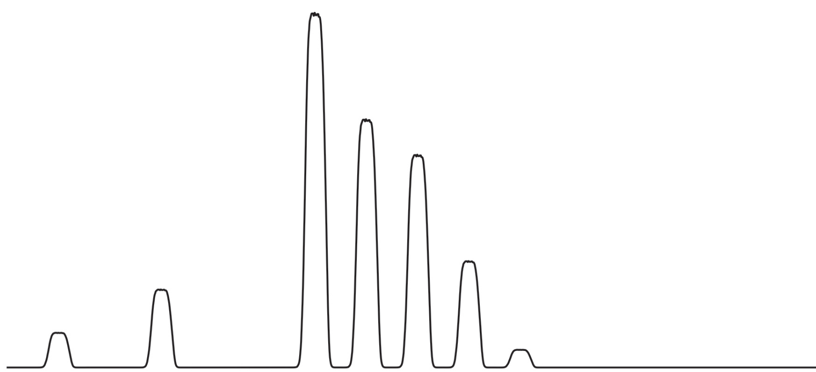
Going Nuclear

How the Atom Will Save the World

TIM GREGORY

THE BODLEY HEAD
LONDON

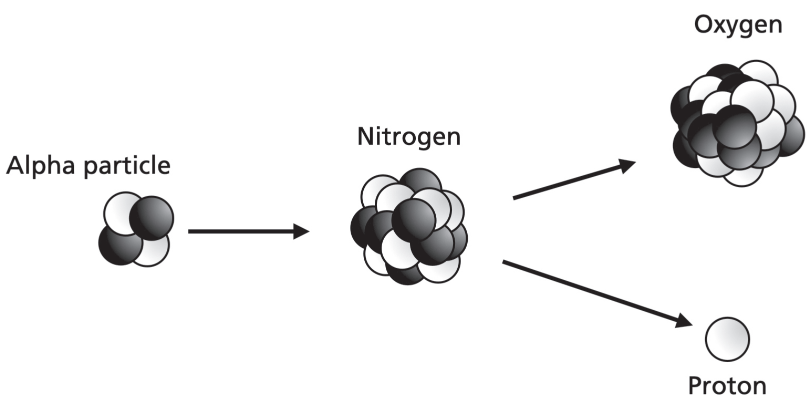


Each pulse marks the presence of a distinct type of atom.

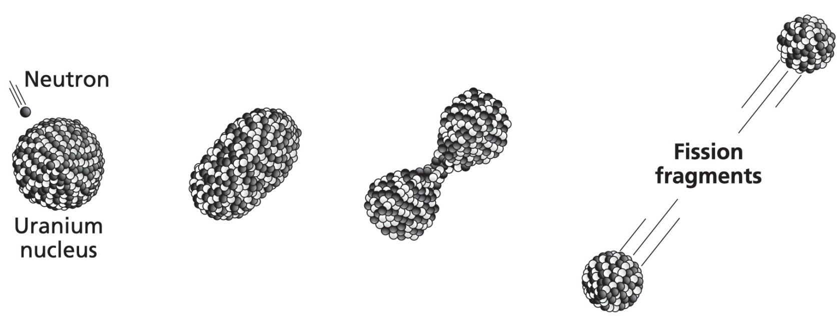
1 **H**																	2 **He**
3 **Li**	4 **Be**											5 **B**	6 **C**	7 **N**	8 **O**	9 **F**	10 **Ne**
11 **Na**	12 **Mg**											13 **Al**	14 **Si**	15 **P**	16 **S**	17 **Cl**	18 **Ar**
19 **K**	20 **Ca**	21 **Sc**	22 **Ti**	23 **V**	24 **Cr**	25 **Mn**	26 **Fe**	27 **Co**	28 **Ni**	29 **Cu**	30 **Zn**	31 **Ga**	32 **Ge**	33 **As**	34 **Se**	35 **Br**	36 **Kr**
37 **Rb**	38 **Sr**	39 **Y**	40 **Zr**	41 **Nb**	42 **Mo**	43 **Tc**	44 **Ru**	45 **Rh**	46 **Pd**	47 **Ag**	48 **Cd**	49 **In**	50 **Sn**	51 **Sb**	52 **Te**	53 **I**	54 **Xe**
55 **Cs**	56 **Ba**	57–71	72 **Hf**	73 **Ta**	74 **W**	75 **Re**	76 **Os**	77 **Ir**	78 **Pt**	79 **Au**	80 **Hg**	81 **Tl**	82 **Pb**	83 **Bi**	84 **Po**	85 **At**	86 **Rn**
87 **Fr**	88 **Ra**	89–103	104 **Rf**	105 **Db**	106 **Sg**	107 **Bh**	108 **Hs**	109 **Mt**	110 **Ds**	111 **Rg**	112 **Cn**	113 **Nh**	114 **Fl**	115 **Mc**	116 **Lv**	117 **Ts**	118 **Og**

57 **La**	58 **Ce**	59 **Pr**	60 **Nd**	61 **Pm**	62 **Sm**	63 **Eu**	64 **Gd**	65 **Tb**	66 **Dy**	67 **Ho**	68 **Er**	69 **Tm**	70 **Yb**	71 **Lu**
89 **Ac**	90 **Th**	91 **Pa**	92 **U**	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**

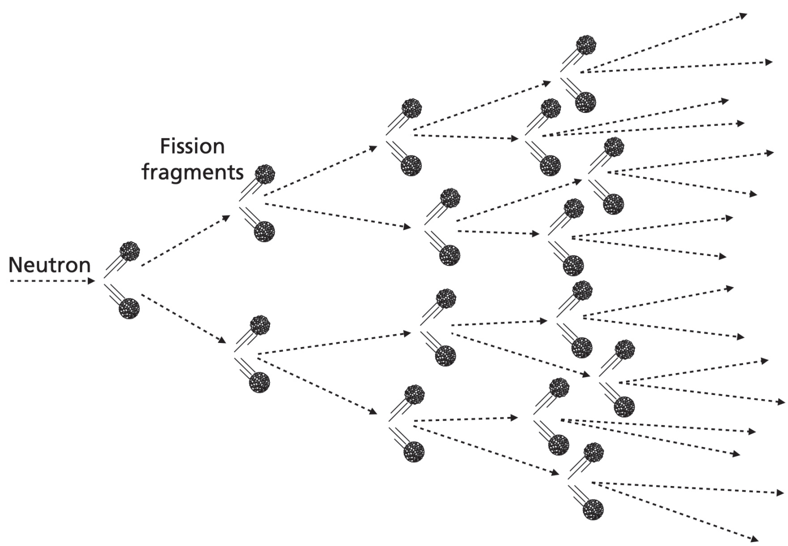
The periodic table condenses the complexity of the world – grapes, mountains, galaxies – into 118 chemical elements.

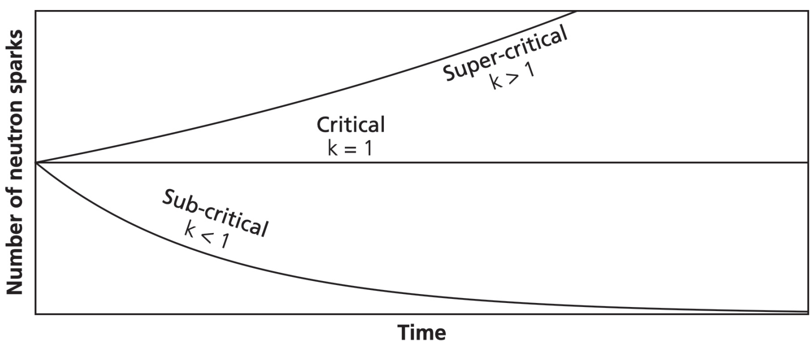


By transforming nitrogen into oxygen, Rutherford and Blackett had changed the fundamental nature of an atom at will. They had

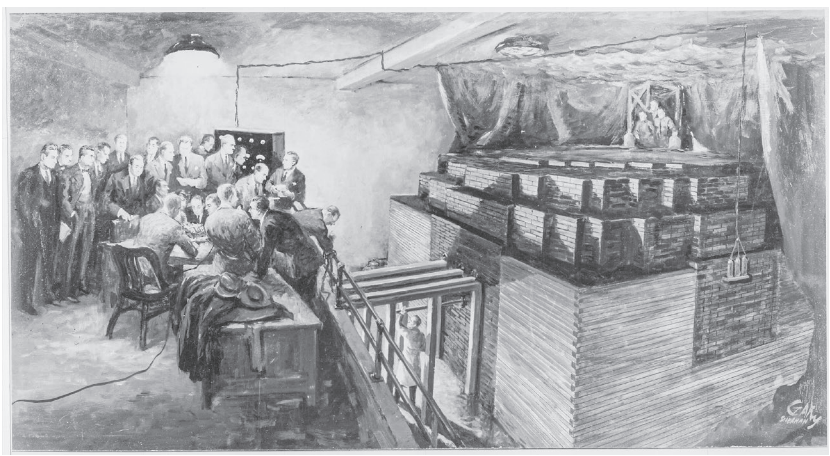


A uranium nucleus splits — or fissions — into two smaller nuclei after being hit by a neutron.

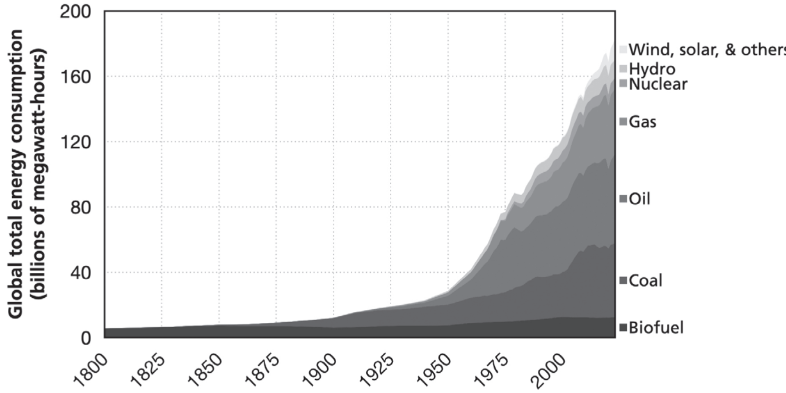

Fission
fragments
Neutron



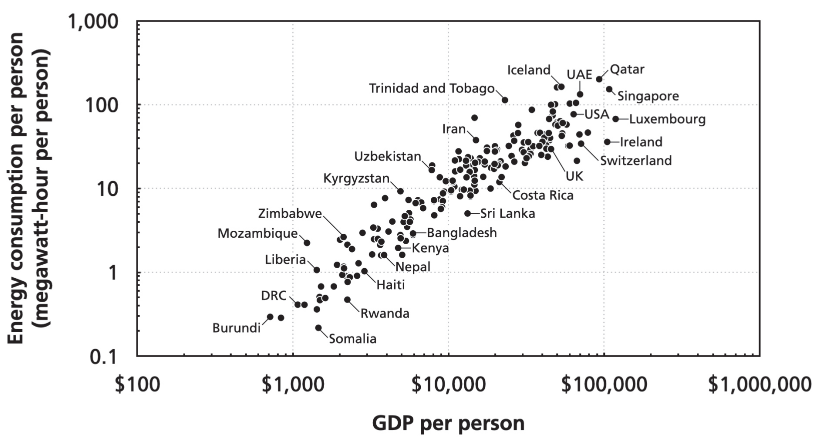
Neutron curves for different k*-values*.



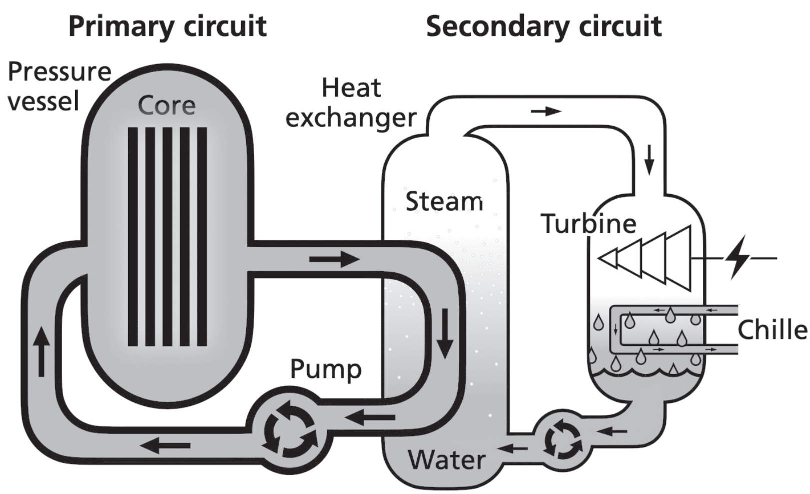
2 December 1942. Fermi and his colleagues watch Chicago Pile-1 — the world's first nuclear reactor — go critical at the inauguration of the Atomic Age. You can see the Suicide Squad atop the reactor. Image courtesy of US National Archives and Records Administration/Science Photo Library.

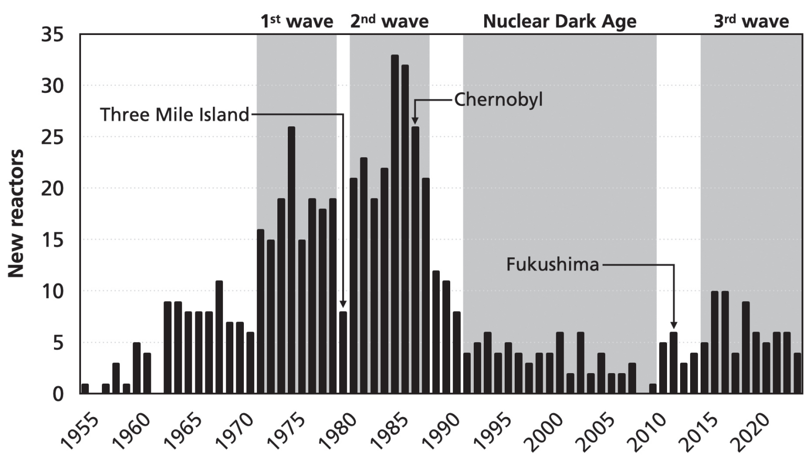


Global energy consumption by source.[4]

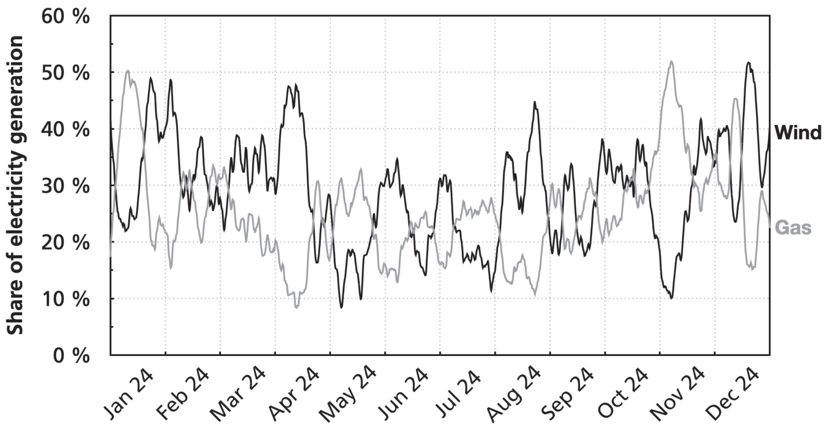


uranic powder is pressed into grape- sized pieces and sin-tered into hard ceramic pellets. From one pellet, a few dozen of which would fit easily in the palm of your hand, a typical nuclear reactor can generate as much electricity as a tonne of coal. Here's one approximately to scale:

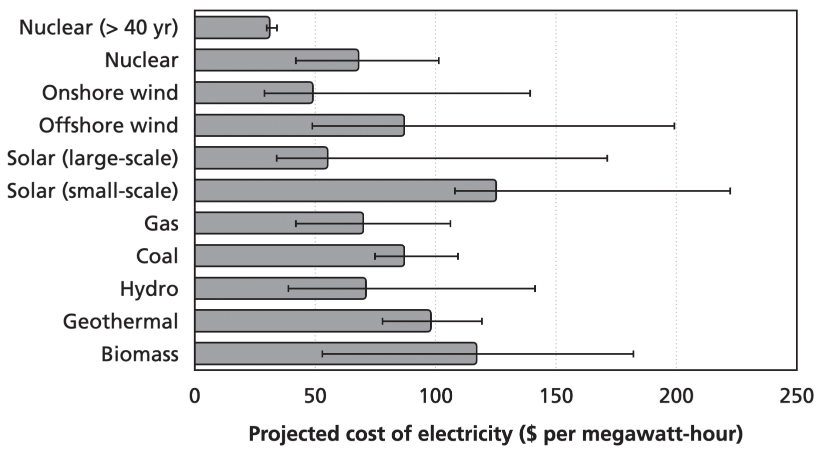

Primary circuit
Secondary circuit
Pressure vessel
Core
Heat exchanger
Steam
Turbine
Chiller
Pump
Water



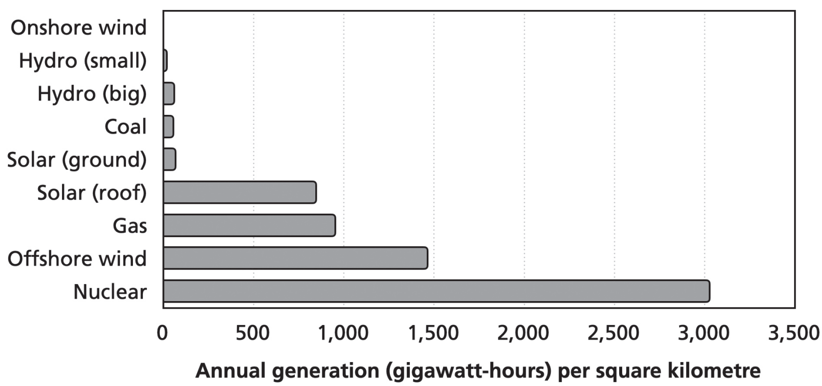
The number of new nuclear reactors connected to the grid each year since the dawn of the Atomic Age.[41]



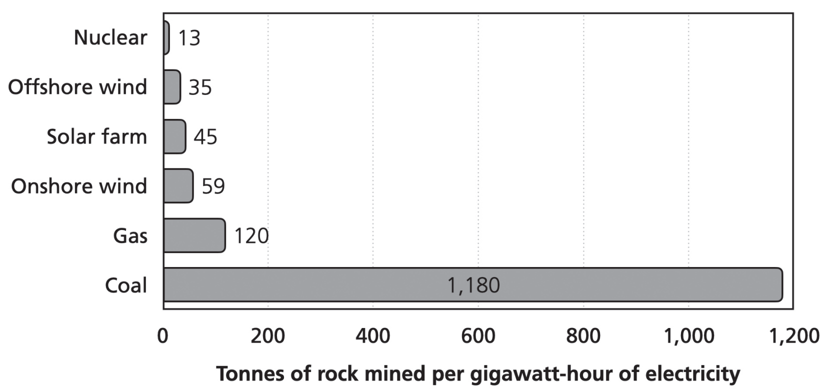
Average wind and gas electricity generation in the UK on a rolling week-by-weekbasisin2024. [29]



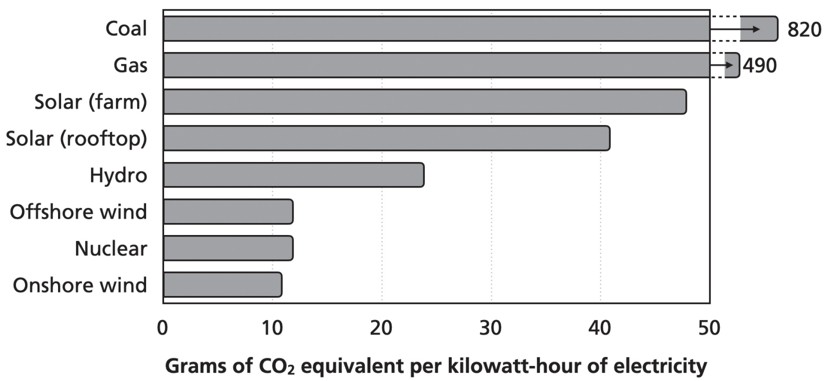
Predicted median levelised cost of electricity by 2025. The upper and lower limits of these predictions are shown by the uncertainty bars.[47]



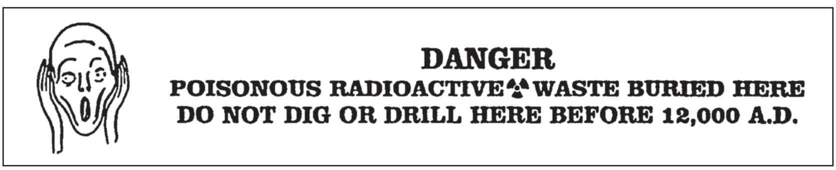
Average electricity concentration of different power sources. Onshore wind is so dilute that it barely registers on this scale.[6]



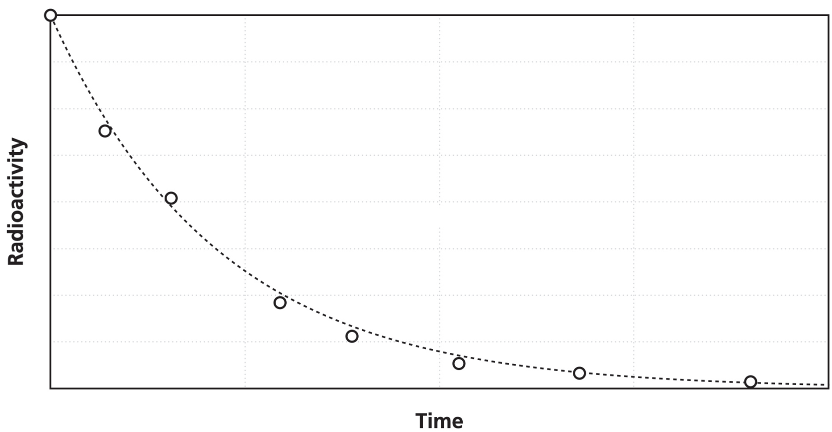
Mining intensity of different electricity sources.[16]



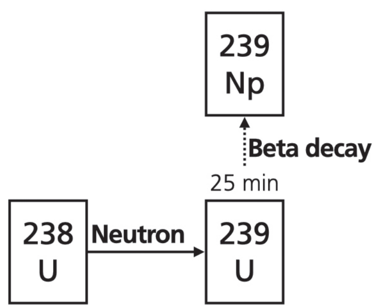
Median CO_2 intensity of electricity sources. Coal and gas are, predictably, off the scale compared to renewables and nuclear.[22]

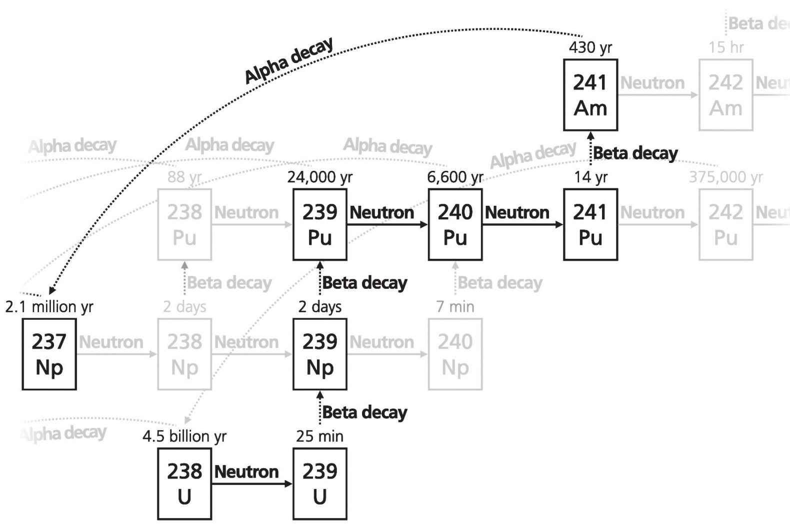


A message of foreboding – designed in 1992 by a group comprising an engineer, an architect, an anthropologist, an archaeologist, a linguist, and an astronomer – designed to ward future generations away from buried nuclear waste. (Image courtesy of Sandia National Laboratories.)

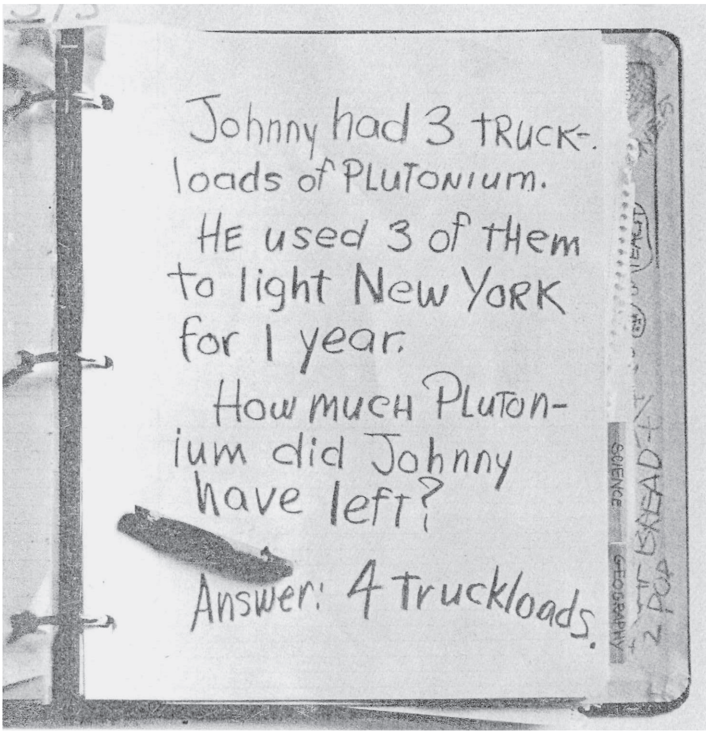


The circles are Rutherford's actual measurements; the decay curve is one I mathematically fit to his data.[3]

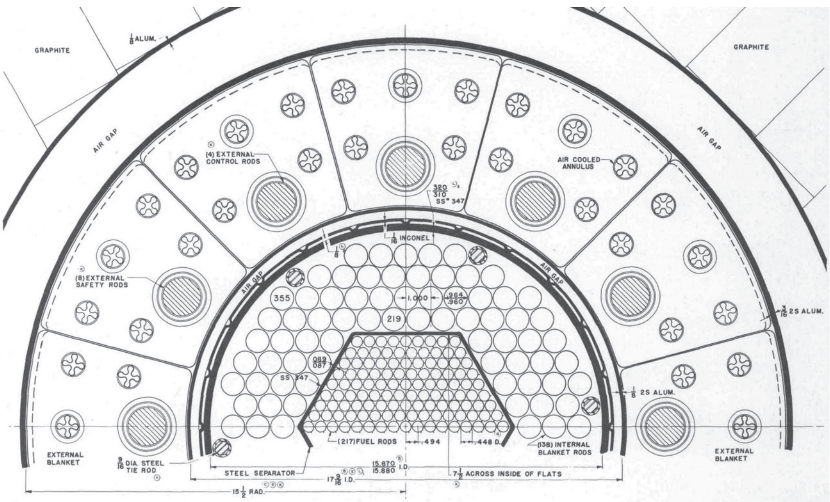

239
Np
Beta decay
25 min
238
U
Neutron
239
U



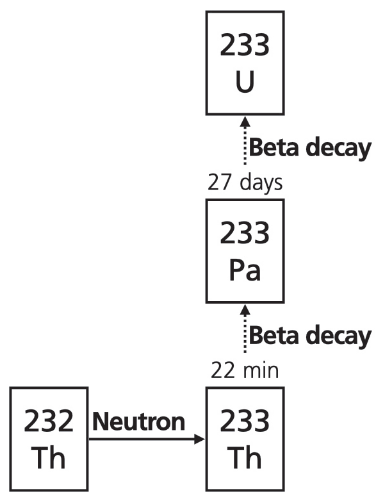
The nuclear reactions that synthesise long-lived isotopes of neptunium, plutonium, and americium. The times above the tiles are half-lives. I've also shown minor nuclear reactions, faded for clarity. There are dozens more nuclear reactions happening simultaneously – plus a criss-cross of radioactive decays – but I had to stop somewhere . . .

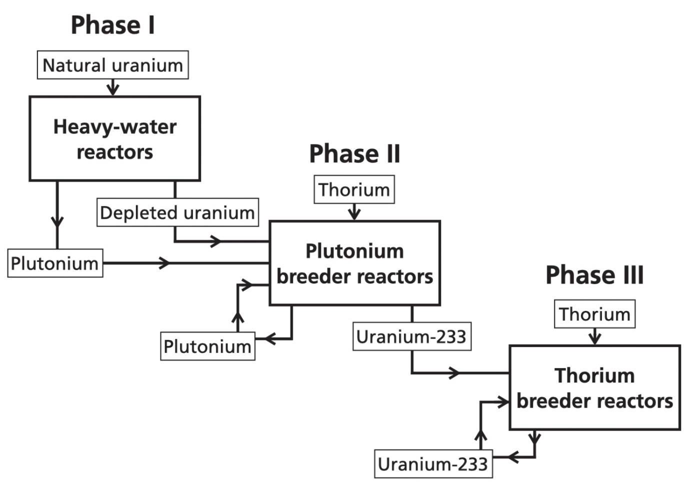


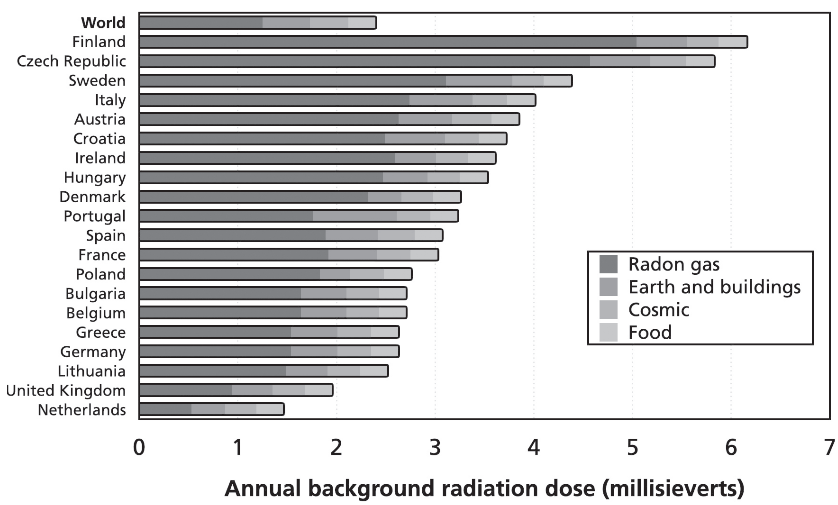
An old joke, scribbled into a notebook, captures the essence of breeder reactors.
(Image courtesy of United States Department of Energy Office of Scientific and Technical Information, *c.* 1950s.)



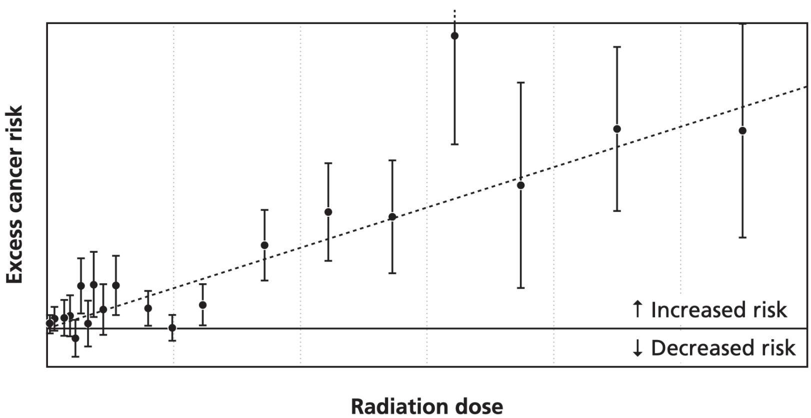
A top-down sketch of Experimental Breeder Reactor 1. All dimensions are in inches. The reactor wraps around full-circle, but it's been cut away in this sketch. (Image courtesy of Argonne National Laboratory.)


233
U
Beta decay
27 days
233
Pa
Beta decay
22 min
232
Th
Neutron
233
Th

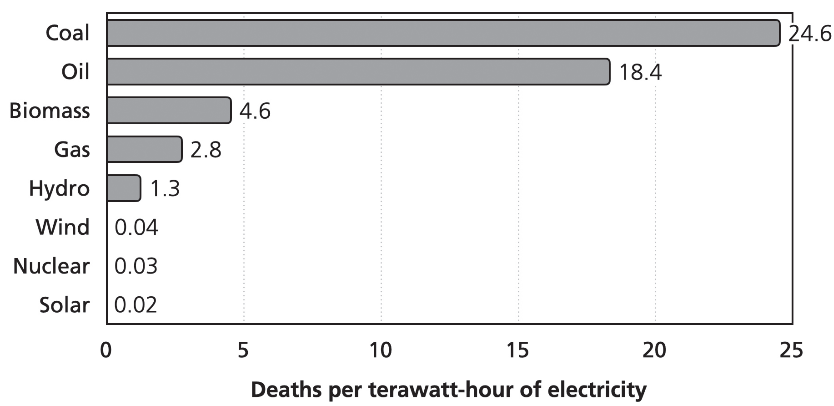

Phase I
Natural uranium
Heavy-water reactors
Depleted uranium
Plutonium
Phase II
Thorium
Plutonium breeder reactors
Plutonium
Uranium-233
Phase III
Thorium
Thorium breeder reactors
Uranium-233



Background radiation from natural sources in 20 of the most populous European nations. I omitted anthropogenic sources of radioactivity, such as atomic bombs and Chernobyl fallout, because they're imperceptible at this scale.[10]

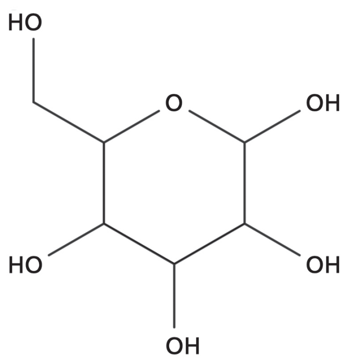


Increase in cancer risk versus radiation dose, furnished with real data collected between 1950 and 2003 in the Life Span Study. I omitted units for clarity because it's the trend that matters.[31]



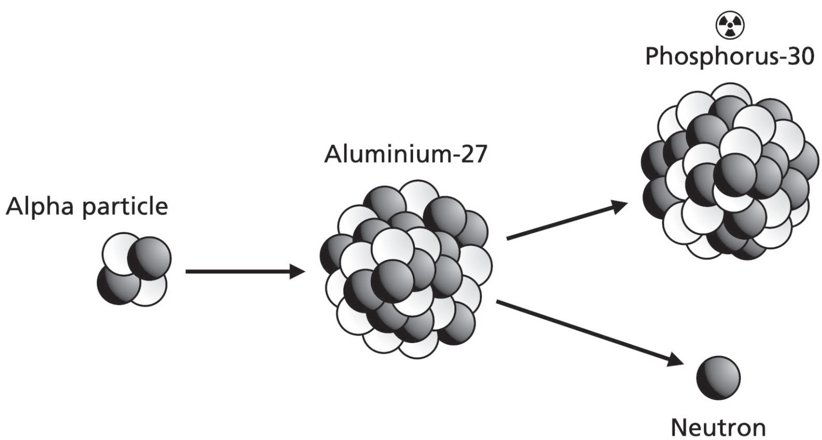
Deaths per terawatt-hour of different electricity sources. Wind, nuclear, and solar are so safe that they're invisible on this scale.[45]

The first X- ray of human bones, taken by Röntgen in 1895. Ludwig was wearing a ring on her third finger. (Image by W. K. Röntgen, courtesy of the Wellcome Collection.)

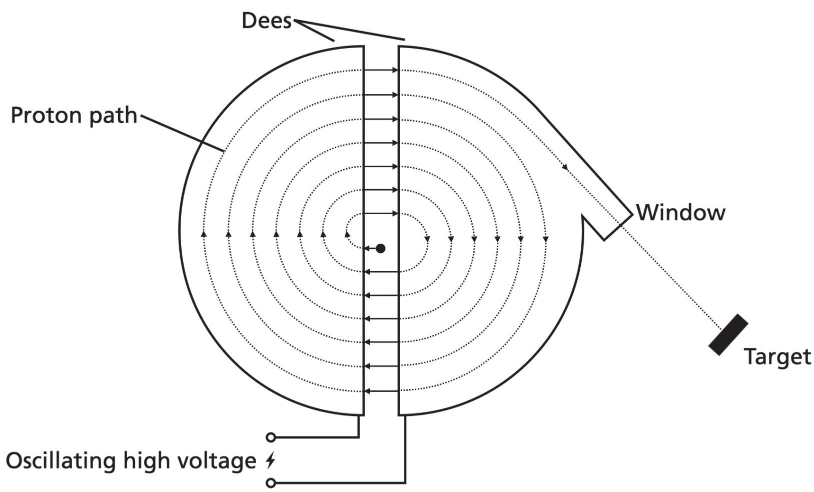


Sketches of humdrum glucose (left) and radioactive fluorodeoxyglucose (right). Note how similar their molecular structures are.

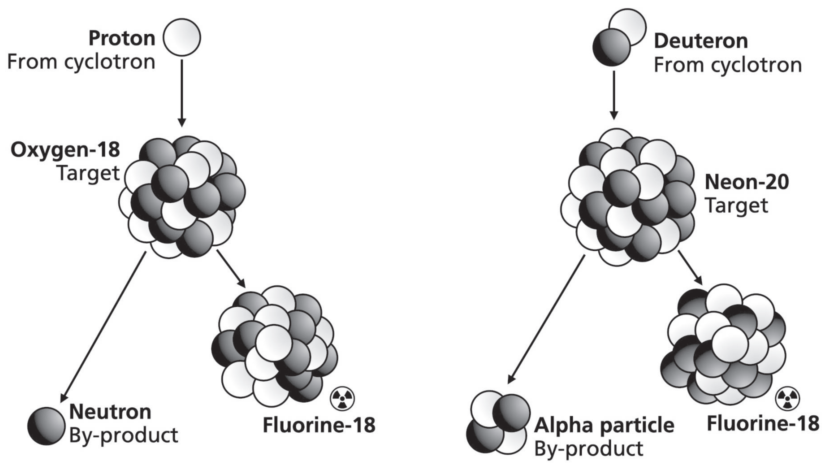
PET/CT scans of a patient from a clinical trial in 2014–2015 during repeat rounds of actinium-225 therapy.[25] (Image courtesy of the Society of Nuclear Medicine and Molecular Imaging.)



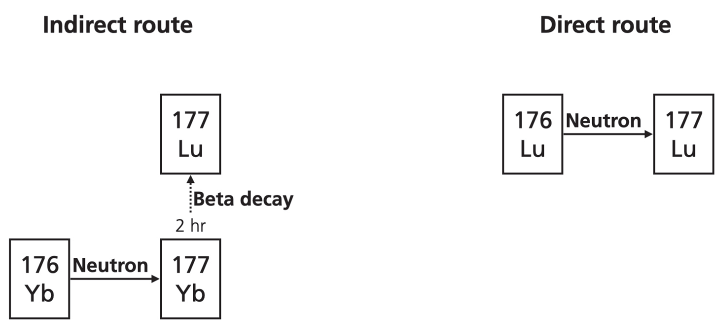
Protons are white; neutrons are black.

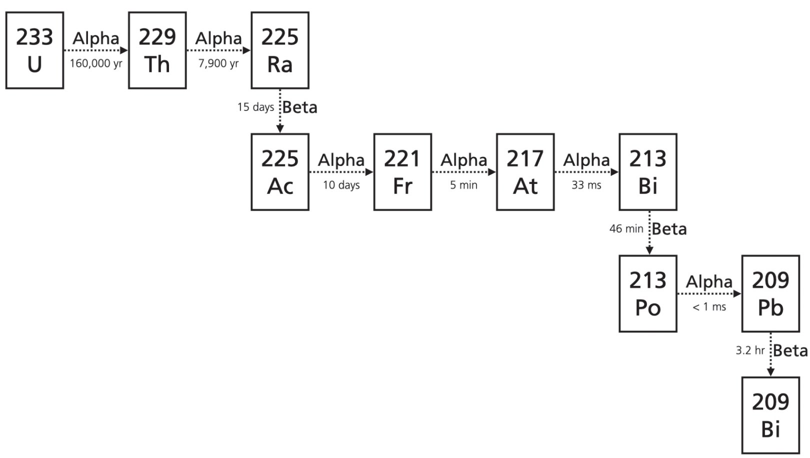


A bird' s- eye- view of a cyclotron. The magnetic field rises up through the dees from underneath and bends the ions into a spiral path.

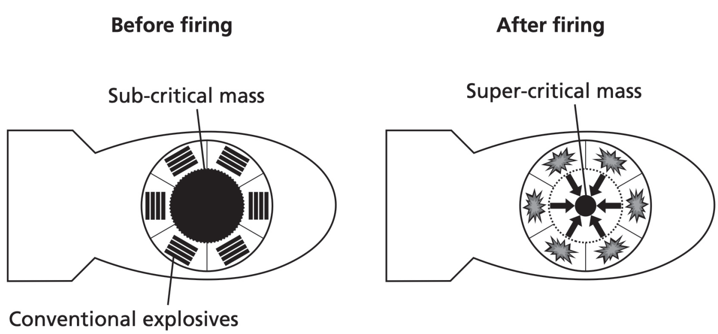


The main production routes for fluorine-18. Protons are white; neutrons are black.

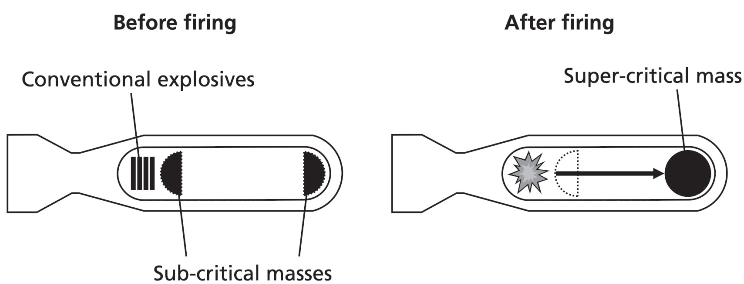

Indirect route
177
Lu
Beta decay
2 hr
176
Yb
Neutron
177
Yb
Direct route
176
Lu
Neutron
177
Lu



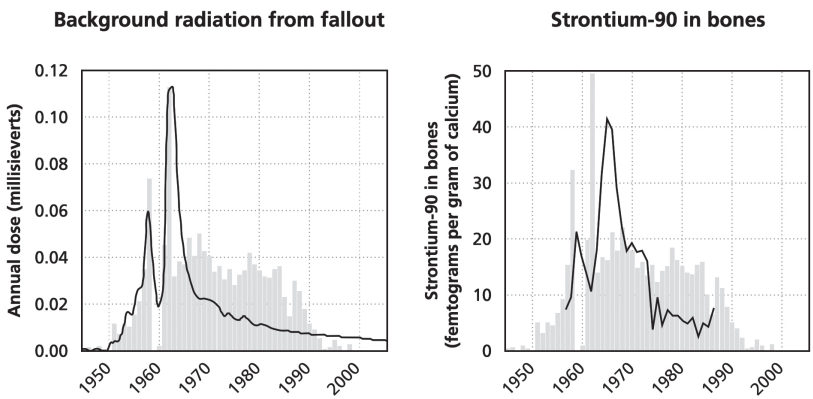
The uranium- 233 decay series. The times next to the decay arrowsarethe half-lives.



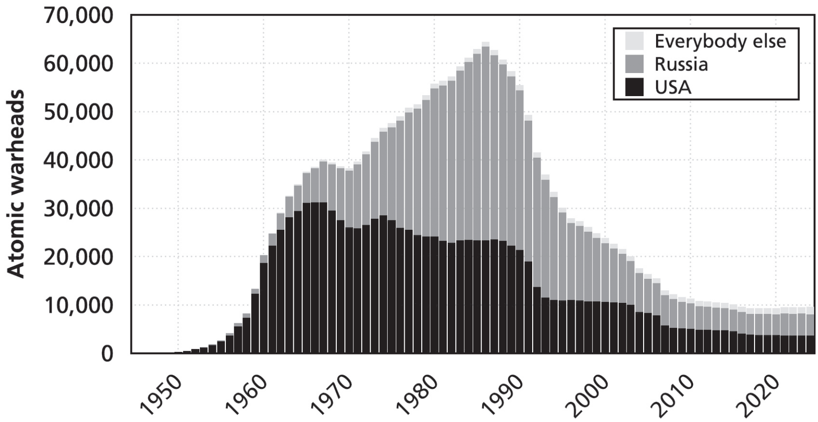
Implosion-type atomic bombs compress a sphere of plutonium to super-criticality.



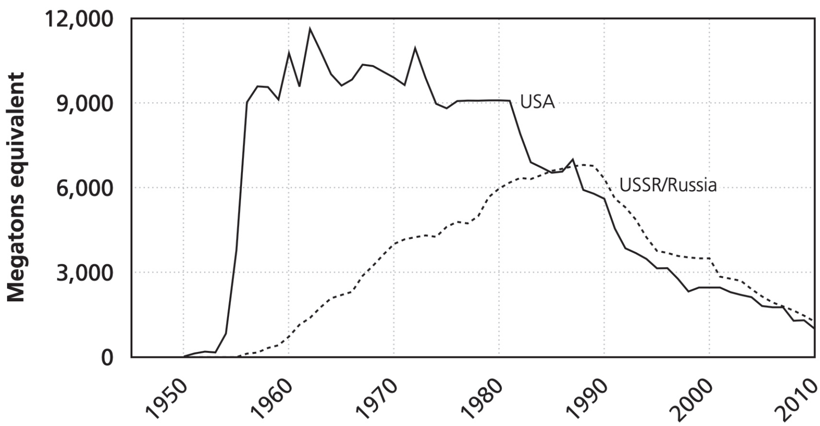
Gun-type atomic bombs slam two sub-critical masses together toachieve super-criticality.



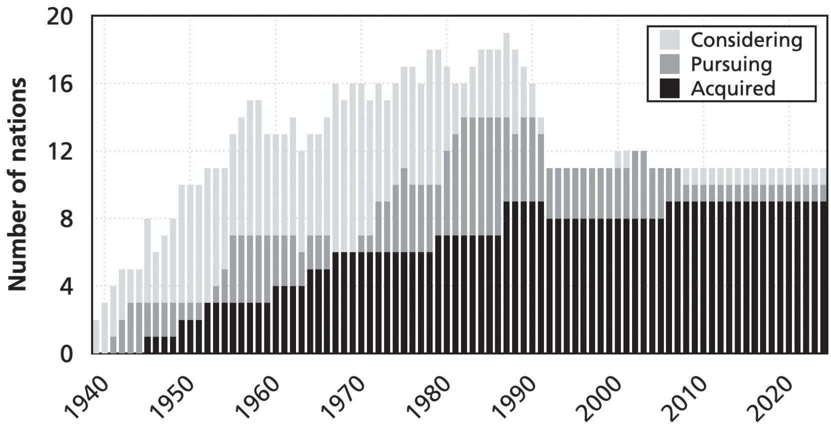
Global radiation dose from atomic bomb fallout (left), and strontium-90 concentrations in the bones of 0–5-year-olds (right). I plotted these datasets against a backdrop of weapons tests. Tests after 1963 were conducted almost exclusively underground, and so their radiological effects were diminished.[14]



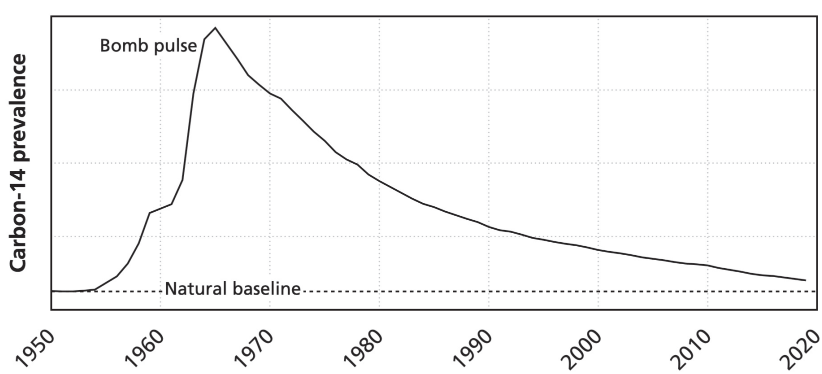
The precise numbers of atomic bombs are state secrets, but these data represent best estimates. This graph doesn't include retired bombs awaiting dismantlement, of which there are (at the time of writing) about 2,500.[20]

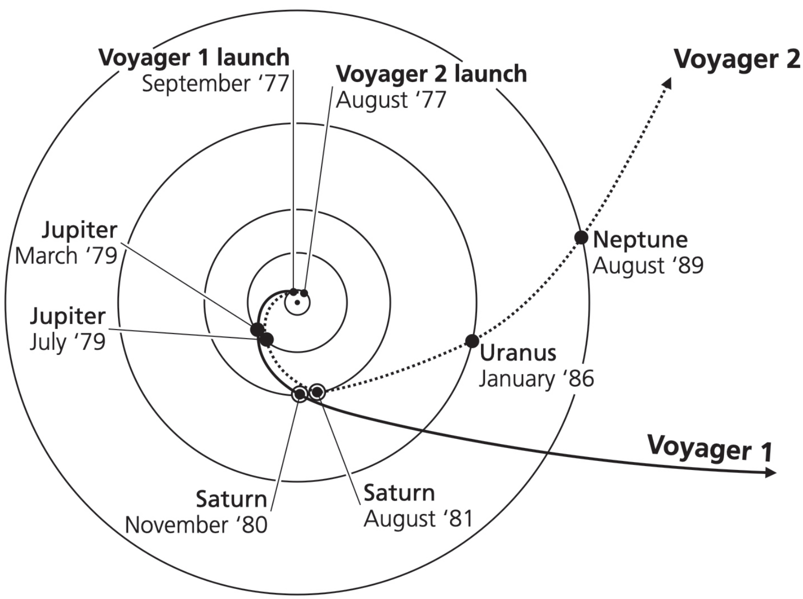


Estimates of the explosive energy of a first atomic strike. I omitted the other atomic bomb nations because their first strikes are too small to see on this scale.[21]

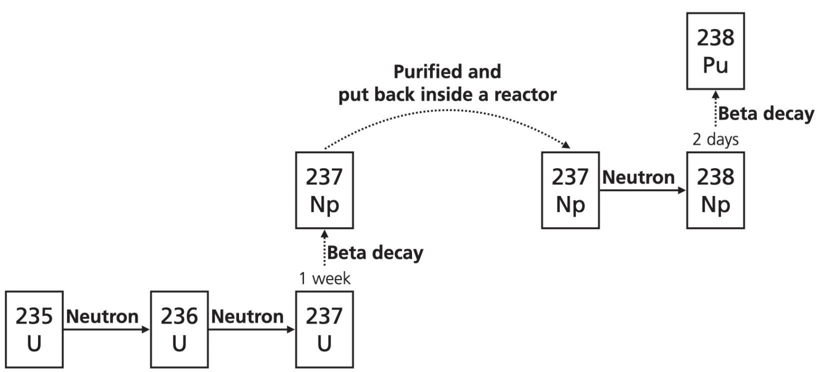


Number of nations that are considering, pursuing, or have acquired atomic bombs. Iran is actively pursuing them; Syria is considering it.[30]


Bomb pulse
Natural baseline
Carbon-14 prevalence
1950
1960
1970
1980
1990
2000
2010
2020

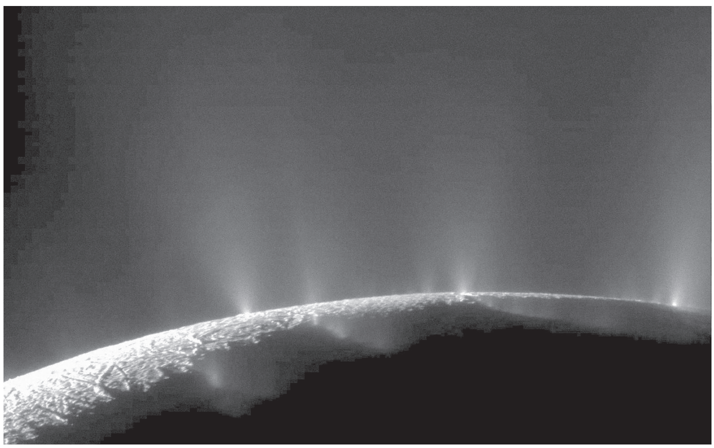


A bird's-eye-view of the solar system showing the Voyagers' *paths. Note that* Voyager 2 *launched 1 month before* Voyager 1 *but was soon overtaken.*

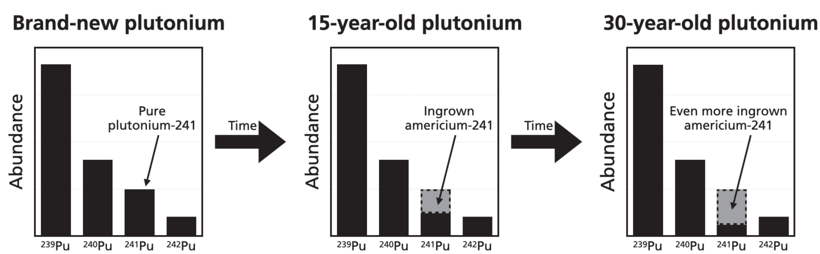


238
Pu
Purified and
put back inside a reactor
Beta decay
2 days
237
Np
237
Np
Neutron
238
Np
Beta decay
1 week
235
U
Neutron
236
U
Neutron
237
U

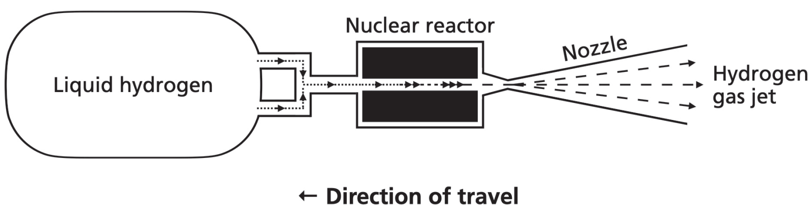
Apollo 12 astronaut Alan Bean lifts a plutonium- 238 fuel element from the Apollo Lunar Module. The finned object by his knees is the battery's casing. (Image courtesy of NASA.)



Plumes of ice – photography by Cassini – gush from cracks in Enceladus' icy crust, hinting that an ocean of liquid water lies beneath.
(Imagecourtesyof NASA/JPL-Caltech/SSI.)



A mass spectrum of reactor-grade plutonium. Only plutonium-241 has a short enough half-life to decay in human timescales. It's replaced by its americium-241 progeny as it ages. (The isotopic fingerprint of reactor-grade plutonium varies between nuclear reactors; my sketch represents a typical light-water reactor.)[9]



A nuclear rocket engine. Gas heated by fission goes one way; the rocket goes the other.

Appendix

Numerical prefixes

We use numerical prefixes as mathematical shorthands. They can be bolted onto the front of any unit, including units of power (watts) and energy (joules, watt-hours, or electron-volts).

Prefix	Symbol	Multiplier		Everyday word
Pico	p	10^{-12}	= 0.000000000001	'Trillionth'
Nano	n	10^{-9}	= 0.000000001	'Billionth'
Micro	μ	10^{-6}	= 0.000001	'Millionth'
Milli	m	10^{-3}	= 0.001	'Thousandth'
—	—	10^{0}	= 1	—
Centi	c	10^{2}	= 100	'Hundred'
Kilo	k	10^{3}	= 1,000	'Thousand'
Mega	M	10^{6}	= 1,000,000	'Million'
Giga	G	10^{9}	= 1,000,000,000	'Billion'
Tera	T	10^{12}	= 1,000,000,000,000	'Trillion'