ABC's of Nuclear Power

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People's Alliance for Clean Energy

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Outline

- ✳ Introduction
- ✳ Some Physics
- ✳ Fuel Cycle
- ✳ Types of Reactors
- ✳ Radioactive Inventory
- ✳ Prospects and Commentary

Equivalence of matter and energy

Basic features is the release of large amount of energy from each fission event: roughly 200 MeV as compared to 1 eV for a typical chemical reaction

This factor of 100 million accounts for the fact that the fission of one pound of uranium is equivalent to that released from burning 1000 tons of coal.

“Fissions" are induced by the absorption of a neutrons by a “fissionable" nucleus. If the fissions can be induced by low-energy neutrons then the material is “fissile"

$$^{235}U + n \rightarrow ^{236} U^* \rightarrow (A_1, Z_1) + (A_2, Z_2) + Nn + Q$$

$Z_1 + Z_2 = 92$, $A_1 + A_2 + N = 236$

Capture of neutron by ^{235}U forms compound nucleus

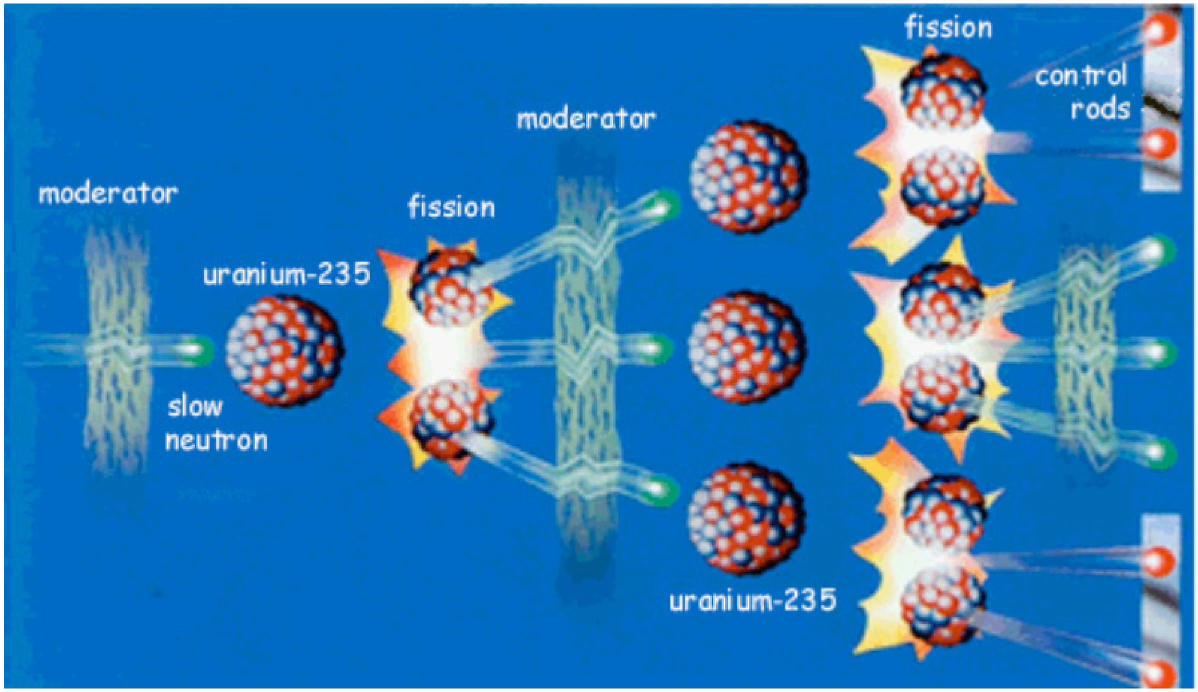
$\simeq$ 2.4 prompt neutrons released per fission event

80% of energy is carried off by fission fragments in form of kinetic energy. Stopped by core materials and the kinetic energy is converted to thermal energy

Fission

Number of fissions is a measure of the energy release but also a fundamental measure of the basic process in a reactor: fissions are the backbone of the nuclear chain reaction but this chain is linked by fission produced neutrons, which themselves produce fissions.

Only naturally occurring fissile material is ^{235}U which constitutes only 0.7% of natural uranium. Most reactors required that the uranium be enriched to contain a higher percentage of ^{235}U



Products of Fission

- The fission products (fission fragments) are nuclides of roughly half the mass of uranium
- Great different number of fission products, each produced in a certain % of fissions
- Most fission products nuclides are *neutron rich*; they decay by β or γ disintegration, are are therefore radioactive, with various half-lives.
- To prevent the release of this radioactivity into the environment the used fuel must stored and isolated.

Chain Reaction, Moderators

- ✳ In a fission reaction, 2 or 3 neutrons are released.
- ✳ These fission neutrons could all go on to initiate other fission events that would liberate more neutrons . . .
  - The number of neutrons rises rapidly and a chain reaction could then be established releasing large amounts of energy.
- ✳ Neutrons moving very fast (energy = 1MeV or speed 107 m/s) and unlikely to be captured by another U-235 nucleus. Have to be slowed down to thermal level (much less than 1 eV).
- ✳ How are the neutrons slowed down in a reactor?

  Moderators are used to slow down the neutrons. Typically consisting of light nuclei: hydrogen, deuterium or carbon. Water (H_2O), heavy water (D_2O) or graphite. Neutrons undergo many interaction before they are thermalized.

What is criticality?

- To sustaining chain reaction requires a balance between the rate at which neutrons are produced by fission and the rate at which they are lost, i.e. by causing further fission, by absorption by the surrounding materials or by leaving the core.
- When the rate of production of neutrons equals the rate of loss, the reaction is said to be critical. This is the operating state of a reactor. If the losses are higher, the reaction dies away.
- In the opposite case, an uncontrollable chain reaction could be established and the core may melt leading to what is popularly known as meltdown.

  Chain reactions are inherently unstable
- Nuclear reactors employ sophisticated (yet well known) design and engineering to control criticality and prevent uncontrolled reaction which could produced significant harm to life and property.

Nuclear Safety Systems

A nuclear power plant is equipped with four major types of safety systems to prevent accidents and reduce their effects if one should occur:

- ✳ A system to quickly shut down a reactor and stop the fission chain reaction.
- ✳ Numerous systems to control reactor pressure and to continue cooling the reactor fuel – that is, to carry away the heat that continues to be generated even after the reactor is shut down.
- ✳ Electrical, control, and instrument systems for safety systems and for monitoring reactor conditions.
- ✳ System of barriers to contain radioactivity if it should escape from the reactor fuel in an accident.

Decay heat

- ✳ Many fission products are still decaying long after the originating fission reaction
- ✳ Energy (heat) frm this nuclear decay is actually produced in the reactor for many hours, days, even months after the chin reaction is stopped. This heat is not neglibible.
- ✳ When the reactor is in steady operation, decay heat represents about 7% of the total heat generated.
- ✳ Even after the reactor shutdown, decay heat must be dissipated safely, otherwise the fuel and reactor core can seriously overheat.

Transuranics

Produced from the absorption of neutrons by ^{238}U: plutonium, americium, curium $\cdots$

for example: $^{238}\text{U} + \text{n} \rightarrow {}^{238}\text{Np} + \beta \rightarrow {}^{239}\text{Pu}$

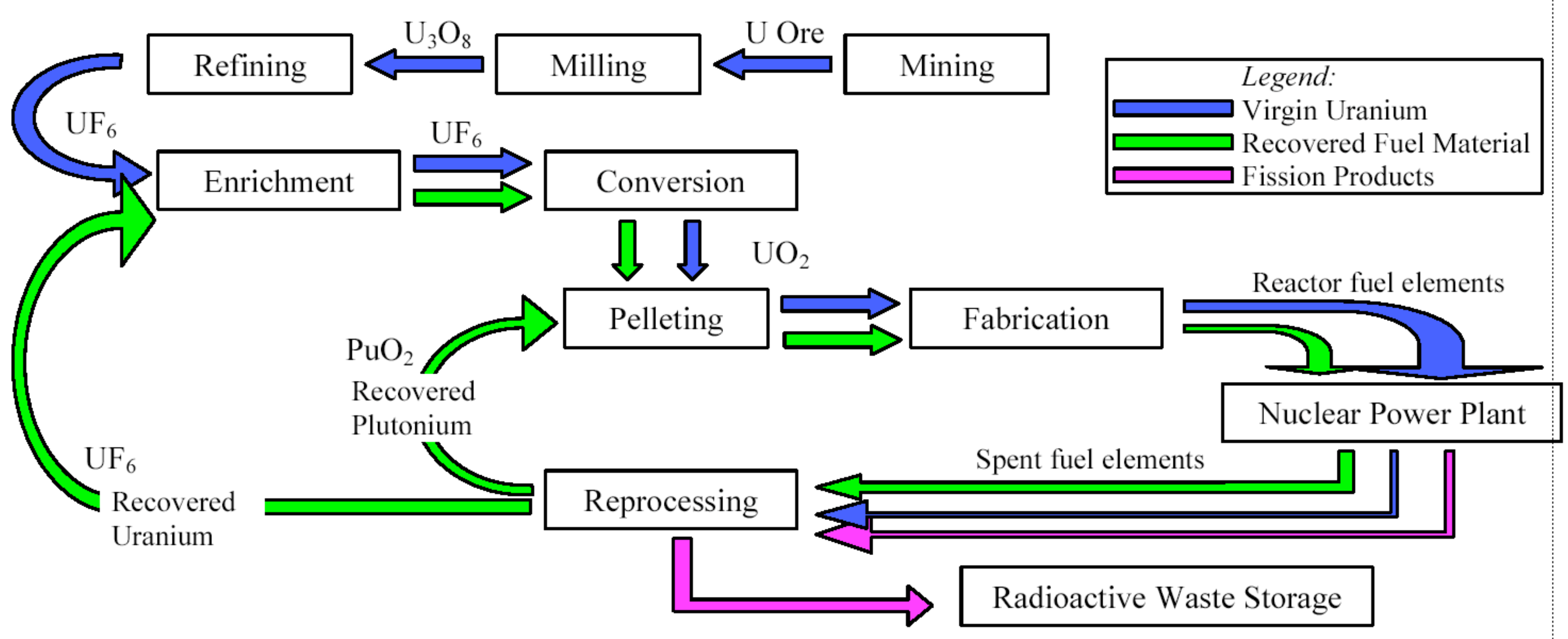
^{238}U is said to fertile because it yields fissile ^{239}Pu

Long half-lives, ^{239}Pu 24,000 years!

Nuclear weapons proliferation: one reactor produces 240Kg/year

Much easier to separate Pu chemically than to enrich uranium.

Fuel Cycle



http://www.antenna.nl/wise/uranium/index.html

Material balance in the nuclear fuel cycle

The following figures make various assumptions[a] but may be regarded as typical for the operation of a 1000 MWe nuclear power reactor:

Mining	22 400 tonnes of 1% uranium ore
Milling	280 tonnes of uranium oxide concentrate (with 224 t U)
Conversion	331 tonnes UF_6 (with 224 t U)
Enrichment	35 tonnes UF_6 (with 24 t enriched U) – balance is 'tails'
Fuel fabrication	27 tonnes UO_2 (with 24 t enriched U)
Reactor operation	7000 million kWh (7TWh) of electricity
Spent fuel	27 tonnes containing 240kg plutonium
	23 t uranium (0.8% ^{235}U),
	720kg fission products, also transuranics.

[a]Concentrate is 80% U, enrichment to 4% U-235 with 0.3% tails assay, 80% load factor for reactor, core load 72 tU, refuelling annually with one third replaced, http://www.world-nuclear.org/info/inf03.htm

Types of Reactors

- ✳ Pressurized water reactor

  In US 69 of 104 reactors are PWR

- ✳ Boiling water reactor

  Remaining 35 are BWR

- ✳ Heavy water reactor
- ✳ Gas-cooled reactor
- ✳ Breeder reactors

What are the fundamental differences, similarities?

The following are essential components/systems of a thermal nuclear fission reactor:

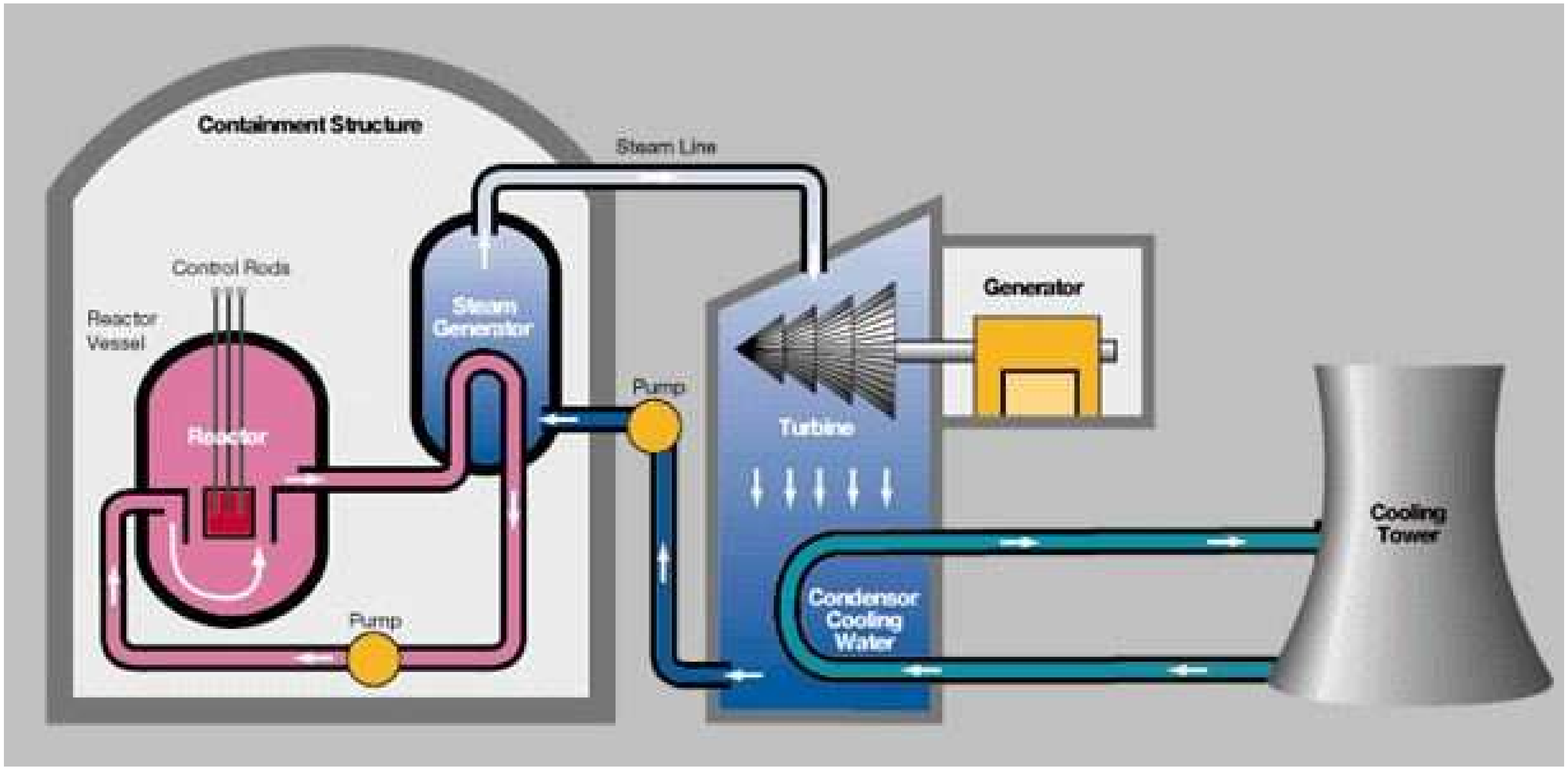
- ✳ The fuel–the fissile material (U-235), either as found in natural uranium or enriched. In some cases plutonium is added. The fuel is produced in the form of metal or oxide pellets.
- ✳ Fuel cladding–a metal shell in which the fuel pellets are contained. It protects the fuel from corrosion and prevents fission products from escaping.
- ✳ A moderator–made of light elements, it slows down the fission neutrons to thermal levels without unduly absorbing them.
- ✳ A coolant–to transport the heat generated from the core to the steam generator for driving the turbine.
- ✳ Control rods–made of neutron absorbing material, these can be moved in or out of the core to control the reaction and maintain it at a critical level or to stop the reaction during shutdown.
- ✳ A pressure vessel–to prevent radioactive material from escaping in case of excessive internal pressure.
- ✳ A containment structure or neutron shield –(concrete or other material) to protect operators and the public from radiation.

Light-water Reactors, PWR and BWR

- ✳ Ordinary water used for coolant and moderator → Advantages
- ✳ Enriched fuel used (UO_2) to sustain criticality since water is such an effective moderator → Smaller reactors

Pressurized Water Reactors

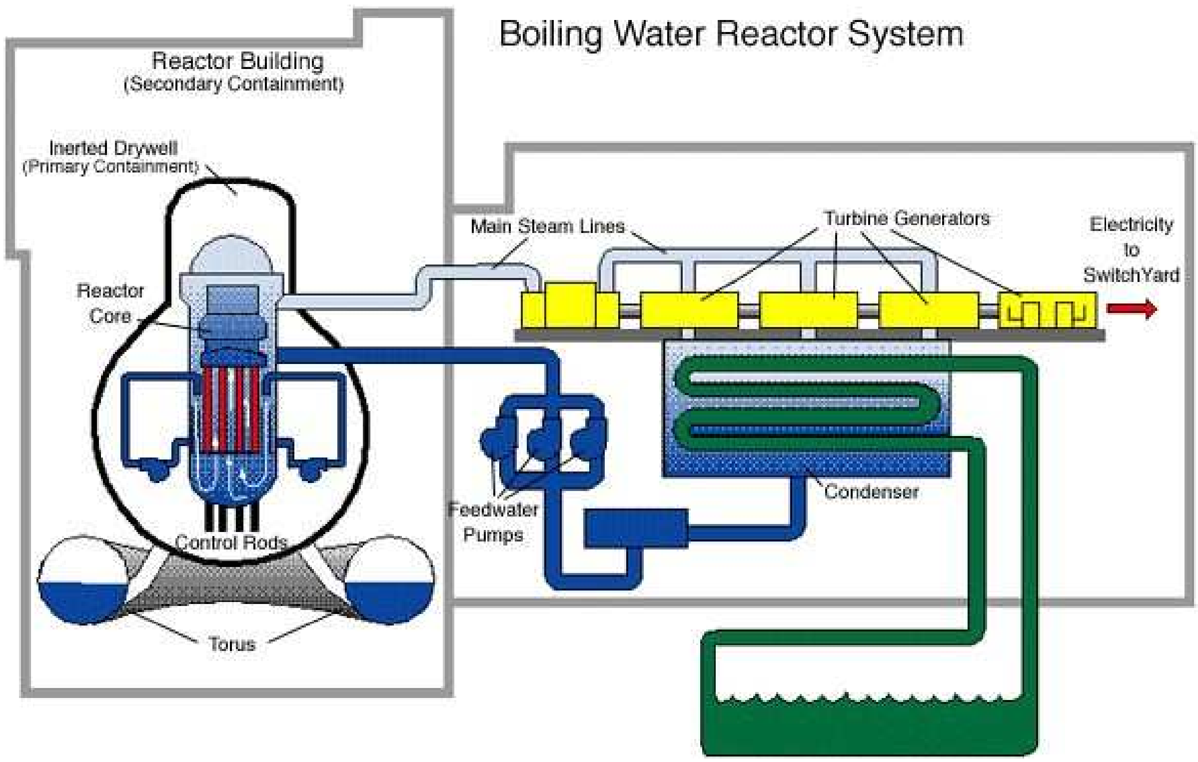
- ✳ Water in reactor vessel is kept under high pressure so that it will not boil (15MPa)
- ✳ Steam generators exchange heat with pressurized water



Boiling Water Reactors

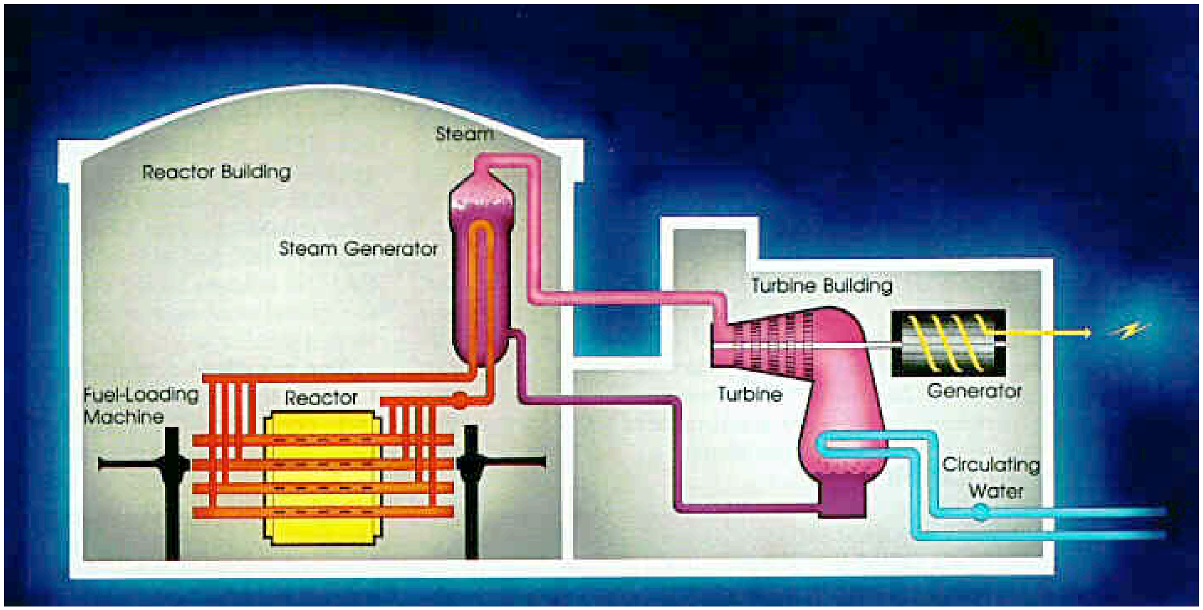
- ✳ Water boils within the reactor under high pressure (7 MPa)
- ✳ Steam generators are not needed → Direct cycle
- ✳ More heat can be absorbed as latent heat
- ✳ Requires more shielding due to contamination by radioactive water

  Same efficiency as PWR, $\simeq 33\%$



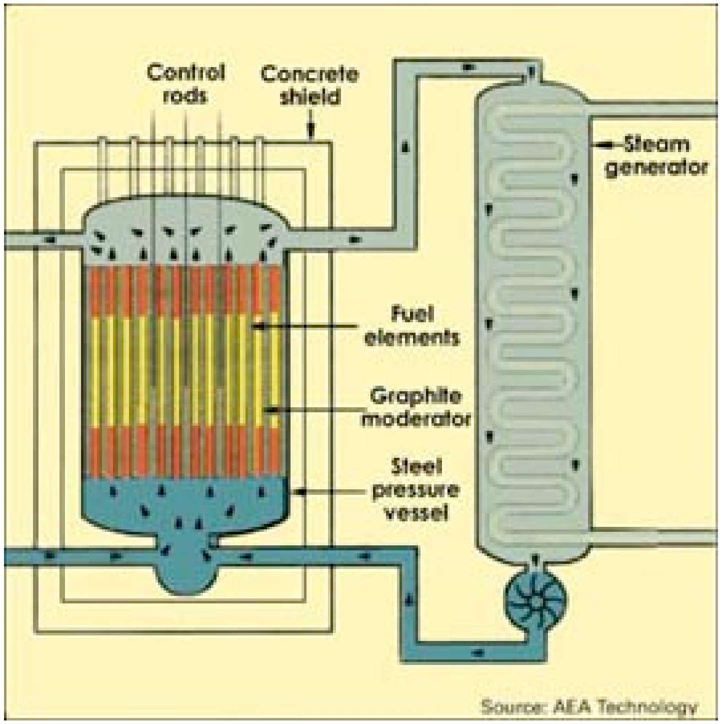
Pressurized Heavy Water Reactor

- ✳ "CANDU" (Canada Deuterium Uranium)
- ✳ Heavy water used as coolant and moderator
- ✳ Natural uranium used for fuel → Advantages
- ✳ Lower efficiency, 29%
- ✳ Re-fueled online → Better availability



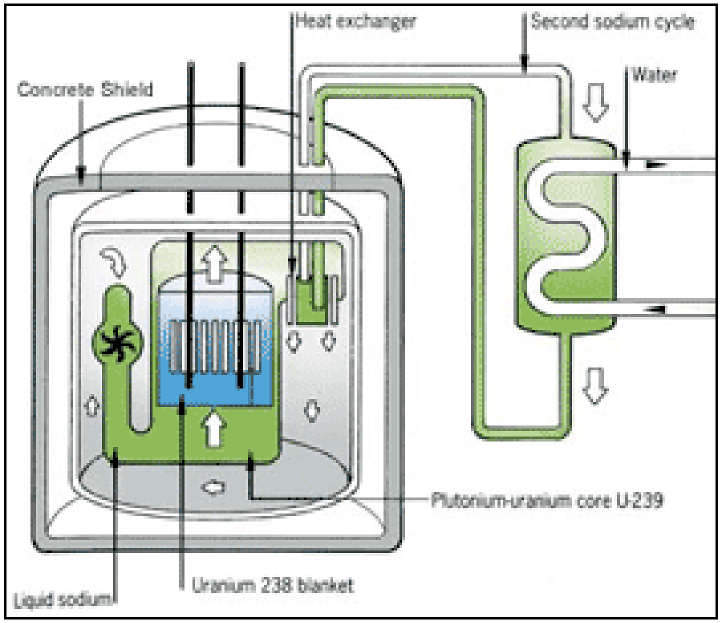
Gas-cooled Reactor

- Originally developed to produce 239Pu
- Graphite moderated
- CO_2 used for coolant (sometimes He)
- Natural uranium fuel
- Efficiency between 40-50%



Breeder Reactors

- ^{235}U is not abundant
- Breeder reactors utilize ^{238}U recovered from enrichment
- Attractive to countries with no uranium resources
- Concern about proliferation of nuclear weapons



Advanced Reactor Design

Reactor Design	Lead Vender(s)	Design Category	Status at NRC
System 80+	Westinghouse BNFL	PWR	Certified
ABWR	GE, Toshiba, Hitachi	BWR	Certified
AP600	Westinghouse BNFL	PWR	Certified
AP1000	Westinghouse BNFL	PWR	Certification
ESBWR	GE	BWR	Pre-certification
SWR-1000	Framatome ANP	BWR	Pre-certification
ACR-700	AECL	PHWR/PWR hybrid	Pre-certification
PBMR	Eskom	HTGR	Pre-certification
GT-MHR	General Atomic	HTGR	Pre-certification
IRIS	Westinghouse BNFL	PWR	Pre-certification
EPR	Framatome ANP	PWR	No application decision
ACR-1000	AECL	PHWR	No application decision

Spent Fuel Discharges[a]

Total U.S. Commercial Spent Nuclear Fuel Discharges, 1968 - 1998			
Reactor Type			
	Number of Assemblies		
	Stored at Reactor Sites	Stored at Away-from-Reactor Facilities	Total
Boiling-Water Reactor	73,538	2,957	76,495
Pressurized-Water Reactor	56,778	491	57,269
High-Temperature Gas Cooled Reactor	1,464	744	2,208
Total	131,780	4,192	135,972
	Metric Tonnes of Uranium (MTU)		
Boiling-Water Reactor	13,230.30	554	13,784.20
Pressurized-Water Reactor	24,412.70	192.6	24,605.40
High-Temperature Gas Cooled Reactor	15.4	8.8	24.2

[a] Energy Information Administration

Radioactive Inventory

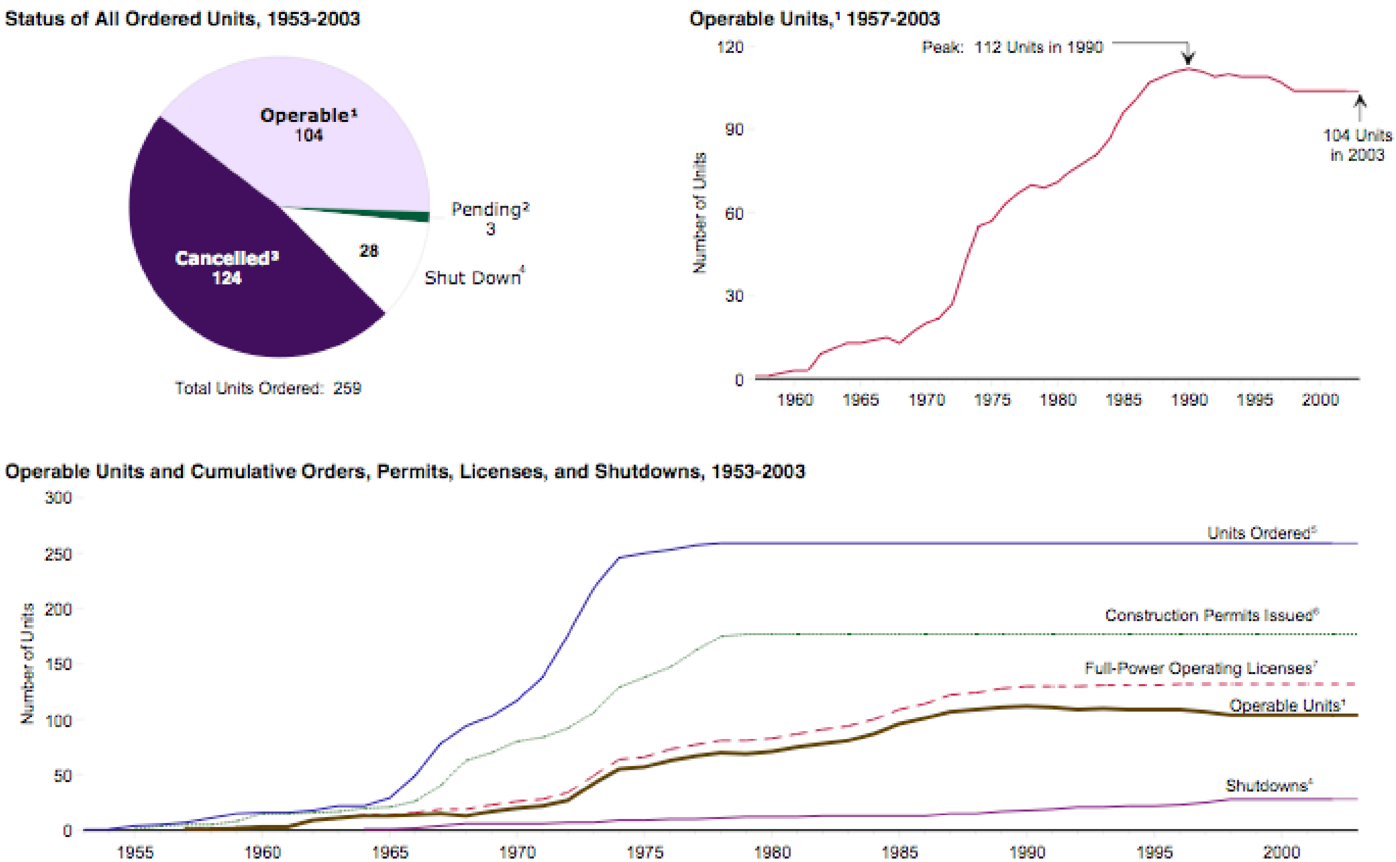
Radioactive Inventory at Shutdown (1000 MWe) PWR		
	Half lives	Quantity (Ci)
Noble gases		
Kr-95, Kr-85m, Kr-87, Kr-88 Xe-133, Xe-135	$0.017 < t_{1/2} < 3950\mathrm{d}$	340×10^6
Iodines		
I-131, I-132, I-133, I-134, I-135	$0.0366 < t_{1/2} < 8.05\mathrm{d}$	715×10^6
Cesiums, Rubidiums		
Cs-134, Cs-136, Cs-137, Rb-96	$13 < t_{1/2} < 11000\mathrm{d}$	1.2×10^6
Telluriums and Antimony		
Te-127, Te-127m, Te-129, Te-129m, Te-131m, Te-132, Sb-127, Sb-129	$1.1 < t_{1/2} < 120\mathrm{d}$	215×10^6
Alkaline earths		
Sr-89, Sr-90, Sr-91, Ba-140	$0.4 < t_{1/2} < 11030d$	366×10^6
Volatile oxides		
Co-58, Co-60, Mo-99, Te-99m Ru-103, Ru-105, Ru-106, Rh-105	$0.25 < t_{1/2} < 1920\mathrm{d}$	557×10^6
Nonvolatile Oxides		
Y-90, Y-91, Zr-95, Zr-97, Nb-95 La-140, Ce-141, Ce-143, Ce-143 Pr-143, Nd-147, Np-239, Pu-238 Pu-239, Pu-240, Pu-241, Am-241 Cm-242, Cm-244	$0.71 < t_{1/2} < 8.9 \times 10^6\mathrm{d}$	3082×10^6

Total = 5.3 billion Curies

APS, Rev. Mod. Phys. 57, July 1985

Nuclear Reactors in the US

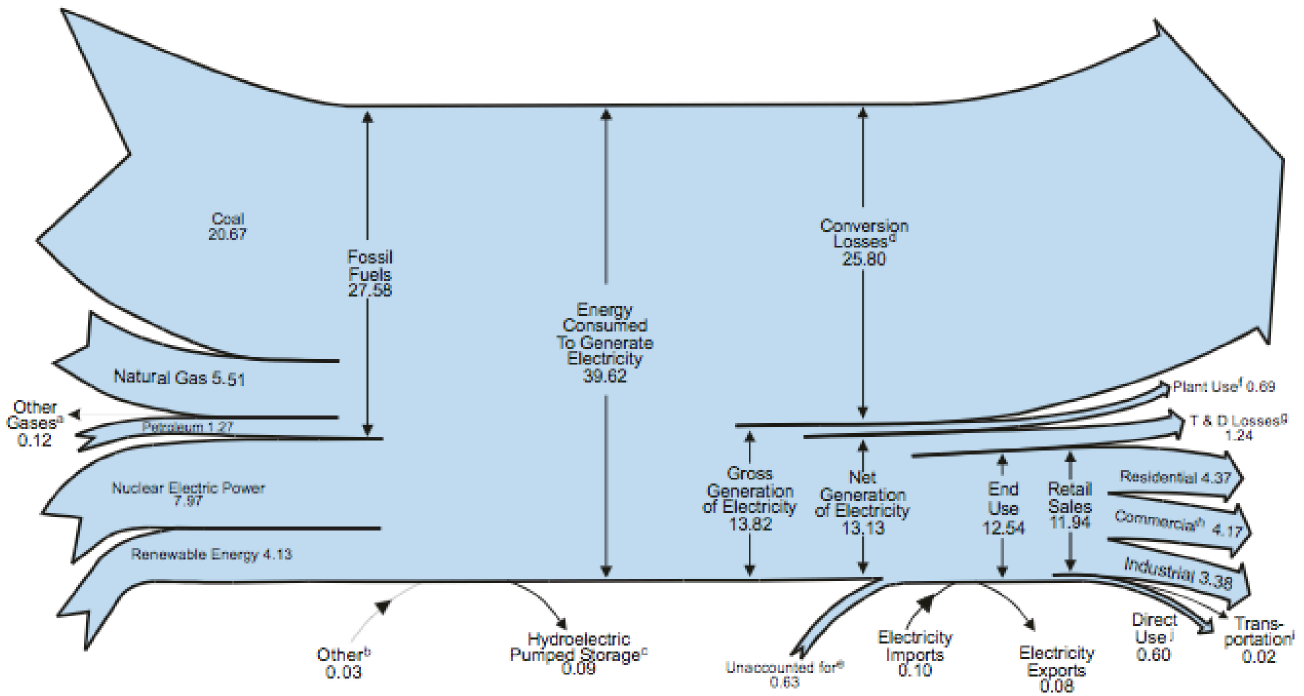
Figure 9.1 Nuclear Generating Units



[1] Units holding full-power operating license, or equivalent permission to operate.
[2] Bellefonte 1 and 2 and Watts Bar 2, where construction has been stopped indefinitely.
[3] Includes WNP 1; the licensee intends to request that the construction permit be cancelled.
[4] Ceased operation permanently.
[5] Placement of an order by a utility or government agency for a nuclear steam supply system.
[6] Issuance by a regulatory authority of a permit, or equivalent permission, to begin construction.
[7] Issuance by regulatory authority of full-power operating license, or equivalent permission.
Note: Data are at end of year.
Source: Table 9.1.

Energy Flow in Electricity Sector

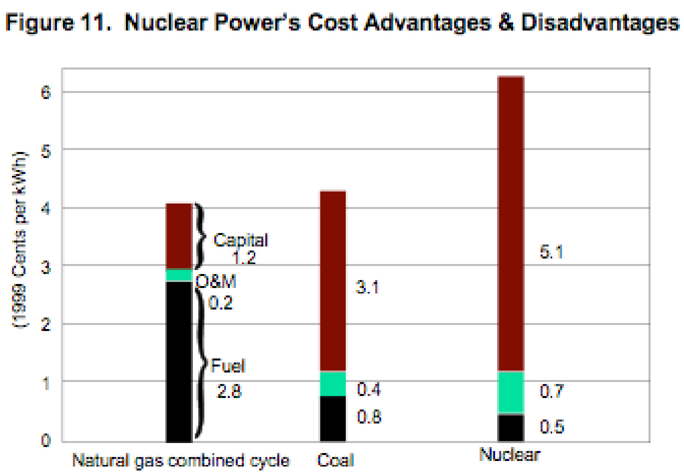
Diagram 5. Electricity Flow, 2003
(Quadrillion Btu)



[a] Blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.
[b] Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, and miscellaneous technologies.
[c] Pumped storage facility production minus energy used for pumping.
[d] Approximately two-thirds of all energy used to generate electricity. See note "Electrical System Energy Losses," at end of Section 2.
[e] Data collection frame differences and nonsampling error.
[f] Electric energy used in the operation of power plants, estimated as 5 percent of gross generation. See note "Electrical System Energy Losses," at end of Section 2.
[g] Transmission and distribution losses (electricity losses that occur between the point of generation and delivery to the customer) are estimated as 9 percent of gross generation. See note "Electrical System Energy Losses," at end of Section 2.
[h] Commercial retail sales plus approximately 95 percent of "Other" retail sales from Table 8.9.
[i] Approximately 5 percent of "Other" retail sales from Table 8.9.
[j] Commercial and industrial facility use of onsite net electricity generation; and electricity sales among adjacent or co-located facilities for which revenue information is not available.
Note: Totals may not equal sum of components due to independent rounding.
Sources: Tables 2.1b-2.1e, 8.1, 8.4a, and A6 (column 4).

Is it Necessary?

Market, despite huge and continuing subsidies, says No!



http://www.eia.doe.gov/cneaf/nuclear/page/analysis/ghg.pdf

Technical problems remain unresolved

New technologies for energy production exist

Huge opportunities exist through savings

Nuclear proliferation and terrorist attacks are driving concerns in US foreign policy. Increasing the use of nuclear power generation only makes the situation worse.