Sustainable Energy

Lecture 8: Nuclear Power

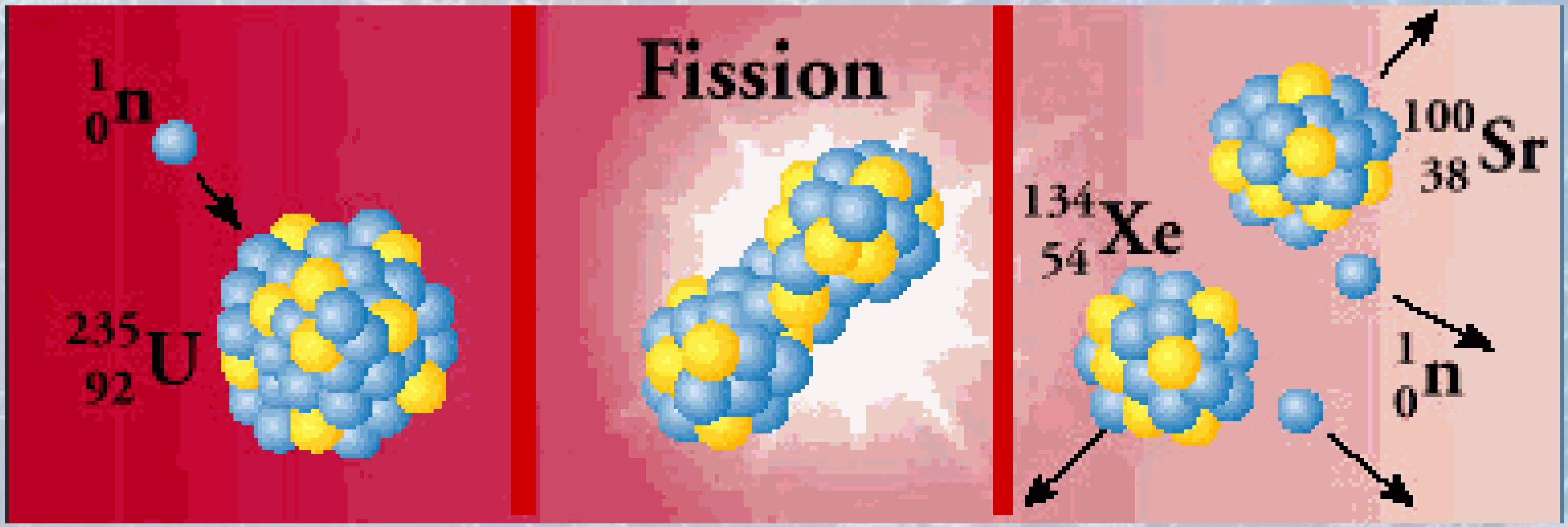
Nuclear Reactors

- Radioactivity was discovered in 1898 by Henri Becquerel in Paris.
- Neutron-induced fission was discovered in 1938 by Meitner, Strassmann and Hahn.
- The amount of energy released in nuclear fission is tremendous compared with conventional combustion technologies.
- A 1,000 Mwe power station running on coal uses 3 million tons of coal per year. A similar nuclear power plant uses 36 tons of enriched uranium.
- The first nuclear power plant, at Calder Hall in the UK, started operation in 1956. Today more than 440 nuclear generation stations are active.
- Nuclear power is the second most abundant source of electrical power generation worldwide.

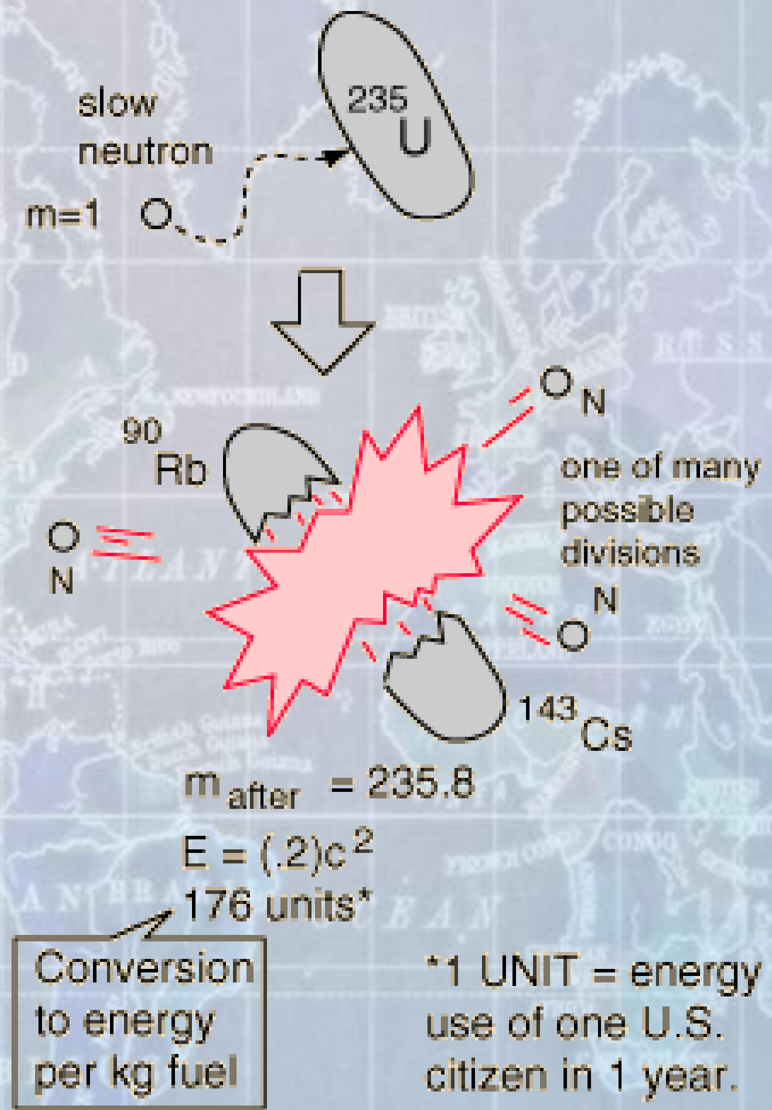
Types of Nuclear Reactors

- The chemical reactions involved in nuclear fission:
  - ^{235}U + ^{1}n fission products + neutrons + energy (~200 MeV)
- Natural uranium is composed of 0.72% U-235 (the fissionable isotope), 99.27% U-238, and a trace quantity 0.0055% U-234 . The 0.72% U-235 is not sufficient to produce a self-sustaining critical chain reaction in U.S. style light water reactors, although it is used in Canadian CANDU reactors. For light-water reactors, the fuel must be enriched to 2.5-3.5% U-235.
- Uranium is found as uranium oxide which when purified has a rich yellow color and is called "yellowcake‟ (U_2O_3). After reduction, the uranium must go through an isotope enrichment process. Even with the necessity of enrichment, it still takes only about 3 kg of natural uranium to supply the energy needs of one American for a year.

Nuclear Fission



Nuclear Fission



Materials used in Nuclear Power

Table 8.2. Essential Fission Power Reactor Functions and Commonly Used Materials

Function or Attribute	Typical Materials
Self-Sustaining Chain Reaction	Fuels: Uranium 233- (U) Uranium 235- (U) Plutonium 239- (Pu)
Conversion into Fissile Materials	Fertile Materials: Thorium 232- (Th) Uranium 238- (U)
Nuclear Fuel Material	U, Pu UO_2, PuO_2 UC, PuC
Reactor Internals and Reactor Vessel Structural Material	Steel Stainless Steel Zircalloy (Zr) Aluminum (Al) Graphite (C)
Neutron Moderator	Water (H_2O) Heavy Water (D_2O or ^2H_2O) Graphite (C) BeO_2
Reactor Coolant	Water (H_2O) Heavy Water (D_2O) Helium (He) Carbon Dioxide (CO_2) Organic fluids Lead (Pb) Lead-Bismuth (Pb-Bi) Sodium (Na) Sodium-Potassium (Na-K) Molten salts
Neutron Absorber (Control) Material	Boron (B) Cadmium (Cd) Gadolinium (Gd) Hafnium (Hf)

Types of Nuclear Reactors…continued

- Reactors can be used to create new fissionable fuel by taking advantage of this equation (breeder reactor):
  - U238 + n -> U239 + Np239 + e^-
  - NP239 -> Pu239 + e^-
- ^{239}U is the most efficient nuclear weapons material. The use of breeder reactors is prohibited in the US outside of weapons production.
- Potentially the world's supply of nuclear fuel could be increased by a factor of 70 by recycling the material from used nuclear fuel.

Types of Nuclear Reactors

- Light-Water Reactors (LWR)
  - 78% of the world's reactors are this type.
  - Light water is used as the reactor coolant.
  - Light water absorbs neutrons more readily than heavy water (D_2O).
  - LWRs cannot become critical using natural uranium; enriched fuel must be used (3-5% enrichment).
    - 75% of the LWRs are pressurized-water reactors (PWRs) and the remaining are boiling-water reactors.
    - In PWRs the coolant remains in liquid state even at 300 degrees because of pressurization.
    - Steam is produced in a heat exchanger and is used in a Rankine cycle system to produce electricity.
    - Each reactors contains 40-50K fuel rods. Each rod is 1cm in diameter and 4m in length. The rods are made of zircalloy cladding and hold stacks of UO_2 pellets.

Types of Nuclear Reactors

- Boiling-Water Reactor (BWR)
  - BWR technology is a derivative of PWR.
  - Water boils within the reactor core and steam flows directly to the turbine.
  - The necessity for the steam generator is eliminated and reactor power changes quickly in response to changes in coolant pressure.
  - Reactor system controls must be more elaborate and quicker acting than with PWR technology.
  - Radioactivity contamination happens in the power conversion system and is more difficult to maintain as a result than a PWR system.

Types of Nuclear Reactors

- RBMK Reactors (Russian designed reactors; reactor of high power of the channel type).
  - These reactors use graphite instead of water as the neutron moderator and water is the coolant.
  - The volume of the reactor is occupied by a block of graphite. Vertical holes in the graphite house metal pressure tubes containing water. Inside the tubes are the fuel rod bundles. The fuel rods can be replaced while the reactor is operating.
  - The Chernobyl reactor was an RBMK unit. About 13 RBMK reactors are still operating in the former Soviet block.
  - During the Chernobyl accident the reactor exploded. There was no containment vessel and the explosion ejected much of the reactor's fuel outside.
  - The US DOE estimated deaths at 4100 among USSR evacuees. Estimates in cancer deaths are perhaps as high as 100K. Various estimates of future cancer deaths have been made. There were some 600,000 cleanup workers; over 10% of those workers are already dead….over 2.4 million people have current health problems as a result of the accident.

Types of Nuclear Reactors

- CANDU Reactor
  - This is a type of PWR reactor developed in Canada in 1978.
  - CANDU reactors use pressurized heavy water as a coolant and low-pressure heavy water as a moderator outside the fuel rods.
  - The CANDU can use natural uranium as a fuel avoiding the expense of enriched fuel. There are additional costs, however, in supplying the heavy water.
  - Online refueling is possible in this style reactor.

Types of Nuclear Reactors

- Gas-Cooled Reactor
  - The oldest large nuclear power economy is in the UK. The first reactors used in the UK were CO_2-cooled.
  - There have been many operating problems in the remaining gas-cooled reactors. As a result this is not a popular technology.
  - Interest remains in this style reactor because it is potentially more efficient than the typical PWR since Brayton cycle technology can be used in the power generation cycle.
  - The technology is also potentially safer than other reactors and may eliminate the need for expensive containment structures.

Types of Nuclear Reactors

- Liquid-Metal Reactor
  - Liquid Metal (cooled) fast breeder reactor (LMFBR). This reactor uses U238 to produce fissionable U239.
    - Liquid metals are used for coolants (liquid sodium or lead-bismuth).
    - The most ambitious breeder reactor of this type was built in France; the 1200MWe, Superphenix. It started operation in 1985.
    - Sodium cooled breeder reactors have been build in countries that have advanced nuclear power programs (Japan, India and Russia).
    - Breeder reactors have turned out to be less economically advantageous because of the low prices and abundance of uranium.

Nuclear Power Fuel Resources

- **Current consumption is about 100K tons/year for uranium.**
- **If we are to use nuclear power to displace fossil fuel generation it will require several orders of magnitude increase in the production of uranium.**

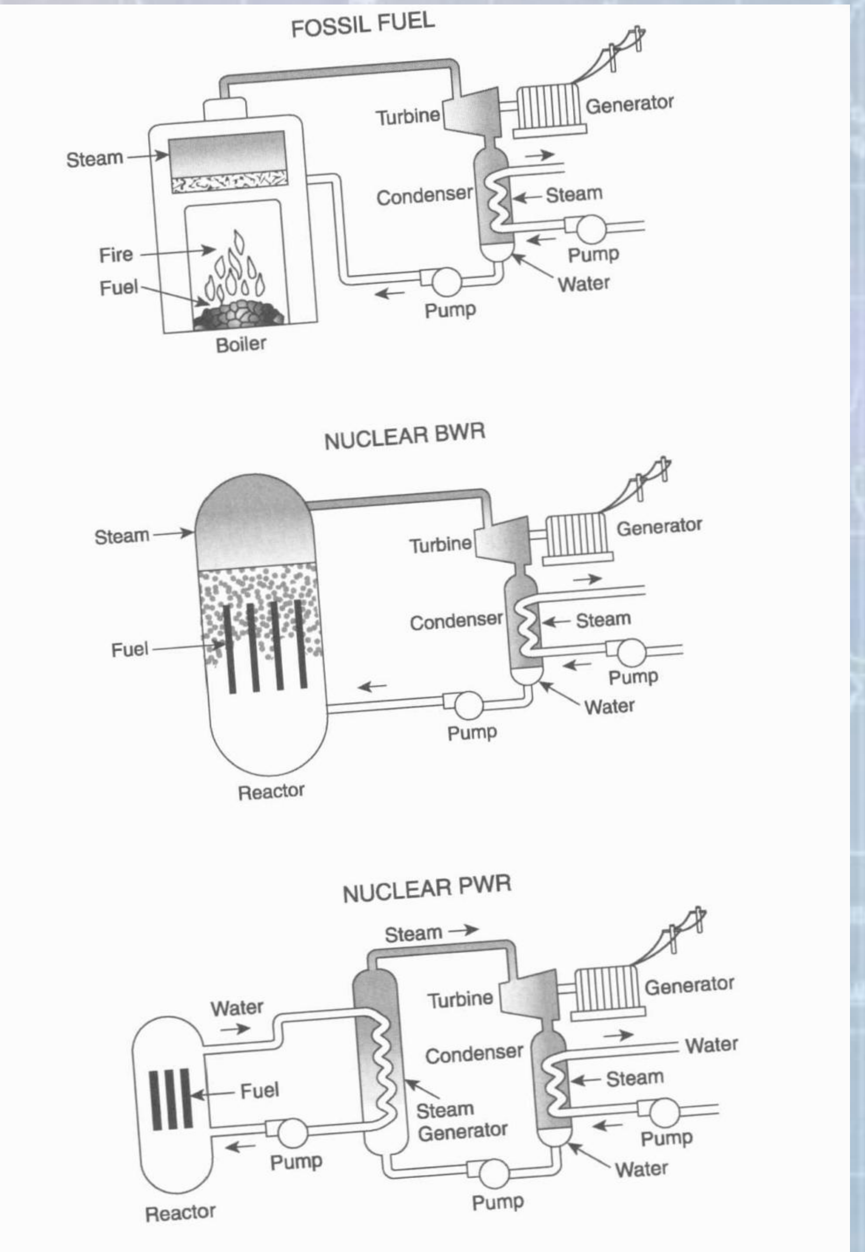
Types of Nuclear Reactors

Table 8.4. Summary of Types of Power Reactors Used Worldwide

Type	Coolant	Moderator	Maximum Coolant Temperature (°C)	Current Deployment	Current Population
Pressurized Water (PWR)	Light Water	Light Water	330	Most nuclear countries	259
Boiling Water (BWR)	Light Water	Light Water	288	Most nuclear countries	92
RBMK	Light Water	Graphite	270	Former Soviet Union	13
Pressurized Heavy Water (PHWR)	Heavy Water	Heavy Water	267	Argentina, Canada, China, India, Korea, Pakistan, Romania	43
Gas-Cooled (GCR)	Carbon Dioxide, Helium	Graphite	741	UK, Russia	32
Liquid Metal-Cooled (LMFBR)	Sodium, Lead, Lead-Bismuth	None	545	France, Japan, Russia, and India	2

Source: Nuclear News, 2002.

Nuclear Plants/BWR/PWR



CANDU Reactor

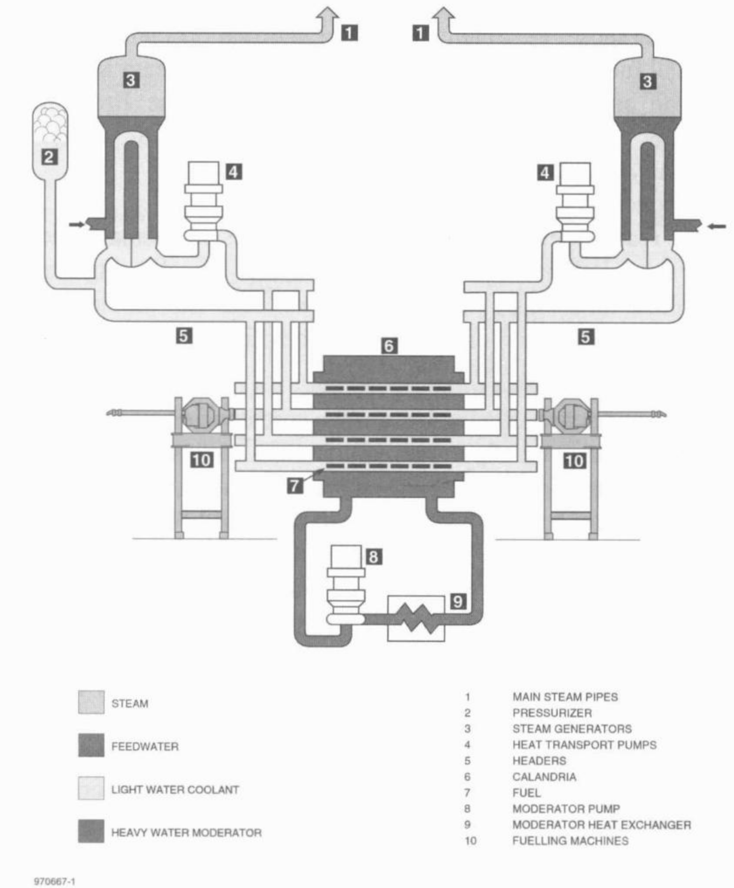
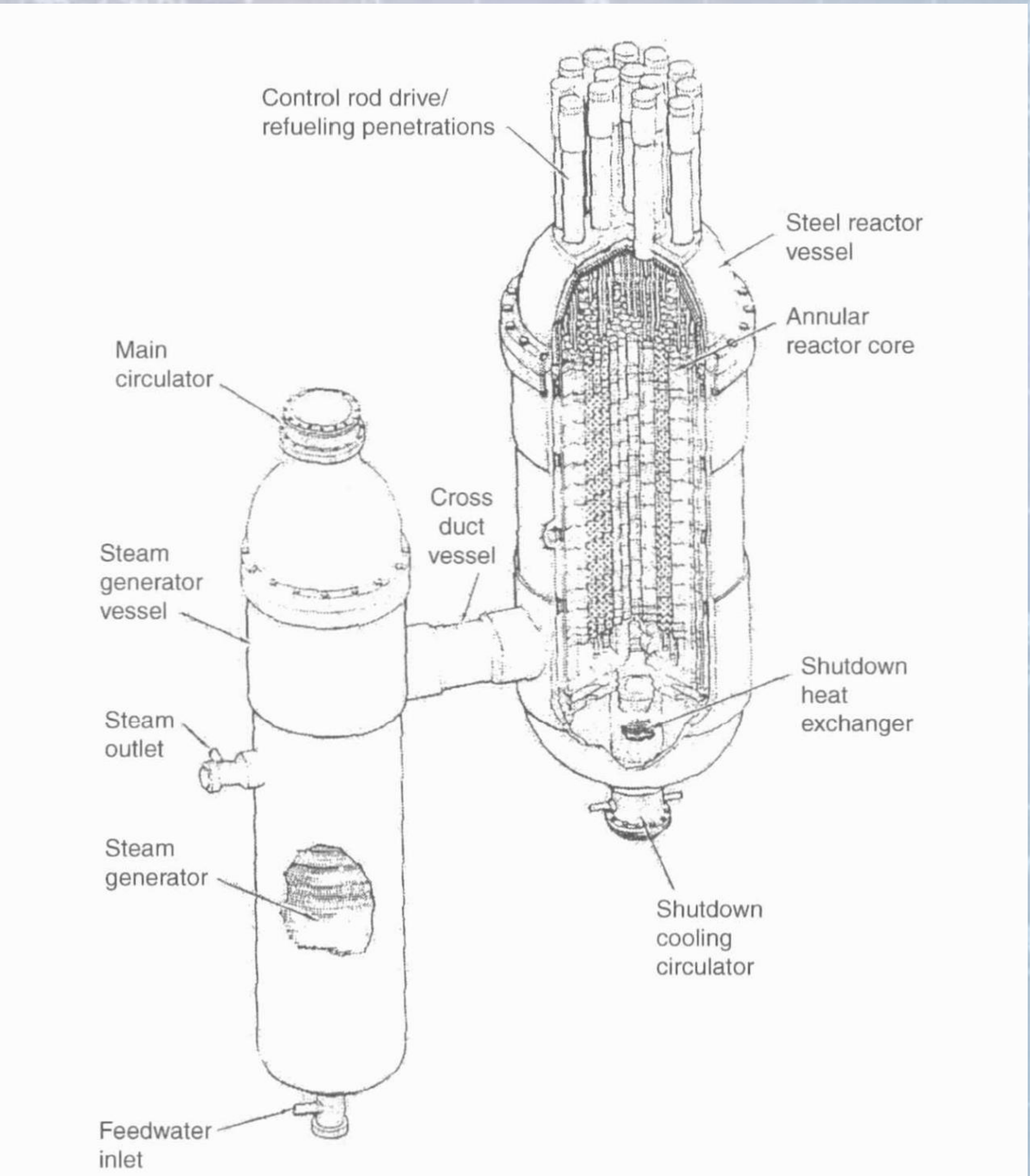
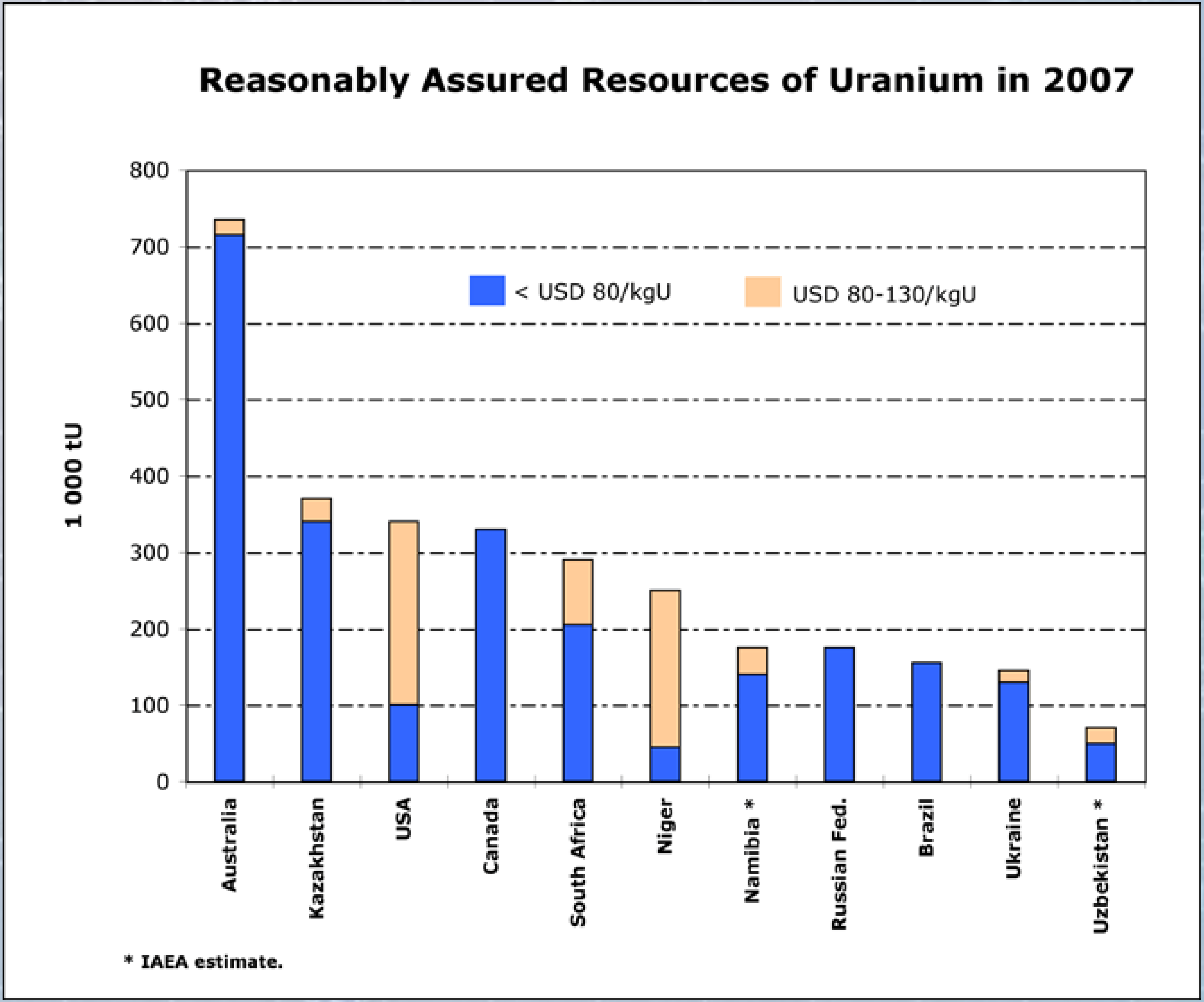


Figure 8.3. Schematic flow diagram for a CANDU power plant. Present CANDU systems are essentially pressurized heavy water reactors. Individual fuel channels pass through a calandria, which contains heavy water moderator with its own circulation system. Heavy water coolant, on the other hand, flows through the fuel channels and raises steam (from ordinary water) in the steam generator. Diagram courtesy of Atomic Energy of Canada, Ltd. (AECL). Source: Nero (1979). Reprinted with permission of Atomic Energy of Canada, Ltd.

HTGR Reactor



Uranium Resources Worldwide



The Nuclear Fuel Cycle

- **Uranium mining**
  - **The highest quality/quantity of ores are found in Canada and Australia.**
- **Uranium milling**
  - **The mills are leaching facilities that separate the uranium from the ore. The resulting solid product (U_3O_8) is then sent to a conversion facility (to UF_6).**
- **Conversion – changes the uranium to gaseous form.**
- **Enrichment**
  - **Gaseous diffusion is used to increase the percentage of U235 in the fuel.**
  - **Gas centrifuge technology is also used to increase the concentration of U235.**
  - **This same technique can produce enriched uranium for nuclear weapons production.**
- **Fuel Fabrication**
  - **The enriched UF_6 is chemically converted into a fuel form such as UO_2 for LWR fuel. The fuel pellets are enclosed in cladding material to form fuel rods. The fresh assemblies can be handled without shielding unless recycled fuel is used.**

Fuel cycle continued

- Spent fuel
  - Most spent fuel is stored on site at the plant.
  - Dry cask storage can be used with older fuel assemblies .
  - The wastes from plants is classified as high level nuclear wastes (HLW).
  - No county has an effective, licensed HLW disposal system.
  - Reprocessing of fuel rods is widely recognized to be uneconomical and is likely to remain so into the foreseeable future.

Future Prospects for Nuclear Energy

- New technologies such as fusion reactors could have a large impact if they become commercially available. Estimates suggest, however, it could be 50-60 years before this technology is advanced enough for commercial use.
- Nuclear power production will increase with many new plants on the drawing board around the world.
- China ordered 100 new plants from Westinghouse Nuclear to be online by 2020!
- There are 35 new applications in the US for nuclear plants.
- There are adequate fuel reserves of uranium for at least 1000 years of use at current rates.