Advances in Nuclear Fuel Fabrication -An Indian Perspective

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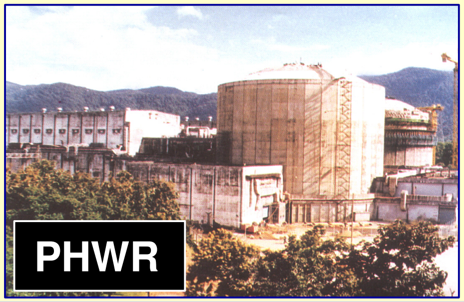
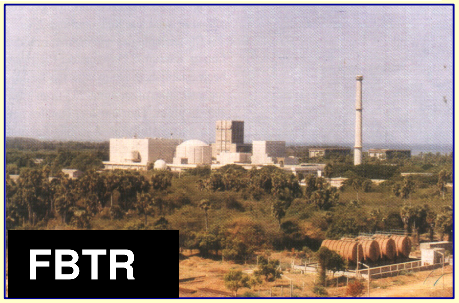
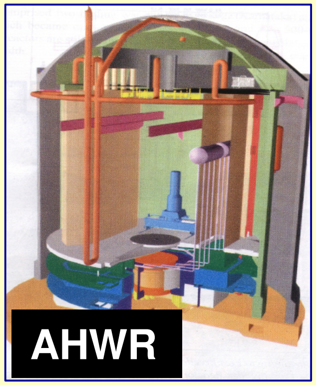
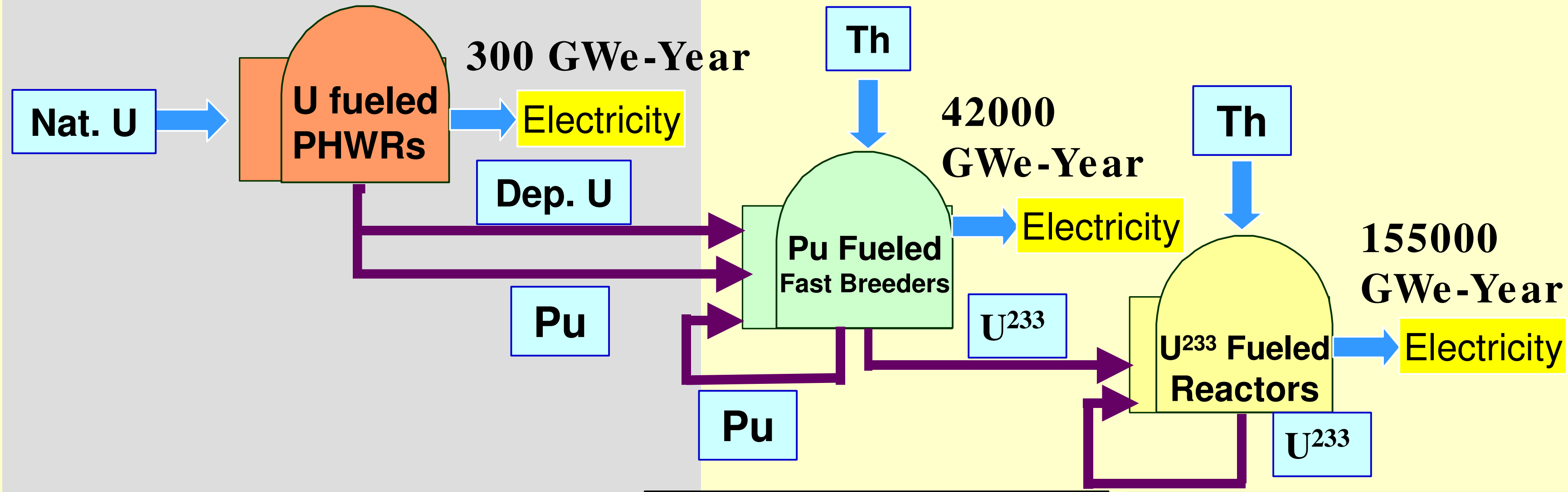
Indian Metal Industry – Shaping the Next Decade,12-13 February, 2011

Three stage Indian Nuclear Power Program









Stage 1	Stage 2	Stage 3
Power generation primarily by PHWR Building fissile inventory for stage 2	Expanding power programme Building U^{233} inventory	Thorium utilisation for Sustainable power programme

Status of Indian Nuclear Power Program

Stage - I
PHWRs

- 18- Operating
- 4 - Under construction
- Several others planned
- POTENTIAL ≅ 10 GWe

LWRs

- 2 BWRs- Operating
- 2 VVERs- Under construction

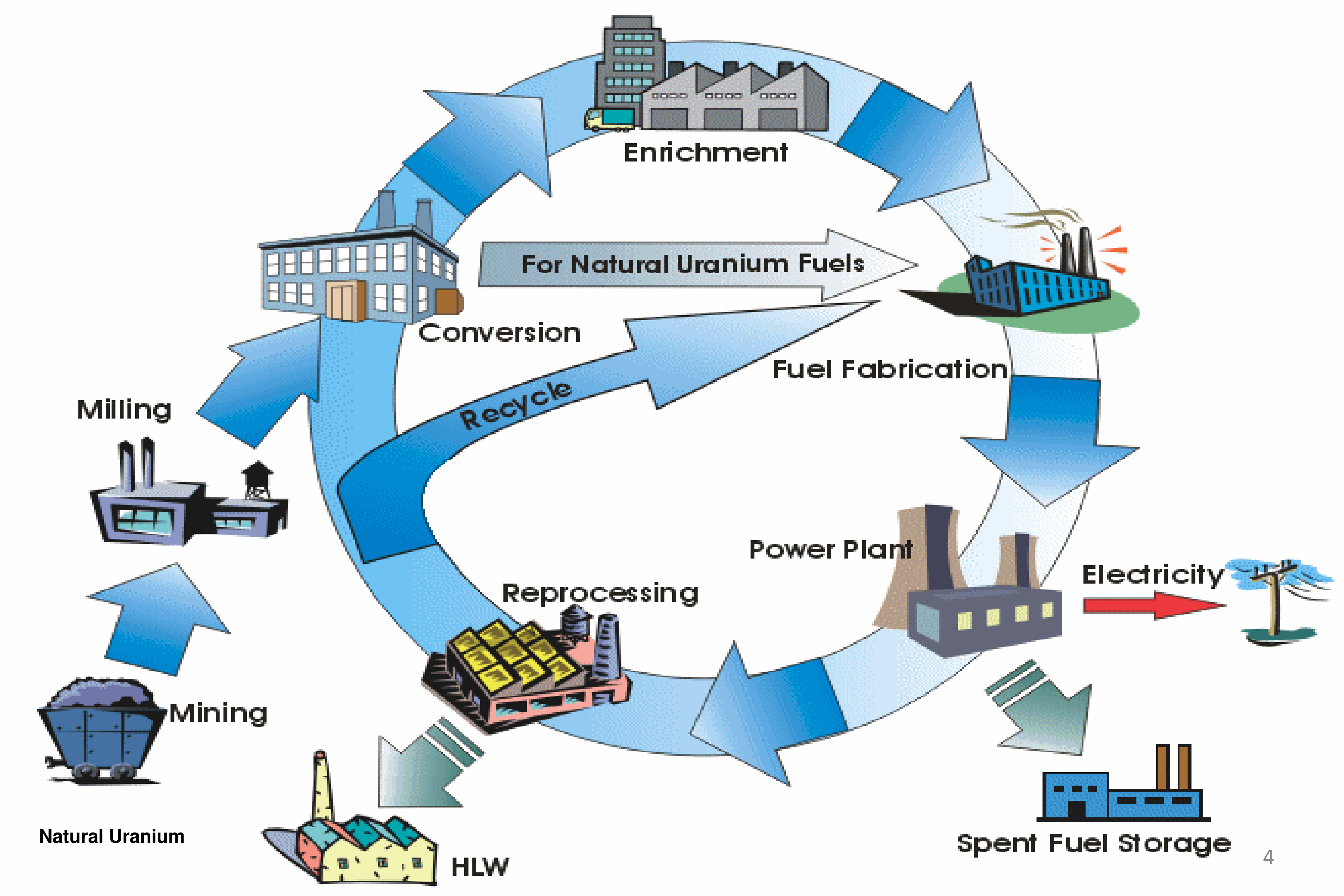
Stage – II
FBRs

- 40 MWth FBTR- Oper.
- 500 MWe PFBR- Under construction
- POTENTIAL ≅ 350 GWe

Stage - III
Thorium Based Reactors

- 30 kWth KAMINI- Oper.
- 300 MWe AHWR- Under development
- CHTR – Under design.
- POWER POTENTIAL ≅ Very Large. Availability of ADS can enable early introduction of Thorium on a large scale.

Nuclear Fuel Cycle



PHWR Evolution

2000s
EXPANSION,
COMMERCIALISATION &
ECONOMY OF SCALES

700 MWe & above

FUTURE PROJECTS

540 MWe

TAPS-3&4

220 MWe

2000s
COMMERCIALISATION

RAPP-3&4

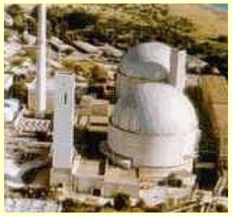
KAIGA-3&4

1990s
CONSOLIDATION

1980s
STANDARDISATION

1980s
INDIGENISATION

1970s
TECHNOLOGY DEMONSTRATION



RAPS-1&2

MAPS-1&2

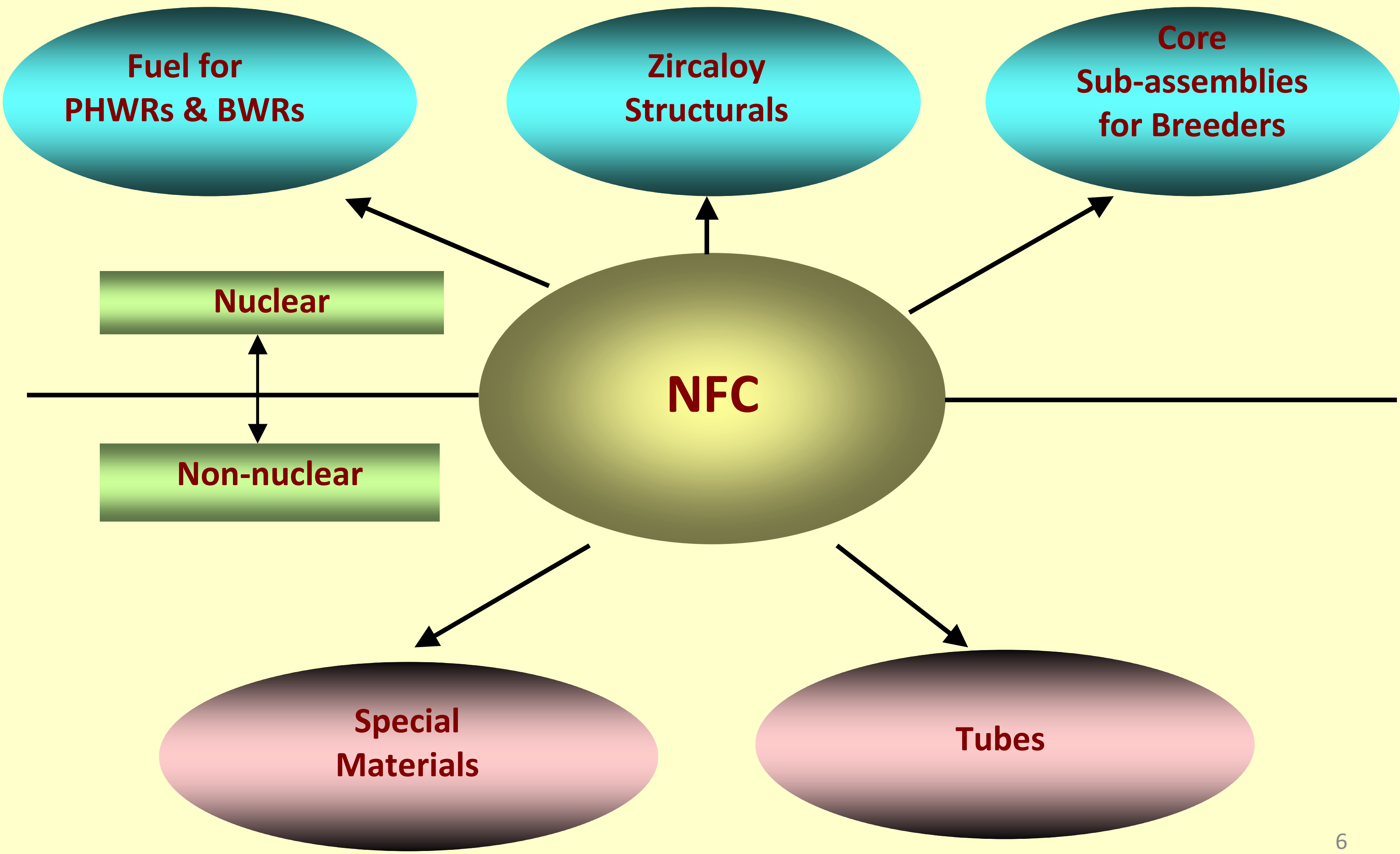
NAPS-1&2

KAPS-1&2

KGS-1&2

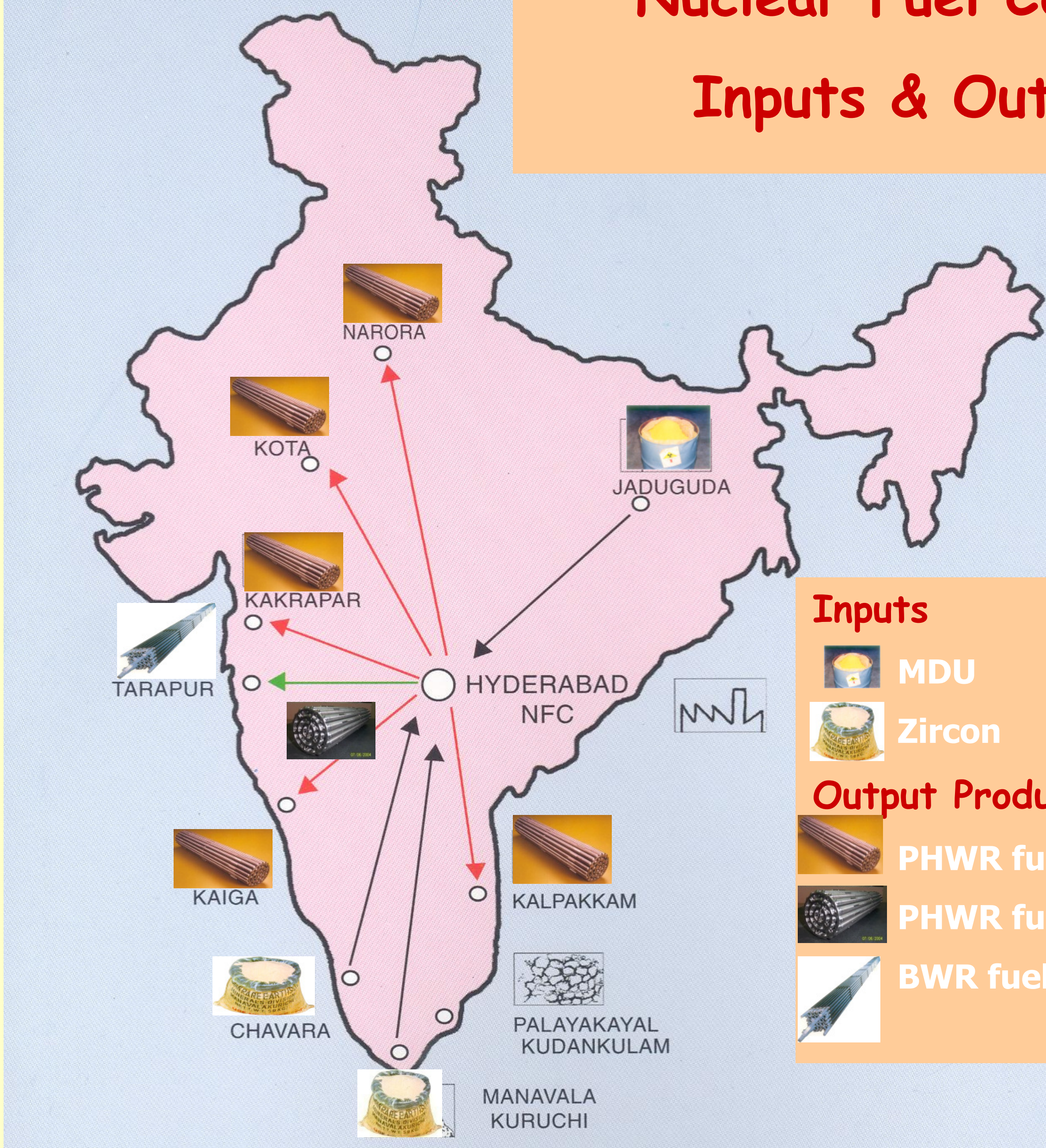
RAPP-5&6

NFC Activities



Nuclear Fuel Complex

Inputs & Outputs



Inputs

MDU

Zircon

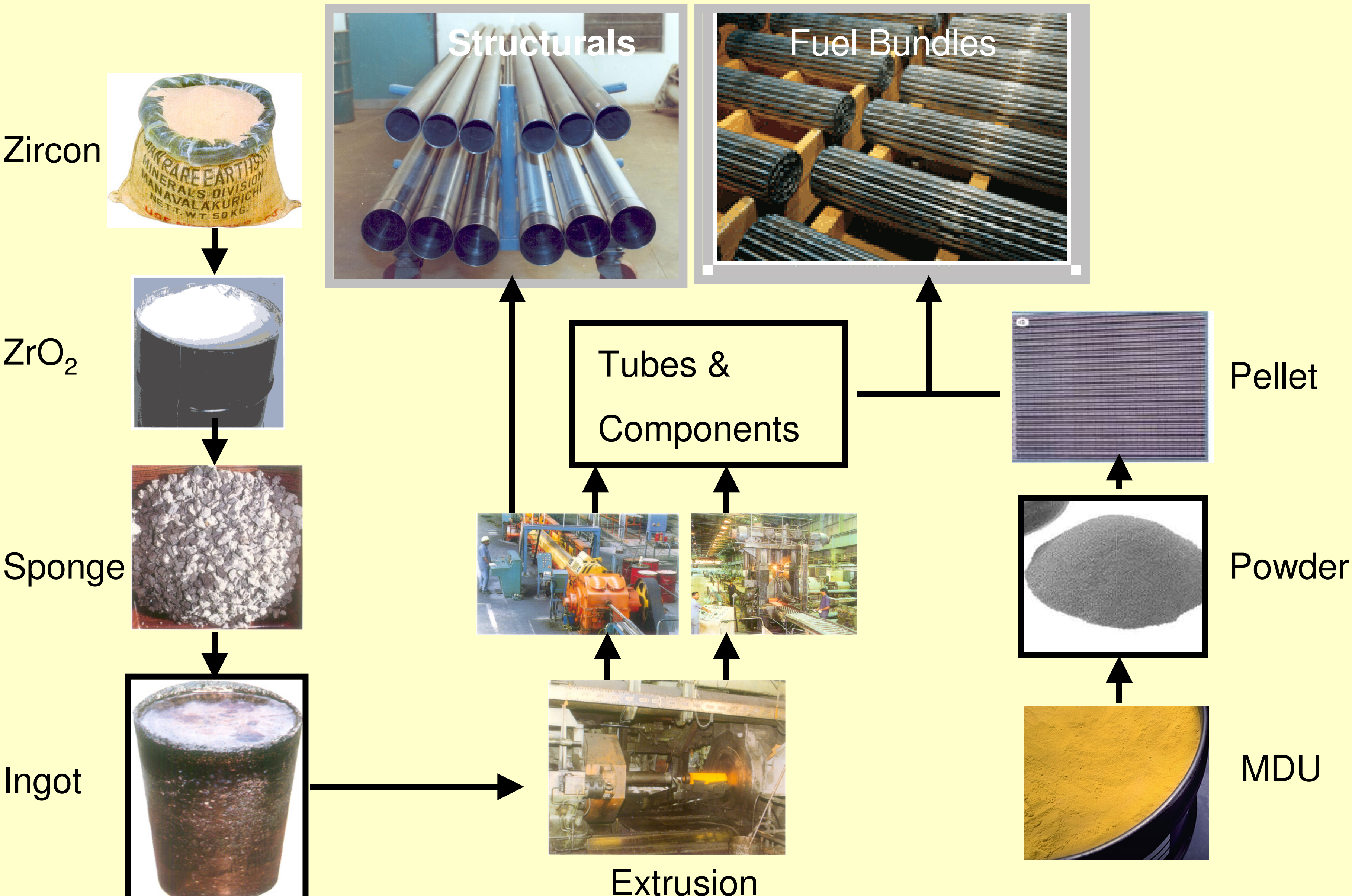
Output Products

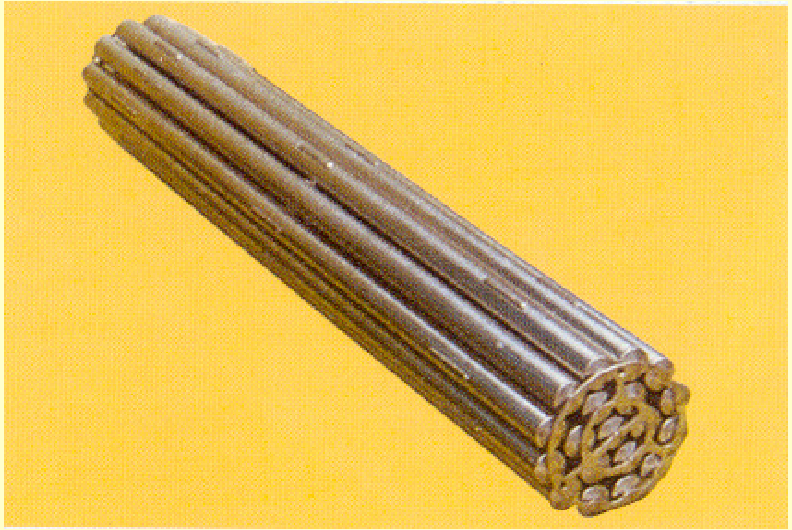
PHWR fuel bundles-220 MWe

PHWR fuel bundles-540 MWe

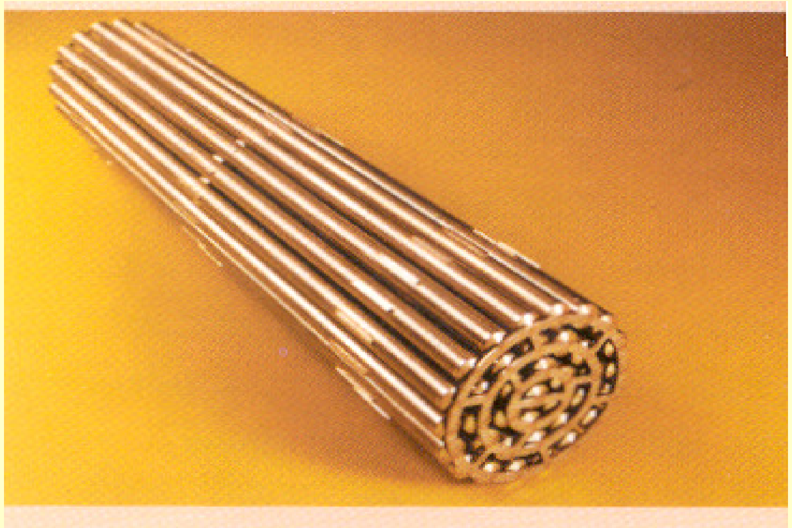
BWR fuel assemblies

Process Flow Sheet - PHWR





19 Ele. PHWR Fuel Assembly



37 Ele. PHWR Fuel Assembly

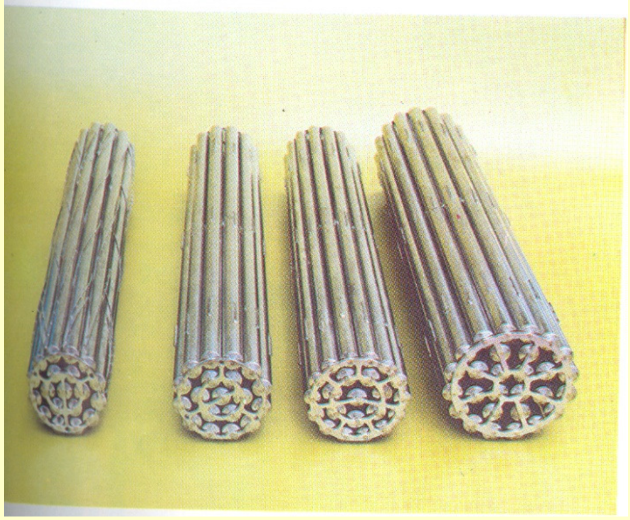
- Standardized for 220 MWe PHWR's.
- Fully Resistance Welded.
- 328 welds per Assembly.
- Generates 7 Lakh Electrical units per Assembly.
- Contain 15.2 Kg of UO_2 Material.

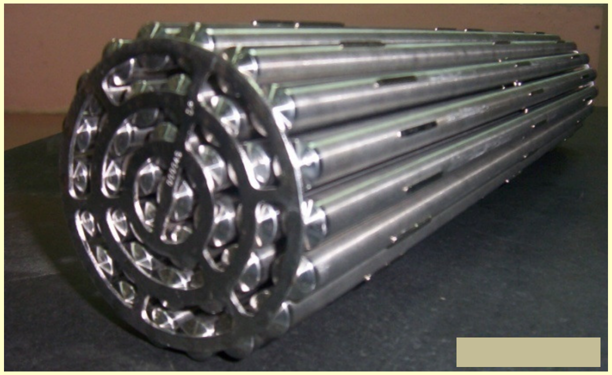
- Standardized for 540/700 MWe PHWR's.
- Fully Resistance Welded.
- 622 welds per Assembly.
- Produces 11 Lakh Electrical units per Assembly.
- Contain 21.5 kg of UO_2 Material

Fuel Assemblies with RU, ThO2, MOX were fabricated and irradiated

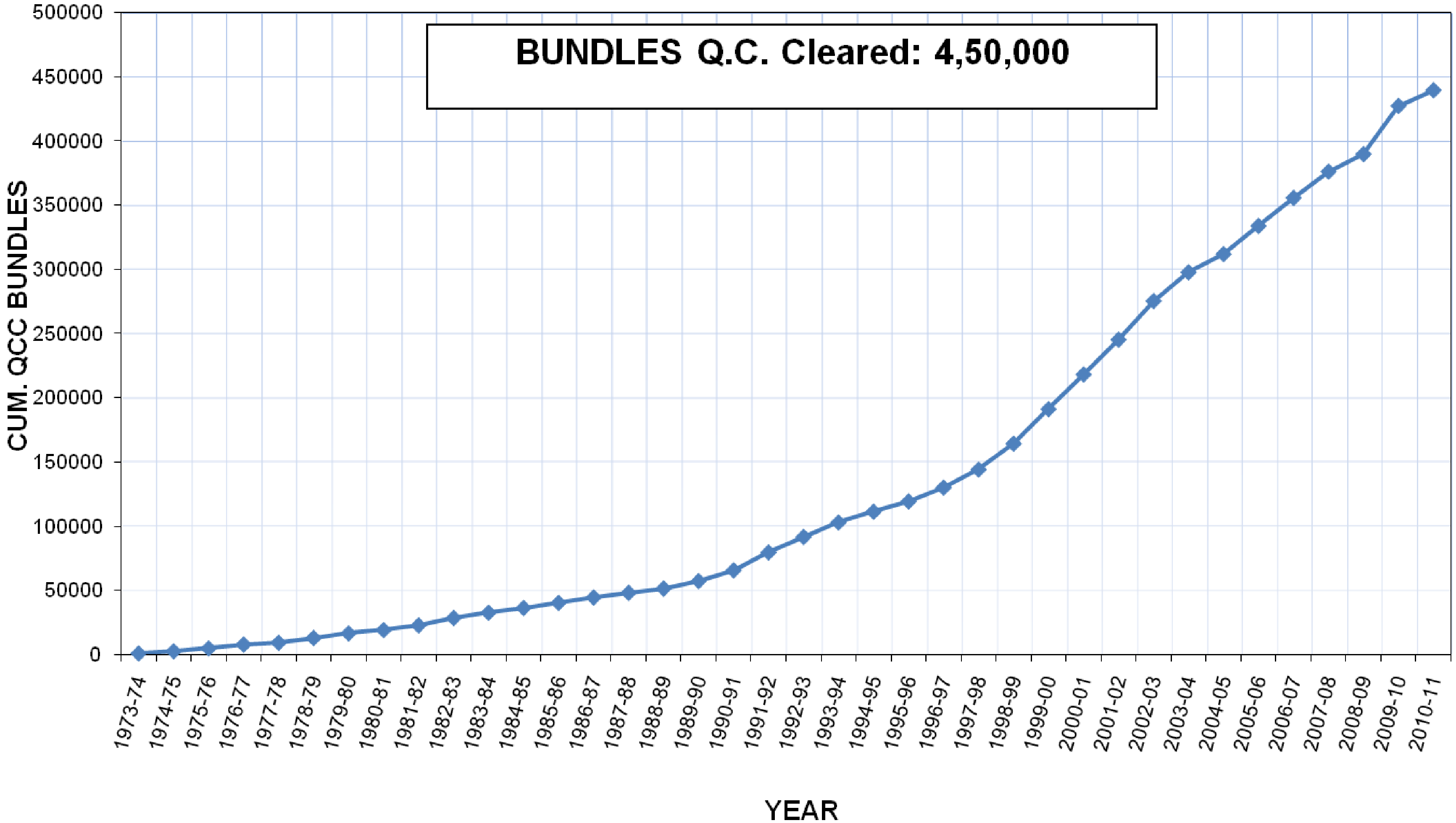
Types of PHWR Bundles Manufactured at NFC

- **19-element wire-wrap Bundle**
- **19-element split spacer Bundle**
- **22-element split spacer Bundle**
- **37-element split spacer Bundle**
- **19-element Thoria Bundles**
- **19-element RU Bundles**
- **37-element RU Bundles**
- **19-element SEU Bundles**





Cumulative Production of PHWR Fuel Bundles at NFC



Reactors in operation and under Construction in India

Unit-Location	Reactor Type	Present Capacity (MWe)	Date of commencing Commercial Operation
TAPS-1, Tarapur, Maharashtra	BWR	160	October 28, 1969
TAPS-2, Tarapur, Maharashtra	BWR	160	October 28, 1969
RAPS-1, Rawabhata, Rajasthan	PHWR	100	December 16, 1973
RAPS-2, Rawabhata, Rajasthan	PHWR	200	April 1, 1981
RAPS-3, Rawabhata, Rajasthan	PHWR	220	June 1, 2000
RAPS-4, Rawabhata, Rajasthan	PHWR	220	December 23, 2000
RAPS-5, Rawabhata, Rajasthan	PHWR	220	February 4, 2010
RAPS-6, Rawabhata, Rajasthan	PHWR	220	March 31, 2010
MAPS-1, Kalpakkam, Tamilnadu	PHWR	220	January 27, 1984
MAPS-2, Kalpakkam, Tamilnadu	PHWR	220	March 21, 1986
NAPS-1, Narora, Uttar Pradesh	PHWR	220	January 1, 1991
NAPS-2, Narora, Uttar Pradesh	PHWR	220	July 1, 1992
KAPS-1, Kakrapar, Gujarat	PHWR	220	May 6, 1993
KAPS-2, Kakrapar, Gujarat	PHWR	220	September 1, 1995
KAIGA-1, Kaiga, Karnataka	PHWR	220	November 16, 2000
KAIGA-2, Kaiga, Karnataka	PHWR	220	March 16, 2000
KAIGA-3, Kaiga, Karnataka	PHWR	220	April 16, 2007
KAIGA-4, Kaiga, Karnataka	PHWR	220	January 19, 2011
TAPS-3, Tarapur, Maharashtra	PHWR	540	August 18, 2006
TAPS-4, Tarapur, Maharashtra	PHWR	540	September 12, 2005

Reactors under Construction

Kudankulam Nuclear Power Project, Units 1&2	LWR (VVER)	2x1000
PFBR, Kalpakkam	FBR	500

Nuclear Power Generation – Future Programmes

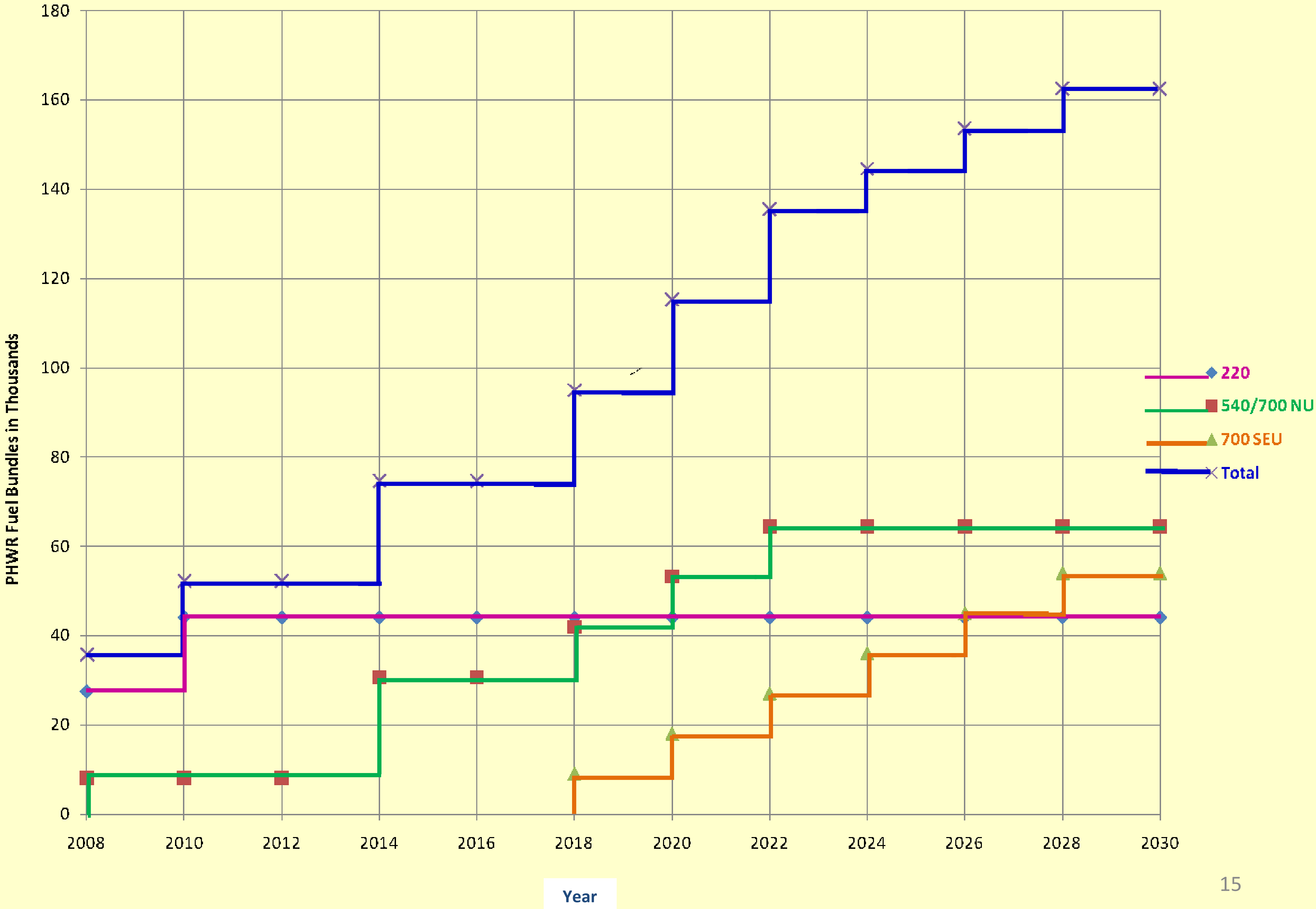
To be fuelled through indigenous sources

- 10 PHWRs of 700 MWe
- 4 FBRs of 500 MWe
- 1 AHWR of 300 MWe

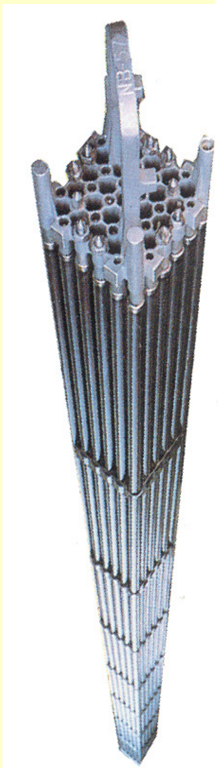
To be fuelled through imports

- LWRs, 40,000 MWe equivalent
- 10 PHWRs of 700 MWe

PHWR Fuel Fabrication Activities in India – Envisaged



BWR Fuel Assembly for Tarapur Atomic Power Stations-1&2



- **ZIRCALOY AND OTHER COMPONENTS**

FUEL TUBES	14.27 OD; 0.88 Wt; 3879 L	35 Nos.
	14.27 OD; 0.88 Wt; 469 L	8 Nos.
SPACER ASSEMBLY		7 Nos.
INCONEL AND SS COMPONENTS		114 Nos.
NUMBER OF WELDS		622 Nos.

- **ENRICHED URANIUM OXIDE**

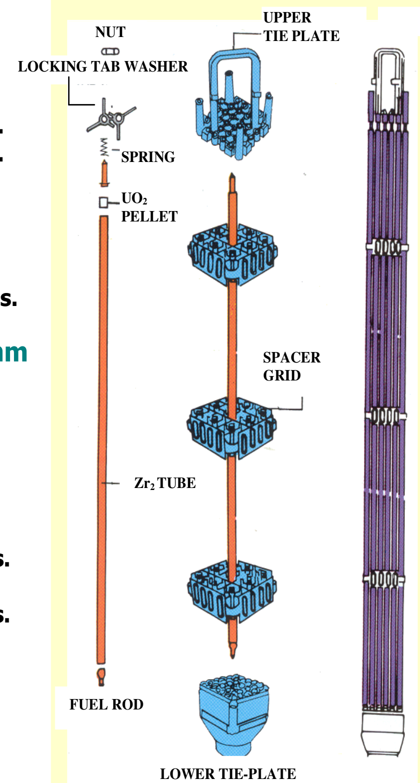
NO OF ENRICHMENTS	3
PELLETS - 12.27 ϕ	9165 Nos.

- **LENGTH OF FUEL ASSEMBLY** 4245 mm
- **WEIGHT OF FUEL PELLETS** 160 Kg

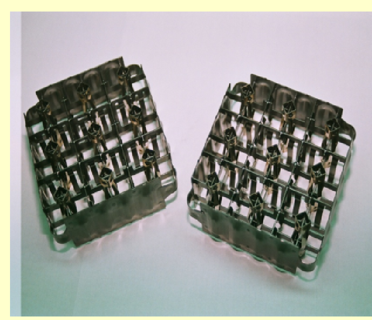
➢ **ONE BWR CORE CONTAINS**

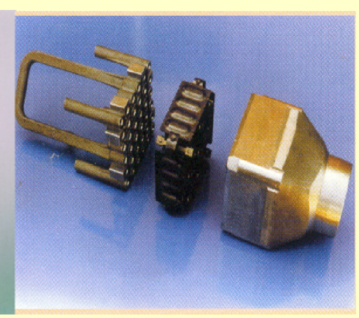
* FUEL ASSEMBLIES	284 Nos.
- CONTAINED ENRICHED URANIUM OXIDE	45 Te
* REPLACEMENT FOR EACH OUTAGE	100 Nos.
- CONTAINED ENRICHED URANIUM OXIDE	16 Te

DIMENSIONS IN “mm”



- Improvements:
  - Fully annealed thick wall fuel sheath.
  - Short and Chamfered Pellets
  - Pre-Pressurization of Fuel Element



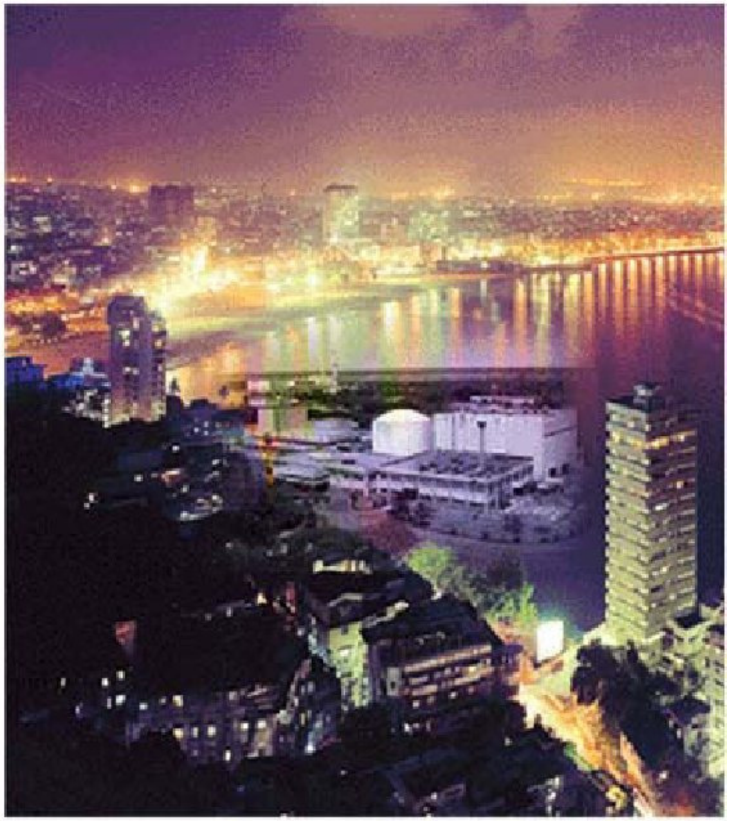


Fast Reactors – Powering the Future

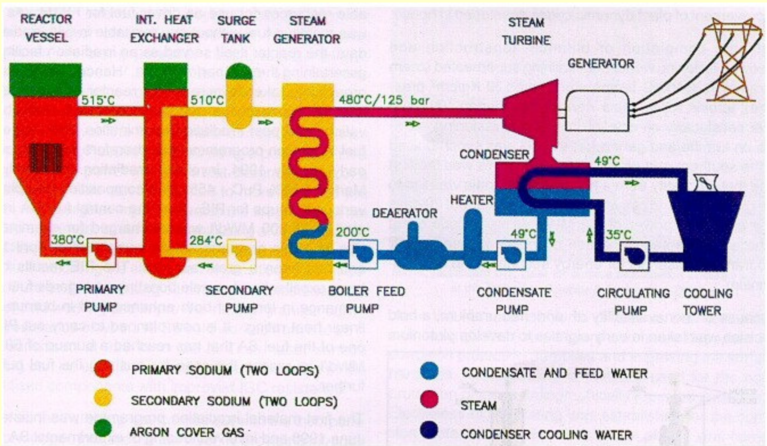
Fast Breeder Test Reactor at Kalpakkam (40MW(th)) is the test bed for development of fuel, blanket and structural materials for FBRs

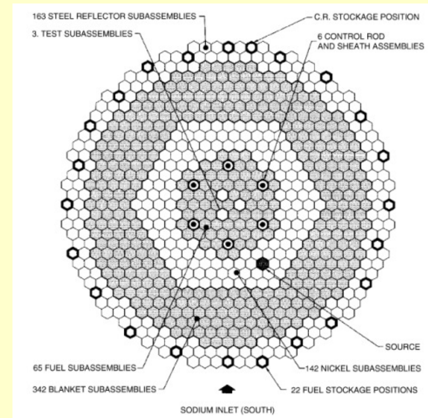
FBTR achieved criticality in 1985 with unique Pu rich mixed carbide fuel developed by BARC.

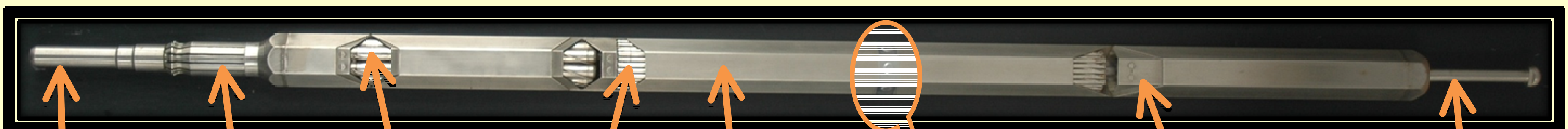
The peak burn-up achieved on MK I is 165 GWD/T.



FBTR Core cross section & Material







Foot Assembly SS 316L

Gripper Spring Nimonic 80A

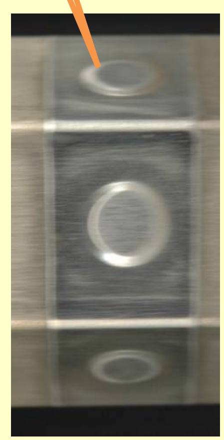
Axial Blanket Clad SS 316L

Fuel Clad SS 316M

OHT SS 316L

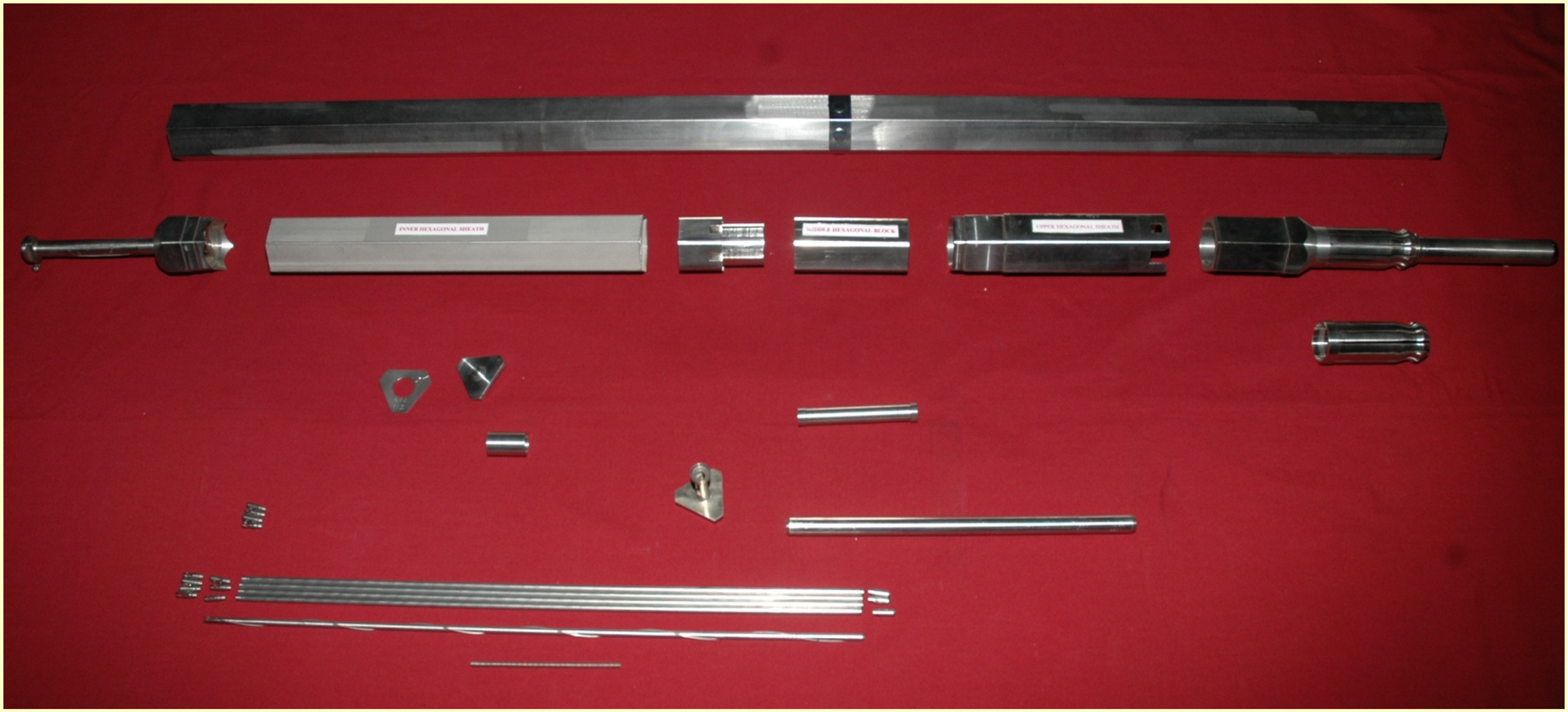
IHT SS 316L

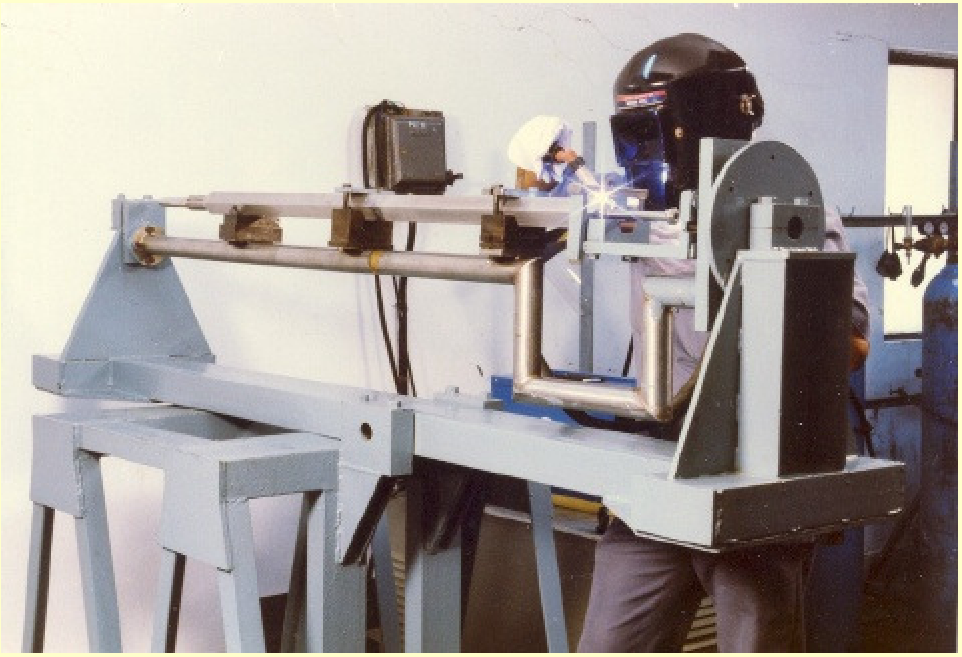
Handling Head SS 316L



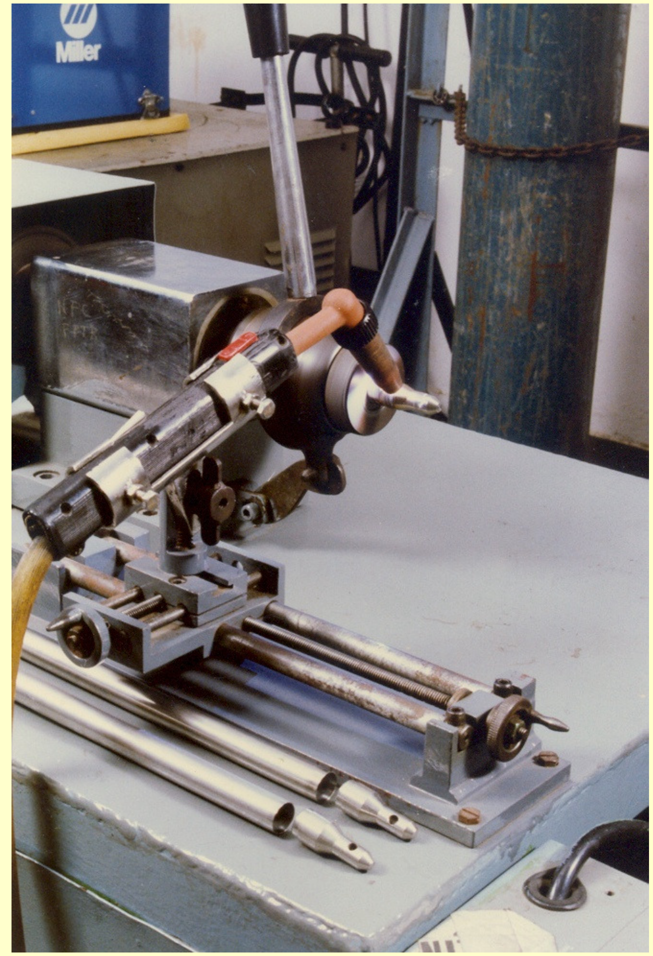
Hard Chrome Plating on OHT Buttons

Components for FBTR Subassemblies

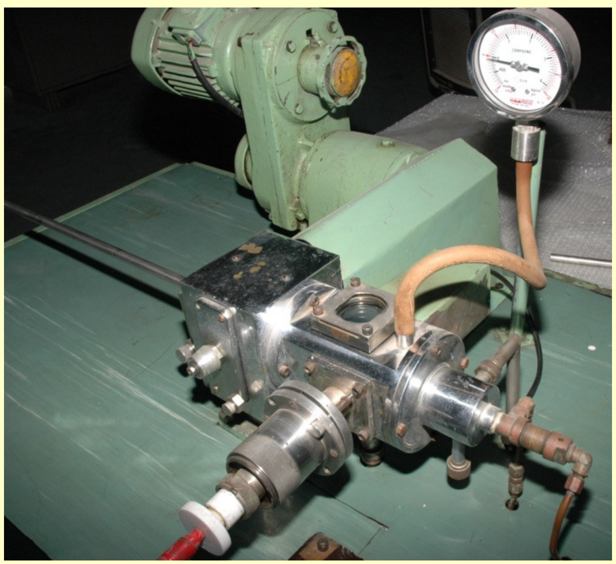




OHT to Foot & Head Portion Welding (GTAW)



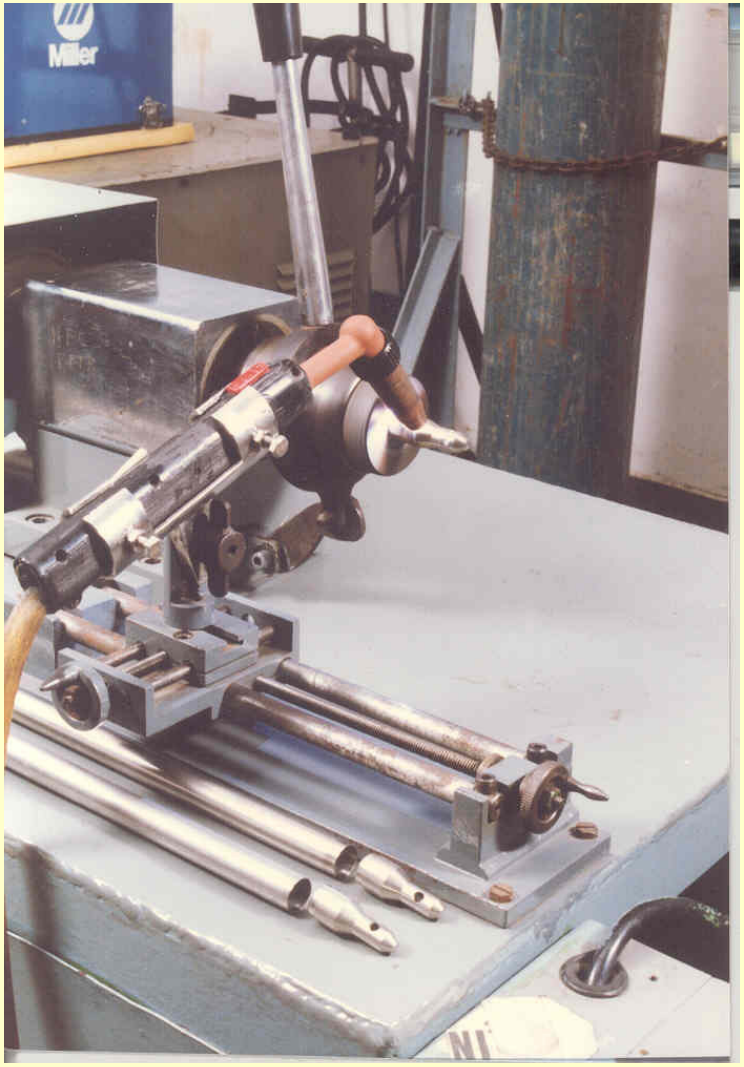
Bottom Plug Welding (GTAW)



Top Plug Welding (GTAW)

Welding Techniques Used for FBTR Subassembly Fabrication

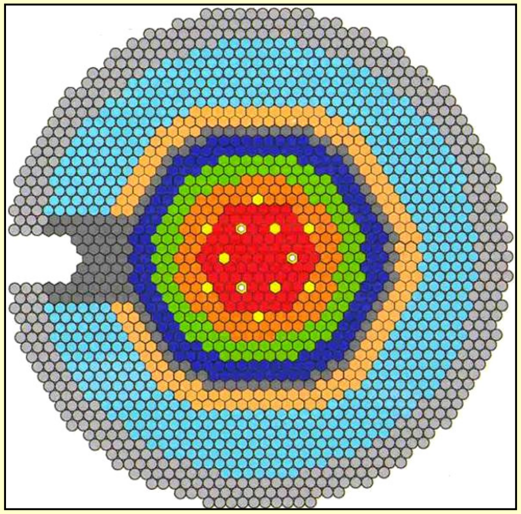
Fabrication of Core Sub-Assemblies for Fast Breeder Test Reactor (FBTR)

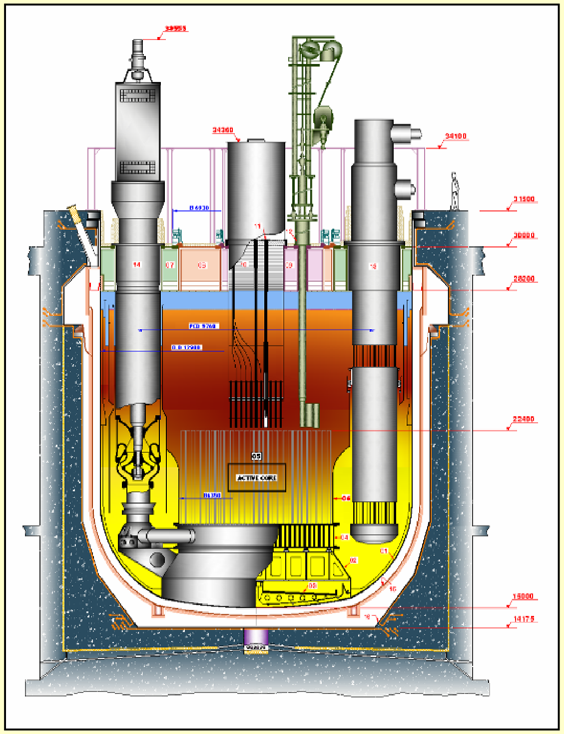


End Plug Welding Machine for Radial Blanket Pin

Wire-Wrap Machine for Radial Blanket Pin

PFBR Core Cross-Section

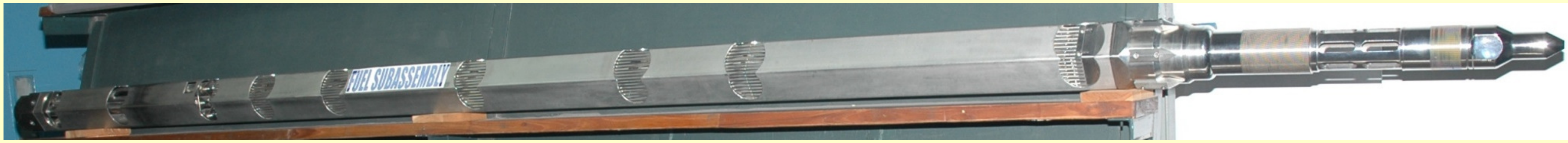




Symbol	TYPE OF SUBASSEMBLY	Nos.
	FUEL (INNER)	85
	FUEL (OUTER)	96
	CONTROL & SAFETY ROD	9
	DIVERSE SAFETY ROD	3
	BLANKET	120
	STEEL REFLECTOR	138
	B4C SHIELDING (INNER)	125
	STORAGE LOCATION	156
	STEEL SHIELDING	609
	B4C SHIELDING (OUTER)	417
	TOTAL SUBASSEMBLIES	1758

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

Materials for PFBR Subassemblies



Fuel Clad Tube - D9

Hexcan- D9

Components- SS 316LN

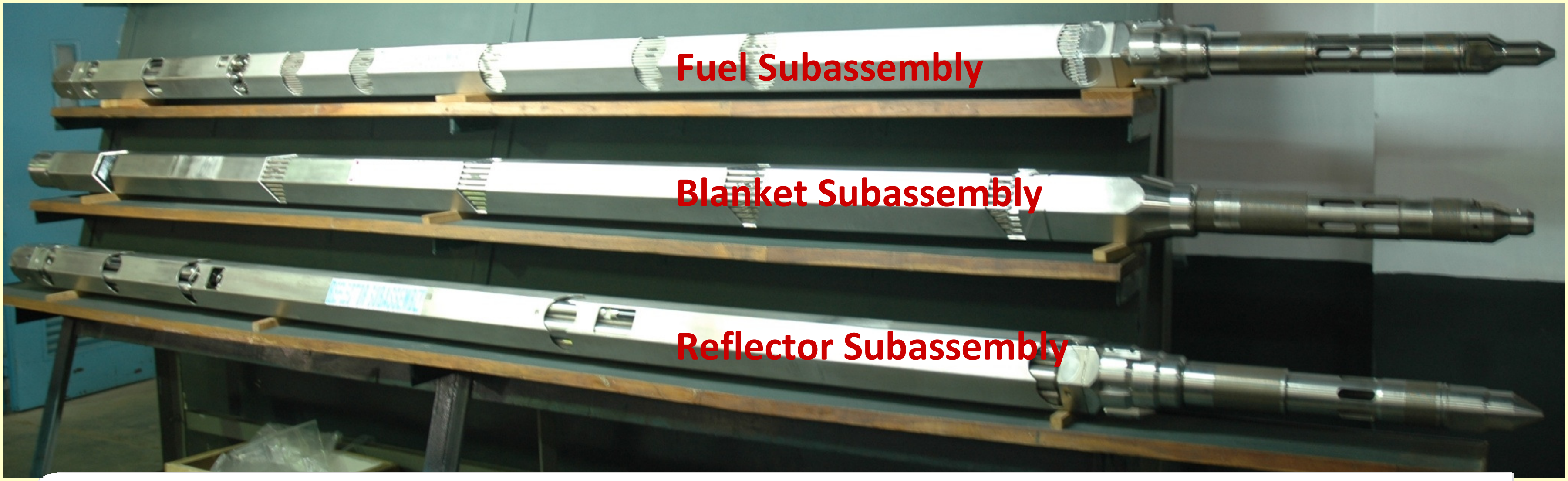
Natural B_4C Pellets

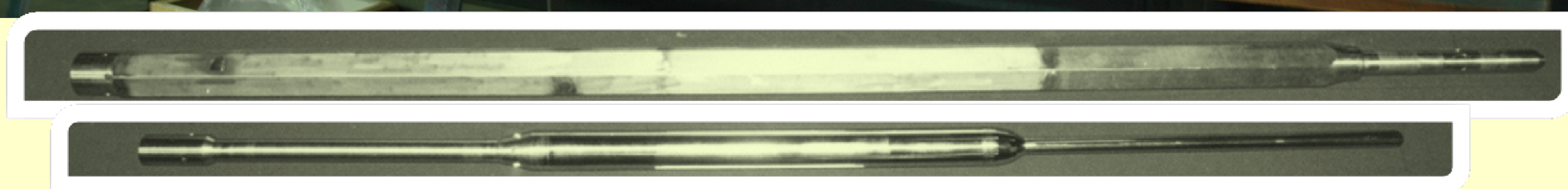
Top Axial Shielding Clad Tube – SS 316LN

Material & Compositions

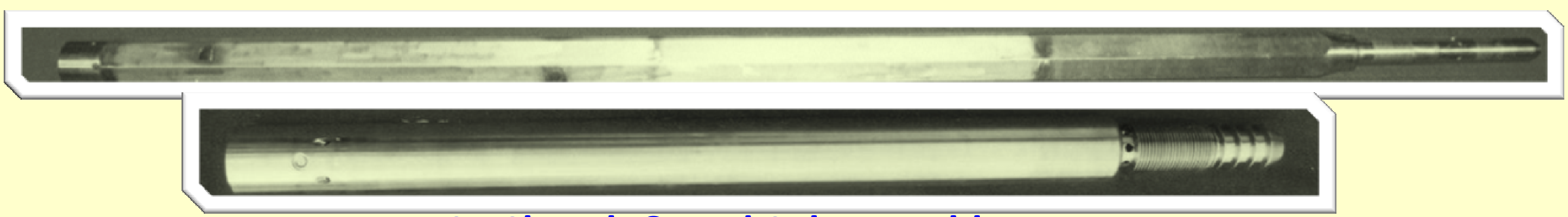
- **D9 for Clad Tubes:** Cr: 13.5-14.5, Ni: 14.5-15.5, Mo: 2, Ti: 5C-7.5C, N: 50 ppm, Inclusion Rating: 1
- **D9 for Hexcan Tubes:** Cr: 13.5-14.5, Ni: 14.5-15.5, Mo: 2, Ti: 5C-7.5C, N: 100 ppm, Inclusion Rating: 4
- **D9 for Spacer Wire:** Cr: 13.5-14.5, Ni: 14.5-15.5, Mo: 2, Ti: 5C-7.5C, N: 50 ppm, Inclusion Rating: 1
- **316LN for Bulk Components:** C: 0.02-0.03, N: 0.06-0.08
- **Spring Wire:** ASTM A-286

PFBR Subassemblies Fabricated





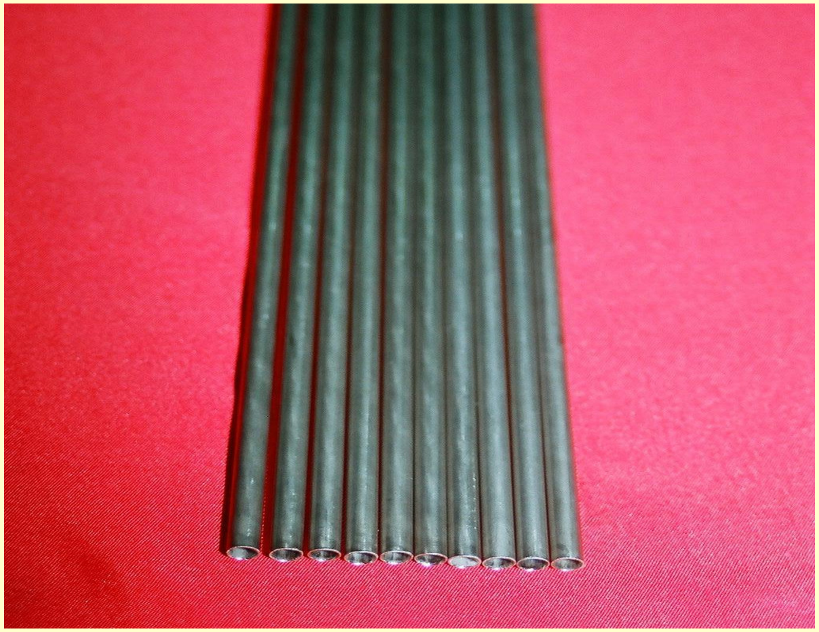
CSR Sheath & Rod Subassembly

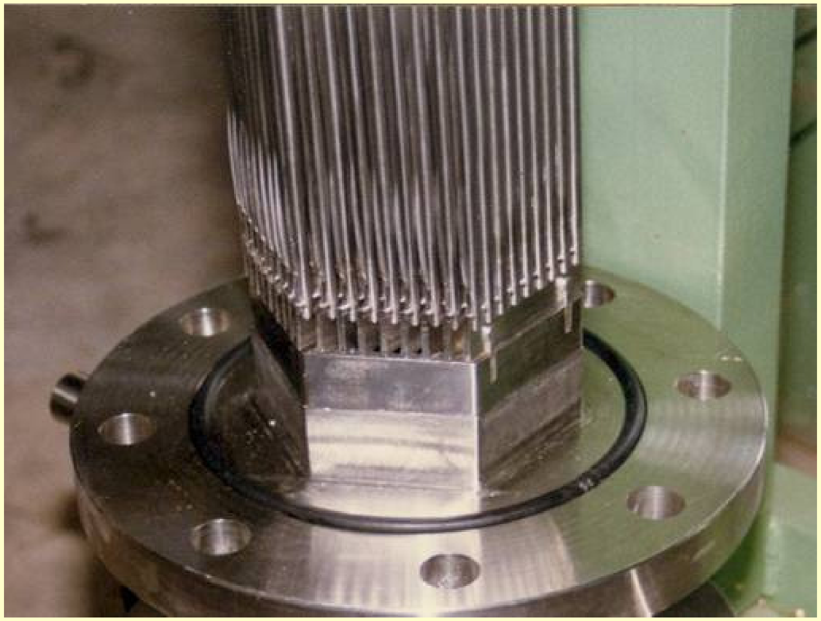


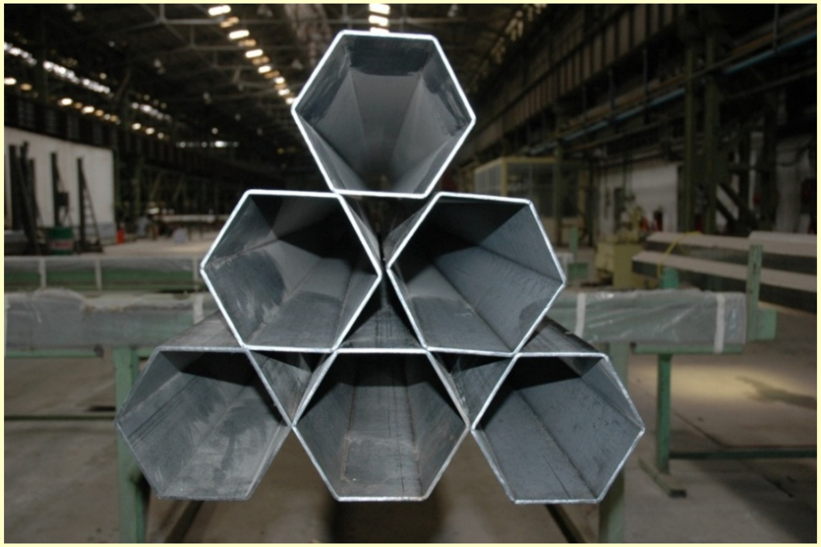
DSR Sheath & Rod Subassembly

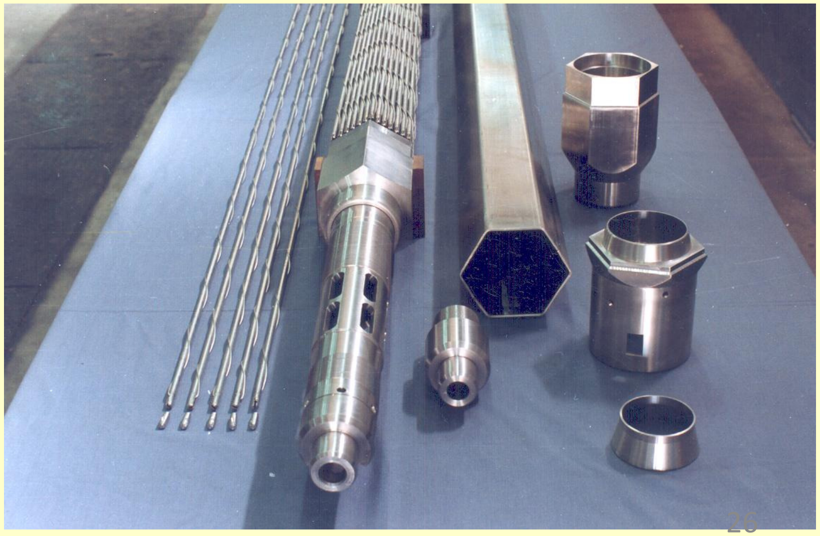
Inner Boron Carbide Subassembly

Manufacture of Core Sub-Assemblies for FBRs



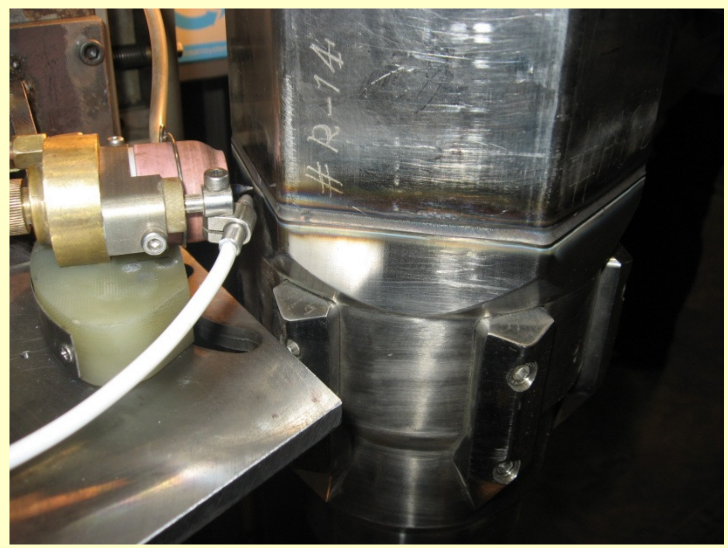






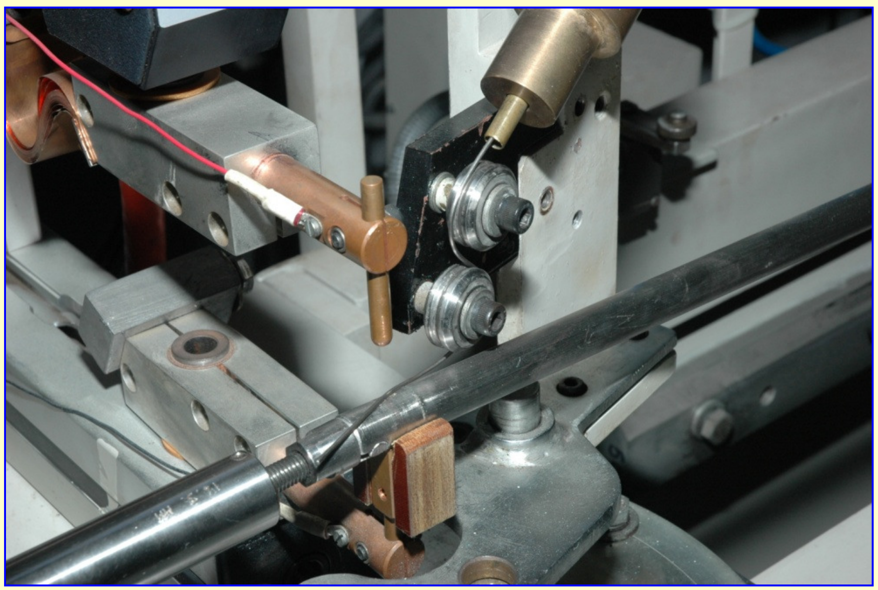
Automatic Hexcan Welding Machine

- Both conventional and orbital techniques with GTAW cum Plasma were applied successfully for hexcan peripheral welding with filler addition.
- Automatic torch inclination with Torch oscillation axis provided for keeping it perpendicular to welding face in synchronization with tube rotation.
- Software based automatic control with feedback system for all critical parameters with recording facilities.
- Arc Distance Control

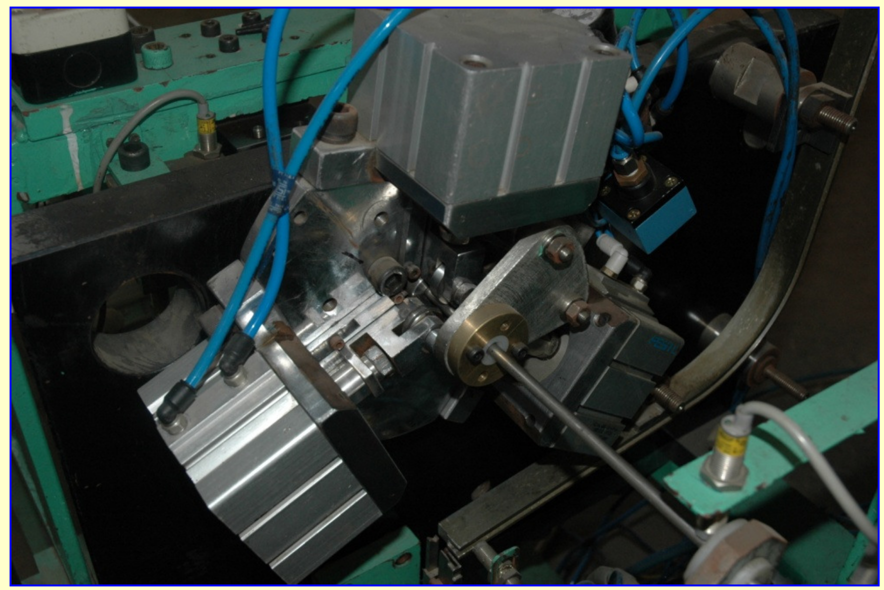


Bottom Plug Welding Machine

Top Plug Welding Machine



Wire Wrapping & Spot Welding Machine



Crimping Machine

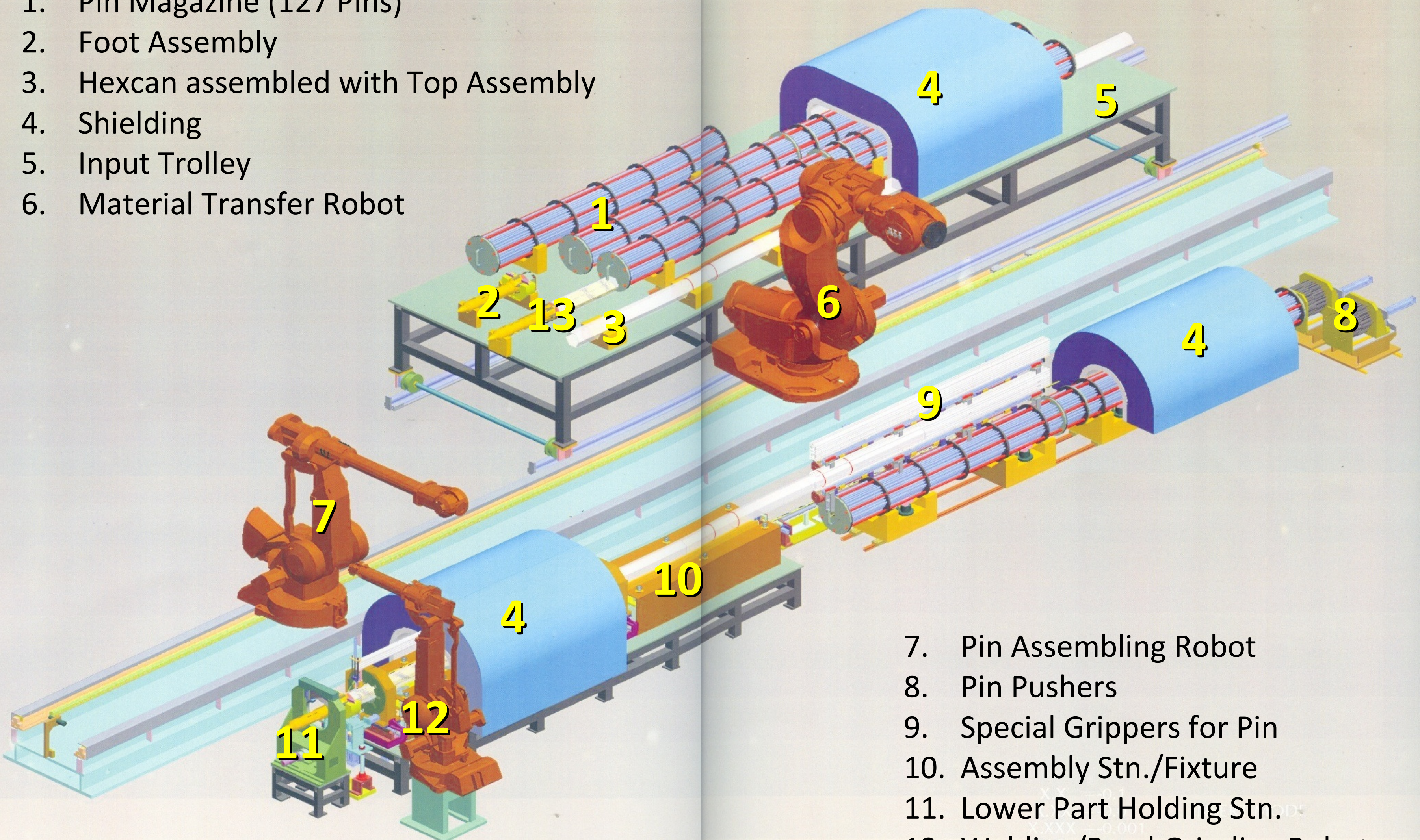
New Fabrication Line of AFFF

WELDING OF FUEL PIN

PFBR FUEL PELLETS

Automatic Pin Assembling Machine

1. Pin Magazine (127 Pins)
2. Foot Assembly
3. Hexcan assembled with Top Assembly
4. Shielding
5. Input Trolley
6. Material Transfer Robot



7. Pin Assembling Robot
8. Pin Pushers
9. Special Grippers for Pin
10. Assembly Stn./Fixture
11. Lower Part Holding Stn.
12. Welding/Bead Grinding Robot
13. Finished Subasembly

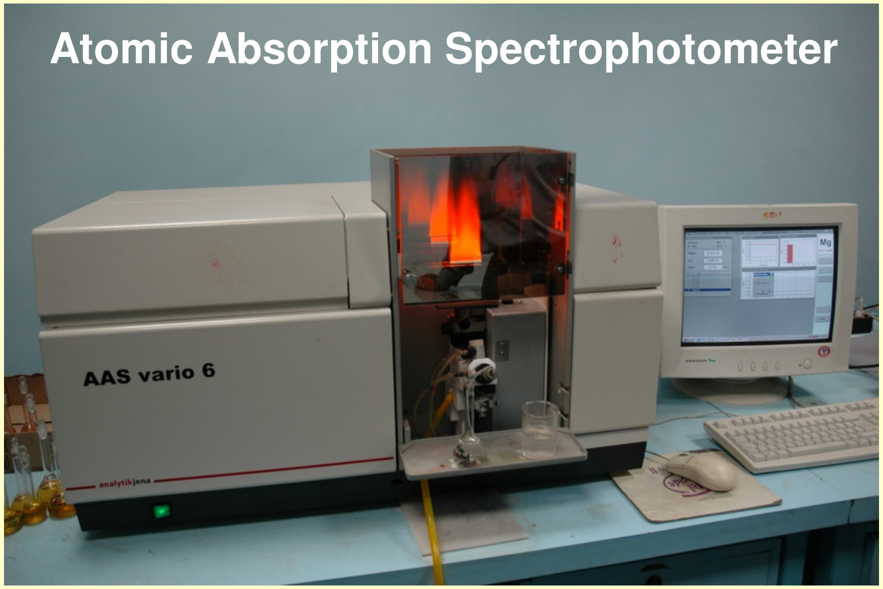
Specifications of Zr-based Materials

Element	*ZrO_2*	*Zr-sponge*	*Zr-2*	*Zr-4*
Al	50	75	75	75
B	0.1	0.5	0.5	0.5
C	-	250	270	270
Ca	50	30	30	30
Cd	0.3	0.5	0.5	0.5
Cl	-	1300	20	20
Co	15	20	20	20
Cr	100	200	500-1500	700-1300
Cu	50	50	50	50
Fe	150	1500	700-2000	1800-2400
H	-	25	25	25
Hf	100	100	200	200
Mg	50	600	20	20
Mn	50	50	50	50
Mo	50	50	50	50
N	-	65	65	65
Na	50	50	-	-
Nb	-	-	100	100
Ni	20	70	300-800	70
O	-	1400	1000-1400	1000-1400
P	-	100	-	-
Pb	20	100	130	130
Rare earths	15	15	-	-
Si	-	120	20	120
Sn	-	-	1.2%-1.7%	1.2%-1.7%
Ta	-	-	200	200
Ti	50	50	50	50
U	3.5	3.5	3.5	3.5
V	-	50	50	50
W	-	50	50	50
Zn	-	100	-	-
Fe+Cr+Ni	-	-	0.18%-038%	0.28%-0.37%

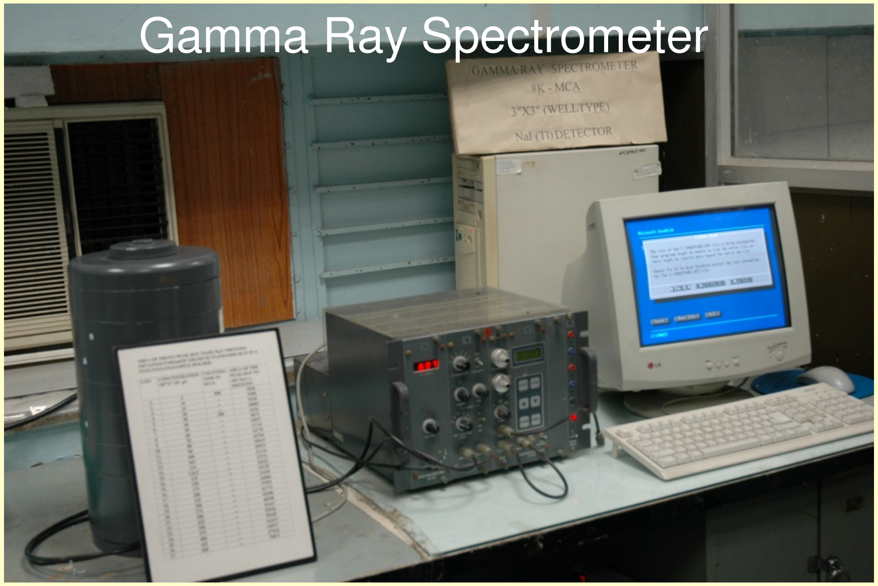
Specifications of Nat. U Powder and Pellets

Element	*NU-powder*	*Nu-pellet*
Ag	1	1
Al	25	50
B	0.3	0.3
C	200	200
Ca	50	50
Cd	0.2	0.2
Cr	15	25
Cu	10	20
Dy.	0.15	0.15
F	10	10
Fe	50	100
Gd	0.1	0.1
H	-	1
Mg	10	50
Mn	5	10
Mo	2	4
Ni	20	30
Si	30	60

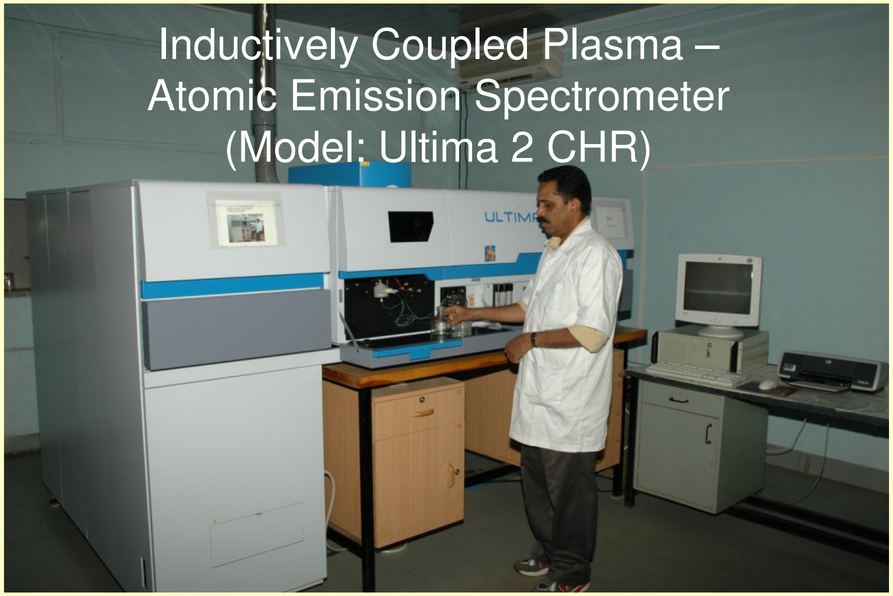
Quality Control at Analytical Laboratory

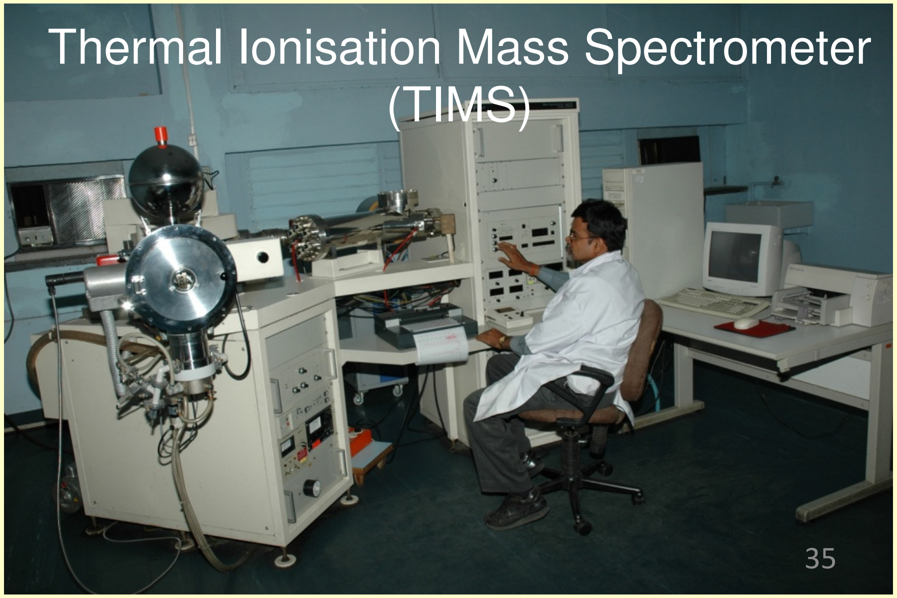


Atomic Absorption Spectrophotometer



Gamma Ray Spectrometer


Inductively Coupled Plasma – Atomic Emission Spectrometer (Model: Ultima 2 CHR)


Thermal Ionisation Mass Spectrometer (TIMS)

Ultrasonic Testing

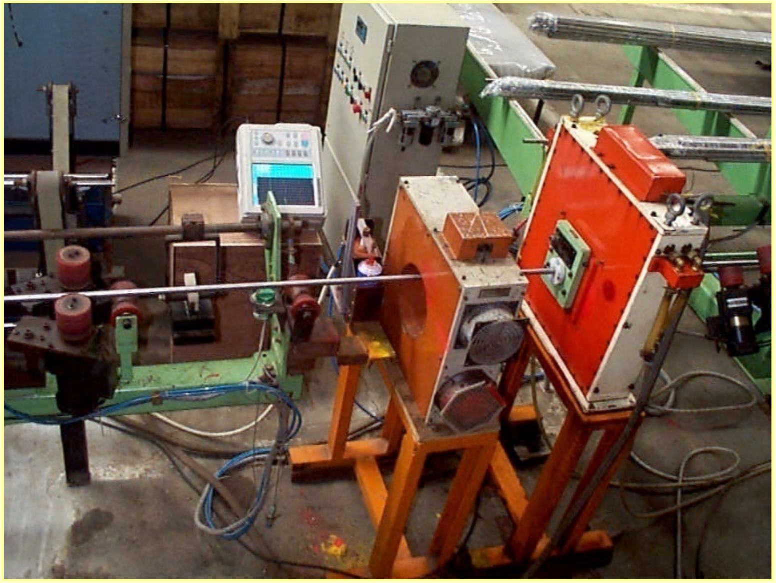
- **Technique:** **Immersion Longitudinal and Transverse**
- **Standard:** **ASME sec III Class I: 5% WT**
- **Wall thickness:** **100% surface coverage**
- **Handling system:** **Automated loading and unloading with** *extended tube transport* **with segregation of defective tubes**

Automated Ultrasonic Testing Unit

23 m long 9Cr-1Mo tubes under testing

Eddy Current Testing

- **Technique:** **Saturation Field Eddy Current Testing (magnetic materials) with OD encircling differential coil**
- **Demagnetization:** **using AC coil immediately after test (Residual Magnetism < 0.1 gauss)**
- **Tube handling:** **Automated loading and unloading with segregation of defectives for 23.1 m length**



Automated Eddy Current Testing Unit

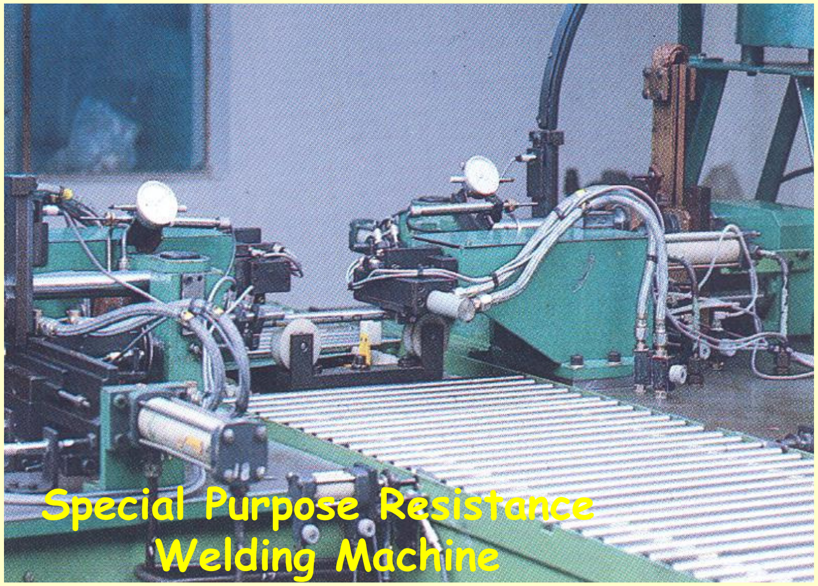
Indigenous Capability to Manufacture Process Equipment

"If an item of equipment is imported from abroad, all one gets is a particular instrument. But if one builds it oneself, an all important lesson in expertise is learnt as well."

Dr. Homi J. Bhabha


High Temperature Sintering Furnace


Calcination / Reduction Furnaces


Special Purpose Resistance
Welding Machine

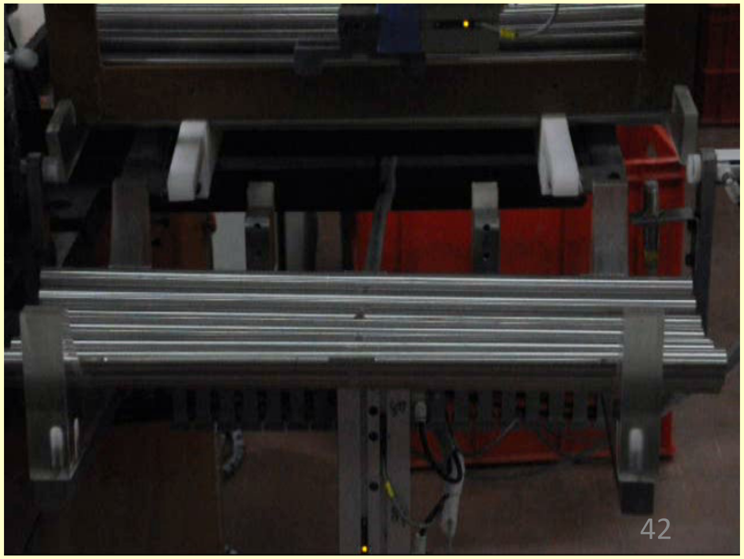

Integrate Spacer / Bearing Pad
Welding Machine

Robotic End Plate Welding Machine

- ✓ Conceptualized, procured and successfully qualified for production of 19 and 37 element PHWR fuel bundles
- ✓ Robot integrated welding stations with other work stations.
- ✓ The productivity has increased by 50%
- ✓ Provision for integrating another end plate welding machine

Integrated Spacer and Bearing Pad Welding Equipment

- Tube handling system
- Pick & place system for appendages
- Internal support system for tube
- Multiple weld heads
- Control system
- Suitable for all element types
- Monitoring of critical parameters
- Detection of appendage positioning
- Dynamic weld schedules
- Data Acquisition System



Automatic Fuel Bundle Inspection Loop

- ✓Conveying Systems
- ✓SCADA Controlled
- ✓Five Axis Robot
- ✓Bundle number identification
- ✓Weight measurement
- ✓Dimension Inspection
- ✓Back Filling and re-circulation of Helium and Argon mixture
- ✓Helium Leak Testing
- ✓Productivity up by 50%

Indigenously Manufactured Equipment

Cold Tube Reducing Mill for Zircaloy Fuel Tubes

Vacuum Baking Oven

Horizontal Vacuum Annealing Furnace for Zirconium Alloy Products

Fuel for LWRs

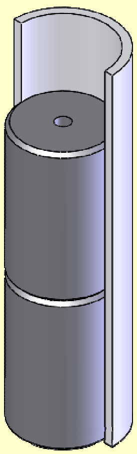
- **34 LWRs/PWRs will be imported for generating 40 GWe.**

- **Fuel fabrication facilities to be set-up with the collaboration of foreign fuel manufacturers.**

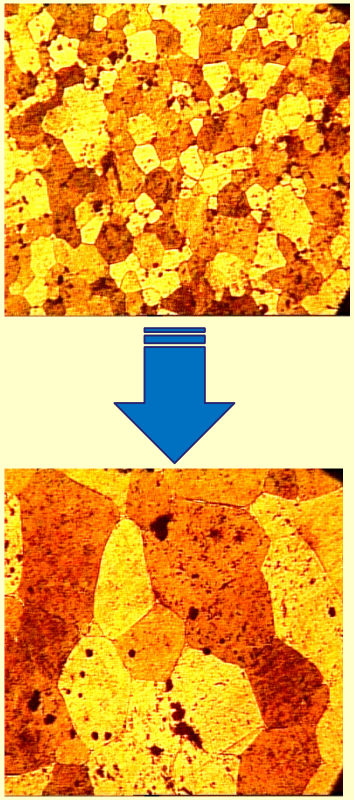
- supply of enriched fuel, UF_6/pellets by foreign fuel manufacturers

- manufacture of zircaloy components in India.

Advanced Fuel Rods for VVER-1000 FA



Parameter	Actual dimension	New dimension
Cladding thickness, mm	0.65	0.57
Pellet diameter, mm	7.57 / 7.60	7.80
Central hole, mm	1.4 / 1.2	0
Average grain size, μm	10	25

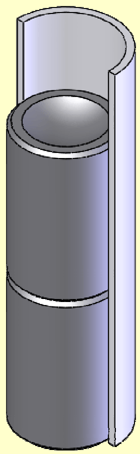


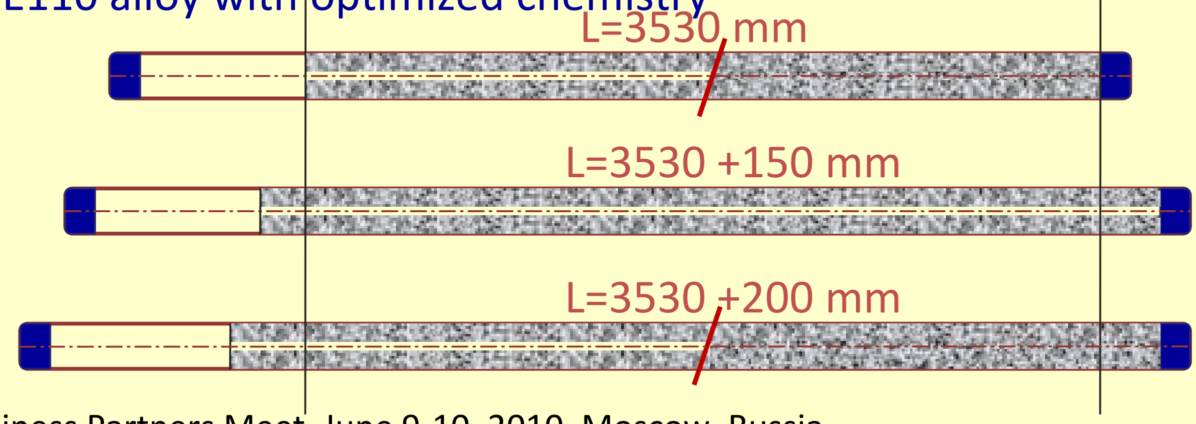
Features that provide fuel rod's service lifetime:

– use of zirconium sponge (since 2009)

– fuel pellets with specified structure

– E110 alloy with optimized chemistry





Source : TVEL Business Partners Meet, June 9-10, 2010, Moscow, Russia

Flow Sheet for Fabrication of Double Wall Clad Tube by cold pilgering process

T – 91 Alloy tube	*Zr – Alloy tube*
Φ11.2 X 1.6mm thk	Φ7.3 X 0.5mm thk
↓	↓
Φ9.5 X 1.2mm thk	Φ6.3 X 0.2mm thk (Annealing)
↓	
Φ7.5 X 0.5mm thk (Stress Relieving)	

↓

Insertion of Zr-Alloy tube inside T-91 tube

↓

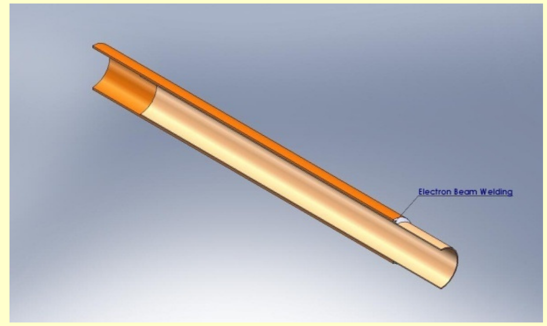
End Fusion of T-91 & Zr-Alloy Tubes Using Electron Beam Welding

↓

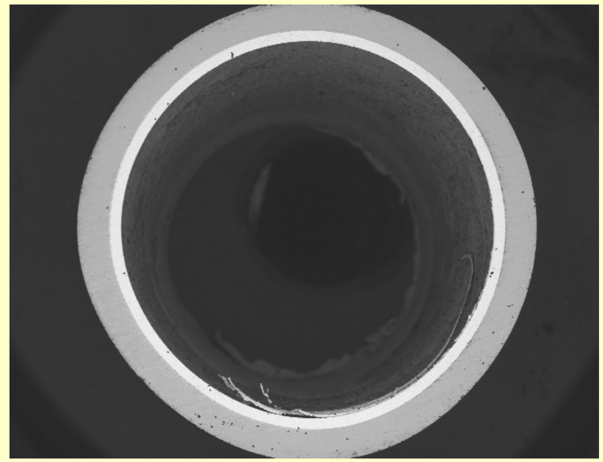
Hydraulic pressurization of inside surface to expand the inner Zr-Alloy tube (to improve surface contact between the tubes)

↓

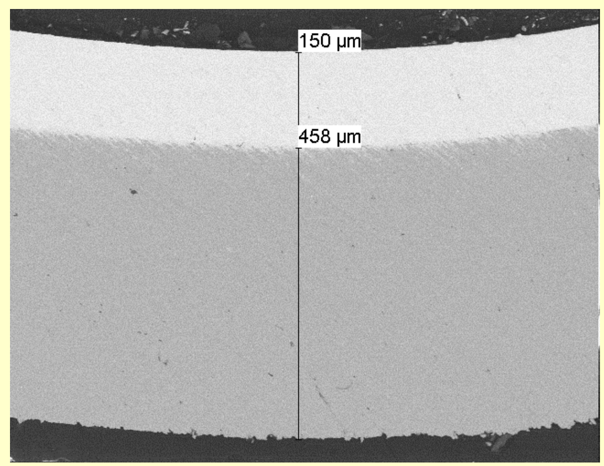
Final Pilgering to Φ6.6 X 0.6mm thk



Schematic showing Electron Beam welded tube joint made prior to pilgering



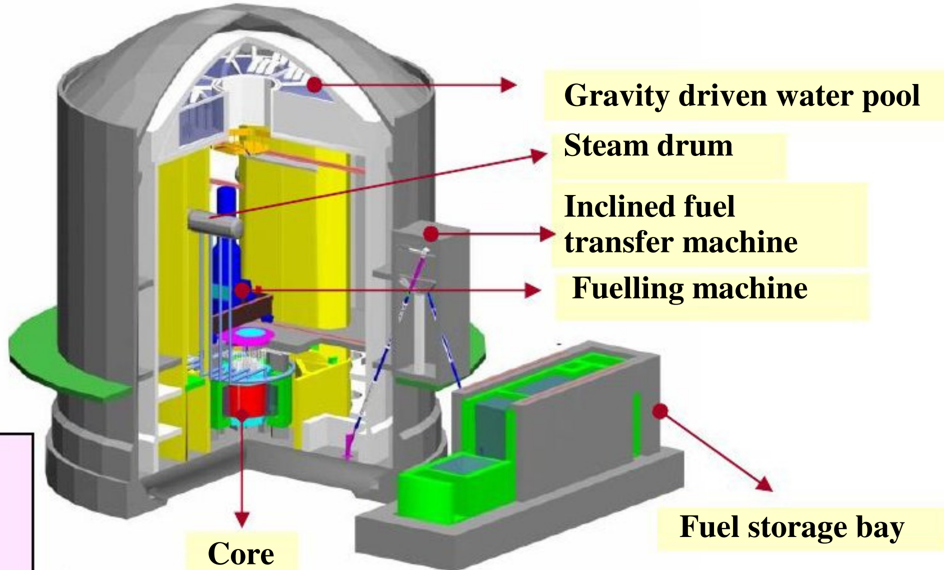
Tube Section showing Outer & Inner Walls of T91 & Zr Alloy



Enlarged View showing no gap at T91-Zr Interface along with wall thickness measurement

Advanced Heavy Water Reactor

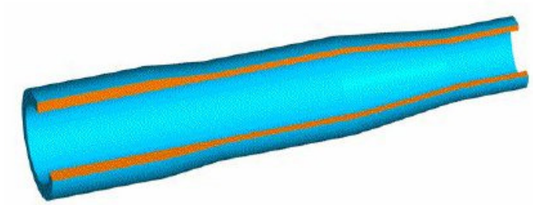
AHWR is a vertical pressure tube type, boiling light water cooled and heavy water moderated reactor using 233U-Th MOX and Pu-Th MOX fuel.



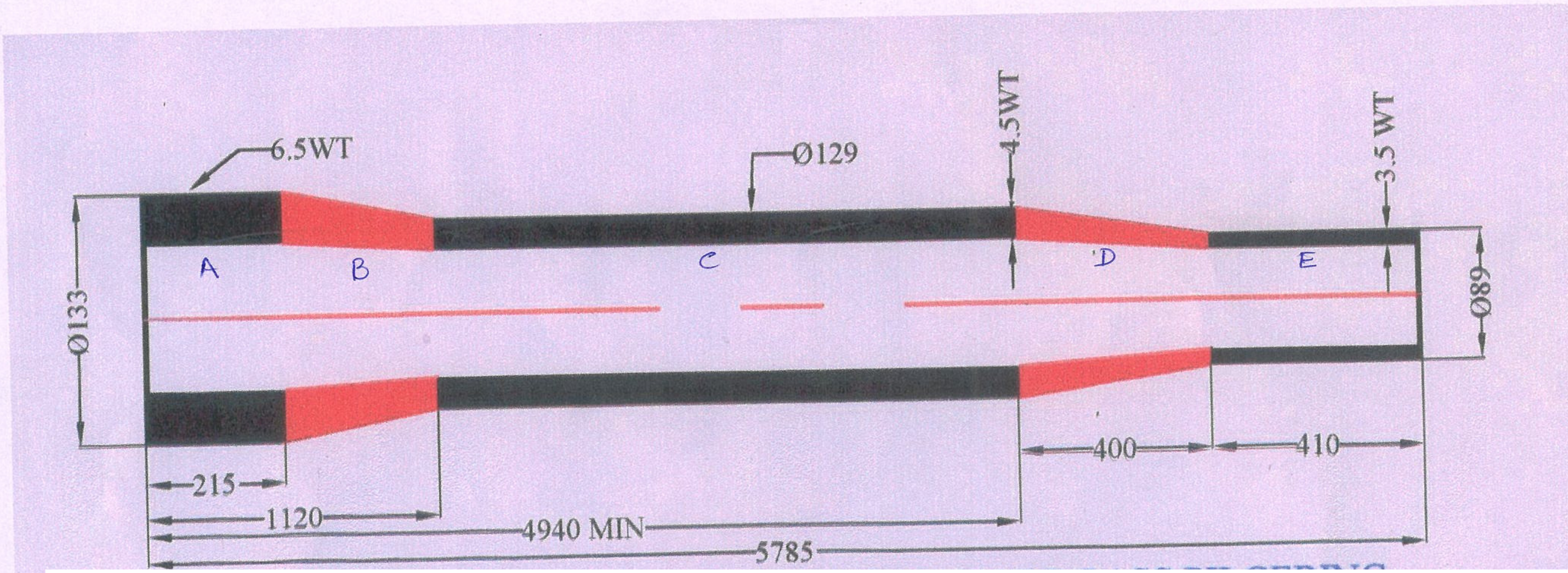
Major Design Objectives

- **Power output – 300 MWe with 500 m3/d of desalinated water.**
- **A large fraction (65%) of power from thorium.**
- **Extensive deployment of passive safety features – 3 days grace period, and no need for planning off-site emergency measures.**
- **Design life of 100 years.**
- **Easily replaceable coolant channels.**

Salient Features of Pressure tube



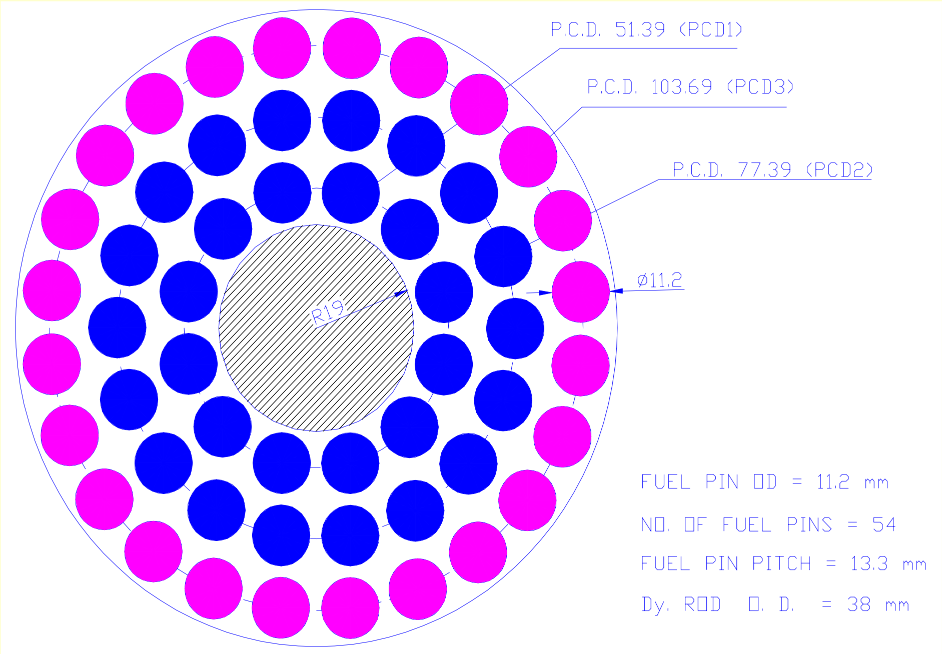
- 120mm ID x 6300 mm length
- Replaceable through top end-fitting
- Unique shape by Pilgering route.
- - Thicker at one end, tapering at the other
- Controlled cold work to achieve required tensile properties.



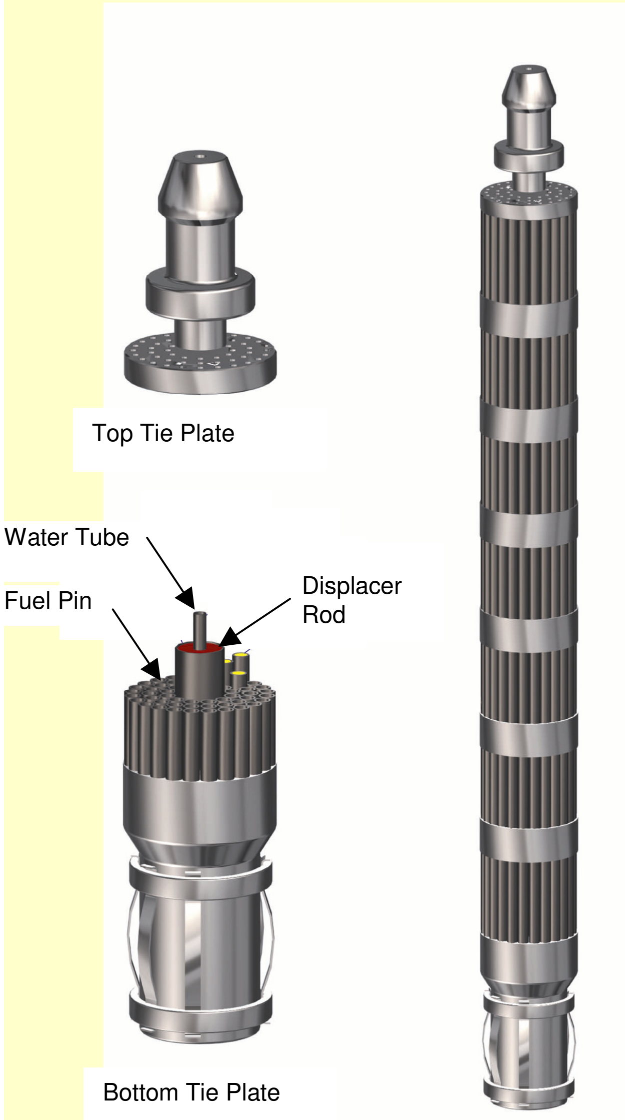
Coolant Tube for Advanced Heavy Water Reactor (AHWR)

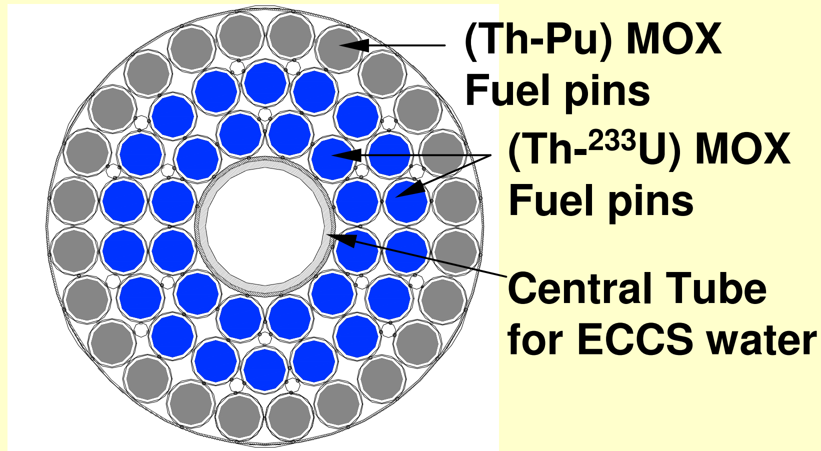
AHWR Fuel

- **54 fuel rods arranged in three concentric pitch circles.**
- **Twenty four (Th + Pu) O_2 fuel rods.**
- **Thirty (Th + U^{233}) O_2 fuel rods.**
- **Hollow cylindrical ZrO_2 displacer rod.**
- **Emergency core cooling water is injected into the cluster through the holes in this displacer rod.**



Main features of AHWR fuel cluster



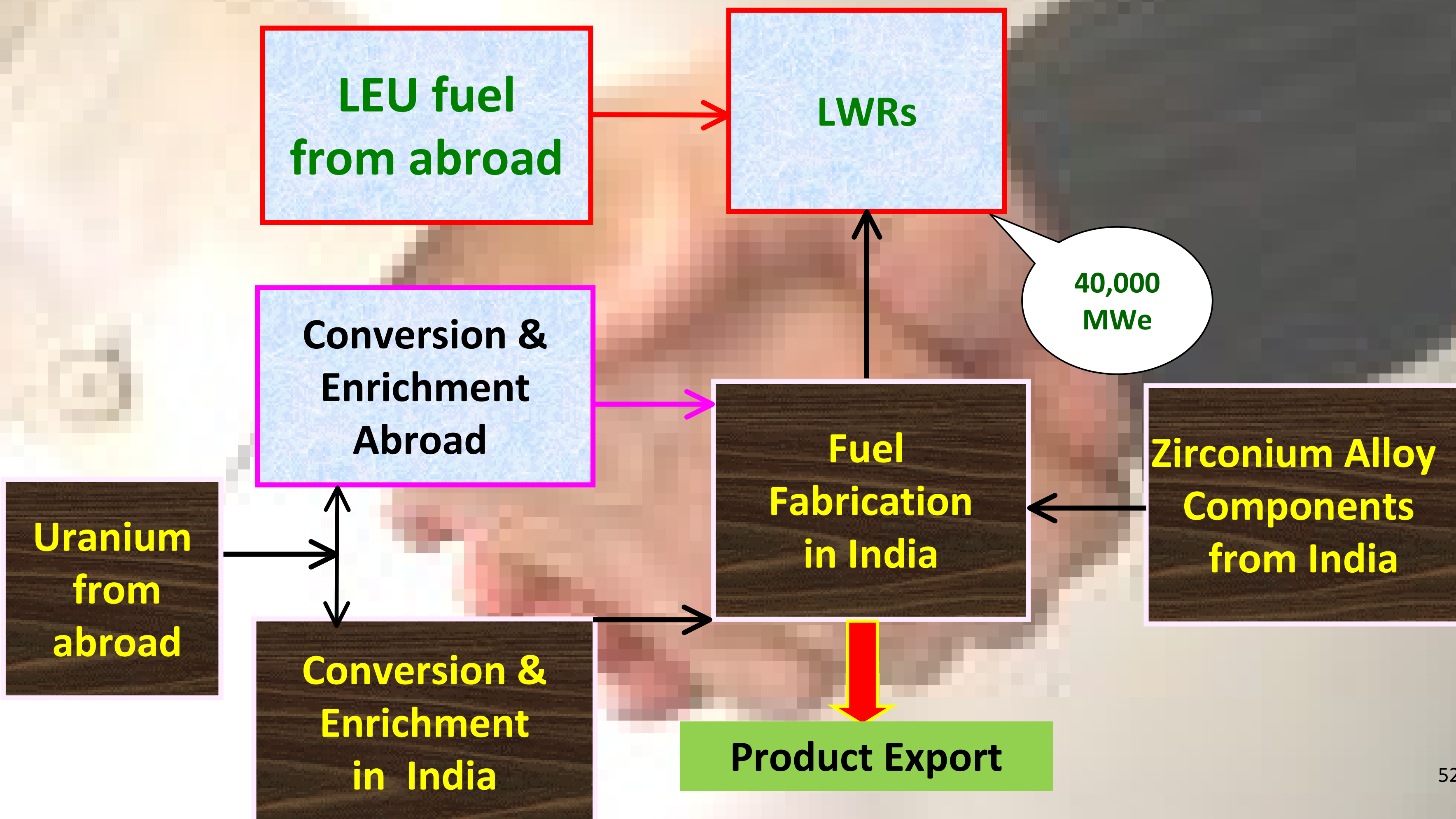


Fuel Cluster Cross-Section

Main Features

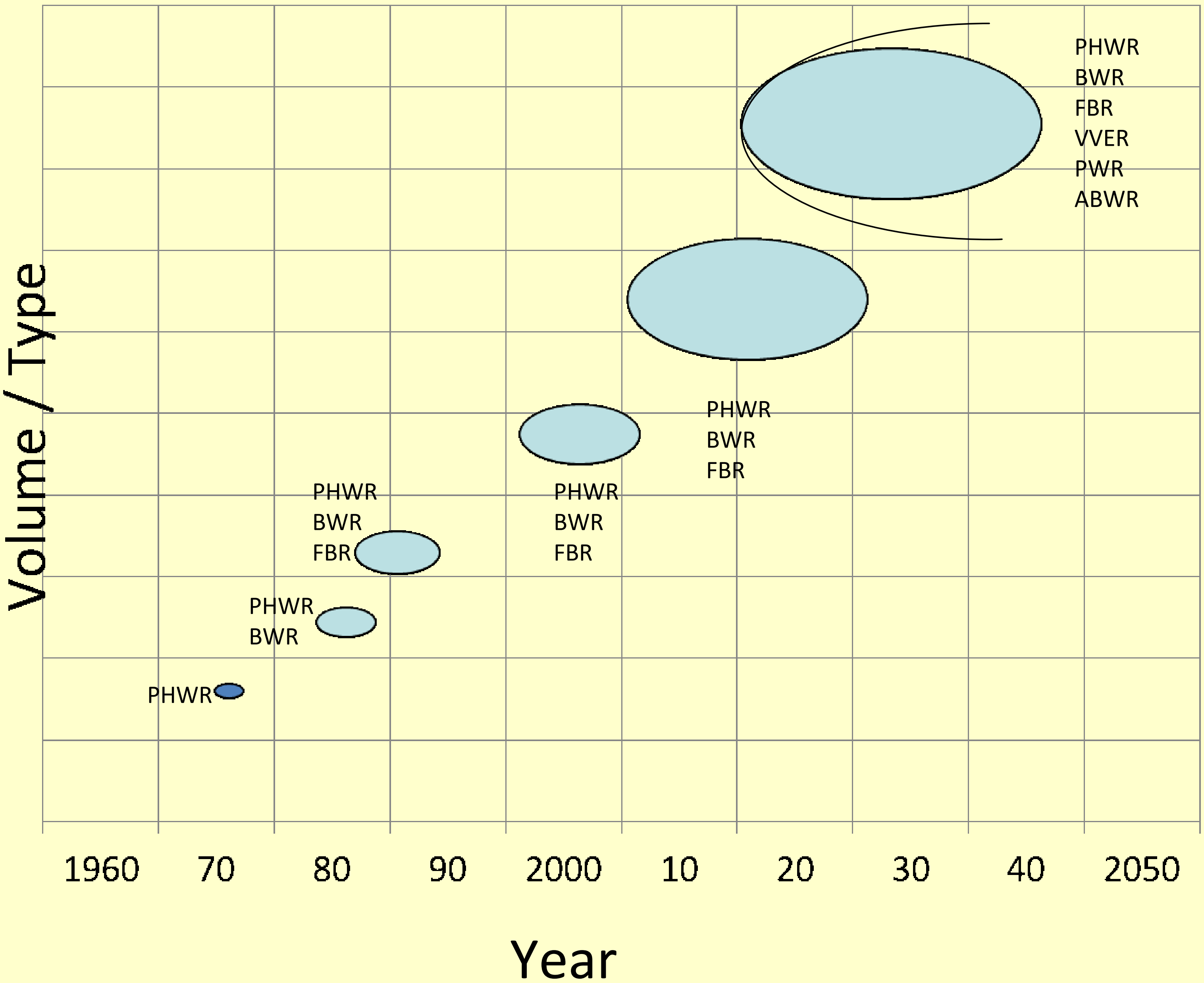
- Thorium bearing fuel [(Th + Pu)O2 MOX, (Th + 233U)O2 MOX]; Enrichment 2.5% (top half) & 4% (bottom half) in the former
- Central (ZrO2-Dy2O3) displacer rod
- Emergency core cooling water injected into the cluster through the holes in displacer rod
- Low pressure drop design

Localization of Fuel Fabrication Facilities for LWRs in India



52

Fuel & Core Sub-assembly activities – a Vision

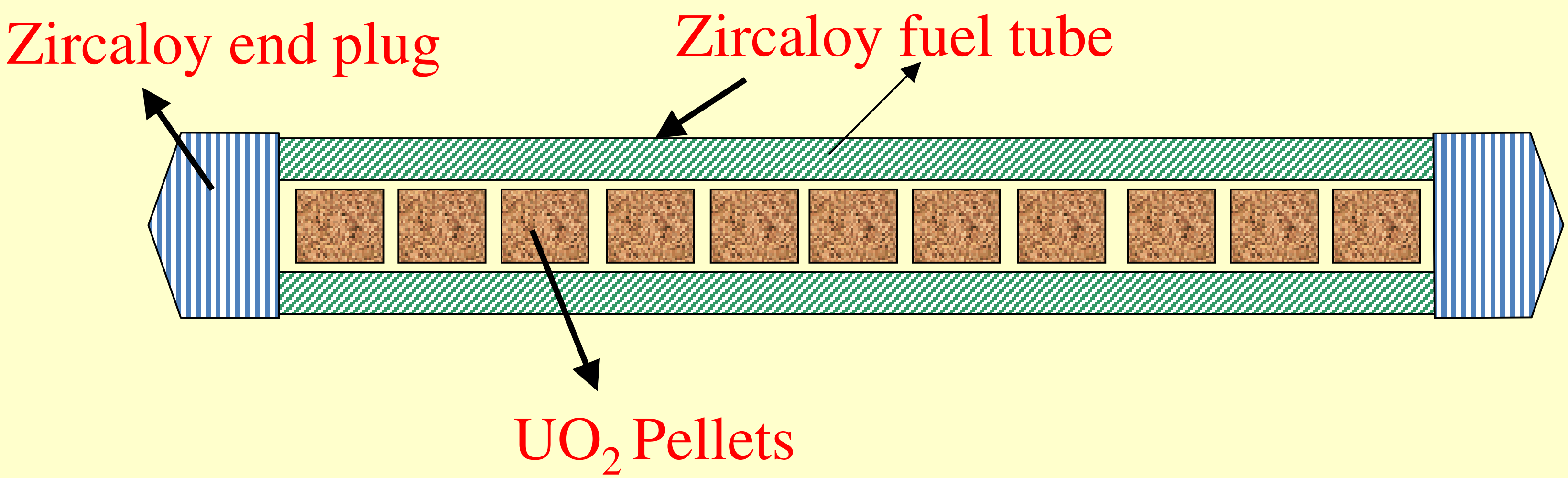


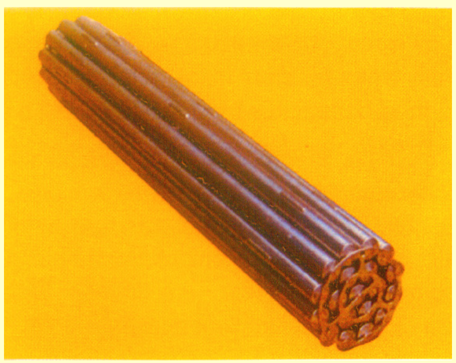
Concluding Remarks

- **For achieving an impressive growth rate in Indian GDP, it is essential to multiply power generation.**
- **India to have best utilization of Thorium through 3-stage Nuclear Power Programme (NPP).**
- **India is matured in closed fuel cycle technologies in the first stage of NPP.**
- **India to multiply nuclear power generation through LWRs and FBRs.**
- **Nuclear Fuel Complex (NFC), having mastered PHWR & BWR Fuel manufacturing technologies, all set to enter fuel manufacturing for LWRs.**
- **Several advanced fuel fabrication technologies, including state-of-the-art automation systems, have been developed indigenously.**

Thank You

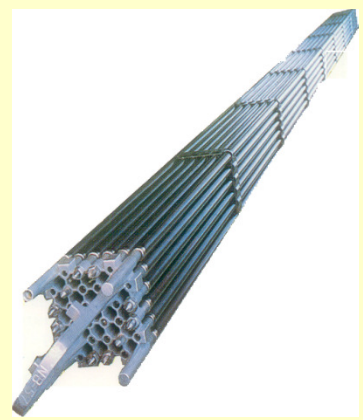
Nuclear Fuel Elements/Assemblies





19-element bundle for PHWR 220

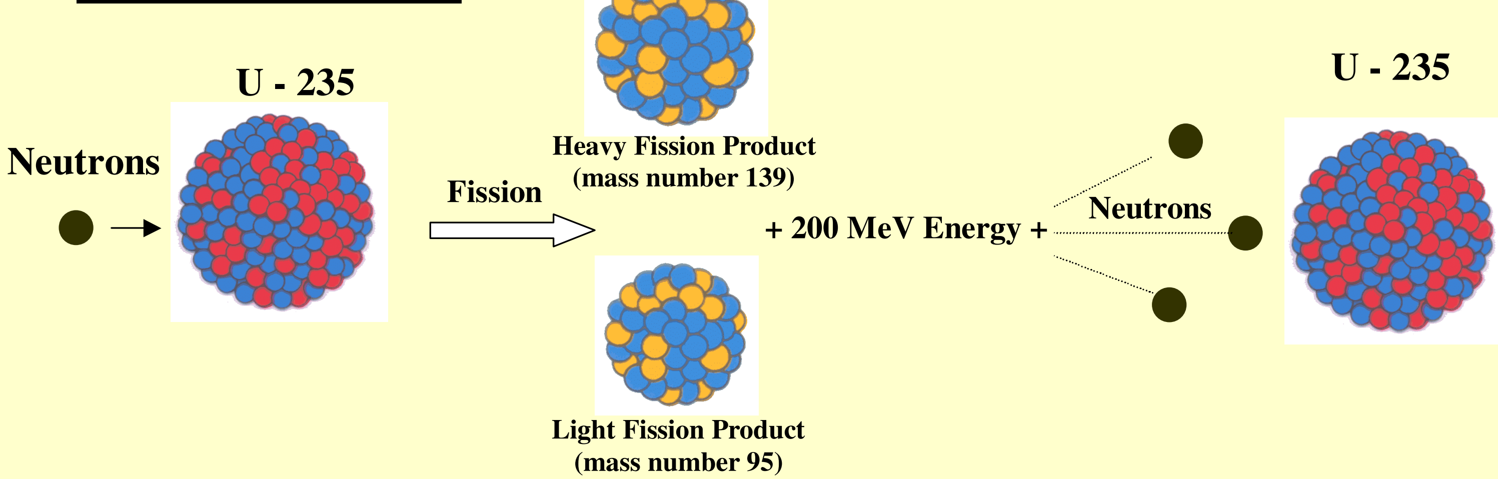
37-element bundle for PHWR 540/700



6x6 element assembly for BWR 160

NUCLEAR FISSION

- **Fission Chain Reaction**



- **Production of Fissile Isotopes Pu^{239} & U^{233}**