THE LAST TWENTY YEARS EXPERIENCE WITH FAST REACTORS : LESSONS LEARNT AND PERSPECTIVE

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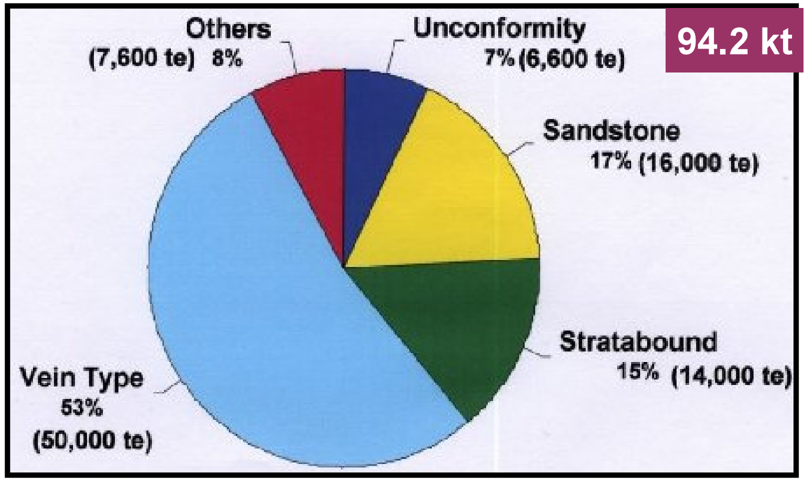
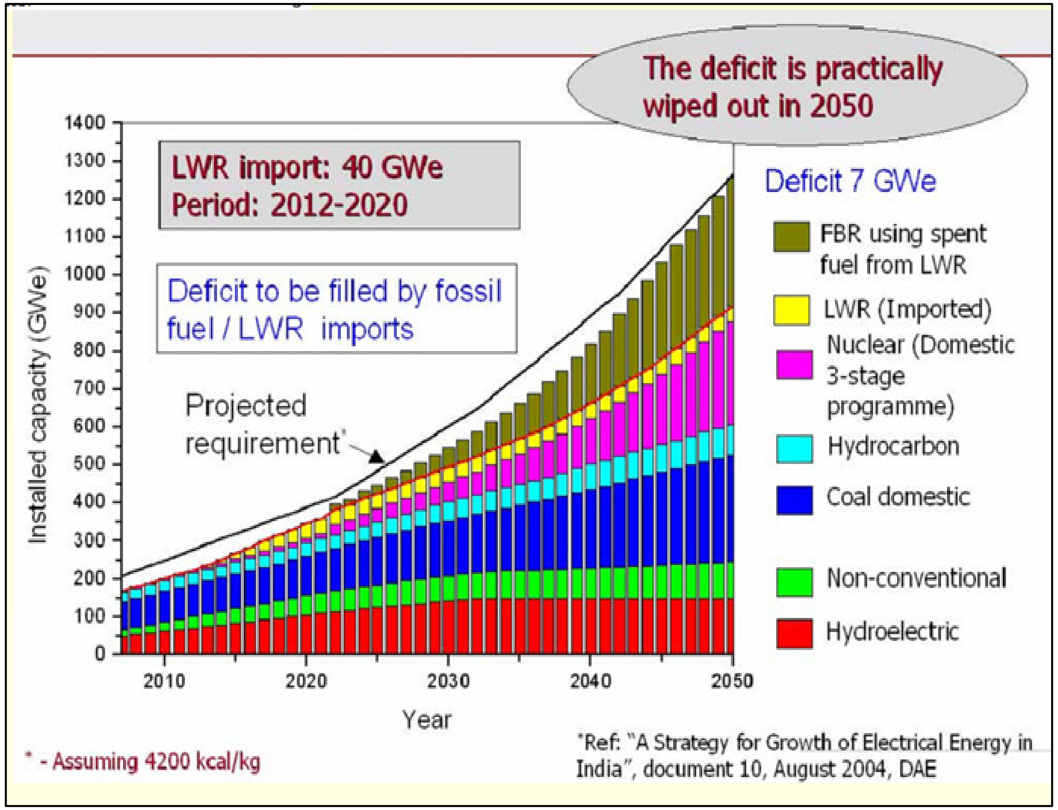
Role of FBR in India

- India is aiming to reach at least a per capita energy consumption of about 2400 kWh/a (current world average) with 8% growth rate by 2031-32.
- Electricity generation capacity of 778 GWe by 2031-32 (4 times in 20 y)
- Ten fold growth over next fifty years

- FBR with closed fuel cycle is essential for effective utilisation of available uranium
- To realise nuclear energy rapidly, breeding is important





FBR Programme in India

- India started FBR programme with the construction of FBTR
- FBTR is a 40 MWt (13.5 MWe) loop type reactor. The design is same as that of Rapsodie-Fortissimo except for incorporation of SG and TG (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
- Govt. granted financial sanction for construction in Sep 2003.
- Construction of PFBR has been undertaken by BHAVINI.
- PFBR will be critical by 2011.
- Construction of 6 more reactors (2x500 MWe at Kalpakkam & 4x500 MWe at a new site) based on PFBR design in a phased manner (MOX fuel). Commercial operation of all six by 2020.
- Beyond 2020, metallic fuelled SFRs with 1000 MWe capacity

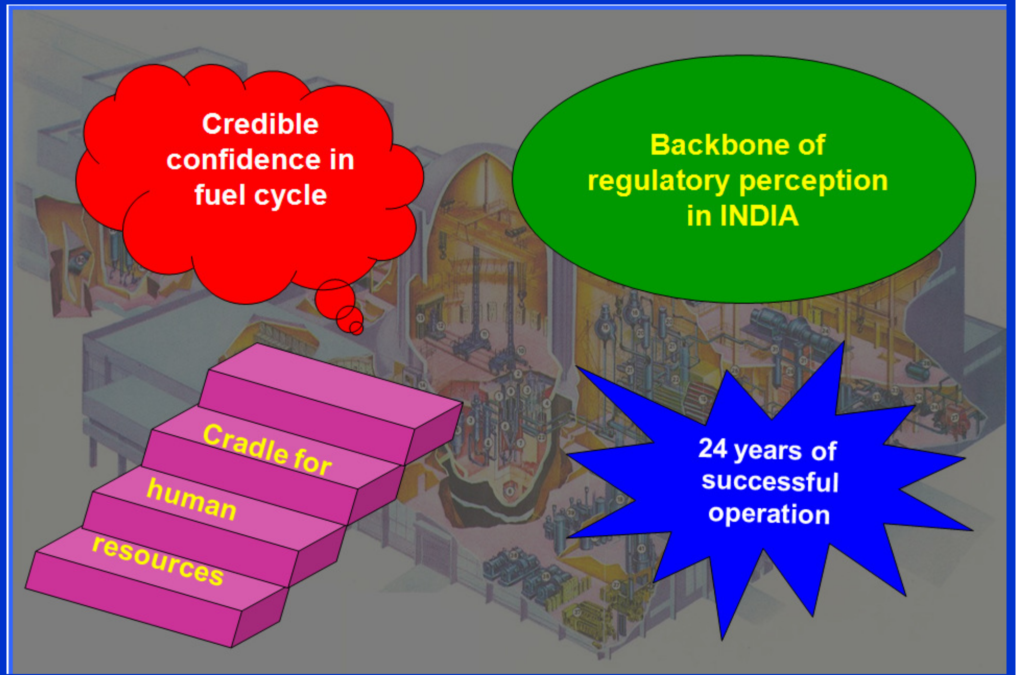
FBTR TODAY

FBTR, in operation since 1985, is the flag-ship of IGCAR and is the test bed for fast reactor fuels and materials. It has completed 15 irradiation campaigns with high availability factors in the recent campaigns. Its unique carbide fuel (55 % PUC & 45 % UC) has set an international record in burn-up by achieving 165 GWd/t without any single cladding failure in the core

- The performance of sodium systems has been excellent. Sodium pumps have crossed 6,00,000 h of cumulative, continuous operation. Steam generators have performed without a single leak incident

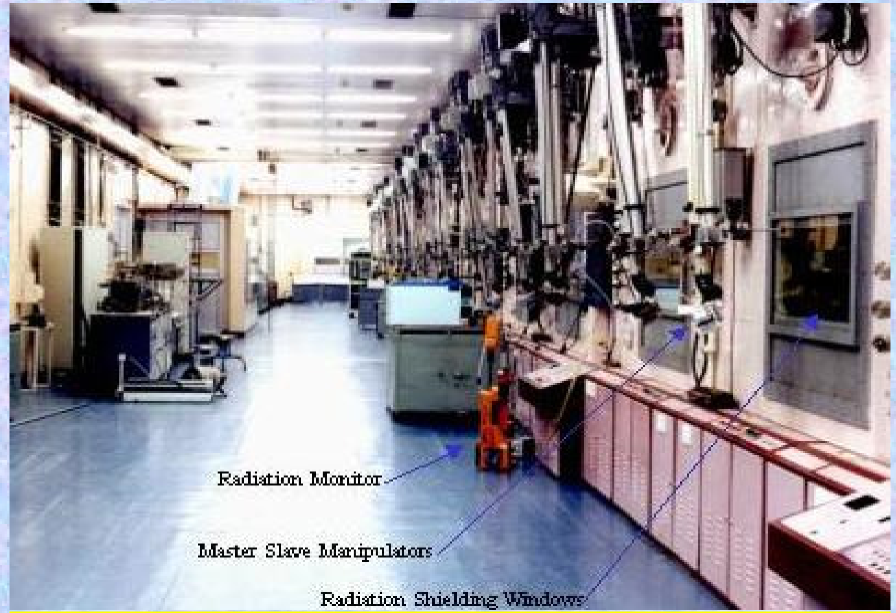
- PFBR test fuel is under irradiation and seen 92 GWd/t burn-up

- 44 % MOX fuel has been inducted in the core

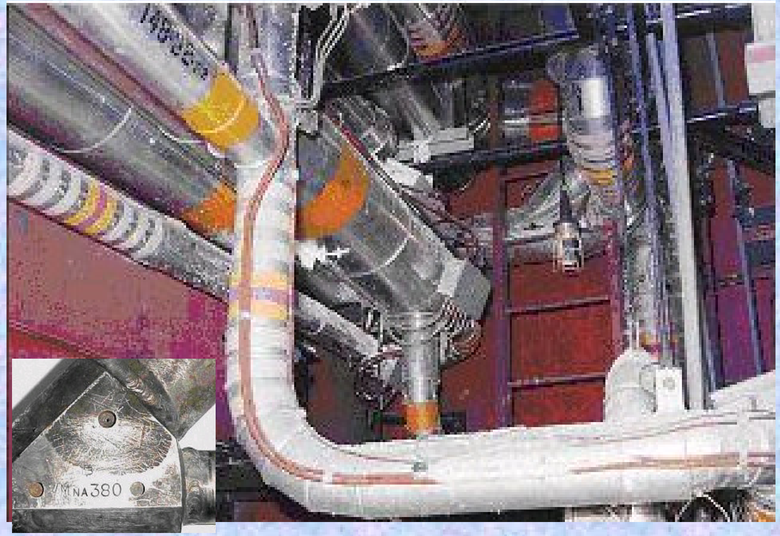


FBTR life extension exercise has been completed to serve for another two decades, in particular for testing of advanced materials and metallic fuel

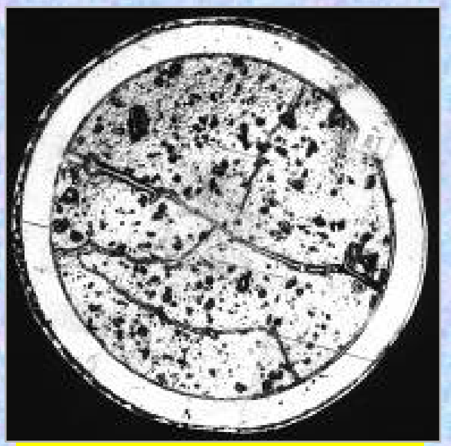
Experiences with FBTR



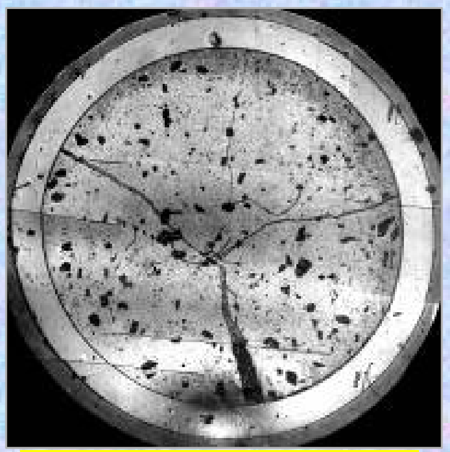
Post Irradiation Examination Facility for FBTR Fuel



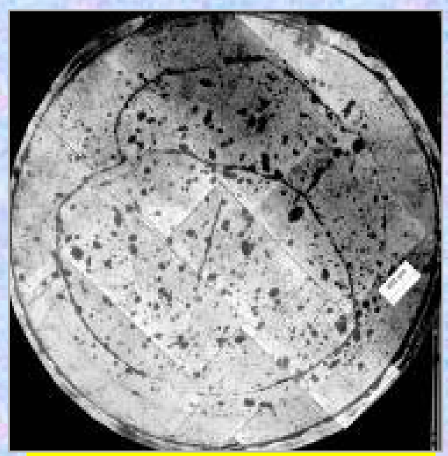
Sodium Leak inside Purification Cabin due to a hole in valve body



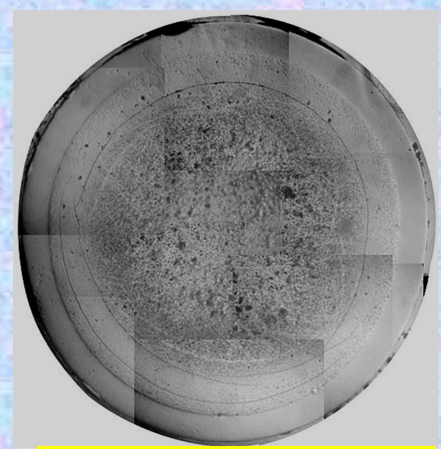
25 GWd/t BURN-UP



50 GWd/t BURN-UP



100 GWd/t BURN-UP

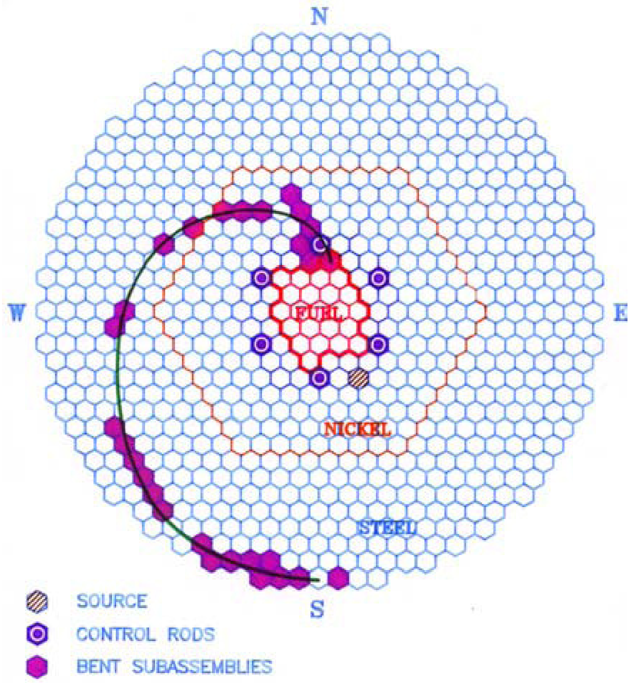


155 GWd/t BURNUP

Experiences with FBTR – contd…

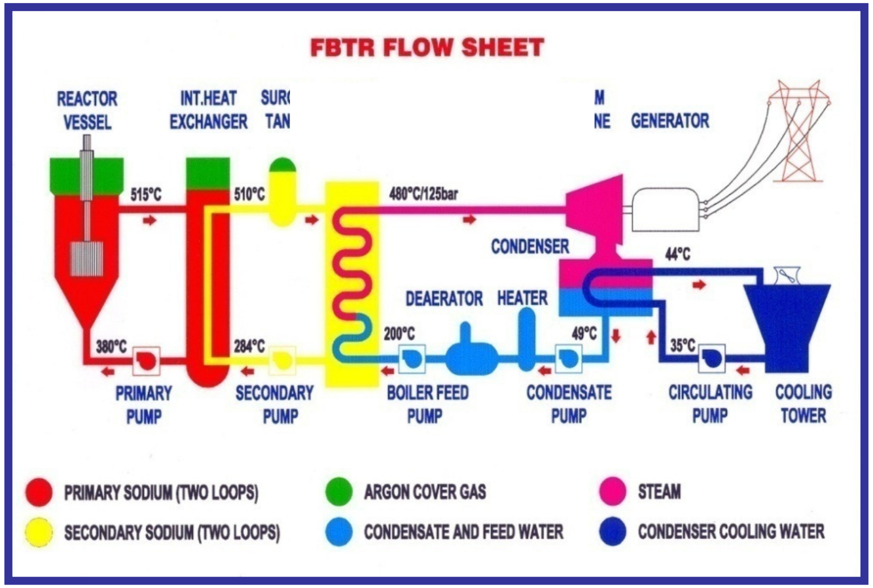
Fuel Handling Incident

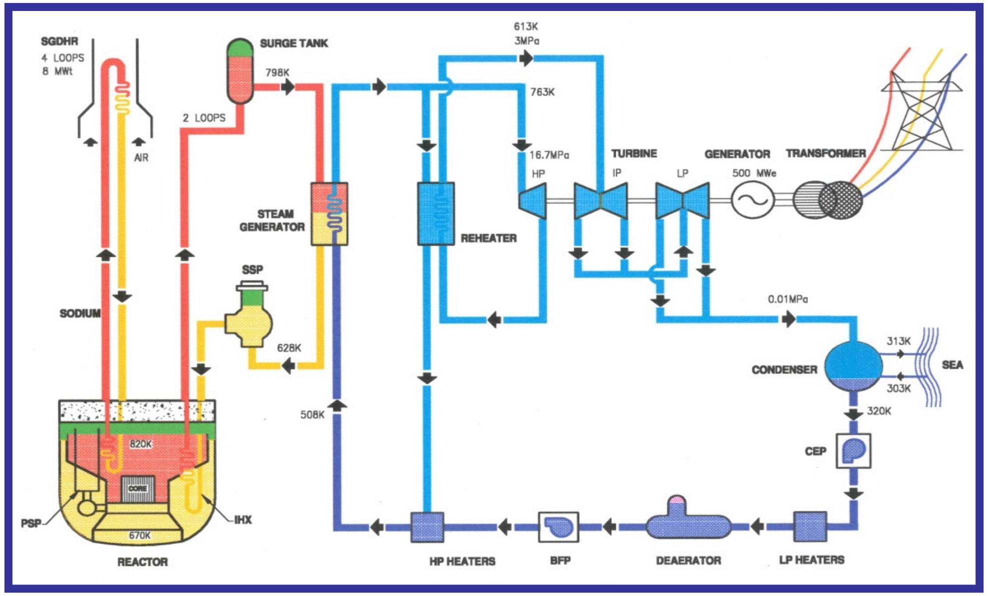
During the transfer of the fuel subassembly from the 3rd ring to the storage location in 1987, the foot of the assembly got bent as it was projecting below the guide tube. This resulted in curtailed movement of the gripper tube and finally jamming of the fuel subassembly along with the gripper tube inside the guide tube.



- **Appropriate remedial measures, including mechanical stopper for fuel handling gripper and redundant interlocks for authorizing plug rotation, were implemented.**
- **Proper maintenance and operating procedures for the fuel handling mechanism were evolved.**
- **The remedial measures were so effective that the subsequent fuel-handling operations (about 600 nos.) have been carried out for the past 20 years without any incidents.**

APPROACH TO BIG LEAP IN FBR PROGRAMME





FBTR

40 MWt

13.5 MWe

Loop type

Fuel: PuC - UC

- 400 r-y worldwide FBR operational experience
- Rich experience with MOX fuel
- 30 y of focused R&D programme involving extensive testing and validation
- Material and Manufacturing Technology Development and Demonstration
- Science based technology
- Peer Reviews
- Synergism among DAE, R&D Institutions and Industries

PFBR

1250 MWt

500 MWe

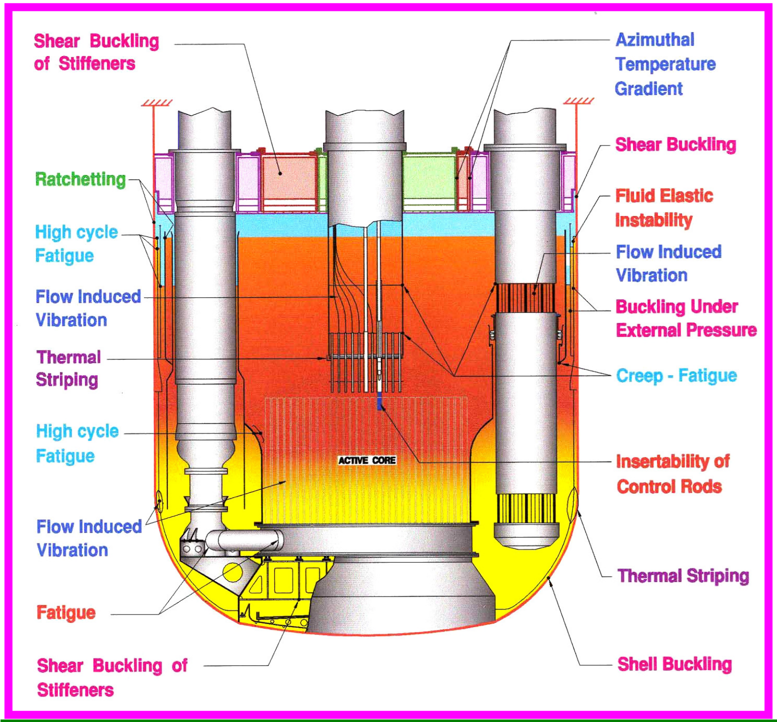
Pool Type

Fuel: UO2-PuO2

key technology domains: Design Challenges, Mechanics & Hydraulics, Materials, Na, ISI & Fuel Cycle

FBR Challenges & Achievemnets

- **Design for long reliable operation of components operating at high temperature (550°C) for design life of 40 years and more**
- **Design of mechanisms operating in sodium and argon cover gas space**
- **Design to accommodate Sodium leak and sodium water reactions**
- **Seismic design of interconnected buildings**
- **Seismic design of pumps, shutdown systems and thin shells with large sodium mass and fluid-structure interaction effects**
- **In-Service Inspection and repair of reactor internals**
- **High temperature fission chambers**
- **Manufacturing of large size thin walled vessels made of stainless steel with stringent form tolerances (< ½ thickness)**
- **Erection of the vessels maintaining tight tolerances on verticality and horizontality.**



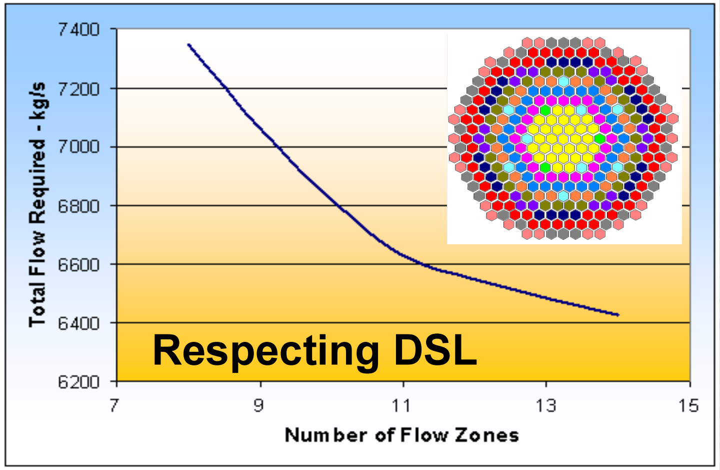
Failure modes considered for the structural design

400 reactor years of worldwide operating experience is an asset to the design

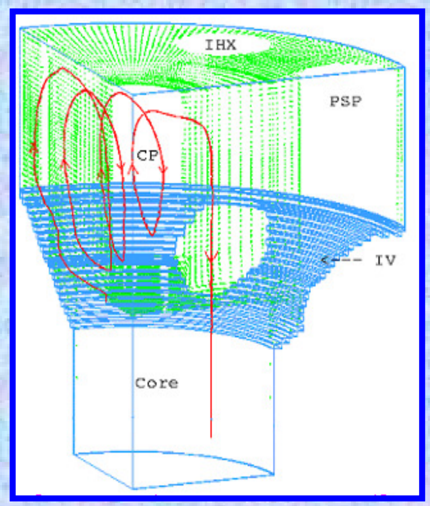
Design to achieve economy with enhanced safety

Core Thermal Hydraulics

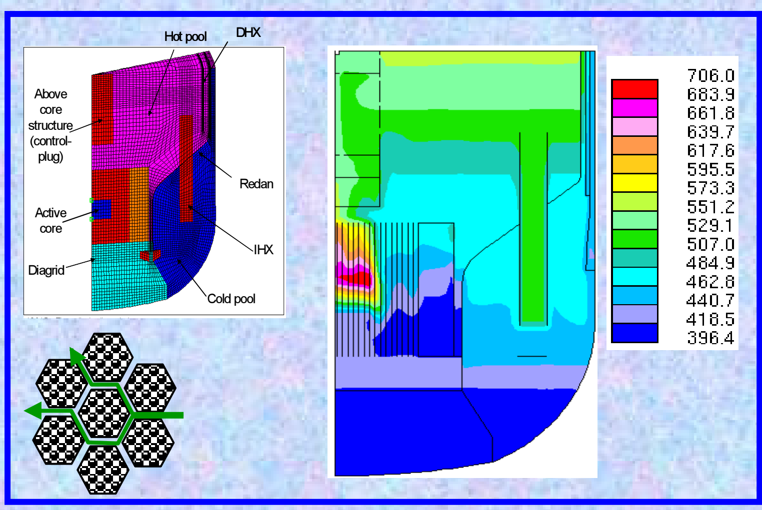
- Optimization of number of flow zones (more number results in complex administrative control for SA loading and lesser number calls for higher pump capacity)
- Temperature / flow distributions within a SA towards deriving accurate hot spot temperatures in fuel, clad and coolant. CFD analysis of 217 pin SA with thin wire wrap demands ~ 1 million mesh size



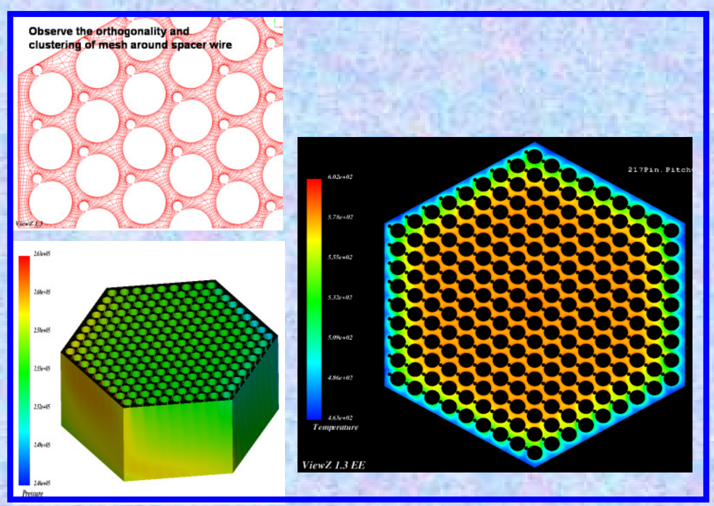
Thermal hydraulics analyses for confirmation of inter wrapper flow, adequacy of number and location of DNDs, carried out to confirm design adequacy for thermal striping criteria & core temp monitoring requirement



Precursor path from SA to detector location

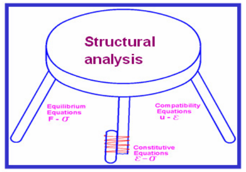


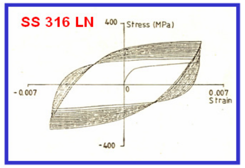
Quantification of Inter-Wrapper Flow during Safety Grade Decay Heat Removal Conditions by CFD Studies



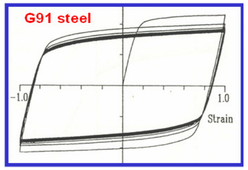
Finite Volume Mesh, Pressure and Temperature Distributions within 217 pin Fuel Subassembly

HIGH TEMPERATURE DESIGN: HIGHLIGHTS





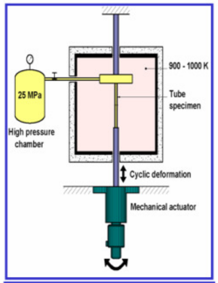
Cyclic Hardening



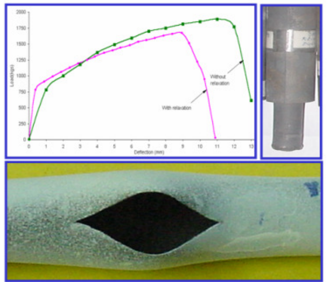
Cyclic Softening

- Accurate prediction of stress / strain
- Appropriate constitutive equations to depict all complex mechanical material behaviour viz. rate and time dependent behaviour, monotonic & cyclic hardening/ softening, plastic memorisation, etc.
- Materials: SS 316 LN for Na components
  G91 steel for SG
- Chaboche Viscoplastic Theory:
  - ❖ 23-parameter model for SS 316 LN
  - ❖ 20-parameter model for G91 steel
- Identification of material parameters using experimental test data with physical meaning of each parameter.

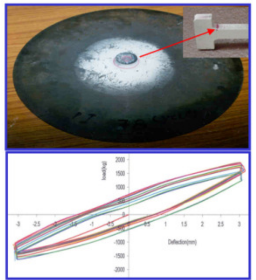
Code development for viscoplastic analysis



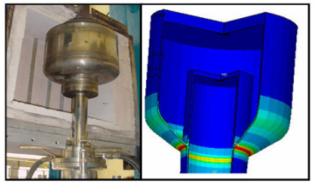
ET test facility



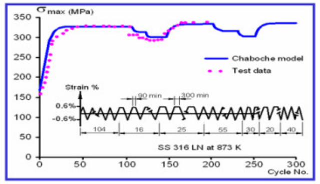
IHX and SG tubes



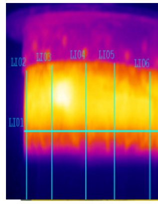
ORNL Plate



Simulation of creep damage in IHX

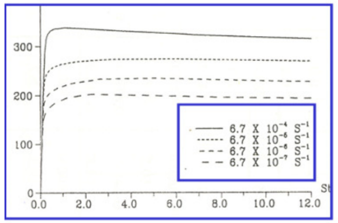


Evolution of maxi. stress



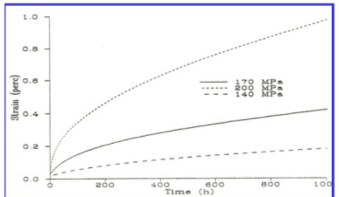
Thermal ratcheting

Experimental validation

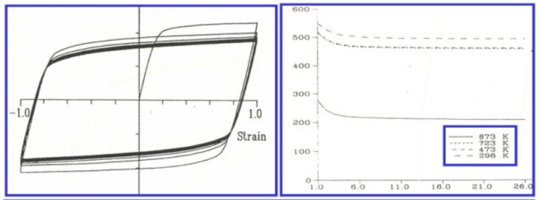


Monotonic softening

- High strain rate sensitivity at ET
- Monotonic hardening at LT and softening at ET
- Cyclic softening (not strong function of temperature)
- Very low primary creep



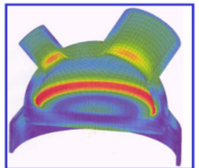
Creep curves



Cyclic softening behaviour of G91

Numerical simulation of modified 9 Cr-1Mo

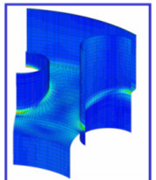
- In-house code CONE with Chaboche model
- Critical Components: Control plug (CP), inner vessel (IV) and steam generator (SG)
- Elastic route of RCC-MR very conservative and hence not economical
- Viscoplastic model provides realistic stresses/ strains & higher operating temp./ longer life.



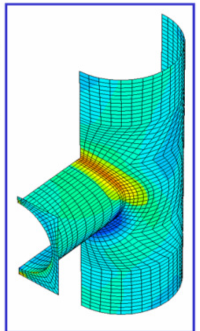
VM stress in SG-Header

Permissible Plant Life – Calendar Years

Analysis method	Operating Temp. °C		
	530	540	550
Elastic	51	17	10
Viscoplastic	132	82	63



VM stress in IV



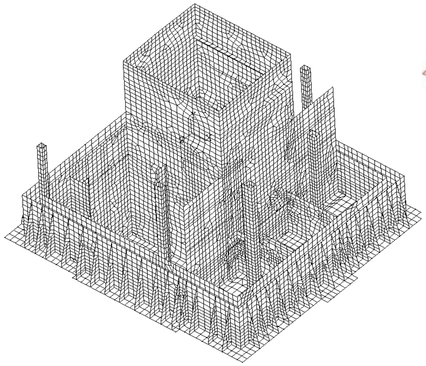
VM stress in SG-Nozzle

Application: Life prediction of PFBR components

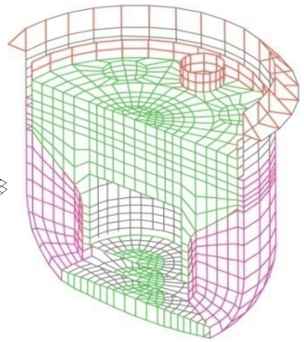
SEISMIC DESIGN

- Development of seismic design criteria
- Analysis of nuclear island connected buildings (NICB) and also extract floor response spectra at various component support locations
- Seismic analysis of reactor assembly to derive seismic forces
- Investigation of buckling of thin shells

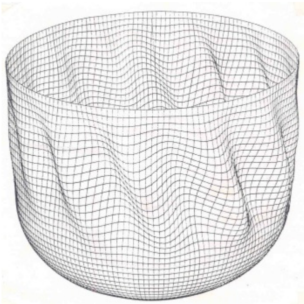
- Ensuring the reactor scramability
- Investigation of pump seizure
- Shake table testing for validation of analysis and qualification
- R&D woks: Behaviour of bearing, non-linear sloshing, parametric instability of thin shells, study of cliff-edge effects, fluid-structure interaction of perforated structures

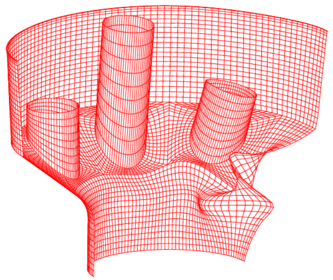


NICB model for seismic analysis

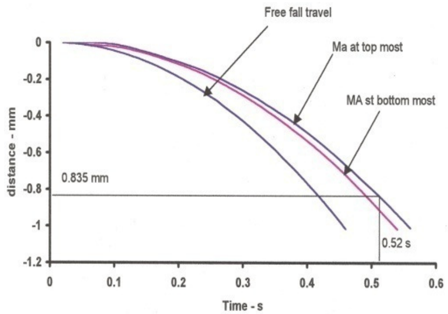


FEM model of RA

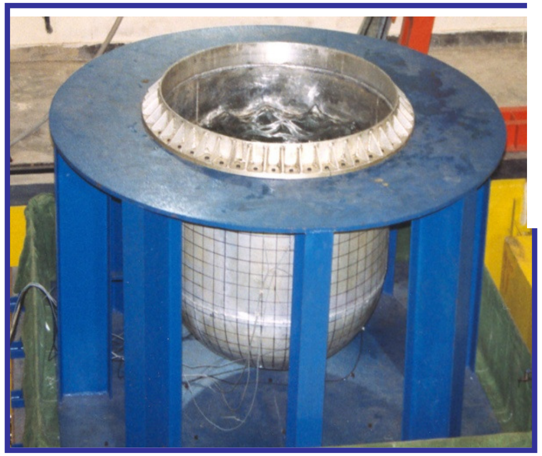




Buckling modes of thin vessels



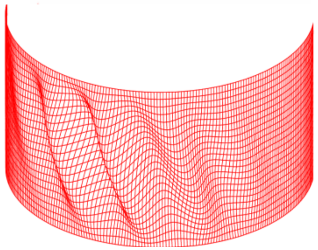
Drop time of absorber rods



Shake table tests on RA model

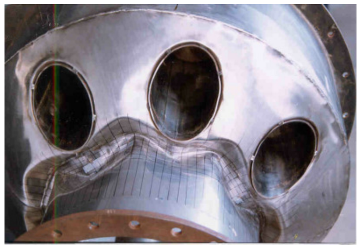
Thickness H - mm	No of tests	Imperfection δ/h	Buckling load - t	
			Test	FEM
0.8	4	2.2 - 3.8	33-54	28-32
1.0	4	1.1 - 4.2	50-69	42-56
1.25	4	1.2 - 3.4	60-73	72-99

Experiment

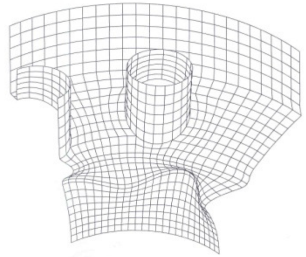


Theory

Loading	Tolerance mm	Test	FEM	Test/ FEM
Pressure P MPa	-2.7 to 1.7	0.9	0.95	0.95
Axial force F- t	-2.9 to 2.5	1.61	1.40	1.15
P plus F	-1.8 to 1.4	0.175 & 1.18	0.151 & 1.18	1.16

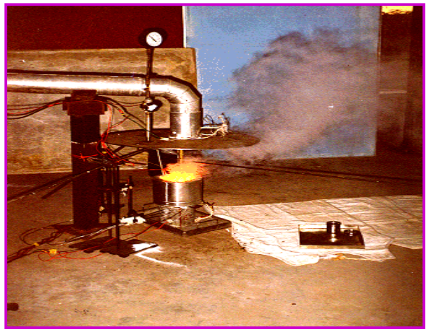


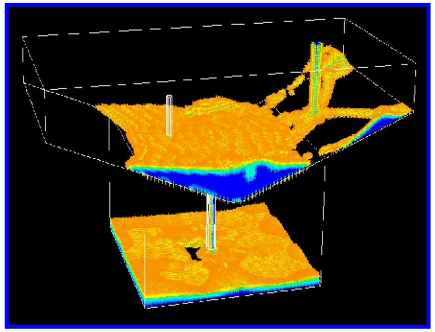
Experiment

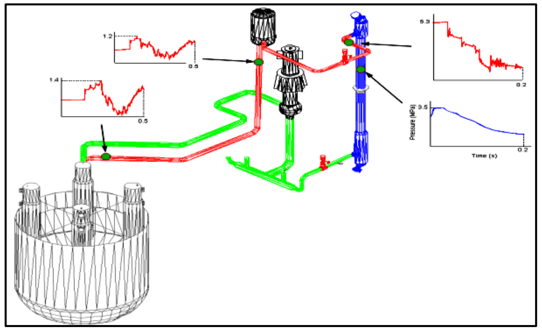


Theory

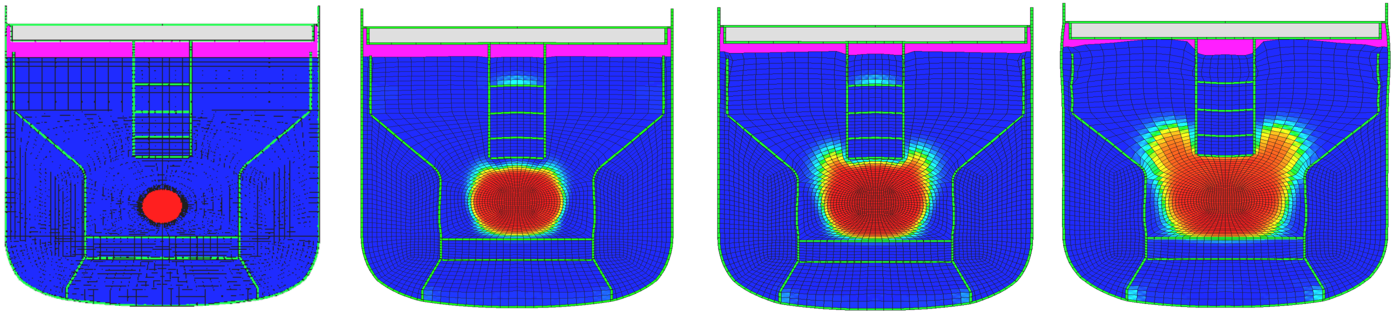
Safety Studies

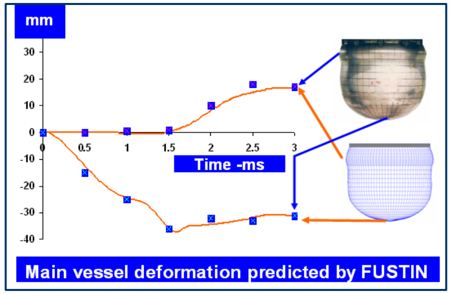




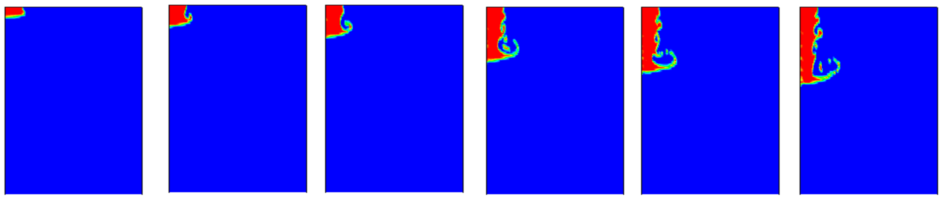


Safety related to Sodium

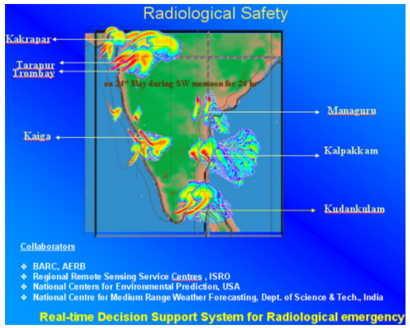




Mechanical Consequences of Core Disruptive accident

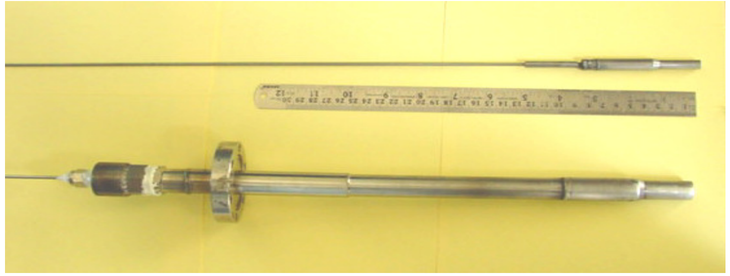


Post Accident Heat Removal Studies

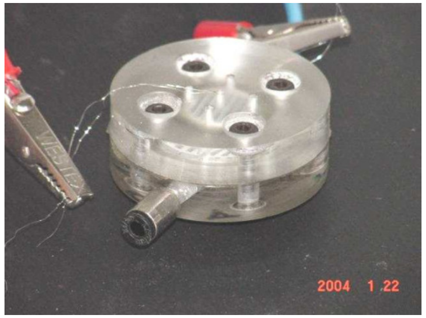


SENSORS FOR SODIUM APPLICATION (DEVELOPED AT IGCAR)

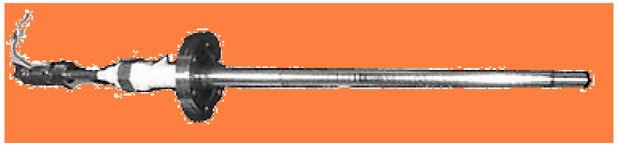
Cover gas hydrogen meter



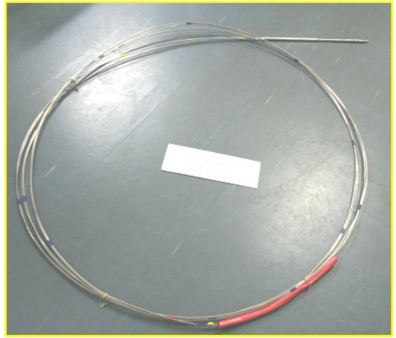
Electrochemical in-sodium hydrogen meter



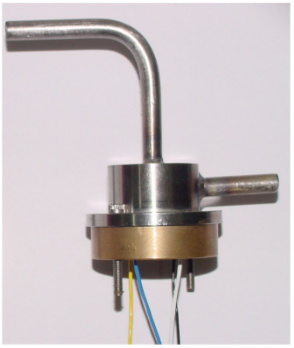
Polymer electrolyte based hydrogen sensor



Electrochemical in-sodium carbon meter

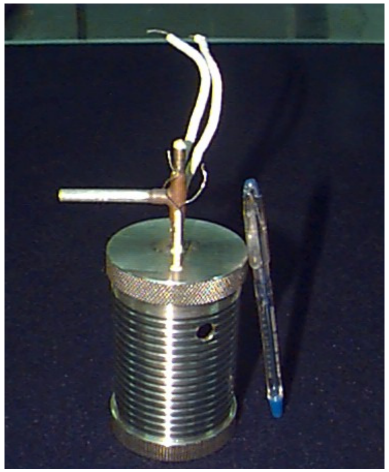


Eddy Current Flow Meter



Semiconductor oxide based Compact hydrogen sensor

Risk Oxygen Meter



Special Features

Temp. range – up tp 450ºC

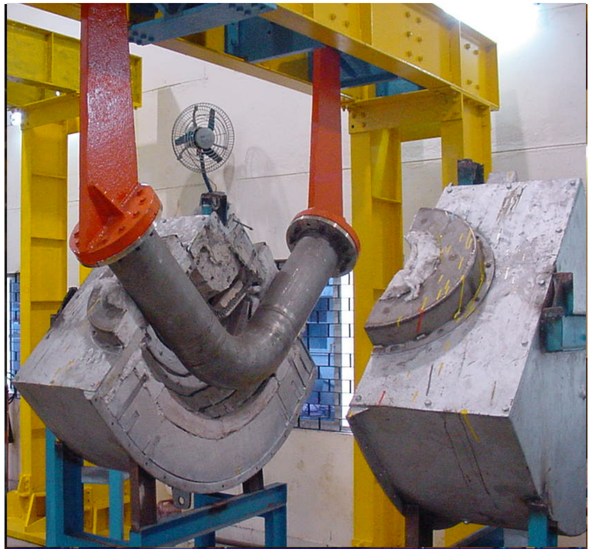
Resolution – from 13 ppb

Sensitivity –ppb to percentage

Response time – from 30 s

Sodium Ionisation Detector

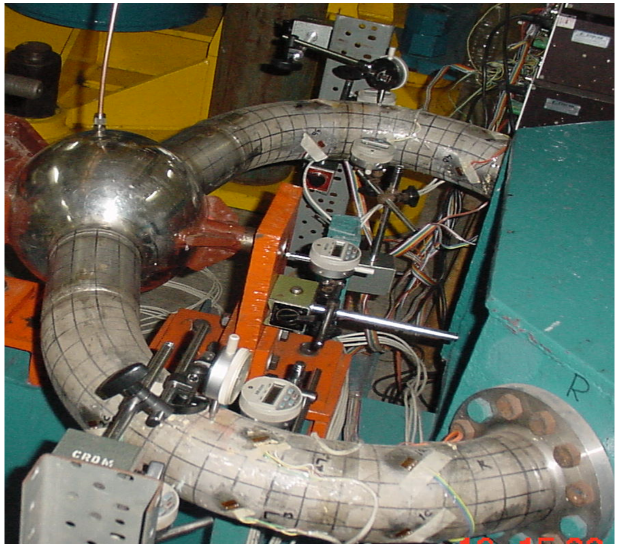
Experimental Program for Qualification of RCC-MR



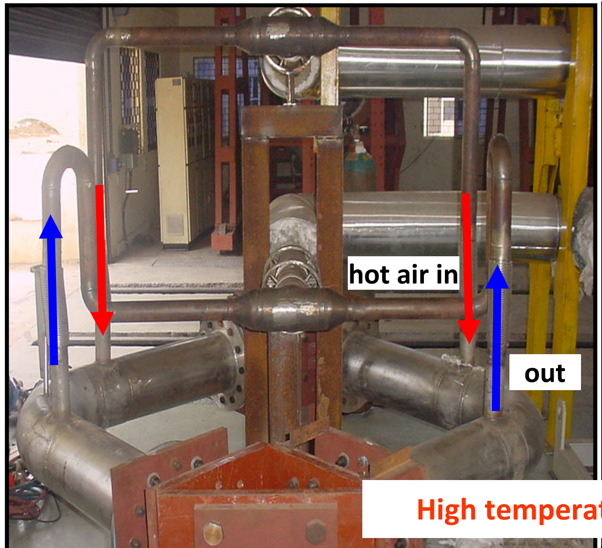
Crack growth tests in bends

SG –Shell-Nozzle Junction Tests

10 t Capacity Shake Table



Thermal ratcheting Primary pipe bends

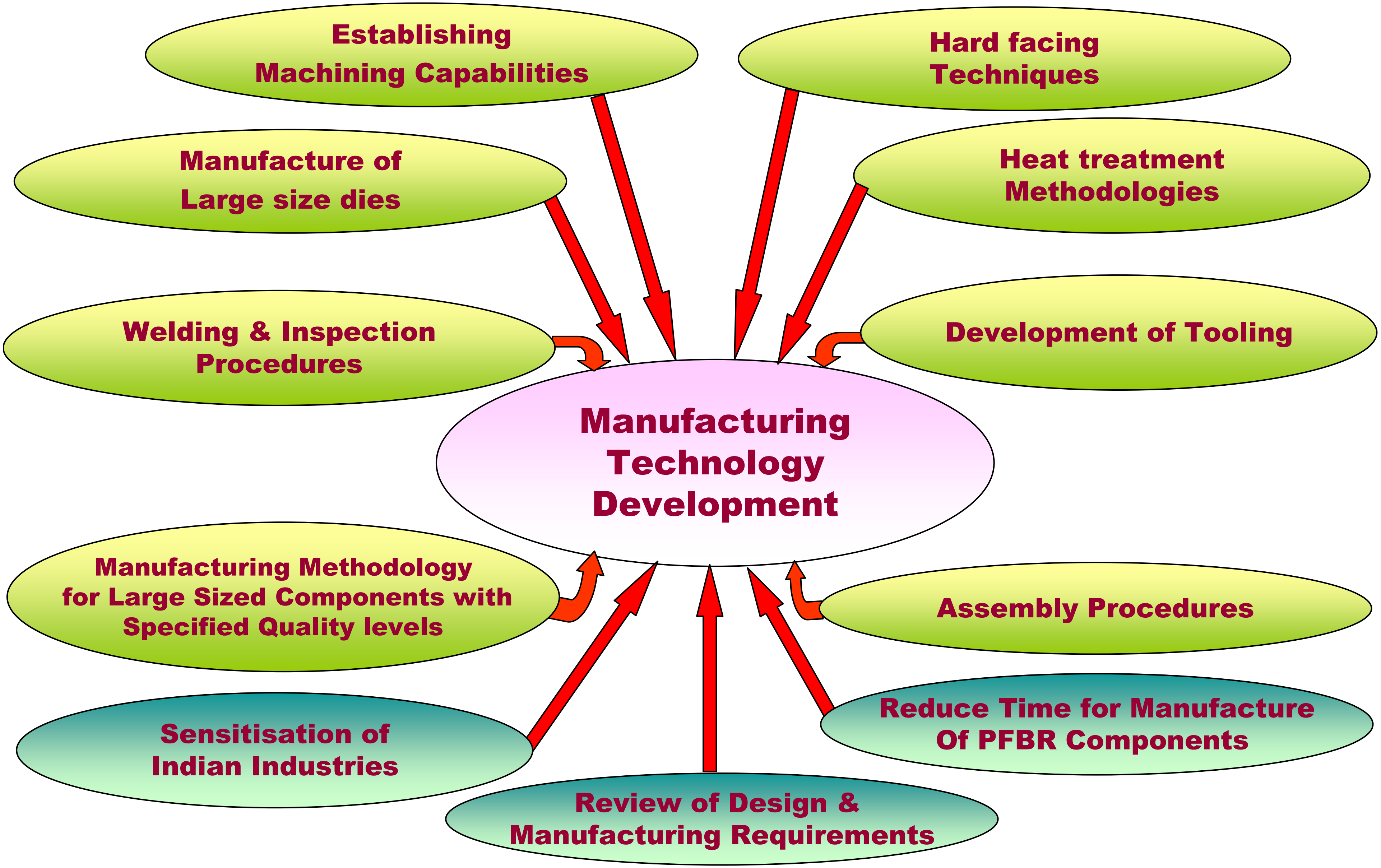


High temperature tests

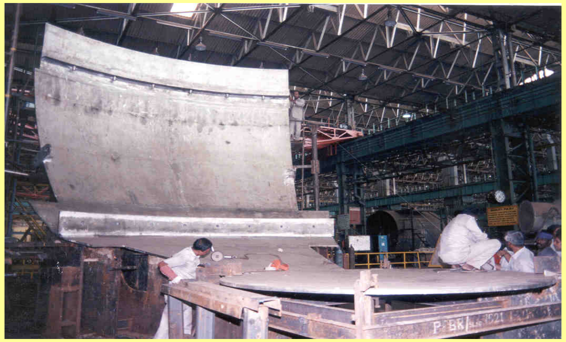
Pipe bends before insulation

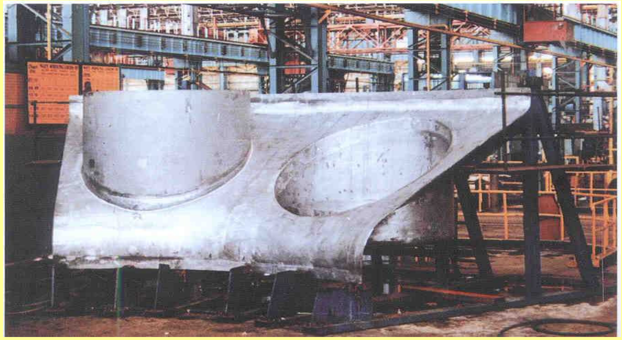
Pipe bends after insulation

Technology Development of Reactor Assembly Components



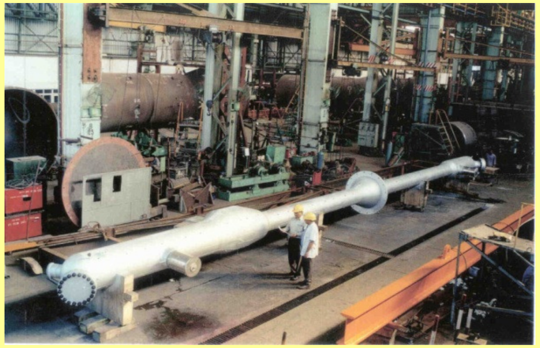
PFBR – MANUFACTURING TECHNOLOGY DEVELOPMENT


Sector of Main Vessel


Sector of Inner Vessel


CSRDM


Sector of Roof Slab


Steam Generator

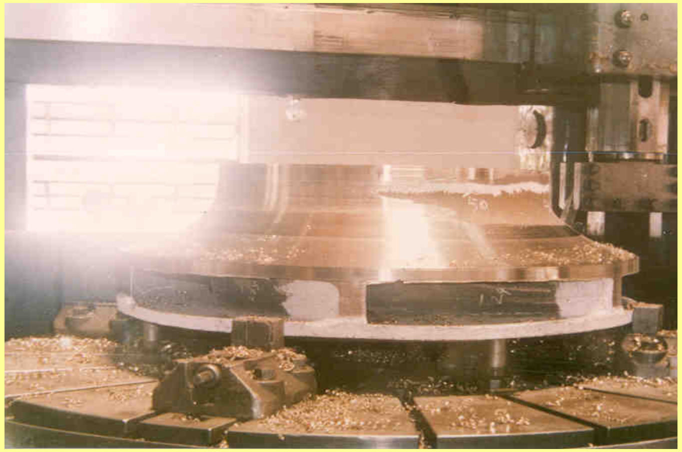

DSRDM


Butterfly Valve

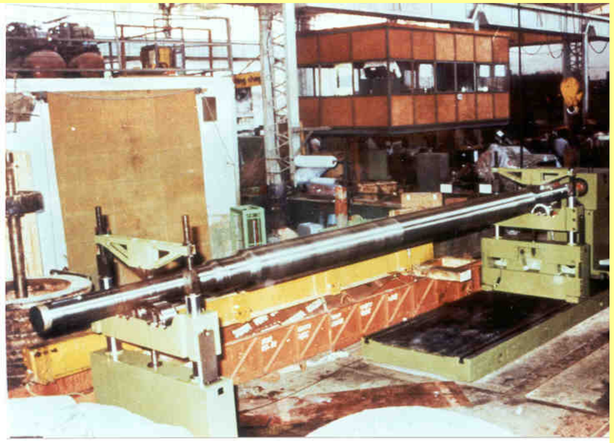

IHX Tube to Tube Sheet Joint Mock up


Large Dia Pipe Fittings

PFBR – MANUFACTURING TECHNOLOGY DEVELOPMENT – contd..


Primary Pump Impeller Casting


Fuel Sub assembly


Primary pump - Shaft


Grid plate sector
Top plate rough machining


Bellow Development
Testing


Transfer Arm
Assembly in progress

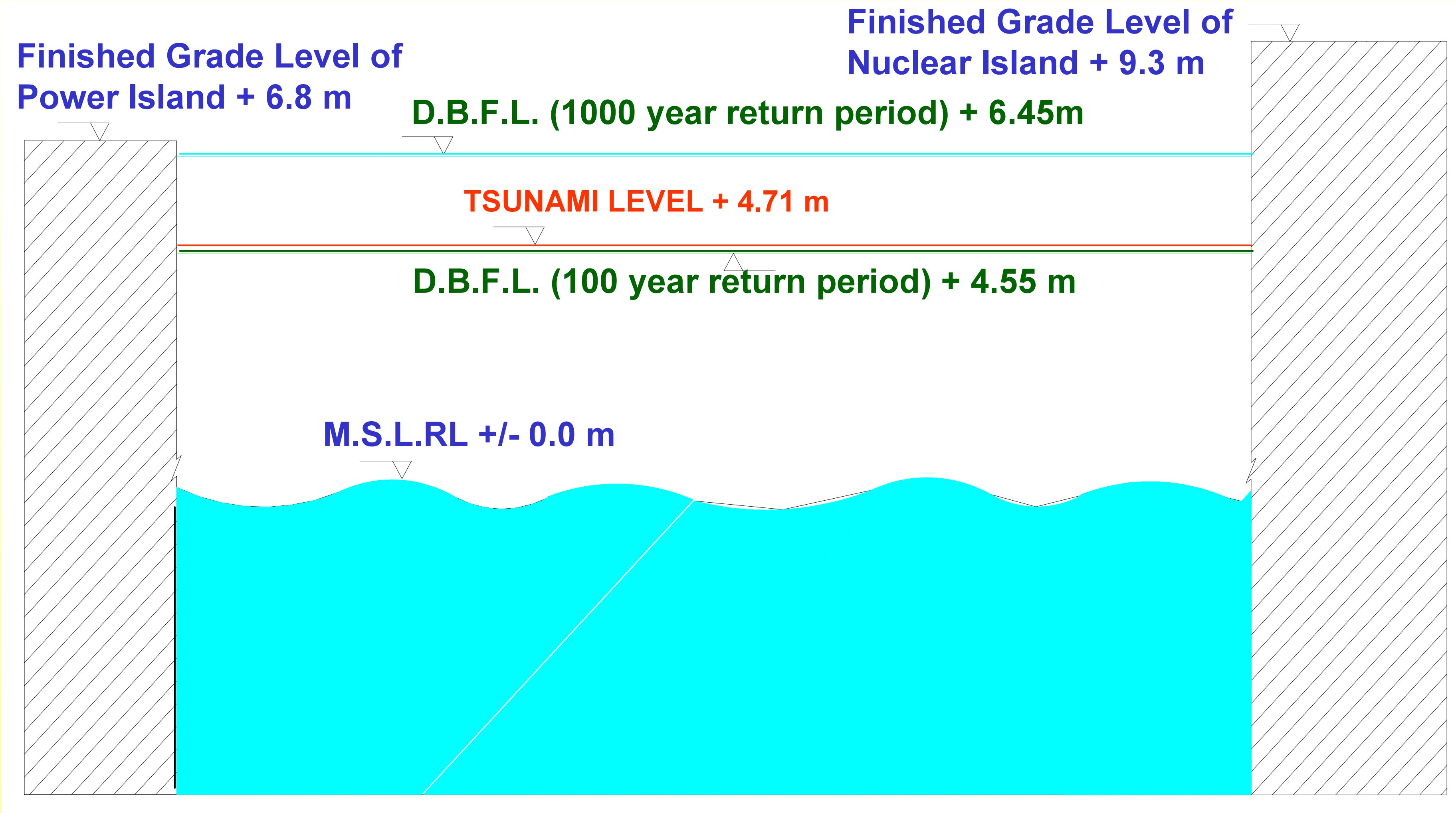
Launching of Fast Breeder Power Reactor

- PFBR was launched on 23rd October, 2004 by Hon'ble Prime Minister Dr. Manmohan Singh during Golden Jubilee Year of DAE
- IGCAR to provide R&D; BHAVINI to bring project management expertise
- Both organizations to work in complete synergy with academic, research and industry

Unveiling of Foundation Stone for FBR Project

PFBR will be critical by Sept 2011

GRADE LEVEL OF NUCLEAR ISLAND, POWER ISLAND AND THE LEVEL OF SEA WATER DUE TO D.B.F. OF 1000 / 100 YEAR RETURN PERIOD AND TSUNSMI LEVEL OCCURRED ON 26th DEC. 2004.



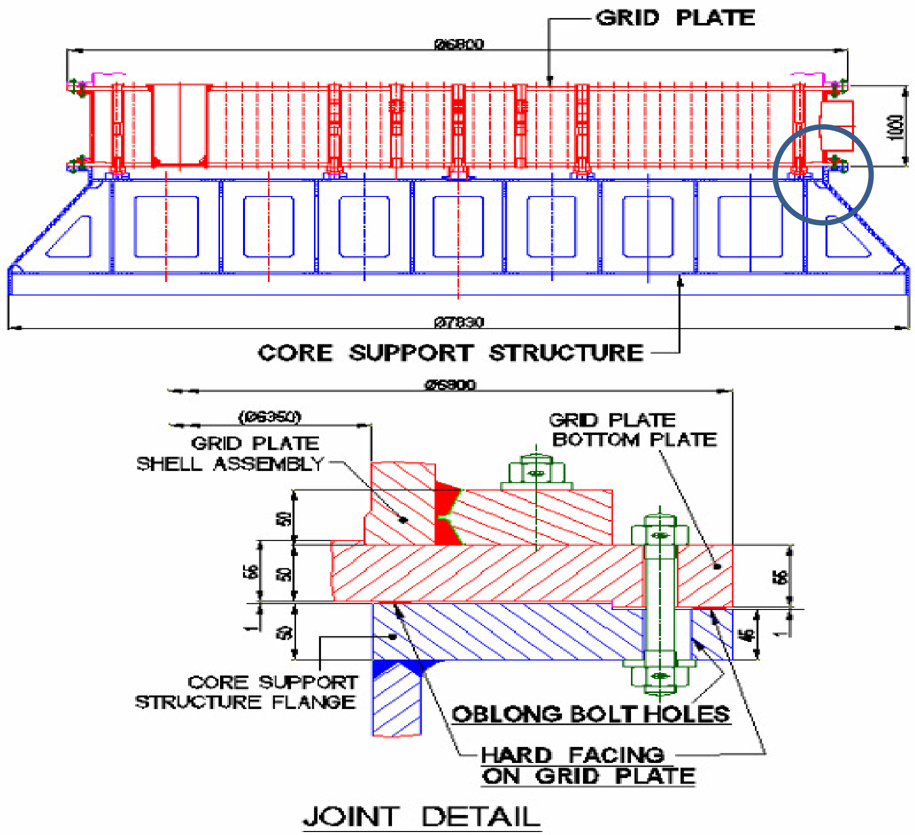
Hard Facing of Grid Plate Bottom Plate

•Grid plate which supports the core is resting on core support structure

•During any hot shock in the cold pool, the grid plate temperature raises from 400^{o}C to 520^{o}C rapidly compared to core support structure

•In order allow the differential expansion of 6 mm and also to have required rigidity against seismic forces, slotted bolted system is provided at the interface

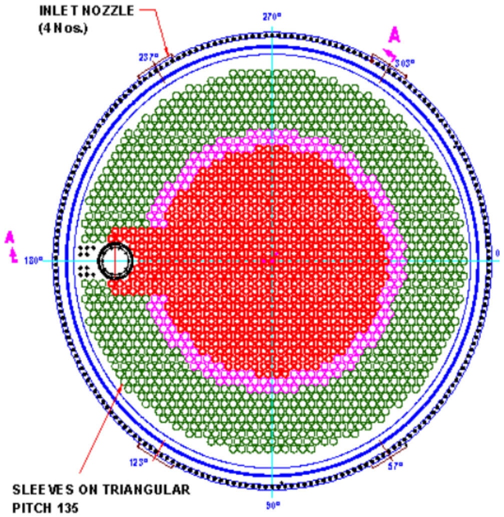
•In addition, to permit free expansion without having any risk of self weld, two annular hard face tracks of diameters 6.38 & 6.77 m are done on the bottom plate at the interface



Nickel based viz. Colmonoy-5 hard facing (cobalt based material such as stellite, is avoided from induced activity considerations

Hard Facing of Grid Plate – contd…

Blue colored circles are the tracks



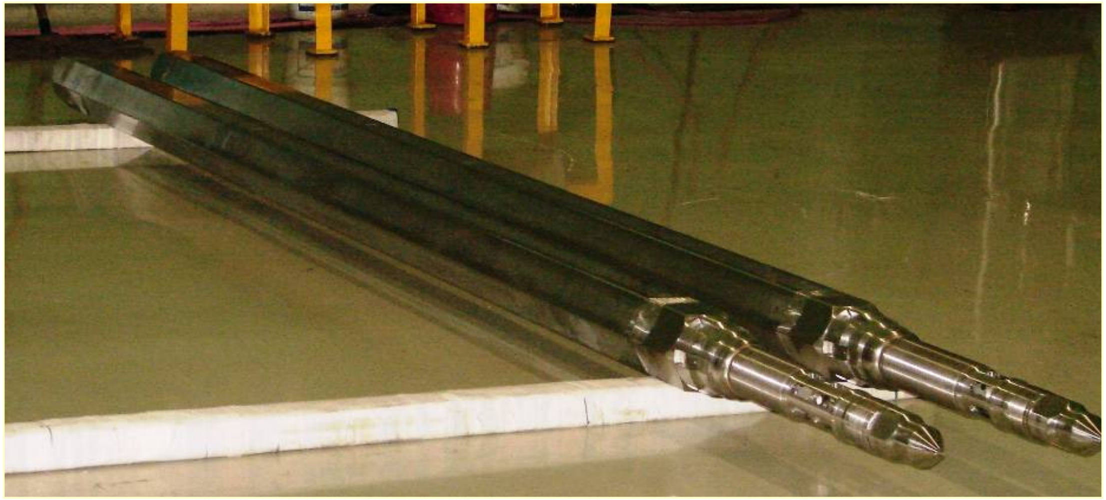
Preparatory work for hard facing

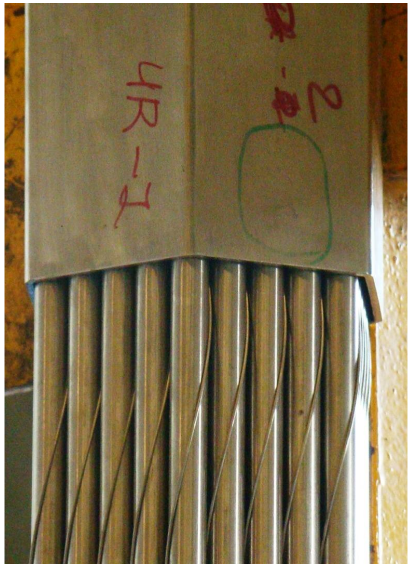
Hard Facing in Progress

Close up view of deposit and PTA torch

A 1 m diameter hard face track was deposited and tested at IGCAR under cyclic thermal loads simulating the reactor conditions to check and ensure the soundness of the hard face deposition. No cracks were noticed after the test.

Core Subassemblies

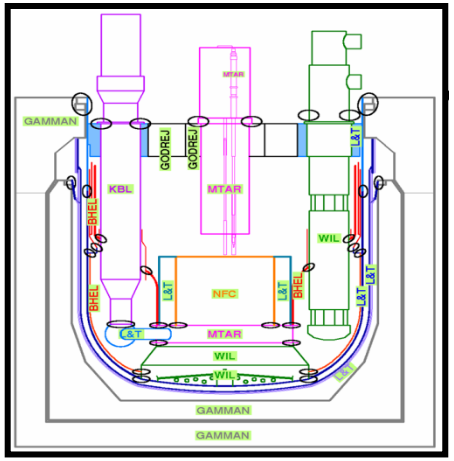




- Shielding assemblies (SS & B4C), Dummy fuel & blanket subassemblies delivered
- Precision machining and assembly requirements met

Achievements in Manufacturing of PFBR components

- Achieving high manufacturing tolerances for thin walled large diameter vessels better than those achieved internationally
- Precise machining tolerances for grid plate
- Indigenous development of hot facing technology with nickel base cobalt free material colomonoy
- Innovative methods of handling without practically no welded attachments on the vessel
- Consistency with the specified stringent erection tolerances

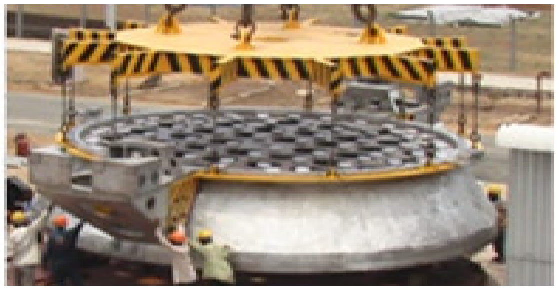


at

Grid plate with primary pipes

Inner vessel

Roof slab

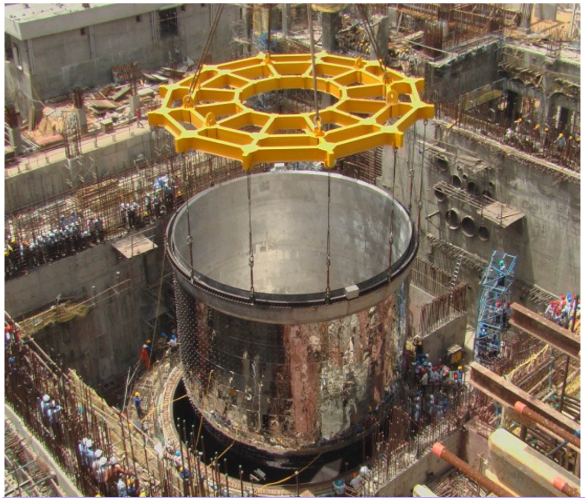


Core support structure

Primary sodium pump

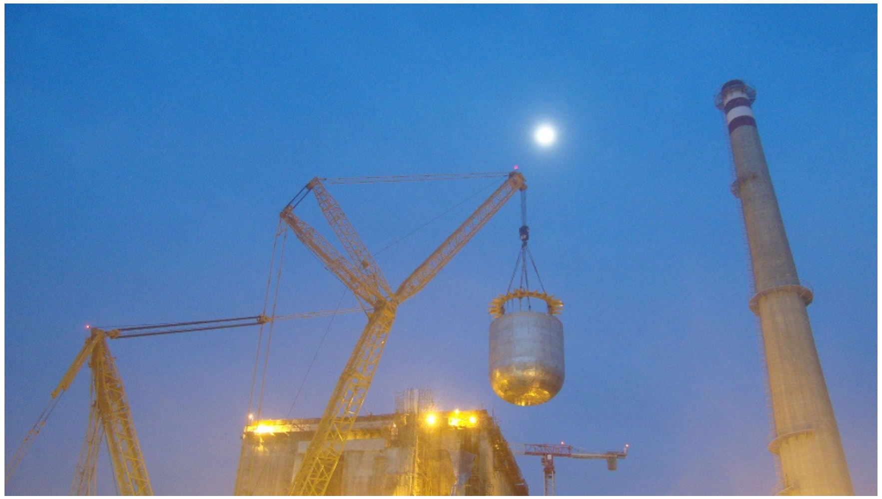
Steam generator

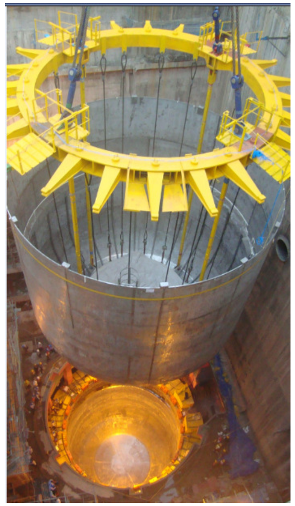
Successful Erection of Thin Shells



- Stringent erection tolerances
- Handling of thin shells without any permanent deformations
- No special welded joints for handling
- Challenging time schedule

Erection of safety vessel on reactor vault in June'08



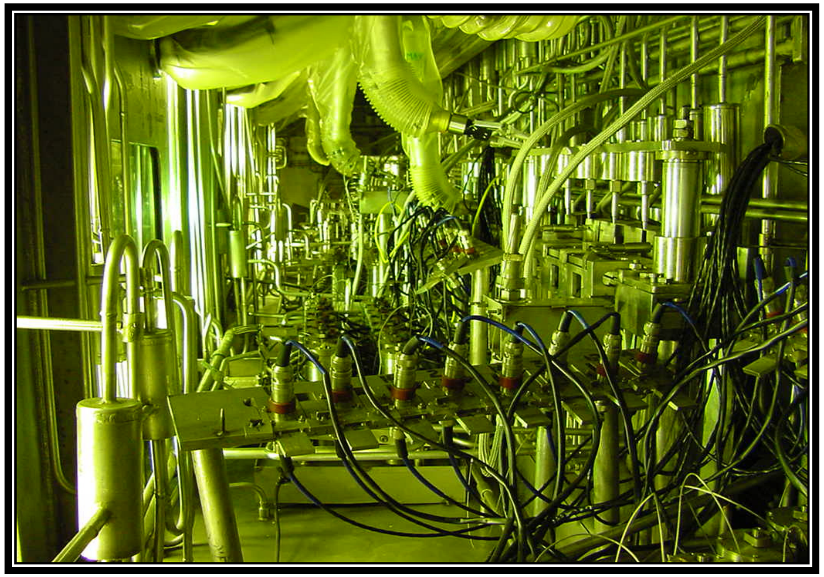


Erection of main on reactor vault in Dec '09

Fuel Cycle for SFR

- **Closed fuel cycle of PFBR through constructing a Fast Reactor Fuel Cycle Facility (FRFCF) at Kalpakkam.**
- **Co-location of the facility**
- **Basic technology is available**
- **The layout of FRFCF has been planned in such a way that expansion of the facility is possible to meet the requirements of two more 500 MWe FBRs**

Fuel discharged from FBTR reprocessed in CORAL. Fuel with burn-up of 150 GWd/t has been successfully reprocessed



Next …….
Technology demonstration in DFR Plant
Commercial demonstration in PFBR fuel reprocessing plant

Strategy of Construction of Future FBRs

- **Enhanced safety and improved economics are twin objectives.**
- **Means to achieve economy quantified: Increased design life to 60 yrs., design load factor of 85%, construction time 5 yrs., reduction in special steel specific weight requirement by ~ 20%, enhanced burn-up in a phased manner (Target: *Unit Energy Cost comparable to that of fossil power plants*)**
- **Mechanisms to achieve enhanced safety are being assessed: Elaborate in-service inspection and repair provisions, increased reliability of shut down systems and decay heat removal system, in-vessel purification system, innovative post accident heat removal provisions.**
- **Science based technologies and breakthroughs at interfaces in science & science with engineering to be harnessed for sustainable technological solutions**
- **Extensive involvement of Industries from developmental stages**
- **Giving due considerations to the innovative features conceived in the FRs under international projects (GEN IV and INPRO)**

IGCAR
- Design
- R&D
- Safety Clearance
- Innovations

BHAVINI
- *Construction*
- *Commissioning*
- *Operation*

IGCAR & BHAVINI
- Planning for future FBRs
- Human Resources

Challenges, Approaches and Targets

Thank You