Fall Term – 2013

Woodrow Wilson School 585b

Living in a Greenhouse: Technology and Policy

Week Eleven: December 4, 2013
Nuclear science and nuclear power

R. H. Socolow

Phil Hannam

Supper together at a restaurant after next week’s final class?

Say, at 6:30 pm

Why learn about nuclear energy?

Why learn about nuclear energy?

1. Nuclear energy is a remarkable story.
2. Humankind is reconsidering a major expansion of nuclear power. Its attractive features include fuel abundance relative to fossil fuels and minimal impact on the atmosphere. Its unattractive features include a potential for severe accidents, an impasse regarding waste disposal, and a coupling to nuclear weapons.
3. Already deployed nuclear power (350 GW world-wide) needs to be managed.
4. Nuclear energy has applications beyond electric power (medical therapy, medical diagnostics, industrial diagnostics, geological dating, submarines, weapons).

Lecture Outline

Nuclear science

Nuclear reactors

Three weaknesses of nuclear power

Fusion, briefly.

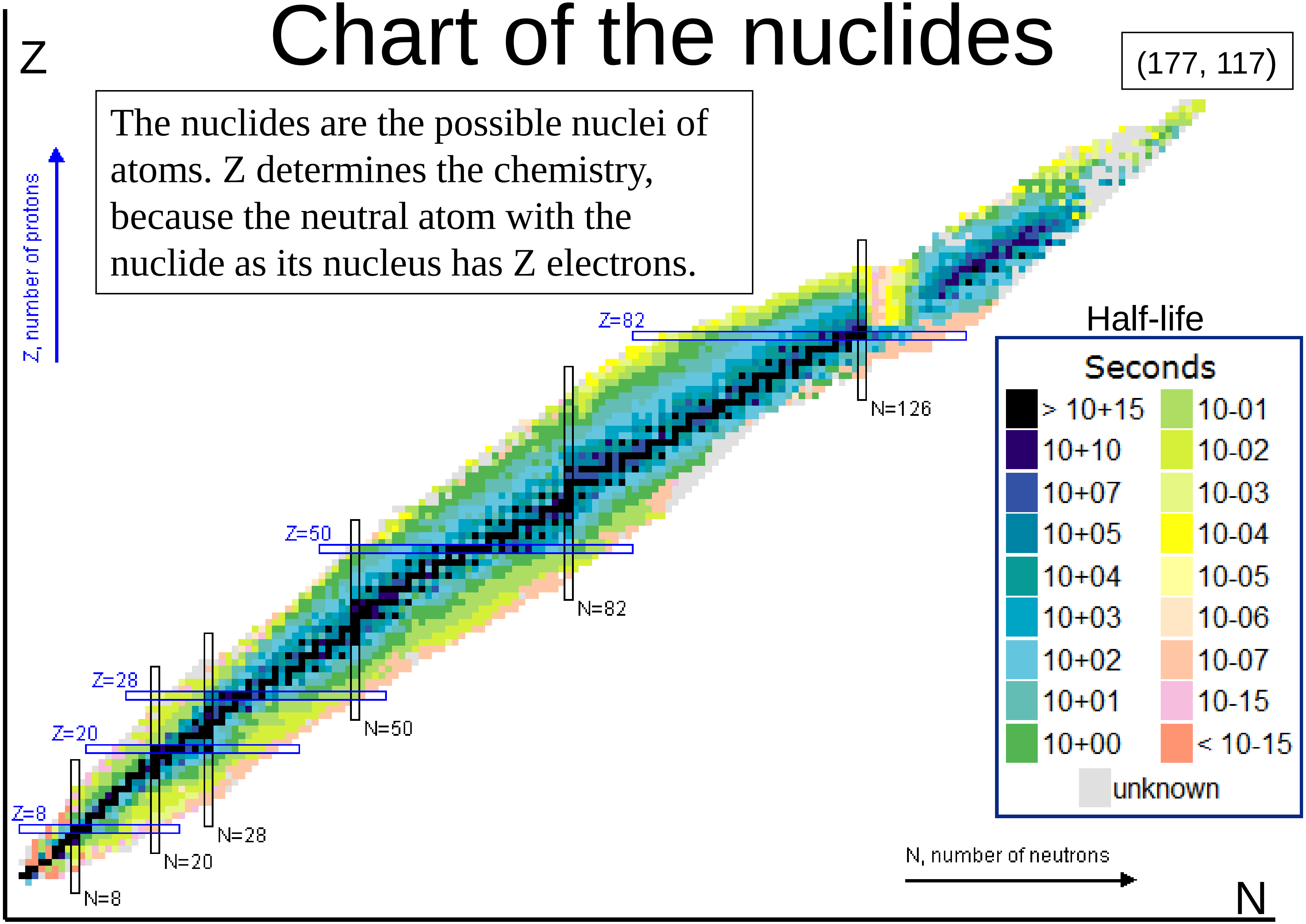
Nuclear energy: Science

1. The nuclides on an N-P grid
2. Binding energy and the vale of stability
3. The electron volt: yet another unit of energy
4. Forms of radioactive decay. The curie.
5. Doses from radiation: The rad and the rem.
6. The heaviest nuclides. Fission.
7. Fission products

8. The lightest nuclides. Fusion. [At the end of this unit.]

Chart of the nuclides

The nuclides are the possible nuclei of atoms. Z determines the chemistry, because the neutral atom with the nuclide as its nucleus has Z electrons.



Source: http://www.nndc.bnl.gov/chart/reZoom.jsp?newZoom=5

The vale of stability

The stable isotopes lie along a curve on a (N, Z) plot that:

1. starts from the origin along the 45^o line;
2. then falls below the 45^o line, curving downward;
3. ends at N = 126, Z = 83 (bismuth-209).

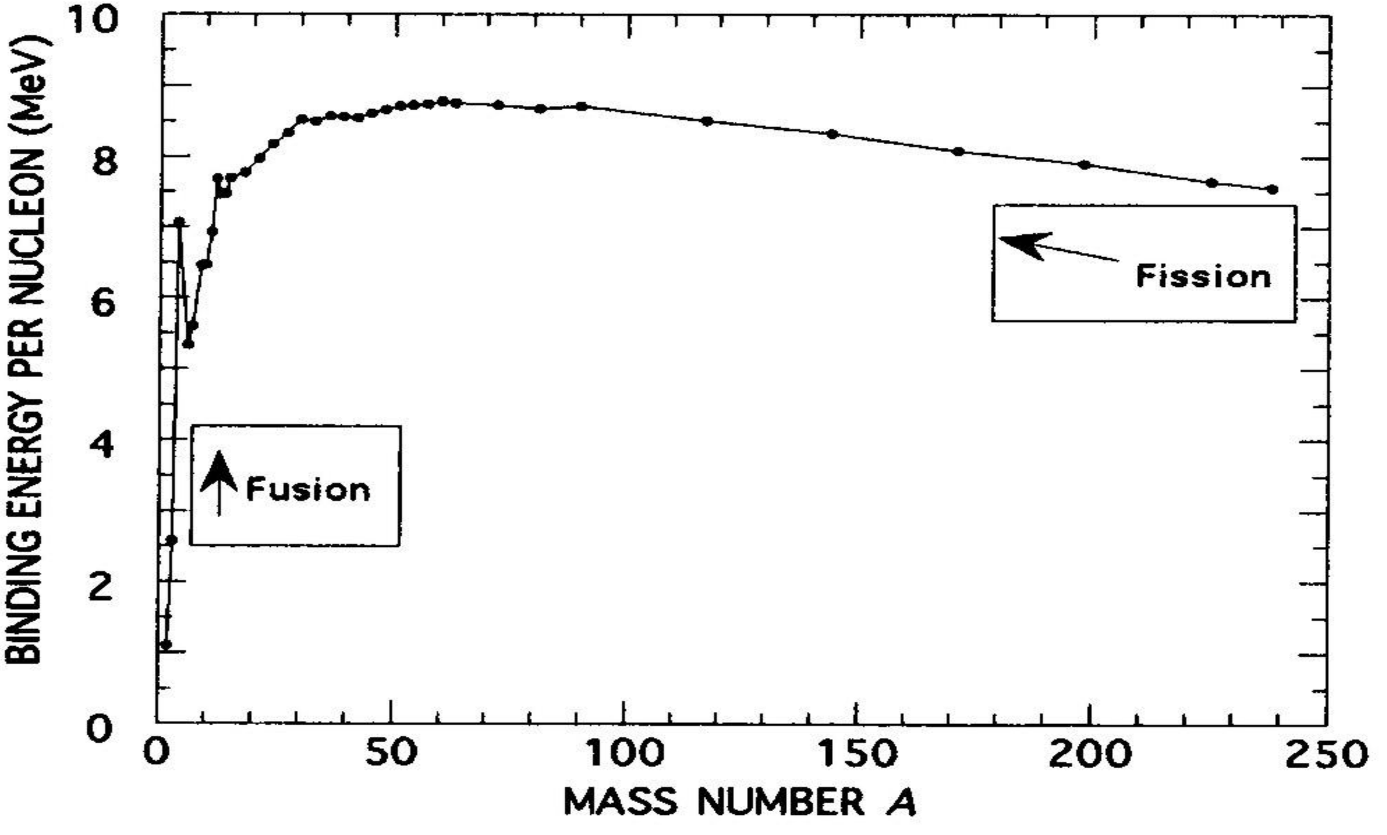
That there are stable nuclei at all is evidence of an *attractive nuclear force* between nucleons (P-P, P-N, and N-N).

Starting from the origin along the 45^o line is a consequence of the *equal strength* of (P-P, P-N, and N-N).

Curving downward (toward more Ns than Ps) is a consequence of the *electrostatic P-P repulsion*, additive with the nuclear force.

Ending (with Bi^{209}) is a sign that the nuclear force is *short range*, falling sharply in strength at distances of a few times the size of a nucleon (N or P).

The Curve of Binding Energy



The binding energy per nucleon of the most stable nucleus at each A, as a function of mass number, A. (A = P + N.)

The electron volt (eV)

The electron volt is a unit of energy for the world of atoms and nuclei. It is equal to the product of a single atomic charge (the absolute value of the charge of an electron or proton) times 1 volt.

The charge of an electron is 1.6×10^{-19} coulombs
1 coulomb x 1 volt = 1 Joule (J).
Therefore **$1\ eV = 1.6 \times 10^{-19}$ J.**

Note: A *faraday* is the total charge of Avogadro's number of electrons. From $(1.6 \times 10^{-19}) \times (6 \times 10^{+23}) = 100{,}000$, we estimate that a Faraday is 100,000 coulombs. It is actually 96,500 coulombs.

The binding energy of H^2

H^2 ("deuteron") is the only stable heavy isotope of hydrogen. It is a bound state of a proton and a neutron, exactly as the hydrogen atom is the bound state of a proton and an electron.

Binding energy of the hydrogen atom: 13.6 eV.

proton (mc^2):	938.280 MeV
electron (mc^2):	0.511 MeV

The rest energy (mc^2) of the hydrogen atom is *15 parts per billion* **less** than the total rest energy (mc^2) of constituents.

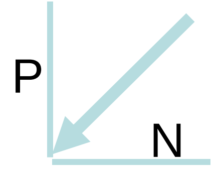
Binding energy of the deuteron: 2.23 MeV

neutron (mc^2):	939.573 MeV
proton (mc^2):	938.280 MeV

The rest energy (mc^2) of the deuteron is *1.2 parts per thousand* **less** than the total rest energy (mc^2) of constituents.

Alpha, beta, and gamma decay

Alpha decay: Large nuclei only. Move 2 squares along the +45^{o} line. N and P both drop by 2. (Nucleus emits a helium-4 nucleus, i.e., an alpha particle.)



Beta decay: All sizes of nuclei. Move 1 square along the -45^{o} line.

In *beta-minus decay*, P increases by 1, N decreases by 1, and an electron is emitted.

In *beta-plus decay*, P decreases by 1, N increases by 1, and a positron is emitted.

Gamma decay: All sizes of nuclei. No movement in N,Z space. A photon is emitted.

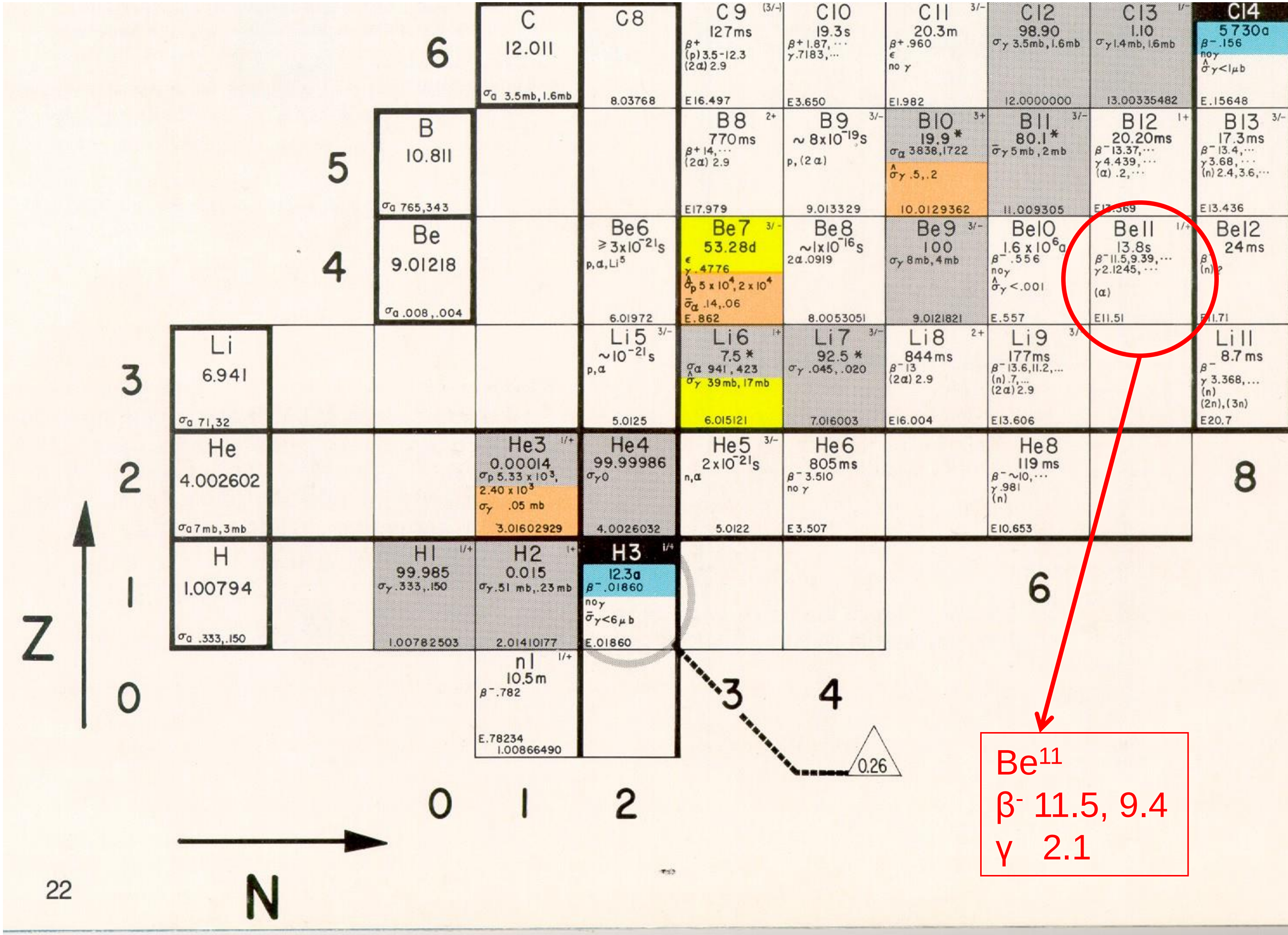


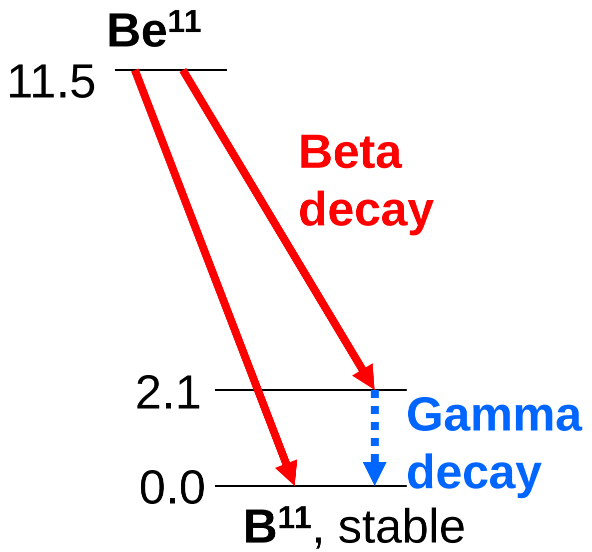
Chart of the Nuclides

Beta and gamma decay energies

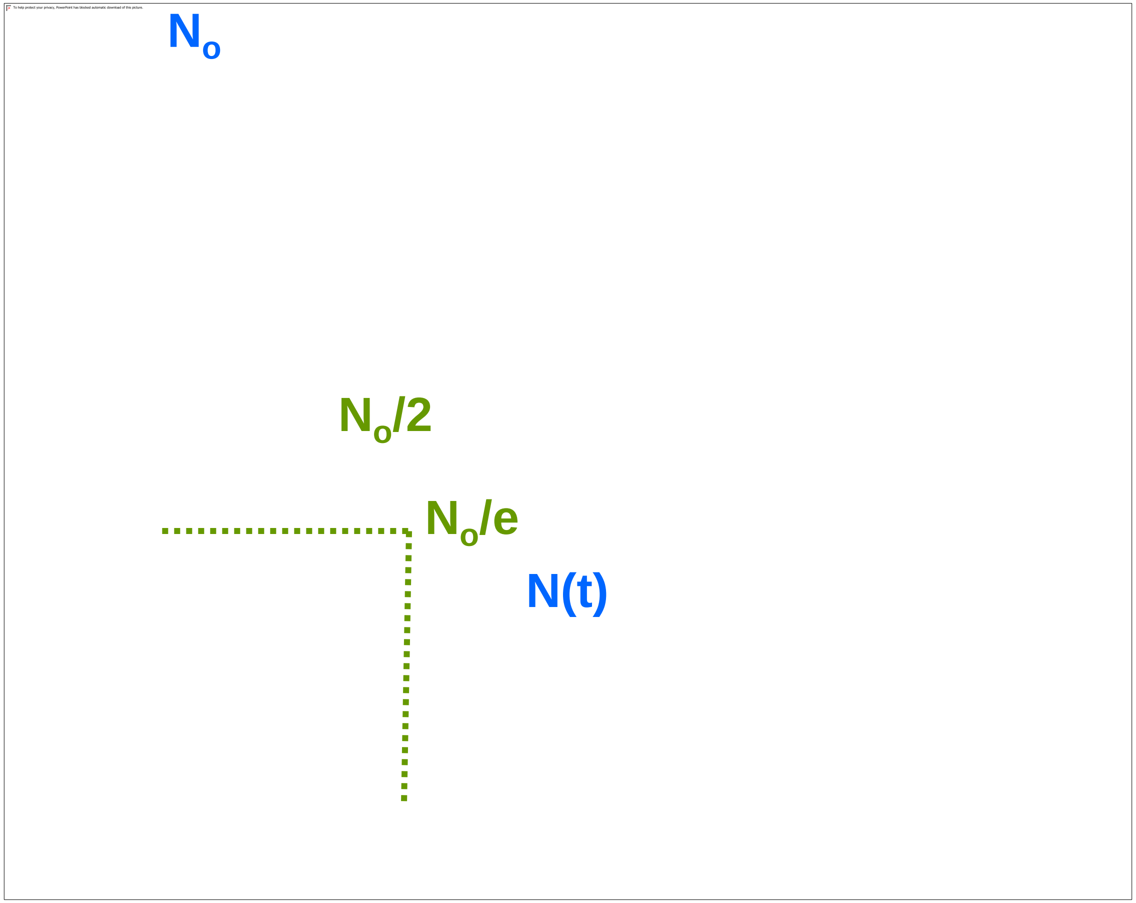
The boxes in the GE Chart of the Nuclides give information about energy release in the principal decay modes.

Example: Beryllium-11, half-life 13.8 sec. Box shows beta energy releases of 11.5 and 9.4 Mev, gamma energy releases of 2.1 MeV. Note that 11.5 – 9.4 = 2.1. What's up?

Answer: Beta-decay of Be^{11} produces both the ground state and an excited state of B^{11}; in the latter case, the excited state, through gamma decay, produces the ground state.



Mean life and half life



Exponential decay:

$dN(t)/dt = - N(t)/\tau$, $N(0) = N_o$

$N(t) = N_o e^{-t/\tau}$

Half life and mean life:

Let $t = T_{1/2}$, when $N(t) = N_o/2$.

Then $1/2 = \exp[-(T_{1/2}/\tau)]$

$$\ln 2 = 0.693 = T_{1/2}/\tau$$

$e = 2.718.$; $1/e = 0.368$

The mean life is longer than the half life.

What is a Curie?

A Curie (Ci) is 3.7×10^{10} decays per second. One curie is approximately the level of radioactivity of one gram of radium. Let's calculate the **half life of radium** (actually, the half life of its longest lived isotope):

Atoms in one gram of radium:

$= (1 \text{ gram})*(6.02*10^{23} \text{ atoms/mole})/(226.0 \text{ g/mole})$

$= 2.66*10^{21}$ atoms.

Mean life: $\boldsymbol{\tau = N/(dN/dt)}$

$= (2.66*10^{21} \text{ atoms present})/(3.7*10^{10} \text{ decays/second})$

$= 7.2 * 10^{10}$ seconds.

Half life = Mean life*0.693 = $5.0*10^{10}$ seconds = **1600 years**.

Derivative units: mCi (millicurie), MCi (megacurie), etc.

Modern unit: 1 Becquerel (Bq) = 1 decay/second.

Radiation exposure: rads and grays, rems and sieverts

The rad is a unit of dose. 1 rad has been absorbed when 0.01 J of nuclear radiation have been absorbed by 1 kg of tissue. *Modern unit:* 1 gray(Gy) = 1 J absorbed/kg = 100 rad

1 rem = 1 rad x (weighting factor)
Weighting factor is 1 for betas and gammas, 20 for alphas.
Modern unit: 1 sievert(Sv) = 1 gray x (weighting factor) = 100 rem.

The mean lethal dose (LD_{50}) is about 500 rem.

Cancers: About 4% incremental risk of dying of cancer for a dose of 50 rem.
Acute vs. chronic dose
"Linear hypothesis"

Sources of radiation exposure

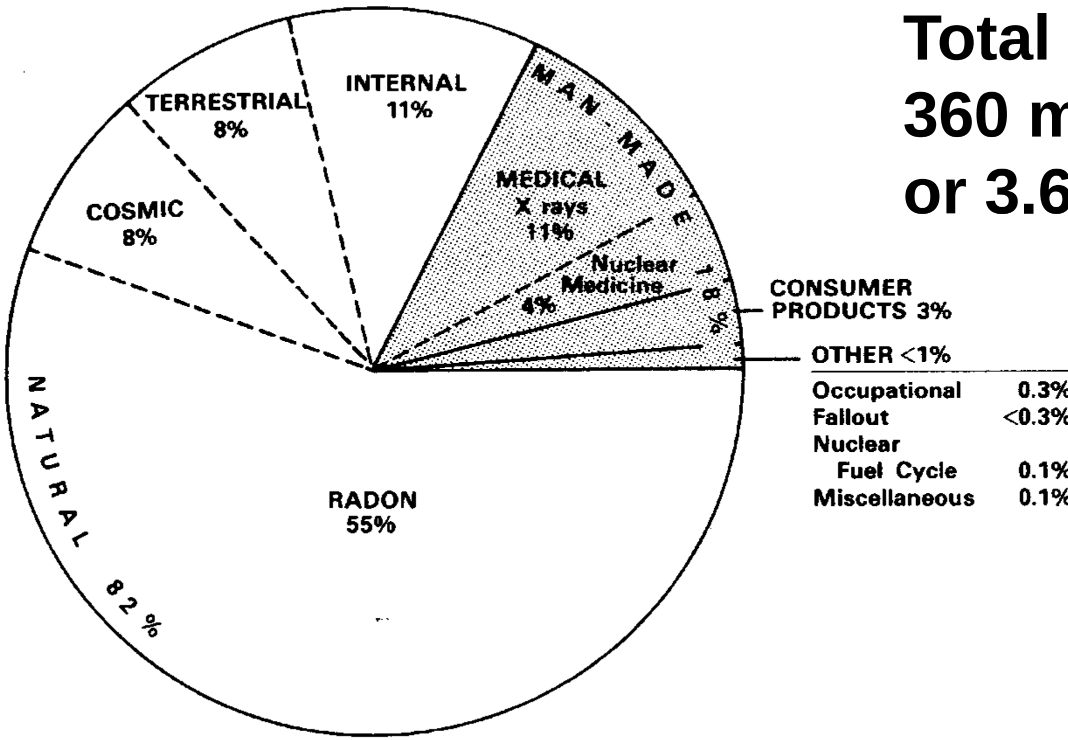


Fig. 8.1. The percentage contribution of various radiation sources to the total average effective dose equivalent in the U.S. population.

Total dose:
360 millirem/year,
or 3.6 mSv/yr.

Units: 1 rem = 1 rad x (weighting factor)
Weighting factor is 1 for betas and gammas, about 10 for alphas.
Modern units: 1 sievert(Sv) = 100 rem; 1 gray(Gy) = 100 rads.

TABLE 15.5

Ionizing Radiation Received by the U.S. Population. Estimated annual effective dose received in one year from various sources, averaged (per person) across the U.S. population.

Source	*Annual dose per person (millirem)*
Natural	
Radon from the ground	200
Cosmic rays	27
Rocks and soil	28
Internal consumption	40
Subtotal	295
Artificial	
Medical and dental X rays	39
Nuclear medicine	14
Consumer products	10
All other[a]	1
Subtotal	64
Grand total	359

[a] Occupational, nuclear weapons, nuclear power and its fuel cycle, and miscellaneous.

SOURCE: National Research Council's fifth committee on the biological effects of ionizing radiation (BEIR V), 1990

1 rem = 1 rad x (weighting factor)

Weighting factor is 1 for betas and gammas, about 10 for alphas.

Modern units: 1 sievert(Sv) = 100 rem; 1 gray(Gy) = 100 rads.

The internal dose from K-40

Facts:

1. One in 8500 K nuclei on Earth is K-40
2. Atomic weight of K: 39.1 (K-39, 93%; K-41, 7%).
3. Half-life of K-40 is 1.25×10^9 yr. (Mean-life, τ, is 1.80×10^9 yr.)

   Therefore, $1.01 * 10^9$ K-40 decays per year per gram of potassium

Assumptions:

1. In a 70 kg person, there are 150 g potassium (0.2%).
2. Each internal K-40 decay deposits 0.6 MeV in body, on average.

   Recall: 1 MeV = 1.6×10^{-13} J

   Therefore,14.5 milli-Joule/yr of radiation is absorbed by 70 kg (body weight).

   Therefore, the dose is ***210 micro-Gray/yr = 21 millirads/yr.***

The Upper End of the Chart of the Nuclides

A new phenomenon: Alpha decay (N+Z change by 4)

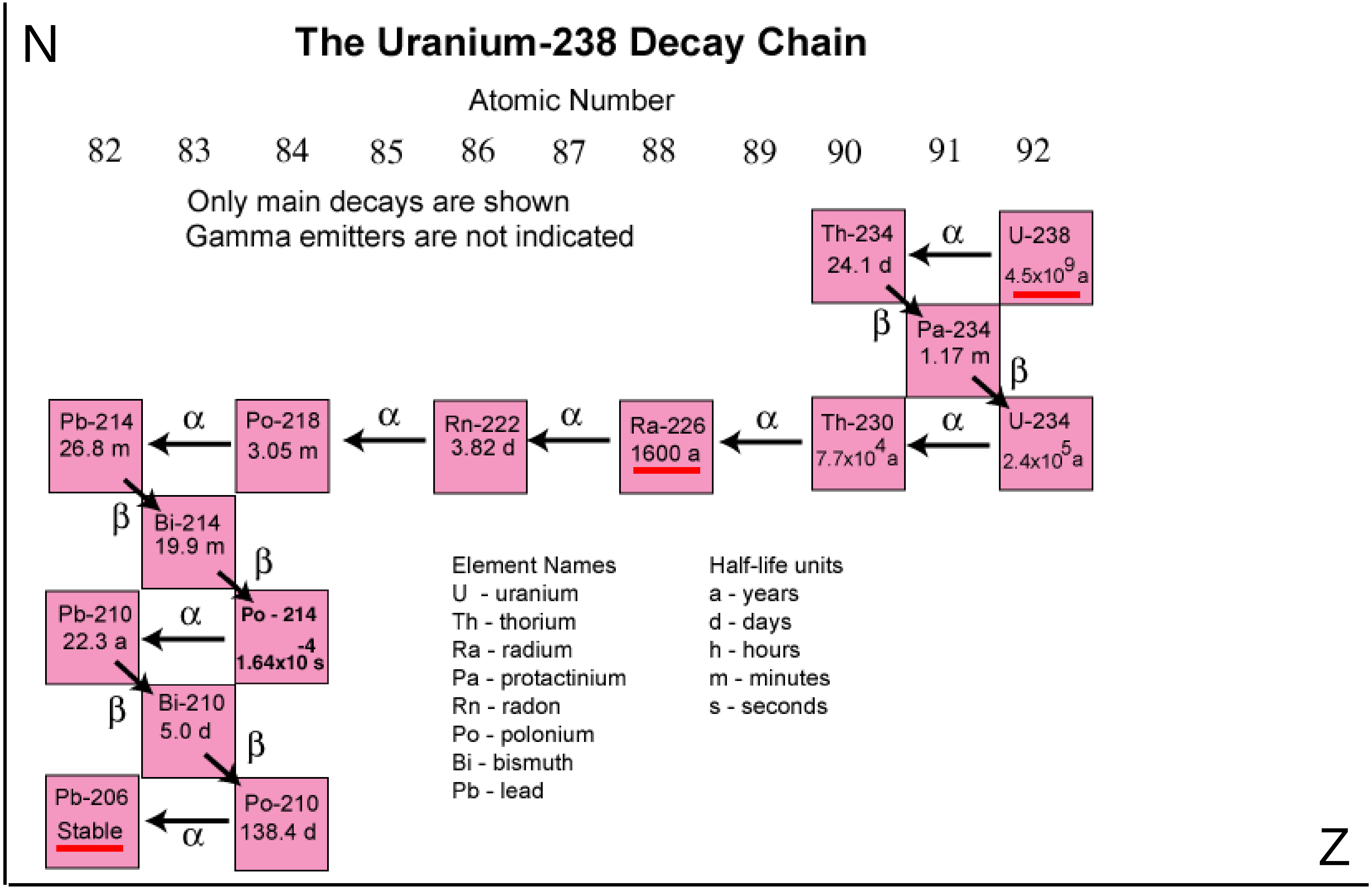
Since beta decay involves no change in (N+Z), a chain of successive alpha and beta decays retains a constant value of the remainder after dividing by four. Thus, there are four distinct decay chains, with remainders 0,1,2,3.

Three large isotopes, even though radioactive, are still around. Their half-lives, therefore, must be so long as to be comparable to or longer than the time since their production at the creation of the solar system.

These isotopes are:

Th-232 (14.0 x 10^9 yrs), parent of a chain with remainder 0, ends at Pb^{208}
U-235 (0.7 x 10^9 yrs), parent of a chain with remainder 3, ends at Pb^{207}
U-238 (4.5 x 10^9 yrs), parent of a chain with remainder 2, ends at Pb^{206}

Uranium-238 decay chain



Neutron-induced fission

It was discovered in December 1938 that uranium, when bombarded with neutrons, breaks into (usually, two) smaller pieces. About 200 MeV is released per fission (about 0.9 MeV per nucleon.)

What else needed to be true for this curiosity to be important?

Neutron-induced fission

It was discovered in December 1938 that uranium, when bombarded with neutrons, breaks into (usually, two) smaller pieces. About 200 MeV is released per fission (about 0.9 MeV per nucleon.)

What else needed to be true for this curiosity to be important?

It was learned a few months later, more than one neutron is released during fission. Chain reactions are possible. Commercial nuclear power becomes a possibility. Fission weapons do also.

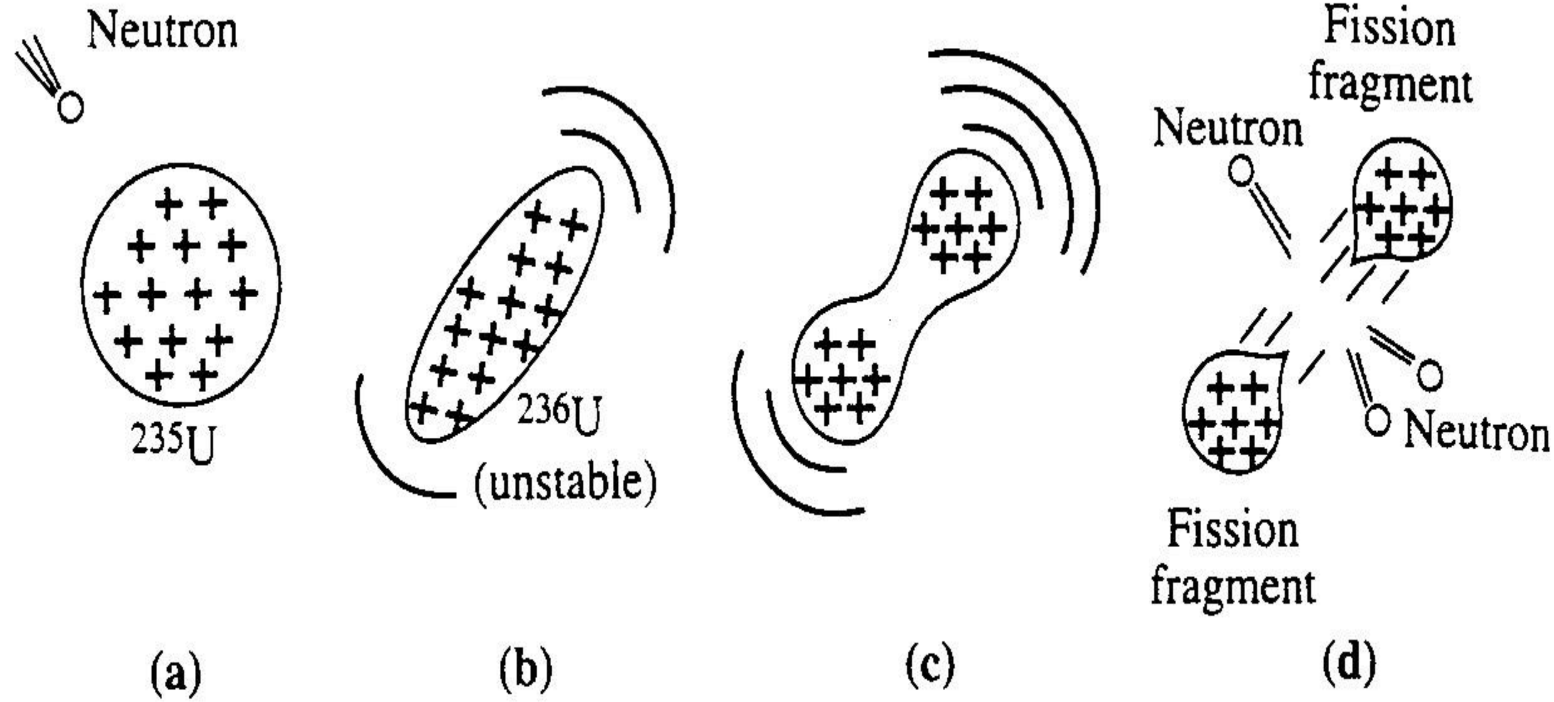


Figure 16.11. The fission of a U nucleus after being struck by a neutron.

So much energy per unit mass!

The fission of a uranium-235 nucleus releases about 200 MeV of energy. Verify the useful approximate fact that the fissioning of one *gram* of uranium releases about 1 megawatt(thermal)-day of energy:

Energy release $= (6\times10^{23}/235)\times(200\times1.6\times10^{-13}\,J) = 8\times10^{10}\,J$;
and $1\ MW_{th}\text{-day} = 8.64\times10^{10}\,J$.

Compare with coal. 1 MW_{th}-day = 86.4 GJ is the heat of combustion of about *3 tons* of coal. Mass ratio is 3 million.

Probability of Fission Products

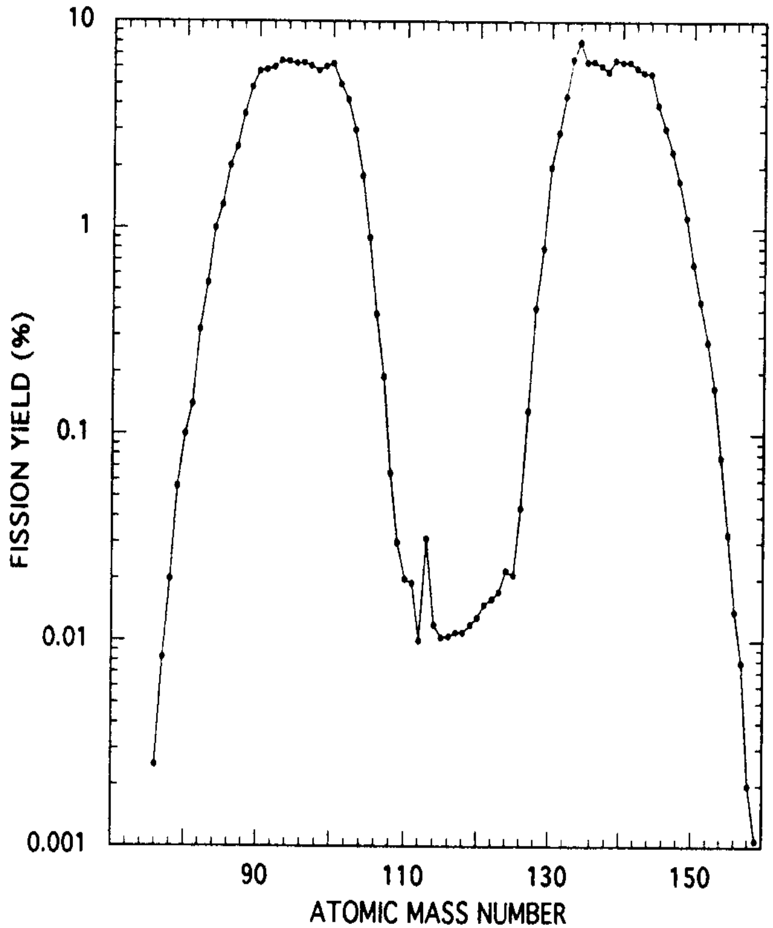


Figure 4.2. Yield of fission fragments as a function of atomic mass number *A* for thermal fission of ^{235}U (in percent per fission).

Fission is probabilistic. The most likely events produce two somewhat unequal big pieces. Note the roughly 5% probability of Sr^{90} and Cs^{137}.

Two outcomes when a neutron hits uranium

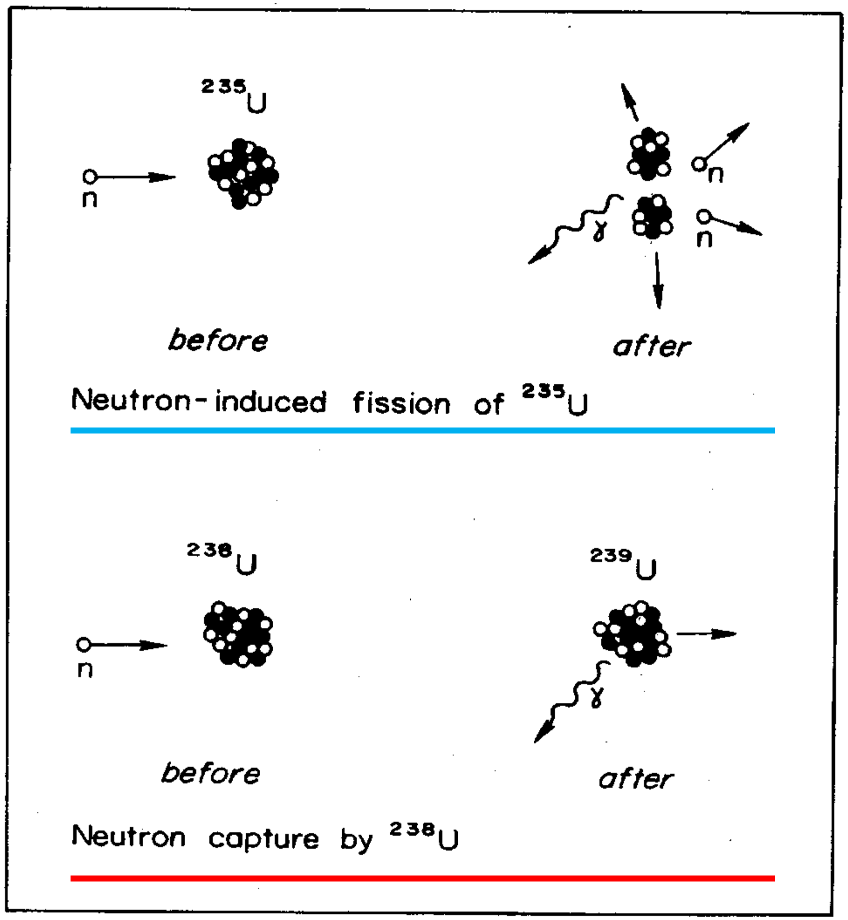


Figure 3-2. NUCLEAR REACTIONS.
The figure illustrates two important types of nuclear reactions. The upper is the fission of uranium 235, the reaction that liberates most of the energy in a uranium-fueled light-water reactor. The lower illustrates the capture of a neutron by uranium 238, the first step in the conversion of uranium 238 to plutonium 239.

Neutron-induced fission of U^{235} produces additional neutrons, which can sustain a chain reaction.

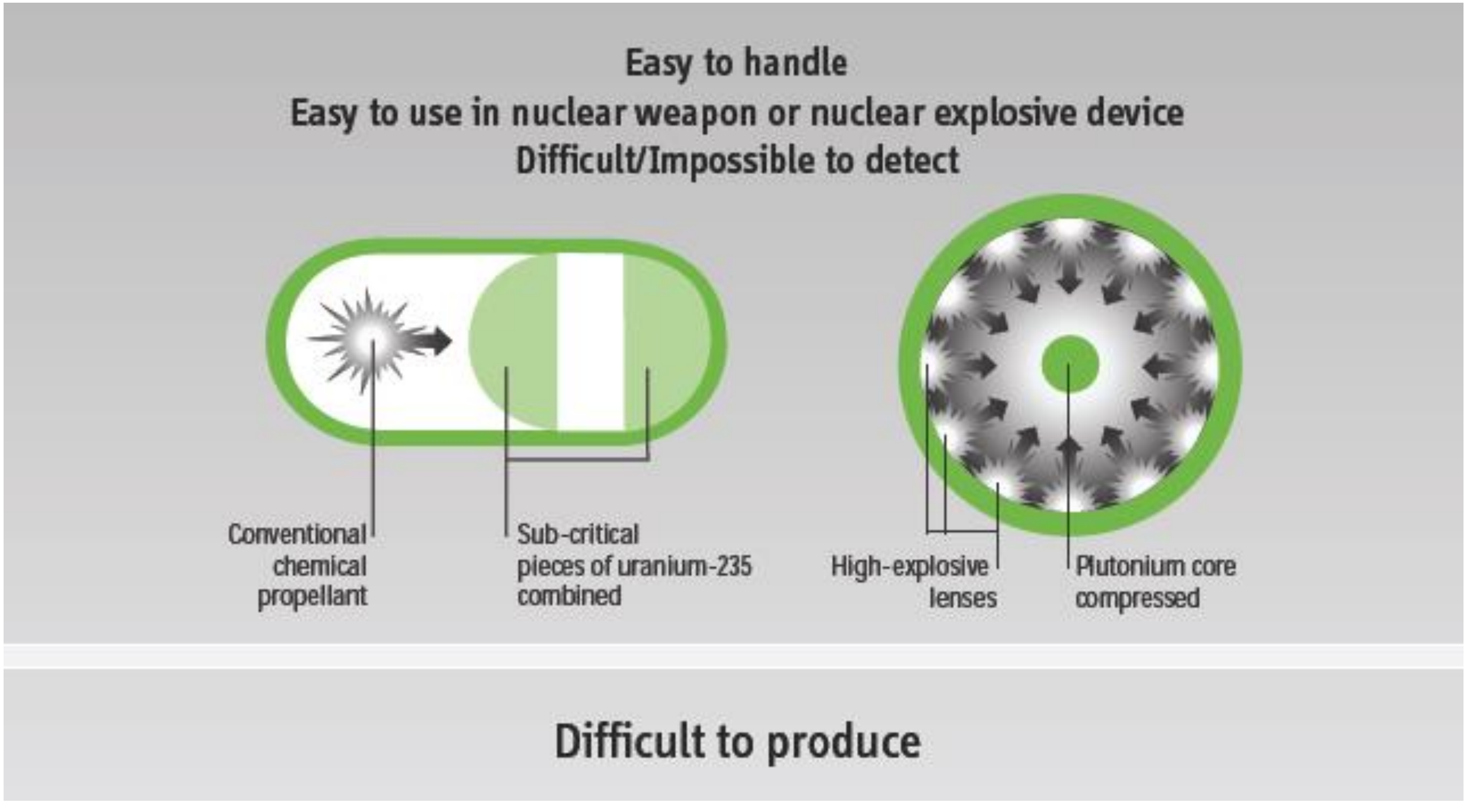
Neutron capture by U^{238} yields U^{239}, which becomes Pu^{239} (after two β-decays).

In a reactor some of the Pu^{239} subsequently fissions, contributing to reactor power.

U^{235} and Pu^{239} are bomb material.

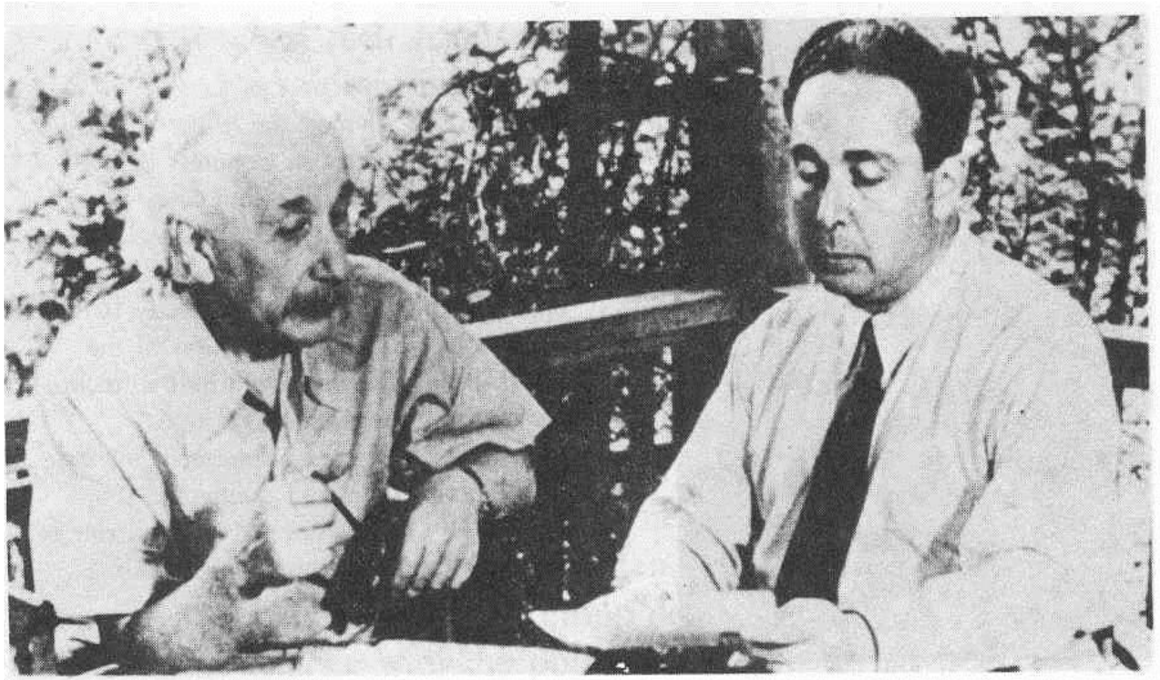
A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 34

U-235 and Plutonium Bombs



Source: Alex Glaser, WWS Seminar, 4-14-09

Leo Szilard, 1898-1964



William Sweet, 1984. *The Nuclear Age,* Congressional Quarterly Inc., p.16

Leo Szilard was probably the first person in the world to become firmly convinced that it would be possible to build an atomic bomb. Fearing that scientists in Nazi Germany might build the weapon, Szilard persuaded Albert Einstein to write to President Franklin D. Roosevelt in August 1939 about the possibility of the United States building an atomic bomb. Szilard made important contributions to the Manhattan Project, but he opposed the use of the bomb against Japan, and after the war he helped found organizations that since that time have been actively promoting nuclear arms control — the Federation of American Scientists and the Council for a Livable World.

"…the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration."
Einstein to Roosevelt, August 2, 1939

New physics and European politics, 1932-39

Discovery of neutron (Chadwick, UK, 1932)
Hitler comes to power (Germany, 1933)

First neutron bombardment of uranium (Fermi, Italy, 1934)
Emigration of many German and other European scientists (1934-38)
Hitler rearms (1935), Anschluss (March 1938), Munich (Sept 1938)

Discovery of fission phenomenon (Hahn and Strassman, Germany, Dec. 1938),

Understanding of fission energy release (Meitner and Frisch, Sweden, Jan. 1939)

Identification of U-235 as the fissionable isotope (Bohr and Wheeler, Princeton, U.S., spring 1939)

Measurement of two to three neutrons per fission (Fermi at Columbia, Joliot in Paris, March 1939)

Hitler invades Poland, WWII begins (Sept 1, 1939)

The Blinding Dawn of the Nuclear Age

Main Points

- Nuclear science is accessible.
- The underlying rules are identical to those used to describe atoms: a quantum mechanics based on discrete energy levels and probabilistic descriptions. But there 10^5 to 10^7 differences in scale.
- At the top of the periodic table, some nuclei can be fissioned by neutrons, and chain reactions are possible. U^{235} and Pu^{239} are fuels for weapons.
- The history of nuclear science and of Hitler's Europe are closely intertwined and provide many What Ifs.

BREAK

Required readings for Week12 Geoengineering

Morton, O. (2007). Is this what it takes to save the world? *Nature*, *447*(7141), 132-136.

Victor, D. G. (2008). On the regulation of geoengineering. *Oxford Review of Economic Policy*, *24*(2), 322-336.
OR
Barrett, S. (2008). The incredible economics of geoengineering. *Environmental and Resource Economics*, *39*(1), 45-54.

Cressey, D. (2013). Climate report puts geoengineering in the spotlight. Nature News. Available: http://www.nature.com/news/climate-report-puts-geoengineering-in-the-spotlight-1.13871

Morrow, D. R., Kopp, R. E., & Oppenheimer, M. (2009). Toward ethical norms and institutions for climate engineering research. *Environmental Research Letters*, *4*(4), 045106.

Hamilton, C. (2013). *Earthmasters: The Dawn of the Age of Climate Engineering*. Yale University Press. *Chapter 1: Why Geoengineering?*

Required readings for Week12 Planetary Stewardship

Gore, A. (1992). *Earth in the Balance* (p. 269). New York: Houghton Mifflin. *Read Chapter 13.*

Schumacher, E. F. (1973). *Small is beautiful: Economics as if people mattered*. Harper & Row. *Read at least the Epilogue. Entire book is recommended.*

Lecture Outline

Nuclear science

Nuclear reactors

Three weaknesses of nuclear power

Fusion, briefly.

The Promise of Nuclear Power

Small flows. To produce the thermal energy required to produce 1000 megawatts of power for a year:

Fission one ton of uranium

Burn 3,000,000 tons of coal.

Abundant resources: uranium and thorium, relative to coal.

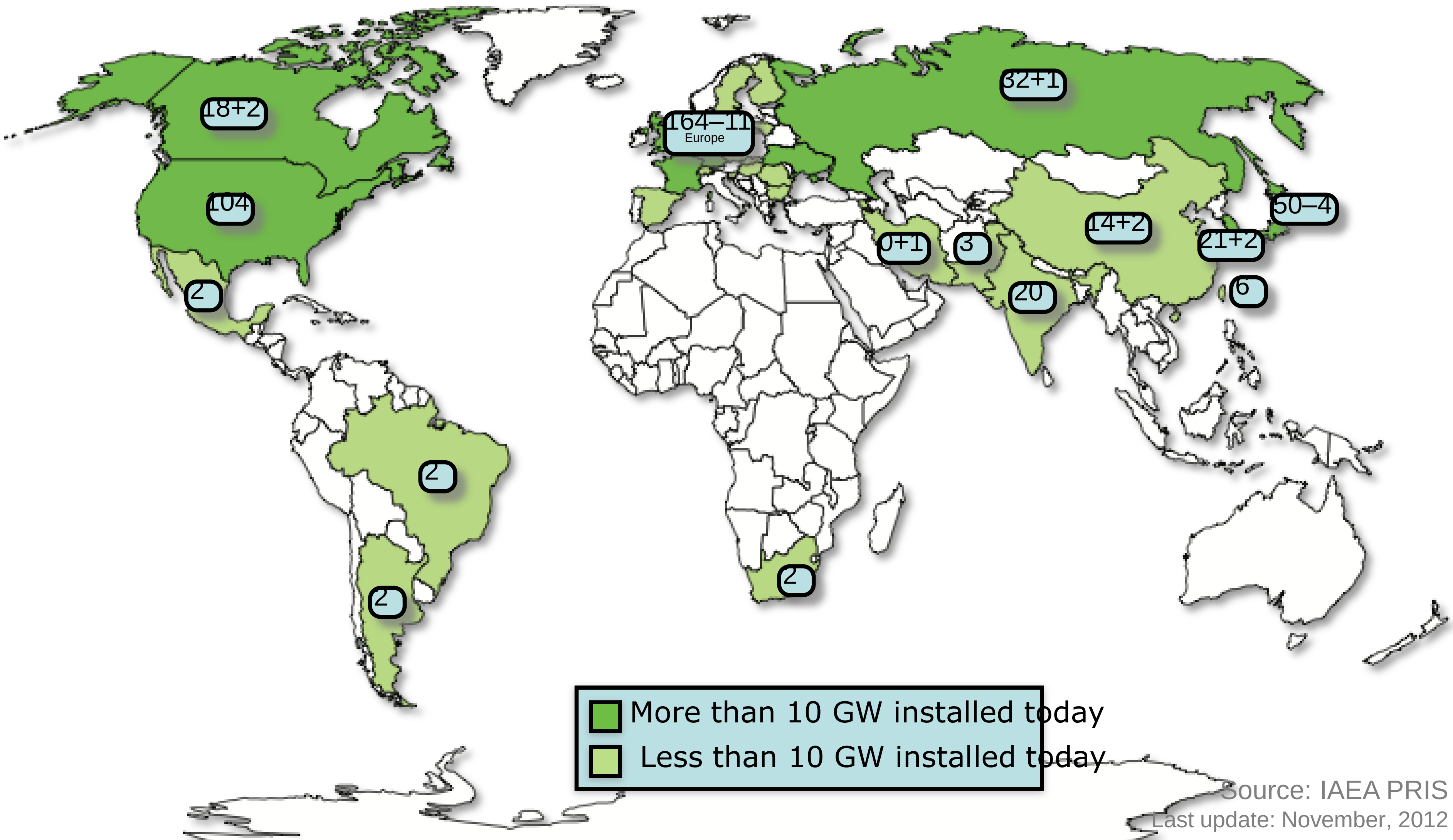
Minimal increments on background radiation (if it works properly)

Minimal CO_2 emissions.

A route to fuels as well as power.

Nuclear Power Reactors in the World, 2012

437 operational reactors (7 fewer than 18 months ago) in 31 countries: ≈13% of global electricity



Source: IAEA PRIS
Last update: November, 2012

Nuclear Power in the United States

104 reactors at 65 sites with an installed capacity of 100 GWe

Not 1000 GW_e, but 100 GW_e

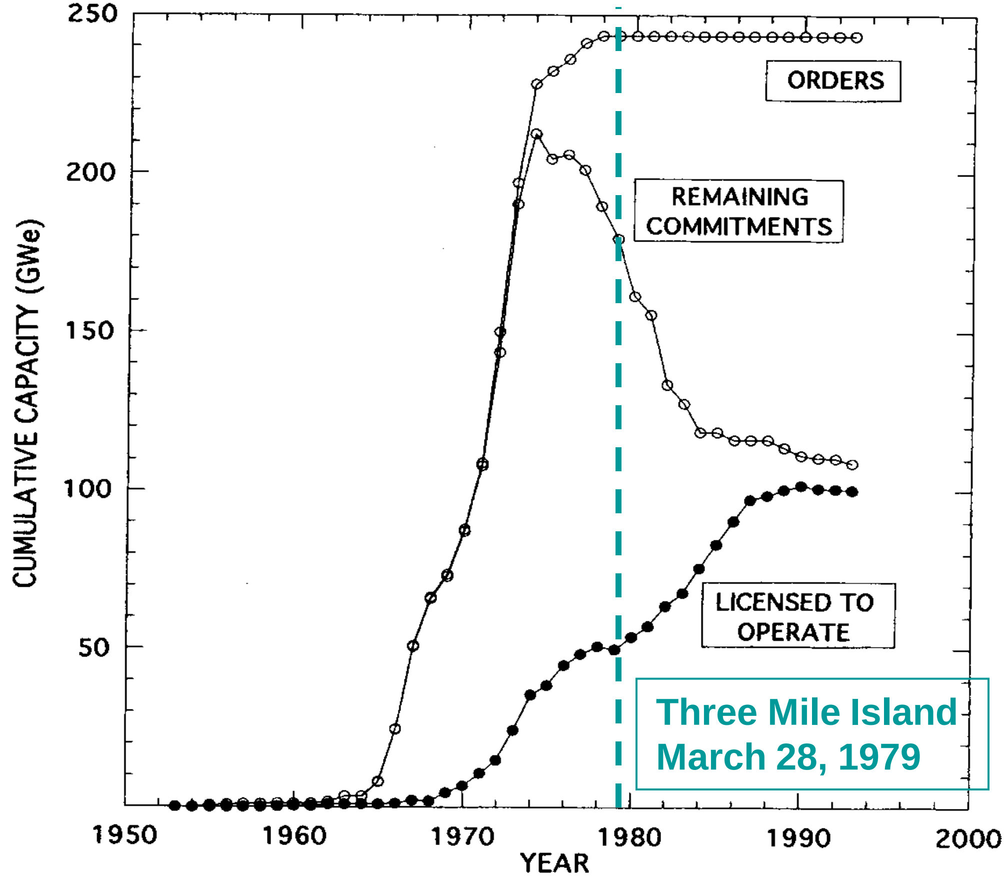
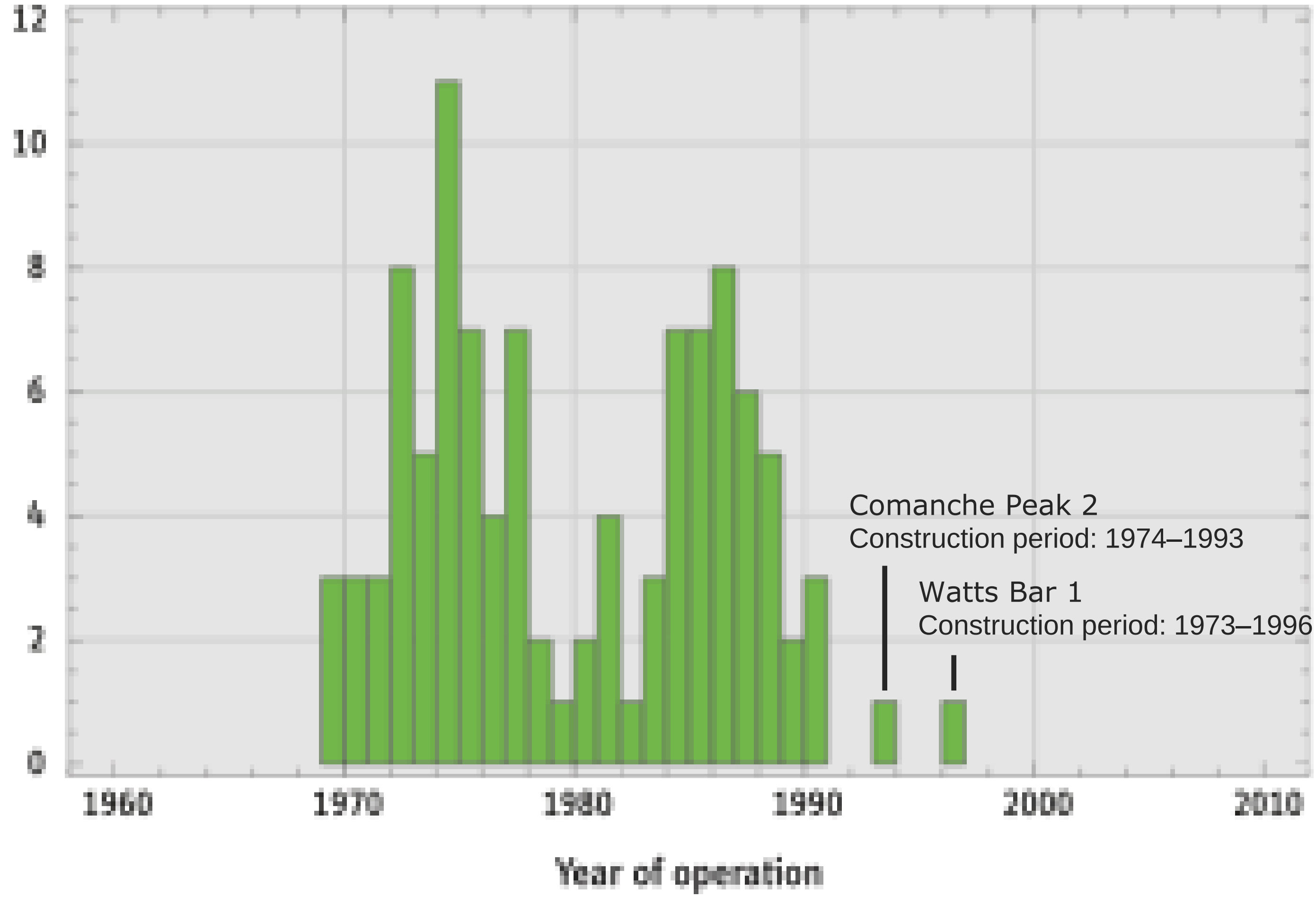


Figure 1.1. Cumulative capacity of reactors ordered, remaining as commitments, and holding operating licenses (including low-power licenses).

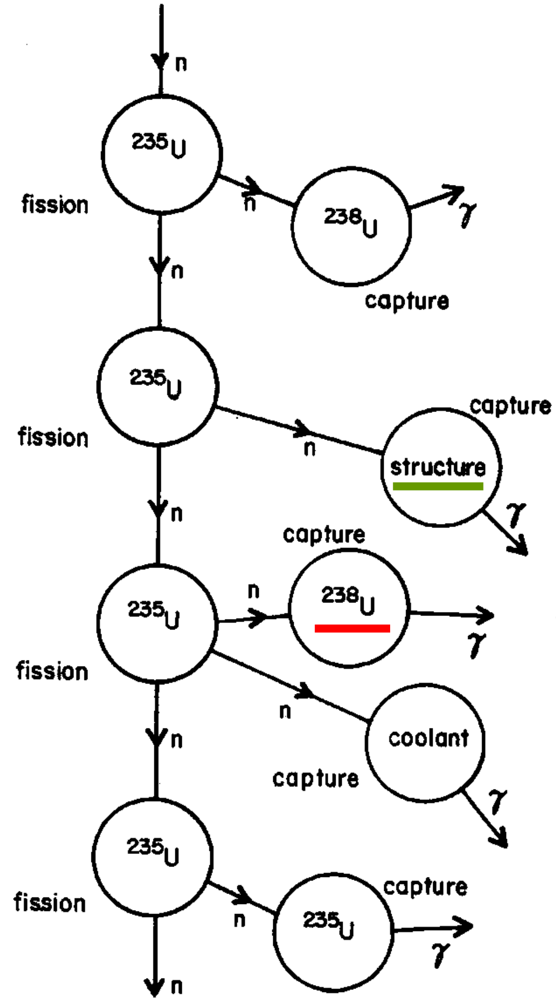
The U.S. Nuclear Reactor Fleet is Aging

104 operational reactors.
About 40% near 40-year life, life-extensions granted.



Neutronics

Figure 1-2. A SCHEMATIC NEUTRON ECONOMY. Fission-produced neutrons can be absorbed in a number of different ways, of which ^{235}U fission is the one that continues the chain reaction. Between the various reactions shown in the figure, neutrons may be slowed down by collisions with moderating material. The economy is balanced if, on the average, one neutron is produced for each one absorbed. (Although each of the reactions shown has heavier products of some sort, we have for simplicity indicated only the resulting neutrons and gamma rays.)



control, enrichment in U^{235}

becomes Pu^{239} (two β-decays);

A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 6

Many paths to reactors

Fuel: Typically, uranium, enriched in U^{235}.
Pu^{239} and U^{233} can replace U^{235}.

Neutrons ("fast" vs. thermalized via a "moderator")
Moderator: H_2O, D_20, graphite,…

Coolant: Water, helium, liquid metal,…

Workable combinations require not absorbing too many neutrons. Canada's CANDU uses D_2O ("heavy water") so as to allow unenriched uranium.

Most of today's reactors

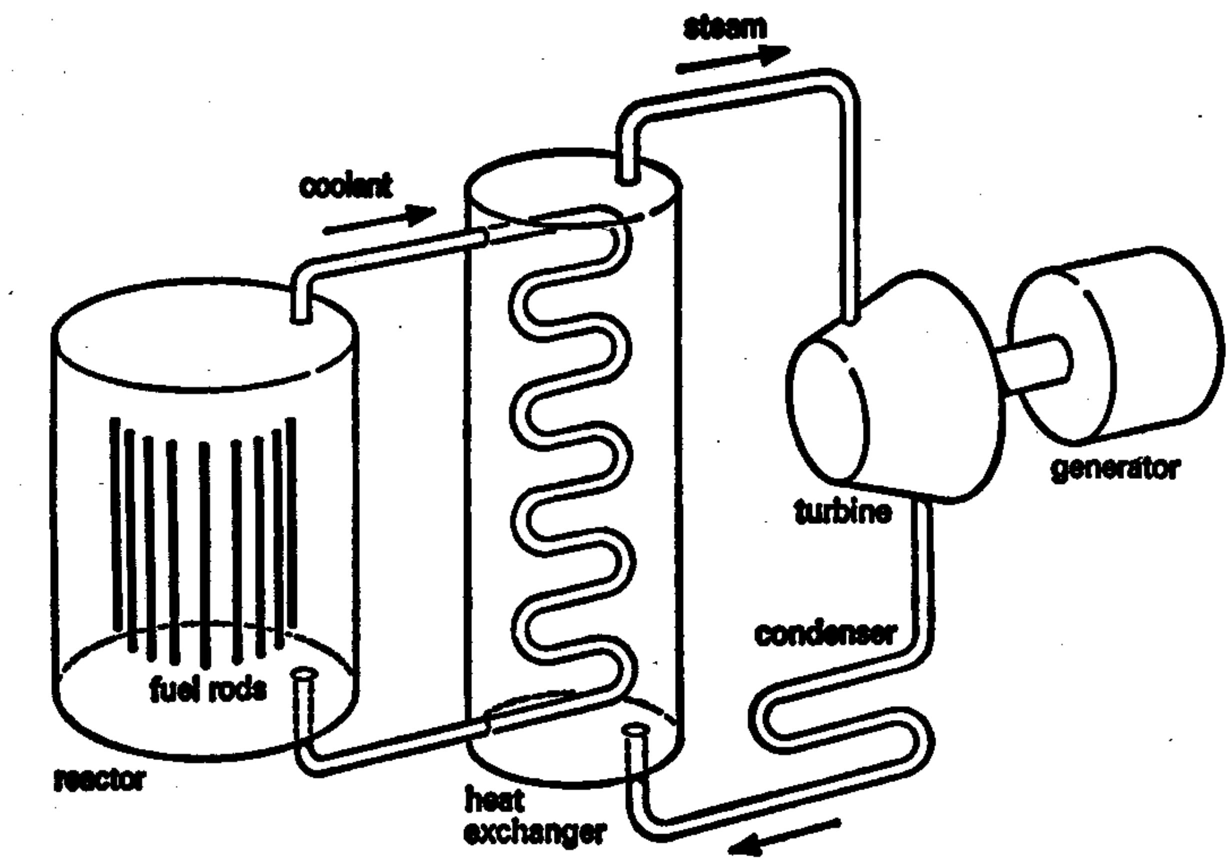


Figure 1 Nuclear power station

Most of the world's reactors today: U fuel enriched to about 5% U^{235}, water moderated, water cooled.

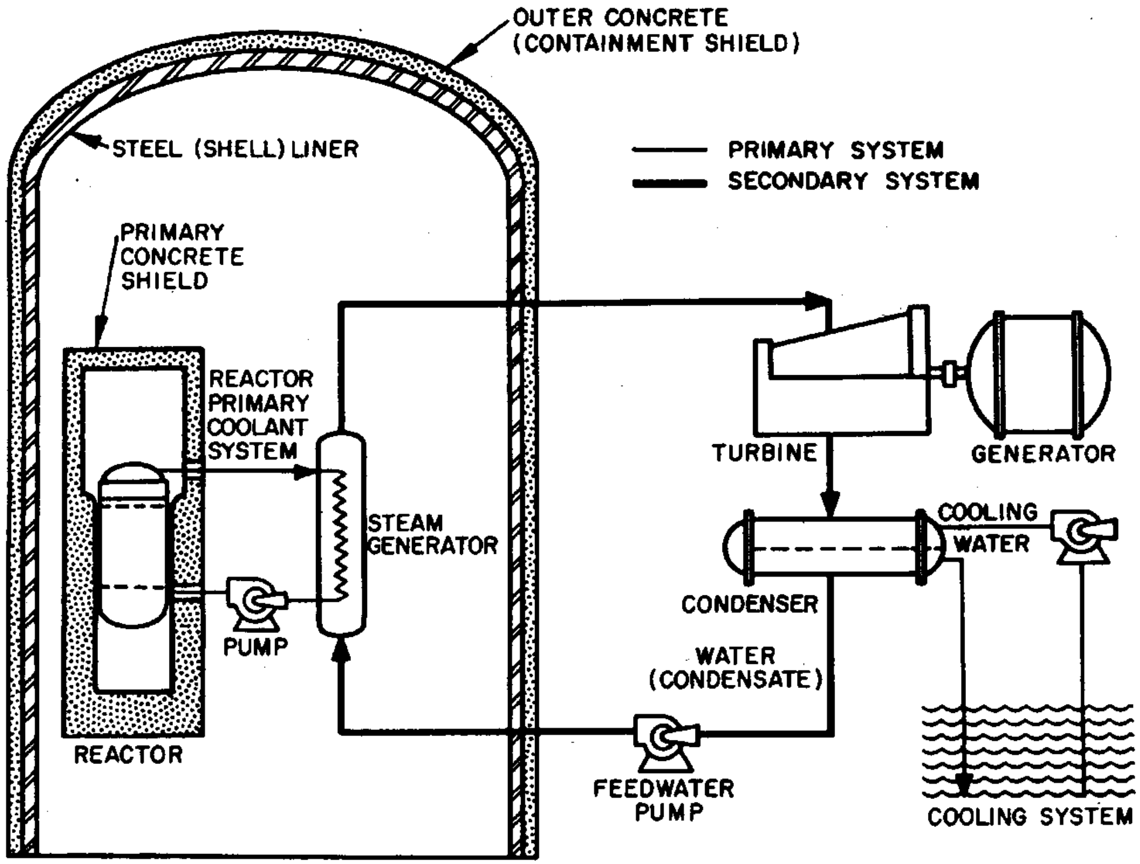


Figure 5-1. SCHEMATIC PRESSURIZED-WATER REACTOR POWER PLANT.
The primary reactor system is enclosed in a steel-lined concrete containment building. Steam generated within the building flows to the turbine-generator system (outside the building), after which it is condensed and returned to the steam generators. (Figure reproduced from ERDA-1541.)

A. Nero. Jr., *The Guidebook to Nuclear Reactors,* p. 78

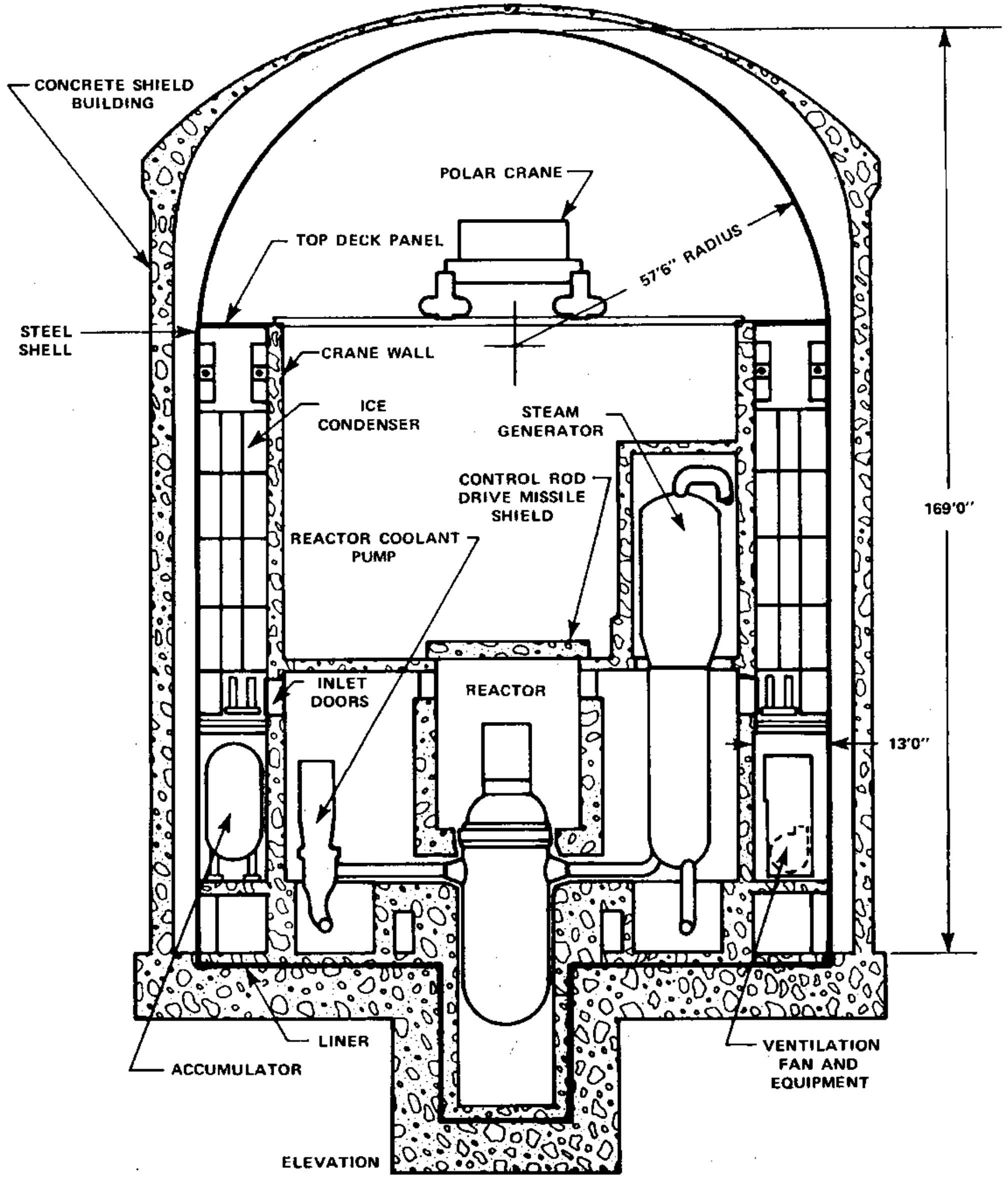
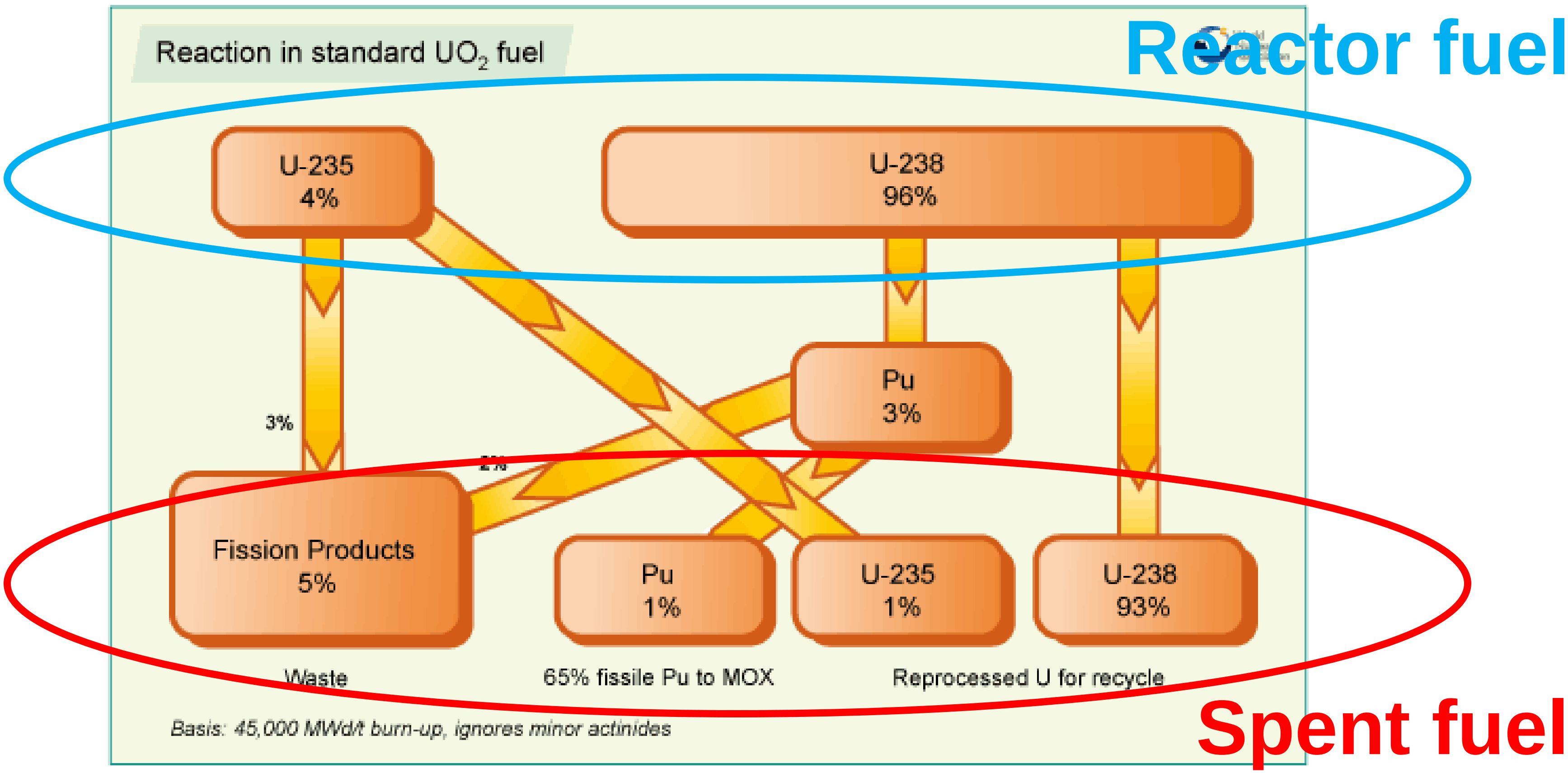


Figure 5-7. CROSS-SECTION OF A PWR CONTAINMENT BUILDING.
The containment building has the entire primary system, as well as various safety systems, in its interior. The building itself is concrete, with a steel shell inside. The safety systems within the building include emergency core cooling systems (note the accumulator), pressure control systems (one form of which may be the ice condenser indicated), and ventilation equipment. (Figure courtesy of Westinghouse Electric Corp.)

A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 87

Flows of U and Pu in a typical reactor



"Burn-up" refers to thermal energy produced via fission. Assuming 32% efficiency, 45,000 MW-days of thermal energy/t_{fuel} → 14,400 $MW_e d/t_{fuel}$. At 1.1% Pu in spent fuel, 1000 MW_e-yr of electricity creates 280 kgPu/yr in spent fuel.

Source: http://www.world-nuclear.org/info/inf29.html#WeaponsDisposition, accessed 11/8/10.

Lecture Outline

Nuclear science

Nuclear reactors

Three weaknesses of nuclear power

Fusion, briefly.

Three weaknesses of nuclear power

Accidents

Three-Mile Island, PA

Chernobyl, the Ukraine

Fukushima Daiichi, Japan

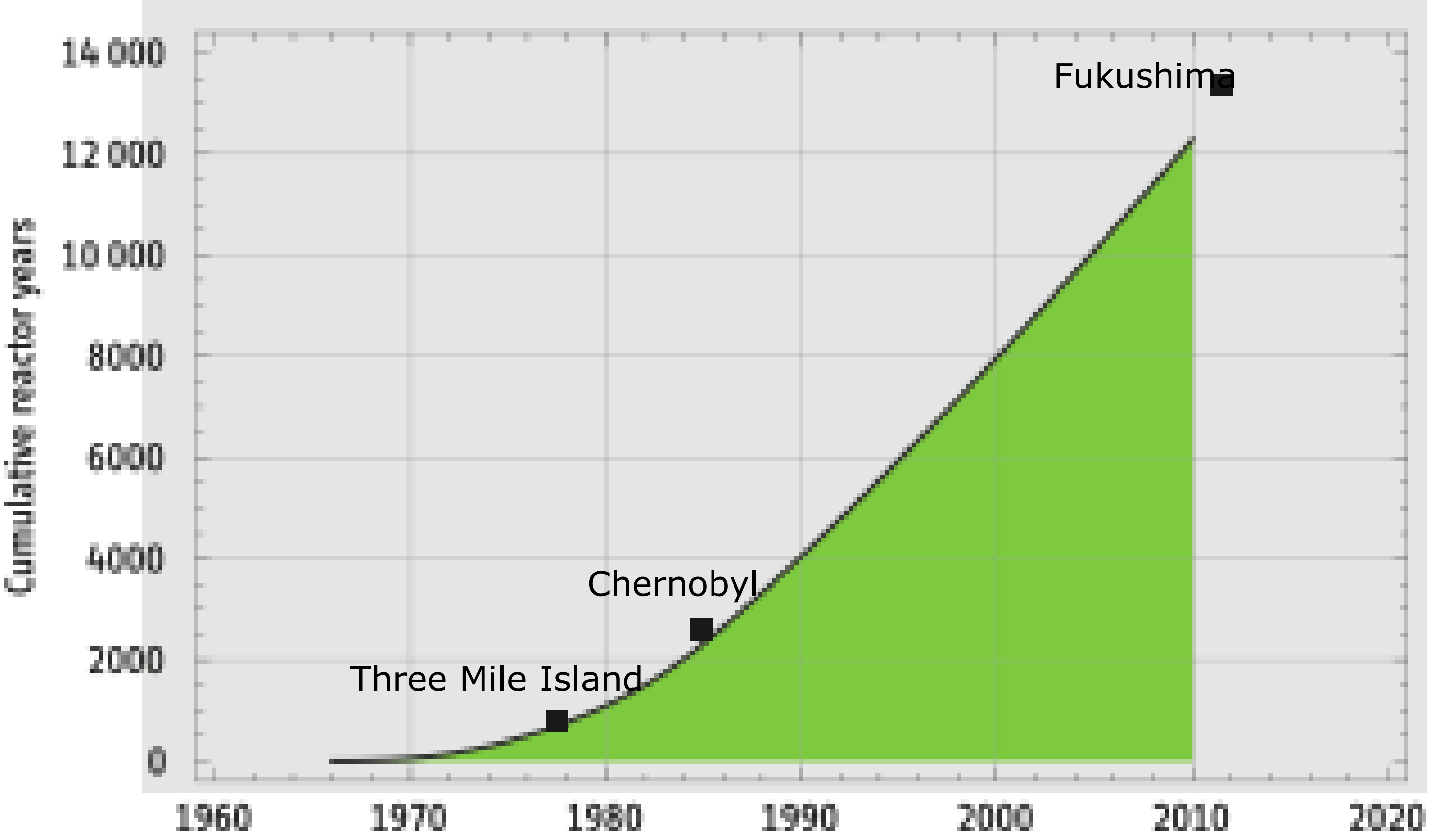
Waste Management (leak-proof for a very long time)

Nuclear Proliferation

1. Uranium route: uranium-235 enrichment
2. Plutonium route: fuel reprocessing

ACCIDENTS

Nuclear Power: Years of Uneventfulness Interrupted by Moments of Sheer Terror



Source: Alex Glaser, *Synergize 2012*, Princeton, Nov, 12–13, 2012. Glaser finds a value for 2010 closer to 14,000 reactor years.

Three Mile Island (1 of 2)

Wednesday, March 28, 1979.

Initial problem was an interruption of water flow in the secondary loop (feedwater flow). The emergency feedwater pump for the primary loop started up as it should have. But valves were in closed position and should not have been.

An island in the Susquehanna River near Harrisburg, PA, upwind from Princeton. 960 MW_e PWR.

Three-Mile Island accident (2 of 2)

Three of the four cooling towers at the Three Mile Island nuclear power plant near Harrisburg, Pa. On March 28, 1979, a malfunction in the plant's reactor cooling system caused one of the worst nuclear accidents in the history of commercial nuclear energy.

With the primary loop not cooled, the pressure relief valve opened in primary loop, as it should have. Control rods shut down the reactor ("trip"). The relief valve then did not close, but a sensor read that it did. There was a large loss of primary loop water. Within two minutes, the steam generators boiled dry.

Concern for a H_2 bubble through the weekend. Evacuations. Princeton University worries.

Negligible radiation releases. Loss of plant!

The Nuclear Age, p. 70

After-heat: A fire you can't put out.

Percent of pre-shutdown power

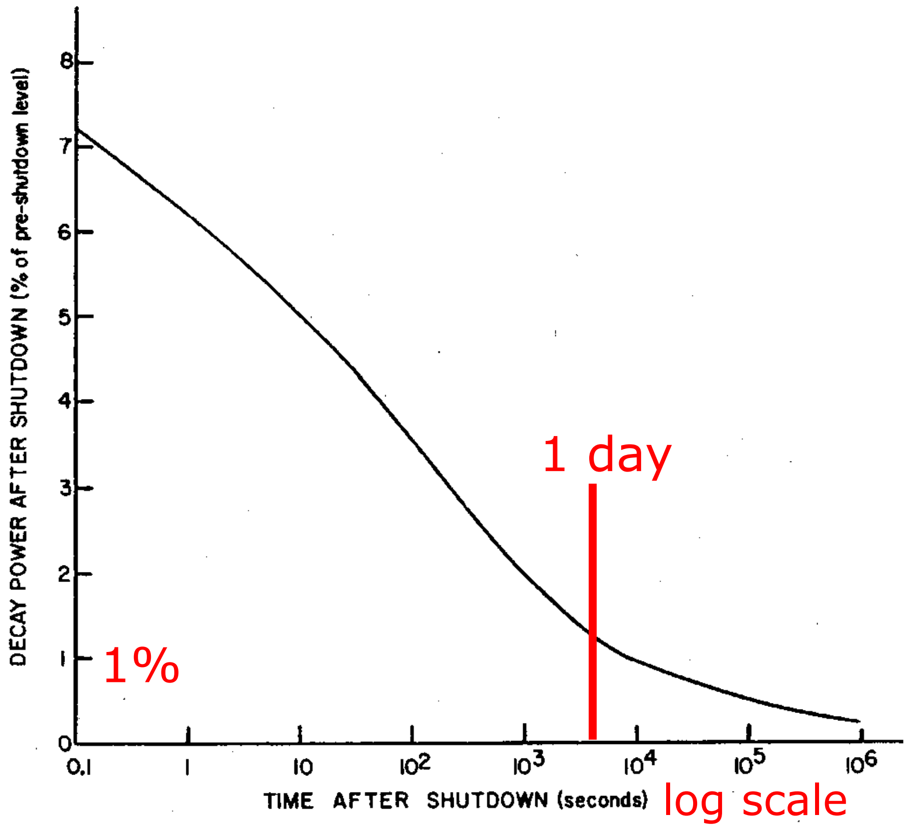


Figure 4-1. THERMAL POWER AFTER REACTOR SHUTDOWN.
After the nuclear chain reaction ceases, radioactivity remaining in the fuel will generate heat as a result of radioactive decay. Assuming that the reactor had been operating for a substantial period, the power generated immediately after shutdown will be approximately 7% of the level before shutdown. For a 3000 MWth reactor, with 1000 MWe capacity, this implies an initial decay power level of about 200 MWth. Due to the rapid decay of short-lived species, this decay heat level decreases rapidly, but is is this heat that imposes the requirement that, in a light-water reactor, cooling water remain available to prevent damage to the fuel.

Source: A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 54

Chernobyl accident

April 26, 1986, 1:24 a.m.

In Ukraine, 130 km north of Kiev, just south of Byelorussia border.

1000 MW_e RBMK. Soviet reactor not build elsewhere (reactor/water/many channels), graphite-moderated, water-cooled. One of four RBMKs running at the site, 17 in the Soviet Union.

Design defects:

> Positive void coefficient (positive feedback from boiling of water) at some operating conditions (related to details of U, C, H_2O)
>
> Insertion of control rods, if in fully withdrawn position, initially makes matters worse.

Test of back-up power over the previous day: Operation at reduced power led to Xe^{135} (9.1 hr half-life) poisoning and full withdrawal of control rods. Further boiling, as low-power test resumed, led to “prompt criticality” and two explosions within 20 seconds.

Fires not fully extinguished until May 6.

First weeks: I^{131} dose

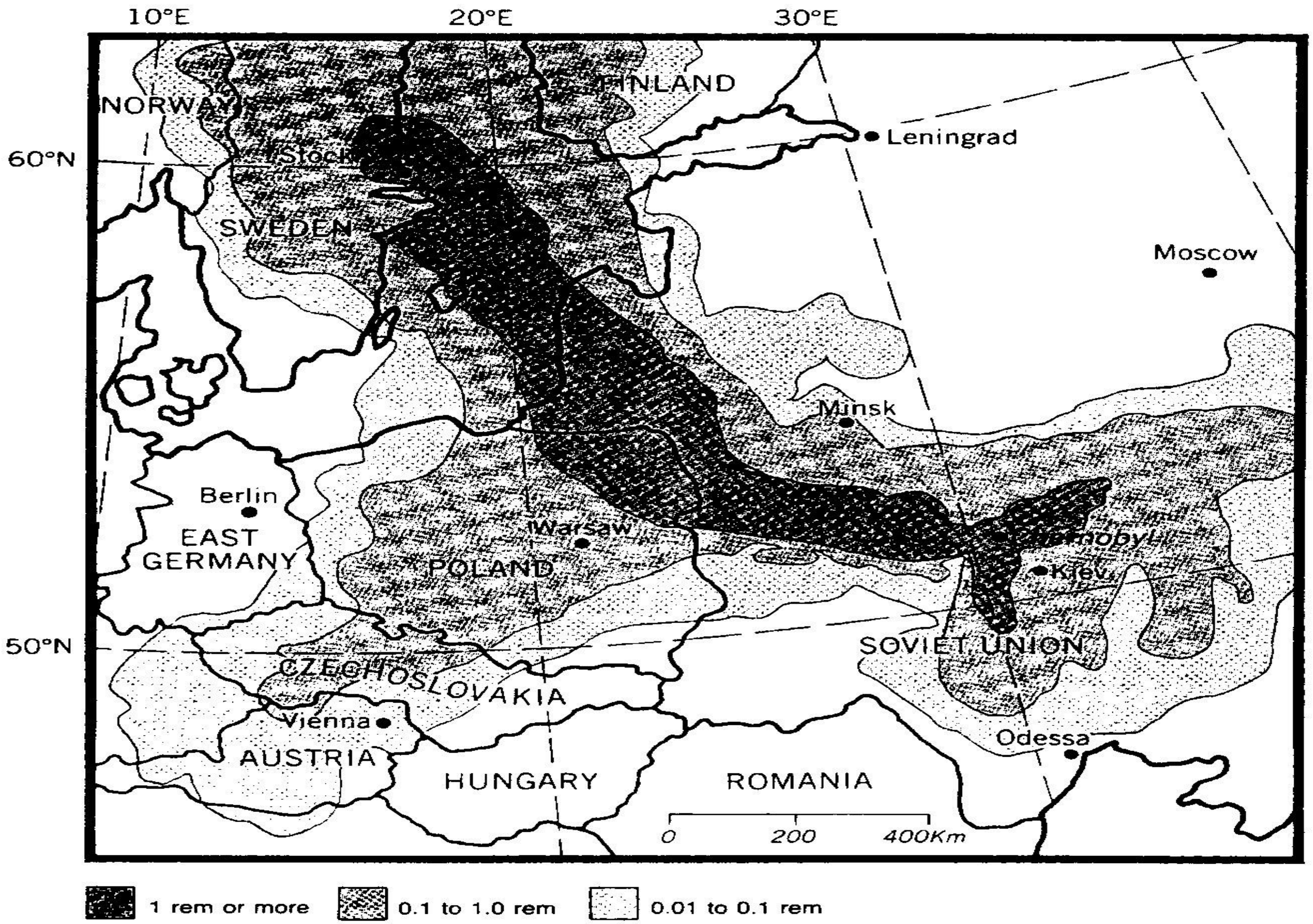


Figure 15.6. The spread of radiation following the Chernobyl accident. During the first four days following the accident, persons in the three gray areas received the iodine radiation exposures indicated.

First few decades: Cs^{137} is #1

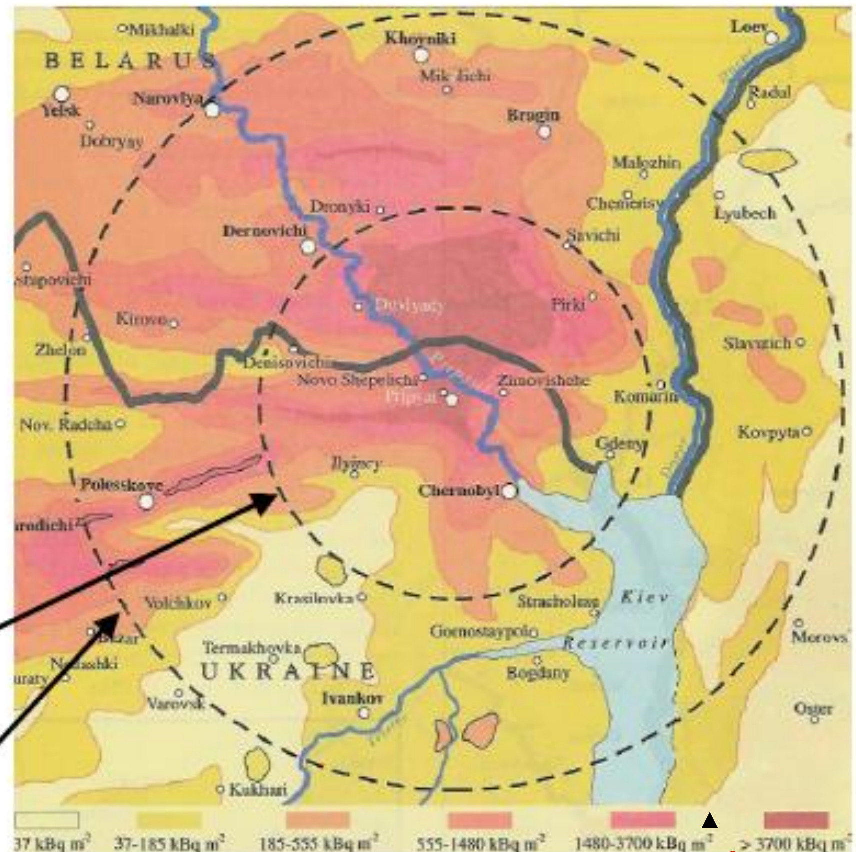
2 MCi of Cs^{137} (30-year halflife) released by Chernobyl

>15 Ci/km^2: radiation control area: > 10,000 km^2 (1/2 of area of NJ)

>50 Ci/km^2): >0.7% chance of radiation-caused cancer death from lifetime external radiation ~ 3100 km^2

18-mile radius (permanently evacuated)

36-mile radius



50 Ci/km^2

(UNSCEAR-2000)

Fukushima Daiichi in better times

***Source*: "After the Deluge: Short and Medium-term Impacts of the Reactor Damage Caused by the Japan Earthquake and Tsunami." Nautilus Institute for Security and Sustainability, March 17, 2011. *Figure 4* : Fukushima Number 1 Nuclear Power Plant**


6
5
1
2
3
4
Fukushima-Daiichi
Plant
Source: TEPCO, undated

Worse times (post March 11, 2011)

Magnitude 9.0 earthquake hits, operating units insert control rods, still need cooling.

Grid power and plant power failed, requiring back-up power for coolant water pumping. Diesel generators, battery backup, and seawater pumps all damaged.

Reactors overheat, releasing radiation via containment cracks, venting of coolant steam, hydrogen build-up and explosions, direct release of contaminated sea water.

Plant’s owner (TEPCO) and Japan’s regulator (NISA) seriously underestimated the vulnerability of backup power.

Accidents and the Dread/Risk Ratio

The dread-to-risk ratio

Dread is deeply felt and deserves respect.

Mutual hostage problem

Will an accident at one plant shut them all down?

The relicensing problem

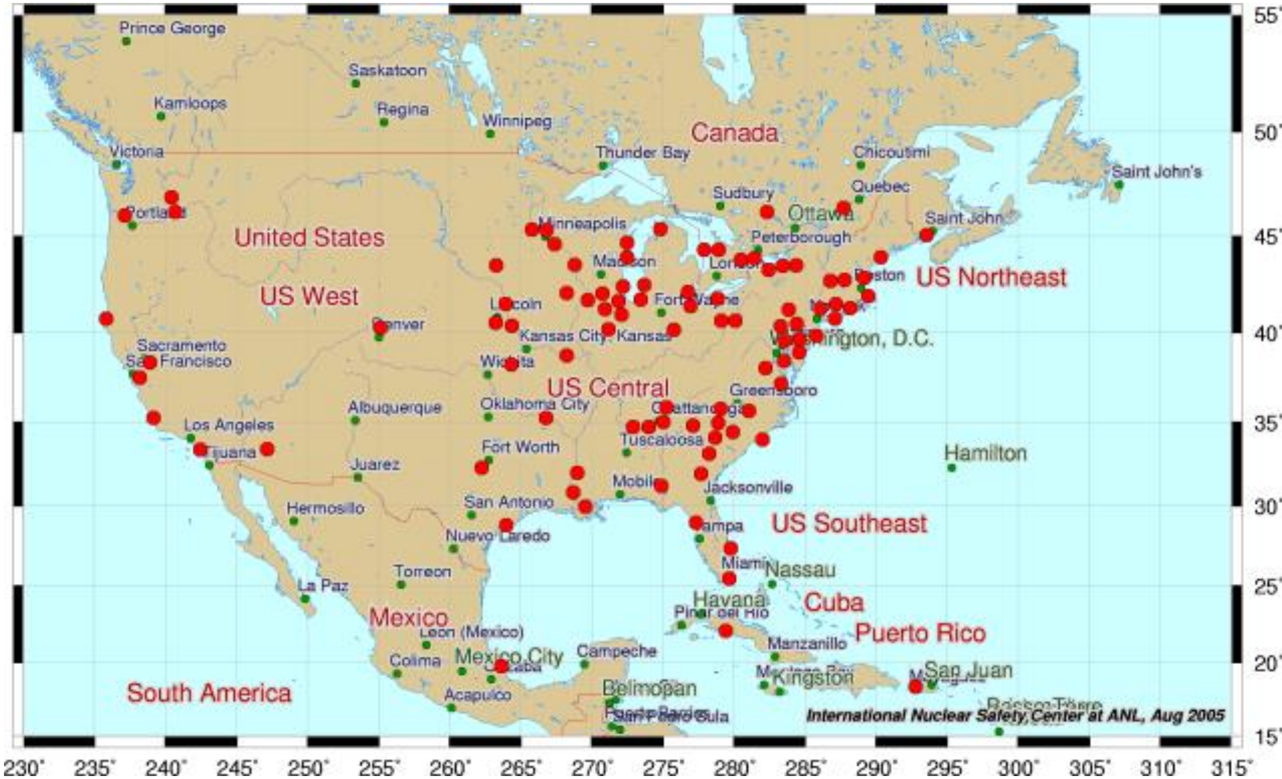
Older plants are more dangerous, because of neutron-weakened structures. But political logic says renew permits and postpone retirement.

WASTE MANAGEMENT

Fission power – with dry-cask storage

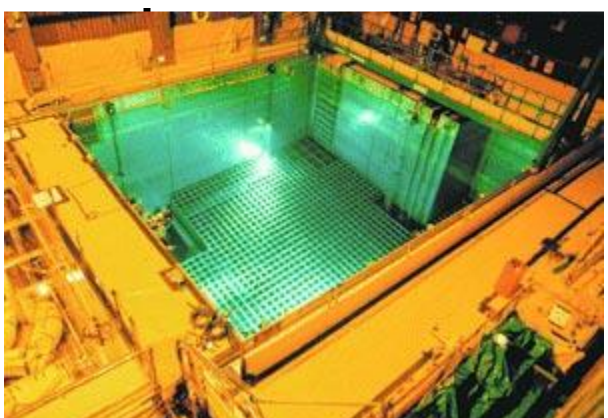
Site: Surry station, James River, VA; 1625 MW since 1972-73,. *Credit*: Dominion.

Current Commercial Nuclear Reactor Spent Fuel Storage

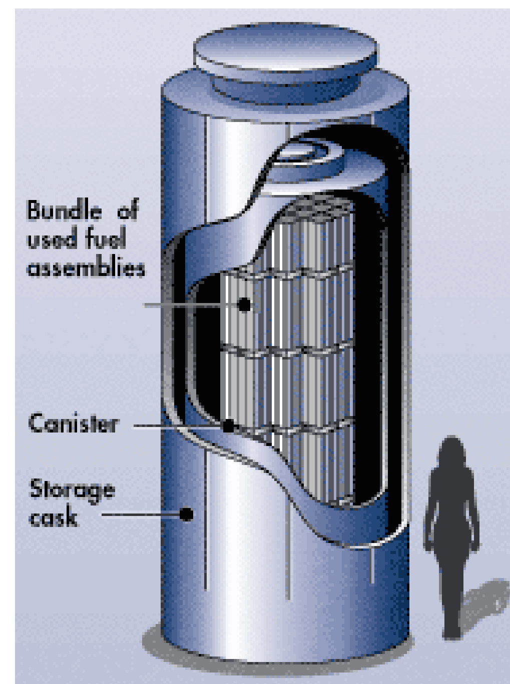


110 commercial reactor sites in the US

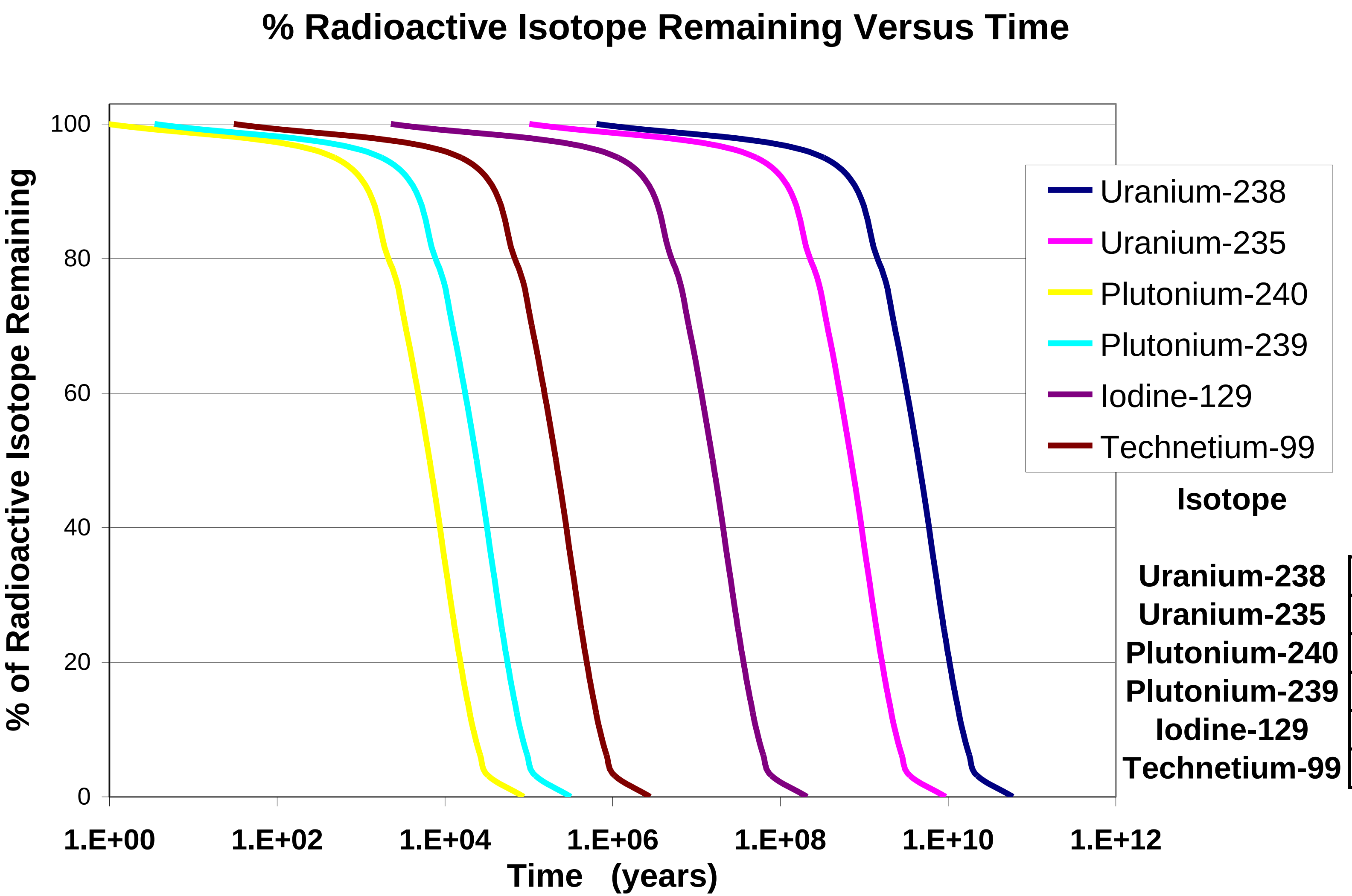
Underwater – spent-fuel storage



Dry storage casks



Long-lived isotopes drive storage goals



Isotope	Half life years
Uranium-238	4.47E+09
Uranium-235	7.04E+08
Plutonium-240	6.58E+03
Plutonium-239	2.40E+04
Iodine-129	1.57E+07
Technetium-99	2.12E+05

Retrievability

Retrievability for some period of time has always been assumed.

But the original promise to the public was that irretrievability could be assured, with no burden passed forwards to future generations

If we cannot yet achieve irretrievability, after all, can a new bargain be struck that promises only retrievability? Irretrievable storage would be postponed until a time, not identified, when greater knowledge makes it achievable.

We would accept that we *were* burdening future generations, as we do when we burn the world's legacy of fossil fuels, reduce the world's biodiversity, and fill the world's natural sinks for CO_2.

Other considerations:

- In the future, plutonium and certain fission products may become valuable resources, worth retrieving.
- On the other hand, retrievable facilities have a greater probability for leakage and dispersal via people and nature.

PROLIFERATION
AND THE FUEL CYCLE

LOOPHOLE

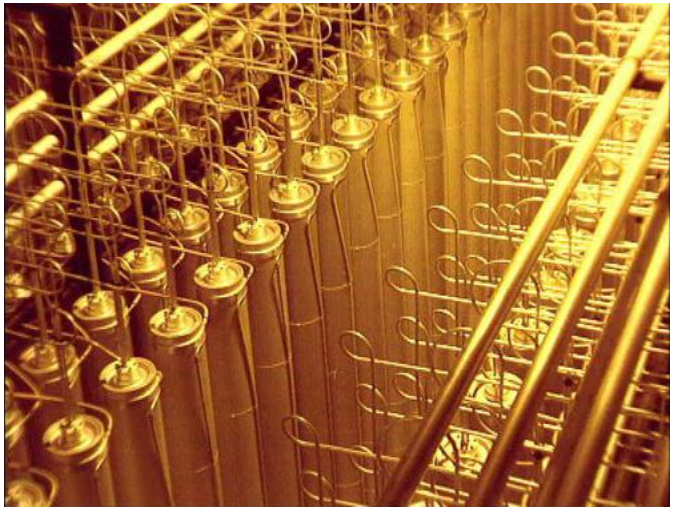
Article IV

1. Nothing in this Treaty shall be interpreted as affecting the **inalienable right** of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination and in conformity with articles I and II

Nuclear-power fuel cycle and nuclear war

Both uranium isotope enrichment (the "front end" of the fuel cycle) and spent-fuel reprocessing to recover plutonium (the "back end" of the fuel cycle) are routes to nuclear weapons.

Nuclear power cannot become a safe global energy source until much stronger international institutions are developed to govern the nuclear power fuel cycle in all countries.



Gas-centrifuges for enrichment

France's reprocessing plant, La Hague

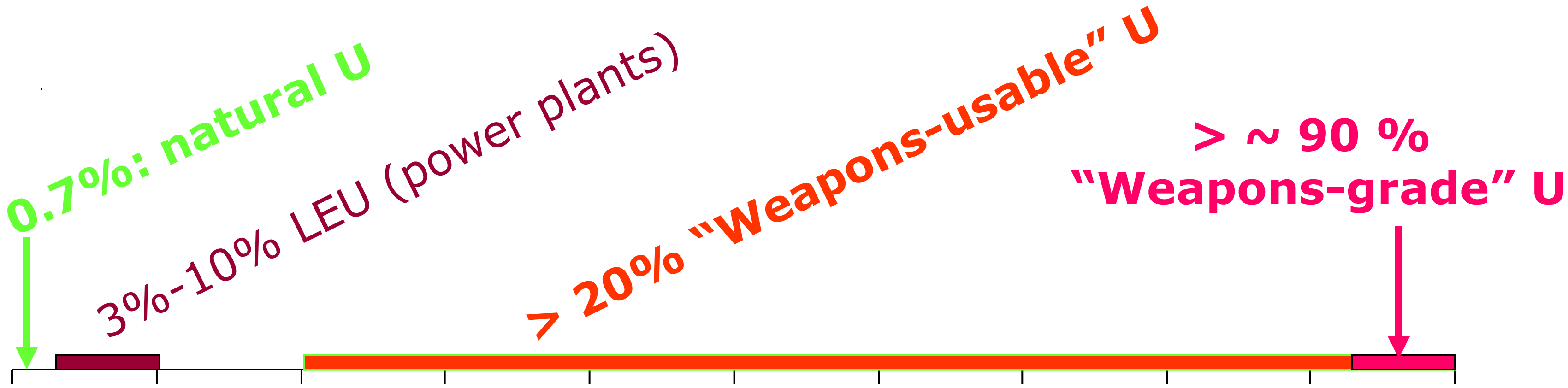
Two main paths to a bomb

U^{235} and Pu^{239} (also U^{233}) are bomb materials

U^{235} exists in nature at 0.007 of natural U. A bomb cannot be made from natural uranium: U must be highly enriched in U^{235}. But the same enrichment facility that can enrich U to reactor-grade concentrations can also enrich to weapons-grade concentrations. So, U^{235} is available from the "front end" of the fuel cycle.

Plutonium does not exist in nature. But when a neutron is absorbed by U^{238}, the result is Pu^{239}. Standard reactor fuel contains Pu^{239} when it is removed from the reactor: about 250 kg for each GW-year of electricity. Pu^{239} can be retrieved from the "back end" of the fuel cycle.

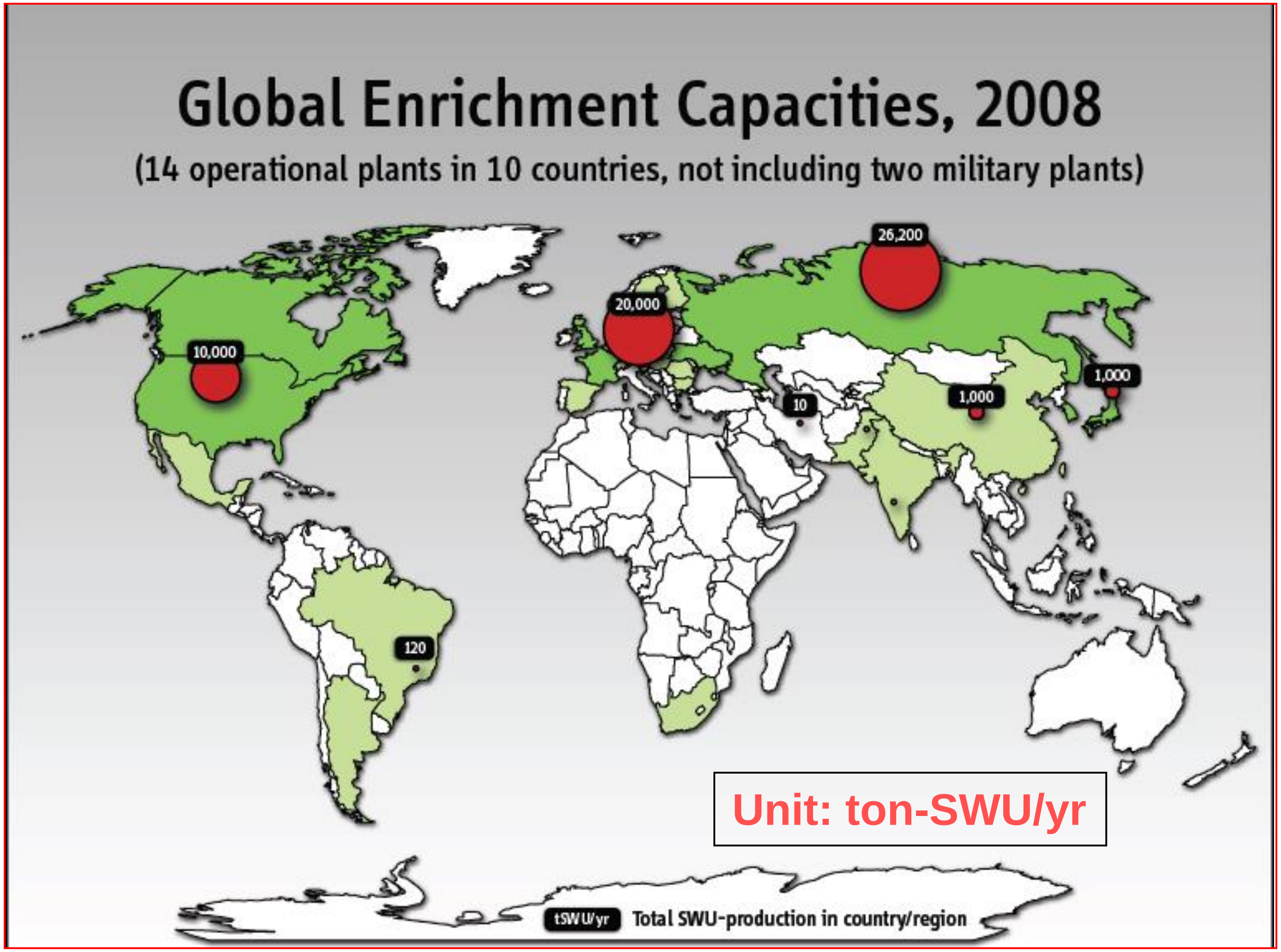
Uranium enrichment



LEU; Low-enriched uranium

HEU: Highly enriched uranium ("weapons-grade" uranium)

Global Enrichment Capacity, 2008

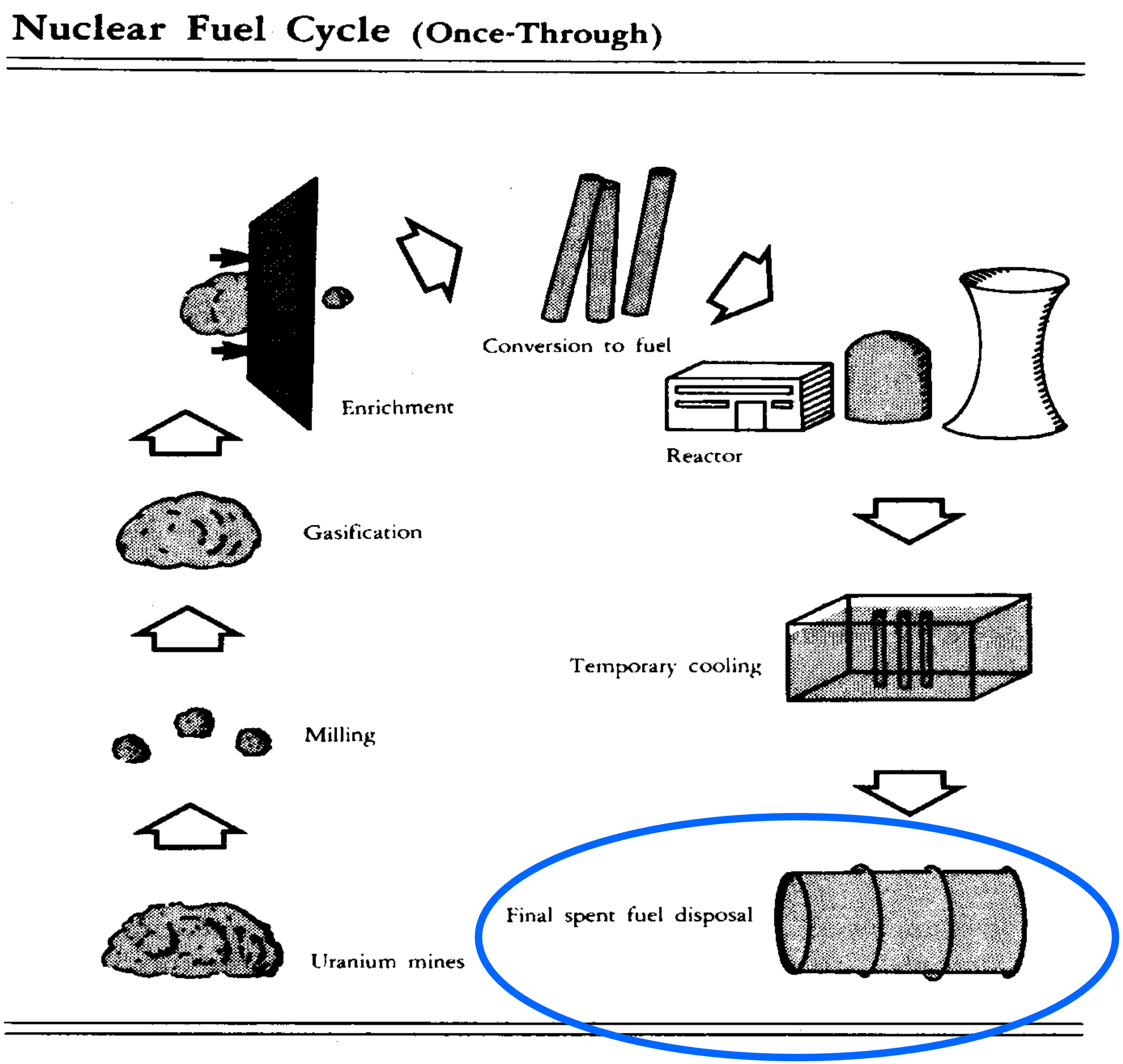


1000 GW plant: 100-150 tSWU/yr

Source: Alex Glaser, MAE Seminar, 4-15-09

A. Q. Khan | The Merchant of Menace
Email this to a friend
Abdul Qadeer Khan stole nuclear designs from the Netherlands, helped Pakistan build a bomb and then created a vast network that traded nuclear secrets and illicit technology across several continents
NETHERLANDS
GERMANY
BRITAIN
SWITZERLAND
ITALY
SPAIN
TURKEY
MOROCCO
SYRIA
IRAN
AFGHANISTAN
KAZAKHSTAN
CHINA
NORTH KOREA
PAKISTAN
LIBYA
EGYPT
SAUDI ARABIA
U.A.E.
NIGER
SUDAN
NIGERIA
MALAYSIA
SINGAPORE
SOUTH AFRICA
Pakistan, Khan's home, where he developed its nuclear-weapons program, then peddled the information and technology
Countries that sought and received Khan's assistance in developing their nuclear-weapons programs
Countries where Khan's network operated
Countries Khan visited for reasons that remain a mystery
KHAN'S DANGERGOUS GAME

"Once-through" fuel cycle



The "once-through" fuel cycle is used exclusively in U.S. civilian reactors.

The Nuclear Age, p. 47

The closed fuel cycle

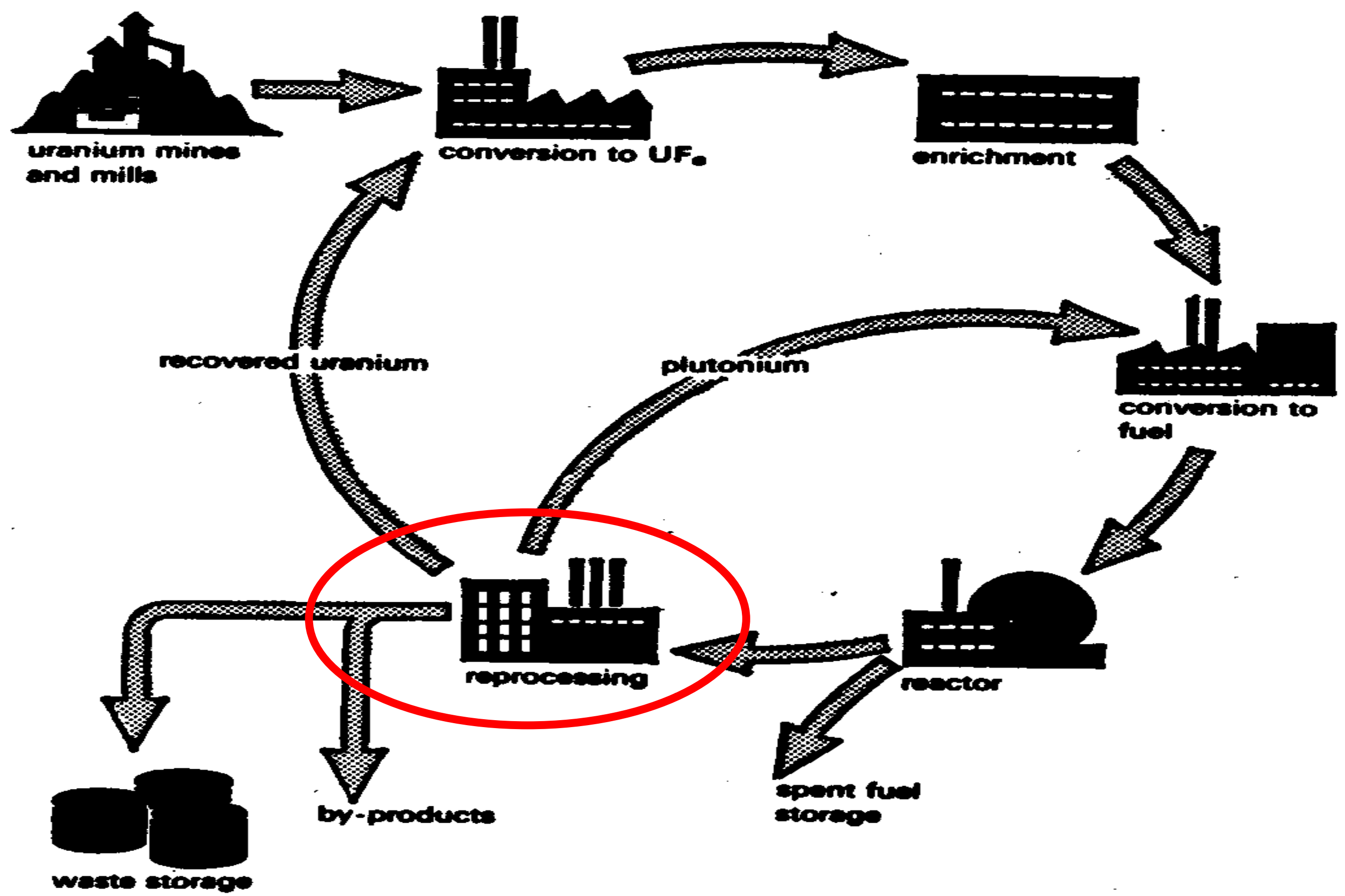


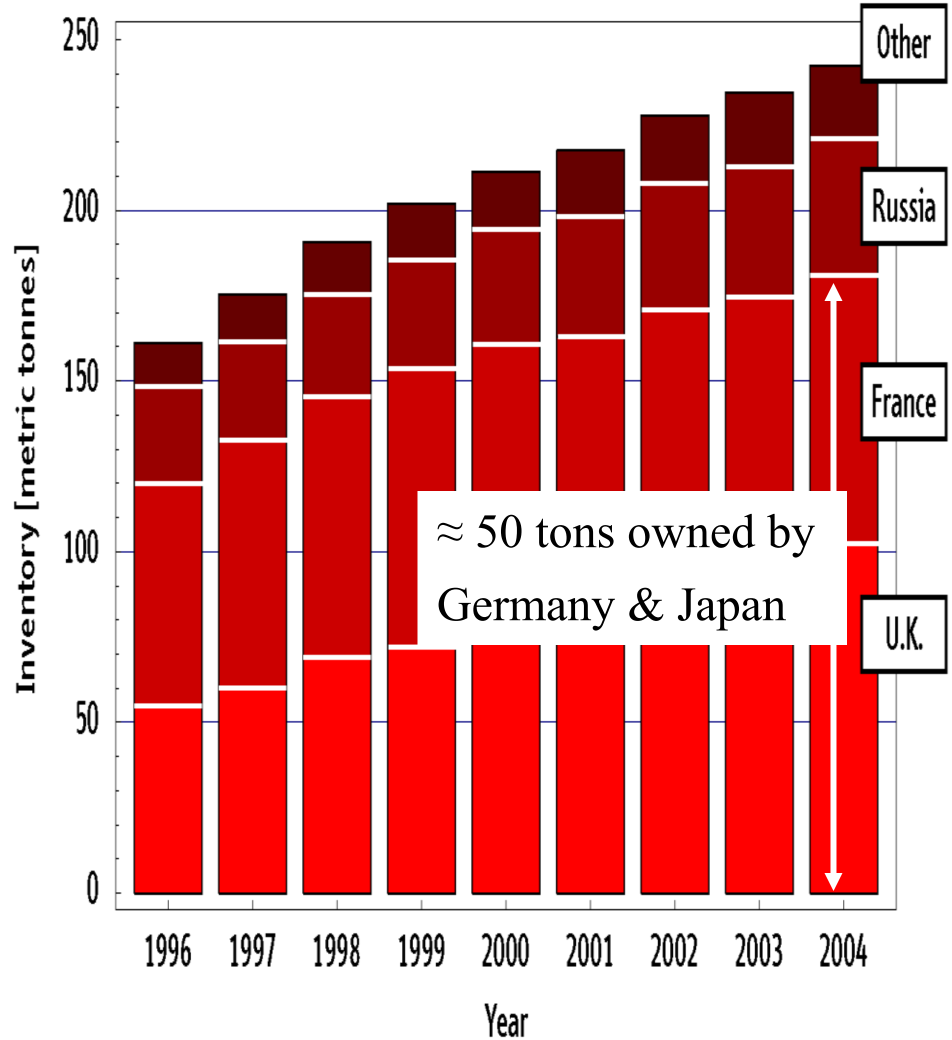
Figure 9 The nuclear fuel cycle with reprocessing.

France’s reprocessing plant at La Hague
(1700 tons/yr)

Separated civilian plutonium

World stock of separated civilian plutonium: 30,000 Nagasaki-equivalents and still growing

(International Panel on Fissile Materials)



What must be acknowledged, when assessing global nuclear-power expansion?

Nuclear power expansion could increase the risk of nuclear war.

A nuclear power plant could be attacked in a war.

Duplicity is rampant today as many countries make the case for their first nuclear power plant.

Bottlenecks will limit the rate of expansion: mining, enrichment, production of pressure vessels, trained people, legal frameworks.

There is little tolerance for error in managing the 350 GW of current reactors and their fuels, if nuclear power is to revive.

The nuclear industry is a poor advocate for itself and doesn't know why.

A world that has delegitimized nuclear weapons provides a more wholesome environment for the prospering of nuclear power.

Main Points

- Most reactors today require low-enriched uranium. Some countries recycle plutonium in spent fuel.
- Accidents: Three Mile Island (1979), Chernobyl (1986), Fukushima Daiichi (2011) undermined the industry.
- Waste management: On-site in dry casks is an attractive, if less than permanent solution.
- Routes to weapons via the nuclear fuel cycle:
  - Weapons-grade U235 via enrichment facilities
  - Separated plutonium via reprocessing and the plutonium economy.
- A substantial global expansion of nuclear power could benefit the climate but has major geopolitical risks.

Lecture Outline

Nuclear science

Nuclear reactors

Three weaknesses of nuclear power

Fusion, briefly

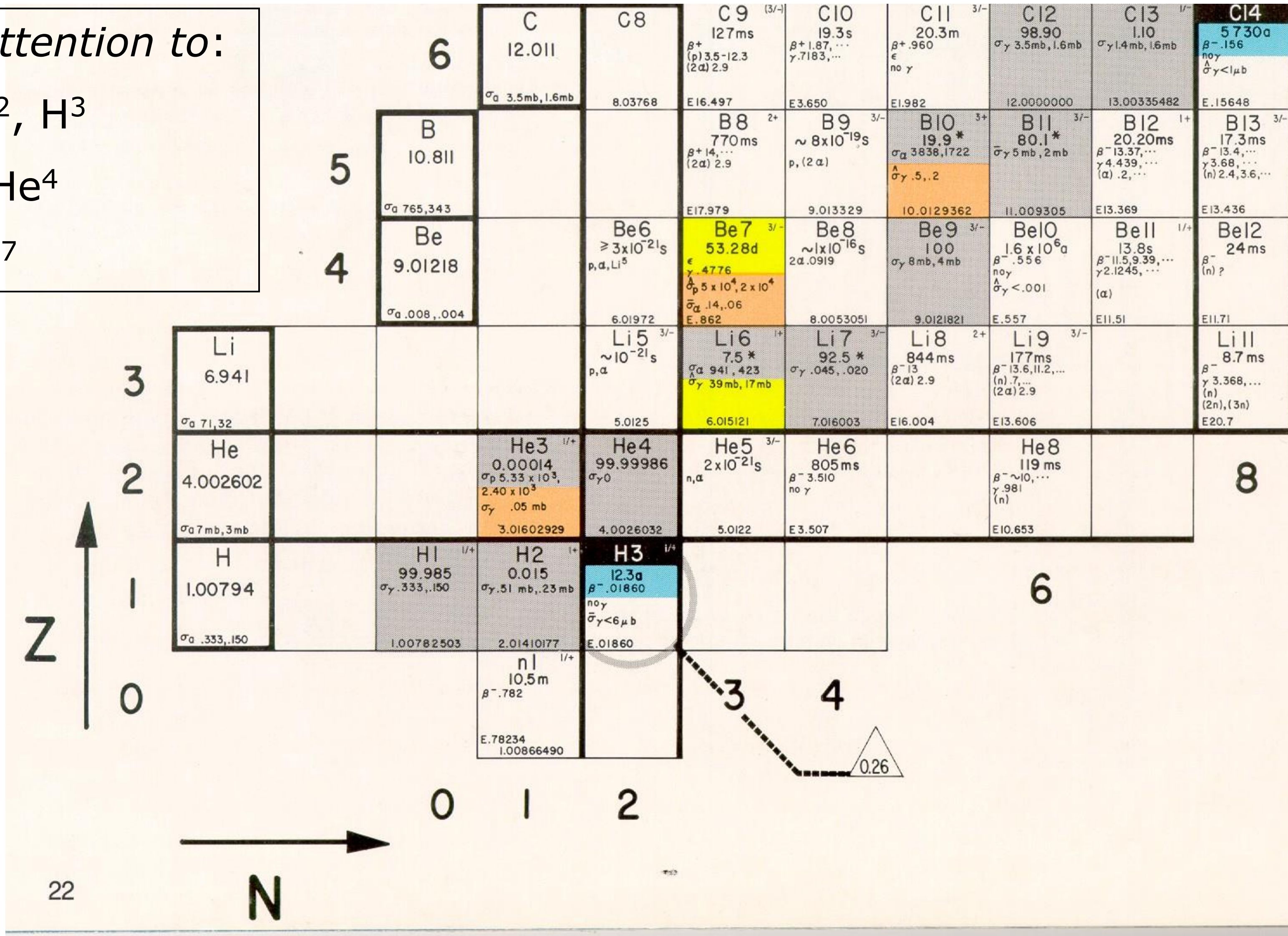
The lightest nuclides

Pay attention to:

H^1, H^2, H^3

He^3, He^4

Li^6, Li^7



Nuclear fusion reactions

I. Deuterium-deuterium (D-D) reaction

D + D → He^3 + n, 50%

→ **T + p**, 50%

Note: T (tritium) is H^3, unstable. Half-life is 12 years.

II. Deuterium-tritium (D-T) reaction.

D + T → He^4 + n.

D-D advantage: D is abundant, T must be manufactured.
D-T advantage: fusion is easier to achieve.

D+T is first-generation fusion. A "lithium blanket" will regenerate T via **Li^6 + n → He^4 + T**.

Li^6 abundance: 7.5%.

Schematic design of a D-T reactor

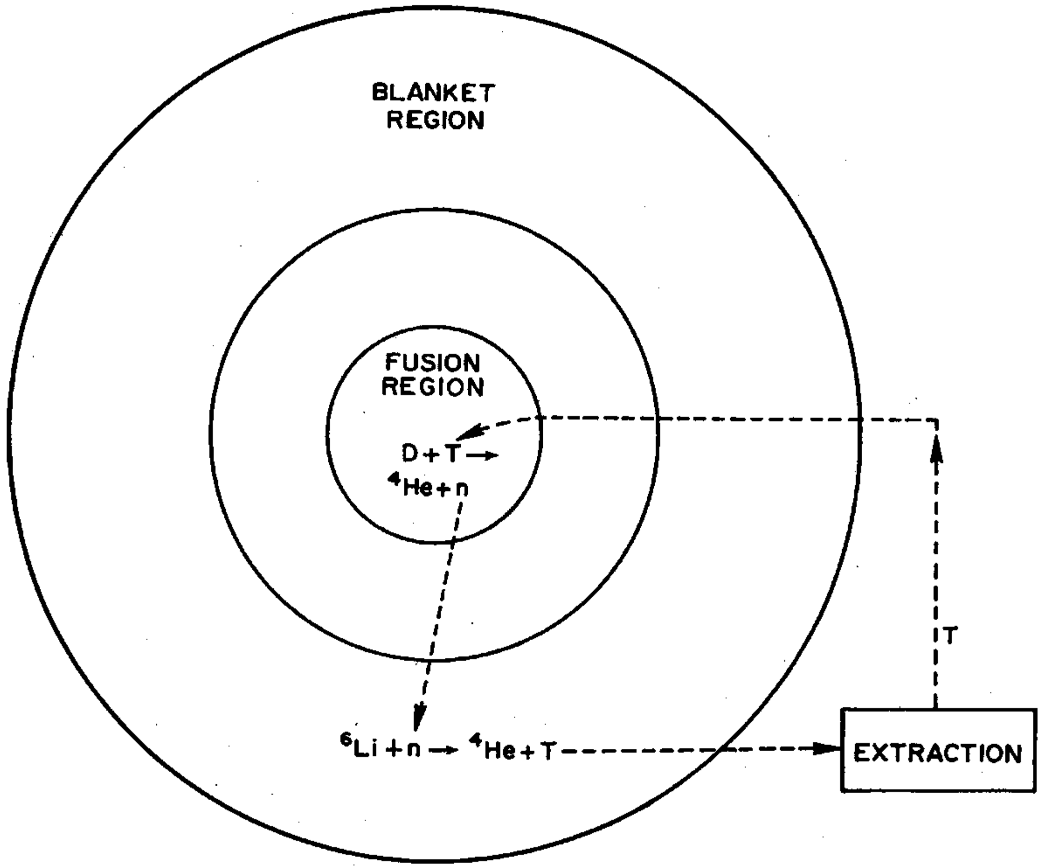


Figure 15-1. SCHEMATIC FUSION REACTOR.
In the fusion region, deuterium and tritium react, producing energetic neutrons. These are stopped in a surrounding blanket. The neutrons react with ^{6}Li to produce tritium for supplying the fusion region; energy is deposited in the blanket, from which heat is removed by a gas or liquid coolant.

A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 236

Fusion power requires confinement

Two approaches: Magnetic confinement and inertial confinement.

In *magnetic confinement* a “magnetic bottle” confines a gas of ionized D and T (overall, charge-neutral). The product of confinement time, temperature, and density is the “figure of merit.” High temperature is key to overcoming the electrostatic repulsion between pairs of nuclei. Magnetic confinement improves with reactor size; this has meant large, expensive experiments.

In *inertial confinement* a beam of photons (via a laser) or ions smashes into and heats a “pellet” of D-D or D-T. Large amounts of external energy are required. The coupling to H-bomb design has kept this field partially classified.

Main Points

- **Fusion of light nuclides is another route to nuclear energy.**
- **It is difficult, but potentially globally significant.**
- **Magnetic confinement (via plasmas) and inertial confinement (beam compression of pellets) are two distinct approaches currently being explored.**

EXTRA SLIDES

Previous Nuclear Energy Problem Set

Abbreviated version

1A. *Age of the Earth* Today there are 215 Pb-207 atoms in the Earth's crust for every U-235 atom... an upper limit on the age of the Earth.

1B. *Space power* Pu-238 power packs have been set on the moon… the mass of Pu-238 needed to provide 10 kW of thermal power.

2. *Fusion* The energy of the neutron released in D-T fusion (D + T → He4 + n) is 14 MeV.

3. (Double credit problem) *Isotopes at Princeton* Write 1-2 pages about a stable isotope ratio or a radioactive isotope used you or a friend (e.g., in molecular biology or geosciences here or in medicine at Princeton Hospital). What properties motivate this application? If the isotope is radioactive, who supplies it, at what cost? What care is taken in its use? What are the rules and practices related to its disposal?

Which isotopes have students written about in the past?

Note: Isotopes in bold are stable

He^3
Be^{10}, soil formation
C^{13}, MRI (C^{12} has no nuclear spin)
C^{14}, archaeology, deep ocean currents
N^{15}, carpenter ants
P^{32}, P^{33}, molecular biology
S^{35}, molecular biology
Xe^{129} (via I^{129}), MRI of lung

Half lives:

Xe^{129}	9 days
P^{32}	14 days
P^{33}	25 days
S^{35}	87 days
C^{14}	5700 yr
Be^{10}	1.6 million years

Second nuclear problem set (never assigned)

1. *Uranium-235 enrichment and separative work* Verify Tom Neff's curve for the combinations of Uranium and SWU required to produce one kg of 4.5%-enriched uranium. (See today's lecture.) Also, compare the separative work required to produce 1) 30 tons of low-enriched uranium, and 2) 20 kg of 90%-enriched uranium (approximately the requirement for a uranium fission bomb). (For the fission plant, you choose the enrichment and the tails. 30 tons is approximately the annual requirement at a 1000 MWe power plant.) What is the ratio?

Guide to the GE Chart of the Nuclides

Top-half colors: Half-life

orange: 1 day – 10 days

yellow: 10 days – 100 days

green: 100 days – 10 years

blue: 10 years – 10,000 years

Half-lives shorter than 1 day or longer than 10,000 years are not a big problem for the waste manager. So carbon-11 (20 minutes) and beryllium-10 (1.6 million years) are uncolored.

Bottom-half colors: neutron absorption cross section

blue: 10 barns – 100 barns

green: 100 barns – 500 barns

yellow: 500 barns – 1000 barns

orange: > 1000 barns

Boron control rods are used to shut down a reactor. The Chart shows that boron-10, the rarer stable boron isotope (20% of boron on Earth), is responsible for the strong neutron absorption.

Gamma Decay

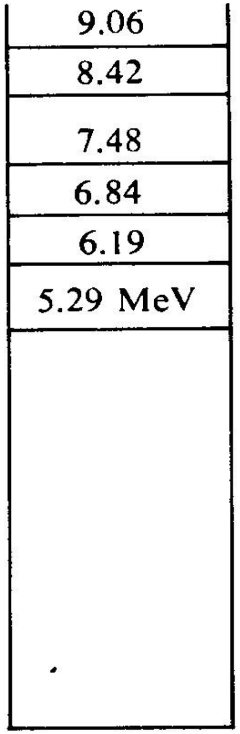


Fig. 2.9 Energy-level diagram for a ^{15}O nucleus.

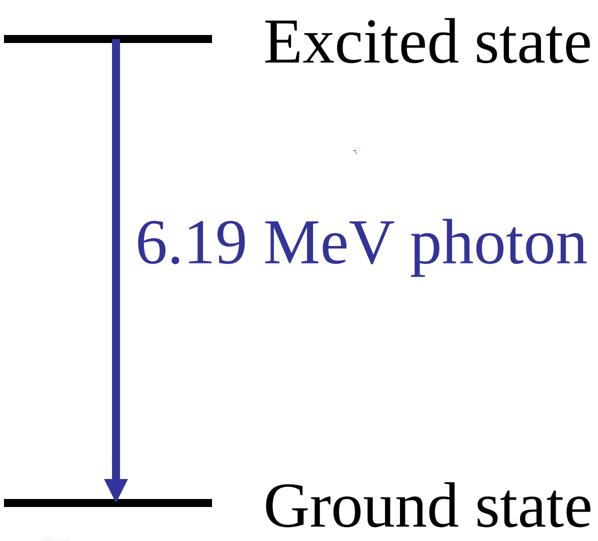
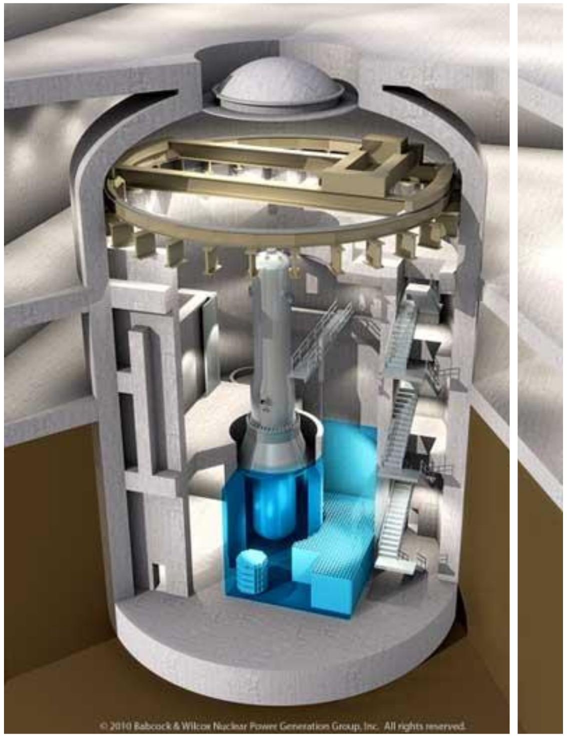


TABLE 15.1
Half-life and Decay Process of Several Radioactive Isotopes

Isotope	*Name of element*	*Decay process*	*Half-life (approx.)*
${}^{14}_{6}C$	carbon	beta	6000 yr
${}^{90}_{38}Sr$	strontium	beta	30 yr
${}^{131}_{53}I$	iodine	beta	8 days
${}^{137}_{55}Cs$	cesium	beta	30 yr
${}^{214}_{84}Po$	polonium	alpha	0.00016 s
${}^{222}_{86}Rn$	radon	alpha	4 days
${}^{226}_{88}Ra$	radium	alpha	1600 yr
${}^{234}_{90}Th$	thorium	beta	24 days
${}^{235}_{92}U$	uranium	alpha	0.7×10^9 yr
${}^{238}_{92}U$	uranium	alpha	4.5×10^9 yr
${}^{239}_{94}Pu$	plutonium	alpha	24,000 yr



Large or Small?

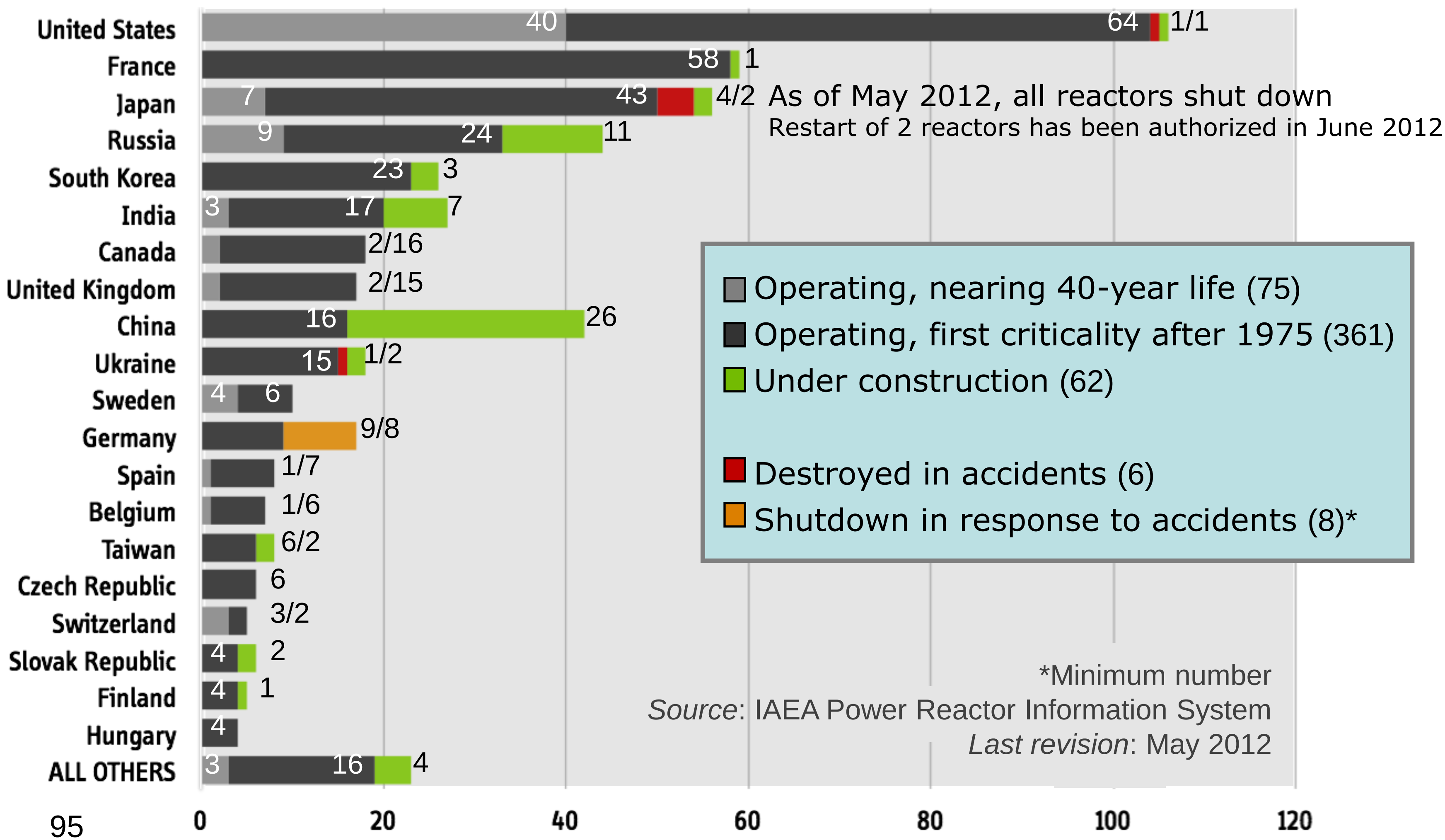
Department of Mechanical and Aerospace Engineering
and Woodrow Wilson School of Public and International Affairs
Princeton University

Synergize 2012
Princeton, November 12–13, 2012

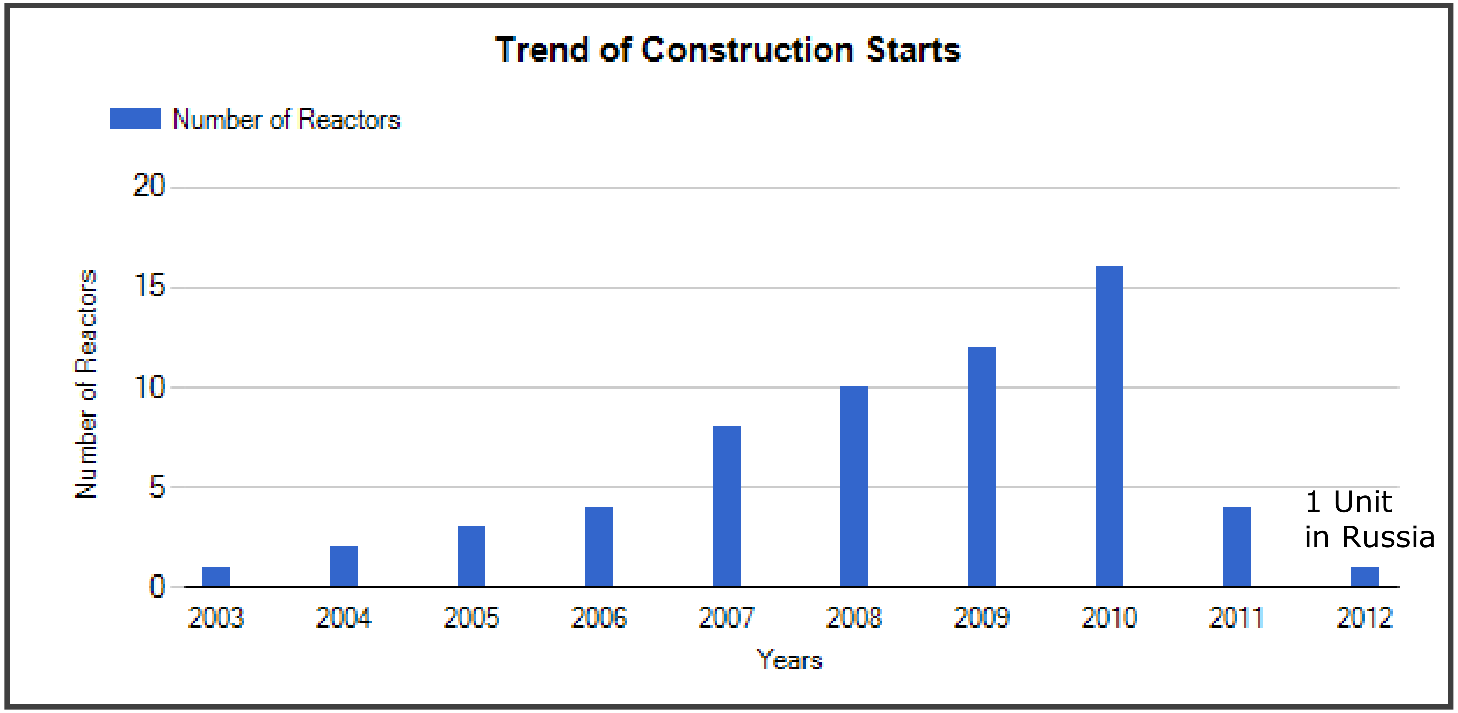
Revision 3

The Global Fleet of Power Reactors is Aging

(20-year life-extensions have already been granted for most U.S. reactors)



Global construction starts by year



Source: Power Reactor Information System (PRIS), International Atomic Energy Agency, http://pris.iaea.org/public/

Information retrieved: June 19, 2012

New Nuclear Power in the United States

Federal Loan Guarantees:
in the Energy Policy Act of 2005, up to $18.5 billion.
Obama Admin. has sought increase to $54.5 billion.

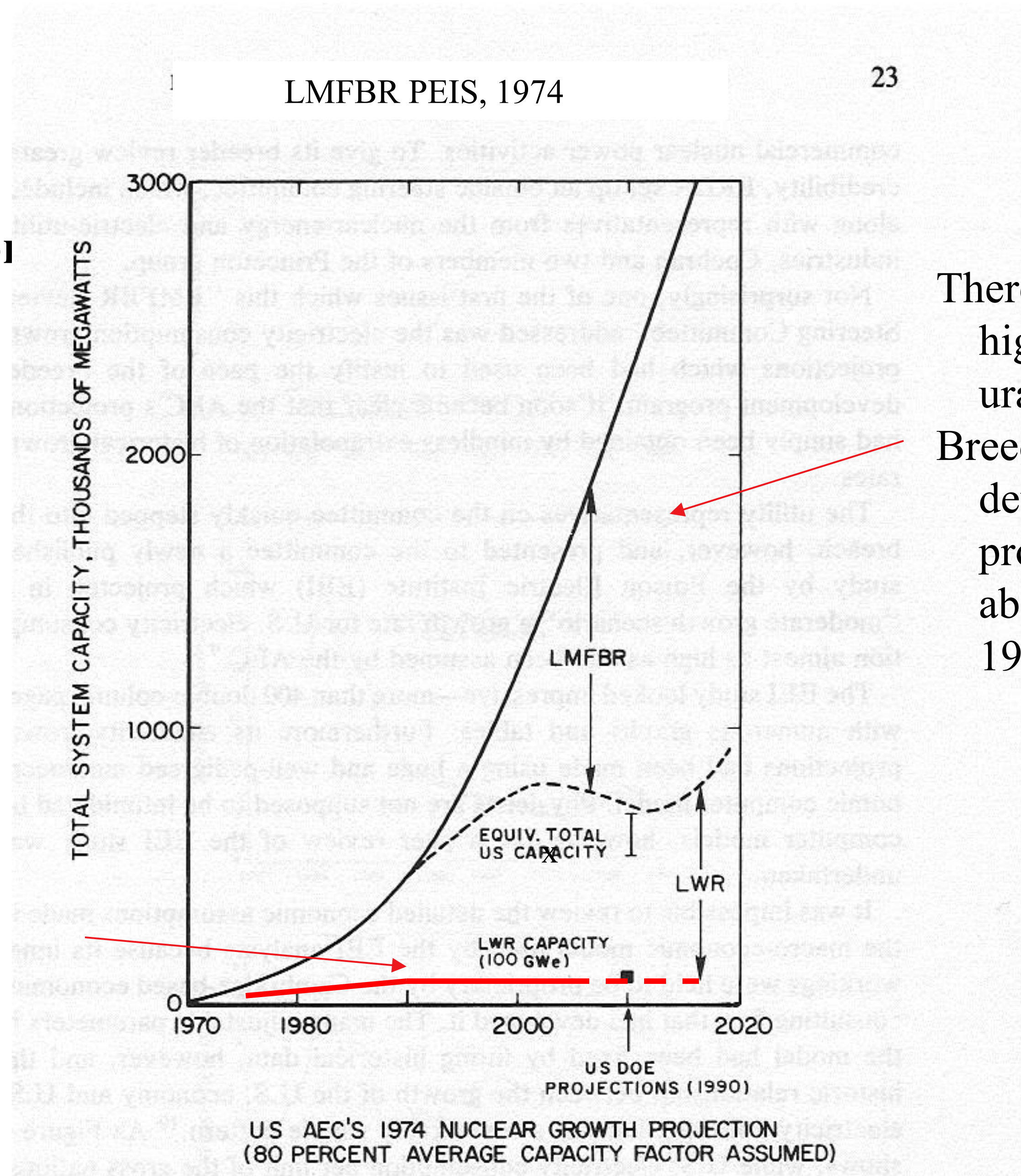
Several proposed construction projects have stalled:
some before and some after the Fukushima Accidents

Vogtle-3 and -4 (Waynesboro, GA) moving forward:
2 x Westinghouse AP-1000, 2200 MWe, expected for 2016, 2017. Combined Construction and Operating License issued Feb 2012. $14 billion investment; $8.3 billion in Federal loan guarantees.

"Let me state unequivocally that I've never met a nuclear plant I didn't like. Having said that, let me also state unequivocally that new ones don't make any sense right now."

John Rowe, Former CEO, Exelon, March 29, 2012. Quoted in
www.forbes.com/sites/jeffmcmahon/2012/03/29/exelons-nuclear-guy-no-new-nukes

1974 U.S. AEC projection for U.S. nuclear power. (We were about to run out of low-cost uranium.)



There is plenty of high-grade uranium ore.

Breeder reactor development program abandoned, 1982.

Actual U.S. nuclear capacity.

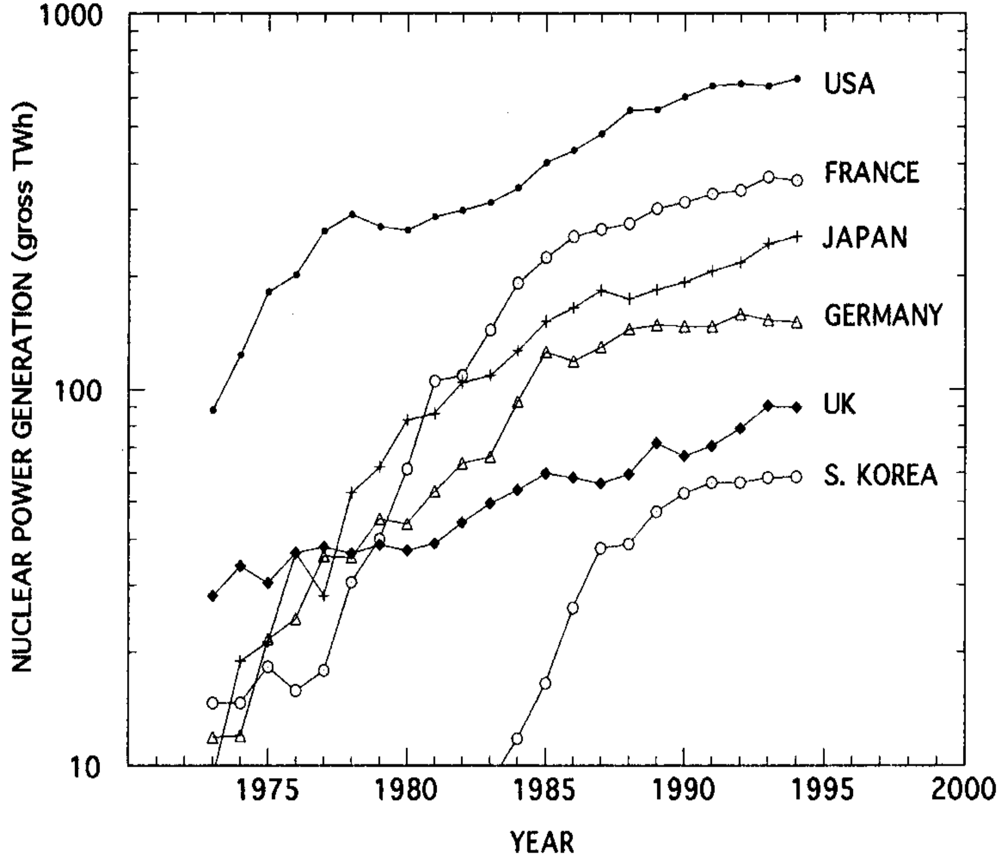


Figure 1.5. Growth of annual nuclear power generation in selected countries, 1973–1994.

Pressurized-Water Reactor

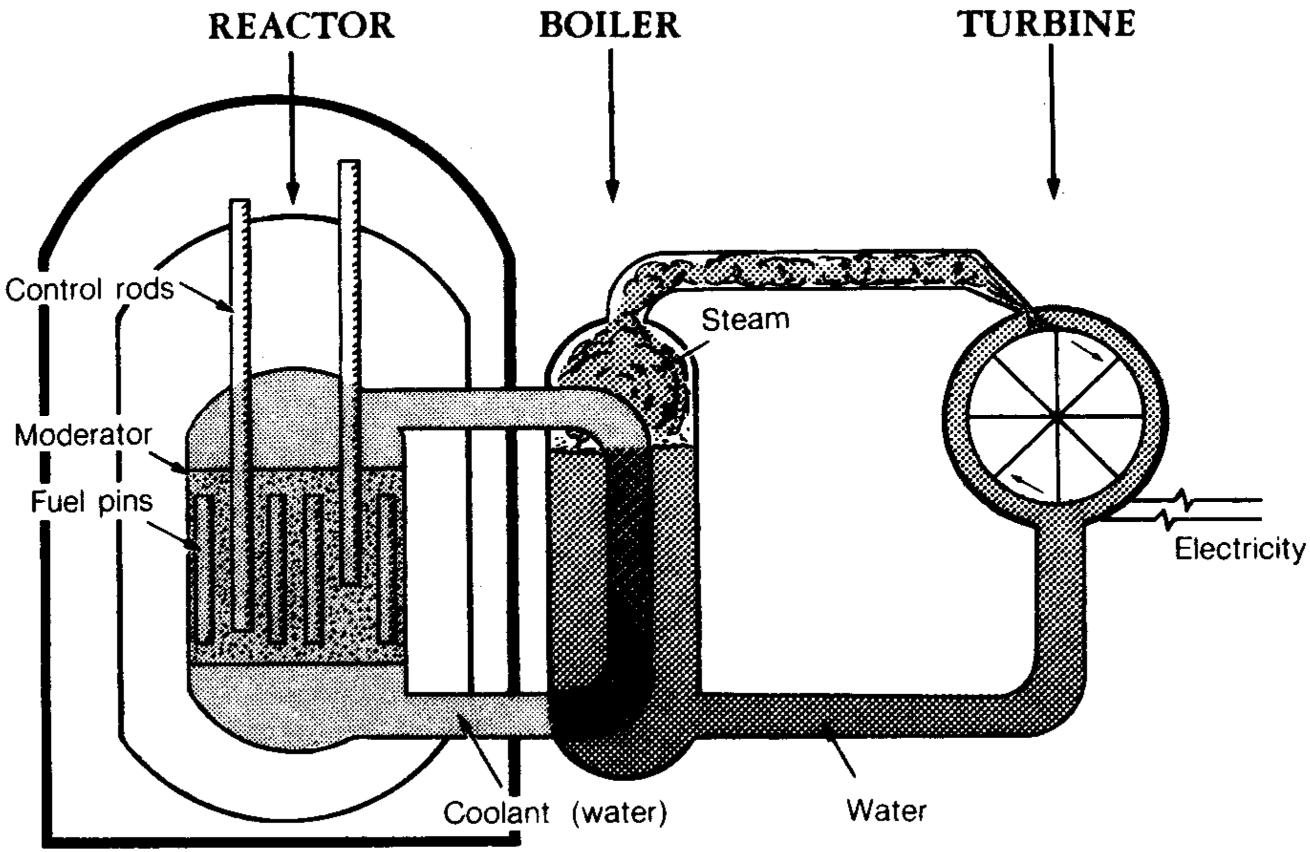


TABLE 2-1.
Representative Characteristics of Commercial Power Reactors (1000-MWe capacity)

	PWR Pressurized-Water Reactor	BWR Boiling-Water Reactor	CANDU Canadian Deuterium-Uranium	HTGR High-Temperature Gas-Cooled Reactor
Coolant	Ordinary water (H_2O)	Ordinary water (H_2O)	Heavy water (D_2O)	Helium gas
Moderator	Ordinary water	Ordinary water	Heavy water[a]	Graphite
Percent ^{235}U enrichment	2-4%	2-4%	0.7%	93% (initial load)
Fertile (bred) nuclide	^{238}U(^{239}Pu)	^{238}U(^{239}Pu)	^{238}U (^{239}Pu)	^{232}Th (^{233}U)
Yearly uranium requirement at equilibrium (tons of U_3O_8)[b]	129	121	125	85
Lifetime uranium requirements (tons of U_3O_8)[b]	4,100	4,020	4,160	2,980
Thermal efficiency (percent)	32-33%	33-34%	28-30%	39%
Approximate once-through external cooling water requirements (gal/min with 15 °F temp. rise)	1,000,000	960,000	1,220,000	740,000
Core type	Fuel rods (bundled into assemblies)	Fuel rod assemblies	Fuel rod assemblies (individually pressurized)	Fuel particles dispersed in graphite blocks
Coolant pressure, psi (MPa)	2,250 (15.5)	1,020 (7.0)	1,490 (10.3)	700 (4.8)
Coolant temperature at exit from core, °F (°C)	620 (327)	545 (285)	590 (310)	1,370 (743)

a. The D_2O moderator is separate from the coolant and is at essentially atmospheric pressure (15 psi).

b. These uranium requirements are abstracted from Table 10-1. They assume recycle of plutonium and uranium for the LWR and BWR, recycle of uranium for the HTGR, and no recycle for the CANDU. (The requirements of present CANDUs are higher than given here.)

…and many others

b.p. is 12.4 MPa at 327°C

A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 23

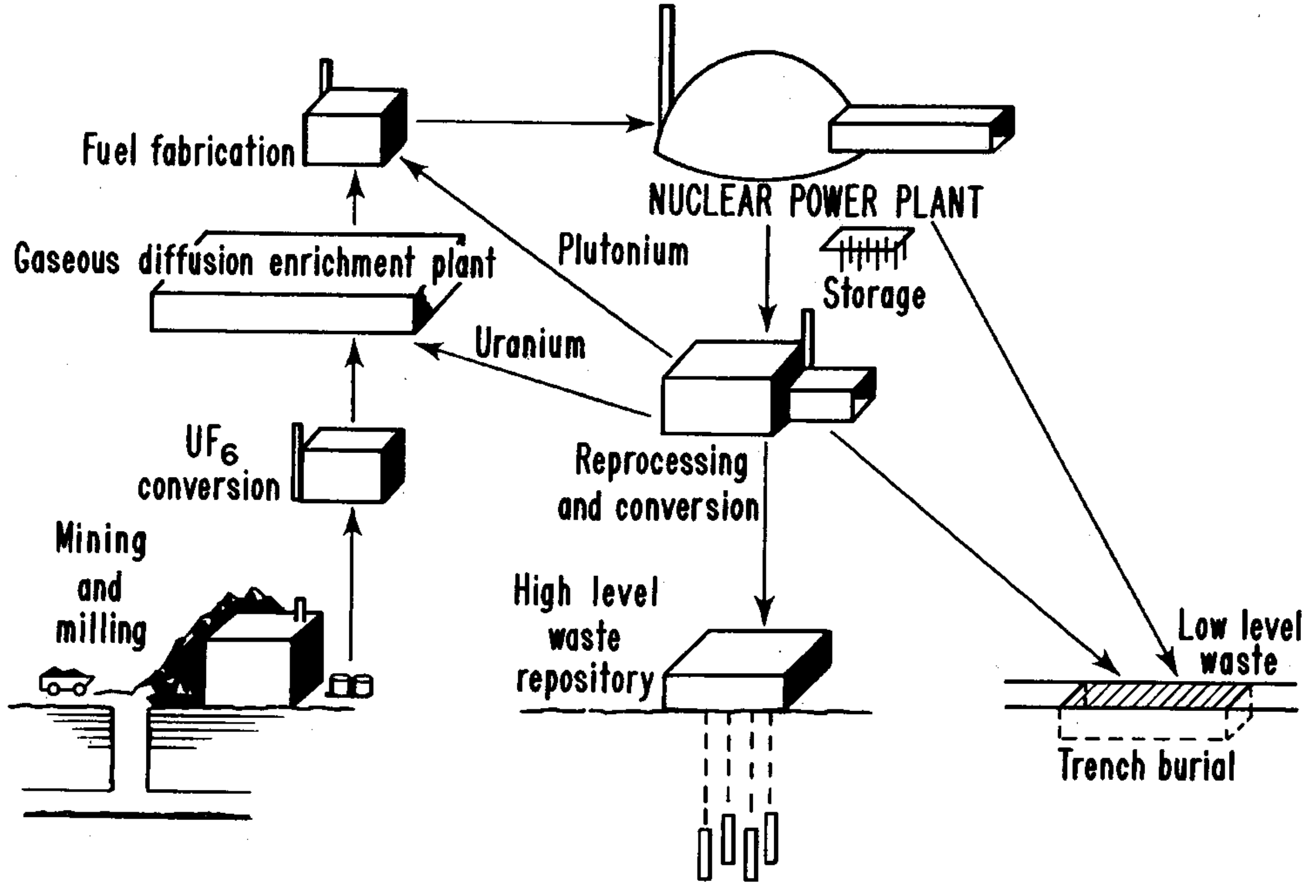
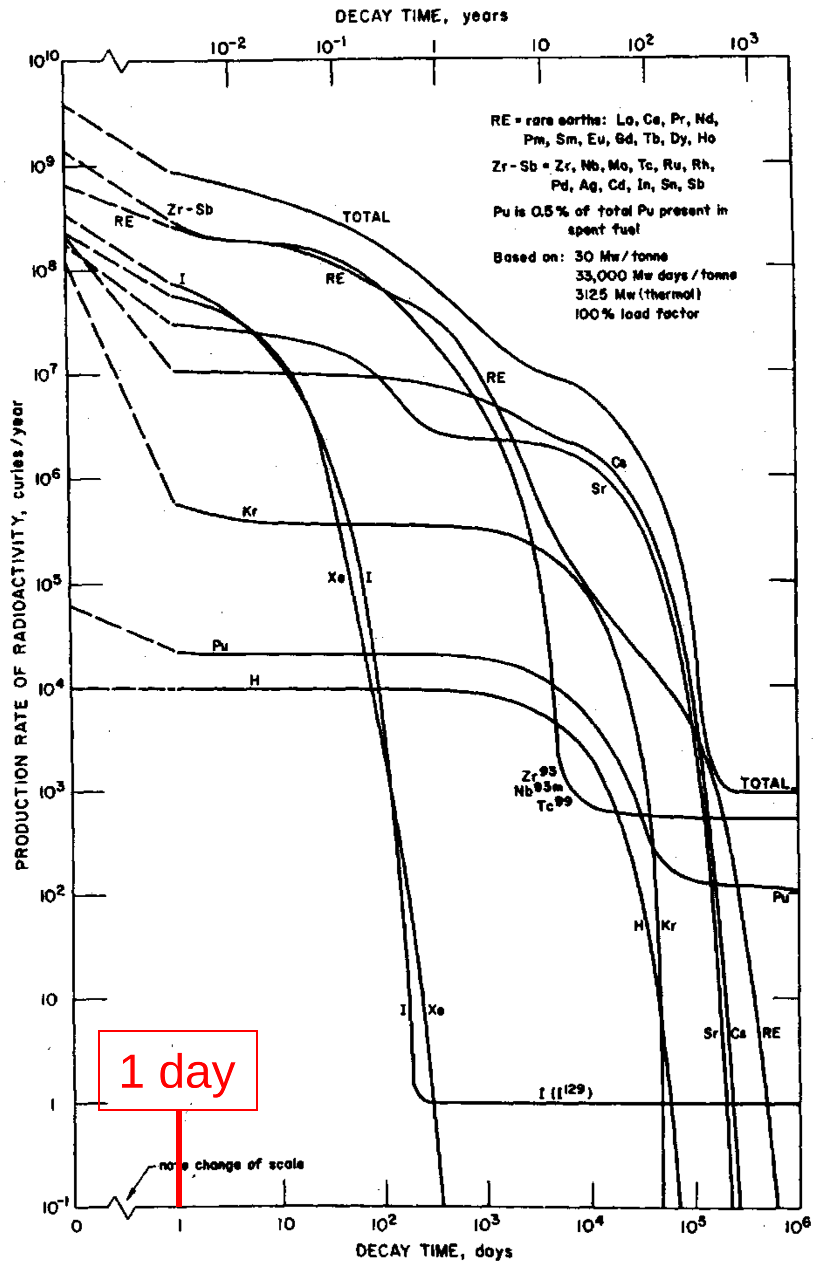


Figure 11-2. MAJOR FACILITIES OF THE LIGHT-WATER REACTOR FUEL CYCLE. The light-water reactor fuel cycle now includes mining and milling operations, facilities for converting yellowcake to UF_6, gaseous diffusion enrichment plants, fuel fabrication plants, and the power plants themselves. A complete fuel cycle which includes recycle of fissile materials would include a reprocessing and conversion plant and a repository for high-level wastes; neither of these facilities now exists. (Figure courtesy of Lawrence Berkeley Laboratory.)

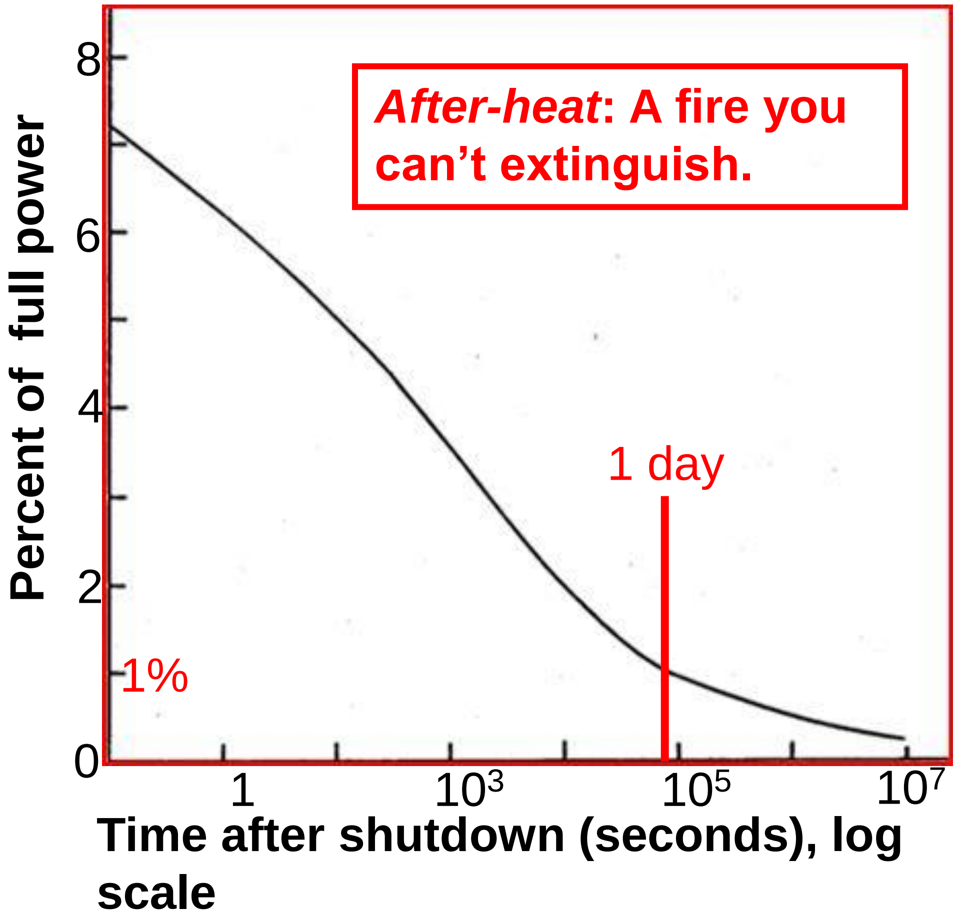
A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 164



A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 172

Nuclear power and "after-heat"

Fukushima Daiichi, before the accident



Source: Nautilus Institute for Security and Sustainability, 2011. *After the Deluge: Short and Medium-term Impacts of the Reactor Damage Caused by the Japan Earthquake and Tsunami.*

Source: A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 54

Chernobyl consequences

Radiation release over the following 10 days. 100% of Kr^{85} and Xe^{133}, 60% of I^{131}, 40% of Cs^{137} and 4% of Sr^{90} in core were released.

Cloud of radiation went North and West, away from Kiev.

Radiation detected in Sweden on April 28 morning at Fosmark nuclear power station. Accident had not been made public by the Soviets.

31 deaths to firemen over the next several months.

"It is anticipated that many additional deaths will occur from these exposures in the future, as is to be expected given the long latent period for radiation-induced cancer" [Bodansky, p. 224].

"Different perspectives on the impact of Chernobyl may be stated as follows: (a) the accident may lead to about 50,000 cancer deaths; (b) Chernobyl will not increase the cancer rate in the former USSR by as much as 0.1%; (c) the average annual exposure from Chernobyl in the former USSR is less than 1% of the average *annual* radiation exposure of an individual in the United States. Depending on which of these formulations appears most appropriate, Chernobyl may be considered a major global disaster or no more than a serious accident. [Bodansky, pp. 227-228.]

No mention of regional land use impacts or European nuclear energy policy reactions in Bodansky.

Accidents

The dread-to-risk ratio

Dread is deeply felt and deserves respect.

“Explaining” that the problem is minimal (K-40 internal dose, cosmic rays, radon) doesn’t work.

The relicensing conundrum

The nuclear industry is doubtful about the wisdom of 80-year permits. Doesn’t that mean that the public should be doubtful about the wisdom of 60-year permits?

The mutual hostage

Will an accident at one plant shut them all down?

The military target

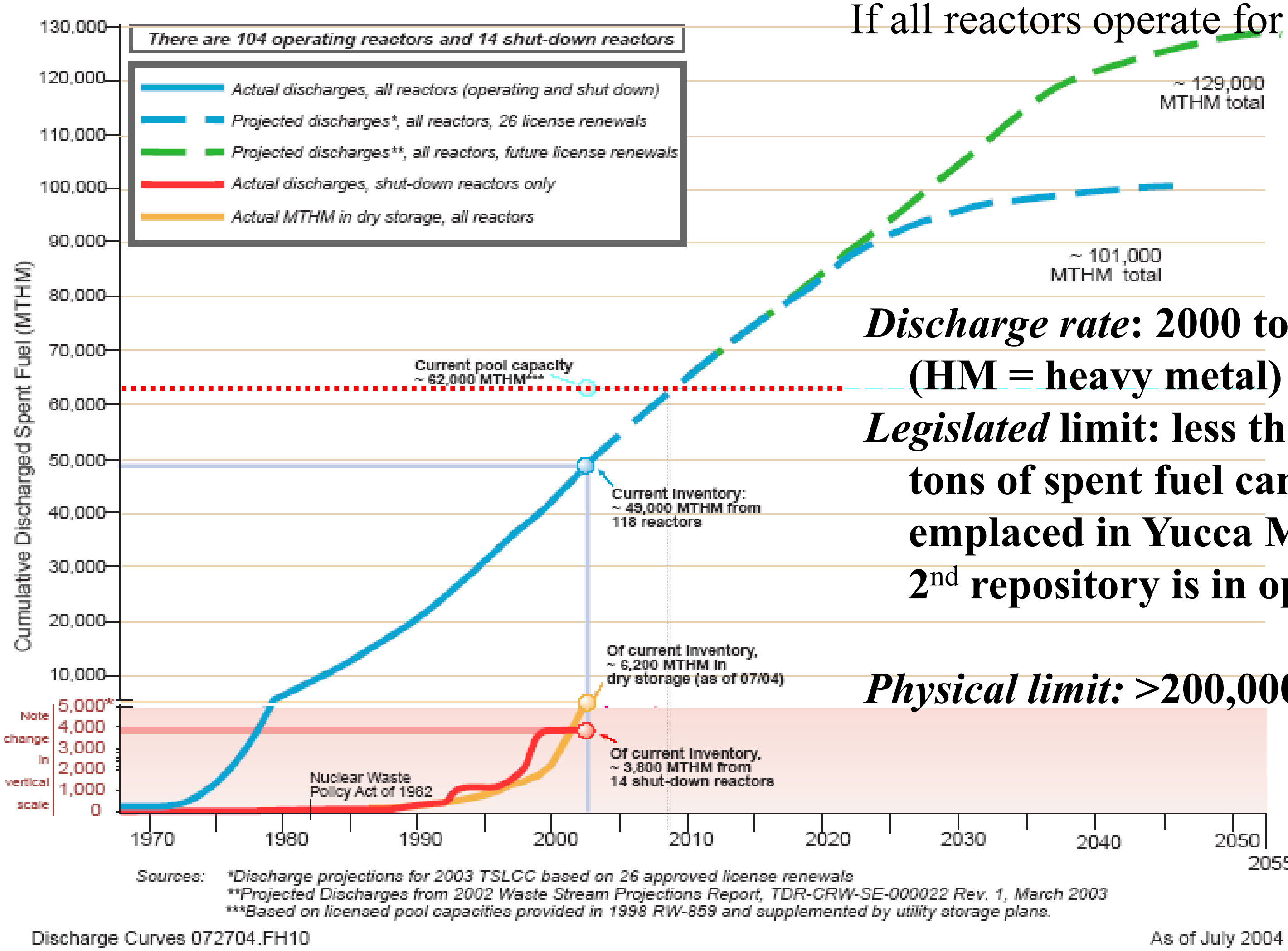
There is no taboo against attacking a nuclear power plant.

The nuclear industry then and now

Risk	Before Collapse	Resurgence stimulus
Economic	Average Cost Of Service (COS) in Rate Base	Markets & Production Tax Credit EPAct2005
Financial	High interest rates (e.g., 17%)	Project Finance & Loan guarantees EPAct2005
Regulatory	Separate construction & operating licenses	Combined Construction and Operating License (COL)
Design	Unique and owner-specific	Standard Design certification Advanced Passive LWR
Economy	Energy growth rate 2xGDP	Less energy-intensive economy, lower demand growth
Construction	Site-specific	Modular construction Ship building, QC, cost
Human element	Minimalist training	Professionalism, heavy training focus

Source: Brian Hamilton, 2007

Historical & Projected U.S. Spent Fuel Discharges (DOE, 2004)



If all reactors operate for 60 years.

***Discharge rate*: 2000 tons HM/yr**
(HM = heavy metal)

***Legislated* limit: less than 63,000 tons of spent fuel can be emplaced in Yucca Mt before 2^{nd} repository is in operation.**

***Physical limit:* >200,000 tons**

Source: Hal Feiveson and Frank von Hippel

U.S. storage requirements

<u>Deep Geological Storage Requirements:</u>

Undisturbed disposal systems for radioactive material shall be designed to provide storage for 10,000 years which does not expose any member of the public to greater than 15 mrem via any potential pathway.

<u>On-Site NRC Regulated Storage Requirements:</u>

Non-permanent storage of nuclear waste which does not expose any member of the public to greater than 25 mrem/yr.

Current on-site storage is designed for ~ 100 years.

Nuclear Waste Storage

What is Nuclear Waste?

- Spent nuclear fuel
- Uranium mill tailings
- Naturally occurring materials (radon)
- Research waste (polonium strips for removing static charge)
- Fire detector alpha-radiation emitters
- Radioactive drugs

Waste Disposal and Retrievability

Isn't it time to ask the world to settle for retrievable storage?

Site: Surry plants on James River, VA; 1625 MW since 1972-73,. *Credit*: Dominion.

A leading alternative, *transmutation*, is peculiar: The goal is to turn isotopes with half-lives of thousands of years into short-lived isotopes.

Would you rather have a 3000-year half-life isotope or a 30-year one?

Yucca Mountain: The U.S.'s Proposed Single High-Level-Waste Repository

Southwest Nevada

Pro

Nearest town ~ 12 miles away. Pop. of ~ 10 people

Storage facility 300 meters below surface, 240 meters above the water table.

14 cm precipitation per year

~1 cm infiltration per year

Total Capacity = 63,000 metric tons commercial nuclear waste
7,000 metric tons military waste

Con

Unsaturated-oxic conditions

Relative humidity in mountain ~ 98%

Storage cask lifetime ~ 10,000 years

DOE Geologist: mountain repository could flood in the next 10,000 years.

An earthquake could displace a slug of water up to repository levels where canisters at near boiling temperatures could crack

Nuclear Waste Storage Outside the US

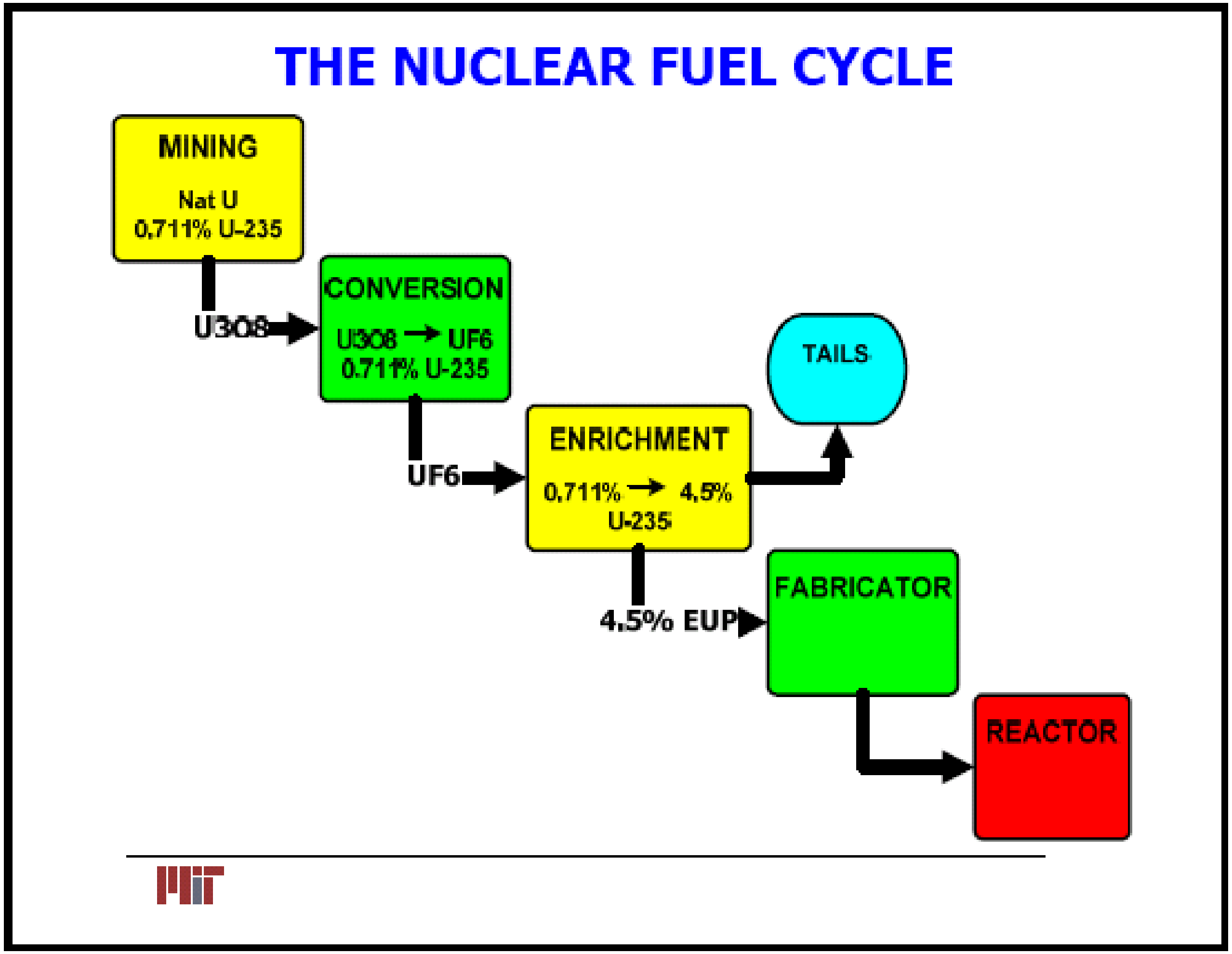
Sweden: KBS-3: waste is encapsulated in iron, then copper, then deposited in a layer of bentonite clay, in a circular hole, drilled in a cave 500 meters below surface into bedrock. After 100,000 years, radioactivity is at the same level as that of uranium ore mined to make the fuel.

Million year lifetime. Saturated conditions-anoxic

France: On-site Storage.

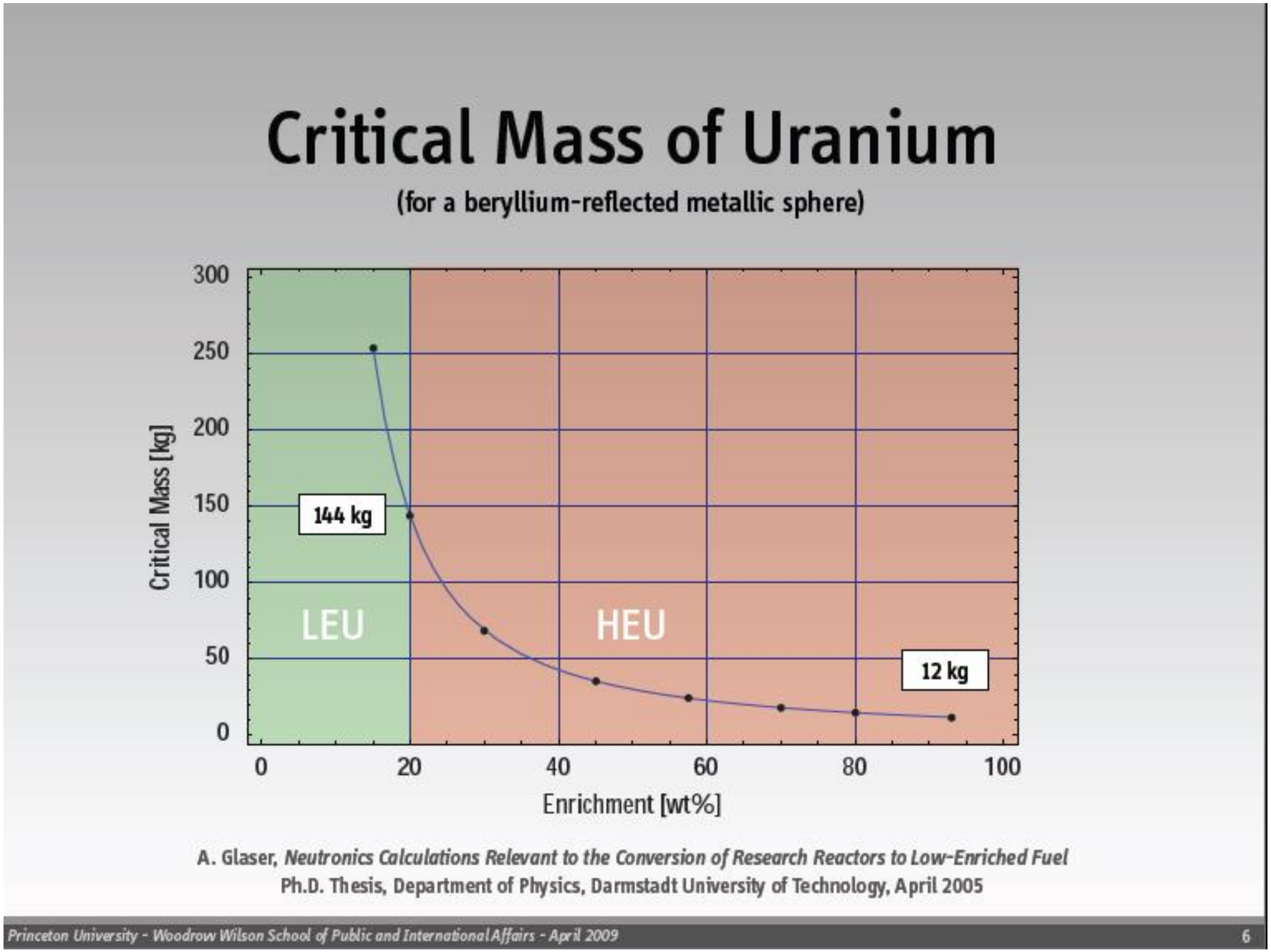
Russia: on-site storage and open waters

Uranium from mine to reactor



Source: Tom Neff, MIT, talk in January, 2007

Critical Mass of Uranium



Source: Alex Glaser, WWS Seminar, 4-14-09

Khan network showed:

- Limitations of traditional policies
- Global diffusion of WMD programs
- Growing access of non-state actors to WMD technology
- Emerging illicit market for WMD
- Increasing number of states with WMD programs who are able to pass the knowledge to third parties

The Plutonium Breeder Reactor

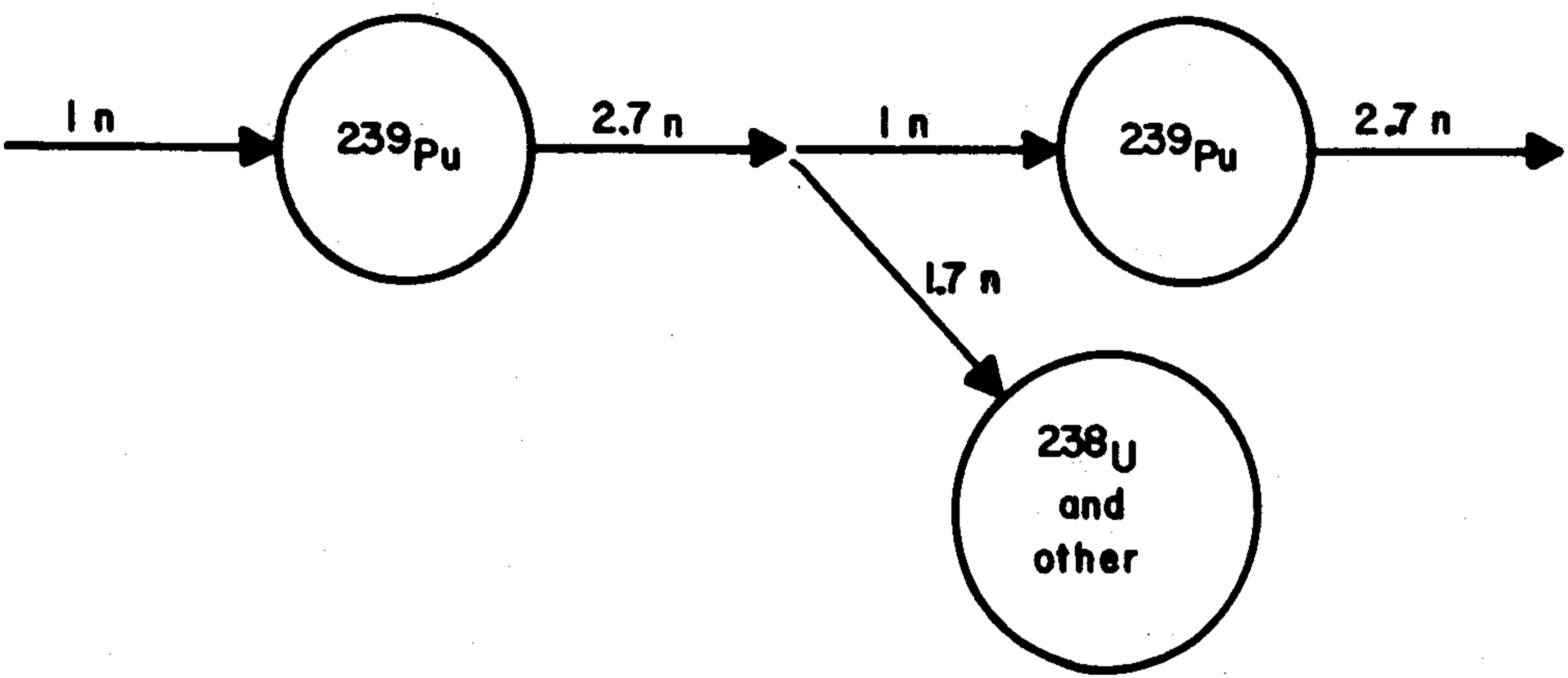


Figure 10-1. SCHEMATIC NEUTRON BALANCE FOR A URANIUM–PLUTONIUM FAST BREEDER REACTOR.

In a neutron spectrum typical of a fast breeder reactor, absorption of 1 neutron by ^{239}Pu yields, on the average, 2.7 neutrons. Of these, 1 is absorbed by ^{239}Pu, maintaining the chain reaction, and 1.7 are absorbed by other material, including fertile material, yielding about 1.2 fissile nuclei, predominantly ^{239}Pu. Thus more fissile material may be produced than is destroyed.

A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 146

Proliferation and the Futility of a Two-tier Supplier-User World

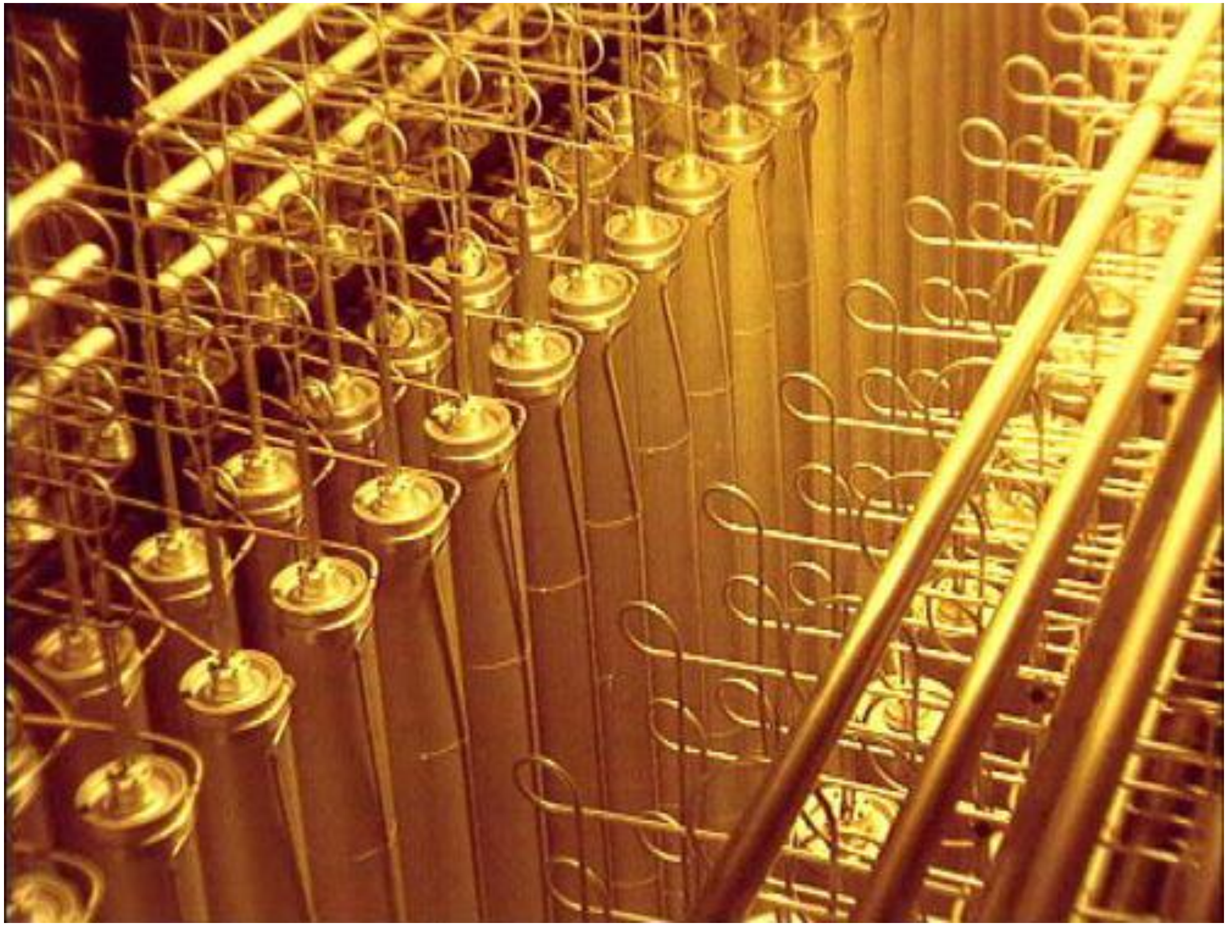
A Story:

In May 2006, in Delhi, I asked several leaders of the Indian nuclear enterprise to comment on the merits of a supplier-user arrangement of the world. They refused to do so until they knew in which category India would be.

If the U.S. had informed them that they were users, would they have gone underground?

More slides about enrichment

A cascade of centrifuges



Enrichment by Cascade

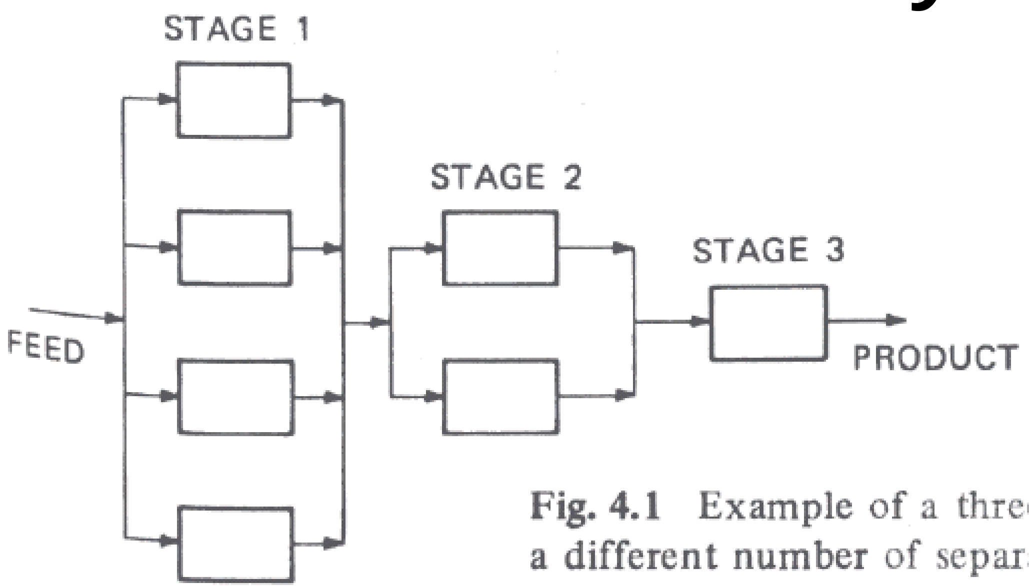


Fig. 4.1 Example of a three-stage cascade, each stage consisting of a different number of separating elements. The tails are not shown.

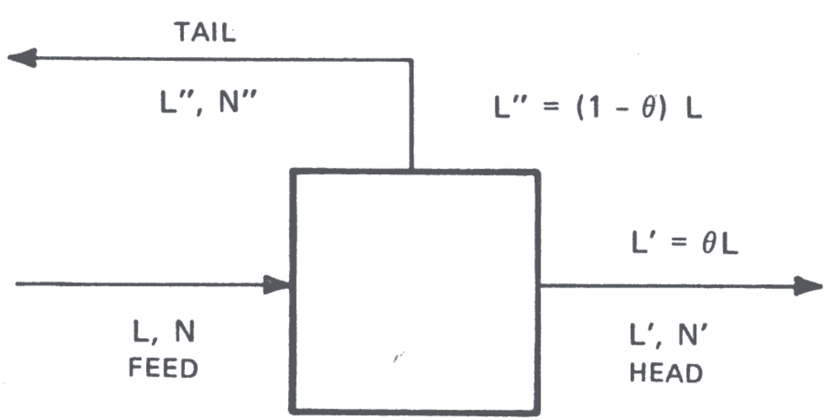


Fig. 4.5 Generic stage in a cascade. L = flow rate; θ = cut; N = mol fraction.

Abundance ratio: R = N/(1-N)
Separation factor: R'/R
Separation gain: R'/R"

Source: Villani, Stelio, 1976. *Isotope Separation.* American Nuclear Society

Six external parameters, two conservation equations

External parameters		
	Mole-fraction (desired isotope)	Flow [mol/s] or amount [mol]
Feed	N_F	F
Product	N_P	P
Waste (tails)	N_W	W

Conservation Equations:

$$F = P + W$$

$$N_F * F = N_P * P + N_W * W$$

Example: *Given* $N_F = 0.007$, $N_P = 0.20$, $N_W = 0.002$, and $F = 1$ mole,

find $P = 0.0253$ mole and $W = 0.9747$ mole.

Cascades and recycling

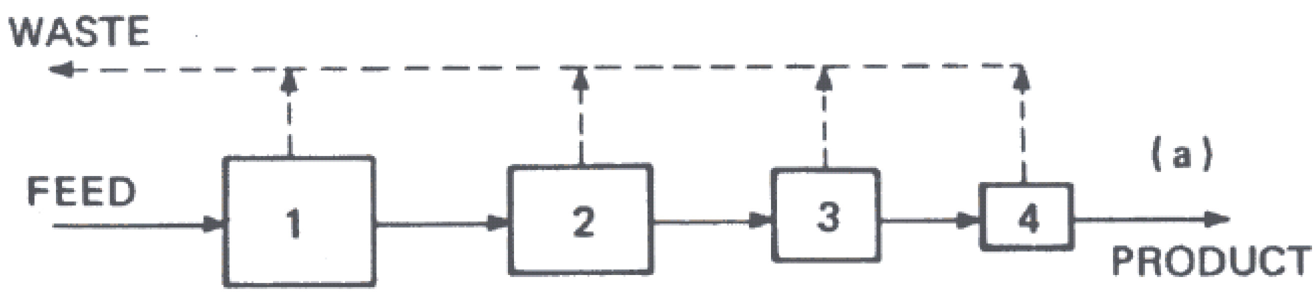
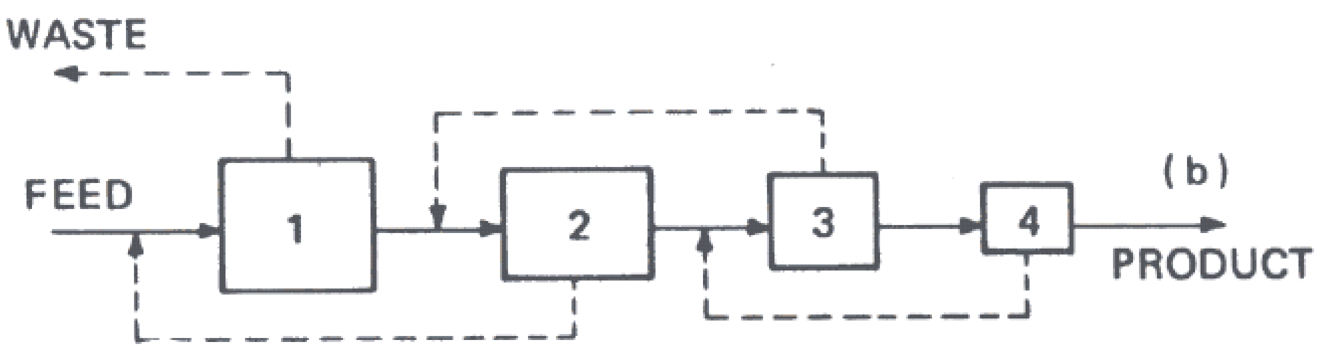


Fig. 4.2 (a) Cascade without recycling,



(b) symmetrical countercurrent cascade.

Source: Villani, Stelio, 1976. *Isotope Separation.* American Nuclear Society

Enrichment and stripping sections

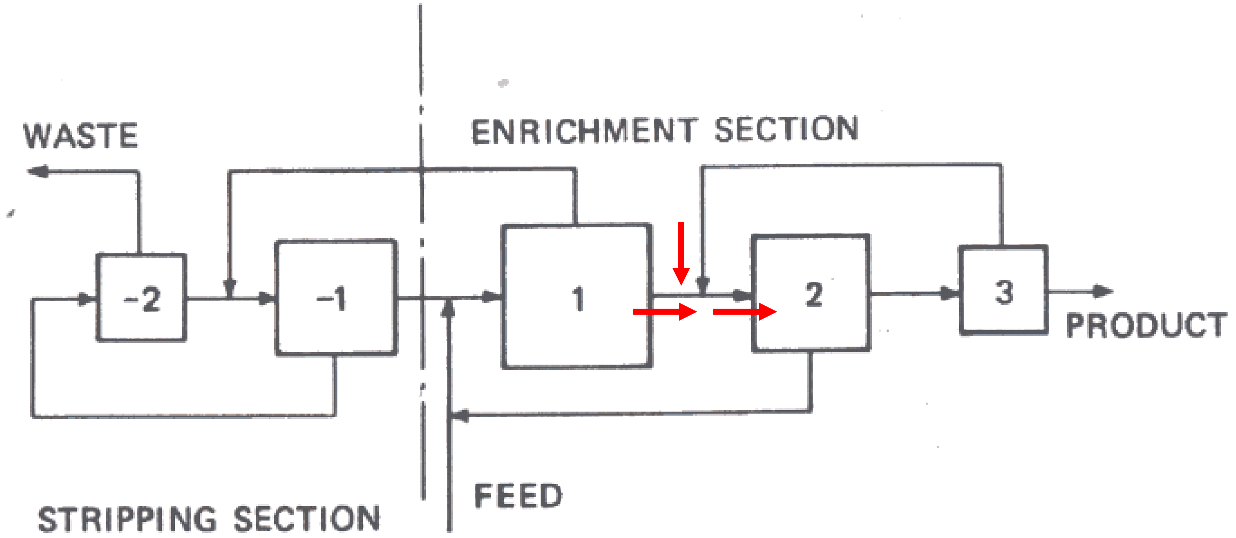


Fig. 4.4 Example of a symmetrical cascade with a stripping section.

"Ideal" cascade: All red arrows have same composition.

Source: Villani, Stelio, 1976. *Isotope Separation.* American Nuclear Society

Ideal cascade: concentration and flow at each stage

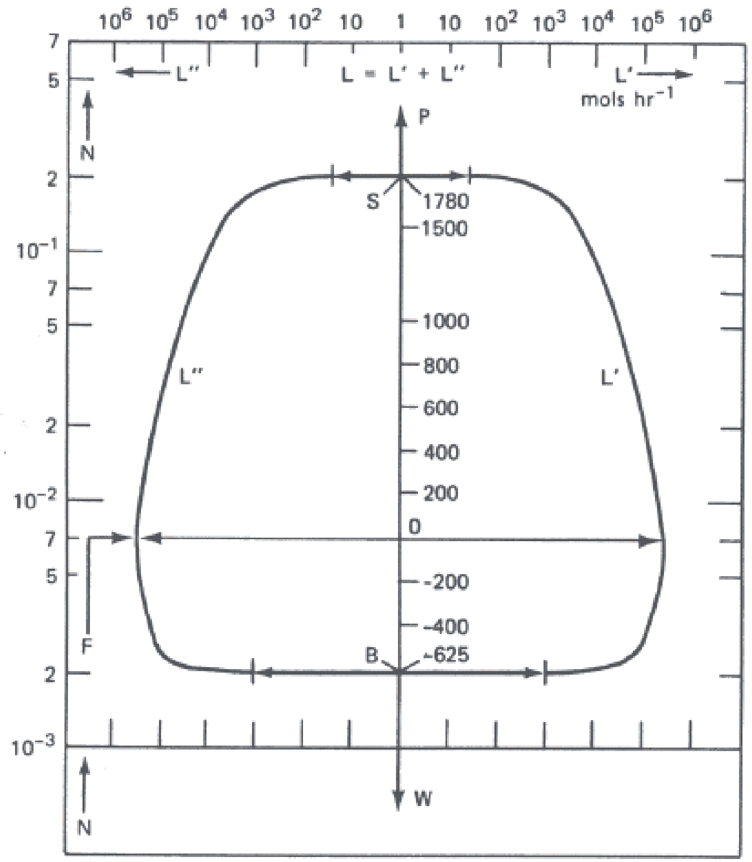


Fig. 4.9 Profile of the loads in an ideal cascade.

Enrichment factor (R'/R) = 1.002, all stages.

External parameters:

N_F = 0.007, F = 1040 mols/hr

N_P = 0.200, P = 26 mols/hr

N_W = 0.002, W = 1014 mols/hr

Note log scales for flows and concentrations.

Source: Villani, Stelio, 1976. *Isotope Separation.* American Nuclear Society

Another view, same cascade

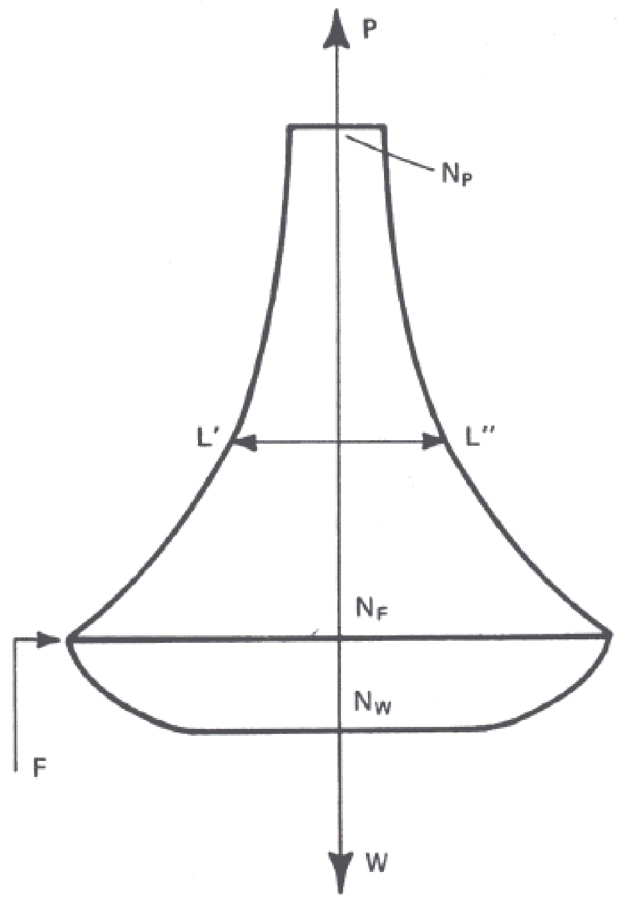
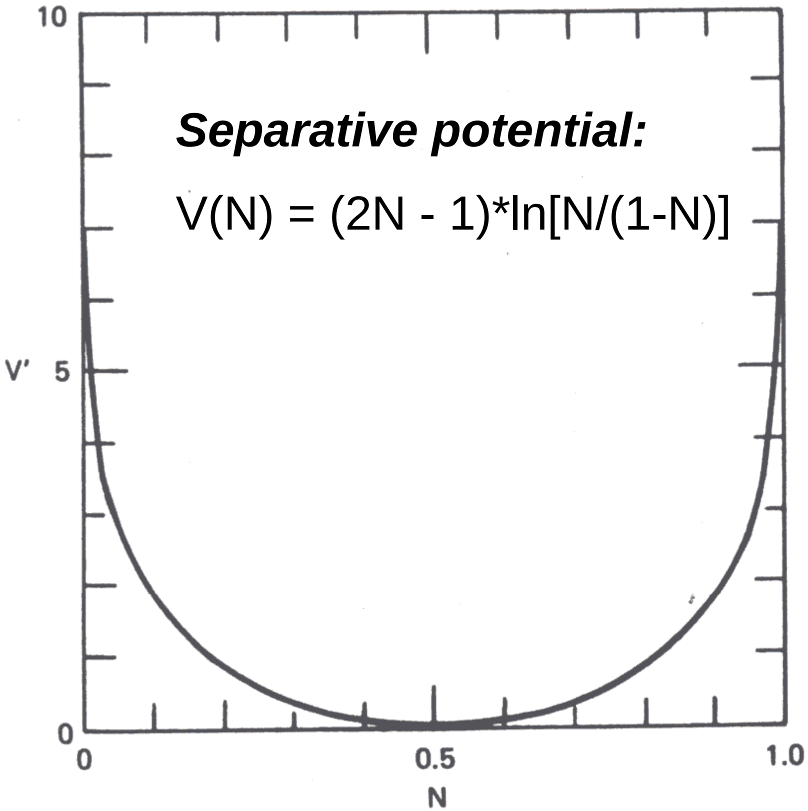


Fig. 4.10 Qualitative representation of an ideal cascade (N on the linear scale).

Source: Villani, Stelio, 1976. *Isotope Separation.* American Nuclear Society

Separative potential and separative work



Separative potential:

V(N) = (2N - 1)*ln[N/(1-N)]

Separative Work:

S = P*V(NP) + W*V(NW) - F*V(NF)

Separative work is defined as the total inter-stage flow across all stages (heads and tails). The (not simple) calculation for an ideal cascade produces this equation. Separative work depends on only external parameters. P, W, and F here are masses (kg); when then are flows (kg/s) the expression defines the separative capacity.

Separative work is the measure of the effort required for any separation by cascade. It is measured in “SWU” (separative work units, pronounced swoo). Enrichment cost is quoted in $/SWU. When not otherwise noted, kg-SWU is understood.

Source: Villani, Stelio, 1976. *Isotope Separation.* Fig 4.14. American Nuclear Society

Example

Enrich natural uranium to 20% U-235, with 2% U-235 in the tails.

External parameters:
F = 1.0000 kg-mole, N_F = 0.007, Find: $V(N_F)$ = 4.885
P = 0.0253 kg-mole , N_P = 0.20, Find: $V(N_P)$ = 0.832
W = 0.9747 kg-mole. N_W = 0.002, Find $V(N_W)$ = 6.188

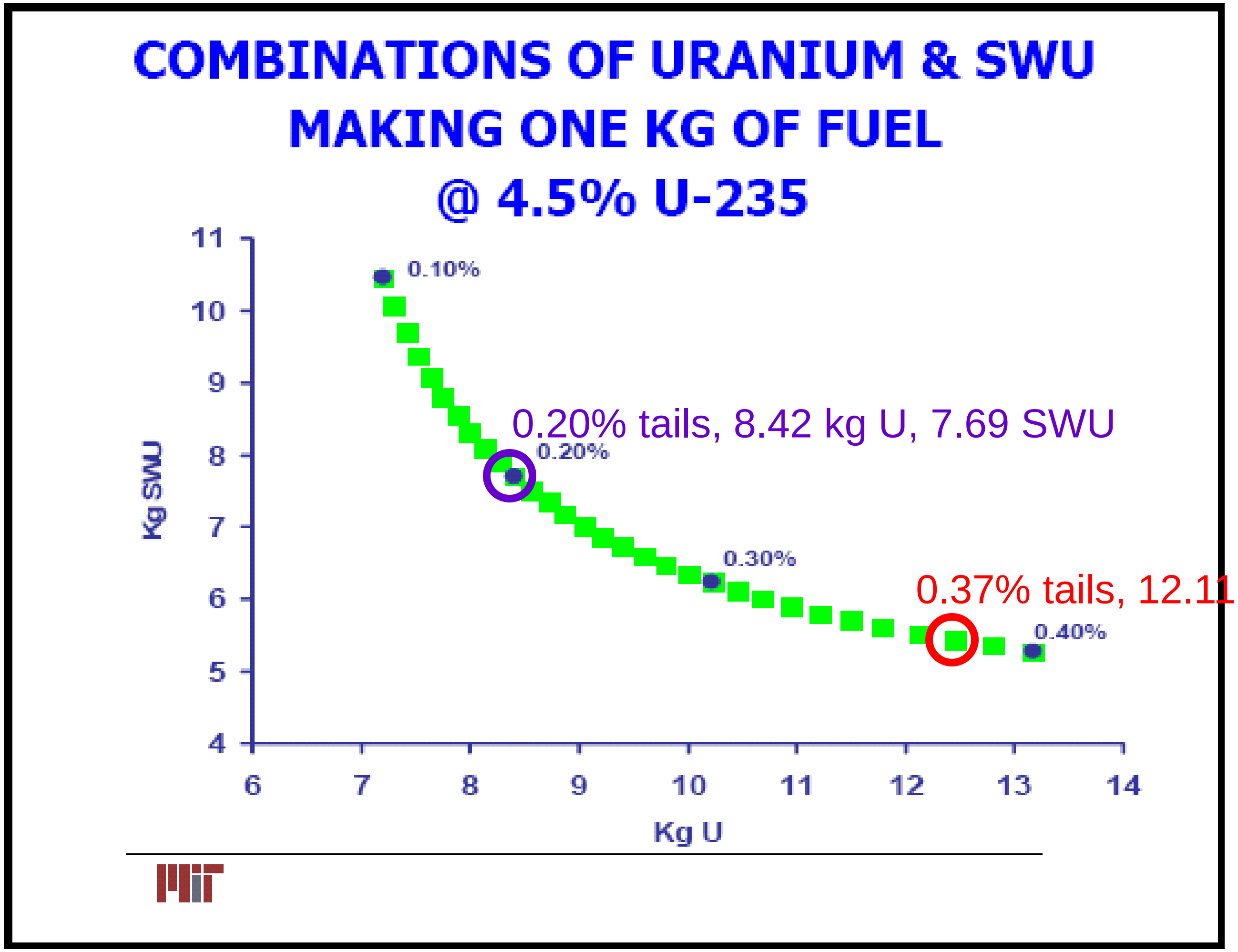
Separative work: S = P*V(NP) + W*V(NW) - F*V(NF) = 1.167 kg-moles per kg-mole of feed.

Since the two isotopes have nearly the same atomic mass, we can also say, approximately:

The separative work is 1.167 kg-SWUs for each kg of *feed*,

or 1.167/.0253 = 46.2 kg-SWU for each kg of (20%-U235) *product.*

Trade-off: kgU *vs*. SWU



Source: Tom Neff, MIT, talk in January, 2007

Tradeoff with costs

ALTERNATE WAYS TO MAKE 1 KG FUEL BY CHANGING TAILS ASSAY

0.37% Tails	lbs U3O8	KgU	Conversion	SWU	Tails	Totals
Amount	31.65	12.11	12.11	5.53	11.11	
Unit Cost	$72	$188	$12	$135	$5	
Total Cost	$2,278	$2,278	$145	$747	$56	$3,226

0.20% Tails	lbs U3O8	KgU	Conversion	SWU	Tails	Totals
Amount	22	8.42	8.42	7.69	7.42	
Unit Cost	$72	$188	$12	$135	$5	
Total Cost	$1,584	$1,584	$101	$1,038	$37	$2,760

- A reactor reload requires about 30,000 kg enriched uranium. Difference in cost of a reload here is thus about $14 million.

Assumes 4.5% enrichment of the fuel.

Source: Tom Neff, MIT, talk in January, 2007

A major expansion of nuclear power?

For the U.S., a major expansion is called a "revival."

For a major expansion to be significant for climate change, it must be global.

For a major global expansion to be sensible, there must be appropriate global institutions to prevent nuclear power becoming a route to nuclear war.

Nuclear power has not grown as its advocates predicted

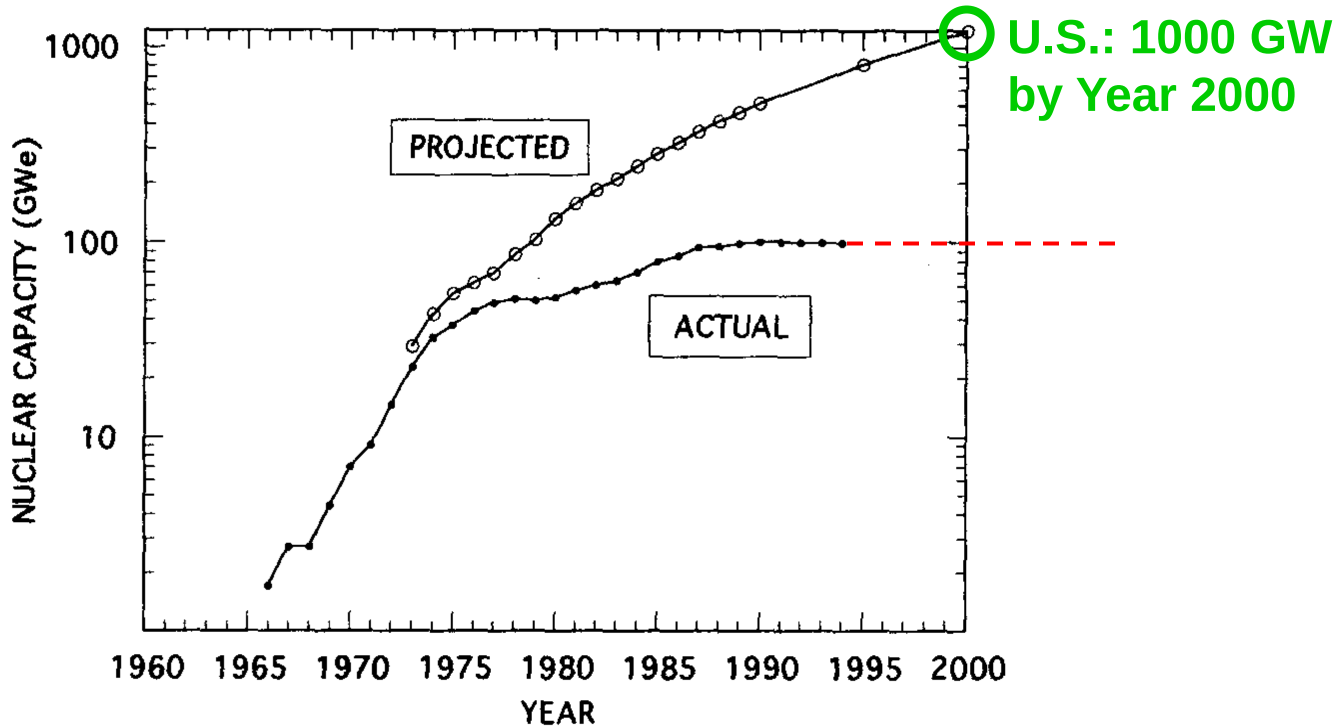
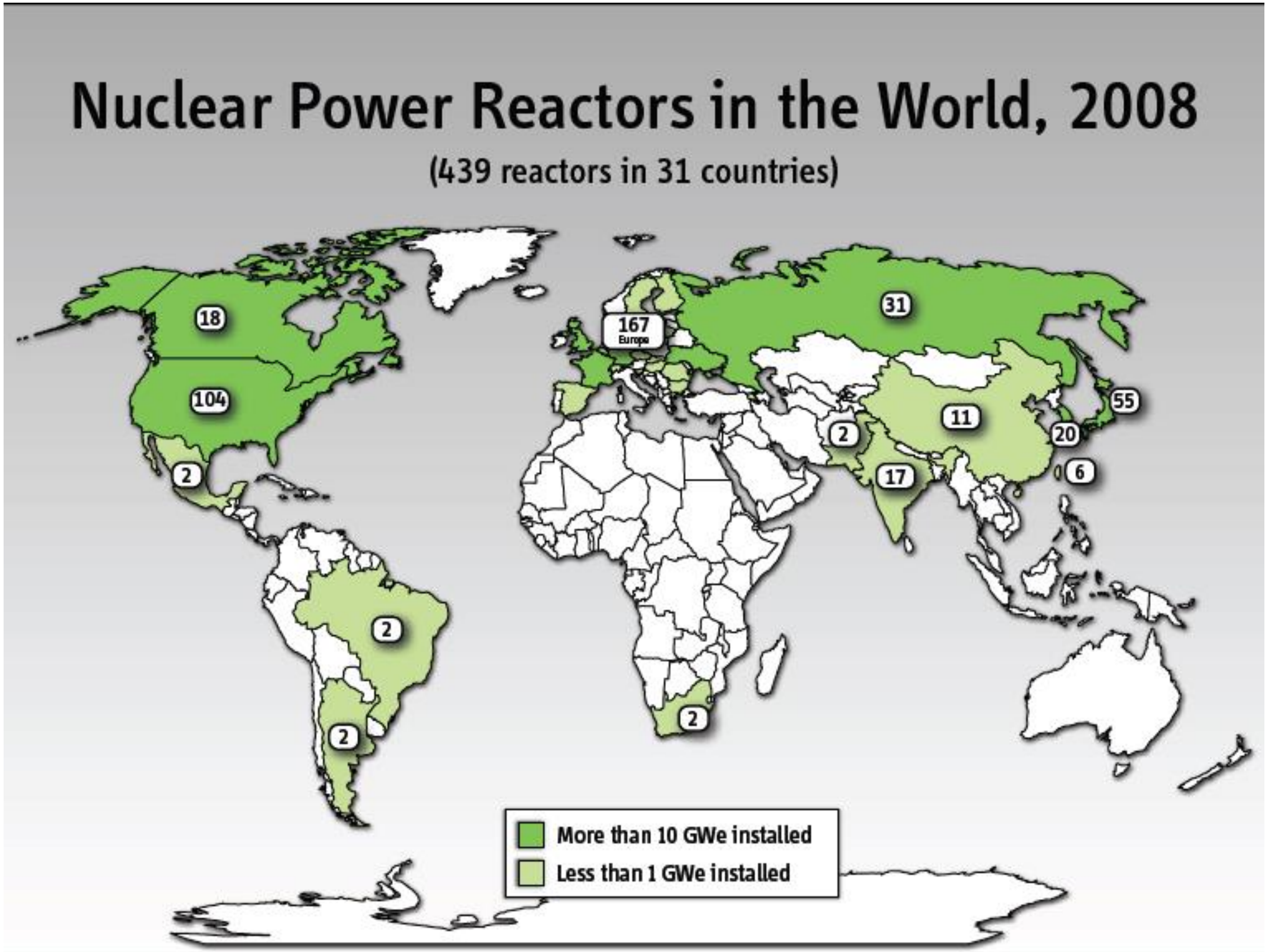


Figure 1.4. Comparison of U.S. nuclear capacity, projected in 1972 and actual.

Global nuclear power, 2008



Source: Alex Glaser, MAE Seminar, 4-15-09

Globally uniform nuclear power

For nuclear power to emerge as a globally significant response to energy insecurity and climate change, many countries will need to develop civilian nuclear programs. The world cannot be one of “suppliers and users” but one of universal rules – the same rules for all countries.

> *Story*: In May 2006 in Delhi, when I asked several leaders of the Indian nuclear enterprise to judge the merits of a supplier-user arrangement of the world, they refused to do so until they knew in which category India would be. If the U.S. informed them that they were users, would they go underground?

Universal rules require substantially greater international governance of civilian nuclear facilities.

Non-Proliferation Treaty (NPT), 1970

The Bargain:

Five weapon states: China, France, Soviet Union, United Kingdom, United States

Non-weapon states will forgo nuclear weapons in return for:

- commitment from weapon states to disarmament
- access to peaceful benefits of nuclear technology

Ratified by all but India, Israel, North Korea & Pakistan

Proliferation-resistant nuclear power

U-235 enrichment

Internationalize all plants, including ours and Iran’s.

Use natural U?

Pu and reprocessing

Stay with once-through fuel cycles.

Postpone reprocessing and the production of Pu fuel.

Revival proposals

- Safety: Create counter-incentives to plant relicensing, so that aging plants are retired.
- Storage: Revise the contract with society in favor of retrievable storage. Deploy dry-cask storage.
- Proliferation, plutonium: Deploy only once-through cycles (indefinitely postpone reprocessing).
- Proliferation, uranium: *Establish a one-tier world.* Immediately place all enrichment facilities, *including ours*, under international governance. (Is there an attractive natural-uranium power plant?)
- Delegitimize nuclear weapons

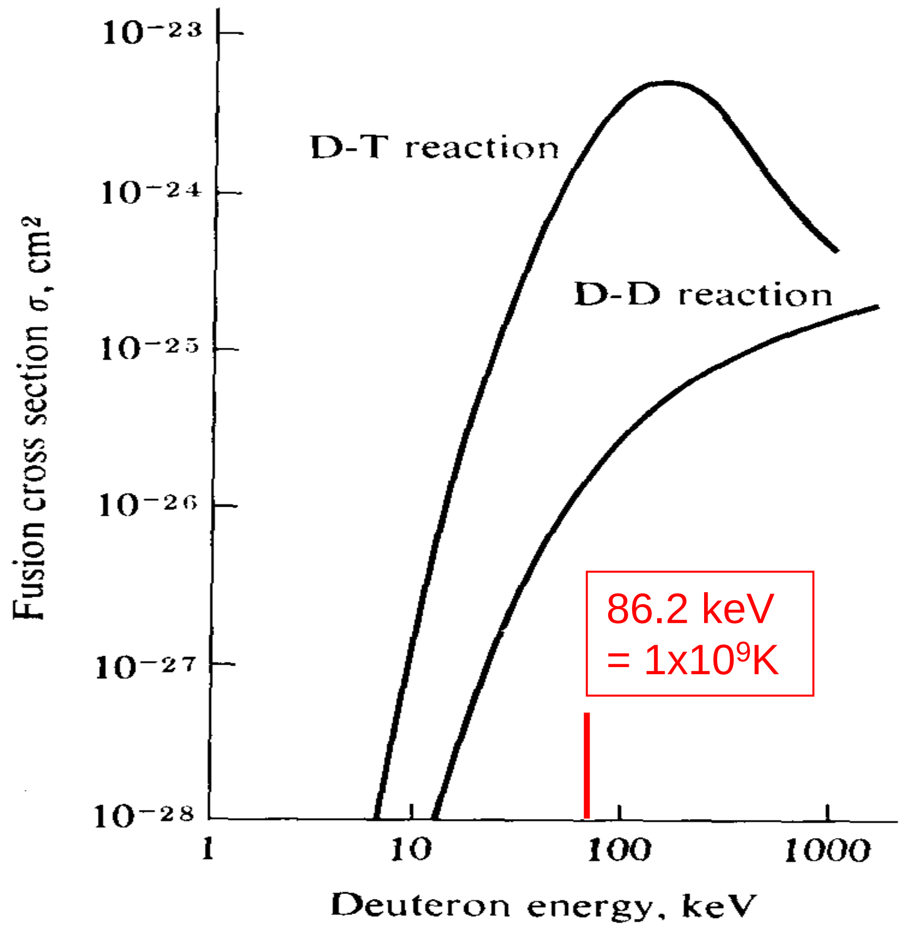


Fig. 4.7 Fusion cross section versus deuteron energy. The variation in fusion cross section is shown as a function of deuteron energy for both the D-D and D-T reactions. [From A. S. Bishop, *Project Sherwood: The U.S. Program in Controlled Fusion.* Reading, Mass.: Addison-Wesley Publishing Co., Inc., 1958.]