Module 06
Boiling Water Reactors (BWR)

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Contents

• BWR Basics
• Technical Data
• Safety Features
• Reactivity Control
• Fuel Assemblies
• Reactor Pressure Vessel
• Development of BWR’s
• SWR-1000
• ABWR
BWR Basics

- H$_2$O as coolant and moderator
- Pressure in water/steam cycle: 70 bar (7 MPa)
- Boiling of water in the core
- Temperature about 300 ºC
- Steam transferred directly from core to turbine generator after passing steam/water separator
- Average power density in core: 50 kW/litre
- Burn-up: ca. 55.000 MWd/t U
- Thermal net efficiency: 34.1%
<table>
<thead>
<tr>
<th></th>
<th>Standard Unit Size 1</th>
<th>Standard Unit Size 2</th>
<th>Standard Unit Size 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal reactor output</td>
<td>MWth</td>
<td></td>
<td></td>
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<tr>
<td>Live steam pressure</td>
<td>bar</td>
<td></td>
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<tr>
<td>Live steam temperature</td>
<td>°C</td>
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<tr>
<td>Live steam flow rate</td>
<td>t/h</td>
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<tr>
<td>Number of fuel assemblies</td>
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<tr>
<td>Fuel rod array per assembly</td>
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<tr>
<td>Active height of core</td>
<td>mm</td>
<td></td>
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<tr>
<td>Average linear heat generation rate</td>
<td>W/cm</td>
<td></td>
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<tr>
<td>Number of control rods</td>
<td></td>
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<tr>
<td>Number of internal recirculation pumps</td>
<td></td>
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<tr>
<td>Pump drive motor rating</td>
<td>kW</td>
<td></td>
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<tr>
<td>Clear diameter of reactor pressure vessel</td>
<td>mm</td>
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<tr>
<td>Clear height of reactor pressure vessel</td>
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<tr>
<td>Clear diameter of containment</td>
<td>mm</td>
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<tr>
<td>Clear height of containment</td>
<td>mm</td>
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</table>
Example: The BWR Krümmel

- Built
  - 1984
  - by KWU
- 1260 MW_{e\,\text{net}}
- 3690 MW_{th}
Technical Data of the BWR Krümmel

• **Fuel assemblies:**
  - Number of fuel assemblies: 840
  - Total length: 4.47 m
  - Active length: 3.71 m
  - Lattice: 9 x 9 rods
  - Weight without shroud: 276 kg
  - Number of rods per assembly: 81
  - Positions for absorber fingers: 205

• **Fuel rods:**
  - Outer diameter 9.62 mm
  - Wall thickness 0.72 mm
  - Fuel: up to 4.02 % enriched UO$_2$, sintered to ceramic pellets of 92% theoretical density
  - Cladding material: Zircaloy 4 (99% Zr, Sn, Fe, Ni)
Technical Data of the BWR Krümmel

- **Control rods:**
  - Number of control rods: 205
  - Cross shaped absorber blades
  - Absorber material: B₄C and Hafnium
  - Absorber length: 3.66 m
  - Driven by electrical motor from bottom to top in - out in normal operation (speed 3 cm/s), total insertion time 122 s
  - Fast shut down hydraulically: Speed 150 cm/s, total insertion time 3.7 s

![ATI Logo](image)
Simplified Cross Section of a BWR
Flow Diagram of a BWR
BWR Cross Section - Details

1. Hochdruckteil der Turbine
2. Niederdruckteil der Turbine
3. Kondensator
4. Generator mit Erregermaschine
5. Zwischenüberhitzer
6. Kühlwasserleitungen
7. Frischdampf
8. Speisewasser
9. Sicherheitsbehälter
10. Reaktordruckbehälter
11. Reaktorkern
12. Umlaufpumpen
13. Steuerstäbe
14. Flursan
15. Brennelemente-Lagerbecken
16. Brennelemente-Wechselschneidemaschine
17. Druckabbausystem
18. Abluftkamin
Safety of BWRs

- In BWR’s steam bubbles have a negative reactivity feedback, if the steam fraction increases in the core the reactor power decreases.
- Two independent shut down systems
- 3 x 100% redundancy in safety systems
- Diverse functions for safety related actions
- Physical separation of safety relevant systems
- Five barriers between the fission products and the environment.
Cross Section of a BWR Containment

- As the pressure vessel is 1/3 taller than with PWR a full pressure containment would be too big.
- Therefore a pressure suppression system is provided.
Reactivity Control of BWRs

- **Control rods:** Are used for
  - normal start-up
  - power adjustment
  - operational shut down
  and for emergency shut down

- **Internal recirculation pumps:**
  - Increasing flow: increases power
  - Reducing flow: reduces power without moving control rods
  - Flow changes the water/steam ratio in the core - negative void coefficient
BWR Control Rods

- Cross shaped blades containing $\text{B}_4\text{C}$
- Enter the core from bottom
BWR Rod-Fuel-Assemblies

1 Lifting Bail
2 Upper Tie Plate
3 Fuel Rod
4 Spacer
5 Lower Tie Plate (Nose Piece)
6 Plenum
7 Active Fuel Zone
8 Water Rod
9 Overall Length
BWR Fuel Rod Geometry

- Druckfeder
- UO₂-Tabletten
- Hüllrohr aus Zircaloy 4
- Isoliertabletten
- UO₂-Tabletten

10 mm
BWR Fuel Pellet Details

obere Endkappe
Schweißnaht
Feder
Hüllrohr: $\varnothing a - 10 \text{ mm}$
$\varnothing d - 0,4 \div 0,9 \text{ mm}$
Isolierpellet (Al$_2$O$_3$)

aktive Brennstoffsäule
600 ÷ 3000 mm

Brennstoff: $\varnothing - 8 \text{ mm}$
$\varnothing h - \varnothing$
Spalt, radial: $\sim 0,10 \text{ mm}$
Isolierpellet
Schweißnaht
untere Endkappe

mit Dish
ohne Dish
Cross Section of BWR Cores

Fuel assemblies

- Source range incore detector assemblies: 4 4 4
- Intermediate range incore detector assemblies: 4 4 4
- Power range incore detector assemblies: 22 33 44
- Neutron sources: 5 5 5
- Alternative positions for neutron sources: 7 7 7
- Alternative positions for source or intermediate range detector assemblies: 4 4 5
- Control rods: 97 145 193
Refuelling Procedure

- PV is opened and internals removed
- Water level is increased to working platform
- Refuelling machine transfers fuel assembly under water
Reactor Pressure Vessel (BWR Krümmel)

- **Basic data:**
  - Height: 22.05 m
  - Inner diameter: 6.78 m
  - Design pressure: 87.3 bar
  - Wall thickness: 17 cm
  - Wall thickness bottom: 23.4 cm
  - Total weight: 790 t
**Reactor Pressure Vessel Cross Section**

- **Vessel head spray system**
- **Steam outlet nozzle with flow limiter**
- **Reactor pressure vessel**
- **Steam separators**
- **Feedwater inlet nozzle**
- **Active zone top end**
- **Control rods**
- **Active zone bottom end**
- **Internal axial-flow coolant recirculation pump**

**Reactor pressure vessel head**
- **Steam dryer**
- **Normal water level**
- **Core flooding system**
- **Core shroud head**
- **Upper core grid plate**
- **Core shroud**
- **Fuel assemblies**
- **Lower core grid plate**
- **Control rod guide tubes**
- **Control rod drives**
Zwentendorf - the Austrian BWR Solution.....
Same Design as NPP Zwentendorf

- **BWR Brunsbüttel:**
  - Energy production since 7/76: 110.8 TWh
  - Life time availability: 55.1%

- **BWR Isar 1:**
  - Energy production since 12/77: 161.7 TWh
  - Life time availability: 75.1%

- **BWR Philippsburg 1:**
  - Energy production since 7/79: 154 TWh
  - Life time availability: 75.3%
Overall data:
- Thermal power: $3370 \text{ MW}_{th}$
- Electrical power: $1254 \text{ MW}_{e}$
- Efficiency: 37.2%

Reactor core:
- Number of fuel assemblies: 664
- Active core height: 3.0 m
- Total uranium weight: 136 t
- Enrichment: 3.5%
- Discharge burn-up: 45 000 MWd/t
- Power density: 51 kW/litre

Reactor pressure vessel:
- Inner height: 23.35 m
- Inner diameter: 7.12 m
- Operational pressure: 75 bar
- Design pressure: 88 bar
- Recirculation pumps: 8
Emergency Condensers
The emergency condensers serve to remove heat from the reactor upon a drop in RPV water level. The tubes of the emergency condensers are submerged in the core flooding pools and are filled with water when the water level in the RPV is normal. If reactor water level should drop, the water drains from the tubes. Steam from the reactor then enters the tubes and condenses, the resulting condensate flowing by gravity down into the RPV. The emergency condensers come into action automatically without any need for electric power or switching operations.

Containment Cooling Condensers
If the containment temperature should rise due to a release of steam into the drywell atmosphere, the containment cooling condensers remove heat from the containment to the water of the shielding/storage pool located above it. These components require neither electric power nor switching operations to begin functioning.

Core Flooding System
When reactor pressure has been sufficiently reduced by depressurization, water from the core flooding pools flows by gravity down into the RPV through flooding lines equipped with self-acting check valves.

Passive Pressure Pulse Transmitters
The passive pressure pulse transmitters are small heat exchangers that operate according to the same principle as the emergency condensers. Upon a drop in reactor water level, pressure builds up on their secondary sides. This pressure is then used to initiate safety-related switching operations (for reactor scram, automatic depressurization and containment isolation at the main steam lines), without any need for electric power or I&C signals.
SWR-1000 Passive Safety Systems

- **Emergency condensers:**
  - If the water level drops in the PV, water from the core flooding pool flows into the PV while steam is condensed **without external power**

- **Containment cooling condensers:**
  - If temperature raises, heat is removed to the shielding/storage pool **without external power**
SWR-1000 Passive Safety Systems

• Core flooding system:
  - When reactor pressure is low water from „core flooding pool“ flows by gravity into the PV

• Passive pressure pulse transmitters:
  - These are small heat exchangers:
  - If water level drops pressure increases on secondary side, this pressure delivers safety related pulses (i.e. scram the reactor) without external power
SWR-1000 Containment

- Safety systems operate on gravity and natural convection
- Extended grace period of 3 days without intervention
- Any core melt remains inside containment
Advanced Boiling Water Reactor
ABWR (GE, Hitachi, Toshiba)

- Simplified construction (only 48 month)
- Simplified operation
- More efficient, less waste
- Licensed in USA Japan and Taiwan

Overall data:
- Thermal power: 3926 MW_{th}
- Electrical power: 1356 MW_{e}
- Efficiency: 37.2 %
ABWR Technical Data

• Reactor core:
  - Number of fuel assemblies: 872
  - Active core height: 3.71 m
  - Total uranium weight: 136 t
  - Enrichment: 3.2 %
  - Discharge burn-up: 32 000 MWd/t
  - Power density: 50.6 kW/litre

• Reactor pressure vessel:
  - Inner height: 21 m
  - Inner diameter: 7.1 m
  - Operational pressure: 73.1 bar
  - Design pressure: 88 bar
  - Recirculation pumps: 10
ABWR Safety Features

- Inherent safety: Negative void and Doppler coefficient
- High operating performance, load following possible
- High plant efficiency, short construction period
- Mostly automated operation
In an ABWR, coolant water is recirculated inside the reactor pressure vessel (RPV) by reactor internal pumps installed within the vessel itself.
• Emergency Core Cooling System (ECCS)

• High Pressure Core Flooder (HPCF) and Reactor Core Isolation Cooling (RCIC) Systems

• Low Pressure Flooder (LPFL) System

• Automatic-Depressurization System
Internet Links

- World Nuclear: www.world-nuclear.org
- KKW Krümmel: www.kernkraftwerk-kruemmel.de/kraftwerk/index.html
- Types of Nuclear Reactors: hyperphysics.phy-astr.gsu.edu/hbase/nucene/reactor.html#c3
- Nuclear Regulatory Commission: www.nrc.gov
- Nuclear Energy Institute: www.nei.org
- Atominstitute of the Austrian Universities: www.ati.ac.at
- Framatome - ANP: www.framatome-anp.com