Reactor Unit and Main Support Systems

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Overview

- Reactor Structures
- Core Conditioning System Flow Paths
- Core Barrel Conditioning System Flow Paths
- Reactivity Control and Shutdown System
- Neutron Source System
- Fuel Handling Storage System

Reactor Unit Functions

Power Generation Functions:

- Provide 400 MW nuclear heat

Safety Functions:

- Control reactivity
- Remove core heat
- Contain radioactive materials

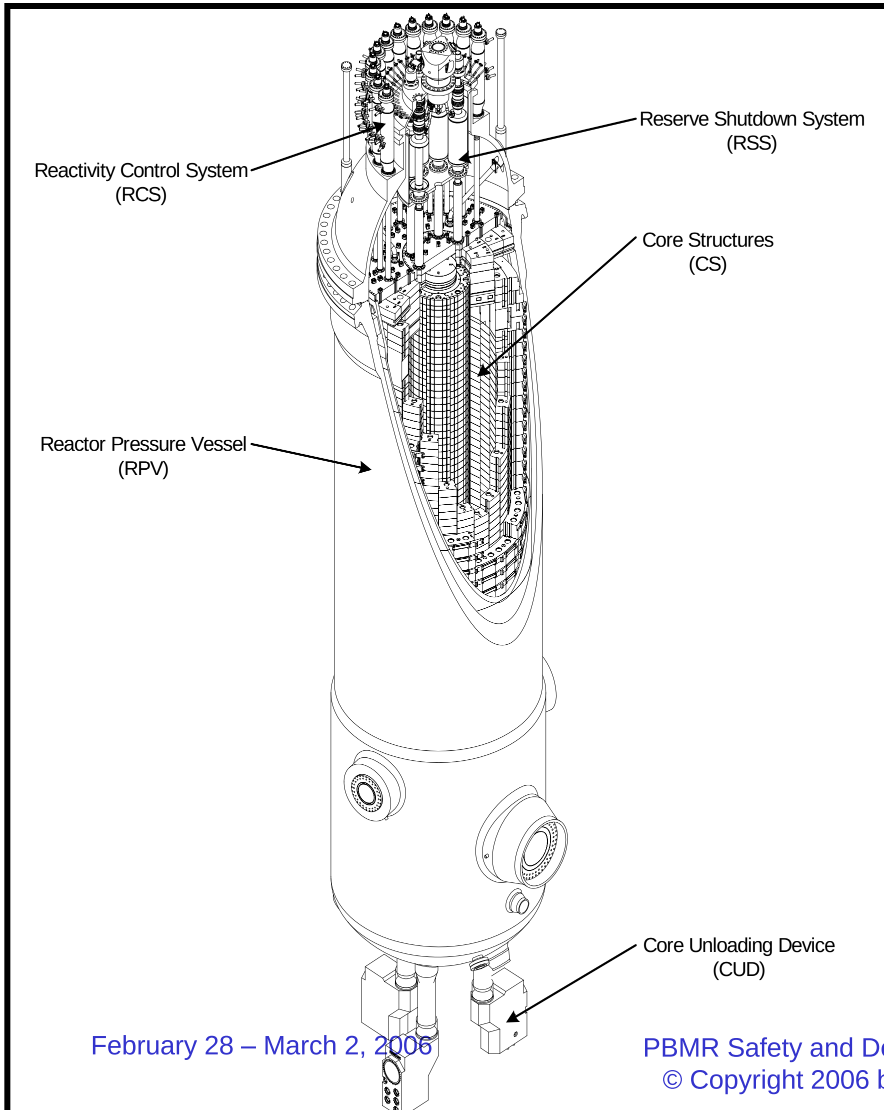
Reactor Unit Parameters

Parameter	Specification
Thermal Power	**400 MW**
Temperatures	**Inlet: 500°C Outlet: 900 °C**
Operating Pressure	**9 MPa**
Core Geometry	**Annular core with a solid centre reflector**
Reactor Pressure Vessel	**Steel**
Reactivity Control System	**24 Control rod channels in the side reflector**
Reserve Shutdown System	**8 SAS channels in the centre reflector**
Fuel Handling System	**3 fueling points in the top reflector and 3 defueling points in the bottom reflector**

RU Functional Allocation

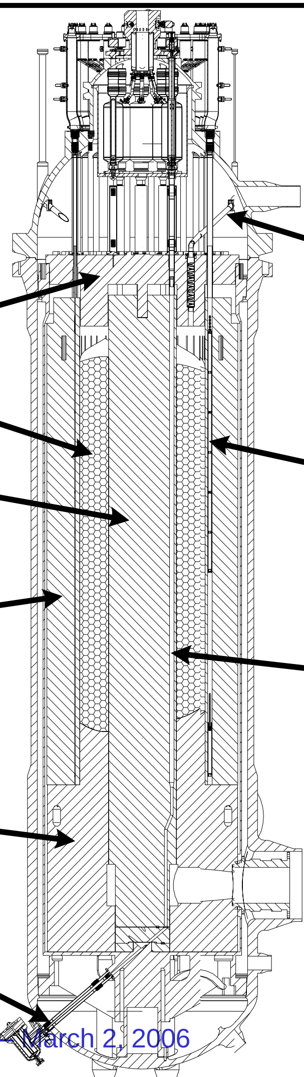
	Fuel	Core Structures	Reactor Pressure Vessel	Reactivity Control System	Reserve Shutdown System
Provide nuclear heat	**nuclear fission**				
Control Reactivity		**maintain core geometry**		**insert neutron absorber**	**diverse shutdown**
Core heat removal		**provide coolable geometry**			
Contain radioactive material	**coated particles**		**contain gas**		

Reactor Unit Layout



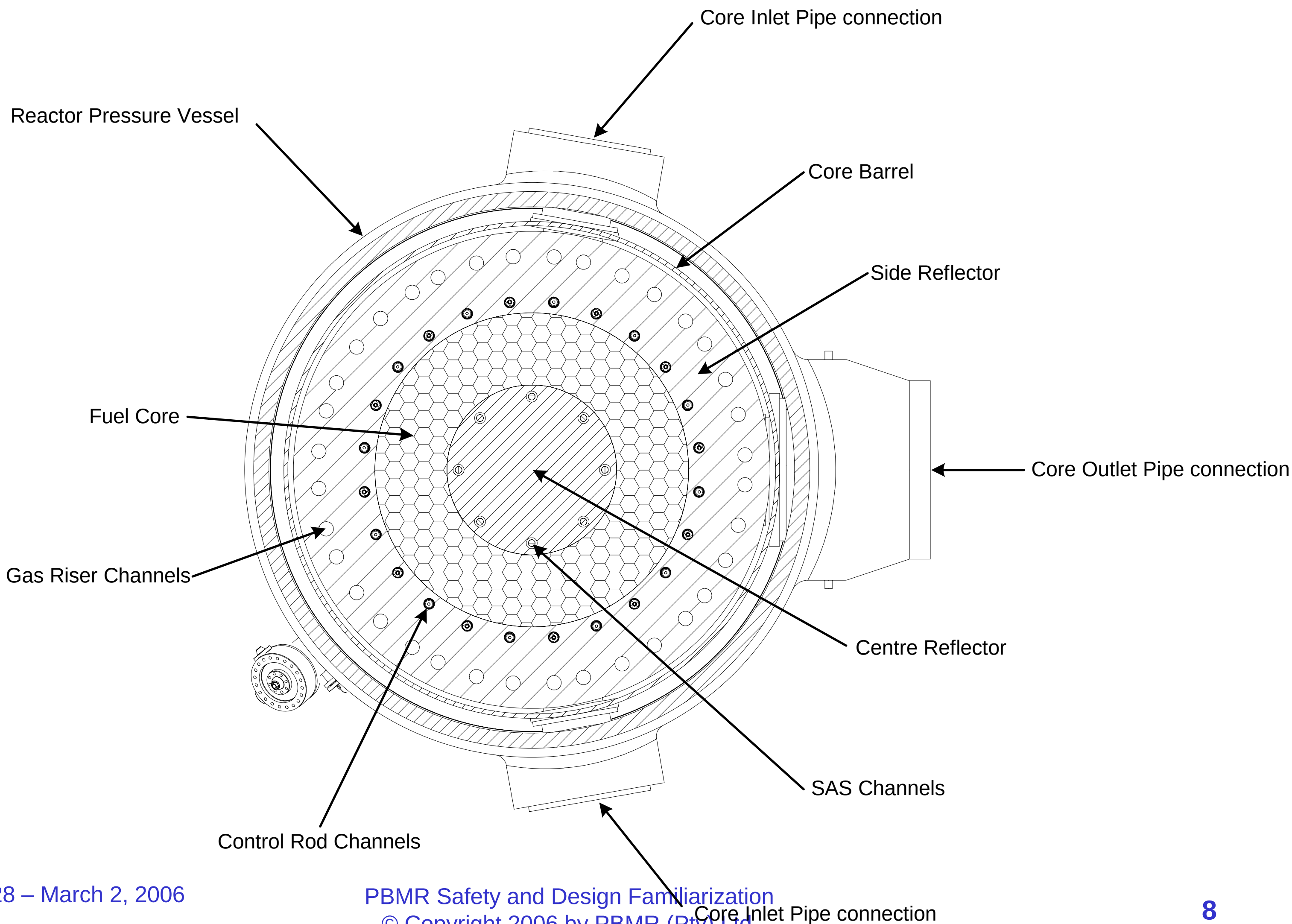
System	Function
Core Structures (CS)	**To form and maintain the core geometry**
Reactor Pressure Vessel (RPV)	**To contain the helium under pressure**
Reactivity Control System (RCS)	**To control reactivity and shutdown the reactor**
Reserve Shutdown System (RSS)	**To shutdown the reactor**
Core Unloading Device (CUD)	**Remove the spheres from the core**

Reactor Unit Vertical Section



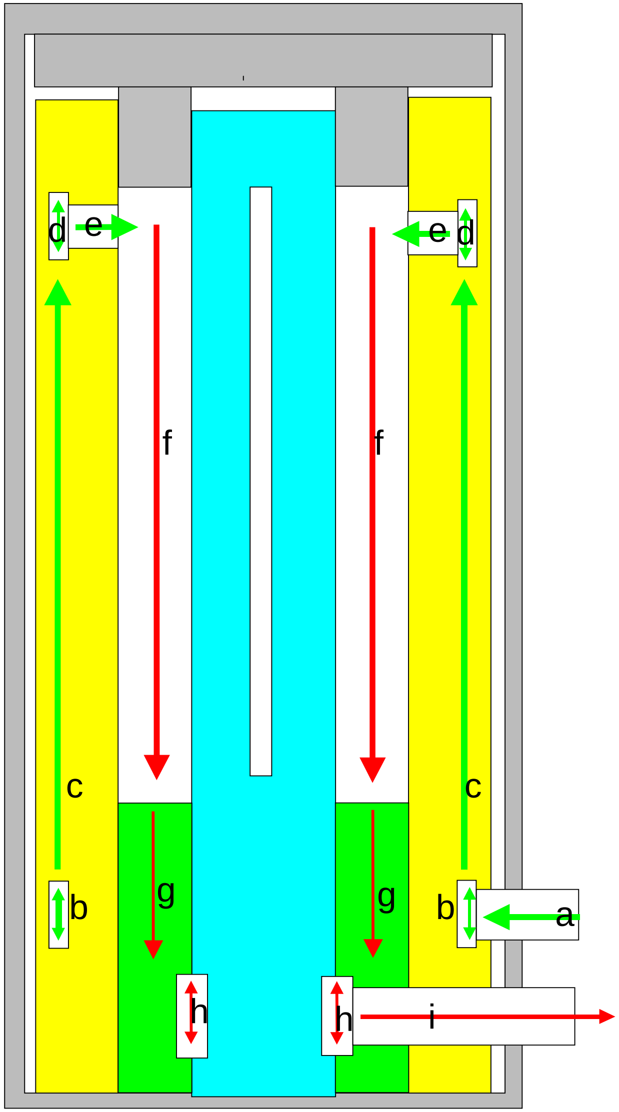
System	Function
Fuel Line	**To feed fuel spheres to the core**
Fuel Core	**To generate heat by nuclear fission**
Bottom, Centre, Side & Top Reflector	**To reflect neutrons back to the core**
Control Rod	**To control the reactivity**
SAS Channel	**To shut down the reactor**
SAS Extraction Point	**To extract the SAS from the SAS Channel**

Reactor Unit Horizontal Section



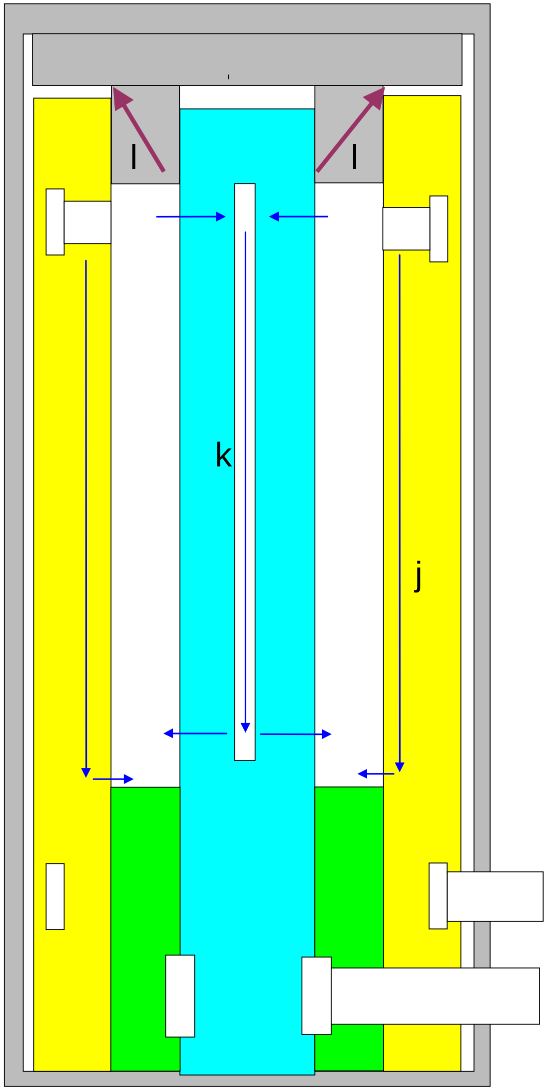
Primary Flow Paths

Key	Description
A	**Core Inlet Pipes – Return the gas from the PCU**
B	**Inlet Plenum – Inside graphite, redistributes the gas to the riser channels**
C	**Riser Channels – Provide a flow path for the gas to the top of the core**
D	**Secondary Core Inlet Plenum – Inside the top of the side reflector. Accumulates the flow from the riser channels before introduction to the core**
E	**Inlet flow slots – Introduce the gas to the core**
F	**Core Flow – The gas flows downwards through the core and absorbs heat**
G	**Core Outlet Flow Slots – Remove the gas from the core**
H	**Outlet Plenum – Accumulates the gas from the outlet slots before returning to the PCU**
I	**Core Outlet Pipe – Returns the gas to the PCU**



Secondary Flow Paths

Key	Description
J	**Control rod cooling flow – This is to provide cooling to the control rod.**
K	**Centre Reflector Cooling Flow – This is to remove heat from the centre reflector.**
L	**Annulus pressurisation flow – Pressurises the annulus between the core barrel and the side reflector.**

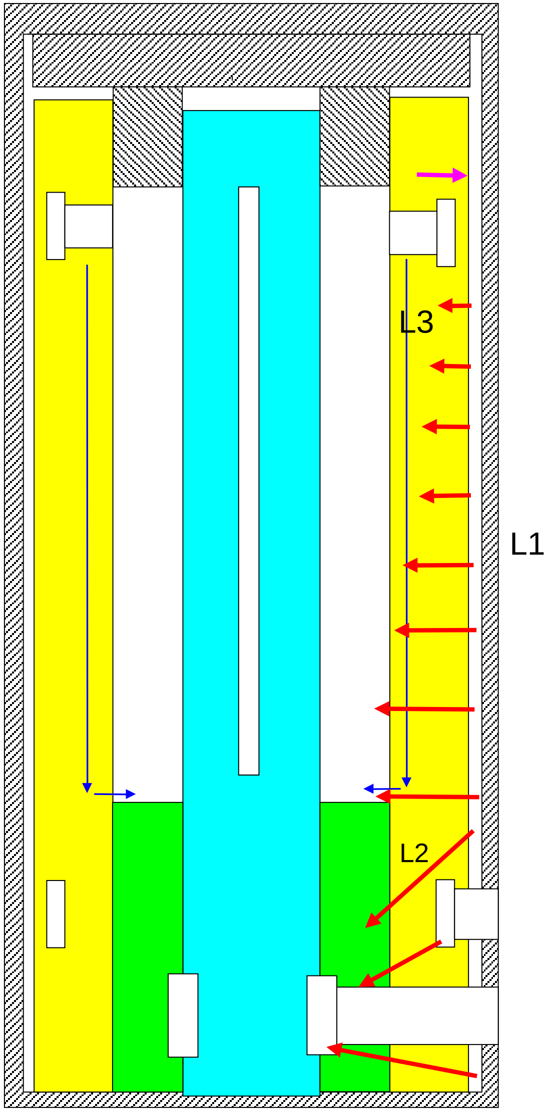


These are engineered flows

Core Structures Leakage Paths

Key	Description
L1	**Across Side Reflector Leakage**
L2	**Inlet to Outlet Leakage**
L3	**Along Side Reflector Leakage**

These are parasitic flows

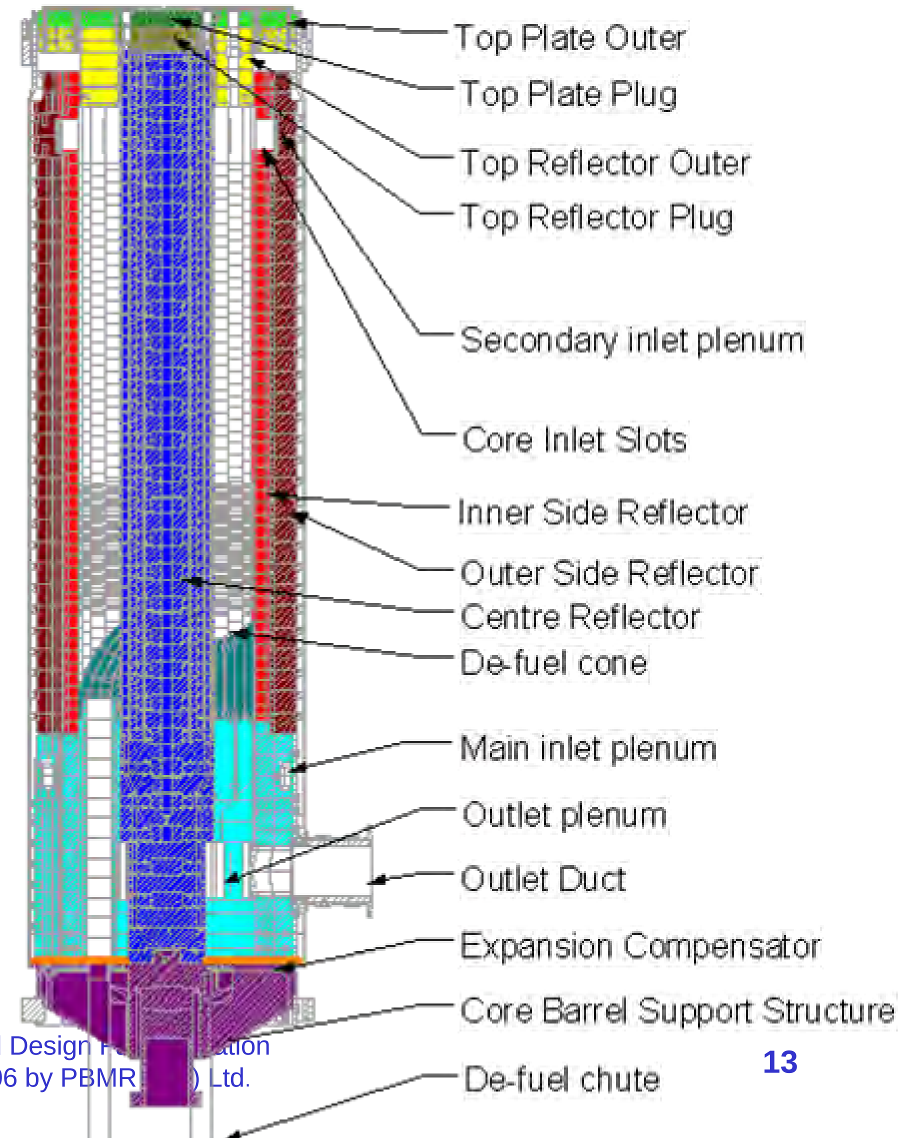


Core Structures Design Codes

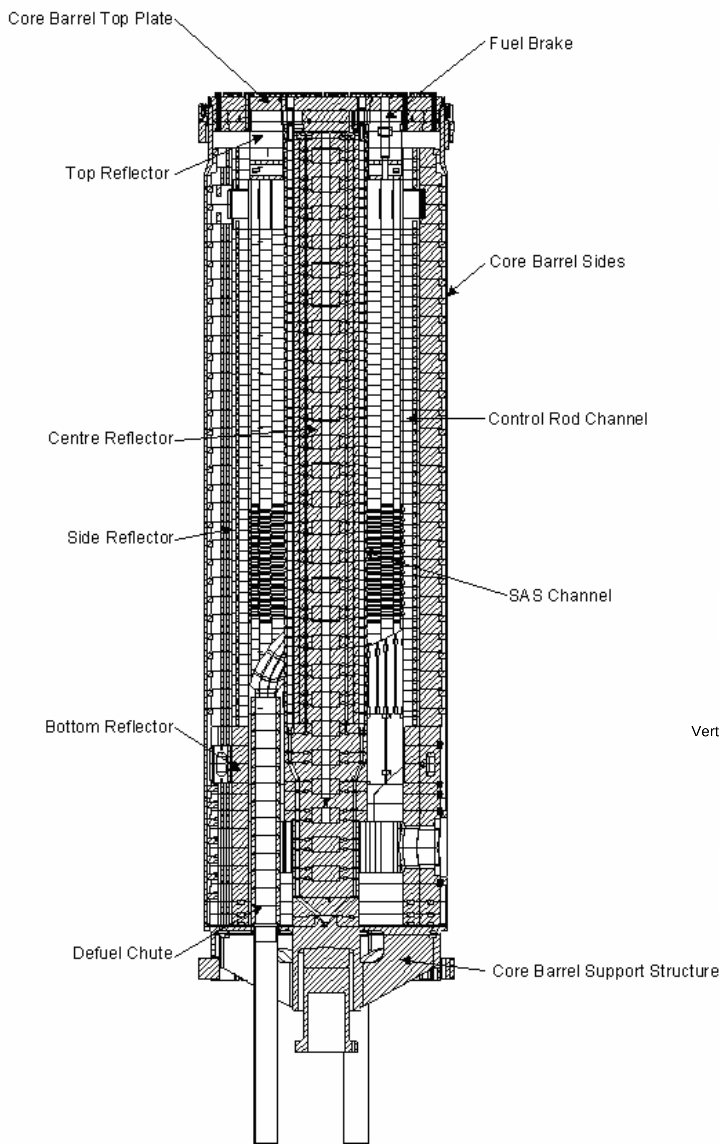
Components	Design Code
All graphite, CFRC and ceramic insulation of the CSC	**Internal rules based on German KTA 3232 “Regulation for design of core internals for high temperature pebble bed reactors”**
All metallic components of the CBA	**ASME III Subsection NG with Code Case N-201-4**

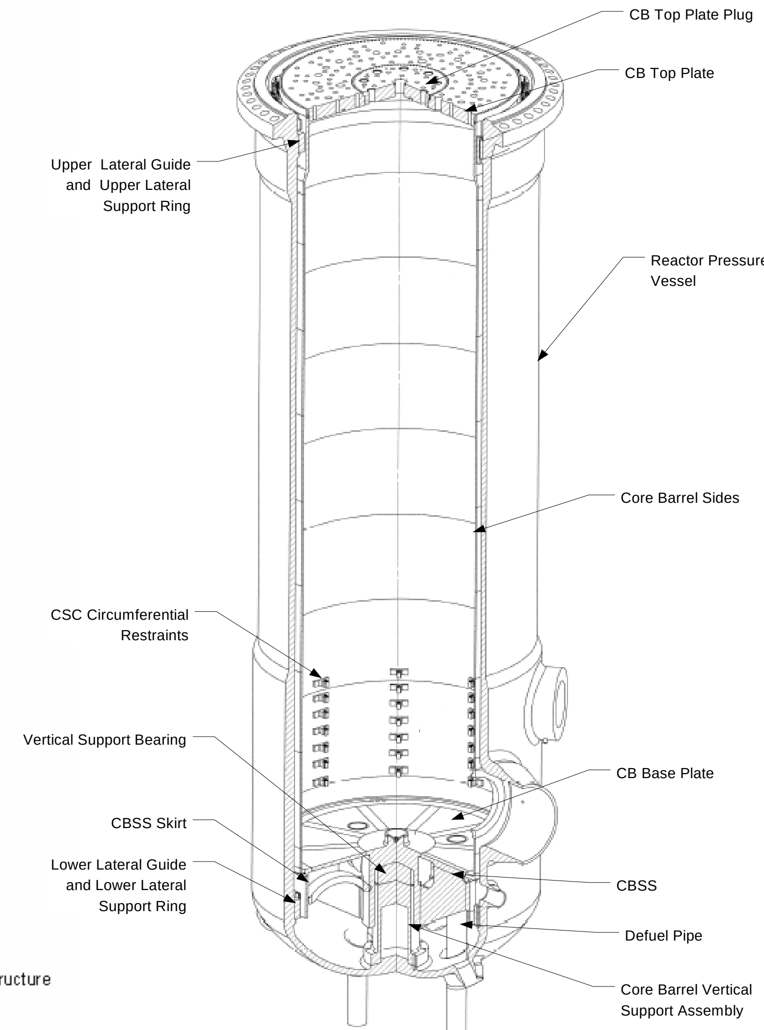
Core Structures Components Identification

- **Identification of the major components of the Core Structures.**



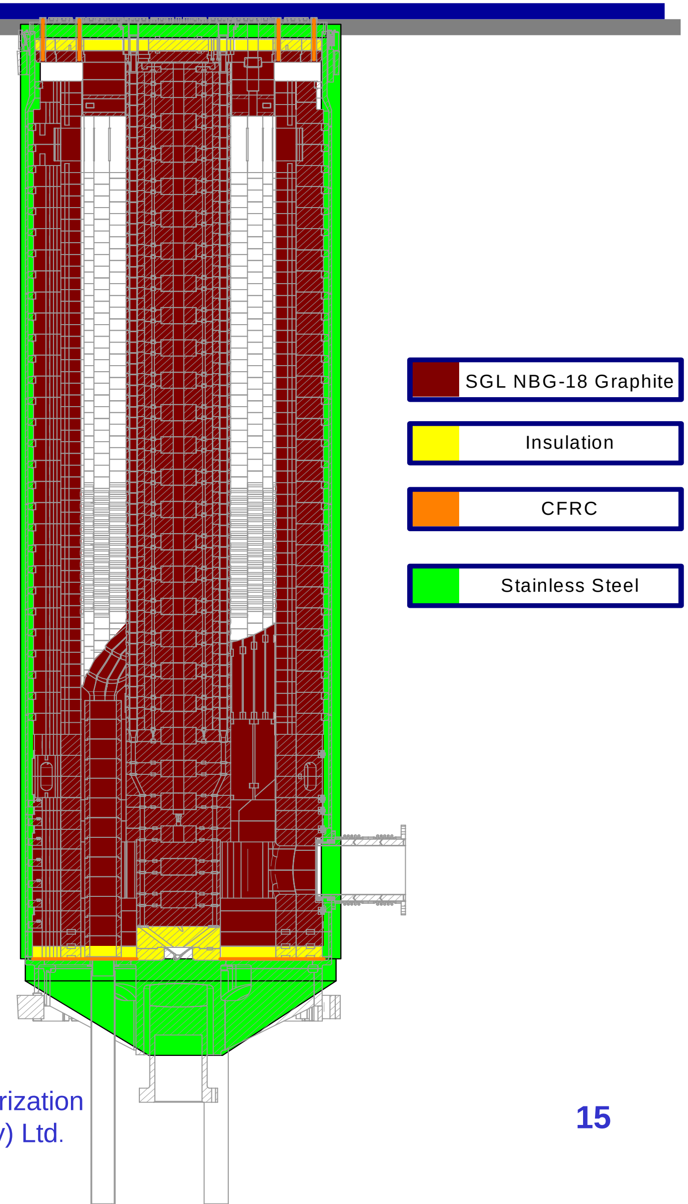
Core Structures





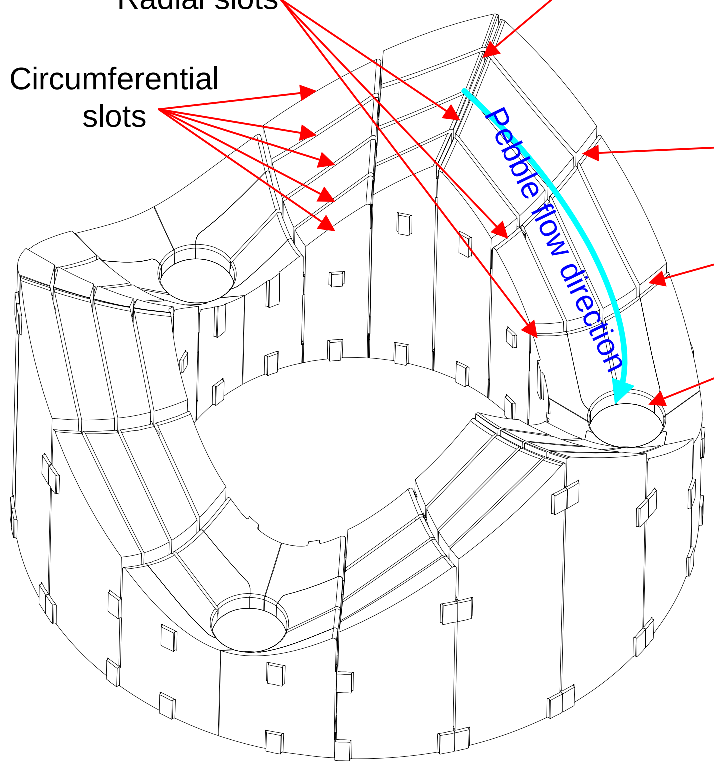
Materials used in the Core Structure Ceramics

- **The construction materials**
- **used for the construction of the**
- **Core Structures Ceramics are:**
  - Graphite NBG-18
  - CMCs (specifically Carbon-Carbon /CFRC)
  - SIGRABOND 1501 YR
  - SIGRABOND 2001 YR
  - Insulation
    - *Fused silica*

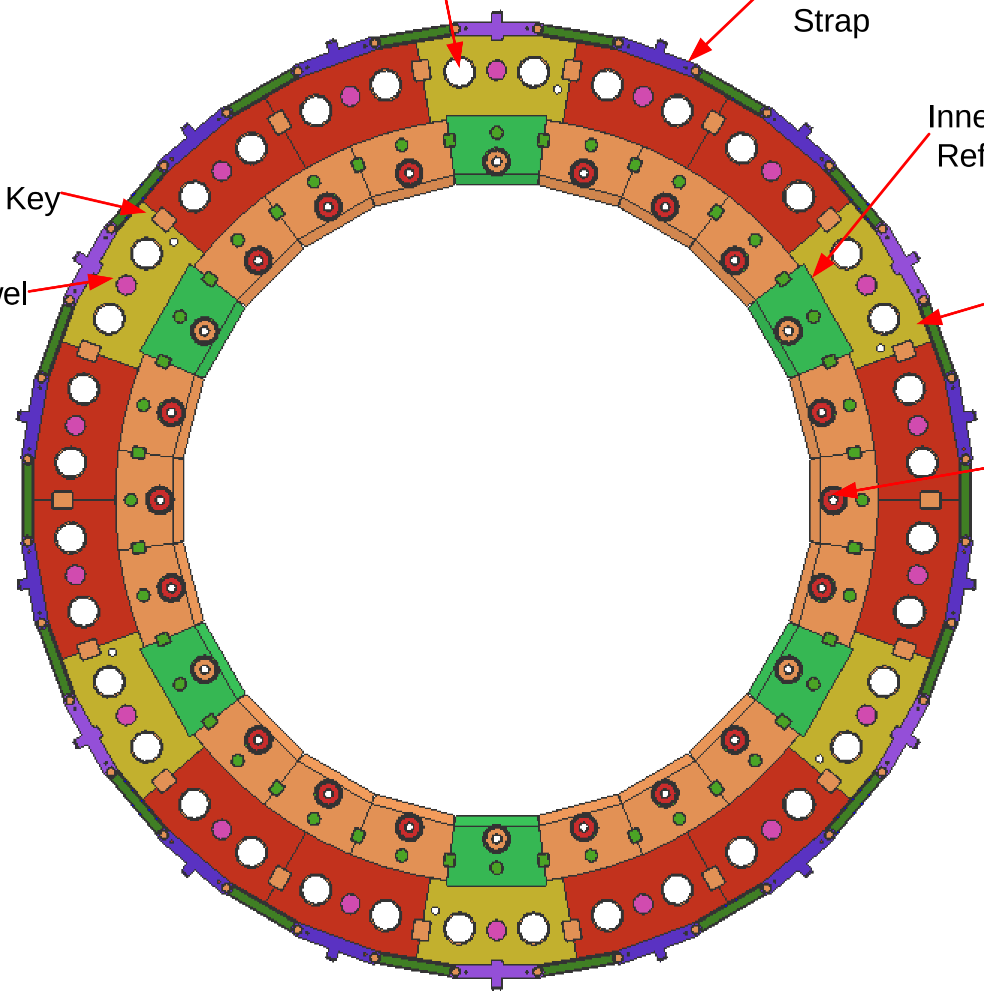


Bottom Reflector: De-fuel Cones

Sphere flow, shaping of the defuel cones and interaction with the gas extraction slots.

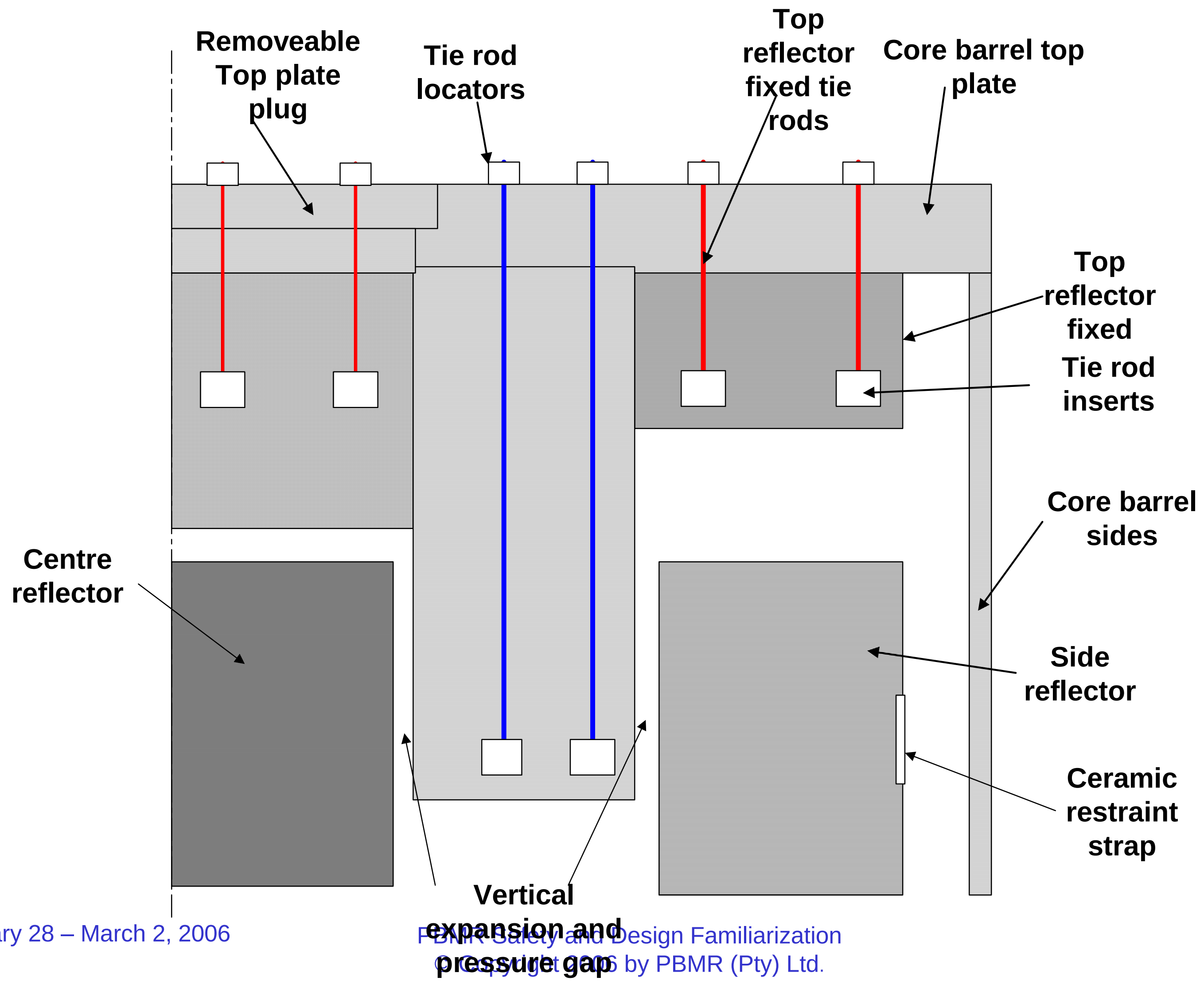


Side Reflector

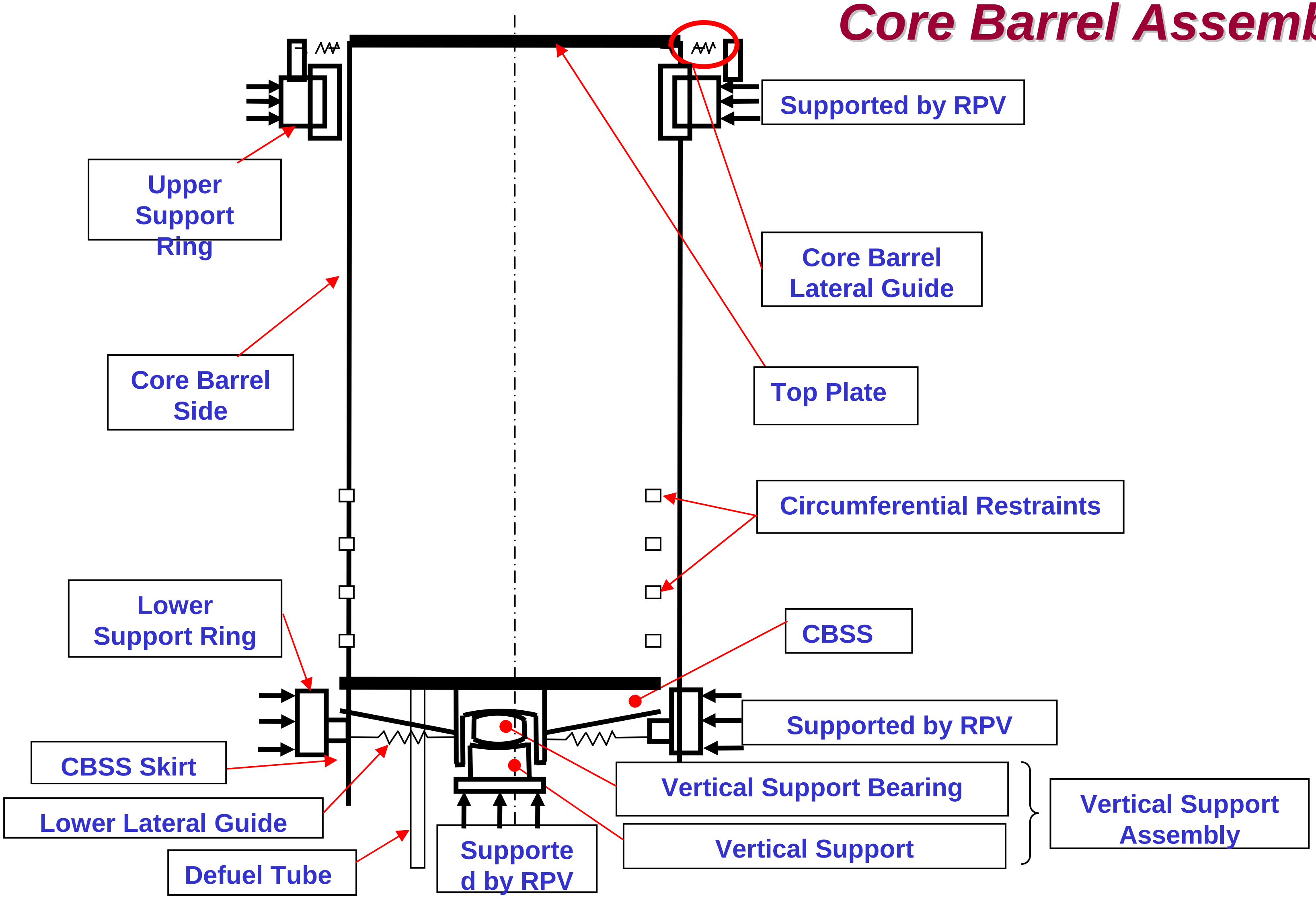


TOP WORK

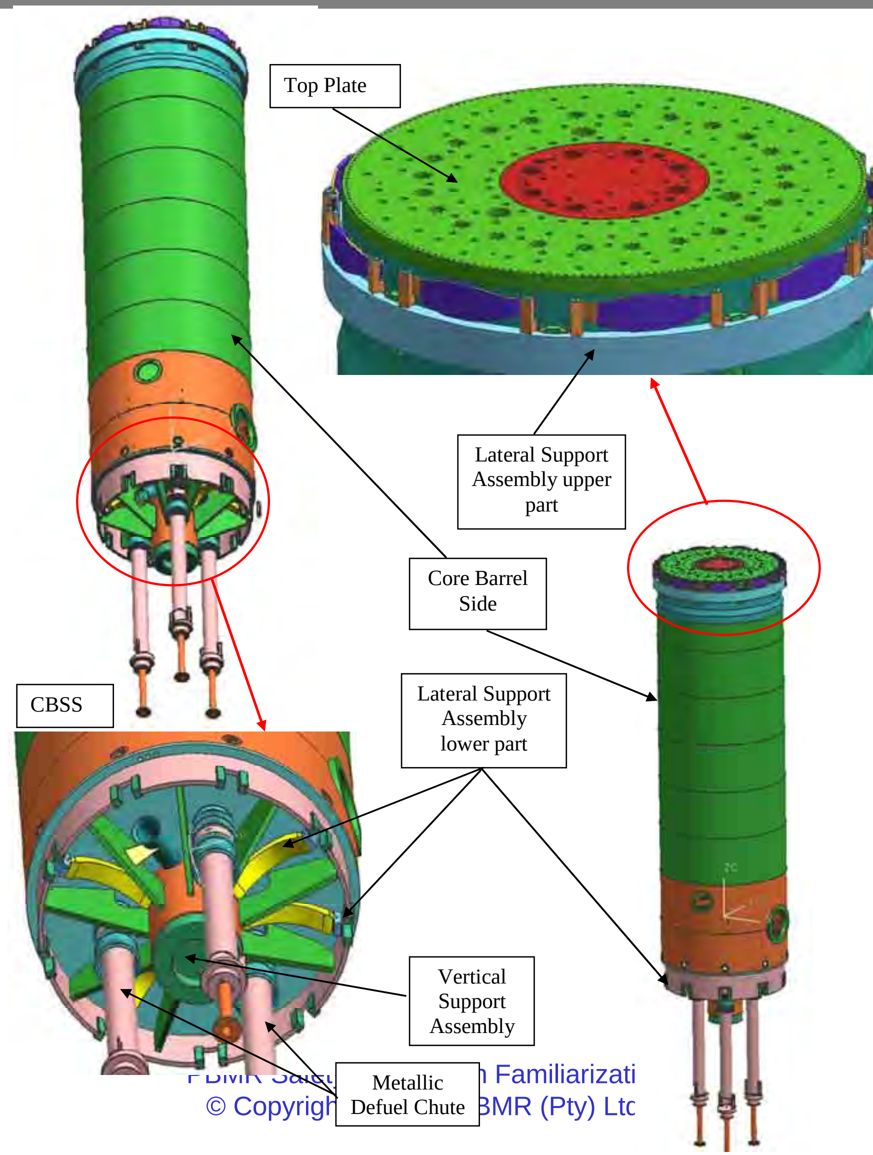
Top Reflector Layout



Core Barrel Assembly



Physical Layout of CBA



Reactivity Control System (RCS)

During Power Operations

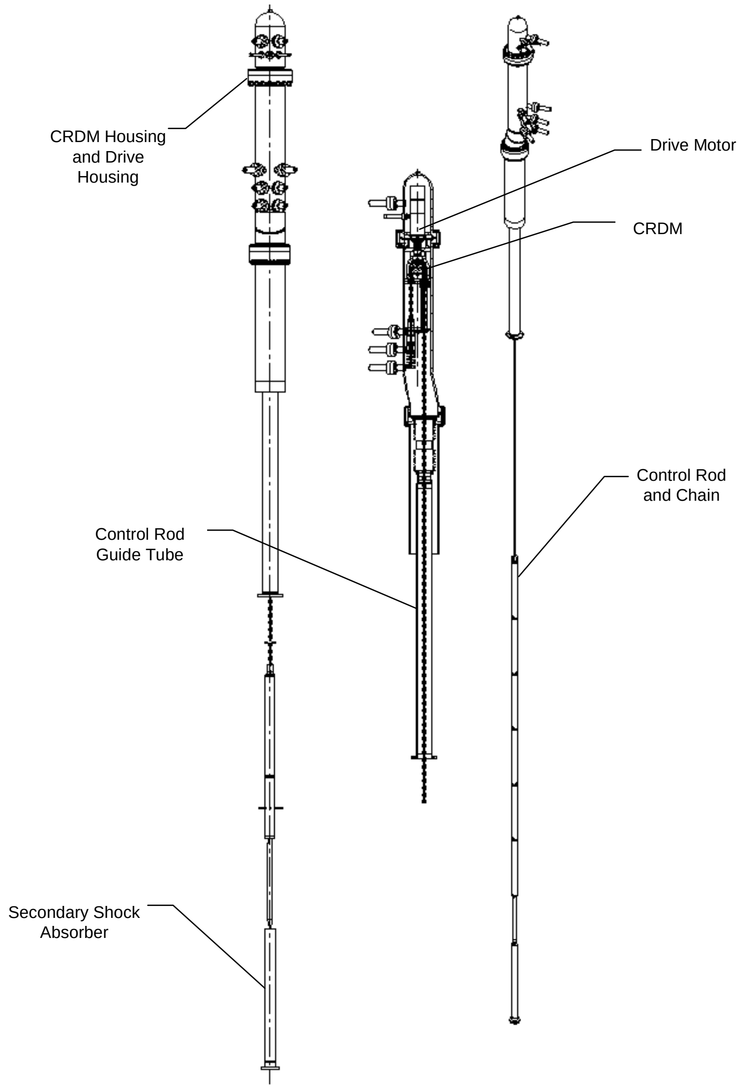
- The RCS consists of 24 control rod units to control the reactivity in the core.

For Shutdown

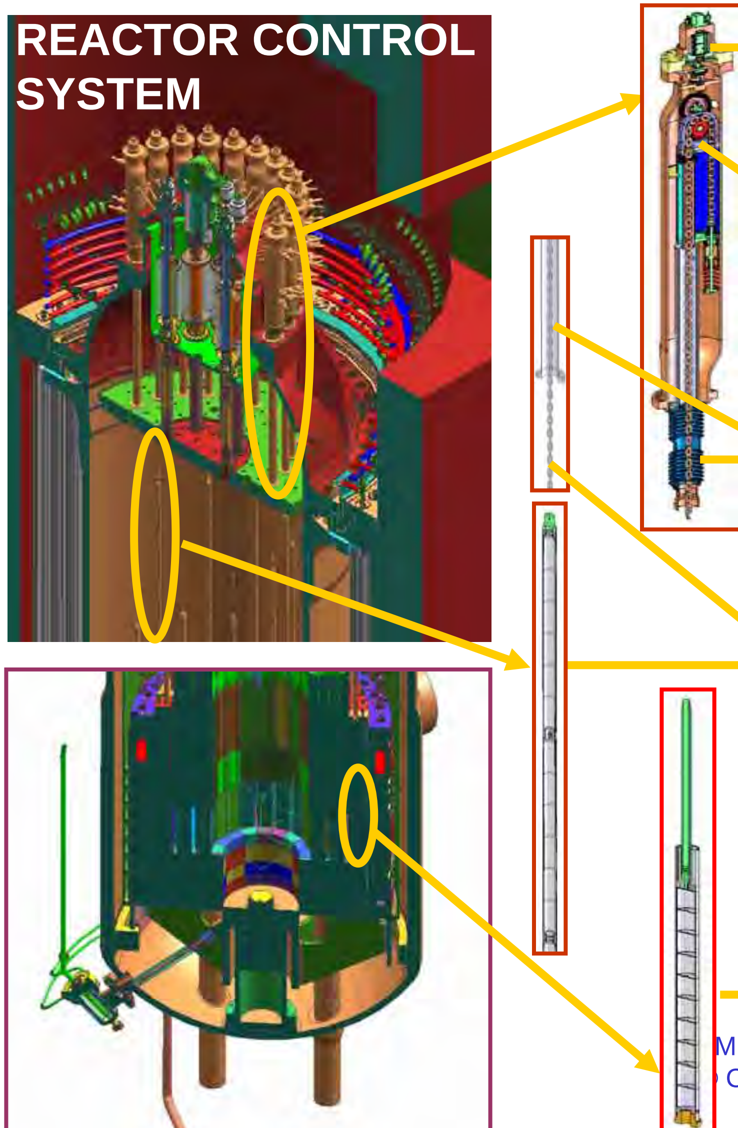
- 12 Control Rods insert into the top half of the core for hot standby.
- To go below hot standby, the additional 12 Shutdown Rods are inserted into the bottom half of the core and take the reactor into hot shutdown.

Control Rod Drives

12 Control Rods
12 Shutdown Rods



Reactivity Control and Shutdown System



RCS Drive Motor

The main function is to keep the RCS rods in position, move the rods up and down and allow insertion during power failure.

Control Rod Drive Mechanism (CRDM)

Transfer rotational movement of the RCS motor into linear movement of the control rods.

RCS Guide Tube

Connects the CRDM housing and the Core Structures and serves as guide for the rod between the CRDM and the Core.

Control Rod & Chain

The function of the Control Rod is to absorb neutrons inside the core whereas the chain connects the CRDM and the Control Rod.

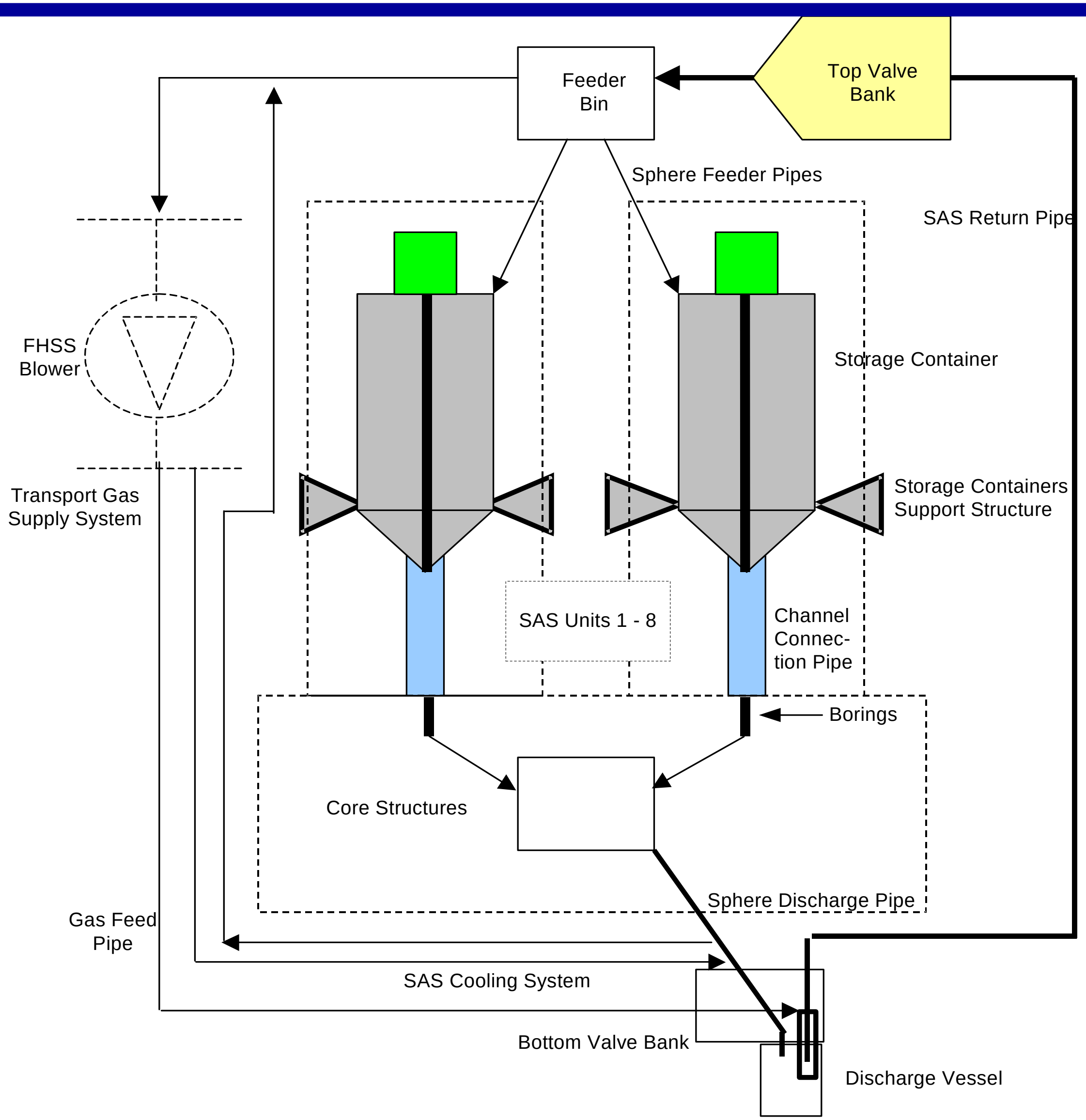
Secondary Shock

The function of the Secondary Shock Absorber is to prevent damage on the Rod and the Graphite Core Sleeve in the inadvertent event of a rod drop.

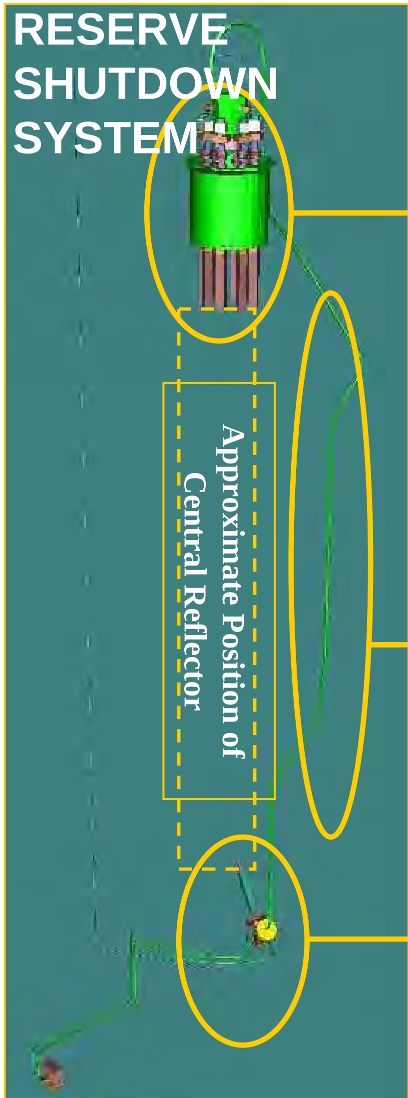
Reserve Shutdown System (RSS)

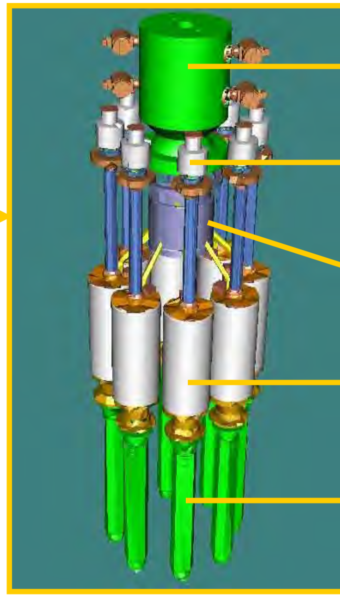
- Consists of 8 units that can insert Small Absorber Spheres (SAS) into the 8 borings of the central reflector.
- SAS are typically inserted to shut the reactor down to ‘cold’ (nominally 100°C) conditions for maintenance operations.

Reserve Shutdown System



Reactivity Control and Shutdown System





RSS Valve – Responsible for separating SAS from conveying gas stream.

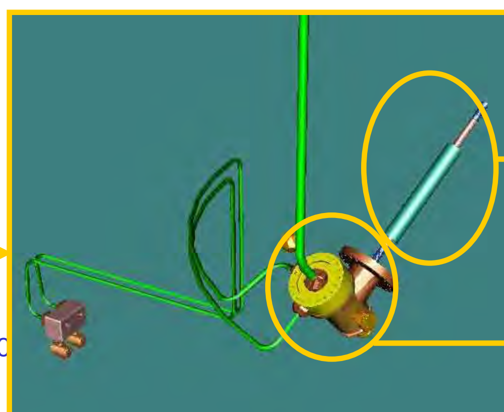
Valve Actuator Ass. – Responsible for insertion of SAS into borings. Designed fail-to-safe.

Feeder Bin – Responsible for overfill and distribution of SAS to containers.

SAS Container – Stores B_4C SAS ready for insertion into borings. 8 containers, 400,000 SAS ea.

SAS Guide Tube – Coaxial tube connecting SAS container to core barrel top plate. Responsible for guiding SAS into borings inside central reflector

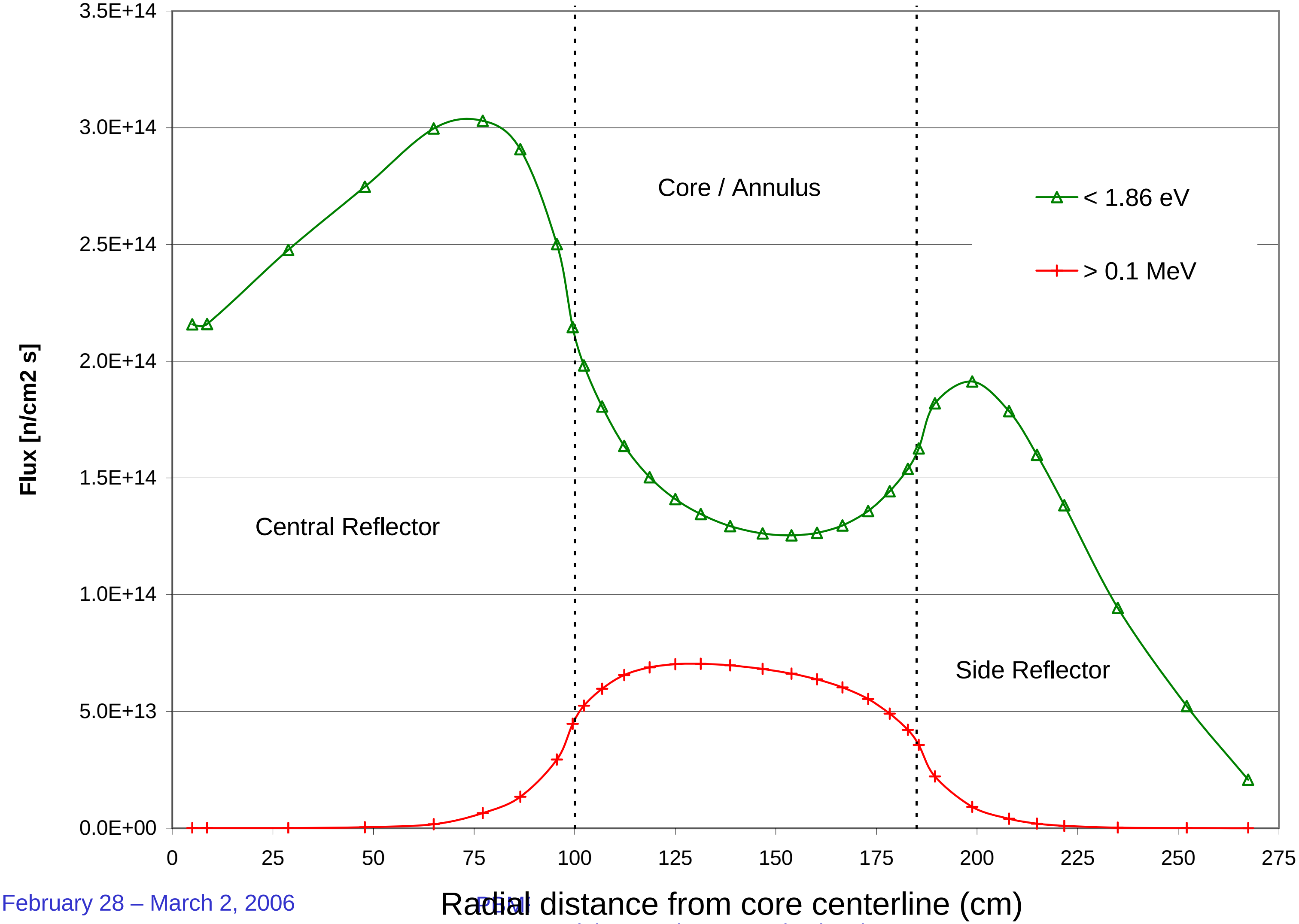
SAS Return Pipe – Coaxial pipe fixed to outside of RPV for pneumatic conveying of SAS to the top of the reactor



SAS Discharge – Coaxial tube responsible for guiding SAS from the borings inside central reflector to the Discharge Vessel

Discharge Vessel – Vessel situated on RPV responsible for stopping SAS flow from the borings and fluidizing SAS for conveying to the top of the reactor

Typical Radial Neutron Flux Distribution



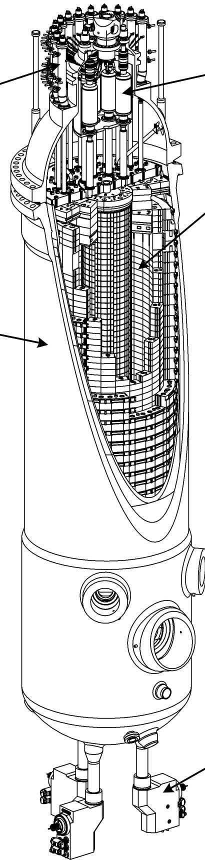
Core Performance

Description	Units	Value
Number of fuel spheres		**~452 000**
Number of fresh fuel spheres loaded per day		**~489**
Average number of fuel spheres circulated per day		**~ 2 936**
Power peaking (regions with mixture of passes)	Q_{max}/Q_{ave}	**2.3**
Power peaking in fuel sphere batches	P_{max}/P_{ave}	**3.1**
Maximum expected power per fuel sphere	**kW/FS**	**2.8**
Average core power density	MW/m^3	**4.78**
Maximum fuel temperature during normal operation	**°C**	**1057**
Average thermal flux (< 1.86 eV)	$10^{13} n.cm^2.s$	**7.69**
Average fast flux (> 0.1 MeV	$10^{13} n.cm^2.s$	**3.31**

Temperature Coefficients at Operating Conditions

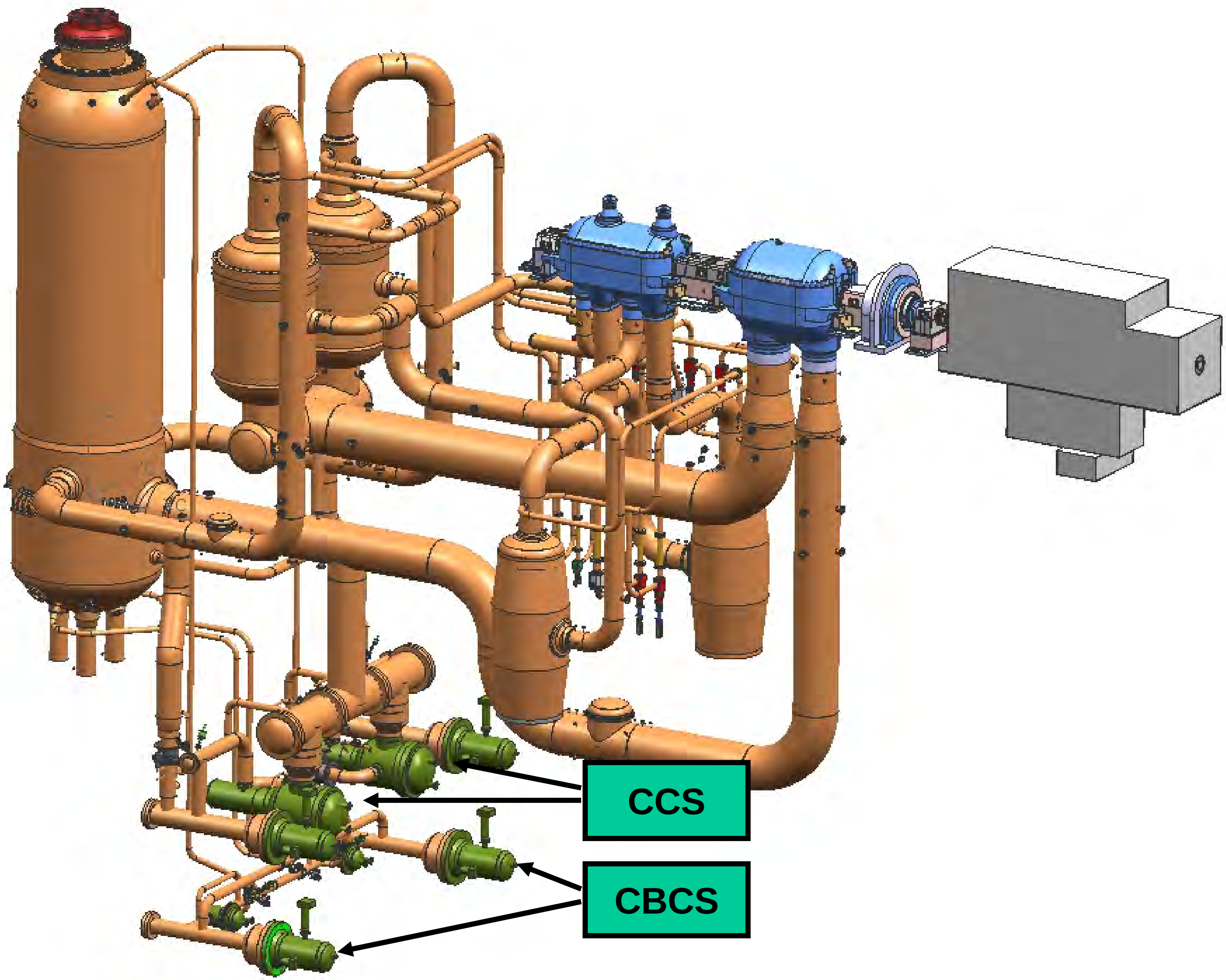
Description	Unit	Value
Fuel (Doppler coefficient of U-238)	**Δk/°C**	**-3.30×10^{-5}**
Moderator	**Δk/°C**	**-3.28×10^{-5}**
Centre Reflector	**Δk/°C**	**$+1.66 \times 10^{-5}$**
Side Reflector	**Δk/°C**	**$+1.26 \times 10^{-5}$**
TOTAL	**Δk/°C**	**-3.66×10^{-5}**

Description of the PBMR Reactor Unit



Core: average height/outer radius	cm	1100 / 185
Core volume	m^3	83.73
Number of core passes of fuel		6
Heavy metal loading of the fuel	g/spher	9
Number of RSS channels		8
Number of RCS channels		24
Start-up fuel enrichment	%	~5.7
Equilibrium fuel enrichment	%	9.6

CCS and CBCS Layout

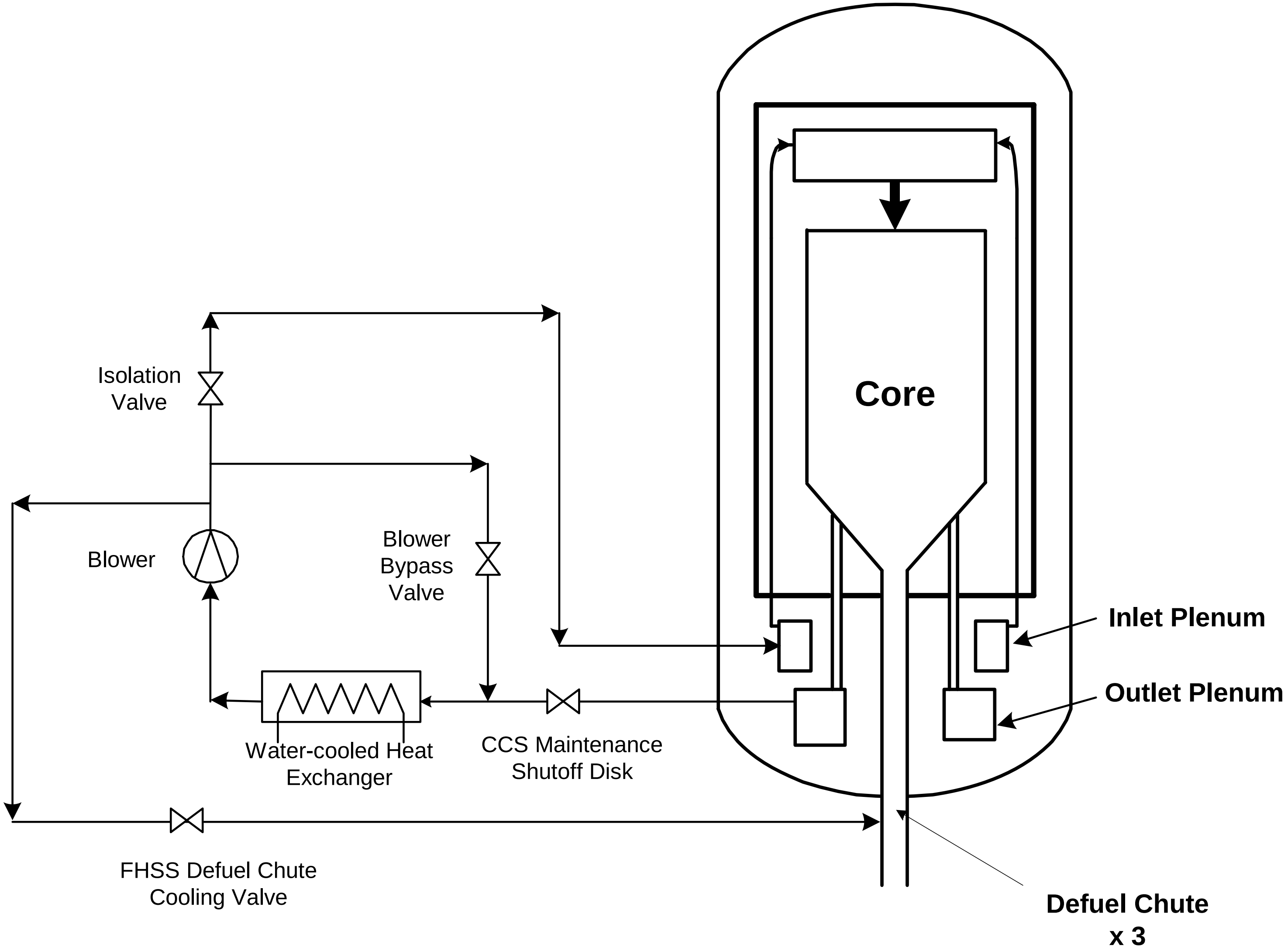


Core Conditioning System (CCS)

The functions of the CCS are to:

- Remove core decay heat from the reactor when the Main Power System is not available.
- Circulate heated nitrogen for the Primary Loop Initial Clean-up System (PLICS). This clean-up system removes moisture from the core graphite structures.
- Provide cooling flow during maintenance to the reactor defuel chute in order to cool the fuel spheres entering the Core Unloading Device.

CCS Process Flow

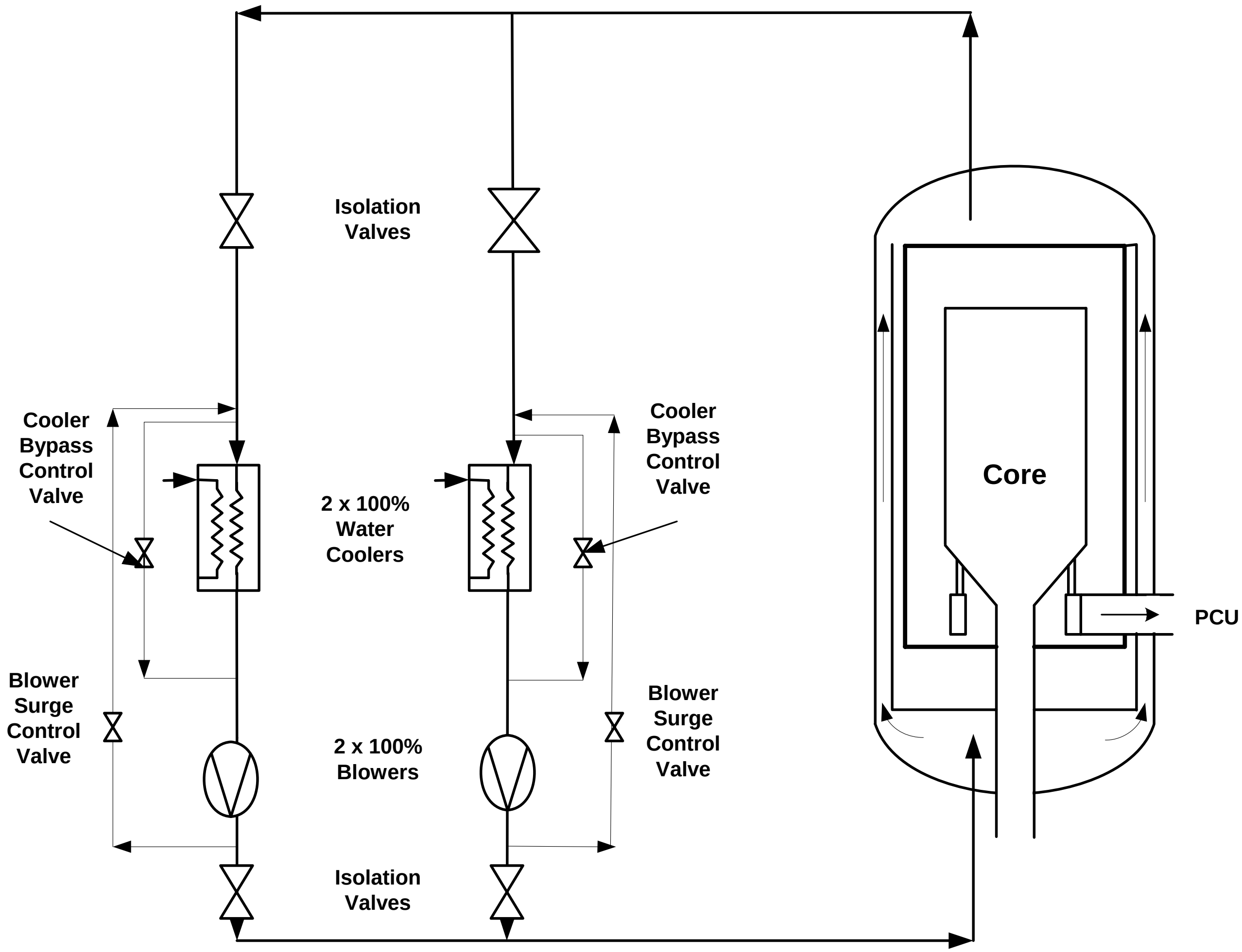


Core Barrel Conditioning System (CBCS)

The functions of the CBCS are to:

- **To control the CB maximum temperature.**
- **To control the minimum temperature of the RPV 'belt line' during all anticipated normal operating conditions during which the reactor is operational and the system is pressurized.**

CBCS Process Flow



Fuel Handling and Storage System

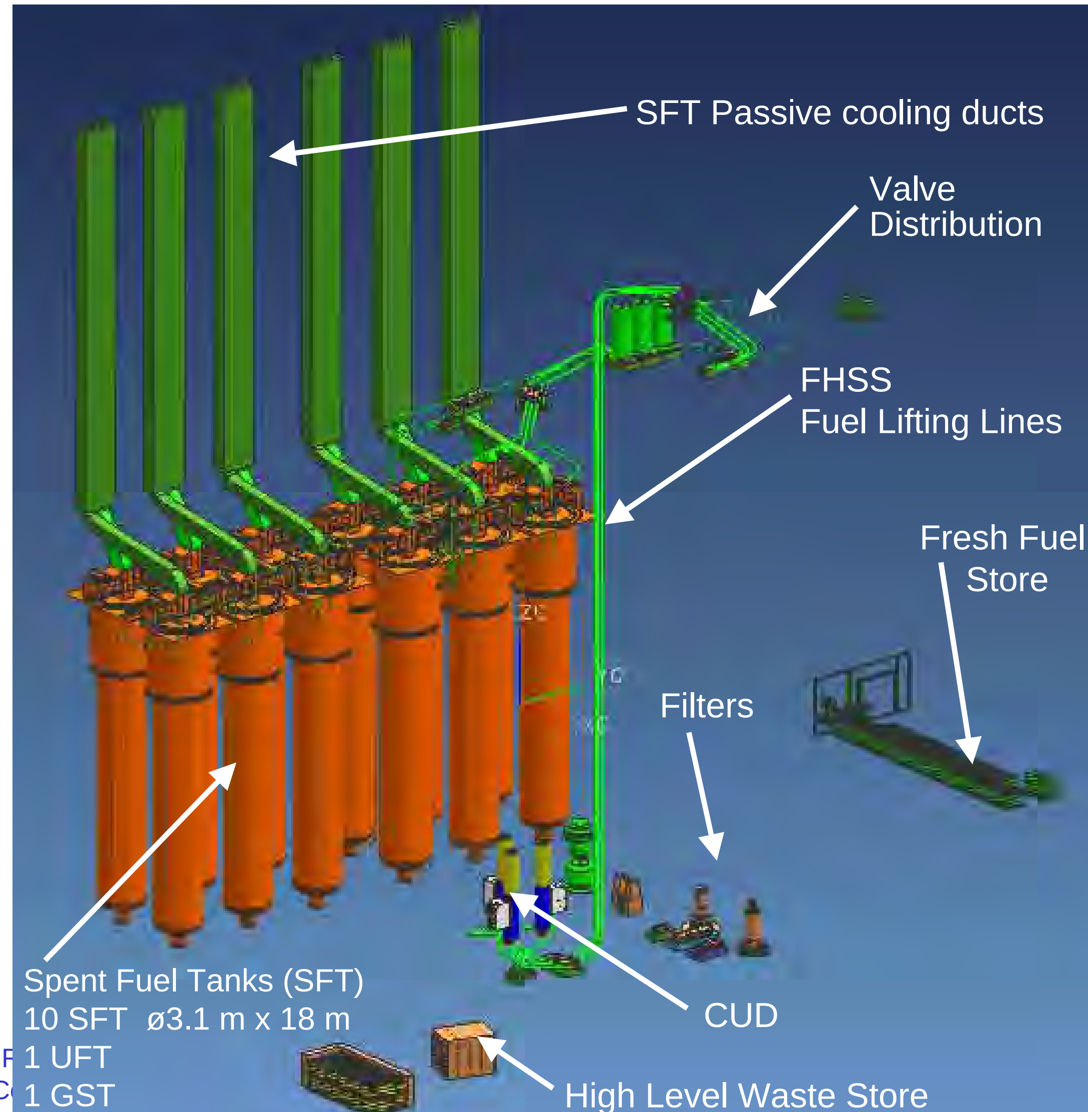
The function of the Fuel Handling and Storage System (FHSS) is to perform all the required fuel manipulations required during the entire life cycle of the PBMR including:

- 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.

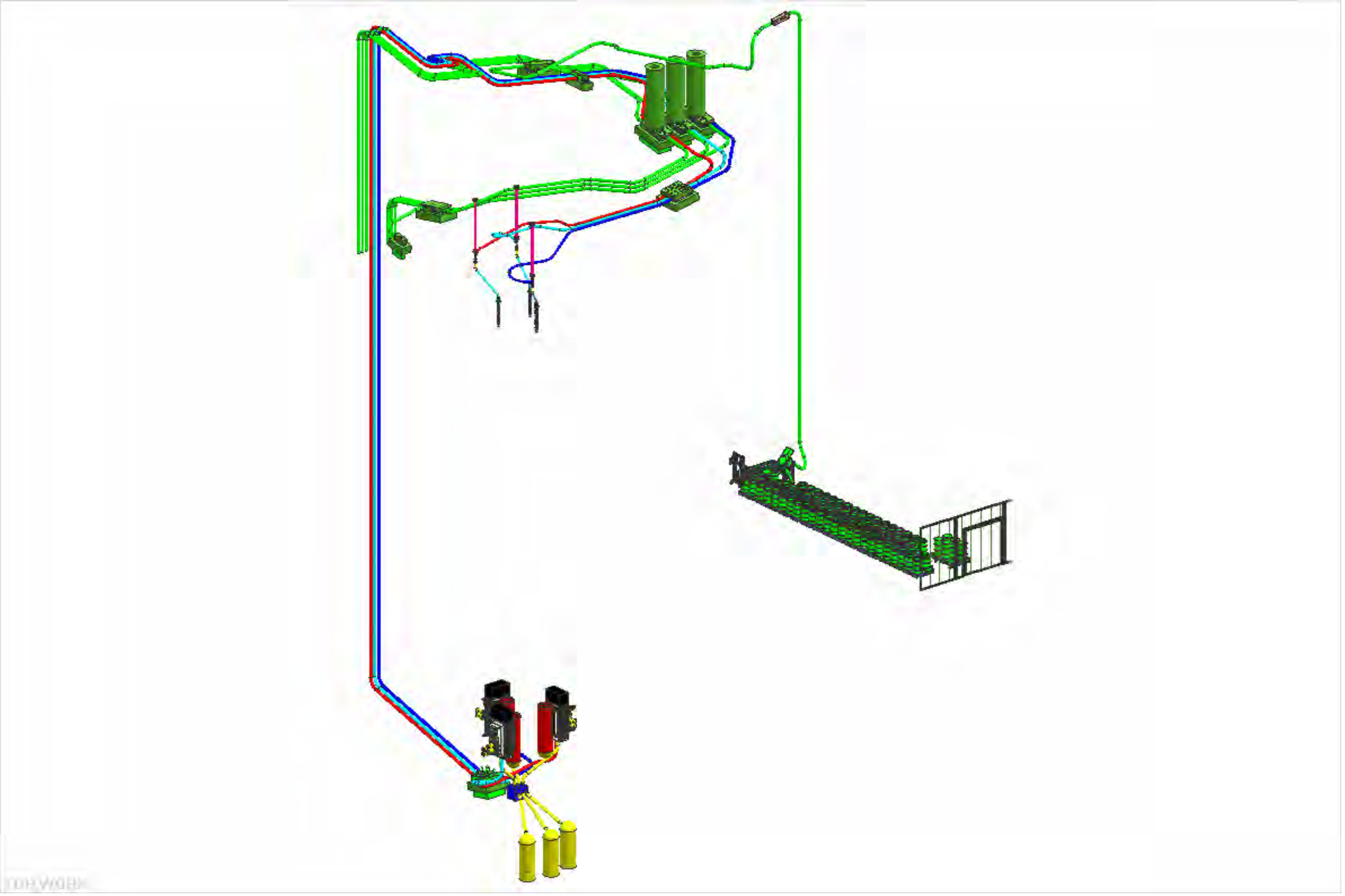
Fuel Handling and Storage System (FHSS)

SPECIFICATION

Medium	Helium
Daily sphere circulation rate	2900
Daily operating time	12 hours
Number of fuel passes through core	6
Operating pressure	1 – 9 MPa
Operating temperature	20 – 260 ºC
Fuel spheres in core	451 555
Fuel sphere feeding points	3
Core defueling points	3
Fresh fuel storage capacity	70 canisters
Fresh fuel canister capacity	1 000 spheres
Spent fuel storage capacity spheres	6 000 000
Number of spent fuel tanks (modular installation as req)	10
Spent fuel period	80 years

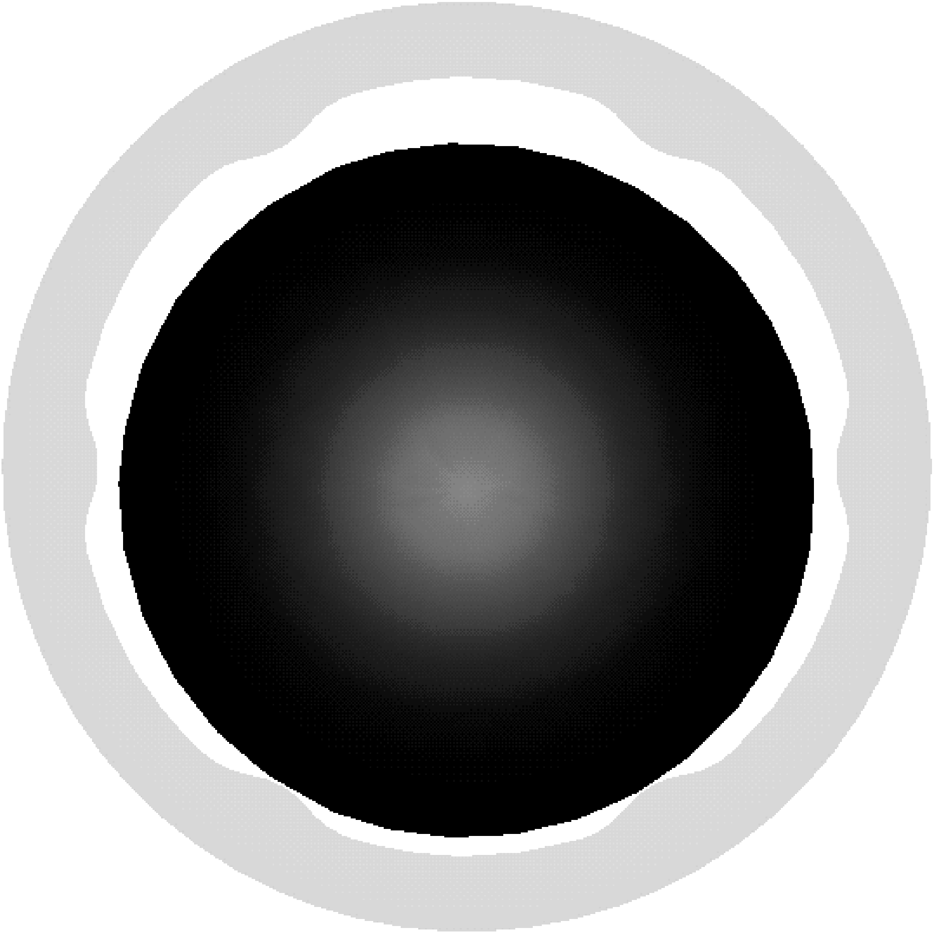


FHSS Fuel Circulation System

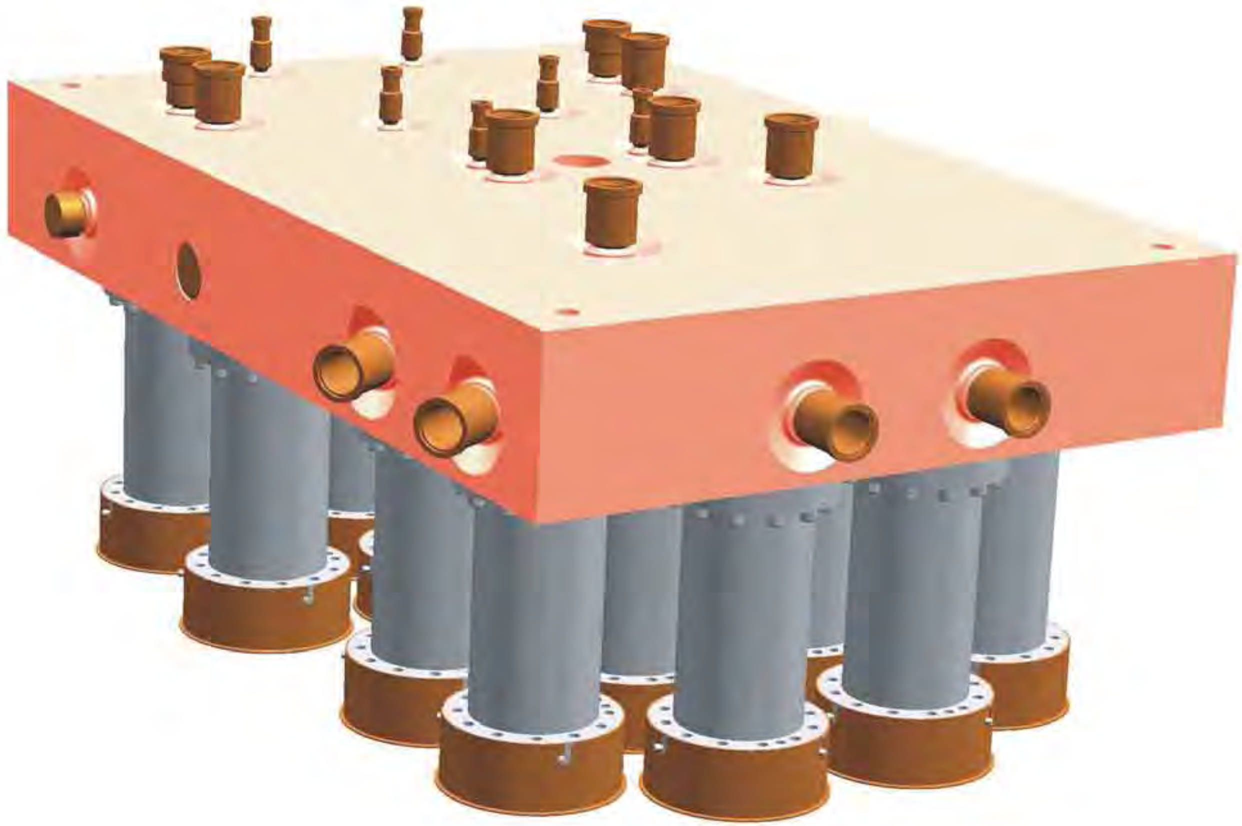


FHSS Piping

- No of ribs: 6
- Pipe OD: 82mm
- Pipe ID: 67 - 63.5mm

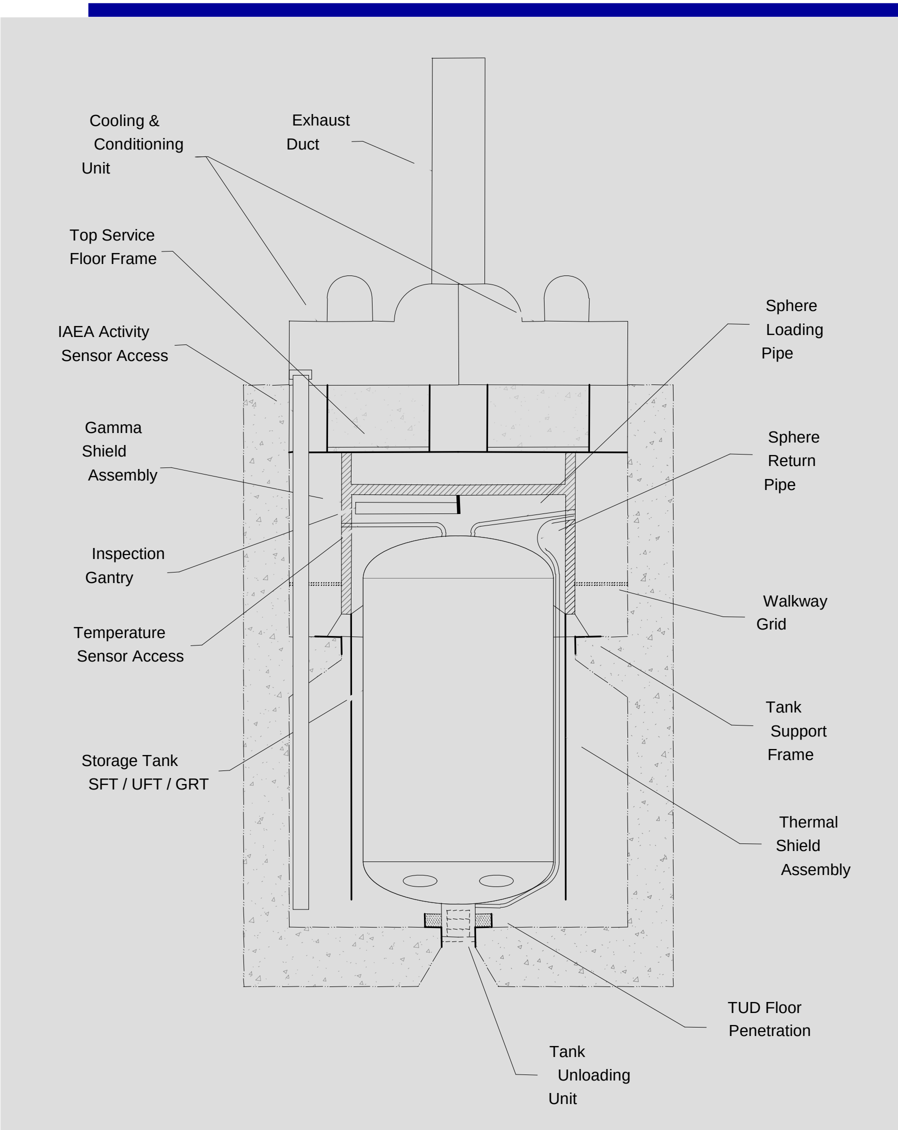


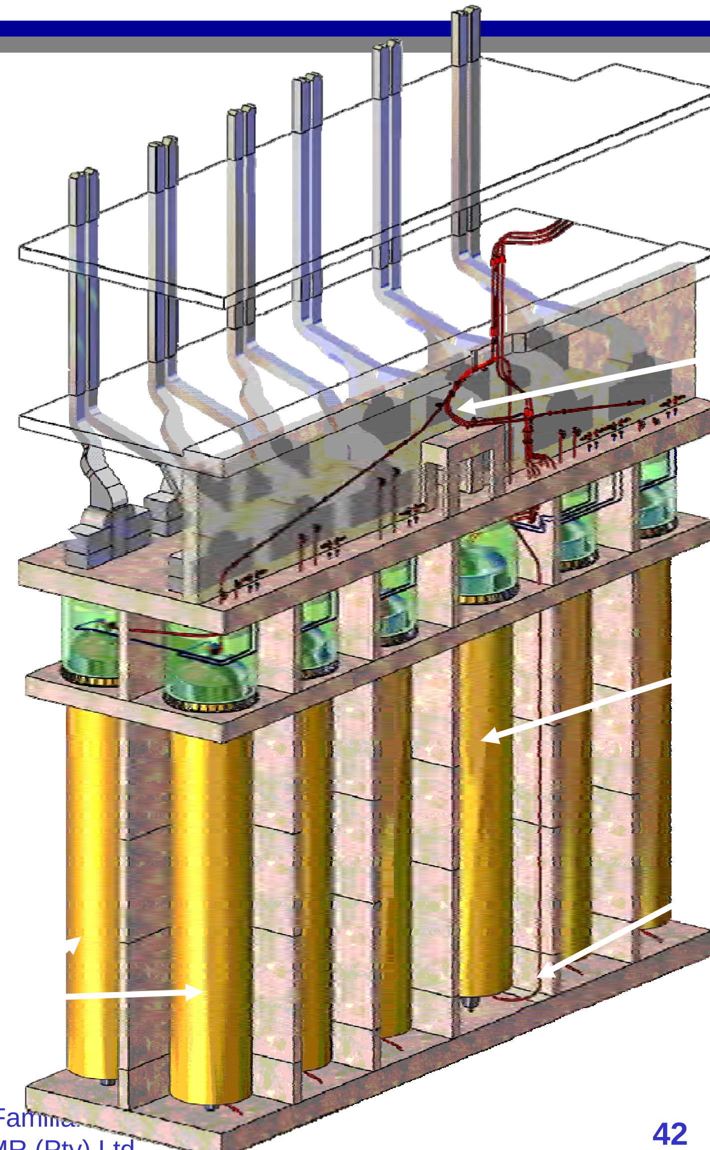
FHSS VALVE BLOCK



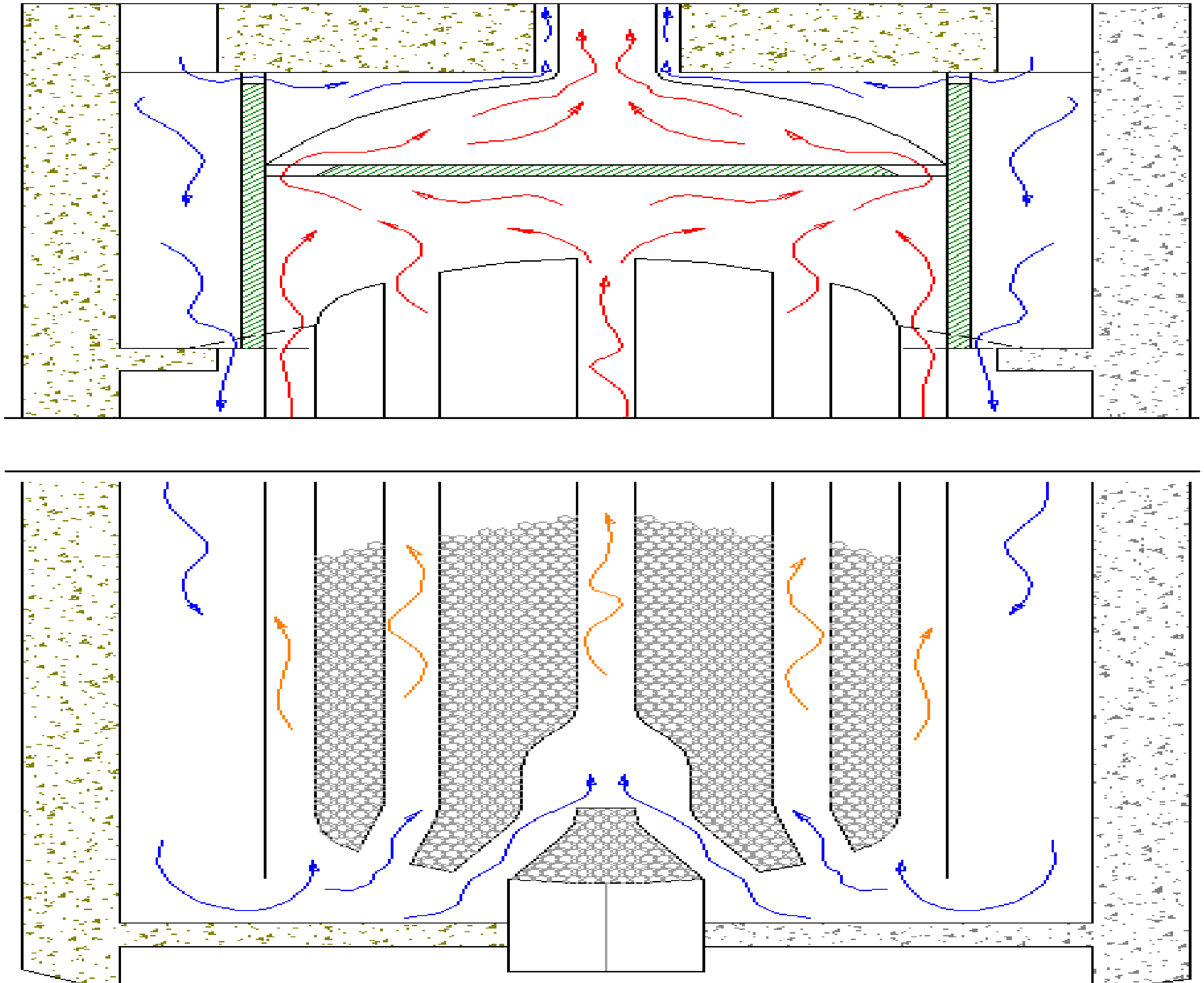
FHSS Valve Insert

FHSS Fuel Storage Unit

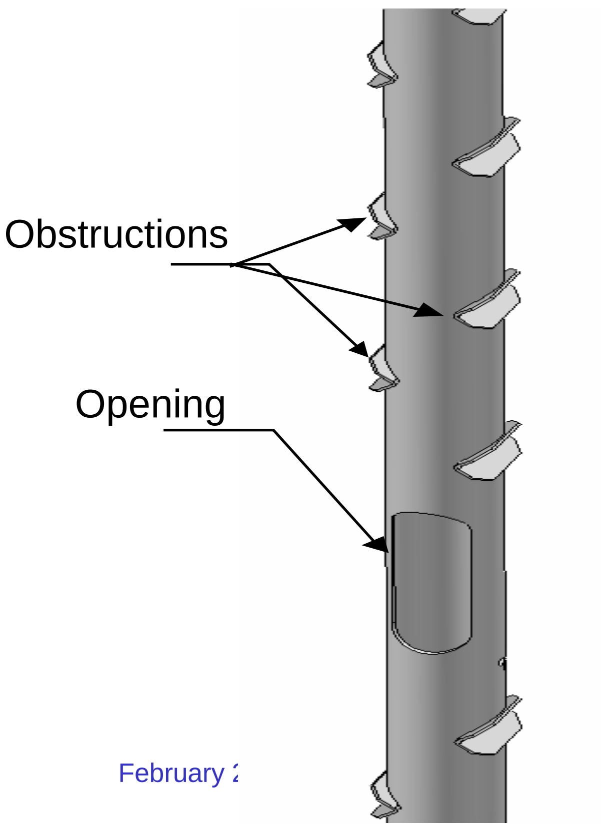


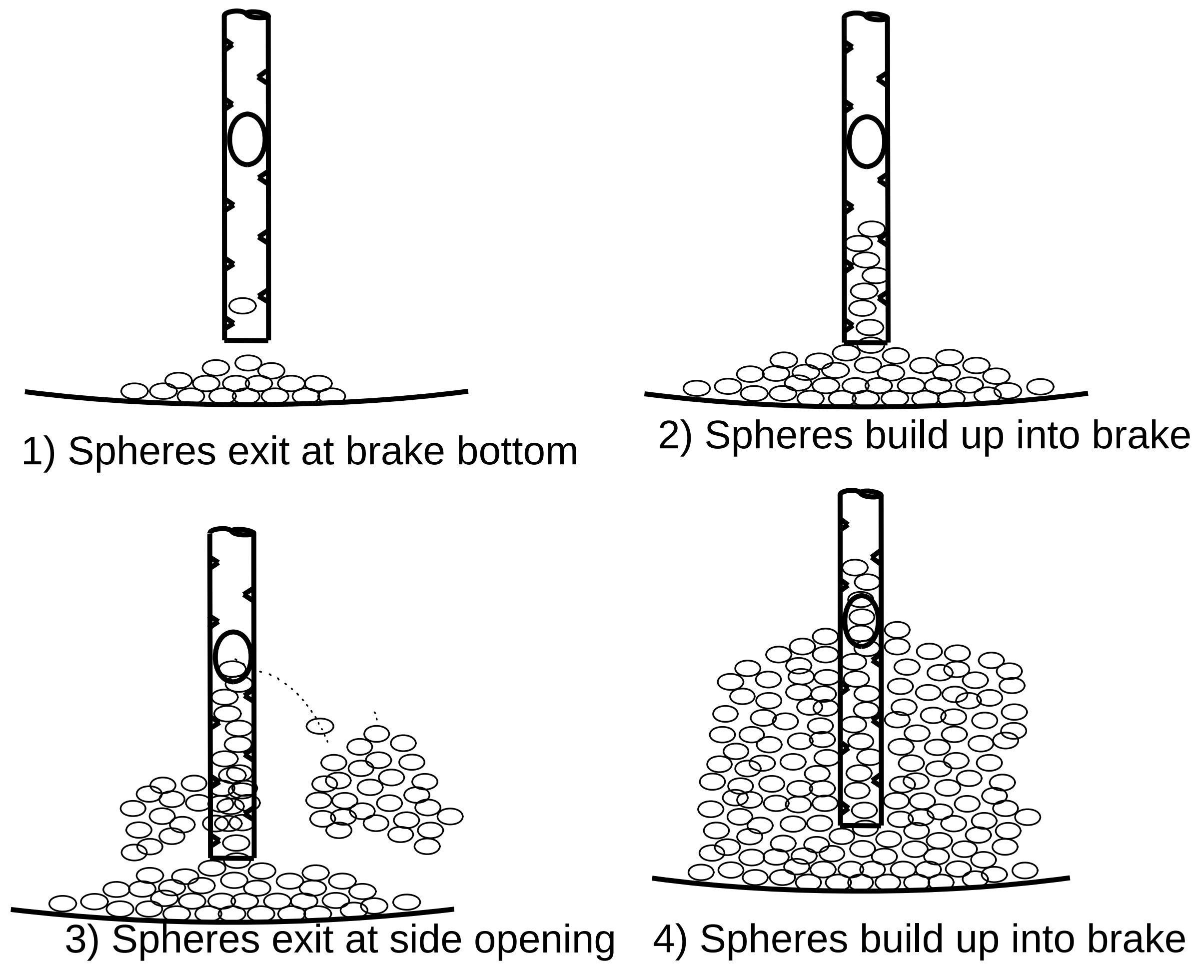


FHSS Storage Tank and Cubicle Airflow

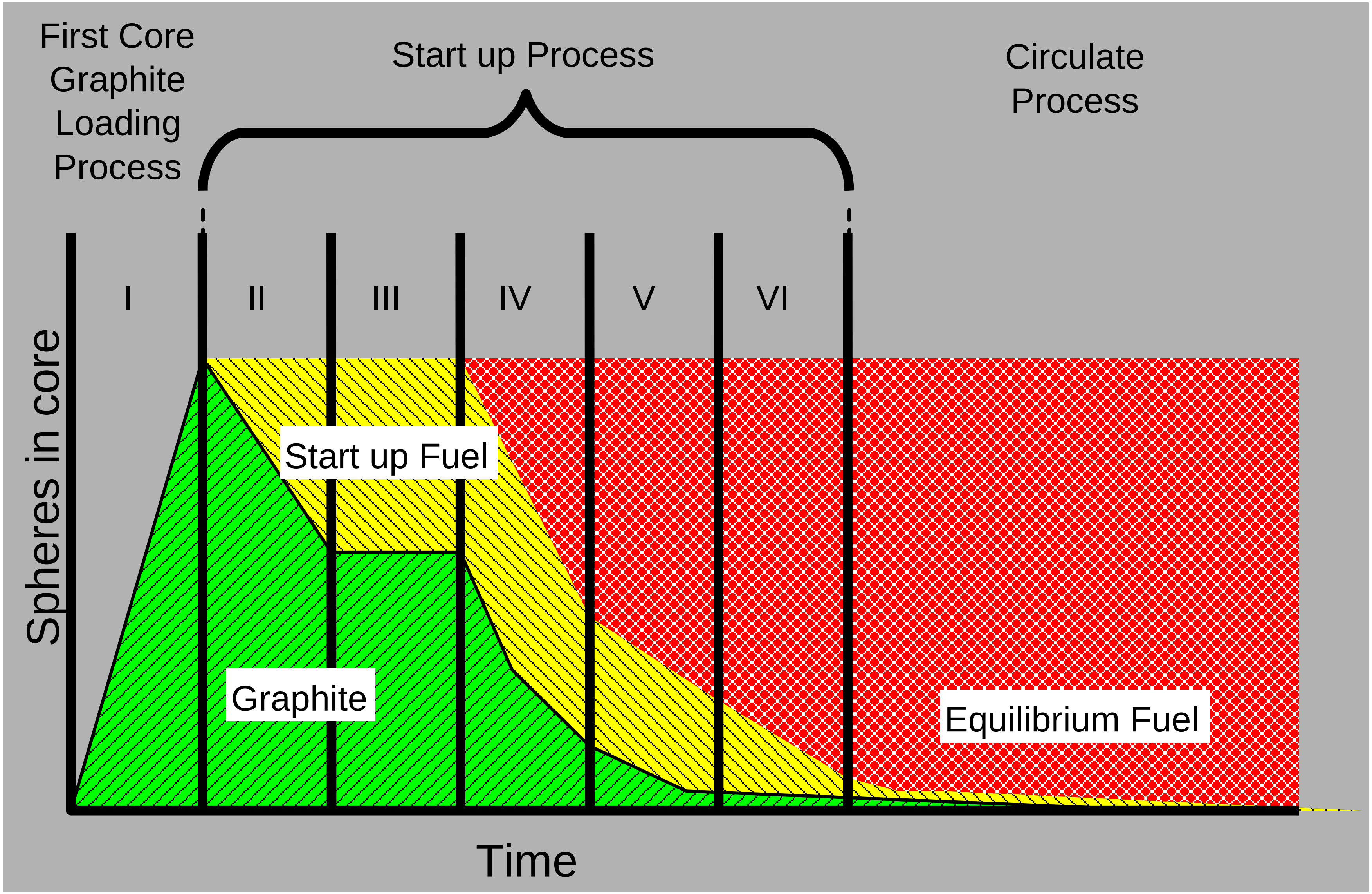


FHSS Mechanical Brake in Storage Tanks



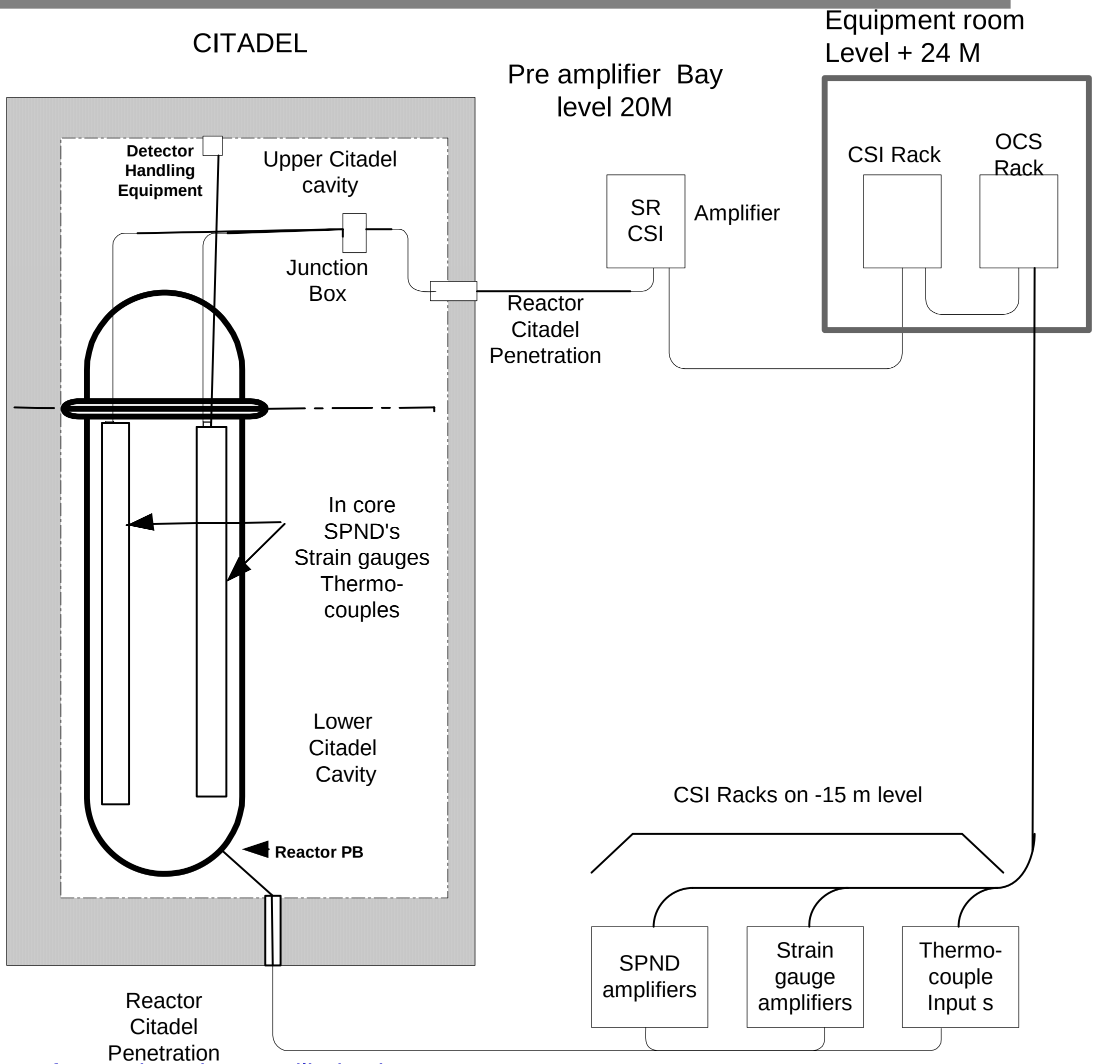


FHSS Fuel Loading



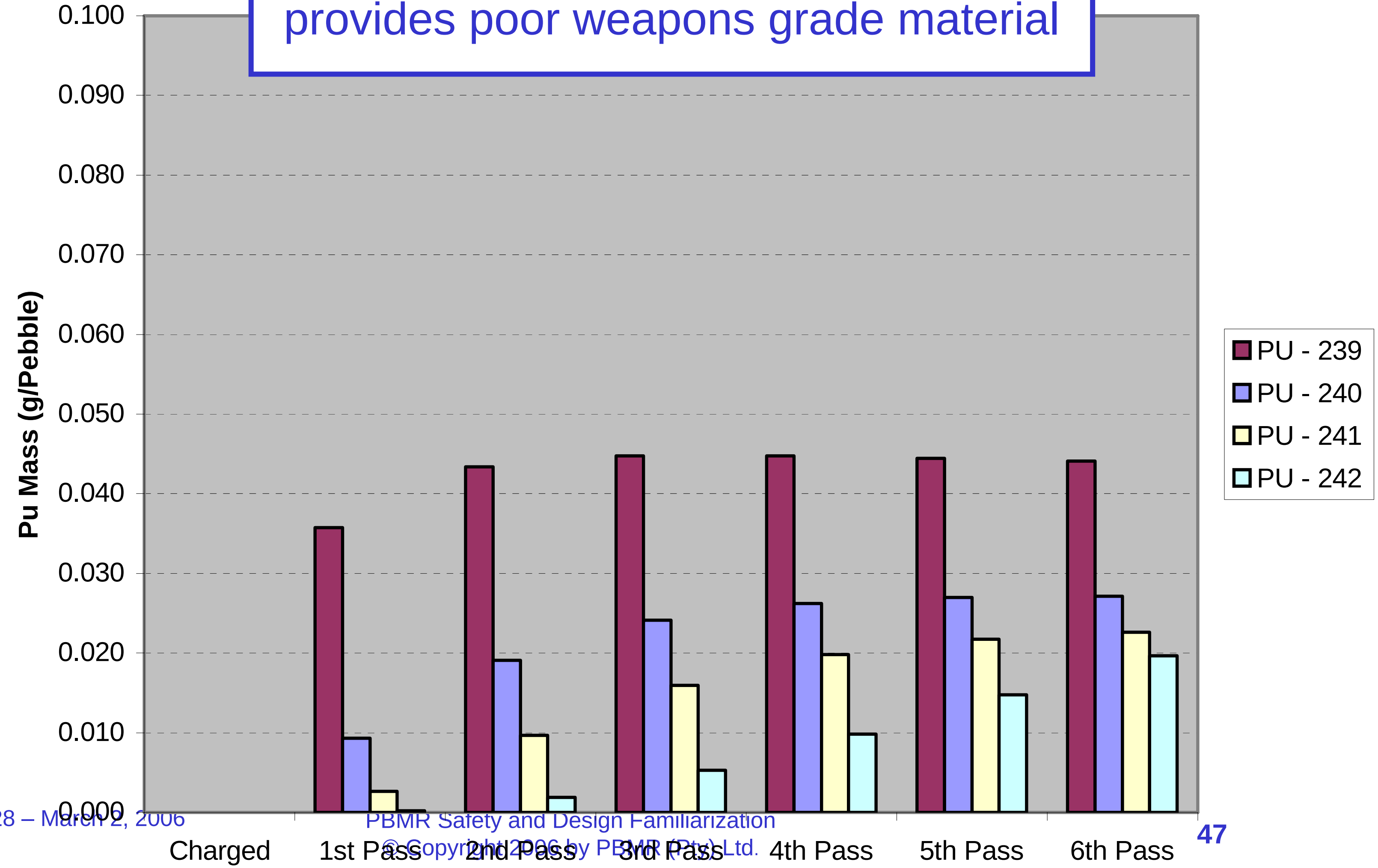
Neutron Source System

To start the reactor with a fresh fuel core, a removable isotopic neutron source is inserted into one of the instrumentation channels until sufficient core neutrons are available to provide a statistically reliable neutron background for start-up.



PBMR Nuclear Materials Safeguards

PBMR Production of Plutonium isotopes provides poor weapons grade material



IAEA Fuel Verification System