ECONOMICS OF FUEL HANDLING SCHEME FOR FUTURE FBRs

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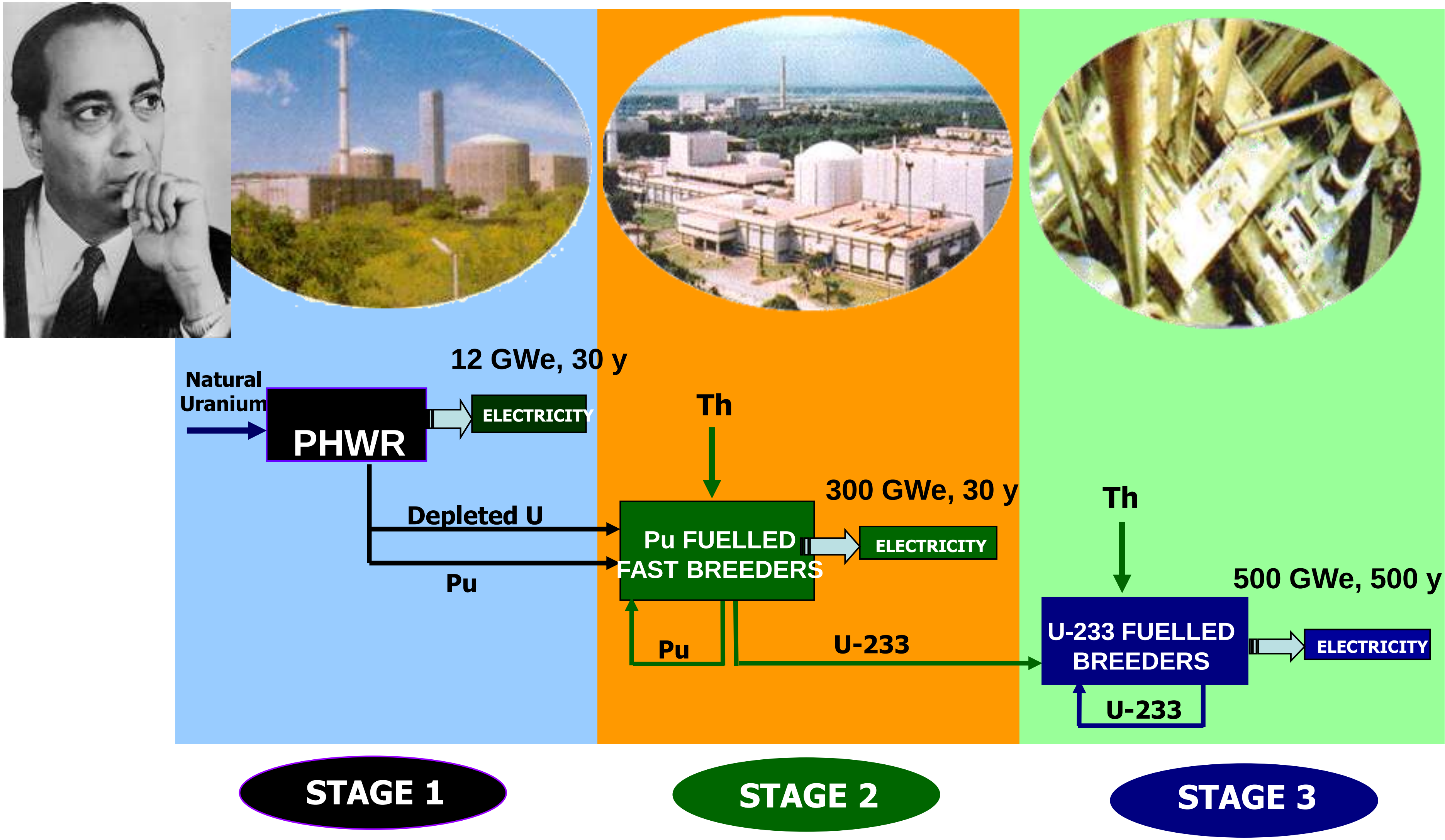
Indian Nuclear Power Programme



Totally 21 Reactors are in operation and 5 are under construction

Nuclear Power Plants in Operation

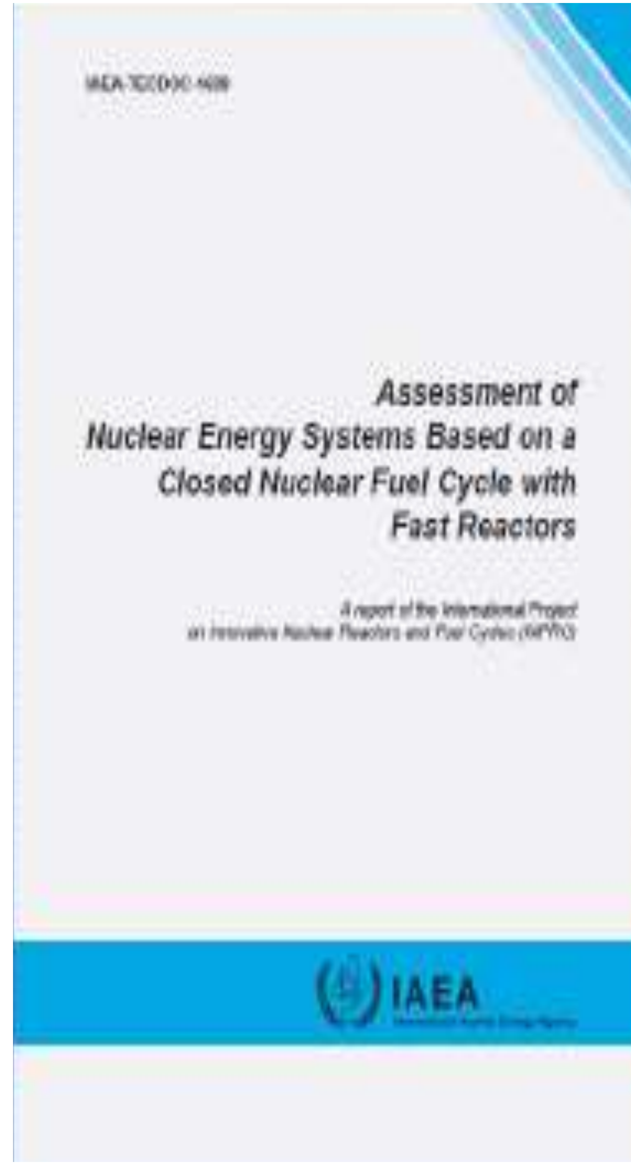
2 BWR

1 PWR

18 PHWRs

Motivation for Improving Economics

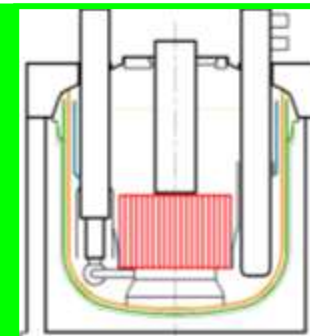
- INPRO Joint Study on 'Assessment of Nuclear Energy Systems based on Closed Nuclear Fuel Cycle with Fast Reactors (CNFC-FR)' was conducted in 2005-2007 with participation from 8 countries including India
- Major indian contributions from Dr. Baldev Raj and Dr P. Chellapandi of IGCAR
- Study observed that operating fast reactors with a closed fuel cycle were not economically competitive with thermal reactor systems or fossil power systems ⇒ Need for innovative designs with improved economy
- Further to demonstrate economic competitiveness, FBR (600 MWe) is currently being designed. Economic aspects of fuel handling scheme of FBRs are worked out



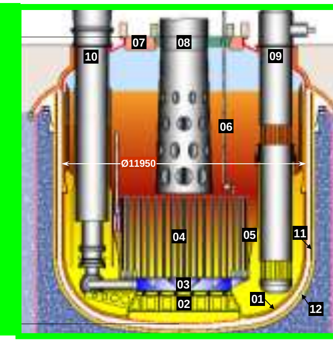
FBR Programme in India

- Indigenous Design & Construction
- Comprehensiveness in development of Design, R&D and Construction
- Synthesis of Operating Experiences
- Focus on National & International Collaborations
- Emphasis on sustaining quality human resources
- Concepts and innovations to enhance safety of SFRs

<u>Future FBR</u>
- 500/1000 MWe
- Pool Type
- Metallic fuel
- Serial constr.
- Indigenous
- Beyond 2025



<u>FBR 1&2</u>
- 500/600 MWe
- Pool Type
- UO2-PuO2
- Twin units
- Indigenous
- From 2023…



<u>*FBTR*</u>
- 40 MWt
- 13.5 MWe
- Loop type
- PuC – UC
- Design: CEA
- Since 1985

<u>PFBR</u>
- 1250 MWt
- 500 MWe
- Pool Type
- UO2-PuO2
- Indigenous
- From 2014

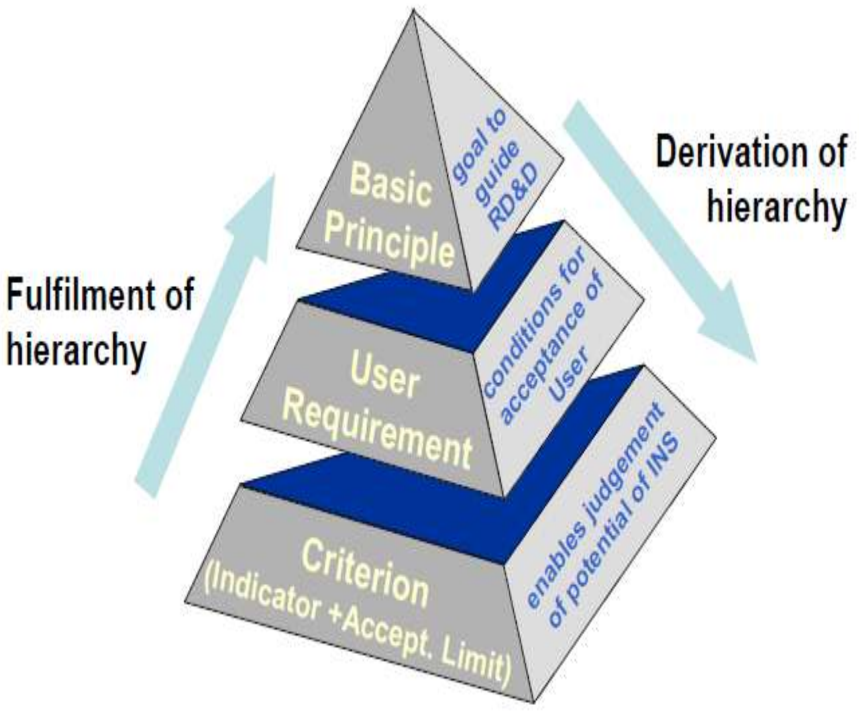
Metallic Fuel Development Activities

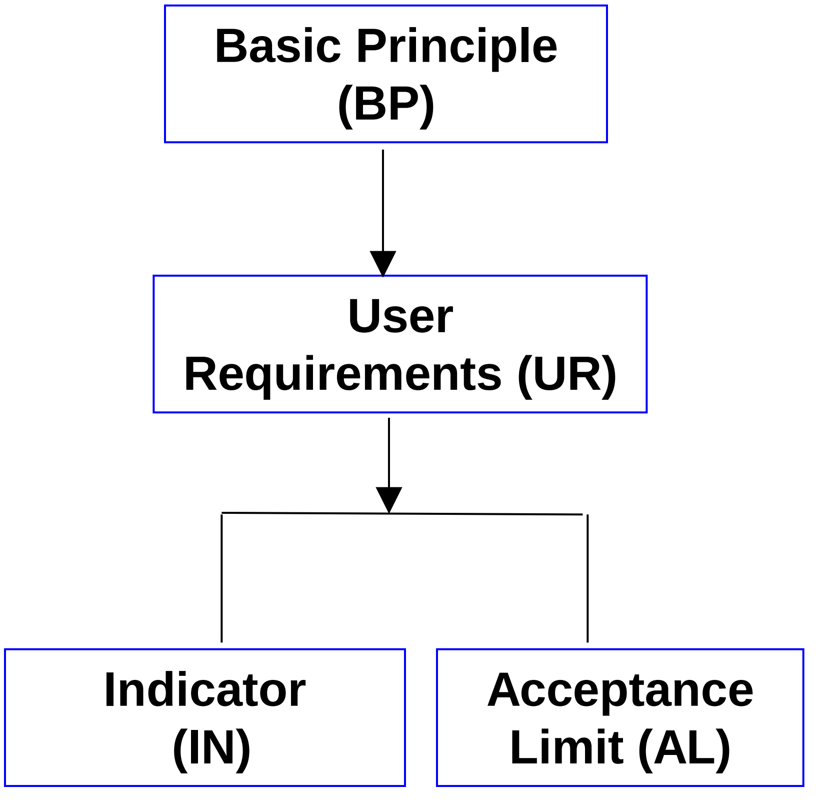
Fast Reactor Fuel Cycle Facility (FRFCF)

The facility will be self contained and have all facilities for recycling the fuel from PFBR, including fuel fabrication & assembly plants, reprocessing and waste management facility

Layout of FRFCF planned in such a way that future expansion would be possible to meet the requirements of two more oxide fuelled FBRs that would be built at Kalpakkam site beyond PFBR.

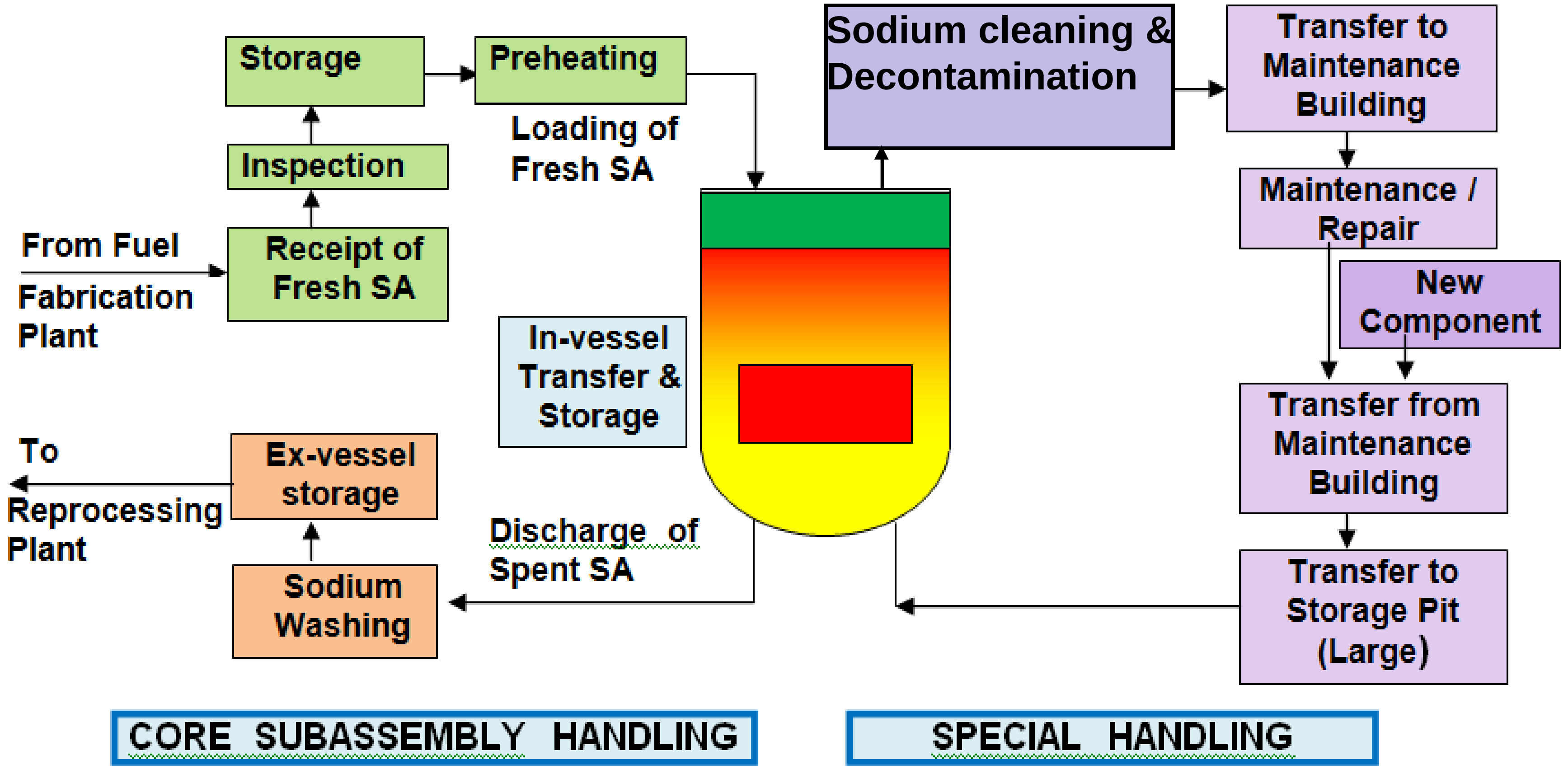
INPRO Basic Methodololgy





Ref : Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual — Overview of the Methodology, IAEA-TECDOC-1575 Rev. 1

FBR Fuel Handling - Sequence



- ❖ Off-line Refuelling
- ❖ Sodium temperature during FH = 200ºC (Targeted to be raised to 250ºC)

Criteria for Economic Assessment of FH Scheme

Basic Principle (BP)	User Requirements (UR)	Indicator (IN)	Acceptance Limit (AL)
Competitive cost for energy generation	Reduction in capital cost of reactor	Specific steel consumption (t/MWe)	Target : 25% reduction as compared to reference design
	Reduction in construction & erection time	Time from First pour of concrete to criticality	Target : 7y for reactor and 3y for fuel handling system
	Faster fuel recycling	Capability to handle short cooled fuel	Target : Max decay power on discharge to reprocessing plant 2.5 kW / SA

Criteria for Economic Assessment of FH Scheme

Basic Principle (BP)	User Requirements (UR)	Indicator (IN)	Acceptance Limit (AL)
Increase in capacity factor	Longer re-fuelling interval	Higher Breeding ratio	Target : ~ 1.15-1.2 (up to 1.4 in the long term)
		Higher Burnup	Target : 150-200 GWd/t
	Shorter fuel handling campaign time	Time to replace spent SA with fresh SA	As minimum as possible
	Reliable operation without incidents	Loss of operational days	Target : Major incidents Nil

Prototype Fast Breeder Reactor (PFBR) is taken as the reference design

Reduction in Capital Cost

- **Simplicity of design :**
- **Design that does not call for stringent tolerance or alignment requirements**

Means :

- **Replacement of Inclined fuel transfer machine with Handling flask ⇒ Reduction in capital cost by 50% for this item**

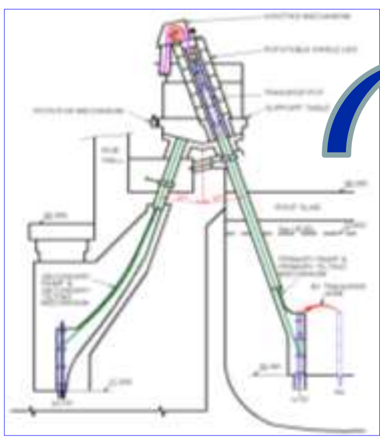
- **Twin or multiple units with sharing of Fuel Handling equipment meeting the regulatory requirements**
- **Offline refueling in fast reactors makes sharing of fuel handlng equipment between twin or multiple units highly economical**

Means :

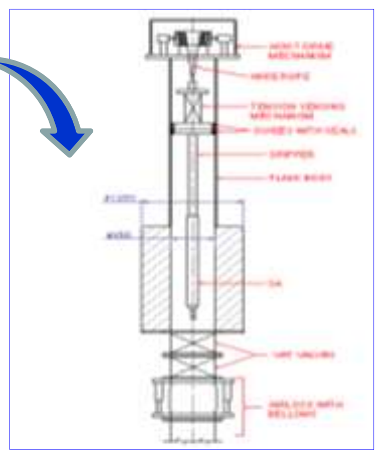
- **For a twin unit 600 MWe FBR, Specific steel consumption for fuel handling system reduces by 55% (CS – 55 % ; SS – 54 %)**

Reduction in Construction & Erection Time

Hardfacing of long & slender rails



IFTM



Handling Flask

❖ **Reduction of Complex Hardfacing :**

- **Minimum complex hardfacing geometries to reduce manufacturing time**
- **Simple designs with minimum manufacturing & erection complexities**

Means :

- **Replacement of IFTM with handling flask expected to save ~ 30% of manufacturing time for this component and 2 months of erection time ⇒ Will help to achieve targeted overall construction time of 7 y (reactor) and 3y (fuel handling system)**

Faster Fuel Recycling

- **Capability to handle short cooled fuel :**

- **PFBR employs two campaigns of internal storage for fuel subassemblies; Decay power of SA on discharge to reprocessing plant is 1.5 kW**

Means :

- **Target is to raise the limit on decay power of SA on discharge to reprocessing plant to 2.5 kW to recycle fuel faster ⇒ Reprocessing capability to be demonstrated for 2.5 - 5 kW**

Demonstration of spent fuel reprocessing

16 Stage Centrifugal Extractor Bank

CORAL facility operation area

Progressive hotter fuel reprocessing

Demonstration fuel Reprocessing Plant (DFRP)

Burn up (GWd/t)	Cooling period (Years)	Sp. Activity, (Ci/Kg)
25	7	300
50	5	800
100	2.5	3000

Spent Fuel Parameters influencing Reprocessing

Increase in Capacity Factor

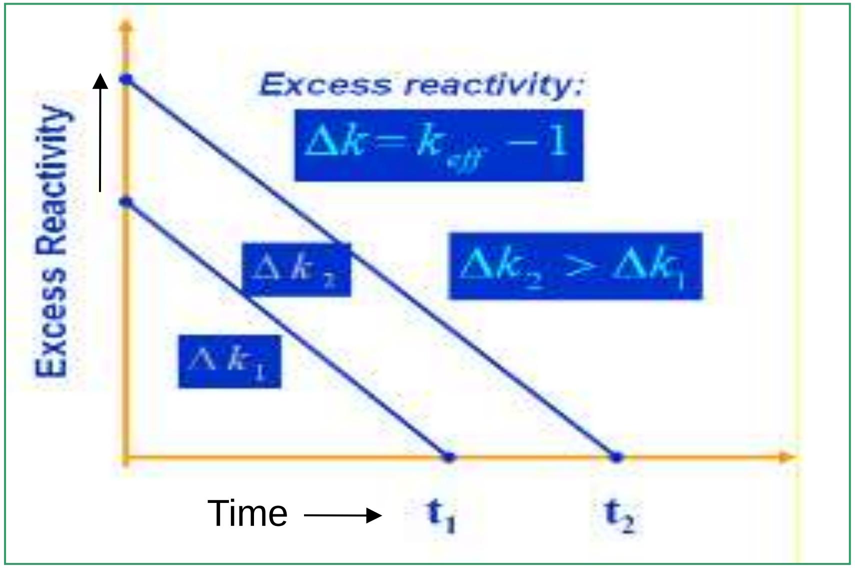
❖ **Longer Refuelling Interval :**

- **Higher Burnup of 150-200 GWd/t as compared to 100 GWd/t for PFBR**

Means :

- **Reactor core design measures to improve burnup**
- **Matching reprocessing capability for fuel with high burnup**
- **Use of Advanced structural material for core ⇒ Oxide Dispersion Strengthened (ODS) ferritic steel for clad and ferritic steel for wrapper, which have the potential to reach 200 dpa**
- **4.2 m long ODS clad tubes already developed; Use of ODS steel has potential to increase the refueling interval (with the matching excess reactivity provided in core) and wrapper material also should have the capability to withstand the irradiation effects due to higher dose**
- **Verification and validation of subassembly bowing by downward viewing using under sodium ultrasonic scanner to give confidence for possible enhancement of burnup**

Reactor Core - Design Measures for High Burnup



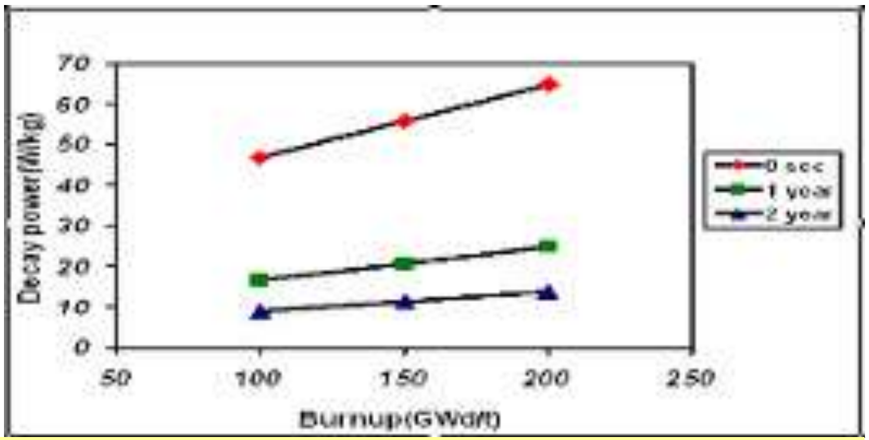
Excess Reactivity Vs Burnup

Parameter	Present	Future
Cycle length (efpd)	180	270
Fuel enrichment (%)	21/28	25/30*
Fraction of core discharge per cycle	1/3	1/4
	61 SA	50 SA
Peak fuel burnup (MWd/t)	100,000	200,000
Peak dpa	82	150

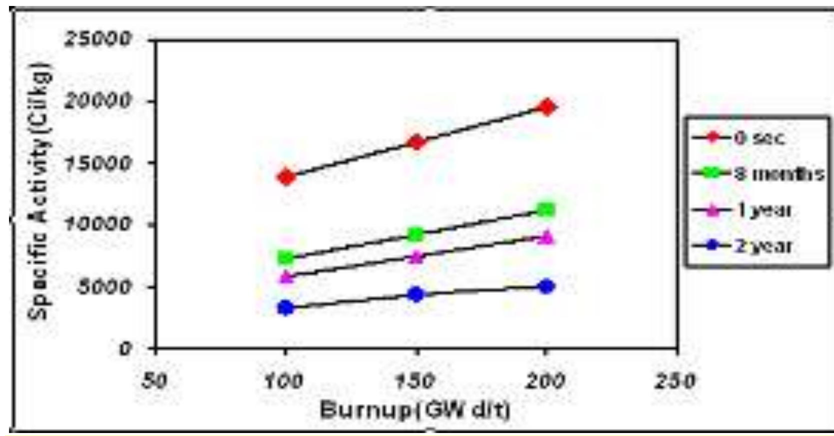
Issues with increased burnup

Excess reactivity & Shutdown margin

B_4C – 90% enrichment, 18 FSA extra

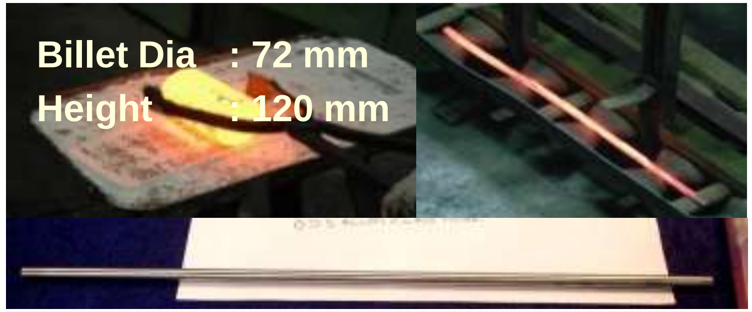


Decay Power Vs Burnup



Specific Activity Vs Burnup

Advanced Clad & Wrapper Development



Clad tubes in ODS Steel

Parameter	Current	Stage-1	Stage-2	Stage-3	Stage-4
Target period		Short	Short to Medium	Medium to Long	Long
Target Burnup GWd/t	100	125	150	200	200
Fuel	Oxide	Oxide	Oxide	Oxide	Metallic
Clad material	D9	IFAC-1 SS	IFAC-1 SS	F-M steel ODS	T91 F-M steel
Wrapper Material	D9	IFAC-1 SS	T9 F-M steel	T9 F-M steel	T9 F-M steel

IFAC-1 SS Clad and Wrapper Development

Void swelling, thermal creep

Optimisation of Ti, Si, P in alloy D9

15 laboratory heats (14Cr-15Ni)

P: 0.025, 0.040

Si: 0.75, 0.95

Ti: 0.16, 0.20, 0.24, 0.30

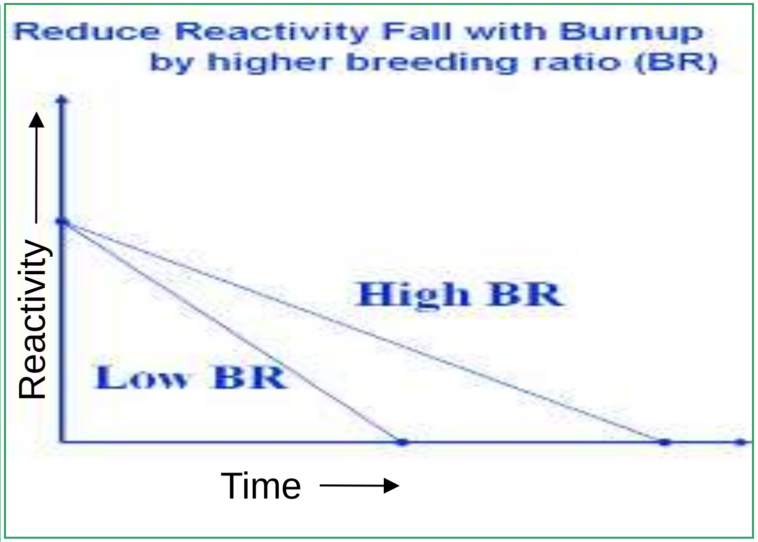
Evaluation (20% CW)

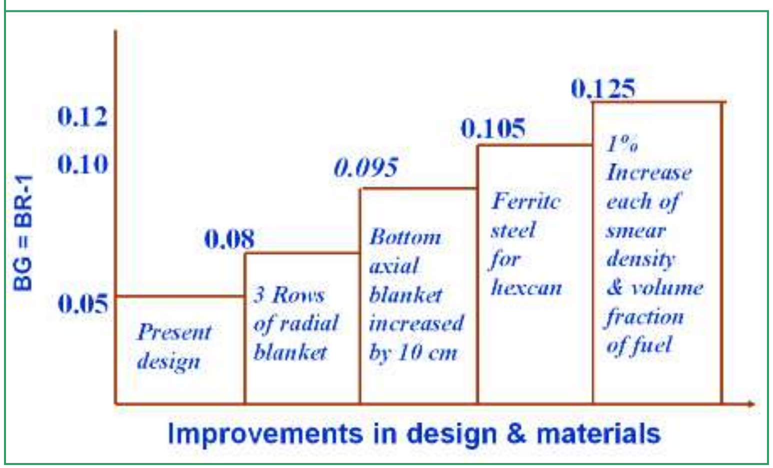
- ✓ Void swelling
- ✓ Creep properties
- ✓ Tensile properties
- ✓ Weldability
- ✓ Microstructural stability

IFAC-1 = Indian Fast Reactor Advanced Clad - 1

Nickel	14.5-15.5
Chromium	13.5-14.5
Nitrogen	0.005
Molybdenum	2.0-2.5
Manganese	1.65-2.35
Boron	0.005
Sulphur	0.01
Carbon	0.035-0.045

Increase in Capacity Factor





BR 1.1 possible for homogeneous oxide core

- **Longer refueling Interval**

  Higher Breeding Ratio

- **Target is to achieve breeding ratio of 1.2-1.4 to generate more Pu by breeding so as to reduce the dependency of Pu from external sources**
- **Rate of Reactivity decrease with Burnup is less for higher breeding ratio**

Means :

- **In the near future, achieving higher breeding ratio will be targeted for oxide core with higher emphasis on reducing sodium void coefficient of reactivity.**
- **In the long term, metal fuel reactors are planned to achieve higher breeding ratio**

Increase in Capacity Factor

❖ **Shorter Fuel Handling Time :**

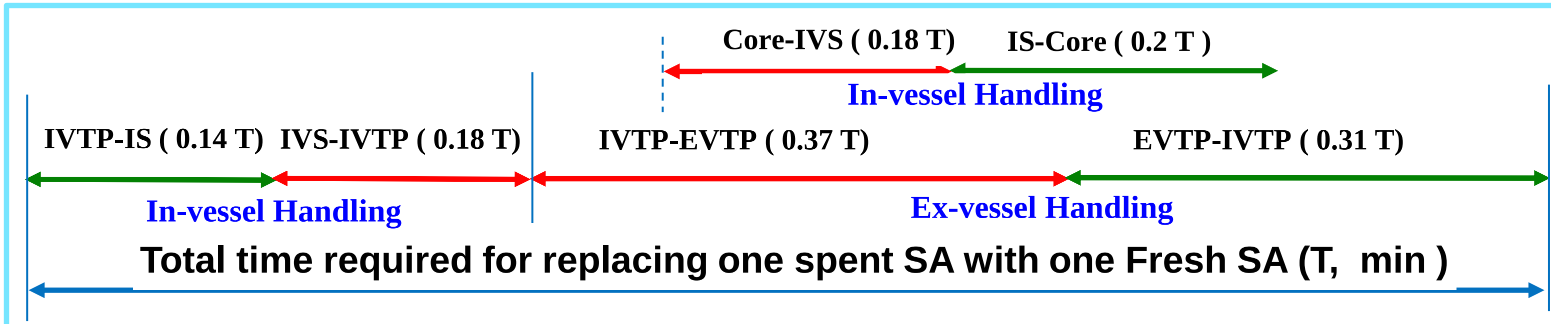
Overall time for fuel handling to be minimum

Means :

Short travel distance between in-vessel to ex-vessel storage in fuel handling route ⇒ Use of sodium storage ; Also subassembly washing can be done after completion of fuel handling in case of sodium storage resulting in significant saving in fuel handling time

- **Match in-vessel handling time with ex-vessel handling time**

⇒ Multiple SA handling for faster exchange of spent SA with fresh SA



Illustrative Handling Time Map

- **Increase in machine speeds (Marginal effect)**
- **Improvement in SA washing methods (long term)**

Increase in Capacity Factor

❖ **Reliable Operation without Incidents :**

- **Sodium is opaque which makes fuel handling operations blind**
- **Fuel handling incidents have serious implications on reactor availability due to long time required for rectification (FBTR, Joyo)**

Means :

- **Ensure positively no physical connection between core and above core devices / fuel handling machines before plug rotation ⇒ use of Under Sodium Ultrasonic Scanner (USUSS)**
- **Extensive use of computers to monitor and verify step by step fuel handling sequence implementation during campaign ⇒ Implemented in PFBR**
- **Use of Fuel Handling Simulator to train and qualify operators before carrying out fuel handling ⇒ Implemented in PFBR**

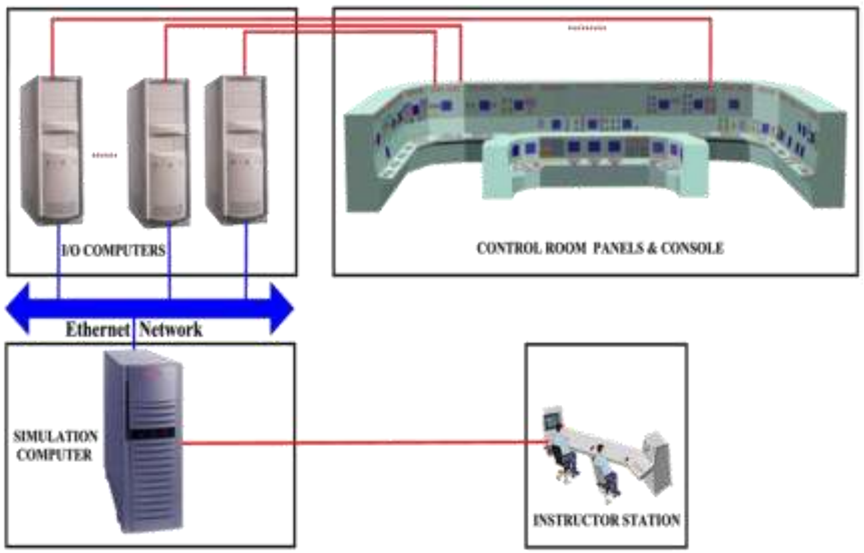
Under Sodium Ultrasonic Scanner

Overall Assembly

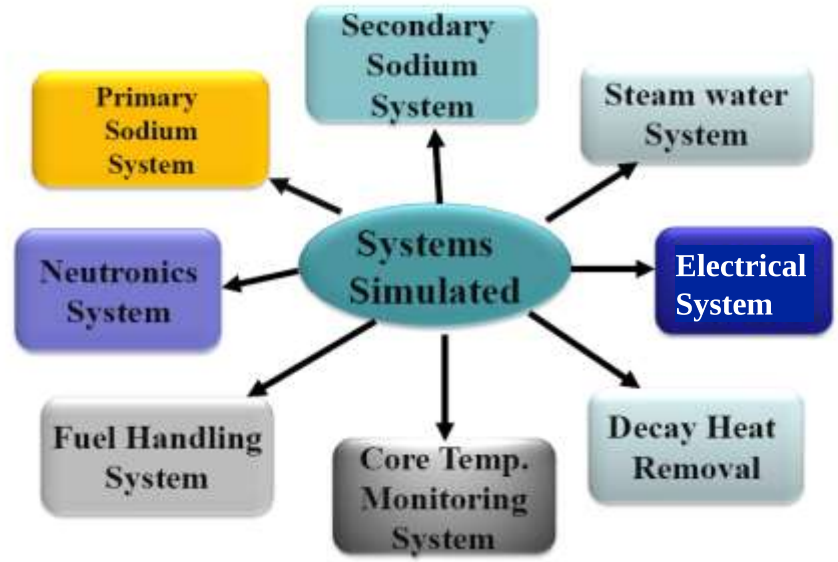
Transducers with MI Cables

- **Under Sodium Ultrasonic Scanner (USUSS) – Designed to scan the above core plenum (in reactor shutdown condition)**
- **Primary aim is to give clearance before first rotation of plugs during fuel handling**
- **Capability to measure subassembly axial growth and radial shift of SA centre due to bowing ⇒ More precise assessment of bowing effects**
- **Works based on Line of sight and Time of flight principles**
- **Employs side viewing transducers for horizontal direction scan and downward viewing transducers for vertical direction scan**
- **Development of high temperature transducers (250°C) ⇒ Higher sodium temperature during fuel handling decreasing fuel handling time**

PFBR Operating Training Simulator



Basic Hardware Architecture



Various Systems Simulated

- Combination of
  - Mathematical models of plant components
  - Control system emulation
  - Man- machine interface
- Various plant conditions simulated
- Operator carries out operations and observes responses as in the reactor

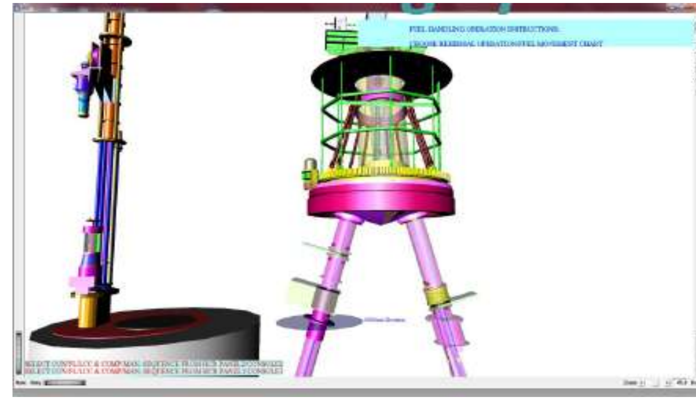
Plant Conditions Simulated

- Start up of Reactor
  - Including First Criticality
- Power Raising Operation
  - Full power
  - Partial power
- Normal steady state operation
- Shutdown of Reactor.
- Fuel Handling state of Reactor
- Malfunctions/ Incidents of plant

PFBR Fuel Handling Simulator

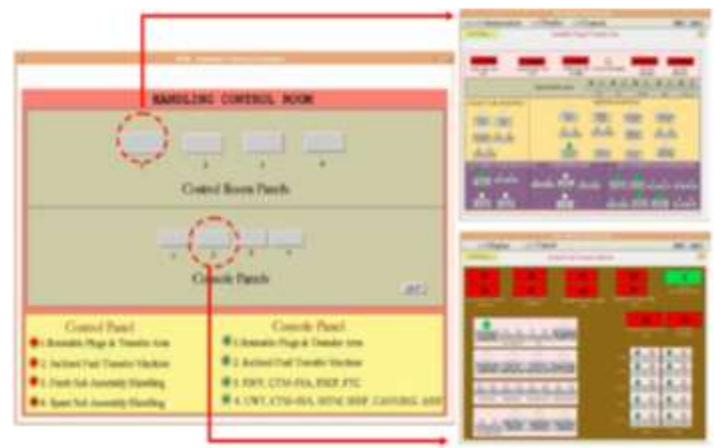
Handling Control Room Panels & Console

Simulator Panels & Console



Real Time 3D Simulation

- **Simulator covers machine operation of Transfer arm, Inclined fuel transfer machine (IFTM) and other fresh subassembly / spent subassembly handling machines**
- **Handling Control Room (HCR) panels and consoles simulated as in the reactor**
- **Certain incidents related to fuel handling system also simulated to check the operator response**



Virtual Panel of HCR Control Panel and Console

Target Goals

- **Phase I (Near Term) :**

  Breeding ratio of 1.05-1.12 (Homogenous oxide core)

  Improved clad material (advanced austenitics e.g IFAC-1I); wrapper (9Cr-1Mo)

  Burnup : 100-125 GWd/t

  Sharing of CH equipment between twin units

  Optimising structural thickness and concrete volumes wherever possible to reduce specific steel consumption / concrete use

  25% reduction in specific steel consumption

  Construction time of 7 y

- **Phase II (Medium Term) :**

  Breeding ratio of 1.15-1.20 (Heterogenous oxide core / metal core)

  Improved clad material (Advanced austenitics / ODS); wrapper (9Cr-1Mo)

  Burnup : 125-150 GWd/t

  Sharing of CH equipment between multiple units

  Construction time of 6 y

Target Goals……

- **Phase III (Long Term) :**

  Breeding ratio of 1.20-1.40 (Metal core)

  Improved clad material (Improved Ferritic clad); wrapper (9Cr-1Mo)

  Burnup : 150-200 GWd/t

  Use of sodium storage

  Construction time of ~ 5 y

Summary of 600 MWe Reactor Features

Parameter	PFBR	CFBR (2014)
Gross Power	500 MWe	600 MWe
Design life	40 years	60 years
Capacity factor targetted	75%	85%
Construction time	11 y	7 y
No. of unit(s)	Single	Twin unit sharing few facilities
Fuel cycle facility	Co-located	Co-located
Fuel Reprocessing	Acqueous	Acqueous

Summary of 600 MWe Reactor Features

Parameter	PFBR	CFBR (2014)
Type of Core	Homogenous	Heterogenous
Fuel	MOX (UO_2-PuO_2)	MOX (UO_2-PuO_2)
Breeding Ratio	1.05	~1.2
Burnup	100 GWd/t (peak)	150-200 GWd/t (Progressive)
Fuel pin dia & No. of pins	6.6 mm, 217	6.6 mm, 217
Coolant	Sodium	Sodium
Primary circuit configuration	Pool (2 PSP, 4 IHX, 2 SSP)	Pool (3 PSP, 4 IHX, 2 SSP)

Summary of 600 MWe Reactor Features

Parameter	PFBR	CFBR (2014)
Steam generator configuration	Steam reheat, Integrated once through, Single wall	Steam reheat, Integrated once through, Single wall
Turbine	One	One
Spent fuel storage	Water	Water

Summary

- Basic INPRO methodology and its application to fuel handling system is brought out.
- To achieve significant cost competitiveness, major user requirements identified are reduction in capital cost, reduction in construction & erection time and faster fuel recycling. To achieve higher capacity factor, the user requirements are longer re-fuelling interval, shorter fuel handling campaign time and reliable operation without incidents.
- Means to achieve the above user requirements including the target indicators and applicable limits are brought out.
- Application of above structured methodology will help in correctly identifying and implementing means to reduce the cost of fuel handling system for future FBRs. It will also help to arrive at the R&D roadmap for implementation.

THANKS FOR YOUR ATTENTION