Storage and Management of Spent Fuel of Fast Reactors in India

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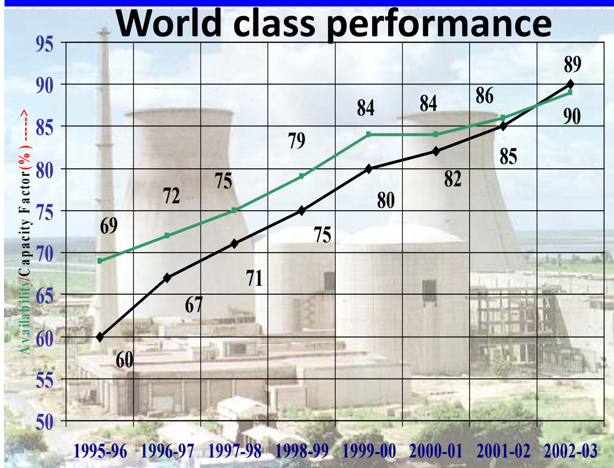
Scope

- FBR Programme in India
- Spent fuel storage – Design variants
- Fuel used in Indian FBR
- FBTR – Fuel subassemblies, spent fuel storage and reprocessing
- PFBR – Fuel subassemblies, spent fuel storage, storage bay design and reprocessing
- Spent fuel management beyond PFBR – CFBR and future metal fuelled reactors
- Summary

Fast Breeder Reactor Programme in India

- India started Fast Breeder Reactor programme with the construction of Fast Breeder Test Reactor.
- Fast Breeder Test Reactor (FBTR) is a 40 MWt (13.5 MWe) loop type reactor. The design is same as that of Rapsodie-Fortissimo except for incorporation of Steam Generator and Turbine Generator (agreement signed with CEA, France in 1969).
- FBTR is in operation since 1985.
- 500 MWe Fast Breeder Reactor Project (PFBR) through indigenous design and construction.
- Government granted financial sanction for construction in Sep 2003.
- Construction of Prototype Fast Breeder Reactor (PFBR) has been undertaken by Bharatiya Vidyut Nigam Limited.
- PFBR will be commissioned by 2011.
- Beyond PFBR: 6 units of 500 MWe Fast Breeder Reactor (twin unit concept) similar to PFBR with improved economy and enhanced safety by 2020.
- Subsequent reactors would be 1000 MWe units with metallic fuel.

THREE STAGE NUCLEAR POWER PROGRAM



Stage – I PHWRs

- 17- Operating
- 3 - Under construction
- Several others planned
- Construction planned for 700 MWe units
- Gestation period being reduced
- POWER POTENTIAL ≅ 10,000 MWe

LWRs

- 2 BWRs Operating
- 2 VVERs under construction

Stage - II
Fast Breeder Reactors

- 40 MWth FBTR - Operating Technology Objectives realised
- 500 MWe PFBR- under construction
- POWER POTENTIAL: Minimum 530 GWe

Stage – III and Beyond
Thorium Based Reactors

- 30 kWth KAMINI- Operating
- 300 MWe AHWR - Under Regulatory Examination
- POWER POTENTIAL = 155,000 GWe-y
- Availability of ADS can enable early introduction of Thorium
- Participation in ITER towards development of fusion technology

Kalpakkam – Unique Nuclear Site in the World housing all Three Stages & Closed Fuel Cycle Facilities

IGCAR – Mission Oriented Centre for Development of Science Based Technology for FBR

Fuel

FBTR

- Mixed carbide
  - 70%PuC-30% UC (Mark I) - Small core.
  - 55% PuC-45% UC (Mark II) - Larger core.

  Metallic Fuel
  - Substantial core in metal fuel by the year 2017.

PFBR

- Proven fuel from fabrication, operation and reprocessing for commercial demonstration reactor.
- Driver fuel $PuO_2 - UO_2$

  Two zones: 20.7% Inner core
  27.7% Outer core

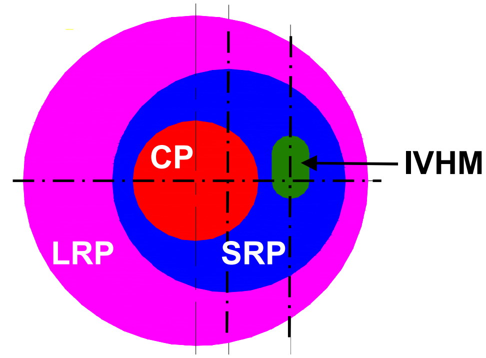
Beyond PFBR: CFBR 1 to 6

- 6 units of 500 MWe mixed oxide

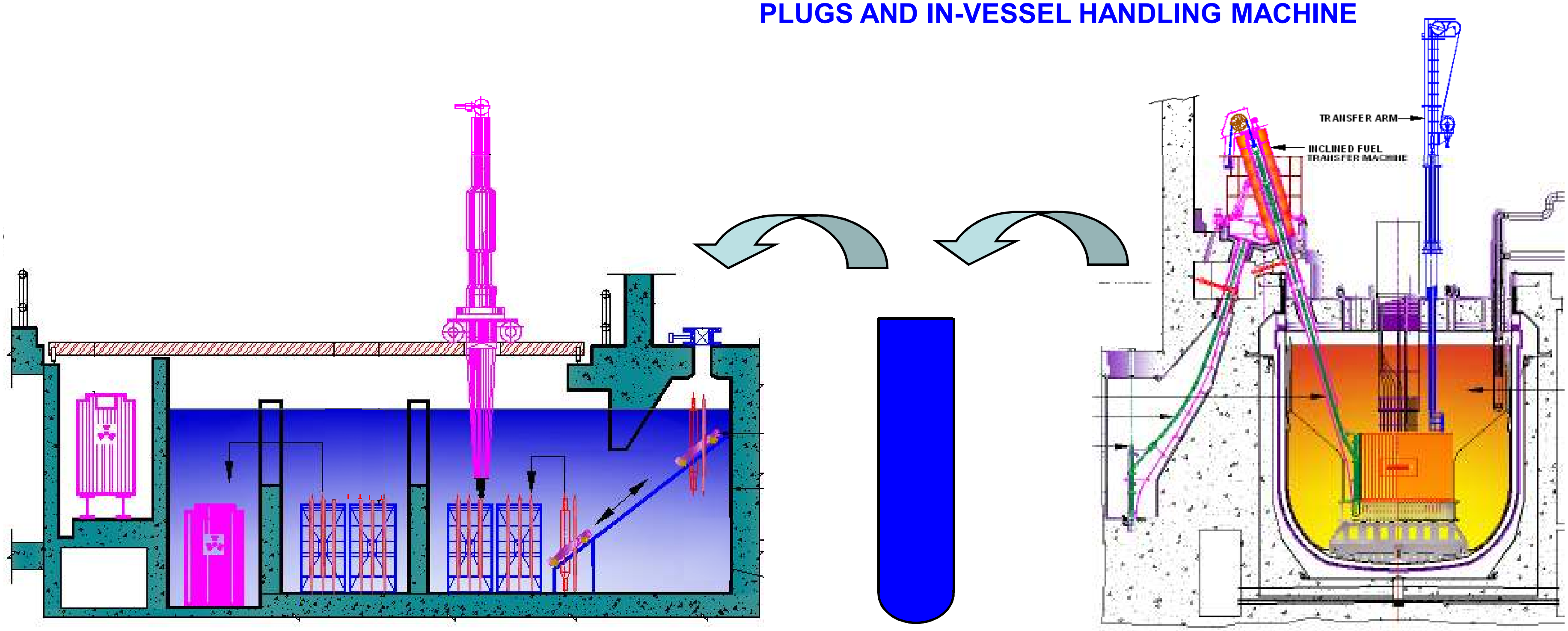
Beyond PFBR + 6 CFBRs

- Metallic Fuel (Lowering doubling time). 1000 MWe. First unit by year 2027.

FBRs – Typical Fuel Handling Scheme



IN-VESSEL HANDLING USING ROTATABLE PLUGS AND IN-VESSEL HANDLING MACHINE



SPENT FUEL STORAGE

WASHING

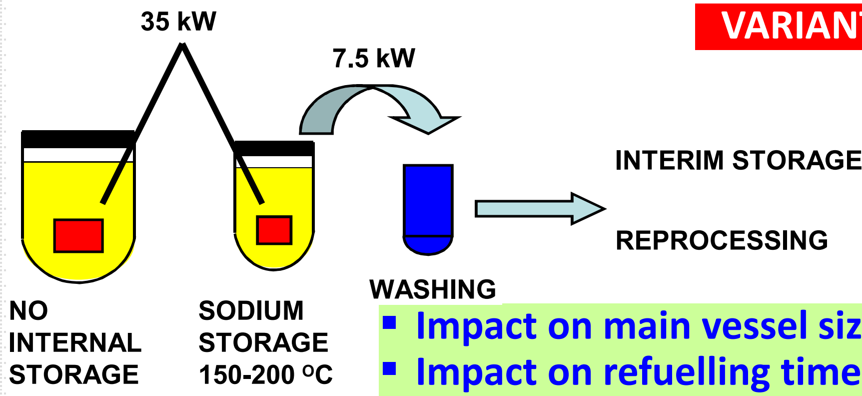
EX-VESSEL TRANSFER

IN-VESSEL TRANSFER AND INTERNAL STORAGE

Spent fuel storage - Design variants

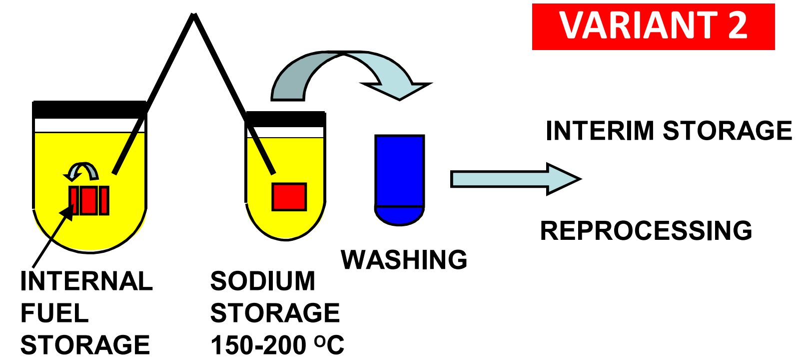
SODIUM STORAGE

VARIANT 1



- Impact on main vessel size
- Impact on refuelling time
- Economics
- Safety

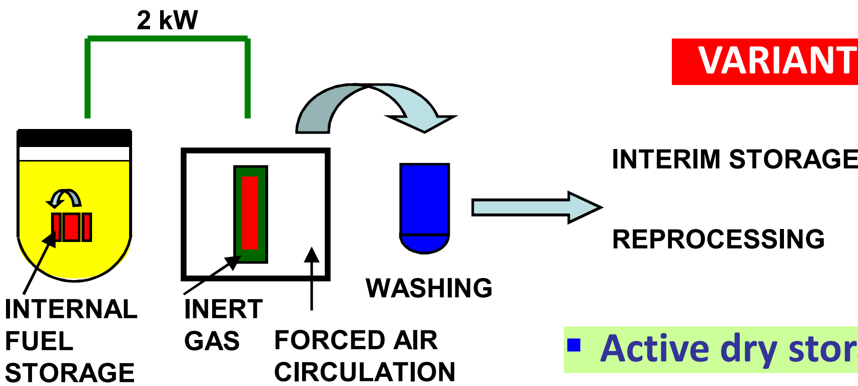
VARIANT 2



- Instead of sodium, NaK could also be a choice

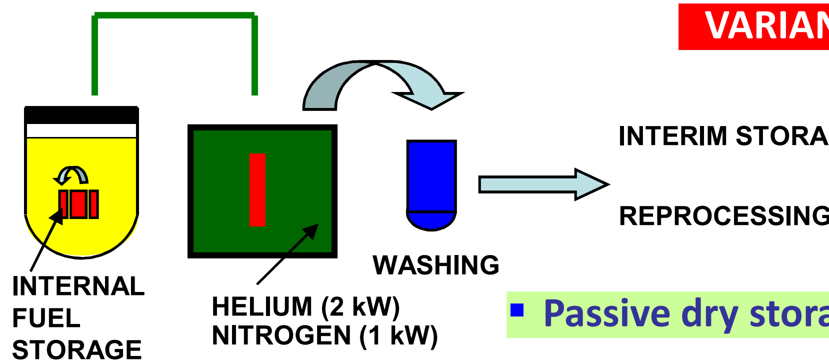
GAS (DRY) STORAGE

VARIANT 1



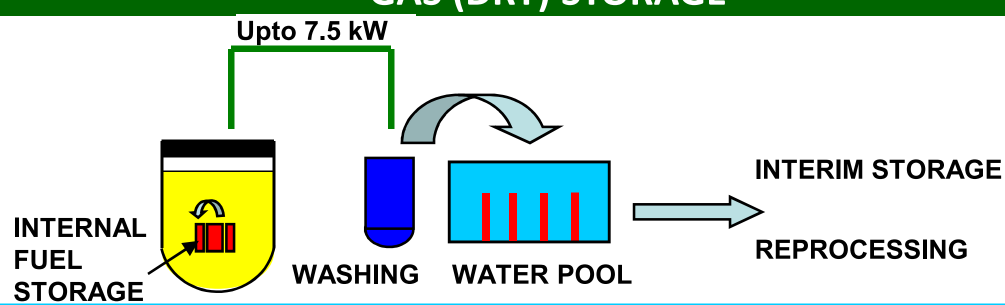
- Active dry storage

VARIANT 2



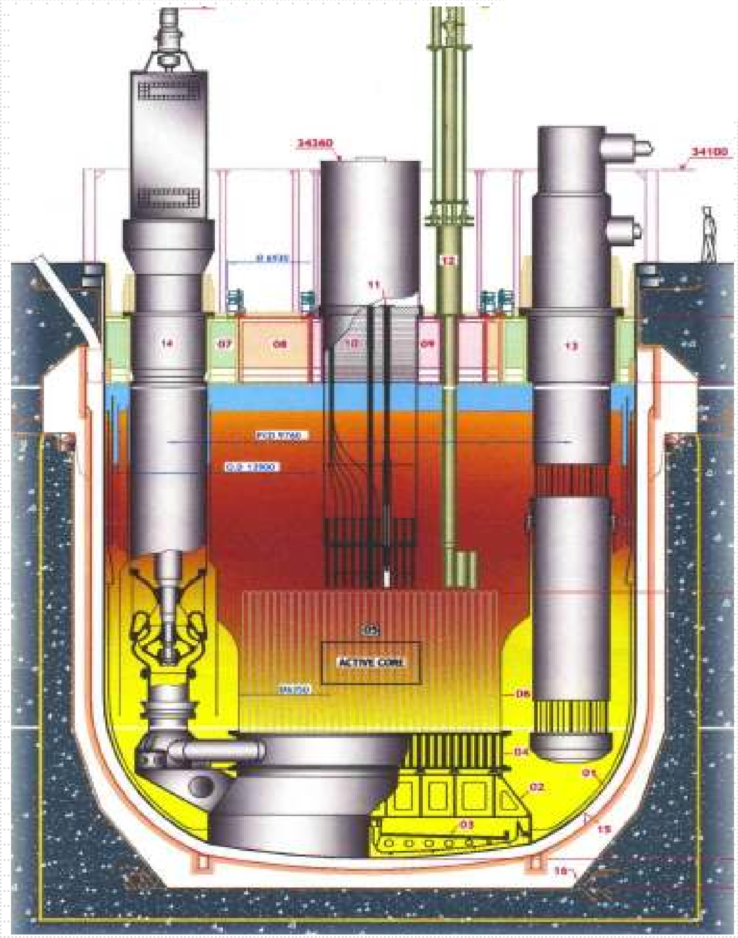
- Passive dry storage

WATER POOL STORAGE



Sodium Storage

- Mini reactor
- Provision of safety vessel surrounding the main storage vessel
- Requires provision of preheating to keep sodium in liquid state when decay power of SA is low
- Requires purification facility to maintain sodium chemistry
- Requires additional cooling system to remove the decay heat of SA – Additional sodium system with Na-Air HX
- Advantages are fuel handling time will be less (increased capacity factor) and capability to transfer SA with decay power of ~ 40 kW from main vessel



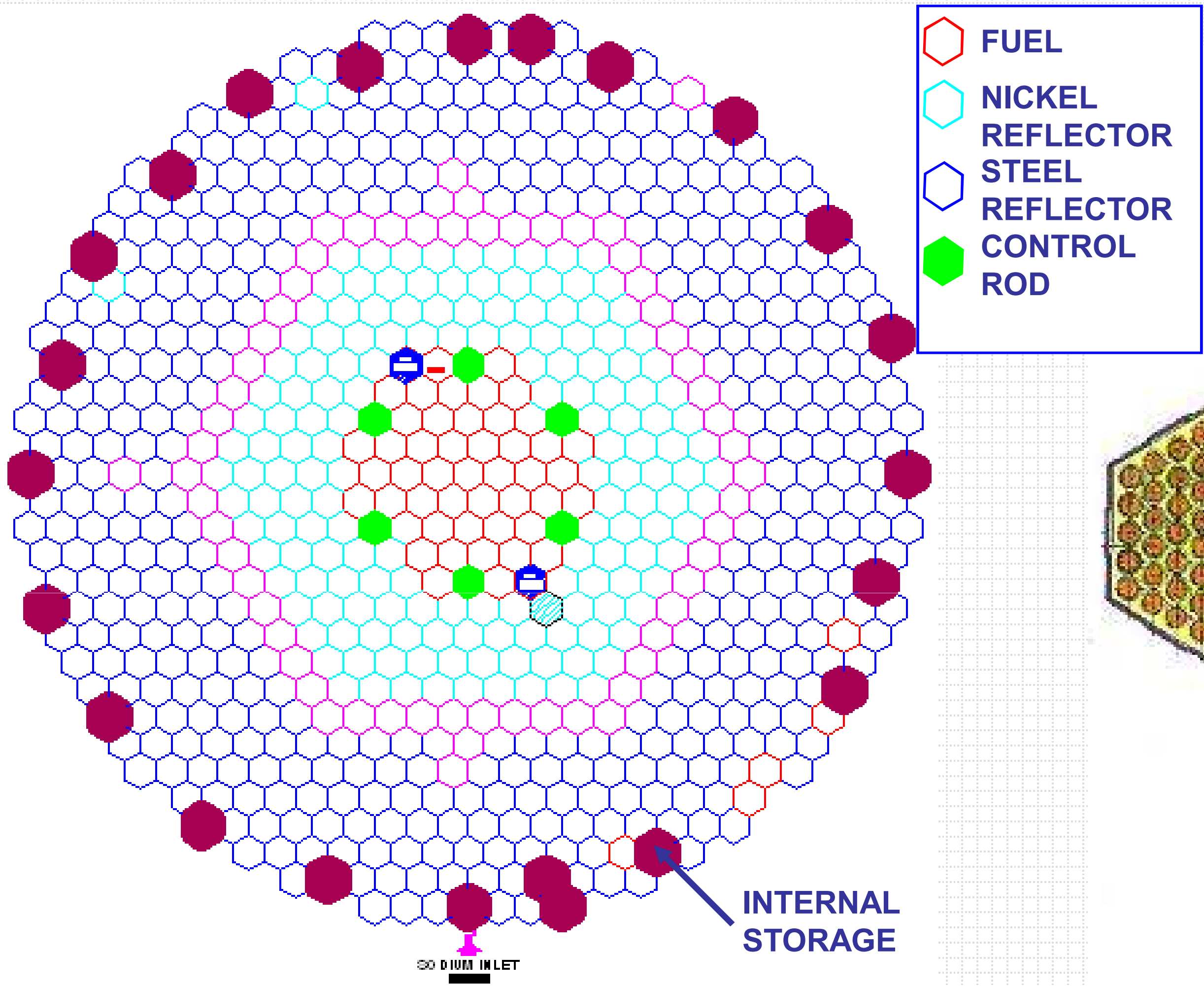
- Possible to unload whole core faster – Permits carrying out Inservice Inspection of core support path – For Gen IV reactors, In-service inspection of core support welds (once in 10 y)
- SPX-1 incident of leak in sodium storage led to abandonment of the concept. Nevertheless an attractive option for future FBRs in some countries

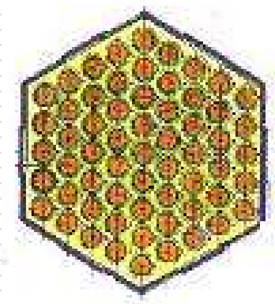
FBTR today

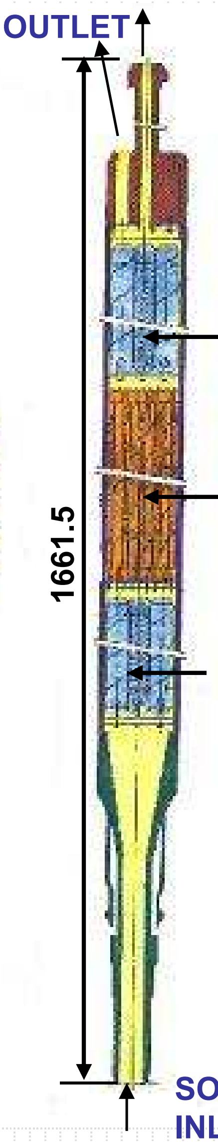
FBTR, in operation since 1985, is the test bed for fast reactor fuels and materials. It has completed fifteen irradiation campaigns with very high availability factors in the recent campaigns. Its unique carbide fuel has set an international record in burn-up (165 GWd/t) without any clad breach.

PFBR test fuel assembly of 37 pins is under irradiation at FBTR and logged burn up of 100 GWd/t burn-up

FBTR Core and Fuel SA

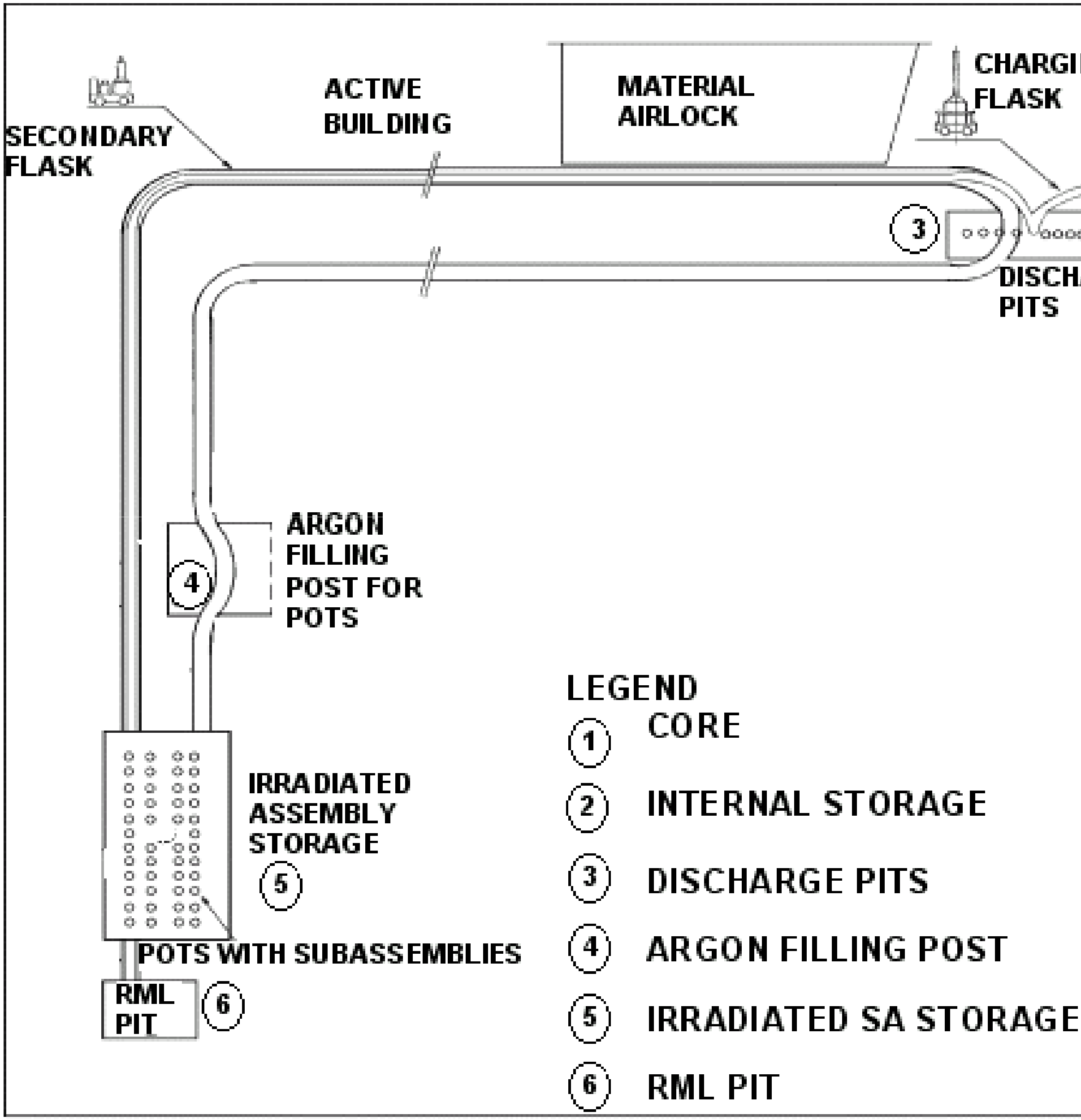






- Internal storage locations in the periphery of the core
- Max decay power during discharge of SA from the core = 400 W

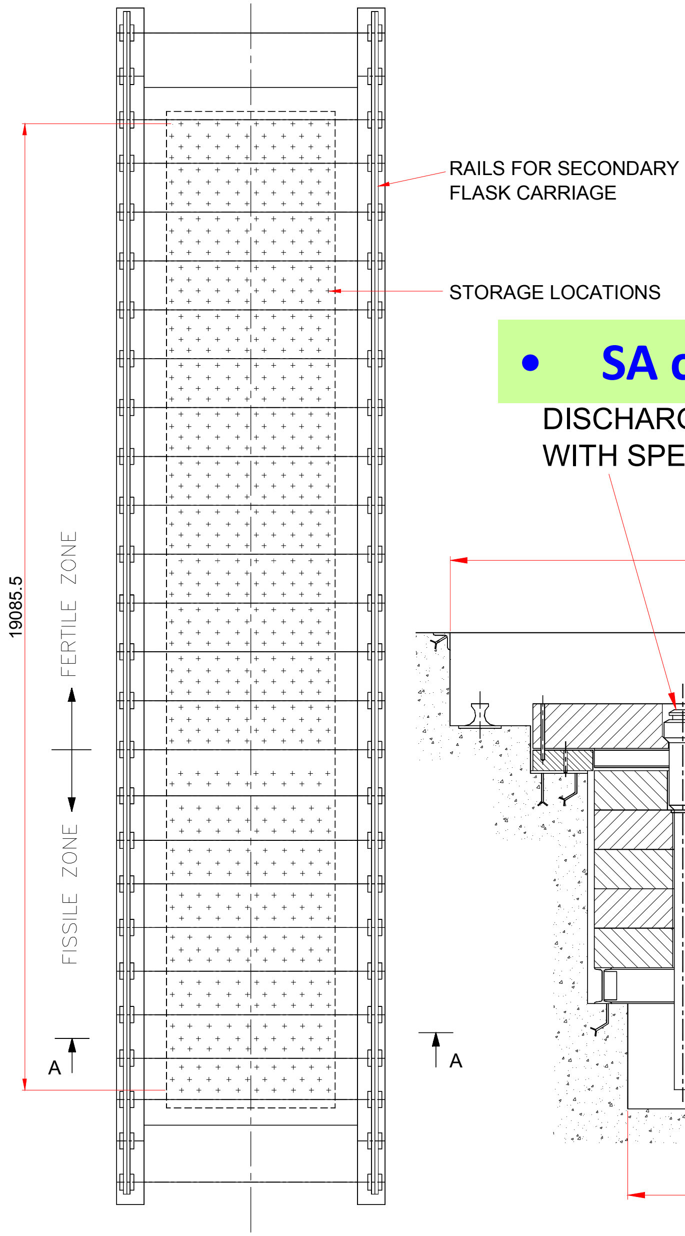
FBTR Fuel Handling Scheme



- Transfer to internal storage using two rotatable plugs
- Canned in argon filled pots in discharge pits
- Transferred to Irradiated storage using secondary flask
- No sodium cleaning within the reactor
- Transferred to RML for alcohol cleaning and dismantling

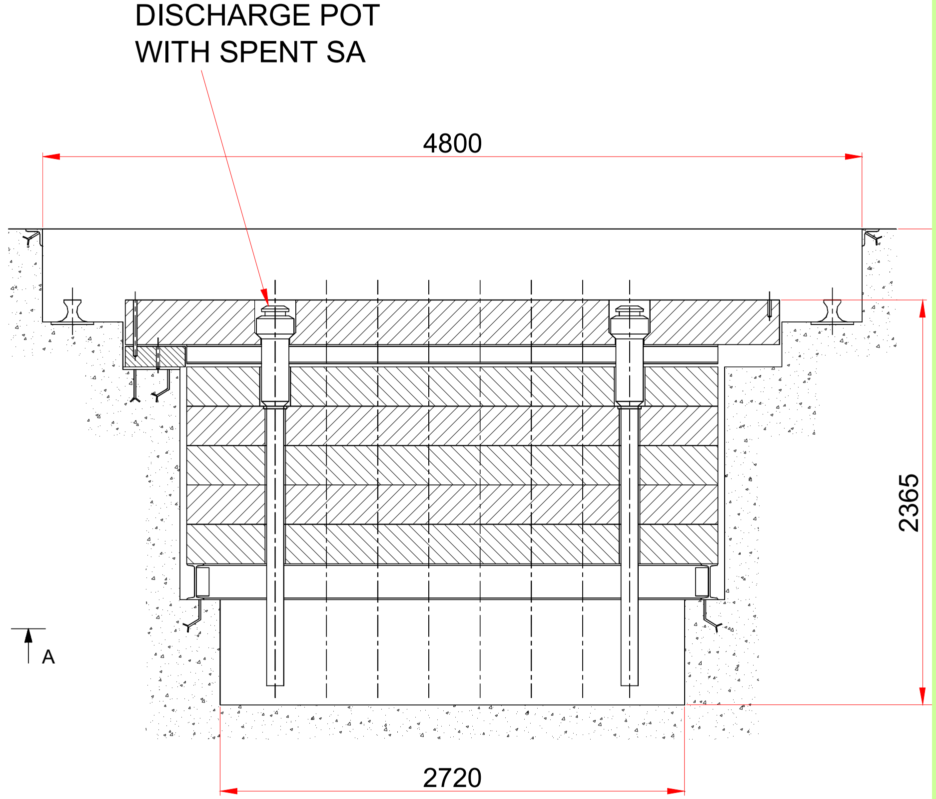
FBTR Irradiated SA Storage

- Dry type storage
- SA canned in argon filled discharge pots
- 203 Fissile and 619 fertile storage zones
- Provision to permit whole core unloading
- SA canned in argon filled discharge pots



PLAN VIEW

- SA canned in argon filled discharge pots



SECTION-AA

- Concrete vault with cast iron shielding
- Forced air cooling (3 x 50% blowers) with provision of emergency power supply
- Low decay power permits dry storage
- Failed SA stored similar to intact SA in pots with additional Sn-Bi sealing

Successful Demonstration of Reprocessing of FBTR Fuel

16 Stage Centrifugal Extractor Bank

CORAL facility operation area

Progressive hotter fuel reprocessing

- Mixed carbide fuels with high Pu with a burn up of 155,000 MWd/t reprocessed for the first time in the world
- CORAL facility demonstrated the successful reprocessing of this high burn up fuel

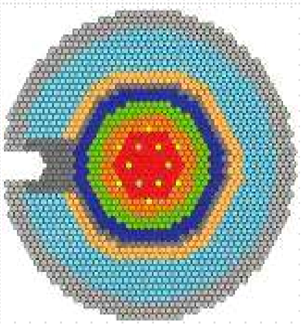
Spent fuels handled so far…

Burn up (GWd/t)	Cooling period (Years)	Sp. Activity, (Ci/Kg)
25	7	300
50	5	800
100	2.5	3000
155	2	4600

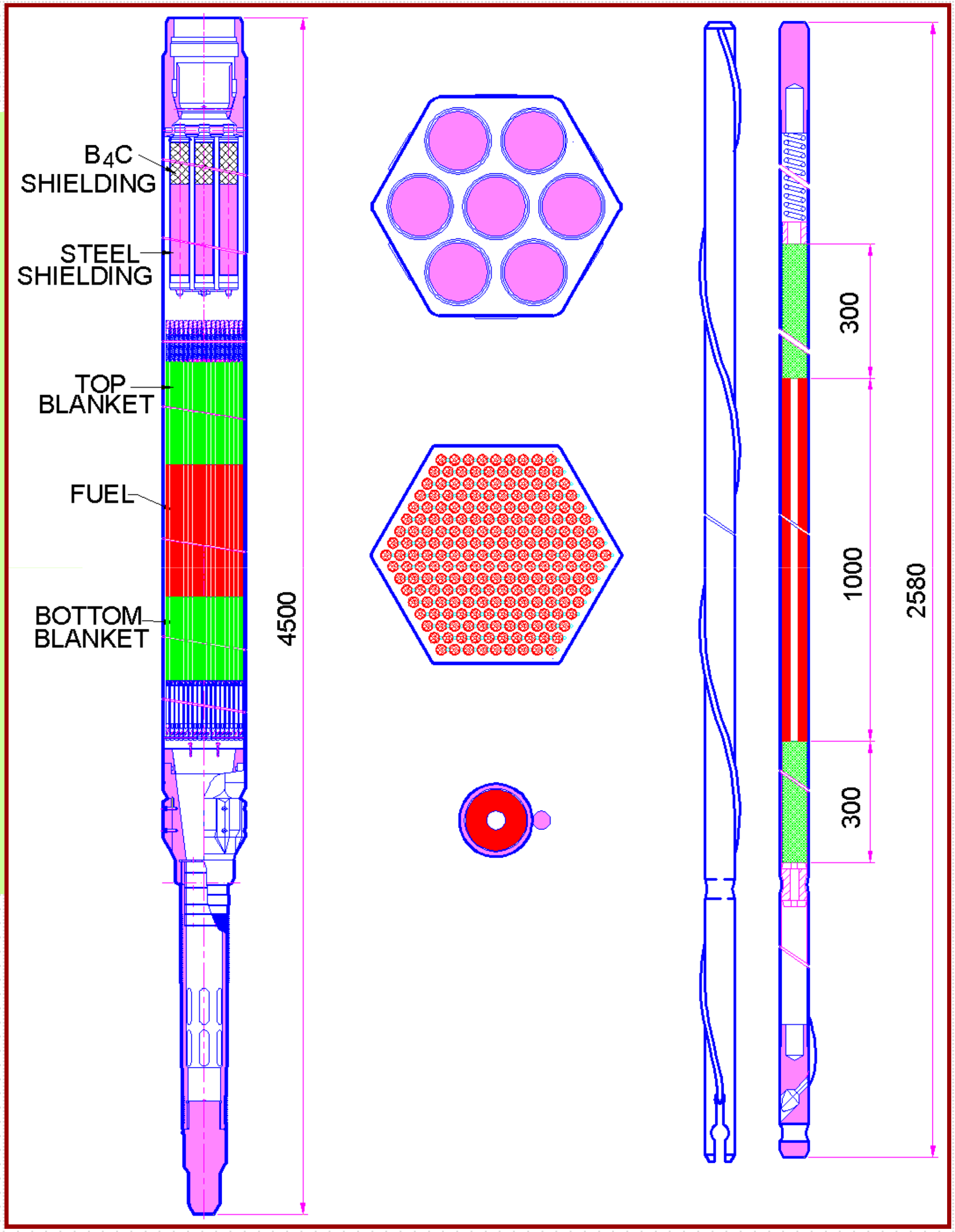
PFBR Fuel Subassembly

Salient Details

Fuel	$(Pu\text{-}U)O_2$
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 & Wrapper	20 % CW D9
Number of Pins	217
Width Across Flats	131.3 mm
Peak target Burn-up	100 GWd/t
Peak neutron dose	85 dpa



No of Fuel SA : 181
Total SA : 1758



PFBR – Decay Power Vs Time

Cooling time(d) after shutdown	Decay Power (kW)
0	463.5
2	34.7
30	11.9
60	8.61
90	6.86
120	5.74
180	4.41
240	3.47

During Internal Storage

Ex-vessel cooling time(d)	Decay Power (kW)
0	3.47
180	1.85
240	1.61
360	1.25
480	1.0
540	0.9
720	0.67
900	0.51

After 240 d of Internal Storage

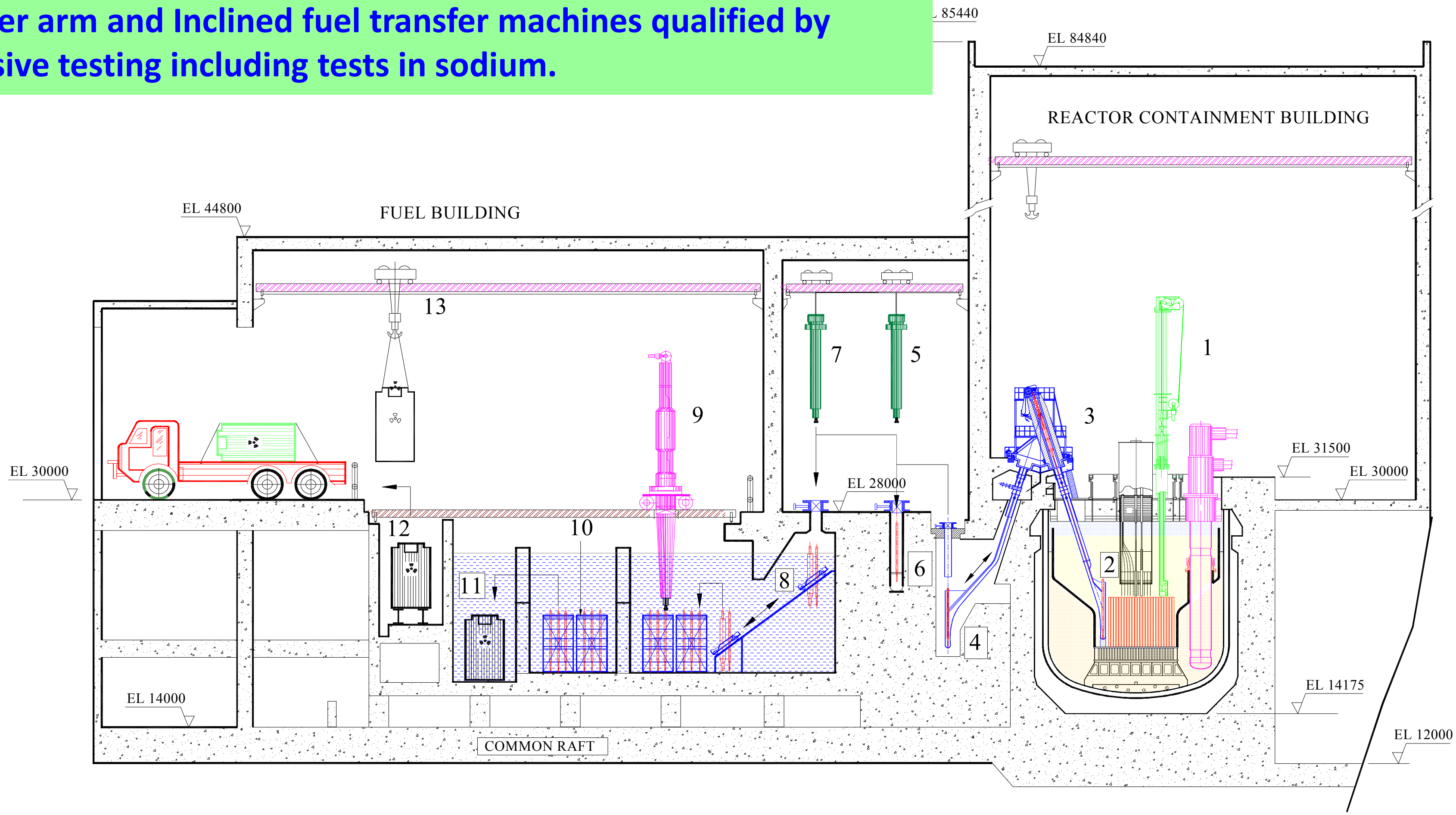
Ex-vessel cooling time(d)	Decay Power (kW)
0	103.06
1	6.69
2	5.39
3	4.76
4	4.34
5	4.03
10	3.11
20	2.27

Blanket SA after no Internal Storage

Decay Power for Fuel (Central) SA

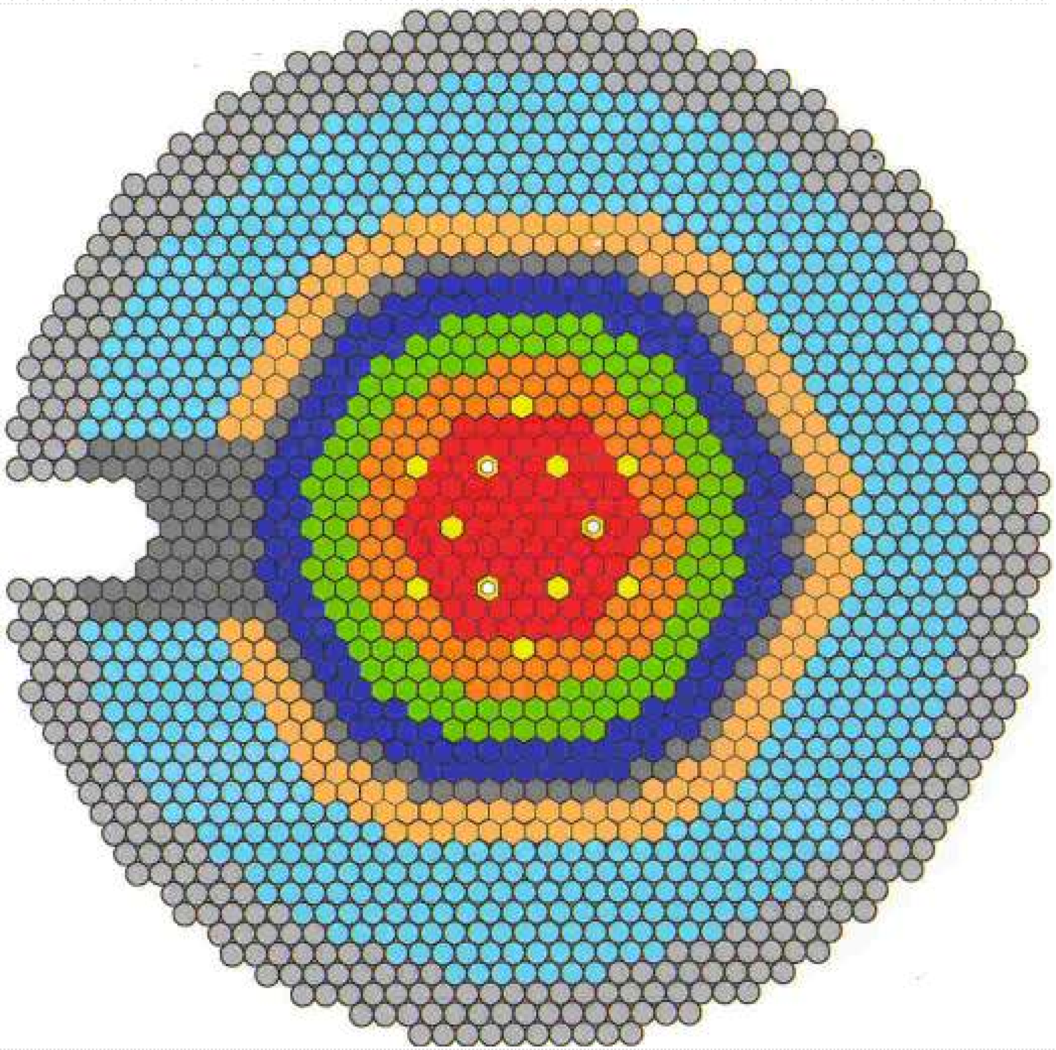
Component Handling and Storage

Transfer arm and Inclined fuel transfer machines qualified by extensive testing including tests in sodium.



1. Transfer arm
2. In-vessel transfer position
3. Inclined fuel transfer machine
4. Ex-vessel transfer position
5. CTM (Fresh SA)
6. Spent SA washing facility
7. CTM (Spent SA)
8. Under-water trolley
9. Spent SA transfer machine
10. Spent SA storage bay
11. Cask loading bay
12. Cask washing bay
13. Shipping cask transfer to reprocessing facility

PFBR Core



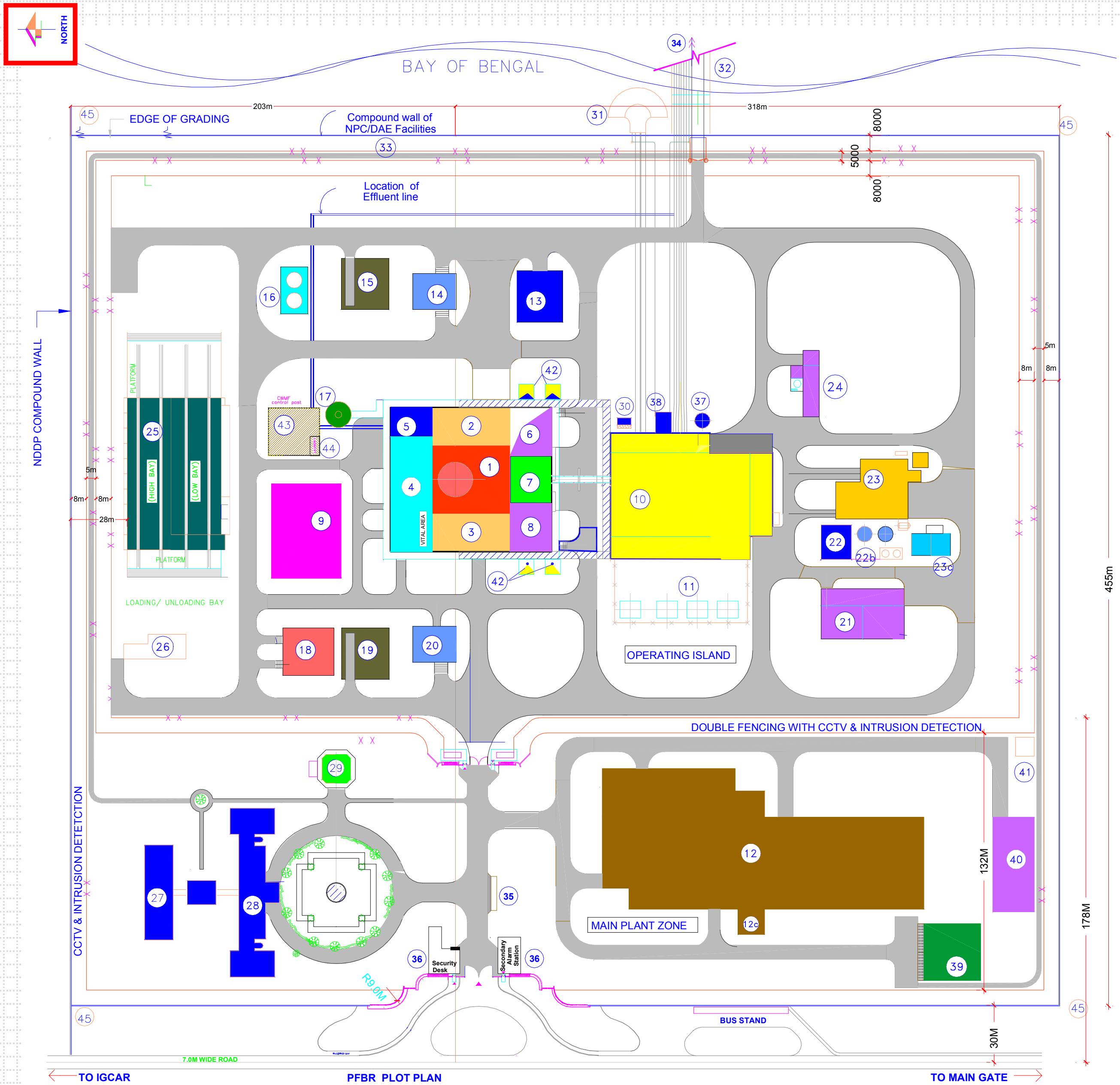
SYMBOL	TYPE OF SUBASSEMBLY	No.
	FUEL (INNER)	85
	FUEL (OUTER)	96
	CONTROL AND SAFETY ROD	9
	DIVERSE SAFETY ROD	3
	BLANKET	120
	STEEL REFLECTOR	138
	B_4C SHIELDING (INNER)	125
	STORAGE LOCATION	156
	STEEL SHIELDING	609
	B_4C SHIELDING (OUTER)	417
	TOTAL SUBASSEMBLIES	1758

- 156 Internal Storage locations are provided
- Max clad temperature during handling and storage = 650 ^{o}C

PFBR Spent Fuel Storage Design

- Water Pool type storage
- Storage capacity to meet two fuel handling campaigns plus one full core unloading (711 storage locations)
- Single concrete tank lined with SS 304 L liner
- Two storage compartments and one cask loading compartment separated by provision for partition door for isolation of any compartment, when required for maintenance. Additionally provision for cask washing provided
- SA stored vertical in bay in storage racks – Total decay heat of stored SA is 480 kW (normal) and 1690 kW (full core unloading)
- Dedicated cooling system, purification system and ventilation system provided.
- Dedicated leakage collection and monitoring system provided
- Designed to meet Seismic Category 1
- Not designed for Aircraft crash since PFBR meets AERB stipulation of minimum screening distance of 8 km (PFBR site is 47 km from nearest chennai airport)
- Fall of components / shipping cask excluded from design – storage bay transfer machine and crane above SSSB designed single failure proof meeting NUREG 0554

Plant Layout

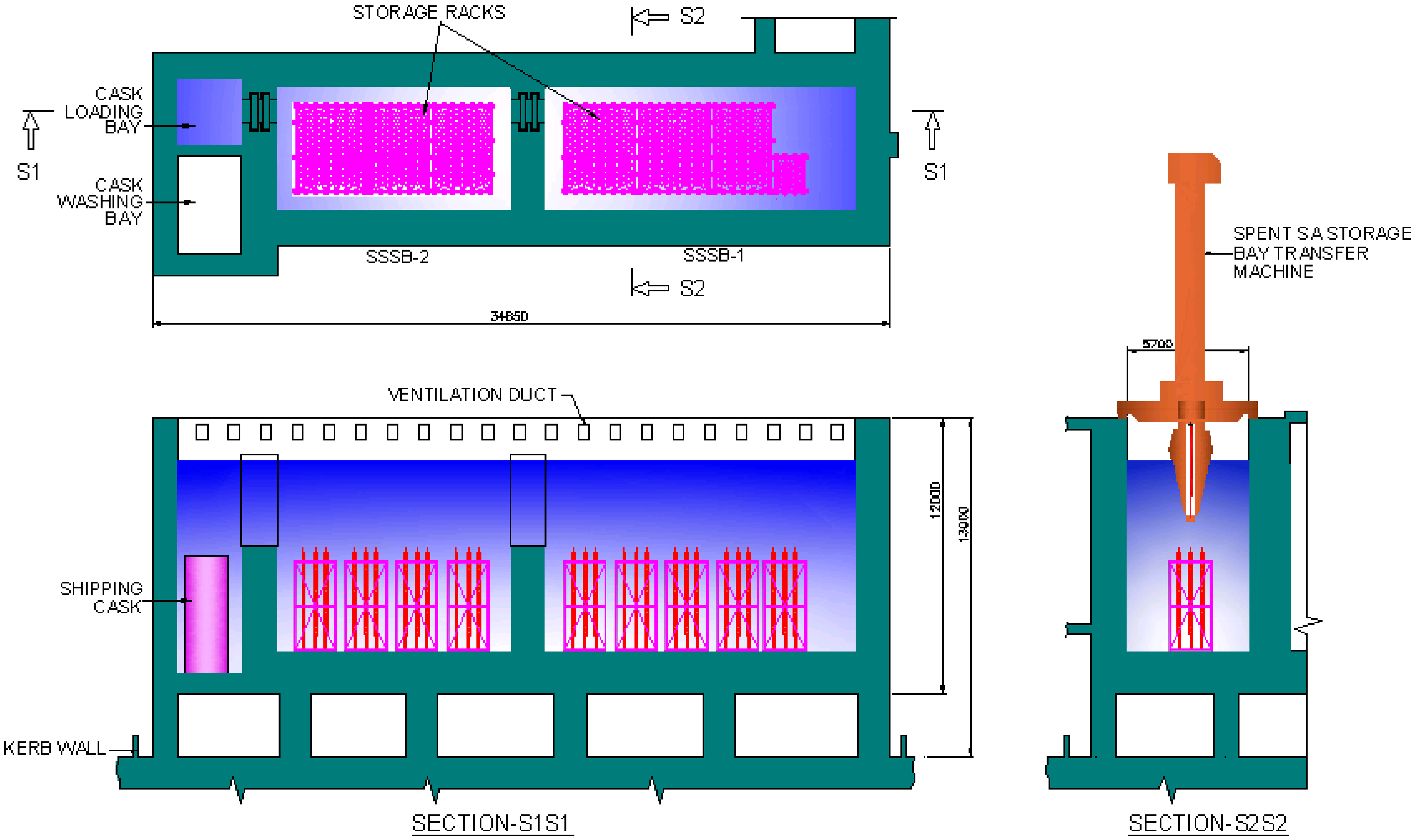


LEGEND:

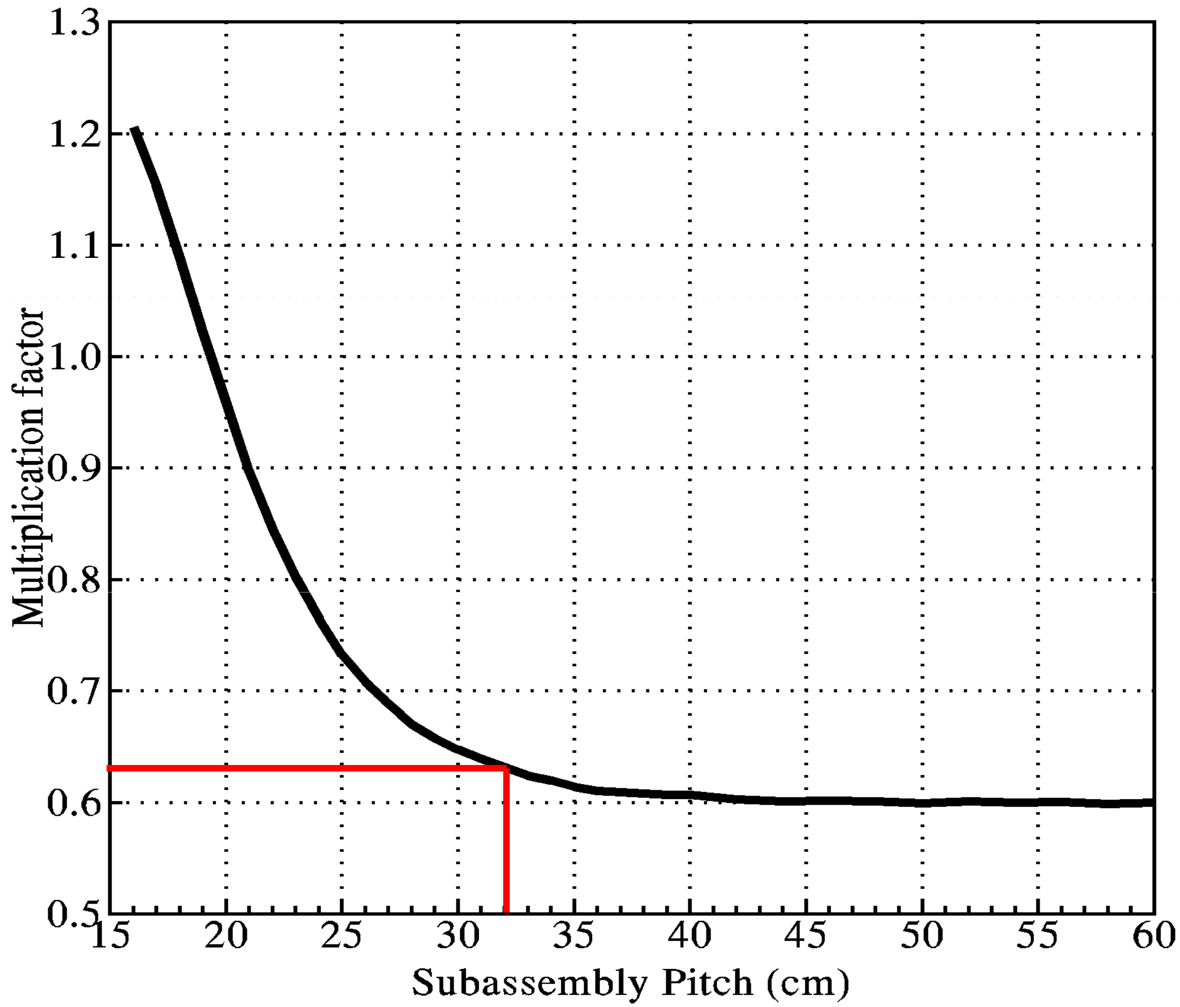
1. REACTOR CONTAINMENT BUILDING
2. STEAM GENERATOR BUILDING-1
3. STEAM GENERATOR BUILDING-2
4. FUEL BUILDING
5. RAD WASTE BUILDING
6. ELECTRICAL BUILDING-1
7. CONTROL BUILDING
8. ELECTRICAL BUILDING-2
9. SERVICE BUILDING
10. TURBINE BUILDING

Reactor containment building & the Fuel building which include the spent fuel storage bay are on common raft from seismic considerations

PFBR Spent Fuel Storage

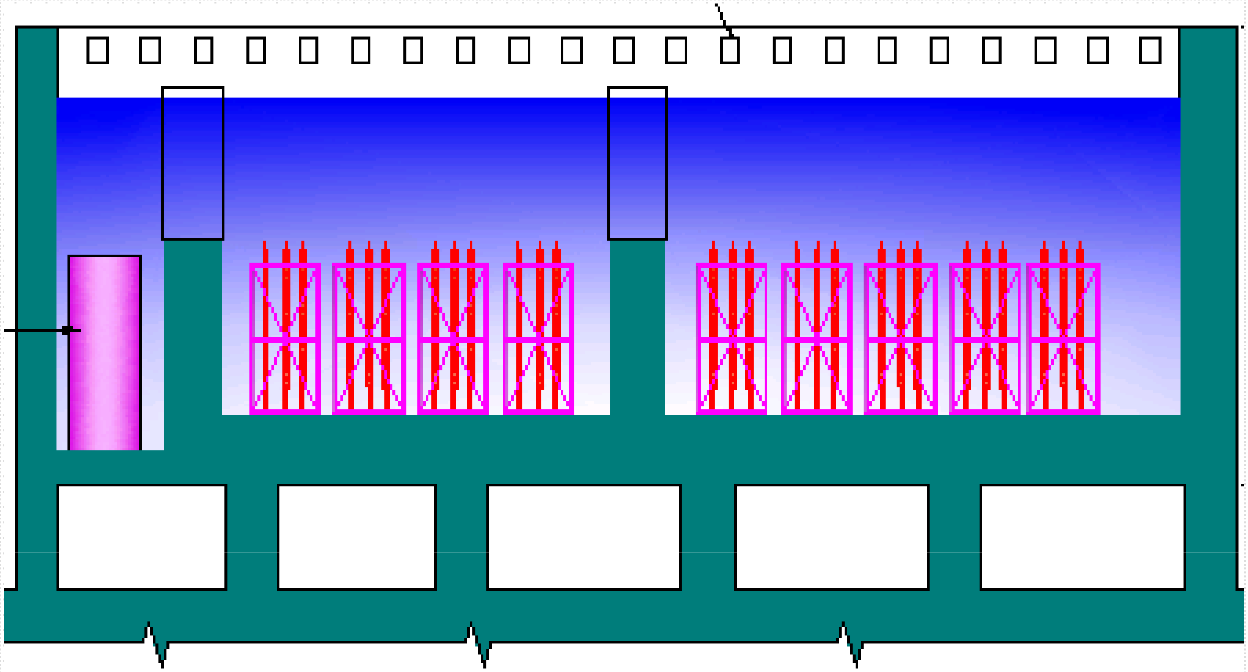


PFBR Spent Fuel Storage – Criticality Considerations



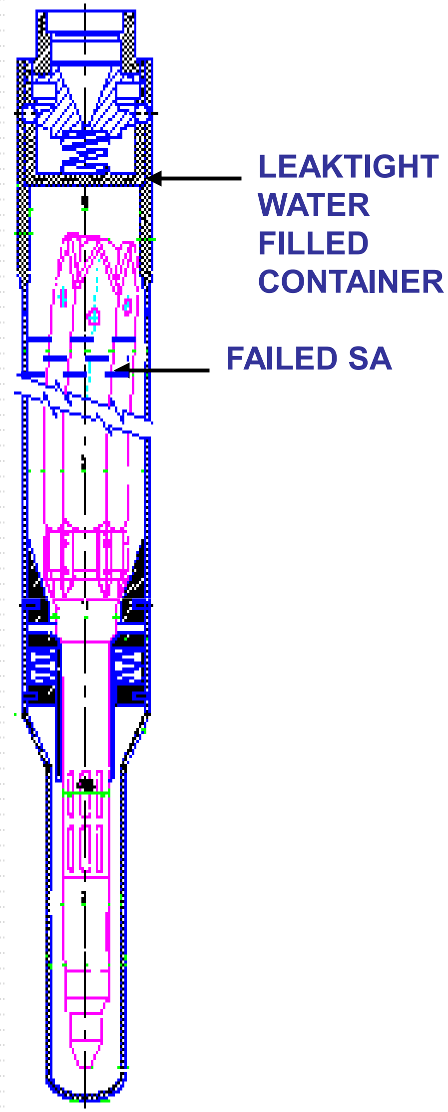
- SA stored in SSSB with geometrical spacing of 320 mm in triangular pitch
- Calculated K_{eff} for normal storage is 0.65 ; With accidental fall of a subassembly considered, Keff is 0.75 ; Uncertainty in analysis is 10% ; Allowable K_{eff} is 0.95

PFBR Intact and Failed SA Storage



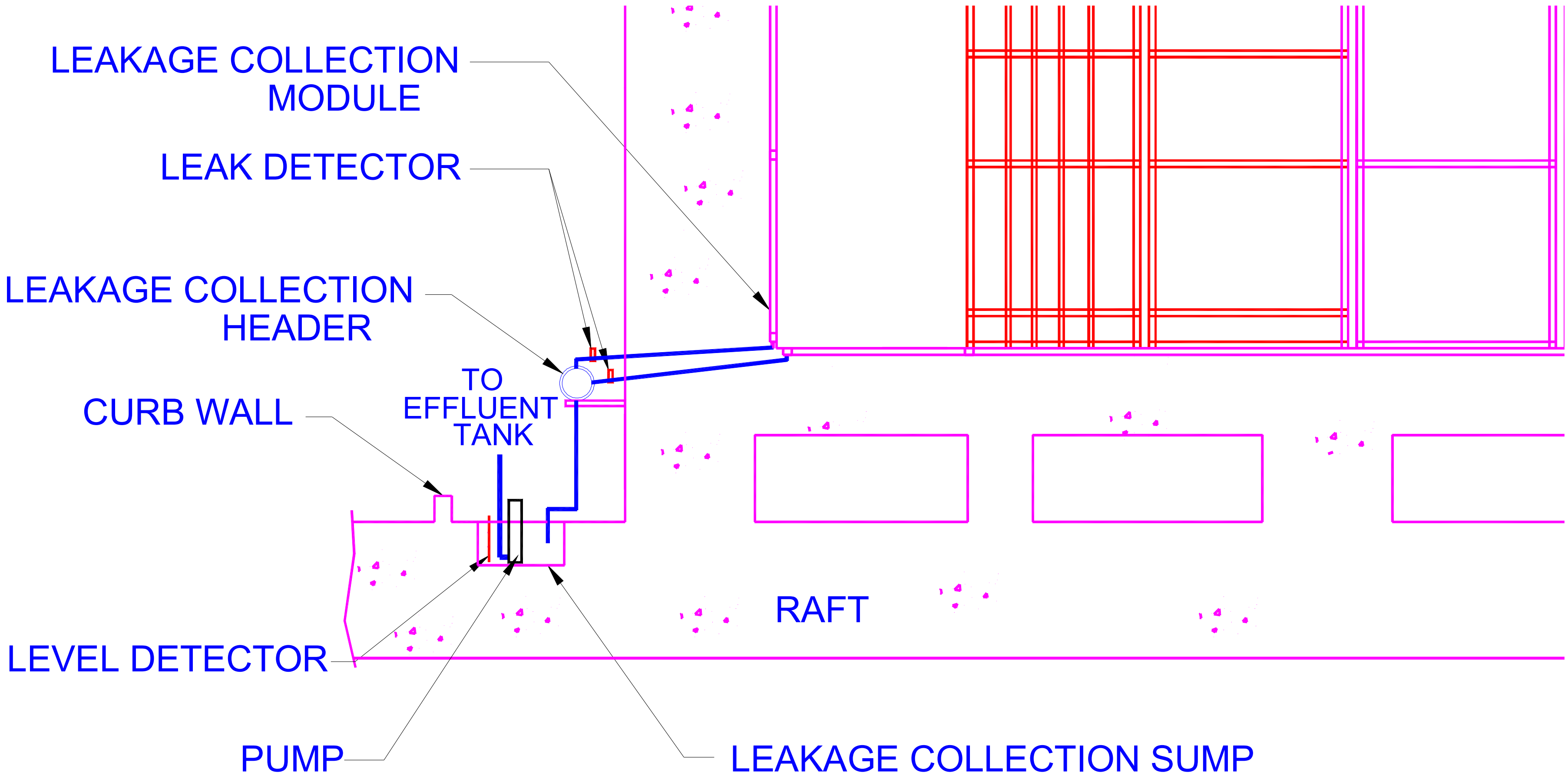
Water Pool storage for both Intact and Failed SA

- Intact SA stored directly in water pool
- Failed SA canned in water filled containers and stored in water pool
- Failed SA recanned in nitrogen filled containers before sending to reprocessing plant

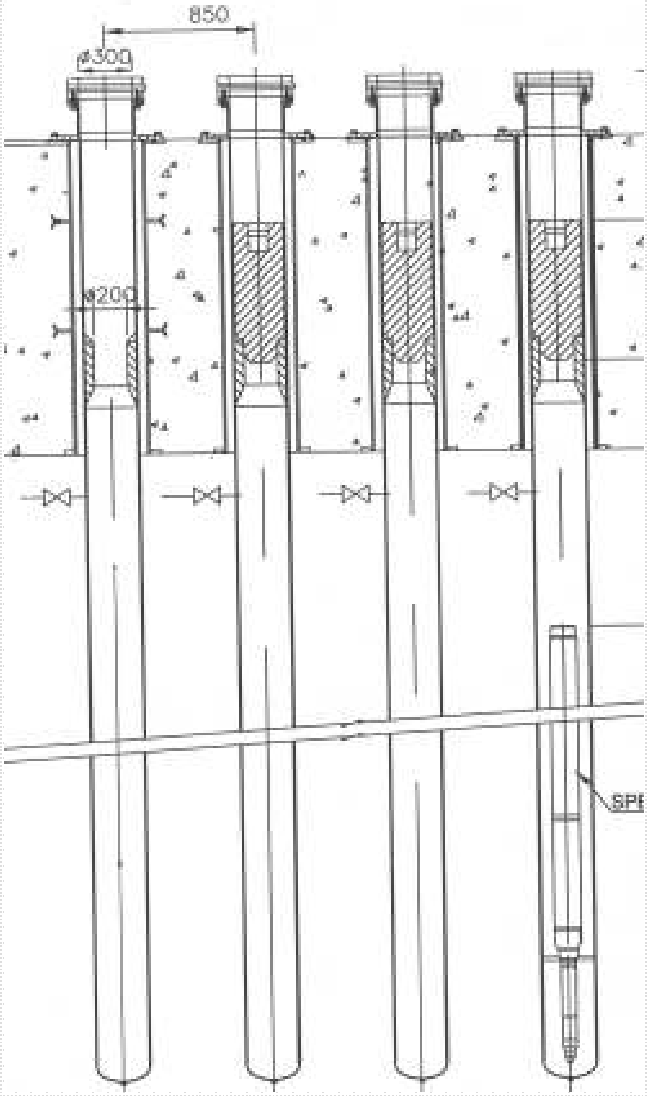


Container with failed SA

PFBR SSSB – Leakage Collection Arrangement



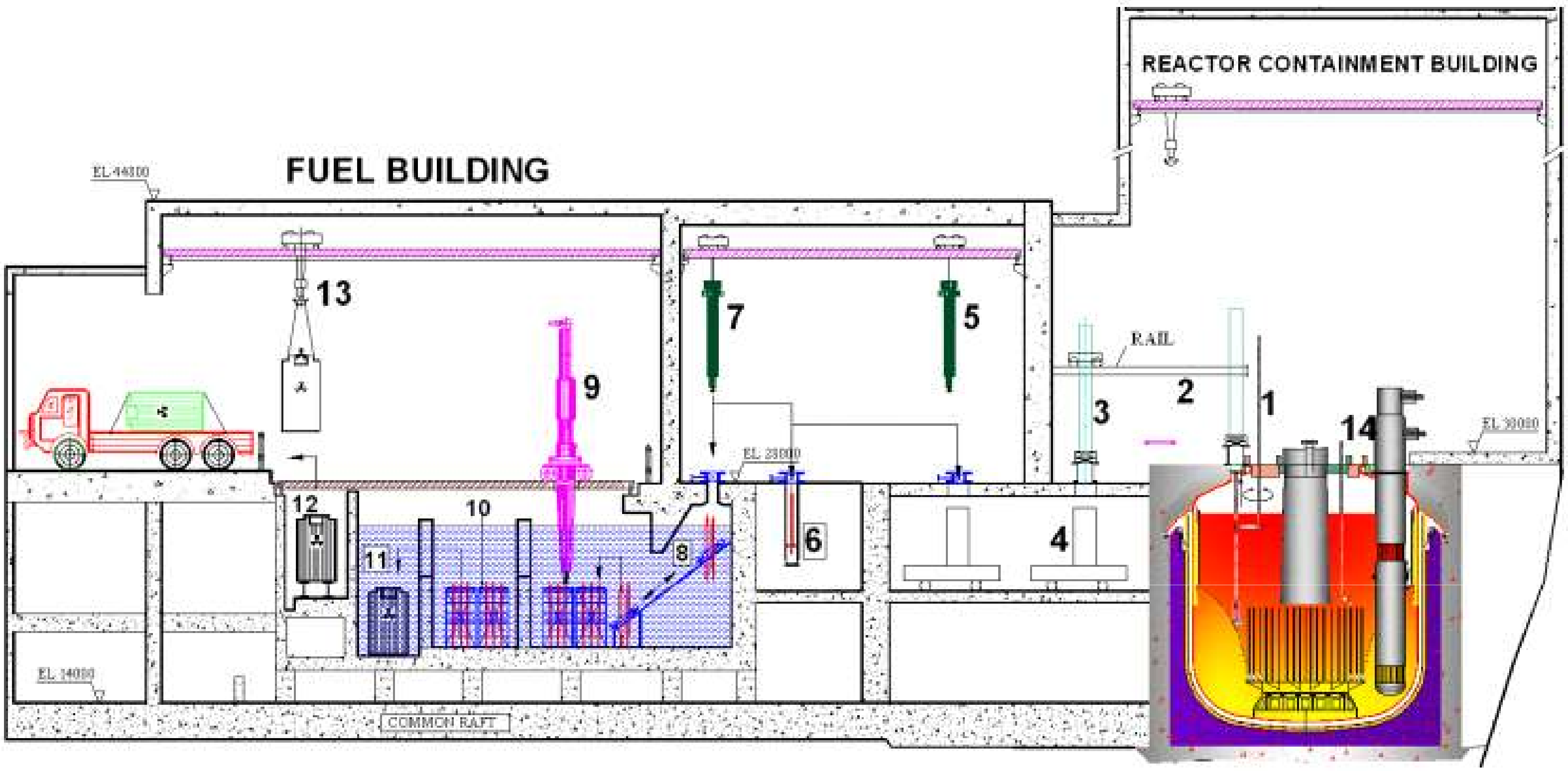
PFBR Spent SA Washing



Washing Facility

- SA washing using steam-nitrogen process
- SA washing carried out as part of fuel handling campaign activities
- Washing facility is duplicated and hence four washing vessels provided (Two stage process of cleaning and rinsing)

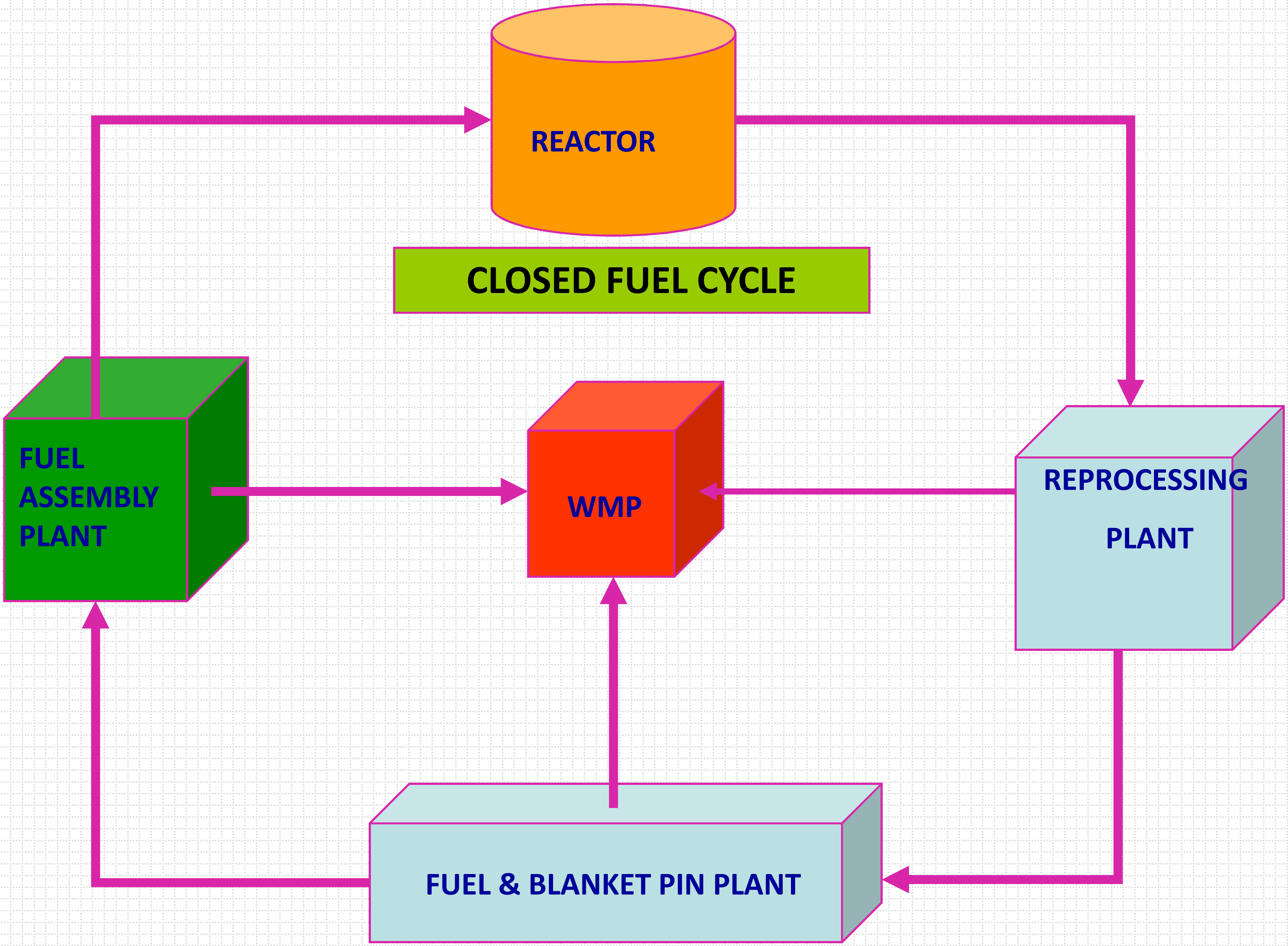
CFBR – Fuel Handling Scheme



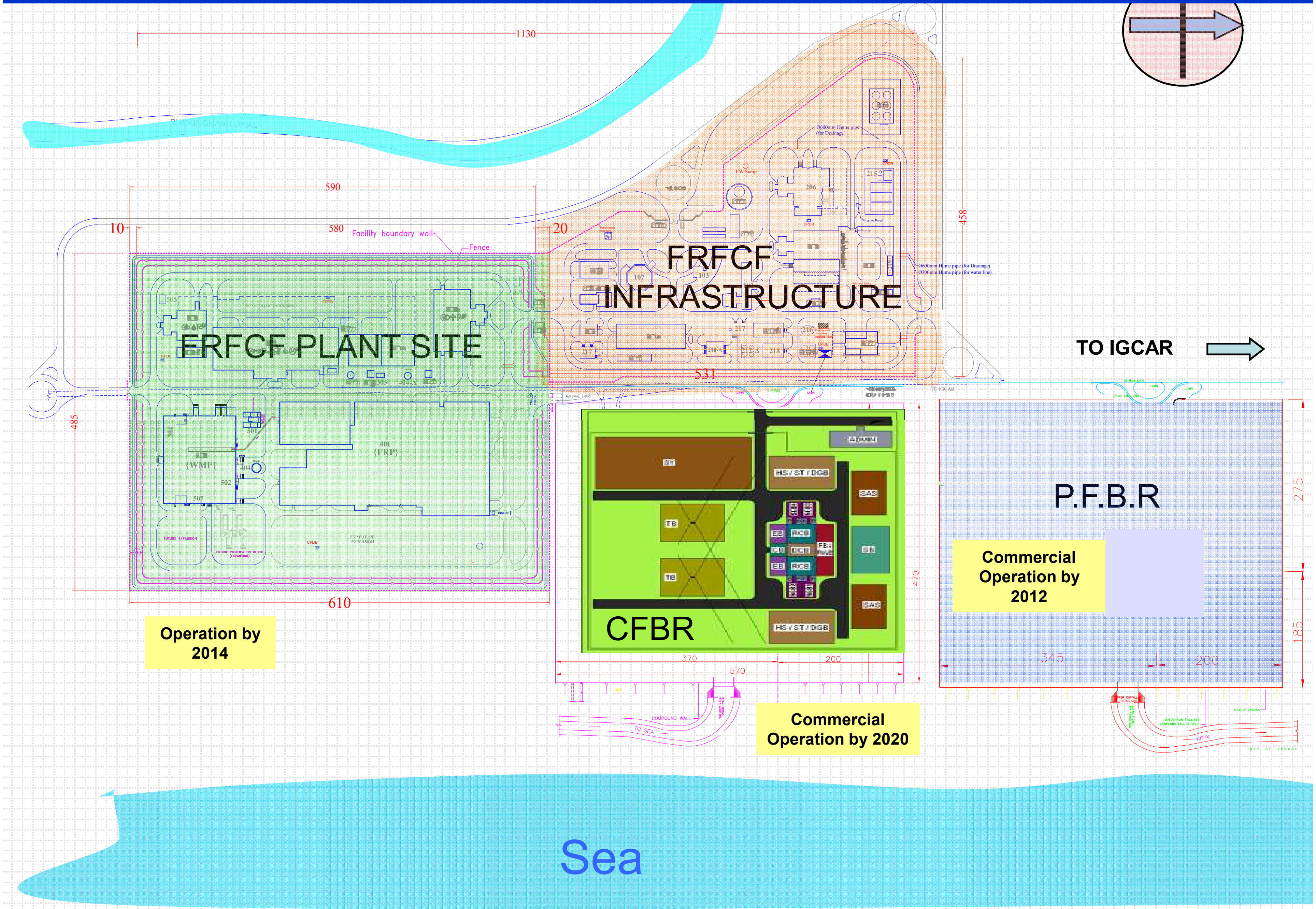
1. TA in LRP
2. Flask carriage
3. SA handling flask
4. SA handling trolley
5. Cell transfer machine (SS)
6. SA washing facility
7. Cell transfer machine (FS)
8. Under water trolley
9. Storage bay transfer machine
10. Spent SA storage bay
11. Cask washing bay
12. Cask loading bay
13. Shipping cask transfer
14. TA in SRP

- Spent fuel storage bay is shared between twin units
- Bay designed to meet normal requirements of twin units plus common full core emergency unloading requirements

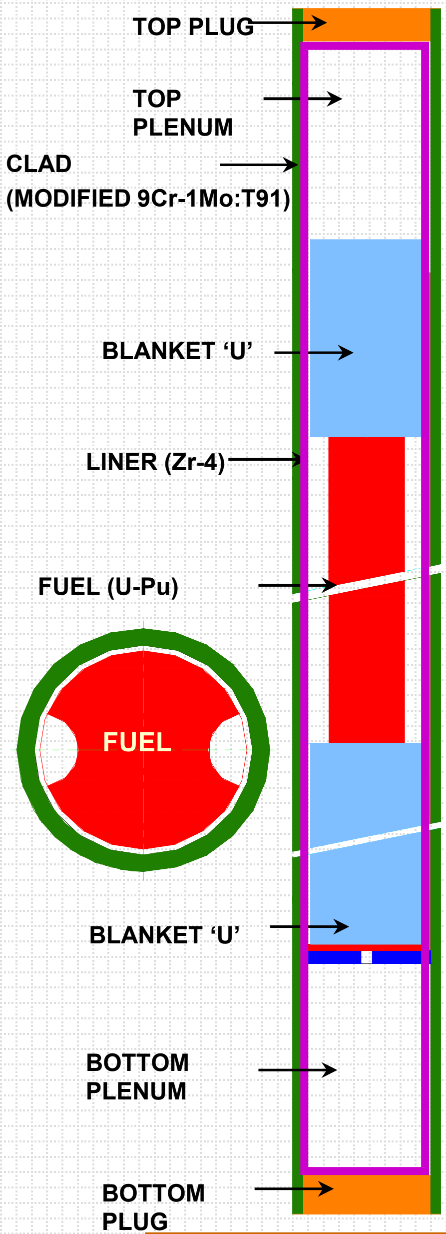
Fast Reactor Fuel Cycle Facility (FRFCF)



Location of FRFCF

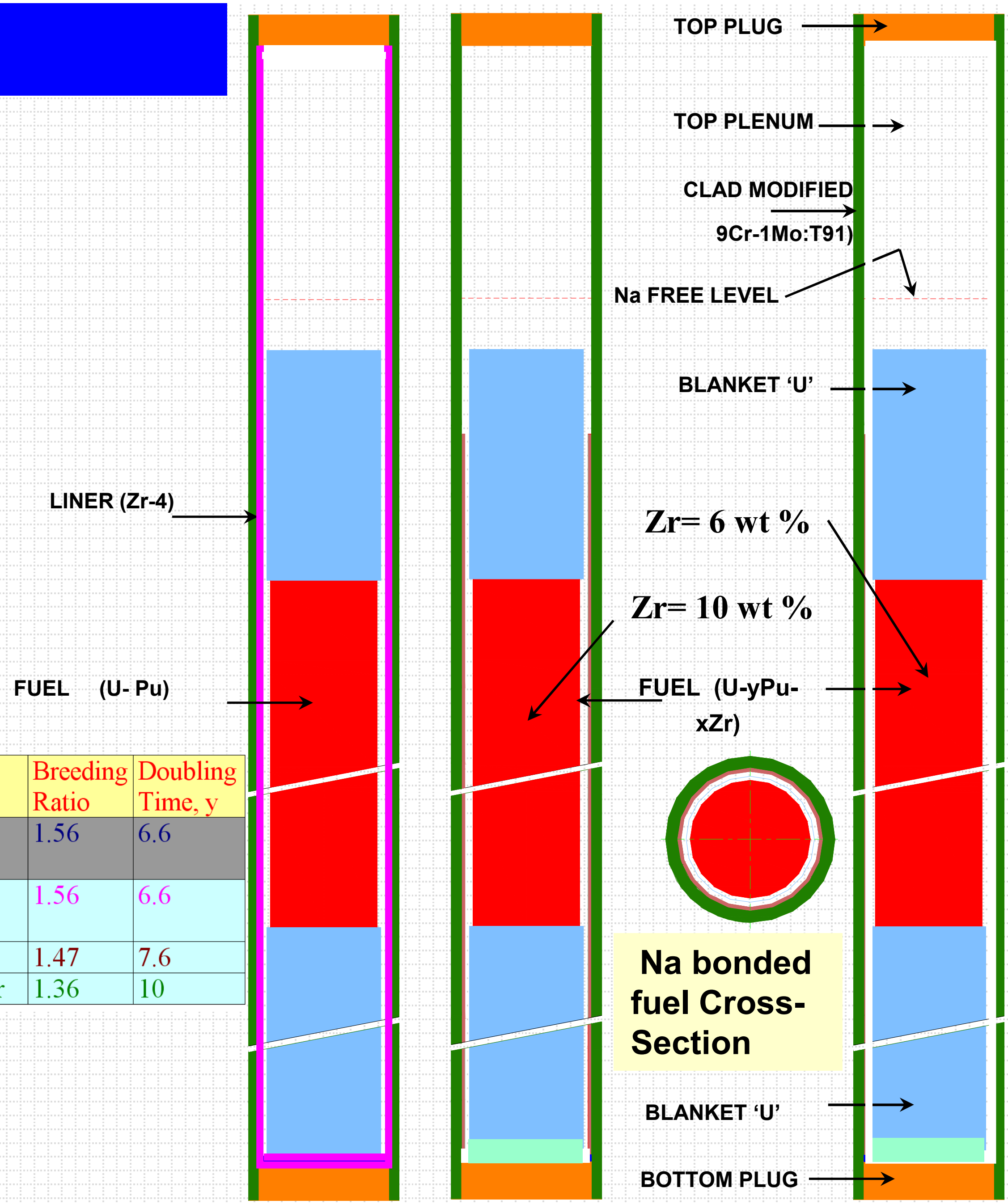


Metallic fuel



Mechanical bonded

Bonding	Fuel	Breeding Ratio	Doubling Time, y
Mechanical	U- Pu + Zr- 4 liner	1.56	6.6
Sodium	U- Pu + Zr- 4 liner	1.56	6.6
	U- Pu- 6 % Zr	1.47	7.6
	U- Pu- 10 % Zr	1.36	10



Sodium bonded

Impact of Spent Fuel Out of Core Cooling Period

Scenario	FBRs Capacity by year 2032 (GWe)		FBRs Capacity by year 2050 (GWe)	
	Indigenous	Under safeguards	Indigenous	Under safeguards
1 year BR 1.47 Pyro	22.5	24	125.5	219
2 year BR 1.5	16.5	19	74.5	144

Very strong incentive to develop pyroreprocessing technology

Spent Fuel Management for Future FBRs beyond CFBR

- **1000 MWe metal fuel reactors planned**
- **Aim is to recycle spent fuel faster to achieve higher growth in the deployment of FBRs**
- **Both helium and sodium bonded fuel considered**
- **Sodium storage considered as an attractive option**
- **Pyroprocessing of spent fuel as an attractive option**
- **R&D on sodium bonding and pyroprocessing already initiated**

Status of Pyrochemical Reprocessing Development

- **Lab. Scale studies on Pu bearing alloys in progress**
- **Engineering scale studies on U alloys initiated**
- **Studies on ceramic and metal waste forms**
- **Plant for processing spent metal fuel from FBTR will be designed based on this experience**

Lab. scale facility

Engineering Scale facility and its inner view

Pu deposit covered with salt

Summary

- Standardized fuel handling system and storage for a commercial fast reactor is yet to be established.
- India's nuclear power programme is based on closed fuel cycle with co-location of fast reactors and associated fuel cycle facility.
- Fast Breeder Test Reactor with carbide fuel is in operation with dry spent fuel storage. Fuel cycle has been closed.
- 500 MWe oxide fuel fast reactors are designed for spent fuel storage in water and internal reactor storage.
- 1000 MWe metal fuel fast reactors are under study to result in faster growth of power with spent fuel storage in sodium, no internal reactor storage and pyrochemical reprocessing.

Thank you