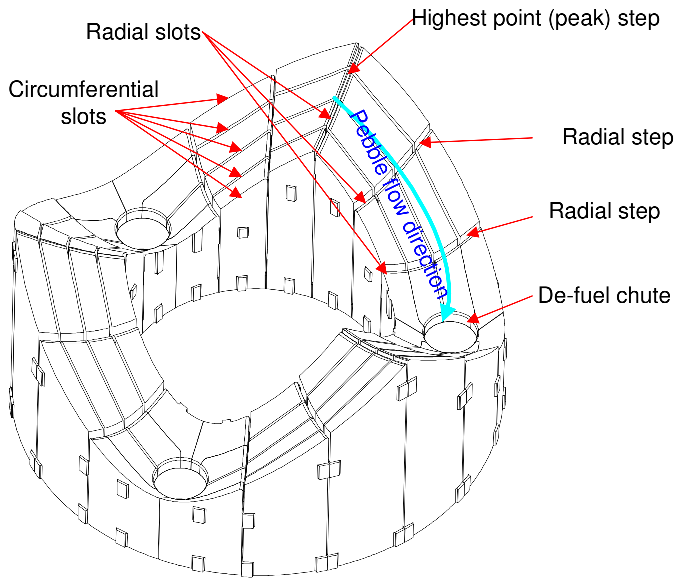

Figure 6: Top layer of the Bottom Reflector showing the defuel cone

The Side Reflector defines the outer boundary of the pebble bed, channels the primary coolant flow from the core inlet plenum to the cavity above the pebble bed, provides access for the RCS, and forms part of the passive heat removal path. The selection of suitable graphite with a high thermal conductivity and heat capacitance for the SR assures the provision of the required passive heat removal path. The SR comprises two main components, the Inner Side Reflector (ISR) and the Outer Side Reflector (OSR).

The OSR, which is approximately 500 mm thick, contains the inlet gas riser channels (see Figure 7). The parts that are used for the construction of the OSR are not subject to high amounts of irradiation damage or high thermal gradients (Controlled to the Reactor inlet temperature by the gas in the riser channels) and thus remain dimensionally stable. This makes the OSR ideal for sealing and the SR sealing keys are incorporated into these parts. The lateral restraint straps that provide support for the core are partially embedded in the OSR blocks.

The ISR comprises 24 columns of graphite blocks to correspond to the number of control rods (see Figure 7). Each column contains a single, sleeved, control rod channel. The bore of the control rod sleeves are approximately 130 mm in diameter and the control rod has a diameter of 105 mm. The play between the control rod and the channel, in combination with the use of segmented control rods, ensures that the control rods can be inserted into the channel even after the parts have been deformed by irradiation induced shrinkage or swelling. The sleeves ensure that the Control Rod channel remains intact even if the ISR block that contains the channel were to fracture. The inner face of the ISR components defines the outer boundary of the pebble bed and in order to prevent the formation of an ordered structure in the spheres in contact with the faces, the faces of the ISR blocks in the lower third of the core are provided with flow disturbance grooves. These flow disturbance grooves break up any ordered structure that might form in the spheres next the block faces and that could impede the flow of these spheres.

All blocks in the columns are vertically dowelled to each other, and keys are provided between the columns to ensure stability of the structure during a seismic event. The components forming the columns are arranged according to the single column principle; this ensures that relative motion between the columns (due to temperature or irradiation induced dimensional changes) is accommodated without the generation of internal loads.

The components of the ISR are all replaceable in case the components cannot perform the required function due to material damage that occurs in the graphite caused by the high temperatures and neutron flux over the lifetime. Current lifetime estimates indicates that one reflector replacement may be required during the design life.

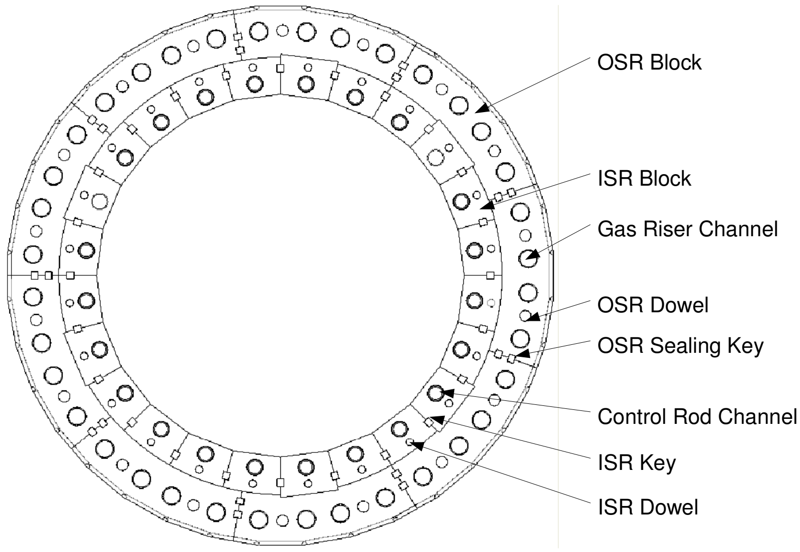

Figure 7: Side Reflector components and features

Lateral Restraint Straps restrain the SR against the lateral loading generated by the pebble bed (also referred to as the Horizontal Silo Pressure). These straps are designed to match the thermal expansion of the core, thus limiting the magnitude of loads build-up during thermal cycling and ensuring that significant gaps are not developed between the SR columns, thus providing improved sealing. This limits the load applied to the fuel to prevent any damage or breakages to the spheres as a result of unmatched thermal expansion of the straps and the core.

The lateral restraint straps are manufactured from alternating links of Austenitic Stainless Steel and Carbon Fibre Reinforced Carbon (CFRC) (refer to Figure 8), allowing for the adjustment of the strap thermal expansion coefficient by changing the ratio between the steel and CFRC lengths. Seismic support snubbers are provided on the metallic strap components to provide a direct load path between the CSC and the CB in the case of a seismic event.

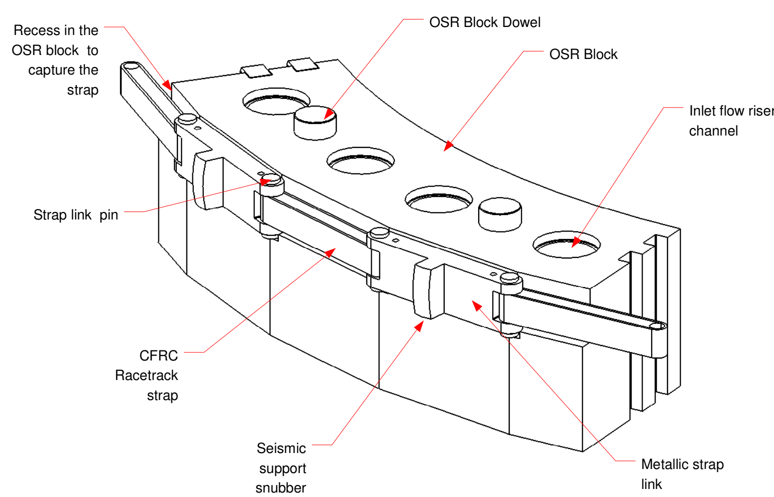

Figure 8: Lateral Restraint Design

The Centre Reflector comprises the CR Structural Spine and the Outer Centre Reflector (OCR). The OCR protects the CR Structural spine from the high levels of fast neutron irradiation. This ensures that the CR Structural Spine is dimensionally stable while ensuring the structural integrity of the CR. The CR is subject to non-uniform loading due to the statistical nature of the pebble bed but the CR Structural Spine and the support that is gained from the pebble bed ensure that the deflection of the CR remains within limits. Is the case of a seismic event, the lateral loads on the CR are transferred through the pebble bed, the SR and to the CBA.

The columns of blocks that comprise the OCR contain the eight, sleeved, RSS channels (see Figure 9). The selection of the SAS concept ensures that the RSS can be inserted into the core, even with severe deformation. The channels, however, are sleeved to provide increased reliability of the channels and make the channel geometry independent of the geometry of the OCR blocks in which the channel is located. Extraction of the RSS is provided for by the continuation of the channels through the CR and the CB Bottom Plate and out through the RPV. The integrity of the channels and the interface between the CR, CB Bottom Plate and the RSS Systems ensure that the SAS remain in the channel after insertion.

The CR is provided with cooling flow to remove heat deposited there during power operation of the core. This is achieved by means of the introduction of cooling flow slots and channels in the blocks of the reflector through which the cooling flow is driven by the pressure differential over the pebble bed. This flow picks up the heat as it passes down through the CR and are returned to the core in the bottom. The outer face of the OCR components defines the boundary of the pebble bed and are also provided with flow disturbance grooves in lower third of the height to prevent the formation of an ordered structure in the spheres.

The entire CR along the height of the core is replaceable. The OCR blocks are the most highly loaded in terms of fast neutron fluence and temperature and are therefore the life limiting components for the replaceable CSC.

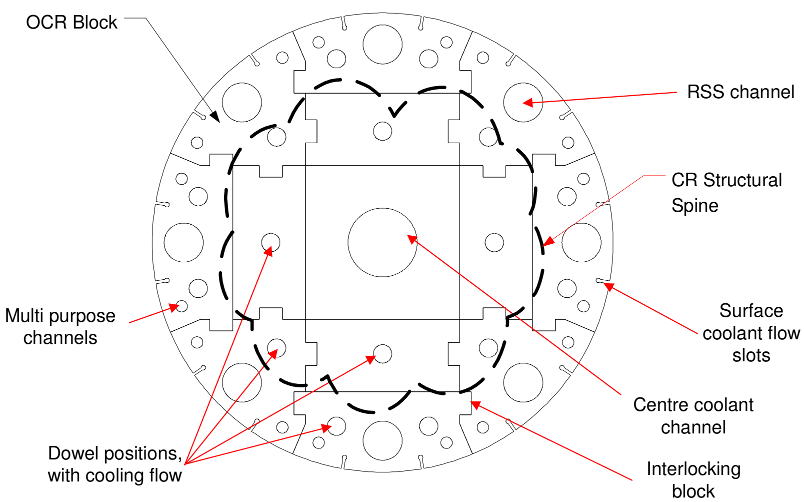

Figure 9: Section through the Centre Reflector Showing Details

The Top Reflector is suspended from the CB Top Plate by means of Tie-rods, manufactured from CFRC. The TR provides for neutron absorption and shielding above the core and also protects the Top Plate from high-temperature gas (particularly during accident conditions). The top layer of blocks is manufactured from a solid insulation material to insulate the Top Plate. The TR blocks are also staggered to prevent a direct gap forming from the hot gas in the core to the Top Plate. Figure 10 shows the top reflector concept.

This concept allow for the different thermal expansions of the CR, SR and CBA whilst remaining stable. The structural integrity of the TR ensures that the interfaces, specifically for the RSS and RCS that pass through it, are ensured.

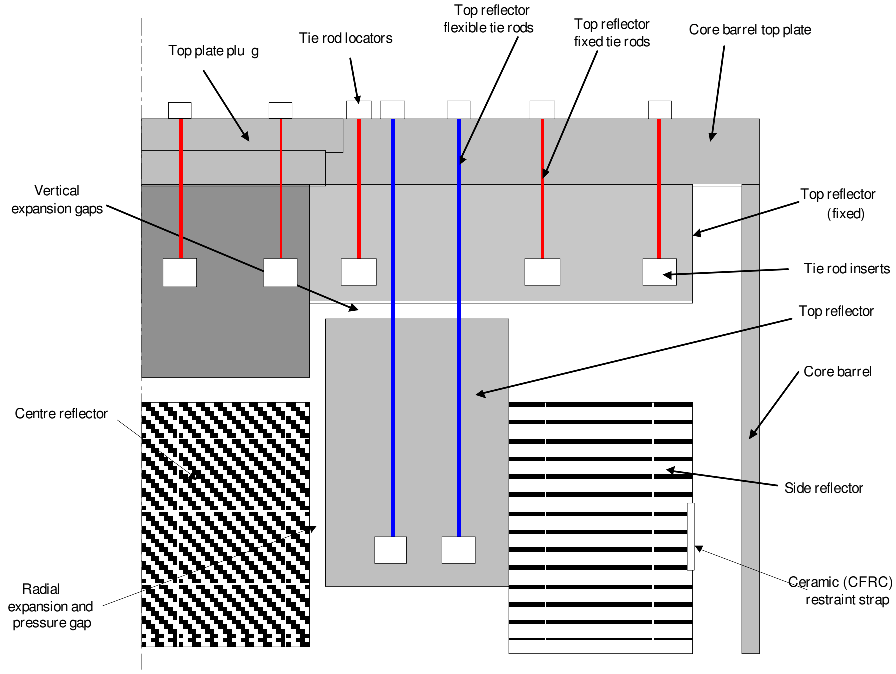

Figure 10: Top Reflector Concept

4. CORE BARREL ASSEMBLY DESCRIPTION

The Core Barrel Assembly consists of all the metallic parts of the CS. Its primary function is to support the CSC during normal operation and accidents. The CBA are designed in accordance with the ASME III Subsection NG and Code Case N-201-4 design codes and the major material used for the manufacture of the components is 300 series austenitic stainless steel.

The CBA is a welded construction comprising three major components. These major components are the Core Barrel Support Structure (CBSS), the Core Barrel Sides and the Core Barrel Top Plate (refer to Figure 12). In addition to the major components, there are several minor components, specifically: the CSC circumferential restraints, the Upper and Lower Support Rings, the Upper and Lower Lateral Guides, and the Core Barrel Vertical Support Assembly. 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.

The primary design requirement for the CBSS is stiffness, as this is required to provide a stable and accurate base on which the CSC can be constructed. 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 Core Barrel Vertical Support Assembly supports the CBA vertically, at a single centre point, from the lower head of the RPV whilst allowing for a small amount of unconstrained angular rotation of the CBSS around any horizontal axis to compensate for possible bowing of the Core Barrel Sides due to any possible uneven temperature distribution. This is accomplished by the spherical contact surfaces of the Vertical Support Bearing within the Core Barrel Vertical Support Assembly.

During normal operation the lower lateral guide (see Figure 11) laterally centers the CBSS and transfers lateral loads between the CBSS and the RPV. The lower lateral guide is sufficiently compliant to allow for core barrel bowing. During a seismic event, the Lower Support Ring augments the Lower Lateral Guide. The Lower Support Ring provides a direct load path between the CBA and the RPV by means of radial keying to the CBSS Skirt. An engineered gap between the radial key and the CBSS restricts the functioning of this mechanism to seismic events.

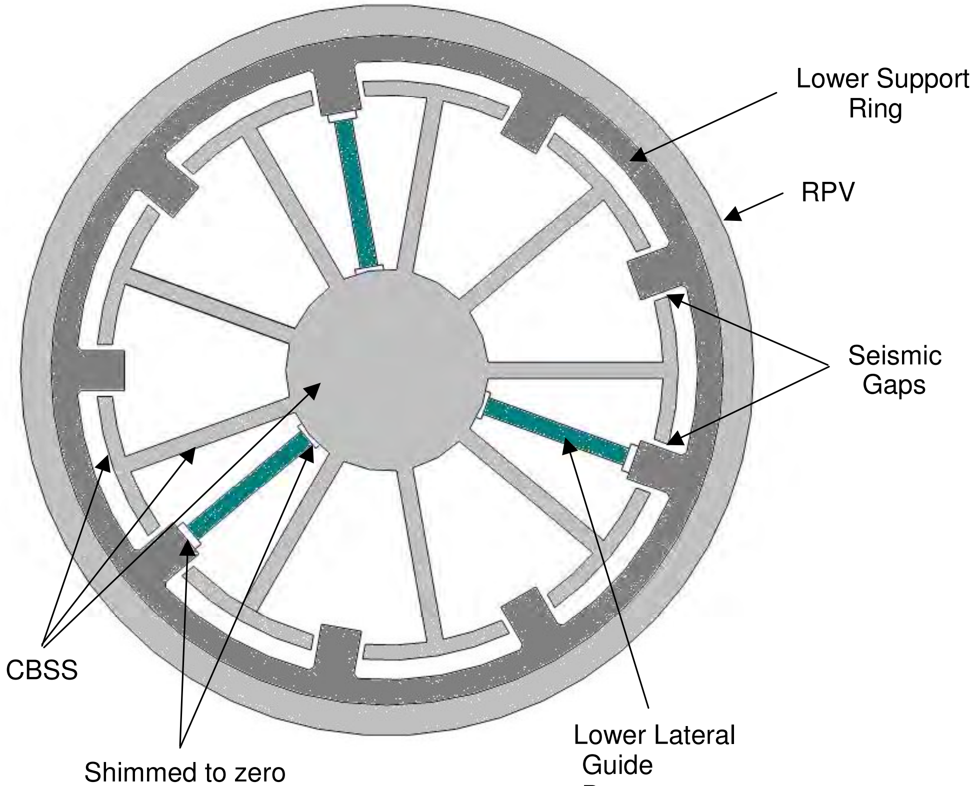

Figure 11: Schematic of the Lower Lateral Guide

The cylindrical portion of the Core Barrel is referred to as the Core Barrel Side. The Core Barrel Side is fabricated from several individual rolled steel courses (rings). The CSC circumferential restraints are welded to the Core Barrel Side. These restraints locate the BR (and thus the CSC) relative to the CBA, while allowing for differences in thermal expansion, and also provide support during seismic events. The Core Barrel Side provides lateral support for the CSC in the region of the core during seismic events when the snubbers on the metallic links in the lateral restraint straps make contact with the side.

The top of the Core Barrel Sides are laterally supported and centered by the Upper Lateral Guide. The Upper Lateral Guide transfers lateral loads between the CBA and the RPV while allowing for differential thermal expansion between the RPV and the CBA in the vertical direction. The Upper Lateral Guide is sufficiently compliant to allow for core barrel bowing and is augmented, during a seismic event, by the Upper Support Ring. The functioning of these components is analogous to the functioning of the Lower Lateral Restraint and the Lower Support Ring. The seismic restraint scheme for the CBA described above ensures that the relative lateral motion between the CS and the RPV during an SSE is limited.

The CB Top Plate Assembly is actually the lid of the CB and the Top Reflector is suspended from the Top Plate. The Core Barrel Top plate is bolted to the top of the Core Barrel Sides and provides for interfaces between the CS and the RCS, RSS and fuel handling. In addition, the Top Plate is provided with a removable plug, specifically for CSC replacement, through which access to the core can be gained.

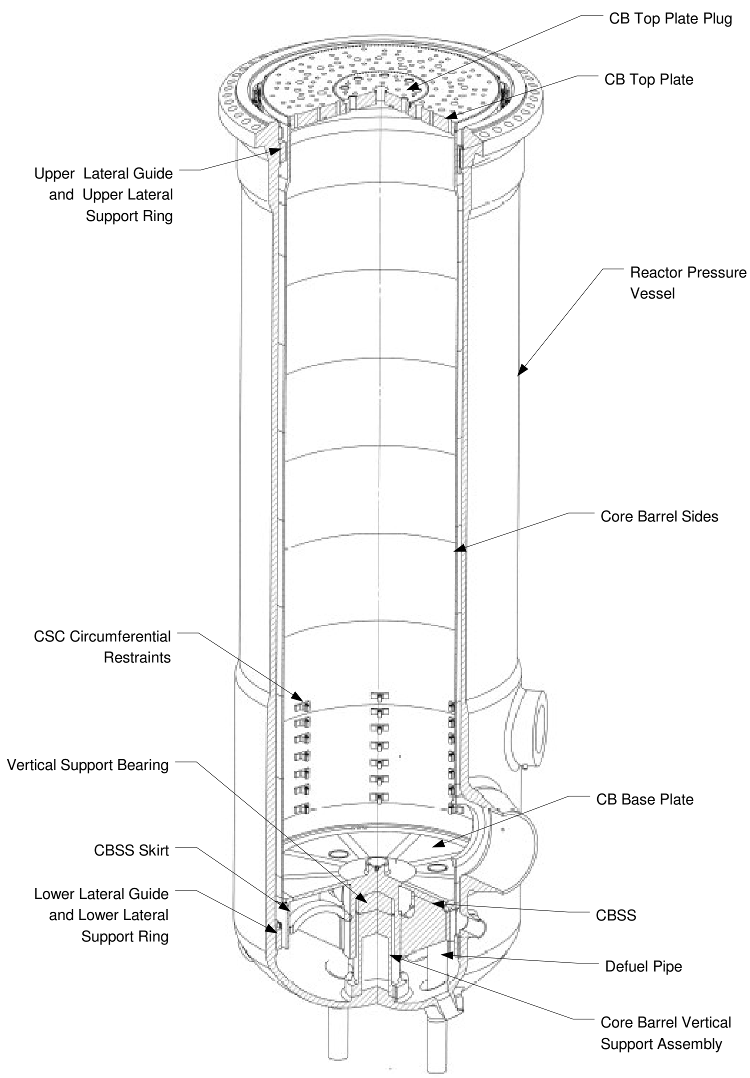

Figure 12: Core Barrel Assembly within the Reactor Pressure Vessel

5. REACTIVITY CONTROL SYSTEM DESCRIPTION

The RCS is used to control the reactivity in the core by mechanically raising and lowering the control rods in borings in the side reflector. The system can also hold the control rods steady in any position in this range of travel. The RCS consists of 24 identical units, which consist of one group of 12 control rods and another group of 12 shutdown rods.

Each unit consists of a Control Rod Drive Mechanism that translates rotational movement, from the drive motor, into linear movement connected by chain to the control rod. The function of the control rods is to absorb neutrons. The control rods consist of six articulated segments containing sintered boron carbide with an outside diameter of 105 mm. The articulated segments together with the oversized boring (130 mm) prevent the control rod from becoming stuck in a boring. Each boring in the side reflector contains a secondary shock absorber to prevent damage to the control rod and the core structures graphite following a chain failure. Refer to the layout in Figure 13 for the layout of a single control rod unit.

Insertion of the rods is by gravity when power is cut to the drive motors (scram activation). During this event, the drop velocity of the RCS units is limited to a pre-determined value. This provides a fail to safe design for the RCS.

The control rods are constructed from high temperature steel and are cooled by a bypass flow from the core during normal operation.

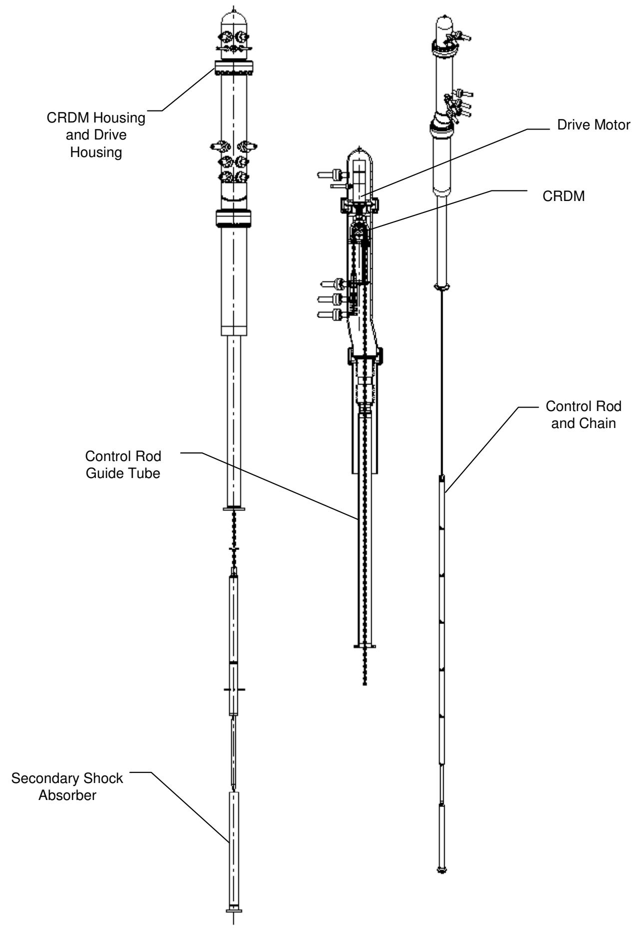

Figure 13: Reactivity Control System Layout of a single control rod

6. RESERVE SHUTDOWN SYSTEM

The Reserve Shutdown System (RSS) consists of eight units that can insert Small Absorber Spheres (SAS) of 10 mm diameter containing natural B_4C into the eight borings of the centre reflector. When inserted, it keeps the reactor subcritical down to cold core temperatures. The RSS serves as a diverse backup system to the RCS.

The SAS are stored in storage containers under the RPV lid but above the top plate of the Core Barrel. Each storage container contains sufficient SAS to fill a complete boring in the centre reflector. This configuration is shown in Figure 2 and Figure 3. The connection tubes between the storage containers and the borings are closed off with a valve. When shutdown is required, the valves of the SAS storage units are merely opened and the SAS flow under gravity into the centre reflector borings. The valve actuation is designed such that the valve will open when the power supply is interrupted. This provides a fail to safe design.

When the SAS needs to be extracted from core, the SAS can be conveyed pneumatically back to the storage containers. This is accomplished by fluidizing the SAS in the discharge vessel in a controlled manner to allow transport of the SAS to the storage container feeder bin. The SAS return pipe conveys the SAS from the discharge vessel to the feeder bin. From the feeder bin the SAS are returned to the storage containers.

The RSS is designed for all normal operation and design basis accidents including seismic and pipe break events. Thus done by the use of high temperature steels closer to the core and by withstanding the pressure differentials occurring during a pipe break. The RSS is also designed to prevent the SAS from inadvertently leaving the borings after insertion.

7. REACTOR PRESSURE VESSEL

The primary functions of the Reactor Pressure Vessel (RPV) are the containment of the helium coolant and providing structural support and alignment for the RU components. The secondary function is the transfer of decay heat from the reactor core via the RPV as part of the passive heat transfer path to the Reactor Cavity Cooling System (RCCS) during loss of forced cooling events.

The RPV (Figure 2) 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 have openings for fuel discharge, the RSS discharge, the CBCS, and an access opening intended for use only during initial installation operations. 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.

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 total RPV length is approximately 30 m and the mass is estimated at 1 250 t. The RPV is designed and constructed to ASME III, Division I, Subsection NB and Code Case N-499-2. 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 highest operational pressure to which the RPV 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. The RPV is operated at temperatures of 280 °C to 300 °C to ensure that it is maintained within the temperature envelope of established neutron fluence data.

8. CONCLUSION

The mechanical design of the PBMR reactor unit has been presented. An overview of the major structural systems and components, their functions and brief design descriptions hah been given. From this design PBMR found that it is possible to design the reactor using existing design codes and materials without the need for extensive material qualification or development. This lowers the cost and risk for a FOAKE design.

PBMR are in the final stages of appointing the suppliers of these components and then detail design and manufacturing will commence. Construction is expected to take place for the Demonstration Power Plant in South Africa from 2007 onwards.s

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