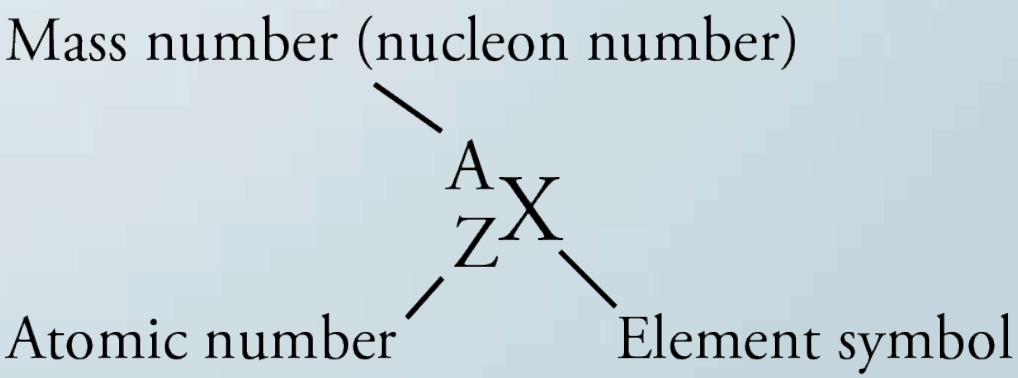
Nuclear Power

IPOL 8512

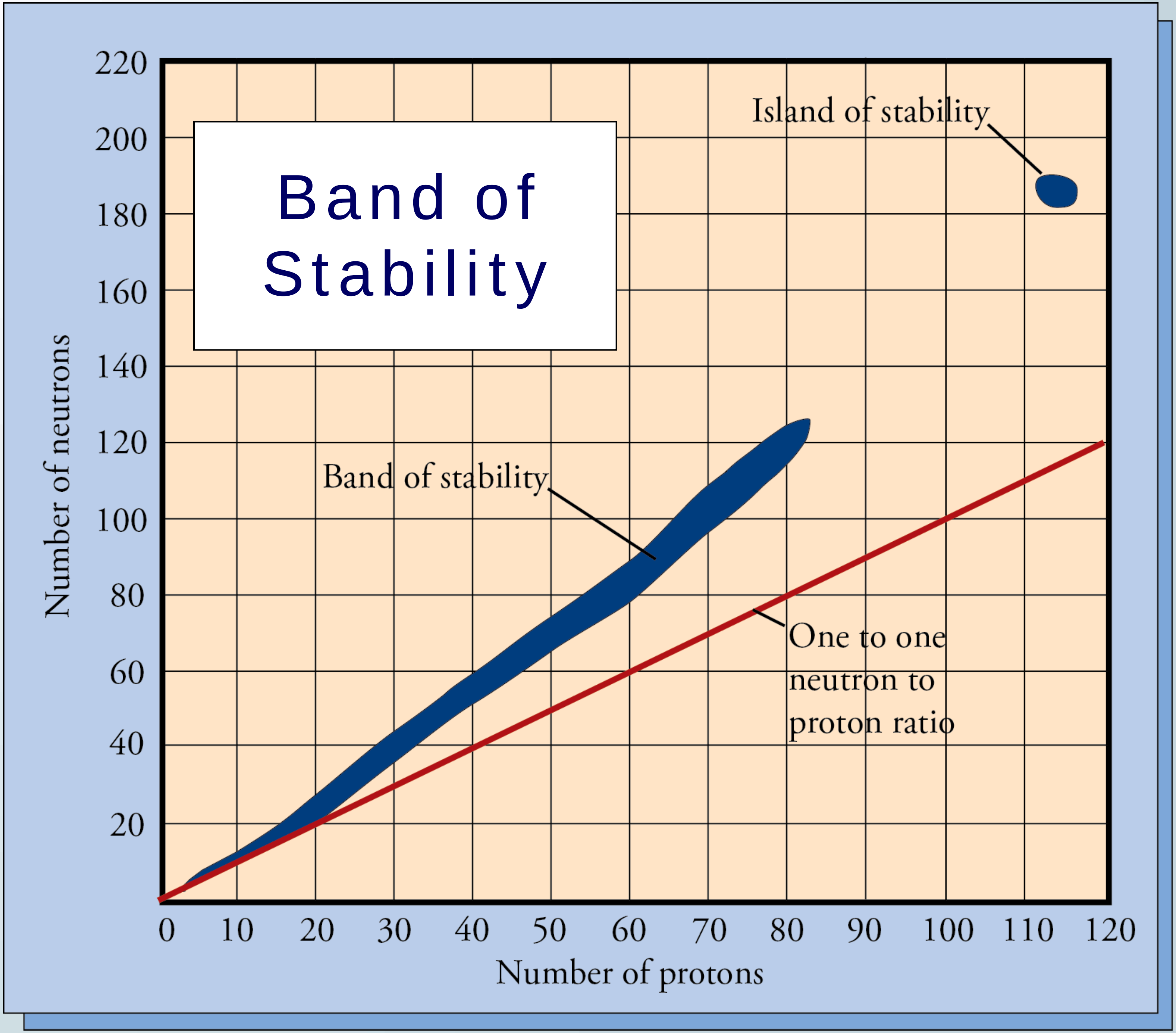
Nuclides

- ***Nuclide*** = a particular type of nucleus, characterized by a specific atomic number and nucleon number
- ***Nucleon number*** or *mass number* = the number of ***nucleons*** (protons and neutrons) in the nucleus of a nuclide.
- Nuclide symbol



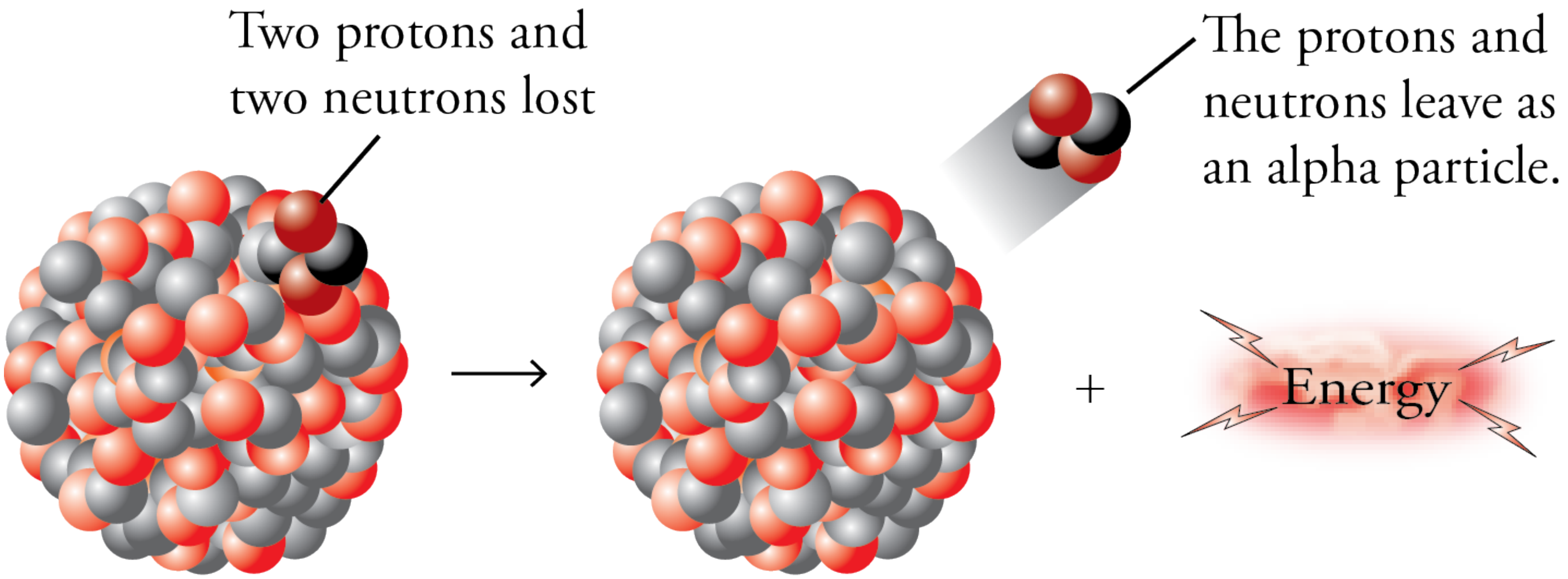
Nuclear Stability

- ***Electromagnetic force*** = the force that causes opposite electrical charges to attract each other and like charges to repel.
- ***Strong force*** = the force between nucleons (protons and neutrons).
- Neutrons increase the attraction from the strong force without increasing electromagnetic repulsion between nucleons.


Band of
Stability
Island of stability
Band of stability
One to one
neutron to
proton ratio
Number of neutrons
Number of protons
220
200
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
110
120

Alpha Emission

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

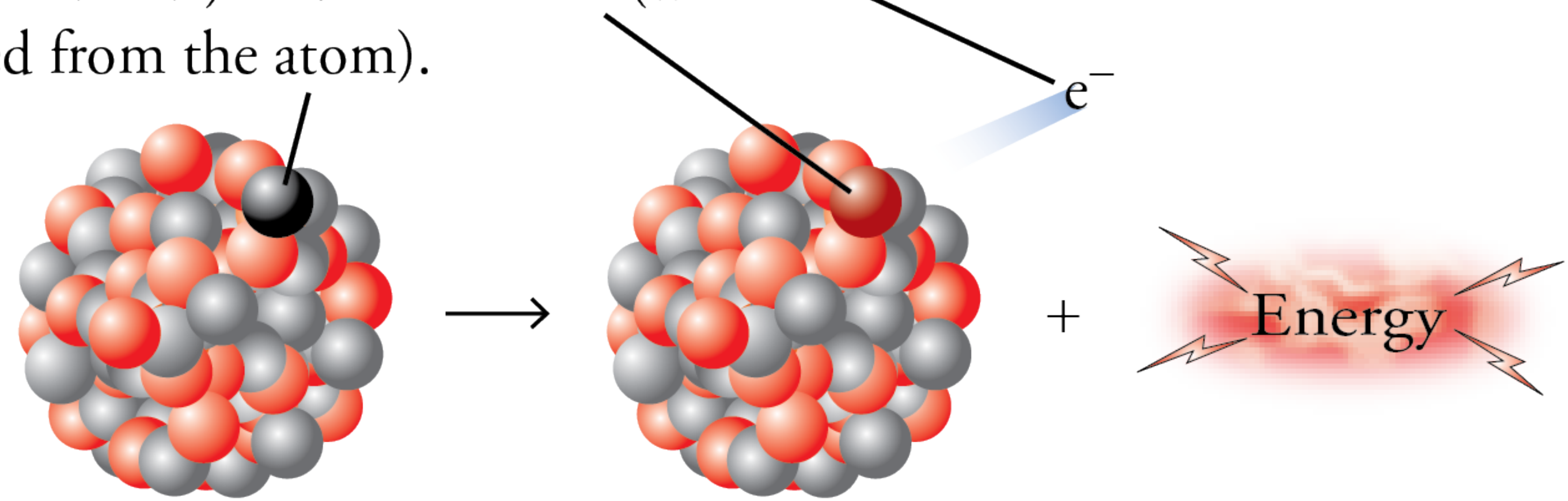


http://preparatorychemistry.com/radioactivity.html

Beta Emission

$$^{131}_{53}\mathrm{I} \longrightarrow {}^{131}_{54}\mathrm{Xe} + {}^{0}_{-1}\mathrm{e}$$

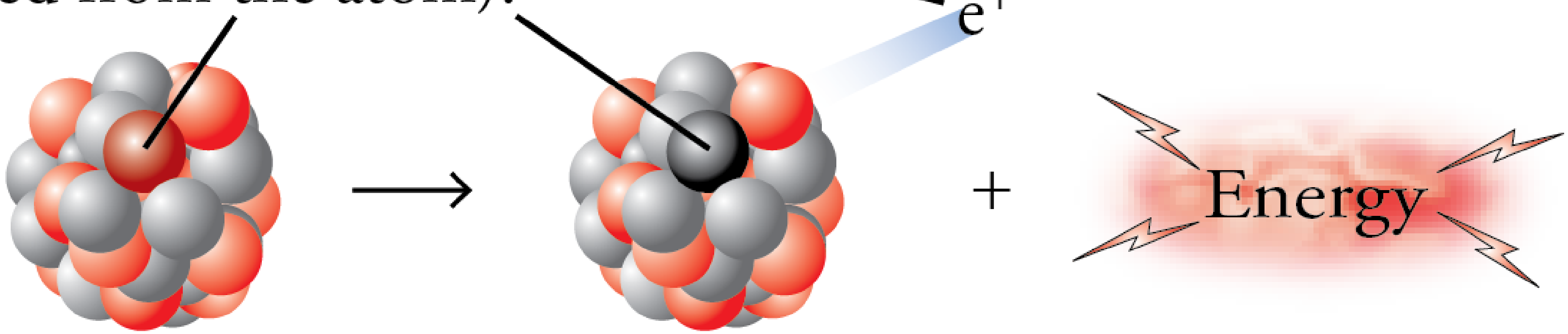
A neutron becomes a proton (which stays in the nucleus) and an electron (which is ejected from the atom).



Positron Emission

$$^{40}_{19}\mathrm{K} \longrightarrow \,^{40}_{18}\mathrm{Ar} + \,^{0}_{+1}\mathrm{e}$$

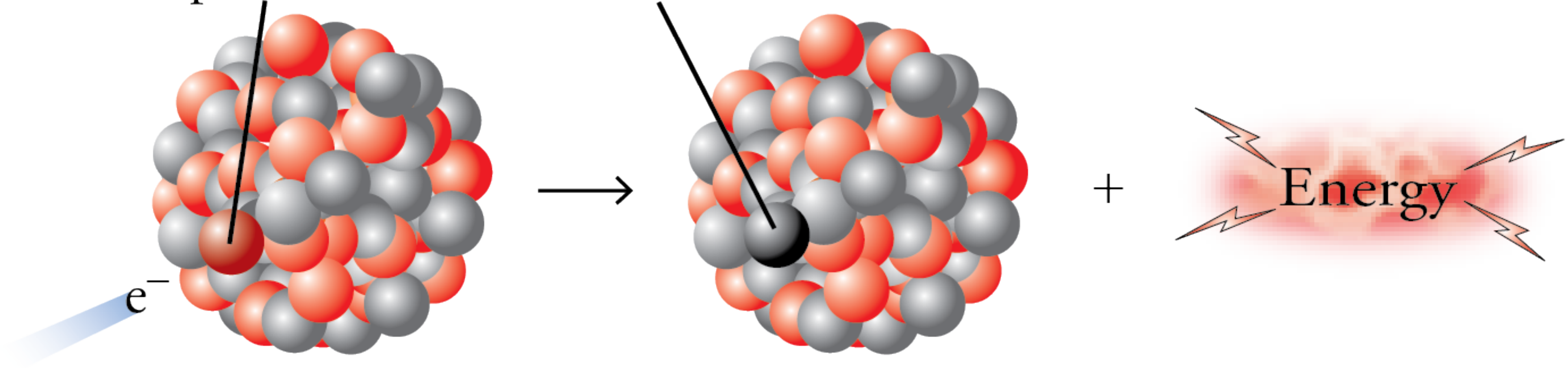
A proton becomes a neutron (which stays in the nucleus) and a positron (which is ejected from the atom).



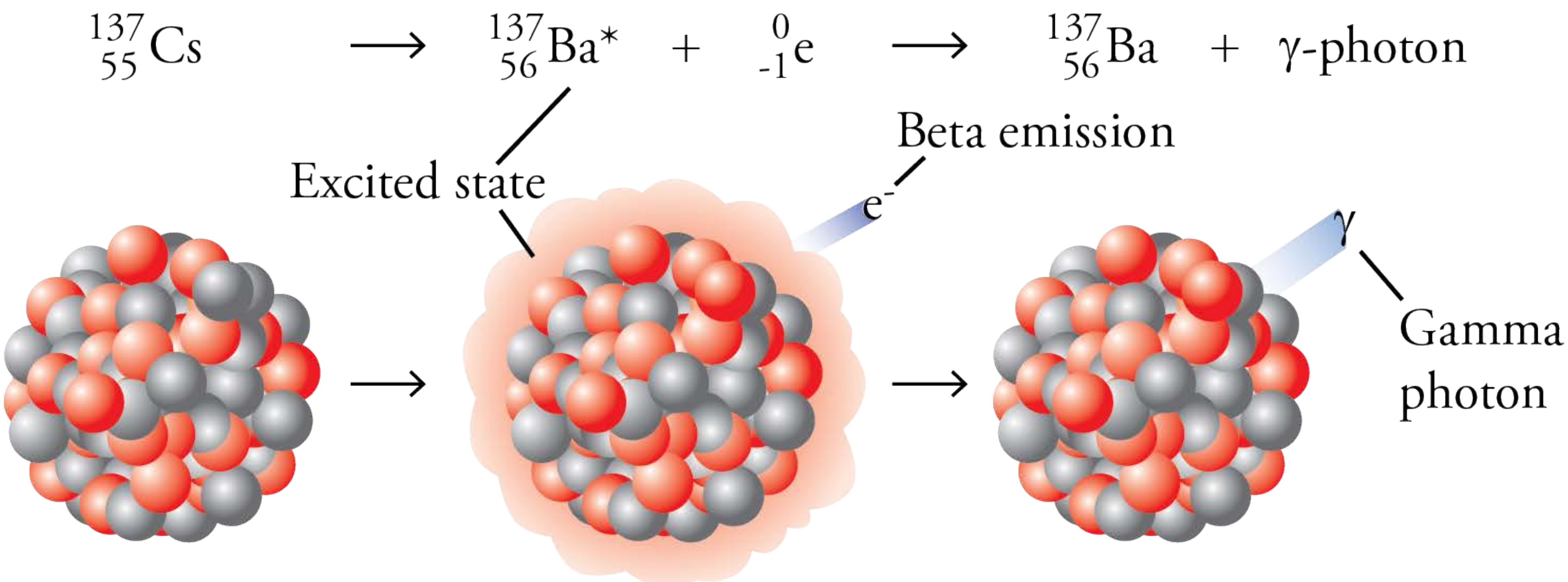
Electron Capture

$${}^{0}_{-1}\mathrm{e} + {}^{125}_{53}\mathrm{I} \longrightarrow {}^{125}_{52}\mathrm{Te}$$

An electron combines with a
proton to form a neutron.



Gamma Emission



Nuclear Reactions

- Nuclear reactions involve changes in the nucleus, whereas chemical reactions involve the loss, gain, and sharing of electrons.
- Different isotopes of the same element may undergo very different nuclear reactions, even though an element’s isotopes all share the same chemical characteristics.
- Unlike chemical reactions, the rates of nuclear reactions are unaffected by temperature, pressure, and the presence of other atoms to which the radioactive atom may be bonded.
- Nuclear reactions, in general, give off much more energy than chemical reactions.

Nuclear Equations

Alpha emission

mass number	238		234	+	4	=	238
	$^{238}_{92}U$	$\longrightarrow$	$^{234}_{90}Th$	+	$^{4}_{2}He$		
atomic number	92		90	+	2	=	92

Beta emission

mass number	131		131	+	0	=	131
	$^{131}_{53}I$	$\longrightarrow$	$^{131}_{54}Xe$	+	$^{0}_{-1}e$		
atomic number	53		54	+	(−1)	=	53

Positron emission

mass number	40		40	+	0	=	40
	$^{40}_{19}K$	$\longrightarrow$	$^{40}_{18}Ar$	+	$^{0}_{+1}e$		
atomic number	19		18	+	1	=	19

Electron capture

mass number	0	+	125	=	125		125
	$^{0}_{-1}e$	+	$^{125}_{53}I$			$\longrightarrow$	$^{125}_{52}Te$
atomic number	−1	+	53	=	52		52

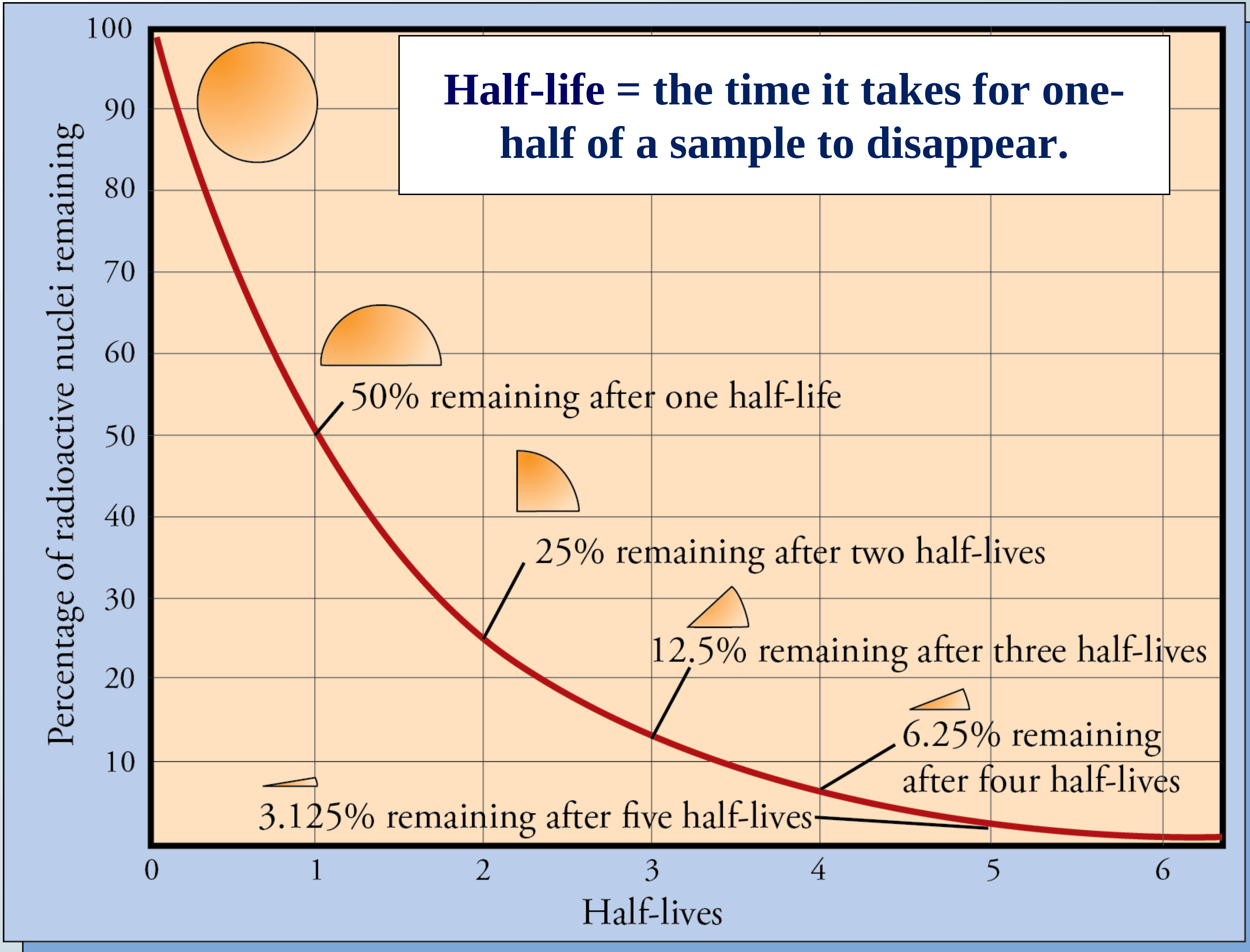
General Nuclear Equations

Alpha emission $\quad {}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$

Beta emission $\quad {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$

Positron emission $\quad {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e$

Electron capture $\quad {}^{0}_{-1}e + {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y$



Half-life = the time it takes for one-half of a sample to disappear.
100
90
80
70
60
50
40
30
20
10
Percentage of radioactive nuclei remaining
50% remaining after one half-life
25% remaining after two half-lives
12.5% remaining after three half-lives
6.25% remaining
after four half-lives
3.125% remaining after five half-lives
0
1
2
3
4
5
6
Half-lives

Exponential Decline and Half-Life

$N(t)$ = amount time t $\quad N_0$ = amount at time 0 $\quad t$ = time
k = rate $\quad k$ has units of 1/time,

$$N(t) = N_0 e^{-kt}$$

When half gone $N(t) = 1/2N_0$

$$\text{so } 1/2N_0 = N_0 e^{-kt_{1/2}}$$
$$2^{-1} = e^{-kt_{1/2}}$$
$$\ln 2^{-1} = \ln(e^{-kt_{1/2}})$$
$$-\ln 2 = -kt_{1/2} \ln e$$
$$\ln 2 = kt_{1/2}$$

$$\frac{\ln 2}{k} = t_{1/2} = \frac{\mathbf{0.693}}{k}$$

Exponential Decline Example

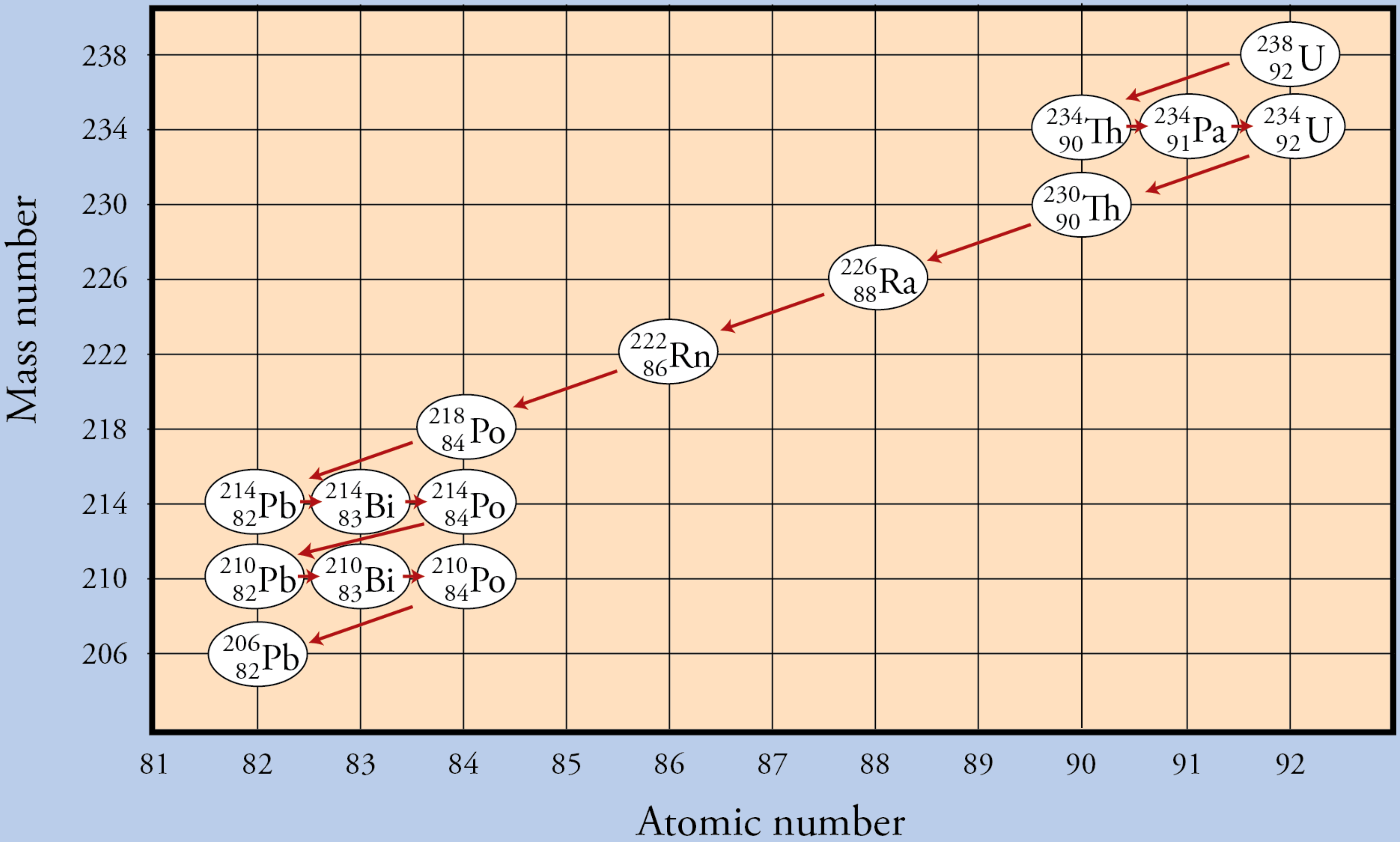
- Iodine-131 has a half-life of 8.0197 days. If we start with 37 GBq (or 1 curie) of I-131, how much is left after 14 days?
  - The **becquerel** (symbol **Bq**) (pronounced: 'be-kə-rel) is the SI-derived unit of radioactivity. One Bq is defined as the activity of a quantity of radioactive material in which one nucleus decays per second. The Bq unit is therefore equivalent to an inverse second, s^{-1}.
  - The curie is a common non-SI unit. It is now defined as 37 GBq.

Iodine-131 has a half-life of 8.0197 days. If we start with 37 GBq (or 1 curie) of I-131, how much is left after 14 days?

$$t_{1/2} = \frac{0.693}{k} \qquad k = \frac{0.693}{t_{1/2}} = \frac{0.693}{8.0197\ \text{day}} = 0.0864\ \text{day}^{-1}$$

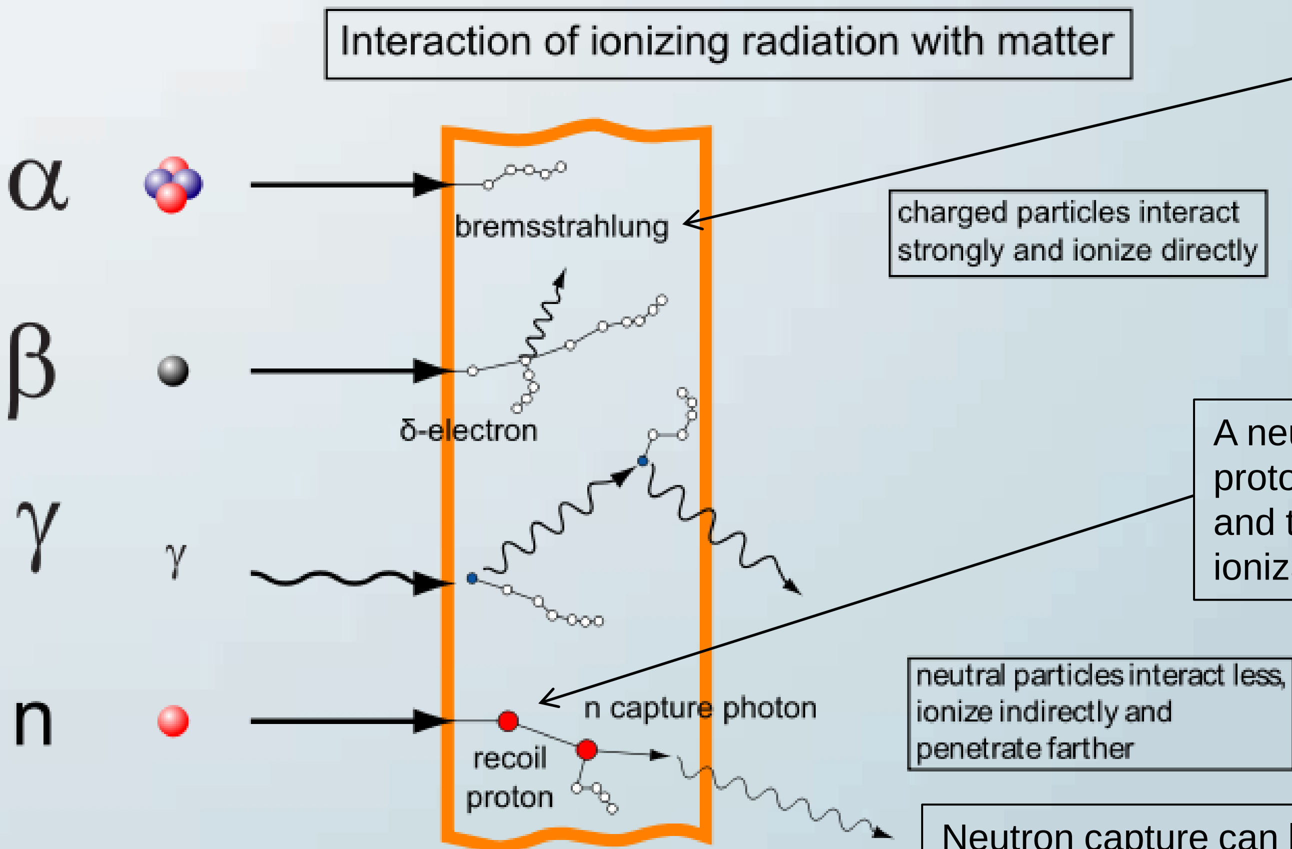
$$S(t) = S_o\, e^{-kt} = 37\ \text{GBq}\ e^{-0.0864\ 1/\text{day}(14\ \text{day})} = \mathbf{11\ GBq}$$

Radioactive Decay Series



Ionizing Radiation

- All of the forms of radioactive emissions can lead to the formation of ions.



The energy lost to deceleration of beta particles is emitted in the form of X-rays called "bremsstrahlung," which translates to "braking radiation".

A neutron can knock a proton out of a nucleus, and the proton can cause ionizations.

Neutron capture can lead to beta decay.

Radiation Effect on Body

- Radioactive emissions ionize atoms and molecules. This leads to free radicals (particles with unpaired electrons). For example,

  $H_2O \rightarrow H_2O\bullet^{+} + e^{-}$

  $H_2O\bullet^{+} + H_2O \rightarrow H_3O^{+} + \bullet OH$

  $H_2O + e^{-} \rightarrow H\bullet + OH^{-}$
- Ionizing radiation is generally harmful and potentially lethal.
- High doses can cause visually dramatic radiation burns, and/or rapid death through acute radiation syndrome.

http://en.wikipedia.org/wiki/Acute_radiation_syndrome

Effects on Body from Inside and Outside

- Internal emitters = emitters of alpha and weak beta particles
  - Cannot penetrate dead outer layer of skin,
  - Dangerous if inside the body (e.g. Pu-239)
- External emitters = emitters of gamma rays, strong beta particles, or neutrons
  - Dangerous from outside the body

http://preparatorychemistry.com/radioactivity.html

Relative Biological Effectiveness

- The ratio of biological effectiveness of one type of ionizing radiation relative to another, given the same amount of absorbed energy.

Type	RBE (QF = quality factor)
x-rays	1
γ-rays	1
β-particles	1-3
α-particles	5-20
neutrons	5-20

http://en.wikipedia.org/wiki/Relative_Biological_Effectiveness

Radiation Dose

- **Physical dose** = energy absorbed per kg of tissue:
  - 1 rad = 100 erg/g = 0.01 Gy
  - 1 Gray (Gy) = 1 J/kg = 100 rad
- **Biological dose** = physical dose × biological effectiveness:
  - QF = Quality Factor
    = RBE = relative biological effectiveness
  - 1 rem = 1 rad × (QF = 1)
  - ? rem = # rad × QF
  - 1 Sievert (Sv) = 1 Gy × (QF = 1) = 100 rem
  - ? Sv = # Gy × QF

Health Effects

Sv	Effect
> 0.25	change in blood counts
> 0.50	temporary sterility
1-2	vomiting, hair loss, etc.
2-3	5-35% fatalities in 30 d
> 3	permanent sterility
4-5	50% fatalities in 30 d ($LD_{50/30}$).
6-8	95% fatalities in 30 d
>10	death in 10 d
> 50	death in 2 d
> 100	immediate death

Health Effects

- ***Deterministic effects*** *that can lead to acute radiation syndrome only occur in the case of high doses (> ~0.1 Gy) and high dose rates (> ~0.1 Gy/h).*
- ***Stochastic effects*** *are those that occur randomly, such as radiation-induced cancer. The consensus of the nuclear industry, nuclear regulators, and governments, is that the incidence of cancers due to ionizing radiation can be modeled as increasing linearly with effective dose at a rate of 5.5% per sievert.*
- *There is general agreement that the risk is much higher for infants and fetuses than adults, higher for the middle-aged than for seniors, and higher for women than for men, though there is no quantitative consensus about this.*
- *The International Commission on Radiological Protection (ICRP) recommends limiting artificial irradiation of the public to an average of 1 mSv (0.001 Sv) of effective dose per year, not including medical and occupational exposures.*

http://en.wikipedia.org/wiki/Sievert

Example: Risk of Cancer

- Because of the uranium content of the granite in the U.S. Capitol Building, radiation levels inside the building are ≈0.85 mSv/yr, which is close to the regulatory limit.
- According to the ICRP model, someone who spent 20 years inside the capitol building would have an extra one in a thousand chance of getting cancer, over and above any other existing risk.

$$? \,\% = 20\,\cancel{\text{y}}\left(\frac{0.85\ \cancel{\text{mSv}}}{1\ \cancel{\text{y}}}\right)\left(\frac{1\ \cancel{\text{Sv}}}{10^3\ \cancel{\text{mSv}}}\right)\left(\frac{5.5\ \%}{1\ \cancel{\text{Sv}}}\right) \approx \mathbf{0.1\%}$$

- An average American would have a one in ten chance of getting cancer during this same 20 year period, even without any exposure to artificial radiation.

Acute Dose Examples

98 nSv	-banana equivalent dose, a whimsical unit of radiation
0.25 µSv	-U.S. limit on effective dose from a single airport security screening
5 to 10 µSv	-one set of dental X-rays
80 µSv	-average dose to people living within 16 km of Three Mile Island accident
0.4 to 0.6 mSv	-two-view mammogram, using weighting factors updated in 2007
2 to 7 mSv	-barium fluoroscopy
10 to 30 mSv	-single full-body CT scan
68 mSv	-estimated maximum dose to evacuees who lived closest to the Fukushima I nuclear accidents
0.67 Sv	-highest dose received by a worker responding to the Fukushima emergency

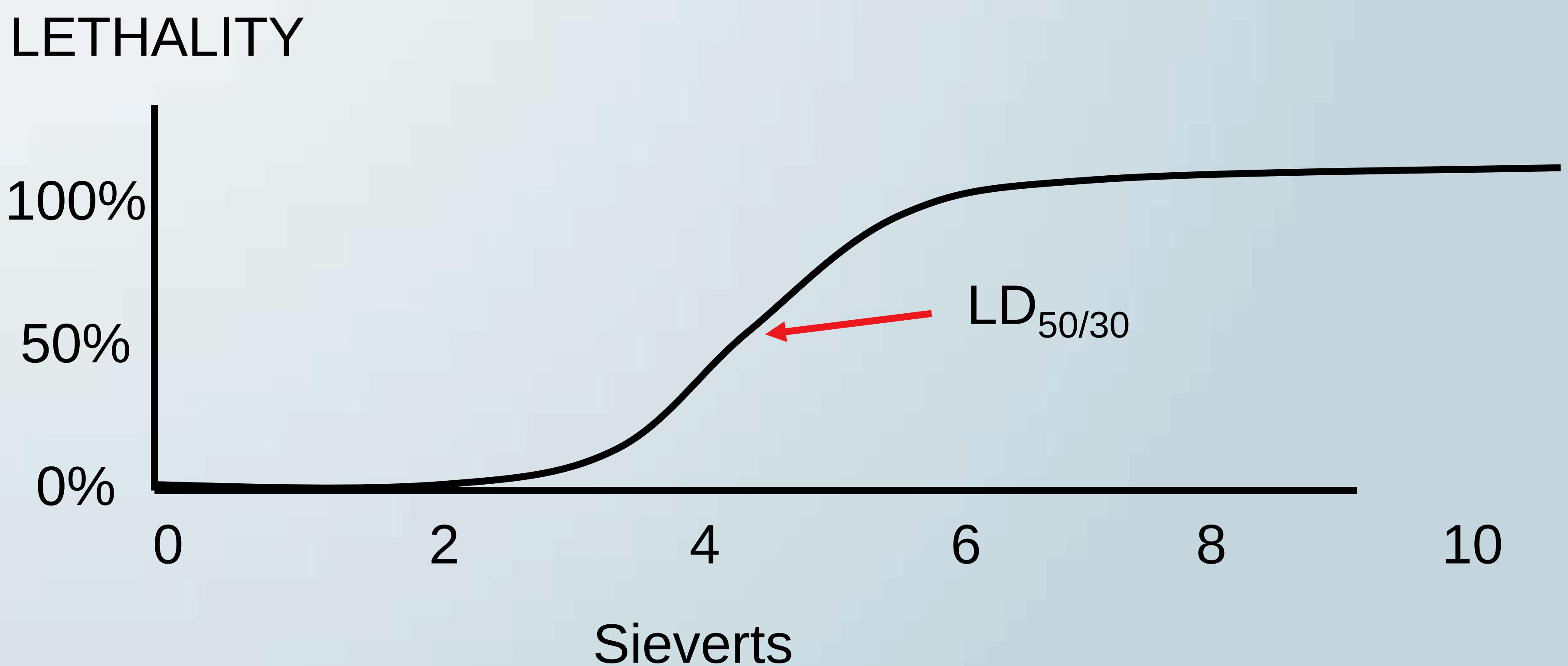
http://en.wikipedia.org/wiki/Sievert

Chronic Dose Examples

1	mSv/yr	ICRP recommended maximum for artificial irradiation of the public, excluding medical and occupational exposures.
2.4	mSv/yr	Natural background radiation, global average
24	mSv/yr	Natural background radiation at airline cruise altitude
9	Sv/yr	NRC definition of a high radiation area in a nuclear power plant, warranting a chain-link fence
>90	kSv/yr	most radioactive hotspot found in Fukushima I in areas normally accessible to workers
2.3	MSv/yr	typical PWR spent fuel bundle, after 10 year cool down, no shielding

http://en.wikipedia.org/wiki/Sievert

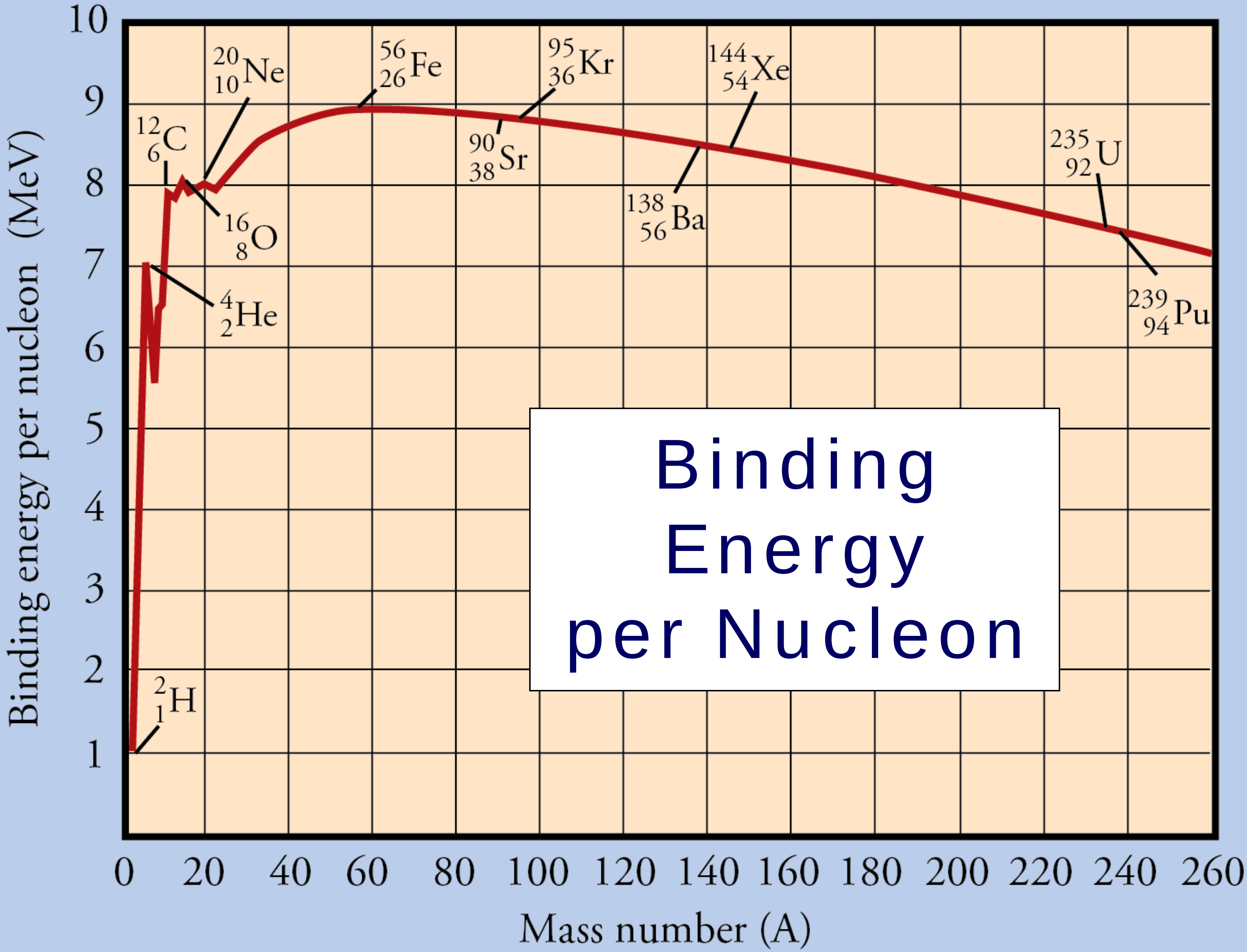
Lethality



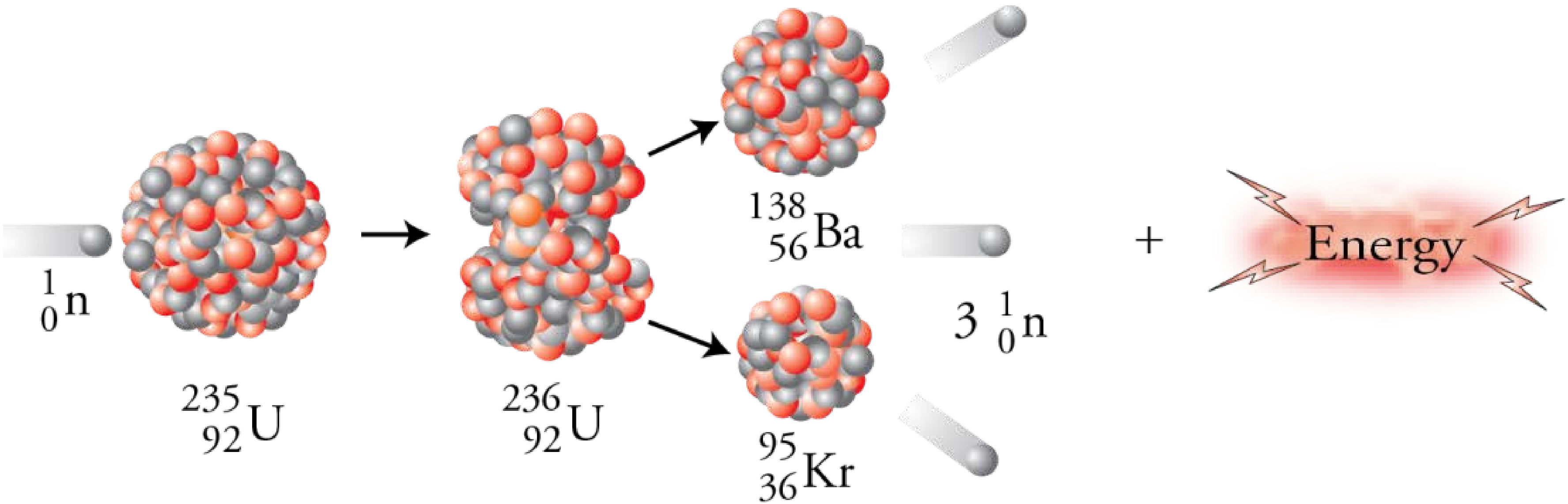
Nuclear Energy

- ***Binding energy*** = the amount of energy released when a nucleus is formed.
- Binding energy per nucleon generally increases from small atoms to atoms with a mass number around 56. Thus fusing small atoms to form medium-sized atoms (***nuclear fusion***) releases energy.
- Binding energy per nucleon generally decreases from atoms with a mass number around 56 to larger atoms. Thus splitting large atoms to form medium-sized atoms (***nuclear fission***) also releases energy.

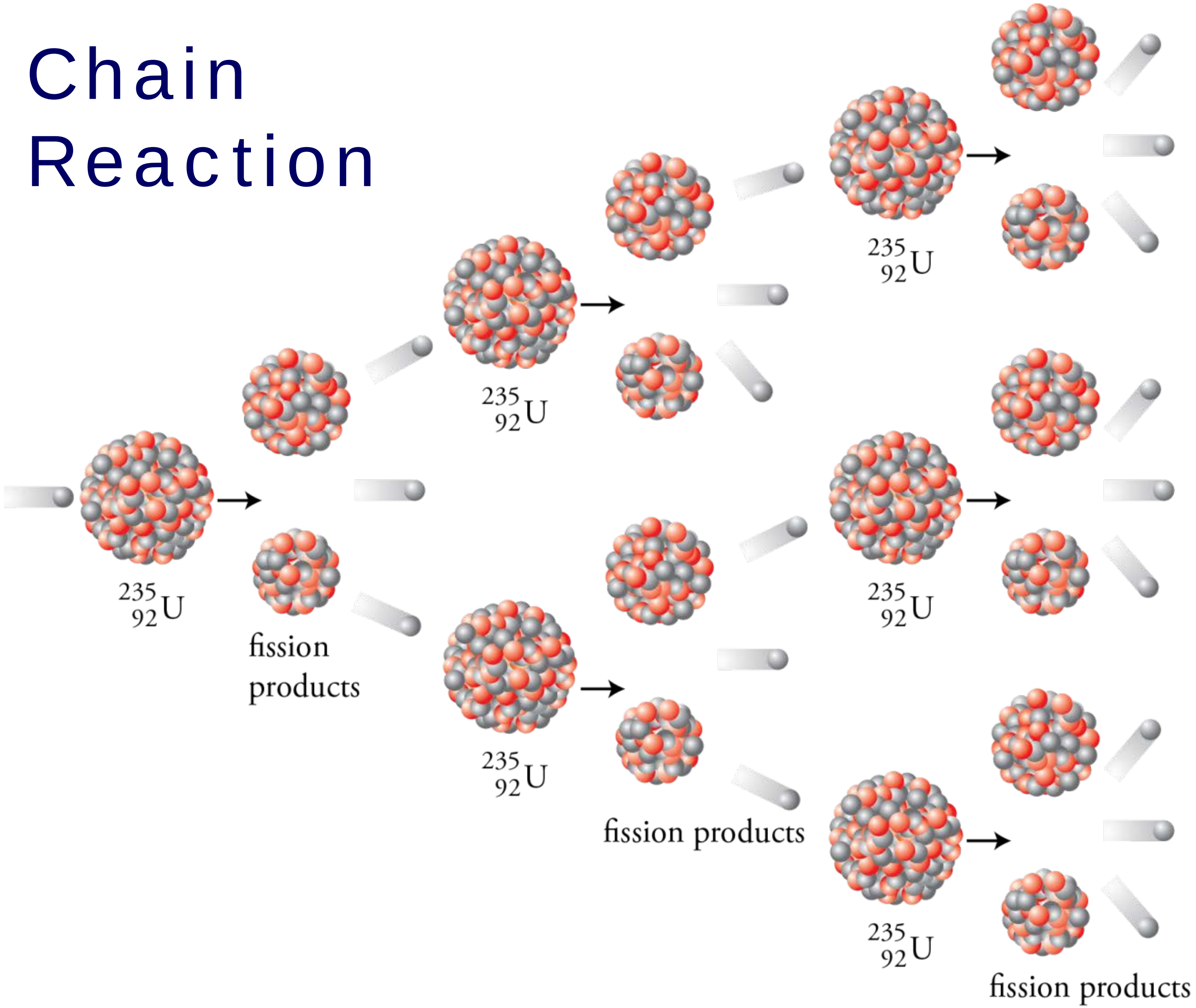
Binding Energy per Nucleon



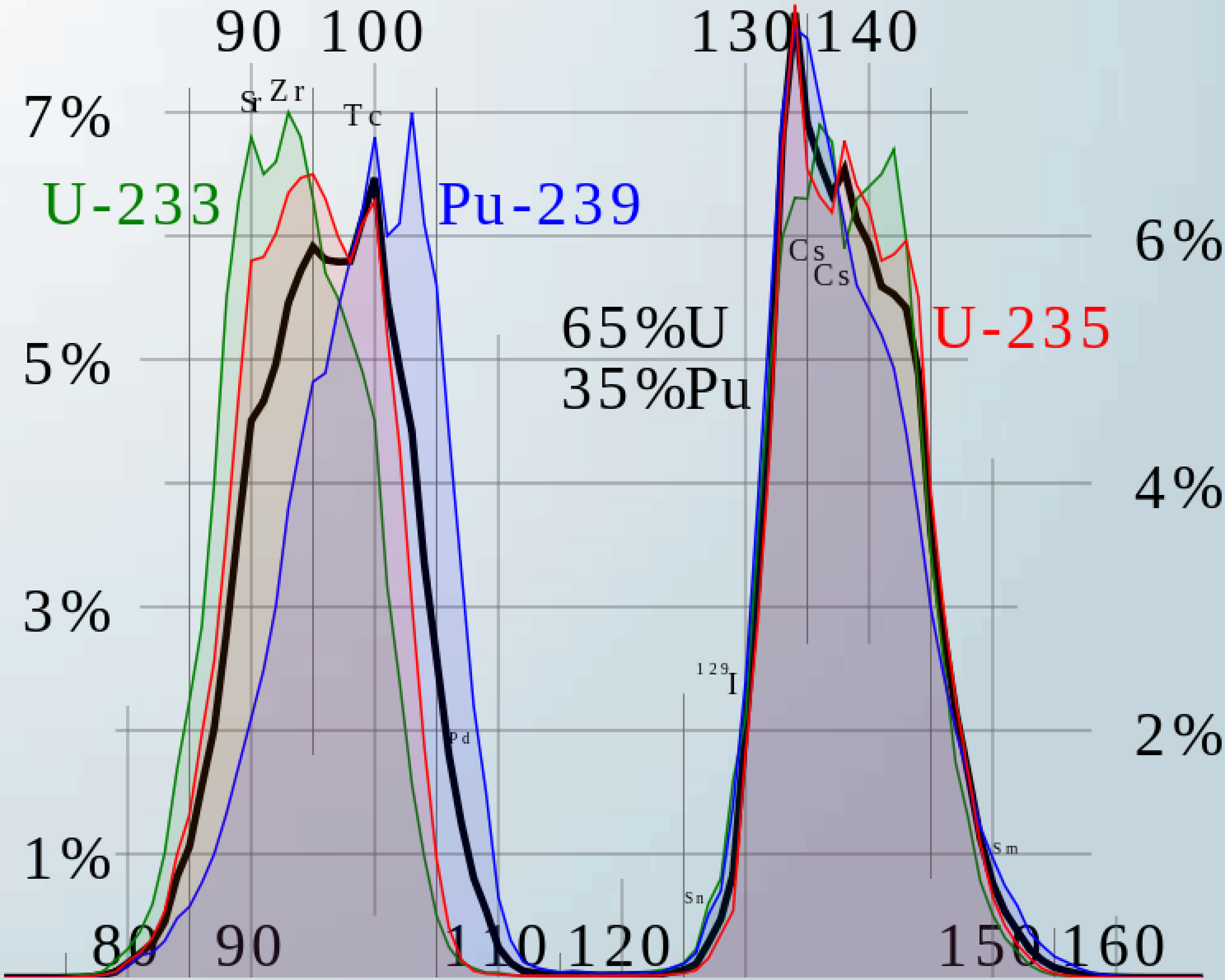
Nuclear Fission



Chain Reaction

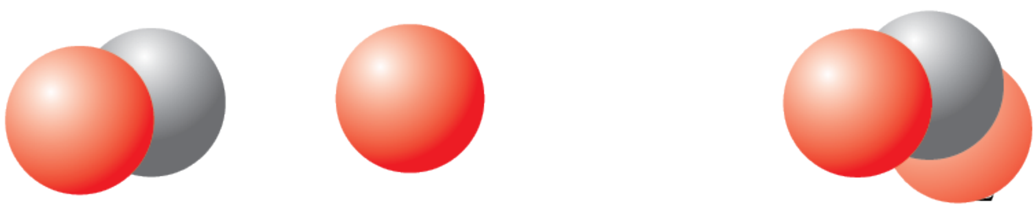


Fission Yield

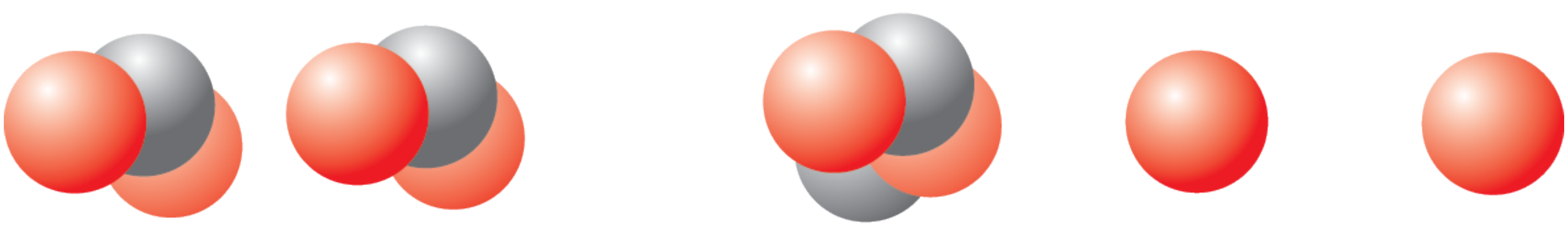


Nuclear Fusion Powers the Sun

$${}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{+1}\mathrm{e}$$

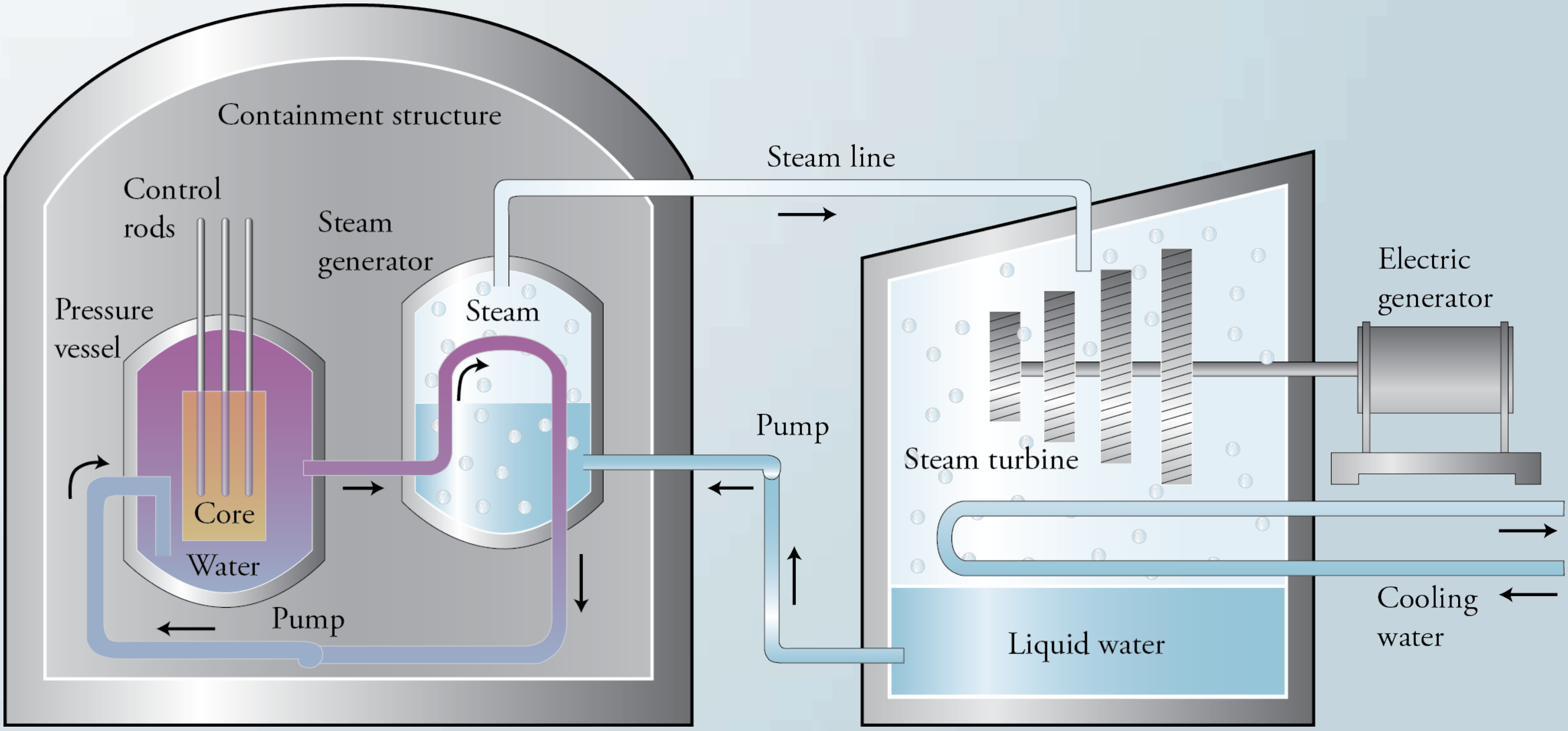


$${}^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He}$$



$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H}$$

Nuclear Power Plant



Nuclear Power Plant

- Fission reactions provide heat, which is used to boil water to create steam, which turns a steam turbine to generate electricity.
- Get heat from
  – Fission reaction
  – Radioactive decay of fission products
  – Gamma rays released converted into heat

Nuclear Power Plant

- To get a sustained chain reaction, the percentage of ^{235}U must be increased over what is found in nature, in part because the unfissionable ^{238}U absorbs too many neutrons, and a sustained fission reaction is not reached.

$$^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{239}_{92}\mathrm{U}$$

$$^{239}_{92}\mathrm{U} \rightarrow ^{239}_{93}\mathrm{Np} + ^{0}_{-1}\mathrm{e}$$

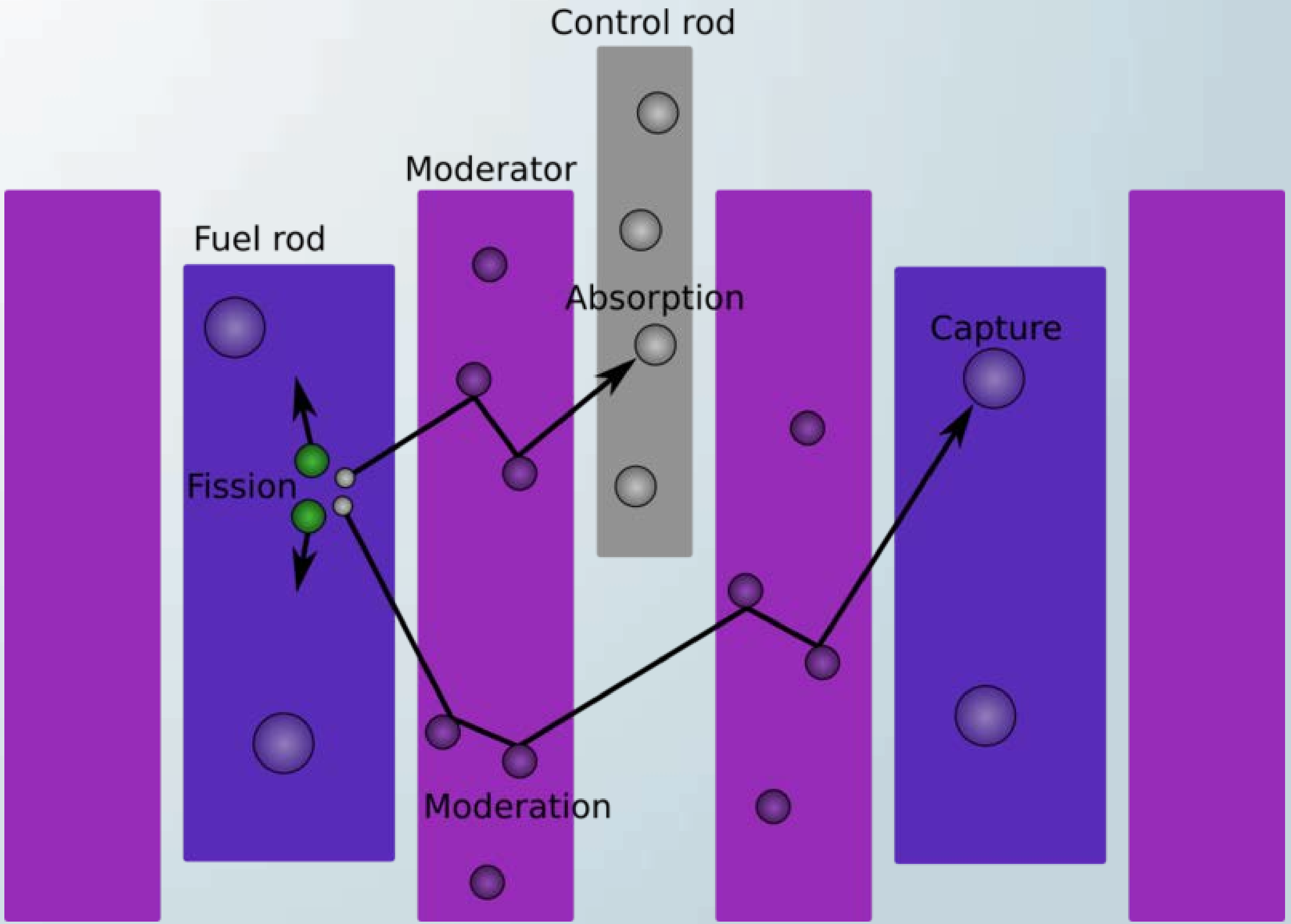
$$^{239}_{93}\mathrm{Np} \rightarrow ^{239}_{94}\mathrm{Pu} + ^{0}_{-1}\mathrm{e}$$

- Fuel rods
  - A typical 1000-megawatt power plant will have from 90,000 to 100,000 kg of enriched fuel packed in 100 to 200 zirconium rods about 4 meters long.

Thermal Reactors

- Thermal reactors use slowed or thermal neutrons.
- Almost all current reactors are of this type.
- A moderator slows neutrons until their kinetic energy approaches the average kinetic energy of the surrounding particles.
  - Moderator can be regular (light) water (74.8% of the world's reactors), solid graphite (20% of reactors) and heavy water (dueterium oxide - 5% of reactors).
- Thermal neutrons have a far higher probability of fissioning the fissile nuclei (^{235}U, ^{239}Pu, and ^{241}Pu), and a relatively lower probability of neutron capture by ^{238}U compared to the faster neutrons that originally result from fission, allowing use of low-enriched uranium fuel. The moderator is often also the coolant, usually water under high pressure to increase the boiling point.

Thermal Reactor



Fast Neutron Reactors

- Use fast neutrons to cause fission in their fuel.
- Do not have a neutron moderator, and use less-moderating coolants.
- Requires the fuel to be more highly enriched in fissile material (about 20% or more) due to the relatively lower probability of fission versus capture by U-238.
- More difficult to build and more expensive to operate.
- Less common than thermal reactors in most applications.

Nuclear Power Plant

- Control Rods
  - Substances, such as cadmium or boron, that absorb neutrons.
  - Control rate of chain reaction
  - Dropped at first sign of trouble to stop fission reaction
- Facility includes instrumentation to monitor and control the reactor, radiation shielding, and a containment building.

Prompt Critical

- **Critical** = if each fission event causes, on average, exactly one other. This causes a self-sustaining fission chain reaction.
- **Supercriticality** = if each fission event causes, on average, more than one other.
- **Prompt critical** = if for each nuclear fission event, one or more of the immediate or prompt neutrons released causes an additional fission event. This causes a rapid, exponential increase in the number of fission events. Prompt criticality is a special case of supercriticality.

Delayed Neutrons

- A small fraction of the fission products that undergo beta decay are excited enough to be able to decay by emitting a neutron.
- The neutron emission happens orders of magnitude later compared to the emission of the prompt neutrons, which are released in the fission reaction.
- The ability of delayed neutrons to cause a new fission reaction is important in the design and safe operation of nuclear power plants.

Delayed Neutrons

- If a nuclear reactor happened to be prompt critical, the number of neutrons would increase exponentially, and very quickly the reactor would become uncontrollable.
- Because of the delayed neutrons, it is possible to leave the reactor in a subcritical state as far as only prompt neutrons are concerned.
- If the fission reaction begins to increase too rapidly, neutron production overall still grows exponentially, but on a time scale that is governed by the delayed neutron production, which is slow enough to be controlled.

Diablo Canyon Nuclear Plant

- At Avila Beach in San Luis Obispo County, California.
- Two 1,100 MWe (MW of electrical energy produced) pressurized-water nuclear reactors operated by Pacific Gas & Electric produce about 18,000 GW·h of electricity annually, supplying the electrical needs of more than 2.2 million people.

Diablo Canyon Nuclear Plant

- Built directly over a geological fault line, and is located near a second fault.
- Originally designed to withstand a 6.75 magnitude earthquake, later upgraded to withstand a 7.5 quake.
- The Nuclear Regulatory Commission's estimate of the risk each year of an earthquake intense enough to cause core damage to the reactor at Diablo Canyon was 1 in 23,810, according to an NRC study published in August 2010.
- In April 2011, in the wake of the Fukushima nuclear incident in Japan, PG&E asked the NRC not to issue license renewals until PG&E can complete new seismic studies, which are expected to take at least three years.

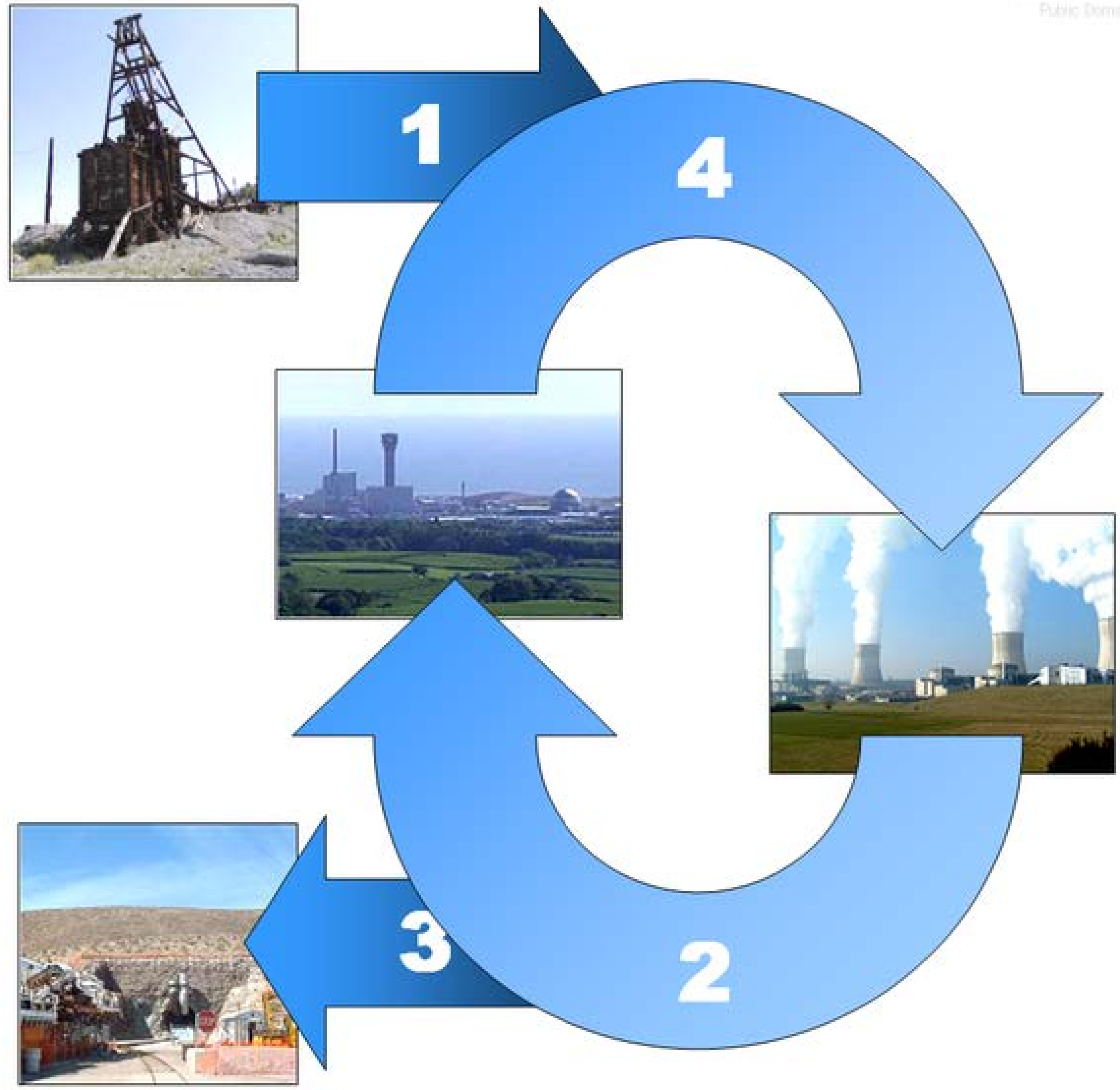
Seismic Tests

- *PG&E wants to use big air guns to emit strong sound waves into a large, near-shore area that includes parts of marine reserves to make three-dimensional maps of fault zones, some of which were discovered in 2008, near its Diablo Canyon nuclear power plant.*
- *But a state study — mandated by Assembly Bill 1632, which was signed into law in 2006 — found the project is likely to have “unavoidable adverse effects” on marine life and the environment. Biologists, environmental groups and fishermen have opposed using the high-energy air guns, saying the blasts have the potential to harm endangered whales, California sea otters and other creatures frequenting these waters.*

http://www.sfexaminer.com/news/2012/09/officials-mull-seismic-tests-near-pges-diablo-canyon-nuclear-plant

Uranium Fuel Cycle

Uranium is mined, enriched and manufactured to make nuclear fuel (1), which is delivered to a nuclear power plant. After usage in the power plant the spent fuel might be delivered to a reprocessing plant (if fuel is recycled) (2) or to a final repository (if no recycling is done) (3) for geological disposition. In reprocessing, 95% of spent fuel can be recycled to be returned to usage in a nuclear power plant (4).



http://en.wikipedia.org/wiki/Nuclear_fuel_cycle

Uranium Ore

- Uranium is one of the more common elements in the Earth's crust, some 40 times more common than silver and 500 times more common than gold.
- The primary uranium ore is uraninite, which is is largely UO_2, but also contains UO_3 and oxides of other metals. It is commonly known as pitchblende.

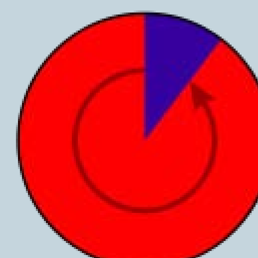
Uranium Enrichment

- Uranium in uranium ore is about 99.3% ^{238}U, which is not fissionable, and 0.7% ^{235}U, which is fissionable.
- Needs to be enriched in ^{235}U to varying degrees (depending on the reactor design) to be useful in a nuclear power plant.

Highly enriched uranium metal

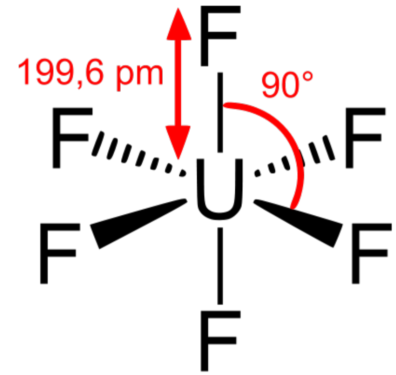
Natural uranium
> 99.2% U-238
0.72% U-235

Low-enriched uranium
(reactor grade)
3-4% U-235

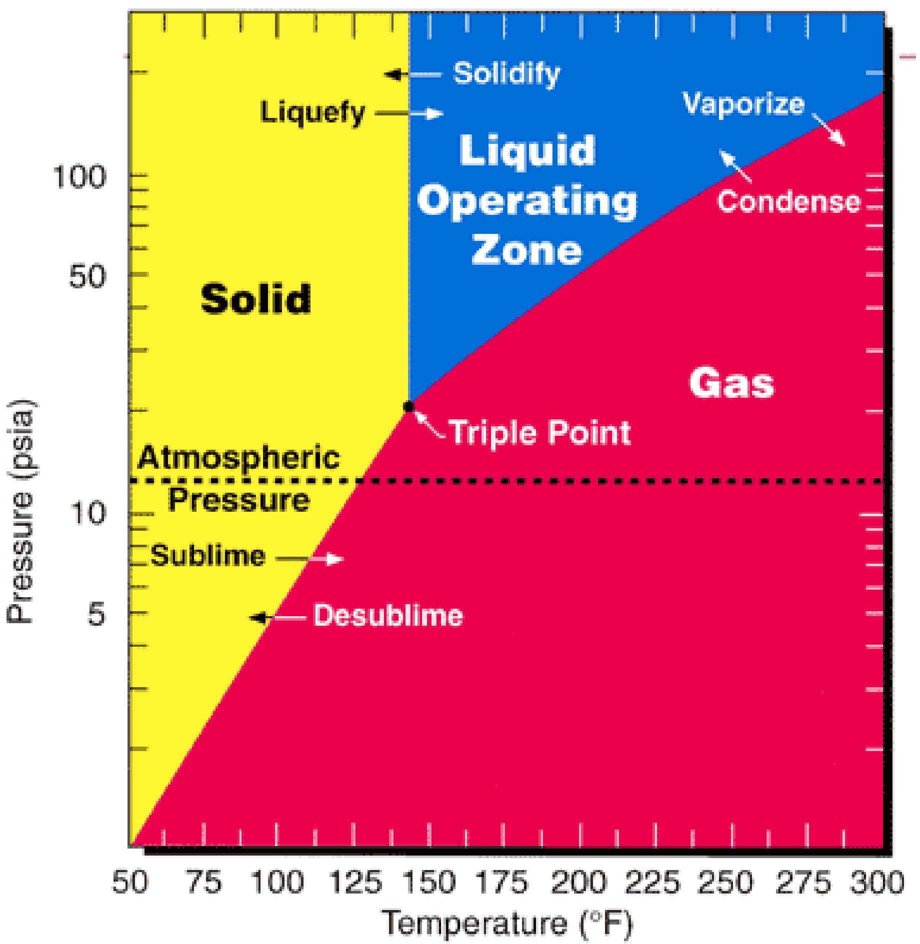


Highly enriched uranium
(weapons grade)
90% U-235

Uranium Enrichment

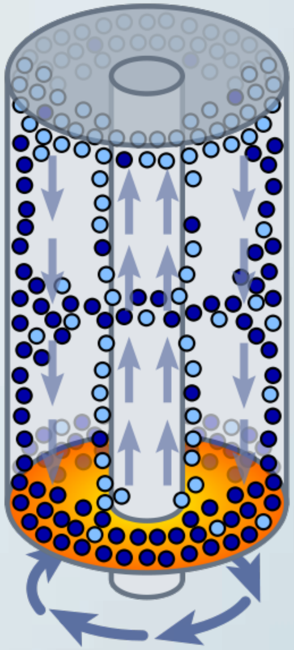


- In a series of steps, the uranium in uranium ore is converted into uranium hexafluoride, UF_6.
- It sublimes (goes directly from solid to gas) at 56.5 °C.
- The UF_6 can be enriched in $^{235}UF_6$ by either gas diffusion (first generation) or using gas centrifuges (second generation), which requires less energy.

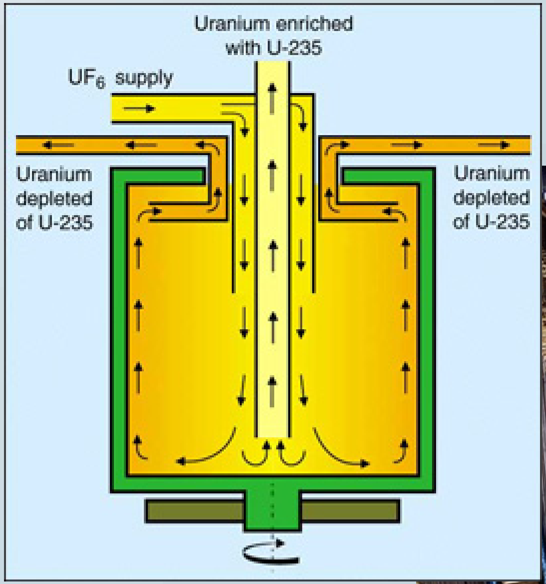


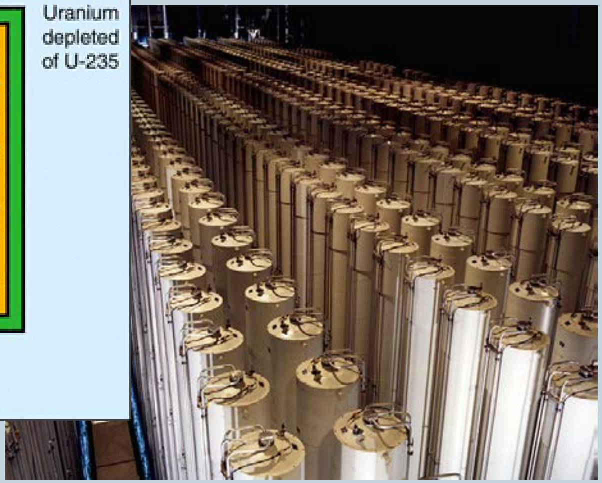
Gas Centrifuge

- Creates a strong centrifugal force so that the heavier gas molecules containing ^{238}U move toward the outside of the cylinder and the lighter gas molecules rich in ^{235}U collect closer to the center.
- A large number of rotating cylinders connected in series and parallel formations.



The bottom of the rotating cylinder can be heated, producing convection currents that move the ^{235}U up the cylinder, where it can be collected.



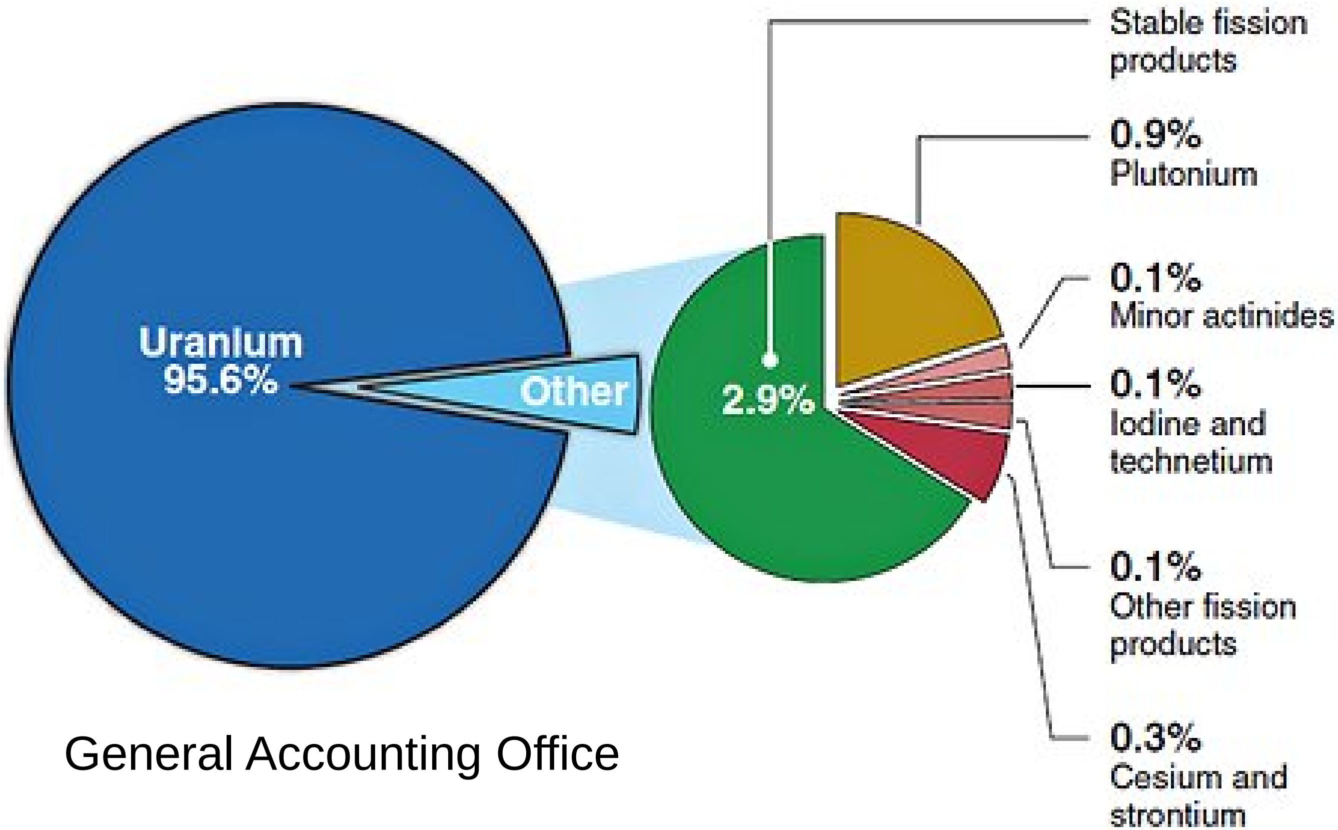


Depleted Uranium

- Most of the depleted uranium produced is stored as uranium hexafluoride, DUF_6, in steel cylinders in open air yards close to enrichment plants.

Spent Fuel Rods

Figure 1: Composition of Spent Nuclear Fuel



General Accounting Office

- Fission products that emit beta and gamma radiation
- Some fissionable U-235 and Pu-239
- Alpha emitters, such as uranium-234, neptunium-237, plutonium-238 and americium-241
- Sometimes some neutron emitters such as californium (Cf).

Nuclear Reprocessing

- Process to chemically separate and recover fissionable plutonium and uranium from irradiated nuclear fuel.
- Purposes
  - Originally reprocessing was used solely to extract plutonium for producing nuclear weapons.
  - The reprocessed plutonium can be recycled back into fuel for nuclear reactors.
  - The reprocessed uranium, which constitutes the bulk of the spent fuel material, can in principle also be re-used as fuel, but that is only economic when uranium prices are high.

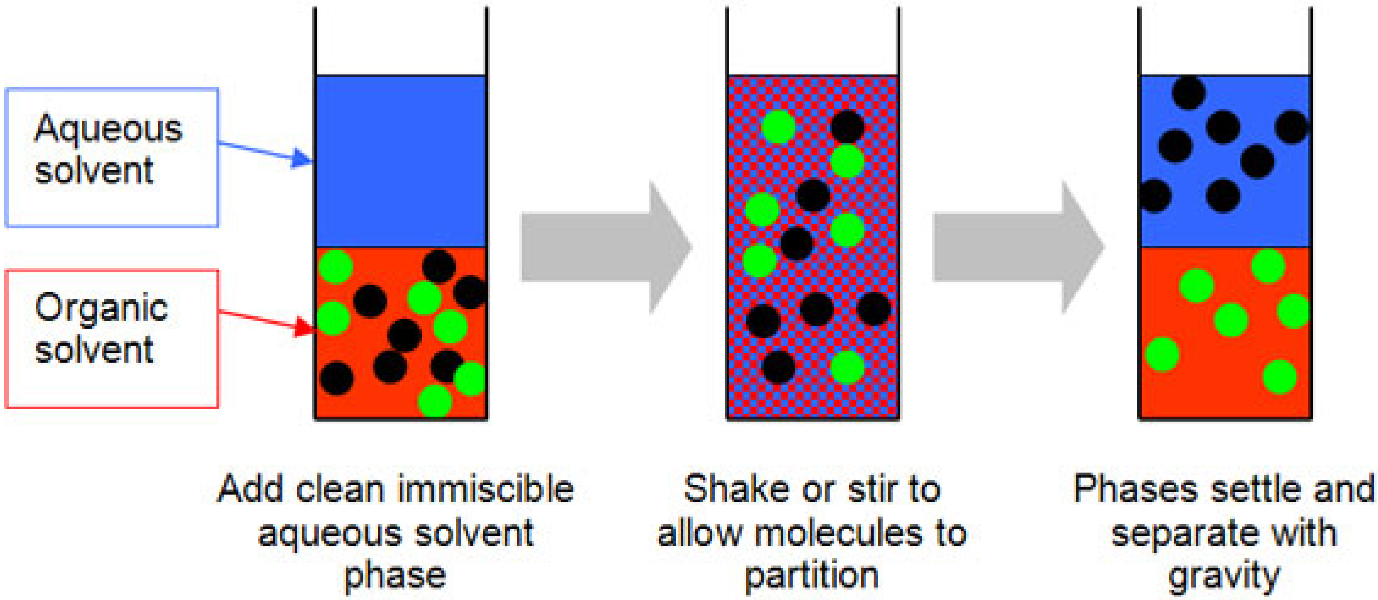
http://en.wikipedia.org/wiki/Nuclear_reprocessing

Nuclear Reprocessing

- Reprocessing of civilian fuel has long been employed in France, the United Kingdom, Russia, Japan, and India
- Briefly done at the West Valley Reprocessing Plant in the United States.
- In October 1976, concerned about nuclear weapons proliferation, President Gerald Ford indefinitely suspended the commercial reprocessing and recycling of plutonium in the U.S.
- In March 1999, the U.S. Department of Energy (DOE) reversed its policy and signed a contract with a consortium to design and operate a mixed oxide (MOX) fuel fabrication facility. There are no customers yet.

http://en.wikipedia.org/wiki/Nuclear_reprocessing

Liquid-Liquid Extraction



Polar compounds will congregate in “aqueous” layer

Non-polar compounds will congregate in “organic” layer

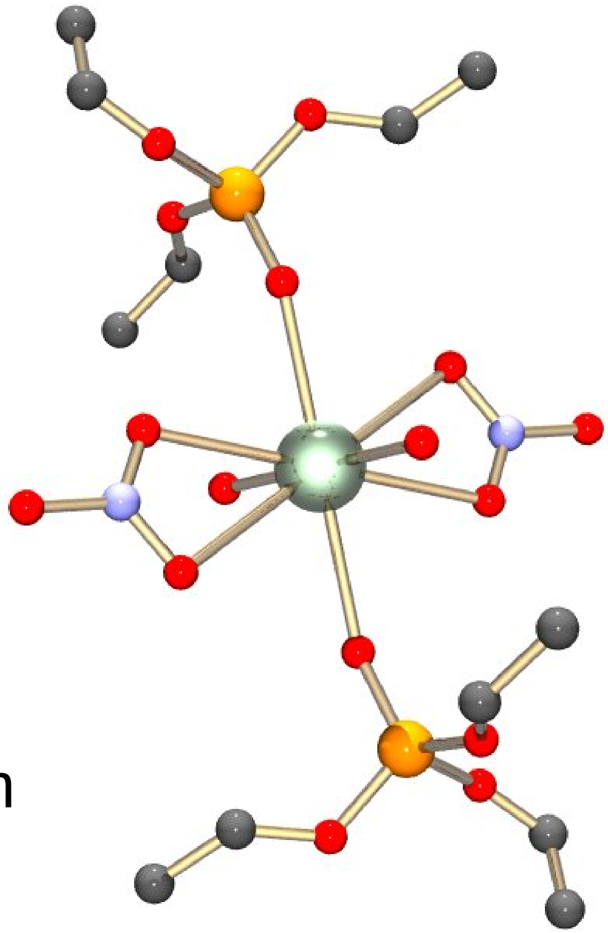
Typically performed in a separatory funnel:

Aqueous layer (polar things)

Organic layer (non-polar things)

PUREX Process

- Dissolve in 7 M HNO_3.
- Filter out solids
- Combine with 30% tributyl phosphate (TBP) to form $UO_2(NO_3)_2 \cdot 2TBP$ and $PuO_2(NO_3)_2 \cdot 2TBP$ complexes.
- Extract with an organic solvent, such as kerosene.
  – $UO_2(NO_3)_2 \cdot 2TBP$ and $PuO_2(NO_3)_2 \cdot 2TBP$ complexes in nonpolar organic solvent
  – Fission products, and transuranium elements americium and curium remain in the aqueous phase.



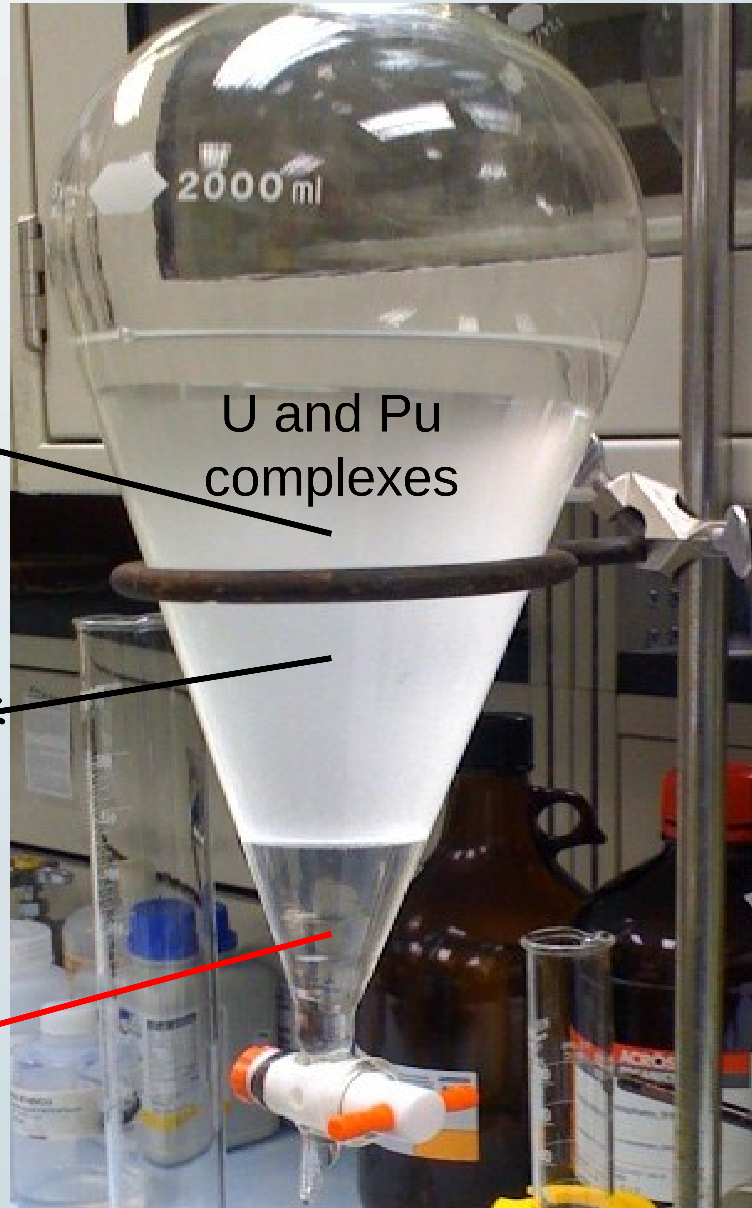
http://en.wikipedia.org/wiki/PUREX

Separation of U, Pu, and Fission Products

On to Uranium purification

On to Plutonium purification

Fission products, minor actinides: discarded as "high level waste"



Nonpolar solvent Layer

Aqueous Layer

PUREX Process

- Plutonium is separated from uranium in a separate extraction by treating the kerosene solution with aqueous iron(II) sulfamate, $Fe(SO_3NH_2)_2$, which reduces the plutonium to the +3 oxidation state. The plutonium passes into the aqueous phase.
- Variations on the PUREX process have been developed.

http://en.wikipedia.org/wiki/PUREX

One Sign of Reprocessing of Nuclear Wastes

- 2002 – China shipped about 20 tons of tributyl phosphate (TBP) to North Korea.
- Considered to be sufficient to extract enough material for three to five nuclear weapons

Nuclear Waste Storage and Disposal

- Nuclides of special concern
  - Tc-99 (half-life 220,000 years) and I-129 (half-life 17 million years), which dominate spent fuel radioactivity after a few thousand years.
  - Np-237 (half-life two million years) and Pu-239 (half-life 24,000 years).
- Needs treatment, followed by a long-term management strategy involving storage, disposal, or transformation of the waste into a non-toxic form.
- Governments around the world are considering a range of waste management and disposal options, though there has been limited progress toward long-term waste management solutions.

http://en.wikipedia.org/wiki/Nuclear_waste_storage#Management_of_waste

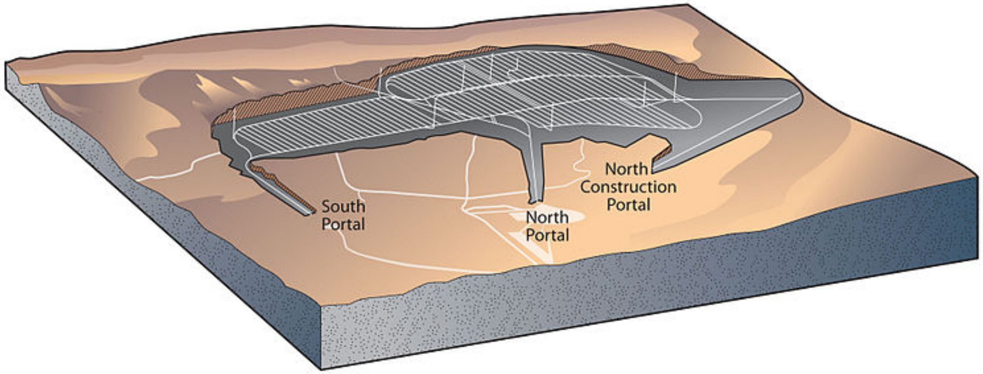
Nuclear Waste Storage/Disposal Possibilities

- "Long term above ground storage", not implemented.
- "Disposal in outer space", not implemented.
- "Deep borehole disposal", not implemented.
- "Rock-melting", not implemented.
- "Disposal at subduction zones", not implemented.
- "Ocean disposal", done by USSR, UK, Switzerland, USA, Belgium, France, Netherland, Japan, Sweden, Russia, Germany, Italy and South Korea. (1954–93) It's not permitted by international agreements.
- "Sub seabed disposal", not implemented, not permitted by international agreements.
- "Disposal in ice sheets", rejected in Antarctic Treaty
- "Direct injection“ of liquid waste, done by USSR and USA.

http://en.wikipedia.org/wiki/Nuclear_waste_storage#Management_of_waste

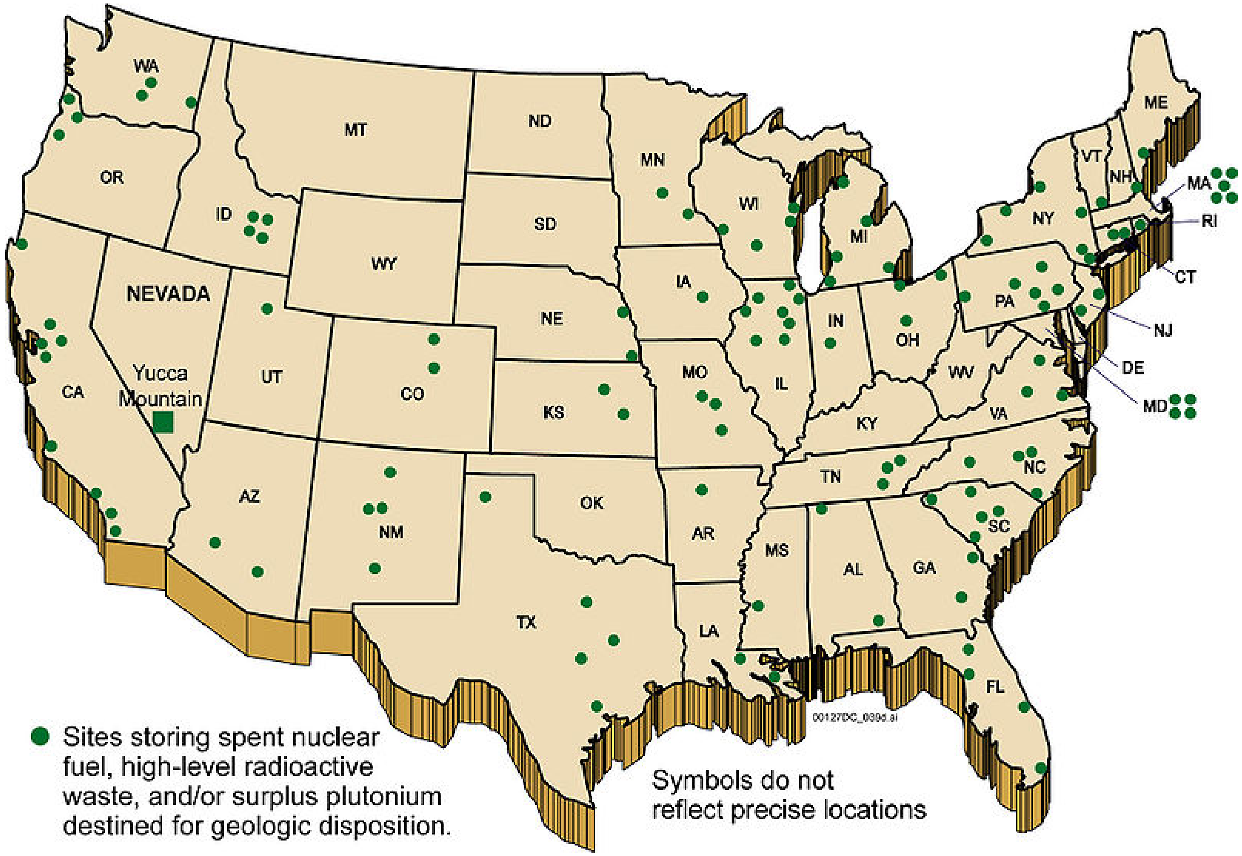
Yucca Mountain Nuclear Waste Repository

- Deep geological repository storage facility for spent nuclear reactor fuel and other high level radioactive waste,
- Approved in 2002 by the United States Congress.
- Project was defunded in 2010.
- The US Government Accountability Office stated that the closure was for political, not technical or safety reasons.



Yucca Mountain Nuclear Waste Repository

- United States without any long term storage site for high level radioactive waste, currently stored on-site at various nuclear facilities around the country



http://en.wikipedia.org/wiki/Yucca_Mountain_nuclear_waste_repository

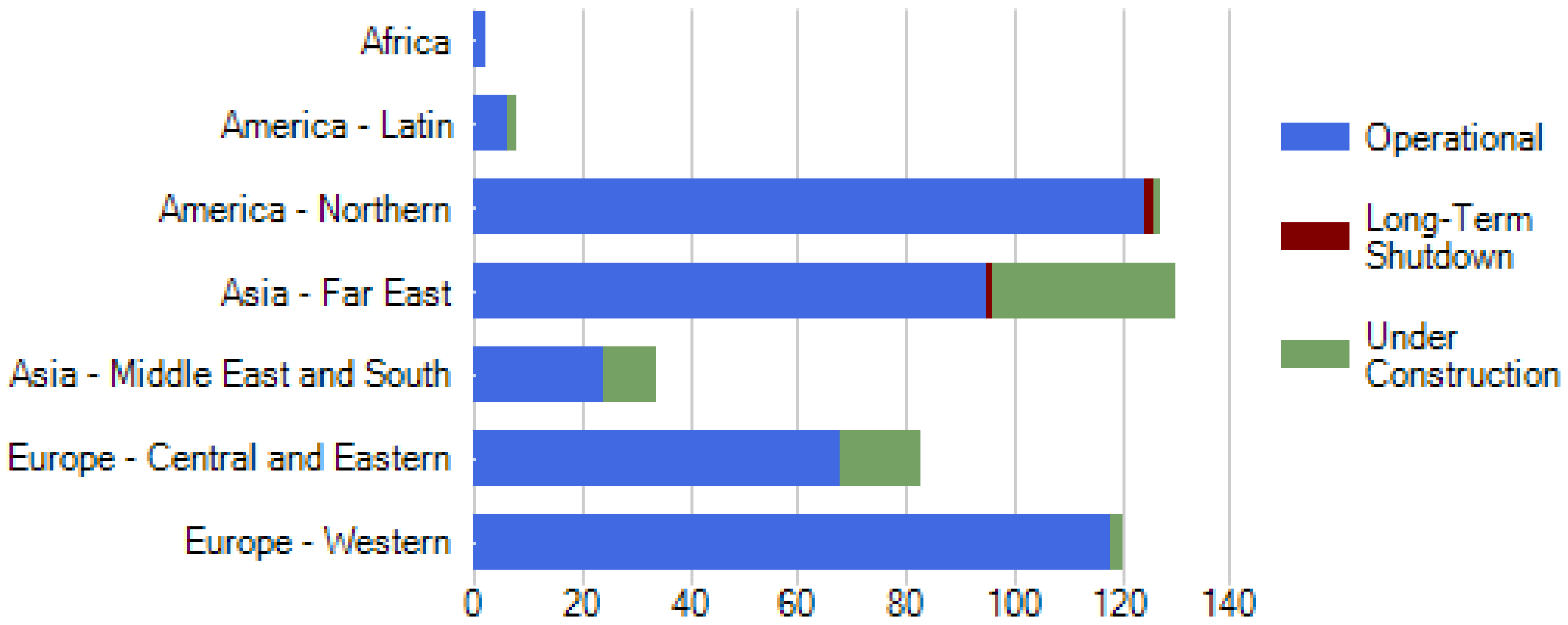
Nuclear Waste Geologic Repository

- The Blue Ribbon Commission established by the Secretary of Energy released its final report on January 26, 2012. It expressed urgency to find a consolidated, geological repository, but also that any future facility should have input from the citizens around it.

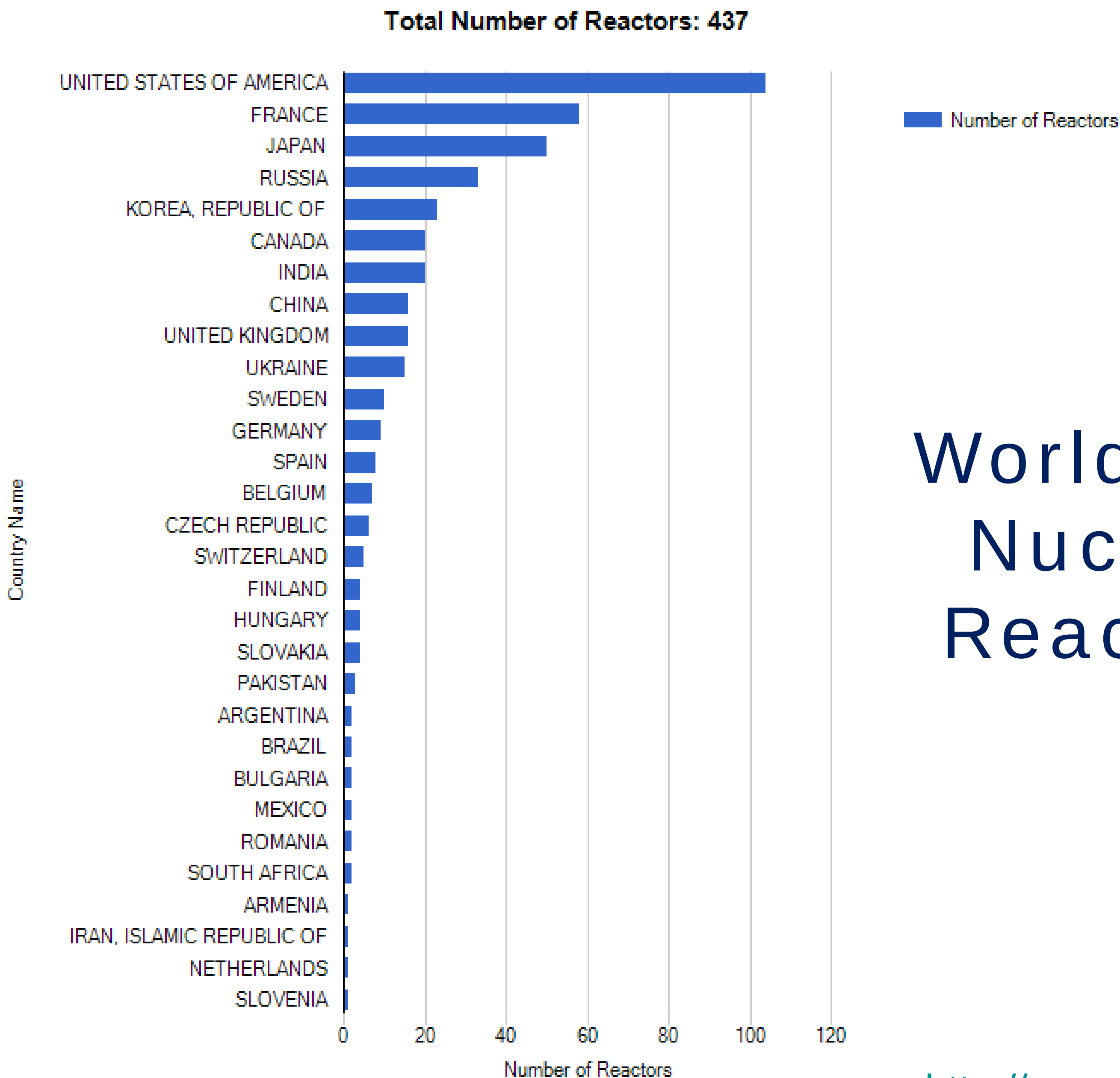
http://en.wikipedia.org/wiki/Yucca_Mountain_nuclear_waste_repository

Status of Nuclear Power

- 437 nuclear power plants in operation
- 371.762 GW_e total installed capacity
- 64 Nuclear power plants under construction.



http://www.iaea.org/pris/

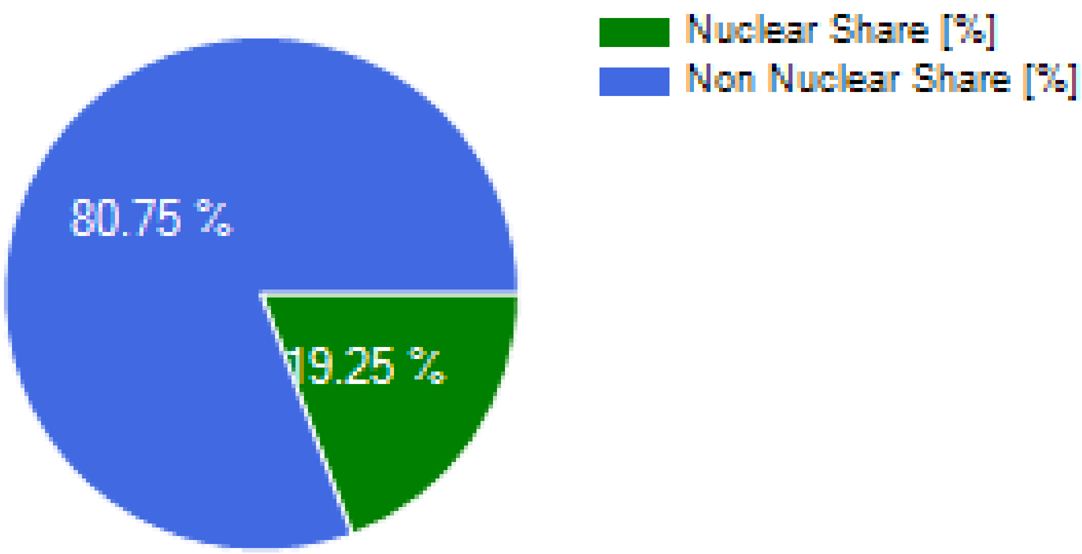


Worldwide Nuclear Reactors

http://www.iaea.org/pris/

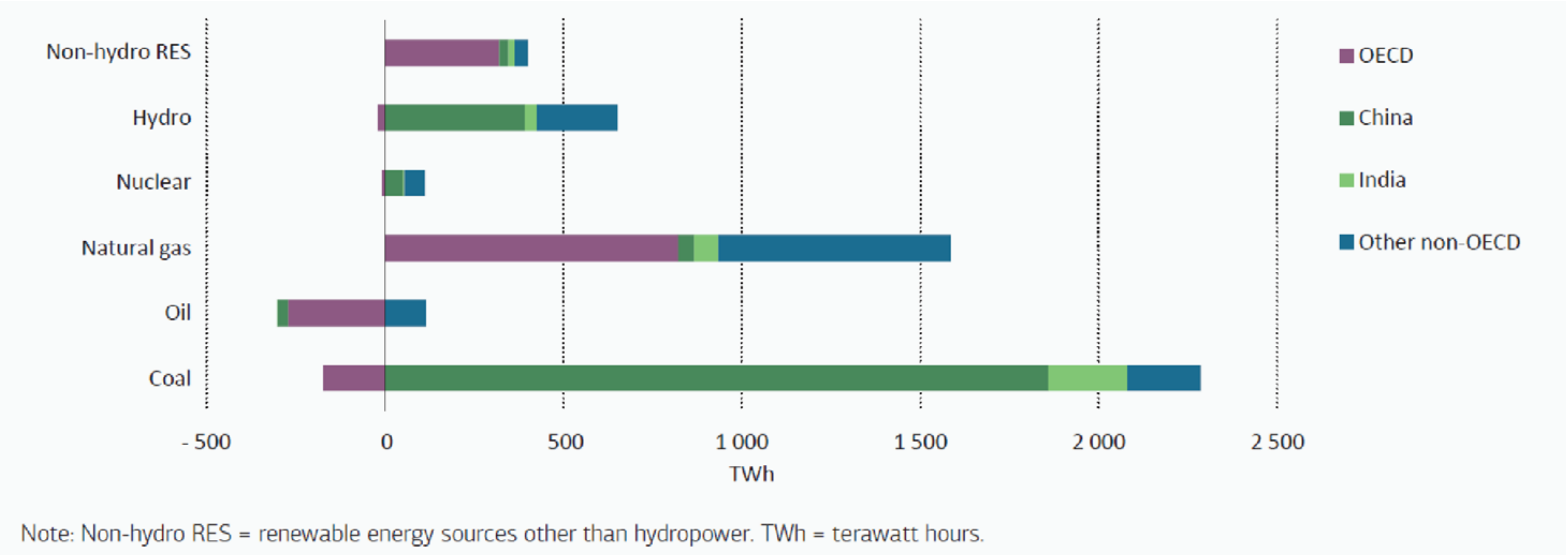
United States

- 104 nuclear power plants
- 1 under construction
- 7.9×10^5 GWh in 2011



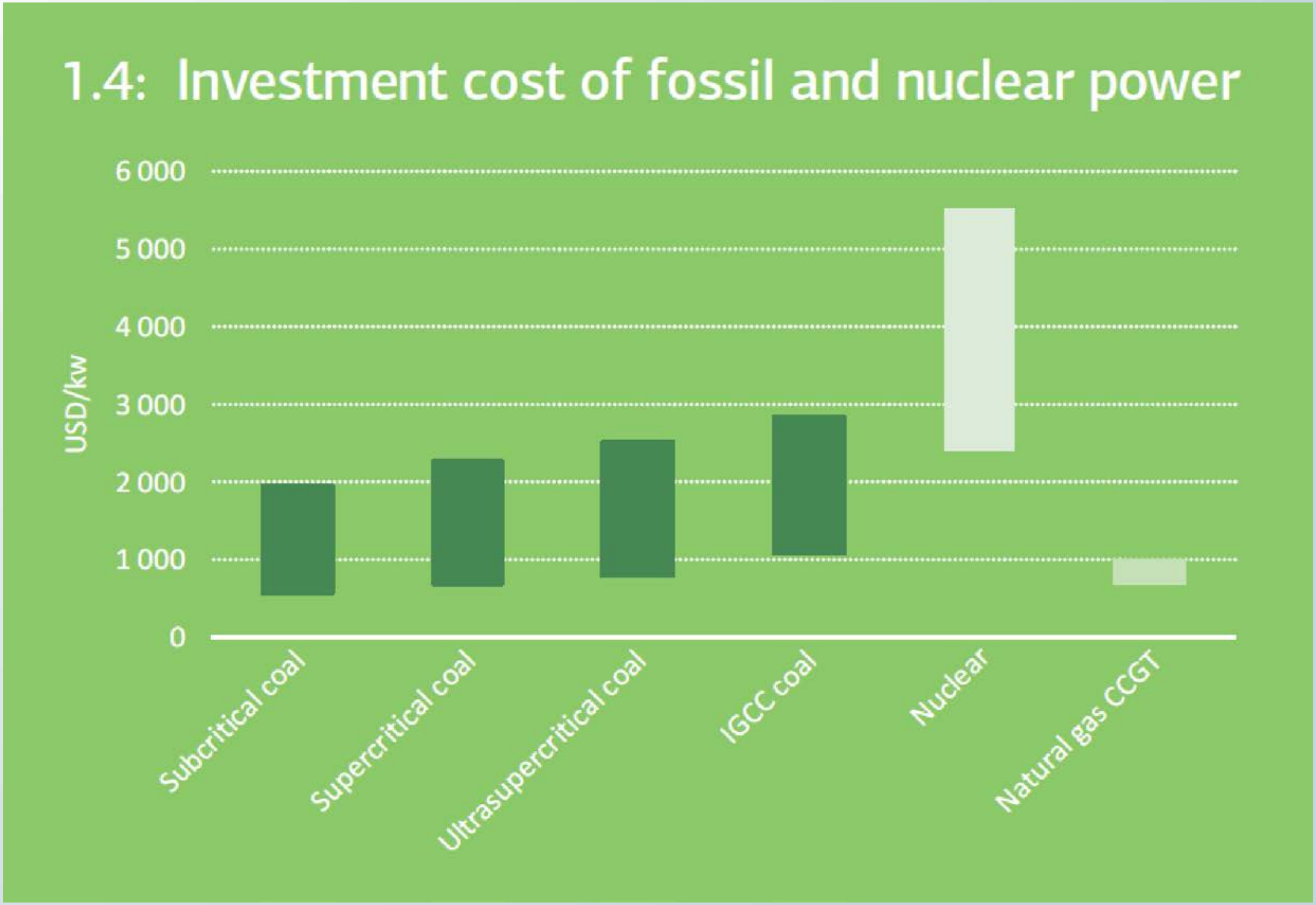
http://www.iaea.org/pris/

Changes in sources of electricity supply, 2000-09



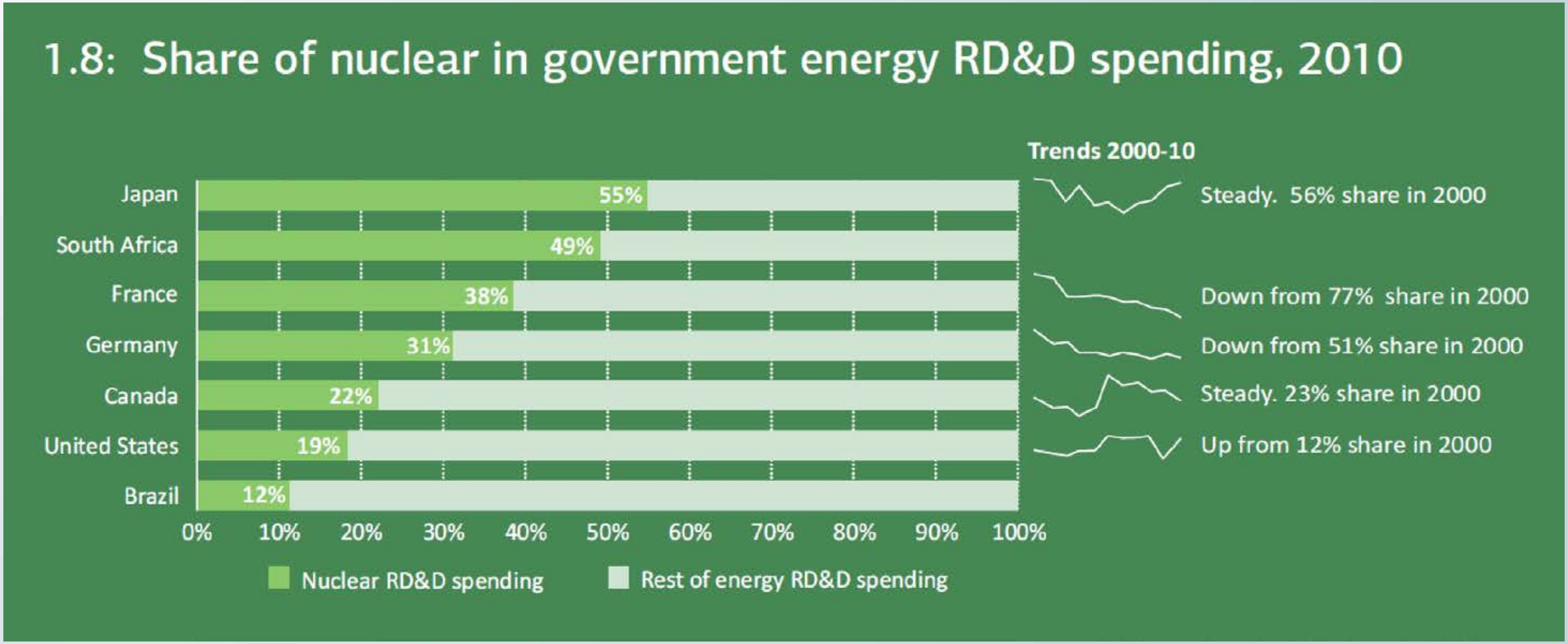
http://www.iea.org/publications/freepublications/publication/Tracking_Clean_Energy_Progress.pdf

Investment Costs for Fossil and Nuclear Power



http://www.iea.org/publications/freepublications/publication/Tracking_Clean_Energy_Progress.pdf

Share of Nuclear Government RD&D Spending



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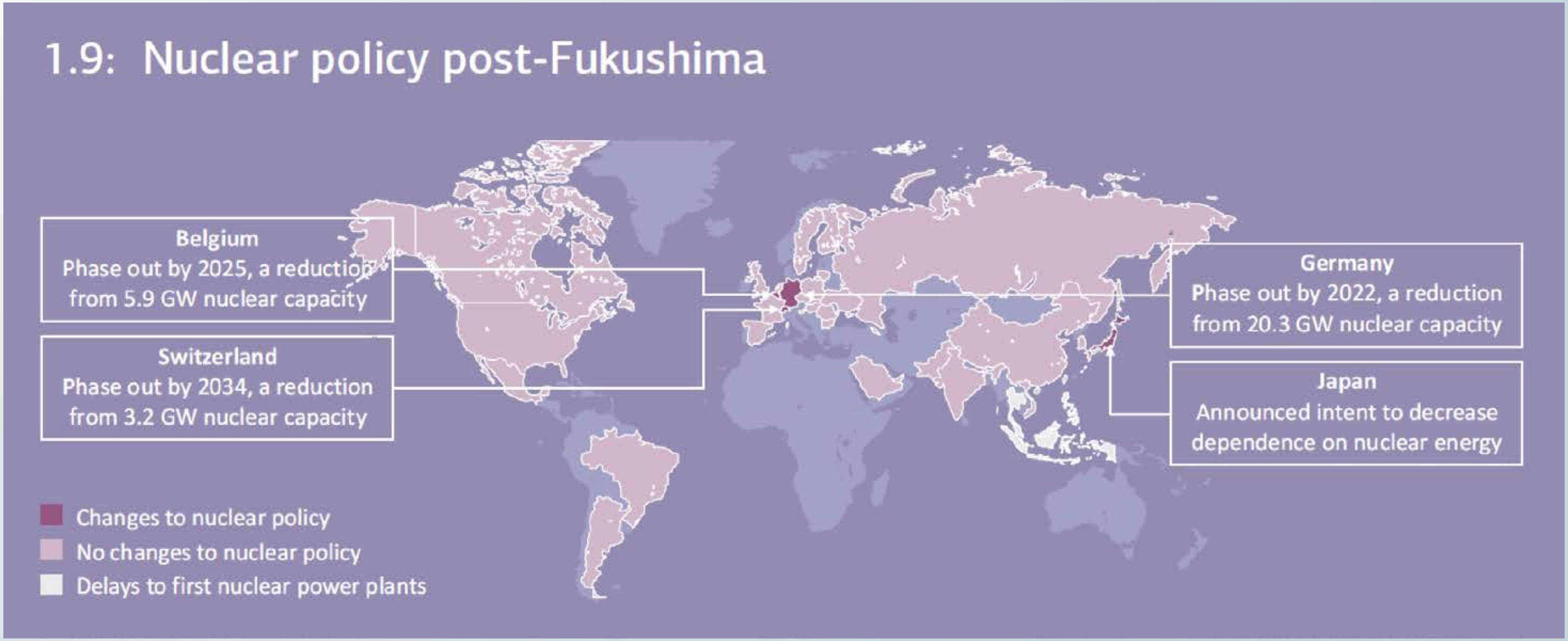
Nuclear Policy Post-Fukushima



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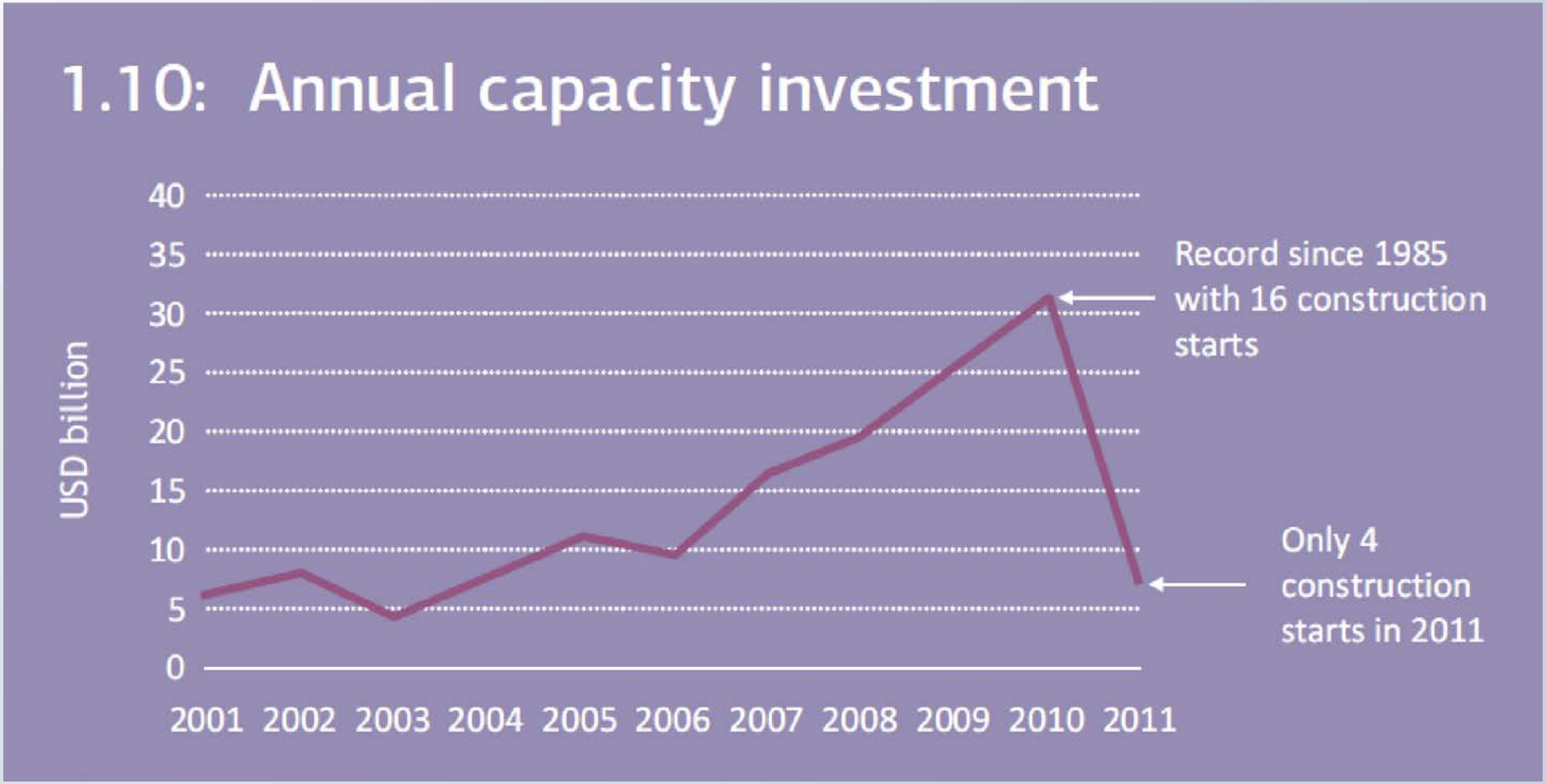
Nuclear Annual Capacity Investment



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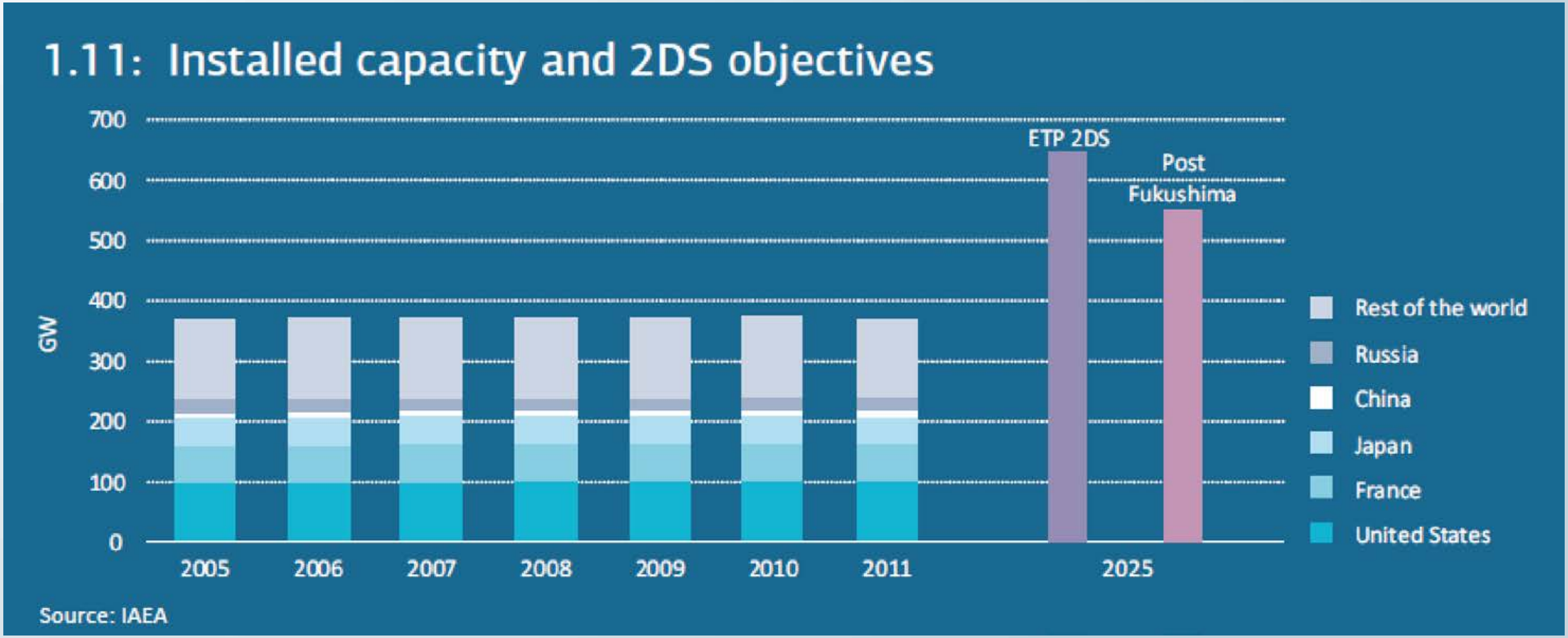
Nuclear Installed Capacity



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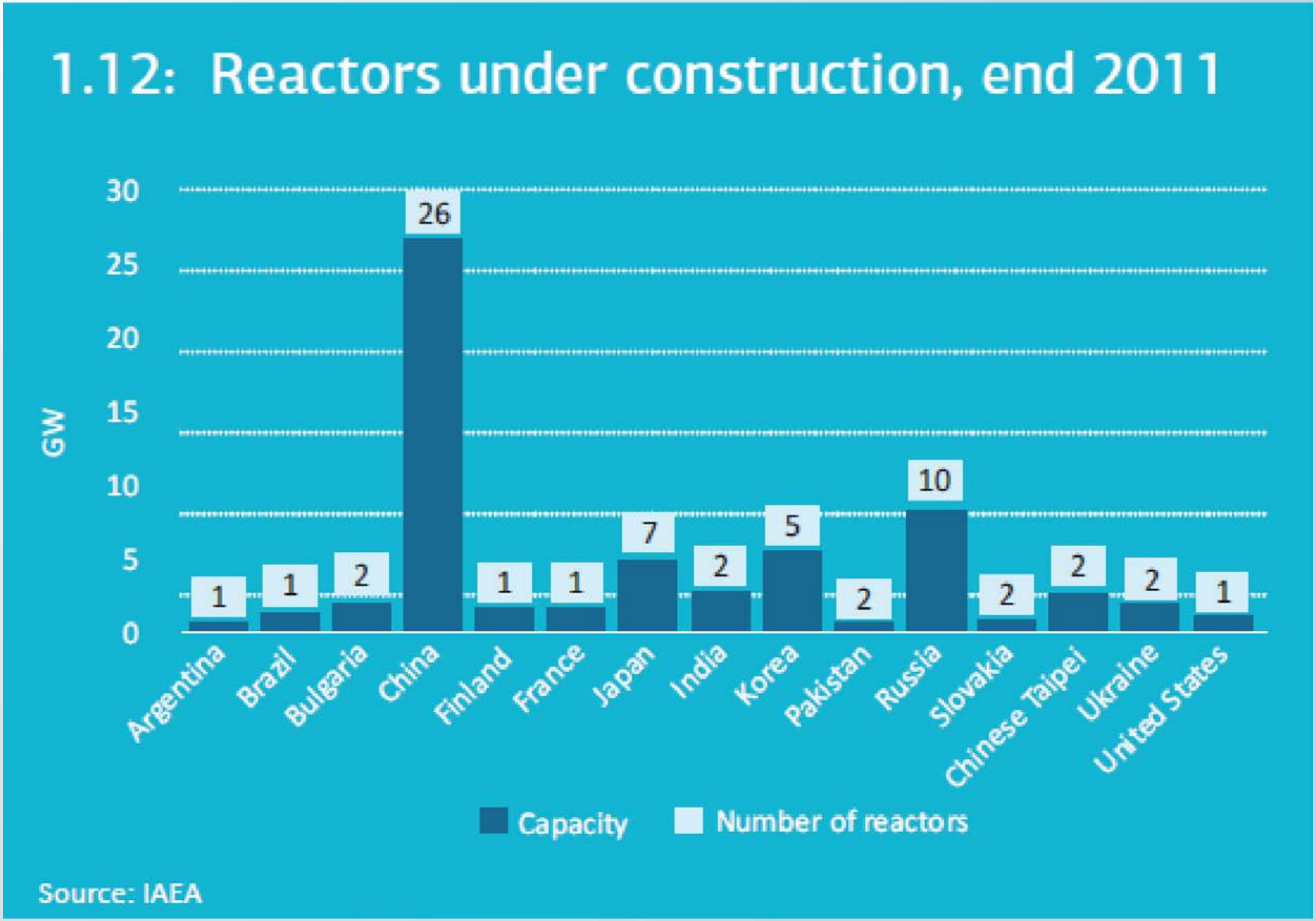
Reactors Under Construction



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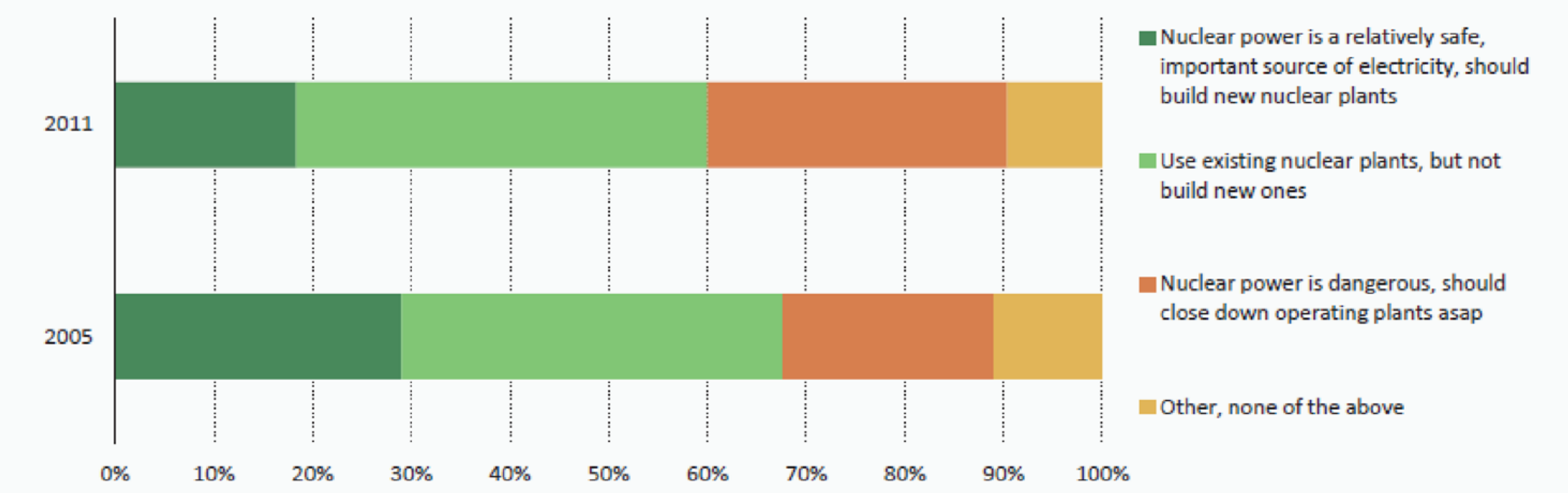
Public Opinion of Nuclear Energy

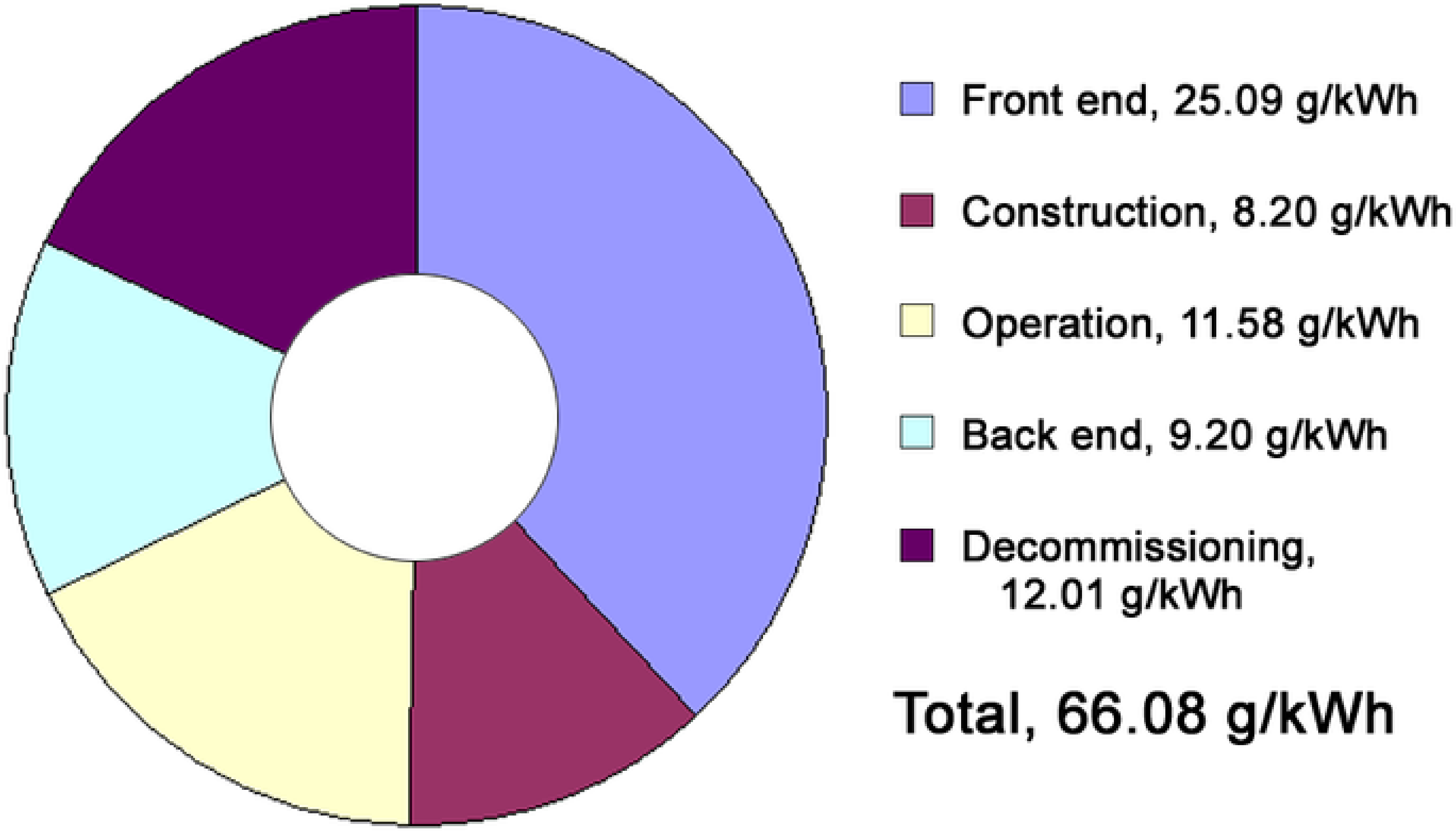


Note: Countries included in survey data include France, Germany, India, Indonesia, Japan, Mexico, Russia, United Kingdom and the United States.
Source: GlobalScan, 2011.

http://www.iea.org/publications/freepublications/publication/Tracking_Clean_Energy_Progress.pdf

Carbon emissions from nuclear power

Sovacool life cycle study survey, 2008



Mean value of carbon dioxide emissions from qualified life cycle studies among 103 surveyed. Includes results of 1997 Vattenfall study.

Lifecycle Greenhouse Gas Emission Estimates for Electricity Generators

Technology	Description	Estimate (g CO2/kWh$_e$)
Wind	2.5 MW offshore	9
Hydroelectric	3.1 MW reservoir	10
Wind	1.5 MW onshore	10
Biogas	Anaerobic digestion	11
Hydroelectric	300 kW run-of-river	13
Solar thermal	80 MW parabolic trough	13
Biomass	various	14-35
Solar PV	Polycrystaline silicon	32
Geothermal	80 MW hot dry rock	38
Nuclear	various reactor types	66
Natural gas	various combined cycle turbines	443
Fuel Cell	hydrogen from gas reforming	664
Diesel	various generator and turbine types	778
Heavy oil	various generator and turbine types	778
Coal	various generator types with scrubbing	960
Coal	various generator types without scrubbing	1050

http://en.wikipedia.org/wiki/Comparisons_of_life-cycle_greenhouse-gas_emissions

Retiring Nuclear Power Plants