Introduction to Nuclear and Particle Physics

Nuclear fission

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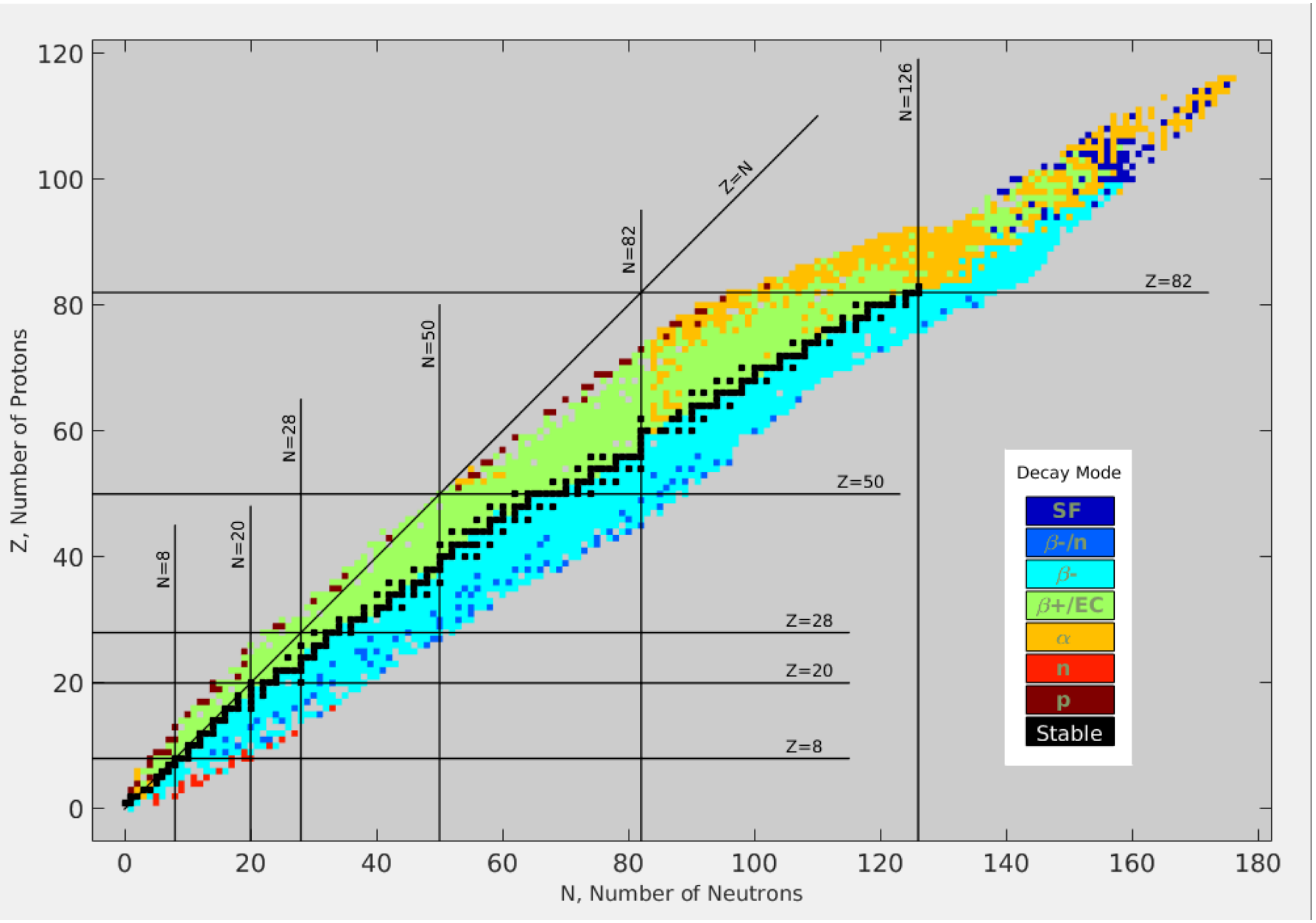
Stability



- Chart of nuclides by type of decay.
- **Black squares are stable** nuclides.
- Nuclides with **excessive neutrons or protons** are unstable to **β–** (light blue) or **β+** (green) decay, respectively.
- At **high atomic number, alpha emission** (orange) or **spontaneous fission** (dark blue) become common decay modes.

Nuclear fission

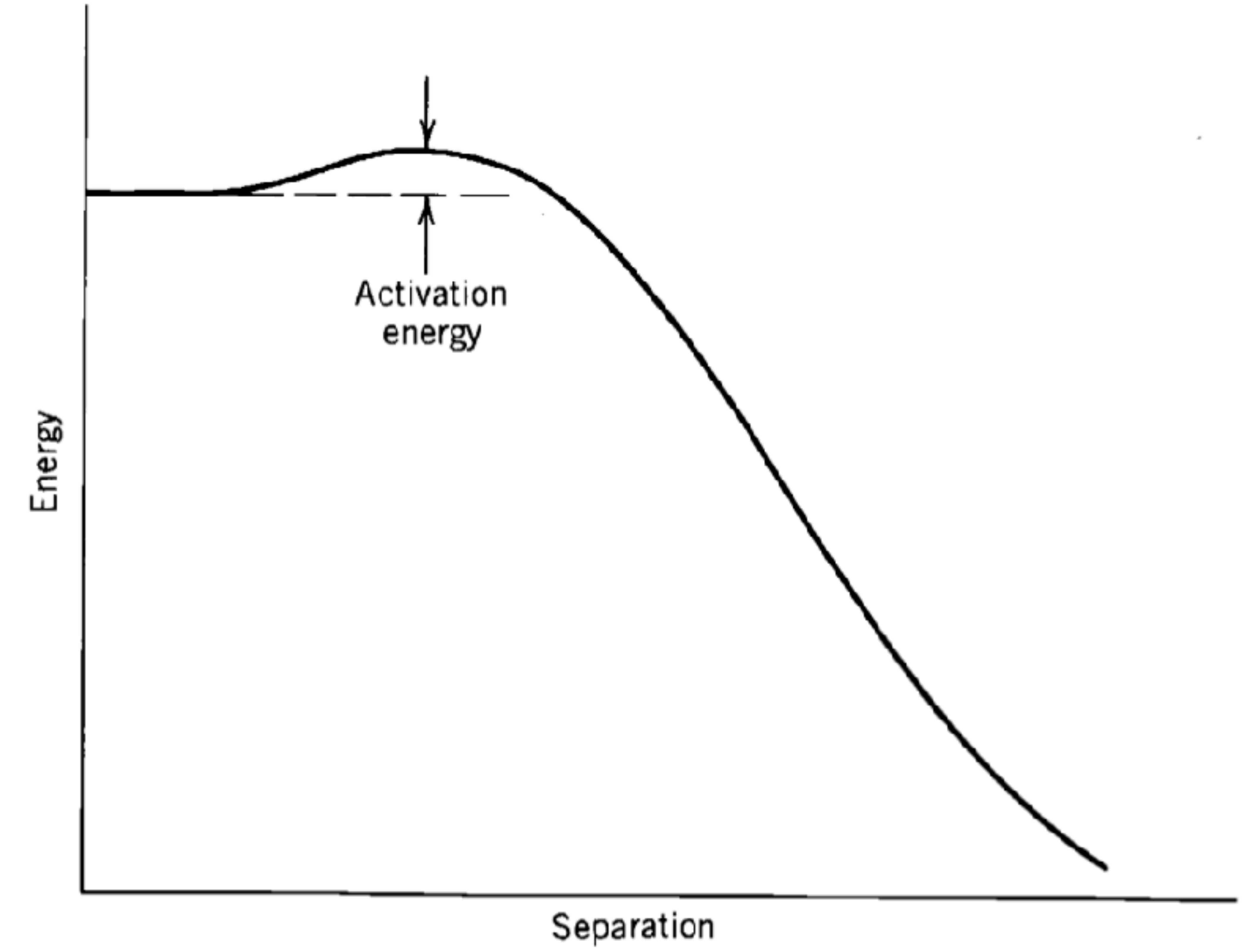


Figure 13.2 A smooth potential barrier opposing the spontaneous fission of ^{238}U. To surmount the fission barrier, we must supply an amount of energy equal to the activation energy.

Nuclear fission

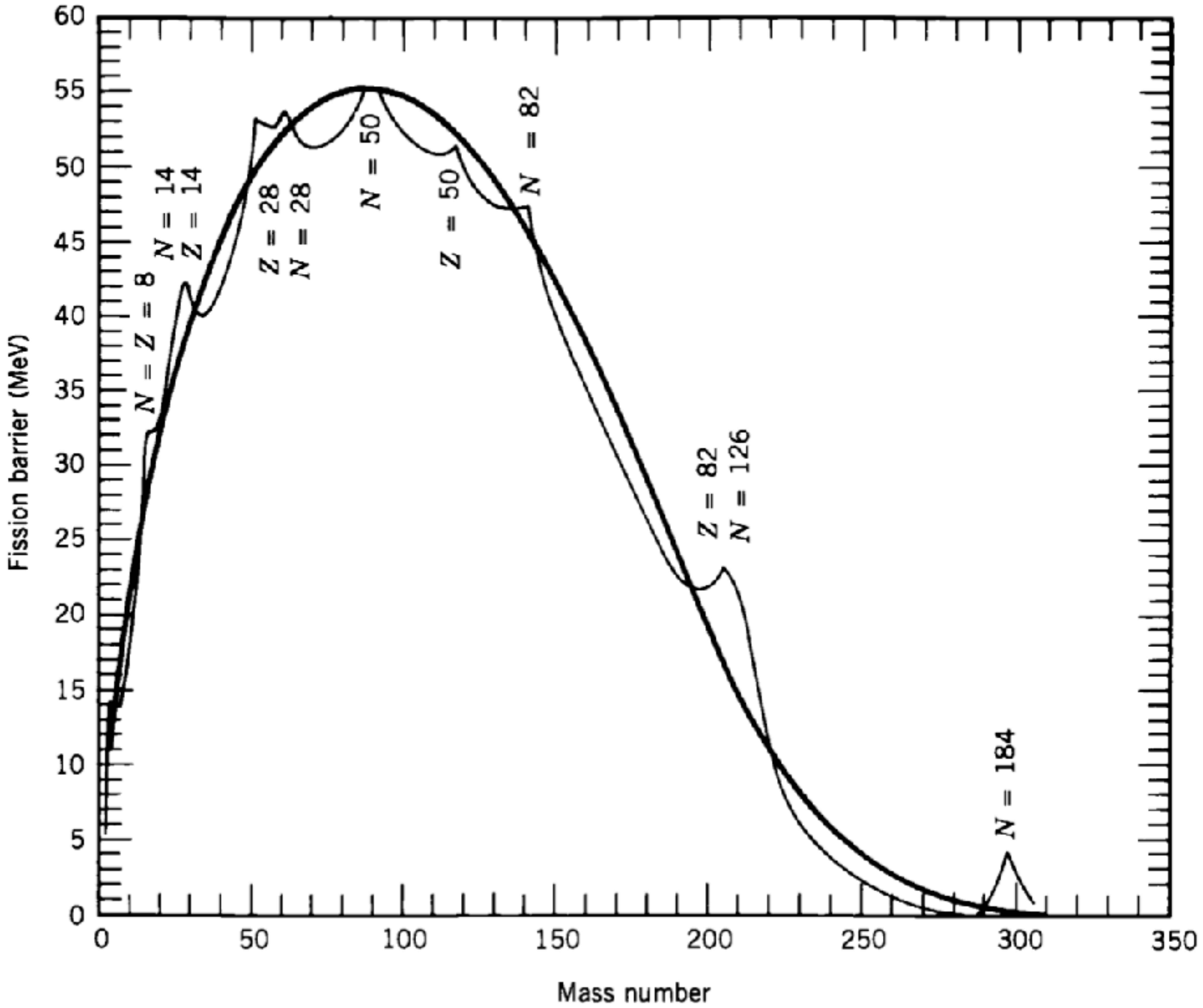


Figure 13.3 Variation of fission activation energy with mass number. The dark curve is based on the liquid-drop model, calculated only for the most stable isotope at each mass number, and the light curve shows the effect of including shell structure. Note the typical 5-MeV energies around uranium, the vanishing energy around mass 280 (making these nuclei extremely unstable to spontaneous fission), and the stability around mass 300 from the expected neutron shell closure. From W. D. Myers and W. J. Swiatecki, *Nucl. Phys.* **81**, 1 (1966).

Explained by the shell model

Nuclear fission

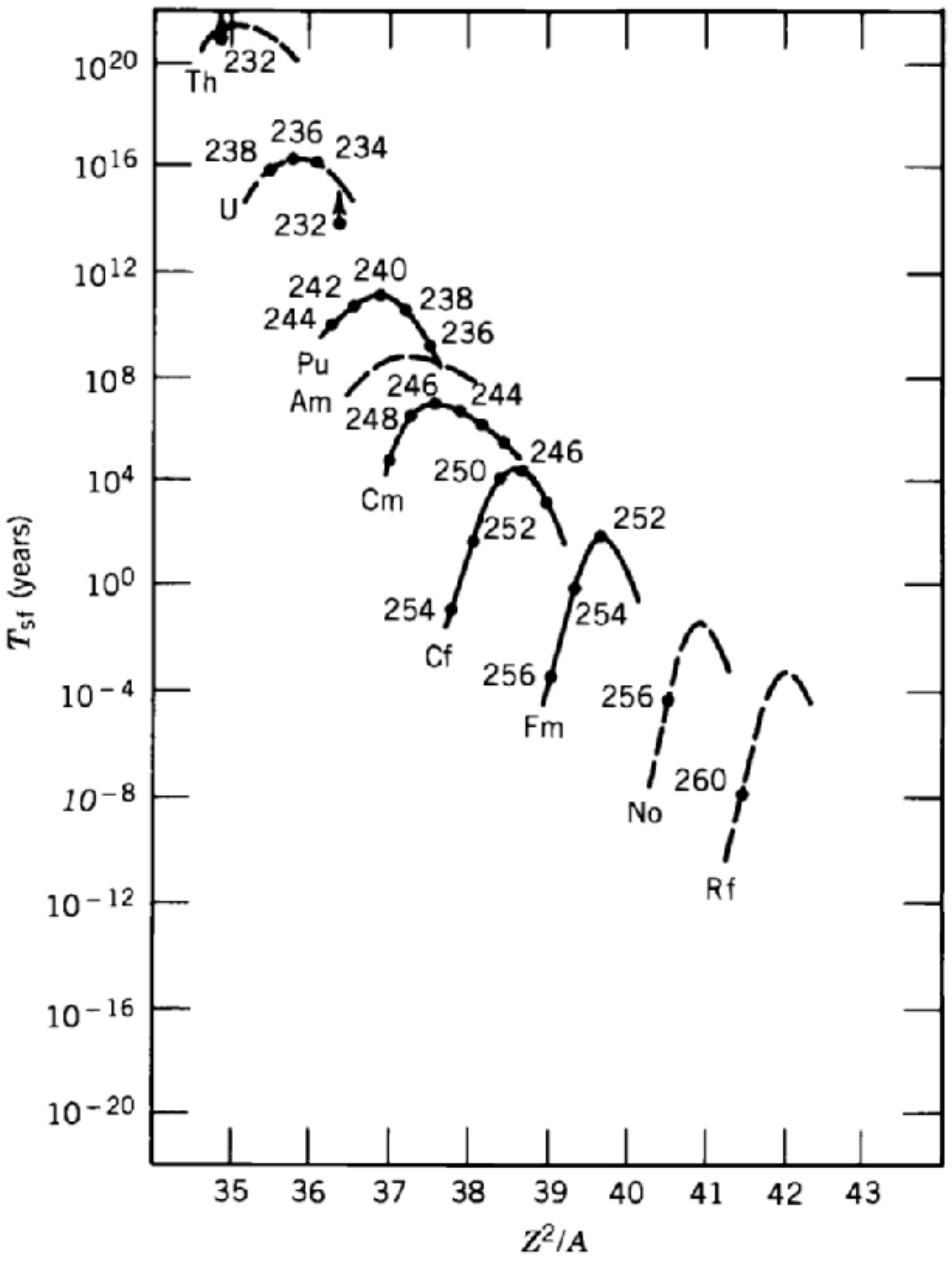


Figure 13.4 Lifetimes for spontaneous fission. There is a general trend of decreasing lifetime with increasing Z^2/A. From V. M. Strutinsky and H. C. Pauli, in *Physics and Chemistry of Fission* (Vienna: IAEA, 1969), p. 155.

Nuclear fission

Explained by the liquid drop model

Figure 13.5 Representation of nuclear shapes in fission.

Fission products

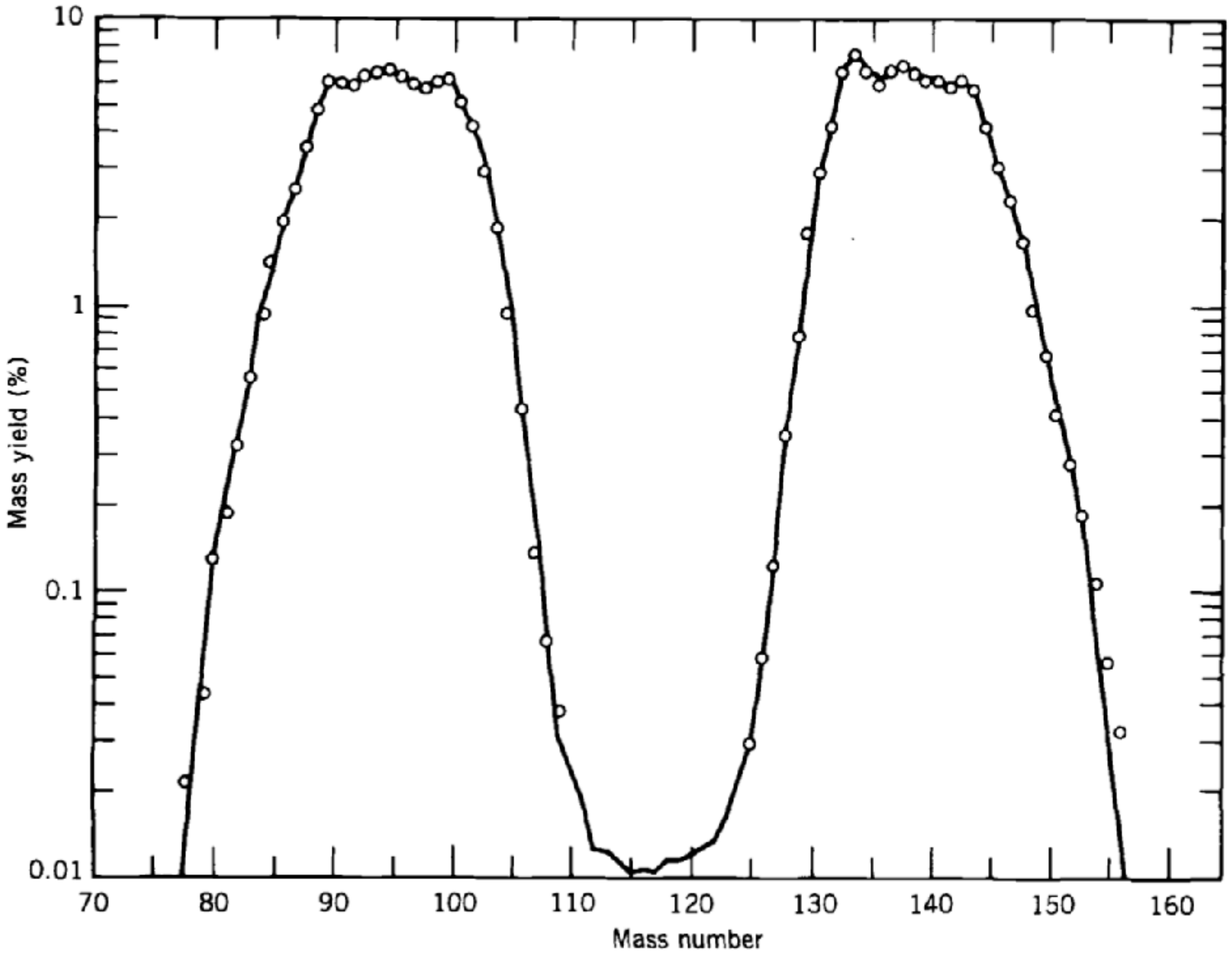
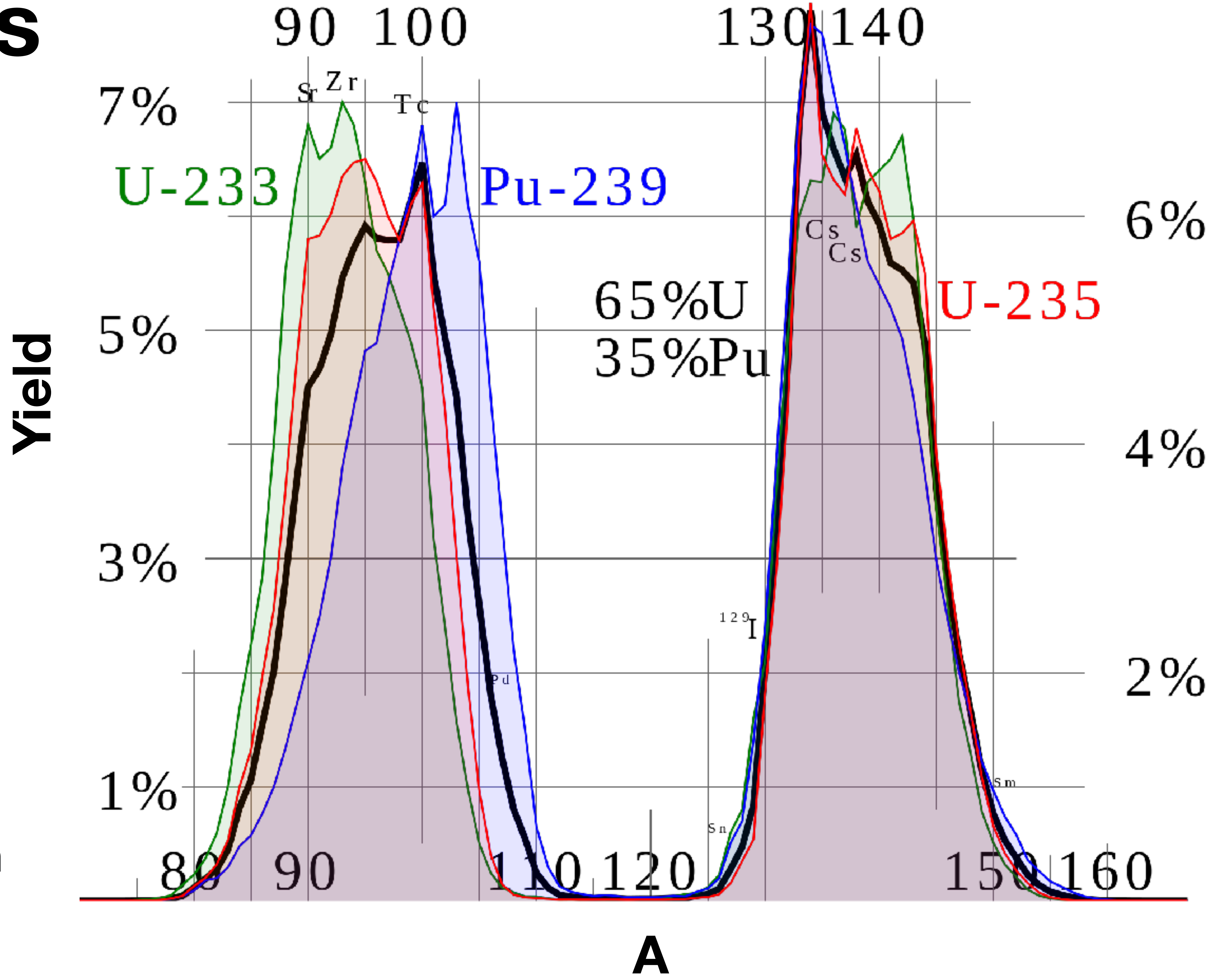


Figure 13.6 Mass distribution of fission fragments from thermal fission of ^{235}U. Note the symmetry of the heavy and light distributions, even in the small variations near the maxima. From G. J. Dilorio, *Direct Physical Measurement of Mass Yields in Thermal Fission of Uranium 235* (New York: Garland, 1979).

Fission products



Fission product yields by mass for thermal neutron fission of uranium-235, plutonium-239, a combination of the two typical of current nuclear power reactors, and uranium-233 used in the thorium cycle.

Neutron emission

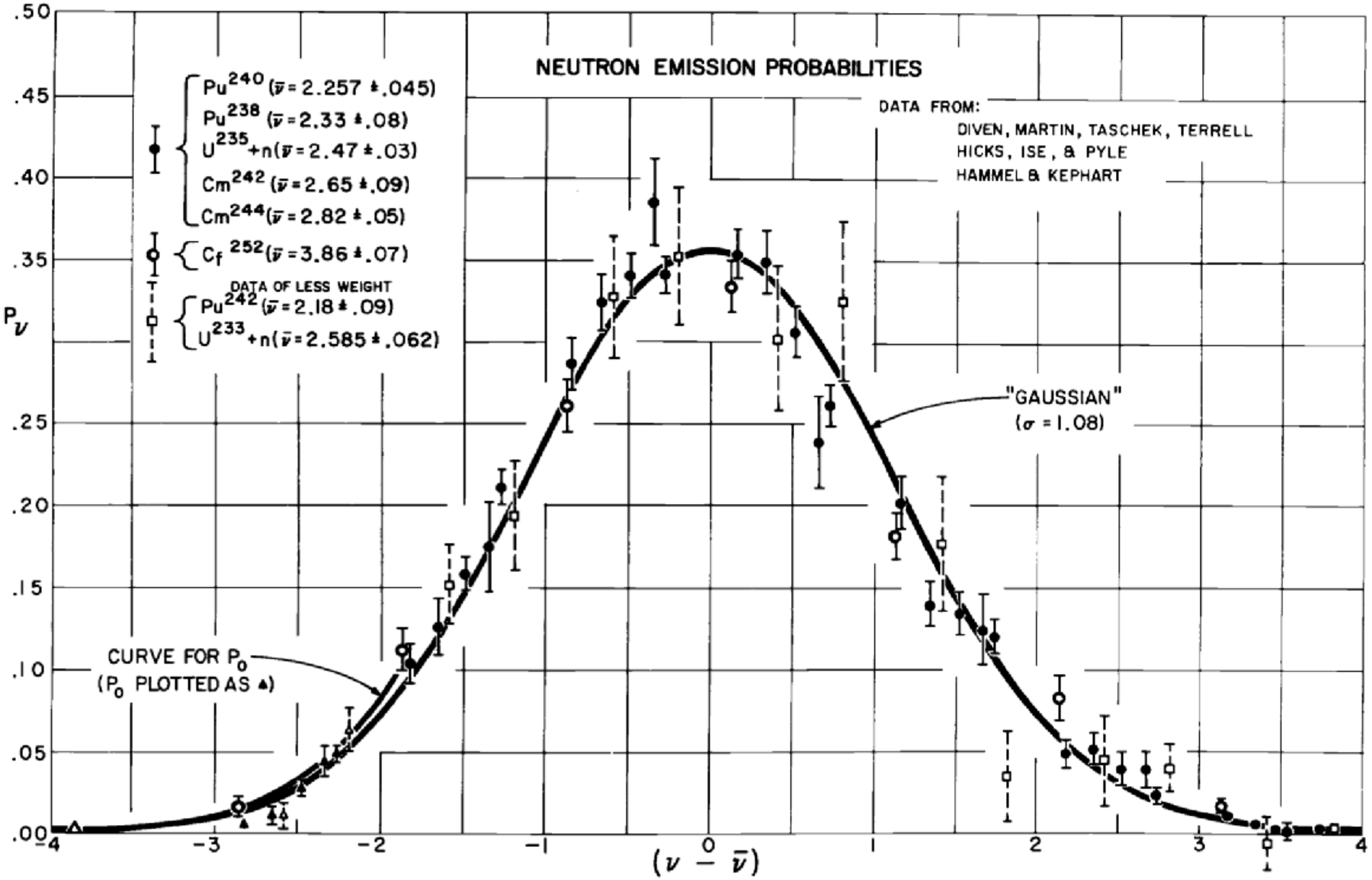


Figure 13.7 Distribution of fission neutrons. Even though the average number of neutrons $\bar{\nu}$ changes with the fissioning nucleus, the distribution about the average is independent of the original nucleus. From J. Terrell, in *Physics and Chemistry of Fission*, Vol. 2 (Vienna: IAEA, 1965), p. 3.

Neutron emission

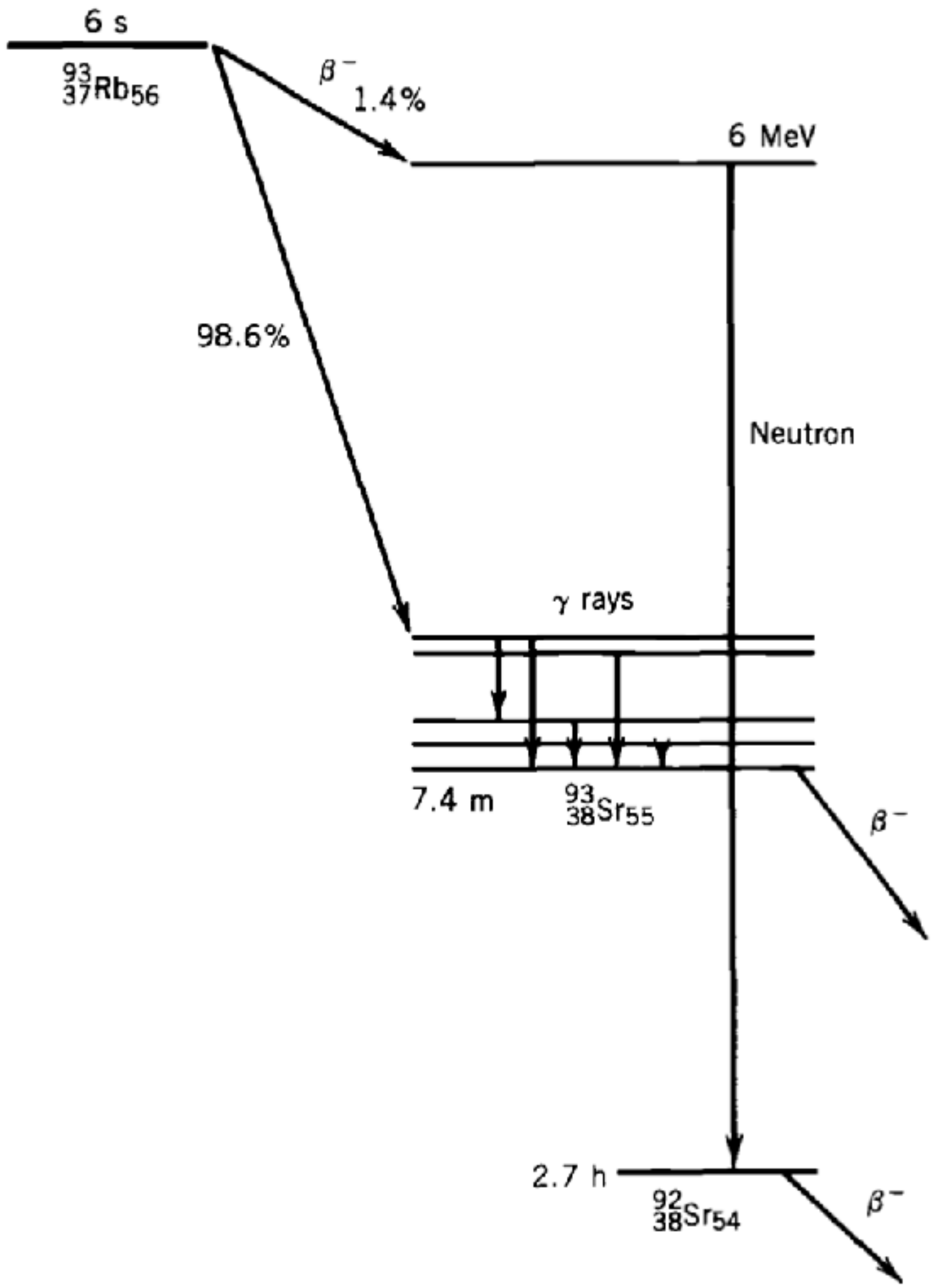


Figure 13.8 Delayed neutron emission from ^{93}Rb. After the original β decay, the excited state of ^{93}Sr has enough energy to decay by neutron emission to ^{92}Sr. The neutrons are delayed relative to the prompt fission neutrons by a time characteristic of the mean lifetime of ^{93}Rb.

Neutron emission

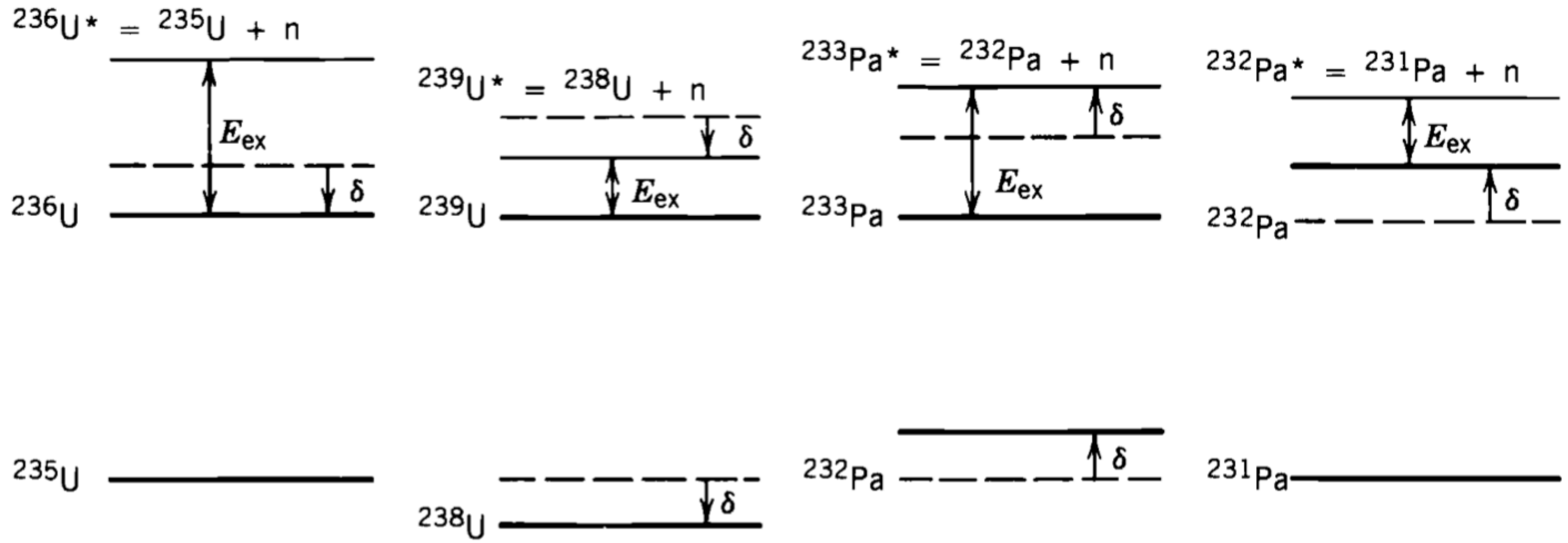


Figure 13.11 Effect of pairing on excitation energies. The dashed levels show the nuclear energies in the absence of pairing, which are then raised or lowered by the amount δ when the effect of pairing is included.

Fission

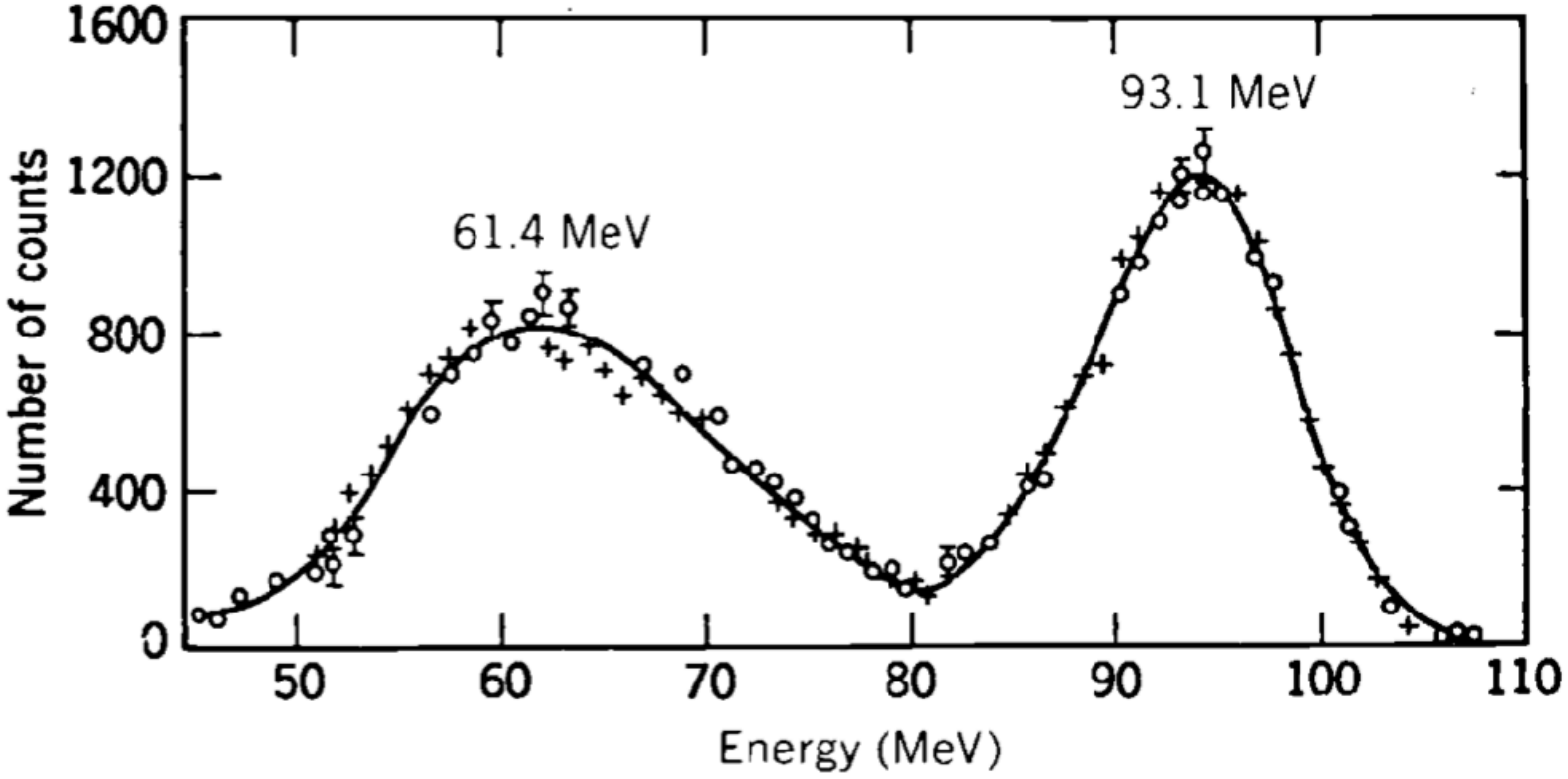


Figure 13.12 Energy distribution of fission fragments from thermal fission of ^{235}U. These data were taken with an ion chamber, which subsequent work showed to be slightly miscalibrated for fission fragments; the deduced energies are about 5 MeV too low. From J. L. Fowler and L. Rosen, *Phys. Rev.* **72**, 926 (1947).

Fission

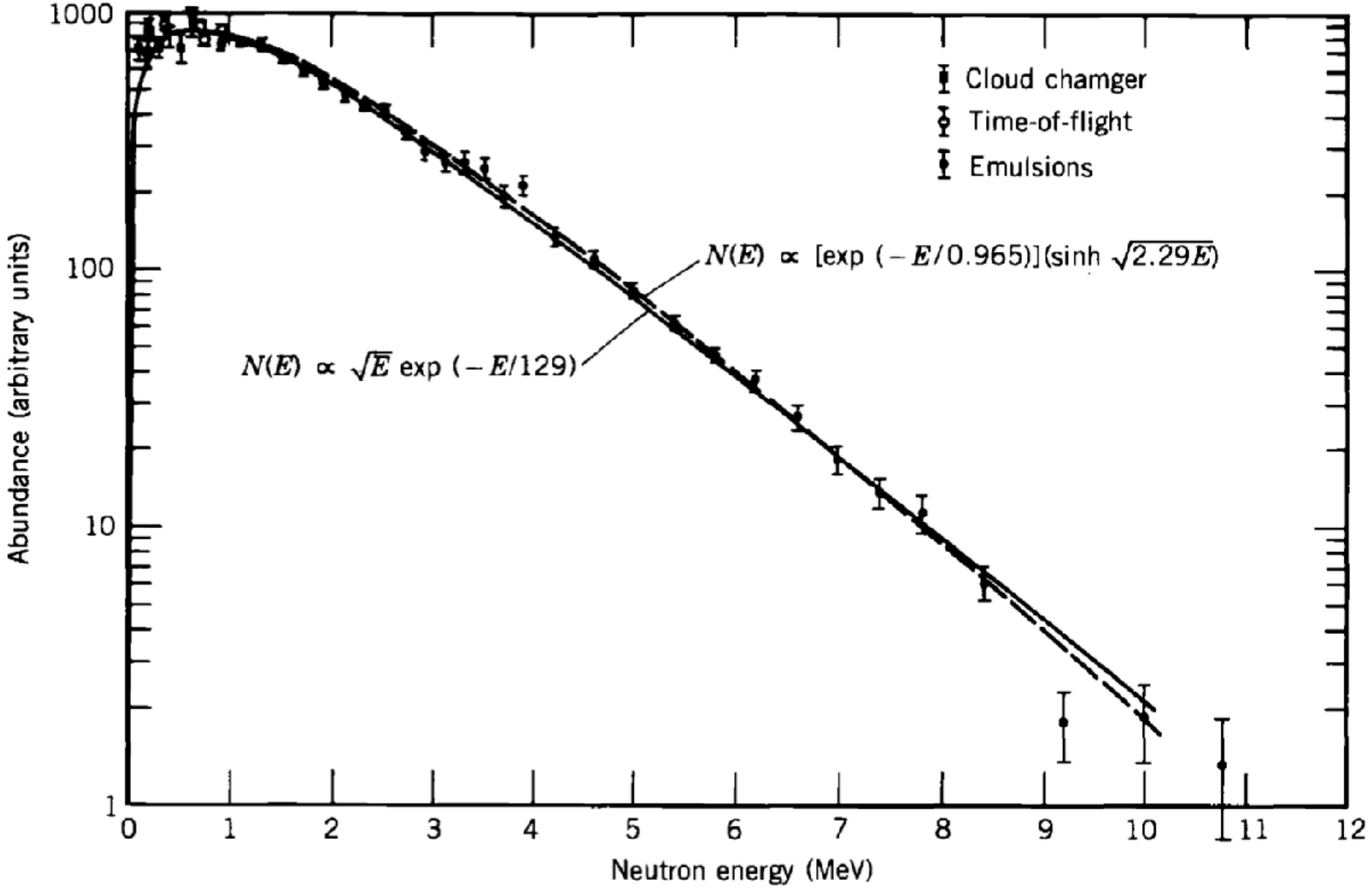


Figure 13.13 Energy spectrum of neutrons emitted in the thermal-neutron fission of ^{235}U. From R. B. Leachman, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy*, Vol. 2 (New York: United Nations, 1956), p. 193.

Fission

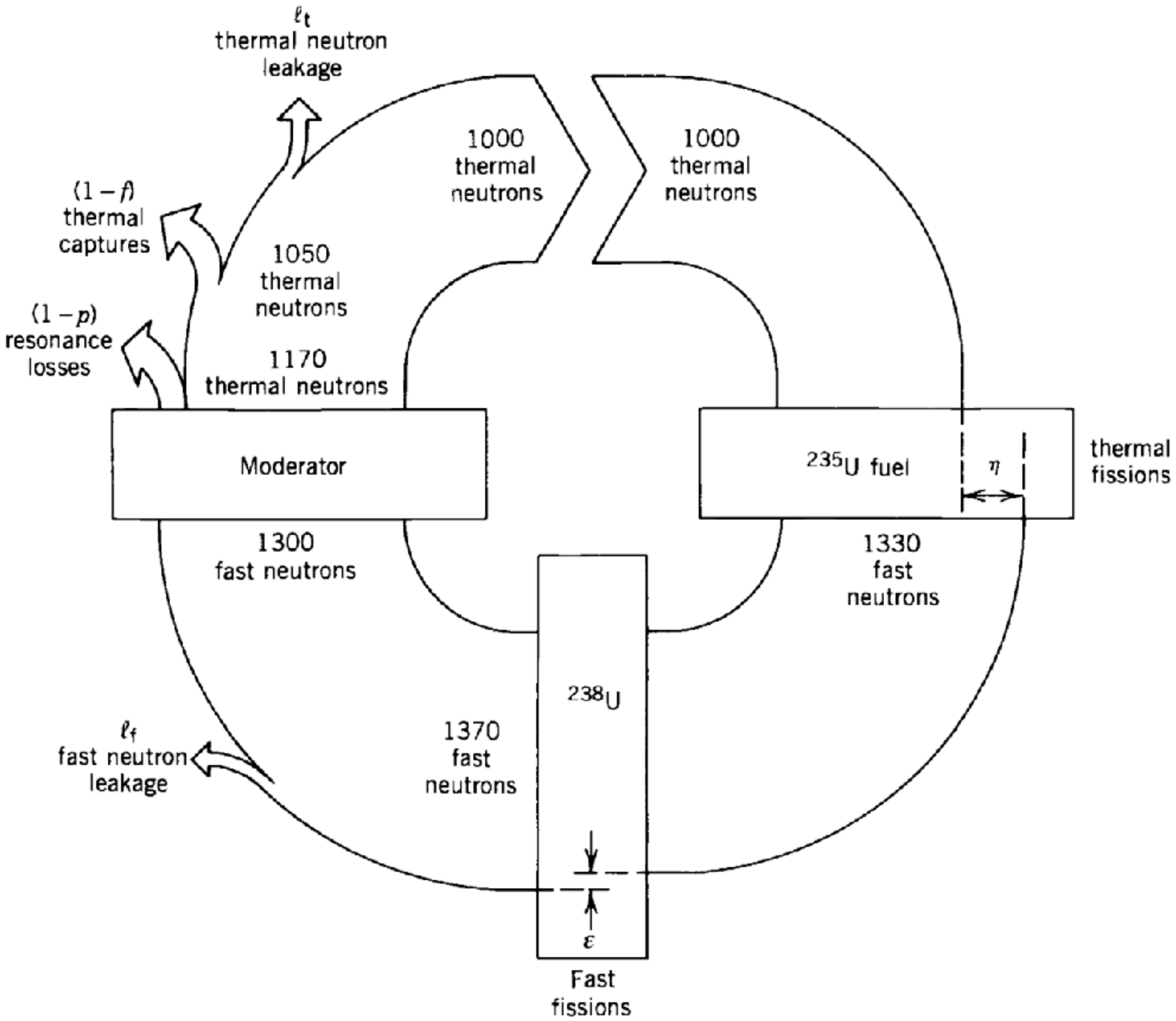
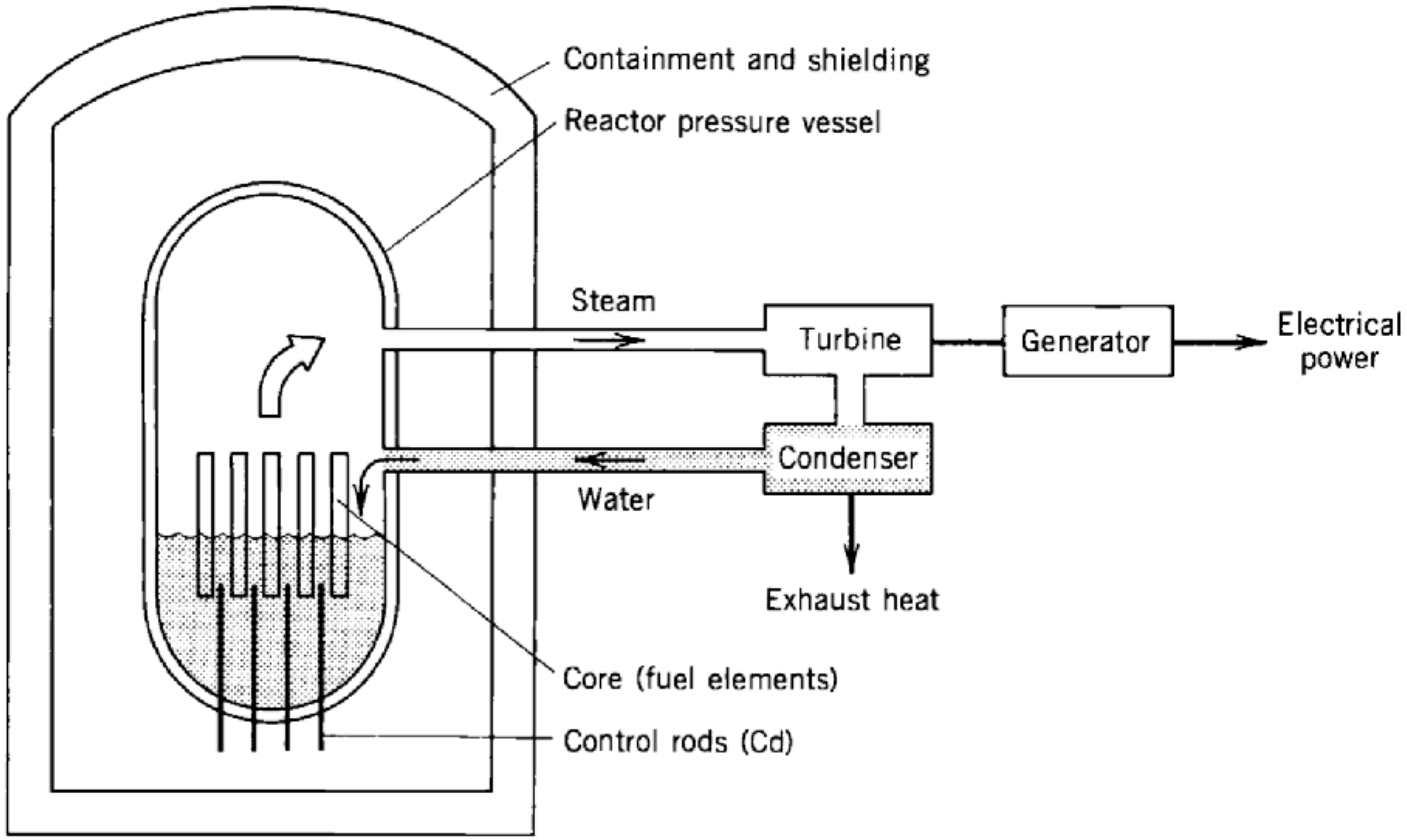


Figure 13.24 Schematic representation of processes occurring during a single generation of neutrons. The cycle has been drawn for a reproduction factor k of exactly 1.000.

Fission



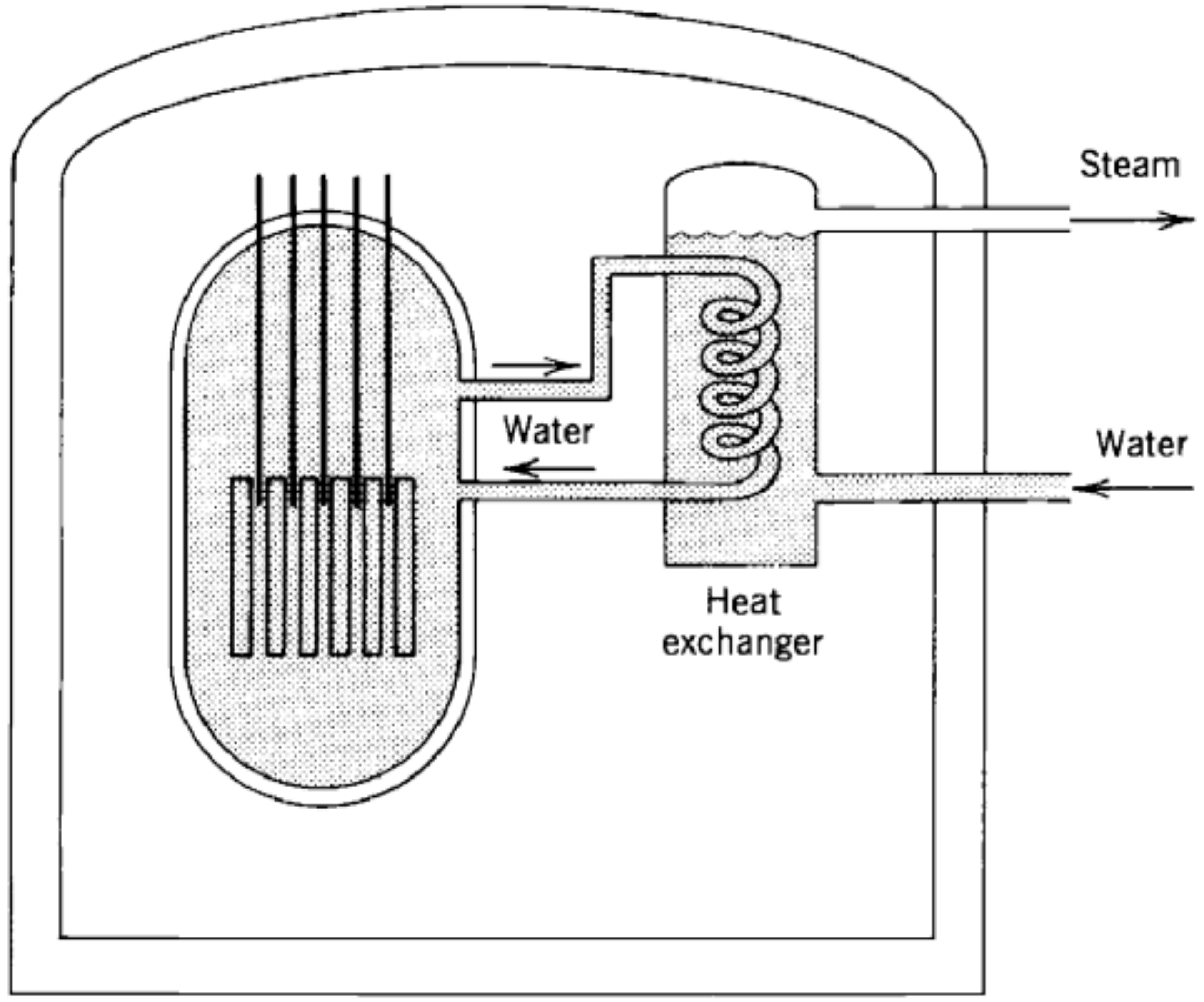
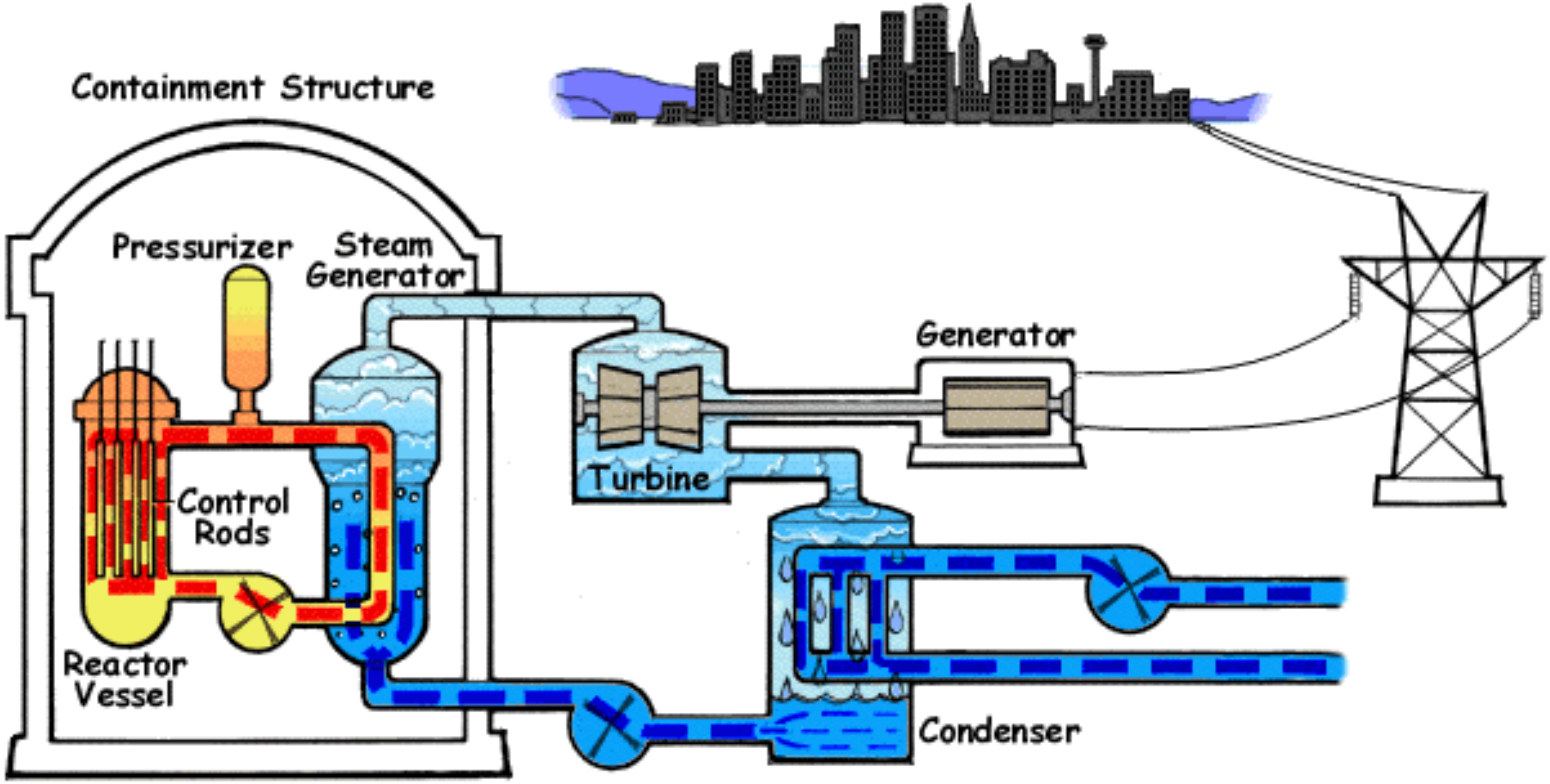


Figure 13.25 Schematic diagram of boiling-water (top) and pressurized-water (bottom) reactors. The core consists of a number of rods containing pellets of uranium oxide in a metal (zirconium alloy or stainless steel) housing. Control rods of cadmium can be inserted into the core to absorb neutrons and keep the power level stable. The boiling-water reactor is shown driving electrical generating equipment. Many details, including the important emergency core cooling system, are omitted.

Fission



Pictorial explanation of power transfer in a pressurized water reactor. Primary coolant is in orange and the secondary coolant (steam and later feedwater) is in blue.

https://en.wikipedia.org/wiki/Pressurized_water_reactor

Fission

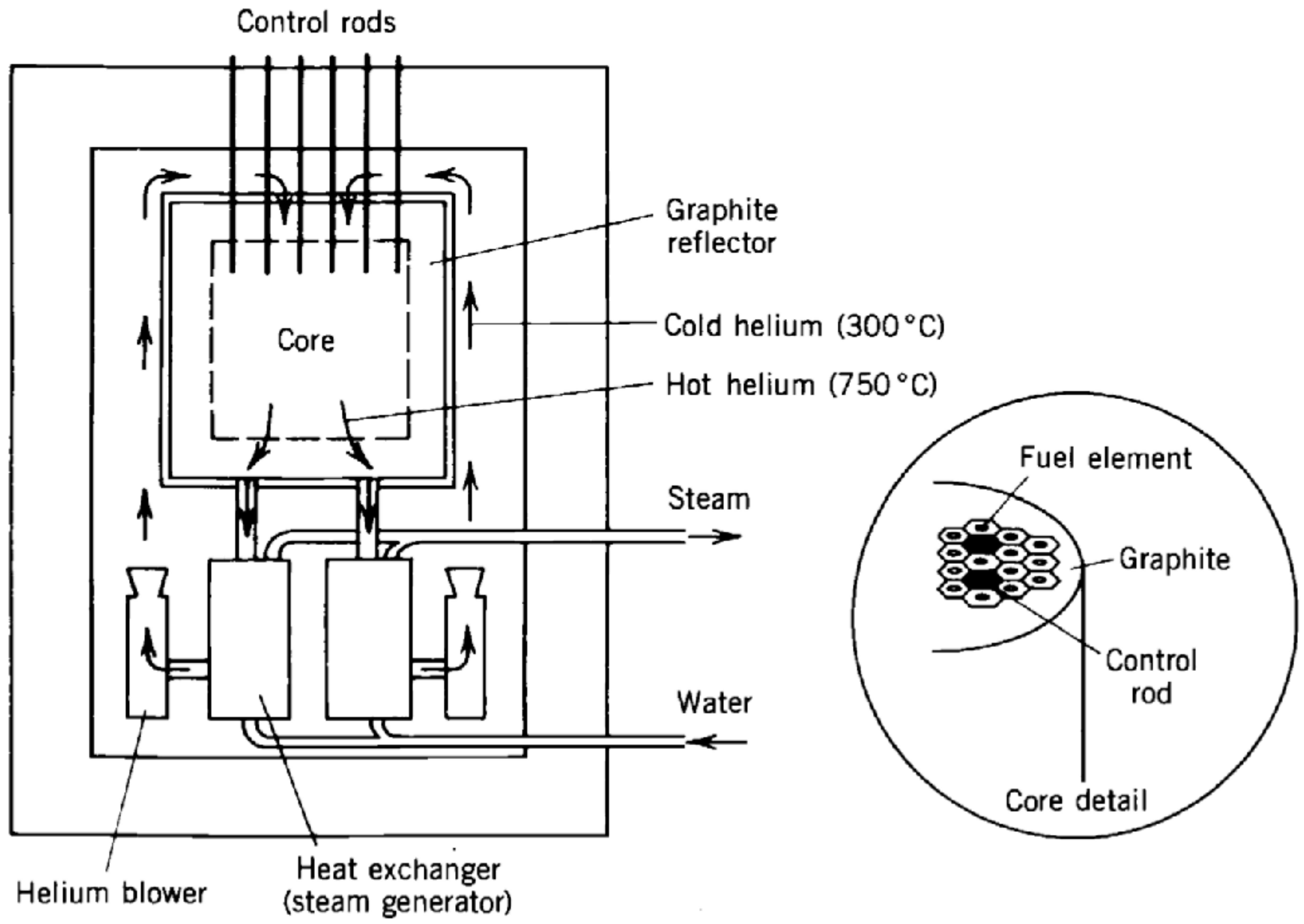
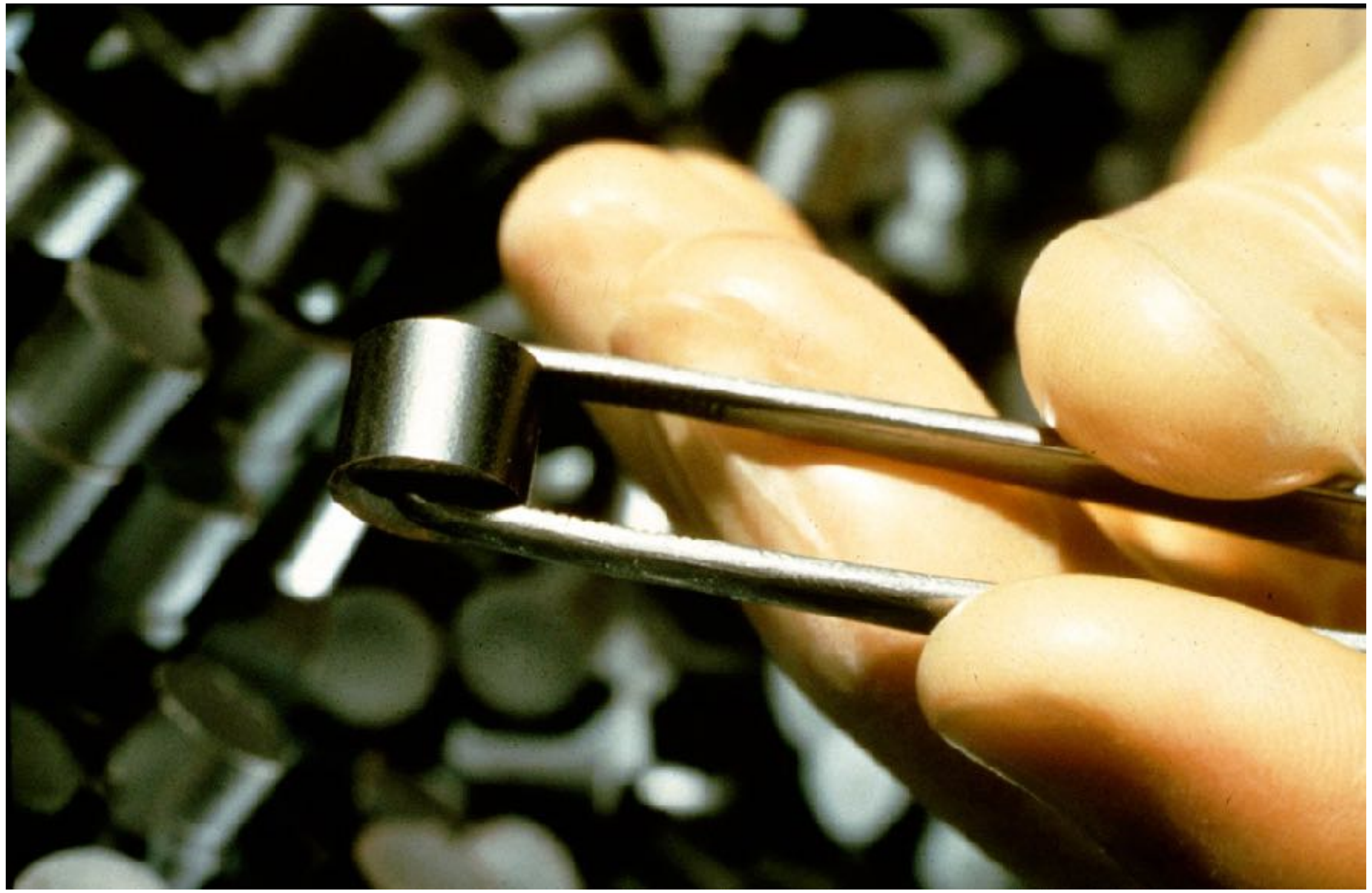


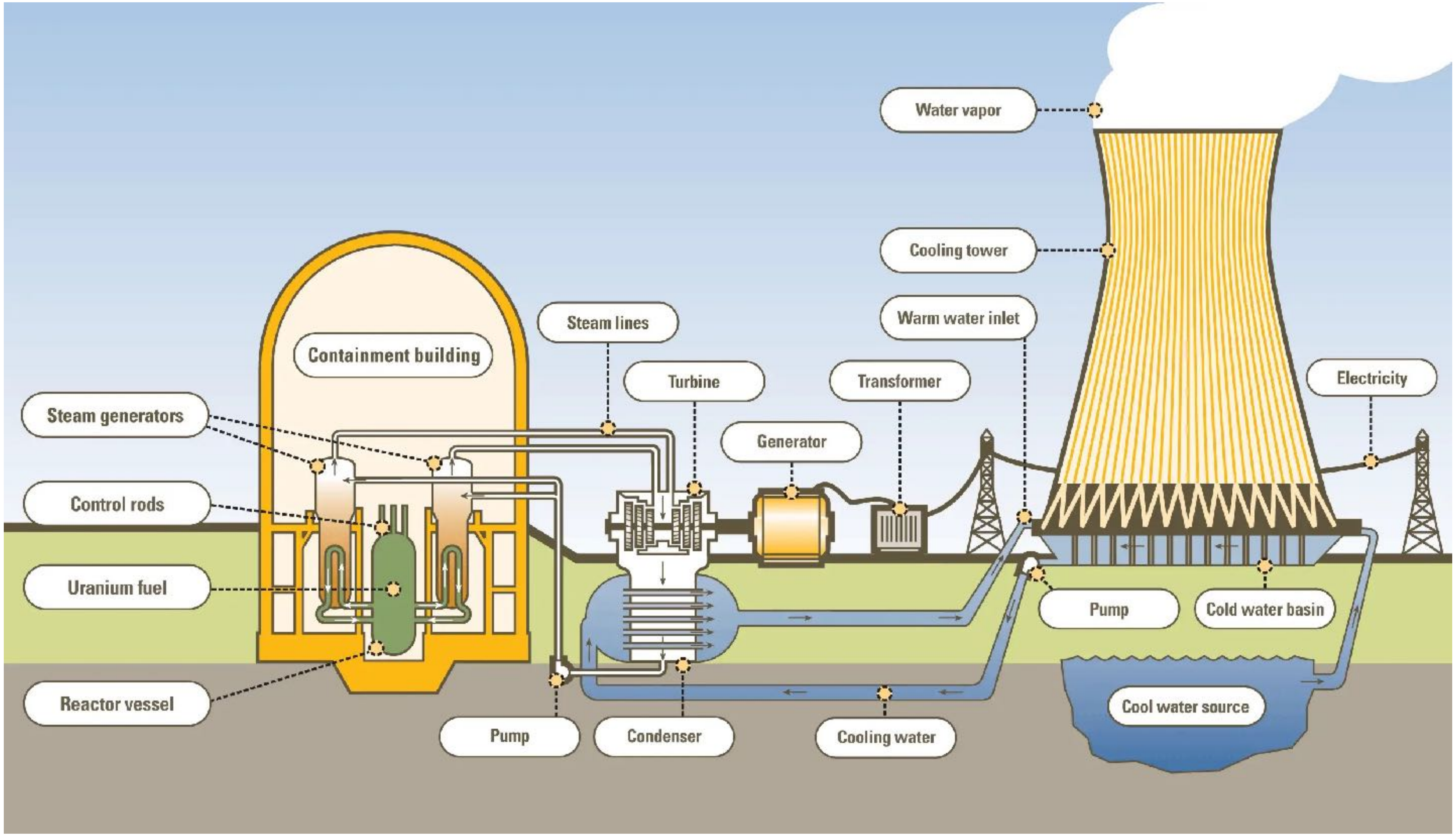
Figure 13.27 Schematic diagram of gas-cooled reactor. Helium gas flows through the core to extract the heat; the helium is then used to produce steam. A detail of the core is shown at right. The fuel elements are in the form of hexagonal rods containing the fissionable material, graphite moderator, and a channel for gas flow. The core is surrounded with a graphite reflector.

Fission

Fuel pellet



Nuclear power plant



https://www.nuclear-power.com/nuclear-power-plant/npp/

Nuclear power plant

The Leibstadt Nuclear Power Plant in Switzerland

https://en.wikipedia.org/wiki/Nuclear_power

Nuclear power plant

Paks nuclear power plant

Hungary

Paks nuclear power plant

Hungary

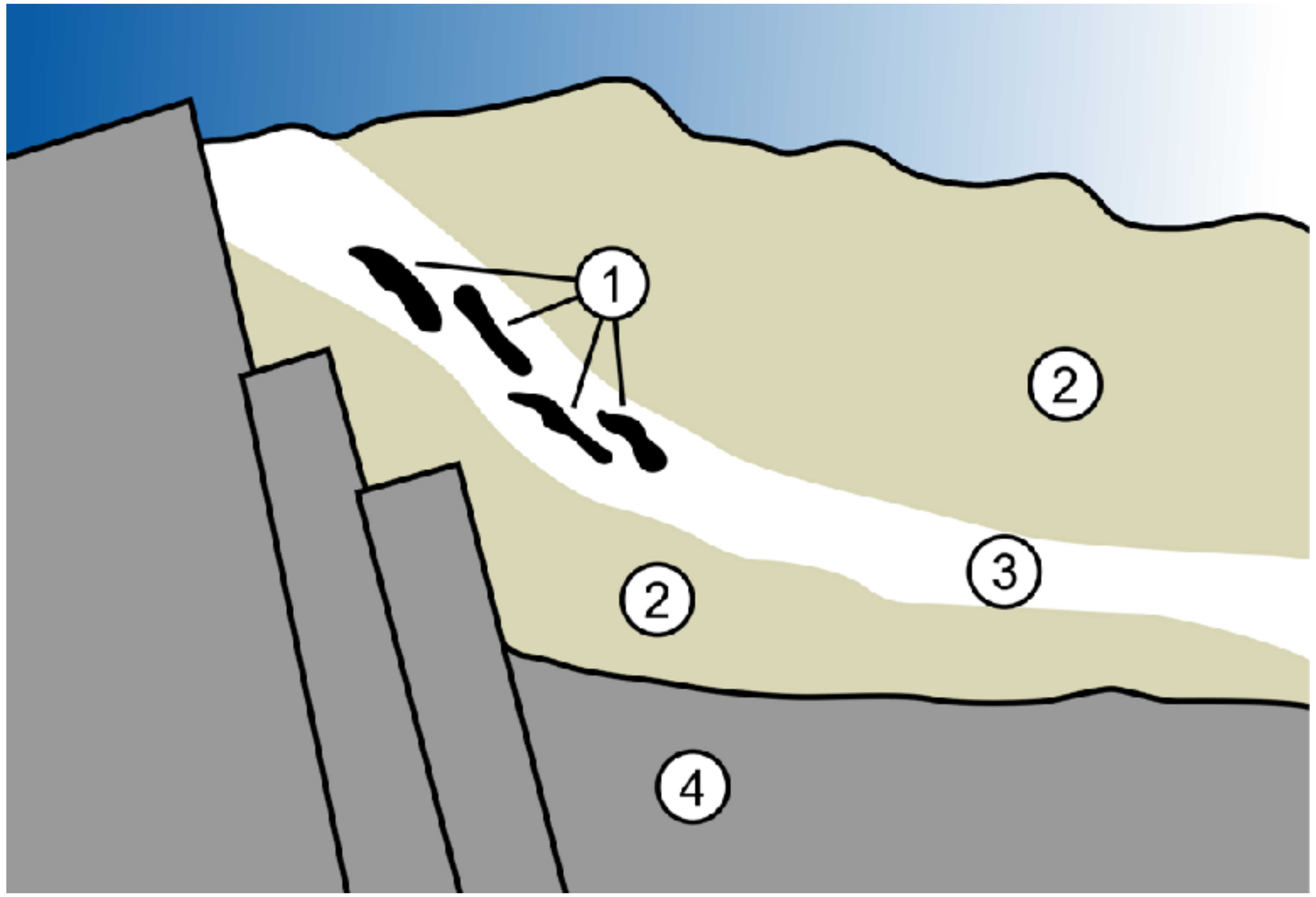
Natural nuclear reactor - Oklo

A natural nuclear fission reactor is a uranium deposit where self-sustaining nuclear chain reactions occur.

The remnants of an extinct or fossil nuclear fission reactor, where self-sustaining nuclear reactions have occurred in the past, can be verified by analysis of isotope ratios of uranium and of the fission products (and the stable daughter nuclides of those fission products).

An example of this phenomenon was discovered in 1972 in **Oklo, Gabon.**

Oklo is the only location where this phenomenon is known to have occurred, and consists of 16 sites with patches of centimeter-sized ore layers. Here self-sustaining nuclear fission reactions are thought to have taken place approximately 1.7 billion years ago, and continued for a few hundred thousand years, probably averaging less than 100 kW of thermal power during that time.



Geological situation in Gabon leading to natural nuclear fission reactors

1. Nuclear reactor zones
2. Sandstone
3. Uranium ore layer
4. Granite

https://en.wikipedia.org/wiki/Natural_nuclear_fission_reactor