Alternative Energy Sources

As we have seen we — the whole $\oplus$ — must cut CO_2 emissions to ~ the pre-industrial level (< 1 GtC / yr) within the next century to obtain $2\times CO_2$ in atmosphere.

We have about 100 years to switch to an alternative energy source

Textbook devotes a ¶ each to various possibilities:

hydroelectric
wind power } used for centuries
solar power

these renewables currently supply only 0.1% of US energy

I would like to focus on one that may surprise you — nuclear power

I believe that the time scale for conversion is so short — 100 years — that widespread use of nuclear power will be essential in the near future.

History of nuclear power

1938 — discovery of nuclear fission by Otto Hahn & Lise Meitner

1942 — first sustained nuclear chain

chain reaction — Enrico Fermi — U. Chicago squash court

1945 — Trinity & Hiroshima explosions Oppenheimer — Los Alamos

Excellent book: *The Making of the Atomic Bomb* by Richard Rhodes recounts this history.

1962 — first commercial power reactor Indian Point — 26 miles N of New York City

Great promise — US electrical energy consumption was then growing at *7% per year* in *post-war boom*.

Nuclear power generation grew impressively.

Currently ~19% of US and 16% of world electricity production

However growth has stalled — no new orders for nuclear power plants in US since *1978*.

Only France, Japan, N & S Korea and Taiwan — all with no petroleum — are actively pursuing nuclear option

Reasons for decline in popularity well-known.

Public distrust, even fear.

Most environmentalists opposed, even though:
- no CO_2 emissions
- no SO_2 — acid rain

Public concerns about safety heightened by two accidents

1979 Three Mile Island — near Harrisburg PA

Cooling pumps stopped — then a pressure release valve became stuck — fuel was partially melted — no explosion

Some radioactive gases released (^{133}Xe & ^{85}Kr)

Decontamination has cost \$2 billion.

Many lawsuits brought by individuals.

No new US orders since then — probably single major cause of decline in US public confidence in nuclear power

Chernobyl, 1986 — near Kiev, Ukraine — a much more serious accident.

Read ¶ from Holland & Petersen.

Next,

let's examine the physics of nuclear power;

At the risk of insulting you, let me remind you what a nucleus is.

Atoms are composed of protons, neutrons & electrons

Their mass is well known.

Measured in atomic mass units (amu)

$$\boxed{1 \text{ amu} = \frac{1}{16} \text{ mass of } {}^{16}\text{O atom}}$$

most common oxygen isotope

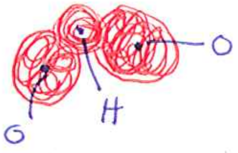
definition

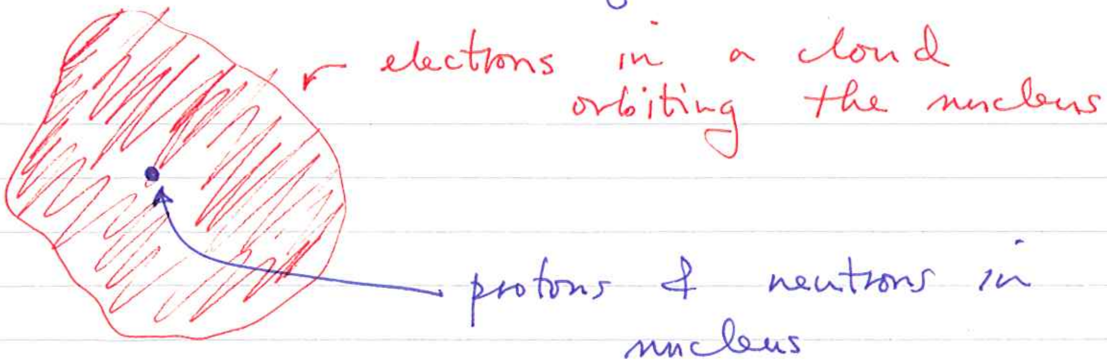
$$\boxed{1 \text{ amu} = 1.67 \cdot 10^{-27} \text{ kg}}$$

proton	1.00758	amu	+ charge
neutron	1.008987	amu	neutral
electron	$5.5 \cdot 10^{-4}$	amu	− charge

A sixth-grader's picture of an atom looks like this:

H_2O molecule





Z = no. of protons (atomic number)
N = no. of neutrons
$A = Z + N$ number of <u>nucleons</u>

Neutral atom : no. of electron = no. of protons — this determines an element's <u>chemistry</u>.

Typical sizes :

$$\boxed{\begin{array}{ll} \text{atom} : & 10^{-10} \text{ m} \\ \text{nucleus} : & 10^{-14} \text{ m} \end{array}}$$

if atom were size of Room 10, nucleus size of head of a pin

The electrons, which weigh less than 0.02 – 0.03% of the atom, take up almost all of the space

the density of matter is really the density of electrons

The nucleus is incredibly small & dense — often said that "matter is mostly empty space"

Density of ^{16}O nucleus :

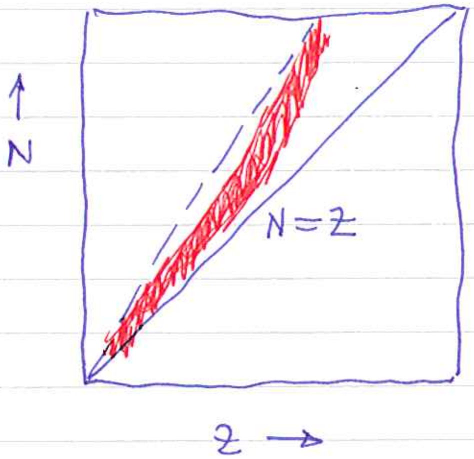
$$\rho \sim \frac{(16)(1.7 \cdot 10^{-27} \text{ kg})}{\frac{4}{3}\pi (10^{-14} \text{ m})^3} \sim 7 \cdot 10^{15} \frac{\text{kg}}{\text{m}^3}$$

density of nuclear matter

$\sim 10^{12}$ that of $\oplus$ as a whole

All elements have more than one *isotope* — number of neutrons in nucleus does not affect number of electrons ⟹ identical chemistry.

Table of nuclides plots N versus Z for all stable isotopes



heaviest stable isotope Z = 83 bismuth Bi

All heavier elements are unstable & *decay*

Many lighter elements have unstable isotopes too — e.g. ^{14}C — above the stable "line" ▨

Uranium (Z = 92) has two naturally occurring radioisotopes (also trace ^{234}U)

0.006%
0.712%
99.282%
> half lives ~ age of ⊕ reason they exist

0.006%	^{234}U
0.712%	^{235}U
99.282%	^{238}U
100.000%	

Both are at the top of complicated decay chains ending eventually in lead Pb.

This *radioactivity* of U is *not* the source of nuclear power.

Why not? Because they are simply <u>not</u> that radioactive — half lives are too long.

Binding energy.

We just weigh a known amount

Atomic mass of ${}^{235}U$: <u>235.11 amu</u>

What is the mass of the constituent nuclei?

$$\left.\begin{array}{l} 92 \text{ protons} \times 1.00758 \\ 143 \text{ neutrons} \times 1.0089[illegible]7 \\ 235 \text{ electrons} \times 5.5 \cdot 10^{-4} \end{array}\right\} = \underline{237.03 \text{ amu}}$$

The difference is the <u>nuclear</u> <u>binding</u> <u>energy</u>

Why this discrepancy? ${}^{235}U$ weighs less than its parts by 1.92 amu!

Where has this mass gone? Into the <u>binding</u> <u>energy</u> of the nucleus — the energy that keeps the nuclei so close together.

To find the binding energy we use the most famous eqn in all of science

When Stephen Hawking wrote *A Brief Passage in Time* was told by publisher that every eqn would cut sales in half.

He insisted on one eqn: $\boxed{E = mc^2}$ ← Einstein

c = speed of light

Binding energy of ^{235}U is

$$E = (1.92 \text{ amu})\left(1.67 \cdot 10^{-27} \frac{kg}{amu}\right)\left(3 \cdot 10^{8} \frac{m}{s}\right)^2$$

$$= 2.88 \cdot 10^{-10} \text{ J}$$

These numbers are so small (and because of the way atomic energies are measured) another energy unit more convenient

1 electron volt (eV) = energy acquired by an electron in accelerating through a potential difference of 1 volt

$$1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ J}$$

A more useful unit in nuclear calculations

$$1 \text{ MeV} = 10^{6} \text{ eV} = 1.6 \cdot 10^{-13} \text{ J}$$

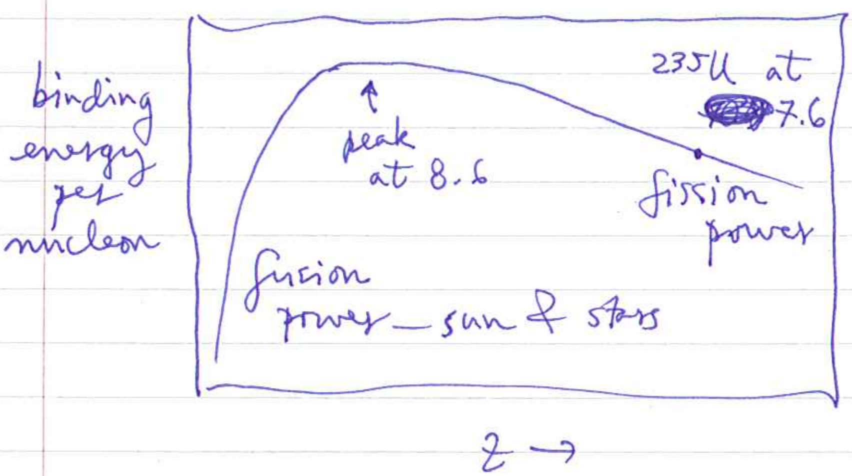
Binding energy of ^{235}U is 1787 MeV

In future we remember $\boxed{(1 \text{ amu}) \times c^2 = 931 \text{ MeV}}$

The binding energy *per nucleon* is

$$\frac{1787}{235} = \boxed{7.6 \text{ MeV / nucleon}} \leftarrow {}^{235}U$$

Can carry out this calculation for all nuclei



This is the famous *Curve of the Binding Energy*

John McPhee was so impressed with this curve & its implications that he wrote a whole book about it.

Fission — ${}^{235}U$ splits *roughly* in two (we'll be more precise later)

The fission products have binding energies of about 8.4 MeV/nucleon

Fission *releases* about $(8.4-7.6) \times 235$

$\approx$ *200 MeV/fission*

So how do we get a ^{235}U nucleus to fission?

Spontaneous fissions are not non-existent but are very rare — in fact they are used as the basis of a geological dating technique.

But fission is strongly promoted by neutron bombardment

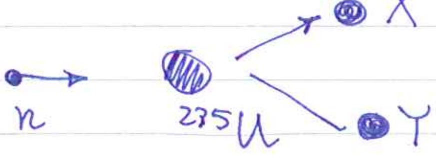
what happens?

Depends on kinetic energy of neutron

Two cases of interest

1. fast neutrons ~ 2 meV
2. slow (thermal) neutrons — 0.025 eV

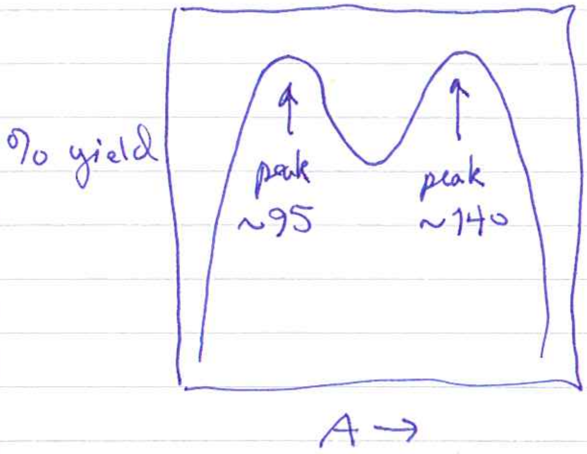
Fast neutrons are emitted in fission reactions



+ 2.5 neutrons (on average)

Spectrum of fission neutrons

The mass spectrum of the fission products is double-peaked



Barium $Z = 56$, $A = 137.34$ was the first fission product discovered prior to WW II by Otto Hahn & Lise Meitner

The distribution of fission energy is given in Glasstone Table 4.23

About 3/4 of the energy is k.e. of the fission fragments. Being heavy they are quickly halted by collisions & deposit their energy as <u>heat</u>

Thermal neutrons — same kinetic energy as neighboring atoms in thermal equilibrium

$$\frac{1}{2}mv^2 = \frac{3}{2}kT \approx 0.025 \text{ eV at room temp}$$

The velocity of a neutron is

$$v = 13.8 \text{ km/sec} \sqrt{E\,(\text{eV})}$$

↖ non-relativistic

Fast neutrons : 2 MeV = 20,000 km/sec
= 7% speed of light

Thermal neutrons :

300°K	2.2 km/s
1000°K	4.0 km/s

Various things can happen when a neutron strikes a nucleus

1. elastic scattering — just bounce off — in the process the neutron slows down a little

2. inelastic scattering

in this case the neutron is briefly absorbed & then re-emitted at a lower energy

This process can lower the k.e. of the re-emitted neutron substantially, in contrast to elastic scattering of fast neutrons

(3) absorption — can be absorbed or captured to yield a new element which then decays

e.g. $^{235}U + n \rightarrow {}^{236}U \rightarrow {}^{232}Th + {}^{4}He$

$\uparrow$ very short half life

$\uparrow$ $2.4 \cdot 10^{7}$ yr so sticks around awhile

$\uparrow$ alpha particle

e.g. $^{238}U + n \rightarrow {}^{239}U \xrightarrow[23.5\,\text{min}]{} {}^{238}Np \xrightarrow[2.3\,\text{d}]{} {}^{239}Pu$

$\uparrow$ long half life — 24,000 yrs

This reaction used in breeder reactors to breed 239 Pu which is also (slow) fissile

(4) finally, fission

The probabilities of these four outcomes is known — depends strongly on k.e. of incoming neutron

[illegible]

Probabilities or <u>cross-sections</u> measured in a strange unit

$1 \text{ barn} = 10^{-28} \text{ m}^2$

Recall nuclear dimension $\sim 10^{-14}$ m

So 1 barn $\approx$ cross-sectional <u>area</u> of nucleus

Cross-sections $\gg$ 1 barn indicate highly probable outcomes

Three important facts

(1) Fission cross-section of ^{238}U $\approx$ <u>zero</u> for incoming neutron energies < 1.4 MeV

(2) Fission cross-section of ^{235}U climbs steeply in thermal regime — strong probability of fission by <u>slow</u> neutrons

This is what Hahn & Meitner found & at first found very difficult to believe (fission — a dramatic event — by slow neutrons)

(3) capture cross-section of ^{238}U has many resonances in range 1 – 1000 eV.

Summarizing :

	%		$\sigma_{fission}$	$\sigma_{capture}$		$\sigma_{inelastic\ scatter}$
^{235}U	0.7		582	112		
		thermal				
^{238}U	99.3	↑ ↓	0	2.7	$\sigma_{elastic\ scatter}$	↓
$^{235}U \approx {}^{238}U$		fast	0.3	0.04	1.5	2.5

If exactly 1 of the 2.5 neutrons emitted during fission gives rise to another fission — self-sustaining chain reaction

If less than 1 — cannot sustain

If more than 1 — Hiroshima

What happens if we add a neutron source to natural uranium (99.3% ^{238}U & 0.7% ^{235}U) ?

First fission yields 2.5 neutrons

$\frac{2.5}{4.3} = 60\%$ undergo inelastic scattering ← their energy is reduced to less than 1.4 MeV
$\Rightarrow$ no chance of fissioning another ^{238}U

$\uparrow 0.3 + 1.5 + 2.5$

Only $\frac{0.3}{4.3} = 7\%$ can cause another fission

Net result — no chain reaction

Two possibilities of obtaining a chain reaction :

(1) separate ^{235}U from ^{238}U and enrich the fuel.
^{235}U can fission by neutrons < 1.4 MeV so the strong inelastic scattering can be overcome

This is how a bomb works — fast neutron fissions with > 1 fissioning neutron per fission
$\Rightarrow$ exponential growth.
Neutron energies in range $\frac{1}{10} - 1$ MeV.

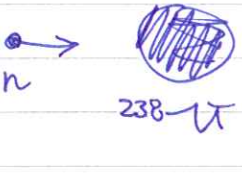
(2) Slow the neutrons down until they are thermal
Then the $\sigma_{fission}$ for ^{235}U ↗

$^{235}U : \sigma_{fission} = 580$ barns @ 0.25 eV

If the neutrons can be slowed down enough (from 2 MeV to 0.25 eV) without other things happening to them along the way, then high $\sigma_{fission}$ of ^{235}U can sustain a chain reaction.

Cannot just rely on elastic scattering by U atoms to slow down the neutrons.

Why not?



[redacted]

[redacted]

[redacted] Takes ~ 2000 collisions to reduce energy from 2 MeV to

[redacted]

0.025 eV

In moving slowly through the ^{238}U capture resonance region 1–1000 eV there is a strong probability of capture $\Rightarrow$ no chain reaction.

Need to add a <u>moderator</u>:

Ideal properties:

(1) light — slow down neutrons in big jumps — more chance to avoid capture

(2) small capture cross section itself

H_2O (atomic mass 18) has

$$\sigma_{capture} = 0.664 \text{ barns}$$

D_2O (mass 20) $\sigma_{capture} = 1.1 \cdot 10^{-3}$ barns great!

↑ deuterium

^{2}H — one neutron + one proton

But note must be very pure.

One other element in a reactor — boron — used for <u>control</u> rods — has a <u>very</u> high capture cross-section for thermal neutrons light water reactors (^1H moderator) must use ^{235}U enriched fuel ; heavy water reactors (^2H) can use natural U

Many different reactor designs, depending on choice of moderator and % enrichment of fuel.

Geometry also important — ① homogeneous reactor — fuel & moderator mixed together ② heterogeneous — more common — all power reactors

fuel rods surrounded by moderator

Graphite was used as the moderator in the first reactor (pile) built by Enrico Fermi in a squash court at the U. of Chicago.

Let's calculate the power output of a reactor:

$$\frac{\text{fissions}}{\text{sec}} = \frac{10^9\ \text{J/sec}}{(0.35)(3.2\cdot 10^{-11}\ \text{J/fission})}$$

As we have seen we get ~ 200 MeV / ~~fusion~~ fission

1 MeV = $1.6\cdot 10^{-13}$ J = $1.6\cdot 10^{-13}$ Watt-sec

A typical large nuclear power plant produces about

1 GW of power
10^9 Watts ⟹ 17 million light bulbs

$$10^9\ W = \left\lfloor \overset{0.35\times}{3.2\cdot 10^{-11}}\right. \frac{\text{Watt-sec}}{\overset{\text{fission}}{\text{fusion}}} \times \frac{\overset{\text{fissions}}{\text{fusions}}}{\text{sec}}$$

$$\Rightarrow \underline{3\cdot 10^{19}\ \overset{\text{efficiency}}{\text{fusions}}/\text{sec}} \times \frac{1}{0.35} = 10^{20}\ \frac{\text{fissions}}{\text{sec}}$$

fissions

How many kg of ^{235}U consumed per year

$$\frac{\overset{10^{20}}{\cancel{3\cdot 10^{19}}}\ \frac{\text{atoms}}{\text{sec}}}{6\cdot 10^{23}\ \text{atoms / mole}} \times 235\cdot 10^{-3}\ \frac{\text{kg}}{\text{mole}} \times 3.14\cdot 10^{7}\ \frac{\text{sec}}{\text{yr}}$$

= [illegible] $\overset{1200}{\cancel{384}}$ kg / yr $\overset{2700\text{ lbs}}{850}$ lbs

170 tons of uranium / year

This is [illegible] 55 tons of uranium per year ^{235}U since ^{235}U is 0.7%

Interesting to compare with conventional (fossil fuel) sources — energy stored in chemical bonds — the fuzzy electron clouds — being released in that case.

Coal — caloric content [illegible]

$$= \overset{2.3\cdot 10^{10}}{\cancel{2.9\cdot 10^{10}}}\ \frac{J}{\text{ton of coal}}$$

$$^{235}U:\quad \frac{10^{9}\ W\ yr \times 3.14\cdot 10^{7}\ \frac{sec}{yr}}{\text{[illegible]}\ \underset{.384}{\cancel{.384}}\ \text{tons}} = \overset{\overset{8.2}{\cancel{2.6}}}{\cancel{8.2}}\cdot 10^{16}\ \frac{J}{\text{ton of } ^{235}U}$$

2.8 [illegible] million

~~2.8 million~~ times as much energy per ton of fuel

Can do the same calculation <u>per atom</u>

^{235}U fission — 200 MeV

1 ton coal has ~ $2 \cdot 10^{28}$ atoms of C

Burning supplies $2.9 \cdot 10^{10}$ J $= 1.8 \cdot 10^{23}$ MeV

$= 1.8 \cdot 10^{29}$ eV

Aside: # C atoms / ton same as # CH_2O molecules

$$\frac{10^6 \text{ gm coal}}{30 \text{ gm/mole}} \times 6 \cdot 10^{23} \ \frac{\overset{\text{molecules}}{\cancel{\text{atoms}}} \text{ of } CH_2O}{\text{mole}}$$

$\nearrow$

$^{12}C\,^{1}H_2\,^{16}O$ $=$

$$\frac{1.8 \cdot 10^{29} \text{ eV / ton}}{2 \cdot 10^{28} \text{ atoms ton}} = \boxed{\text{9 eV released in oxidation of one } CH_2O \text{ molecule}}$$

$$\frac{200 \text{ MeV}}{9 \cdot 10^{-6} \text{ MeV}} =$$

$$\boxed{\text{22 million times as much on a per atom basis}}$$

Makes sense: $22 \cdot 10^6 \times \left(\frac{40}{235}\right) = 2.8 \cdot 10^6$

Suppose we compare with coal
(assumed to be pure graphite)

$$\boxed{n \rightarrow {}^{235}U \begin{matrix} \nearrow X \\ \searrow Y \end{matrix} + 2.5\,n \quad \text{releases } 200 \text{ MeV}}$$

Burning one carbon atom in coal

$$\boxed{C + O_2 \rightarrow CO_2}$$

Burning one ton of coal releases $2 \cdot 10^{10}$ J

One ton contains $\frac{10^6 \text{ gm/ton}}{12 \text{ gm/mole}} \times 6 \cdot 10^{23} \frac{\text{atoms}}{\text{mole}}$

$$= 5 \cdot 10^{28} \text{ C atoms/ton}$$

So the combustion of one C atom releases

$$\frac{2 \cdot 10^{10} \text{ J/ton}}{5 \cdot 10^{28} \text{ atoms/ton}} = 4 \cdot 10^{-19} \frac{\text{J}}{\text{C atom}}$$

$$\boxed{\text{energy released} = 2.5 \text{ eV / C atom}} \qquad 1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ J}$$

$$\boxed{\begin{array}{l} \text{A factor of } 8 \cdot 10^7 \text{ greater on a per atom basis} \\ \text{or } 8 \cdot 10^7 \times \frac{12}{235} = 4 \text{ million times greater on a per kg basis} \end{array}}$$

The conventional argument in favor of nuclear power is that the factor of 10^6 or more gained in using nuclear rather than chemical energy buys a lot of safety

A few remarks about reactor design — concept of inherent safety

Lets follow the adventures of the

(1) $\nu = 2.5$ fast neutrons

released per fission of a ^{235}U nucleus

Some are immediately captured by ^{238}U and ^{235}U leading to an amount left :

(2) η where

$$\eta = \frac{N(235)\,\sigma_f(235)}{N(235)\,\sigma_{f+c}(235) + N(238)\,\sigma_c(238)}\,\nu$$

$$\eta = 1.33 \quad \text{for natural } U$$

This is the # of fast neutrons released per ~~neutron absorbed~~ slow neutron absorbed by the U.

(3) Now they must be slowed down by the moderator — some get captured in resonances — depends on moderator weight — ~~others get captured in moderator~~

Factor $\eta \overset{p}{\cancel{\varepsilon}}$ are thermalized

↑ ~~escape probability~~ resonance escape probability

(4) Finally after thermalization a fraction f are absorbed by the moderator or fuel cladding, etc. — not by the U

$\eta \overset{p}{\cancel{\varepsilon}} f$

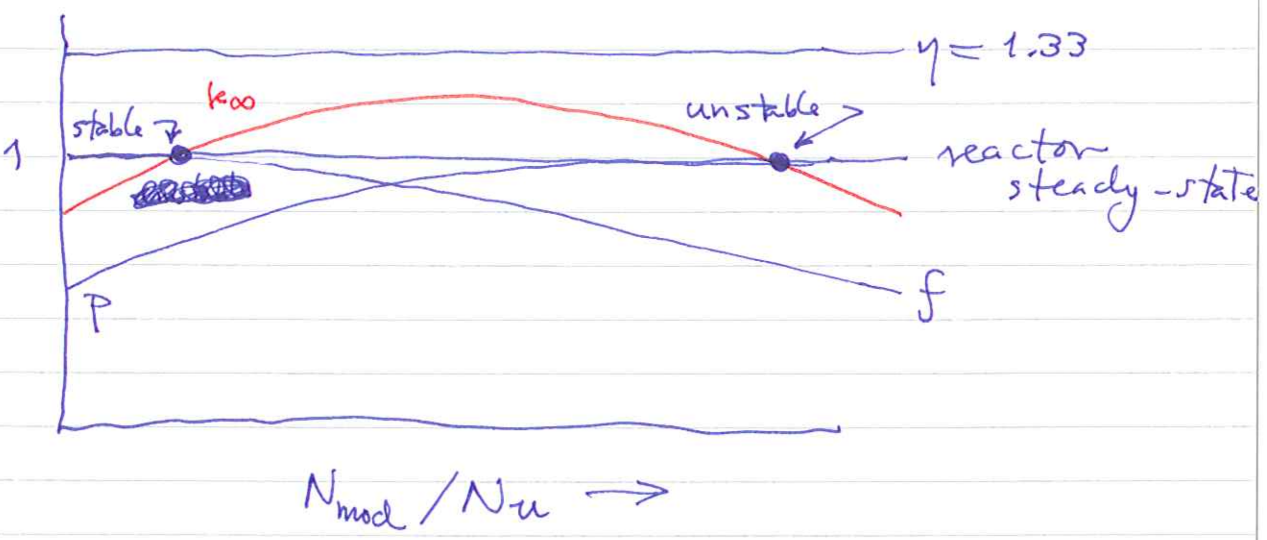
(5) FINALLY, a fraction l leak out of the reactor

$$\boxed{k = \eta \overset{p}{\cancel{\varepsilon}} f (1 - l) : \quad \text{Four-factor product}}$$

We wish the reactor to operate at $k = 1$

$k = (1 - l) k_\infty$ ← an infinitely big reactor

Consider a plot of k_∞ versus moderator / fuel fraction



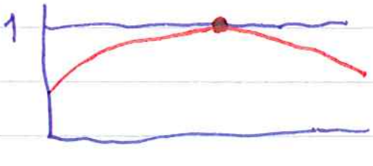
The leftmost operating point is inherently stable w.r.t. temperature changes

If moderator is H_2O

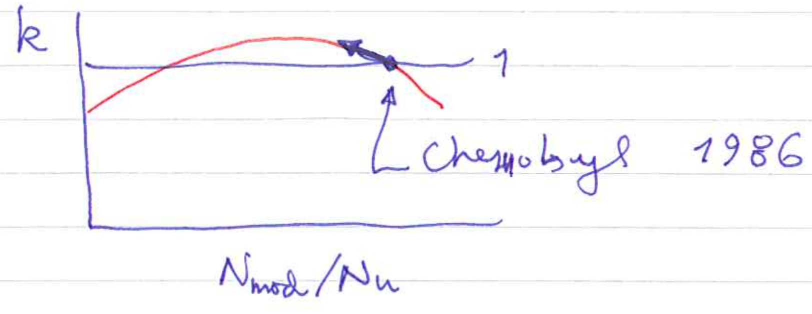
- reactor heats up
- H_2O boils
- N_{mod} / N goes down
- $k \rightarrow$ less than 1 $\Rightarrow$
- reactor shuts down

Note that excessive leakage of neutrons $1-l$ lowers the whole red curve:

Too much leakage and reactor won't work at all — leads to concept of critical mass



Chernobyl-type reactor operates at the other (unstable) equilibrium point



Operators were performing an experiment during which k became greater than 1 — could not be corrected in time — melting led to explosive chemical reactions between Zr cladding & H_2O — explosion breached containment (not as strong as in Western reactors)

Availability of uranium is no problem

It is a common trace element, naturally enriched in the continental crust

Average crustal concentration ~ 1 ppm

Enough that it must be taken into account in quantitative studies of continental heat flow — decay produces heat also.

Current deposits being mined occur where ground H_2O has dissolved uranium and transported it as

UO_2^{2-} : uranyl ion

Then re-precipitate in reactions such as

$$2UO_2^{2-} + C + 2H_2O \rightarrow \underset{\substack{\uparrow \\ \text{pitchblende} \\ \text{ore}}}{2UO_2} + CO_2 + 4H^+$$

Largest such hydrothermal deposit in west in Athabasca Basin in northern Saskatchewan.

Has half the world's low-cost reserves.

Widespread US reserves in Colorado Plateau

Current deposits being mined are 1% or more (10,000 ppm) uranium

Highest-grade ores > 10% uranium — these are so radioactive they are difficult to mine — but they constitute only ~ $1/10^6$ of crustal reservoir

Current rate of extraction (worldwide):

~~[illegible] 10^8 tons of U per year~~

$$\boxed{\sim 10^8 \text{ pounds} \sim 5 \cdot 10^4 \text{ tons / yr}}$$

Uranium ore (grade > 1000 ppm or 0.1%) ~ 10^8 tons ⟹

enough to last 2000 years at current rate

For every tenfold decrease in grade there is a thirtyfold increase in amount of recoverable U in crustal rocks

Between 100 and 1000 ppm — $5 \cdot 10^9$ tons — enough to last 100,000 years.

The supply of U in the crust is practically inexhaustible.

Price of uranium is not what makes nuclear power uncompetitive at present time — it is low price of fossil fuels, esp. coal — and licensing costs, etc.

Other problem on which geology has a bearing — <u>disposal</u> of <u>nuclear wastes</u>

Spent fuel from reactors is <u>highly radioactive</u> — easy to see why

The <u>fission products</u> are <u>radioactive</u>.

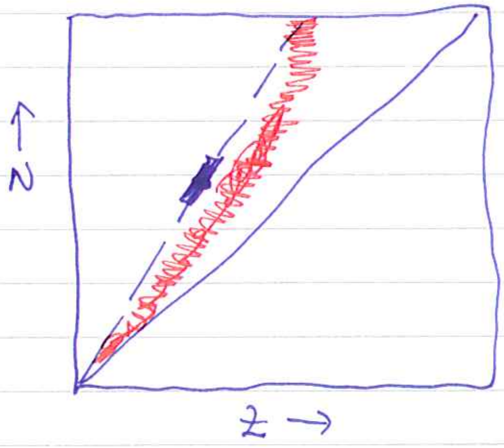


Chart of nuclides

Fission products lie along ▮ above the stable curve ▨

As a result they are <u>unstable</u> — decay by both α and β decay.

Many short-lived as well as long-lived radionuclides in fuel.

Unit of radioactivity

1 curie = radioactivity of 1 gram of radium

$$\boxed{1 \text{ curie} = 3.7 \cdot 10^{10} \text{ disintegration/second}}$$

Fig. 11.37 shows decay of radioactivity of fuel assembly of a typical 1 GW light-water reactor

In curies per fuel ~~[illegible]~~ rod

Right after removal of spent fuel — 10^6 curies

Decayed by factor of 100 to 10^4 curies after 100 years

Another 10,000 years to decay another factor of 100 to 10^2 curies.

Spent fuels are not really "hot" after about 1000 years.

This typical required containment time.

US has not decided on a permanent waste depository — site chosen (Yucca Mtn, Nevada — 2 congressmen) still being studied by DOE.

Until then fuel is being kept in swimming pools on site.

Yucca Mtn is dry & desolate but in Basin & Range — active extension and volcanism (within past 500,000 years)

Would be encapsulated in glass or "synrock" first

Other options have been considered

- on seafloor near trenches (subduct it)
- blast into space — launches not reliable enough
- salt deposits — not as dry as first thought

The New York Times (Aug 27, 1993) has estimated that an Indian reservation or county willing to rent a patch of dry ground ≈ 1/2 area of Central Park could collect ~ $50 million / year for at least 20 years.

Solar radius = $7 \cdot 10^8$ m

Total radiant energy

$$(6.4 \cdot 10^7)(4\pi)(7 \cdot 10^8)^2$$

$$= 3{,}9 \cdot 10^{26} \text{ W}$$

$$29 \text{ MeV} = (29)(1.6 \cdot 10^{-13} \text{ J/MeV})$$

$$= 4.6 \cdot 10^{-12} \frac{\text{W sec}}{\text{fusion}} \quad (\text{J/fusion})$$

$$\text{fusions/sec} = \frac{3.9 \cdot 10^{26} \text{ J/s}}{4.6 \cdot 10^{-12} \text{ J/fusion}} = 8.5 \cdot 10^{37} \text{ fusions/sec}$$

$$\boxed{\text{or: } 3 \cdot 10^{38} \text{ H atoms fused per second}}$$

No of H atoms in sun

$$M_{\odot} = 2 \cdot 10^{30} \text{ kg}$$

$$\text{No. of atoms} = \frac{2 \cdot 10^{30} \text{ kg}}{1.7 \cdot 10^{-27} \text{ kg/amu}} = 1.2 \cdot 10^{57} \text{ atoms in sun}$$

at this rate

$$\underline{\text{Lifetime}} \text{ of } \underline{\text{sun}} = \frac{1.2 \cdot 10^{57} \text{ atoms}}{3 \cdot 10^{38} \text{ atom/sec}}$$

$$= 4 \cdot 10^{18} \text{ secs} = \underline{100 \text{ billion years}}$$ ← neglects stellar <u>evolution</u>

Not true— actually Sun will become a white dwarf after it has consumed 15% of its H

Actual lifetime only 10–15 b.y. because of rapidly accelerated burning during red giant stage.

Two "fuel cycles" are operative in the sun

<u>proton</u> – <u>proton</u>:

$$^1H + p \to \overset{\text{deuterium}}{{}^2H} + \beta^+ + \nu \qquad (\times\ 2)$$

$$^2H + p \to \underset{\text{tritium}}{{}^3H} + \gamma \qquad (\times\ 2)$$

$$\underline{^3H + {}^3H \to {}^4He + 2p}$$

net result $4\,{}^1H \to {}^4He + 2\beta^+ + 2\gamma + 2\nu$

<u>carbon</u> – <u>nitrogen</u> cycle — more important in more massive ★'s

<u>PPPL</u> at <u>Princeton</u> — world's leader in development of <u>controlled</u> <u>fusion</u>

Currently suffering from massive budget decline.

Many advantages, if could be harnessed.
Clean — fuel is H_2, esp. deuterium & tritium

$$\overset{\text{deuterium}}{{}^2H} + \overset{\text{tritium}}{{}^3H} \to {}^4He + n + \boxed{17.6\ \text{MeV}}$$

Main reaction of interest in current designs

Magnetic confinement of plasma — <u>Tokamak</u>

FUSION POWER

The curve of the binding energy indicates that the other way to extract nuclear energy is by fusion of light elements.

This is how the sun & other stars produce their energy.

The details are much more complicated but the basic solar reaction is

$4\,{}^{1}H \rightarrow {}^{4}He$ in a multi-step process

${}^{4}He$: 4.003 amu

Constituent parts

$2\,{}^{1}H + 2n$: 4.034 amu

Difference $4.034 - 4.003 = 0.031$ amu
$= 29$ MeV

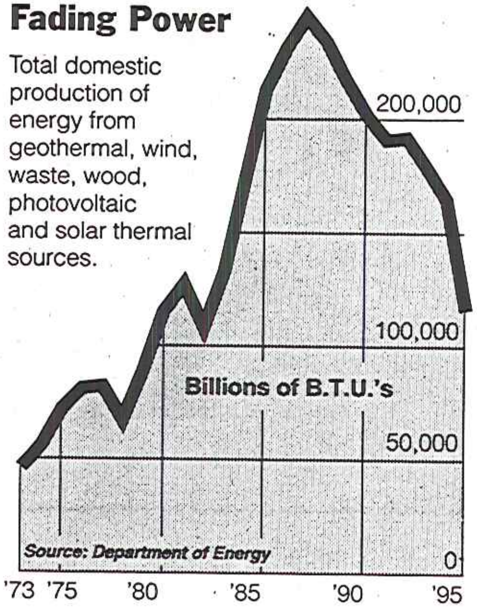
Or: 7 MeV for each hydrogen atom fused

What is the rate of solar fusion needed to supply solar radiation?

$$u = \sigma T^4 = 5.67 \cdot 10^{-8} \,(5800\ {}^{\circ}K)^4$$
$$= 6.4 \cdot 10^{7}\ W/m^2$$

Fading Power

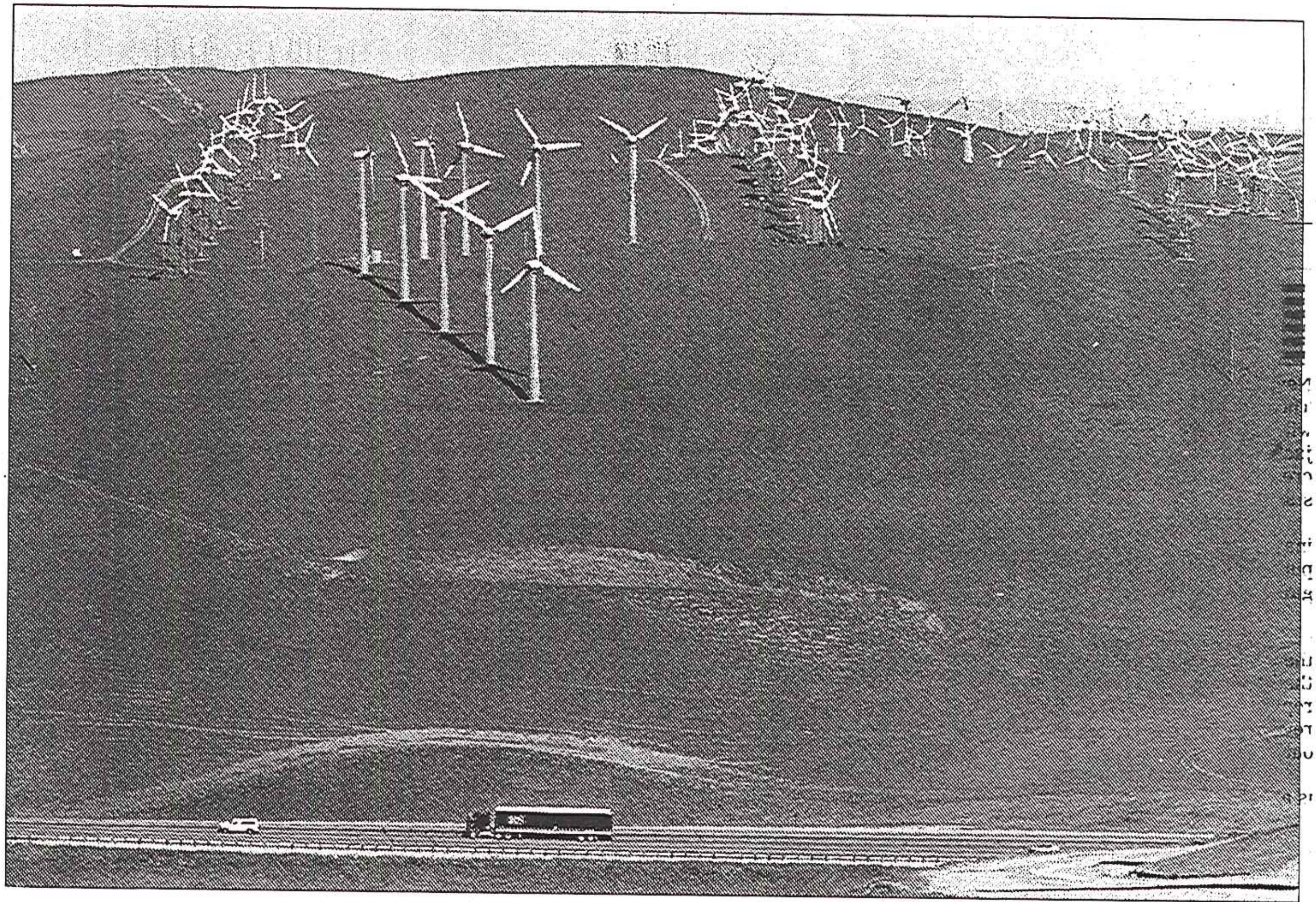
Total domestic production of energy from geothermal, wind, waste, wood, photovoltaic and solar thermal sources.



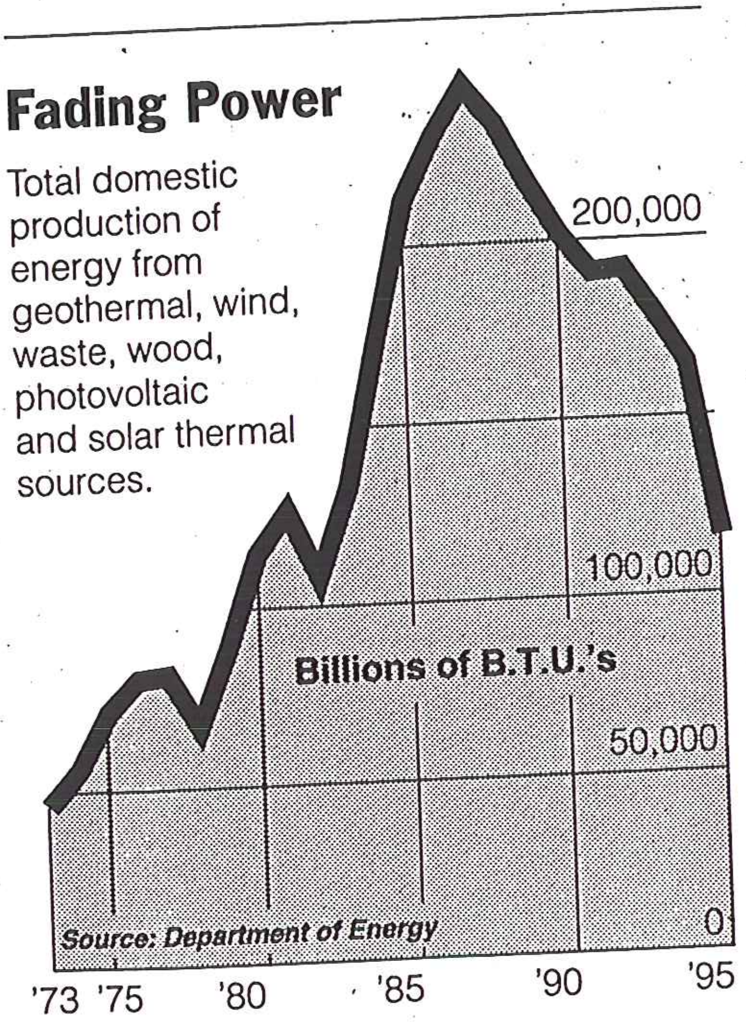
Source: Department of Energy

The New York Times

Deregulation has distracted utilities from developing other sources of energy.



Photographs by Jim Wilson/The New York Times



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

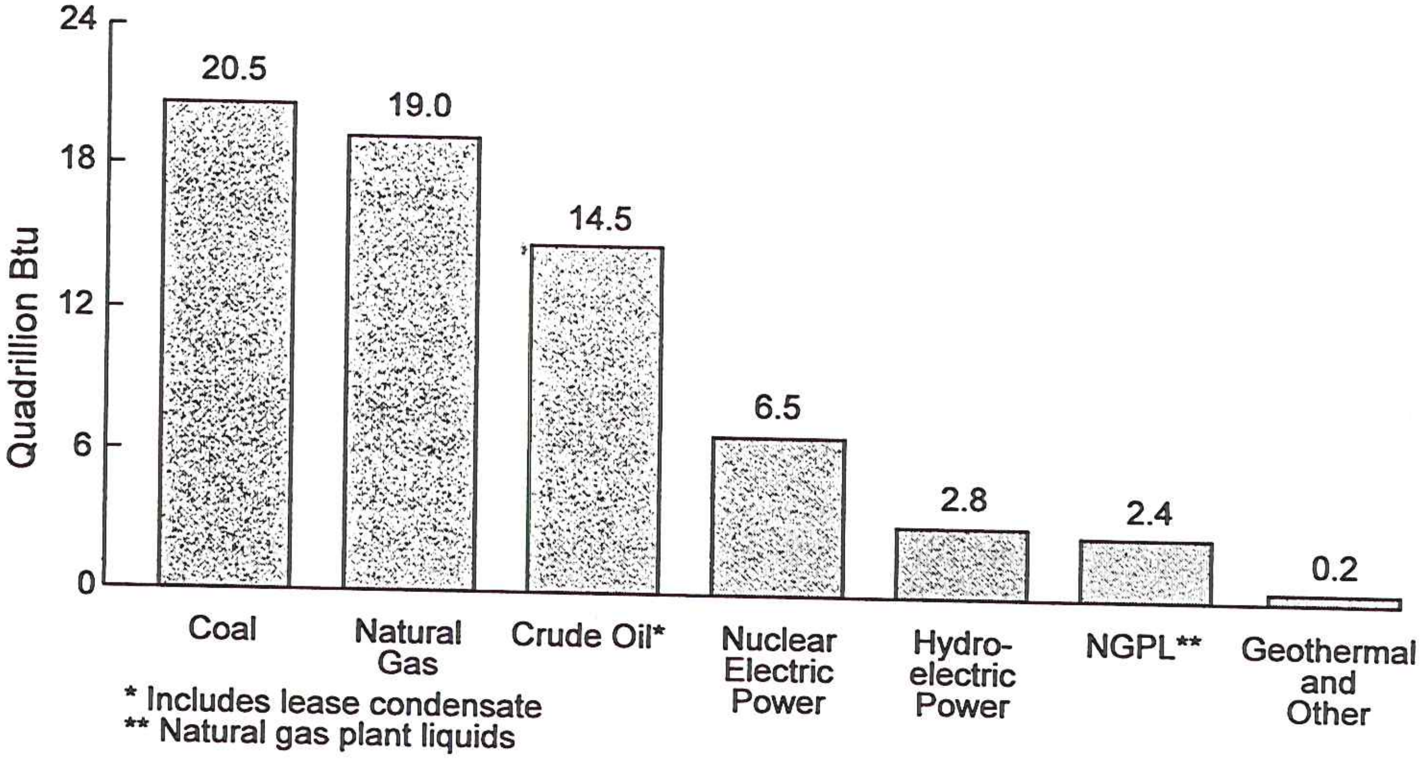
Renewables (US):

100,000 billion BTU

= 0.1 quads out of a US total of ~80 quads/yr

i.e. about 0.1%!

Figure 8.28. The major sources of energy produced in the United States during 1993. NGPL = natural gas pressurized liquid. (*Annual Energy Review 1993*)



* Includes lease condensate
** Natural gas plant liquids

Figure 11.35. Nuclear Generating Units, December 31, 1993. (*Annual Energy Review 1993*)

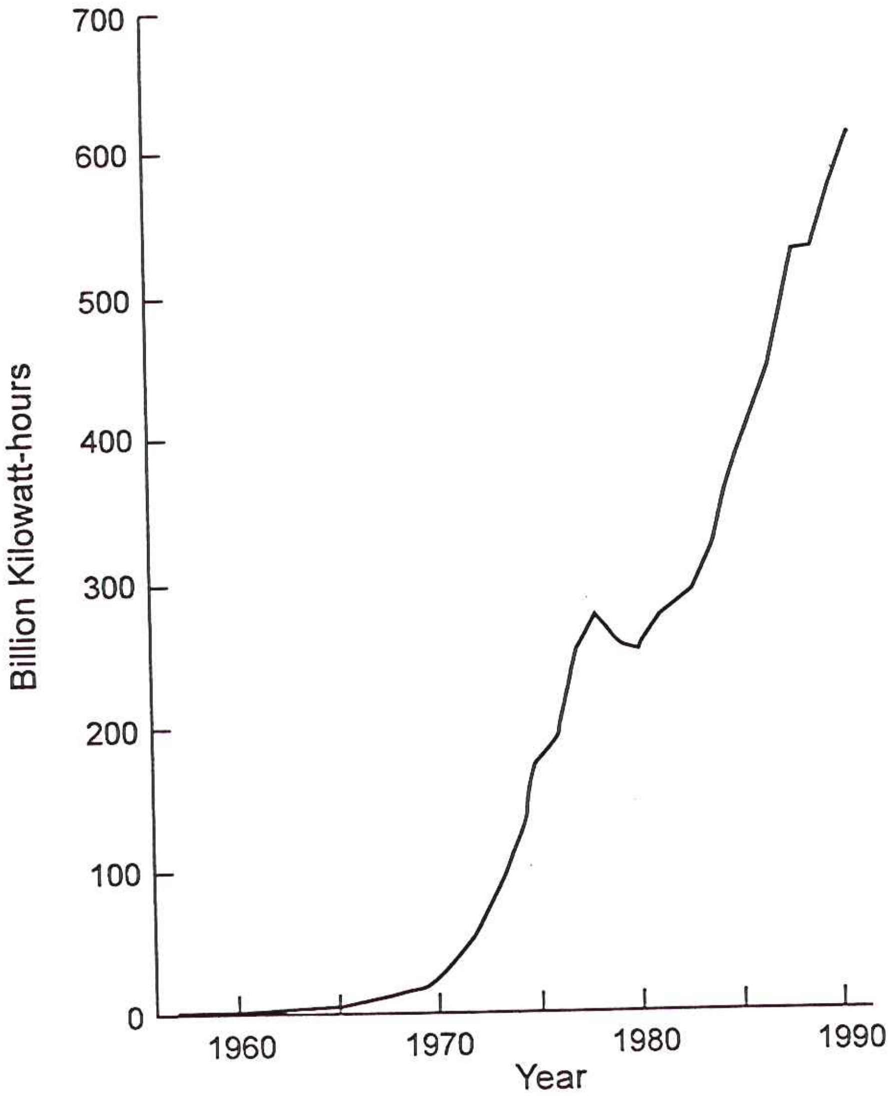
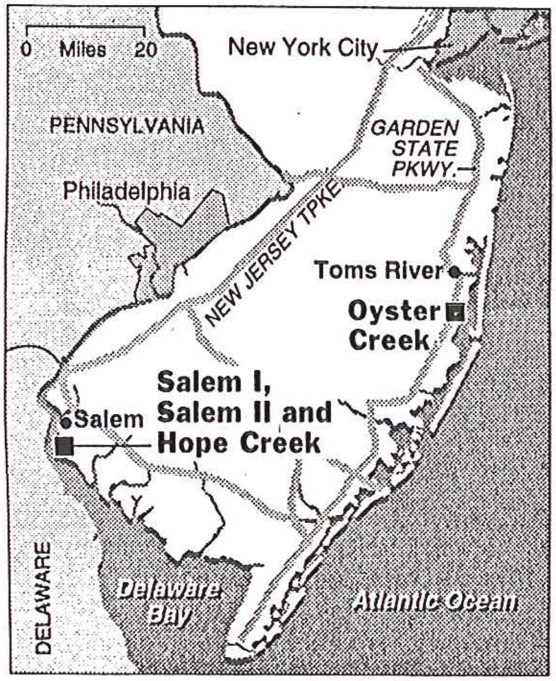


Figure 11.25. Net nuclear generation of electricity in the United States, 1957–91. (*Annual Energy Review 1991*)

AT ISSUE

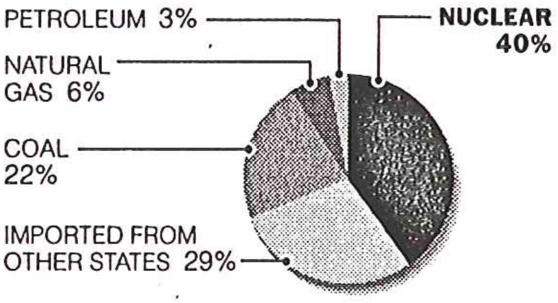
Powering the State: An Uncertain Future

New Jersey depends heavily on nuclear power to generate its electricity. But shutdowns at the Public Service Electric and Gas Company's Salem nuclear reactors have raised both the cost and the prospect that the state may have to look to cheaper alternatives.

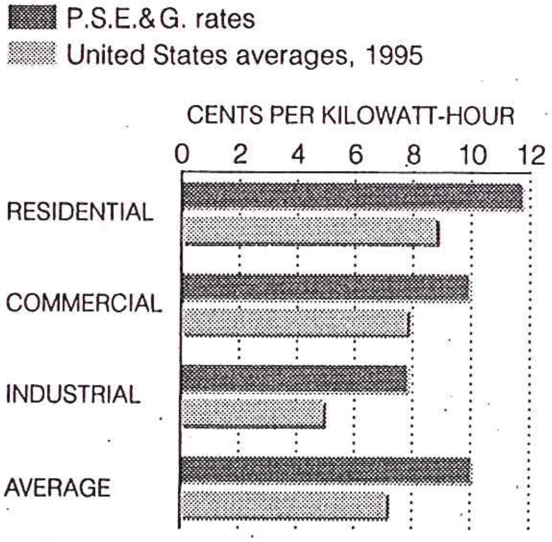


WHERE IT COMES FROM

Sources of electricity in New Jersey, 1990



WHAT IT COSTS



Sources: N.J. Board of Public Utilities, Prudential Securities

The New York Times

Altered Economics In Connecticut Lead To A-Plant Closing

By ANDREW C. REVKIN

Faced with high operating costs and rising competition from other electricity sources, the owners of a Connecticut nuclear power plant with one of the best longterm performance records in the nuclear industry decided yesterday to shut it down permanently.

The decision to close the Connecticut Yankee plant, in Haddam Neck on the Connecticut River about 20 miles southeast of Middletown, could signal that similar plants, including New York's Indian Point 3, may also be imperiled by changing economics and the availability of abundant power from non-nuclear sources, power industry experts said. Except for Shoreham on Long Island, which was never fully operational, Connecticut Yankee would be the first commercial plant in Connecticut, New York or New Jersey to close in 22 years.

Although it is the oldest active commercial nuclear plant in the United States, Connecticut Yankee generated power more than 71 percent of the time in its 28 years of service, putting it in a performance category with many plants half its age.

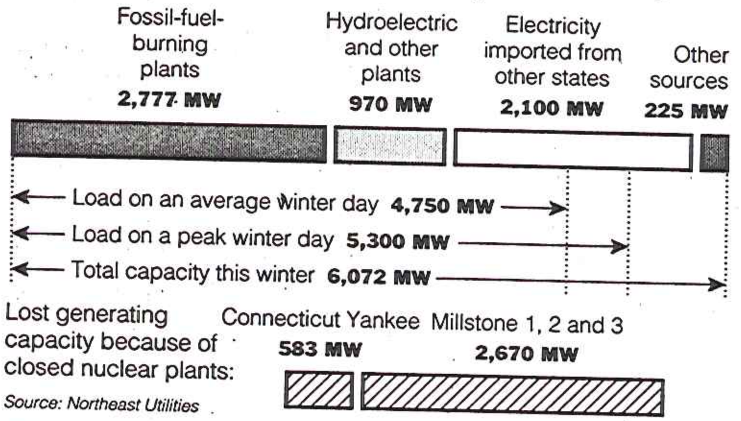
But lately, Federal nuclear inspectors had identified a spate of safety problems at the plant and three others in Connecticut — Millstone 1, 2 and 3 — run by its primary owner,

Continued on Page B14, Column 1

A CLOSER LOOK

Making Do Without Nuclear Power

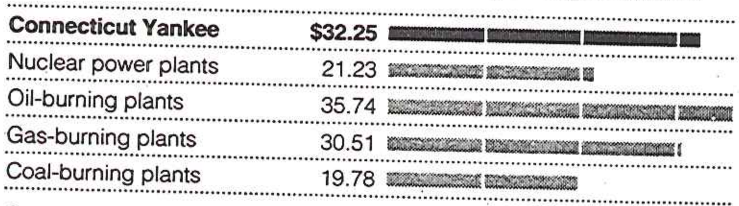
The owners of the Connecticut Yankee nuclear plant — shut down since July for safety reasons — have decided to close it permanently. Connecticut's three other reactors are also out of service. Here is where the state will get its power this winter, expressed in megawatts.



Source: Northeast Utilities

Comparing the Costs

Rising costs were a factor in the decision to close Connecticut Yankee. Here is how its operating, maintenance and fuel costs compare with those of power plants nationwide. Figures are the five-year averages, 1990–94, expressed in dollars per megawatt-hour.



Source: Utility Data Institute

The New York Times

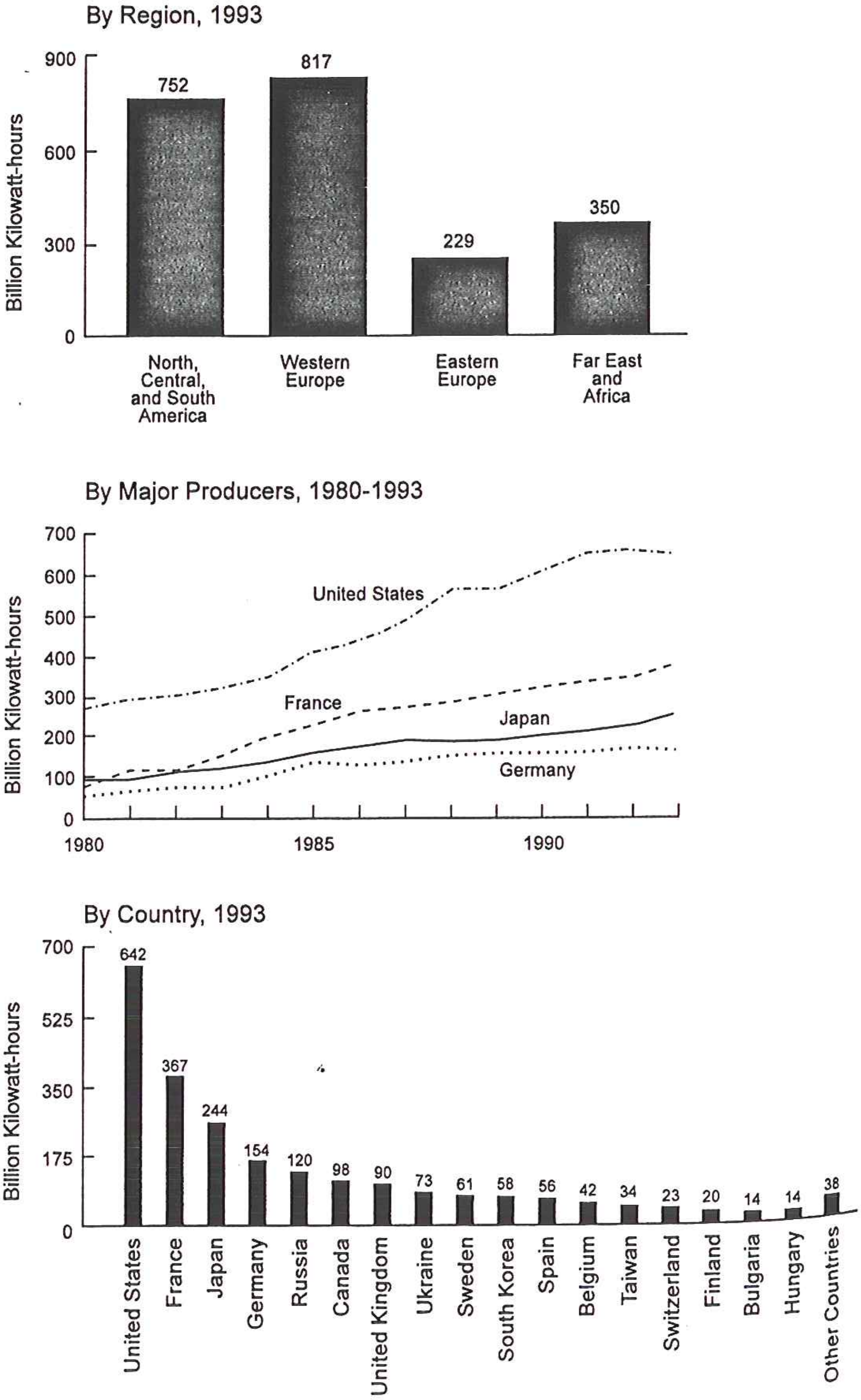


Figure 11.26. Nuclear electricity gross generation (*Annual Energy Review 1993*)

By Region, 1993

By Major Producers, 1980-1993

By Country, 1993

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

	Status (6/30/89)[a]		Annual generation[b] (GWyr)		Percent nuclear[c] 1988
Country	Number of units	Capacity (GWe)	1976	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.

Seven years after the accident at Three Mile Island, a much more serious accident occurred in the former USSR at Unit 4 of the Chernobyl nuclear plant, about 80 kilometers north of Kiev in the Ukraine (plate 43). The accident was clearly due to a chain of inexcusable operating errors by the staff of the power station. The combination of their fundamental violations of safety rules made the reactor unstable. The technicians lost control of the reactor, which suffered a prompt neutron power burst. At 1:23 A.M. on April 26, 1986, Unit 4 reached one hundred times normal power. Some of the fuel disintegrated and evaporated the cooling water. This caused a steam explosion, which sheared off the top of all 1,661 pressure tubes in the graphite-moderated tube reactor, lifted the 1,000-ton cover off the core, ruptured the inadequate containment, dislodged the refueling crane, discharged hot molten and/or pulverized fuel to an altitude of at least 7.5 kilometers, and started some thirty fires. The release of radionuclides, which was the largest ever recorded in a technological accident, continued for ten days. Dispersed radioactivity reached all of the countries in northern Europe and triggered emergency protection measures in many European countries (May 1990; Hohenemser, Goble, and Slovic 1992).

Dry weather, favorable siting, evacuation of 116,000 people, and—above all—dispersal of radionuclides to high altitudes (see fig. 11.36) contributed to holding the immediate deaths to thirty-one. However, some estimates suggest that the worldwide dispersal of reactor core material may lead to as many as 50,000 to 100,000 cancer fatalities worldwide over the next 50 years (see, for instance, Hohenemser 1988 and Chernousenko 1991). Since these fatalities are spread over such a long time period, the projected cancer fatalities are expected to exceed normal cancer fatalities by more than 1% only for the evacuees from the vicinity of Chernobyl. For non-Soviet Europe the projected increase in the cancer fatalities is only about 0.1%.

Since the accident, the stricken reactor has been encased in a concrete shell, which is cracking. A new containment shell is to be constructed. A second reactor was shut down after a fire in 1991. The other two 1,000-megawatt reactors at the site are still in operation at the center of a restricted zone roughly 30 kilometers in radius, which is managed by the Pripet Research Industrial Association (PRIA). The zone will probably require special management for 100–150 years. PRIA employees live outside the zone, but about one thousand people have returned to live inside the zone, mostly pensioners who expect the health risks of Chernobyl to matter less in old age.

About one million cubic meters of soil have been scraped up and placed in some six hundred trenches. Hundreds of artesian wells have been drilled to replace the contaminated water supply of a large part of the area (Ausubel 1991). Pulses of heavy metals and radionuclides have washed down through the Dnieper River basin, where tens of millions of people obtain their drinking water. The major ecological problem during the next few years will probably be due to the presence of radionuclides—particularly strontium, cesium, and plutonium—in the soil.

The events leading up to the Chernobyl accident involved a dramatic sequence of faulty judgments and arrogance on the part of the operators. It was also a consequence of deliberately overriding safety devices and procedures. As a result, the scale of the accident was equal to "worst case" projections for pressurized water reactors. Since the design of the Chernobyl reactor differed substantially from that of Western LWRs, the accident says little about the likelihood of a Chernobyl-scale accident in the United States.

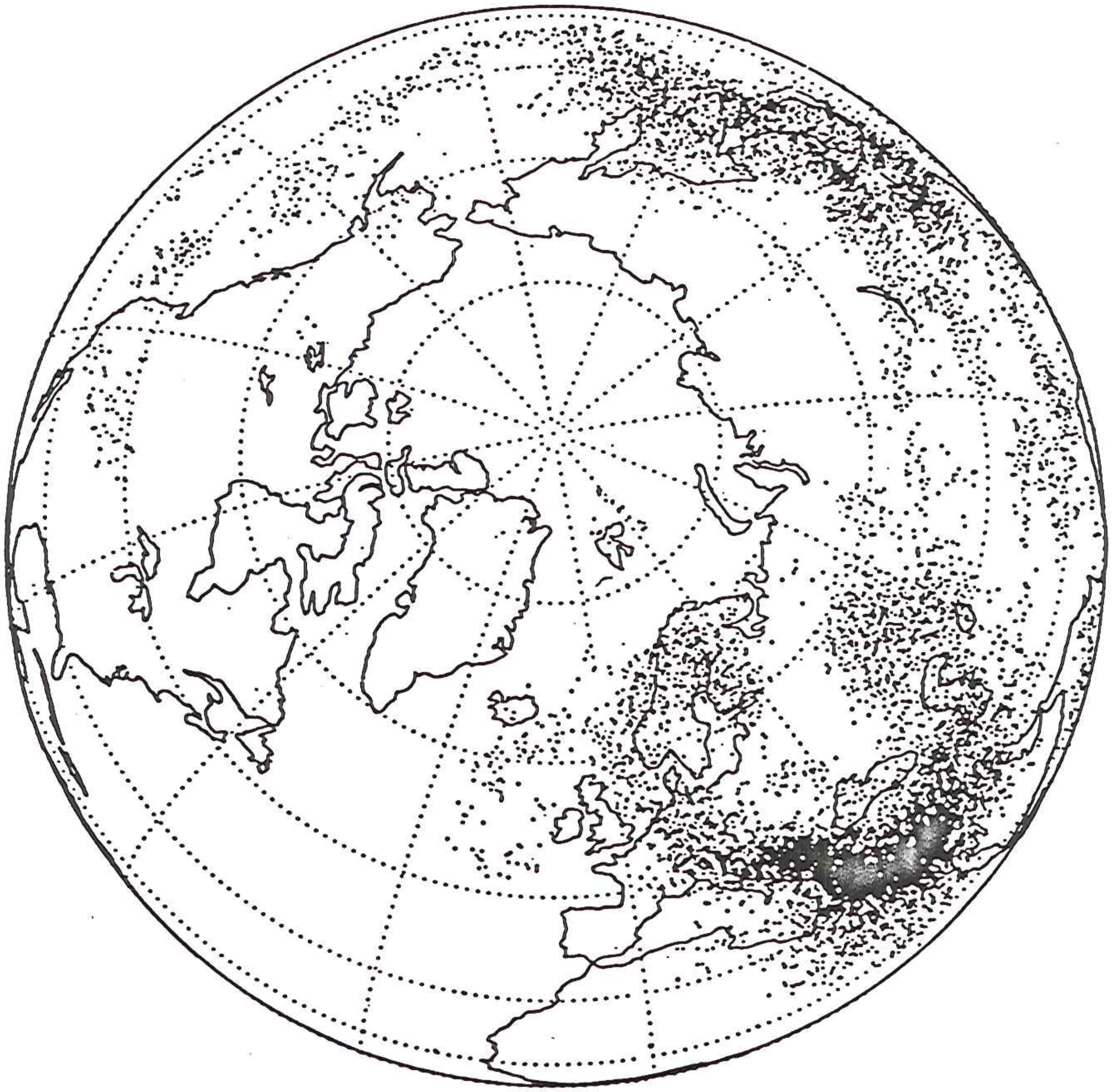


Figure 11.36. Calculated spatial distribution of radioactivity over the Northern Hemisphere 10 days after the Chernobyl accident, as illustrated by the Lawrence Livermore National Laboratory. (Lange, Dickerson, and Gudiksen 1988).

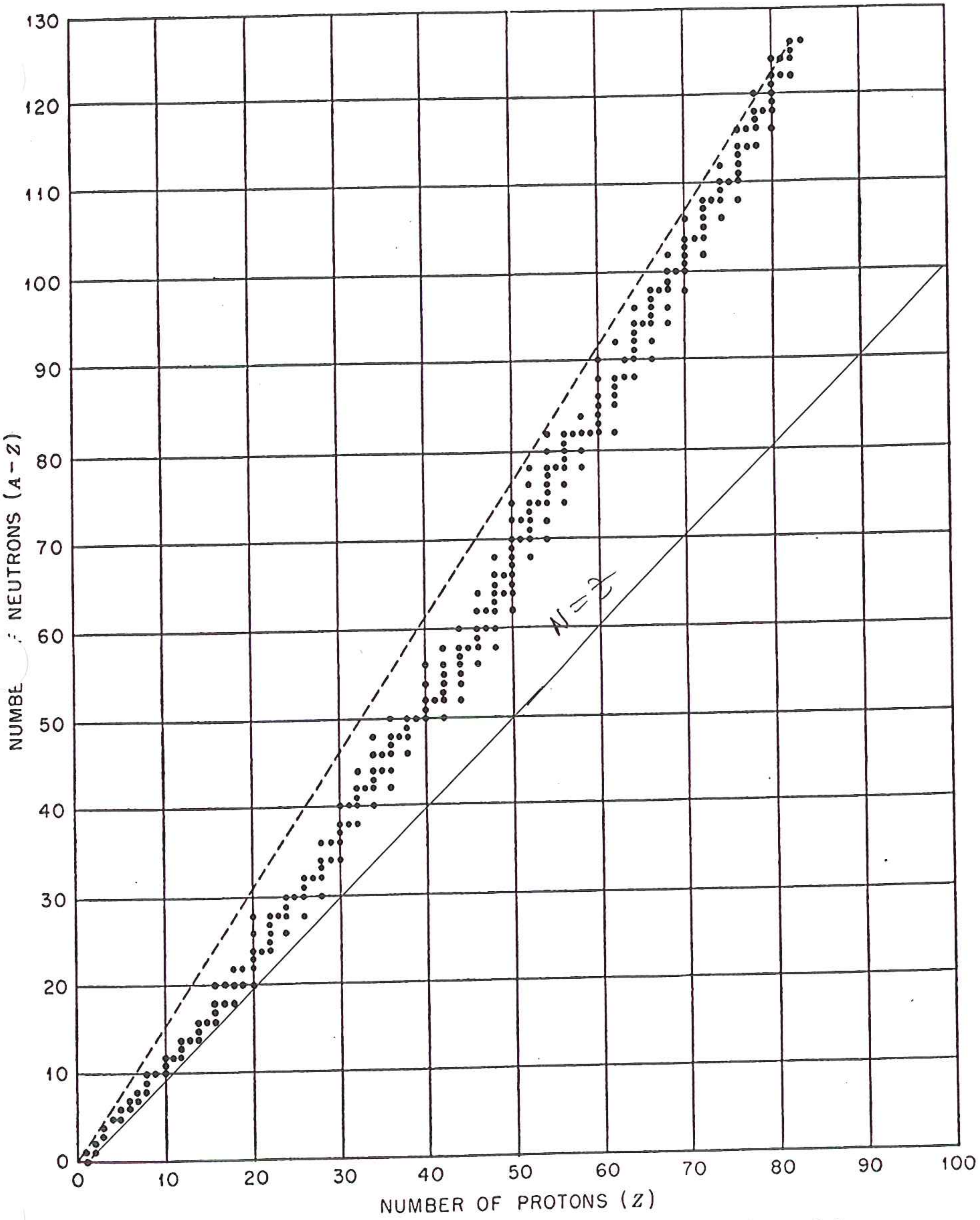


FIG. 1.15. Numbers of neutrons and protons in stable nuclei

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

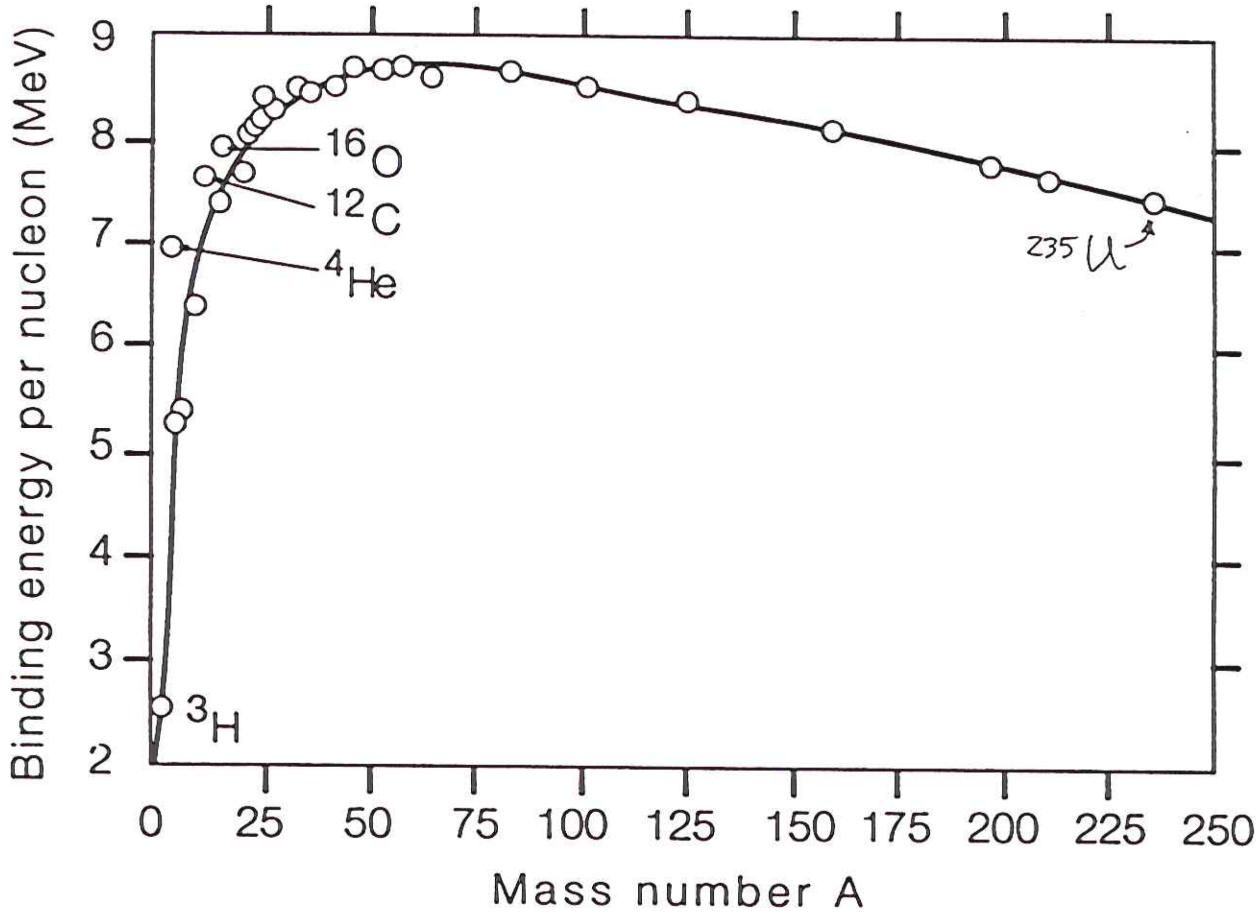
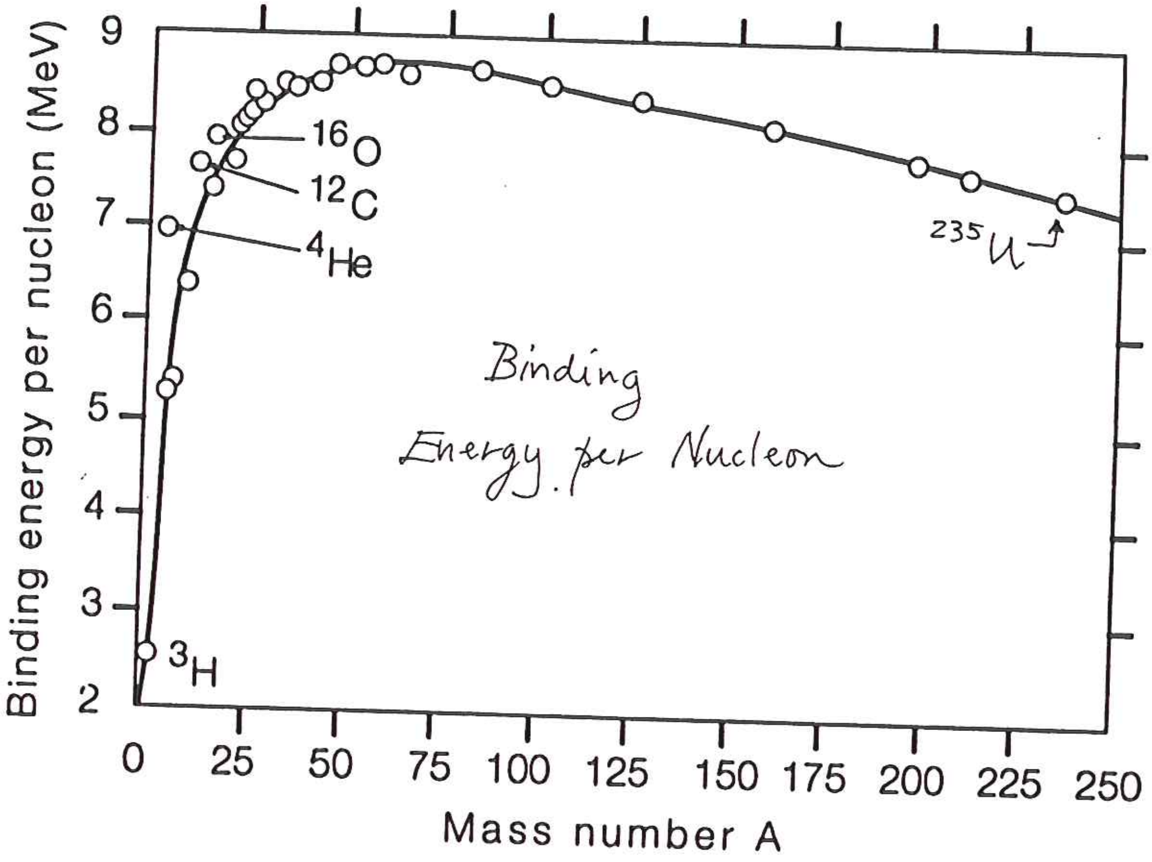


Figure 4.37 Binding energy per nucleon versus the mass number *A* for stable nuclei



Example: ^{235}U mass 235.11 amu

Mass of constituent parts:

$$\left.\begin{array}{l} 92 \text{ protons} \times 1.00758 \text{ amu} \\ 143 \text{ neutrons} \times 1.00897 \text{ amu} \\ 92 \text{ electrons} \times 5.5 \cdot 10^{-4} \text{ amu} \end{array}\right\} \text{total } 237.03 \text{ amu}$$

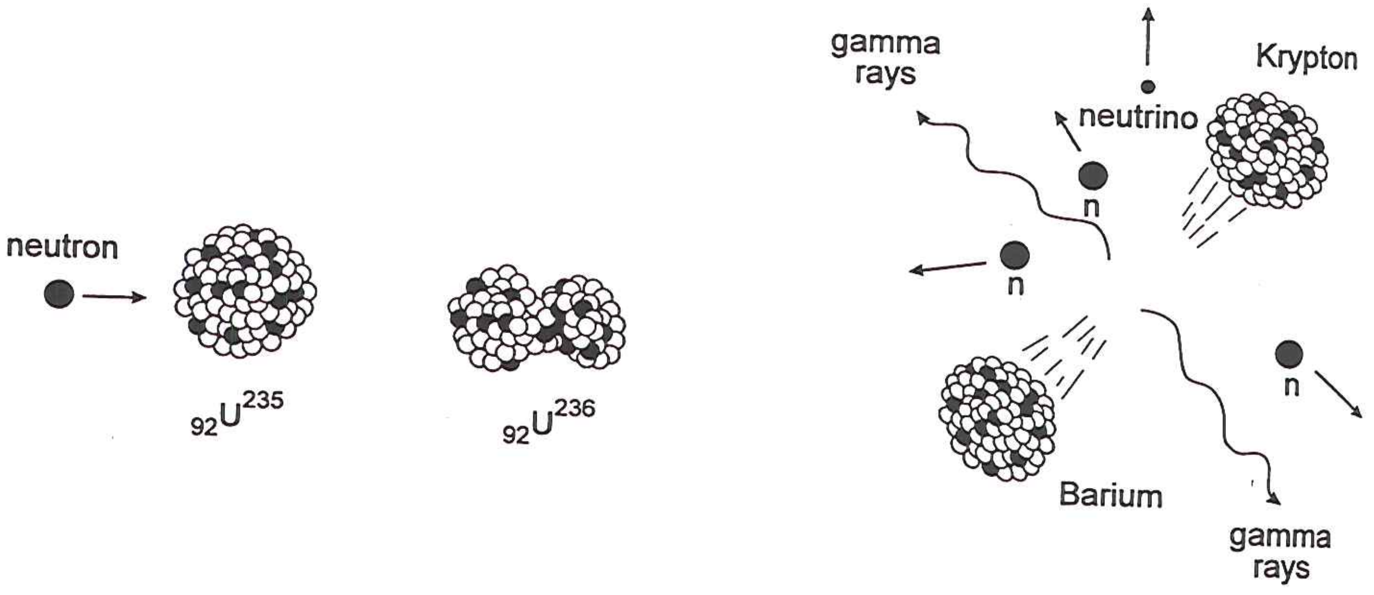
Difference — 1.92 amu — is the nuclear binding energy: holds the protons in the nucleus

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

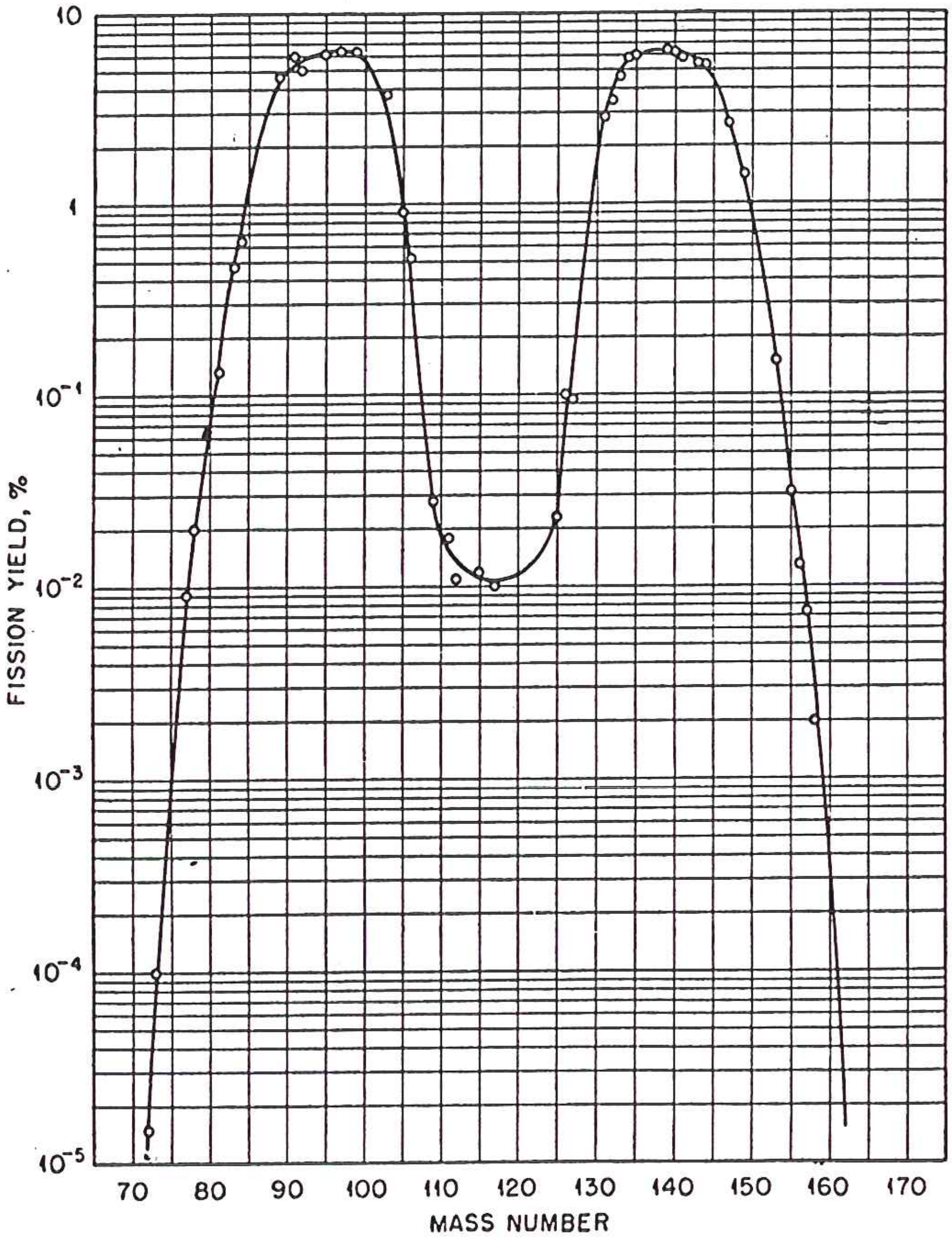
So: $(1.92 \text{ amu}) \times c^2 = 1787$ MeV

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

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.



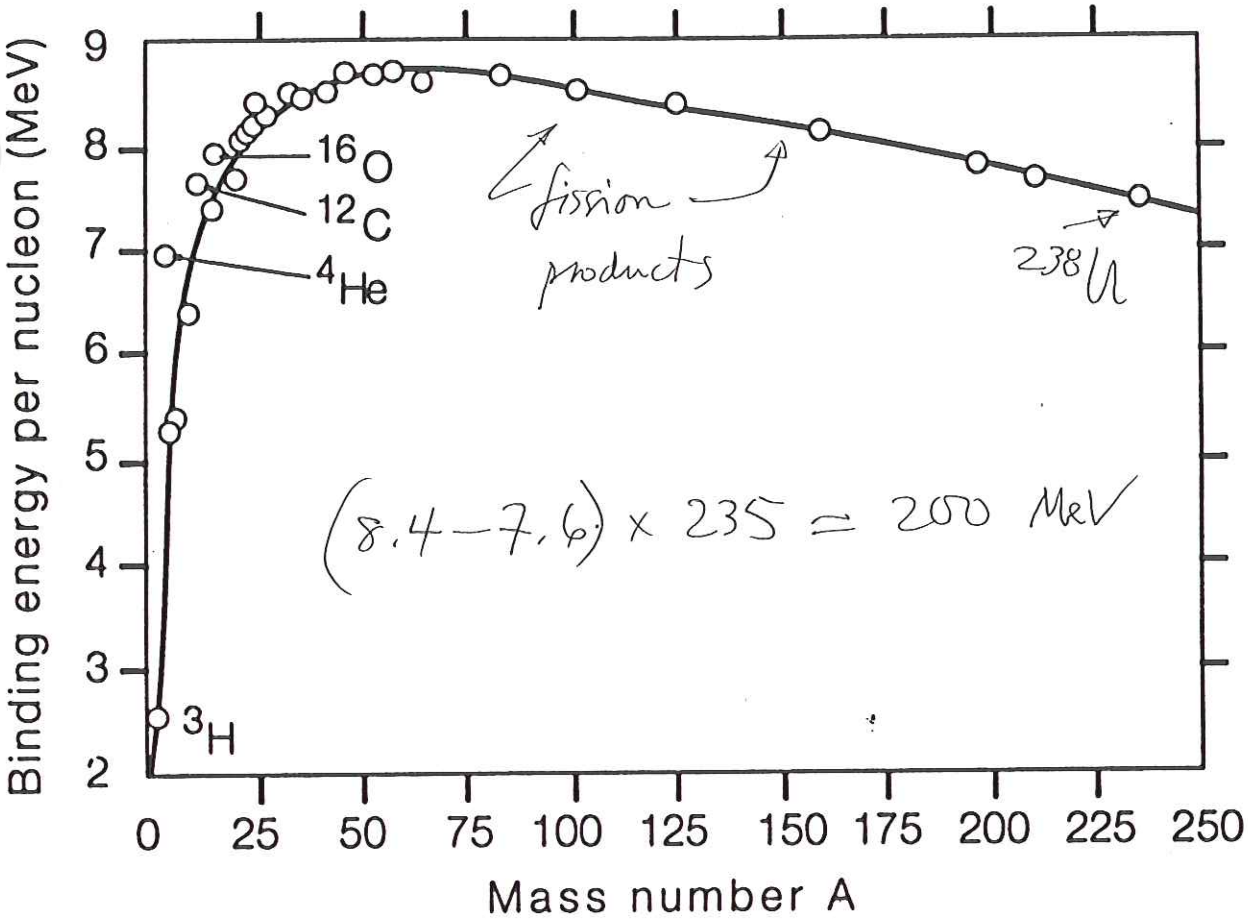
$$_on^1 + {}_{92}U^{235} \longrightarrow {}_{92}U^{236} \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_on^1 + \gamma \text{ rays} + \text{neutrinos}$$



^{92}Kr

^{141}Ba

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



$(8.4-7.6) \times 235 \simeq 200$ MeV

Fission of one ^{235}U nucleus releases about 200 MeV

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

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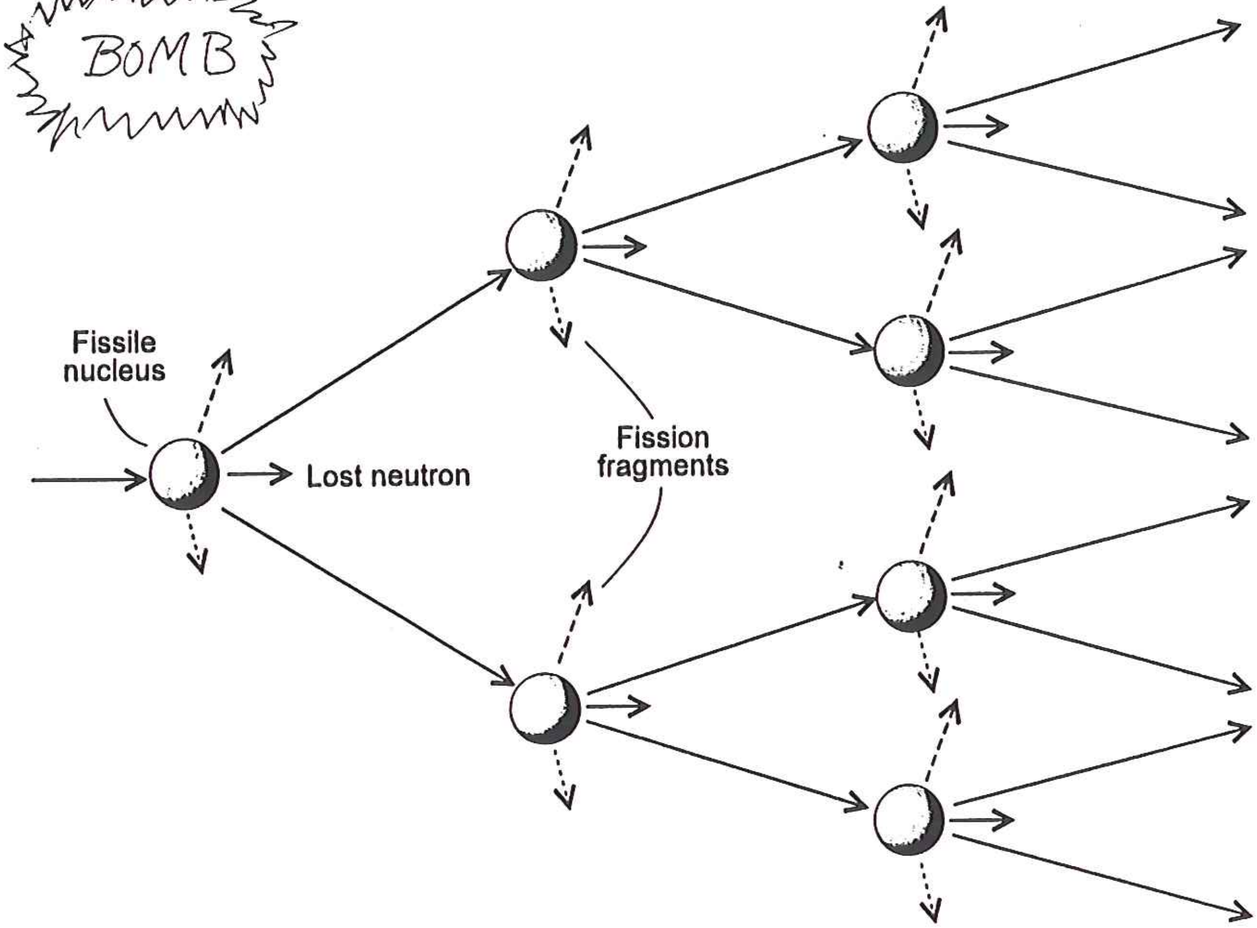
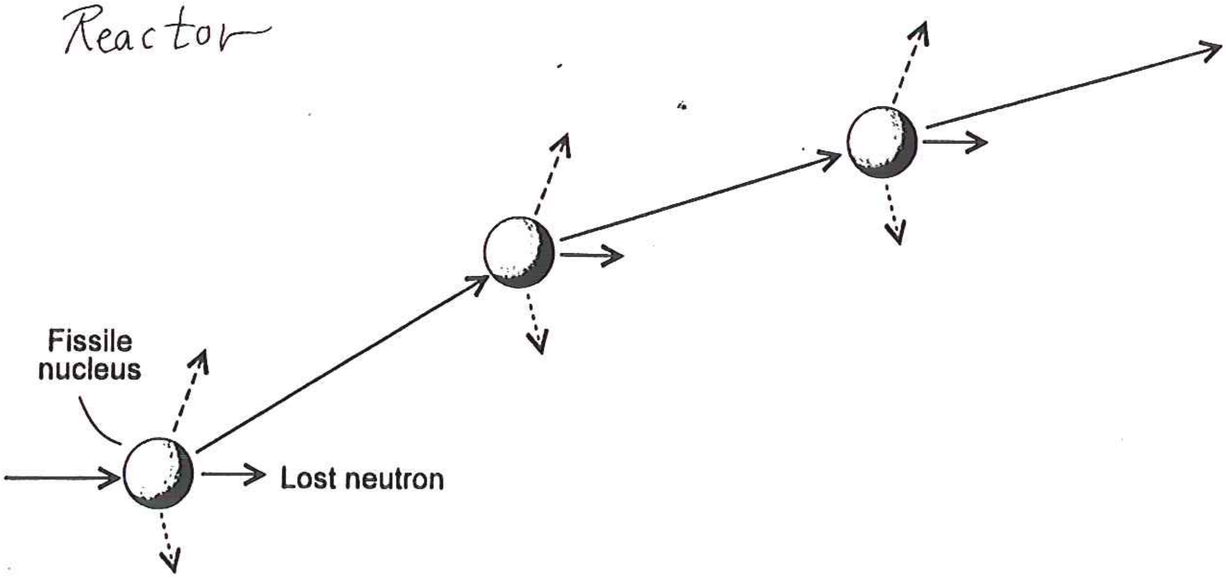
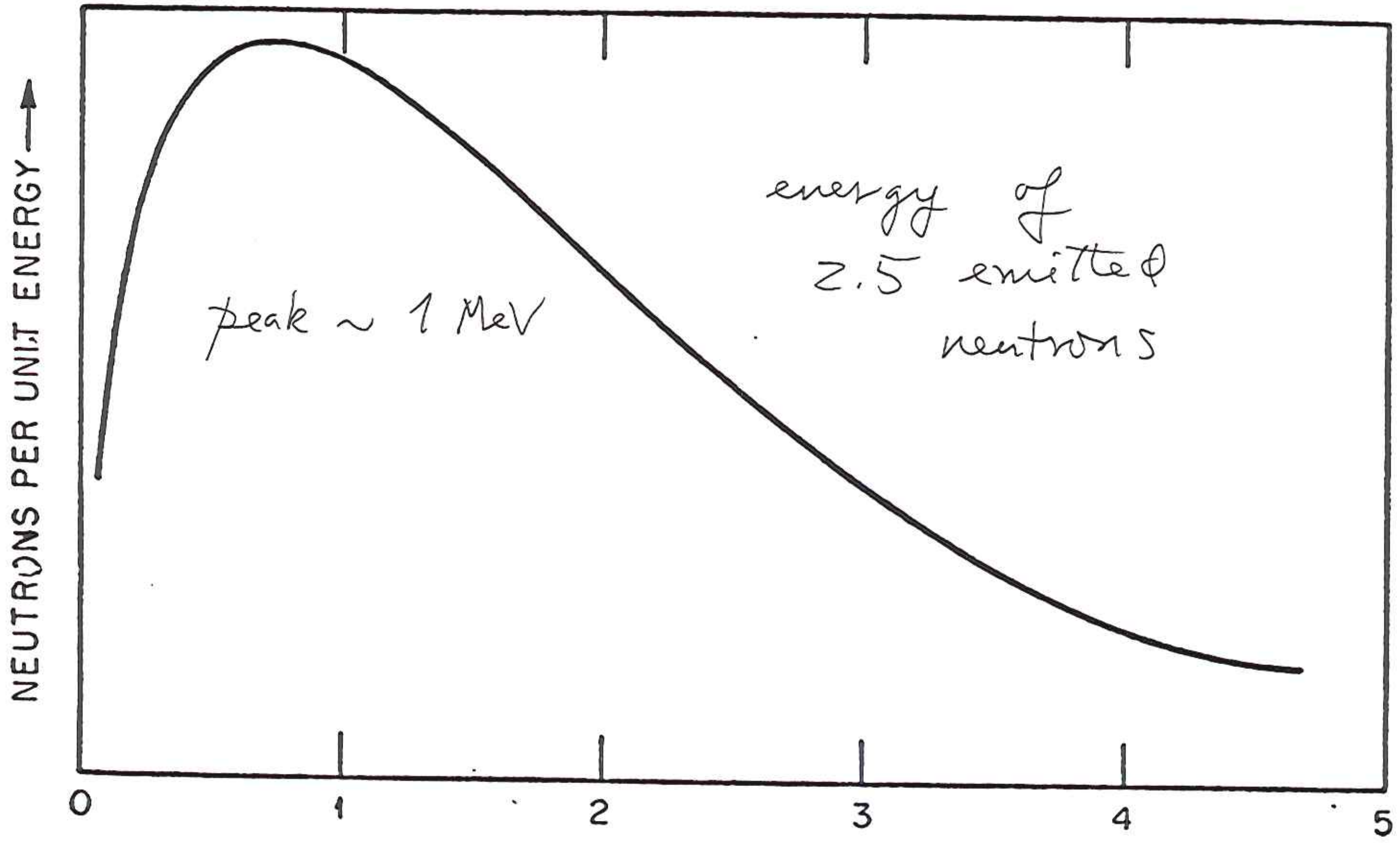


Reactor





peak ~ 1 MeV

energy of
2.5 emitted
neutrons

FIG. 4.7. Fission neutron energy spectrum

neutrons with energy less than ~ 1 MeV cannot fission ^{238}U

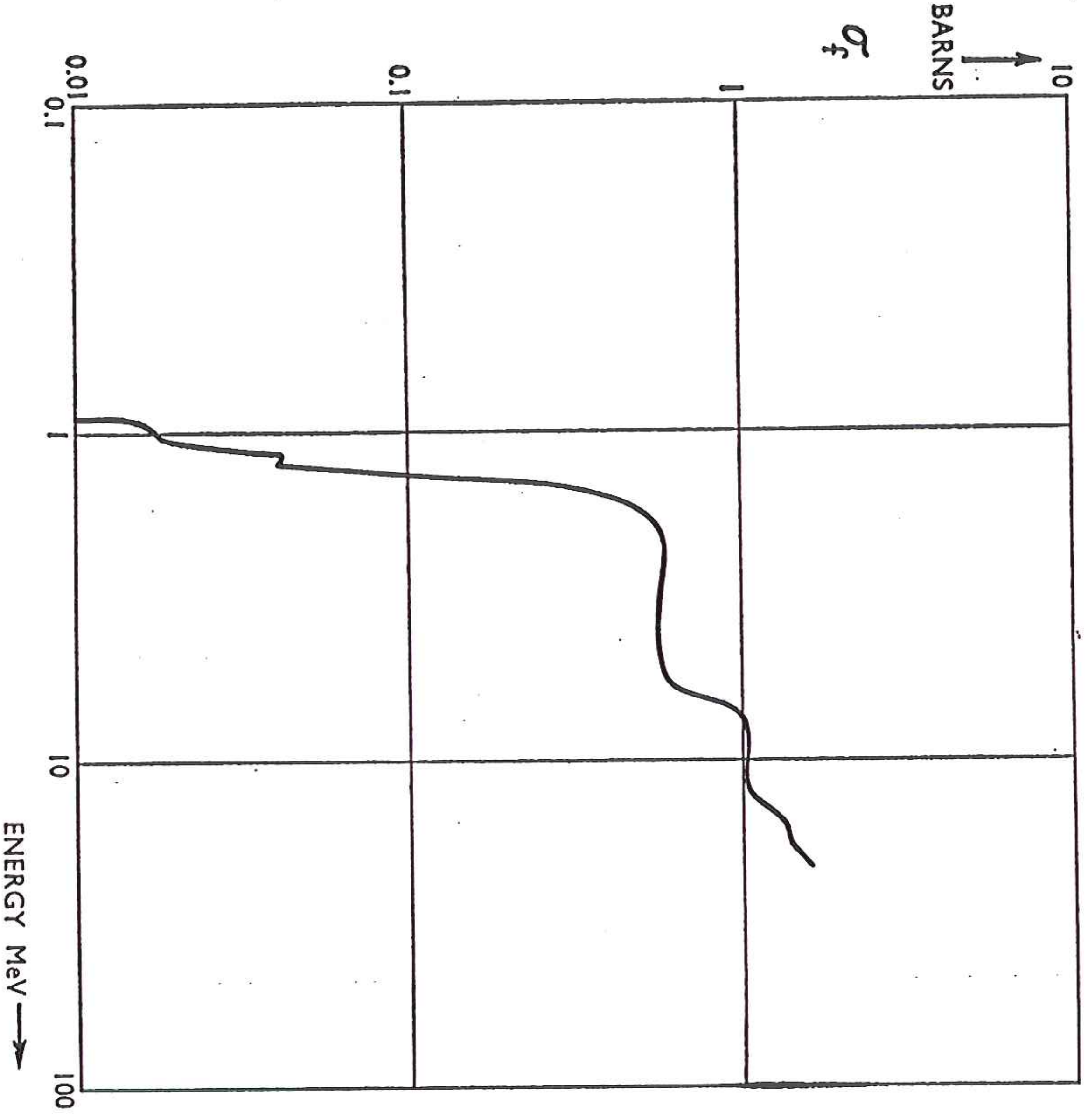


FIG. 7. Fission cross-section of U^{238}.

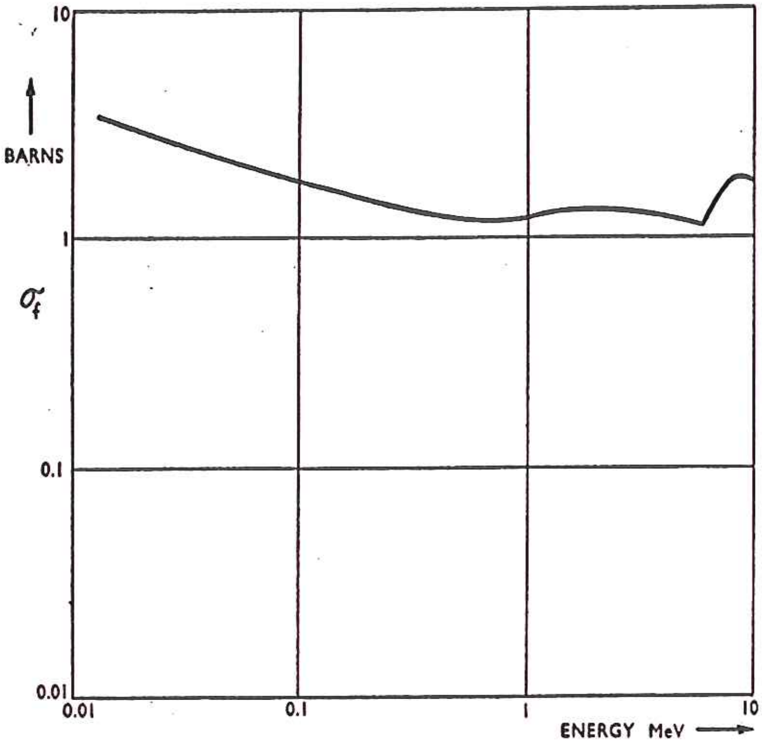


FIG. 6c. Fission cross-section of U^{235}.

fission probability of 235U much higher for slow (thermal) neutrons

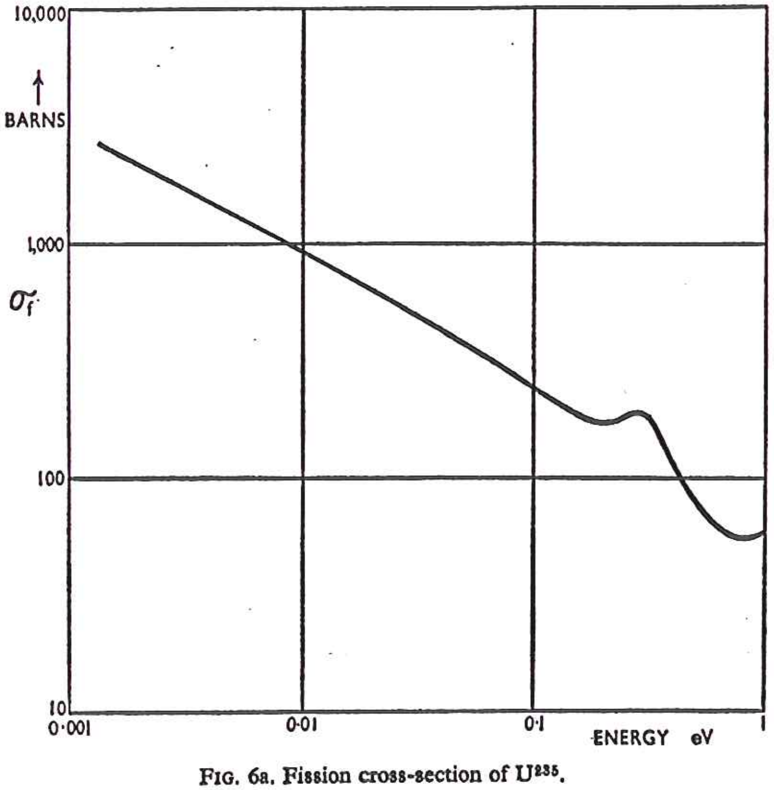


FIG. 6a. Fission cross-section of U^{235}.

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

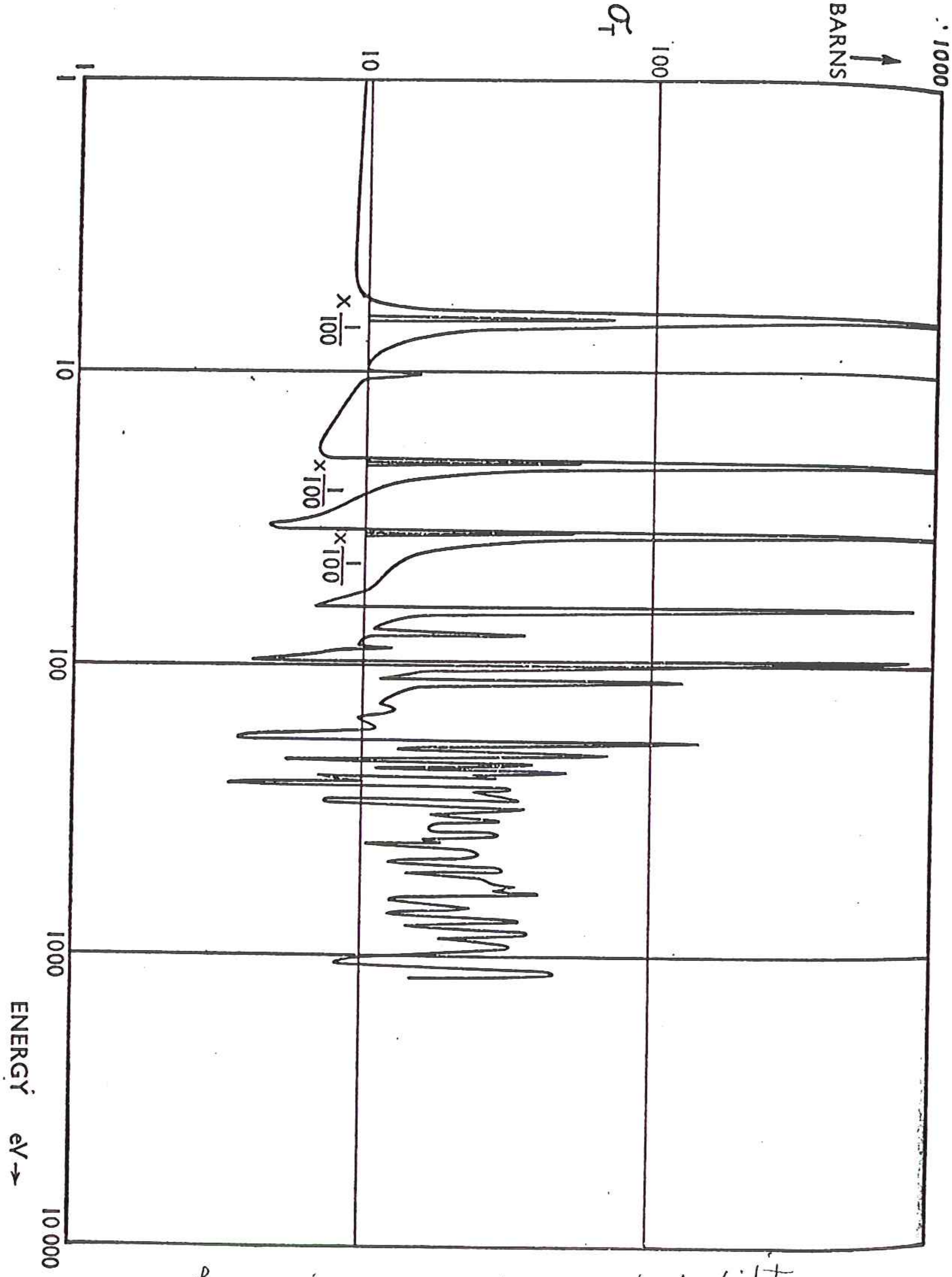


FIG. 4b. Total cross-section of U^{238}.

There is a strong probability of capture rather than fission for intermediate-energy neutrons

	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

	% 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.)

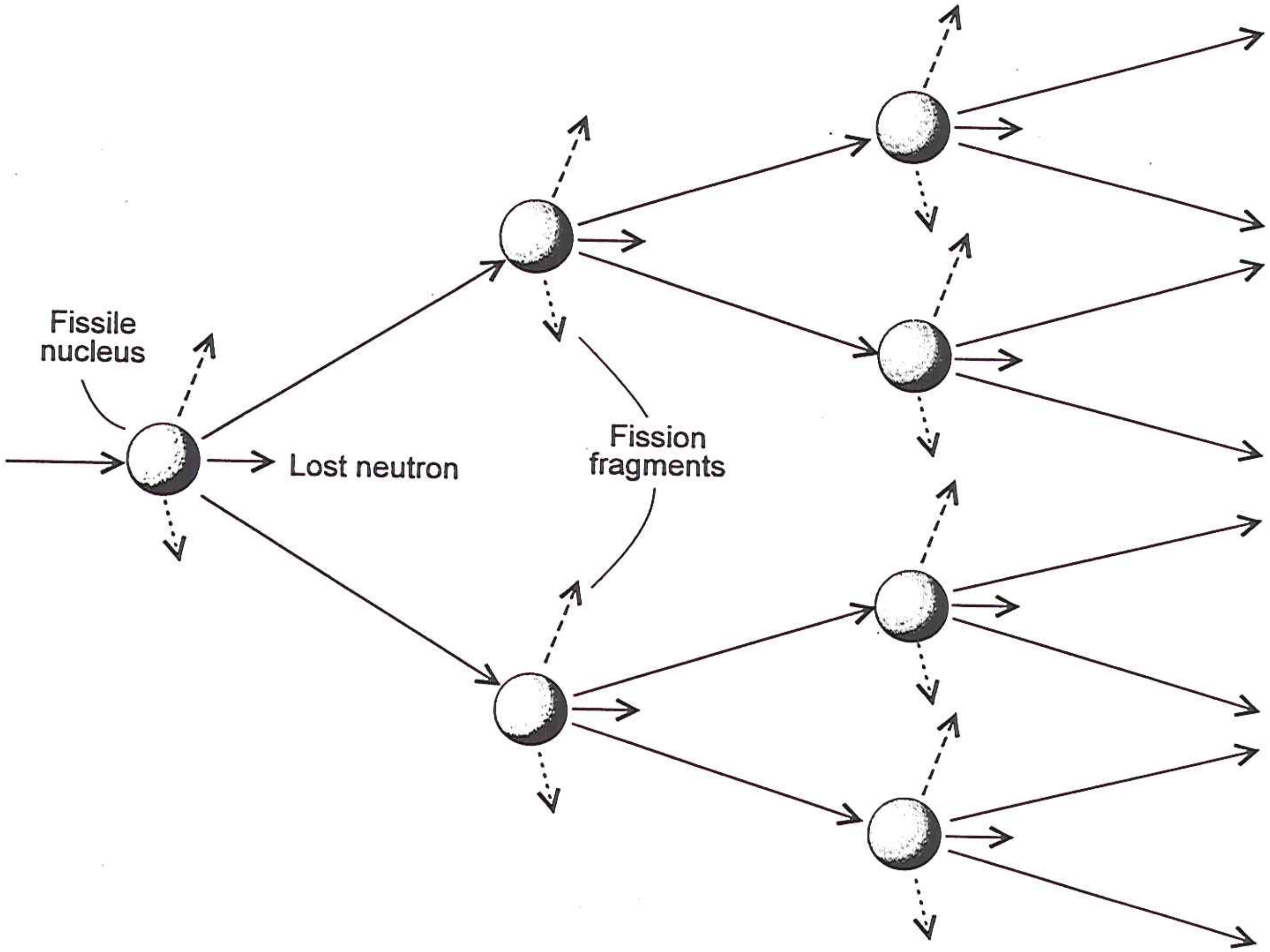


Figure 11.29. Schematic diagram illustrating a chain reaction in a fissile material.

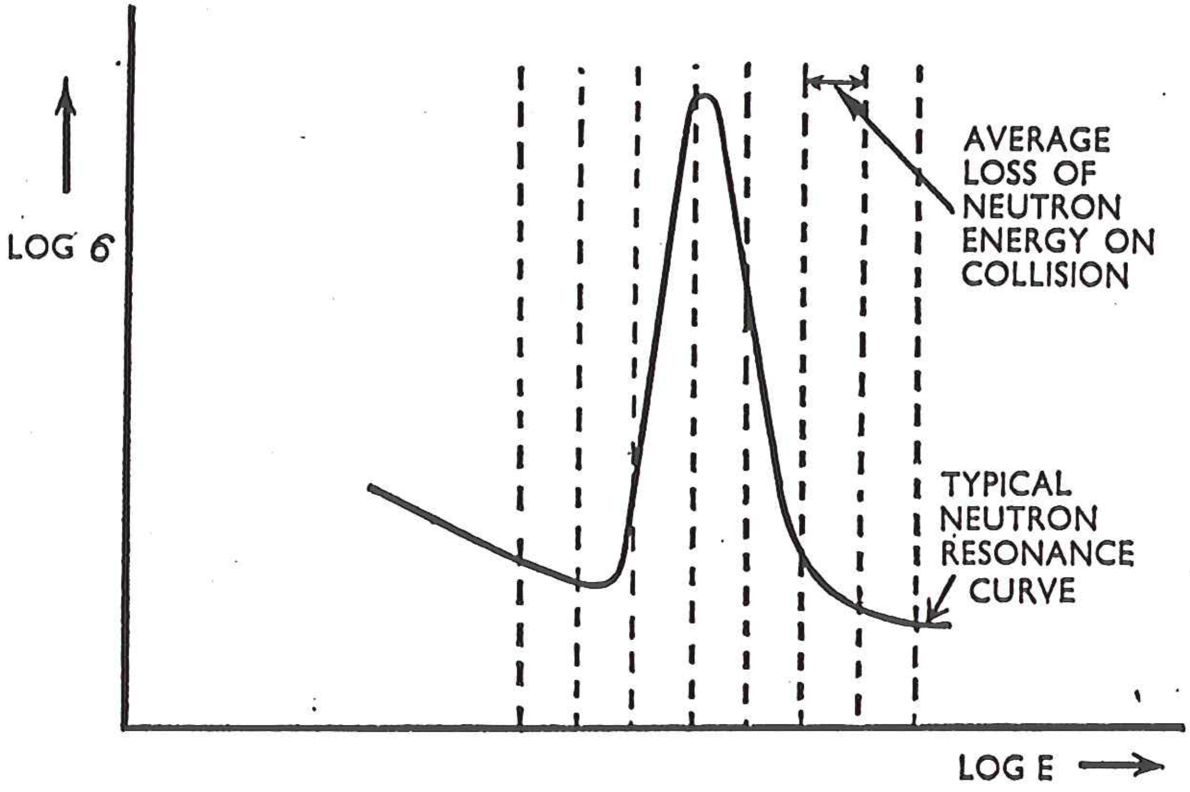


FIG. 1. Neutron capture in a uranium resonance.

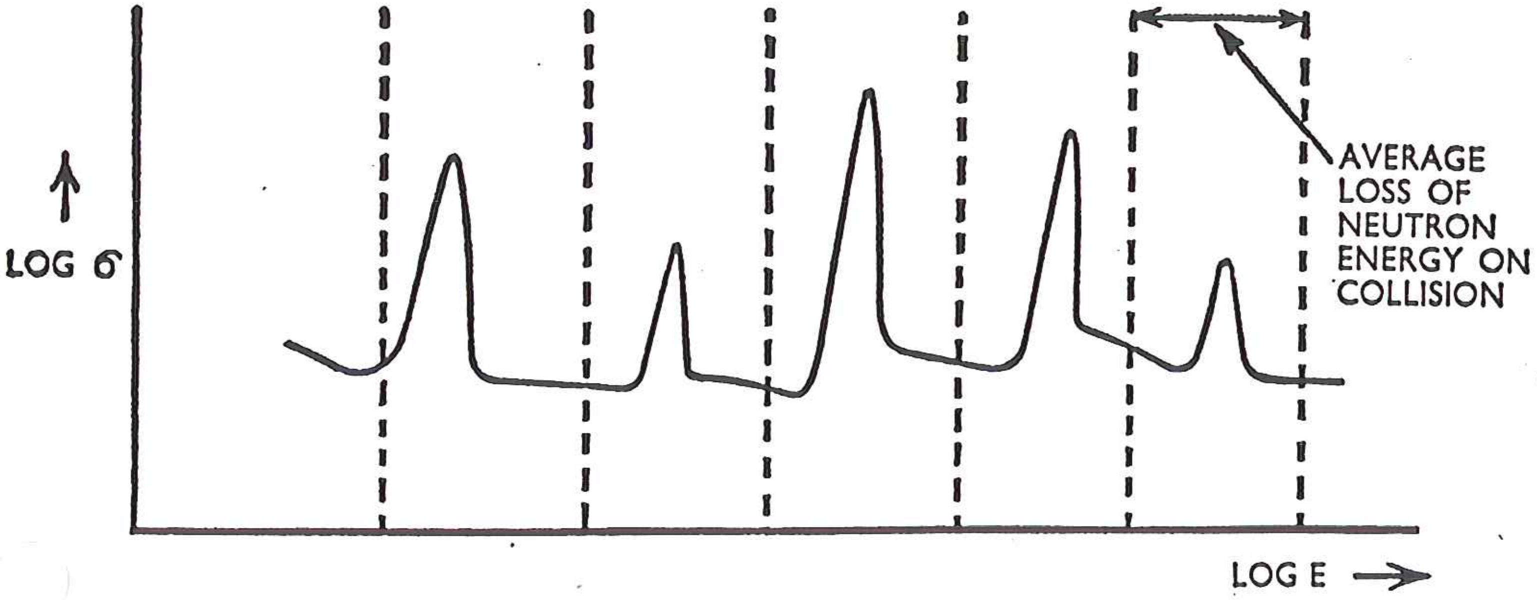


FIG. 3. Neutron scattering by light nuclei past resonances.

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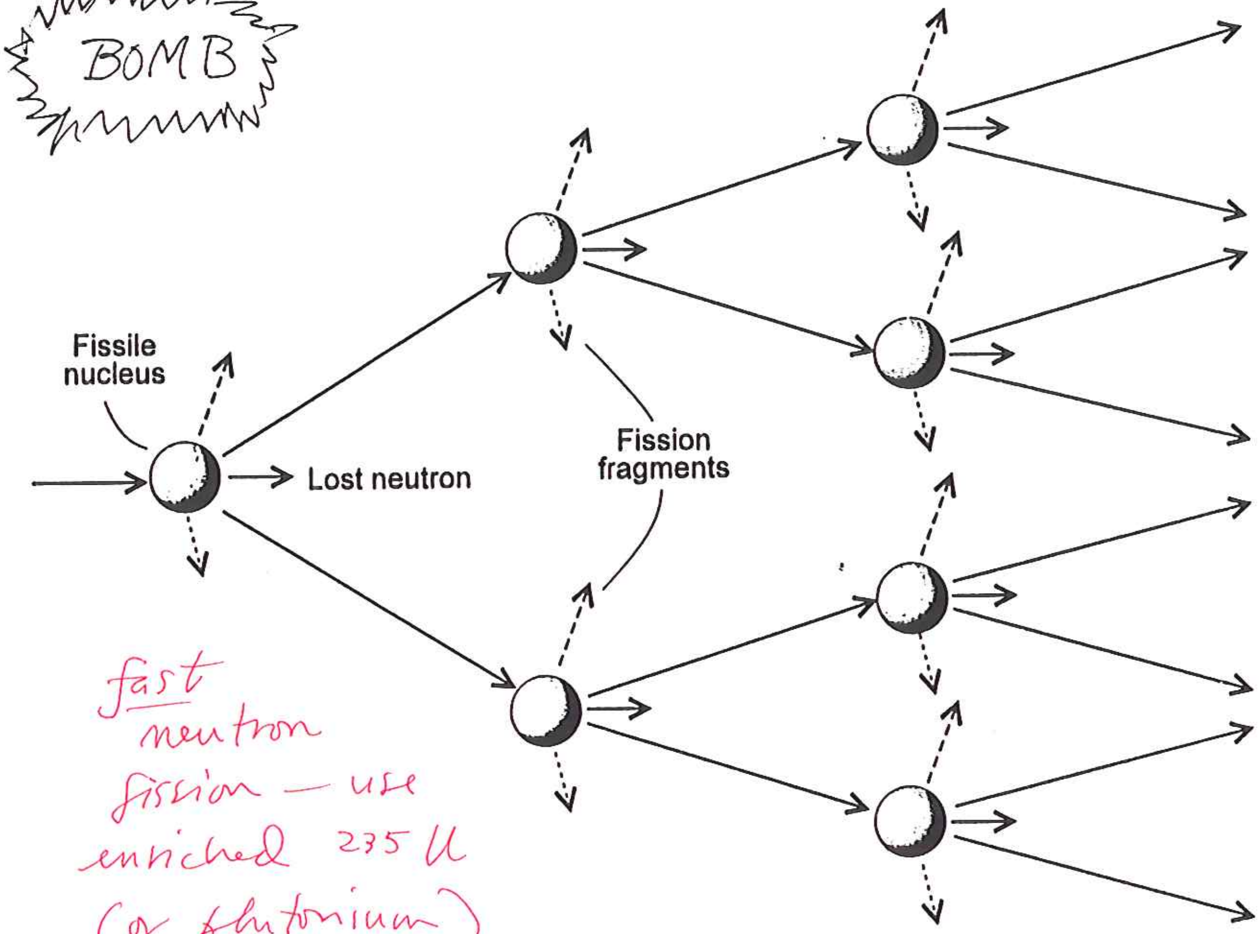
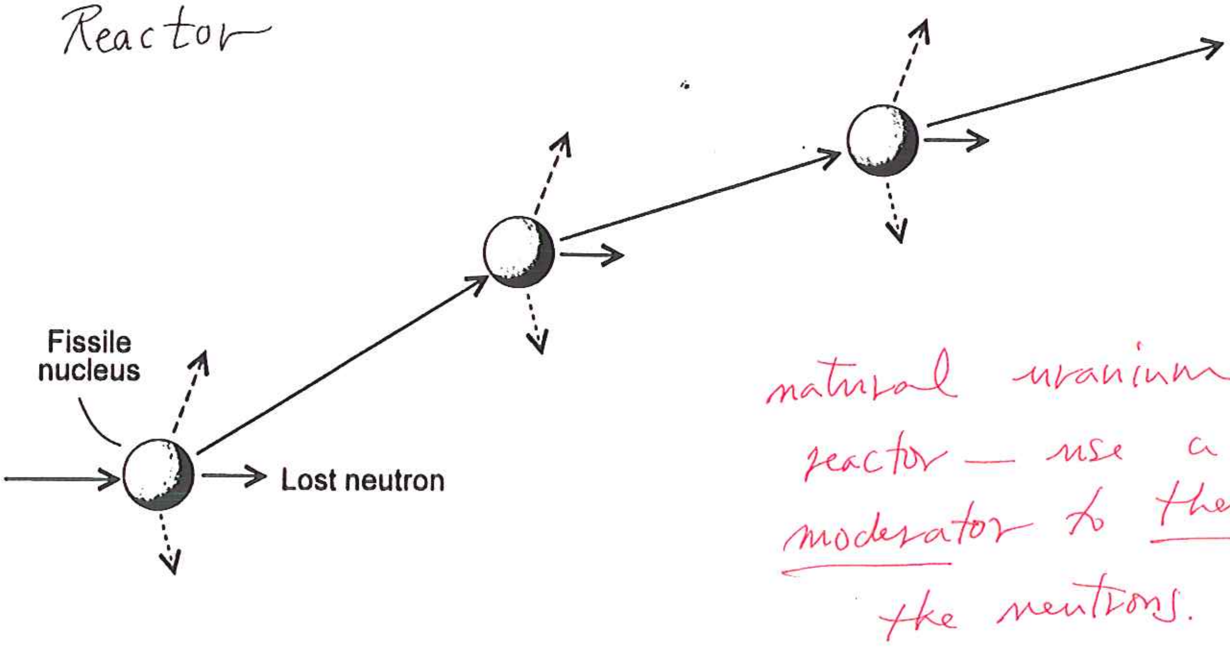


fast neutron fission — use enriched 235 U (or plutonium)

Reactor



natural uranium reactor — use a moderator to thermalize the neutrons.

Moderator	Density gm/cm^3	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	$1{\cdot}14 \times 10^{-3}$ (per molecule)	20·03	36
D_2O (99·75% by molecules)	1·10	$2{\cdot}8 \times 10^{-3}$ (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	$4{\cdot}5 \times 10^{-3}$	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)

Useful moderator properties

- light — N_s small
- low capture cross-section

boron — very high capture cross-section —
used for control rods

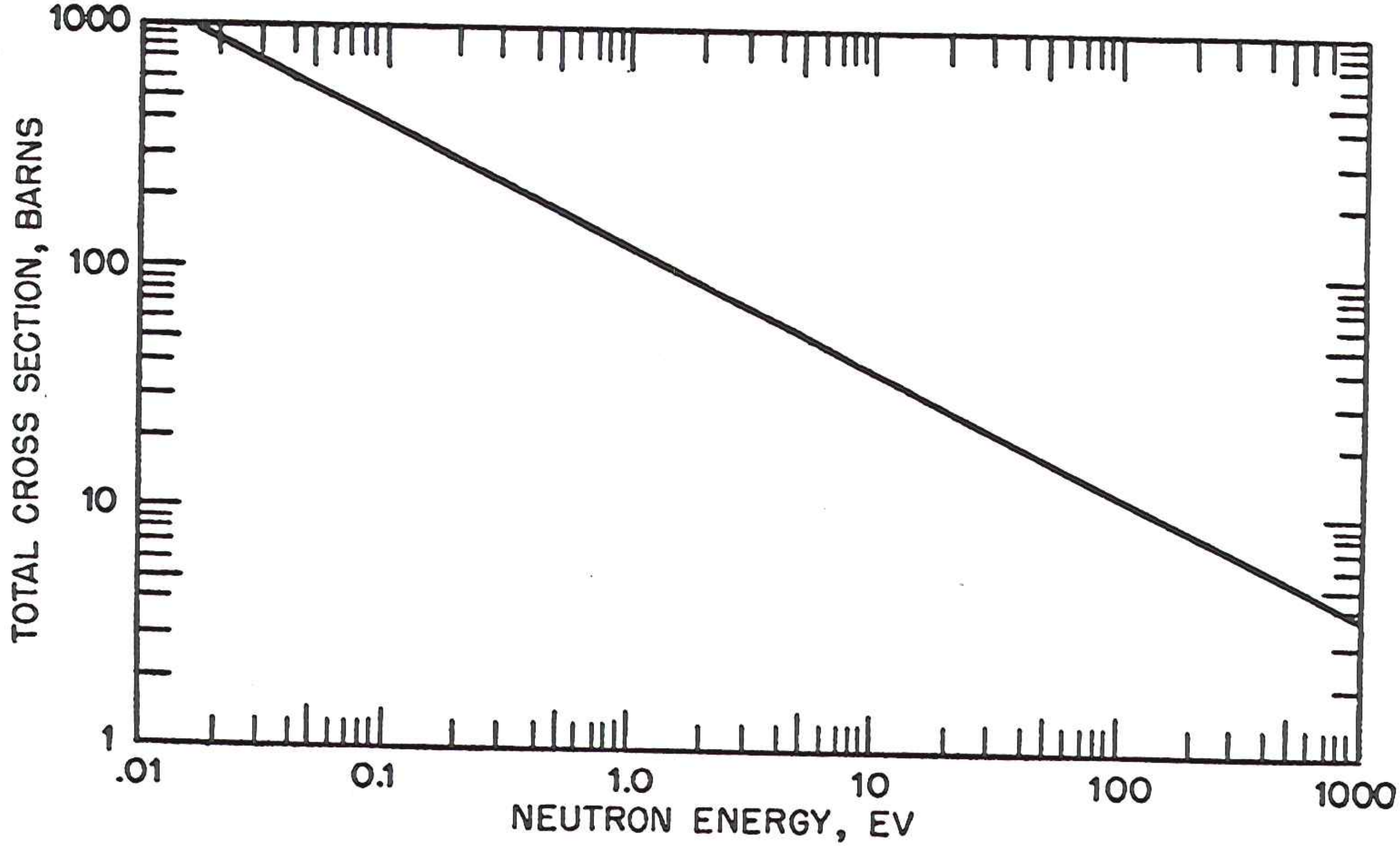


FIG. 3.76. Cross section of boron as function of neutron energy

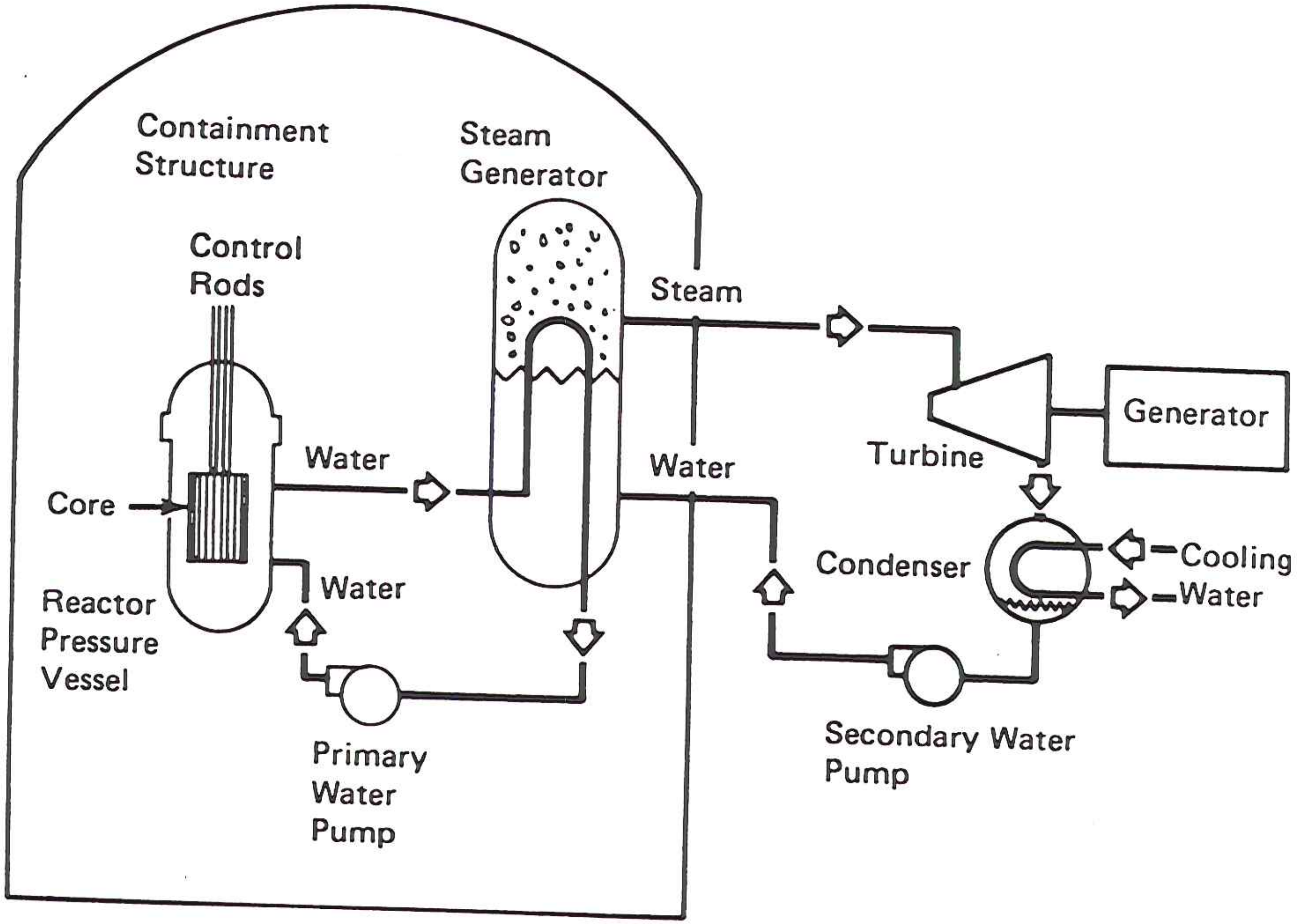


Figure 11.31. Schematic diagram of a pressurized water reactor (PWR) power system. (Nuclear Energy Policy Study Group 1977)

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.

Number of fast neutrons released per slow neutron absorbed by natural uranium (0.7% ^{235}U):

$$\eta = \frac{0.007\ \sigma_f(235)}{0.007\ \sigma_{f+c}(235) + 0.993\ \sigma_c(238)} \times 2.5 = 1.33$$

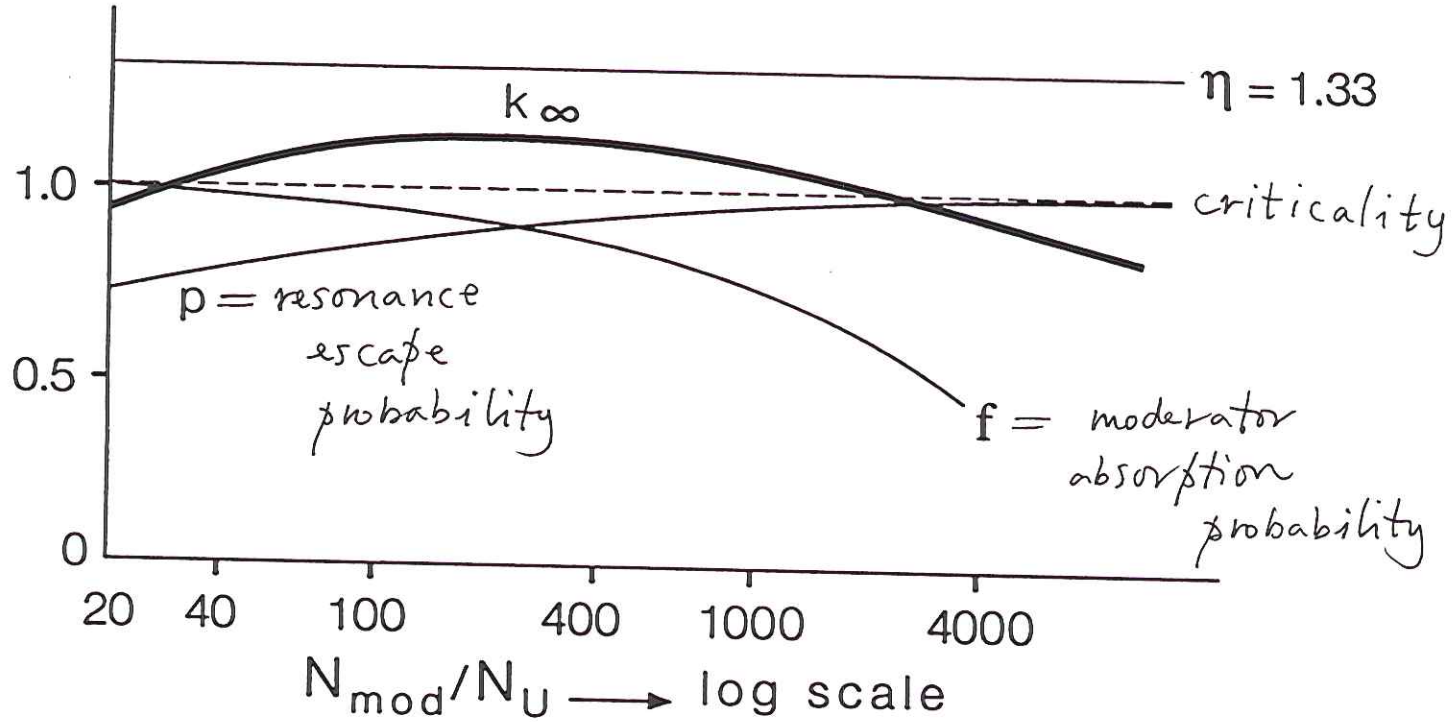


Figure 4.40 Reactor physical parameters for natural uranium as a fuel and D_2O as a moderator. Horizontally one finds the ratio of their atoms or molecules. (Reproduced by permission of H. van Dam/J. E. Hoogenboom from Dr J. E. Hoogenboom lecture notes, IRI, Delft, Netherlands)

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

← 130,000 tons/yr

Source: NUEXCO, 1992.

In comparison worldwide coal "production" is $3 \cdot 10^9$ tons contains ~1/2 of world's low—cost reserves

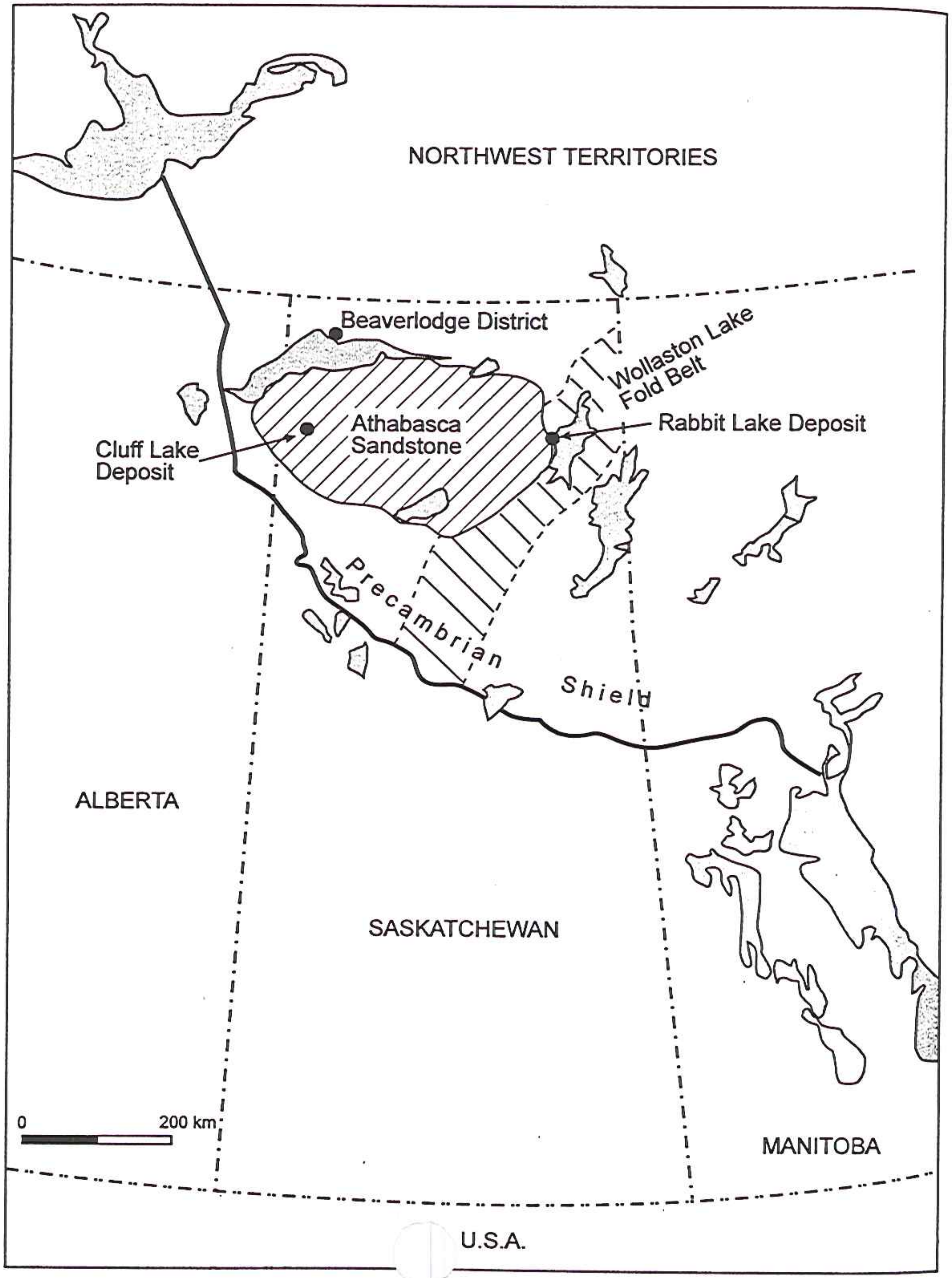
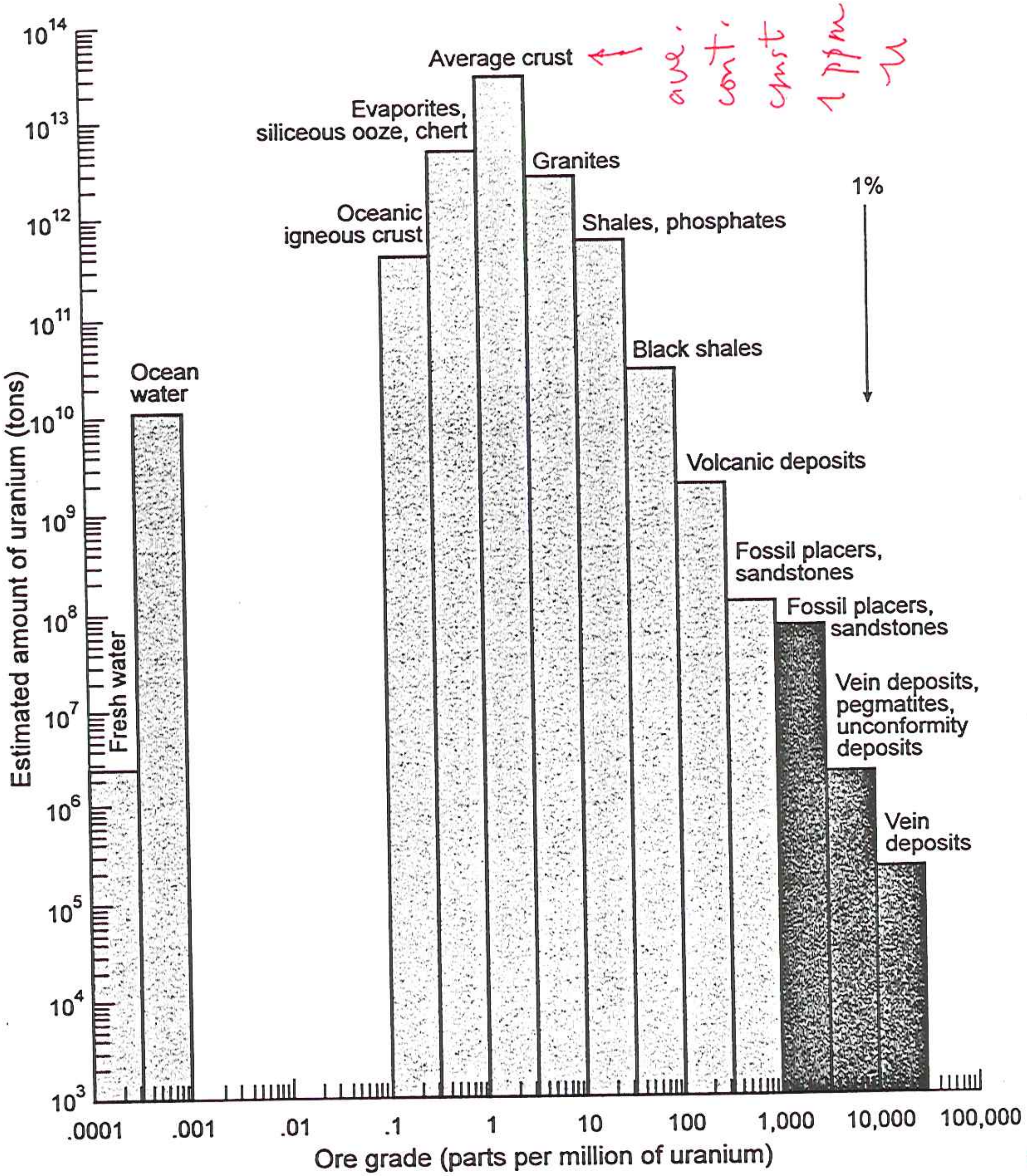


Figure 9.20. The Athabasca Basin in Saskatchewan, Canada. (Rich, Holland, and Petersen 1977)

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)



ave. cont. crust 1 ppm U

tenfold decrease in grade ⇒ thirtyfold increase in amount

high-grade only 10^{-6} of total reserves

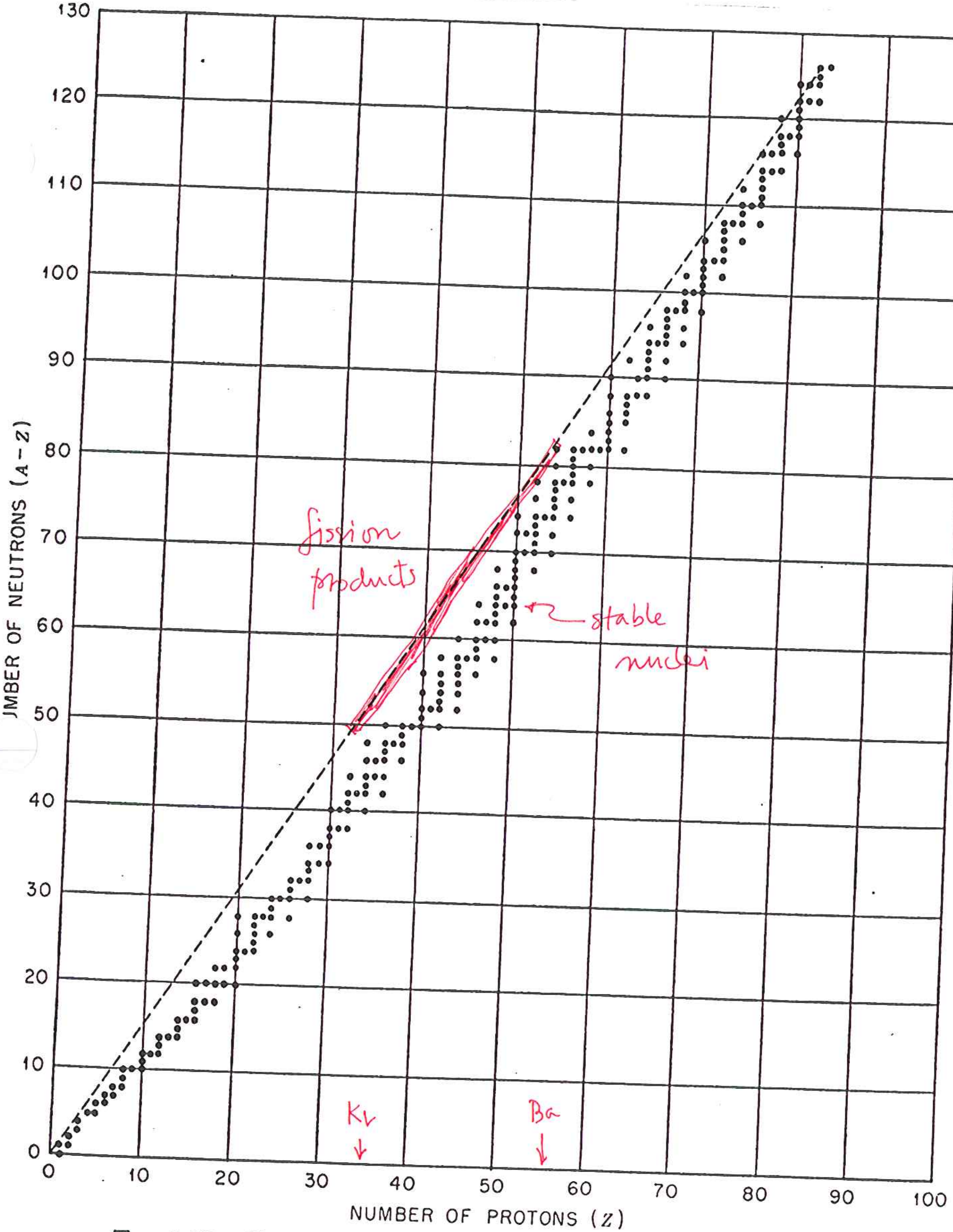
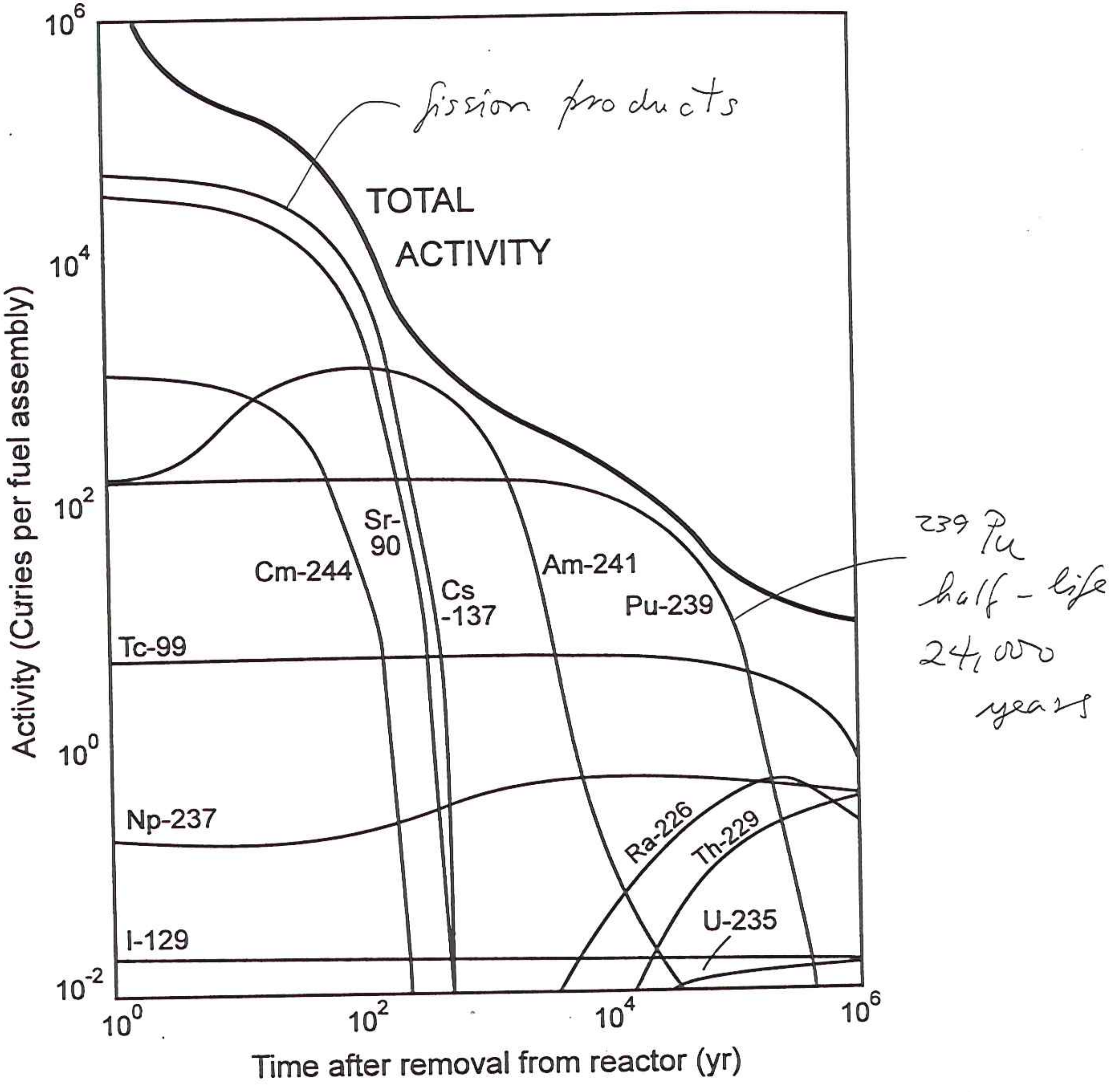


FIG. 1.15. Numbers of neutrons and protons in stable nuclei

1 Curie =
3.7·10^{10}
disintegrations/sec



fission products

239 Pu
half-life
24,000
years

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

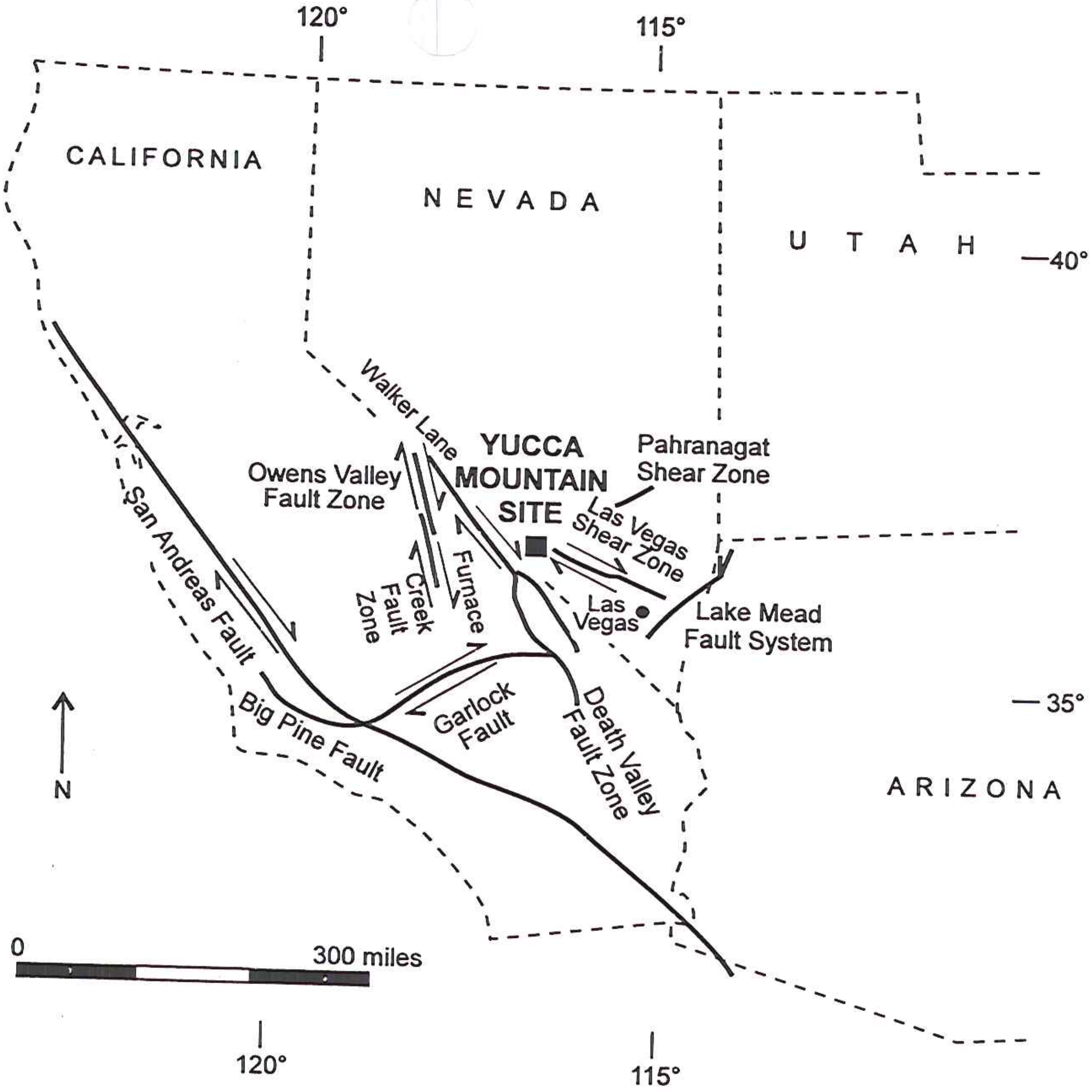


Figure 11.40. Location of Yucca Mountain, the proposed site for a permanent HLW repository in the southwestern United States. Also shown are major strike-slip faults of the southern Great Basin and vicinity. (Tien et al. 1985)

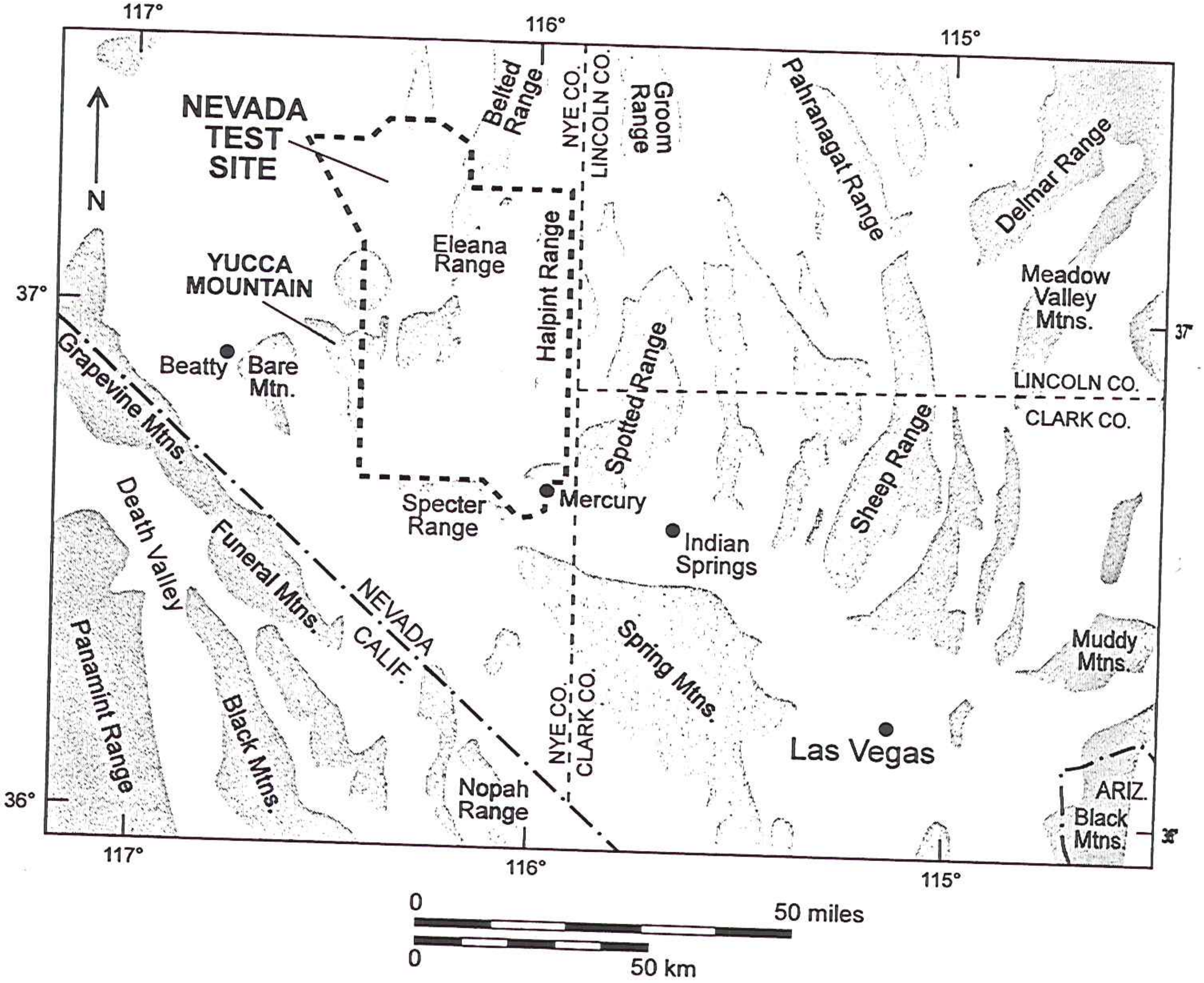


Figure 11.41. Topography of southwestern Nevada and the location of Yucca Mountain and the Nevada Test Site (NTS). Note location of Las Vegas. (Tien et al. 1985)

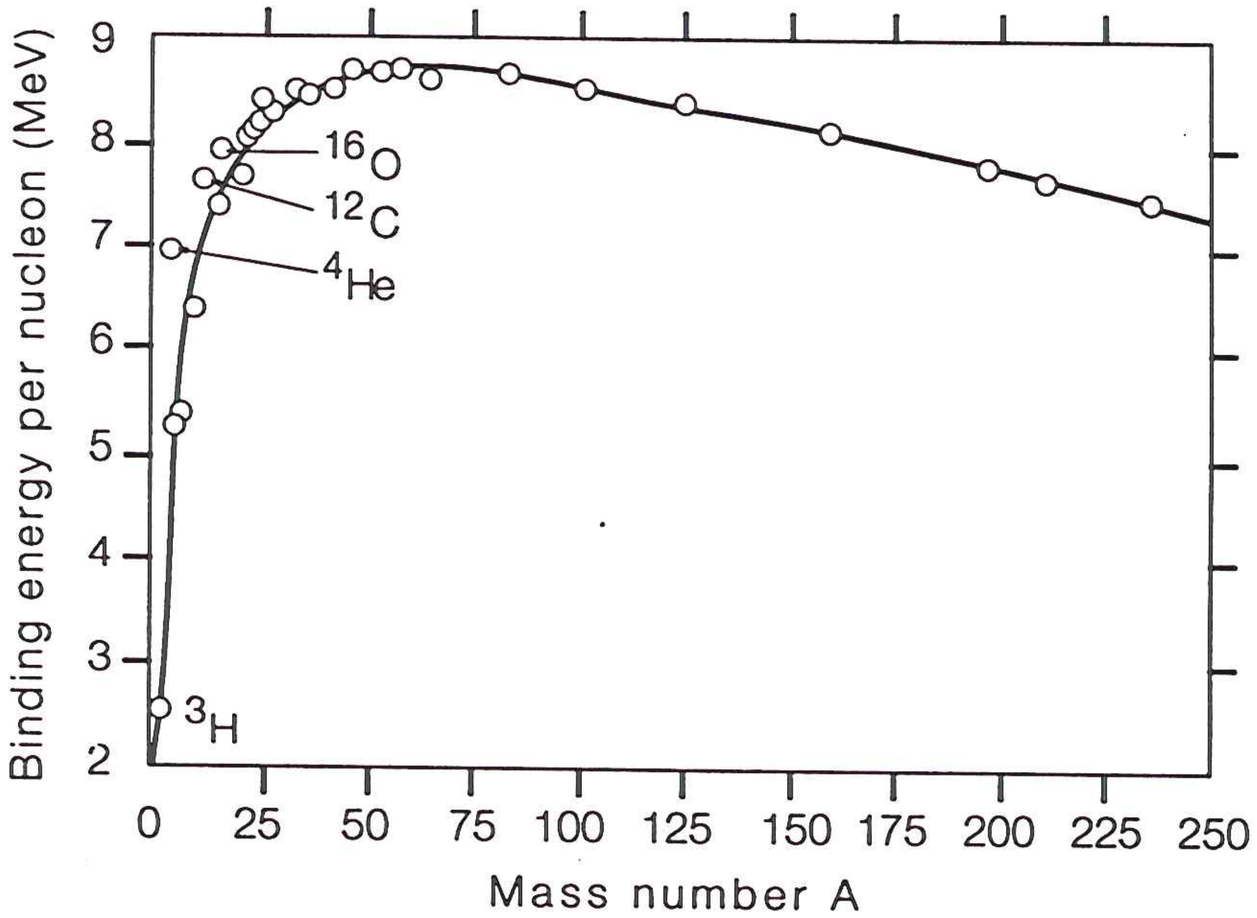


Figure 4.37 Binding energy per nucleon versus the mass number *A* for stable nuclei

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:*

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

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

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

The first reaction of this series amounts to a β^+-decay of ^2He formed by the collision of the two protons: Even though the lifetime of ^2He 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 ^3He does not react with either ^1H or ^2H, its concentration builds up until further reactions remove it as fast as it is formed. The reaction $^3He(^3He,2p)^4He$ was first suggested by C. C. Lauritsen and has been detected in the laboratory. The participation of the reactions starting with $^3He(\alpha,\gamma)^7Be$ 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 $^{2}\mathrm{D}$ and $^{3}\mathrm{T}$, although the more proper notation would have been $^{2}\mathrm{H}$ and $^{3}\mathrm{H}$.

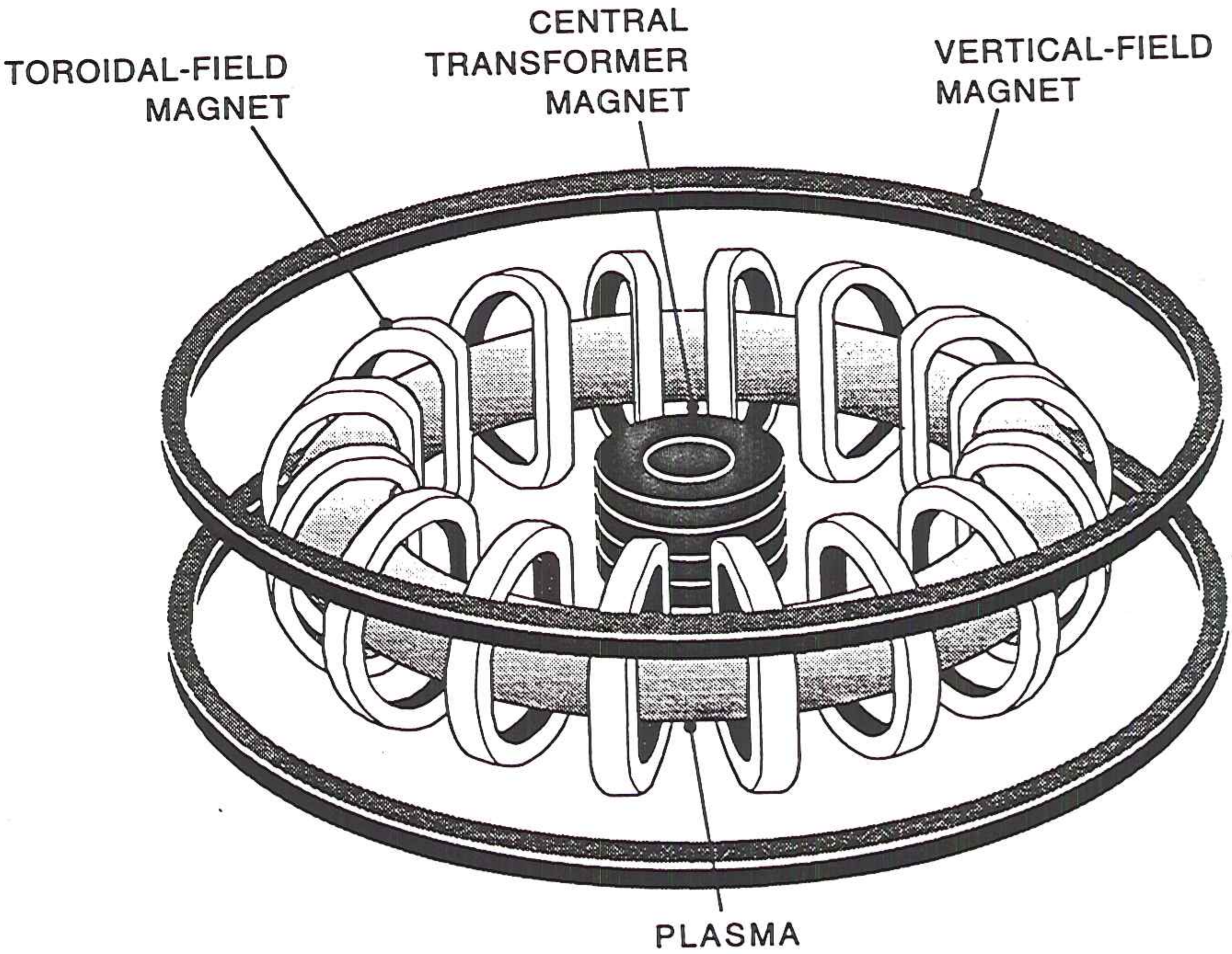
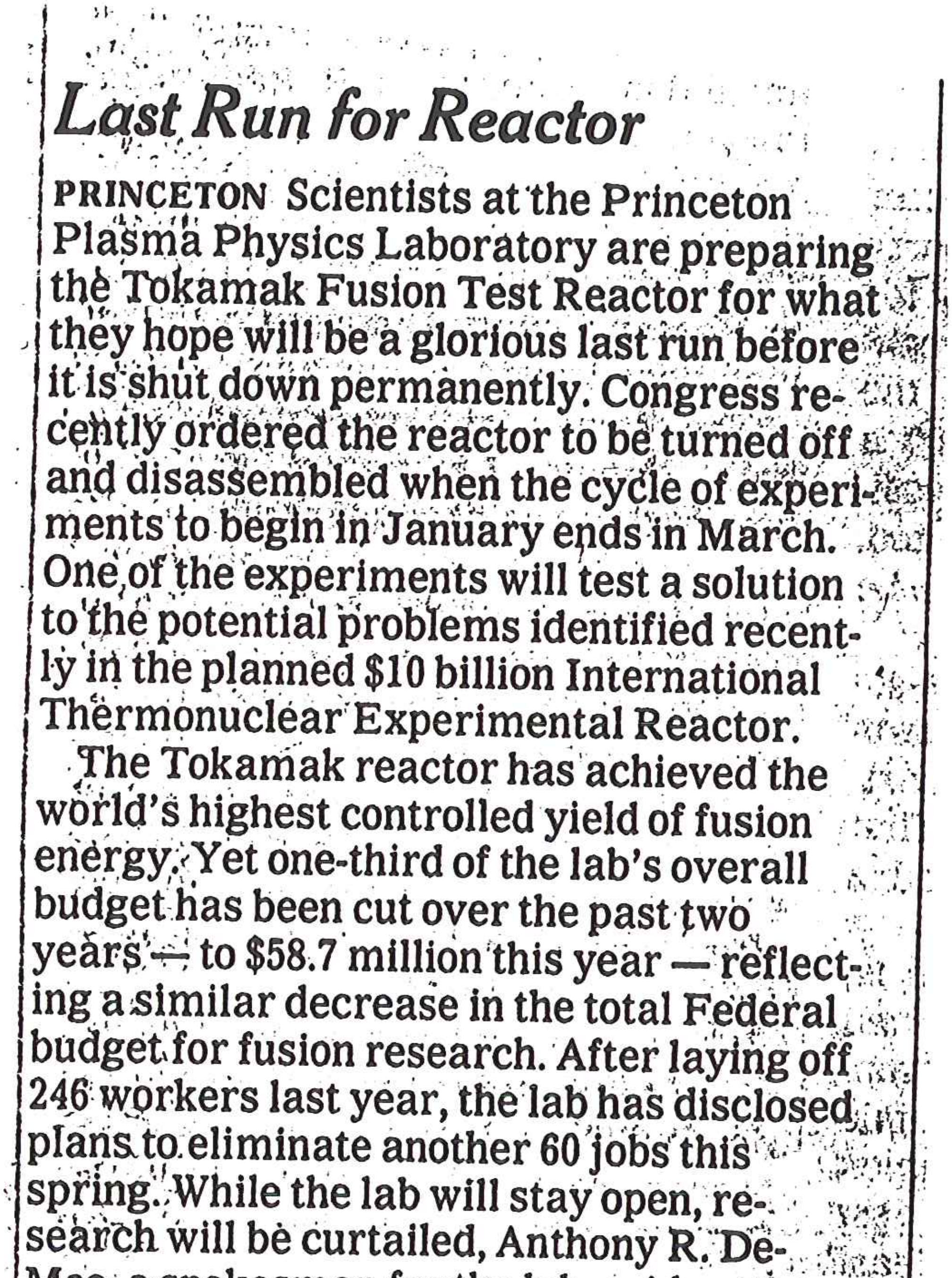


Figure 4.41 Principle of the Tokamak design. The main magnetic field is toroidal; the vertical field provides a centripetal Lorentz force by which the ions follow the main toroid. Other magnets produce induction currents that heat the plasma as far as required.



Last Run for Reactor

PRINCETON Scientists at the Princeton Plasma Physics Laboratory are preparing the Tokamak Fusion Test Reactor for what they hope will be a glorious last run before it is shut down permanently. Congress recently ordered the reactor to be turned off and disassembled when the cycle of experiments to begin in January ends in March. One of the experiments will test a solution to the potential problems identified recently in the planned $10 billion International Thermonuclear Experimental Reactor.

The Tokamak reactor has achieved the world's highest controlled yield of fusion energy. Yet one-third of the lab's overall budget has been cut over the past two years — to $58.7 million this year — reflecting a similar decrease in the total Federal budget for fusion research. After laying off 246 workers last year, the lab has disclosed plans to eliminate another 60 jobs this spring. While the lab will stay open, research will be curtailed, Anthony R. DeMeo, a spokesman for the lab, said yesterday.

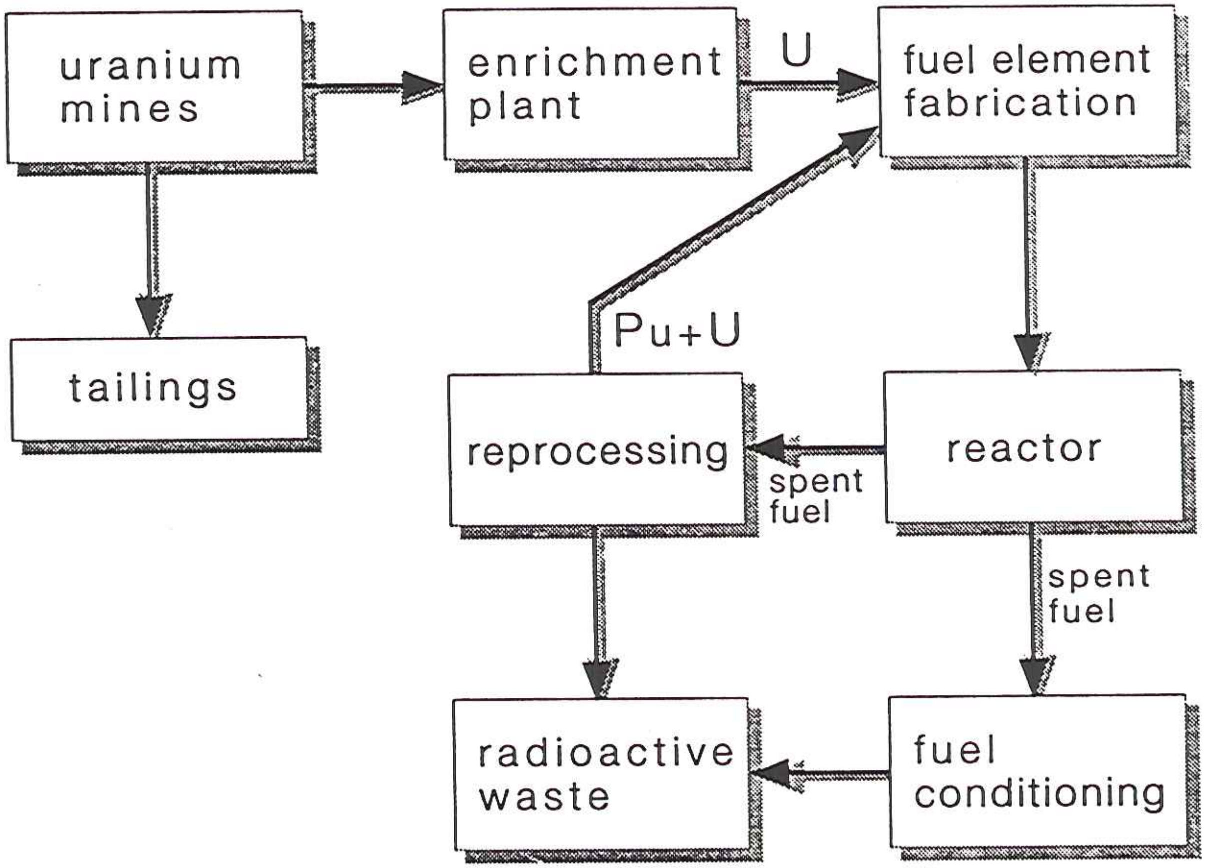


Figure 4.47 The nuclear fuel cycle. From the reactor one either uses the residual U and Pu again by reprocessing or prepares the fuel elements for storage as radioactive waste (no real cycle)

extra

100 slow neutrons absorbed by U^{235} to cause fission
↓
200 fission neutrons
|→ 40 leak out during slowing down
↓→ 20 absorbed by U^{238} during slowing down
140 neutrons slowed down
↓→ 10 leak out as slow neutrons
130 slow neutrons available for absorption
↓→ 30 absorbed by moderator, U^{238}, poisons, etc.
100 slow neutrons (absorbed by U^{235} to cause fission)

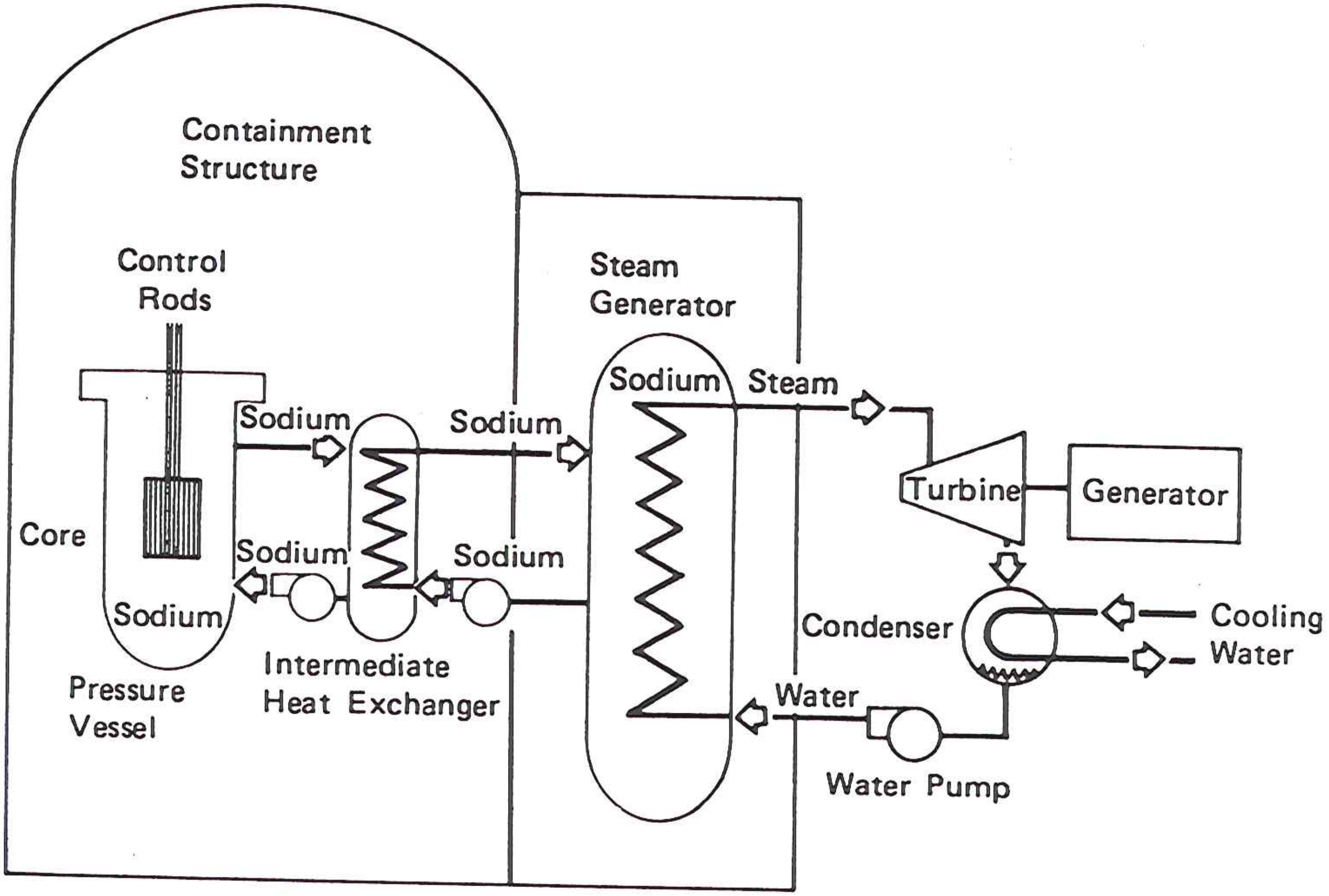


Figure 11.34. Schematic diagram of a liquid-metal, fast breeder reactor power station (LMFBR). (Nuclear Energy Policy Study Group 1977)

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

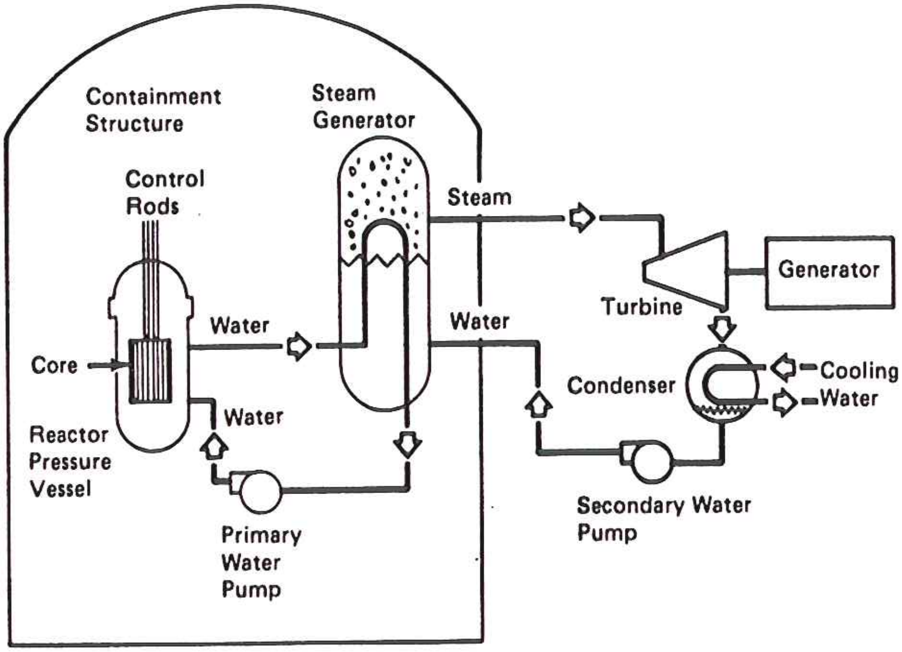


Figure 11.32. Schematic diagram of a heavy water reactor power system (HWR) of the CANDU type. (Nuclear Energy Policy Study Group 1977)

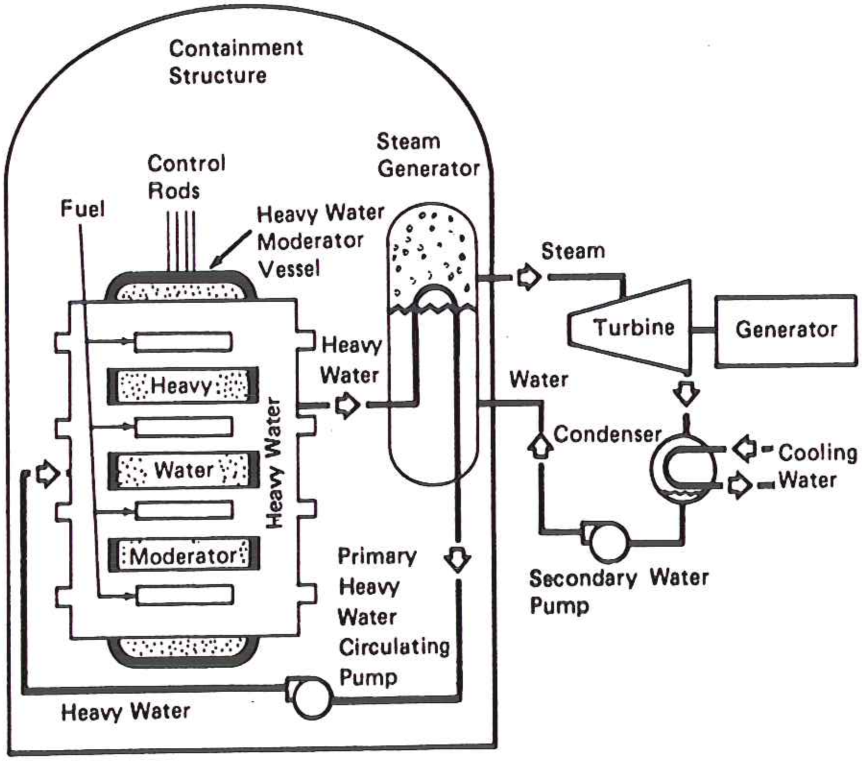


Table 9. World commercial primary energy production: 1988 vs 1973.*[a]

	1973 (quad)	1988 (quad)	Diff (quad)	Ratio 88/73	1973 (%)	1988 (%)
Crude oil	119.7	125.4	5.7	1.05	48.9	37.6
Natural gas liquids	4.2	7.2	2.9	1.69	1.7	2.2
Dry natural gas	43.2	67.1	23.9	1.55	17.7	20.2
Coal	61.8	93.0	31.2	1.50	25.3	27.9
Hydroelectric power	13.5	21.3	7.8	1.58	5.5	6.4
Nuclear power	2.2	19.1	16.9	8.77	0.9	5.7
TOTAL	244.7	333.1	88.4	1.36	100.0	100.0

*No adjustment made for 0.3% difference in number of days.

a. Data from Ref. 18; 1973 data adjusted for small differences in the two Ref. 18 series.

Table 11.3. Assessment of Advanced Reactor Technologies by the Committee on Future Nuclear Power Development of the U.S. National Research Council, 1992

		Evaluation Criteria							
Reactor Designation	*Available Design Information*	*Safety*	*Economy*	*Market Suitability*	*Fuel Cycle*	*Safeguards & Physical Security*	*Maturity of Devel-opment*	*Licensing*	*Overall Assess-ment*[a]
ABWR	○	○	○	○	◑	◑	○	○	○
APWR	○	○	○	○	◑	◑	○	○	○
SYS 80+	○	○	○	○	◑	◑	○	○	○
AP 600	◑	○	◑	○	◑	◑	◑	○	○
SBWR	◑	○	◑	○	◑	◑	◑	○	○
CANDU	○	○	●	◑	◑	◑	○	◑	◑
SIR	◑	○	◑[b]	●	◑	◑	●	●	●
MHTGR	◑	○	●	●	◑	◑	●	●	●
PIUS	●	○	◑[b]	●	◑	◑	●	●	●
PRISM-LMR	●	○	●[c]	●[c]	○	◑	●	●	◑

Legend rating: ○ high ◑ moderate ● low

Reactor designations: ABWR, advanced boiling water reactor; APWR, advanced pressurized water reactor; Sys 80^+, system 80^+ large evolutionary LWR; AP 600, advanced pressurized 600 water reactor; SBWR, simplified boiling water reactor; a mid-sized LWR with passive safety feature; CANDU, Canadian deuterium uranium reactor; SIR, safe integral reactor; MHTGR, modular high temperature gas-cooled reactor; PIUS, process inherent ultimate safety reactor; PRISM, power reactor, innovative small module, liquid metal reactor.

[a] Overall assessment was mostly driven by market suitability.

[b] Lack of design maturity results in great uncertainty relative to vendor cost projections.

[c] Long-term economy and market potential could be high, depending on uranium resource availability.