Radioactivity

Lecture 20

Radioactivity and Nuclear Energy

First man splitted the atom,

now the atom splits man.

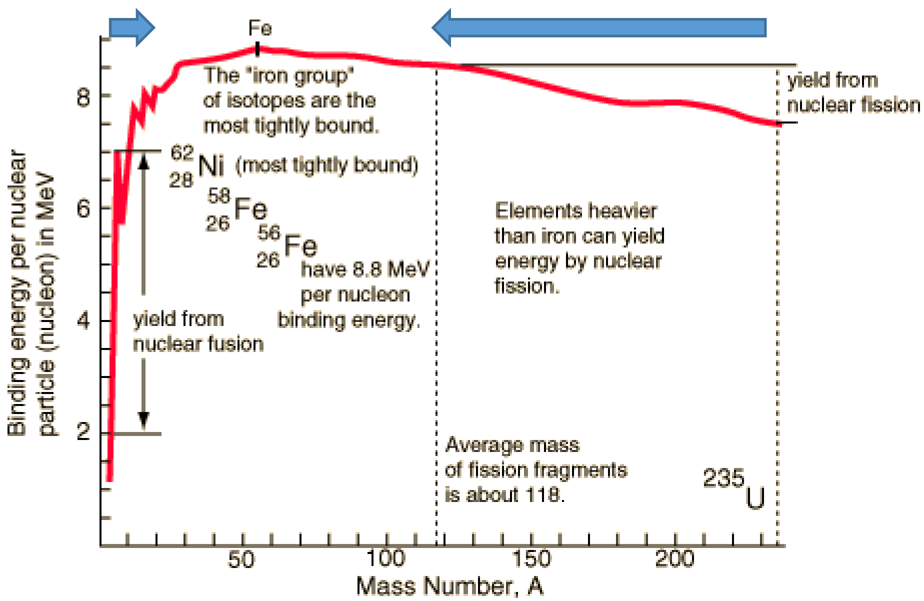
Gerhard Uhlenbruck

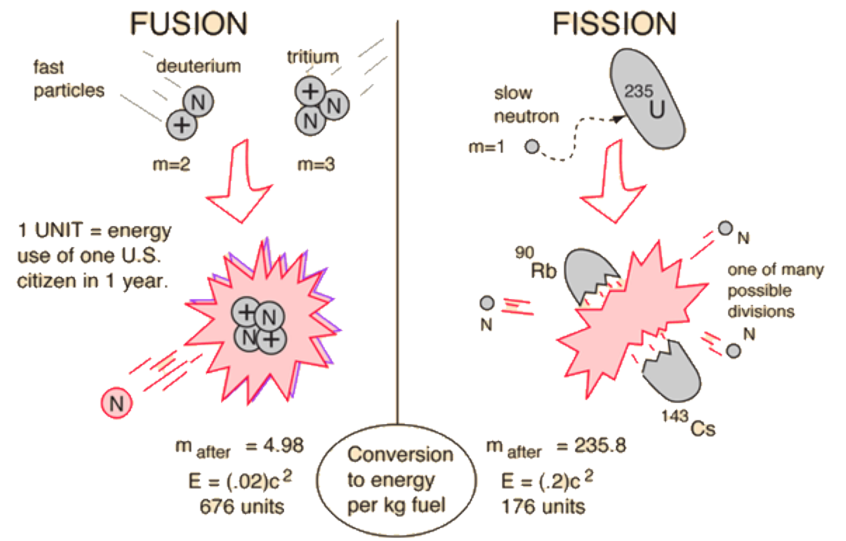
What are the issues with Nuclear Energy?

- Nuclear energy is the efficient energy source, it transforms matter into energy according to $E=m\cdot c^2$. In energy generation efficiency nuclear energy is superior to all other sources!
- It has a price, multiple issues of technical and emotional nature!
- Fusion versus Fission
- The issues of fission technologies:
  - ➢ fuel production through mining
  - ➢ fuel efficiency by different fission modes,
  - ➢ fuel burning control by neutron moderation and absorption
  - ➢ fuel poisoning through fission products
  - ➢ what to do with the fission products?
- The handling of nuclear waste!

Nuclear Energy Production

Fusion Fission

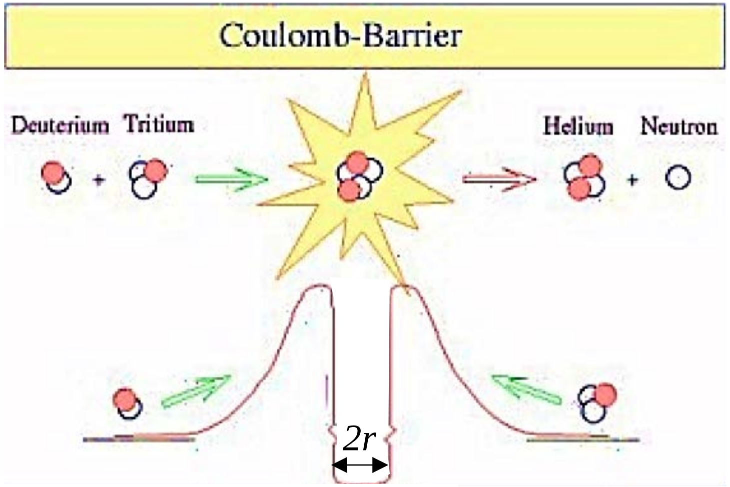




The energy release per atomic mass unit is 0.7MeV for fission and 6.2MeV for fusion, fusion is the more effective nuclear reaction!

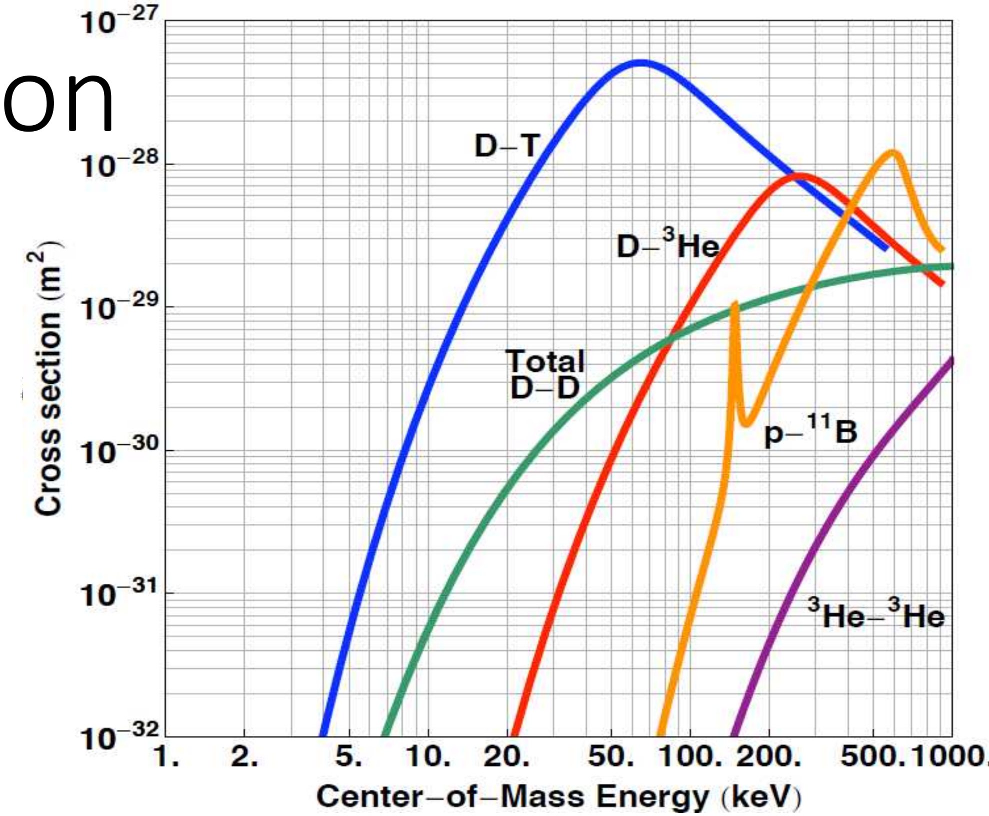
Fusion occurs by the nuclear reaction between two light hydrogen isotopes, such as d+d ($^{2}H+^{2}H$), or d+t ($^{2}H+^{3}H$), while fission is the neutron induced splitting of ^{235}U or ^{239}Pu into two lower mass isotopes between mass 100 and mass 130.

Challenges in fusion



$r = r_0 \cdot A^{1/3}$

$r_0 = 1.25\, fm = 1.25 \cdot 10^{-13}\, cm$



Typical energy of particles in sun: $E = k \cdot T$, with $T = 15\ MK$ and $k = 1.38064852 \cdot 10^{-23}\ \mathrm{m^2\ kg\ s^{-2}\ K^{-1}}$ $= 4.47 \cdot 10^{-18}\ \mathrm{J} = 2.8 \cdot 10^{-5}\ \mathrm{MeV} = 28\ \mathrm{eV}$: far below the energy of the Coulomb barrier.

Because of quantum mechanical wave behavior of particles, they can tunnel through Coulomb barrier with a certain probability, which determines timescale of slow stellar burning.

Typical energy of particles on Earth: $E = k \cdot T$, with $T = 300\ K$ and $k = 1.38064852 \cdot 10^{-23}\ \mathrm{m^2\ kg\ s^{-2}\ K^{-1}}$ $= 4.14 \cdot 10^{-21}\ \mathrm{J} = 2.6 \cdot 10^{-8}\ \mathrm{MeV} = 26\ \mathrm{meV}$: even further below the energy of the Coulomb barrier.

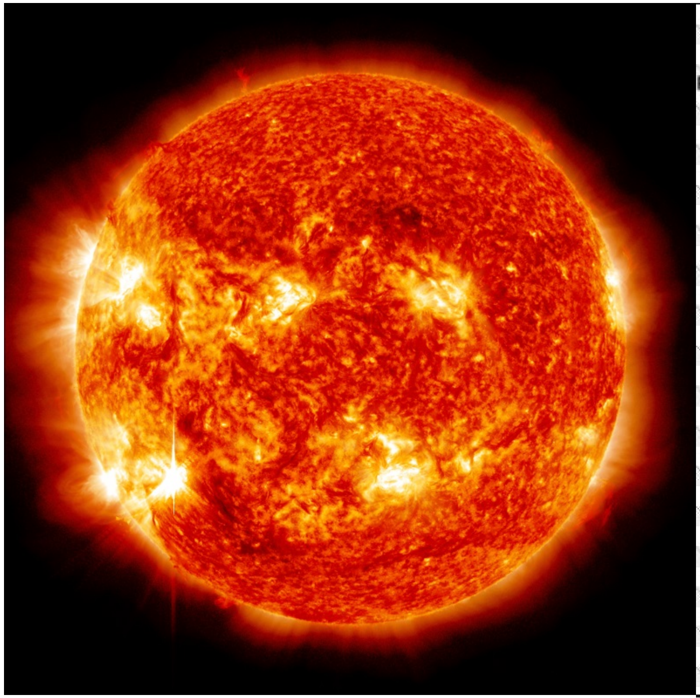
Earth temperatures are far too low for spontaneous fusion, artificial hot plasmas are needed for bringing the particles together at a reasonable rate for sufficient energy generation!

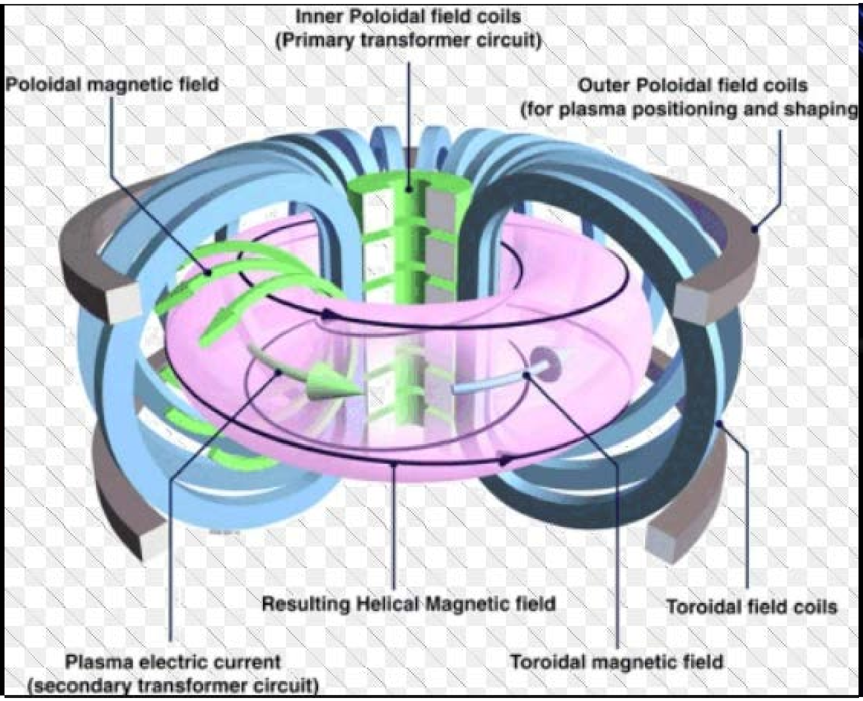
Confinement of hot Plasmas

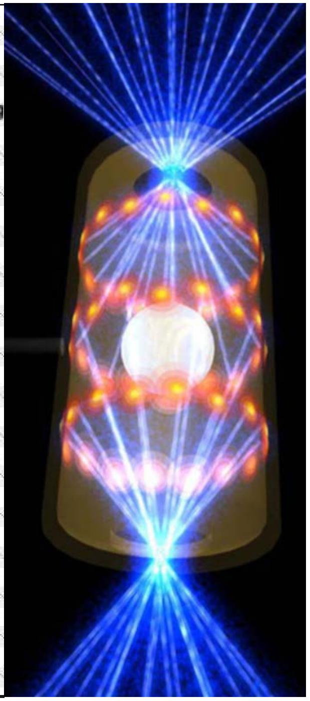
Gravitational confinement

Magnetic confinement

Inertial confinement



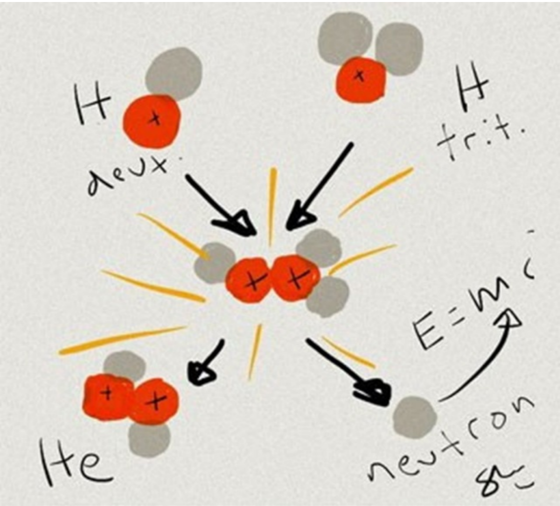


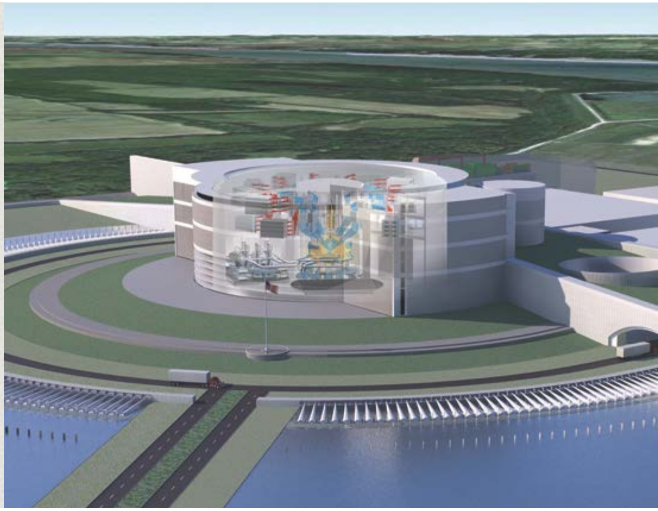


Nature's approach

human approach

ITER and LIFE





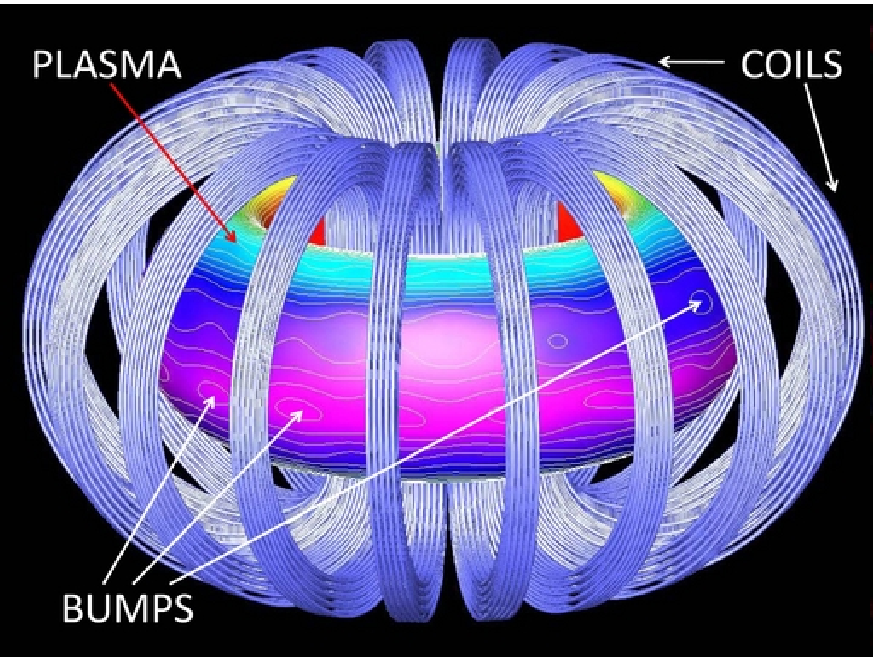
ITER ("The Way" in Latin) is is being constructed in southern France. 35 nations are collaborating to build the world's largest tokamak ("toroidal chamber with magnetic coils."), a magnetic fusion device that has been designed to prove the feasibility of fusion as a large-scale and carbon-free source of 500 MW power with a power use of 50 MW. ITER is presently under construction.

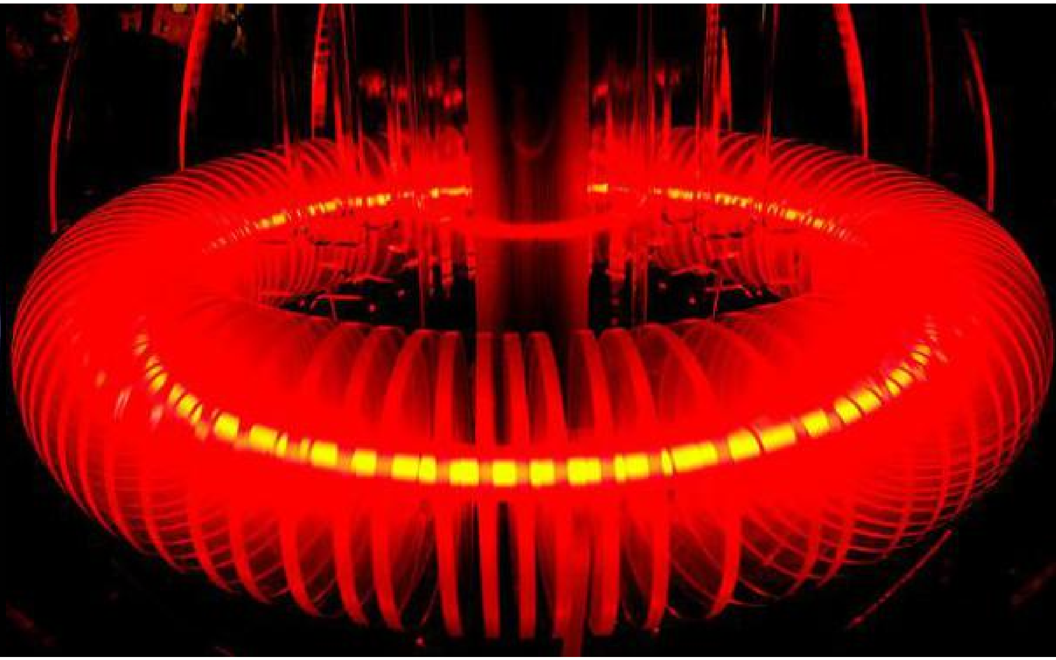
LIFE (“Laser Inertial Fusion System”) was a plan to develop the technologies necessary to convert the laser-driven inertial confinement fusion concept being developed in the National Ignition Facility (NIF) into a practical commercial power plant, using a 10Hz pulsed high power laser system to generate inertial fusion energy and generate a high neutron flux to drive a sub-critical fission reactor. The LIFE concept promised to be a source of 900 MW power with a power use of 70 MW. LIFE was put on holed by LLNL, because of NIF failure to reach ignition.

Plasma fusion

through magnetic confinement

A major advantage of fusion reactors is the small if not negligible amount long-lived radioactive decay products! Light radioactive isotopes are short-lived and produce additional energy through the decay heat.

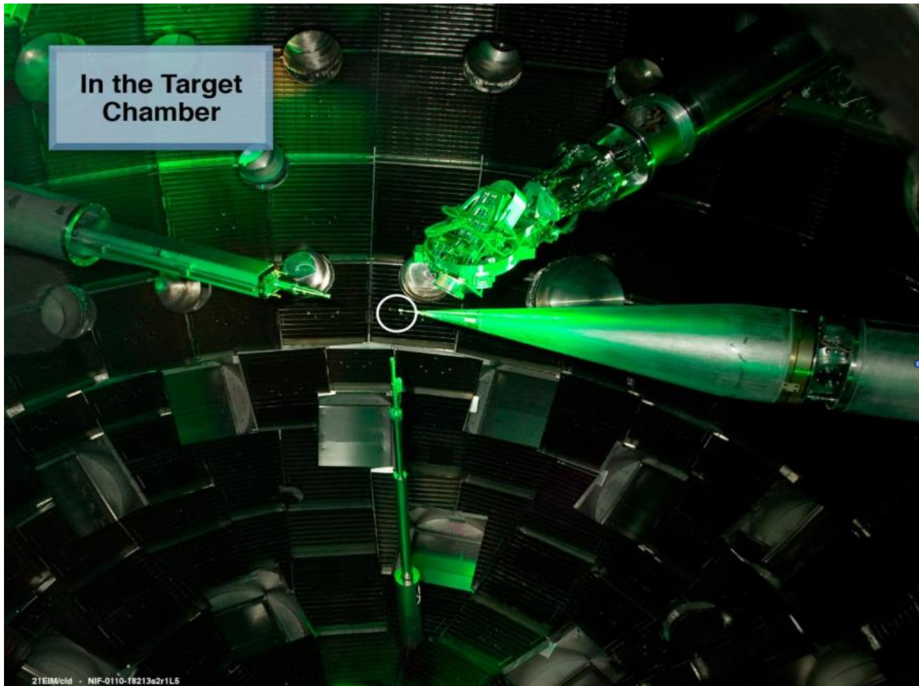


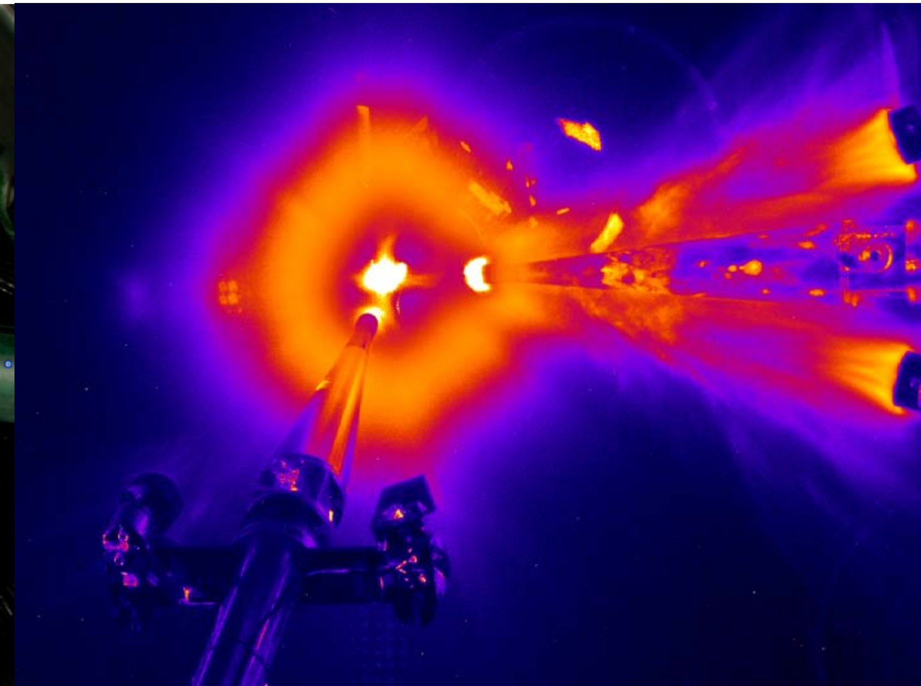


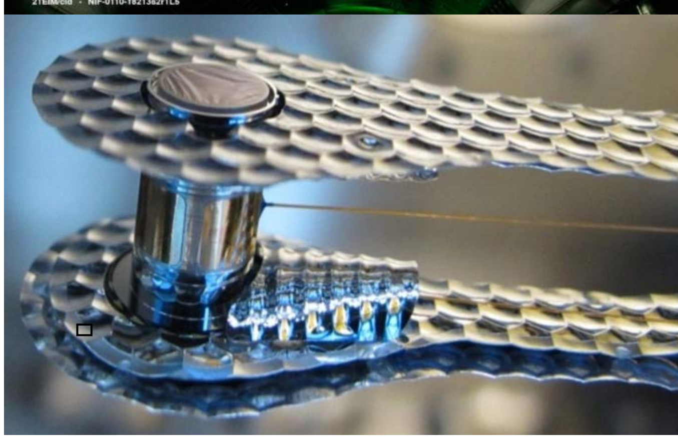
Plasma has to have temperatures of ten times the temperature in the core of the sun to generate the required energy output. The plasma is contained by magnetic fields 10,000 times that of the Earth’s field. The shape of the fusion plasma is dictated by the magnetic field generation. These provides enormous technical challenges that have not been achieved yet. The main project towards the goal is the international ITER project in France, but there are still a number of smaller projects in the US, CHINA, and Germany.

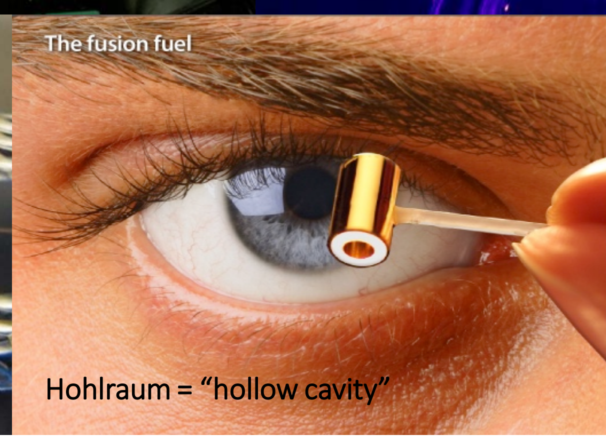
Laser Induced Fusion
through inertial confinement

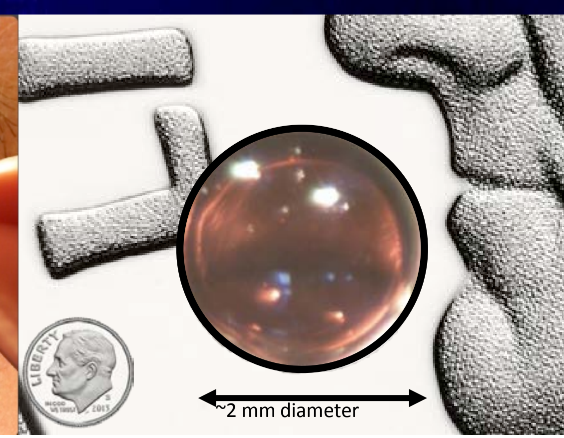
195 Peta-Watt Lasers aiming at one spot generating an implosion of capsule reaching temperatures and densities close or superseding solar values.



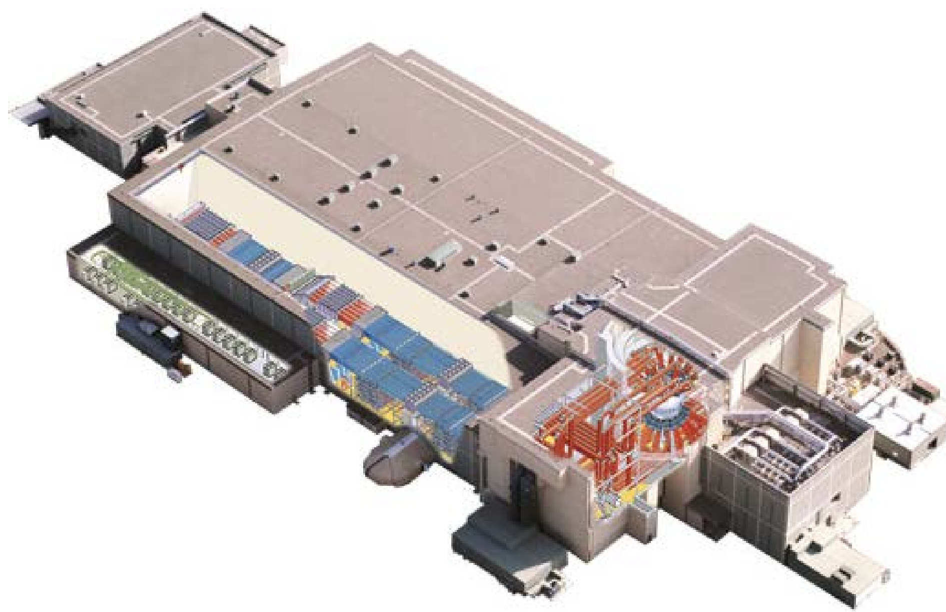




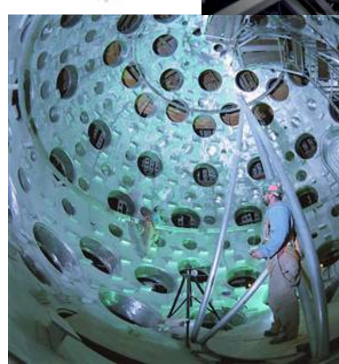


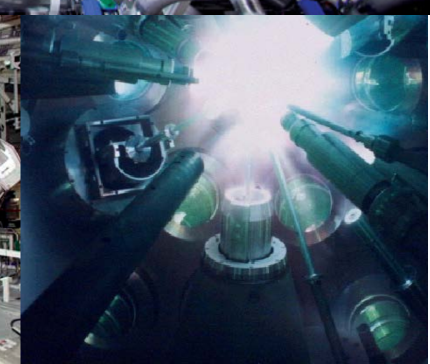


National Ignition Facility as Prototype

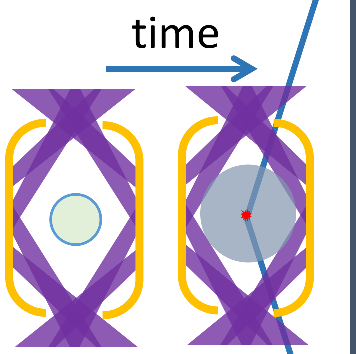


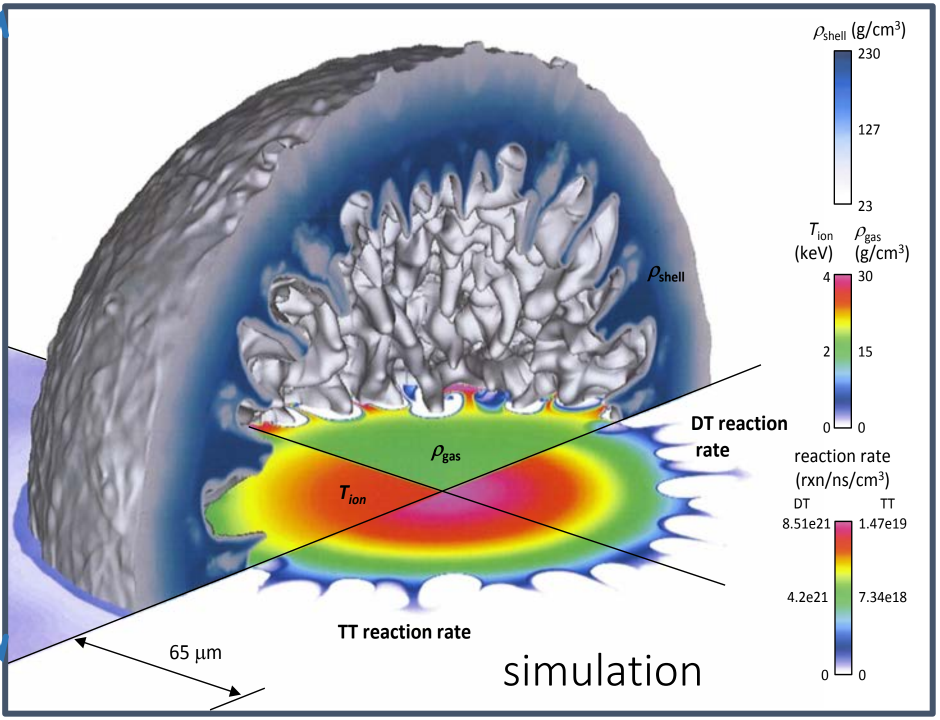
195 high power laser amplification system

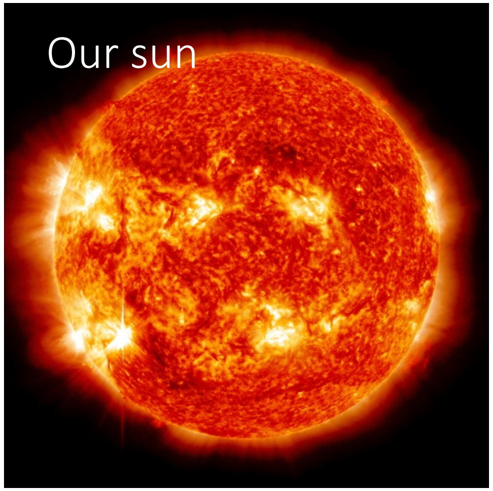




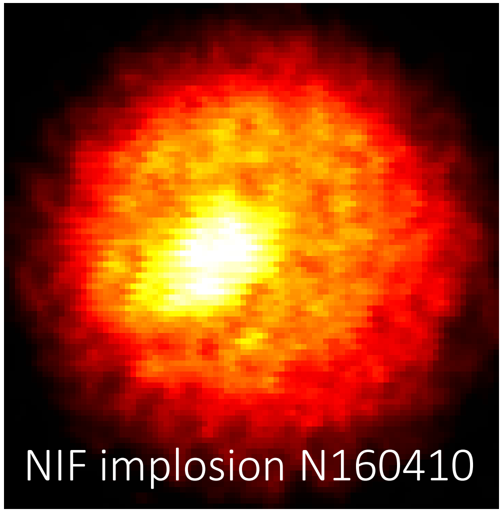
NIF shot conditions







M_{Sun}~2×10^{33}g

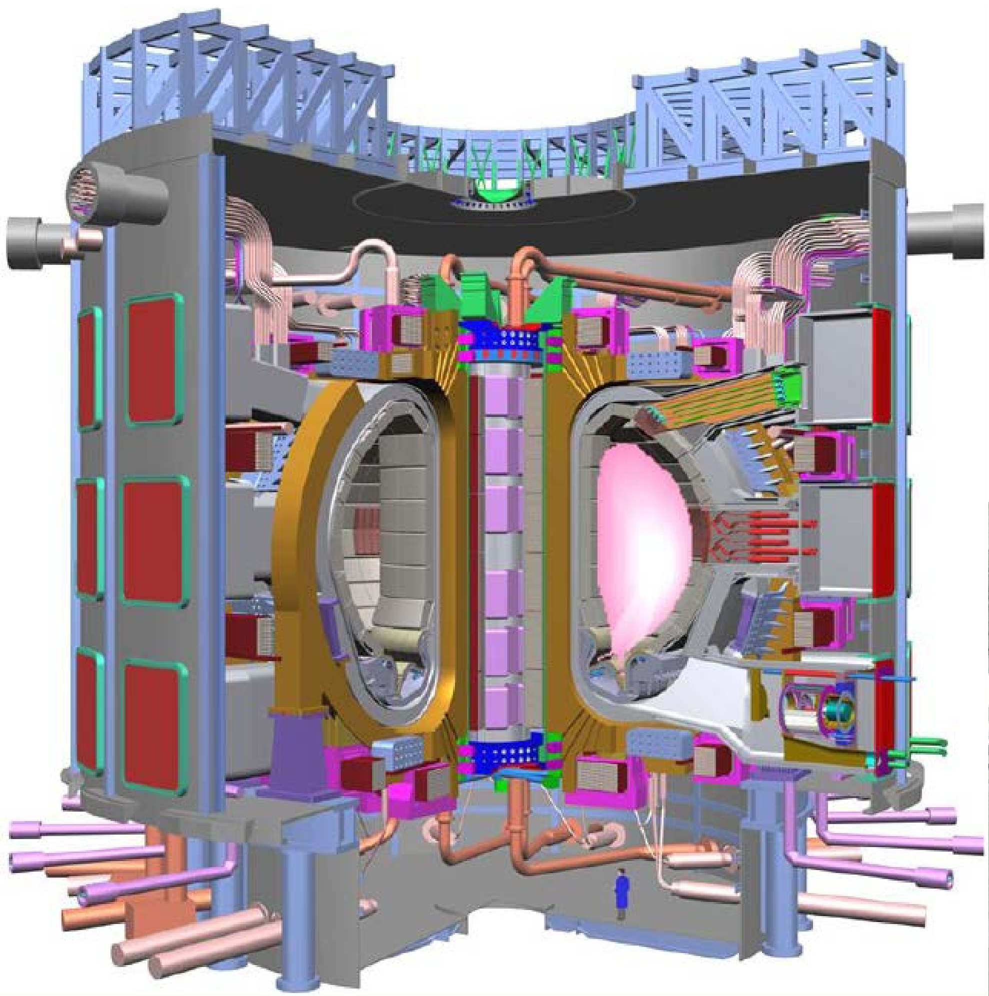


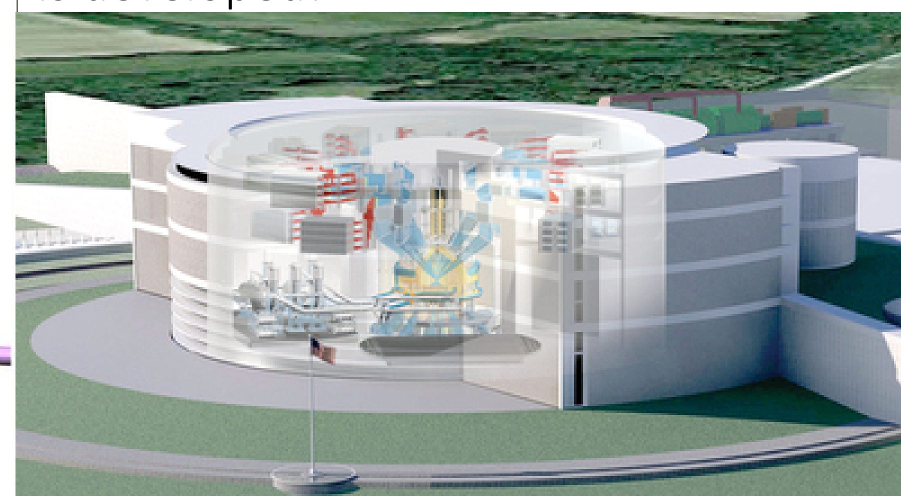
M_{impl}~6×10^{-6}g

Shot physics is not fully understood yet. Rapid convective processes seems to inhibit the production and release of positive net energy. A problem is the limited frequency or shot-rate, three shots/day, desired rate is 100 shots/second, a three million times improvement is necessary!

Time-line 30-50 years

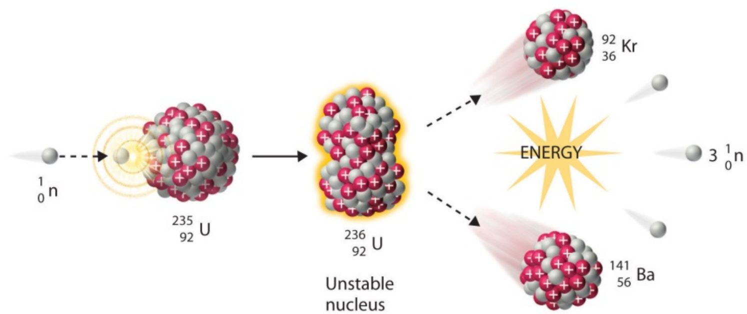
The general statement is that it takes 30-50 years towards reliable energy production by fusion, but the world cannot wait, the energy demand is growing exponentially! Nuclear fission is one of the existing options for bridging the time until a reliable fusion concept is developed!

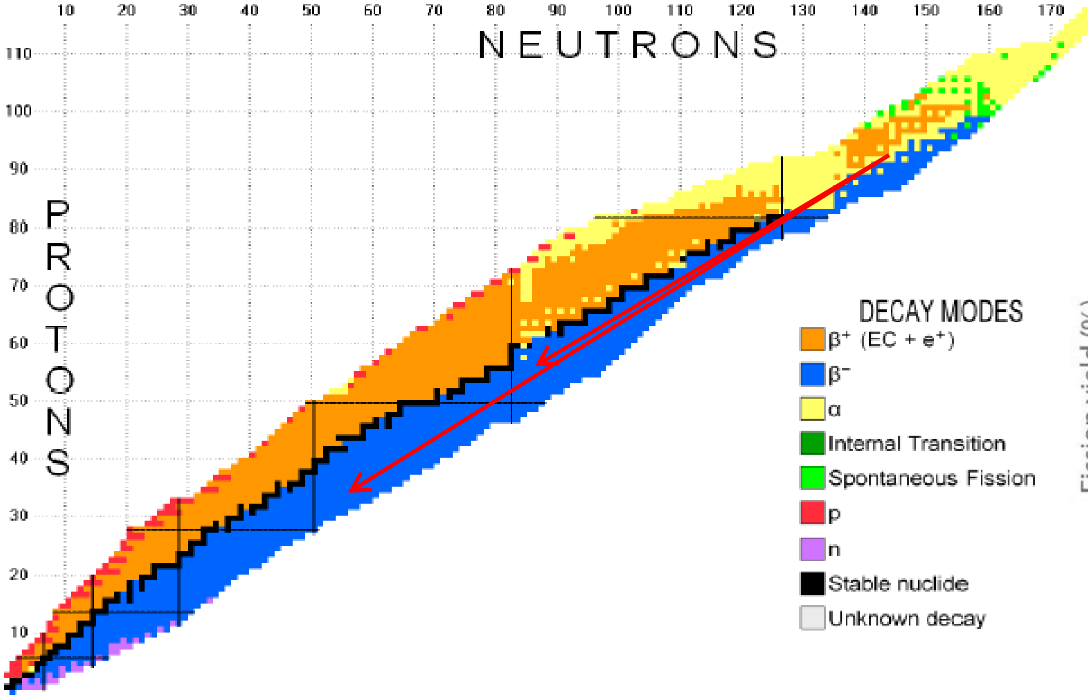


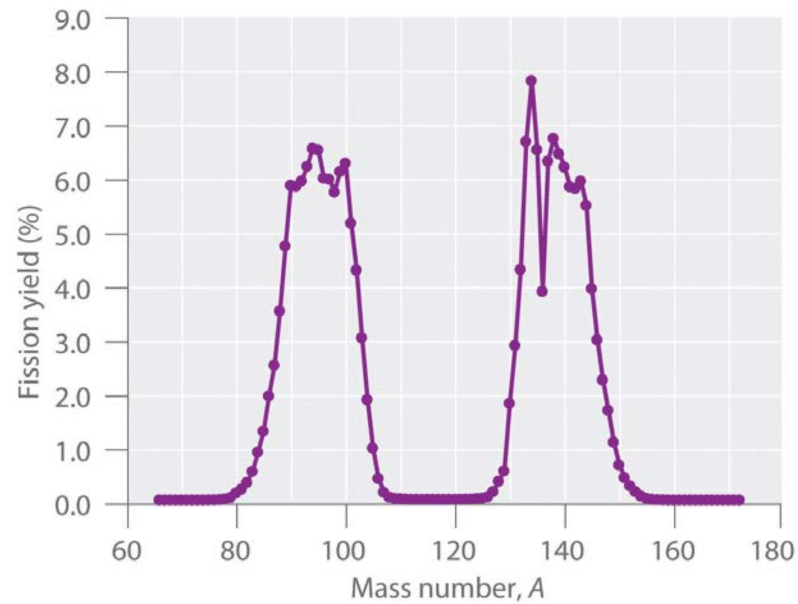


Present concepts: ITER LIFE

Challenges in Fission



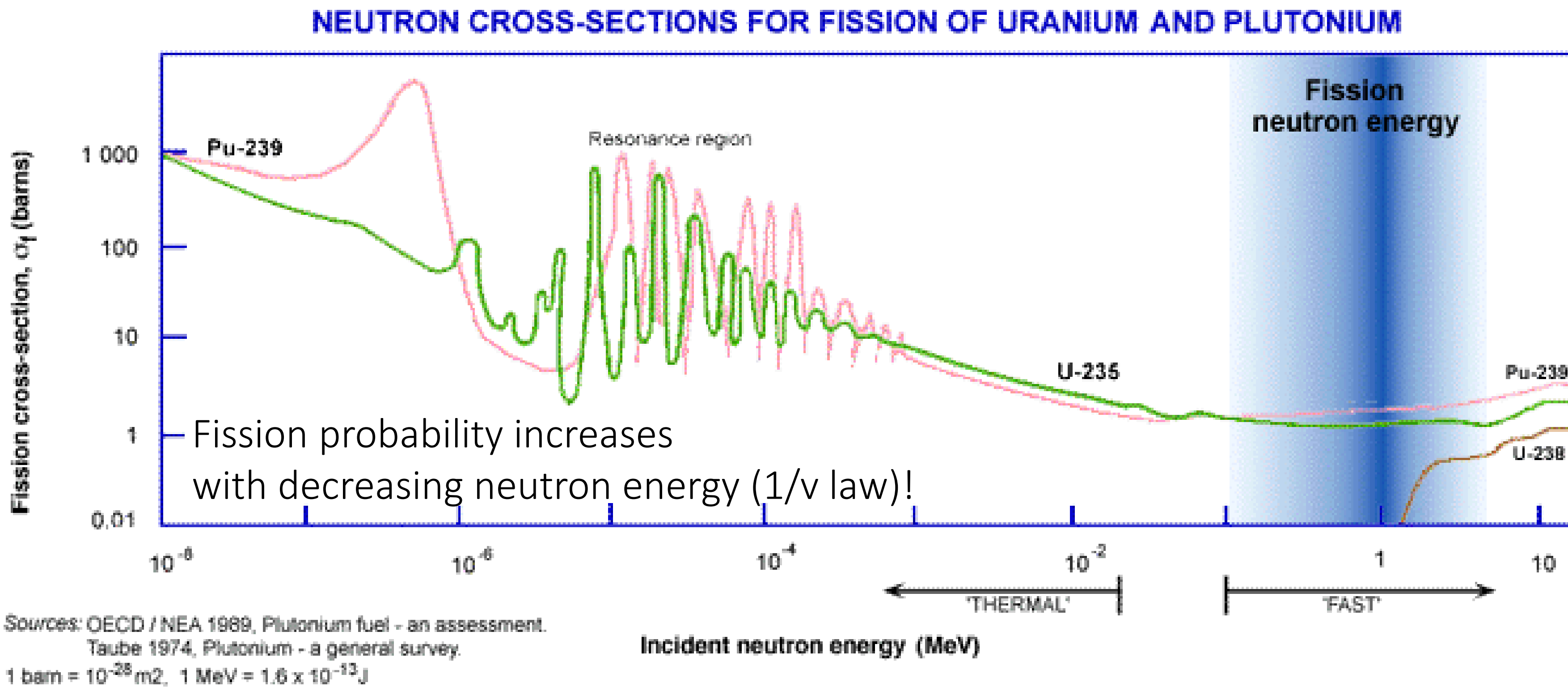




Heavy nuclei can fission by breaking up in two lower mass nuclei. The fission products come in a double bump distribution of pairs of neutron rich radioactive isotopes. Fission produces long-lived radioactivity.

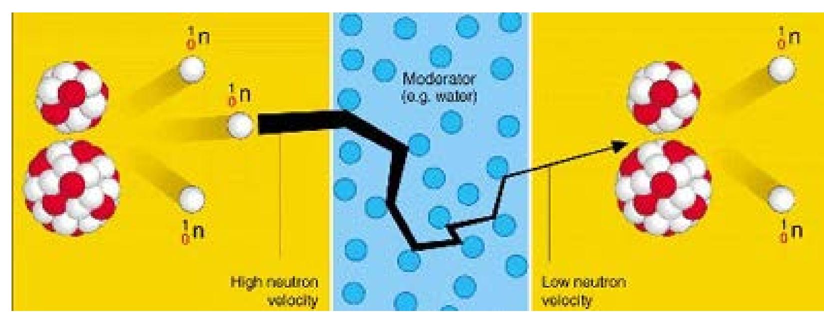
Each fission event produces additional free neutrons that trigger the next fission event in dense fissionable material.

Thermalization

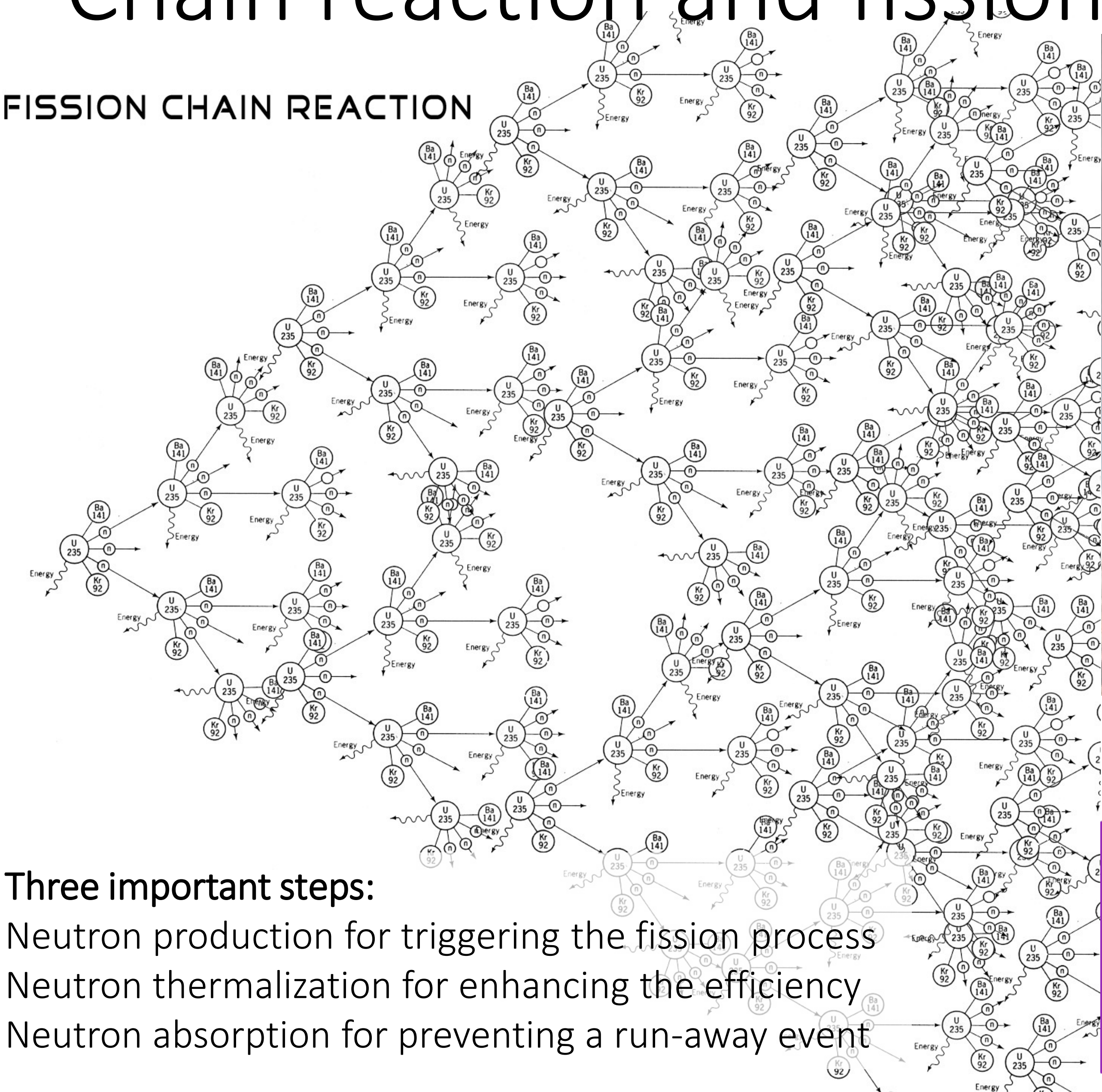


Fission probability increases
with decreasing neutron energy (1/v law)!

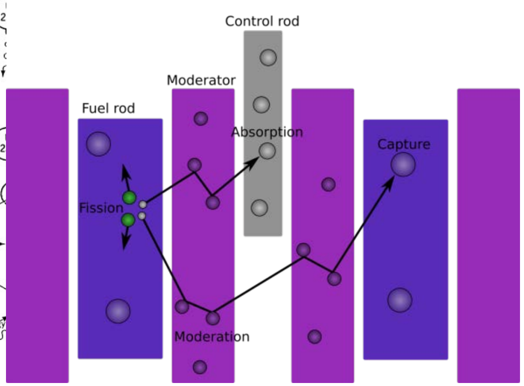
Fission neutrons are emitted with high energy and have to be slowed down (moderated) to be efficiently captured by uranium or plutonium. The moderator material must be low Z material to pass on a large amount of energy from neutron to scattering particle. The material also must have a low cross section for neutron absorption since the high neutron flux needs to be maintained.



Chain reaction and fission cycles



controlled



Three important steps:

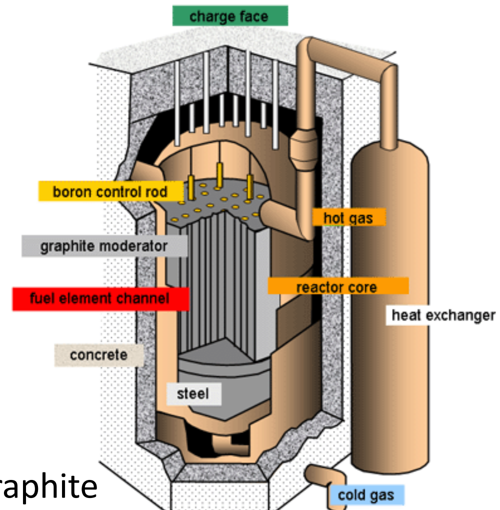
Neutron production for triggering the fission process

Neutron thermalization for enhancing the efficiency

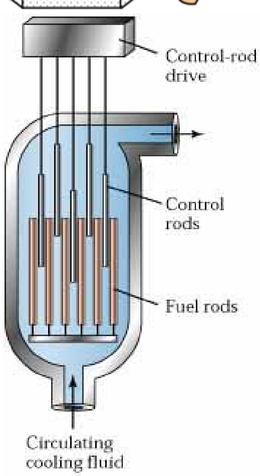
Neutron absorption for preventing a run-away event

Control rods

The control rods are embedded in a matrix between fuel elements and moderators. Their main mission is to control the neutron flux to prevent the reactor from becoming critical.

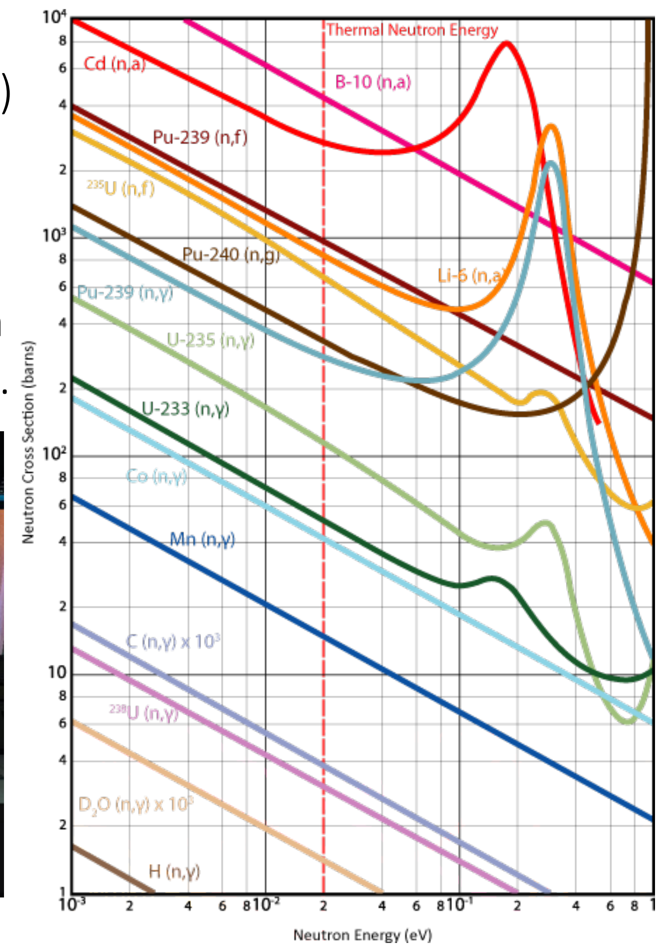


graphite moderator

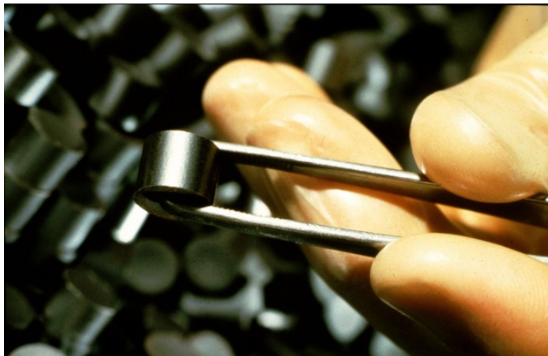


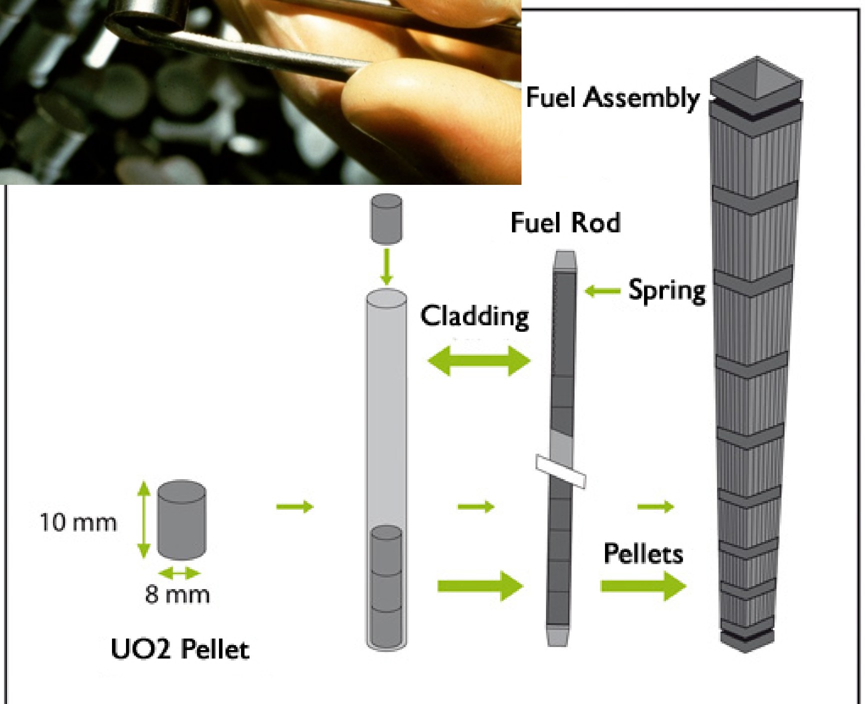
water moderator

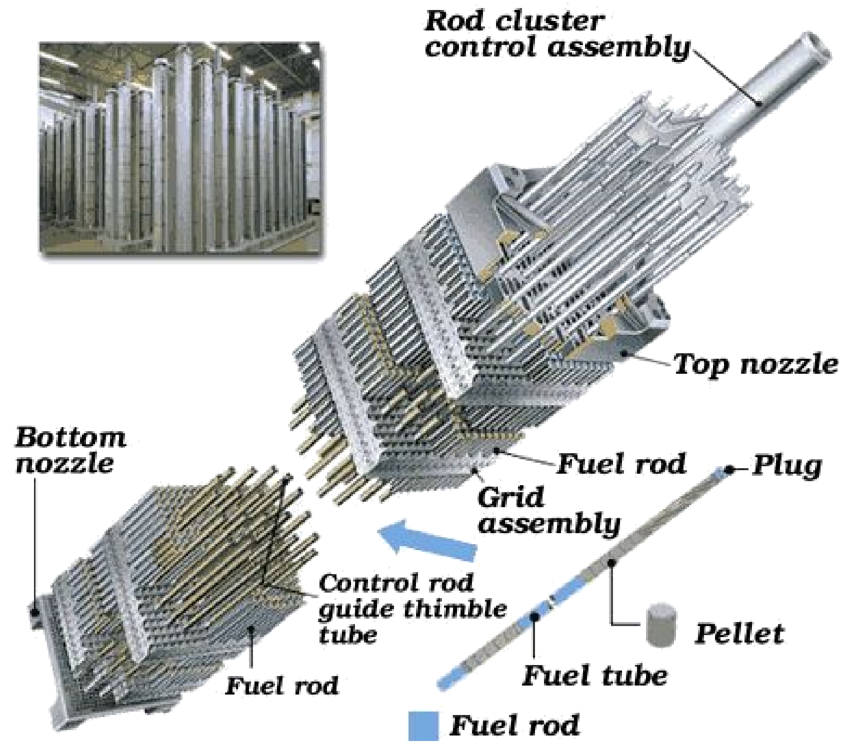
The two favorite materials are Cadmium and Boron , because of their high neutron capture cross section. The reaction $^{10}B(n,\alpha)^{7}Li$, produces stable ^{7}Li that can easily be removed. ($^{10}B(n,\alpha)^{8}Li$ negligible) Neutron absorption on cadmium at thermal energies is driven by $^{113}Cd(n,\gamma)^{114}Cd$, forming a stable ^{114}Cd isotope. Subsequent neutron capture produces short-lived ^{115}Cd.



Fuel elements





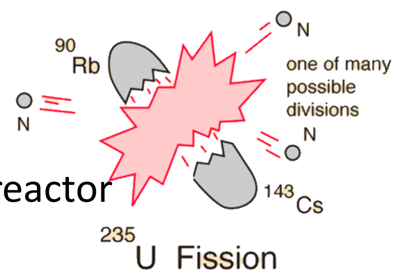


The assembly of fuel and moderator elements is an engineering problem towards optimized operation, safety, assembly, and disassembly for storage and recycling.

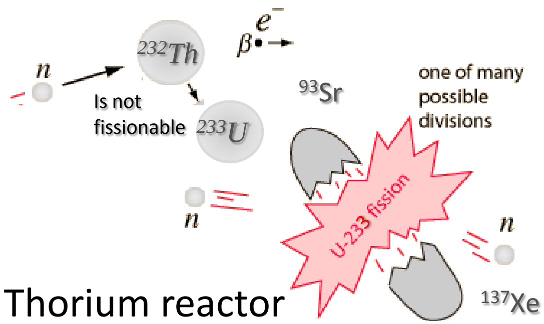
Alternative fission reactions

Nuclear Fuel Breeder

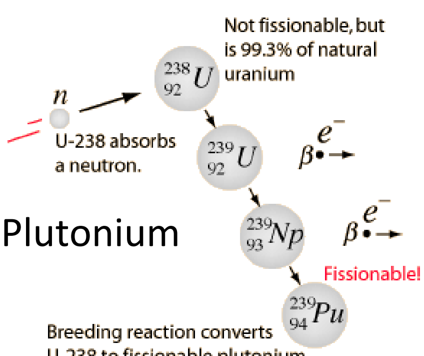
Uranium reactor

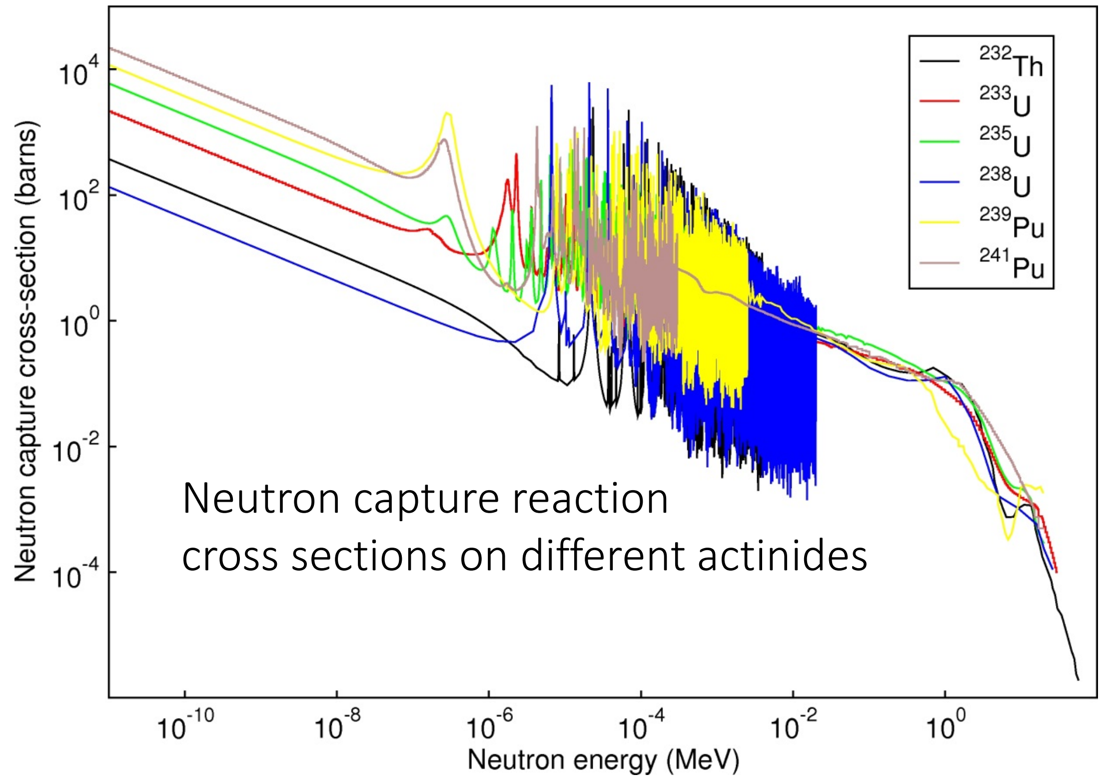


Thorium reactor



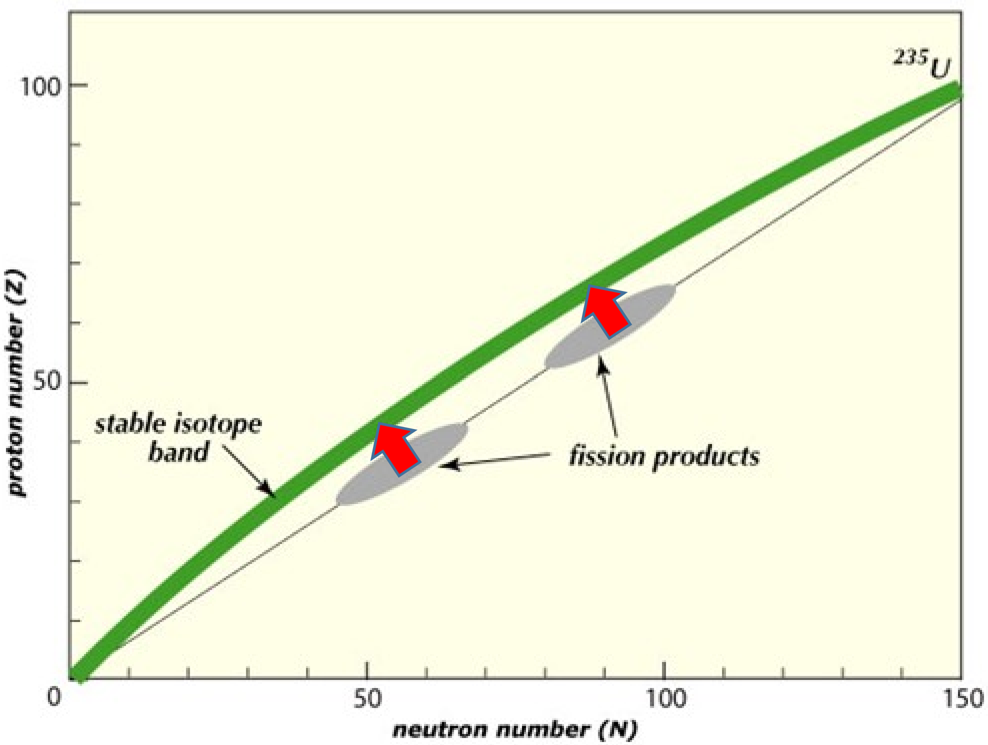
Breeder Plutonium reactor

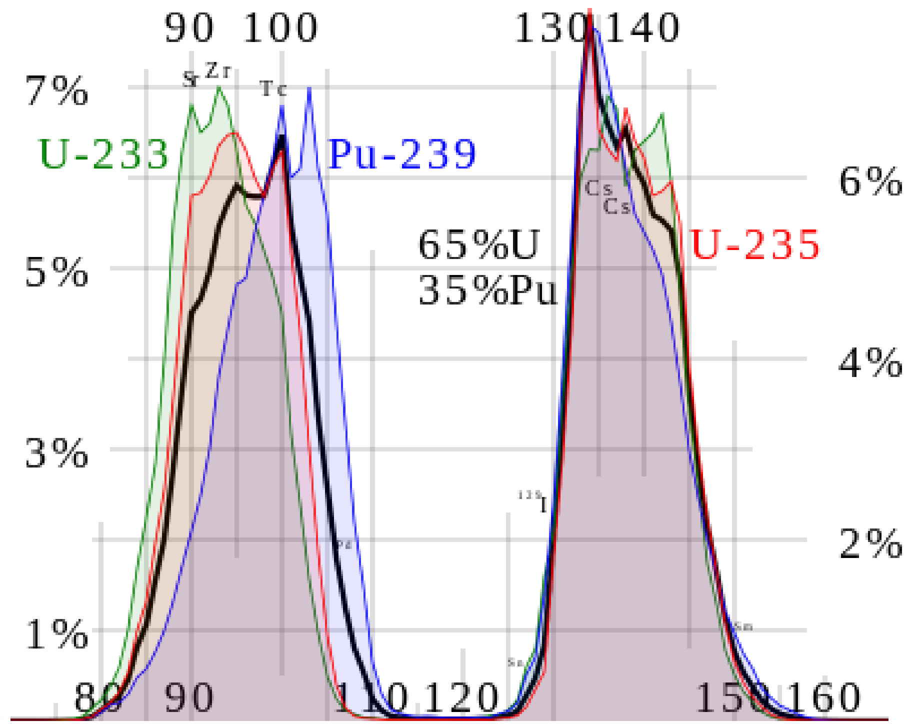




The breeding of nuclear fuel doesn't solve the issues associated with radioactive fission products but enhances the efficiency and reduced the fuel costs since ^{228}U and ^{232}Th is much more abundantly available than the rare ^{235}U. This removes and important costly aspect of fuel separation and preparation. Breeder also rely on fast neutrons and need no moderator materials.

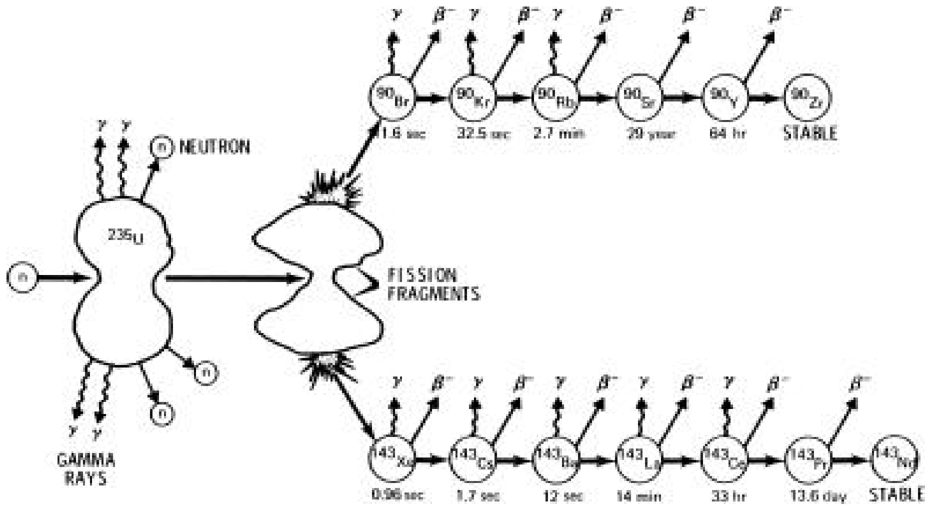
Fission Process



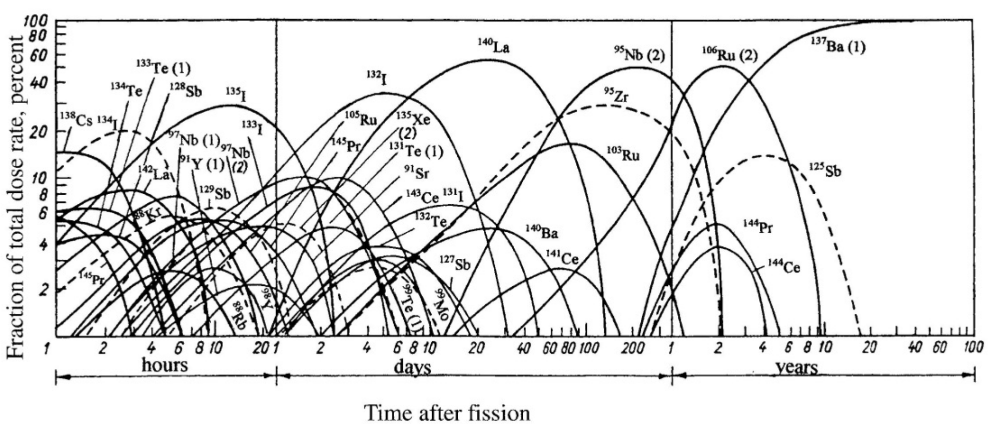


Fission product yields by mass for thermal neutron fission of ^{235}U, ^{239}Pu, a combination of the two typical of current nuclear power reactors, and ^{233}U used in the thorium cycle. The fission products are very neutron-rich and therefore highly radioactive and decay by β decay back to stability. Long-lived isotopes in the ^{233}U decay chains are: ^{93}Zr $T_{1/2}=1.5\cdot10^{6}$ y, ^{137}Cs $T_{1/2}=30$ y;

Fission products



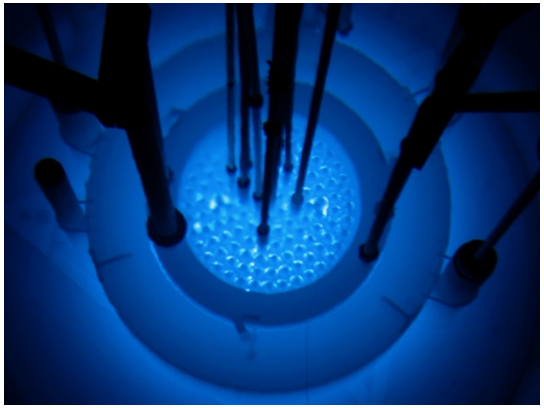
Uranium fission and possible fission products in subsequent β^- decay processes along the isobaric lines towards stability. These decay chains originate from the primary fission product distribution.

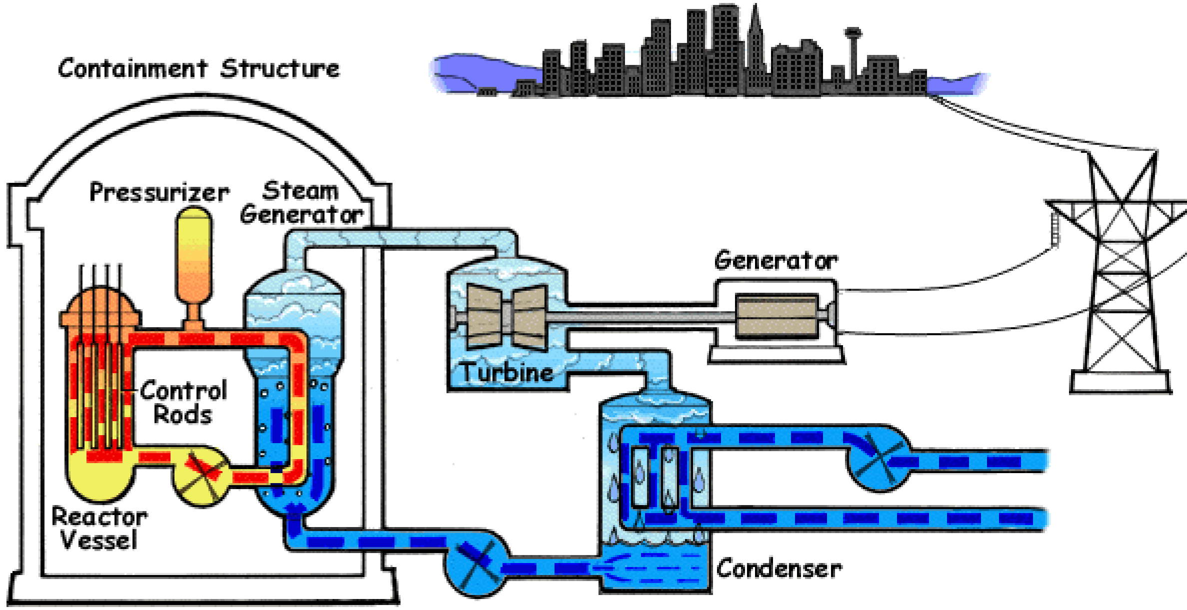


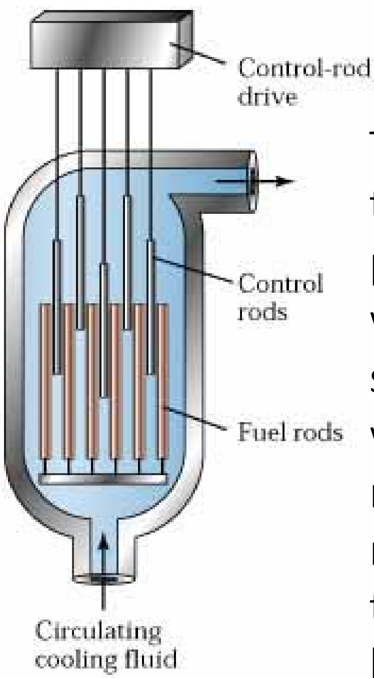
Medium-lived fission products				
Prop: Unit:	$t_{½}$ (a)	**Yield** (%)	**Heat** (keV)	βγ
^{155}Eu	4.76	0.0803	252	βγ
^{85}Kr	10.76	0.2180	687	βγ
^{113m}Cd	14.1	0.0008	316	β
^{90}Sr	28.9	4.505	2826	**β**
^{137}Cs	30.23	6.337	1176	β**γ**
^{121m}Sn	43.9	0.00005	390	βγ
^{151}Sm	96.6	0.5314	77	β

Long-lived fission products				
Prop: Unit:	$t_{½}$ (Ma)	**Yield** (%)	**Heat** (keV)	βγ
^{99}Tc	0.211	6.1385	294	β
^{126}Sn	0.230	0.1084	4050	β**γ**
^{79}Se	0.327	0.0447	151	β
^{93}Zr	1.53	5.4575	91	βγ
^{135}Cs	2.3	6.9110	269	β
^{107}Pd	6.5	1.2499	33	β
^{129}I	15.7	0.8410	194	β

The basic technical principles



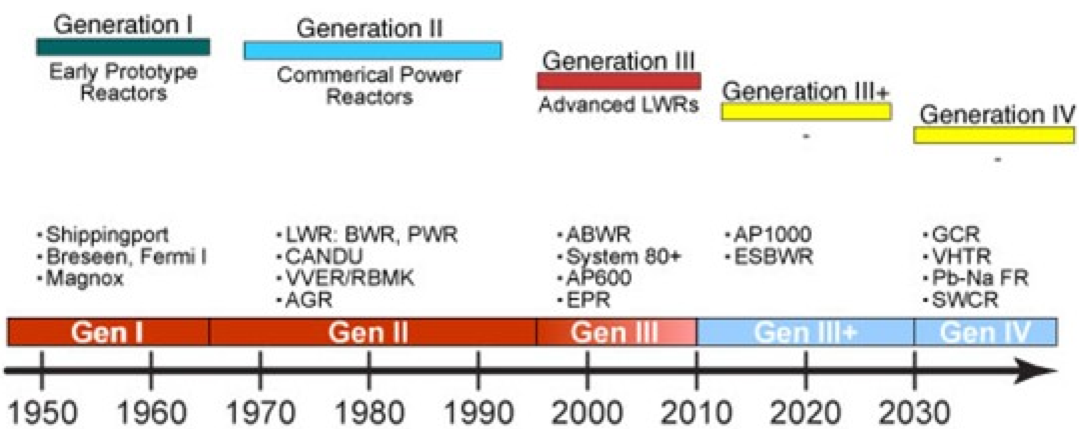




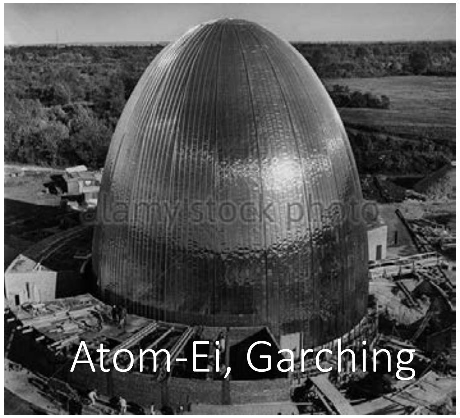
The cooling water that also functions as moderator for neutrons circulates through the reactor core and carries the heat that is generated by the fission process away in a closed water cycle, heating water in a secondary cycle. The water in the first cycle is radioactive from fission products the water in the second cycle should not be radioactive unless a leak has occurred. The hot water or steam in the second cycle drives the turbine. The control rods are made of Boron containing material since Boron has a large cross section for neutron capture. If in place the released fission neutrons are absorbed and the chain fission reactions stops. But there is still substantial decay heat being released, which requires continuous cooling!

Reactor Generations

Technical developments and safety concerns – sometimes even new physics results - drive the change in the different reactor generations from the early prototypes such as the pile to latest generation of reactors with high neutron flux to high energy out-put. A reactor life-time is 40-50 years, Public and political concerns often lead to administrative delays forcing the lifetime extension with consequences in aging and safety reduction.




Pile, Chicago

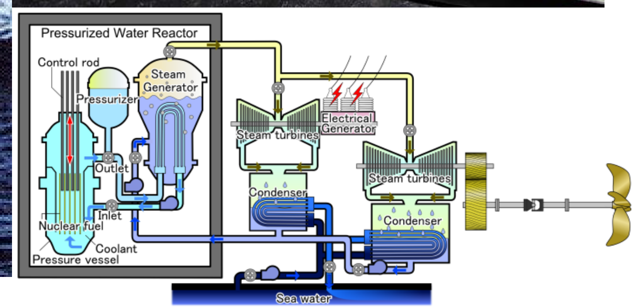


Atom-Ei, Garching


CANDU, Canada

The pressurized light water reactor

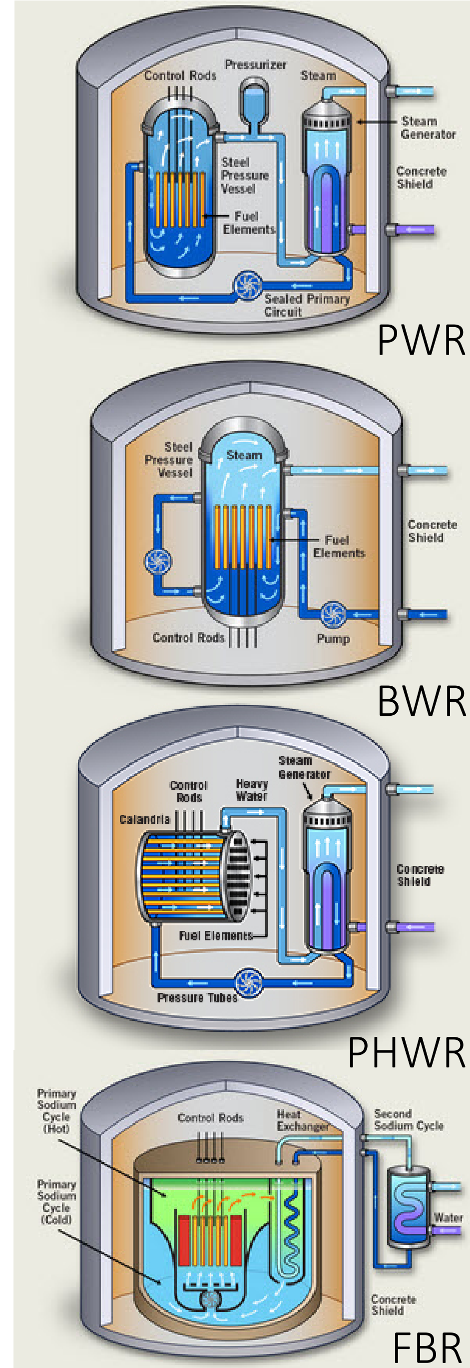
The PLWR is the present is the most used reactor type, developed at Oak Ridge and utilized for the nuclear submarine development under Admiral Rickover.



The **Light Water Reactor (LWR)** concept of water cooling seemed the obvious choice since water was available in large abundance. Rickover was also charged with the development of reactor types for peaceful applications (Atoms for Peace) and he continued with the same type despite the fact that it had more risk factors than other versions developed at Oak Ridge. He trusted in technical competence of military staff with rigid command structure. The industrial military complex had started, military requirements dictated the direction of civilian developments.

Reactor types and coolants

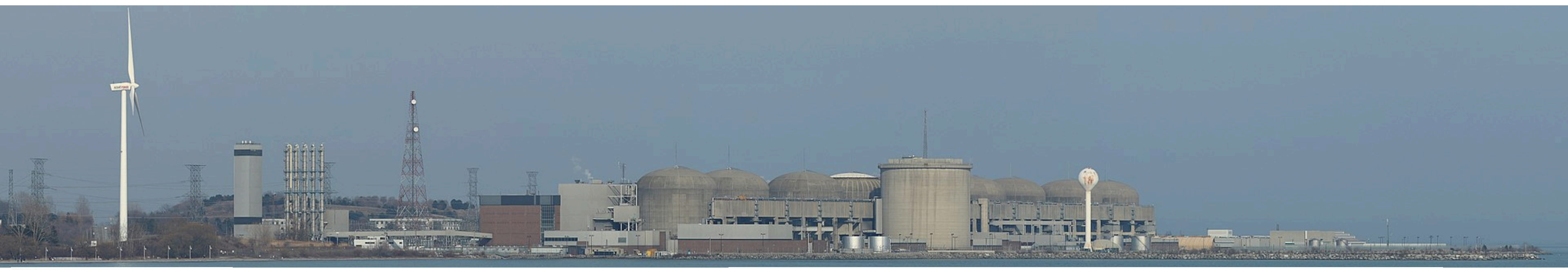
Reactor type	Fuel	Moderator	Coolant	Number
Pressurized water reactor (PWR)	Enriched UO_2	Water	Water	290
Boiling water reactor (BWR)	Enriched UO_2	Water	Water	78
Pressurized heavy water reactor (PHWR)	Natural UO_2	Heavy water	Heavy water	47
Light water graphite reactor (LWGR)	Enriched UO_2	Graphite	Water	15
Gas-cooled reactor (GCR)	Natural U, enriched UO_2	Graphite	Carbon dioxide	14
Fast breeder reactor (FBR)	PuO_2 and UO_2	None	Liquid sodium	3

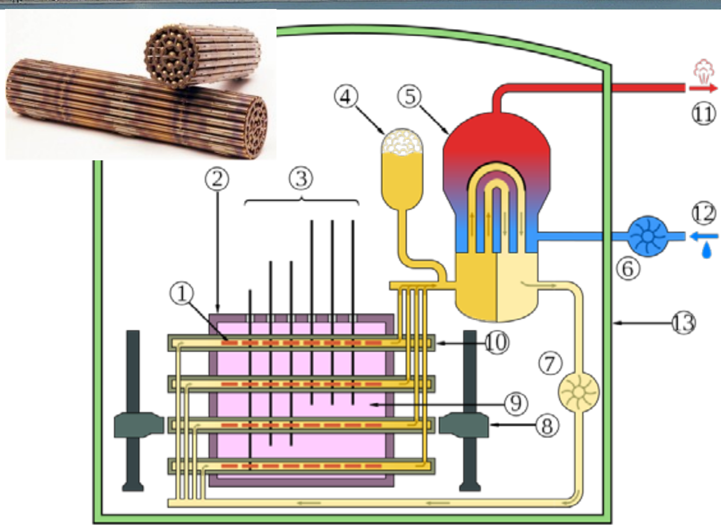


CANDU third generation reactor

The **CANDU**, for **Canada Deuterium Uranium**, is a Canadian pressurized heavy water reactor design used to generate electric power. III generation CANDU reactors use pressurized light water as the coolant. This reduces the cost of implementing the primary cooling loop, which no longer has to be filled with expensive heavy water.

The design also uses only slightly enriched uranium, enriched by about 1 or 2% to increase the burn-up ratio, allowing bundles to remain in the reactor longer, so that only a third as much spent fuel is produced. This reduces the refueling frequency.





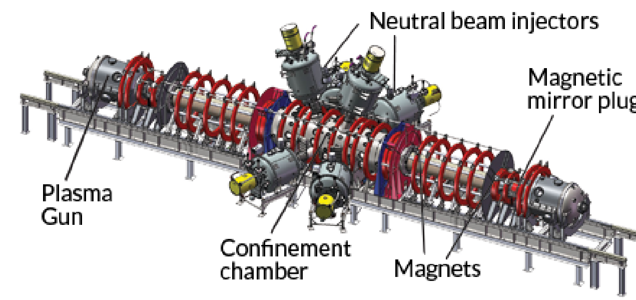
Schematic diagram of a CANDU reactor: Hot and cold sides of the primary heavy-water loop; hot and cold sides of secondary light-water loop; and cool heavy water moderator in the **calandria**, along with partially inserted adjuster rods (as CANDU control rods are known).

1. Fuel bundle
2. Calandria (reactor core)
3. Adjuster rods
4. Heavy water pressure reservoir
5. Steam generator
6. Light water pump
7. Heavy water pump
8. Fueling machines
9. Heavy water moderator
10. Pressure tube
11. Steam going to steam turbine
12. Cold water returning from turbine
13. Containment building made of reinforced concrete

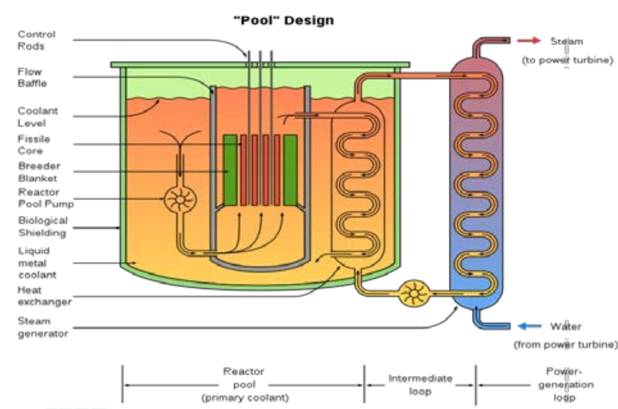
Other reactor types with potentially far advanced features

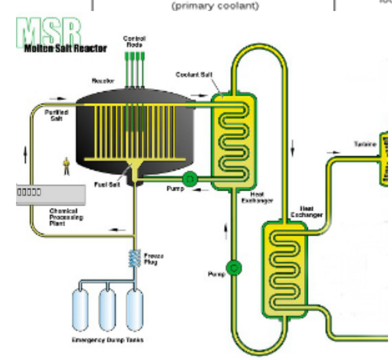
- <u>Boron Reactor</u>: a-neutronic fusion reactor device based on the $^{11}B(p,2\alpha)^{4}He$ reaction with little radioactive output from isotopic impurity $^{10}B(p,\alpha)^{7}Be(e^{-}\nu)^{7}Li$ ($T_{1/2}$=53 d). High intensity proton beam injected into a hot boron plasma in the magnetic confinement chamber
- <u>Liquid Metal Reactor (LMR)</u>: uses liquid sodium of lithium as coolant and uranium and/or thorium as fuel elements with a different distribution of fission products. Production of radioactive ^{24}Na occurs by neutron capture, but ^{24}Na has only 15 h half life. No stable ^{8}Li!
- <u>Molten Salt Reactor (MSR)</u> : the uranium fuel is dissolved in the sodium fluoride salt coolant which circulates through graphite core channels to achieve some moderation. Fission products are removed continuously and the actinides are fully recycled. A secondary coolant system is used for electricity generation.

Tri Alpha Energy model



Liquid Metal cooled Fast Breeder Reactors (LMFBR)

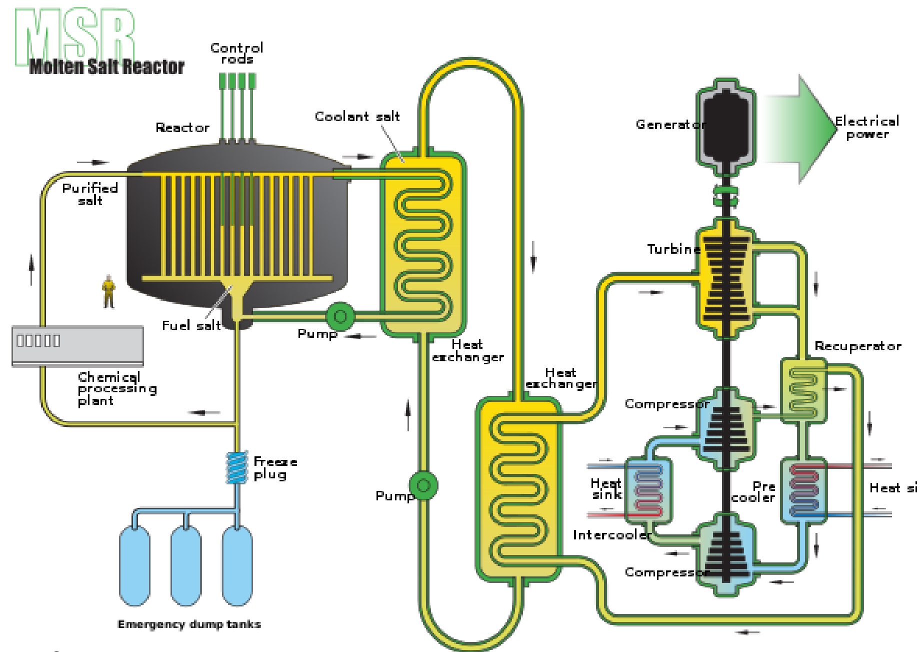




Thorium Reactor

Special version of Molten Salt Reactor (MSR)

The thorium reactor uses ^{232}Th as fuel converting it by neutron capture to fissible ^{233}U by n capture ^{232}Th(n,γ) ^{233}Pr($\beta^{-}\nu$)^{233}U. It removes the costs for the production and possible enrichment of ^{235}U as fission source.



The salts concerned as primary coolant, mostly lithium-beryllium fluoride and lithium fluoride, remain liquid without pressurization from about 500°C up to about 1400°C, in marked contrast to a PWR which operates at about 315°C under 150 atmospheres pressure.

The main MSR concept is to have the fuel dissolved in the coolant as fuel salt, and ultimately to reprocess that online. Thorium, uranium, and plutonium all form suitable fluoride salts that readily dissolve in the LiF-BeF2 (FLiBe) mixture, and thorium and uranium can be easily separated from one another in fluoride form. Fuel life is estimated at 4-7 years, with high burn-up.

ORNL development program was defunded in 1976. Private companies in Europe pick up the challenge. In 2016 Nobel prize winning physicist Carlo Rubbia, former Director General of CERN, claimed that one of the main reasons why research was cut is that thorium is difficult to turn into a nuclear weapon

LWR during Normal Operation

Material is being contained, in fuel rods and need to be separated in fuel facilities

Radioactivity accumulates in the fuel rods and may act as neutron poison – capture neutrons with subsequent γ-emission instead of fission. The efficiency of the fuel rod gradually declines and the fuel-rod has to be replaced and regenerated. This opens the problem of short-term storage and long-term deposition of radioactive waste.

Yield of Fission Products

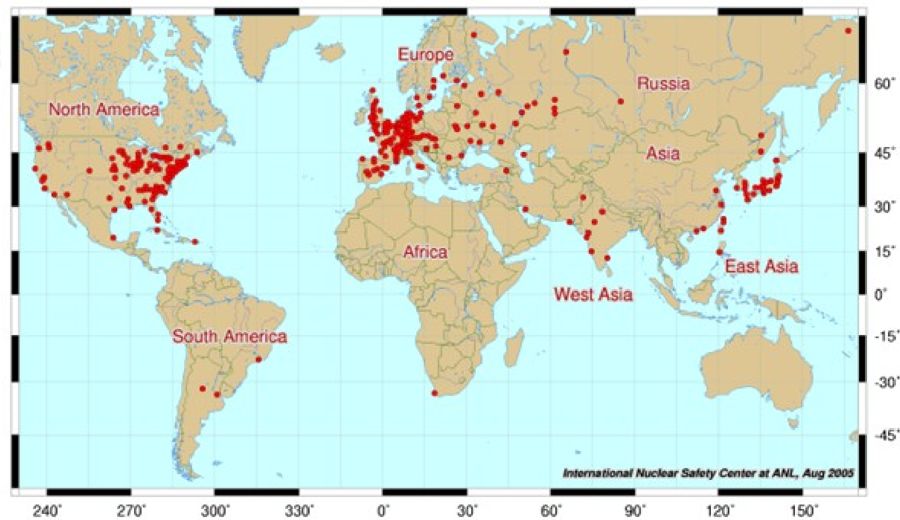
By yield

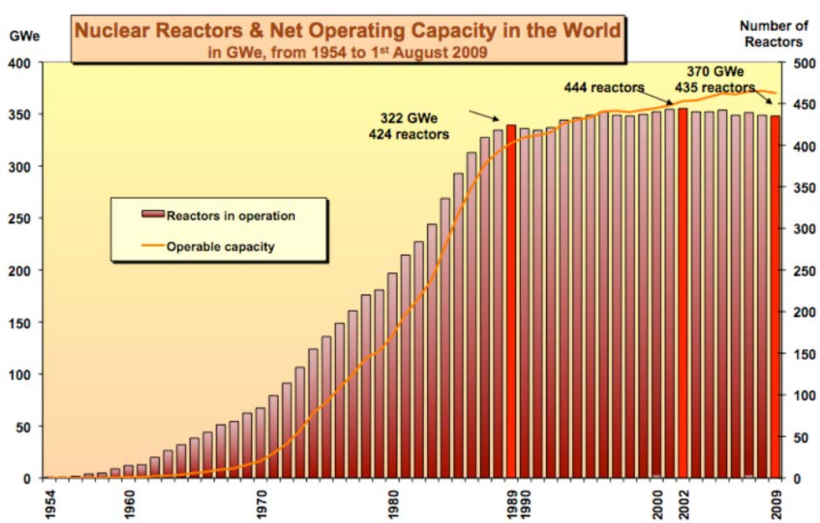
Yield	Element	Isotope	Halflife
6.7896%	Caesium	$^{133}Cs \rightarrow ^{134}Cs$	2.065 y
6.3333%	Iodine, Xenon	$^{135}I \rightarrow ^{135}Xe$	6.57 h
6.2956%	Zirconium	^{93}Zr	1.53 My
6.1%	Molybdenum	^{99}Mo	65.94 h
6.0899%	Caesium	^{137}Cs	30.17 y
6.0507%	Technetium	^{99}Tc	211 ky
5.7518%	Strontium	^{90}Sr	28.9 y
2.8336%	Iodine	^{131}I	8.02 d
2.2713%	Promethium	^{147}Pm	2.62 y
1.0888%	Samarium	^{149}Sm	virtually stable
0.9%[2]	Iodine	^{129}I	15.7 My
0.4203%	Samarium	^{151}Sm	90 y
0.3912%	Ruthenium	^{106}Ru	373.6 d
0.2717%	Krypton	^{85}Kr	10.78 y
0.1629%	Palladium	^{107}Pd	6.5 My
0.0508%	Selenium	^{79}Se	327 ky
0.0330%	Europium, Gadolinium	$^{155}Eu \rightarrow ^{155}Gd$	4.76 y
0.0297%	Antimony	^{125}Sb	2.76 y
0.0236%	Tin	^{126}Sn	230 ky
0.0065%	Gadolinium	^{157}Gd	stable
0.0003%	Cadmium	^{113m}Cd	14.1 y

By half-life

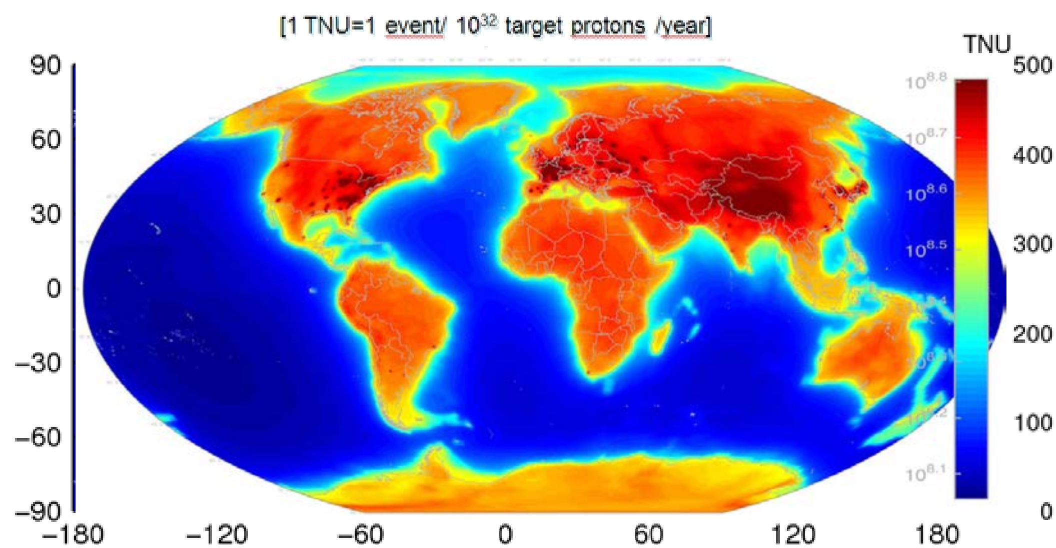
Yield	Isotope	Halflife
2.8336%	^{131}I	8.02d
0.3912%	^{106}Ru	373.6d
6.7896%	$^{133}Cs \rightarrow ^{134}Cs$	2.065y
2.2713%	^{147}Pm	2.62y
0.0297%	^{125}Sb	2.76y
<0.0330%	$^{155}Eu \rightarrow ^{155}Gd$	4.76y
0.2717%	^{85}Kr	10.78y
<0.0003%	^{113m}Cd	14.1y
5.7518%	^{90}Sr	28.9y
6.0899%	^{137}Cs	30.17y
<0.4203%	^{151}Sm	90y
6.0507%	^{99}Tc	211ky
0.0236%	^{126}Sn	230ky
0.0508%	^{79}Se	327ky
6.2956%	^{93}Zr	1.53My
<6.3333%	^{135}Cs	2.3My
0.1629%	^{107}Pd	6.5My
0.6576%	^{129}I	15.7My
<1.0888%	^{149}Sm	nonradioactive
<0.0065%	^{157}Gd	nonradioactive

Reactor Locations, US and World-Wide

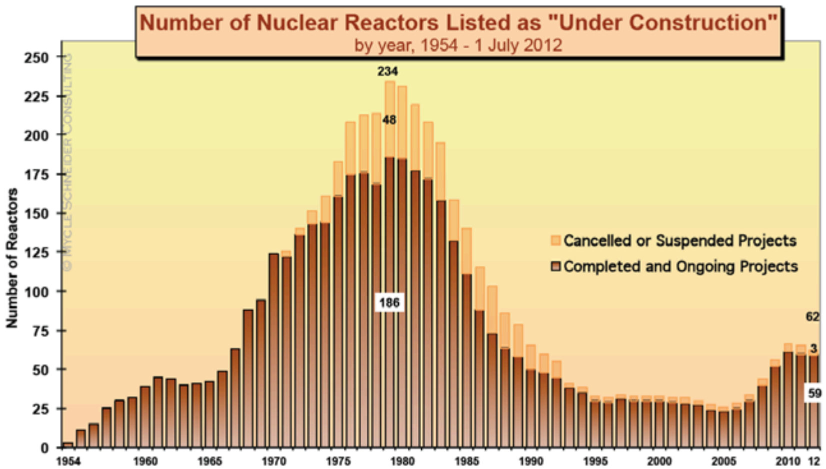


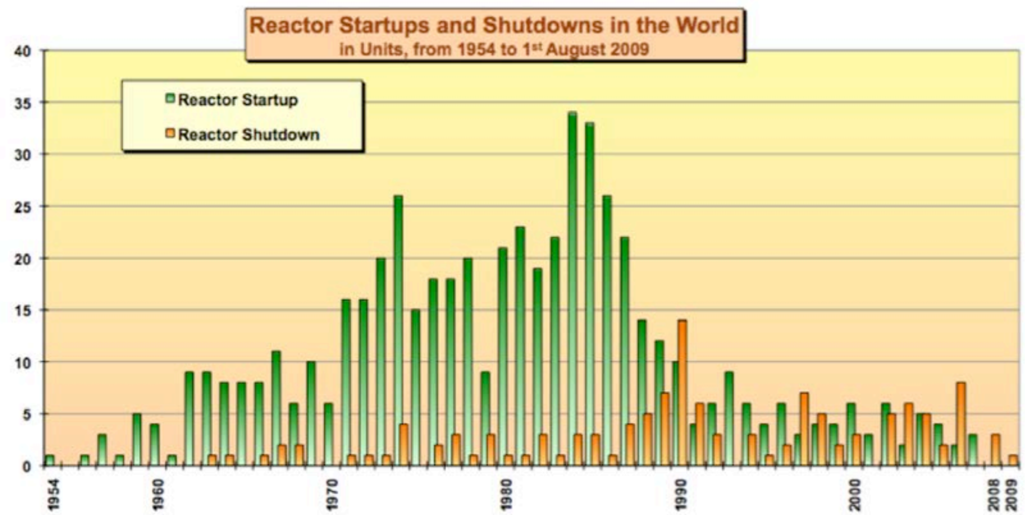


Map of neutrino flux

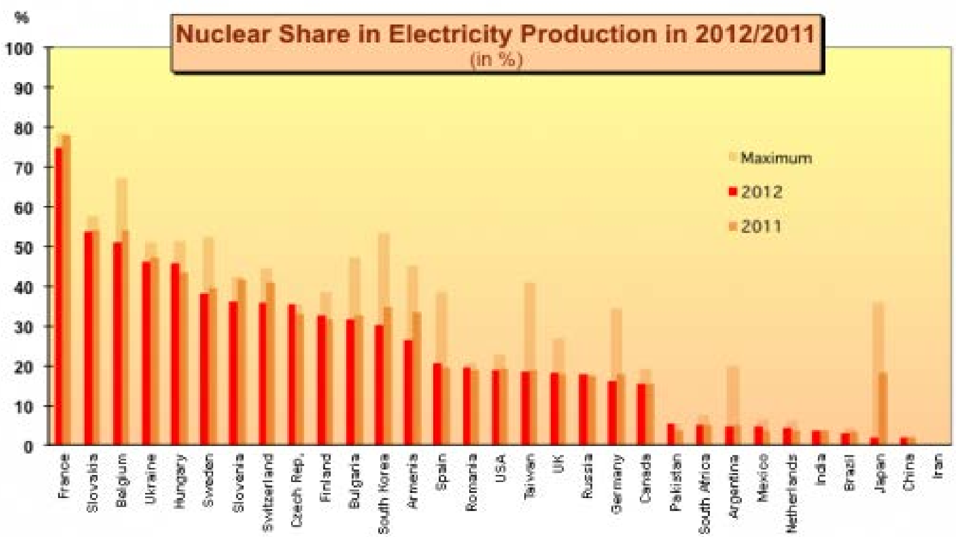


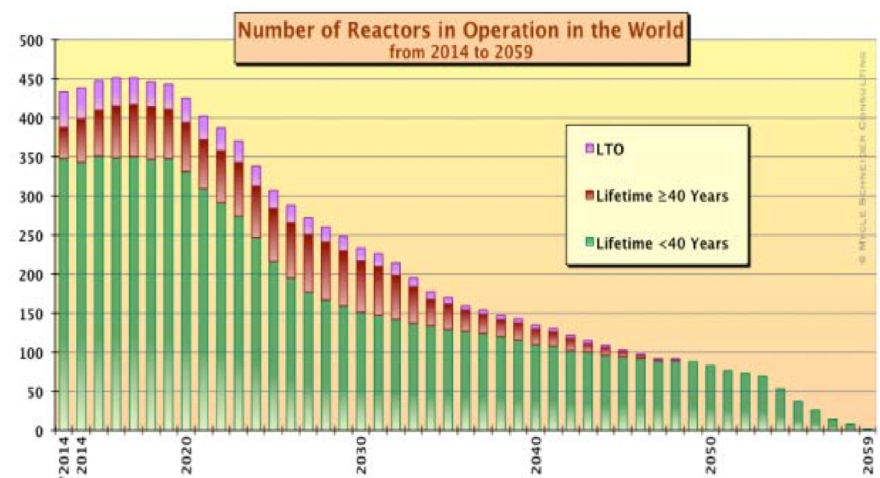
Nuclear Reactor Budgeting





Clear indication of decline in nuclear energy production, peak in 1975-1980





Peoples Republic of China

As of May 2017, the China has 37 nuclear reactors operating with a capacity of 32.4 GW and 20 under construction with a capacity of 20.5 GW. Additional 34 more reactors are planned, providing 58 GW of capacity by 2020. Mostly traditional LWR types. Modern developments show more diversification, e.g. liquid salt reactors.

Two AECL 728MW CANDU-6 reactors at the Qinshan Nuclear Power Plant, the first went online in 2002, the second in 2003. CANDU reactors use low grade reprocessed uranium from conventional reactors as fuel, reducing China's storage issues.