NTEC Module: Water Reactor Performance and Safety

Lecture 1: Introduction to water reactors

G. F. Hewitt

Imperial college London

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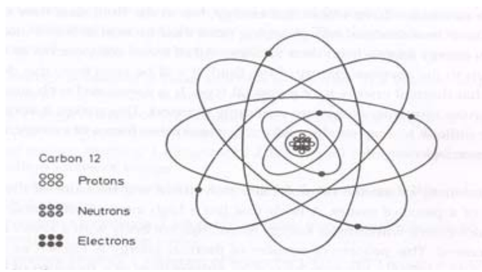
ATOMIC PARTICLES



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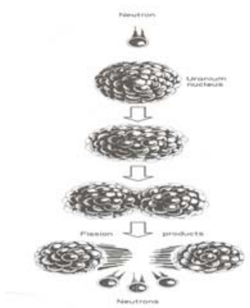
NUCLEAR FISSION

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



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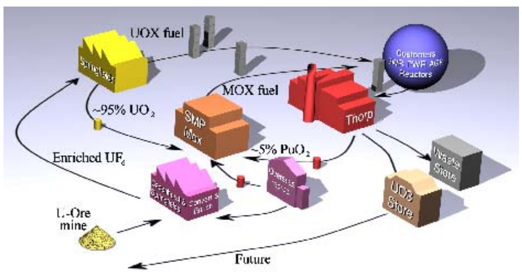
NUCLEAR FUEL CYCLE



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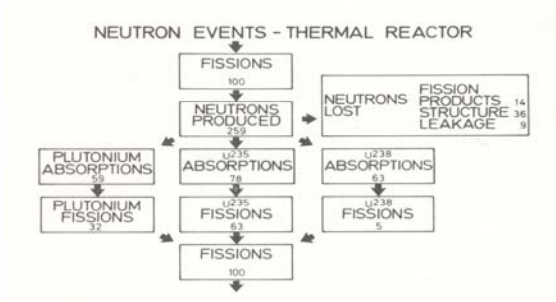
NEUTRON HISTORIES IN THERMAL REACTOR



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POWER FROM URANIUM

U-235 → 1 kg produces 8×10^{13} joules

(80 terrajoules)

≈ 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

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

	Energy (10^{12} J)
Fission products	64
Fission neutrons	2
Prompt γ radiation	3
Fission product decay	
β radiation	3
γ radiation	3
Neutrinos	5
Total	80

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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

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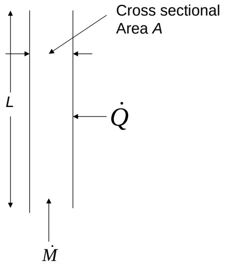
Figure of merit for coolant I



"Figure of merit" defined for *lowest* pumping power P for given $L, A, \dot{M}, \dot{Q}$ and temperature rise ΔT.

Pressure drop across channel given by :

$$\Delta p = \frac{1}{\rho}\left(\frac{\dot{M}}{A}\right)^2 \frac{2fL}{D}$$

f = friction factor

f proportional to $\mathrm{Re}^{-0.2} = \left(\frac{\dot{M}D}{A\rho}\right)^{-0.2}$

Figure of merit for coolant II

Pumping power P

$$P = \Delta p \dot{V} = \Delta p \dot{M} / \rho$$

$$P = \frac{1}{\rho^2}\left(\frac{\dot{M}^3}{A^2}\right)\left(\frac{2fL}{D}\right)$$

Heat transferred $\dot{Q}$ given by

$$\dot{Q} = \dot{M} c_p \Delta T$$

Thus;

$$P = \frac{1}{\rho^2 A^2}\left(\frac{\dot{Q}^3}{{c_p}^3 \Delta T^3}\right)\left(\frac{2fL}{D}\right)$$

Figure of merit for coolant III

$$f \propto \mathrm{Re}^{-0.2} = \left(\frac{\dot{M}D}{A\eta}\right)^{-0.2} = \left(\frac{\dot{Q}D}{Ac_p\Delta T\eta}\right)^{-0.2}$$

Thus, P is proportional to:

$$\frac{2L}{A^{1.8}D^{1.2}}\left(\frac{\dot{Q}^{2.8}}{\Delta T^{2.8}}\right)\frac{\eta^{0.2}}{{c_p}^{2.8}\rho^2}$$

For fixed $A, L, \dot{Q}$ and ΔT, P is a minimum when

$$\frac{\eta^{0.2}}{{c_p}^{2.8}\rho^2} \text{ is a minimum}$$

or when FIGURE OF MERIT $F = \frac{c_p^{2.8}\rho^2}{\eta^{0.2}}$ is a MAXIMUM

Figure of merit for coolant IV

Table 3.1 Physical Properties of Reactor Coolants

Coolant	Melting point (°C)	Boiling point (°C)	Physical properties given at T (°C)	Physical properties given at p (atm)	Density (kg/m³)	Viscosity [Ns/m² (× 10⁶)]	Specific heat (kJ/kg °C)	Thermal conductivity (W/m °C)	Figure of merit	Macroscopic thermal neutron absorption cross section (cm⁻¹)
Light water	0	100	270	54	767	102	5.14	0.059	53	0.017
Heavy water	4	101	270	54	845	113	5.27	0.049	67	2.8×10^{-5}
Sodium	98	883	550	1	817	230	1.26	6.1	1	0.011
p-Terphenyl	213	427	400	1	880	100	2.2	0.013	6.5	0.008
Helium	−272	−269	450	40	3.08	36	5.2	0.028	1.1×10^{-3}	2×10^{-9}
Carbon dioxide	−57	−78	450	40	29.5	30	1.2	0.07	1.7×10^{-3}	10^{-7}

α Value $\frac{C_p^{2.8}\rho^2}{\mu^{0.2}}$ Relative to sodium (= 1).
Source: Etherington (1958).

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 (D_2O) has lower neutron absorption and natural uranium can be used. Expensive!

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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. H_2O splits into H_2 and O_2 which enter steam phase where recombination is much slower than in liquid. O_2 causes stress corrosion cracking.
  - Steam circuit slightly radioactive.

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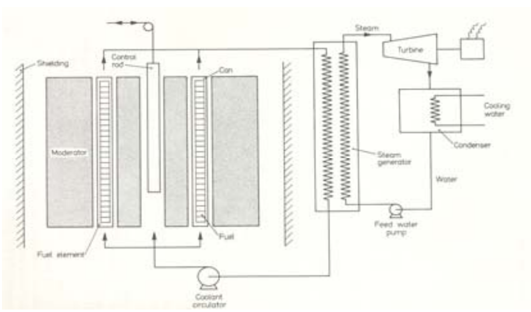
BASIC COMPONENTS OF A NUCLEAR REACTOR



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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

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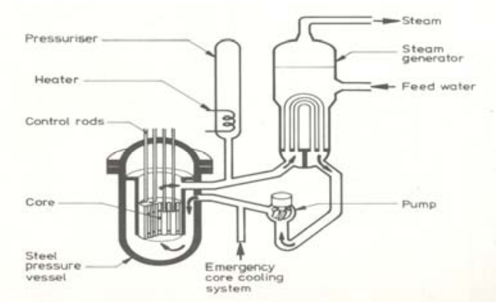
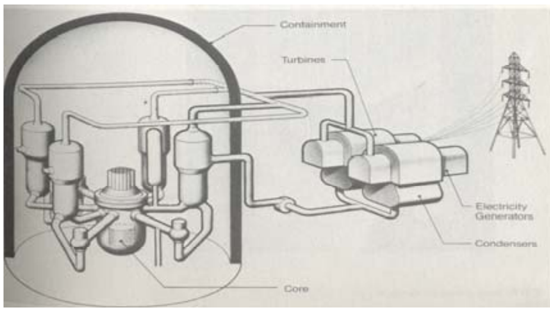
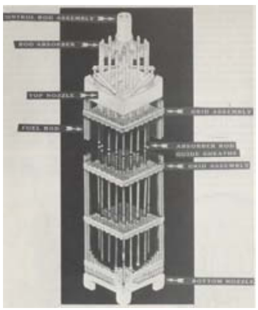
Pressurised Water reactor (PWR) I
Schematic diagram



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



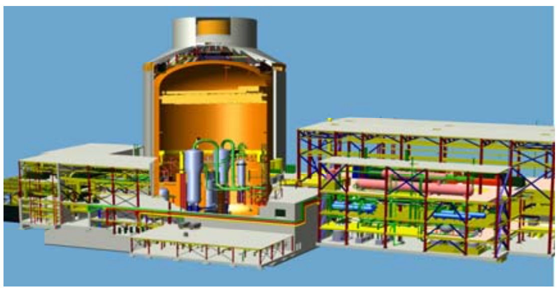
Pressurised Water reactor (PWR) III
Fuel design



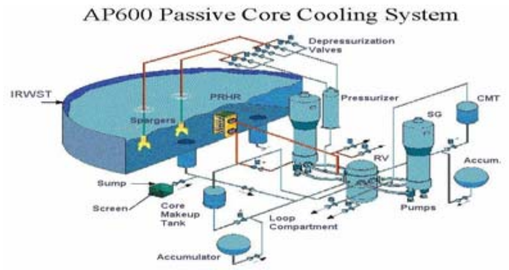
Fuel rod consists of uranium dioxide pellets in (pressurised) zirconium alloy (zircalloy) can.

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



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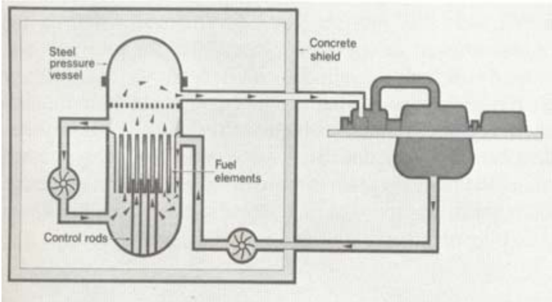
Boiling water reactor I
Typical flow circuit



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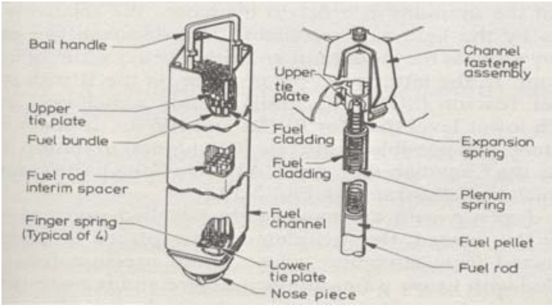
Boiling water reactor II
Typical fuel element



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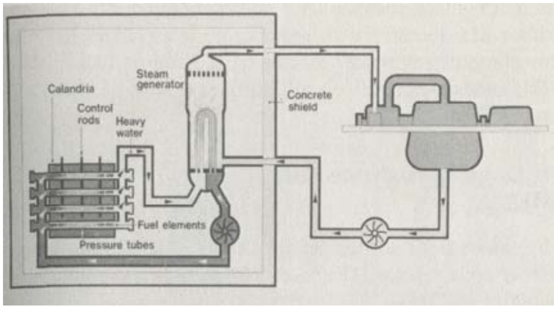
CANDU Reactor I
Flow circuit



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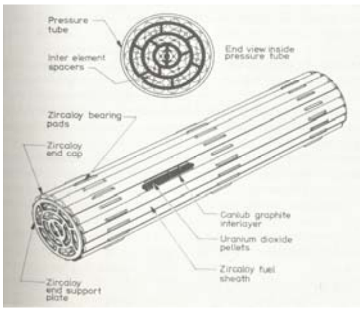
CANDU Reactor I
Fuel element

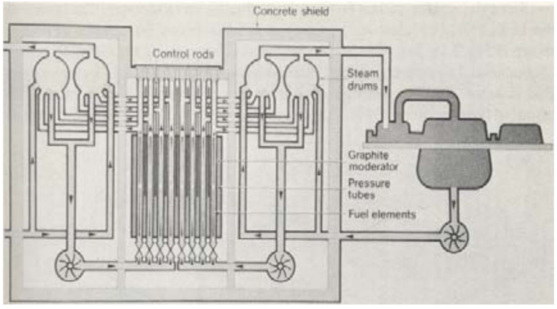


Natural uranium
(no enrichment)

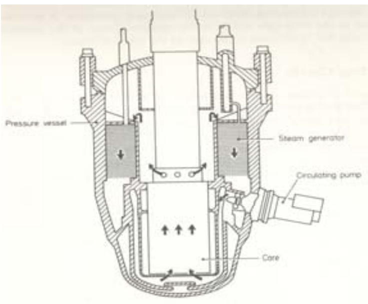
Heavy water
investment high

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)