Pressurised Heavy Water Reactor (PHWR) Technology
- It’s relevance today

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Homi Bhabha Chair Professor
Bhabha Atomic Research Centre Mumbai
W.B. Lewis Lecture
Pacific Basic Nuclear Conference, Vancouver, Canada
August 25, 2014
Bhabha-Lewis Friendship

Shared Views

• Importance of Neutron economy
• Natural Uranium – Heavy Water Reactor
• Use of Thorium in the long run
• Sustainable nuclear energy future
Concept of Valubreeder (U-Th cycle)

- Thorium thermal neutron near-breeder
- Net fissile fuel credit can exceed basic inventory charges
- Natural U + Th + slightly enriched U or Pu

W.B. Lewis (1908-1987)
Indian three stage programme

Thorium in the centre stage

Stage 1: Power generation primarily by PHWR
Building fissile inventory for stage 2

Stage 2: Expanding power programme
Building U^{233} inventory

Stage 3: Thorium utilisation for
Sustainable power programme

U^{233} Fueled Reactors

U^{233} Fueled Fast Breeders

Dep. U

300 GWe-Year

42000 GWe-Year

155000 GWe-Year

Nat. U

Dep. U

Pu

Pu

Electricity

Electricity

Electricity

Homi Jehangir Bhabha (1909-1966)
Neutron Inventory: The Deciding Factor For Choosing Appropriate Fuel Cycle

- Using external fissile material U235, Pu or an external accelerator driven neutron source, Th-U233 cycle can be made self-sustaining.

- U233 has excellent nuclear characteristics both in thermal and fast neutron spectrum.

- Th is excellent host for Pu and enables deeper burning of Pu.

Neutron economy is directly related to fissile economy since it takes just one neutron to make one new fissile atom – W.B. Lewis (1966)
Pressurised Heavy Water Reactor (PHWR) Technology

**Conceptual Development**

- Making a power reactor with natural uranium-best fissile utilisation per ton of mined uranium
- Heavy water moderator
- Channel type reactor
- Continuous bi-directional fuelling
- Versatility for use of different fuel cycle

“*If I had to pick one person who contributed most to the success of the Canadian nuclear power program it would be W.B. Lewis*” – J.L. Gray (*Nuclear Journal of Canada*)

Natural Uranium
Slightly Enriched Uranium
$\text{UO}_2 + \text{PuO}_2$ MOX
$\text{Th-U}^{233}$
Best Fissile Utilisation Per Ton of Mined Uranium

PHWR, 1000 MWe, 7000 MWd/T

- 169 Tons N.U.
- 5 Kg, MA
- 16.7 Tons Dep. U
- 650 Kg Pu
- 1.25 Tons F.P.

Fast Reactor

Annual Fuel Requirement for PHWR and PWR for 1000 Mwe

- 165 Tons Dep U
- 1000 MWe
- 23 Kg, MA
- 250 Kg Pu
- 23.6 Tons R.U.

Storage

PWR

- 190 Tons N.U.
- 25 Tons 4% En U
- 45000 MWd/T
- 6000 MWd/T of natural U
- 1.15 Tons F.P.
## Pressurised Heavy Water Reactor Deployment Worldwide

<table>
<thead>
<tr>
<th>Country</th>
<th>No. of PHWRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>19</td>
</tr>
<tr>
<td>India</td>
<td>18</td>
</tr>
<tr>
<td>South Korea</td>
<td>4</td>
</tr>
<tr>
<td>China</td>
<td>2</td>
</tr>
<tr>
<td>Argentina</td>
<td>1+2</td>
</tr>
<tr>
<td>Romania</td>
<td>2</td>
</tr>
<tr>
<td>Pakistan</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>49</strong></td>
</tr>
</tbody>
</table>

**Tarapur 540 MWe**
Douglas Point to Rajasthan

Douglas Point Reactor,
First Criticality: 15 November, 1966

RAPS-1,
First Criticality: August 11, 1972
Evolution of PHWR Technology in India for 220 MWe Units

✓ Core Physics
- Continuous discharge model to Multiple bundle shift model.
- Optimum positioning of reactivity devices to obtain their desired worths.
- Extensive experimentation in Narora Reactor
  Experience gained utilised in power optimisation, fuel performance and loading Thoria, MOX & SEU fuels

✓ Control and Shut Down Systems
- Moderator level control replaced by Shim Rods
- Moderator dump replaced by 2 fast & independent shutdown systems
- Automatic Liquid Poison Addition / Passive Injection system to augment worth of shutdown systems

✓ Materials
- New Fabrication Route for Zr-2.5Nb Pressure Tubes
- Introduction of Seamless Calandria Tubes
- Continuation of Zr-Nb-Cu Garter Spring
- Spot Welded Spacers & Pads

✓ Containment Design
- Single Containment → Double Containment → Steam Generator Entry Ports → Stainless Steel Lining
- RAPS (Same as DPGS)
  - Moderator dumping
- NAPS 220MWe onwards
  - Two independent Shut Down Systems
    - Mechanical Shut off Rods
    - Liquid Shut off Rods
ALPAS: Automatic Liquid Poison Addition System
GRAB : Gravity Addition of Boron
LPIS  : Liquid Poison Injection System

ALPAS

GRAB

CALANDRIA

LPIS
Shut Down & Control Systems for 540 & 700 MWe PHWRs

2 Independent Shut Down Systems

Independent Control of 14 Zones
Evolution of PHWR Technology in India – Seismic design
Evolution of PHWR technology in India – Containment

RAPS- Single Containment

NAPS- Double Containment

Suppression pool
Evolution of PHWR technology in India – Containment

Double Containment standardised for all 220MWe and 540 MWe
Evolution of PHWR technology in India - Containment

- Lined containment
- Containment pressure suppression by Spray
- Passive decay heat removal
Why PHWRs are relevant today?

Large thermal inertia in Beyond Design Basis Scenario

- Pressure tube ballooning
- Moderator as heat sink

Time for operator action

<table>
<thead>
<tr>
<th>Component</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderator</td>
<td>20 hrs.</td>
</tr>
<tr>
<td>Calandria vault water</td>
<td>57 hrs.</td>
</tr>
</tbody>
</table>

Data for 540 MWe

- Inherent Safety
- Economy in Small Size
- Uninterrupted Operation
- Choice of Fuel Cycle Options

Moderator
260 Te

Calandria Vault
Water
680 Te
Performance & Economics of Indian Pressurised Heavy Water Reactors (PHWR)

<table>
<thead>
<tr>
<th></th>
<th>Indian PHWRs (700 MWe)</th>
<th>Global Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital Cost (2008 Basis)</strong></td>
<td>1700* $/kWe</td>
<td>&gt; 5000 $/kWe</td>
</tr>
<tr>
<td><strong>Construction period</strong></td>
<td>5-6 years</td>
<td>5-6 years</td>
</tr>
<tr>
<td><strong>UEC $/MWh</strong></td>
<td>60</td>
<td>80 - 100</td>
</tr>
</tbody>
</table>

Capital Cost of recently completed units

- **TAPS – 3 & 4** (540 MWe)
  - Rs. 58850* million
  - ~ 1200* $/kWe

- **Kaiga – 3&4** (220 MWe)
  - Rs. 26000* million
  - ~ 1300* $/kWe

*Cost figures pertain to the Indian domestic context. In the international context these figures will be location dependent.*
PHWR Performance in India

 Availability and Capacity Factor

Recent Continuous Operation (Number of days)

RAPS-5 has exceeded two years of continuous operation on August 3, 2014
Relevance of PHWRs in today’s context—Fuel versatility

- UO₂ + PuO₂
- UO₂ + ThO₂ (Thorium utilisation)
- Nat.U + Enriched U
- LWR + PHWR in tandem

<table>
<thead>
<tr>
<th>Bundle Type</th>
<th>Maximum burnup (MWD/Te)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOX-7</td>
<td>20000</td>
</tr>
<tr>
<td>Thorium</td>
<td>13000</td>
</tr>
<tr>
<td>Recycled Depleted Uranium</td>
<td>9000</td>
</tr>
<tr>
<td>Natural Uranium</td>
<td>22000</td>
</tr>
<tr>
<td>SEU</td>
<td>25000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MOX 19-element Fuel Bundle</th>
<th>Natural U Elements</th>
</tr>
</thead>
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<td>MOX-7</td>
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<tr>
<td>Thorium</td>
<td>250</td>
</tr>
<tr>
<td>SEU</td>
<td>50</td>
</tr>
<tr>
<td>Recycled Depleted Uranium</td>
<td>Large</td>
</tr>
</tbody>
</table>
Comparison of behaviour of Thoria & Urania based fuels

- Inherently stable
- Single valency
- Lower diffusivity
- Better thermal conductivity
- Higher FG retention

ThO₂ fuel more tolerant for clad failure!

Failed ThO₂-4%PuO₂

Failed UO₂-4%PuO₂

ThO₂-4%PuO₂

Failed ThO₂-4%PuO₂

Failed UO₂

\[ \text{Failed ThO}_2-4\%\text{PuO}_2 \]

\[ \text{Failed UO}_2 \]
Fission Gas Bubbles & Channels in Irradiated Fuel

Higher thermal conductivity of thoria leads to lower operating temperatures and lower Fission Gas Release

No FG channels in ThO2+4%PuO2

Fission Gas channels in UO₂

Burnup 4,400MWd/t

Burnup 15,000MWd/t

Burnup 18,400MWd/t
PHWRs - Some concerns

Concerns
- Small positive void coefficient
- Tritium background inside containment
- Opening of pressure boundary daily for on power refueling.
- Zirconium alloy in pressure boundary

Solutions
- Reduced lattice pitch
- Burnable poison
- Light water cooling
  - Enriched fuel
- High burn up fuel
  - Reduced refueling
- Proven performance of zirconium alloy as pressure boundary material
Indian Advanced Heavy Water Reactor (AHWR-Pu)

AHWR is a 300 MWe vertical pressure tube type, boiling light water cooled and heavy water moderated reactor using $^{233}$U-Th MOX and Pu-Th MOX fuel.

Major design objectives
- 65% of power from Th
- Void Coefficient negative
- Several passive features
  - 10 days grace period
  - No radiological impact
  - Additional Passive shutdown system
- Design life of 100 years.
- Easily replaceable coolant channels.

Design validation through extensive experimental programme.

Pre-licensing safety appraisal by AERB

Site selection in progress.

AHWR-Pu is a Technology demonstrator for the closed thorium fuel cycle.
Passive Features of AHWR

- Passive core cooling by natural circulation
- Passive decay heat Removal by Isolation Condensers
- Passive shutdown system
- Passive ECCS injection by Accumulators & GDWP
- Passive Containment Coolers
Heat Removal Paths under Normal Operation & Shut down Condition and Passive Shut-down System

Steam overpressure can passively shut down reactor
Transients following station black-out and failure of wired shut-down systems

Peak clad temperature hardly rises even in the extreme condition of complete station blackout and failure of primary and secondary shutdown systems.
In India 40% of households do not have access to electricity.
Meeting the balance requirement through fossil fuels (coal) would involve about 3 to 4 billion tonnes of CO₂ emissions per annum.
Adopting closed fuel cycle also reduces nuclear waste burden

Radiotoxicity of spent fuel is dominated by:
- FPs for first 100 years.
- Subsequently, Pu (>90%).
- After Pu removal, Minor Actinides specially Am (~9%).

With early introduction of fast reactors using (U+Pu+Am) based fuel, long term radiotoxicity of nuclear waste will be reduced.
Fuel Cycle & Sustainability

“A development that meets the needs of the present without compromising the ability of future generations to meet their own needs”
- Brundtland Commission 1987

Important considerations for sustainability are:
- Environment
  - Clean concentrated energy
- Resources
  - Fissile material
  - Fertile material
  - Neutrons
- Long lived nuclear waste
- Safety and security
- Economy

We have an obligation towards our next generation
Reprocessing capacity matching with FBR fuel requirement

Vitrified HLW inventory presently stored in engineered interim storage facility
Performance evaluation of FBTR carbide fuel through Post Irradiation Examination

Micrographs of fuel pin cross section at the centre of fuel column after 25 & 50 & 100 GWd/t burn-up

- Excellent performance of Mixed Carbide Fuel canned in Stainless Steel Tubes up to a maximum burn up of 165 GWd/t
- Doubts raised on achieving high burn up in fast reactor fuel due to radiation damage and transmutation processes in the cladding material

There is also no news yet on PuC + UC but I would expect it to be worse – W.B. Lewis (AECL-2584, 1966)
Indian Prototype Fast Breeder Reactor

Thermal Power (MWth): 1250
Electrical output (MW): 500
Fuel material: (U,Pu)O₂
Coolant: Molten Sodium
Prototype Fast Breeder Reactor, Kalpakkam

- Physical progress of the Project: >95%
Induction of LWRs of Large Capacity (> 1000 MWe)

- Power Parks from LWRs (6-8 units each. Total ~ 40 GWe)
- Progressively growing equipment supply chain from within India
- Development of Indigenous LWR
- Tying up Fuel supply
Evolving Fuel Cycle

- **U (Natural)**
- **U (enriched)**
  - MOX Fuel
- **MOX Fuel**
  - Heterogeneous Recycling
  - Irradiated Pins (high specific activity, short life)
  - Oxide Fuel in Fast Reactors
    - Long doubling time
    - Burning MA will increase doubling time

- **PHWR**
  - U (~ 1.2% Enriched)

- **LWR**
  - U (depleted)

- **FR**
  - Am, Np

- **PUREX**
  - MA partitioning

- **Disposal**

- **Recovery of FPs**

- **Storage ~ 100 years**

FPs

- Pu

Cm
### Advantages
- Use of natural fuels only
- 140 tons U consumption during reactor life
- High burnup of Th ~ 100 GWd/t

### Disadvantage
- Low $k_{eff}$ ~0.9 and gain nearly 10 with Pb target
- Accelerator power ~ 60 MW for a 200 MWe ADS

### Fuelling Scheme
- Initial fuel: Nat. U & Th
- Normal refuelling of U bundles (~ 7 GWd/t)
- Th will reside longer
  - $^{233}$U generation adds reactivity
  - Compensate by replacing some U by Th
- Th increases and U decreases
- Ultimately fully Th core
  - In situ breeding and burning Th

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Thorium utilisation in PHWR - ADS: Once through mode

![Diagram showing spallation target, subcritical reactor, 1-2 GeV proton accelerator, and the fuel cycle process.](image)
Rediscovering PHWRs

- Sustained energy production by effective utilisation of both fissile & fertile elements.
- Versatile fuelling options
- Technology for world wide users
  - New entrants
  - Utilisation of reprocessed fuel from LWRs

Possibility of India-Canada co-operation in spreading PHWR technology

Thanks for your attention