PBMR Design Basics

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Presentation Outline

- Design Objective and Process
- Selection of Fuel, Moderator, and Coolant
- Safety Design Approach
- Pebble Bed Core Design
- Fuel Design
- Online Fueling
- Brayton Cycle
- Use of Proven Technologies

PBMR Design Process

Top Requirements

- User/utility
- Regulator
- Vendor
- Government

1. Protect Public

- Select fuel, moderator, coolant w/ inherent characteristics
- Specify fuel quality and performance & size reactor for passive safety

2. Generate Power

- Add features and/or requirements to those for public safety

3. Protect Plant

- Add features and/or requirements to those for safety and power generation

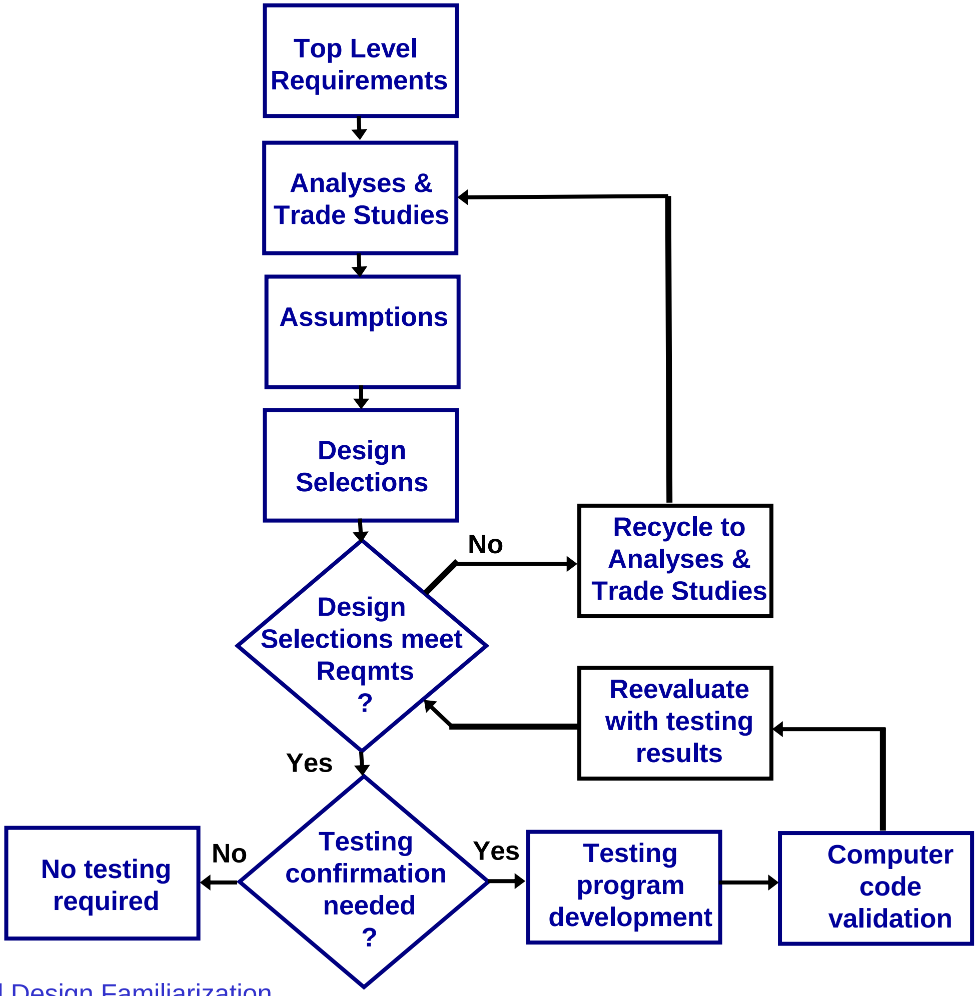
4. Provide Emergency Planning

- Specify emergency planning as needed

PBMR Design Basics

- Objective: Provide safe, economic reliable power
- Select compatible fuel, moderator, & coolant with inherent characteristics
- Utilize proven technologies
- Design reactor with passive safety features

Iterative Design Approach



PBMR Design and R&D Philosophy

- Base the PBMR on technology demonstrated on the AVR, THTR, and other early gas reactors where sufficient successful experience exists
- Utilize materials, components and processes that have a proven nuclear industry track record or proven industrial record to the maximum extent
- Conduct research and development to address technology applications new to the PBMR nuclear applications or where PBMR conditions go beyond existing industry experience data
- Develop test facilities that are capable of additional confirmatory benchmarking of PBMR analytical codes for the PBMR design conditions

Application of German Technology Base to PBMR Design

- **AVR (15 MWe)**
  - Pebble bed core configuration
  - Pebble fuel
  - Steel reactor vessel

AVR (1967-88)

- **THTR (300 MWe)**
  - Reactor and auxiliary component design rules
  - Proven component designs
- **HTR-Module Concept (80 MWe)**
  - Safety concept certification
  - Steel reactor vessel

THTR (1985-89)

THTR Systems, Experience, and Applicability to PBMR

System	Experience	Applicability
Coated Particle	Excellent	Yes
Fuel Element	Excellent	Yes
Graphite Reactor Internals	Good	Yes
Metallic Reactor Internals	Good	Partial
Control Rods (reflector)	Good	Yes
Control Rods (Core)	Poor	N/A
Circulator	Excellent	Partial
Steam Generator	Excellent	N/A
Nuclear Instrumentation	Excellent	Outdated 70's
Control	Good	Outdated 70's
Plant Protection System	Good	Outdated 70's
Fuel Handling System	Good	Yes
Helium Purification System	Excellent	Yes
Misc Auxliary System	Excellent	Partial
HVAC	Fair	Partial

Definition of Inherent

Inherent

- *"Existing in something as a permanent or essential attribute"*

Concise Oxford English Dictionary 11th Edition 2004

- *"Existing in someone or something as a permanent and inseparable element, quality or attribute"*

Random House Unabridged Dictionary 1997

Permanent:

- *"Lasting or remaining unchanged indefinitely, or intended to be so"*

Concise Oxford English Dictionary 11th Edition 2004

Inherent Characteristics of PBMR Fuel-Moderator-Coolant

- **Ceramic-coated Fuel**
  - **High temperature capabilities**
  - **Chemical compatibility with coolant and moderator**
- **Graphite Moderator**
  - **High temperature capabilities**
  - **High heat capacity**
  - **Chemical compatibility with fuel and coolant**
  - **Large neutron migration length for neutron stability**
- **Helium Coolant**
  - **Single phase**
  - **Chemically and neutronically inert**
  - **Low stored thermal energy**

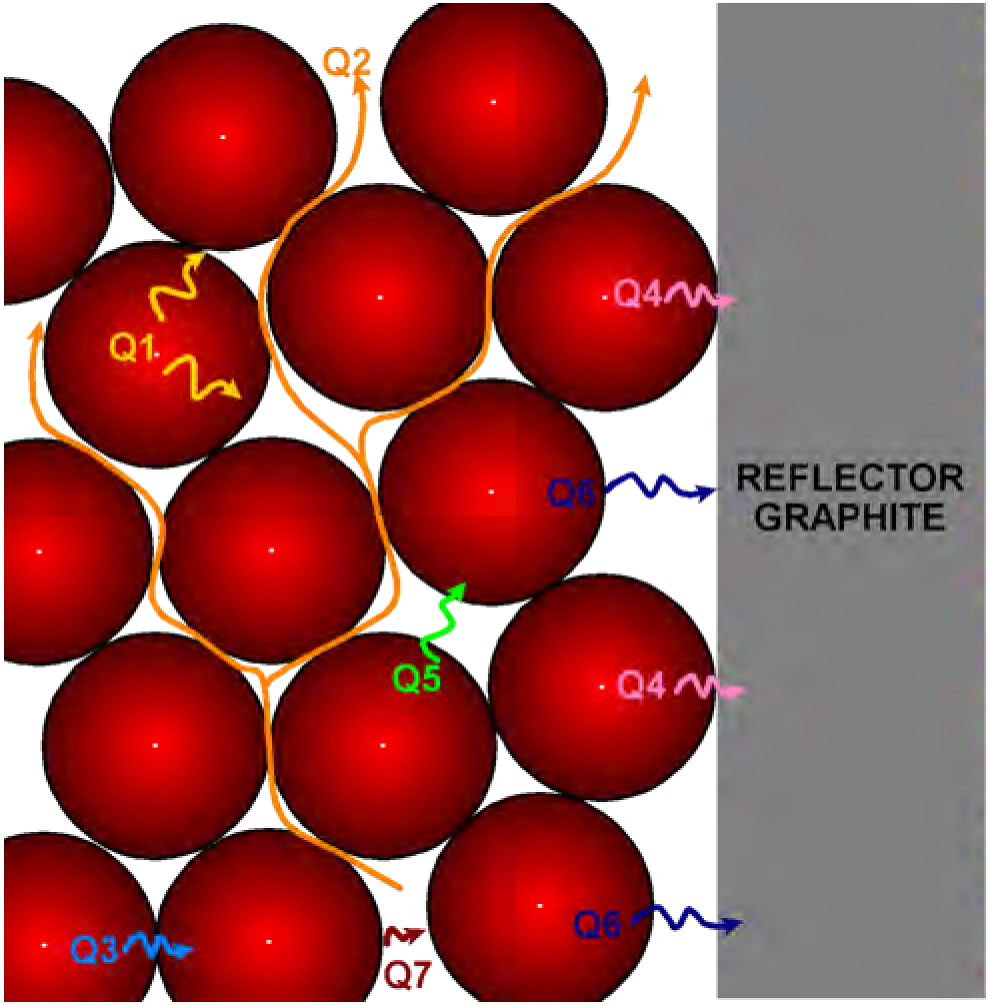
Definition of Passive Design Features

- **Design features engineered to meet their functional requirements *without***
  - Needing successful operation of systems with mechanical actions such as pumps, blowers, HVAC, sprays
  - Depending on availability of electric power
  - Relying on operator actions
- **PBMR passive design features utilize inherent characteristics.**

PBMR Designed with Passive Design Features

- **Core sized and shaped to take advantage of fuel's high temperature capability and graphite's high heat capacity within reactor vessel**
  - Low power density
  - Tall, slender, annular core
  - Uninsulated reactor pressure vessel

Heat Transfer in the Pebble Bed



Q1: Conduction from the centre of the pebble to the surface

Q2: Convection from the pebble surface to the gas

Q3: Point contact conduction between the pebble surfaces that are in contact with one another

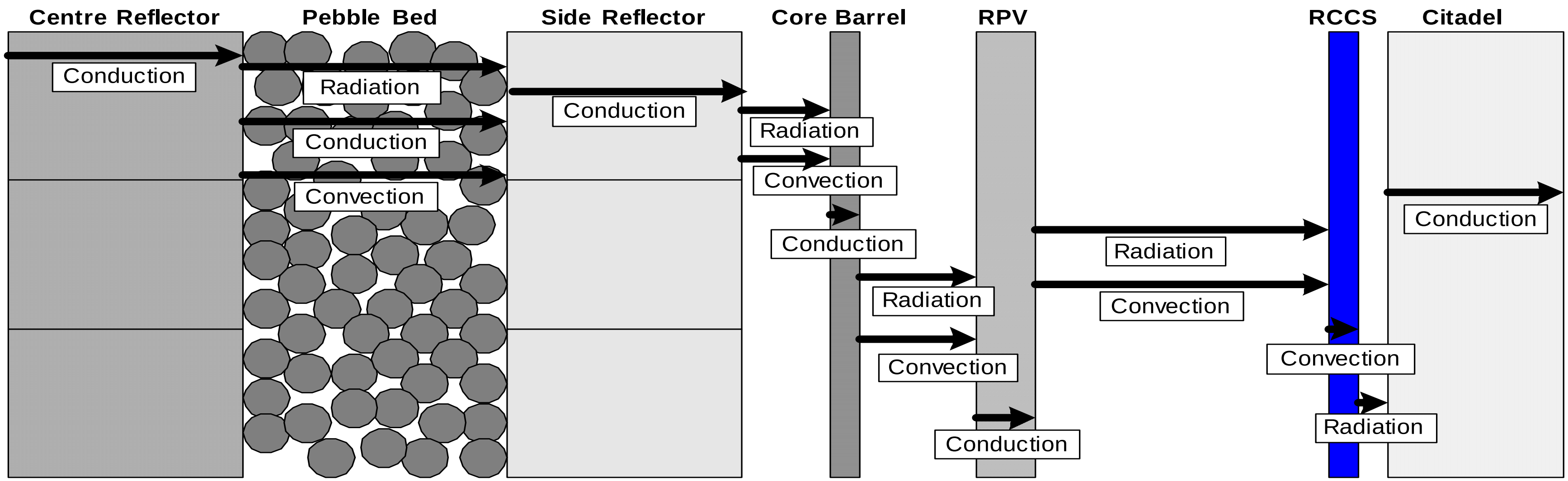
Q4: Point contact conduction between the pebble surfaces that are in contact with the reflector

Q5: Thermal radiation between the pebble surfaces

Q6: Thermal radiation between the pebble surfaces and the reflector

Q7: Conduction in the gas

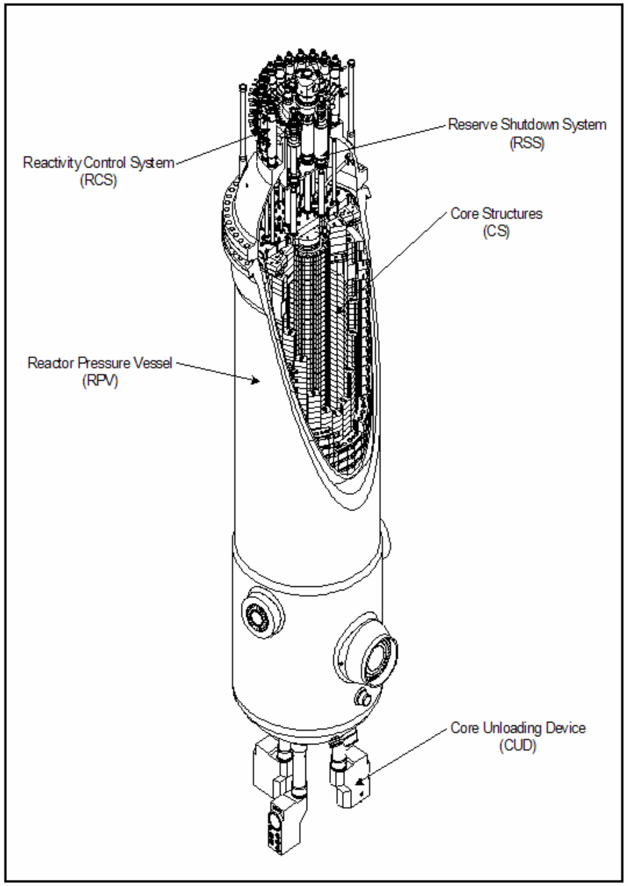
PBMR Passive Heat Transfer

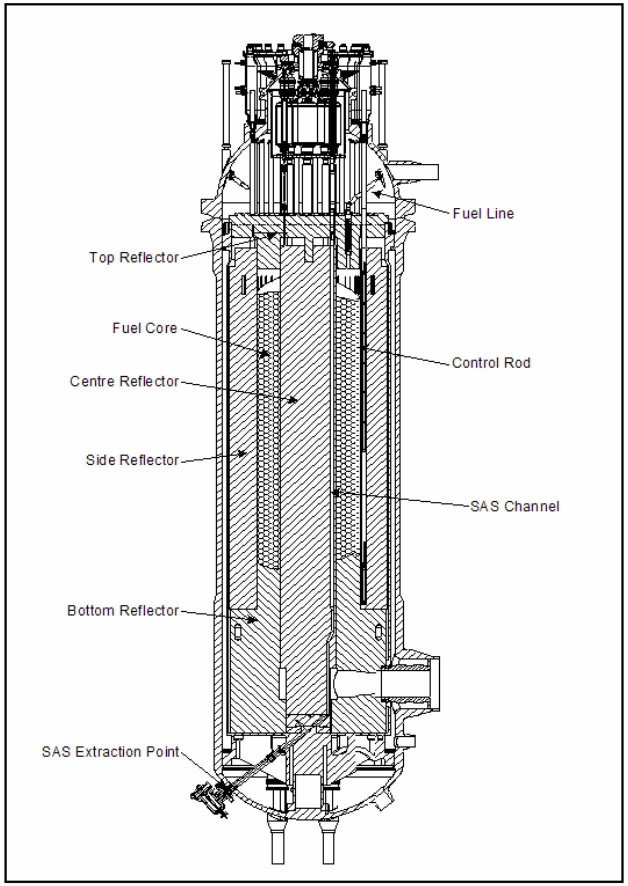


- ***Heat transfer mechanisms are passive and do not require helium coolant pressure.***
- ***Annular core geometry provides for short heat transfer path to the outside of RPV resulting in acceptable fuel temperatures.***
- ***Relatively low thermal power compared to existing reactors***

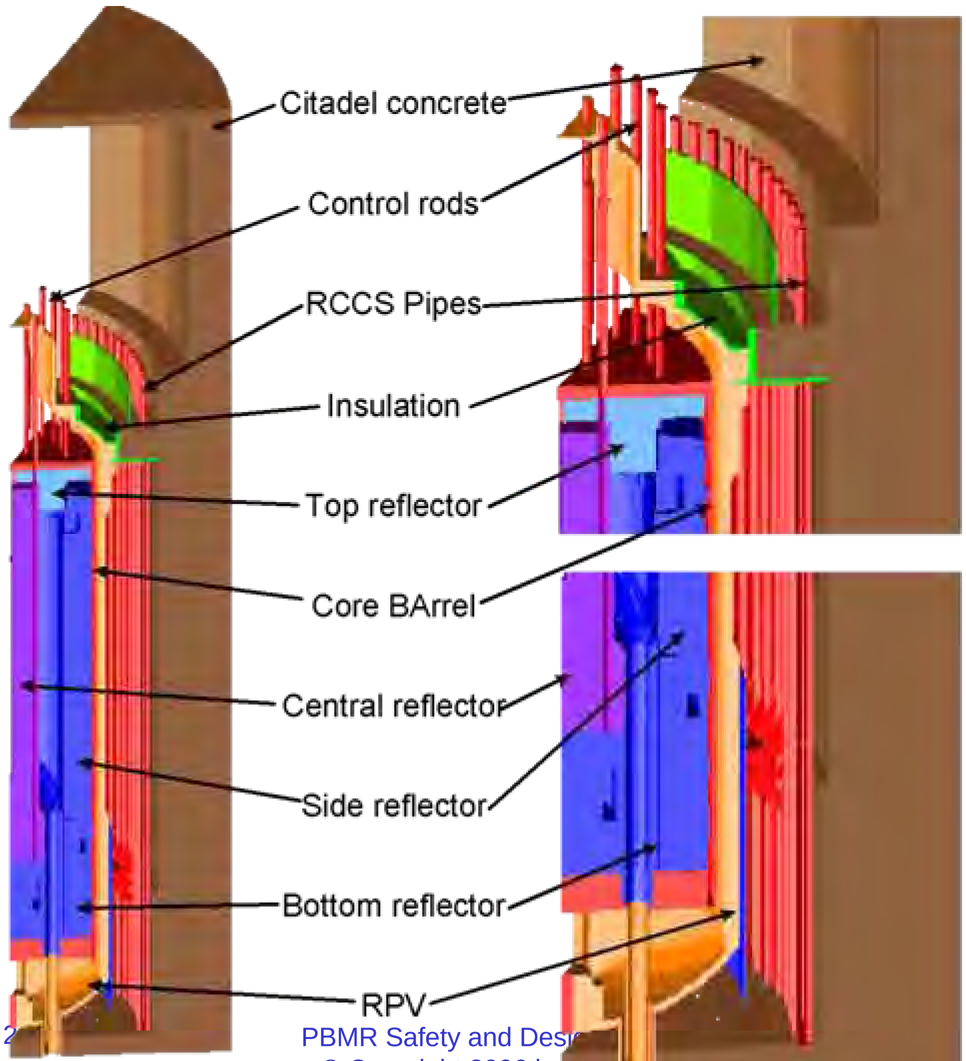
PBMR Core Size and Shape

- ***All ceramic***
- ***Low power density***
- ***Large thermal capacity***



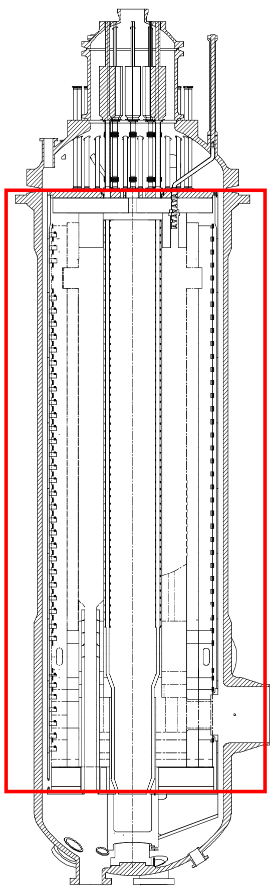


Reactor and Cavity 60° Sector

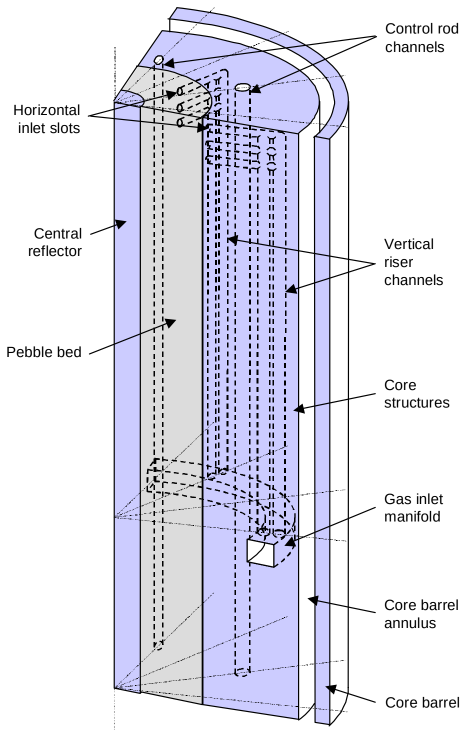


DLOFC Maximum Fuel Temperature Distribution

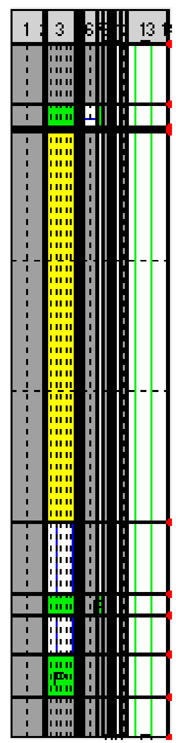
Reactor Layout

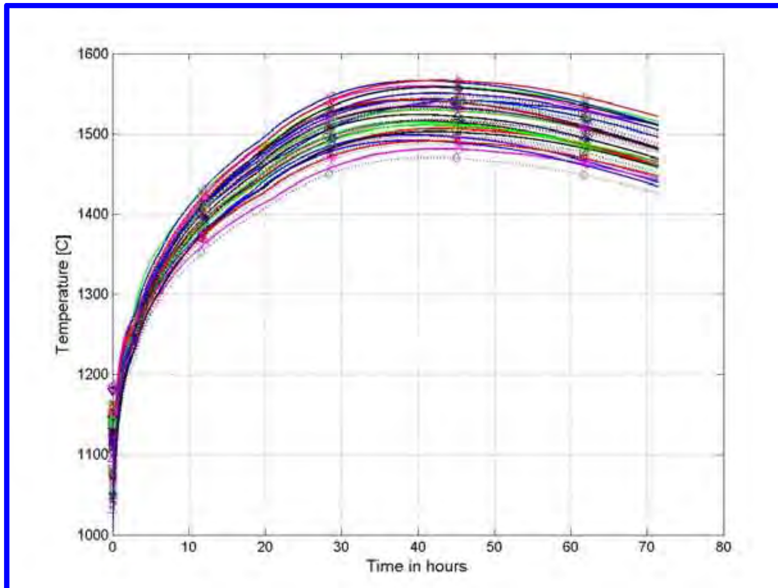


Simplified Model



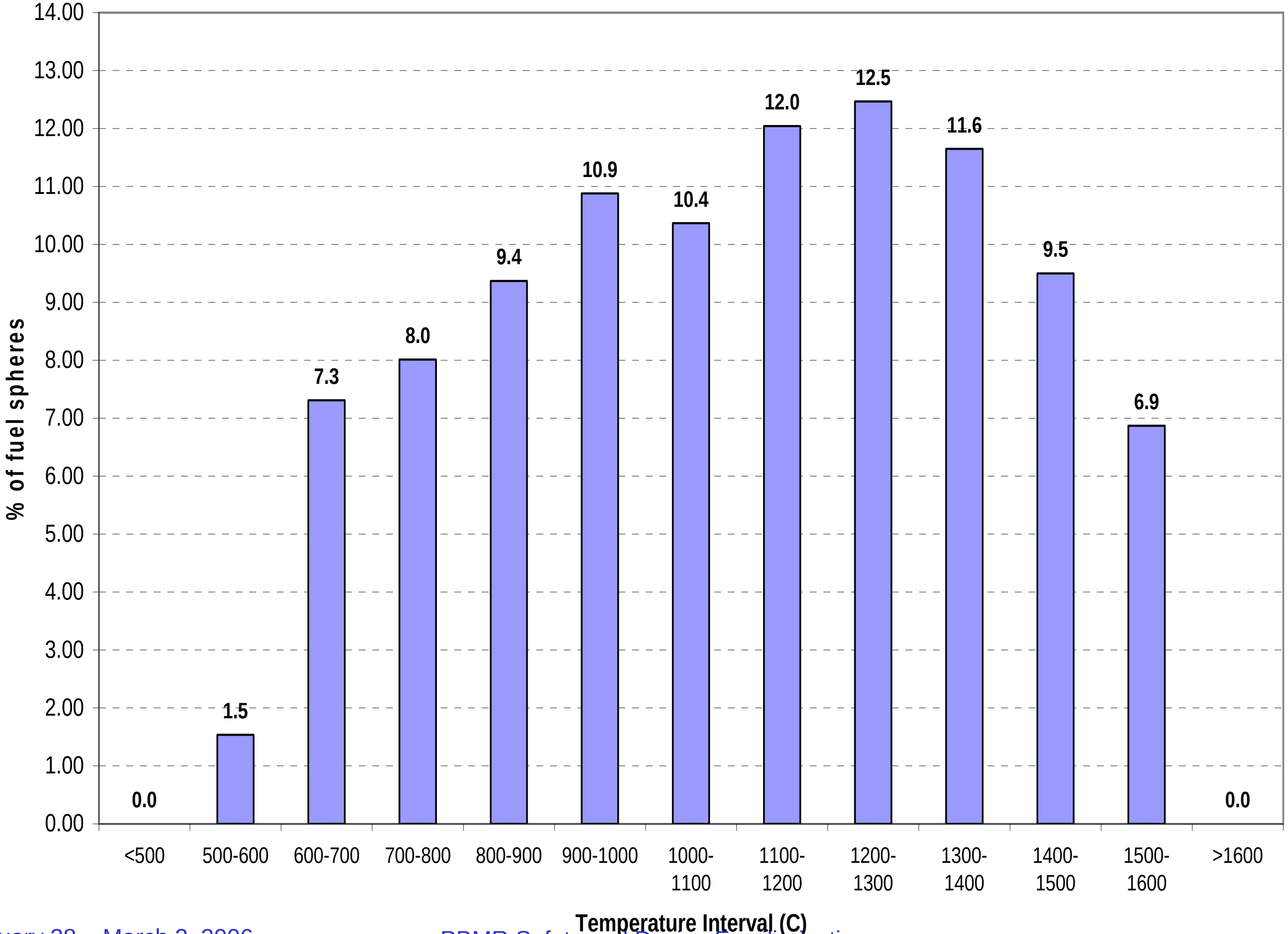
Flownex Model Layout



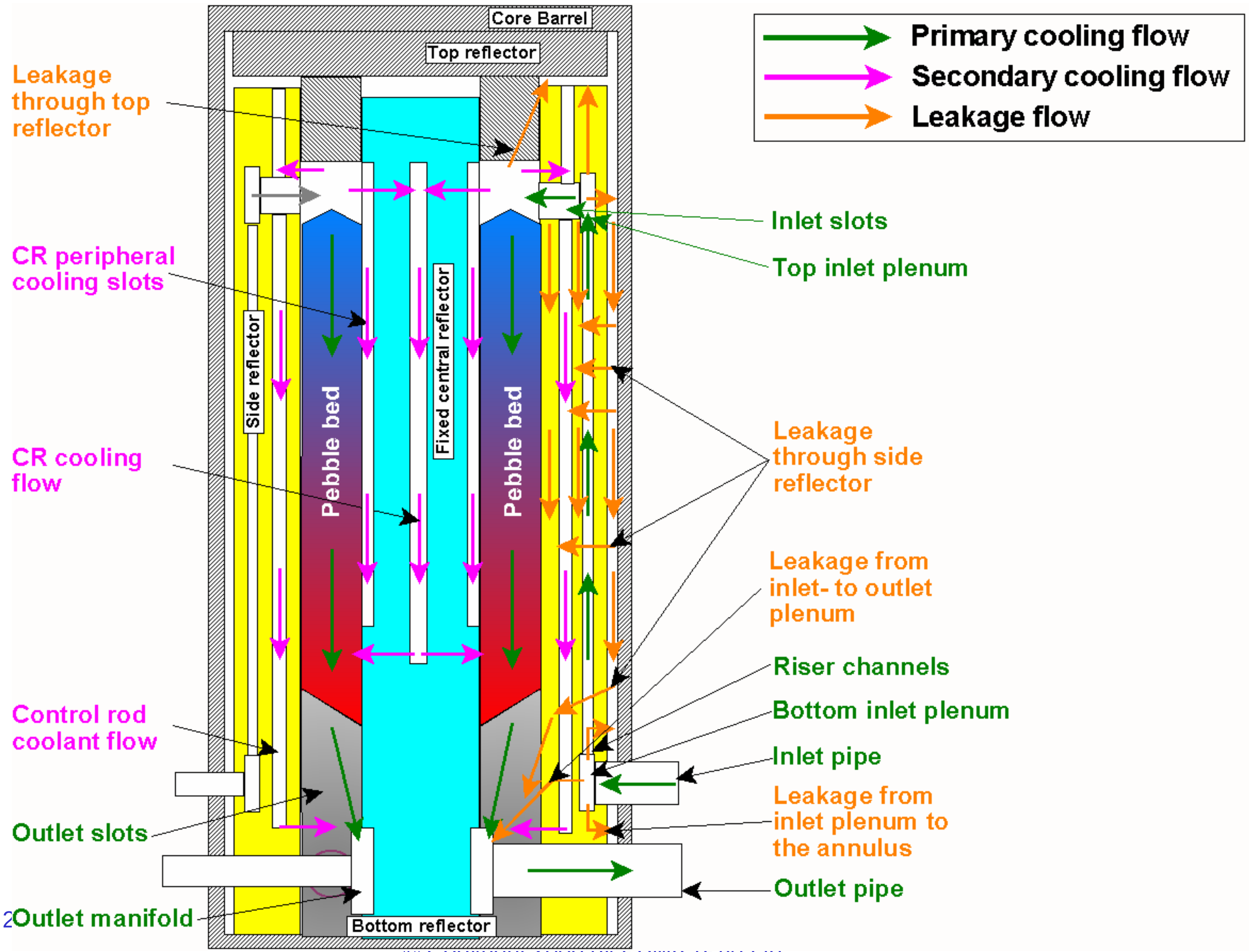


Transient Results

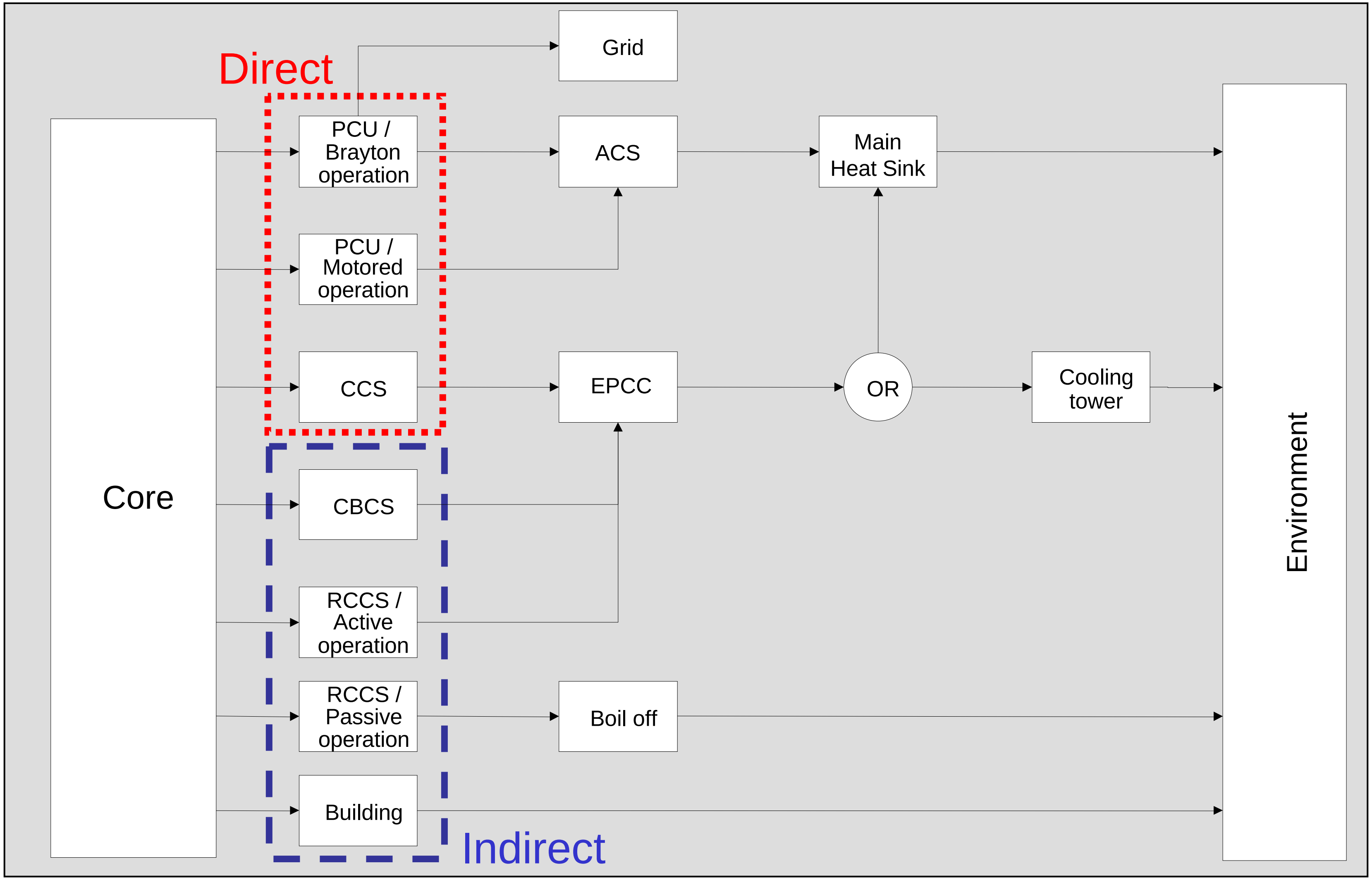
Number of Fuel Spheres In Temperature Intervals during Passive Heat Removal



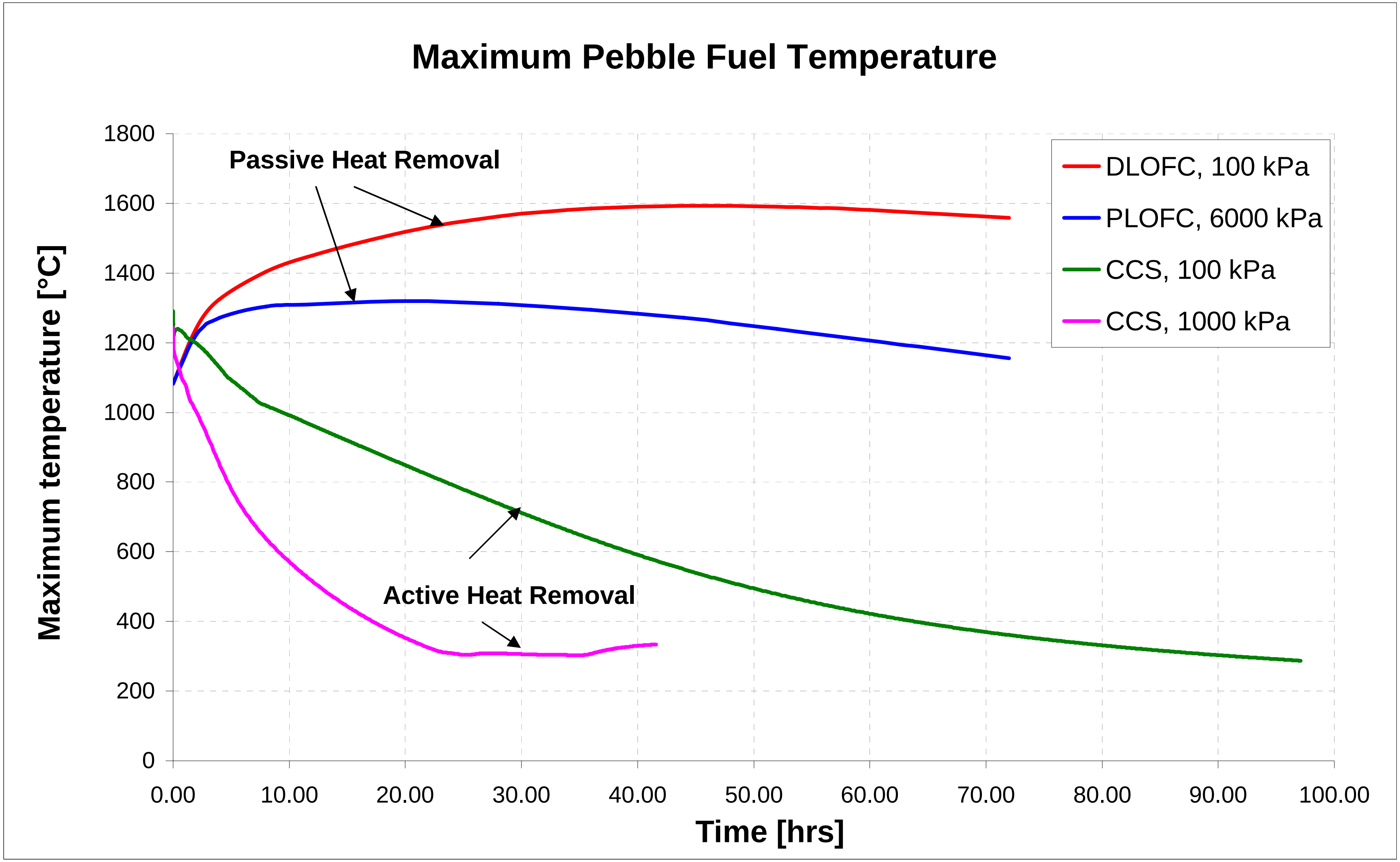
Schematic of Flow Paths in the Core



PBMR Heat Removal Paths



Representative Fuel Temperatures with Passive and Active Heat Removal



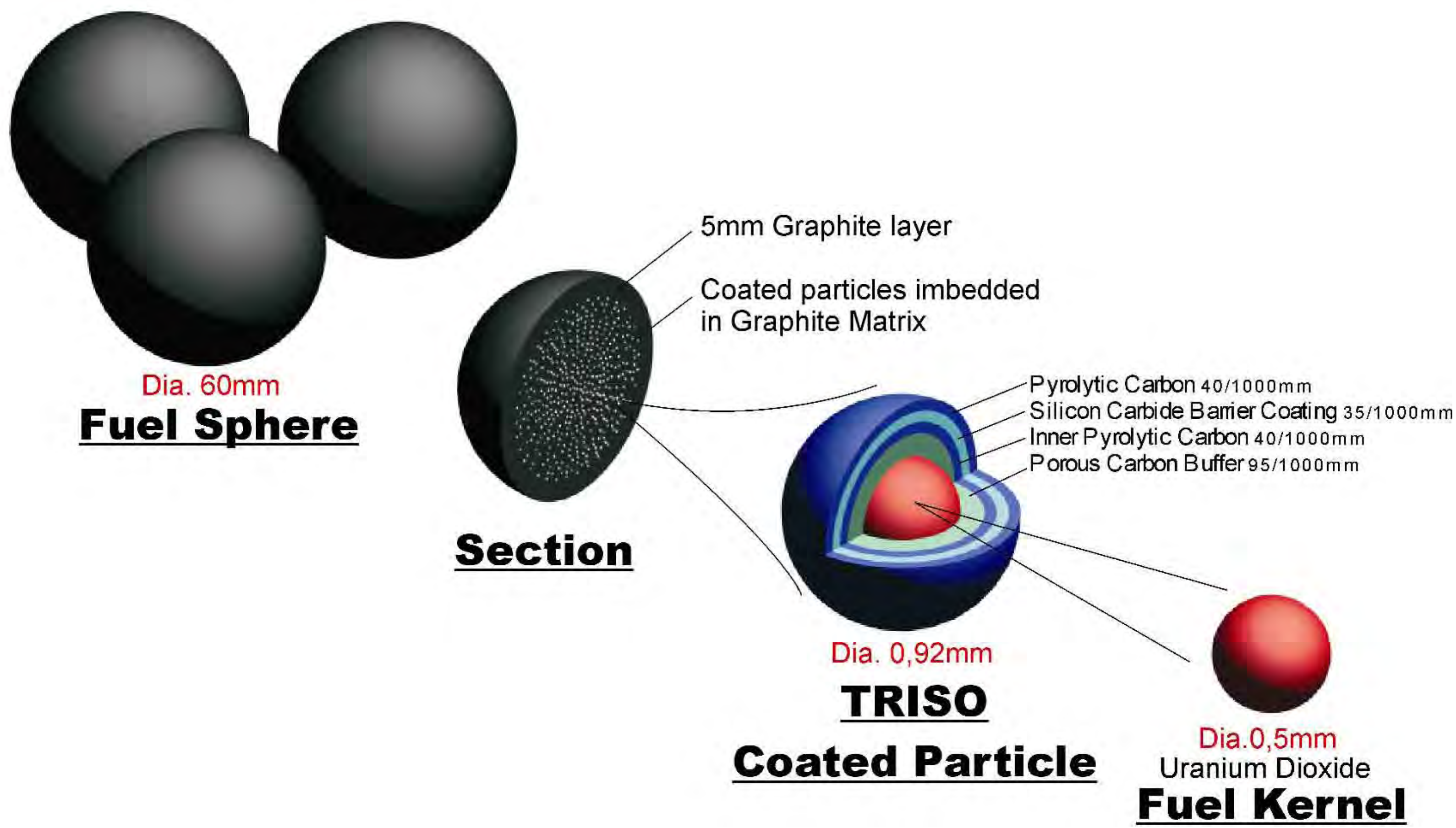
PBMR Designed with Passive Design Features

- **Fuel and core designed to take advantage of pebble bed neutronic features**
  - Large negative temperature coefficient
  - Low excess reactivity
  - Core height limited for xenon stability
  - Annular core provides azimuthal xenon stability
  - Self-regulating behavior due to close fluid-neutronic coupling

PBMR Fuel Design Philosophy

- **Use German final fuel sphere specifications (1988 AVR 21-2 & Proof Test)**
- **Produce a product equivalent to the German product**
- **Specify PBMR operational envelope within that established by German irradiation tests**
- **Perform PBMR-specific irradiation tests**

Fuel Quality and Form



HTR Fuel Sphere Development in Germany

Phases of Coated Particle Testing

1972

$(Th,U)O_2$ BISO
for AVR and THTR

1977

$(Th,U)O_2$ BISO
$(Th,U)O_2$ TRISO
$UC/_{22}$ ThO TRISO
for PNP and HHT

1982

UO_2 TRISO
Material
Testing

1989

UO_2 TRISO
Reference Test
for HTR-Modul
and HTR-500

German Fuel Design Philosophy

- **Develop a stable process that produces a product of consistent quality**
- **Produce a product under strict quality control**
- **Irradiate the product and measure its fission product retention capability**
- **Include the process in the specification**

Definition of Manufacturing Equivalence

- **Using the German 1988 specification – which includes the specification of the coating process**
- **Using ‘similar’ direct materials**
- **Using the same manufacturing process and identical equipment for critical processes**
- **Using the same QC process**

Why Pebble Bed?

- **Continuous fueling**
- **Constant core conditions**
- **Burn-up improvement**
- **Core outlet temperatures**
- **Flexibility in core design**
- **Mass fuel production**
- **Spent fuel handling and storage**

Continuous Fueling

- **Planned availability higher because of continuous fueling**
  - THTR and AVR experience support PBMR estimates.
- **Design only needs small excess reactivity for load following purposes**
  - PBMR excess needed is 1.3% Δk for 40 to 100% control

Core Conditions Are Constant

- **Equilibrium core is constant for plant life**
  - Equilibrium core conditions exist for > 90% of plant life.
- **No need to redesign core at every outage**
  - After defueling outage equilibrium core conditions are restored in a few months.
- **Small top to bottom fuel mixture difference**
  - Average burn-up difference between top & bottom is less then 10,000 MWd/tU.

Fuel Burn-up

- High fuel utilization
- Base equilibrium burn-up ~92 GWd/mtU
- Equal fuel burn-up for discharged pebbles
- Average core fission product inventory low with continuous removal of spent fuel

Core Operating Temperature

- High core outlet temperature beneficial to direct cycle
- Direct cooling of spheres gives relatively low fuel temperatures.
- Radionuclide releases during normal operations are minimized due to limited peak core temperatures.
- Ag releases are minimized to limit contamination of turbo-machinery.

Flexibility In Core Design

- **Higher enrichment for higher burn-up can be introduced in standard plant design.**
- **Excess reactivity is constantly adjustable by regulating feeding rate of fuel.**

Mass Fuel Production

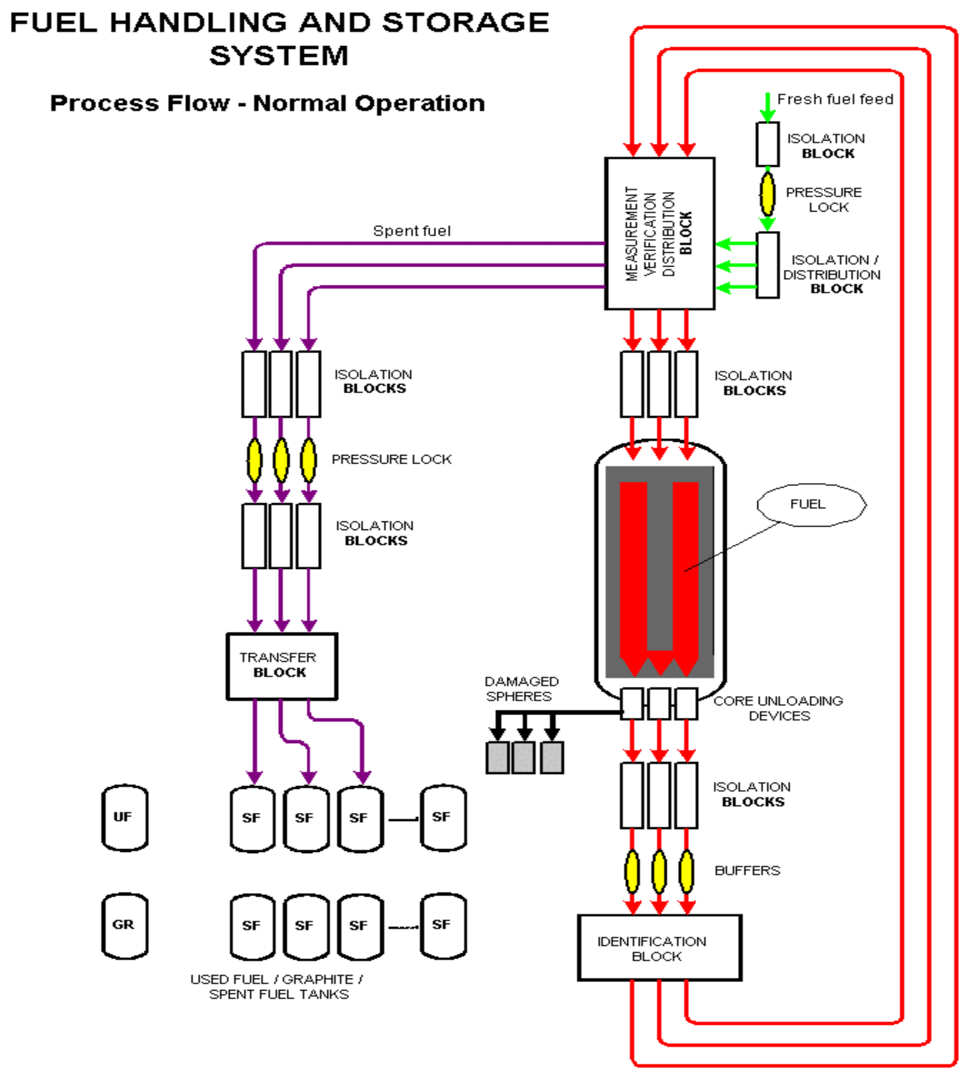
- **Standardized single-enrichment fuel reduces manufacturing costs.**
- **No burnable poisons**
- **Single component fuel element**

Spent Fuel Handling and Storage

- Continuous removal of spent fuel completely automated
- Future higher burn-up will reduce spent fuel volumes.

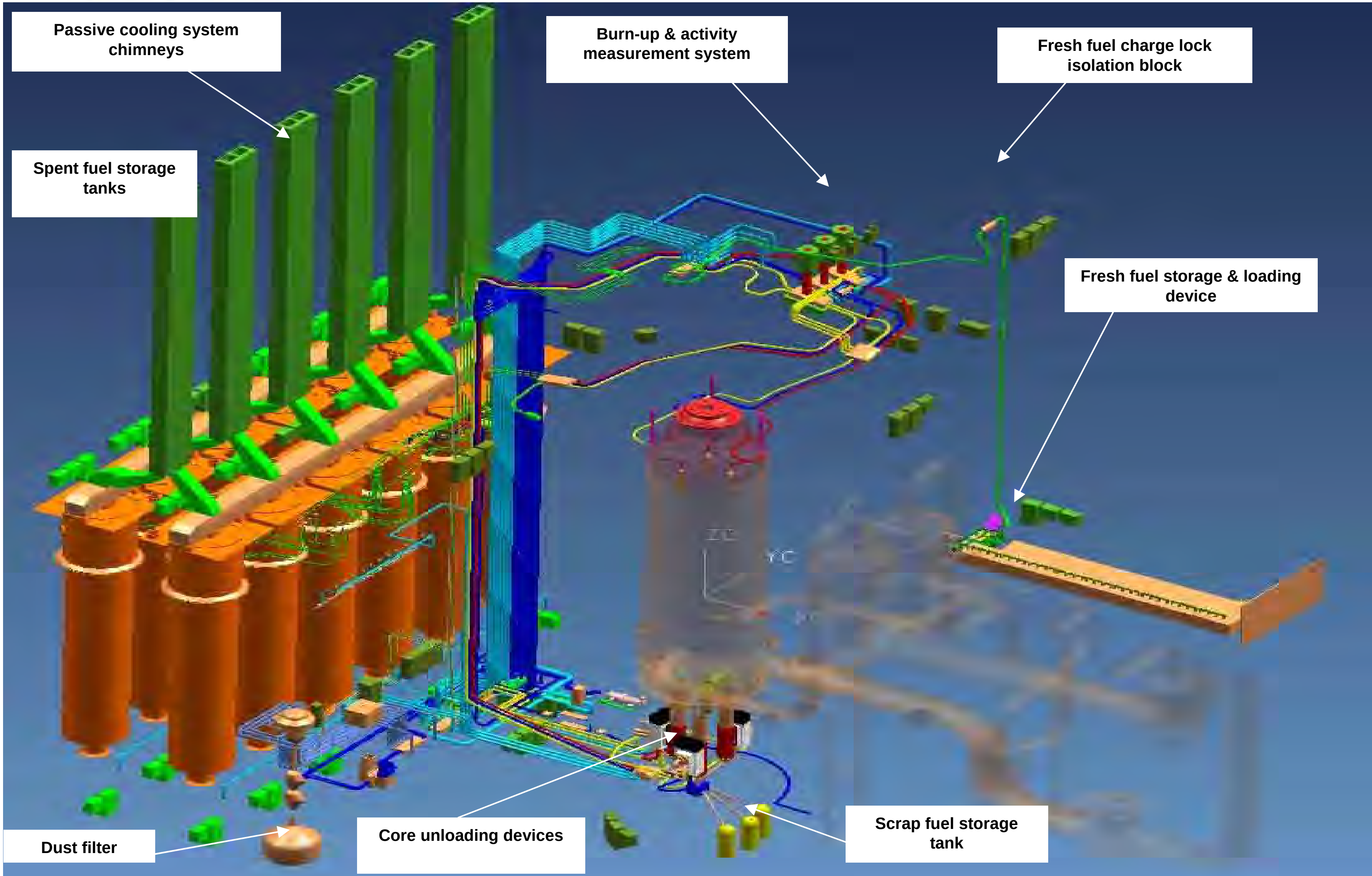
On-Line Fueling

- *High availability*
- *Reduction of required excess reactivity*
- *Low power profiles*

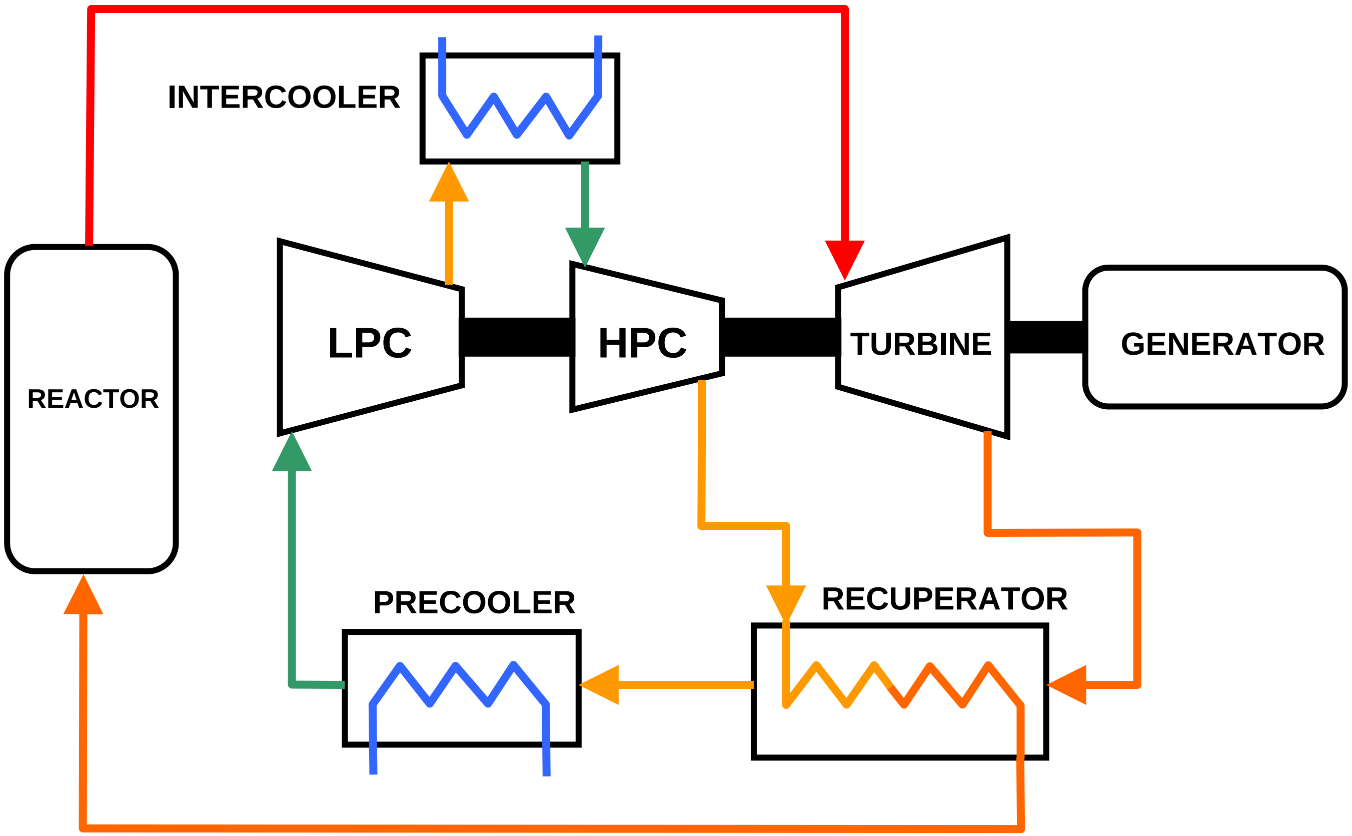


P B M R

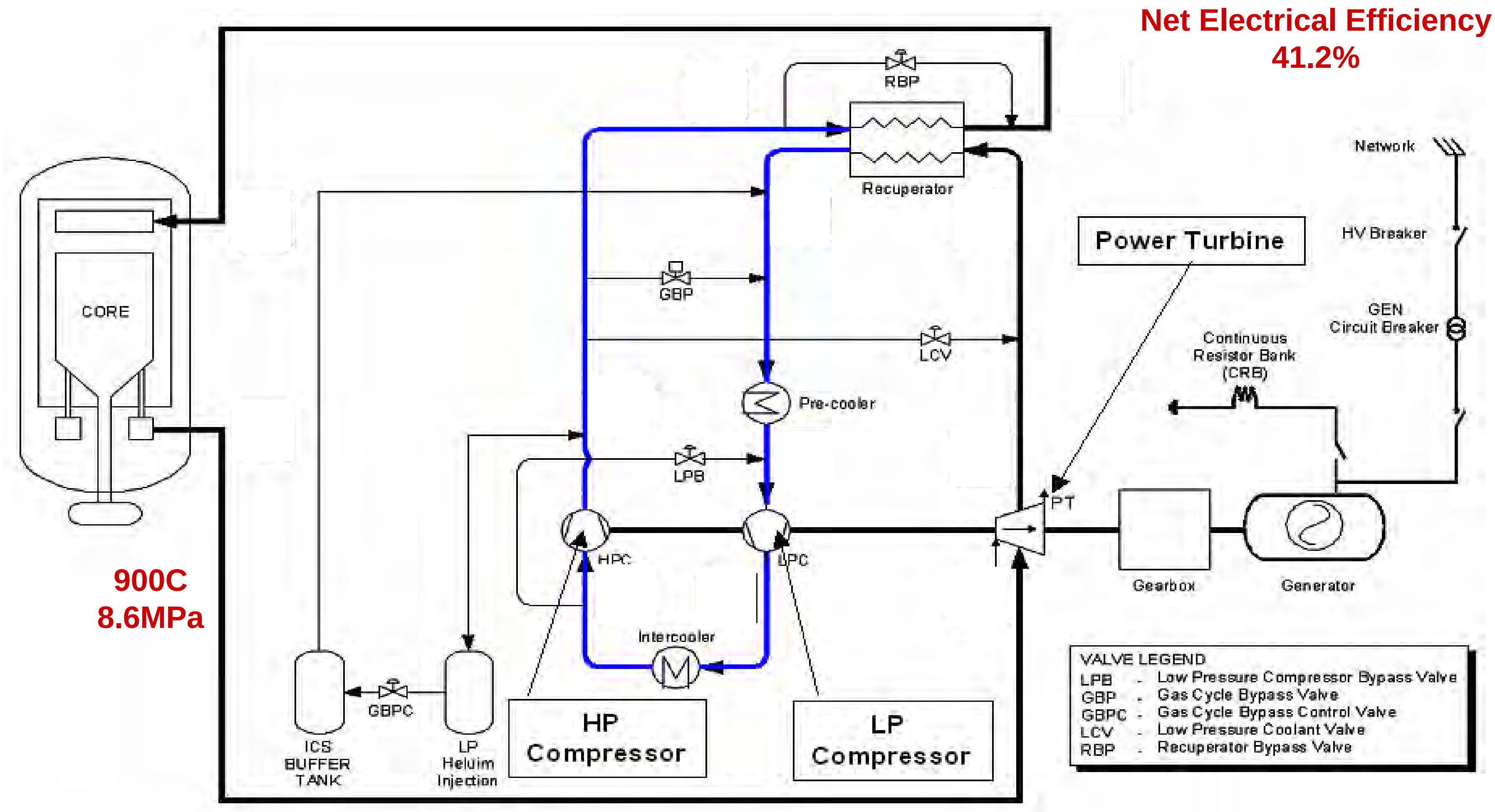
Fuel Handling and Storage System

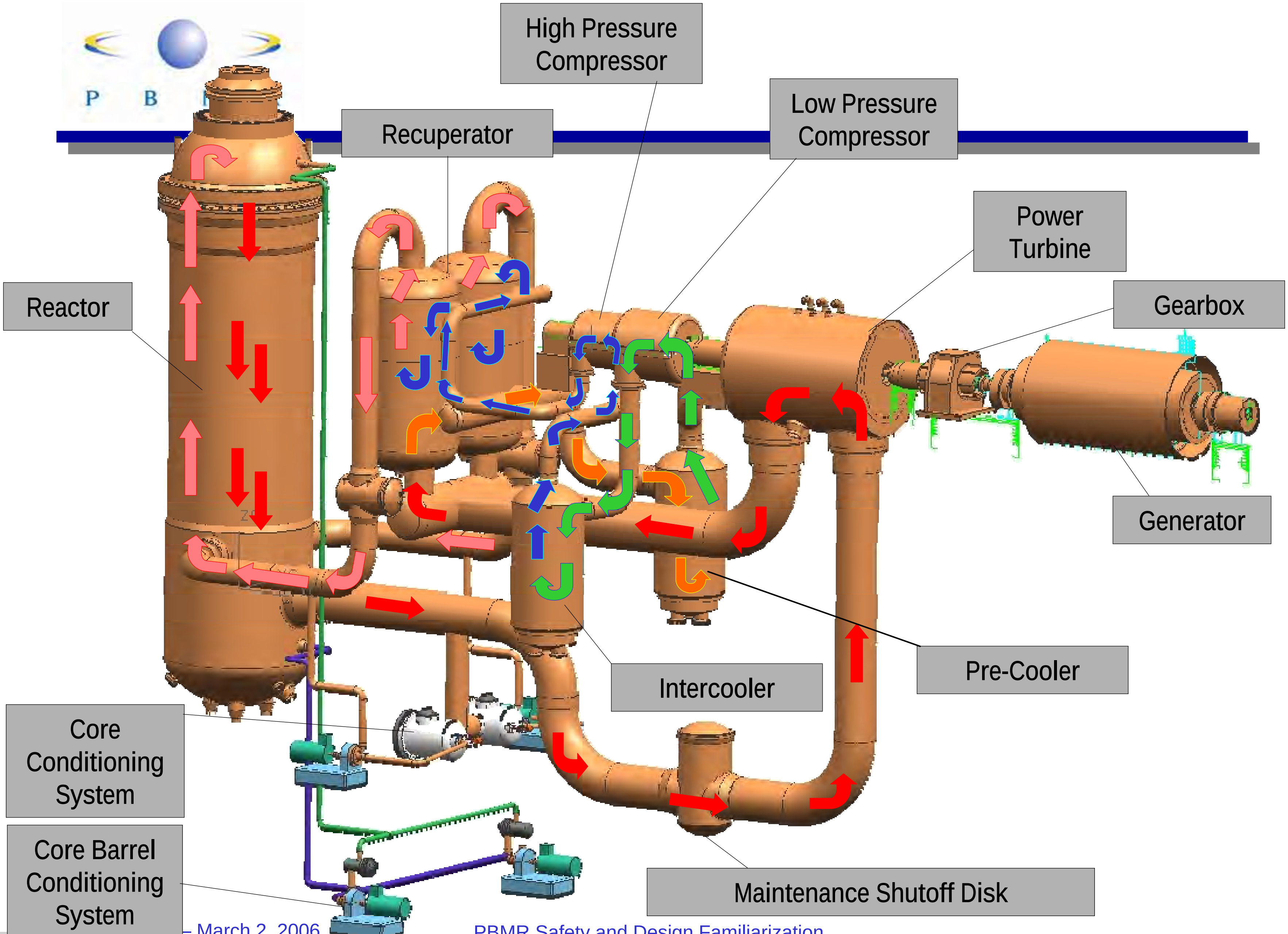


Direct Brayton Cycle Helium Circuit



Power Conversion Cycle





High Pressure Compressor
Low Pressure Compressor
Recuperator
Power Turbine
Reactor
Gearbox
Generator
Pre-Cooler
Intercooler
Core Conditioning System
Core Barrel Conditioning System
Maintenance Shutoff Disk

Use of Proven Technologies

- Fuel to be equivalent to German HTR-Modul Proof test fuel
- Fuel Handling System uses same component designs used in AVR and THTR.
- Core structures design derived from lessons learned in the German HTR program
- Reactor pressure vessel of LWR type and materials
- Helium turbine tested in Germany with a view to using it in a direct cycle application
- Components in the horizontal TG set, e.g., dry gas seal, oil lubricated bearings, conventional generator