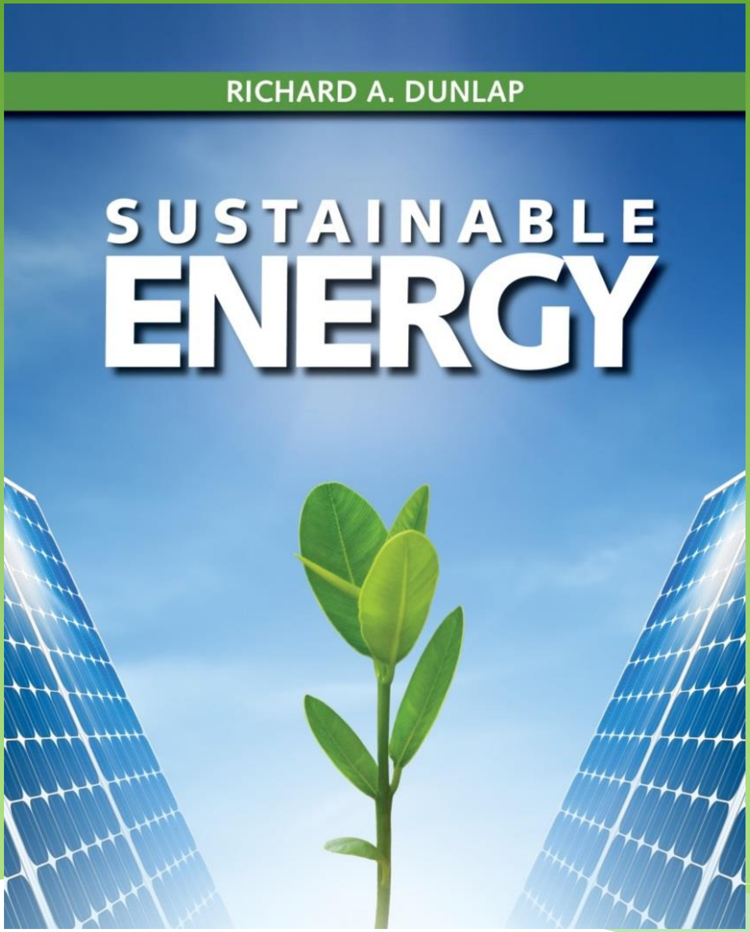
Sustainable Energy



Chapter 6

* Energy from Nuclear Fission

CENGAGE Learning

Learning Objectives

- The relationship between nuclear binding energy and the mechanism for extracting nuclear energy by fission.
- Differences between spontaneous and induced fission and the importance of the Coulomb barrier.
- Fission processes in the isotopes of uranium.
- Critical reactions and thermal reactor control.
- The types of thermal fission reactors and their properties.
- The world use of fission energy.
- The availability and production of uranium worldwide.
- Nuclear reactor safety and the reasons and consequences of nuclear accidents.
- Methods for nuclear waste disposal.
- New designs of thermal reactors with improved safety features.
- The principles of operation and advantages of a fast breeder reactor.

Fission energy

Nuclear reactions can be endothermic or exothermic and either require additional energy to proceed or produce excess energy, respectively.

Reactions in which the total mass increases are endothermic and reactions where the total mass decreases are exothermic.

Changes in the mass represent changes in the nuclear binding energy.

Exothermic reactions

Exothermic reactions can be used to produce useful energy in the form of heat which can be used to generate electricity.

Fission reactions

Fission reactions represent the breaking up of nuclei into lighter components.

The *B*/*A* curve shows that the fission of heavy nuclei is exothermic.

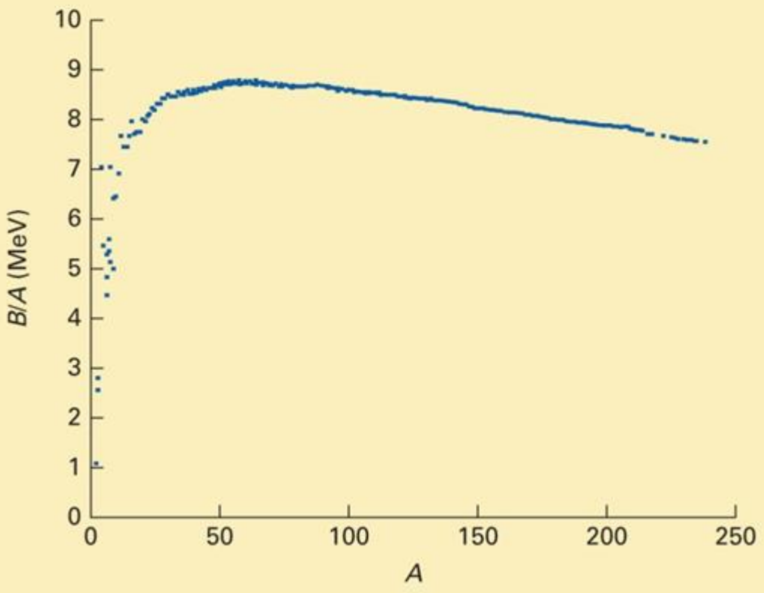


Figure 6.1: Average binding energy per nucleon as a function of the number of nucleons.

Based on R.A. Dunlap An, Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004)

Energy per fission

^{238}U is an example of a heavy nucleus that produces energy when undergoing fission.

^{238}U has binding energy of about 7.57 MeV per nucleon for a total nuclear binding energy of

$$(238)\times(7.57\ \text{MeV}) = 1800\ \text{MeV}$$

If a ^{238}U nucleus breaks into two nuclei with 119 nucleons then each fission fragment will have about 8.50 MeV per nucleon for a total binding energy of

$$(238)\times(8.50\ \text{MeV}) = 2020\ \text{MeV}$$

For an energy release of

$$(2020\ \text{MeV}) - (1800\ \text{MeV}) = 220\ \text{MeV per fission}$$

Coulomb barrier

Neutrons and protons are trapped inside the potential well caused by the strong interaction.

Outside the well protons are subject to the repulsive Coulombic force.

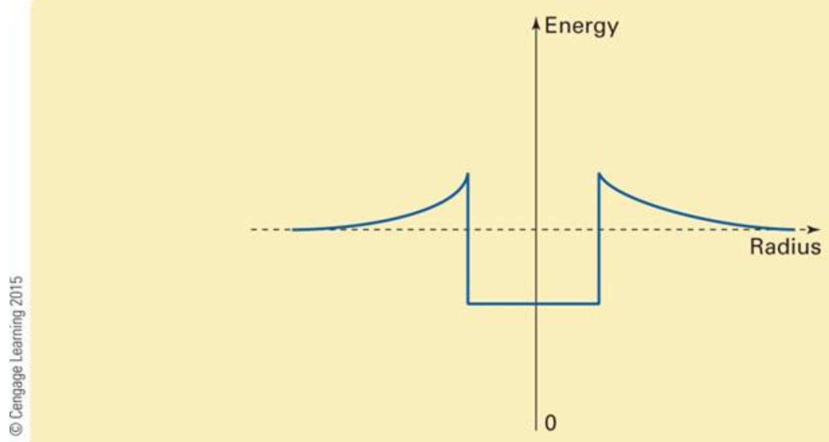


Figure 6.2: Simplified model of the potential energy of a nucleus as a function of distance from the origin. The deep square well results from the attractive strong interaction, and the portion outside the square well results from the repulsive Coulombic interaction for the protons.

Spontaneous fission

Spontaneous fission is a very slow process because the positively charged fission fragments must overcome the Coulomb barrier. This requires about 6 MeV of energy.

The probability of fission can be greatly increased by providing additional energy to the nucleus.

One convenient way of providing energy is by neutron bombardment.

Isotopes of Uranium

Uranium and Thorium are the only two naturally occurring elements that are suitable for nuclear fission.

All current reactors use uranium as a fuel.

Isotopes of uranium

- ^{235}U 0.72% naturally abundant
- ^{238}U 99.28% naturally abundant

Neutron reactions with uranium

Excess energy becomes available when a uranium nucleus is bombarded with a low energy neutron

$$n + {}^{235}U \rightarrow {}^{236}U + 6.54\ \text{MeV} \qquad (6.2)$$

$$n + {}^{238}U \rightarrow {}^{239}U + 4.78\ \text{MeV} \qquad (6.1)$$

Fissile and non-fissile nuclei

^{235}U is fissile because the energy released in the neutron reaction is greater than the Coulomb barrier and this will cause fission to occur (referred to as induced fission)

^{238}U is non-fissile because the energy release in the neutron reaction is less than the Coulomb barrier and fission will not occur

Typical fission reactions

Fissile ^{235}U can be used as a fission reactor fuel.

A typical fission process might be

$$n + {}^{235}U \rightarrow {}^{236}U \rightarrow {}^{137}I + {}^{96}Y + 3n \qquad (6.3)$$

The left over neutrons (in this case three of them) are explained by the Segrè plot - heavy nuclei require a greater N/Z ratio than lighter nuclei to be stable.

Thus when a heavy nucleus breaks into two lighter nuclei neutrons will be left over.

These neutrons are what fuel further induced fission processes and create a chain reaction.

Segrè plot

Based on R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, (2004).

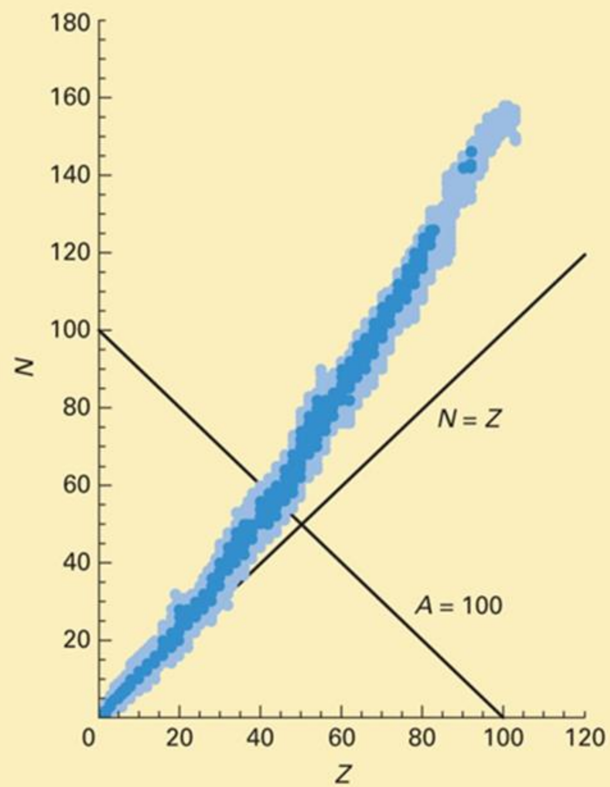


Figure 5.1: Segrè plot of stable nuclei (dark blue area) and unstable nuclei (light blue area).

Fission yield

The fission yield is the distribution of the sizes of the fission fragments.

Typically one fragment has about 90 nucleons and one fragment has about 140 nucleons.

These fragments almost always have more neutrons than required for a stable nucleus and they decay by β decay until they are stable.

Graph of fission yield

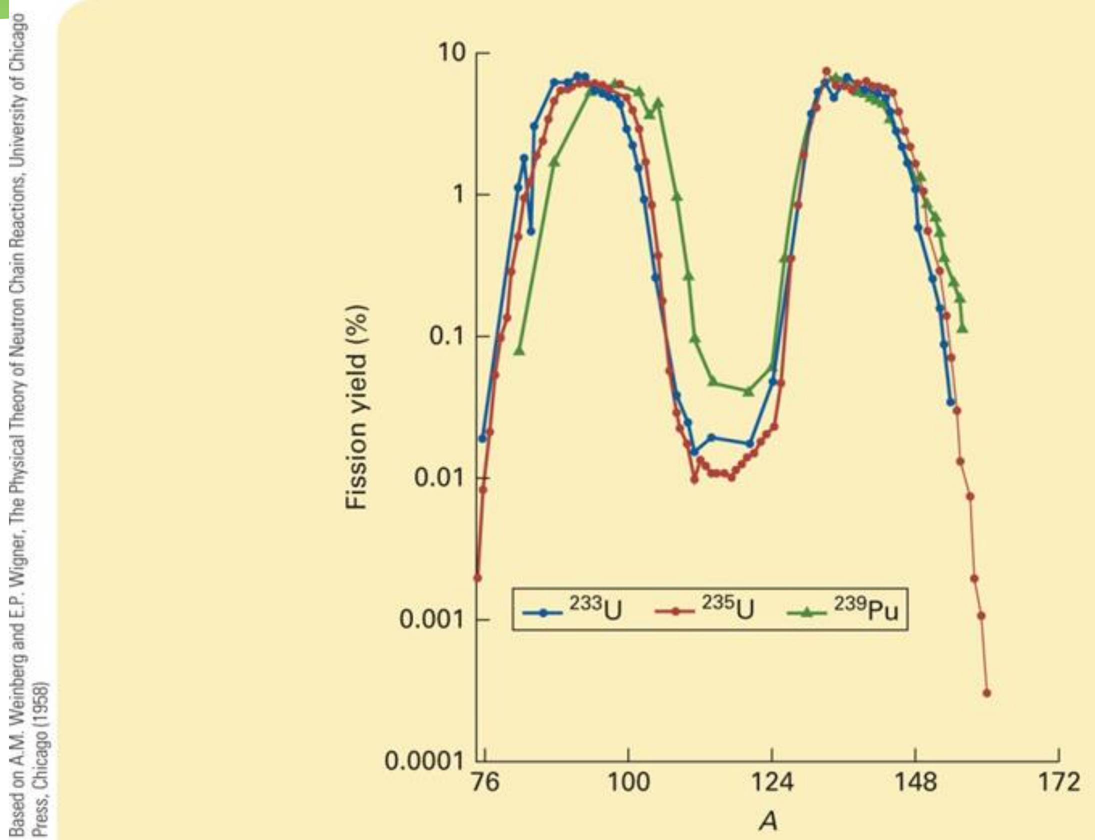


Figure 6.3: Fission yield for some fissile nuclei.

Stable chain reaction in uranium

If exactly one fission neutron goes on to induce another fission then the chain reaction will be stable.

If, on the average, less than one fission neutron induces further fissions, then the reaction will die out.

If, on the average, more than one fission neutron induces further fissions, then the reaction will be uncontrolled.

We need to insure that the chain reaction is stable.

What happens to the neutrons?

A neutron can undergo one (or more) of several processes

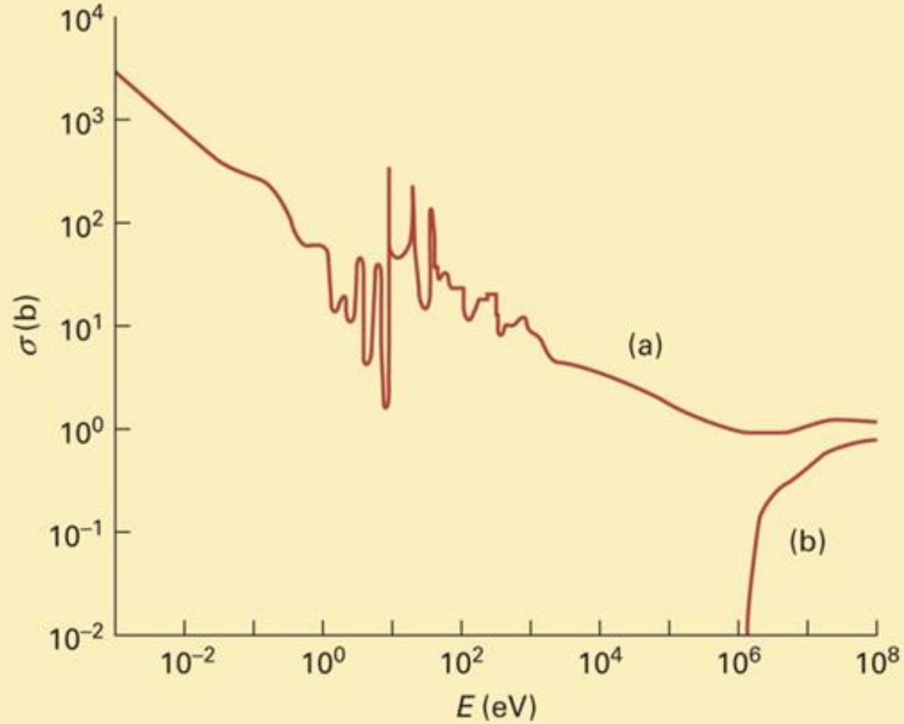
1. It can be absorbed and induce fission

2. It can be absorbed and be captured by undergoing the (n,γ) reaction

3. It can exit from the uranium without undergoing reactions 1 or 2

4. It can scatter from a nucleus and lose energy and still undergo reactions 1, 2, or 3

Fission cross sections for ^{235}U and ^{238}U



Based on R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004)

Figure 6.4: Fission cross sections in barns for (a) ^{235}U and (b) ^{238}U nuclei. The cross section is the apparent area of a uranium nucleus as seen by an approaching neutron and is a measure of the probability that a reaction will occur.

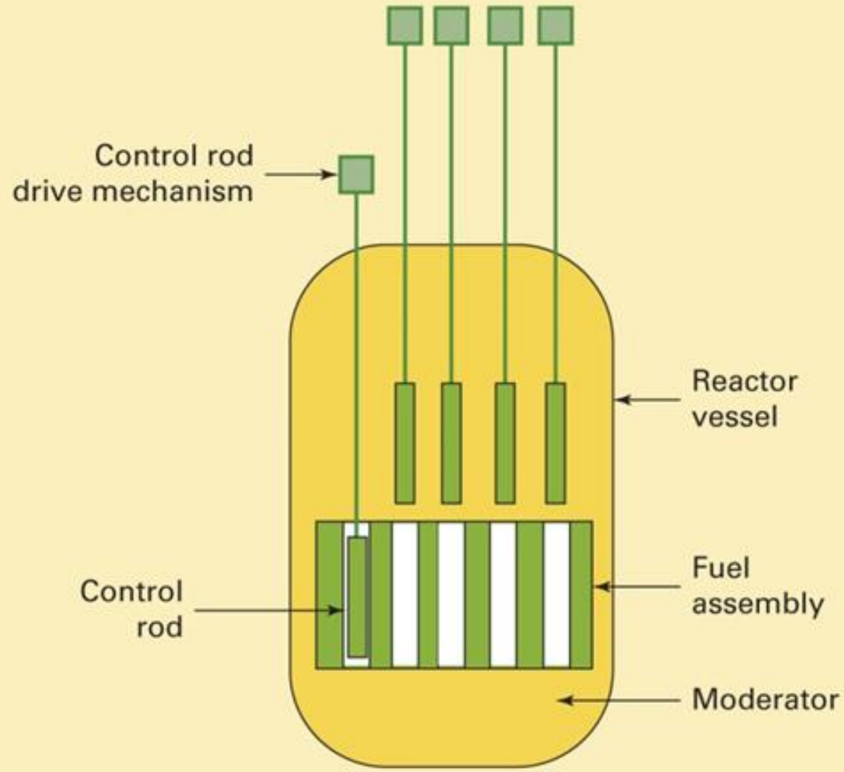
The best way to induce fission

The best way of inducing fission is to allow a neutron to be incident on a ^{235}U nucleus at very low energy.

Neutrons are emitted with energies around 2 MeV so they need to be slowed down - this reactor design is a thermal neutron reactor.

This situation is acheived by the design of the reactor

Typical fission reactor design



Based on from R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004)

Figure 6.5: Design of a thermal nuclear reactor core showing the fuel elements, the control rods, and the moderator.

Important components of the fission reactor

1. fuel assembly - mixture of ^{235}U and ^{238}U

2. moderator - material that will slow down neutrons as them travel from one fuel element to the next

3. control rods - material that absorbs neutrons to prevent them from reaching another fuel element

Fission reactor control

We need to insure that exactly 1 neutron induces another fission in order to create a controlled chain reaction.

Fission reactions are much too fast to control by moving control rods.

Delayed neutrons

Fission fragments are not β stable.

Sometimes a fission fragments releases a neutron rather than undergoing β decay.

This occurs very slowly.

Control of these delayed neutrons allows for control rods to be adjusted to maintain a controlled chain reaction.

Delayed neutron emission from a fission fragment

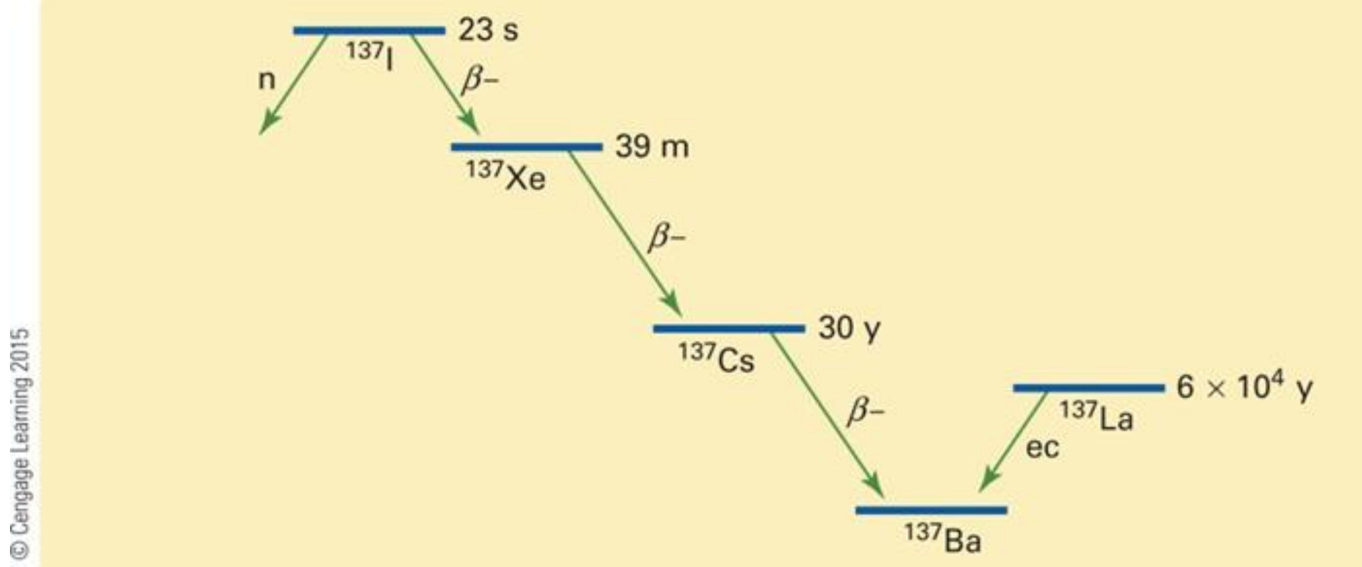


Figure 6.6: β decay of a fission fragment with 137 nucleons (^{137}I) to β stable ^{137}Ba showing delayed neutron emission from ^{137}I.

Types of fission reactors

Different types of fission reactors differ in the material that is used for the moderator and the way in which heat is extracted from the reactor.

Moderator materials

An effective moderator material must

1. be fairly dense (to have a high density of nuclei for reactions)

2. be comprised of light nuclei (to maximize the energy transfer during collisions with neutrons)

3. not absorb neutrons but merely slow them down

4. not produce hazardous materials during reactions with neutrons

5. be relatively nontoxic, inexpensive and chemically stable

Acceptable moderator materials

Commercial power reactors use one of three moderator materials

- H_2O
- D_2O
- graphite

Heat transport methods

Heat may be transported out of the reactor to operate turbines using the following methods

- Boiling water reactor - where the water which cools the reactor boils to produce stem to drive the turbine
- Pressurized water reactor - where the water used to cool the reactor is kept under pressure and transfers its heat to water which boils by means of a heat exchanger
- Air cooled reactors - where air is used to cool the reactor and transfers heat to water through a heat exchanger

Schematic of a boiling water reactor

Water is used as both the moderator and the coolant

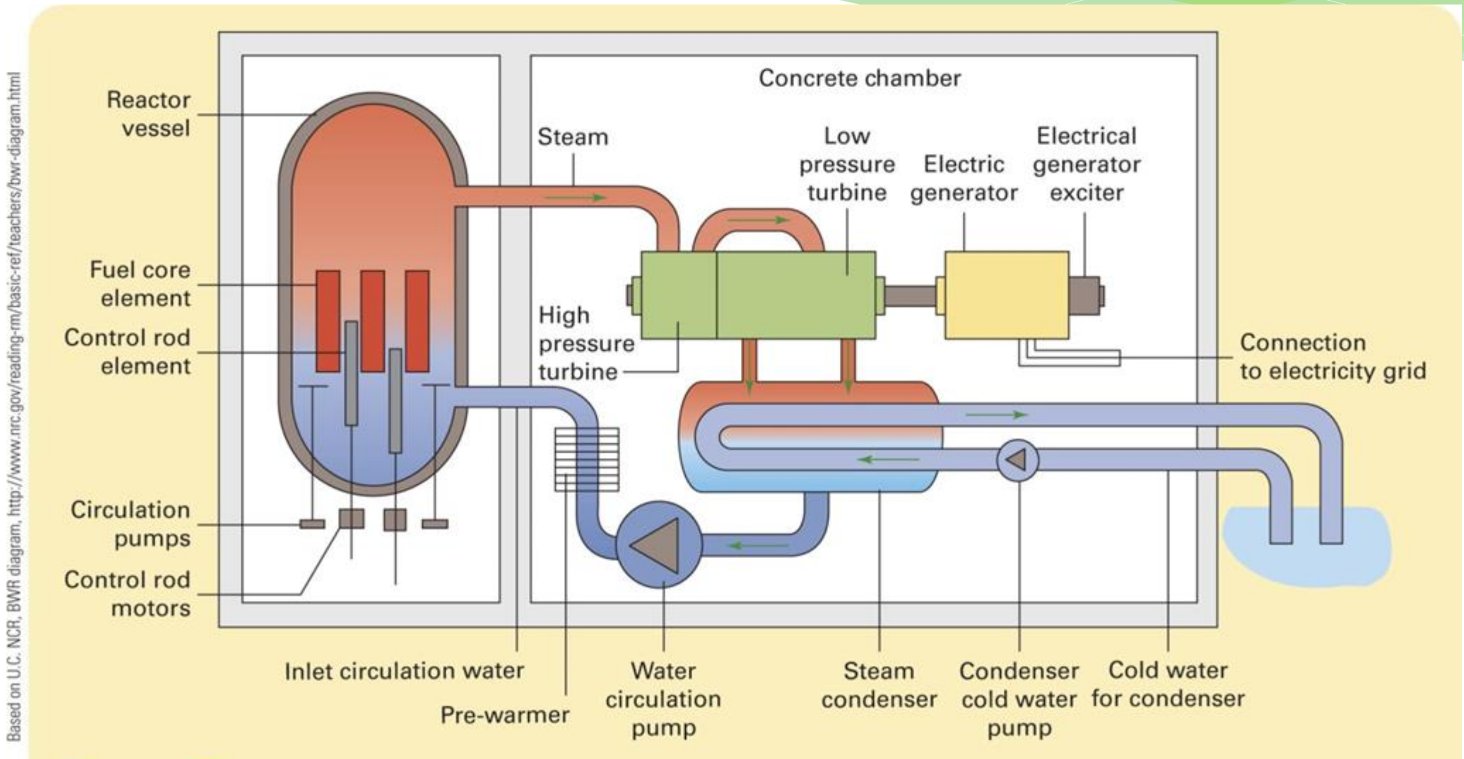


Figure 6.8: Schematic of the design of a BWR.

Schematic of a pressurized water reactor

The moderator and coolant may be either H_2O or heavy water (D_2O)

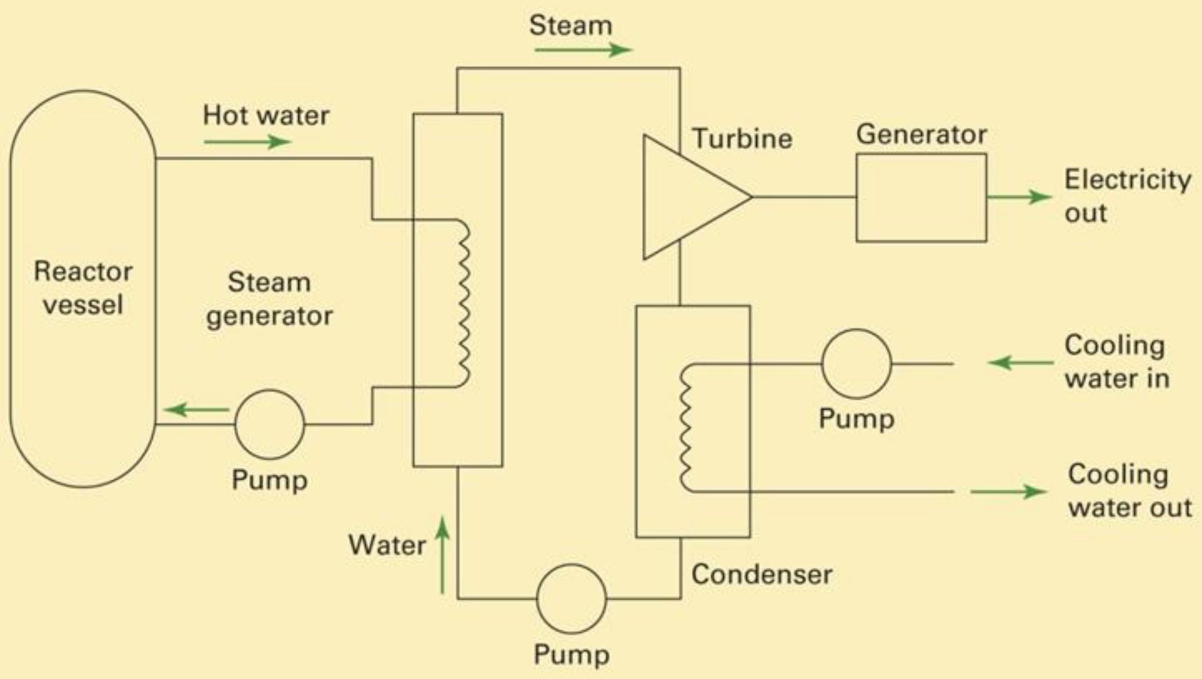


Figure 6.10: Schematic of a PWR.

Based on R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004)

PWR facility in New Hampshire

Figure 6.11: Seabrook Nuclear Generating Station in New Hampshire U.S., a 1244-MW_e PWR. The reactor core is contained inside the dome-shaped containment building at the right.

Gas (He) cooled graphite moderated reactor

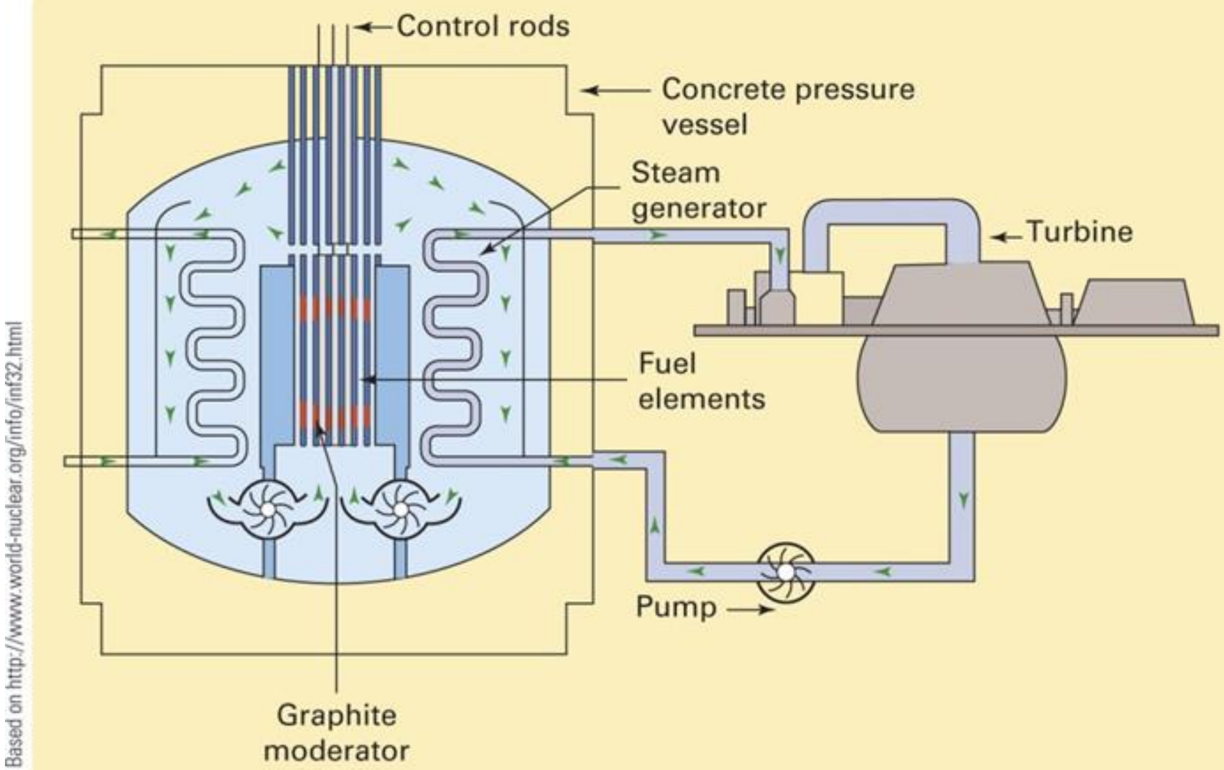


Figure 6.13: Schematic of a gas-cooled, graphite-moderated nuclear reactor.

Water cooled graphite moderated reactor

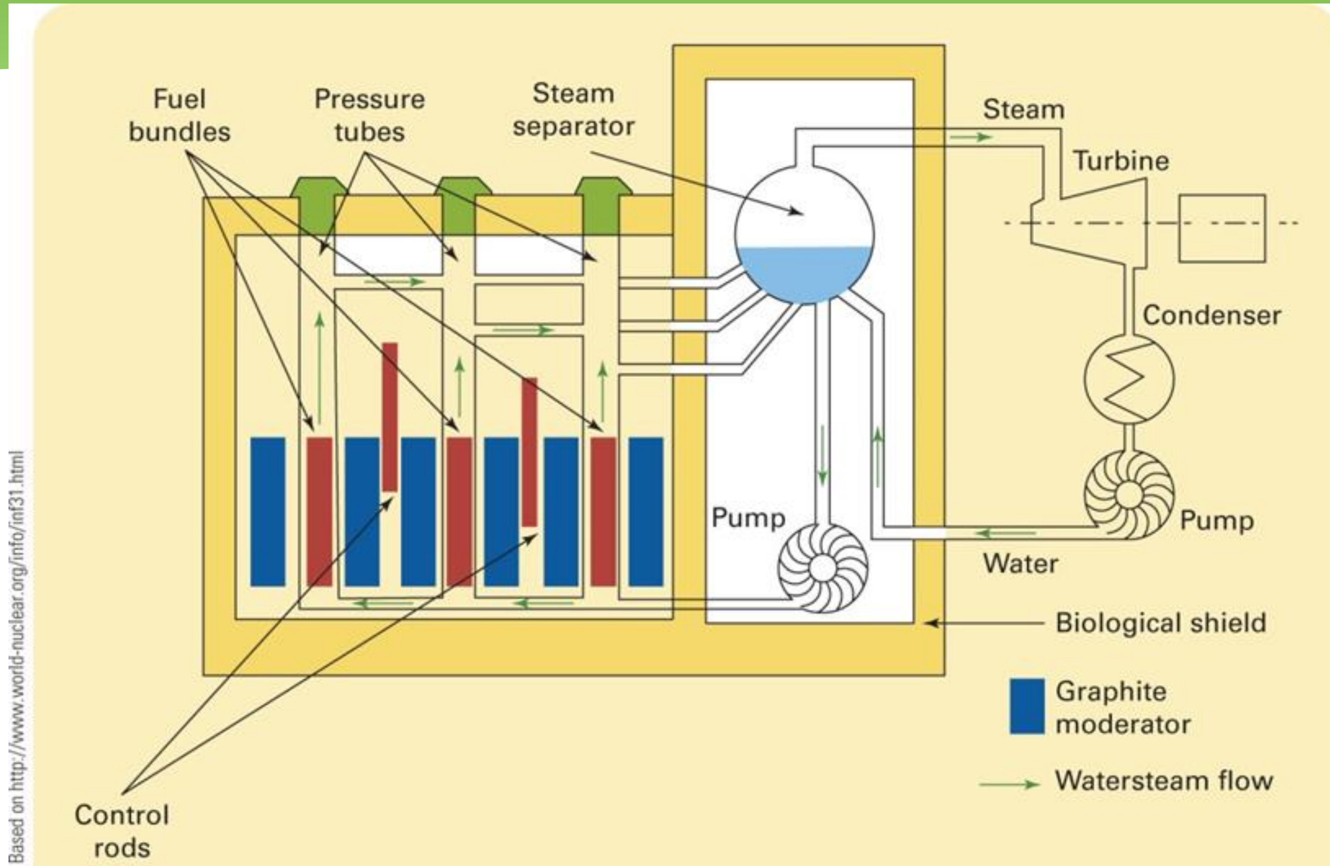


Figure 6.15: Schematic of a RBMK reactor.

Applications of fission power

The first fission reactors became operational in the late 1950s

Considerable growth until 1980s

Little growth since about 1990

Number of fission reactors in the United States

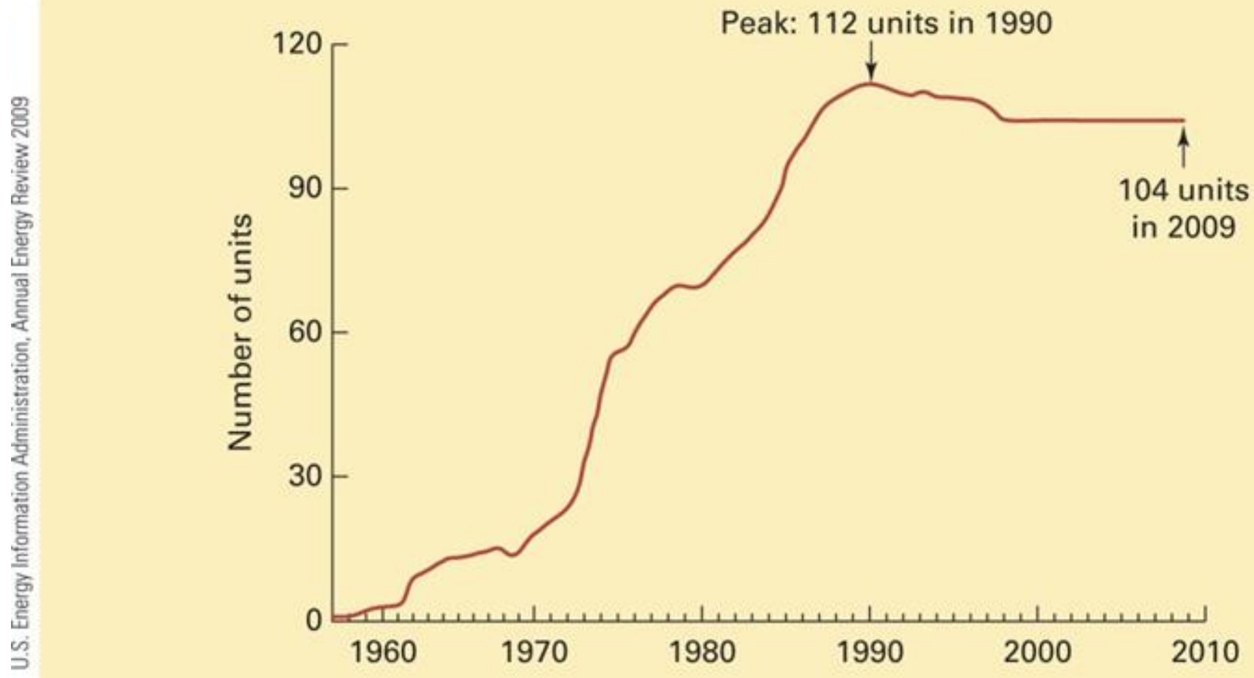


Figure 6.16: Total nuclear generating capacity (operable units, 1957–2009) in the United States as a function of year.

Annual construction starts worldwide

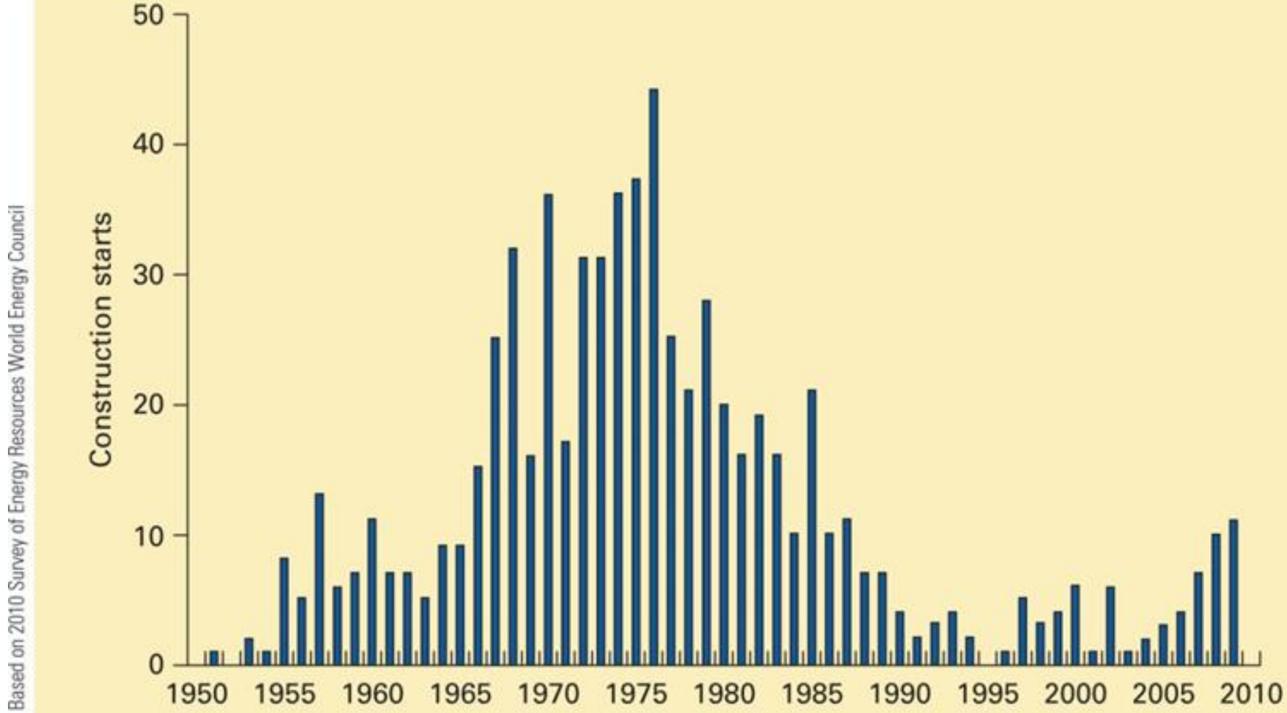


Figure 6.17: Annual changes in the world nuclear generating capacity.

Nuclear reactors worldwide

There are currently 437 operational nuclear reactors world wide. France produces more than 75% of its electricity from nuclear energy and is the world leader in fraction of electricity produced by fission reactors.

Uranium resources

Australia has the greatest uranium resources

Table 6.2: Proved resources of uranium as of 2009 recoverable at less than US$260 production cost.

country	resources (10^3 t)
Australia	1677
Kazakhstan	832
Russia	568
Canada	542
United States	473
South Africa	296
Namibia	284
Brazil	277
Niger	277
Ukraine	221
China	170
Uzbekistan	115
Jordan	114
India	82
Mongolia	50
other	328
world total	**6306**

Based on data from 2010 Survey of Energy Resources World Energy Council.

Uranium production

About 60% of world production is from Canada, Kazakhstan and Australia

Table 6.3: Production of uranium in 2008 for major producing countries.

country	production (t/y)
Canada	8995
Kazakhstan	8513
Australia	8425
Namibia	4388
Russia	3510
Niger	3028
Uzbekistan	2326
United States	1492
Ukraine	834
China	790
South Africa	570
other	1009
world total	**43,880**

Based on data from 2010 Survey of Energy Resources World Energy Council.

Production vs use

In recent years production has been consistently less than use

Extra uranium comes from

- stored uranium resources
- reprocessed reactor fuel
- decommissioned nuclear weapons

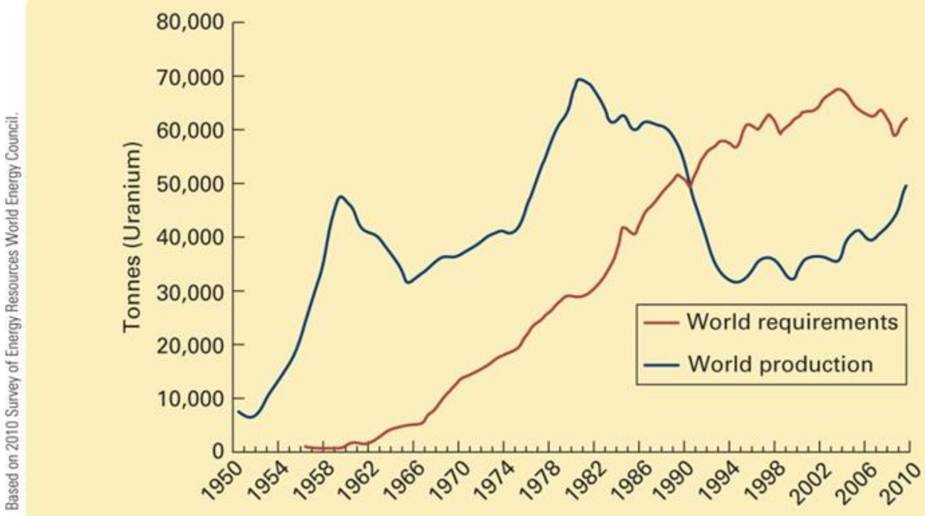


Figure 6.18. Uranium production and reactor requirements since 1950.

Lifetime of uranium resources

Using current nuclear power reactors and current approaches to uranium fuel use known resources will last for about 35 years.

The longevity of nuclear resources can be extended by several approaches

- Fuel reprocessing
- Development of reactors that use lower grade fuel
- Fast breeder reactors
- Use of thorium as a fuel

Nuclear safety

Three notable nuclear accidents have occurred at commercial power reactors

- Three Mile Island
- Chernobyl
- Fukushima

Three Mile Island (Pennsylvania)

Reactor that suffered accident is farthest to the right in the photograph - Typical U.S. PWR design

Figure 6.19: Three Mile Island Nuclear Generating Station prior to the accident of 28 March 1979.

Three Mile Island accident

March 28, 1979

Failure of a water pump caused the reactor to overheat.

A small amount of radioactive material released to the atmosphere.

No immediate adverse health effects.
No anticipated long term health effects.

Chernobyl

In Soviet Union (now part of the Ukraine)

Water-cooled graphite-moderated reactor

Typical Russian design (RBMK)

Chernobyl accident

Began April 25, 1986

Reactor became unstable as a result of some operator tests.

Overheating of reactor caused water to decompose, releasing hydrogen which exploded.

Reactor after accident

Figure 6.21: Chernobyl reactor 4 after the accident of April 26, 1986.

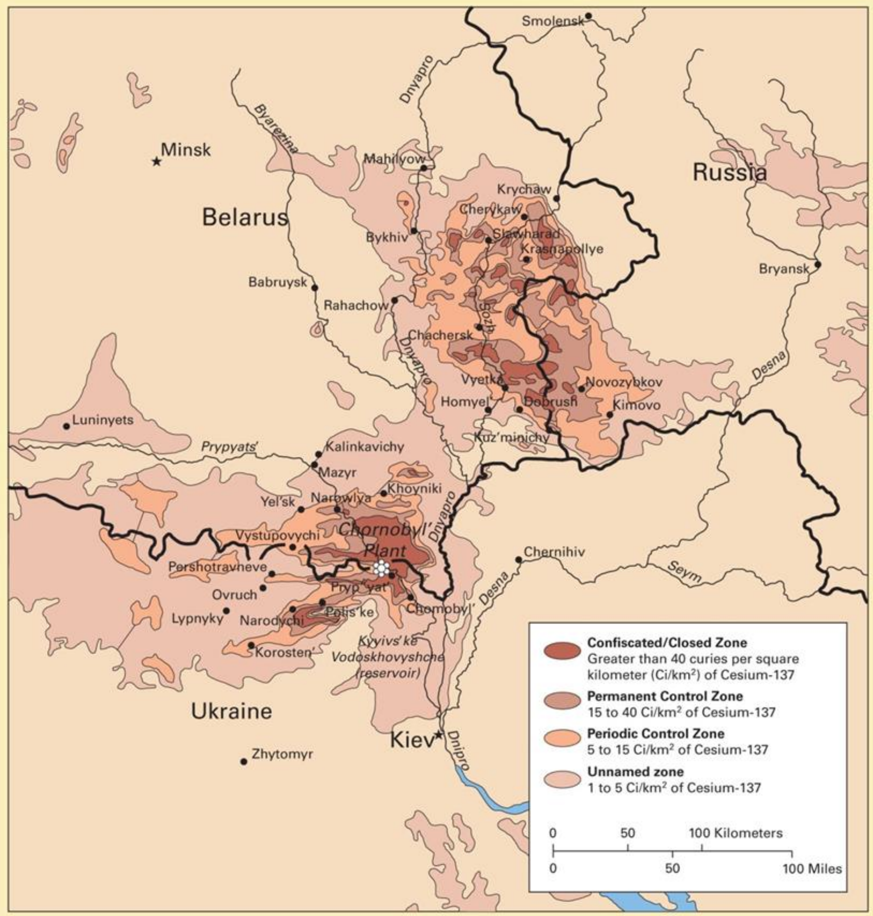
Consequences of the Chernobyl accident

31 immediate deaths

25 additional identified deaths

Substantial quantity of radioactive material released into environment

Contamination resulting from Chernobyl accident



CIA, Handbook of International Economic Statistics, 1996

Figure 6.23: Radiation levels in the contaminated area around Chernobyl as of 1996.

Long term health effects of Chernobyl

Table 6.4: Estimated long-term effects of Chernobyl in terms of increased cancer risk in the former Soviet Union and Europe.

region	population affected (millions)	natural cancer deaths	chernobyl cancer deaths	increase in cancer deaths (%)
Soviet Union	279	35,000,000	6500	1.9
Europe	490	88,000,000	10,400	1.2

Fukushima Dai-ichi

Facility consisting of six BWRs

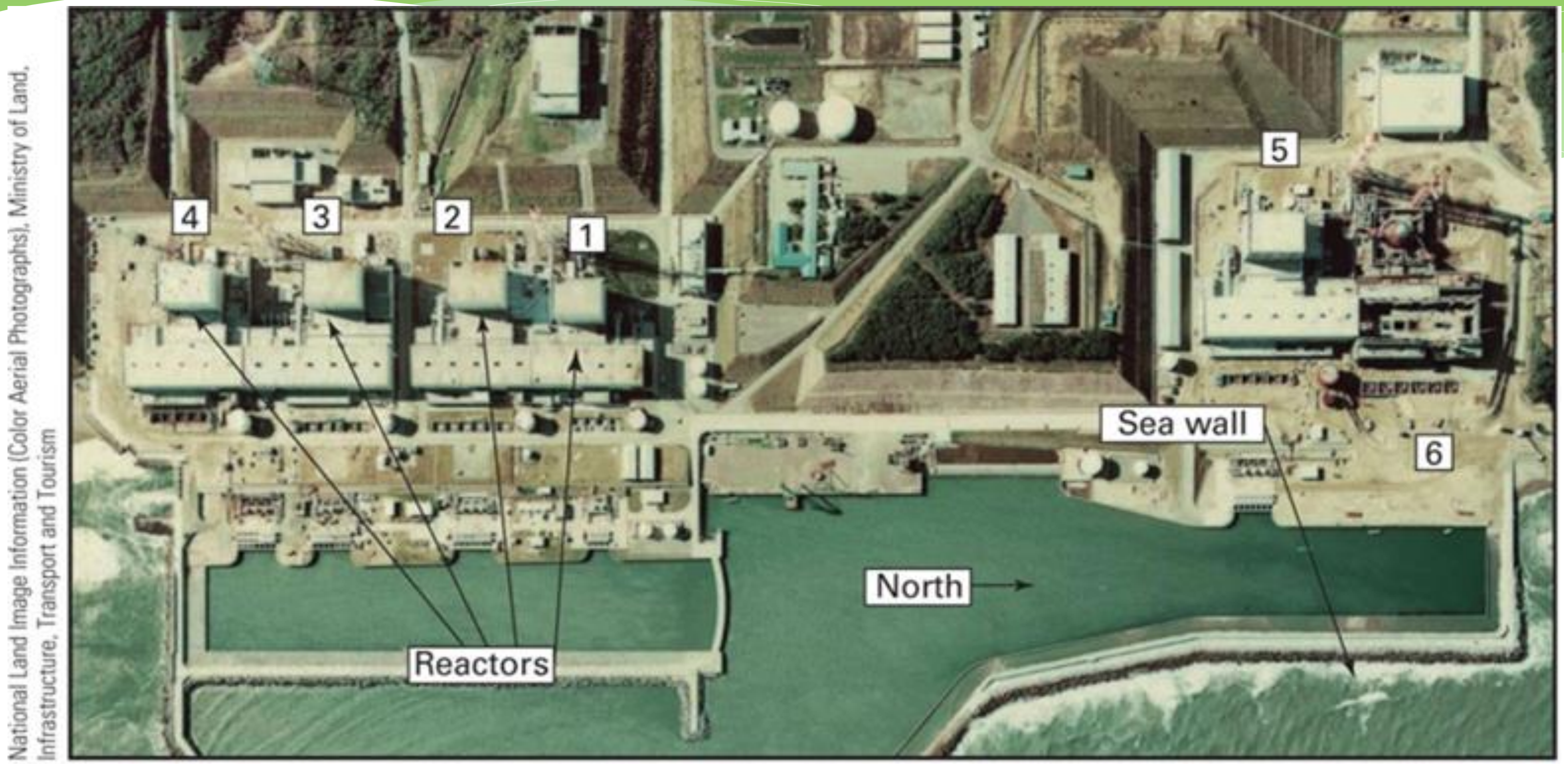


Figure 6.24: Fukushima Dai-ichi nuclear facility in Japan prior to the nuclear accident of 2011. The reactors are the square buildings, with number 6 still under construction. A portion of the seawall structure is seen to the right.

Fukushima accident

Accident on March 11, 2011

Electrical infrastructure damaged by tsunami caused by off-shore earthquake

Loss of coolant caused reactors to overheat leading to explosions

Estimated release of radioactive material about 10 - 20% that of Chernobyl

Long term health effects yet to be determined

Fukushima after accident

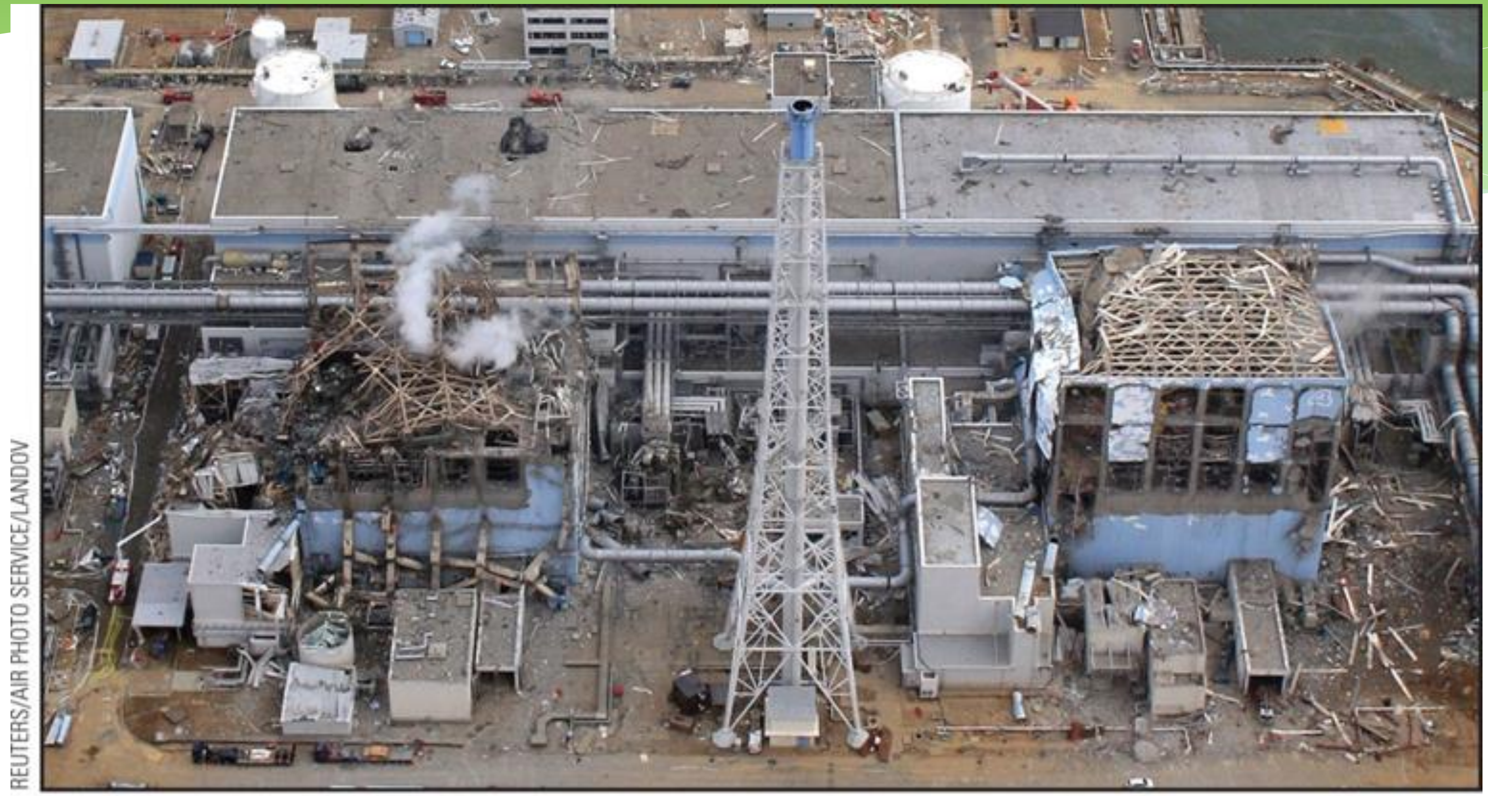


Figure 6.26: Damage to Fukushima Dai-ichi nuclear facility reactors 3 (left) and 4 (right) on March 20, 2011.

Risk assessment

Production of energy involves risk to humans

- Risk may be to occupational workers in the power industry
- Risk may be to the general public

Occupational risk

Occupational risk may be from

- extraction of resources from the earth
- processing resources
- transportation of resources
- operation of the generating station

Risk of nuclear power

Table 6.5: Anticipated number of fatalities per GWy_e of electricity generated from coal and uranium.

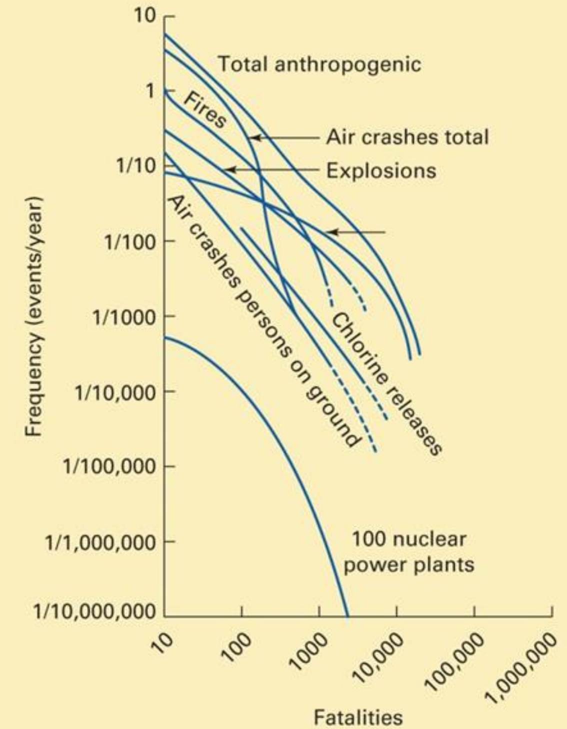
resource	mining	processing	transportation	generating station	total
coal (deep mines)	1.7	0.02	2.3	0.01	4.0
uranium	0.2	0.001	0.01	0.01	0.22

Cengage Learning

Occupational risk of nuclear power is small because small quantities of uranium produce considerable power (compared to coal)

Risk to the general public

Rasmussen report from 1975



Reactor Safety Study: An assessment of Accident Risks in U.S. Commercial Nuclear Power Plants U.S. Nuclear Regulatory Commission (1975) WASH-1400 (NUREG 75/014) p. 2

Figure 6.27: Relationship for frequency as a function of fatalities for anthropogenic disasters as predicted by the Rasmussen report.

Frequency of events decreases with increasing number of fatalities

Total risk of energy production

Table 6.8: Normalized relative total risk (to occupational workers and the general public) of producing electricity by different methods.

electricity source	relative risk
coal	100
oil	67
wind	33
solar (photovoltaic)	23
methanol (biofuel)	10
hydroelectric	1.5
nuclear	0.3
natural gas	0.2

Based on data from Kraushaar and Ristinen . . .

Sources of risk

Some sources of risk associated with energy production

- coal - mostly from air pollution
- solar - mostly from large amount of manufacturing required because of low energy density
- hydroelectric - dam failures

Nuclear waste disposal

Radioactive nuclear waste must be disposed of safely

Radioisotopes are

- fission products
- actinides (uranium and radioactive by-products produced by neutron reactions)

Typical half lives

- Fission fragments - tens of years
- Actinides 1000s to 100,000s years

Decay of nuclear waste

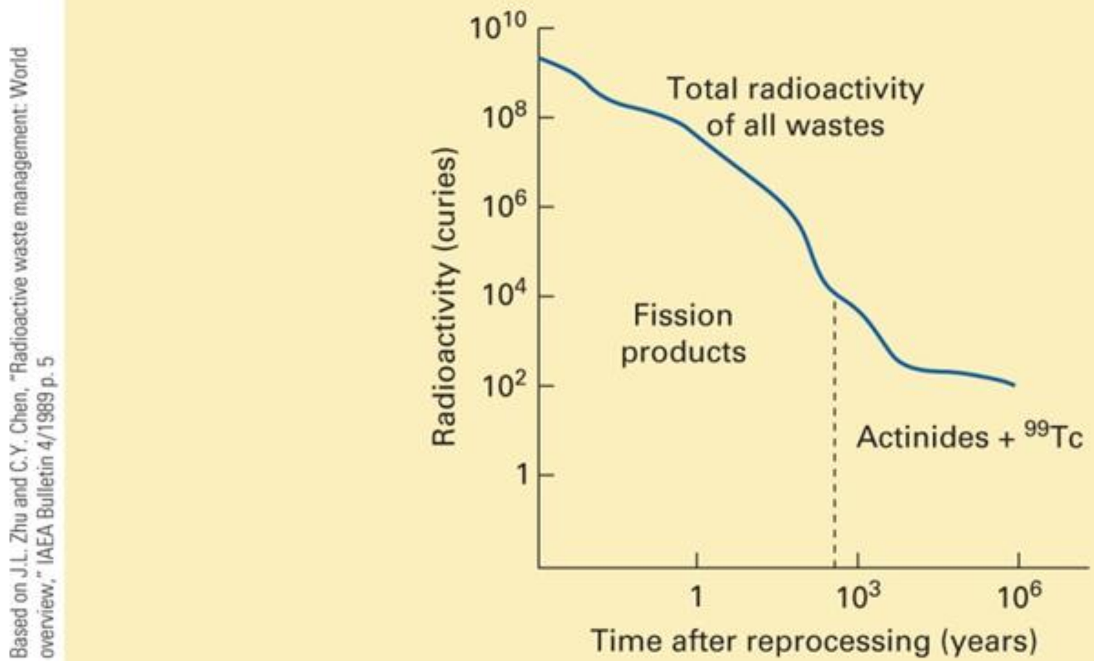


Figure 6.30: Activity as a function of time in spent reactor fuel.

Volume of radioactive waste

Since the energy content of uranium is so high, the actual amount of waste is relatively small.

All the commercial reactors ever operated have produced a total amount of high-level radioactive waste with the volume of a cube 40 m on a side.

Methods of waste disposal

Probably the most practical method of radioactive waste disposal (at present) is to store it underground.

Advanced reactor design

New reactor designs have attempted to deal with safety issues.

A promising design is the pebble bed reactor.

Pebble bed reactor

Variation on the gas cooled graphite moderated reactor

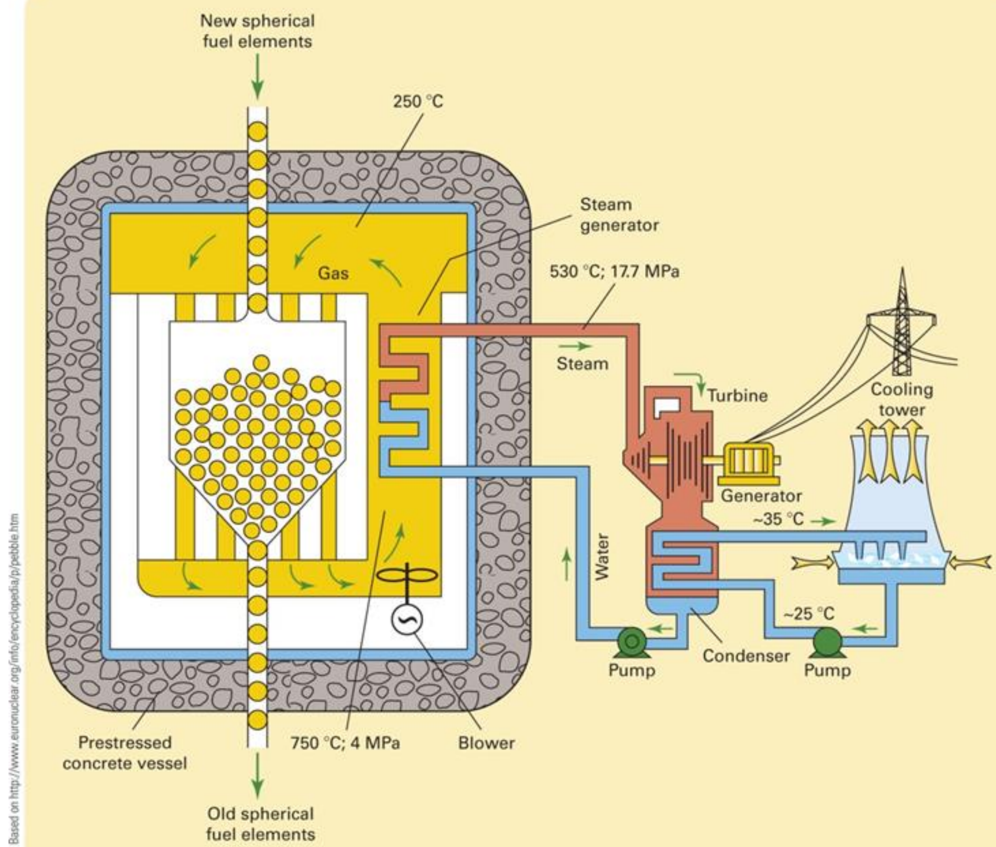


Figure 6.34: Schematic of a pebble bed reactor.

Pebble bed reactor fuel pellet

Fuel is in the form of uranium spheres imbedded in a larger spherical fuel element made of graphite.

The spherical fuel element also acts as the moderator.

Highly temperature resistant fuel pellets are designed to avoid overheating even in the event of total loss of coolant.

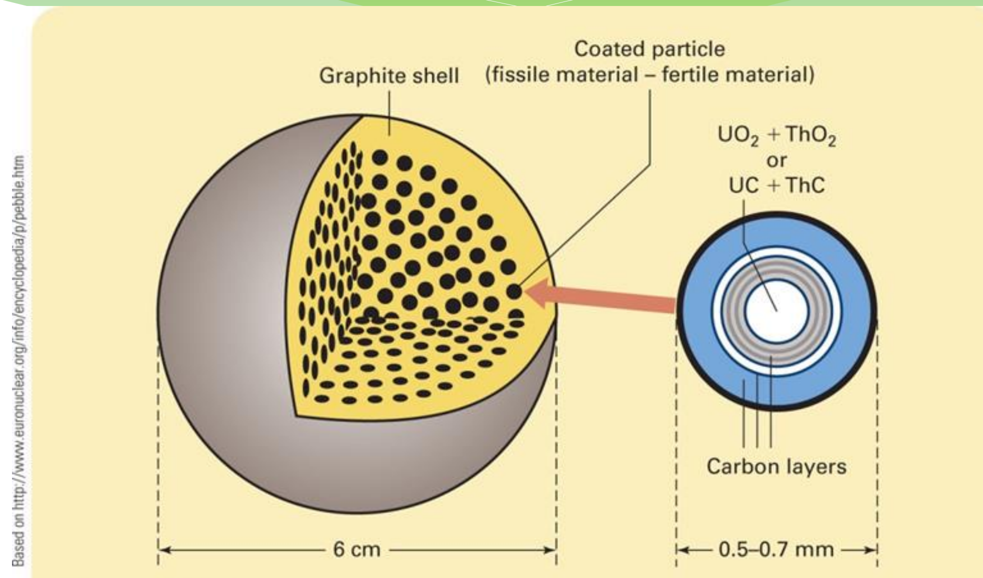


Figure 6.33: Fuel element for a pebble bed reactor.

Fast breeder reactors

Thermal neutron reactors only extract energy from ^{235}U and not ^{238}U (which is more than 99% of all uranium).

^{238}U can also be used to produce energy because it can be converted in to a fissile material by the fast neutron reaction

$$n + {}^{238}U \rightarrow {}^{239}U + \gamma \qquad (6.6)$$

This is followed by

$$^{239}U \rightarrow {}^{239}Np + e^- + \bar{\nu}_e \rightarrow {}^{239}Pu + e^- + \bar{\nu}_e \qquad (6.7)$$

^{239}Pu is fissile and can be used like ^{235}U in a reactor.

Fast breeder reactor

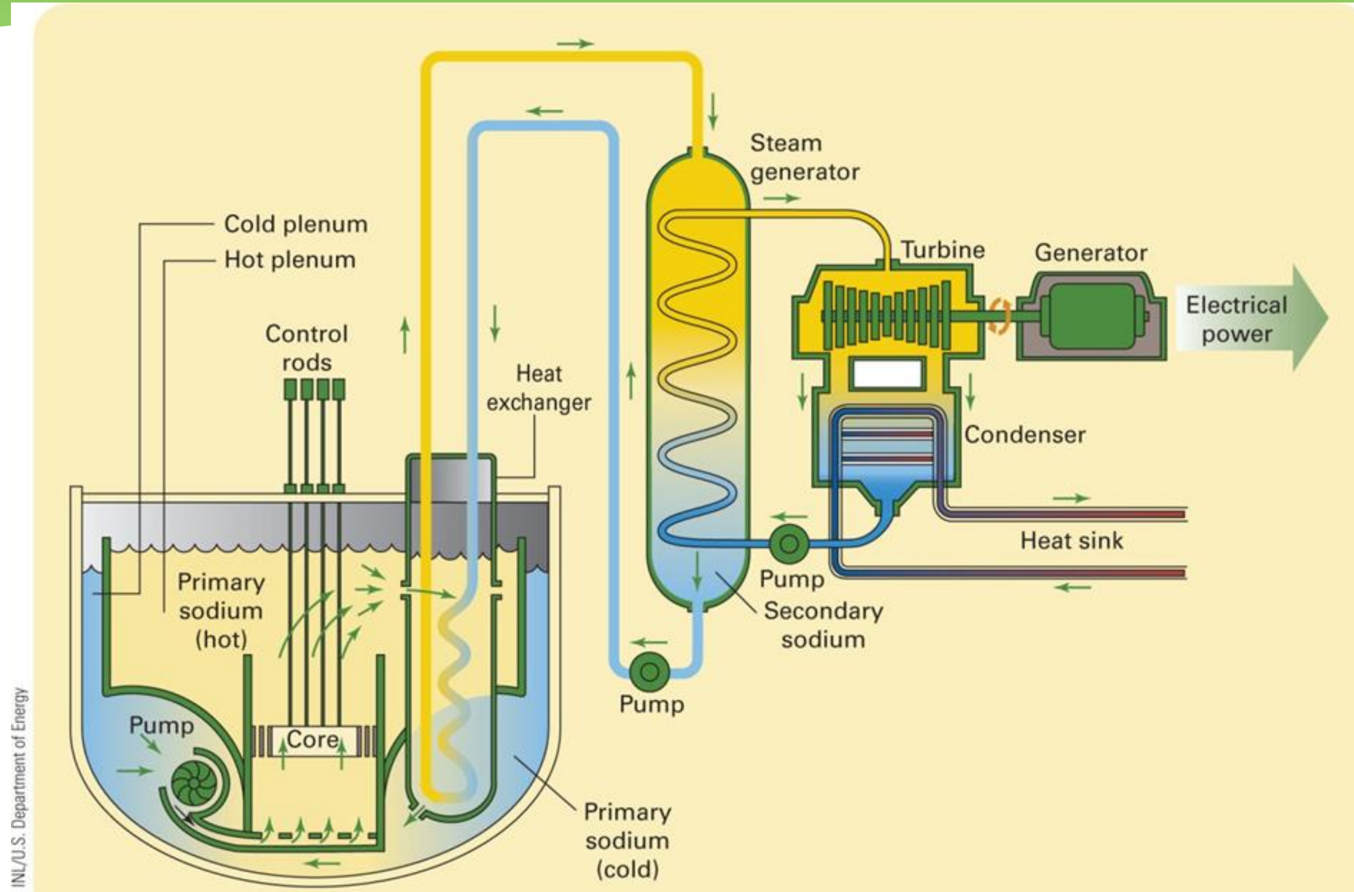


Figure 6.35: Schematic of a sodium-cooled LMFBR.

Thorium reactors

^{232}Th is a naturally occurring non-fissile nuclide.

It can be converted into fissile ^{233}U by the neutron reaction

$$n + {}^{232}\text{Th} \rightarrow {}^{233}\text{Th} + \gamma \quad (6.9)$$

which is followed by the β decays

$$^{233}\text{Th} \rightarrow {}^{233}\text{Pa} + e^- + \bar{\nu}_e \rightarrow {}^{233}\text{U} + e^- + \bar{\nu}_e \quad (6.10)$$

^{232}Th is much more abundant on the earth than uranium and can greatly extend the longevity of nuclear power.

Summary

- The fission of heavy nuclei can provide useable energy
- ^{235}U is a fissile isotope of uranium and ^{238}U is non-fissile
- Fissile materials can be used in thermal neutron reactors to create a controlled chain reaction
- Thermal reactors use a moderator to reduce neutron energy and control rods to maintain the reaction
- Suitable moderators are H_2O, D_2O and graphite
- The nuclear power industry grew considerably in the 1970s and 1980s but has remained fairly constant since then
- Australia has the greatest known uranium resources
- Canada, Kazakhstan and Australia are the leading uranium producers
- Nuclear safety and waste disposal are major concerns for the future of nuclear power
- New reactor designs utilize methods that can provide improved safety and greatly increase the lifetime of nuclear power