Nuclear Fission

- Neutron interacts with uranium atom causing fission
- Several neutrons are formed in fission which go on to cause other fissions
- Energy is released

Nuclear Fuel Cycle

Atomic Particles

- Carbon 12
- Protons
- Neutrons
- Electrons
NEUTRON HISTORIES IN THERMAL REACTOR

POWER FROM URANIUM

U-235 → 1 kg produces $8 \times 10^{12}$ joules
(80 terajoules)
≈ 3 million kg of coal

1000MW power station

↓

3.5 kg of uranium per day

2.5 kg to lukewarm cooling water

1.5 kg useful energy

DISTRIBUTION OF ENERGY FROM FISSION
OF 1 kg OF U-235

General requirements for reactor coolants

Ideal coolant would have:
- High specific heat capacity ($c_p$)
- High heat transfer coefficient
- Good nuclear properties
  - low neutron absorption
  - no radioactive isotopes formed
  - appropriate moderation properties (none in fast reactor)
- Low cost and easy availability
- Compatibility with reactor circuit
- Easily pumped – low viscosity

NO COOLANT FULFILLS ALL THESE REQUIREMENTS
Figure of merit for coolant I

Cross sectional Area $A$

Figure of merit $D$ defined for lower pumping power $P$ for given $L$, $A$, $M$, $Q$ and temperature rise $\Delta T$.

Pumps deep channel given by:

$\Delta T = \frac{1}{\rho \cdot \frac{A}{D}} \frac{M^2}{Q}$

$P = \text{friction factor}$

$P$ proportional to $\text{Re}^{-0.2} = \left( \frac{MD}{A \cdot \text{Re}} \right)^{-0.2}$

Figure of merit for coolant II

Pumping power $P$

$P = \Delta T \frac{M^2}{A} \frac{2 \pi L}{D}$

Heat transferred $Q$ given by

$Q = \frac{M}{\text{Re}} \cdot \Delta T$

Thus,

$P = \frac{1}{\rho \cdot L^3} \left( \frac{Q^2}{A^2 \cdot \text{Re} \cdot \Delta T} \right) \frac{2 \pi L}{D}$

Figure of merit for coolant III

$P = \frac{MD}{A \cdot \text{Re}} = \left( \frac{MD}{A \cdot \text{Re}} \right)^{0.2}$

Thus, $P$ is proportional to:

$\frac{M^2}{A \cdot \Delta T} \left( \frac{Q^2}{A^2 \cdot \text{Re} \cdot \Delta T} \right) \frac{2 \pi L}{D}$

For fixed $A$, $L$, $Q$ and $\Delta T$, $P$ is a minimum when

$\frac{M^2}{A \cdot \Delta T} = \frac{Q^2}{A^2 \cdot \text{Re} \cdot \Delta T}$

is a minimum

or when FIGURE OF MERIT $F = \frac{M^2}{Q^2 \cdot \text{Re}}$ is a MAXIMUM

Figure of merit for coolant IV

Table 3.1 Physical Properties of Reactor Coolants

<table>
<thead>
<tr>
<th>Coolant</th>
<th>Density (g/cm³)</th>
<th>Thermal Conductivity (W/m·K)</th>
<th>Thermal Diffusivity (m²/s)</th>
<th>Thermal Expansion Coefficient (1/°C)</th>
<th>Viscosity (cP)</th>
<th>Heat of Oxidation (kJ/kg)</th>
<th>Shock Wave Absorption (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light water</td>
<td>1.0</td>
<td>2.7</td>
<td>0.012</td>
<td>5.0</td>
<td>0.008</td>
<td>5.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Heavy water</td>
<td>1.1</td>
<td>2.5</td>
<td>0.015</td>
<td>5.3</td>
<td>0.010</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Sodium</td>
<td>10.3</td>
<td>2.0</td>
<td>0.02</td>
<td>5.0</td>
<td>0.1</td>
<td>1.1</td>
<td>0.001</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.02</td>
<td>1.5</td>
<td>0.01</td>
<td>5.0</td>
<td>0.005</td>
<td>5.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Helium</td>
<td>0.027</td>
<td>2.0</td>
<td>0.005</td>
<td>1.2</td>
<td>0.02</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>1.5</td>
<td>1.5</td>
<td>0.01</td>
<td>5.0</td>
<td>0.05</td>
<td>5.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

A Whirl (°C) is required for a minimum of $1$.

Source: Oblique (199).
Water as a reactor coolant I

- Single phase light water has:
  - High availability and low cost
  - High Figure of Merit
- but problems are:
  - Low boiling point. High pressure required to achieve even moderate thermodynamic efficiencies
  - Neutron absorption relatively high – enriched uranium required for light water reactors
  - Corrosive at high temperature – special containment materials required. Strict control of water chemistry required.
- Single phase heavy water (D₂O) has lower neutron absorption and natural uranium can be used. Expensive!

Water as a reactor coolant II

- Boiling light water advantages
  - Direct steam generation in reactor (no steam generators required)
  - Can operate at lower pressure for same thermodynamic efficiency
- Boiling light water disadvantages
  - Radiolysis problem. H₂O splits into H₂ and O₂ which enter steam phase where recombination is much slower than in liquid. O₂ causes stress corrosion cracking.
  - Steam circuit slightly radioactive.

Types of water cooled reactors

- Pressure vessel types
  - Pressurised water reactor (PWR)
  - Boiling water reactor (BWR)
- Pressure tube types
  - CAnadian Deuterium Uranium (CANDU)
  - Boiling water, graphite moderated direct cycle reactor (RBMK)
- Integral water reactors
  - Marine reactor
Pressurised Water reactor (PWR) I
Schematic diagram

Pressurised Water reactor (PWR) II
Typical four-loop station

Pressurised Water reactor (PWR) III
Fuel design
Fuel rod consists of uranium dioxide pellets in (pressurised) zirconium alloy (zircalloy) can.

Typical bundle of fuel rods: 17 x 17 12 ft (3.66 m) rods on a square pitch.

Pressurised Water reactor (PWR) IV
AP1000 Schematic
Pressurised Water reactor (PWR) IV
Passive cooling in AP600

Boiling water reactor I
Typical flow circuit

Boiling water reactor II
Typical fuel element

CANDU Reactor I
Flow circuit
CANDU Reactor I
Fuel element

- Natural uranium (no enrichment)
- Heavy water
- Investment high
- Pressure tube reactor (problems with Pressure tubes)

RBMK Reactor

Integral pressurised water reactor
Marine applications

Conclusions

- Light water most popular coolant despite problems (high pressure, corrosion, neutron absorption)
- PWR most popular reactor and likely to be the main type for the future
- BWR becoming competitive in new versions
- CANDU has short construction time (avoids pressure vessel, off-site manufacture)