FBRs - Realising the Visionary’s Mandate

by

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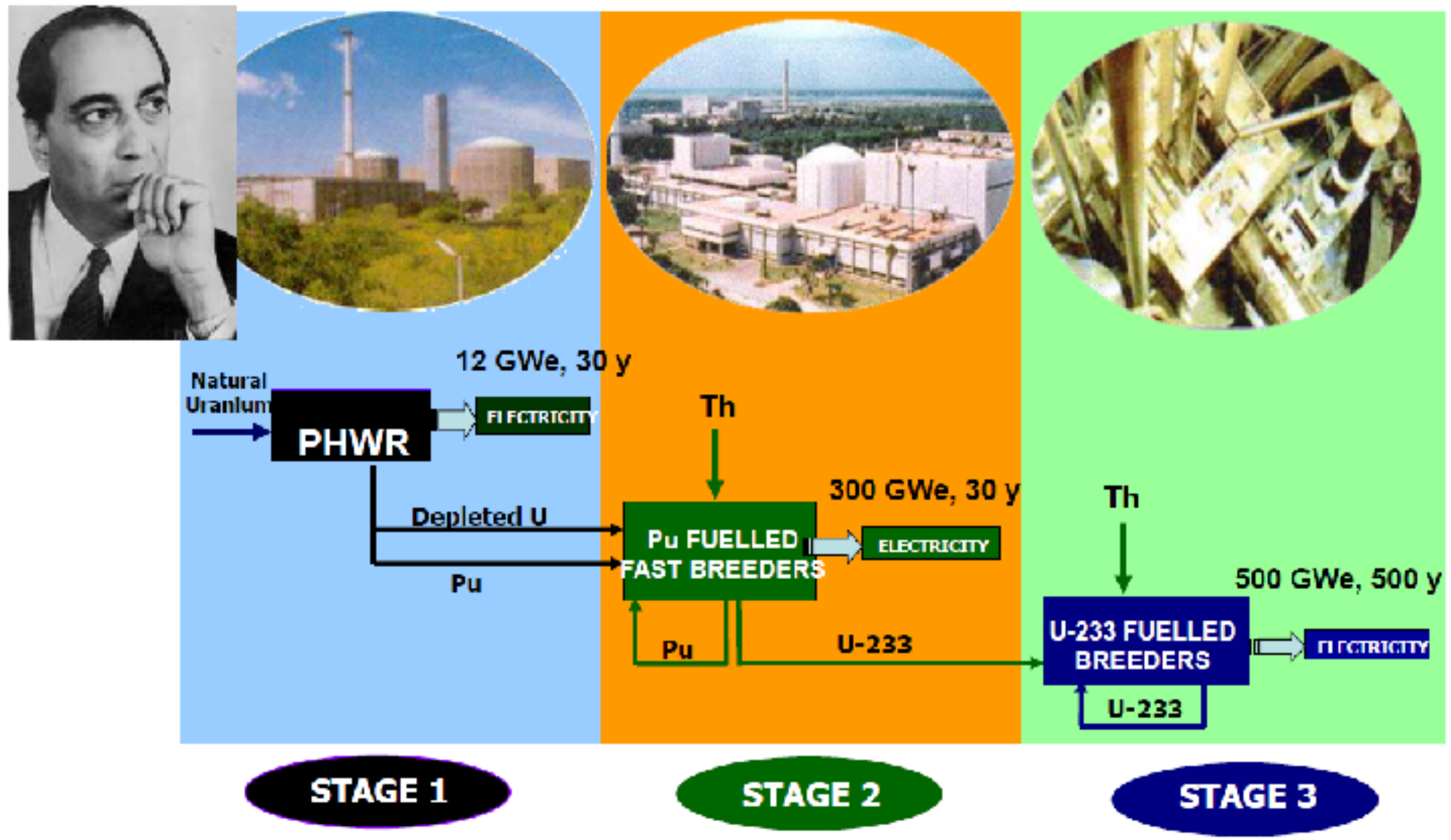
THREE STAGE NUCLEAR POWER PROGRAMME



Total Installed Capacity: 8780 MWe from 25 Reactors; 9 Reactors under Construction

WHY FAST REACTOR?

- ❖ **Better uranium utilization**
- ❖ **Capable of burning Minor Actinides**
- ❖ **Production of U^{233} for Thorium Use**

Reactor	CR	UU
Thermal-Once through	0.6 to 0.8	0.4 to 0.7 %
Thermal-Reprocessing		1.0 to 3.0 %
Fast Reactors	1.02- 1.20	60 to 70 %

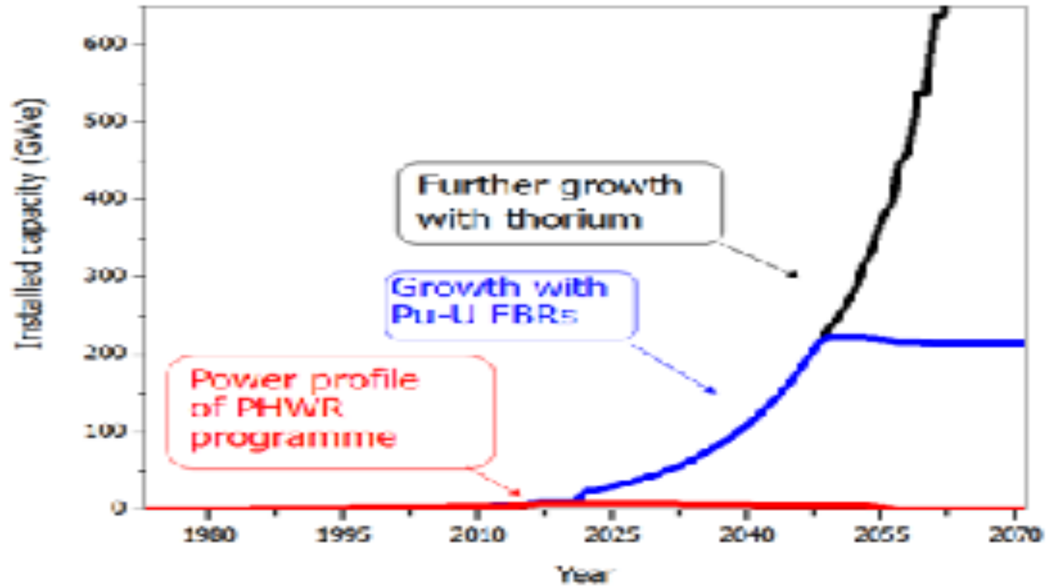
$$Uranium\ Utilization, UU = \left(\frac{Amount\ of\ Uranium\ fuel\ fissioned}{Amount\ of\ Uranium\ resource\ input} \right)$$

Function of:

- Burn-up fraction
- Loss during reprocessing & re-fabrication
- Conversion ratio, CR.

CR = fissile atoms produced / fissile atoms destroyed

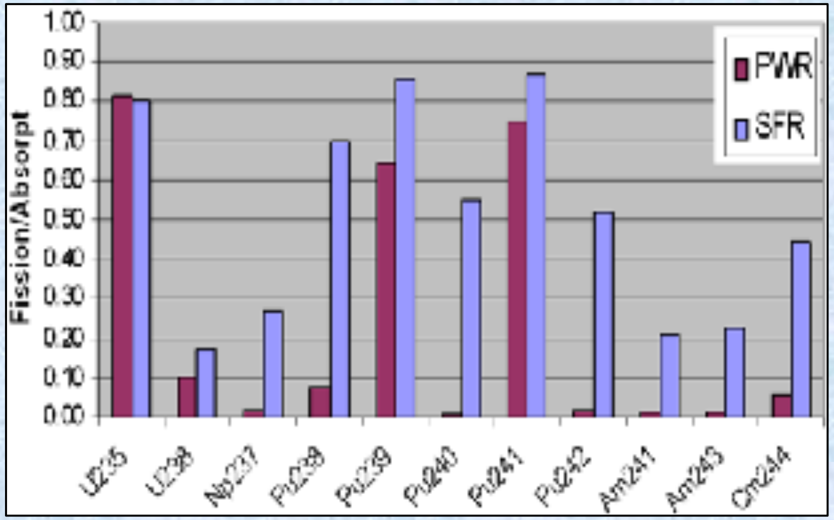
- **In PHWR, 0.6% gets used in energy production**
- **In FBR, UU increases to > 70%.**

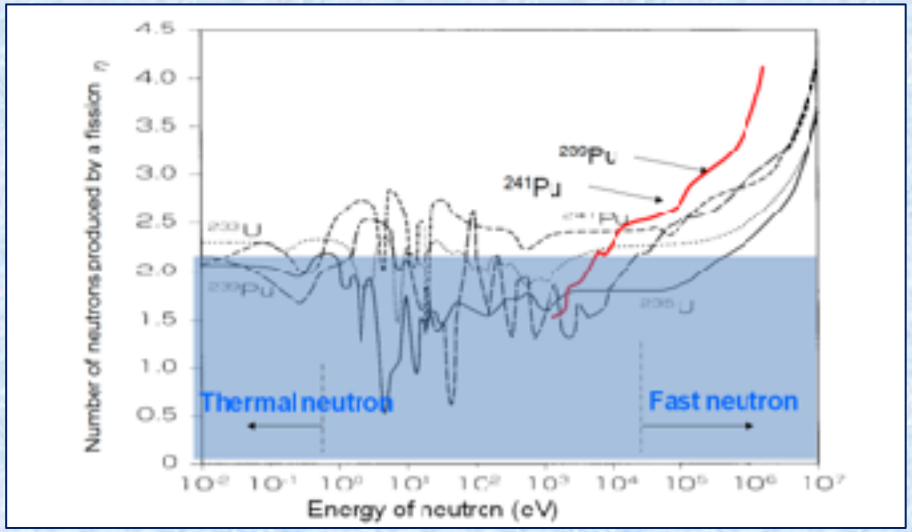


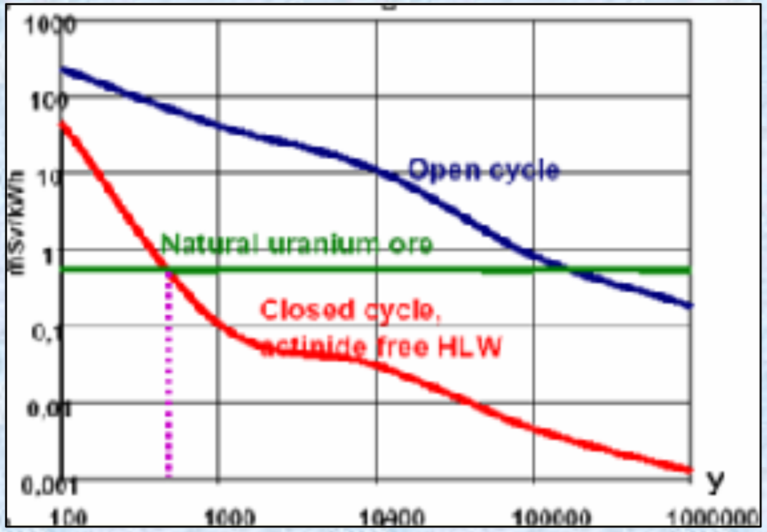
Results of a typical case study

Advantages of Fast Spectrum Reactors

- Fission fraction is higher in fast spectrum (FRs have favorable neutron economy with respect to thermal neutron spectrum reactors)
- High thermodynamic efficiency.
- With advanced materials for the fuel clad and wrapper, higher burn up can also be achieved
- A fast reactor is ‘flexible“ in the sense that, it can be used as breeder or burner or sustainable reactor.
- There are potential benefits of a closed fuel cycle based on fast reactors for waste management.
- It is easier to transmute TRU or MA in a fast reactor core and there is less impact on the fuel cycle (e.g. at fuel fabrication). It is then possible to have a sustainable close cycle, with reduced burden on a deep geological storage







FBRs FOR SUSTAINABILITY

- **A technology suitable for large scale exploitation**
- **Achieves effective utilization of U resource**
- **Can be used to convert T_h to U^{233} for effective utilization of thorium**
- **Can be used to burn minor actinides**
- **Can provide critical liquid metal technology and high temperature design inputs for ADS, fusion and HTR**

FBR PROGRAMME IN INDIA

- **India started FBR programme with the construction of FBTR**
- **FBTR is a 40 MWt (13.5 MWe) loop type reactor.**
- **FBTR is in operation since 1985**
- **500 MWe Prototype Fast Breeder Reactor (PFBR) through indigenous design and construction**
- **Construction of PFBR has been successfully completed by BHAVINI**
- **Beyond PFBR: 2 units of MoX Fuelled 500 MWe FBR similar to PFBR with improved economy and enhanced safety features.**
- **Subsequently, metallic fueled reactors of 500/1000 MWe capacity are planned**

EVOLUTION OF FBR PROGRAMME IN INDIA

FBTR (1985)
40 MWt (15 MWe)
Loop Type
Carbide Fuel

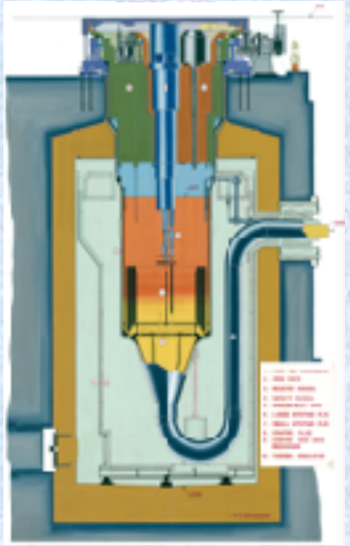
PFBR (2026)
1250 MWt (500 MWe)
Pool Type /MOX Fuel

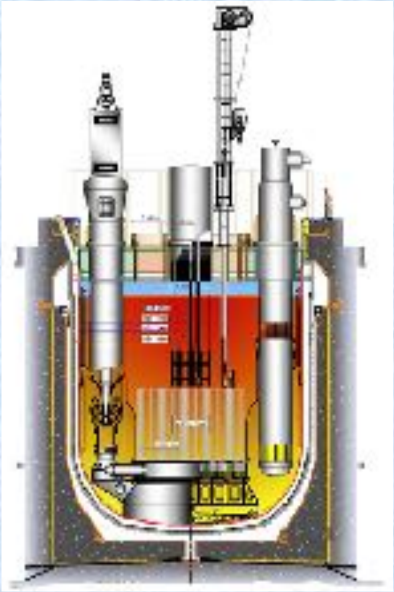
FBR-1&2 (2037-38)
1250 MWt (500 MWe)
Pool Type /MOX Fuel

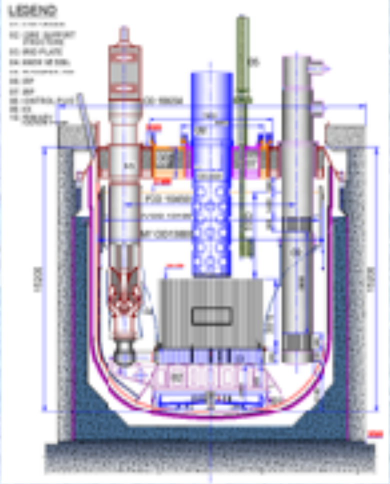
FBTR-2 (2035)
100 MWt (40 MWe)
Loop Type
Metal Fuel / Carbide Fuel

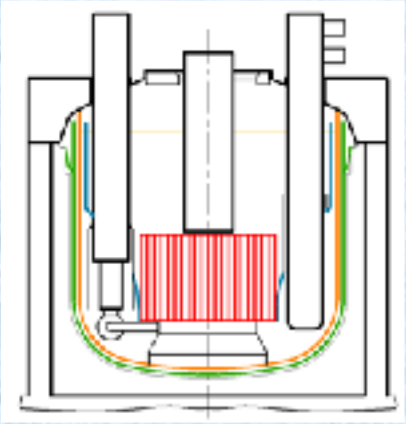
Metal Fuel Reactor
500/1000 MWe
Pool Type
Metal Fuel

Reduced Capital Cost



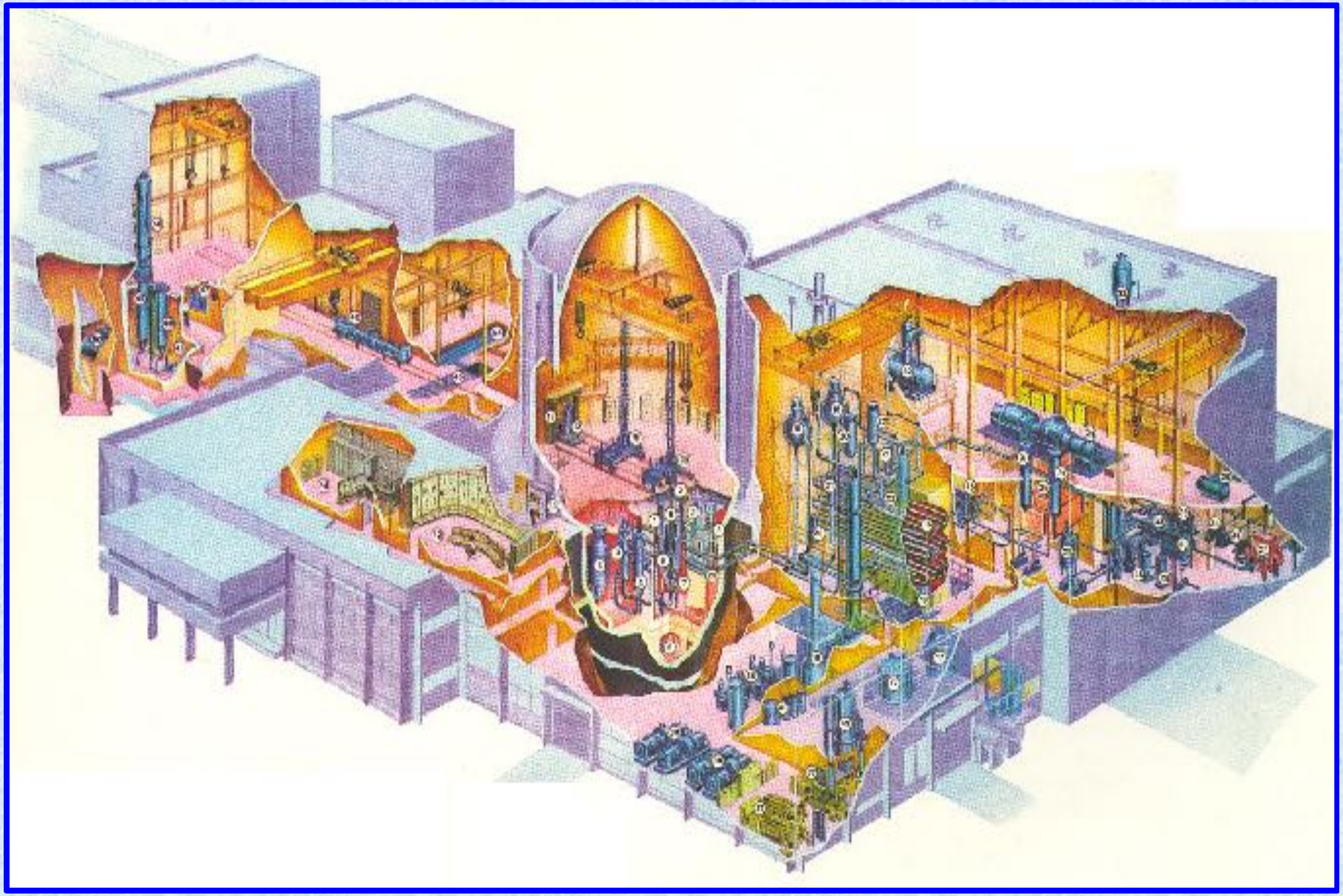






Enhanced Safety

FAST BREEDER TEST REACTOR

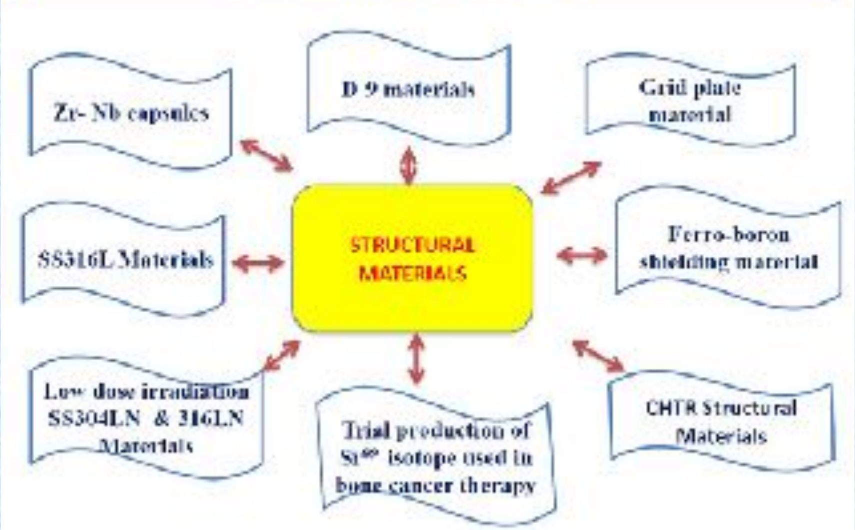


IMPORTANT OBJECTIVES AND PARAMETERS ACHIEVED

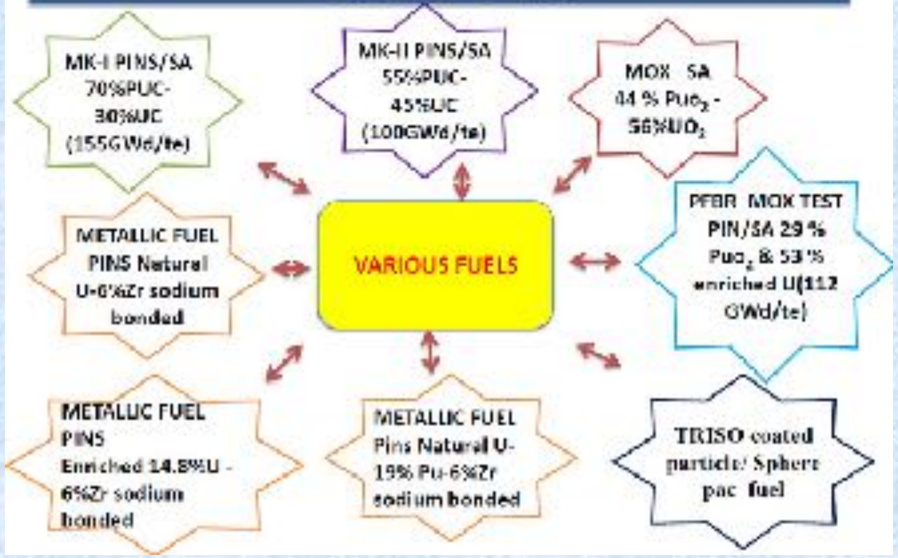
- ***TO DEMONSTRATE THE ENGINEERING FEASIBILITY OF LIQUID METAL COOLED FAST BREEDER REACTOR (LMFBR) IN INDIA***
- ***TO ACT AS AN IRRADIATION TEST BED FOR LMFBR MATERIALS DEVELOPMENT***
- ***TO DEVELOP SODIUM COOLANT AND COMPONENT TECHNOLOGY***
- ***TO DEVELOP FBR FUEL REPROCESSING TECHNOLOGY***
- ***TO DEVELOP A NUCLEUS OF PERSONNEL FOR THE DESIGN, CONSTRUCTION AND OPERATION OF FUTURE FAST BREEDER REACTORS***
  - ***40 MWt MWe***
  - ***Peak LHR of 400 W/cm***
  - ***Peak Flux of 3.15 x 1015 n/cm2/s***
  - ***Peak burn-up of 165 GWd/t***
  - ***Total operating time : ~53,000 h***
  - ***High power operation : ~35,000 h***
  - ***Thermal energy produced : ~520 GWh***
  - ***Electricity generation : ~35 million units***
  - ***Reactor inlet/outlet temperatures : 393 / 490 C***

IMPORTANT OBJECTIVES FULFILLED

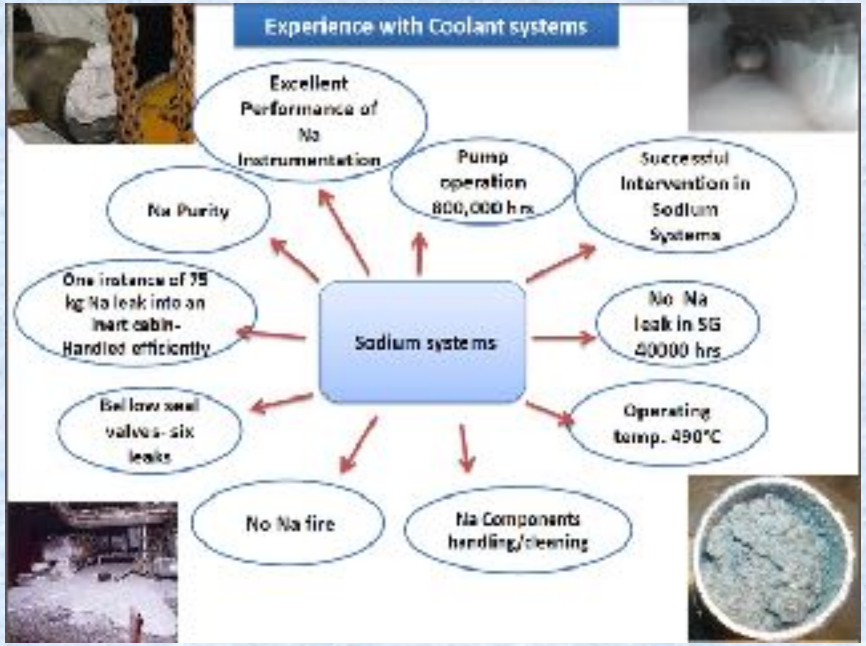
Irradiation of Materials



Irradiation of fuels

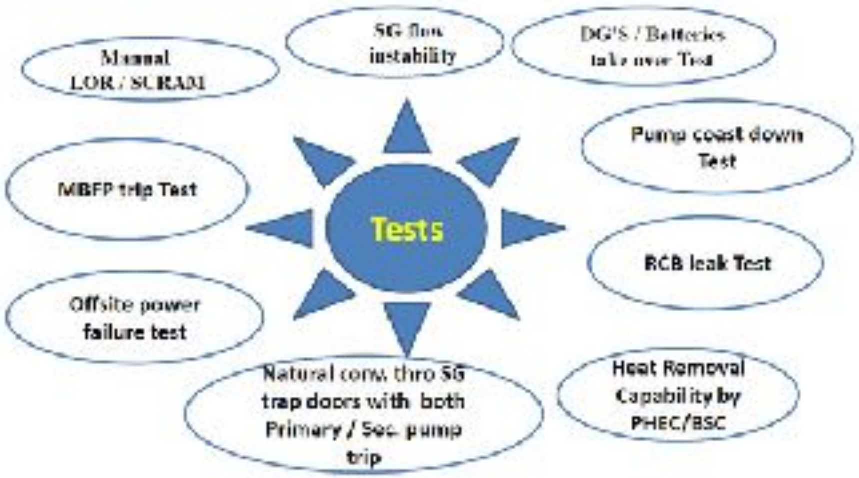


Experience with Coolant systems



SAFETY RELATED TESTS

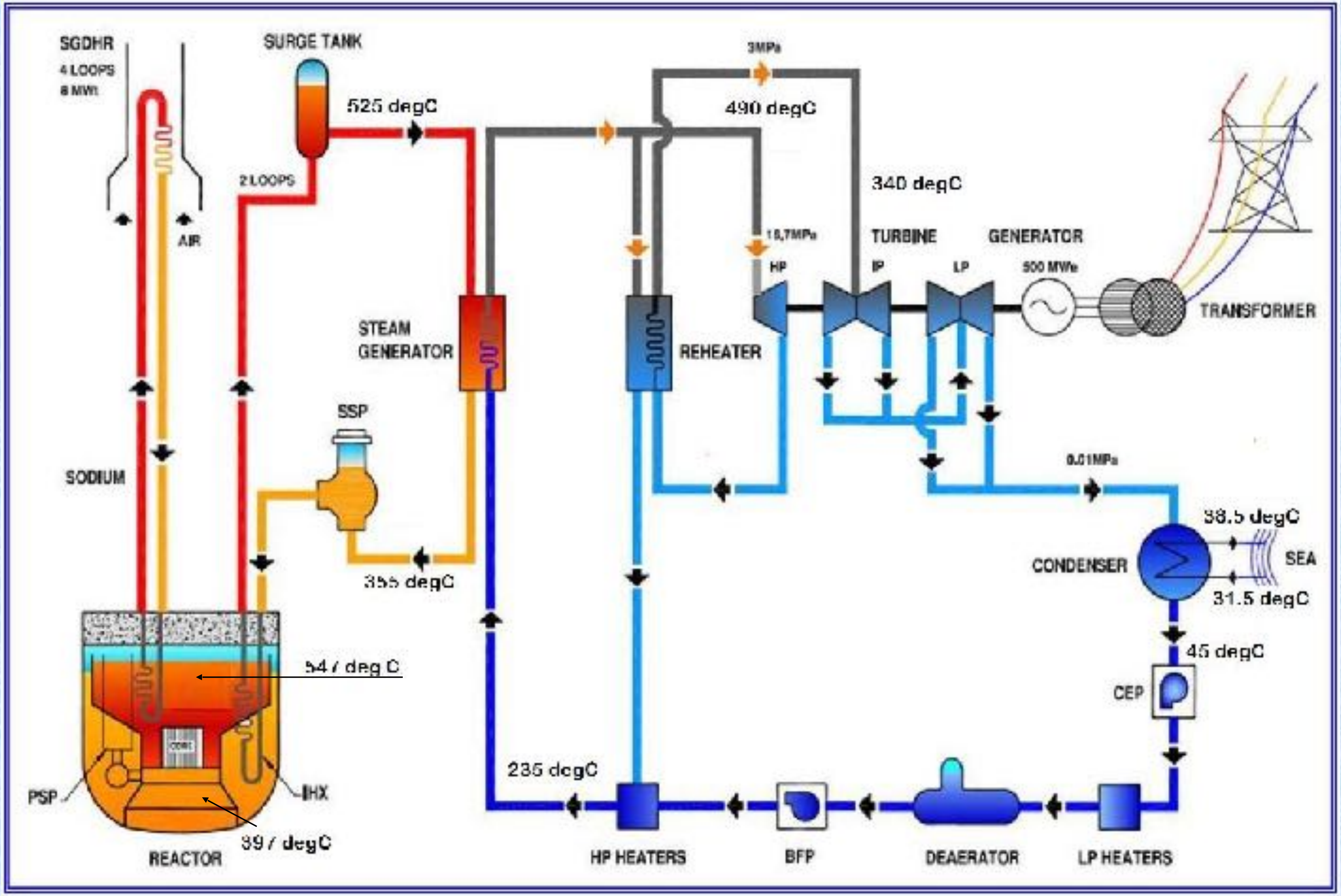
It is desirable to repeat most of the tests for the current enlarged core. Perhaps, the most important is to test for passive decay heat removal under black-out conditions- not earlier agreed to by AERB



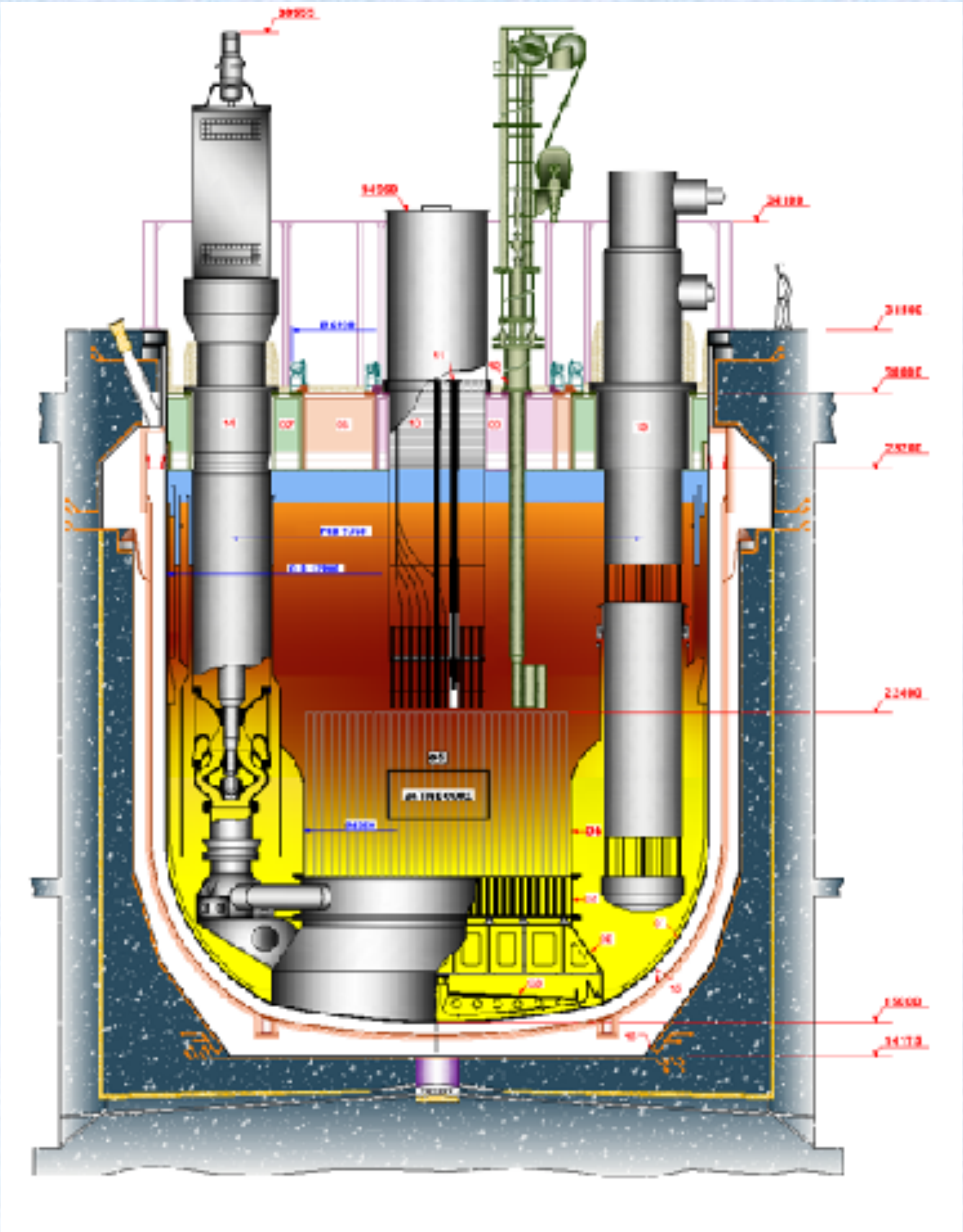
PROTOTYPE FAST BREEDER REACTOR

Parameter	PFBR
Power, MWe	500
Fuel	MOX
Reactor coolant inlet/outlet temp, °C	397 / 547
Core layout	Homogeneous
No. of enrichment zones	2
Fissile enrichment, %	20.7 / 27.7
Fissile inventory, kg	1980
Breeding ratio	1.05
Secondary loops	2
No. of Primary Sodium Pump	2
No. of IHX	4
No. of Secondary Sodium Pump	2
No. of SG / loop (tube height, m)	4 (23 m)
Steam temp/Pressure (°C / MPa)	490 / 17
Main vessel diameter, m	12.9
Load factor, %	75

FLOW SHEET OF
PROTOTYPE FAST BREEDER REACTOR (PFBR)



PFBR Reactor Assembly



01	Main Vessel
02	Core Support Structure
03	Core Catcher
04	Grid Plate
05	Core
06	Inner Vessel
07	Roof Slab
08	Large Rotating Plug
09	Small Rotating Plug
10	Control Plug
11	CSRDM / DSRDM
12	Transfer Arm
13	Intermediate Heat Exchanger
14	Primary Sodium Pump
15	Safety Vessel
16	Reactor Vault

PFBR – CHOICE OF COOLANT

Choice of Coolant: Sodium is chosen as coolant from following considerations:

- ❖Unanimous choice for all the large size fast reactors, worldwide —> High level of technical maturity has been achieved.
- ❖It has got non-moderating properties, essential for FBRs.
- ❖Its low vapour pressure permits high temperature without vaporisation —> High thermodynamic efficiency and thin walled components.
- ❖Its high thermal conductive results in high heat transfer coefficients, even at low velocities —> required heat transfer areas are low
- ❖It causes negligible corrosion of structural materials at high temperature over long periods of operation.
- ❖Larger margin between operating temperature (~860K) and boiling point (~1160K) gives sufficient safety margin for heat removal under emergency conditions and enables good passive decay heat removal

The challenges in handling / usage of Sodium is addressed through suitable design provisions

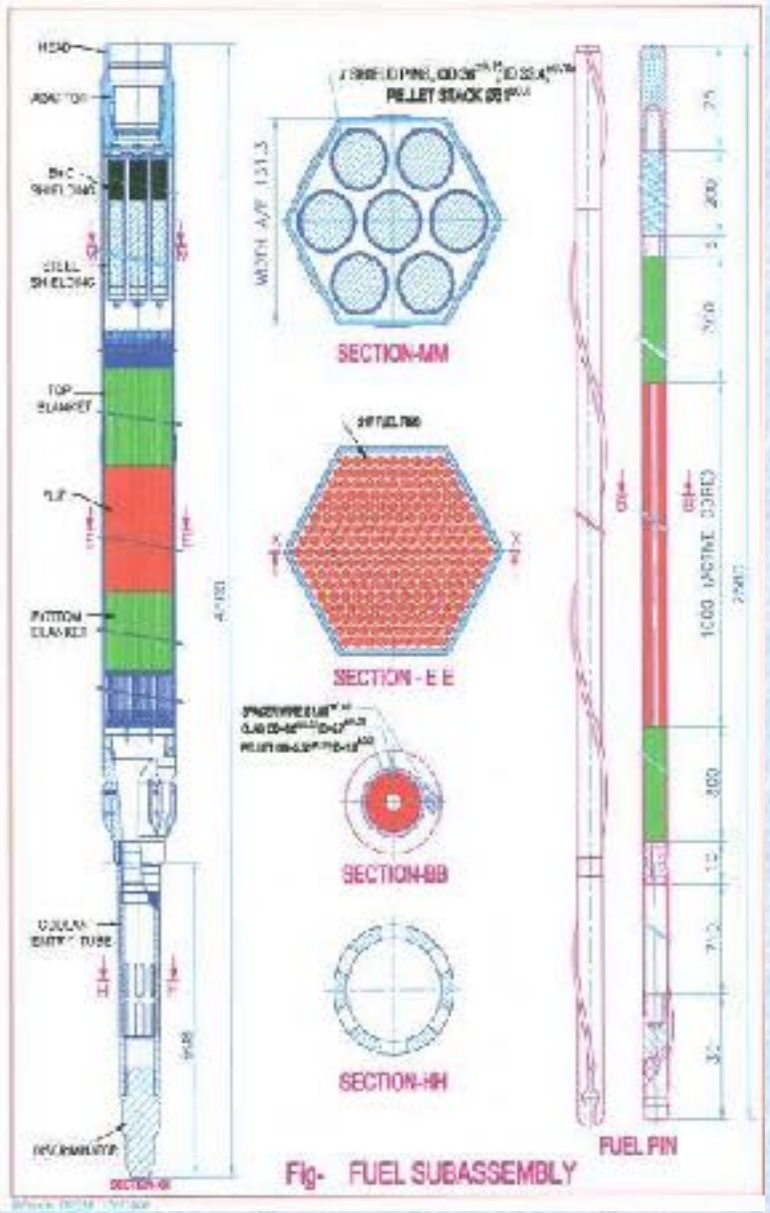
PFBR – MAIN OPTIONS: FUEL

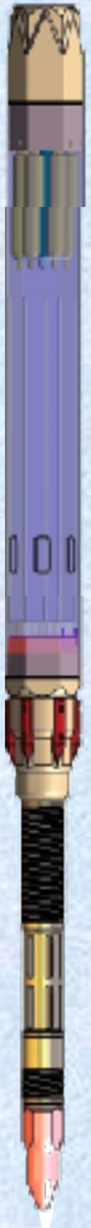
MOX (PuO_2-UO_2) is chosen for PFBR from following considerations:

- ❖PuC-UC is being used as fuel for FBTR due to non-availability of enriched Uranium for mixed oxide option.
- ❖No uranium enrichment needed for PFBR.
- ❖Safety issues with Fabrication of Carbide fuel (pyrophorocity) & higher fabrication cost.
- ❖Lower burn-up of carbide fuel when compared to oxide fuel, due to high swelling rate.
- ❖Proven fuel cycle is essential for large power plant - Reprocessing of Carbide fuel in industrial scale is not yet done whereas oxide fuel has proven reprocessing technology.
- ❖MOX was the choice of most of the large sized FBRs.
- ❖Technology of MOX fuel is very similar to UO2 and extensive experience exist in India.

PFBR FUEL SUBASSEMBLY

Fuel	**: (Pu-U)O2**
Pellet OD/ID	**: 5.55 / 1.8 mm**
Pin OD/ID	**: 6.6 / 5.7 mm**
Peak Linear Power	**: 450 W/cm**
Active core height	**: 1000 mm**
Breeding Ratio	**: 1.05**
Clad and Wrapper	**: 20 % CW D9**
Number of pins	**: 217**
Width Across Flats	**: 131.3 mm**
Peak target Burn-up	**: 100 GWd/t**
Peak neutron dose	**: 82 dpa**
Blanket	**: Depleted UO2**
Blanket pellet	**: 5.55 mm**
Axial blanket	**: 300 mm each on either side**





Way Forward for FBR 1&2

A roadmap is prepared for the Fast Breeder Reactor development beyond PFBR.

The design of FBR 1&2 will be improved by incorporating the experiences from design, R&D, safety review, construction and commissioning of PFBR.

Though, conceptual design of a 600 MWe FBR core with reduced sodium void coefficient was initially made, following were noted during the discussions among the stake holders:

- ❖ The changes to static components like reactor assembly components (an increase of 1m in diameter & length) and heat exchangers (an increase of ~1 m in length) can be implemented without much difficulty and without losing the experiences gained.
- ❖ However, the changes to dynamic components like pumps, shutdown & handling mechanisms calls for fresh development effort and testing before putting them in reactor.
- ❖ Also, major changes to core & fuel design calls for detailed safety reviews, afresh.

Hence, with an aim to minimise the design changes w.r.t. PFBR and restricting the changes to only bare essential, which are to overcome the challenges faced during PFBR construction & commissioning.

Way Forward for FBR 1&2 (Contd.)

- Accordingly, it is proposed to repeat PFBR (500 Mwe, twin units) with changes limited to incorporate feedback from PFBR as well as to meet revised safety criteria.
- Design of the reactor would be by IGCAR and project would be executed by BHAVINI - As followed for PFBR
- The plant operating parameters are kept same as PFBR
- Fuel building would be shared between the two units
- The reactor design would be based on

  - Addressing the issues faced in the design, R&D, safety review, construction and commissioning experience of PFBR

  - Compliance with the new regulatory requirements
- Measures taken to enhance safety and thereby to meet the new regulatory requirements include

  - Practical elimination of severe accident scenarios

  - Stroke limiting device to eliminate UTOPA

  - Hydraulically suspended absorber rods to eliminate ULOFA

  - Additional secondary sodium based decay heat removal system

Way Forward for FBR 1&2 (Contd.)

Design measures considered based on feedback experience from PFBR

- Change in fuel handling concept - adopting straight pull machines instead of IFTM
- Guard pipe concept for secondary sodium piping instead of leak collection trays
- Additional Support for Reactor Assembly.
- Reactor Vault upper lateral construction to facilitate installation of SV after the complete construction/casting of Reactor Vault.
- Redundant support for core support structure.

Motivation for FBTR-2

For faster growth of nuclear generating capacity, large number of 500 / 1000 MWe Metallic Fuel reactors need to be built.

Only metal fuelled reactors can have shorter Reactor Doubling Time (DT) of 8 to 10 y.

Insufficient metal fuel irradiation data in literature to go directly with full scale power reactors -> Irradiation of metallic fuels in FBTR-II: understanding & demonstration of

- Fuel performance & reliability (< 1/10000 pin failures)
- Fuel utilization (> 100 GWd/t burn-up)
- Safety (Inherent safety during ATWS/ULOFA)

Power reactor fuel pin size can be tested 1:1 in FBTR-2

Establish and demonstrate Pyro-processing capability for power reactors

Continuity of fast neutron spectrum research reactor as remaining life of FBTR is ~ 5 EFPY

FBTR II- Objectives

Primary Objectives:

- Testing metal fuel SA of power reactor size (1000 mm active core height) for its performance & for understanding overall core behaviour
- Core safety experiments with metal fuel to the extent possible
- To establish closed fuel cycle technologies

Secondary Objectives:

- Demonstration of large scale H_2 production (Cu-Cl cycle at 520 C).
- Temperature controlled materials irradiation and testing.
- Demonstration of MA incineration (MA bearing fuel testing/ Reactor physics and dynamics)
- Radio-isotope production
- Sensor calibration

FBTR 2 - Plant Parameters

Reactor Thermal Power	: 100 MWt
Reactor inlet temperature	: 360°C
Reactor outlet temperature	: 510°C
IHX Secondary inlet temperature	: 318°C
IHX secondary outlet temperature	: 488°C
Feed water inlet temperature	: 210°C
Steam temperature	: 460°C
Primary sodium flow rate	: 525 kg/s
Secondary sodium flow rate	: 230kg/s per loop
Feed water flow rate	: 21.5 kg/s per loop
Steam Pressure	: 125 kg/ cm^2 (a)

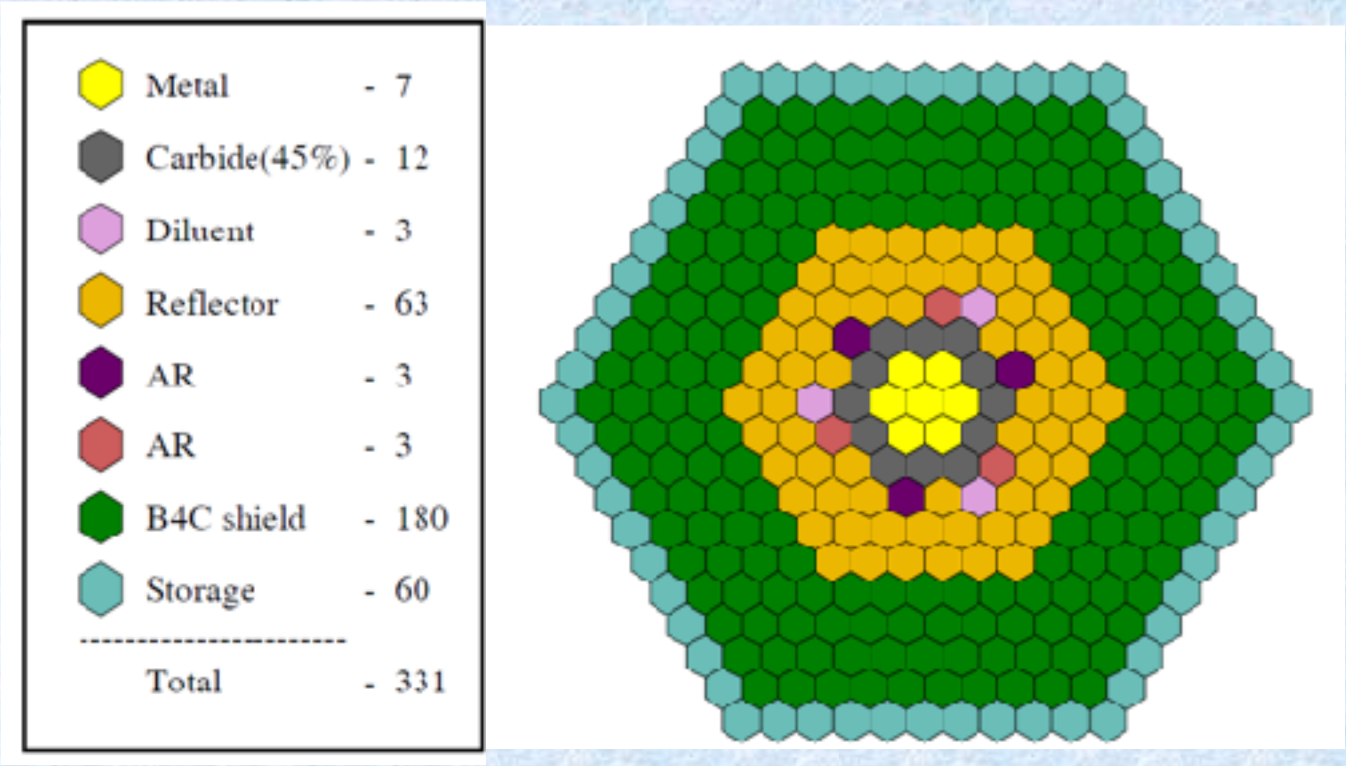
CORE DESIGN OF FBTR-2

Major objectives of Core Design:

To test the full-scale metal fuel SA as envisaged in the commercial scale metal fuelled reactor:

A. Parameters to be simulated:

- ❖LHR (450 W/cm)
- ❖Burnup: 100 GWd/t
- ❖Safe operation Irradiation performance - slumping, density changes, material performance etc.)
- ❖Performance of metal fuel under design basis transients.



Hybrid Core: Reactor power = 100-120 MWt

B. Demonstration of closed fuel cycle

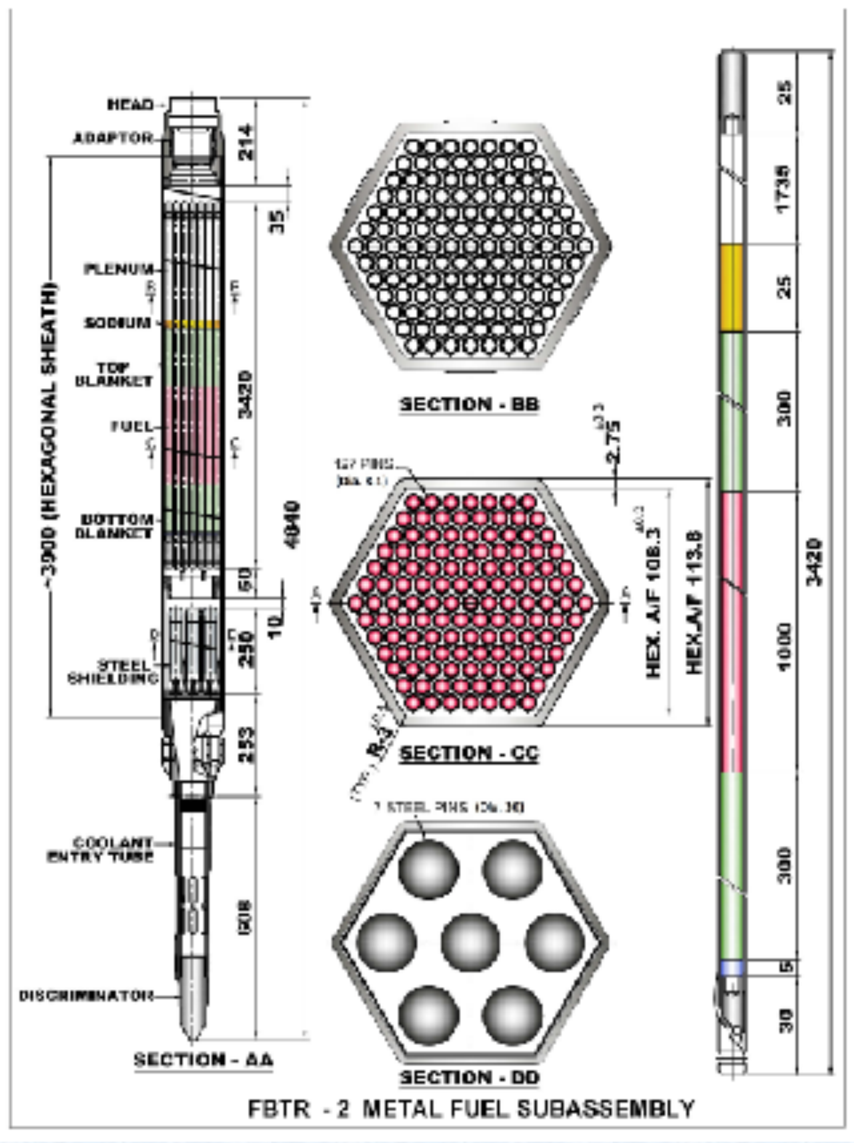
- ❖ Initially, FBTR-2 starts with a hybrid core with seven / four central ternary metal fuel (U-23Pu-6%Zr) subassemblies (SAs) and the rest with ~45% enriched carbide fuel SAs.
- ❖ Later, it is proposed to transition to full metal core to study the safety aspects of metal core.
- ❖ The SA and pin designs will be identical for the hybrid and metal fuel core designs.

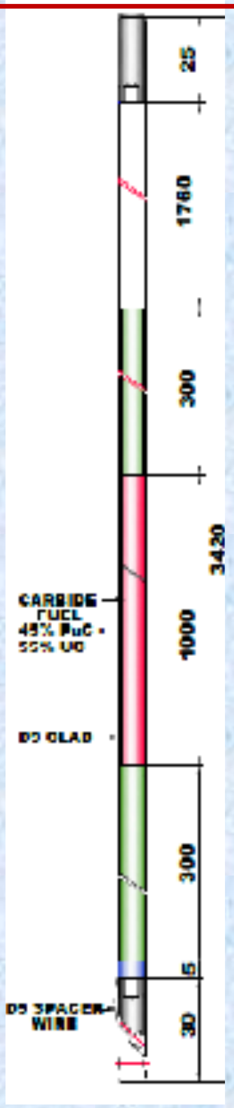
Comparison with FBTR & PFBR Major Design Parameters

Parameter	FBTR	PFBR	FBTR - 2
Reactor thermal power	40 MWt	1250 MWt	100-120 MWt
Reactor type	Loop	Pool	Loop
Fuel	(U, Pu) C – Carbide fuel with 70% Pu	MOX fuel with 21% & 28% PuO2	(U-45%Pu)C as driver fuel & U-19%Pu-6%Zr, Metal fuel (Hybrid core)
Core diameter	~ 560 mm	~ 2.2 m	~ 590 mm
Pu inventory	~ 170 kg	~ 2t	Pu mass = 78 kg + PuC mass = 328 kg
Reactor inlet temperature	380°C	397°C	360°C
Neutron flux (Peak)	3.24 x 10^{15} n/cm^2-s	8 x 10^{15} n/cm^2-s	4 x 10^{15} n/cm^2-s
Cycle length	~92 days	185 days	200 days
Number of SAs	~ 70	181	19
Peak LHR	400 W/cm	450 W/cm	450 W/cm (470 W/cm for MC)
SA maximum power	620 kW	~ 8 MWt	~ 4.5 MWt (Metal) 5.6 MWt (Carbide)
Clad material	SS 316 M	20% CW D9	T91/T92
Wrapper material	SS 316 L	20% CW D9	Plain 9Cr-1Mo ferritic steel
Fuel pin diameter	5.1 mm	6.6 mm	8.1 mm (Metal) & 6.6 mm (Carbide)
Fuel column height	320 mm	1000 mm	1000 mm
Wrapper dimension	49.8 mm (Outside WAF max.)	131.6 mm (Outside WAF max.)	113.8 mm (Outside WAF)
SA length & Pin length	1661.5 mm / 531.5 mm	4500 mm /2580 mm	4840 mm / 3420 mm
Number of fuel pins/SA	61	217	127 (Metal) / 169 (Carbide)
Target burn-up	155 GWd/t (attained)	100 GWd/t	100 -150 GWd/t
CSR SAs	6 (90% B10 enrichment)	9 (67% B10 enrichment)	3 (90% B10 enrichment)
DSR SAs	-	3 (67% B10 enrichment)	3 (90% B10 enrichment)

CORE DESIGN OF FBTR-2 – SALIENT DESIGN PARAMETERS

- Reactor Power : 100 - 120 MWt
- No. of fuel SAs : 12 MC + 7 Metal Fuel
- No of pins/ SA : 127 (MF) & 169 (MC)
- Peak LHR : 470 W/cm for MC & 450 W/cm for Metal
- Target burn-up : 100-150 GWd/t (for pin life)
- Driver Fuel : Mixed Carbide with 45 % enrichment
- Test Fuel material : U-23%Pu-6%Zr
- Fuel- clad gap : He bonded for MC & Sodium bonded for MF
- Clad & Hexcan : D9 for MC & T92 (clad) for MF; 9Cr-1Mo (hexcan)
- Clad dimensions : 6.6. mm for MC and 8.1 mm for MF
- Fuel pellet/slug : 6.06 mm (OD-MF) 5.4646 mm (OD-MC)
- Fuel column : 1000 mm
- Blanket column : 300 mm (Bottom) /300 mm(Top)
- Pin & SA length : 3420 mm & 4840 mm
- Hexcan WAF : 113.8 (Outer) / 108.3 (Inner) mm





Carbide Fuel Pin

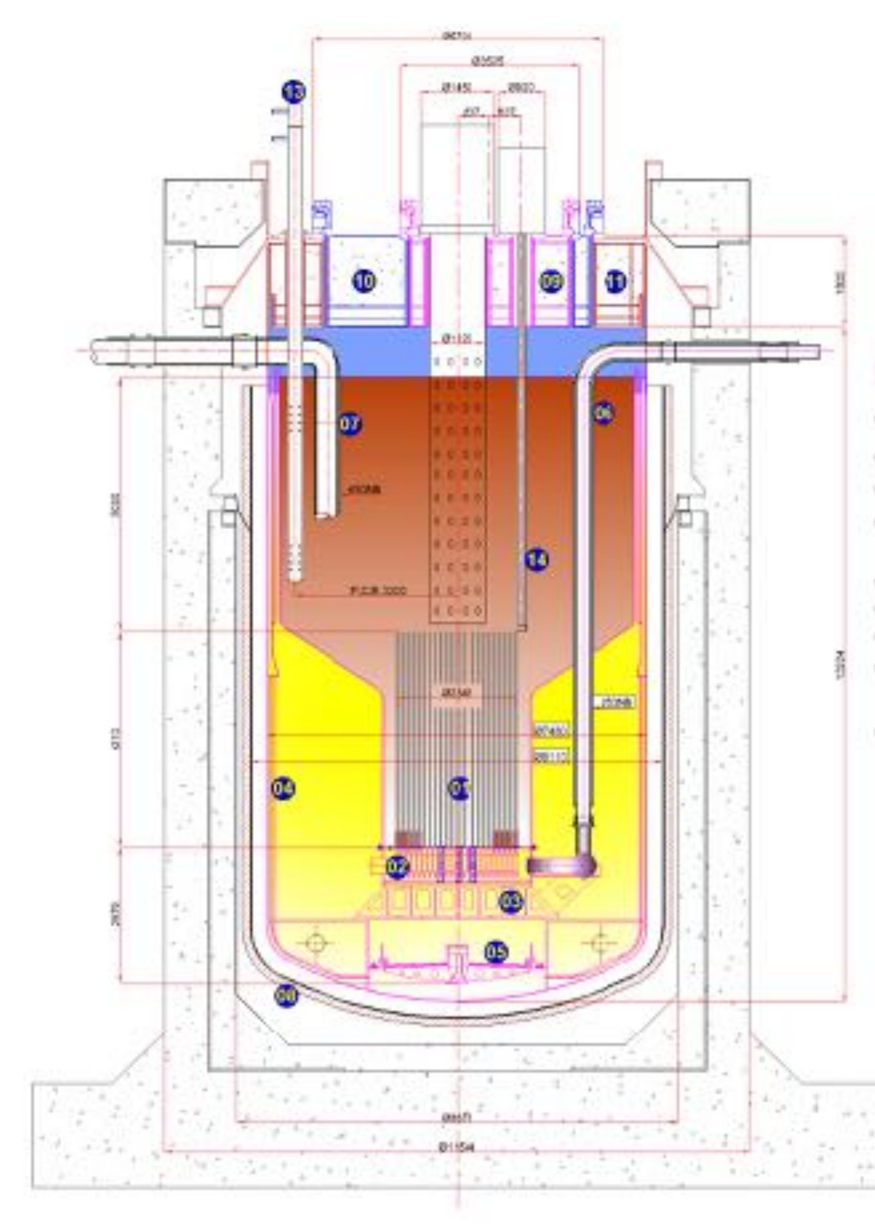
FBTR-2 CORE OPERATING CONDITIONS

- Reactor core inlet/outlet temperatures : 360°C/510°C
- Maximum total flux at core centre & DPA : 4 x 10^{15} n/cm^2-s DPA: 100-150 (Target)
- Cycle length : 200 days
- Residence time of SA in core : 3-4 years (for a peak burn-up of 100 GWd/t)
- Residence time of SA for cooling : In core: ~ 3 years ; (Preliminary)
- Fission gas pressure at 100 GWd/t : ~ 6.7 Mpa (Metal fuel Pin)
- Decay heat of SA during discharge : < 400 W (Studies under progress)
- Clad inside hotspot temperature limits for different Design Basis Events for Metal Fuel (based on preliminary studies)
  - Cat 1 – 650°C
  - Cat 2 – 720°C
  - Cat 3 – 770°C
  - Cat 4 – 970°C
- Peak SA power : 4.5 MWt
- Peak SA coolant flow : 24.1 kg/s (considering 620°C as clad temp. limit for T91)
- Pressure drop in fuel bundle region : 77.1 m of Na
- Total core Pressure drop : ~ 100 to 105 m of Na

Absorber SAs:

- CSR SAs: 3 Nos. (Pellet with 90% B10 enrichment
- DSR SAs: 2 Nos. (Pellet with 90% B10 enrichment
- 19 pin cluster with pin diameter of 19.3 mm

Conceptual Design of Reactor Assembly of FBTR-2



- ✓ **Loop type concept for primary circuit**
- ✓ **Two secondary loops**
  (1 PSP & 1 IHX per loop)
- ✓ **Box type top shield**
- ✓ **No vessel penetration within sodium height**
- ✓ **450 NB Outlet & 250 NB Inlet Pipes (2 Nos. each)**
- ✓ **Decay heat removal path – Well Defined as in Pool Type**
- ✓ **Designed to meet Safety criteria for future FBR.**
- ✓ **MV Diameter of ~7.48 m & RA Height of ~15 m**
- ✓ **Redundant support for RA & Core Support Structure.**

Selection of Primary Circuit Concept

Basic Parameters to decide the Concept

Design Feasibility:

- ❖Thermal Hydraulic aspects
- ❖Seismic & Structural behaviour
- ❖Absence / presence of Vessel penetrations

Safety:

- ❖Decay heat removal capacity in case of unavailability of secondary sodium circuit
- ❖Thermal inertia to absorb thermal shocks
- ❖LOCA & spread of radioactive sodium in case of accidents
- ❖Risk of Pump impeller to core interaction

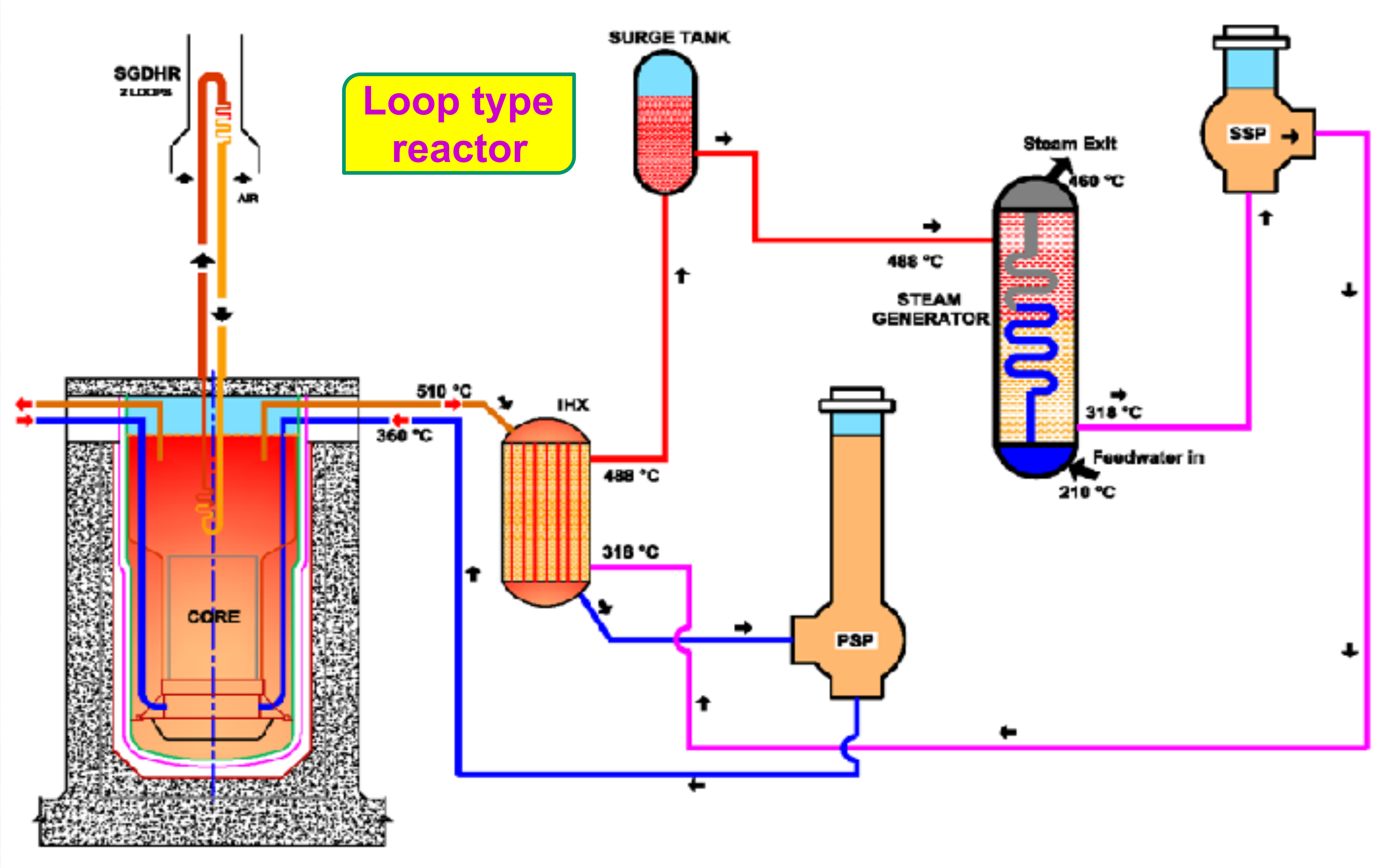
Economic Benefits

Construction time

Operation & maintenance aspects

Based on detailed assessment, Loop configuration is found to be apt and cost-effective for FBTR-2 and Chosen

FBTR-2 Heat Transport System



Technological Challenges & Make in India Opportunities

- Except for fuel and core structural materials, the reactor technology is similar to PFBR & FBTR - No technological challenges are expected.
- Fresh fuel fabrication - Challenges are expected in casting / assembling fuel pins of 1 m length.
- T92 Clad Material development has been initiated.
- Fuel re-fabrication - remote fabrication - large technological challenges are expected.
- Pyro-processing - Demonstration with Uranium feed is completed - Demonstration with Plutonium feed and Large scale deployment - several challenges are expected.
- Several items were imported for PFBR, which needs to be indigenised to the extent possible under make in India initiative.

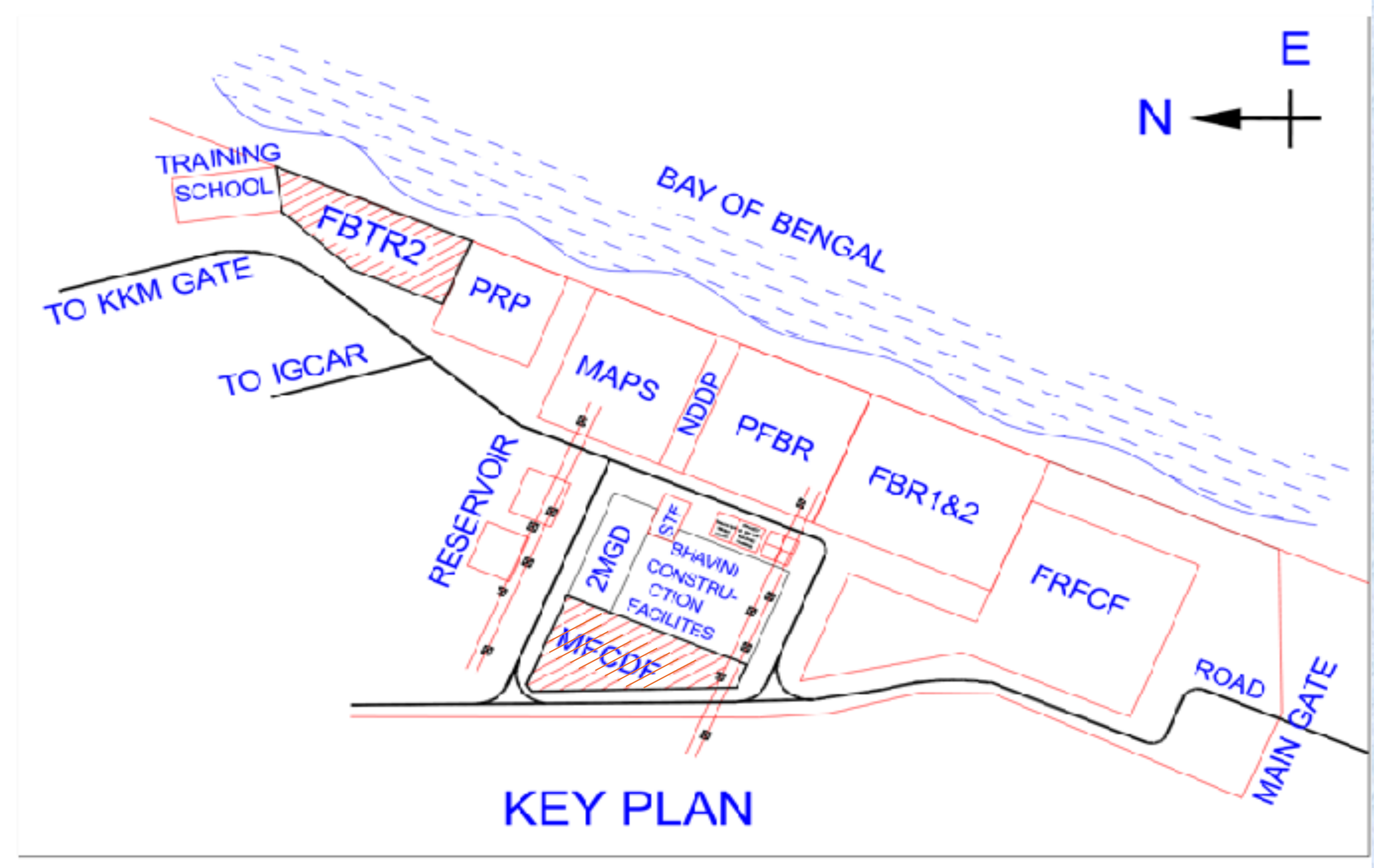
  -Large diameter radiation resistant inflatable seals in silicone

  -Large diameter ring forgings above 5.5 m diameter

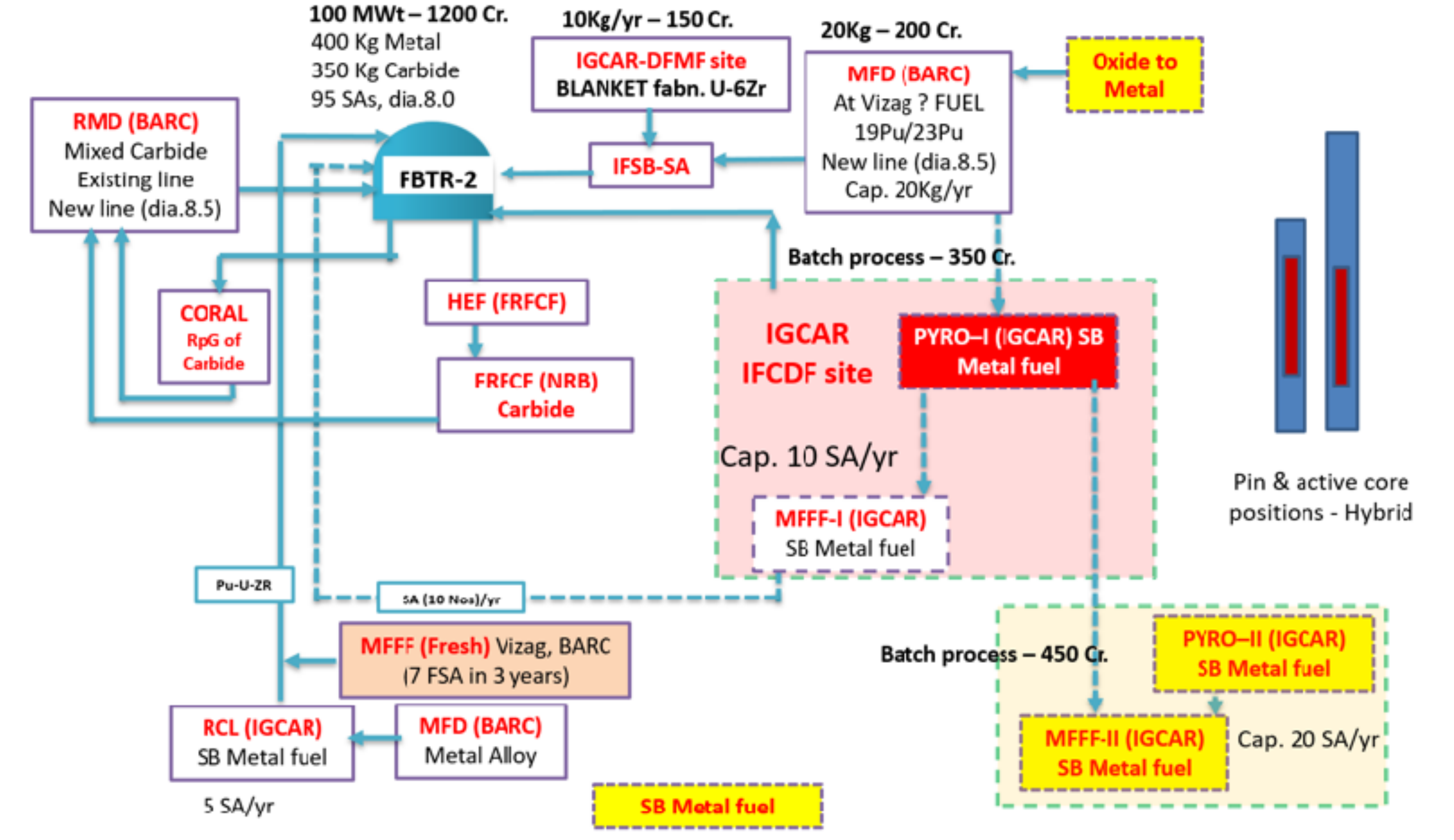
  -VFD system for PSP / SSP

  -Snubbers and Frozen seal valves
- Actions have been initiated for indigenous development

SITE LOCATION



FBTR-2 Fuel Fabrication Facility - Flow Sheet



FBTR-2: Pyro-processing of Spent Fuel

Pyrochemical Reprocessing or Pyroprocessing - a non-aqueous, high temperature reprocessing method based on molten salt electrorefining - suitable for metal fuel.

Molten salt Electrorefining: Separation of actinides from fission products - based on the Thermodynamic stabilities of chlorides of Fuel and FPs

Electrolyte: LiCl-KCl eutectic at 500° C

2- 10 wt. % of UCl_3 is added at the start of the process

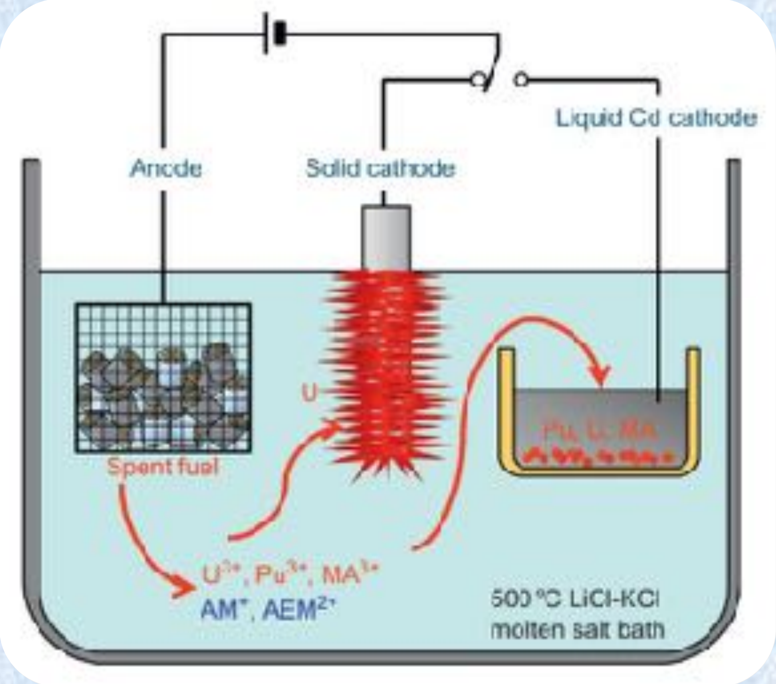
Anode (INPUT): Chopped spent fuel loaded in perforated Steel Basket

Cathodes (INPUT): Steel (for U) & liquid Cadmium (for Pu,U, MA combined)

FISSION PRODUCTS

Alkali (Rb, Cs), Alkaline Earth (Ba, Sr) & Rare E (Lanthanides): remain in salt phase as chlorides.

Noble metals (Ru, Rh): remain as metals in the anode basket.



Schematic of Electro-refining Cell

Pyro Process: Advantages and Challenges

- ✓ Ability to handle short cooled fuels
  - – Reduction in overall Doubling Time
- ✓ No Aqueous Reagents
  - – Less criticality problems
- ✓ Low process volumes
  - – Compact plant
- ✓ No high level liquid waste generated
  - – Easier Waste Management
- ✓ Minor Actinide recycle potential
- ✓ (Co-deposition of MA with U, Pu)
  - – Easier Waste Management
- ✓ Product in metallic form
  - – Simple process
- ✓ At no stage pure Pu is obtained
  - –Inherently Secure

- ✓ Low Decontamination factors
  - – remote fabrication
- ✓ High temperature process
  - – Selection of materials and proper design
- ✓ Batch process
  - – remote handling
- ✓ Requirement of high pure argon environment
  - - Argon systems

THANKS FOR THE ATTENTION