Roadmap for Indian activities

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Electricity in India

- Between April, 2014 and January, 2015 the electrical energy availability in India was 868,591 MU against a requirement of 903,104 MU
- Per capita consumption less than a third of world average
- Shortages: Energy & Peak Power
- Power cuts, load shedding
- Huge demand & growing further
- Current share of nuclear energy: 3.6%
- Nuclear share must increase multifold to meet energy demands without leading to unmanageable environmental burden
Three Stage Nuclear Power Programme

**STAGE 1**
- Natural Uranium
- PHWR
- 10 GWe
- ELECTRICITY
- Depleted U
- Pu

**STAGE 2**
- Pu FUELLED FAST BREEDERS
- Pu
- U-233
- 500 GWe
- Th
- ELECTRICITY

**STAGE 3**
- U-233 FUELLED REACTORS
- U-233
- Very Large
-Th
- ELECTRICITY
Three Stage Indian Nuclear Power Programme – Current Status

Stage-1 (Current Generation Thermal Reactors)
- 18 PHWRs operating
- 4 PHWRs under construction
- 3 LWRs under operation
- 1 LWR under commissioning

Stage-2 (Fast Breeder Reactors)
- 1 FBTR under operation since 1985
- KAMINI (30 kWt) operating since 1996
- AHWR Critical Facility operating since 2008

Stage-3 (Thorium Based Reactors)
- One 500 MWe PFBR in advanced stage of construction

Current installed capacity: 5780 MWe

Plan to install 13,480 MWe by 2022 on progressive completion of projects under commissioning/construction and new projects that have been sanctioned.
## Additional reactors under pre-project stage

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Capacity (MW)</th>
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<tbody>
<tr>
<td><strong>Indigenous Reactors</strong></td>
<td></td>
<td></td>
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<tr>
<td>CMAPP 1&amp;2</td>
<td>Chutka, Madhya Pradesh</td>
<td>2 x 700</td>
</tr>
<tr>
<td>Mahi Banswara, 1&amp;2</td>
<td>Mahi Banswara, Rajasthan</td>
<td>2 x 700</td>
</tr>
<tr>
<td>Kaiga 5&amp;6</td>
<td>Kaiga, Karnataka</td>
<td>2 x 700</td>
</tr>
<tr>
<td>FBR 1&amp;2</td>
<td>Kalpakkam, Tamilnadu</td>
<td>2 x 500</td>
</tr>
<tr>
<td>AHWR</td>
<td>Location to be decided</td>
<td>300</td>
</tr>
<tr>
<td><strong>Reactors with Foreign Cooperation</strong></td>
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<td></td>
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<tr>
<td>JNPP 1&amp;2</td>
<td>Jaitapur, Maharashtra</td>
<td>2 x 1650</td>
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<tr>
<td>Kovvada 1&amp;2</td>
<td>Kovvada, Andhra Pradesh</td>
<td>2 x 1500</td>
</tr>
<tr>
<td>Chhaya Mithi Virdi 1&amp;2</td>
<td>Chhaya Mithi Virdi, Gujarat</td>
<td>2 x 1100</td>
</tr>
</tbody>
</table>
PHWR evolution

- 1970s: Technology Demonstration
- 1980s: Standardisation
- 1990s: Consolidation
- 2000s: Commercialisation

220 MW

540 MW

700 MW
KAPP 3&4
RAPP 7&8
Performance of PHWRs

- **Operational**
  - High Availability Factors - more than 90%
  - High Plant Load Factors - above 80%
  - 10 reactors recorded continuous run of >1 year
  - RAPS5: 765 days of continuous operation (2nd longest continuous run in history, and longest in last two decades)

- **Safety**
  - Over 396 reactor-years of safe operation
  - No incidence of radioactivity release beyond stipulated limit of the Regulatory Body AERB
  - Peer Reviews by WANO
  - IAEA OSART Team Review of RAPS 3&4

Positive report by IAEA Operation Safety Review Team (OSART) team
AHWR is a vertical pressure tube type, boiling light water cooled & heavy water moderated reactor using $^{233}$U-Th MOX & Pu-Th MOX in closed fuel cycle and AHWR-LEU using LEU-Th MOX fuel in once through fuel cycle.

**Major design objectives: AHWR (Ref.)**
- A large fraction (~60%) of power from thorium
- Extensive deployment of passive safety features – 7 days grace period, and no radiological impact in public domain
- Addresses insider threat
- Design life of 100 years
- Easily replaceable coolant channels

**Salient features:**
- Power level- 300 MWe
- Main Heat Transport loop height- 39 m
- Coolant- Boiling light water
- Heat removal by natural circulation
- Moderator: Heavy water
- Lattice pitch: 225 mm square
- Number of coolant channels: 452
- Small local peaking factors (flat fuel flux distribution)
- Two independent functionally diverse shut down systems
- Passive Poison Injection directly into fuel cluster as an additional shutdown system
- Small excess reactivity (On-power refuelling)
- Number of control rods- 24

**AHWR (Reference)**
- Fuel $[\text{(Th, }^{233}\text{U) MOX}]$
- Fuel $[\text{(Th, Pu) MOX}]$
- Fuel $[\text{(Th, Pu) MOX}]$ with Gd
- Displacer rod
- Displacer tube

**AHWR-LEU**
- Fuel $[\text{(Th, LEU) MOX}]$
- Fuel $[\text{(Th, LEU) MOX}]$ with Gd
- Displacer rod
- Displacer tube

**Role of AHWR passive systems to address insider threat scenario**

**Peak clad temperature hardly rises even in the extreme condition of complete station blackout and failure of primary and secondary shutdown systems**

**AHWR can withstand Fukushima type scenario for more than 100 days**
Indian HTR and MSBR programme

(a) Compact High Temperature Reactor, 100 kWt reactor for technology demonstration
(b) 600 MWth IHTR for large scale hydrogen production
(c) And (d) Pool Type and Loop-In-Tank type IMSBR concepts under study as options for Third Stage
Accelerator Driven sub-critical reactor Systems for Thorium Utilisation

Accelerator Driven Sub-critical reactor System (ADSS) is being developed for Thorium utilisation as well as for transmutation of nuclear waste in dedicated minor actinides burner reactor with inherent safety against power excursions. Development includes following three major elements:

### Development of a high current high energy proton accelerator

**Stage-1:** 30 mA 20 MeV Linac injector (LEHIPA)

- Low Energy Beam Transmission line
- RFQ
- Drift Tube Linac
- 1.3 MW Klystron
- 60 kW RF System

**Stage-2:** 1 GeV and 30 mA superconducting linac:
A major program for augmentation of the infrastructure required for development of a 1 GeV linac has also been launched

### Target development studies related to heat removal and window damage (irradiation creep and void swelling)

- LBE thermal-hydraulic experimental test facility

### Reactor program

- Basic theoretical studies, advanced computer codes and compilation of nuclear data
- Experimental program for subcritical ADS, including subcriticality measurement and monitoring
- Several ADS concepts have been evolved: one way coupled, thorium burner, power producing Th breeder, Molten Salt Breeder ADS.

Experimental sub critical facility
Evolution of thorium fuel cycle development in India

- Use of thoria in PHWR
- Thoria pellets irradiation in research reactor
- Dismantling of irradiated bundle and Post-irradiation examination
- Irradiated fuel reprocessing and fabrication
- KAMINI research reactor: $^{233}$U-Al Fuel
- AHWR critical facility

Thorium extraction

Oct. 12-15
ThEC
Thorium Energy Conference 2015
Mumbai India
Gateway to Thorium Energy
Mining of thorium

Beach sands of India contain rich deposits of monazite (thorium ore), ilmenite, zircon, etc. The total minerals established so far include about 11.93 million tonnes of monazite containing 1.07 Million tonne of Thorium oxide.

**Composition of Monazite**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorium as ThO₂</td>
<td>9%</td>
</tr>
<tr>
<td>Rare Earths as REO</td>
<td>58.5%</td>
</tr>
<tr>
<td>Phosphorus as P₂O₅</td>
<td>27%</td>
</tr>
<tr>
<td>Uranium as U₃O₈</td>
<td>0.35%</td>
</tr>
<tr>
<td>Calcium as CaO</td>
<td>0.5%</td>
</tr>
<tr>
<td>Magnesium as MgO</td>
<td>0.1%</td>
</tr>
<tr>
<td>Iron as Fe₂O₃</td>
<td>0.2%</td>
</tr>
<tr>
<td>Lead as PbO</td>
<td>0.18%</td>
</tr>
<tr>
<td>Insolubles</td>
<td>3%</td>
</tr>
</tbody>
</table>

Monazite, which contains about 9% ThO₂ and 0.35% U₃O₈, is a phosphate of thorium, uranium and rare earth elements. Thorium is extracted with trace uranium as by-product.

**Beach Sand Minerals**

- **ILMENITE & RUTILE**: TITANIUM (52%)
- **ZIRCON**: ZIRCONIUM (3.2%)
- **MONAZITE**: THORIUM & RARE EARTHS (1.13%)
- **SILLIMANITE**: ALUMINIUM
Thorium in Indian reactors

**CIRUS:**
- Thoria rods irradiated in the reflector region for $^{233}$U production
- Irradiations of (Th, Pu) MOX fuels in Pressurised Water Loop to burnup of 18 GWd/te.

**PURNIMA-II (1984 -1986):** First research reactor using $^{233}$U fuel.

**PURNIMA-III (1990-93):** $^{233}$U-Al dispersion plate type fuel experiments.

**KAMINI:** Research reactor operating at 30 kW power, commissioned at Kalpakkam in 1996. Reactor based on $^{233}$U fuel in the form of U-Al alloy, for neutron radiography.

- Thoria bundles irradiated in the blanket zone of Fast Breeder Test Reactor (FBTR)
- $^{233}$U-MOX fuel being irradiated in FBTR

- Three PHWR stations at Kakrapar, Kaiga and Rajasthan (units 3&4) have irradiated a total of 232 thorium bundles, to maximum discharge burnup of 14 GWd/te. The power produced by the bundle just before discharge (600 FPD) was about 400 kW.
The PIE was carried out for one of the discharged bundles from Kakrapar unit-2, which had seen 508 full power days.

- Dissolution tests done for uranium isotope composition and fission products and compared with theoretical evaluations.

- Power distribution shows peaking at the outer pins for UO₂ bundle and at intermediate pins for thoria bundle.

- Fission products (¹³⁷Cs) migrate to thoria pellet cracks unlike up to periphery in UO₂ fuel.
Fuel fabrication technology

Experience with fabrication of thoria-based fuel
- Thoria bundles for PHWRs
- Thoria assemblies for research reactor irradiation
- Thoria based MOX pins for test irradiations

Fabrication process was similar to that of UO₂ & (U-Pu)MOX

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Technique</th>
<th>Type of facility</th>
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</thead>
<tbody>
<tr>
<td>(Th-LEU) MOX</td>
<td>Powder-Pellet</td>
<td>Conventional UO₂</td>
</tr>
<tr>
<td>(Th-Pu) MOX</td>
<td>Powder-Pellet</td>
<td>Glove Box</td>
</tr>
<tr>
<td>(Th-²³³U)MOX</td>
<td>Powder-Pellet, Sol-Gel Microsphere Pelletization</td>
<td>Fully shielded facility</td>
</tr>
<tr>
<td></td>
<td>Pellet Impregnation</td>
<td>Partially shielded facility</td>
</tr>
<tr>
<td></td>
<td>Coated Agglomerate Pelletization</td>
<td>Partially shielded facility</td>
</tr>
</tbody>
</table>

Glove box facility for (Th-Pu) MOX

Experience with fabrication of thoria-based fuel:
- Thoria bundles for PHWRs
- Thoria assemblies for research reactor irradiation
- Thoria based MOX pins for test irradiations

Fabrication process was similar to that of UO₂ & (U-Pu)MOX
Fuel reprocessing technology

**Areas under study**
- Dissolution
- THOREX for industrial scale
- Third phase problems
- 3-component separation for irradiated (Th, Pu)MOX
- Tackling gamma radiation from $^{232}\text{U}$ daughters products

**Development of THOREX Process Flowsheet using laboratory studies**

**Actinide Separation Demonstration Facility**
- Industrial scale facilities setup for partitioning of high level liquid waste

**Engineering scale facilities at Trombay for reprocessing irradiated Thoria fuel**

**Uranium Thorium Separation Facility (UTSF)**
- Used for reprocessing thorium irradiated in research reactors

**Power Reactor Thorium Reprocessing Facility (PRTRF)**
- Commissioned in January 2015 for reprocessing of thoria fuel bundles irradiated in PHWRs

(a) Shielded glove boxes
(b) Laser Assisted Fuel Bundle Dismantling
(c) Shielded cubicle for processing of thorium lean waste
(d) Cell view of PRTRF
AHWR critical facility for thorium based fuel physics studies

AHWR Critical Facility has been designed for conducting lattice physics experiments to validate AHWR physics calculations. There is enough flexibility to arrange the fuel inside the core in a precise geometry at the desired pitch for facilitating study of different core lattices based on various fuel types, moderator materials and reactivity control devices. This facility attained its criticality in April 2008.

The fuel cluster of present reference core consists of 19-pin metallic natural uranium fuel with aluminum cladding.

**Experiments performed**

Reference core
- First approach to criticality; Dynamic tests for the shut down device
- Measurement of critical height, level coefficient of reactivity etc.
- Measurement of reaction rates and neutron spectrum
- Radial flux profile in experimental cluster

Thorium related experiments
- Experiments with (ThO$_2$-U) Mixed Pin Cluster
  - Critical Height Measurement with one mixed Pin
  - Fine Structure Flux Measurement inside mixed pin cluster
  - Axial gamma scanning of the central ThO$_2$ pin of mixed pin cluster
  - Level Coefficient of Reactivity Measurement with mixed pin cluster
  - Integral experiments with ThO$_2$ -U mixed pin cluster and ThO$_2$-PuO$_2$ cluster

Experiments with special Thorium based cluster
- Critical height measurement experiments with one lattice location fuelled with a six pin (Th-(1%)Pu) MOX cluster and a special six pin (Th-LEU) MOX cluster
- Axial flux measurements in (U-ThO$_2$-U) Sandwich Cluster
- Critical Height and Fine Structure Flux measurement experiments with a specially designed (U-ThO$_2$-U) Sandwich Cluster (In Extended Reference Core of AHWR-CF)

**Features**

- Thermal Neutron Flux (Ave) : $10^8$ n/cm$^2$/sec
- Nominal Fission power : 100 Watts
- Variable lattice pitch : $\geq 215$ mm
- Types of cores : Reference core, AHWR Core and PHWR Core
KAMINI - the only reactor operating with $^{233}$U as fuel in the world now

KAMINI (KAlpakkam MINI) is a 30 kWth, $^{233}$U (20 wt%) -Al alloy fuelled, demineralised light water moderated and cooled, special purpose research reactor. Beryllium oxide (BeO) is used as reflector and cadmium is used as absorber material in the safety control plates. The reactor functions as a neutron source with a flux of $10^{12}$ n/cm$^2$/s at the core center. Core cooling is by natural circulation of the coolant. It is used for:

- Neutron radiography of both radioactive and non-radioactive objects (e.g. FBTR fuel pins)
- Neutron activation analysis.
- Carrying out radiation physics research,
- Irradiation of large number of samples, and
- Calibration and testing of neutron detectors.

Neutron radiography of irradiated FBTR control rod

Neutron radiography of MOX fuel pin

Chandrayaan (Indian lunar probe) mission critical devices were successfully inspected at KAMINI

Neutron radiography of space components
Indian collaborative efforts

- As one of the seven Members of ITER
  - Components & Systems
  - TBM Development
- CERN-LHC collaboration
- Fermi Lab collaboration
- Indo-French collaboration
- Associated partner in Jules Horowitz Reactor
- Foundation Course on Nuclear Energy for Bangladesh Atomic Energy Commission personnel
Expected outcomes from ROADMAPS

- Evaluate the expected timelines of advanced reactor systems in the global perspective
  - Identify potential stumbling blocks in the development and deployment of technologies, so that they can be addressed in development of similar technologies in India
  - Outline developments in Thorium utilisation technologies and non electric applications
- Emphasise suitability of proven SMRs for use in niche areas
  - PHWR-220 has proven itself as a safe and reliable reactor with proven track record
- Identify possible collaborative developmental areas
  - Identify reactor systems that have similar aims and characteristics.
  - It is entirely possible that aims and objectives of similar reactor systems may be entirely different – identify areas of overlapping technical collaboration.