Introduction to Heavy Water Reactor

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Definition of Heavy Water Reactor

• Heavy water cooled and heavy water moderated:
  – Currently operating HWRs

• Light water cooled and heavy water moderated:
  – ACR 1000 (AECL, Canada)
  – AHWR (BARC, India)
  – CANDU-SCWR (AECL, Canada)
Overview on HWR Deployment
(2011.12.01, IAEA PRIS Database)

• HWR is the second most dominant reactor type

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Units in Operation</th>
<th>Units under Construction</th>
<th>Capacity in Operation (GWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light water reactor</td>
<td>368</td>
<td>58</td>
<td>335.1</td>
</tr>
<tr>
<td>Heavy water reactor</td>
<td>47</td>
<td>4</td>
<td>23.1</td>
</tr>
<tr>
<td>Gas cooled reactor</td>
<td>17</td>
<td></td>
<td>8.7</td>
</tr>
<tr>
<td>Fast reactor</td>
<td>2</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>Total</td>
<td>434</td>
<td>64</td>
<td>367.5</td>
</tr>
</tbody>
</table>

• Countries operating HWRs (7):
  Argentina, **Canada**, China, India, Korea, Pakistan, and **Romania**
Type of Operating HWRs (1)

• Pressure Tube Type
Type of Operating HWRs (2)

• Pressure Vessel Type
General Characteristics of Operating HWRs

- Heavy water cooled and heavy water moderated
- Coolant and moderator are physically separated
- Natural uranium fuel
- On-power refueling
- Two independent and diverse shutdown systems:
  - SDS1: absorber rods
  - SDS2: liquid poison injection
Characteristics of Pressure Tube Type HWRs (1)

- Dominant type of HWR: All commercial HWRs except Atucha 1 and 2 (Argentina)
**Characteristics of Pressure Tube Type HWRs (2)**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural uranium fuel</td>
<td>- No need for uranium enrichment. Fuel manufacturing is simple and easy.</td>
<td>- Generate higher volume of spent fuel</td>
</tr>
<tr>
<td></td>
<td>- Very little excess reactivity hold-up. Require very small reactivity worth for reactivity control system.</td>
<td>- Require short refuelling interval. Adopt on-power refuelling.</td>
</tr>
<tr>
<td></td>
<td>- High neutron economy. Minimize uranium resource consumption.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Easy for storage and handling of new and spent fuel with minimal criticality concerns.</td>
<td></td>
</tr>
<tr>
<td>On-power refuelling</td>
<td>- Reduce the outage time</td>
<td>- Need to maintain fuelling machines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Increases the possibility of coolant leakage by frequent opening of coolant boundary.</td>
</tr>
</tbody>
</table>
### Characteristics of Pressure Tube Type HWRs (3)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Separated low pressure and low temperature moderator | - Reactivity control mechanisms (RCM) penetrate the moderator, not coolant pressure boundary. RCMs are not affected by transient of coolant system. The event of control rod withdrawal is excluded inherently.  
- Large amount of moderator acts as an ultimate heat sink for accident. | - Need to maintain an additional moderator system.                                                                                           |
| Positive void reactivity coefficient                   |                                                                                                                                                                                                           | - Require fast acting reactor shutdown system for a loss of coolant accident. Employ two independent and diverse reactor shutdown systems. |
# Deployment Status of Pressure Tube Type HWRs

<table>
<thead>
<tr>
<th>Country</th>
<th>Model</th>
<th>Gross Power (MWe)</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina (1)</td>
<td>CANDU 6</td>
<td>648</td>
<td>Embalse</td>
</tr>
<tr>
<td>Canada (18)</td>
<td>PHWR</td>
<td>540-542</td>
<td>Pickering-1 and 4 to 8 (6)</td>
</tr>
<tr>
<td></td>
<td>CANDU 6</td>
<td>675-680</td>
<td>Gentilly-2, Point Lepreau (2)</td>
</tr>
<tr>
<td></td>
<td>PHWR</td>
<td>805-891</td>
<td>Bruce-3 to 8 (6)</td>
</tr>
<tr>
<td></td>
<td>PHWR</td>
<td>934</td>
<td>Darlington-1 to 4 (4)</td>
</tr>
<tr>
<td>China (2)</td>
<td>CANDU 6</td>
<td>700</td>
<td>Qinshan 3-1 to 3-2</td>
</tr>
<tr>
<td>India (21)</td>
<td>PHWR</td>
<td>100</td>
<td>Rajasthan-1 (1)</td>
</tr>
<tr>
<td></td>
<td>PHWR</td>
<td>200</td>
<td>Rajasthan-2 (1)</td>
</tr>
<tr>
<td></td>
<td>PHWR</td>
<td>220</td>
<td>Rajasthan-3 to 6, Kaiga-1 to 4, Kakrapar-1 to 2, Madras-1 to 2, Narora-1 to 2 (14)</td>
</tr>
<tr>
<td></td>
<td>PHWR</td>
<td>540</td>
<td>Tarapur-3 to 4 (2)</td>
</tr>
<tr>
<td></td>
<td>PHWR</td>
<td>700</td>
<td>Rajasthan-7, Kakrapar-3 to 4 (3) construction</td>
</tr>
<tr>
<td>Korea (4)</td>
<td>CANDU 6</td>
<td>622-730</td>
<td>Wolsong-1 to 4</td>
</tr>
<tr>
<td>Pakistan (1)</td>
<td>PHWR</td>
<td>137</td>
<td>Kanupp</td>
</tr>
<tr>
<td>Romania (2)</td>
<td>CANDU 6</td>
<td>706</td>
<td>Cernavoda-1 to 2</td>
</tr>
</tbody>
</table>
CANDU 6 (1)

- Designed by AECL (Candu Energy)
- Operated in Argentina (1), Canada (2), China (2), Korea (4), and Romania (2)
- 2 loops: Each loop has 2 SGs and 2 Pumps (figure of 8 configuration)
- Gross power: 622-730 MWe
- 380 fuel channels
- Core inlet/outlet temperatures: 266/310 °C
- Primary system pressure: 10 MPa(a)
- SG pressure/temperature: 4.7 MPa(a)/260 °C
- Outlet temperature and pressure of moderator system: 69 °C, 24 kPa(g)
CANDU 6 (2)
Pressure Vessel Type HWR: Atucha-1/2 (1)

- Designed by Siemens
- In operation and under construction in Argentina
- Core consists of vertical fuel channels within the pressure vessel
- Coolant and moderator are kept at nearly the same pressure
- The heat in the moderator water is used to preheat the feedwater (moderator outlet temperature is 210°C)
### Pressure Vessel Type HWR: Atucha-1/2 (2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Atucha-1</th>
<th>Atucha-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross power (MWe)</td>
<td>367</td>
<td>745</td>
</tr>
<tr>
<td>No. of channels</td>
<td>252</td>
<td>451</td>
</tr>
<tr>
<td>No. of coolant loops</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Coolant/moderator pressure (MPa)</td>
<td>11.3</td>
<td>11.5</td>
</tr>
<tr>
<td>Core inlet temperature (°C)</td>
<td>265</td>
<td>280</td>
</tr>
<tr>
<td>Core outlet temperature (°C)</td>
<td>299</td>
<td>312</td>
</tr>
<tr>
<td>Moderator outlet temperature (°C)</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>ID of pressure vessel (m)</td>
<td>5.360</td>
<td>7.368</td>
</tr>
<tr>
<td>SG pressure (MPa)</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>SG temperature (°C)</td>
<td>255</td>
<td></td>
</tr>
<tr>
<td>Containment</td>
<td>Steel sphere/concrete cylinder</td>
<td></td>
</tr>
</tbody>
</table>
Advanced HWR Designs - ACR1000 (1)

- Same as CANDU 6 primary system configuration
- Combines CANDU and PWR technology
- Light water coolant and heavy water moderator
- Low enrichment uranium fuel. Higher burnup and negative void reactivity coefficient
- Compact core design
- Containment with steel liner
- Adopt passive safety systems
  - Elevated reserve water system
  - Core make-up tanks
Advanced HWR Designs – AHWR (1)

- Being developed by BARC, India
- Combines existing PHWR and BWR technology
- Boiling light water coolant and heavy water moderator
- Vertical fuel channels
- $\text{Th-U}^{233} + \text{Th-Pu MOX fuel}$
- Coolant is circulated by natural circulation for normal operation
- Adopt many passive safety systems:
  - Gravity driven water pool
  - Isolation condenser for decay heat removal
  - Passive containment cooling system
Advanced HWR Designs – AHWR (2)
Advanced HWR Designs – CANDU-SCWR (1)

- SCWR (Super Critical Water Cooled Reactor)
  - Critical condition of water: 22.1 MPa(a), 374°C
  - High thermal efficiency
  - Thermal & fast spectrum
Advanced HWR Designs – CANDU-SCWR (2)

• Under development by AECL, Canada
• Similar to CANDU reactor but with the following differences:
  – Tighter lattice pitch to reduce heavy water cost
  – Light water coolant as supercritical conditions
  – Modified fuel channel design with internal insulation to accommodate the higher coolant pressure and temperature
HWR Fuel Cycle Flexibility

- HWR design with the most efficient neutron economy allows a high degree of fuel cycle flexibility
- Natural uranium
- Slightly enriched uranium (0.9-1.2%)
- Recovered uranium
- DUPIC (Direct Use of irradiated PWR fuel in Candu reactor) fuel cycle
- MOX fuel
- Thorium fuel cycle
IAEA TRS-407

  - Text book for HWRs
  - HWR evolution
  - Characteristics of HWRs
  - Economics of HWRs
  - Safety aspects of HWRs
  - HWR fuel cycles
  - Vision of advanced HWR designs
  - Parameters of the principal types of HWR

Recent IAEA Activities to Support HWR Technology Development

- **TWG**
  - TWG on Advanced Technologies for Heavy Water Reactors

- **CRP**
  - Benchmarking Severe Accident Computer Codes for Heavy Water Reactor Applications
  - Natural Circulation Phenomena, Modelling and Reliability of Passive Systems that Utilize Natural Circulation
  - Establishment of a Thermo-physical Properties Data Base for Materials of LWRs and HWRs
  - Prediction of Axial and Radial Creep in HWR Pressure Tubes

- **ICSP**
  - Inter-comparison of HWR Thermal-hydraulic Computer Codes for LBLOCA
  - Inter-comparison of HWR Thermal-hydraulic Computer Codes for SBLOCA
  - HWR moderator subcooling requirement

- **ICA**
  - the role of HWRs in the efficient utilization of fissionable resources
Recent and Planned Meetings to Support HWR Technology Development

- Workshop on Prediction of Axial and Radial Creep in HWR Pressure Tubes, 16-18 Nov. 2011, Vienna, Austria
- Technical Meeting on Fuel Design and Licensing of Mixed Cores for Water Cooled Reactors, 12 – 14 Dec. 2011, Vienna, Austria
- 4th Research Coordination Meeting of CRP on Benchmarking Severe Accident Computer Codes for Heavy Water Reactor Applications, 1 – 4 May 2012, Ottawa, Canada
- 13th Meeting of TWG on Advanced Technologies for Heavy Water Reactors, 18-20 June 2012, Vienna, Austria
- Course on Science and Technology of Super Critical Water Cooled Reactors, 16-21 July 2012, Hamilton, Canada
- Course on Natural Circulation Phenomena and Passive Safety Systems in Advanced Water Cooled Reactors, 23 – 27 July 2012, Corvallis, USA
- 1st Research Coordination Meeting of CRP on the Prediction of Axial and Radial Creep in HWR Pressure Tubes, 1 – 2 Nov. 2012, Vienna, Austria