Reactor Physics and Safety Aspects of Fast Neutron Reactors with Associated Closed Fuel Cycle

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COMMITMENT TO FBR TECHNOLOGY

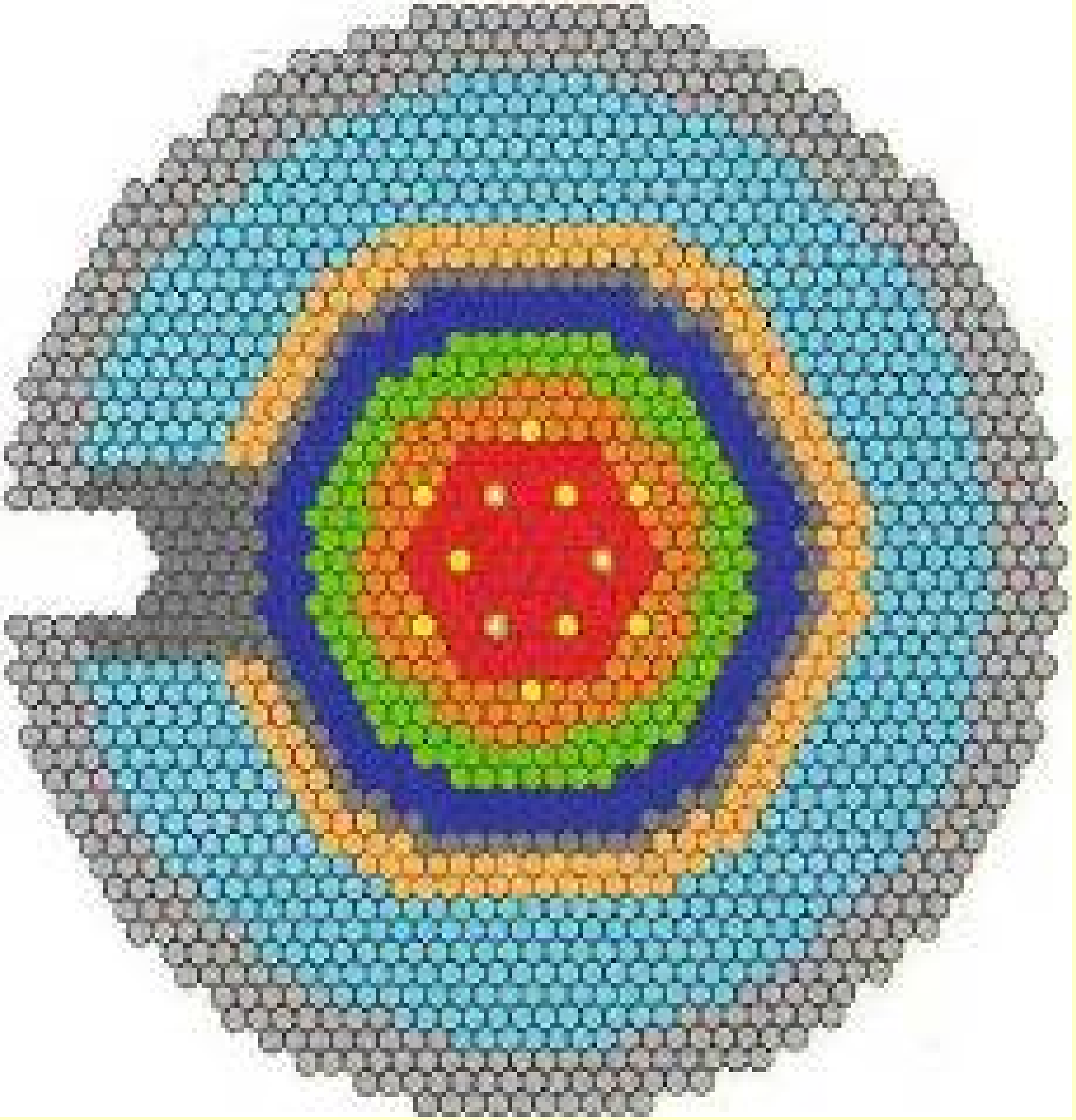
- Present PHWR once through fuel cycle potential - 10 GWe for 40 y – First stage
- Present emphasis on exploration of new U deposits
- 14 PHWR under operation
- Import of U under IAEA safeguards
- Reprocessed Pu from PHWR cycle in closed FBR cycle – 1000 GWe for 50 y and U-233 breeding from thorium - Second stage
- Th-U breeders fast and thermal – Third stage

PFBR (500 MWe) UNDER CONSTRUCTION

- Power – 1250 MWt
- Fuel - MOX
- Pu enrichments (core-1/core-2) - (21 %/ 28 %)
- Coolant circuit – pool type
- Number of primary pumps - 2
- Number of intermediate heat exchangers – 4
- Peak heat rating – 450 w/cm
- Refuelling interval – 180 full power days
- Core fraction replaced – one third
- Peak burnup – 100 GWd/t
- Reactor life time – 40 y

PFBR CORE

SYMBOL	TYPE OF SUBASSEMBLY	No.
⬢	FUEL (INNER)	85
⬢	FUEL (OUTER)	96
⬢	CONTROL AND SAFETY ROD	9
⬡	DIVERSE SAFETY ROD	3
⬢	BLANKET	120
⬢	STEEL REFLECTOR	138
⬢	B_4C SHIELDING (INNER)	125
⬢	STORAGE LOCATION	156
●	STEEL SHIELDING	609
●	B_4C SHIELDING (OUTER)	417
	TOTAL SUBASSEMBLIES	1758



PFBR SAFETY REVIEW

- Initial review of design by internal safety committee of IGCAR
- Project design safety committee of AERB

  Basis for review – AERB codes and guides
  - IAEA codes and guides
- Being first of its kind, comprehensive and systematic review of separate chapters of Preliminary Safety Analysis Report by separate expert groups
- Emphasis on

  (a) Test results from other fast reactors
  (b) Generic problems in other fast reactors
  (c) Efficacy of improvements tested

IN-CORE FUEL MANAGEMENT

- **Computer code FARCOB developed**
- **Validated against FBTR core and international benchmarks**

BN-600 MOX Core Benchmark (IAEA-CRP)
(3D Diffusion)

Parameter	ANL	EU	JNC	IGCAR
keff – BOC - EOC	0.99592 0.97162	1.01546 0.98914	1.00713 0.98323	1.00136 0.97671
Reactivity loss	0.02511	0.02621	0.02414	0.02520
Doppler constant (k_D) BOC EOC	-0.00685 -0.00687	-0.00683 -0.00732	-0.00646 -0.00703	-0.00684 -0.00731
Change in k_D	0.00002	0.00049	0.00043	0.00047

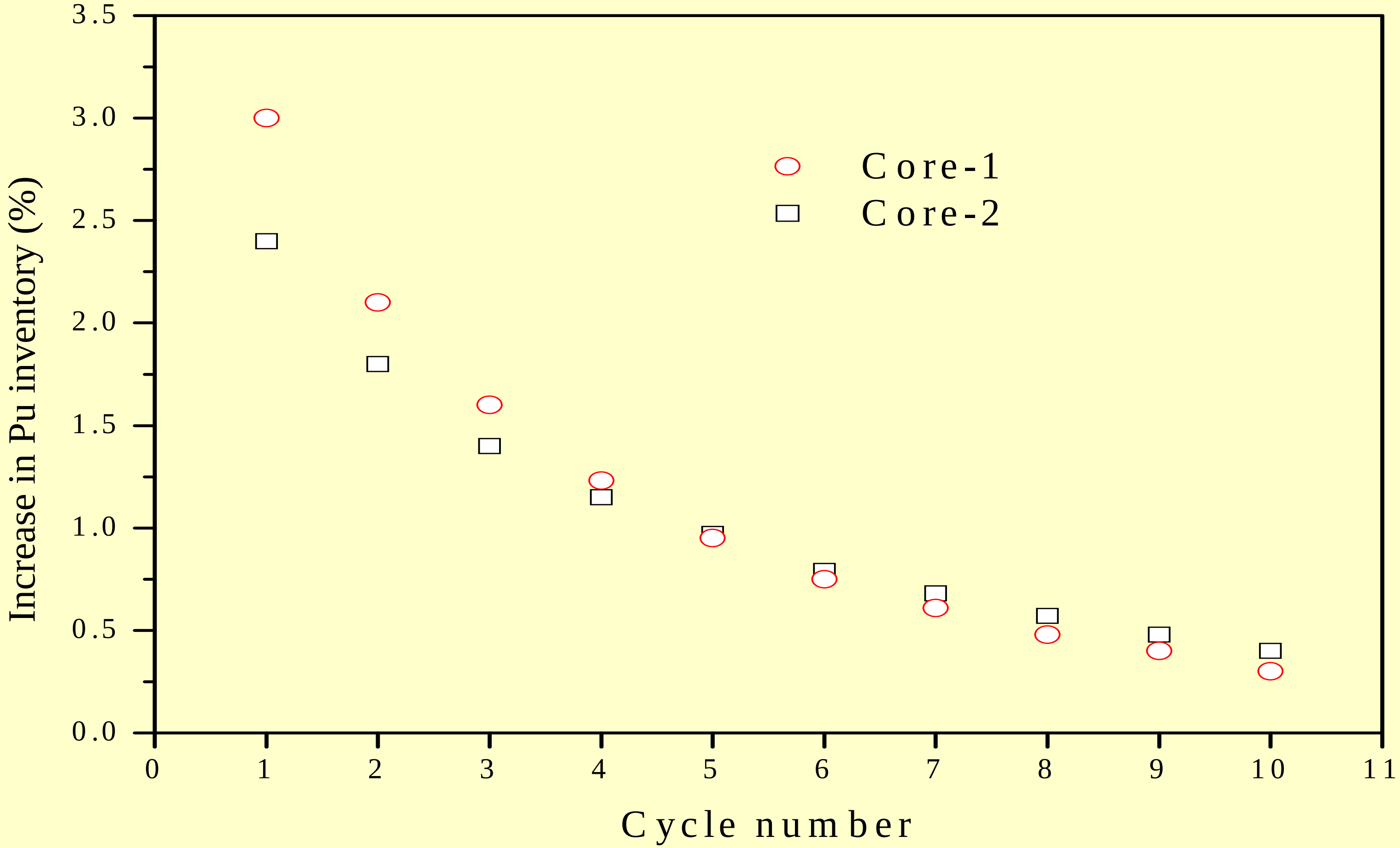
CLOSED FUEL CYCLE

- **In vessel cooling period – 240 d**
- **Reprocessing period – 240 d**
- **Fabrication period - 240 d**
- **Pu-239 reactivity equivalence used to judge quality of Pu after each recycle**
- **With Pu inventory of 2 cores, 10 fuel cycles (60 refuelling) correspond to 40 y**
- **Net Pu enrichment change over 10 fuel cycles**

  core-1: 21% to 23.4%,

  core-2: 28% to 31%

Pu INVENTORY CHANGE WITH MULTI-RECYCLE



SUSTAINING NUCLEAR POWER GROWTH – METAL FUELLED FBR (FBR-M)

- Require low fuel Doubling Time
- Metal fuel in FBR can provide high fuel breeding
- U-Pu-Zr and U-Pu with Zr lined clad

FBR-M (500 MWe)

Parameter	U-Pu-Zr(10%)	U-Pu-Zr(6%)	U-Pu / Zr liner
Pu enrichments	15.4/20.6	13.6/18.2	12.7/17.1
Pu inventory (t)	1.93	1.97	2.16
Breeding ratio	1.24	1.36	1.44
Doppler constant (pcm)	-408	-470	-501
Na void worth ($)	4.6	5.1	6.0

SAFETY ASPECTS OF FBR-M

- Compared to MOX core , metal core has lower Doppler constant and significantly higher Na void worth
- Concern of reactor safety under unprotected loss of flow accident (ULOFA)
- IGCAR study show that despite the high Na void worth, ULOFA of metal core is realtively benign
- Na voiding is low and happens only on reactor top – Net reactivity is –ve after 30 minutes

SUMMARY RESULTS OF ULOFA

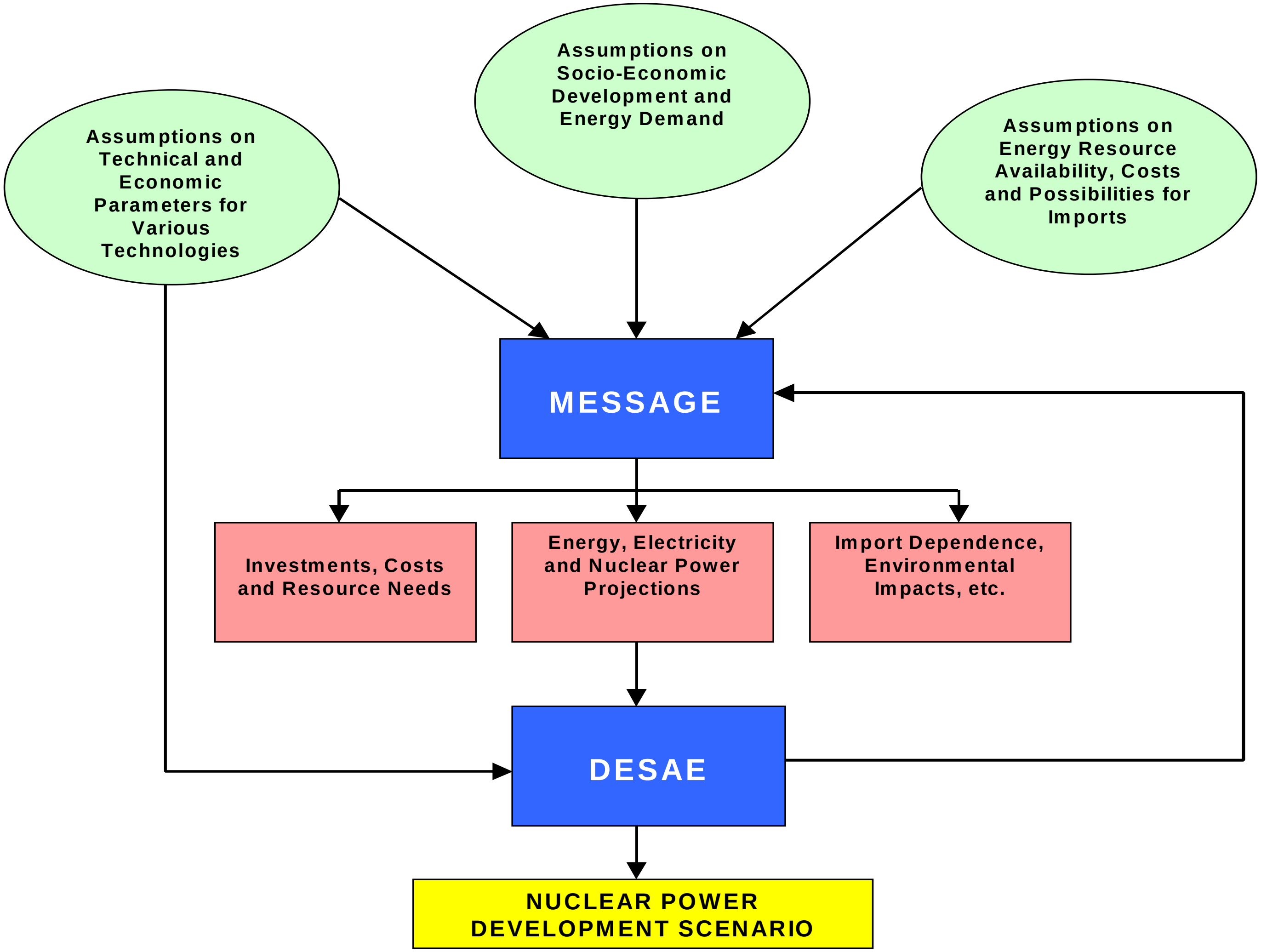
Conditions after 1800s of ULOFA	U-Pu-Zr(10%)	U-Pu-Zr(6%)	MOX core
Reactor power (MWt) Net reactivity ($) Net Na void fraction Fuel melting fraction	18* -0.51 -0.036 0.0	18* -0.52 0.036 0.0	Fuel melted and core damaged at 80s

*Decay power not added

POSSIBLE POWER GROWTH SCENARIO WITH FBR-M IN INDIA

- **IAEA computer codes MESSAGE & DESAE linked under INPRO work**
- **Nuclear material balances and maximum achievable power growth with Pu from PHWR studied**
- **PHWR component peaks at about 2022-2032**
- **Imported LWR component is low**
- **1000 MWe FBR-M with Breeding ratio = 1.6**
- **FBR-M introduced after 2020**
- **FBR-M expected to sustain the power growth**

NUCLEAR POWER SCENARIO



Assumptions on Technical and Economic Parameters for Various Technologies

Assumptions on Socio-Economic Development and Energy Demand

Assumptions on Energy Resource Availability, Costs and Possibilities for Imports

MESSAGE

Investments, Costs and Resource Needs

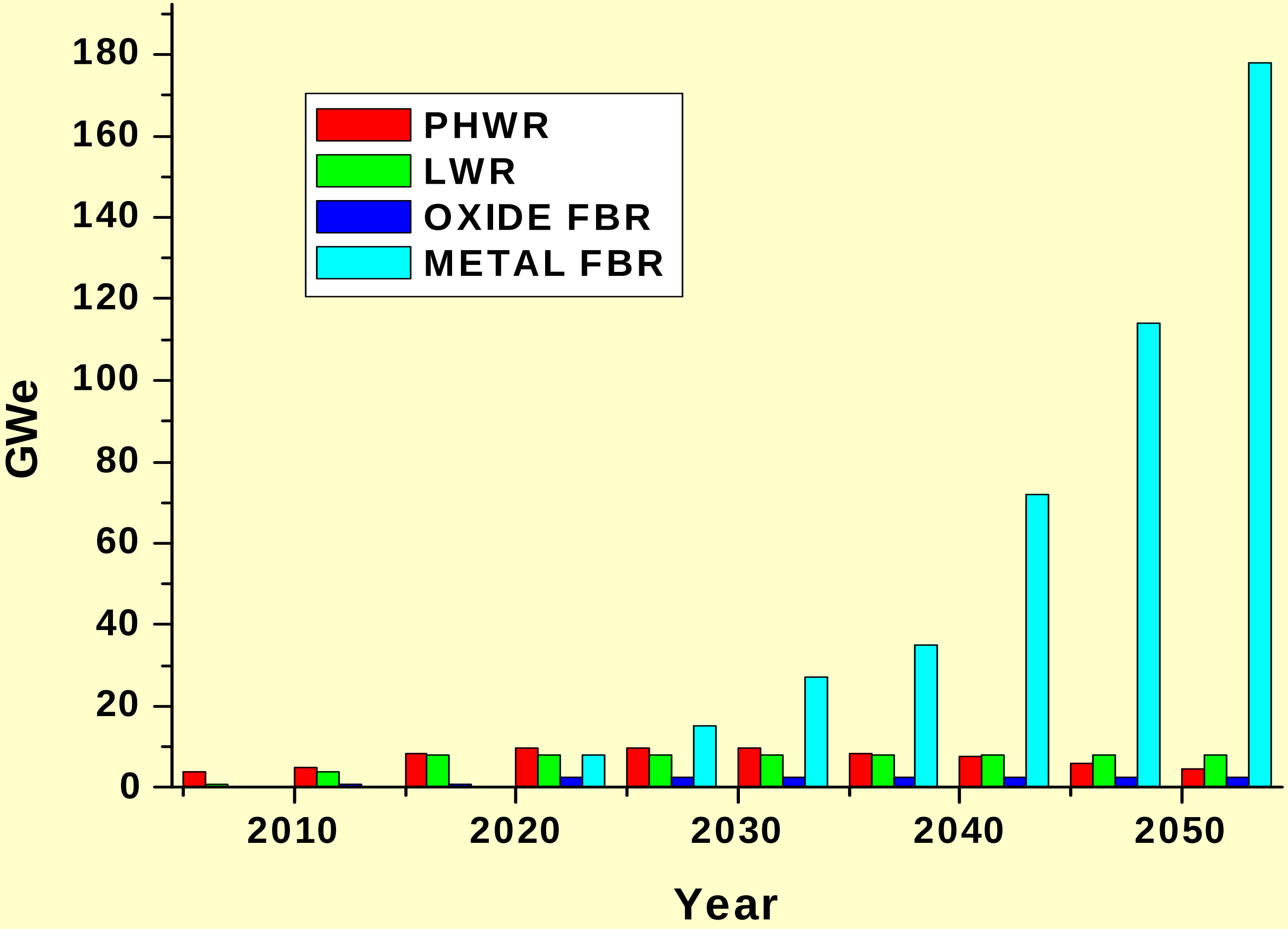
Energy, Electricity and Nuclear Power Projections

Import Dependence, Environmental Impacts, etc.

DESAE

NUCLEAR POWER DEVELOPMENT SCENARIO

A POSSIBLE POWER SCENARIO



ADVANTAGES OF THE USE OF FBR FOR MA TRANSMUTATION

- **Hard neutron spectrum reduces capture to fission ratios compared to thermal**
- **Penalty on core parameters with homogeneous mixing of MA is mild in FBR compared to thermal reactor – (eg. required Pu enrichment reduces)**
- **Existing fuel fabrication facilities handling Pu for FBR can accommodate MA with some strengthening of shields**

MA PRODUCED IN PHWR

- MA to be partitioned and mixed with FBR core fuel.
- MA produced in PHWR-540 in life time is 112 kg
- Typical composition of MA in discharged fuel (zero cooling)
- Np-237 - 88.6 %
- Am-241 - 5.4 %, Am-242m - 0.045 %, Am-243 - 5.13 %
- Cm-242 - 0.67 %, Cm-243 - 0.004 %, Cm-244 - 0.15%

- With cooling of few years, Cm-242 decays out
- Pu-238 content is only 0.1 % in PHWR Pu

DESIGN OF MA BURNER FBR

- PFBR design altered for MA burner
- Depleted UO_2 radial blanket replaced by ThO_2
- For thorium utilisation in India (to get fissile U-233), it is not advisable to mix MA in the blankets
- Cycle length – 180 fpd with 1/3 core refueling
- MA loaded in core per cycle – 130 kg
- Transient behaviour is well with in acceptable limits (IAEA-CRP)
- Fuel gamma activity is 2 times higher and neutron source is 4 times higher than PFBR fuel

COMPARISON OF PHYSICS PARAMETERS OF MA BURNER AND PFBR

Parameter	PFBR	MA Burner
No. of core sub-assemblies PuO_2 enrichment (%) (Pu + MA) inventory (kg)	85/96 21.0/28.0 1970	85/102 19.5/27.1 2321
Doppler co-efficient (pcm)	- 658	- 610
Delayed neutron fraction (pcm)	343	338
Sodium void reactivity of core (%)	1.6	1.8

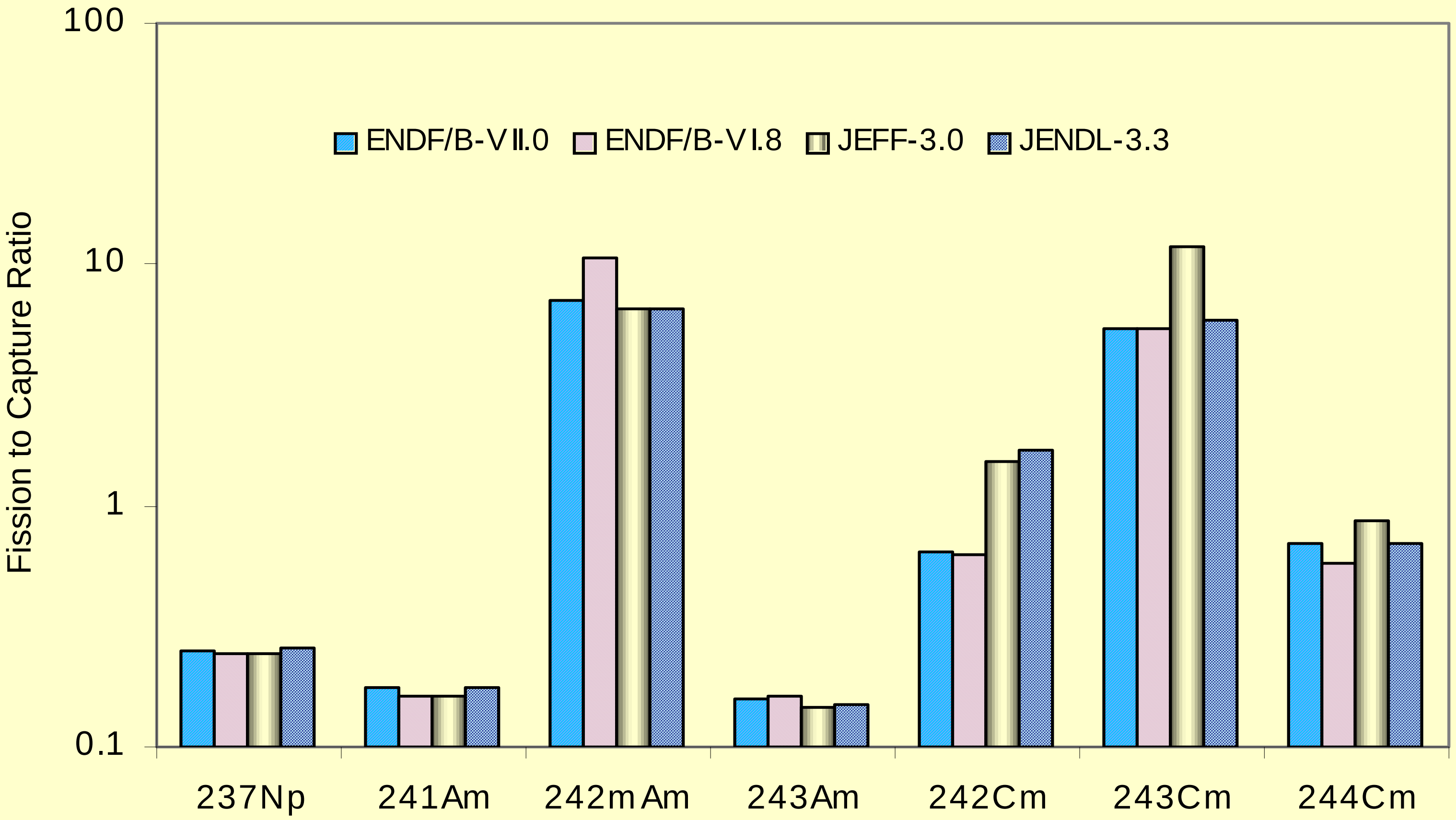
Fuel And Ma Inventory Change in One Cycle

Material	BOC	EOC
Pu in core	1.88 t	1.85 t
MA in core	0.368 t	0.336 t
MA incineration is 32 kg (8.5 %)		
Pu in axial blanket	0.079 t	0.127 t
	Pu gain 48 kg	
MA gain in radial and axial blankets	Insignificant - 50gm each in radial and axial	
U-233 in radial blanket	0.621 t	0.664 t
	U-233 gain 43 kg	
ThO_2 in axial blankets produce 31 kg U-233		

EFFECT OF SPREAD OF EVALUATED MA NUCLEAR DATA

- **MA data used from JENDL 3.3, JEFF 3.0 ENDF/B-VI.8 and ENDF/B-VII.0**
- **Fuel Doppler constant - ± 5%**
- **Na void worth - ± 10 %**
- **Delayed neutron fraction (β) - ± 2 %**
  Individual isotope β differences are 10 to 20 %
- **Reactivity loss in a cycle ± 3%**

COMPARISON OF CAPTURE TO FISSION RATIO



VALUABLE FISSION PRODUCTS FROM FBR FUEL CYCLE

	1 GWe for 1 y (75 % capacity)
Element/Isotope	**kg**
Cs (Cs-137)	143.7 (44.6)
Sr (Sr-90)	16.8 (10.2)
Ru	108.2
Rh	39.1
Pd	83.0

Rh and Ru become inactive few tens of years after separation

COST REDUCTION OF FUEL CYCLE

Multiple units at a given site

- Sharing of facilities outside nuclear island
- Sharing of fuel handling facilities of two units
- Sharing of operation and maintenance

Road map for higher fuel discharge burnups

- Aim for 200 GWd/t peak burnup with right choice of structure materials
- Radiation damage models and micro-structurecharacterization of materials
- Ferritic martensitic steels and Oxide Dispersion Steels (ODS) are the viable choices

REACTOR PHYSICS ASPECTS OF HIGH BURNUP OXIDE CORE

Parameter	PFBR	Future Oxide
Breeding ratio	1.05	1.16
Cycle length	180	270
Fuel enrichment (Pu %)	21/28	23/31
Fraction of core discharged	1/3	1/4
Peak burnup (GWd/t)	100	200

SPECIFIC INNOVATIVE DESIGN FEATURES

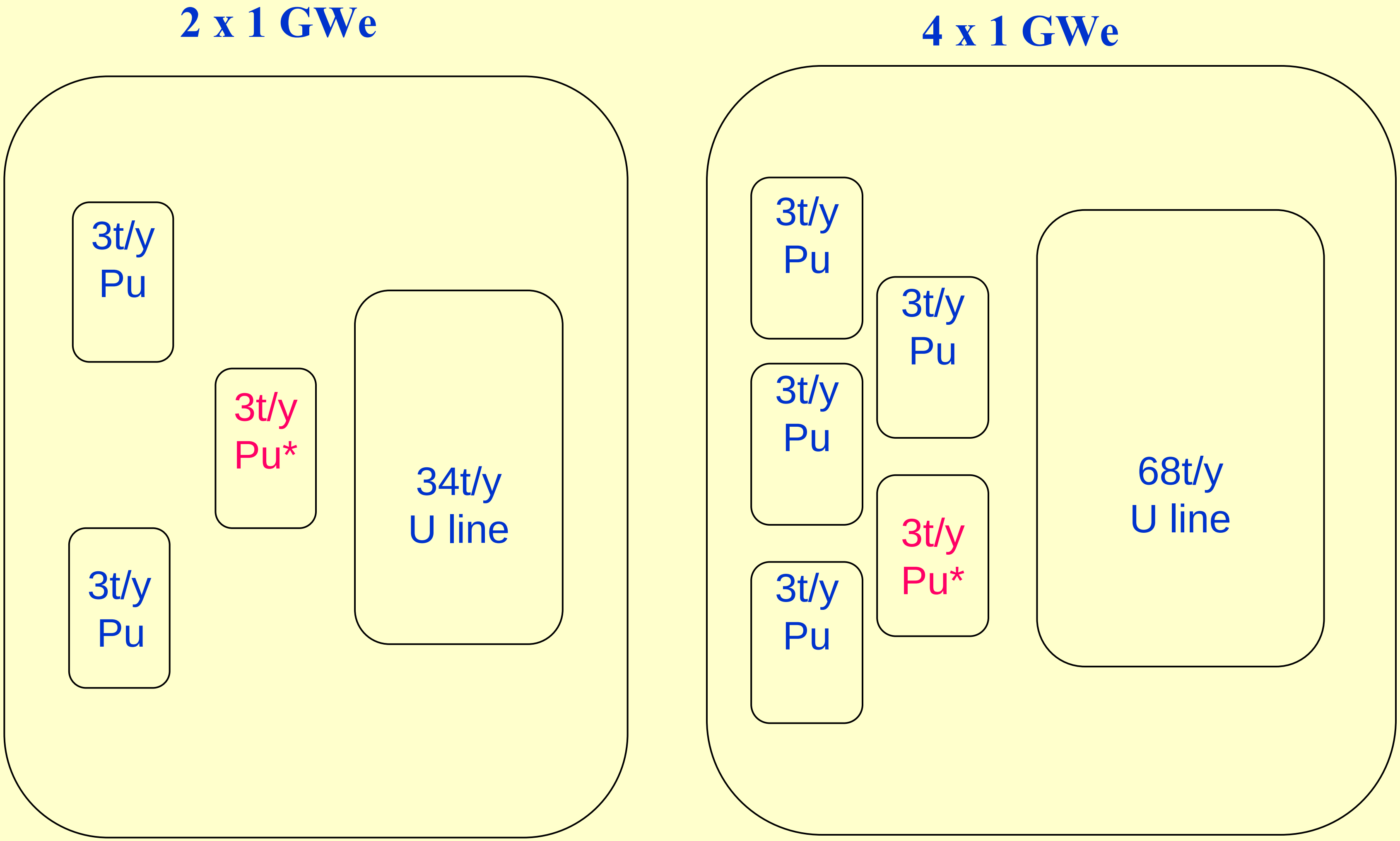
- **Innovative shield materials - reduction of incore shielding cost**
- **Four instead of two inlet pipes from primary pump header to grid plate – reduction of grid plate height**
- **Bean shaped IHX to reduce vessel diameter**
- **Machining of annular gaps to reduce complementary shields**
- **Design of single rotating plug with retractable control plug**

CO-LOCATED FUEL CYCLE FACILITIES FOR MULTIPLE UNITS

- **Co-located fuel cycle facilities provide**
  (a) higher physical protection
  (b) favourable economics
  (c) proliferation resistance (eg. co- processing of U Pu and MA)

- **In a 4 x 1 GWe fuel cycle facility compared to 2 x 1 GWe facility, it is found that per GWe**
  (a) capital cost is 30 % lower
  (b) operation and maintenance is 10 % lower

COMPARISON OF FUEL CYCLE PARKS



2 x 1 GWe

3t/y Pu

3t/y Pu*

3t/y Pu

34t/y U line

4 x 1 GWe

3t/y Pu

3t/y Pu

3t/y Pu

3t/y Pu

3t/y Pu*

68t/y U line

*stand by

CONCLUSIONS (1)

- India is committed to FBR technology for sustaining nuclear power growth as PHWR power programme is limited
- Emphasis on multi-disciplinary & inter-disciplinary research and human resource
- PFBR under construction at Kalpakkam
- In-core fuel management planned using well validated computer codes

CONCLUSIONS (2)

- Need to shift to high breeding metallic fuels to achieve significant nuclear power growth
- Studies show that despite higher Na void reactivity effect, metal FBR core is safe under ULOFA
- Studies on fissile and fertile material balances conducted in co-operation with IAEA show that with Pu from PHWR as input, it is possible to sustain high growth rate of metal fuelled FBR

CONCLUSIONS (3)

- Valuable fission products like radio active Cs, Sr as well as platinum group metal Rh, Ru and Pd can be extracted from FBR fuel cycle for societal applications
- With some design changes, MA burner FBR fuel cycle along with Th utilisation possible

CONCLUSIONS (4)

- **COST REDUCTION OF FUEL CYCLE**

  (a) Multiple units at same site, enhanced design life and higher fuel burnups

  (b) Specific innovative features for next FBRs

  (c) Co-located fuel cycle facilities provide higher physical protection, favourable economics and proliferation resistance

THANK YOU