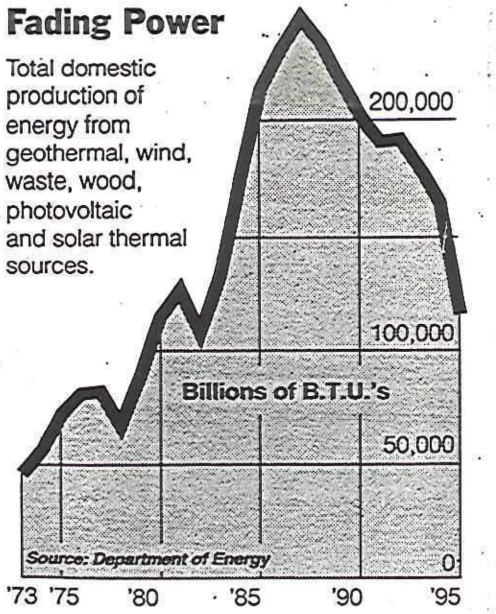


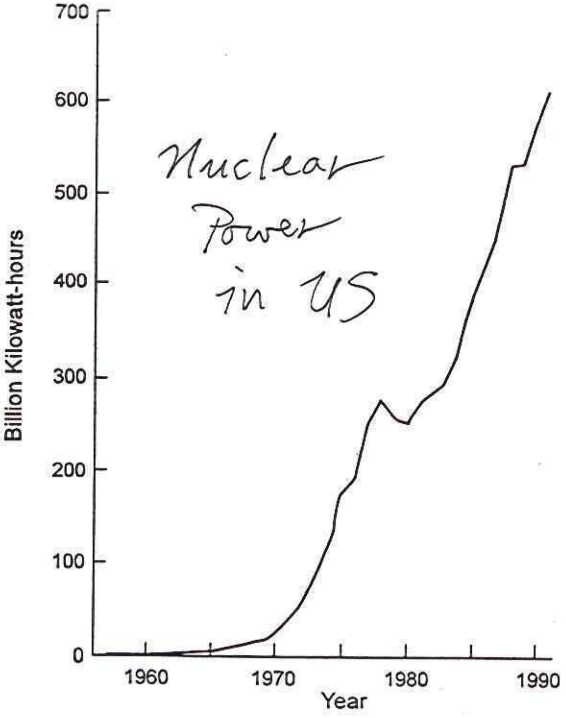
Fading Power

Total domestic production of energy from geothermal, wind, waste, wood, photovoltaic and solar thermal sources.

Source: Department of Energy

The New York Times

Fall '97
never got
to nuclear



Nuclear
Power
in US

Figure 11.25. Net nuclear generation of electricity in the United States, 1957–91. *(Annual Energy Review 1991)*

Figure 11.26. Nuclear electricity gross generation *(Annual Energy Review 1993)*

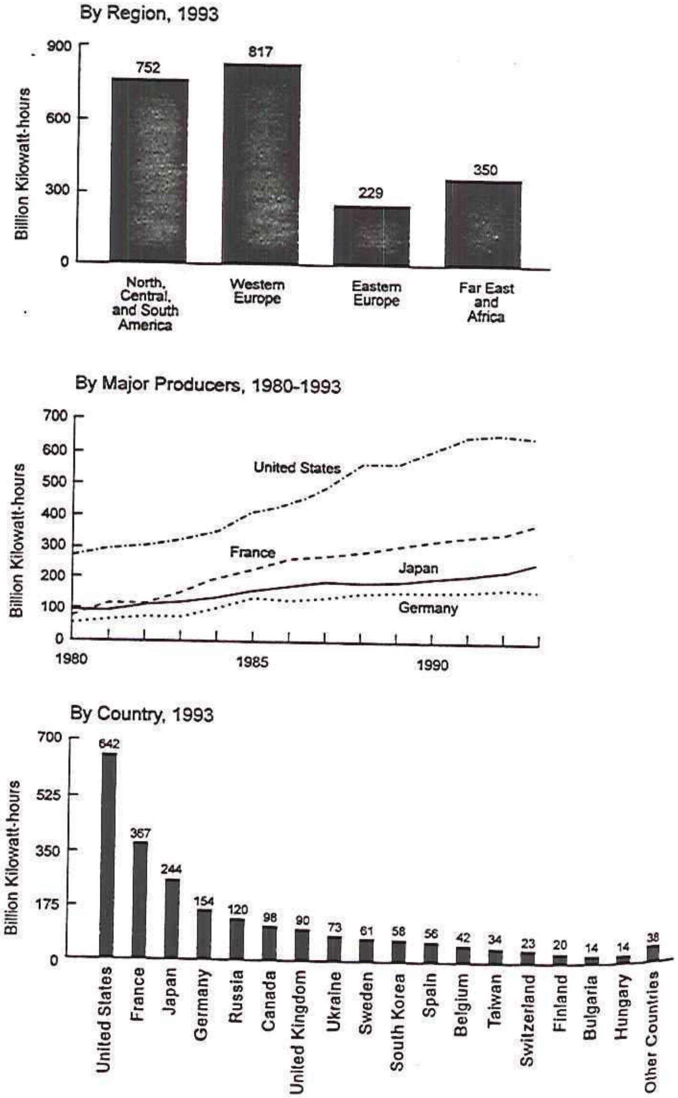


Table 10. World nuclear power: capacity (net gigawatts), generation (net gigawatt-years), and fraction of all electricity.

Country	Status (6/30/89)[a] Number of units	 Capacity (GWe)	Annual generation[b] (GWyr) 1976	 1988	Percent nuclear[c] 1988
United States	110	97.6	21.8	60.1	19.5
France	55	52.6	1.7	29.7	70
USSR	56	33.8	2.7	23.3	13
Japan	38	28.3	4.0	18.7	23
Germany, West	24	22.7	2.7	15.7	34
Canada	18	12.2	2.0	8.9	16
Sweden	12	9.7	1.7	7.5	47
United Kingdom	40	12.4	4.0	6.3	19
Spain	10	7.5	0.8	5.5	36
Belgium	7	5.5	1.1	4.6	66
Korea, South	9	7.2	0.0	4.3	47
Taiwan	6	4.9	0.0	3.4	41
Switzerland	5	3.0	0.9	2.5	37
Czechoslovakia	8	3.3	0.0	2.4	27
Finland	4	2.3	0.0	2.1	36
Hungary	4	1.6	0.0	1.4	49
Bulgaria	5	2.6	0.5	1.3	36
South Africa	2	1.8	0.0	1.2	7
Germany, East	5	1.7	0.6	1.2	10
India	6	1.2	0.3	0.7	3
Argentina	2	0.9	0.3	0.6	11
Yugoslavia	1	0.6	0.0	0.4	5
Netherlands	2	0.5	0.4	0.4	5
Brazil	1	0.6	0.0	0.03	0.3
Pakistan	1	0.1	0.1	0.02	0.6
Mexico	1	0.7	0.0	0.00	0
Italy	2	1.1	0.4	0.00	0
World Total	434	316.4	46.0	202.4	17

a. Data from Ref. 21, p. 63.
b. Data from Ref. 18: IEA 1983, p. 26; IEA 1988, p. 24.
c. Data from Ref. 22, p. 1.

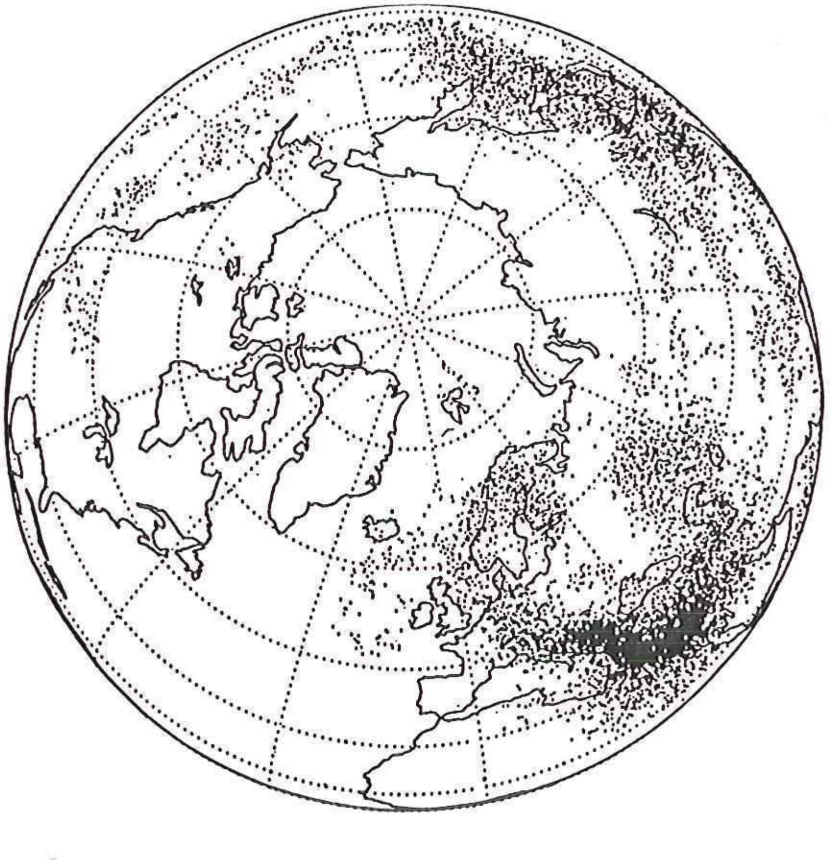


Figure 11.36. Calculated spatial distribution of radioactivity over the Northern Hemisphere 10 days after the Chernobyl accident, as illustrated by the Lawrence Livermore National Laboratory. (Lange, Dickerson, and Gudiksen 1988).

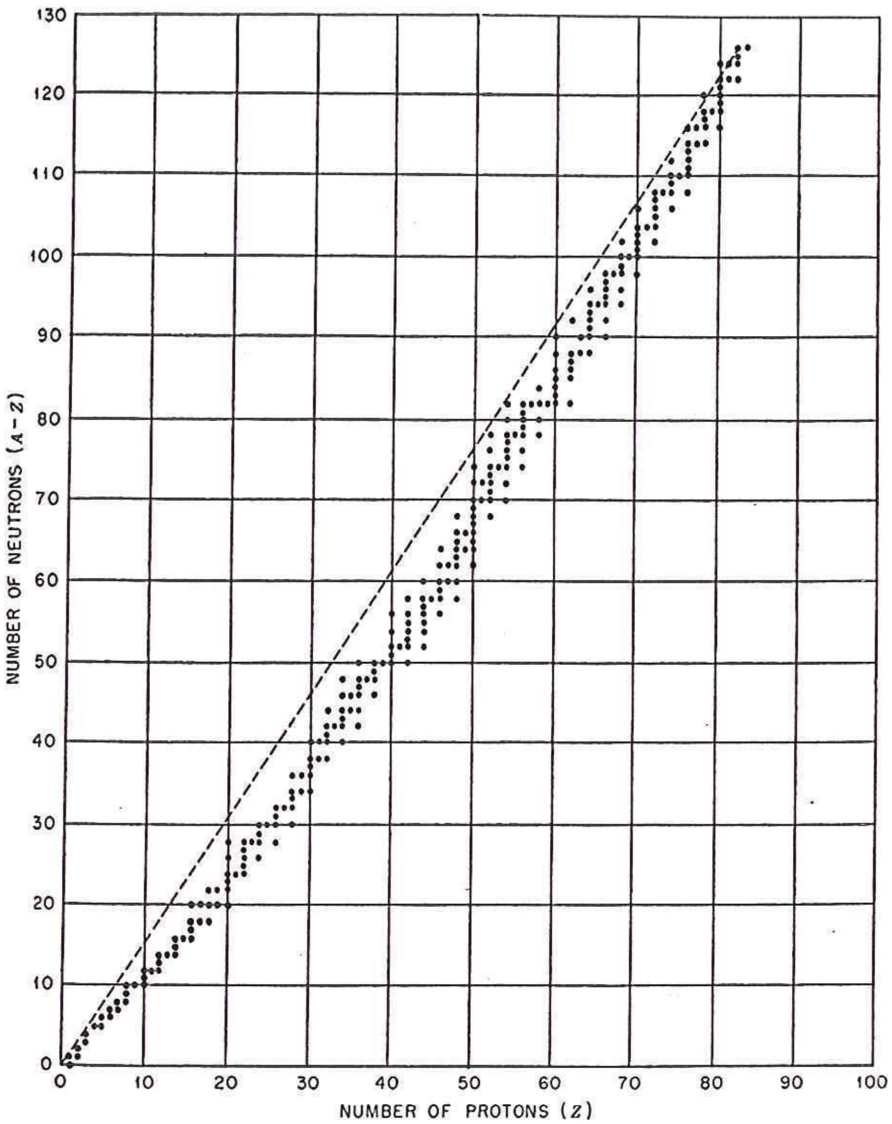


FIG. 1.15. Numbers of neutrons and protons in stable nuclei

TABLE 1.10. ISOTOPIC COMPOSITION OF NATURAL URANIUM

Mass Number	*Per Cent*	*Isotopic Mass (amu)*
234	0.006	234.11
235	0.712	235.11
238	99.282	238.12

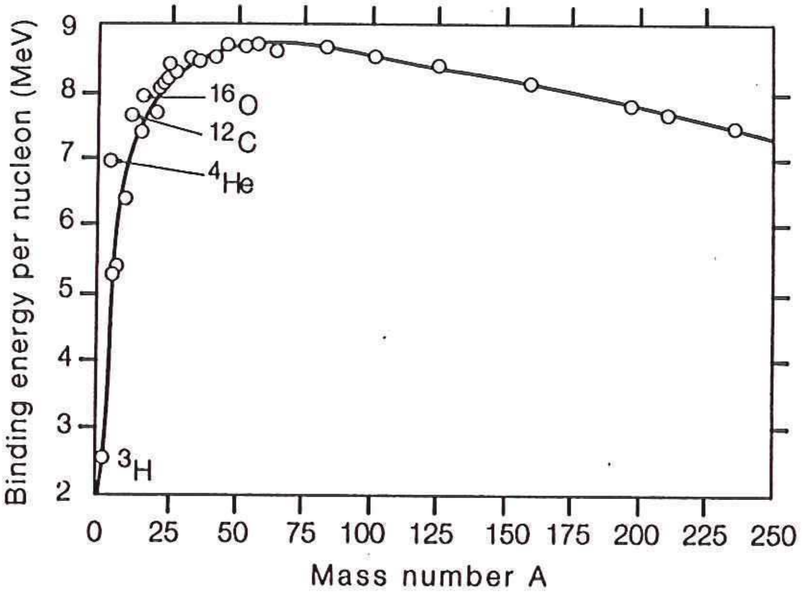


Figure 4.37 Binding energy per nucleon versus the mass number *A* for stable nuclei

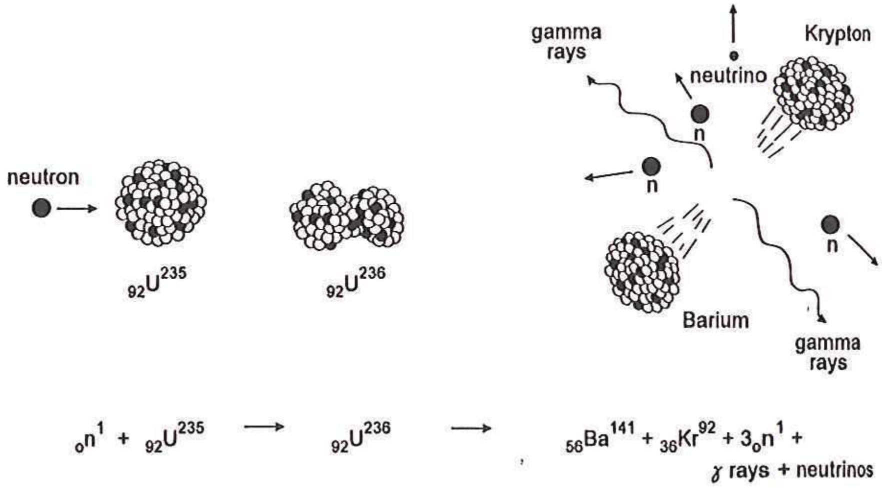
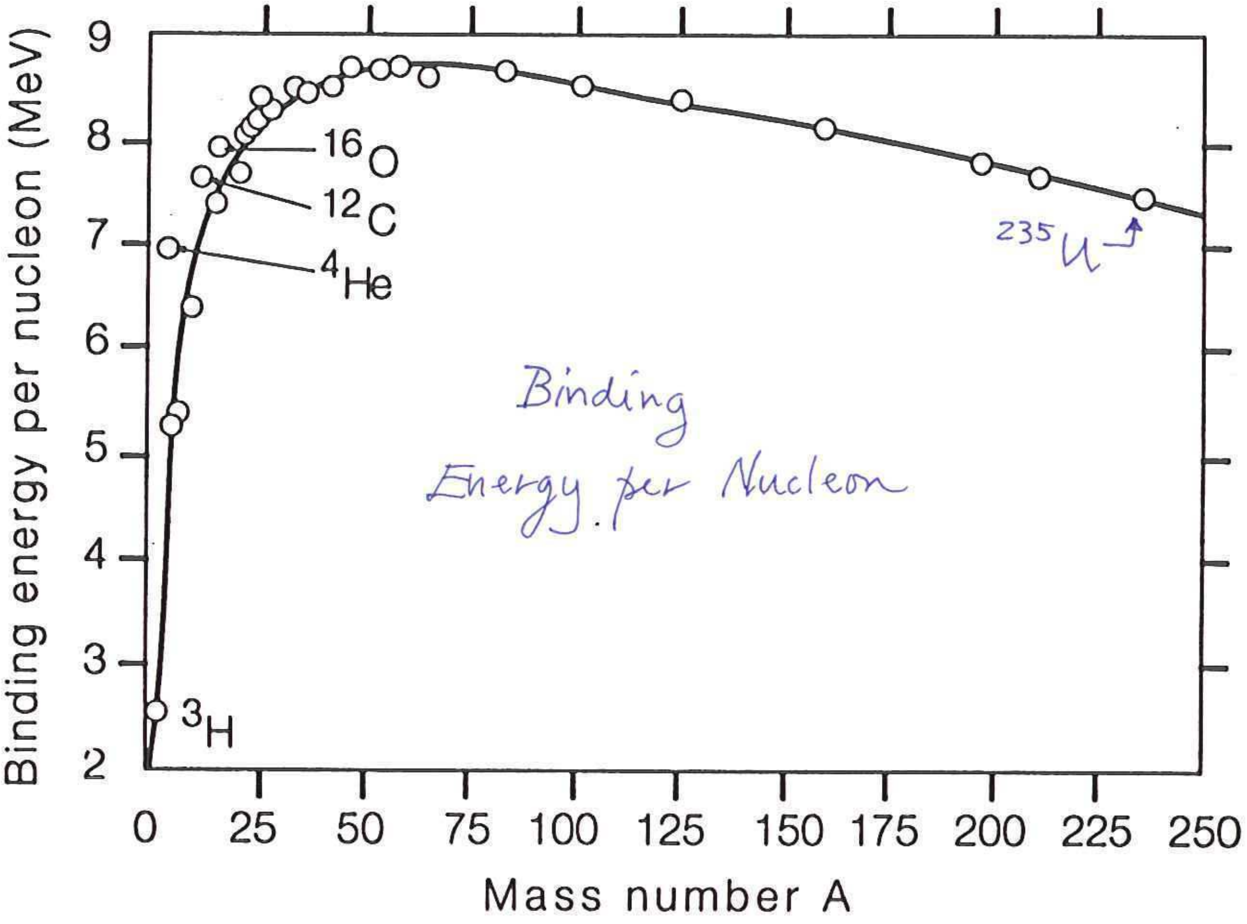


Figure 11.28. Diagrammatic representation of the reaction of a neutron with a ^{235}U nucleus. The reaction produces ^{236}U, which, in this instance, fissions into barium, krypton, neutrons, neutrinos, and gamma rays.



Example : ^{235}U mass 235.11 amu

Mass of constituent parts :

92 protons × 1.00758 amu
143 neutrons × 1.00897 amu
92 electrons × $5.5 \cdot 10^{-4}$ amu

} total 237.03 amu

Difference — 1.92 amu — is the <u>nuclear</u> <u>binding</u> <u>energy</u>: holds the protons in the nucleus

$E = mc^2$ $(1 \text{ amu}) \times c^2 = 931$ MeV

So : $(1.92 \text{ amu}) \times c^2 = 1787$ MeV

$$\boxed{\frac{1787 \text{ MeV}}{235 \text{ nucleons}} = 7.6 \text{ MeV/nucleon}}$$

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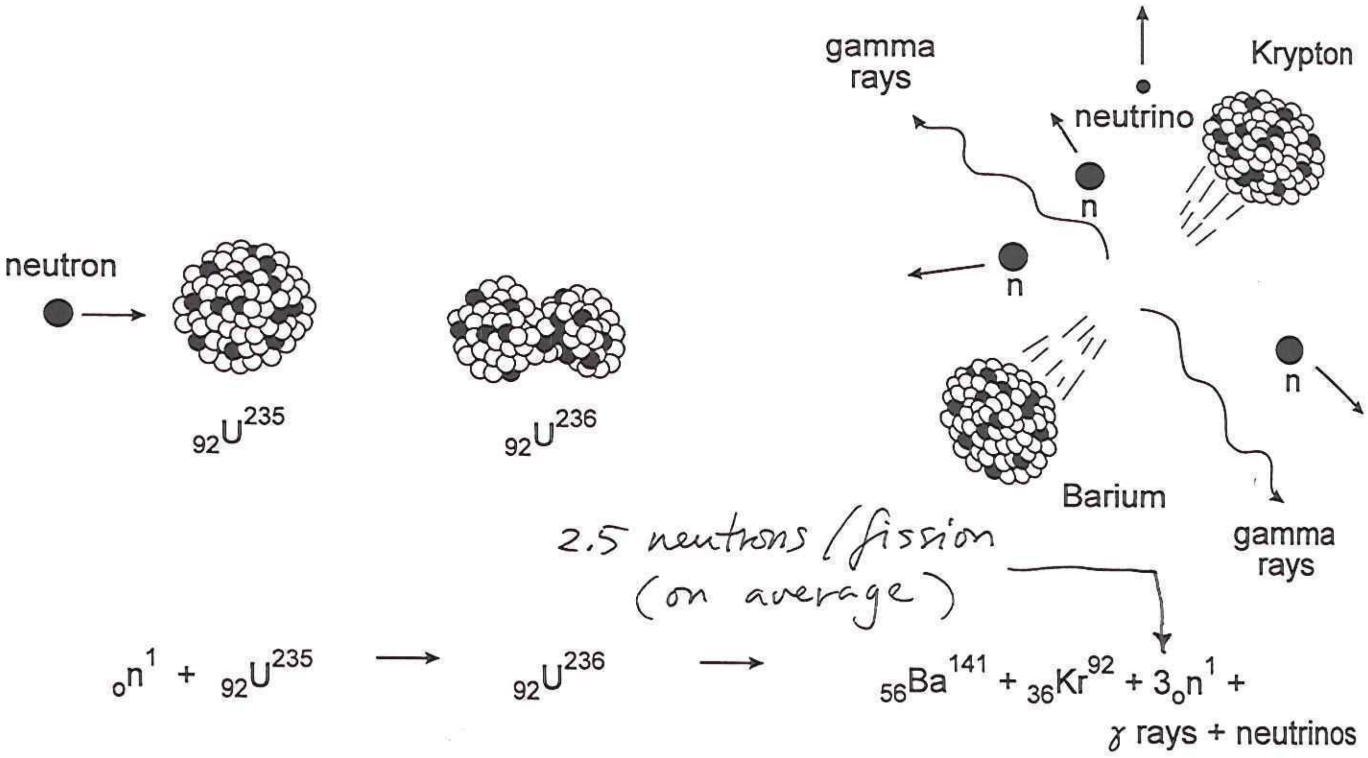
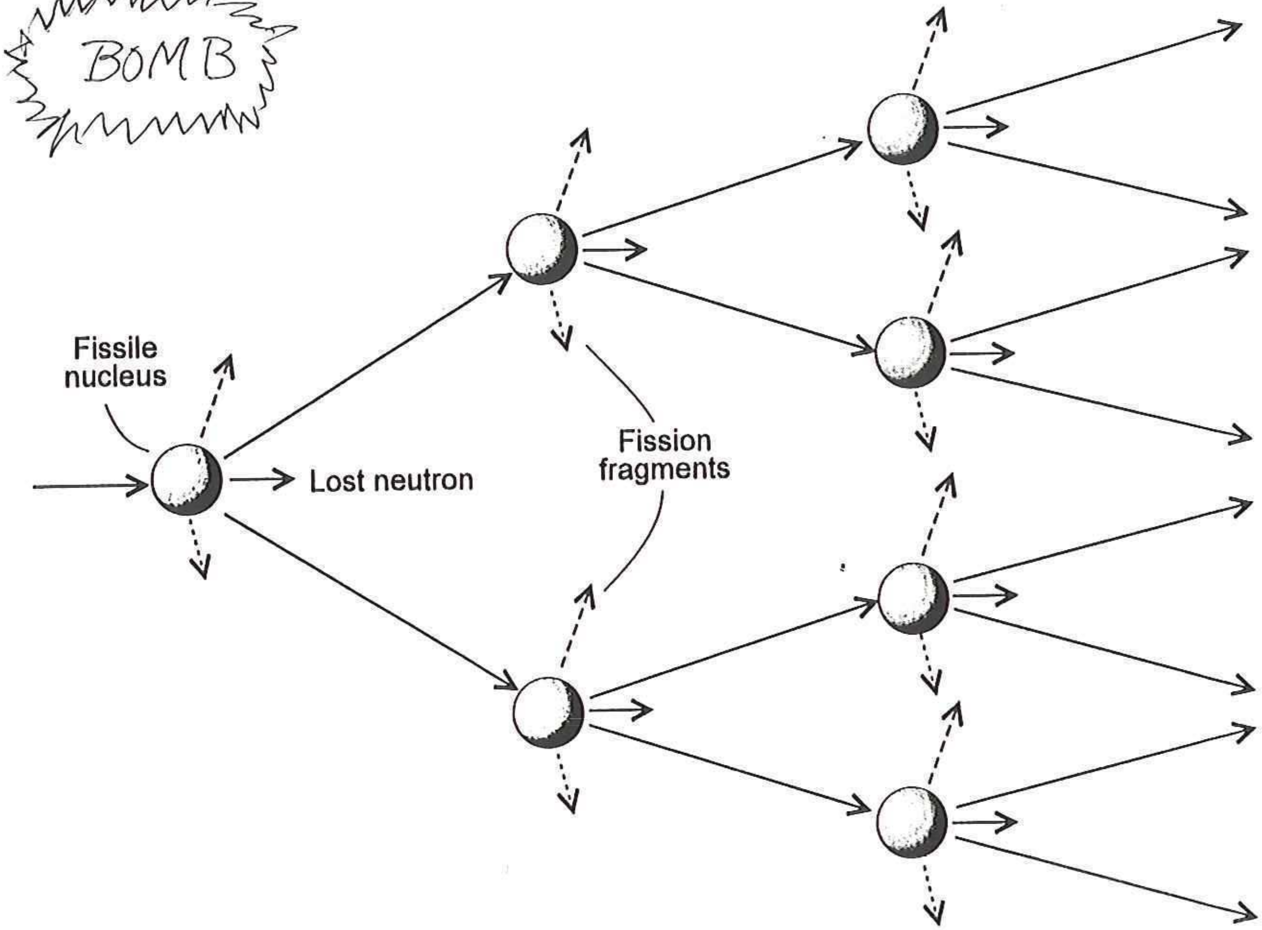


$$_{0}n^{1} + {}_{92}U^{235} \longrightarrow {}_{92}U^{236} \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\,{}_{0}n^{1} + \gamma \text{ rays} + \text{neutrinos}$$

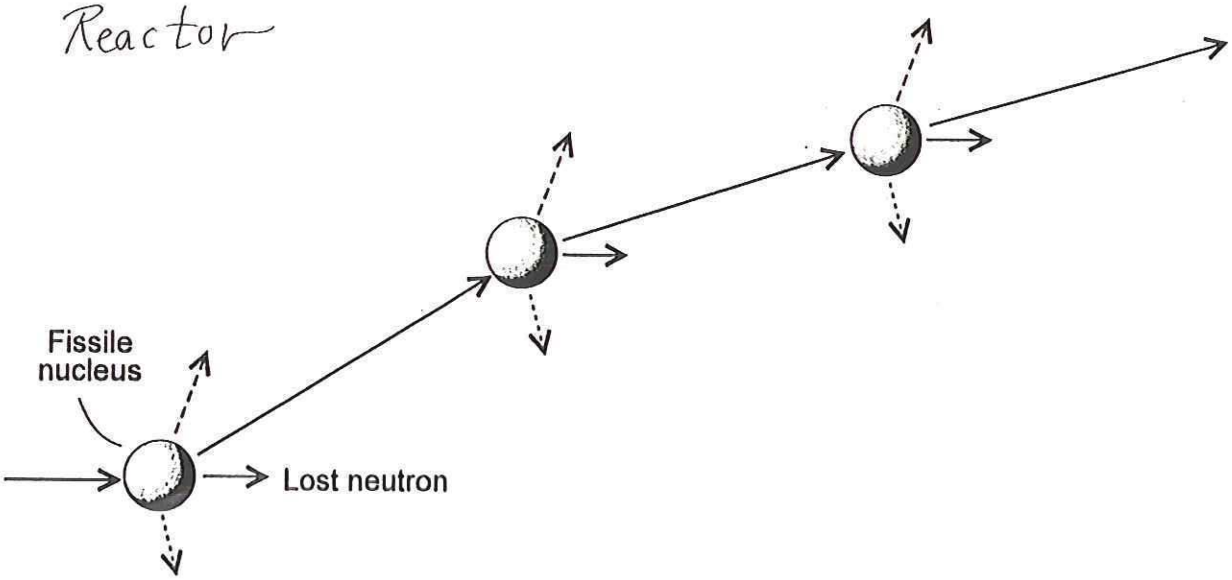
2.5 neutrons / fission
(on average)

Figure 11.28. Diagrammatic representation of the reaction of a neutron with a ^{235}U nucleus. The reaction produces ^{236}U, which, in this instance, fissions into barium, krypton, neutrons, neutrinos, and gamma rays.

BOMB



Reactor



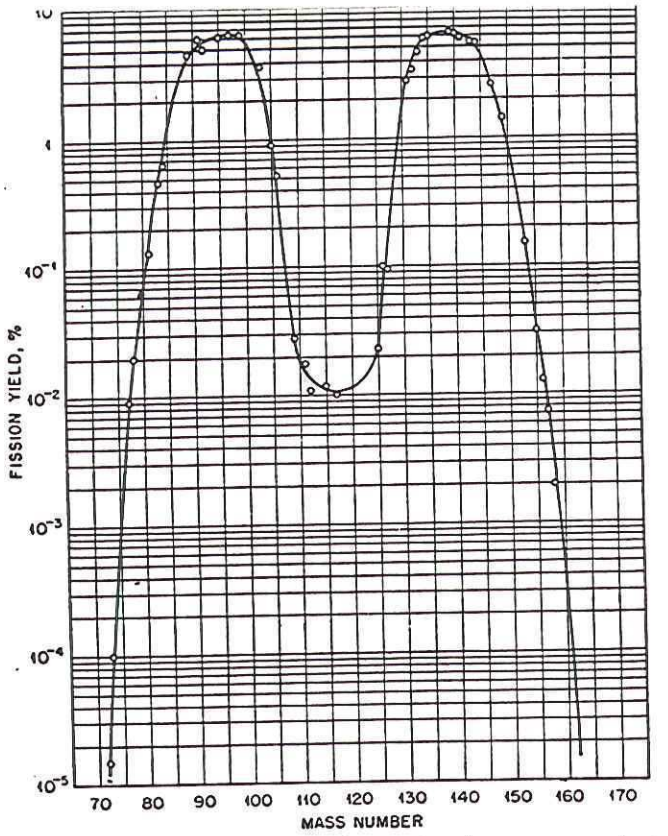


FIG. 4.13. Fission yields of products of various mass numbers

TABLE 4.23. DISTRIBUTION OF FISSION ENERGY

Kinetic energy of fission fragments	162 Mev
Beta decay energy	5
Gamma decay energy	5
Neutrino energy	11
Energy of fission neutrons	6
Instantaneous gamma-ray energy	6
Total fission energy	195 Mev

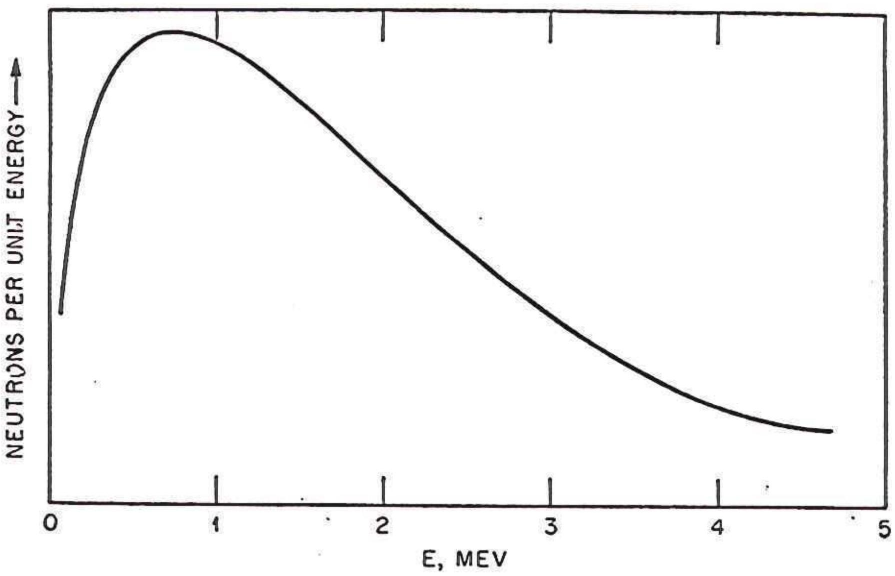


FIG. 4.7. Fission neutron energy spectrum

TABLE 3.18. "ENERGIES" AND "SPEEDS" OF THERMAL NEUTRONS AT VARIOUS TEMPERATURES

Temperature		"Energy" (ev)	"Speed" (cm/sec)
(° K)	(° C)		
300	27	0.026	2.2×10^5
400	127	0.034	2.6
600	327	0.052	3.1
800	527	0.069	3.6
1000	727	0.086	4.0

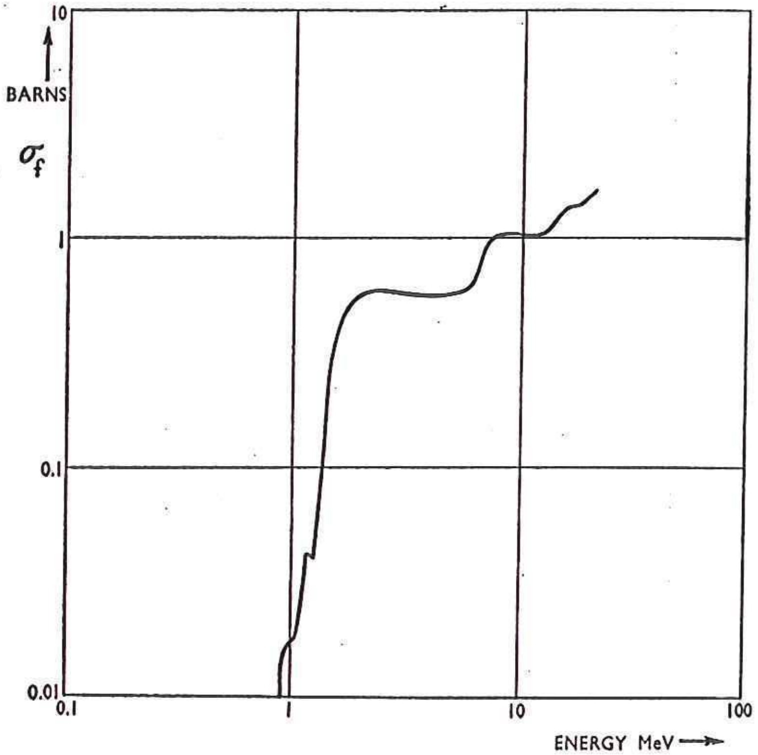


FIG. 7. Fission cross-section of U^{238}.

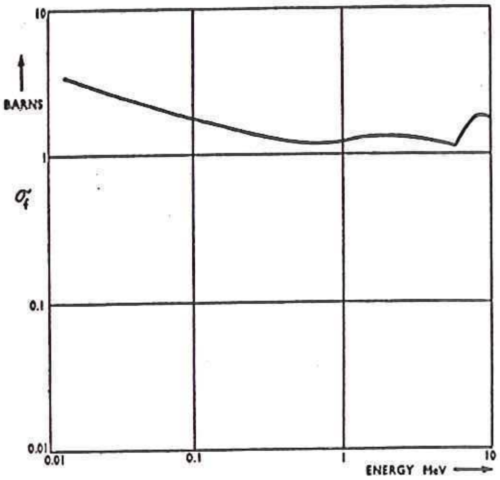


FIG. 6c. Fission cross-section of U^{235}.

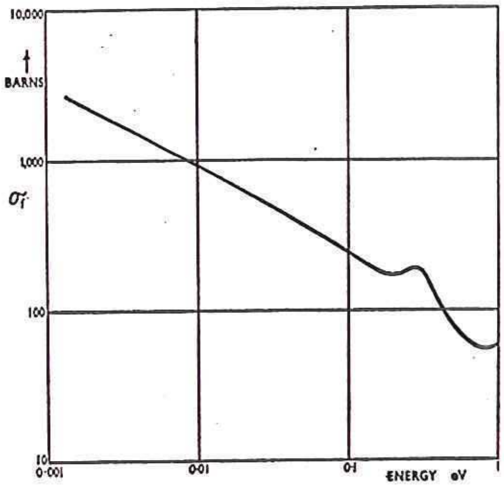


FIG. 6a. Fission cross-section of U^{235}.

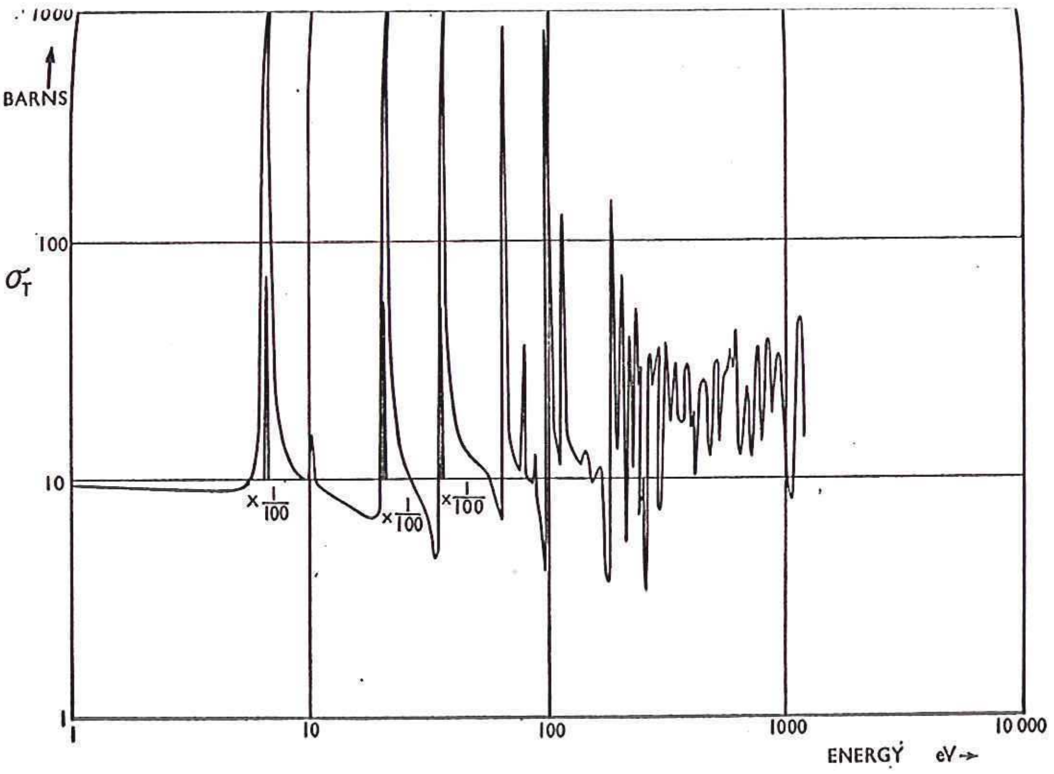


FIG. 4b. Total cross-section of U^{238}.

	% by weight	parts by atom	σ_f	σ_c	σ_a	σ_s
U^{235}	0·715	1	582	112	694	
U^{238}	99·3	138	0	2·71	2·71	
U			4·19	3·50	7·69	8·3

TABLE 2. Uranium Cross-Sections in barns at Thermal Energy (2200 m per sec.) The value of σ_s is the average value over a Maxwell distribution.)

	σ_f	σ_c	σ_s	σ_t
U	0.29	0.04	1.5	2.47

TABLE 3. Natural Uranium Cross-Sections in barns for Fast Neutrons

Moderator	Density gm/cm³	σ_c in barns (2200 m/sec)	Atomic or Molecular Weight	N_s (approx.
H_2O	1·00	0·664 (per molecule)	18·02	20
D_2O (pure)	1·10	$1·14 \times 10^{-3}$ (per molecule)	20·03	36
D_2O (99·75% by molecules)	1·10	$2·8 \times 10^{-3}$ (per molecule)	20·03	36
Be	1·85	10×10^{-3}	9·01	88
BeO	2·8	10×10^{-3}	25·01	105
Graphite	1·6	$4·5 \times 10^{-3}$	12·01	115

TABLE 3. Moderator Cross-Sections and Numbers of Collisions to Slow a Fission Neutron Down to Thermal Energy. (In the case of graphite the density and cross-section are representative values)

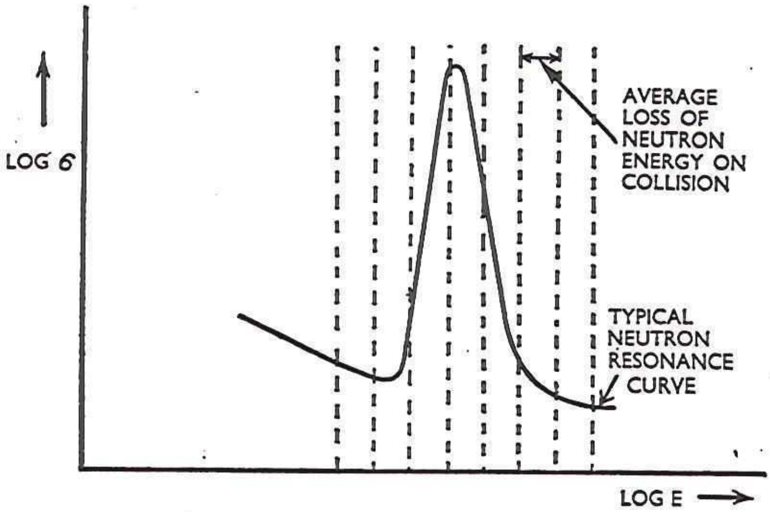


FIG. 1. Neutron capture in a uranium resonance.

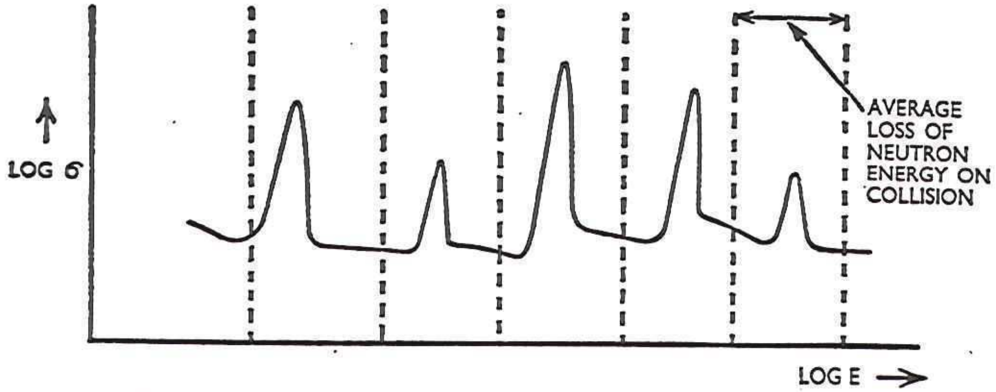
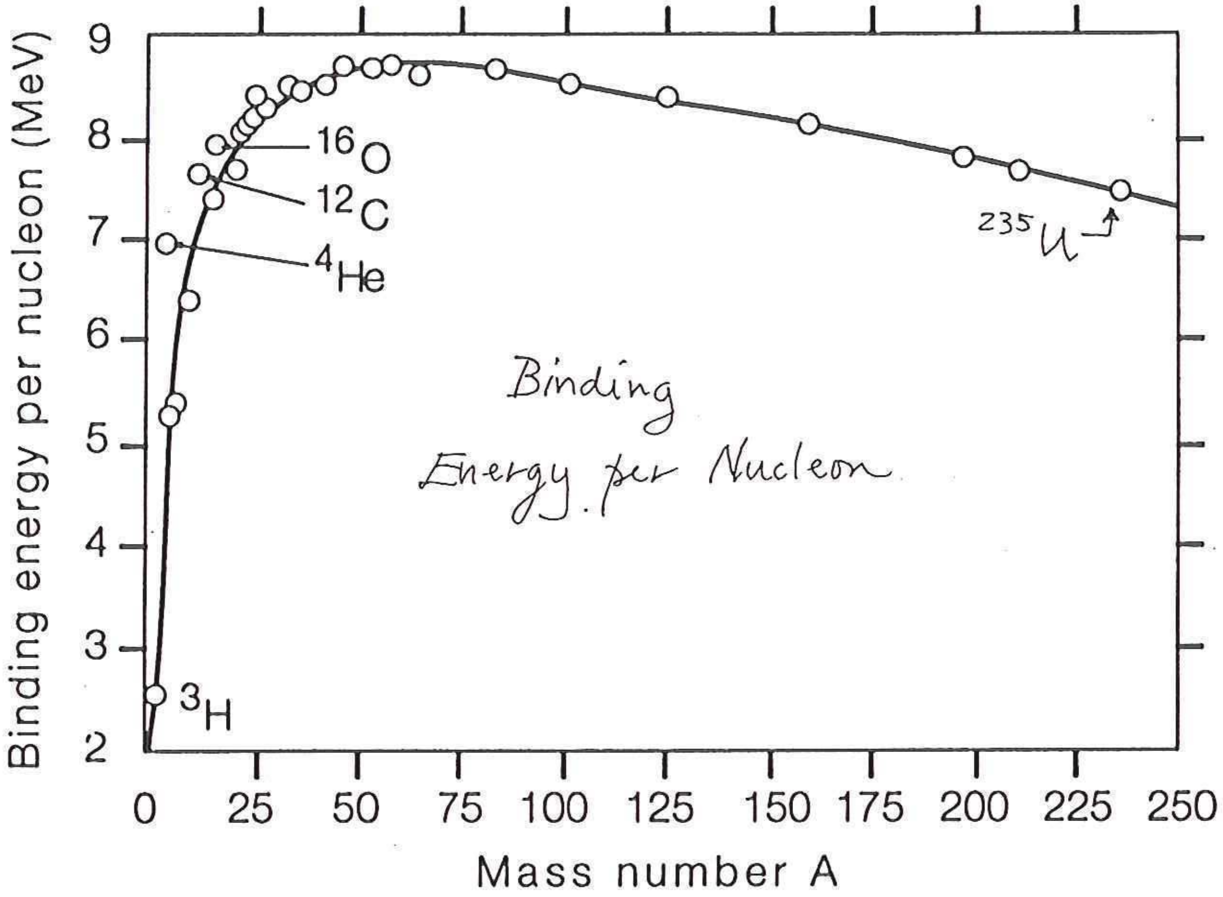


FIG. 3. Neutron scattering by light nuclei past resonances.



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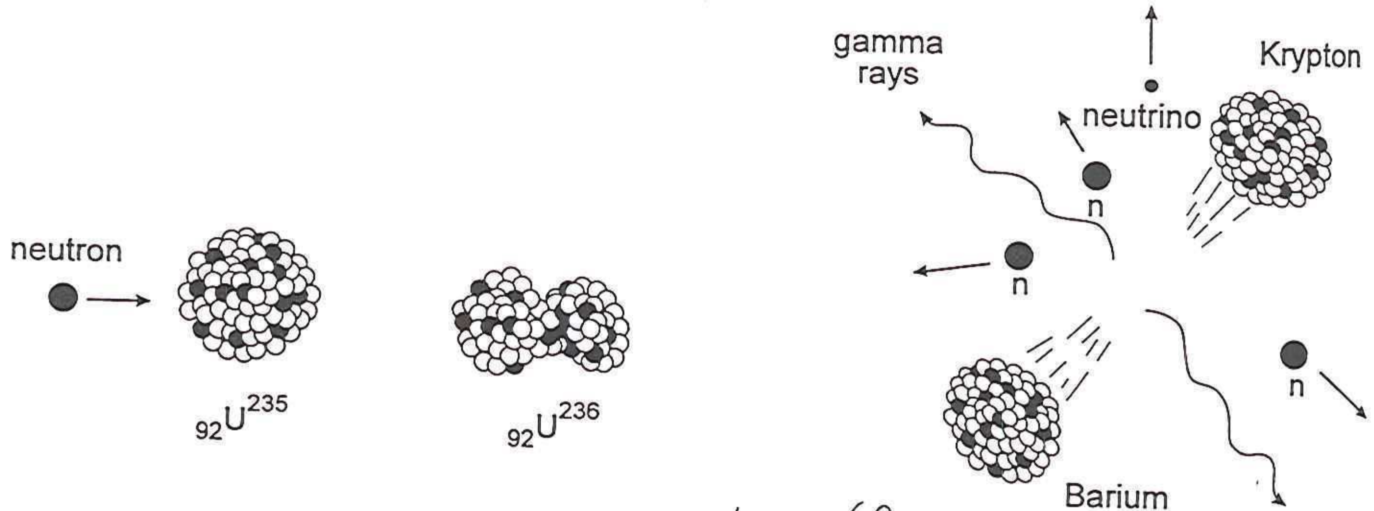


Figure 11.28. Diagrammatic representation of the reaction of a neutron with a ^{235}U nucleus. The reaction produces ^{236}U, which, in this instance, fissions into barium, krypton, neutrons, neutrinos, and gamma rays.

2.5 neutrons / fission (on average)

$$_0n^1 + {}_{92}U^{235} \longrightarrow {}_{92}U^{236} \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\,{}_0n^1 + \gamma \text{ rays} + \text{neutrinos}$$

Table 4.5 Typical data on current nuclear reactors.[a] (Summarized and reproduced by permission of John Wiley & Sons from James J. Duderstadt and Louis J. Hamilton, *Nuclear Reactor Analysis*, Wiley, New York, 1992, pp. 634–5).

	PWR	BWR	CANDU	HTGR
Fuel	UO_2	UO_2	UO_2	UC, ThO_2
Enrichment (% ^{235}U)	≈2.6	≈2.9	Natural	93.5
Moderator	H_2O	H_2O	D_2O	Graphite
Coolant	H_2O	H_2O	D_2O	He
Electric power (MW_e)	1150	1200	500	1170
Coolant out (°C)	332	286	293	755
Maximum fuel temperature (°C)	1788	1829	1500	1410
Net efficiency (%)	34	34	31	39
Pressure in reactor vessel (bar = 10^5 Pa)	155	72	89	50
Conversion ratio[b]	≈0.5	≈0.5	≈0.45	≈0.7
Specific power (MW_{th}/ton fuel)	37.8	25.9	20.4	77

[a] PWR = pressurized water reactor where the pressure prevents steam formation. Steam is produced in a second loop by a heat exchanger. BWR = boiling water reactor, where the steam is generated in the reactor itself. CANDU = Canadian deuterium–uranium reactor. HTGR = high-temperature gas-cooled reactor.

[b] The conversion ratio shown is the number of fissible Pu nuclei formed per fission from the present ^{238}U and Pu nuclei in the reactor.

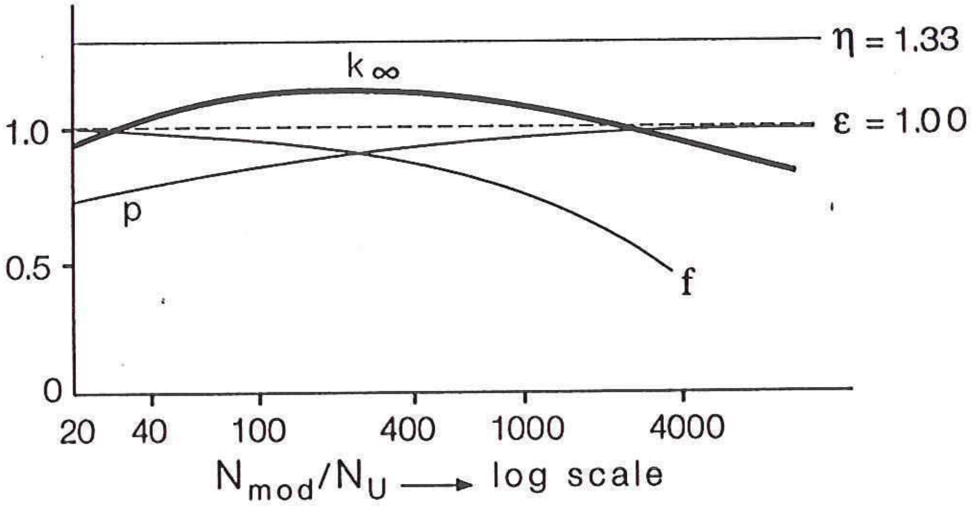


Figure 4.40 Reactor physical parameters for natural uranium as a fuel and D_2O as a moderator. Horizontally one finds the ratio of their atoms or molecules. (Reproduced by permission of H. van Dam/J. E. Hoogenboom from Dr J. E. Hoogenboom lecture notes, IRI, Delft, Netherlands)

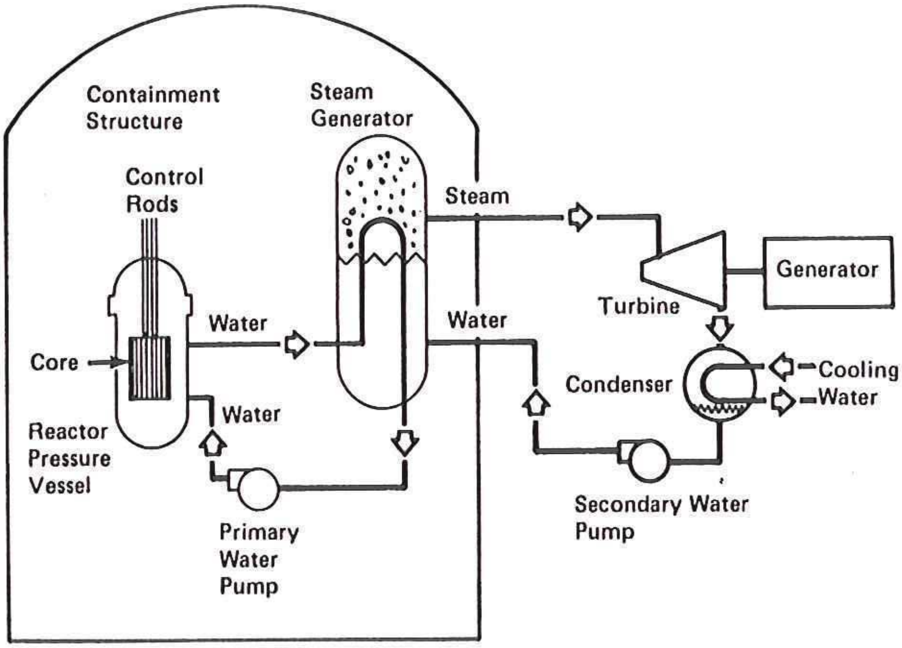


Figure 11.31. Schematic diagram of a pressurized water reactor (PWR) power system. (Nuclear Energy Policy Study Group 1977)

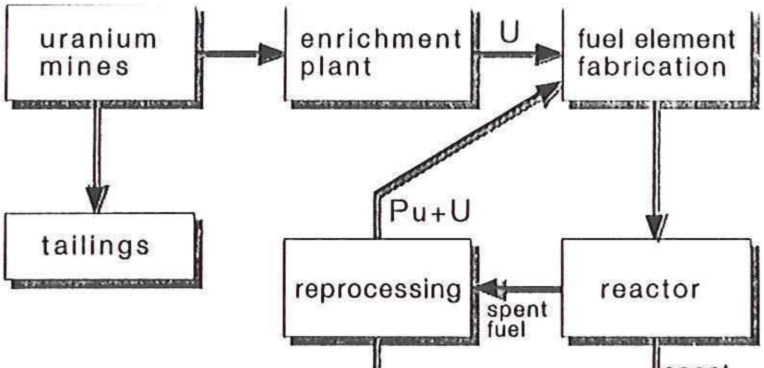


Figure 4.47 The nuclear fuel cycle. From the reactor one either uses the residual U and Pu again by reprocessing or prepares the fuel elements for storage as radioactive waste (no real cycle)

Table 9.10. World Production of Uranium, 1992 (in million pounds equivalent U_3O_8)

Western Production	
Canada	24.2
Niger	7.7
Australia	6.1
France	5.6
United States	5.1
Namibia	4.3
South Africa	4.3
Gabon	1.4
Others	2.0
Total	60.7
Eastern Production	ca. 34

Source: NUEXCO, 1992.

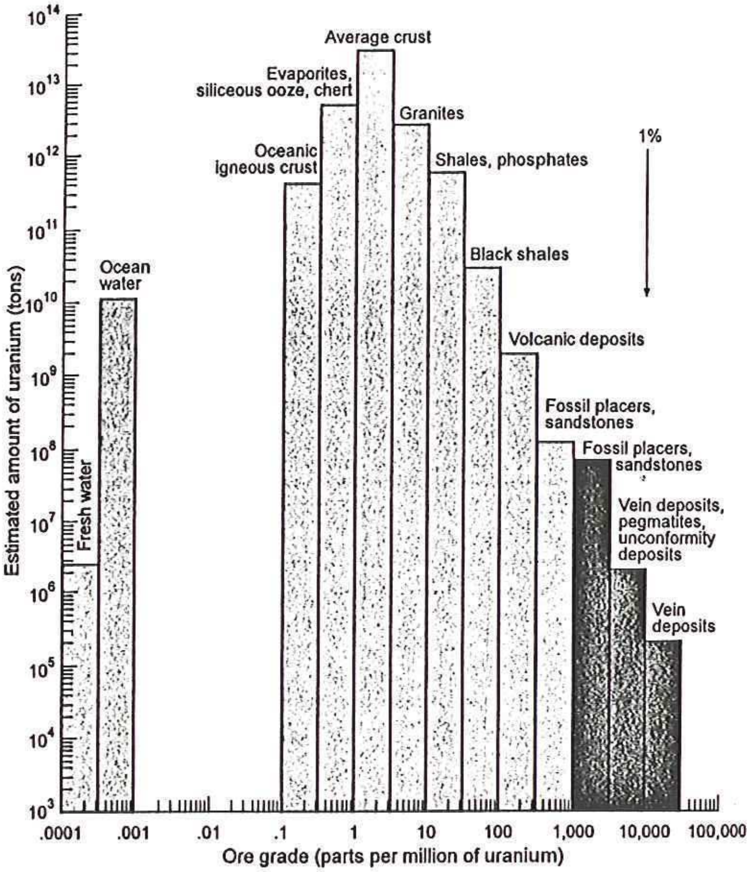


Figure 9.23. The distribution of uranium in the Earth's crust; a plot of the estimated amount of uranium versus ore grade in parts per million of uranium. The bars represent various categories of uranium deposits or repositories of uranium in descending order of uranium content. The three bars on the right represent deposits of the type now being mined specifically for uranium. For approximately every tenfold decrease in grade there is a thirtyfold increase in the amount of recoverable uranium. (Deffeyes and MacGregor 1980)

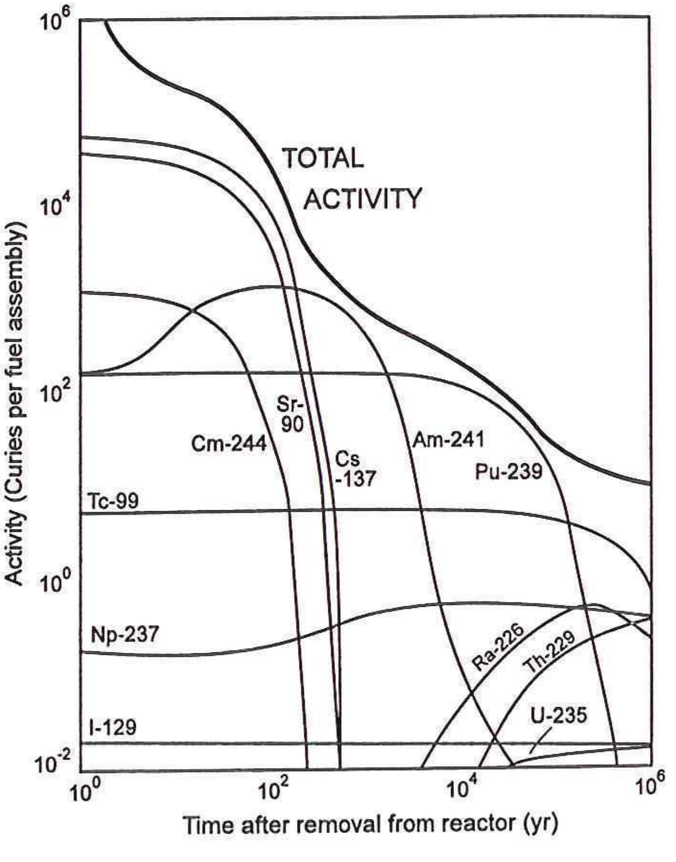


Figure 11.37. Radioactive decay of nuclides in a fuel assembly from a light water reactor. (Brookins 1984)

The Sun

The first such possible series was suggested by Bethe;[2] it is called the *carbon cycle* because the first reaction involves an atom of ^{12}C which is successively transmuted by the addition of protons and by β^+-decays, finally to yield an α-particle *and a* ^{12}C *atom:*

$$\begin{array}{ll} (a) & {}^{12}C + p \rightarrow {}^{13}N + \gamma \\ (b) & {}^{13}N \rightarrow {}^{13}C + \beta^+ + \nu \\ (c) & {}^{13}C + p \rightarrow {}^{14}N + \gamma \\ (d) & {}^{14}N + p \rightarrow {}^{15}O + \gamma \\ (e) & {}^{15}O \rightarrow {}^{15}N + \beta^+ + \nu \\ (f) & {}^{15}N + p \rightarrow {}^{12}C + {}^{4}He \end{array} \tag{1}$$

Using an obvious notation, the above reactions may be abbreviated

$$^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(\beta^+\nu)^{15}N(p,\alpha)^{12}C$$

More recently, another series of reactions, in which only hydrogen is needed as the original reactant, has been devised. This series is called the proton-proton cycle. In the abbreviated notation used previously, it is

$$\begin{array}{l} {}^{1}H(p,\beta^+\nu)^{2}H(p,\gamma)^{3}He(^{3}He,2p)^{4}He \\ \qquad\qquad\qquad \hookrightarrow (\alpha,\gamma)^{7}Be(e^-,\nu)^{7}Li(p,\gamma)^{8}Be(\alpha)^{4}He \\ \qquad\qquad\qquad\qquad\qquad \hookrightarrow (p,\gamma)^{8}B(\beta^+\nu)^{8}Be(\alpha)^{4}He \end{array} \tag{2}$$

The first reaction of this series amounts to a β^+-decay of ^{2}He formed by the collision of the two protons: Even though the lifetime of ^{2}He against decay back into two protons is extremely short, the stupendous number of collisions that occur inside a star allows a modest rate of formation of deuterium. The second reaction is well known and occurs rapidly, even at the low bombardment energies prevailing in stellar interiors. Since ^{3}He does not react with either ^{1}H or ^{2}H, its concentration builds up until further reactions remove it as fast as it is formed. The reaction $^{3}He(^{3}He,2p)^{4}He$ was first suggested by C. C. Lauritsen and has been detected in the laboratory. The participation of the reactions starting with $^{3}He(\alpha,\gamma)^{7}Be$ in stellar energy generation processes has been treated by Fowler[1] who points out that they are probably the dominant ones for the sun.

4.5.2 *POWER BY NUCLEAR FUSION*

From Fig. 4.37 it was concluded that fusion of the lightest nuclei could lead to energy gains. In practice the following reactions are possible:

$$^{2}\mathrm{D} + {}^{3}\mathrm{T} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{n} + 17.6\,\mathrm{MeV} \tag{4.270}$$

$$^{2}\mathrm{D} + {}^{2}\mathrm{D} \rightarrow {}^{3}\mathrm{He} + {}^{1}\mathrm{n} + 3.27\,\mathrm{MeV} \tag{4.271}$$

$$^{2}\mathrm{D} + {}^{2}\mathrm{D} \rightarrow {}^{3}\mathrm{T} + {}^{1}\mathrm{H} + 4.03\,\mathrm{MeV} \tag{4.272}$$

$$^{2}\mathrm{D} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + 18.3\,\mathrm{MeV} \tag{4.273}$$

In these equations deuterium and tritium are indicated by ^{2}D and ^{3}T, although the more proper notation would have been ^{2}H and ^{3}H.

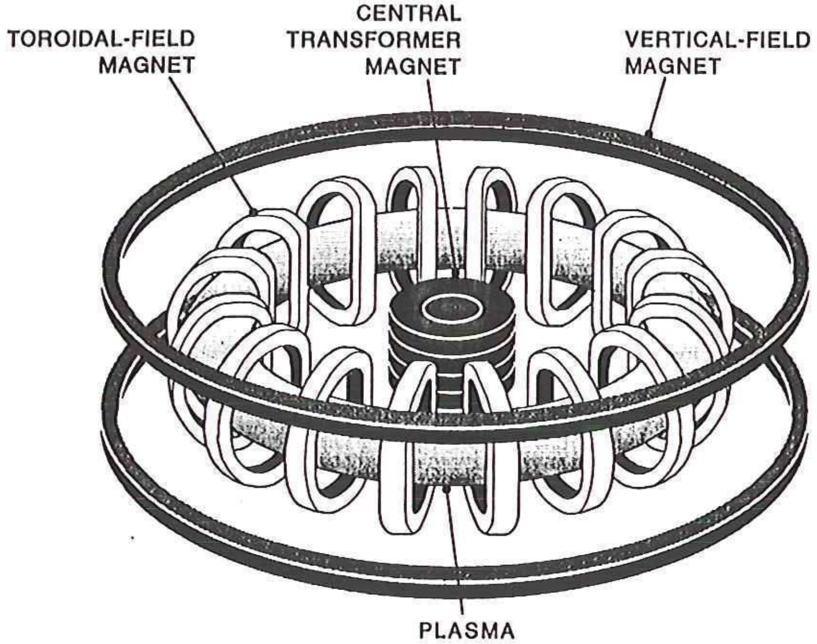
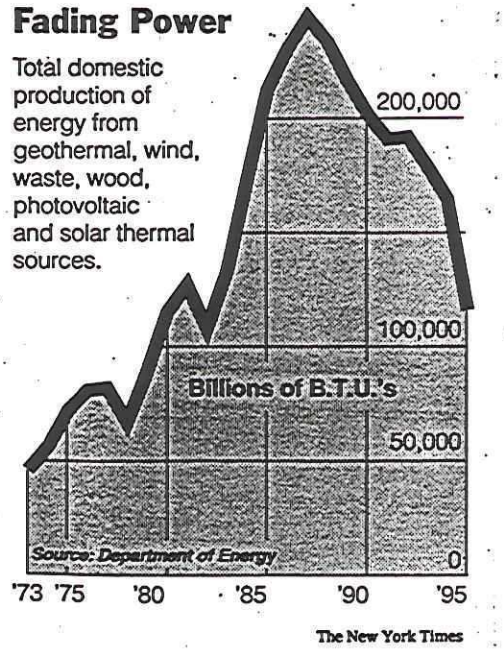


Figure 4.41 Principle of the Tokamak design. The main magnetic field is toroidal; the vertical field provides a centripetal Lorentz force by which the ions follow the main toroid. Other magnets produce induction currents that heat the plasma as far as required.



Fading Power

Total domestic production of energy from geothermal, wind, waste, wood, photovoltaic and solar thermal sources.

Source: Department of Energy

The New York Times

In US, renewables have fallen by ~ a factor of two to ~ 0.1% of total (0.1 quads out of 80)

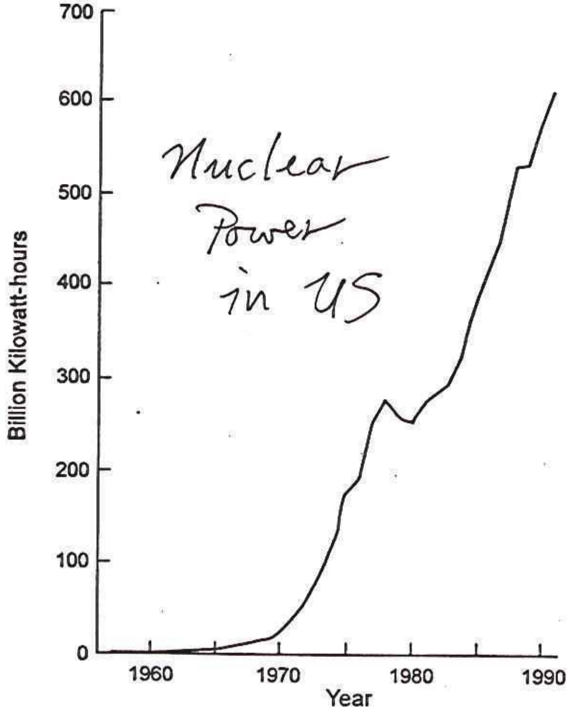
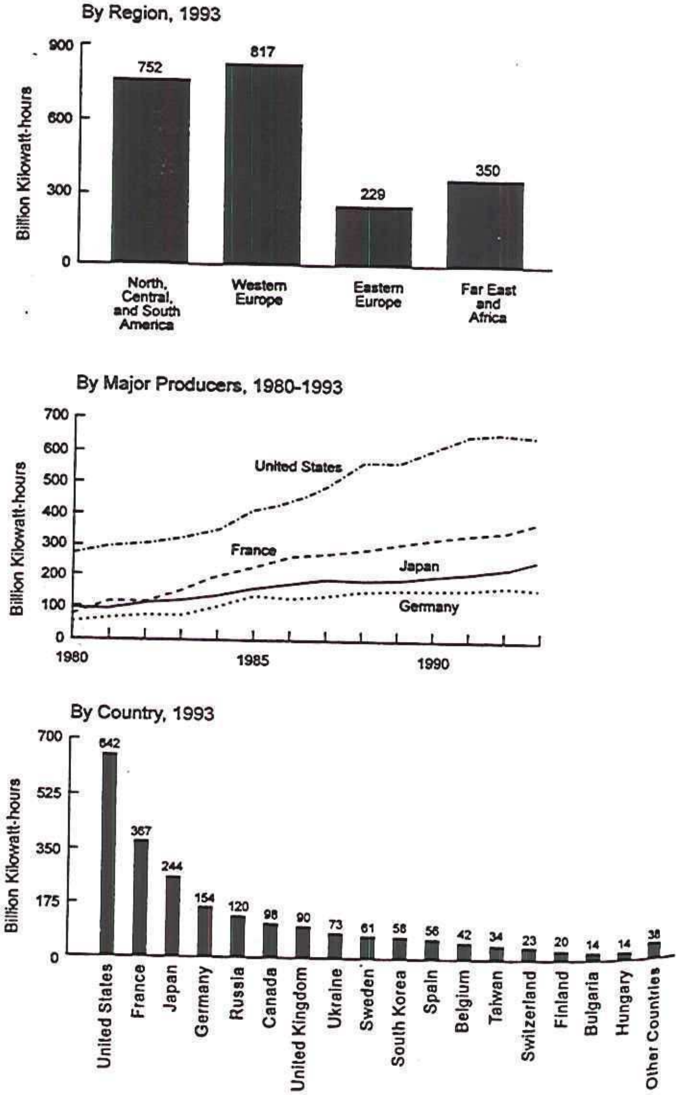


Figure 11.25. Net nuclear generation of electricity in the United States, 1957–91. (*Annual Energy Review 1991*)

Figure 11.26. Nuclear electricity gross generation (*Annual Energy Review 1993*)



By Region, 1993

By Major Producers, 1980-1993

By Country, 1993

Nuclear Power References :

Glasstone & Edlund , The Elements of Nuclear Reactor Theory , Van Nostrand , 1952

SK8215.395.2

Hill , Textbook of Reactor Physics , Allen & Unwin , 1961

SK8215.462