Nuclear Energy: Controlled Fission and Fusion

IE350

Fission

- Break into parts
- Decay

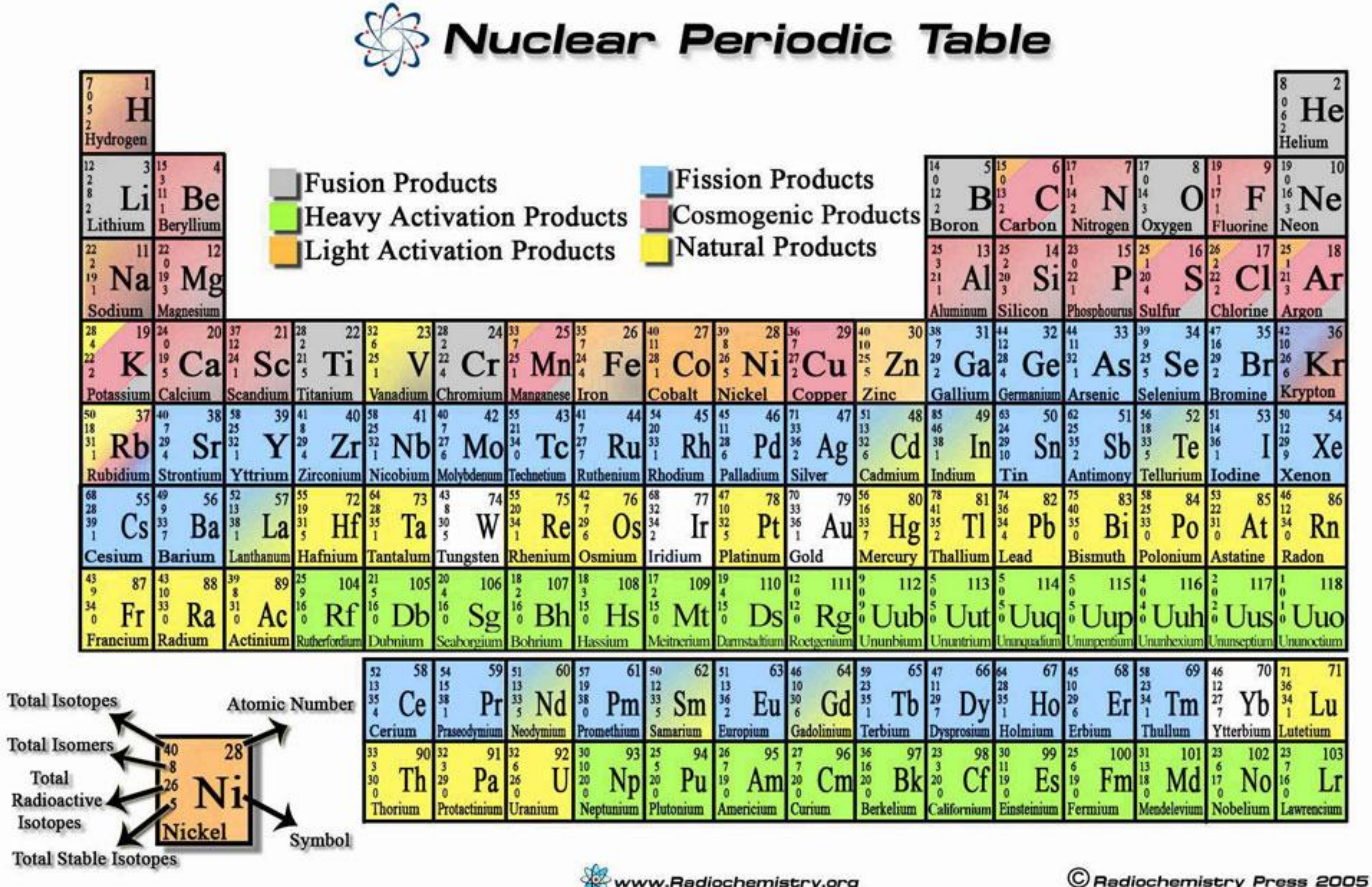
Atomic Structure

Operation of a nuclear reactor depends upon various interactions of neutrons with atomic nuclei

- protons (p); neutrons (n); electrons (e)
- protons or neutrons = nucleons
- Atomic number Z= # of protons (H=1, He=2…U=92)
- Mass number A, # of nucleons, A=p+n=Z+n or n=A-Z
- Isotopes – same Z but different A

  e.g. U – 234, 235, 238

  U (235) = 92p+143n


Nuclear Periodic Table
Fusion Products
Heavy Activation Products
Light Activation Products
Fission Products
Cosmogenic Products
Natural Products
Total Isotopes
Total Isomers
Total Radioactive Isotopes
Total Stable Isotopes
Atomic Number
Symbol
Nickel
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Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** Hydrogen 1.008																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012											5 **B** Boron 10.811	6 **C** Carbon 12.011	7 **N** Nitrogen 14.007	8 **O** Oxygen 15.999	9 **F** Fluorine 18.998	10 **Ne** Neon 20.180
11 **Na** Sodium 22.990	12 **Mg** Magnesium 24.305											13 **Al** Aluminum 26.982	14 **Si** Silicon 28.086	15 **P** Phosphorus 30.974	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.453	18 **Ar** Argon 39.948
19 **K** Potassium 39.098	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.956	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.942	24 **Cr** Chromium 51.996	25 **Mn** Manganese 54.938	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933	28 **Ni** Nickel 58.693	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.38	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.631	33 **As** Arsenic 74.922	34 **Se** Selenium 78.971	35 **Br** Bromine 79.904	36 **Kr** Krypton 84.798
37 **Rb** Rubidium 84.468	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.906	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.906	42 **Mo** Molibdenum 95.95	43 **Tc** Technetium 98.907	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.906	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.868	48 **Cd** Cadmium 112.414	49 **In** Indium 114.818	50 **Sn** Tin 118.711	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.6	53 **I** Iodine 126.904	54 **Xe** Xenon 131.249
55 **Cs** Cesium 132.905	56 **Ba** Barium 137.328	57-71 Lanthanides	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.948	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.085	79 **Au** Gold 196.967	80 **Hg** Mercury 200.592	81 **Tl** Thallium 204.383	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.980	84 **Po** Polonium [208.982]	85 **At** Astatine 209.987	86 **Rn** Radon 222.018
87 **Fr** Francium 223.020	88 **Ra** Radium 226.025	89-103 Actinides	104 **Rf** Rutherfordium [261]	105 **Db** Dubnium [262]	106 **Sg** Seaborgium [266]	107 **Bh** Bohrium [264]	108 **Hs** Hassium [269]	109 **Mt** Meitnerium [268]	110 **Ds** Darmstadtium [269]	111 **Rg** Roentgenium [272]	112 **Cn** Copernicium [277]	113 **Uut** Ununtrium unknown	114 **Fl** Flerovium [289]	115 **Uup** Ununpentium unknown	116 **Lv** Livermorium [298]	117 **Uus** Ununseptium unknown	118 **Uuo** Ununoctium unknown

57 **La** Lanthanum 138.905	58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.908	60 **Nd** Neodymium 144.243	61 **Pm** Promethium 144.913	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.925	66 **Dy** Dysprosium 162.500	67 **Ho** Holmium 164.930	68 **Er** Erbium 167.259	69 **Tm** Thulium 168.934	70 **Yb** Ytterbium 173.055	71 **Lu** Lutetium 174.967
89 **Ac** Actinium 227.028	90 **Th** Thorium 232.038	91 **Pa** Protactinium 231.036	92 **U** Uranium 238.029	93 **Np** Neptunium 237.048	94 **Pu** Plutonium 244.064	95 **Am** Americium 243.061	96 **Cm** Curium 247.070	97 **Bk** Berkelium 247.070	98 **Cf** Californium 251.080	99 **Es** Einsteinium [254]	100 **Fm** Fermium 257.095	101 **Md** Mendelevium 258.1	102 **No** Nobelium 259.101	103 **Lr** Lawrencium [262]

Energy/Mass Equivalence

$E=mc^2$ $c = 3x10^{10}$cm/s = $3x10^8$m/s

E (joules) = m(kg) x 9 x 10^{16}

E (kWh) = m(kg) x 25 x 10 ^{9}

1 kg = 25 Bn kWh ≈ 5 x Armenian electric power consumption.

Electron volt unit = 1.6 x 10^{-19} joules

1 Mev = 1.6 x 10^{-13} joules

E (Mev) = m(kg) x $9x10^{16}/1.6x10^{-13} = 5.6x10^{29}$ m(kg)

E (Mev) = m(g) x $9x10^{12}/1.6x10^{-13} = 5.6x10^{26}$ m(kg)

Binding Energy (Table 2.4)

B.E./A = 931/A [Zm_H + m_n (A-Z) – M] Mev/nucleon

931 is equivalent to $5.6x10^{26}$ divided by Avogadro No. = $6.02x10^{23}$

m_H = 1.008; m_n = 1.009

M = in amu (atomic mass unit)

1 amu = 1.660×10^{-24} gm

1. Atomic Mass Unit

amu – atomic mass unit, used to describe the mass of an atom

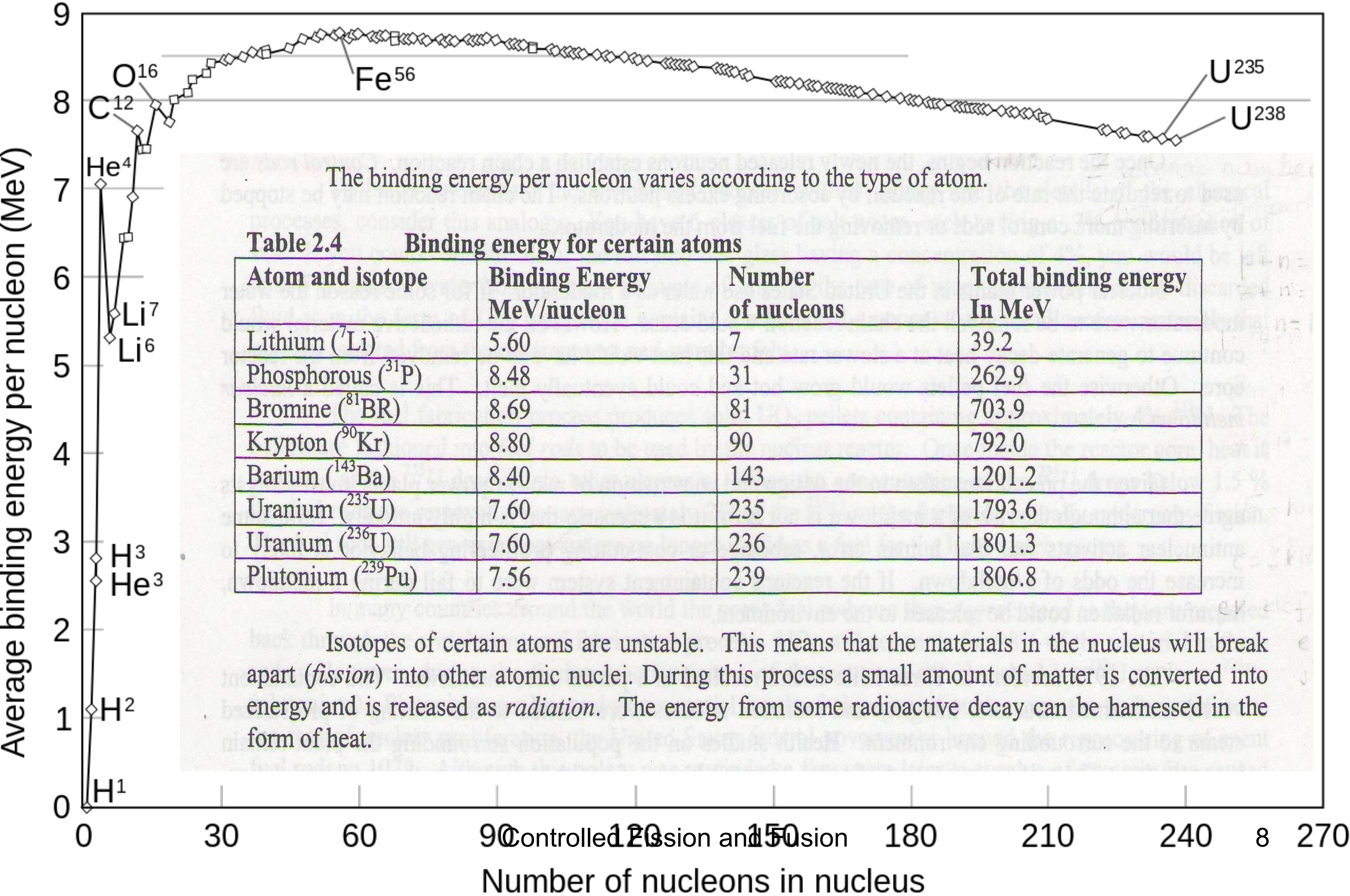
1 amu = 1.66×10^{-24} g

Example:

How many amu are in 27.0 grams of mercury?

$$27.0 \text{ g Hg} \times \frac{1 \text{ amu Hg}}{1.66 \times 10^{-24} \text{ g Hg}} = 1.63 \times 10^{25} \text{ amu Hg}$$

Binding Energy

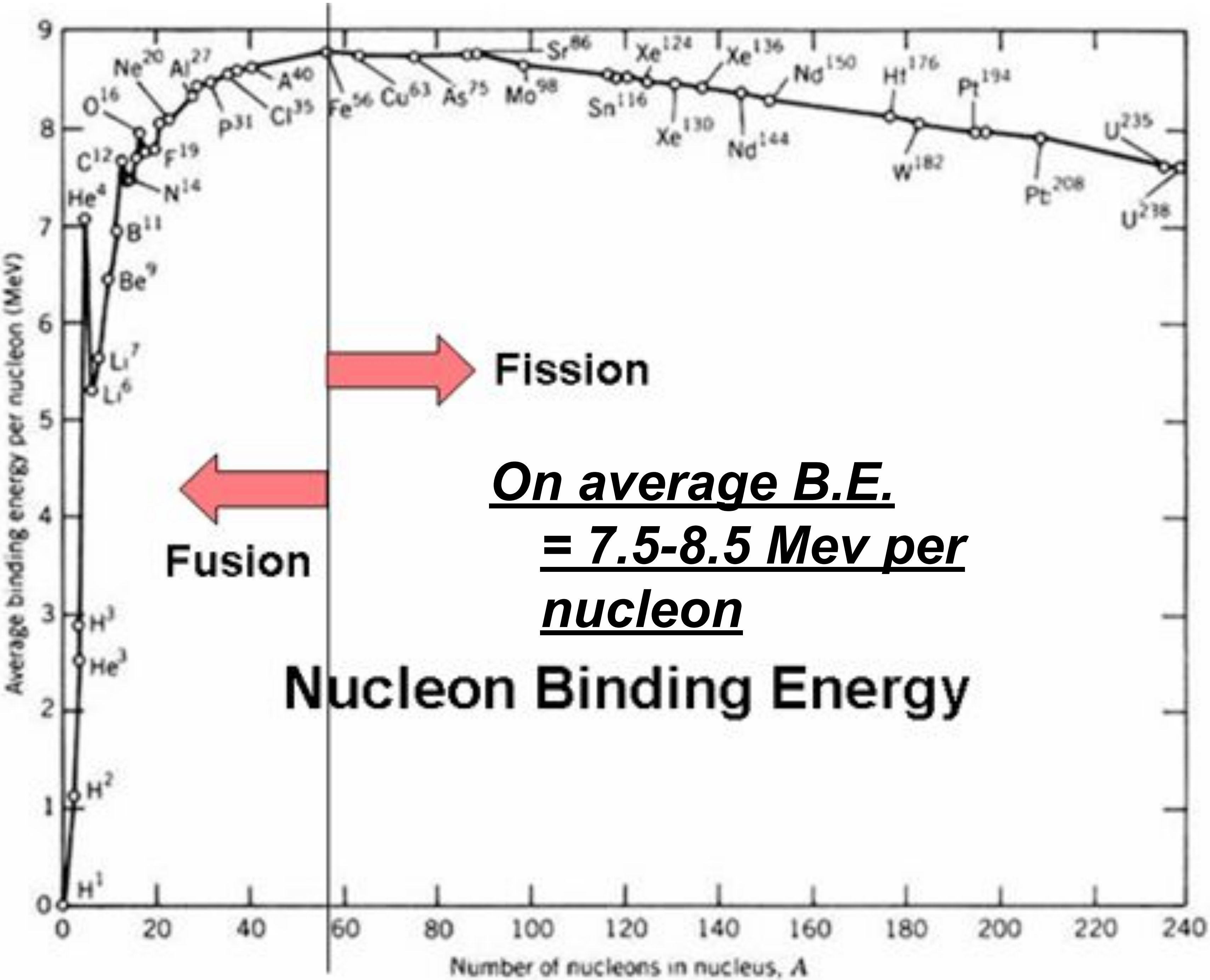


The binding energy per nucleon varies according to the type of atom.

Table 2.4 Binding energy for certain atoms

Atom and isotope	Binding Energy MeV/nucleon	Number of nucleons	Total binding energy In MeV
Lithium (^{7}Li)	5.60	7	39.2
Phosphorous (^{31}P)	8.48	31	262.9
Bromine (^{81}BR)	8.69	81	703.9
Krypton (^{90}Kr)	8.80	90	792.0
Barium (^{143}Ba)	8.40	143	1201.2
Uranium (^{235}U)	7.60	235	1793.6
Uranium (^{236}U)	7.60	236	1801.3
Plutonium (^{239}Pu)	7.56	239	1806.8

Isotopes of certain atoms are unstable. This means that the materials in the nucleus will break apart (*fission*) into other atomic nuclei. During this process a small amount of matter is converted into energy and is released as *radiation*. The energy from some radioactive decay can be harnessed in the form of heat.



<u>On average B.E. = 7.5-8.5 Mev per nucleon</u>

Nucleon Binding Energy

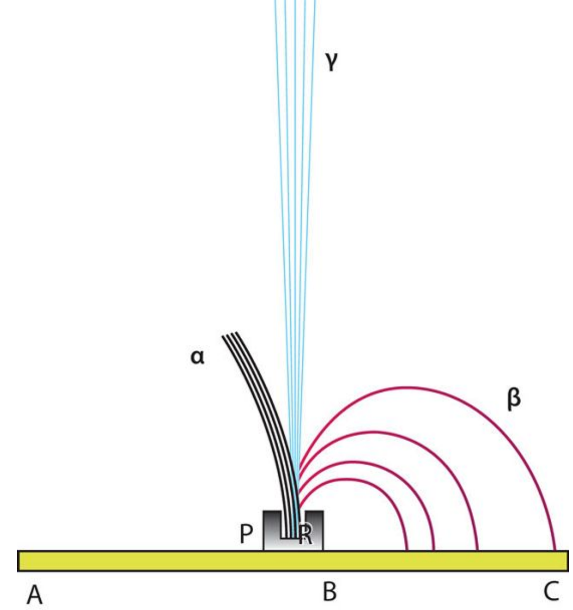
Radioactivity

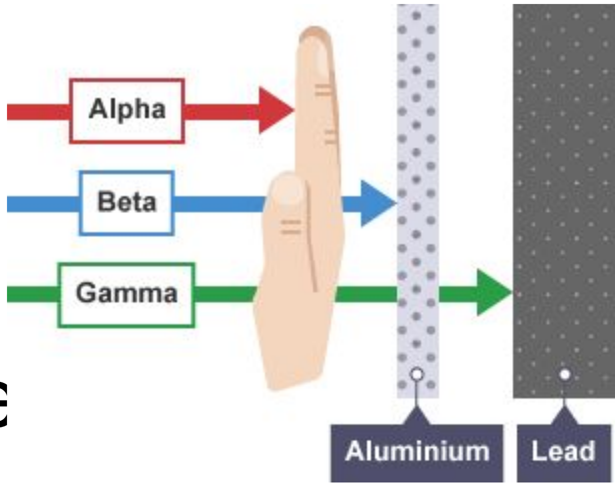
Unstable elements; from Z=84-92

Unstable nucleus emits characteristic particles (radiation)

α - particles (2p); β - particle (e) and gamma rays (γ)

The fission process is one such decay or splitting of the unstable atom such as uranium.





The Fission Process

- Occurs only with nuclei of high Z (and mass)
- Only 3 nuclides are fissionable by neutrons of all energies (slow/thermal; fast)

  U-233, 235 and Pu-239, called fissile nuclides
- Of these only U-235 occurs in nature. The other two are generated by neutron capture
- Fission releases large amount of energy and creates a chain reaction.

U-235 → Fission product A + Fission product B + Energy

92p +143n → U235 + 235 x 7.6 Mev

92p + 143n → A and B + 235 x 8.5 Mev

Subtracting the two B.E. expressions

U-235 → fission products + 210 Mev

Thus fission of one U-235 nucleus releases 200 Mev energy compared to C(12) combustion releasing 4ev

Ergo, U-235 yields 2.5 million times more energy than same weight of carbon

[or, 1 lb of U-235 =1400 tons of 13,000 Btu/lb. coal]

Radioactive Decay of Uranium

$$n + {}^{235}U \rightarrow {}^{90}Kr + {}^{143}Ba + 3\,n$$

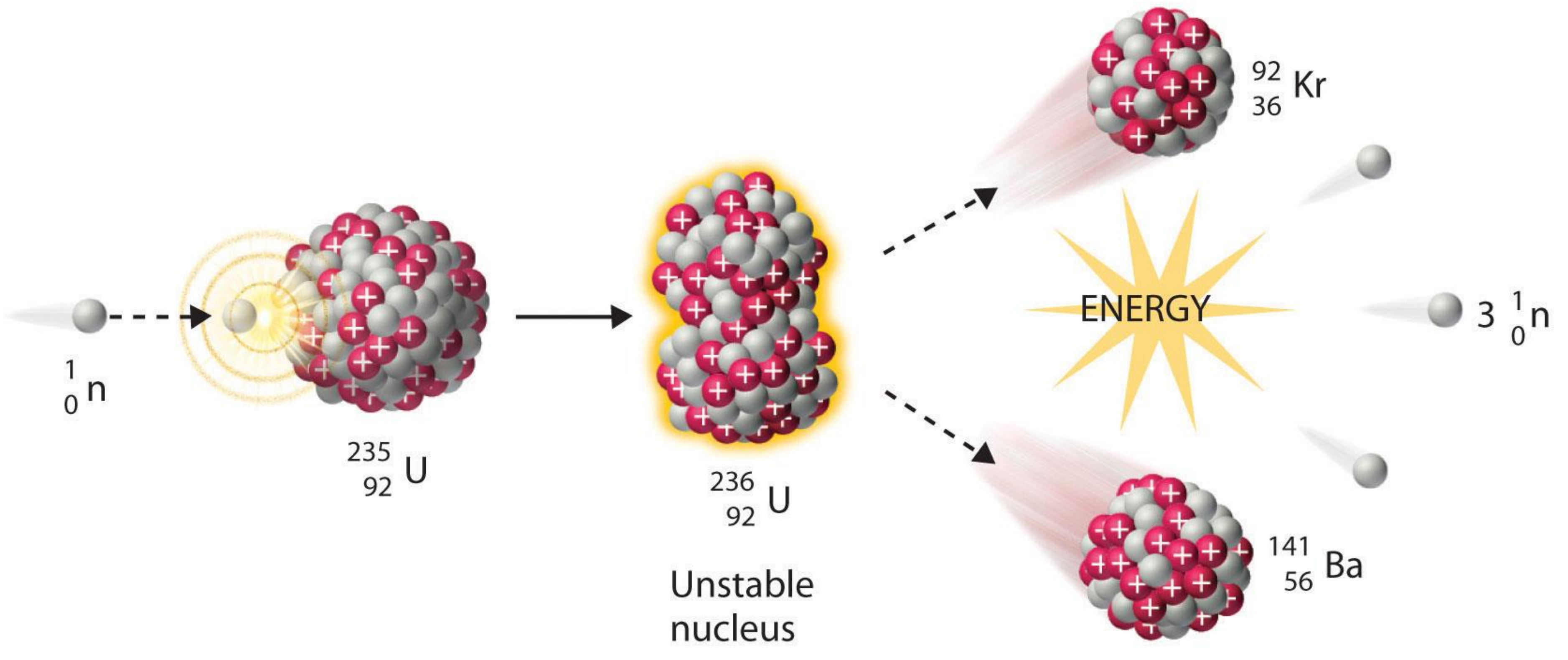
Notice that the number of nucleons on each side of the equation is equal. However, the initial and final atoms have different binding energies. Using Table 2.4 we can calculate the differences in binding energy of the two sides of the decay reaction (a free neutron has no binding energy).

Board

$$n + {}^{235}U \rightarrow {}^{90}Kr + {}^{143}Ba + 3\,n$$

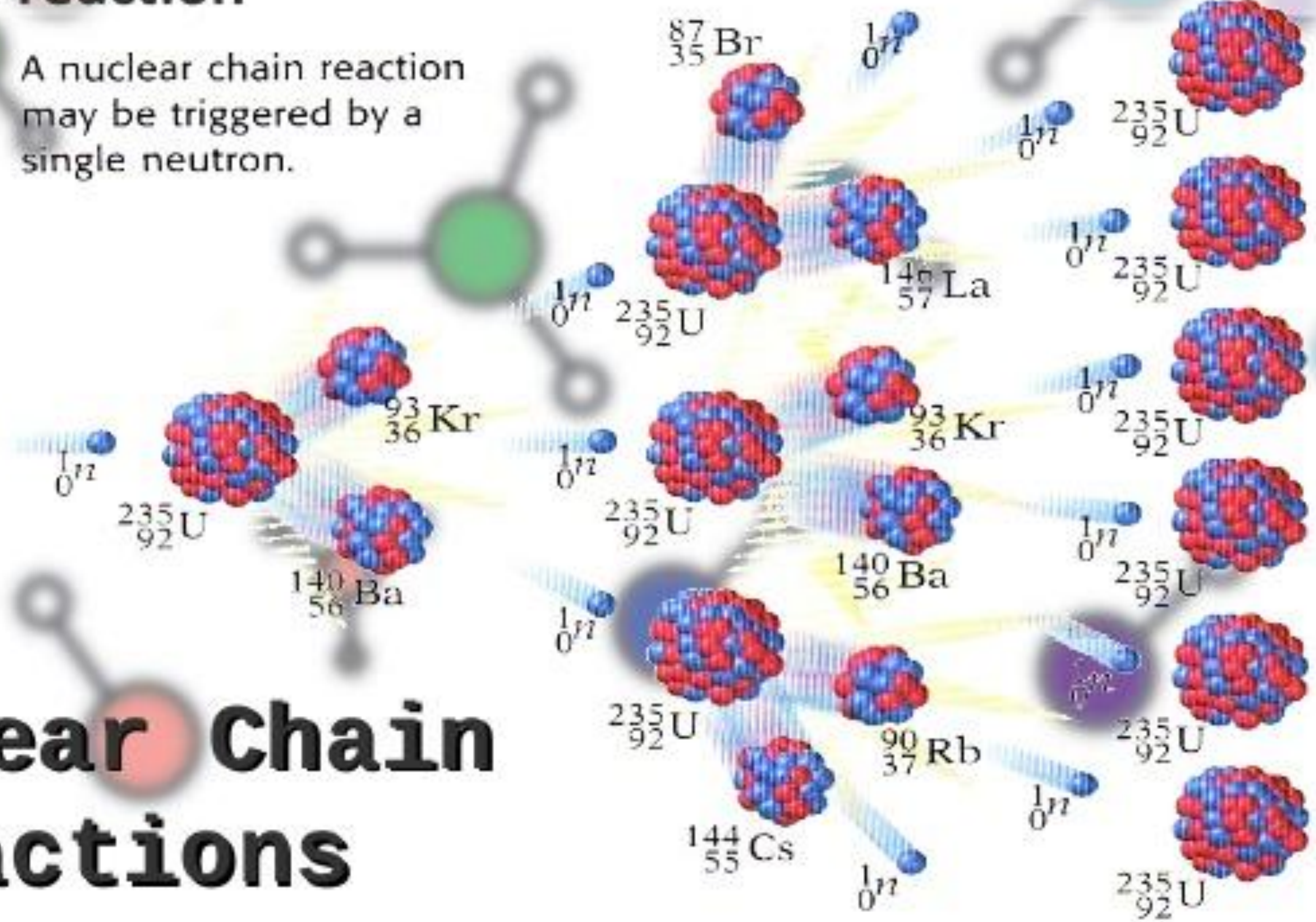
$$1793.6\ \text{MeV} \rightarrow 792\ \text{MeV} + 1201.2\ \text{MeV}$$

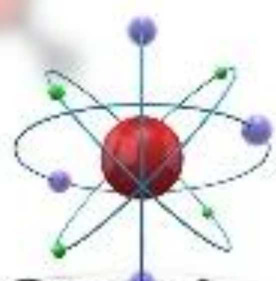
$$\rightarrow 1993.2\ \text{MeV}$$


1
0 n
235
92 U
236
92 U
Unstable
nucleus
92
36 Kr
ENERGY
3 1
0 n
141
56 Ba

Nuclear fission releases more neutrons which trigger more fission reactions

- The number of __neutrons__ released determines the success of a chain reaction





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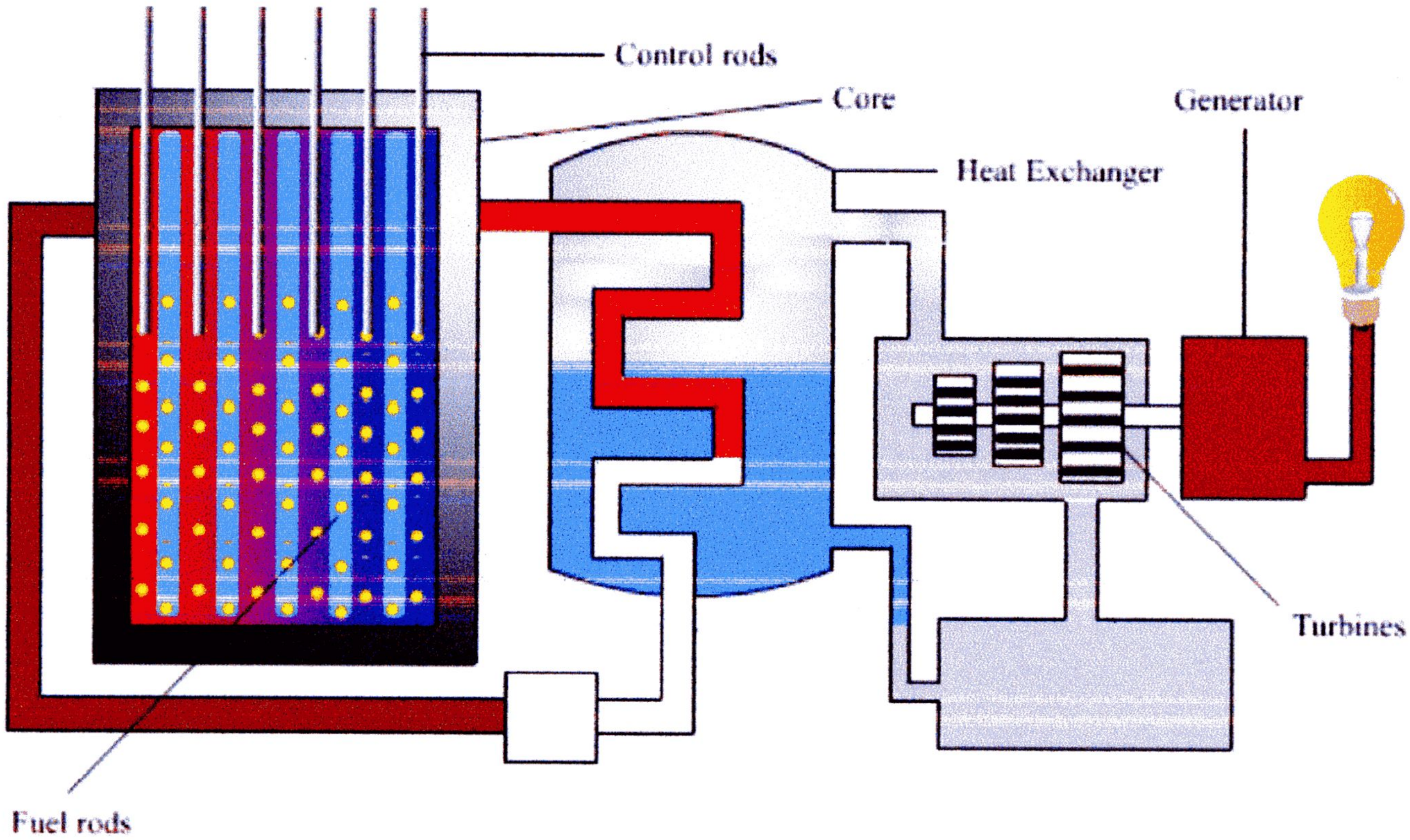
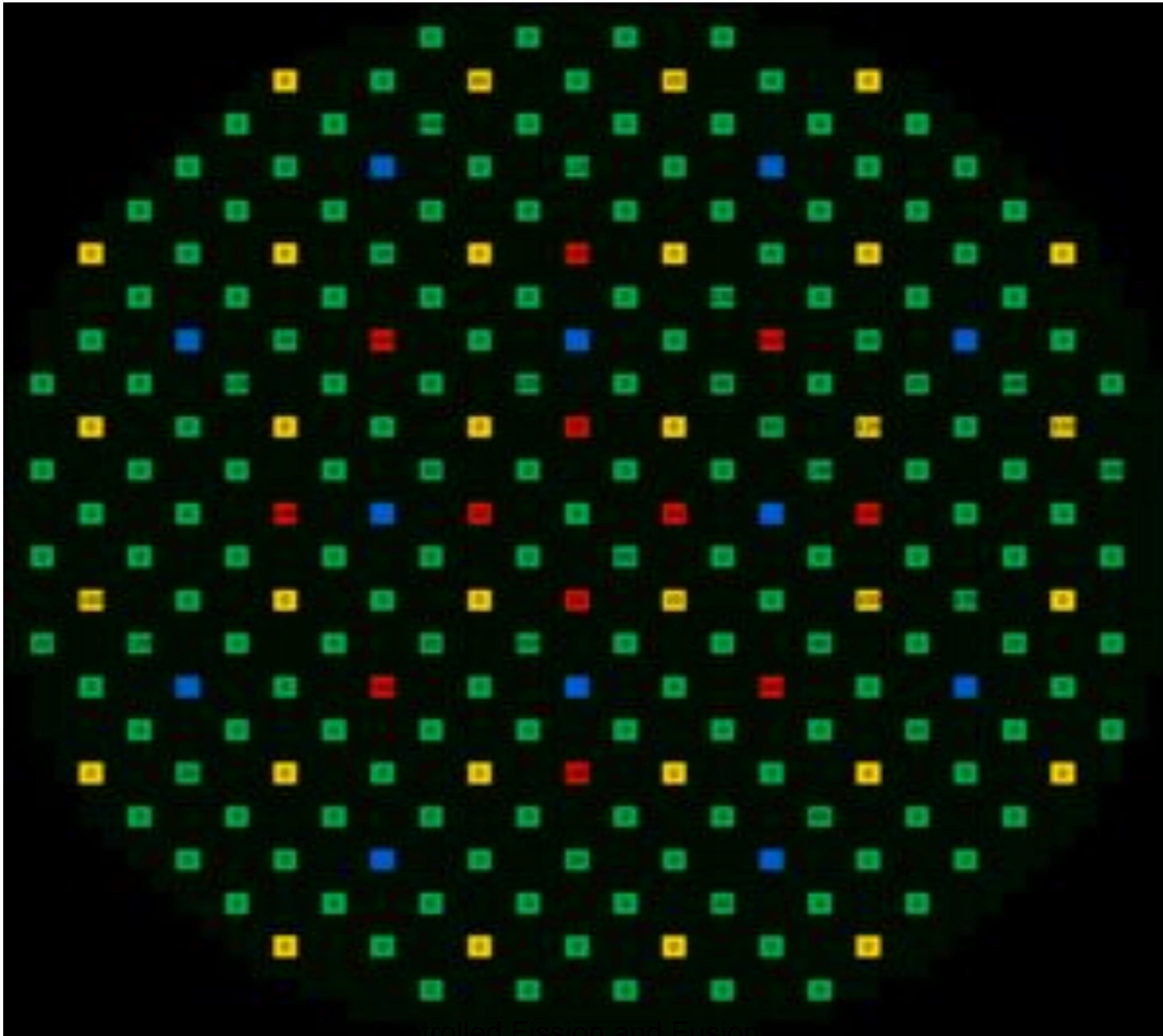
Nuclear Chain Reactions

Schematic Representation of Nuclear Reactor System



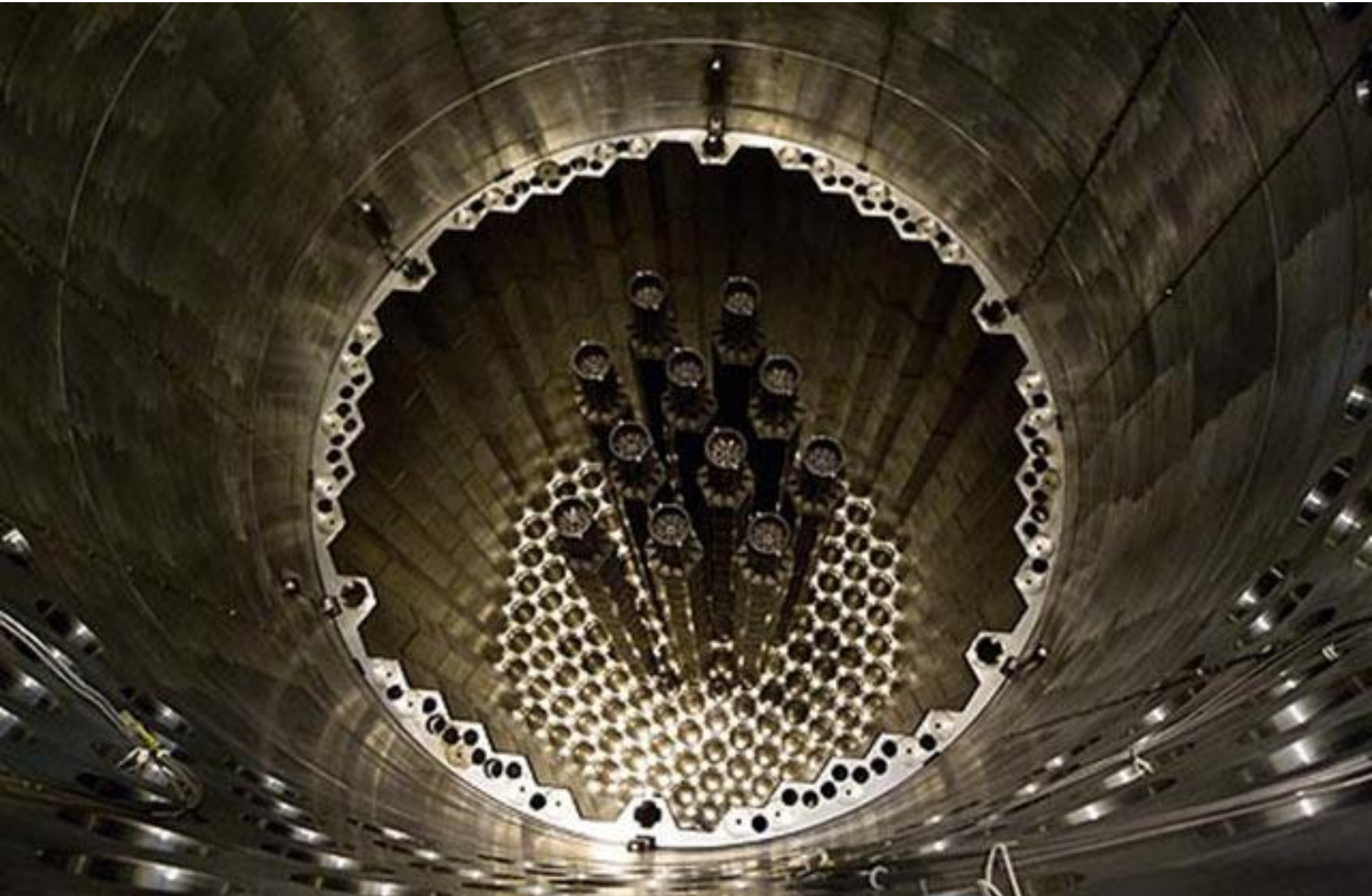


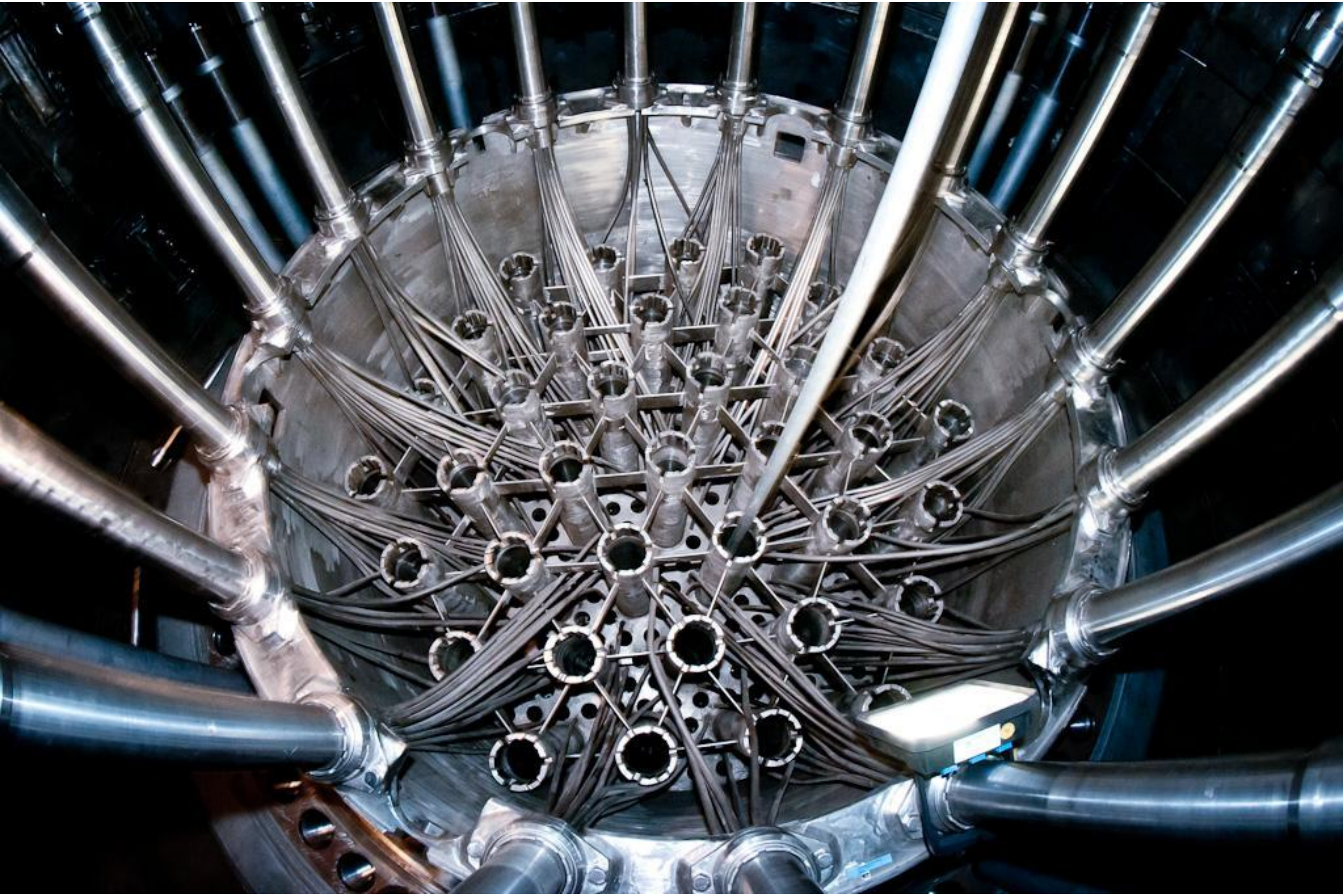
Specifics of Light water reactors - LWR

- Uranium oxide, enriched to 3-5% U-235
- Moderator and coolant, purified ordinary water; heavy water; graphite.
- Control rods: neutron absorbing-Cd, Hf, Boron
- Steam generator and Containment
- PWR – water coolant at 150 atm; heated to 325C superheated water generates steam in a second loop and operates a turbine
- BWR – boils within the core at lower pressure; piped directly to turbine generator
- LWR are re-fueled every 12-18 months, where 25% of the fuel is replaced

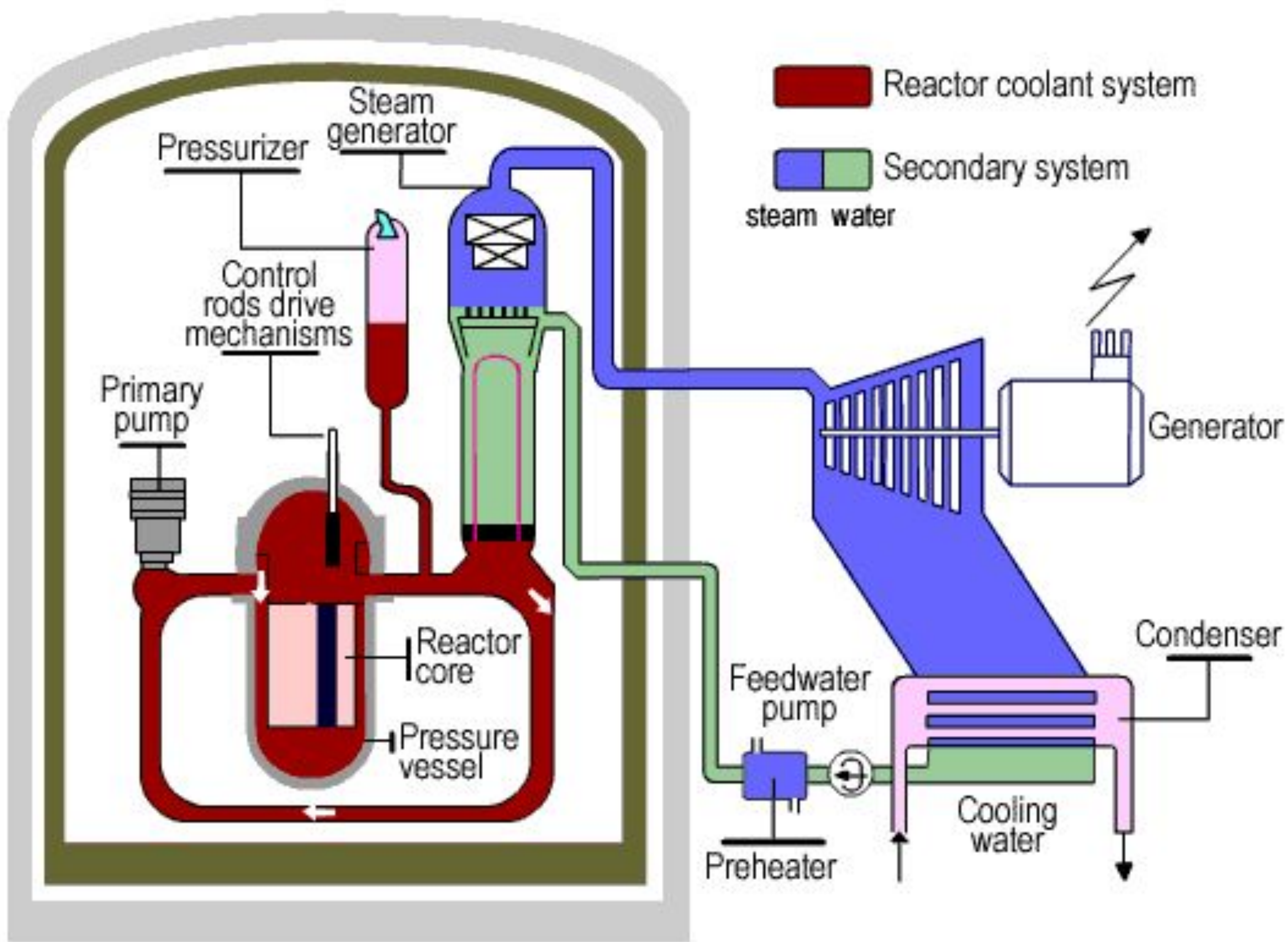
New NPP for Armenia

- 1000MWe; $5billion
- Metzamorenergatom, 50-50Russian-Armenian joint stock company; will fund 40%; 60% other investors
- VVER-1000,model V-392; 60yr life
- If 60yr life, retail price of 1 kWh < 7 cents.
- Fuel type is UO_2





PWR animation



Three types of reactors

(for others see handout)

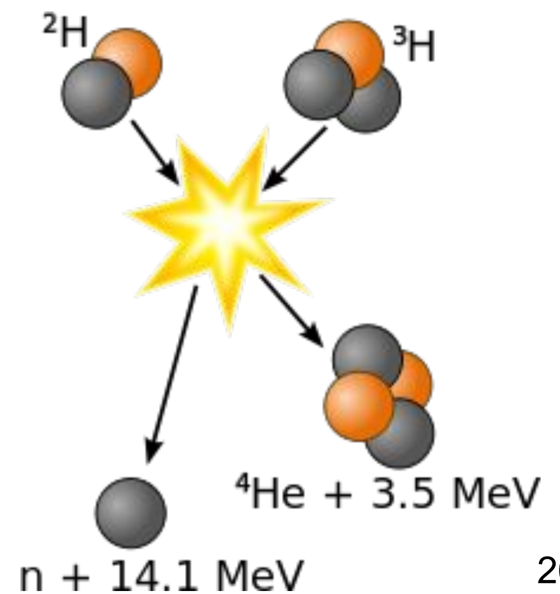
1. Light and Heavy Water Reactors
   a. LWR/PWR
   b. LWR/BWR
   (Medzamor is a PWR-VVER 440 Model)
2. Propulsion Reactors (PWR family)
   Naval vessels / submarines
3. Liquid metal Cooled Fast Breeder Reactors (LMFBR)
   Produces more fuel than it consumes
   (U-238 absorbs neutrons and converts it to PU-239)
   Molten metal is the coolant liquid

TABLE 13.1. PLANT PARAMETERS

Reactor	Primary Coolant Conditions		Steam Conditions		Cycle Efficiency (Per cent)		Core Power Density (kw/liter)		Fuel Material		Average Fuel Exposure (Mw-days/tonne)	
	Current	Potential	Current	Potential	Current	Potential	Current	Potential	Current	Potential	Current	Potential
Pressurized water	2000 psia subcooled	2000 psia bulk boiling	600 psia (sat.)	1000 psia (sat.)	28	30	55	80	UO_2	UO_2	13,000	19,000
Boiling water	1000 psia (sat.) dual cycle	1400 psia (sat.) direct cycle	1000 psia (sat.)	1400 psia (sat.)	29	30	30	50	UO_2	UO_2	11,000	19,000
Superheat		1400 psia 1000°F		1400 psia 1000°F		38		50		UO_2		19,000
Organic cooled	120 psia 575°F	300 psia 725°F	600 psia 550°F	1000 psia 700°F	29	34	20	44	U-3½% Mo	UO_2	4500	19,000
Sodium-graphite	30 psia 900°F	30 psia 950°F	800 psia 850°F	2400 psia 1000°F	34	41	5	8	U-10% Mo	UC	11,000	19,000
Fast breeder	30 psia 900°F	30 psia 900°F	800 psia 850°F	800 psia 850°F	34	34	850	850	U-10% Mo	PuO_2	1½ w/o	50,000
Heavy water	750 psia subcooled	800 psia boiling dir. cycle	150 psia (sat.)	750 psia (sat.)	23	26	26	35	Nat U		3960	7000
Gas cooled (natural uranium)			500 psia 650°F		24		0.75		Nat U		3000	
Gas cooled (enriched fuel)	300 psia 1050°F	400 psia 1200°F	950 psia 950°F	950 psia 950°F	33	33	0.75	1.28	UO_2	UO_2	10,000	18,000

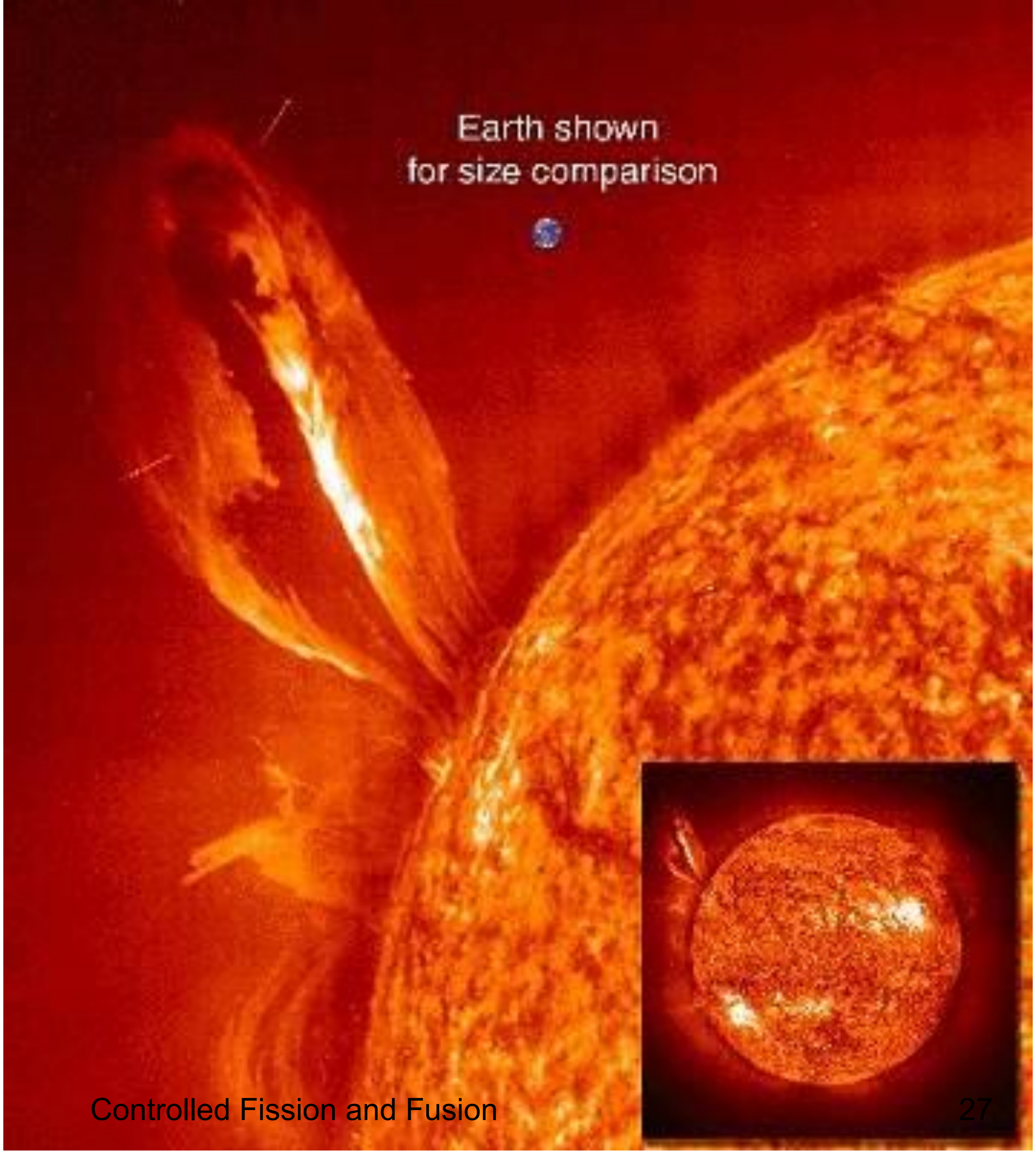
Fusion

- Merging of nuclei = Fusing nuclei together

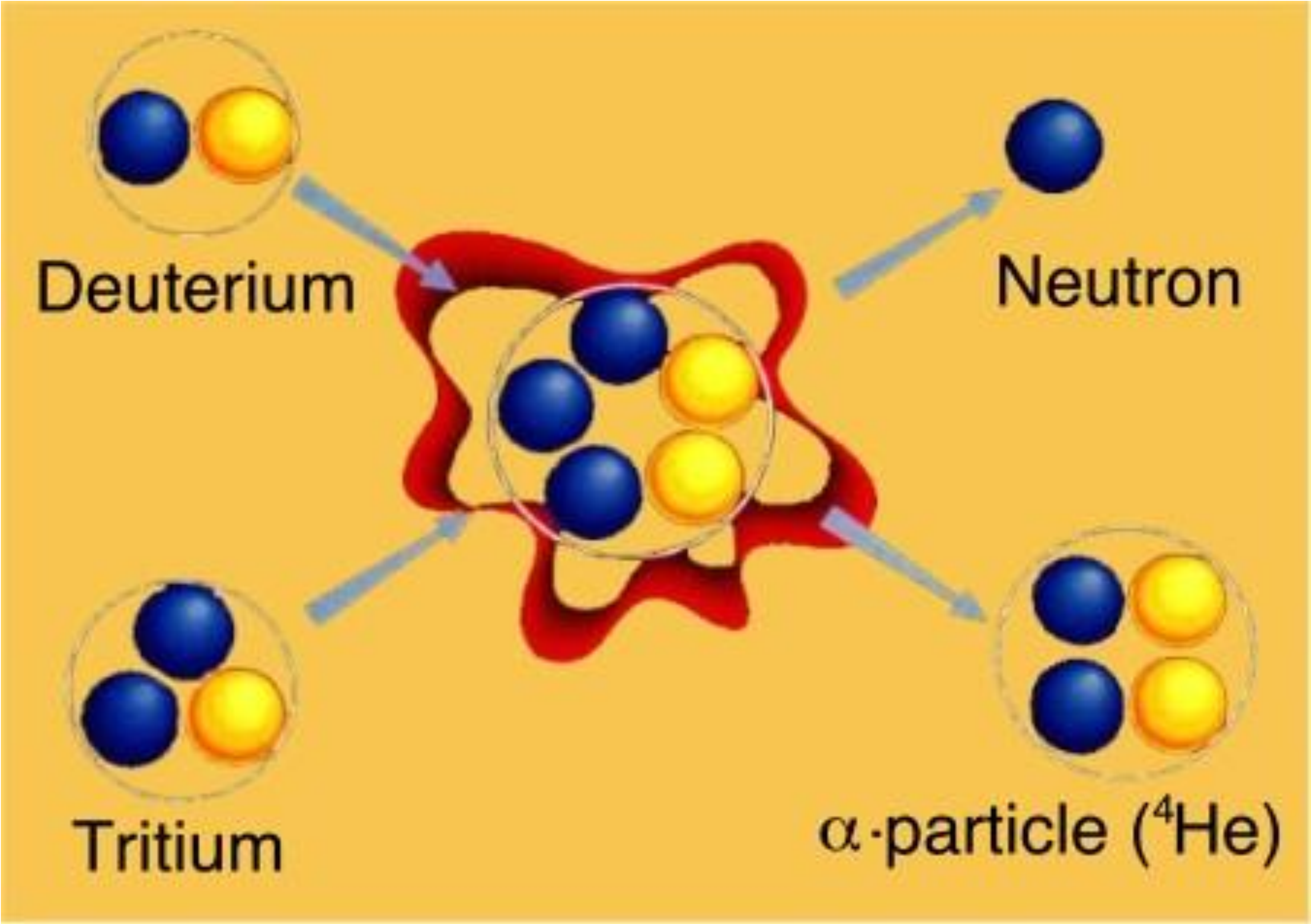


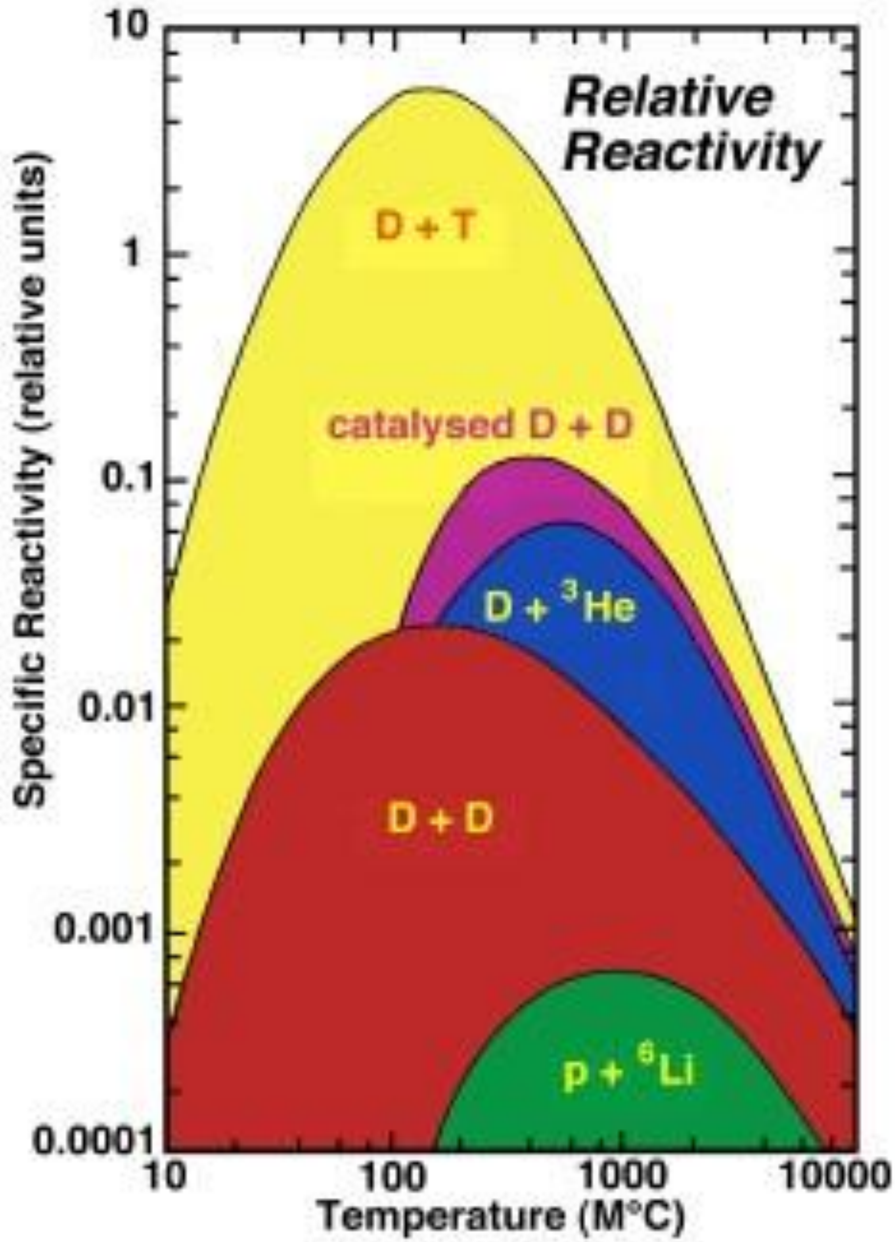
"God's version of a fusion reactor"

165,000 TW of sunlight hit the earth every day



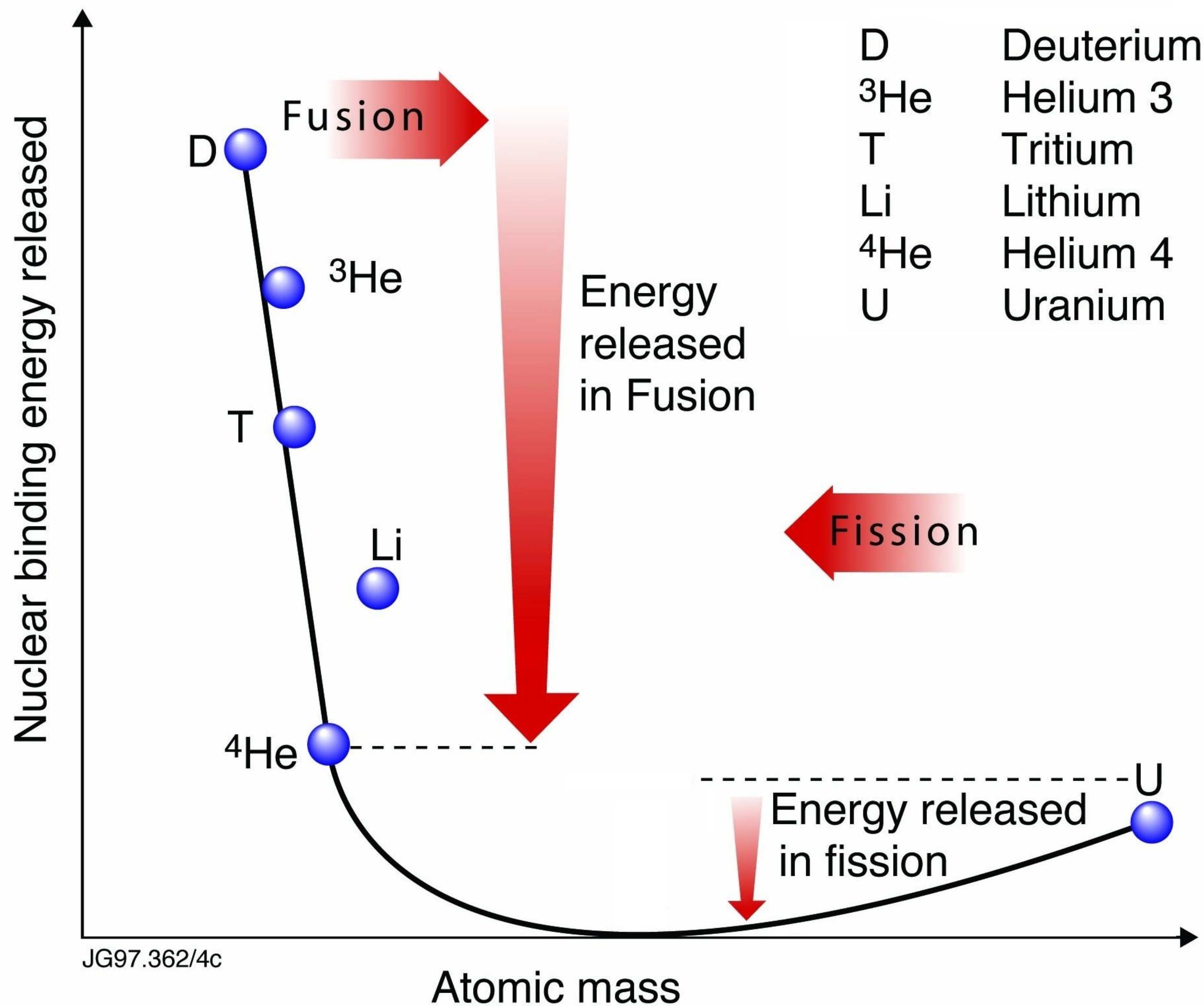
Controlled Fusion





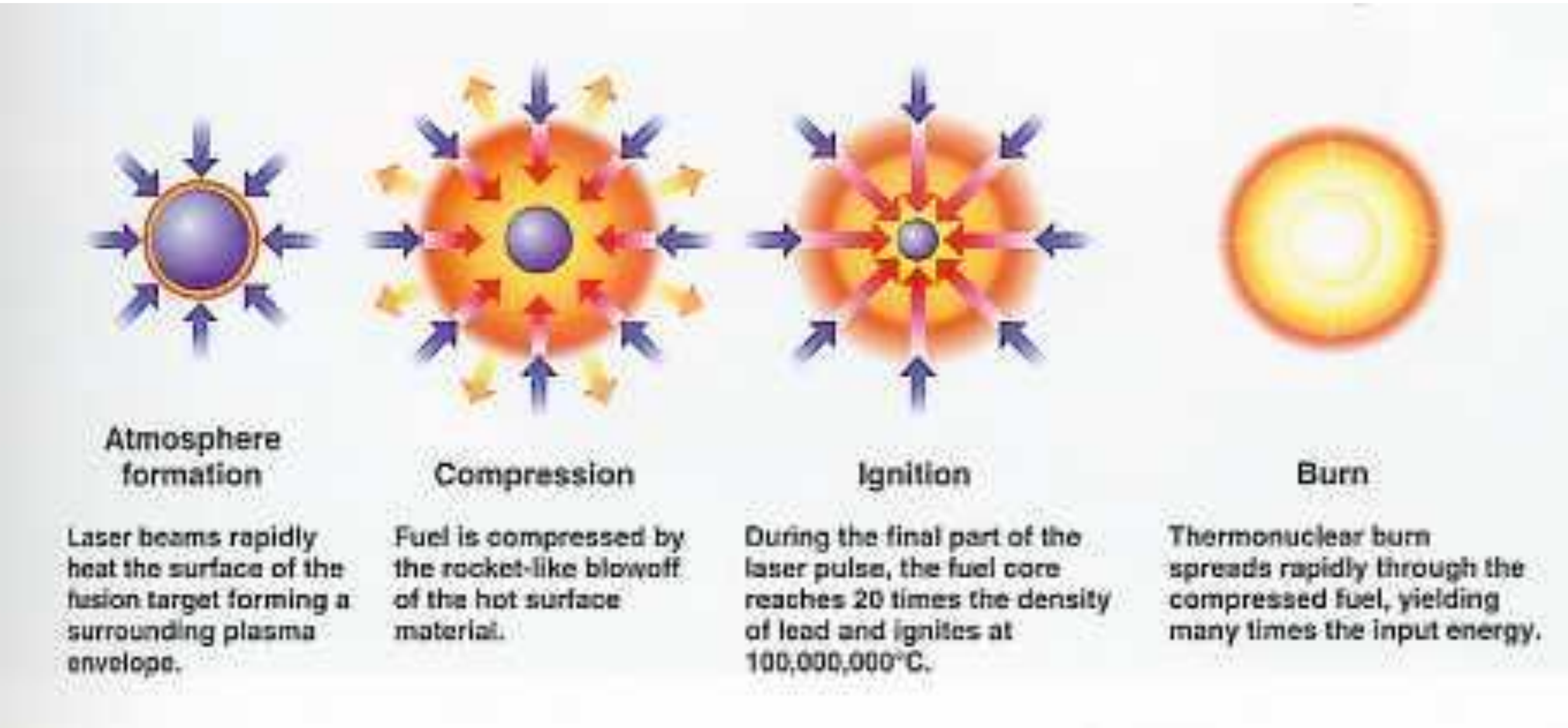
*Net Power = Efficiency * (Fusion - Radiation Loss - Conduction Loss)*

- *Net Power* is the net power for any fusion power station.
- *Efficiency* how much energy is needed to drive the device and how well it collects power.
- *Fusion* is rate of energy generated by the fusion reactions.
- *Radiation* is the energy lost as light, leaving the plasma.
- *Conduction* is the energy lost, as momentum leaves the plasma.

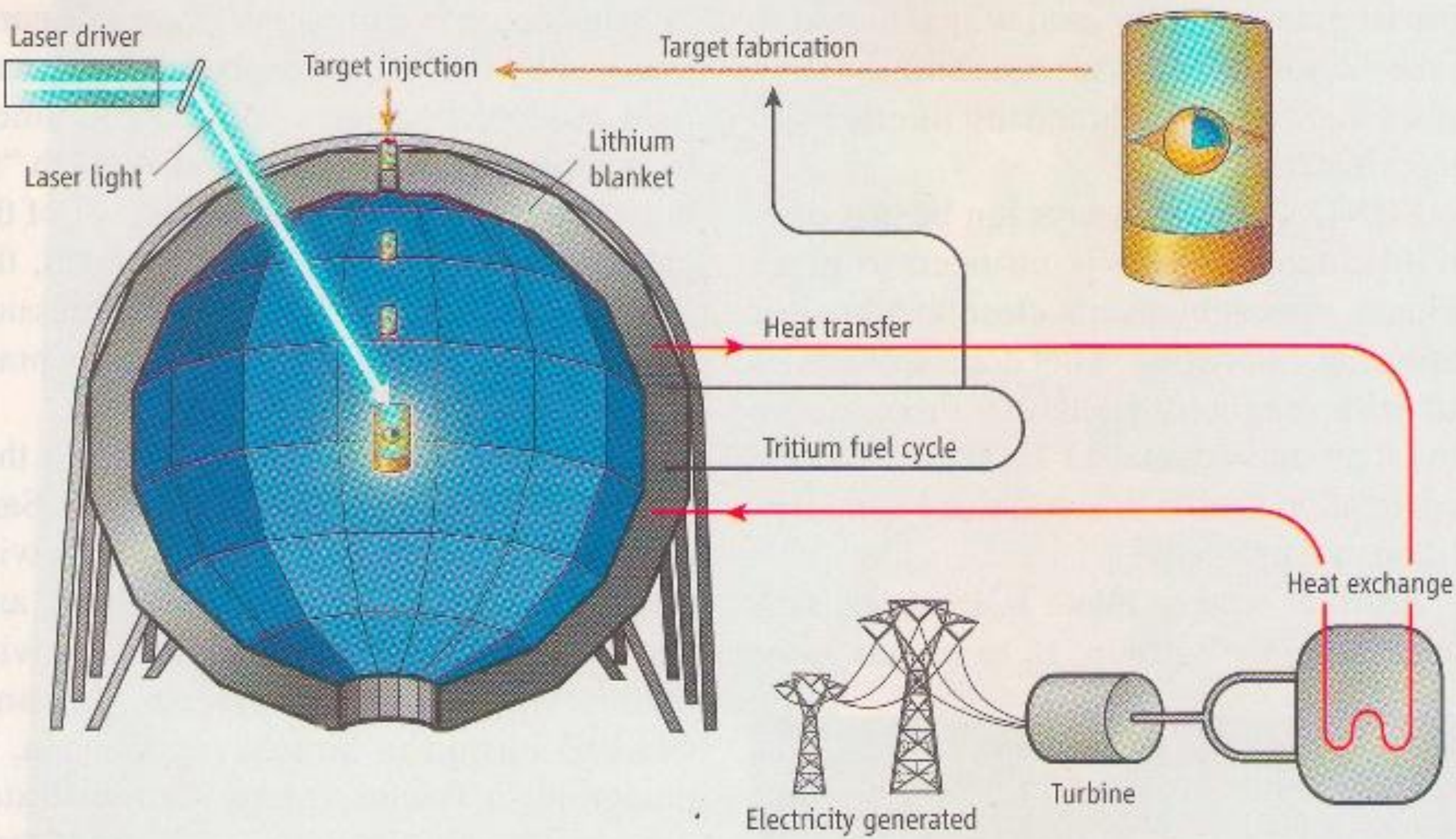


D Deuterium
3He Helium 3
T Tritium
Li Lithium
4He Helium 4
U Uranium
Fusion
Fission
D
3He
T
Li
4He
U
Energy released in Fusion
Energy released in fission
Nuclear binding energy released
Atomic mass
JG97.362/4c

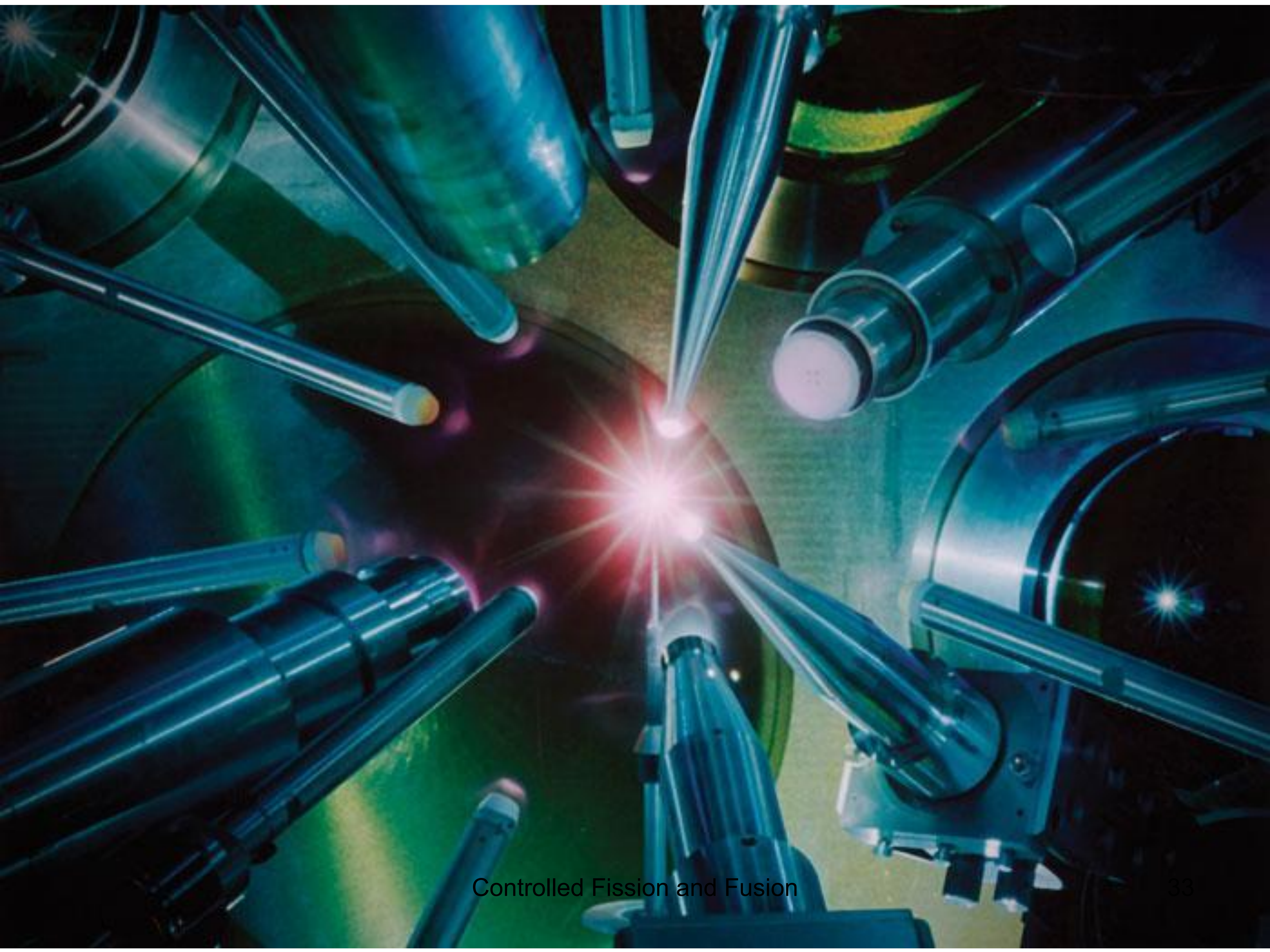
Inertial Confinement



KEY ELEMENTS OF AN INERTIAL CONFINEMENT FUSION POWER PLANT

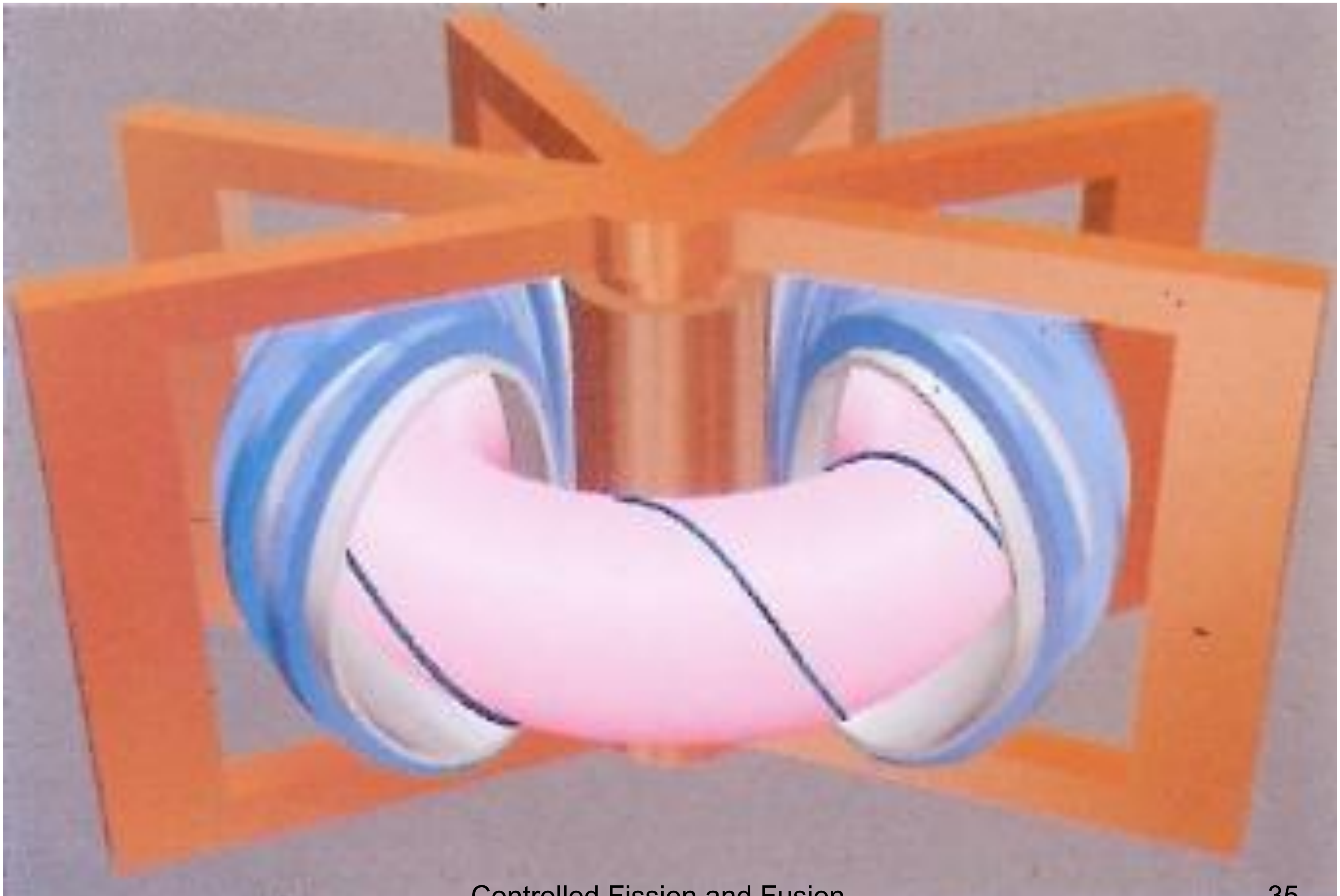


Rapid fire. Any inertial fusion plant will need a driver, such as lasers; a large chamber to absorb the heat from neutrons with a lithium blanket to breed tritium fuel; and a way to make targets and drop them into place. Each component poses technical challenges.

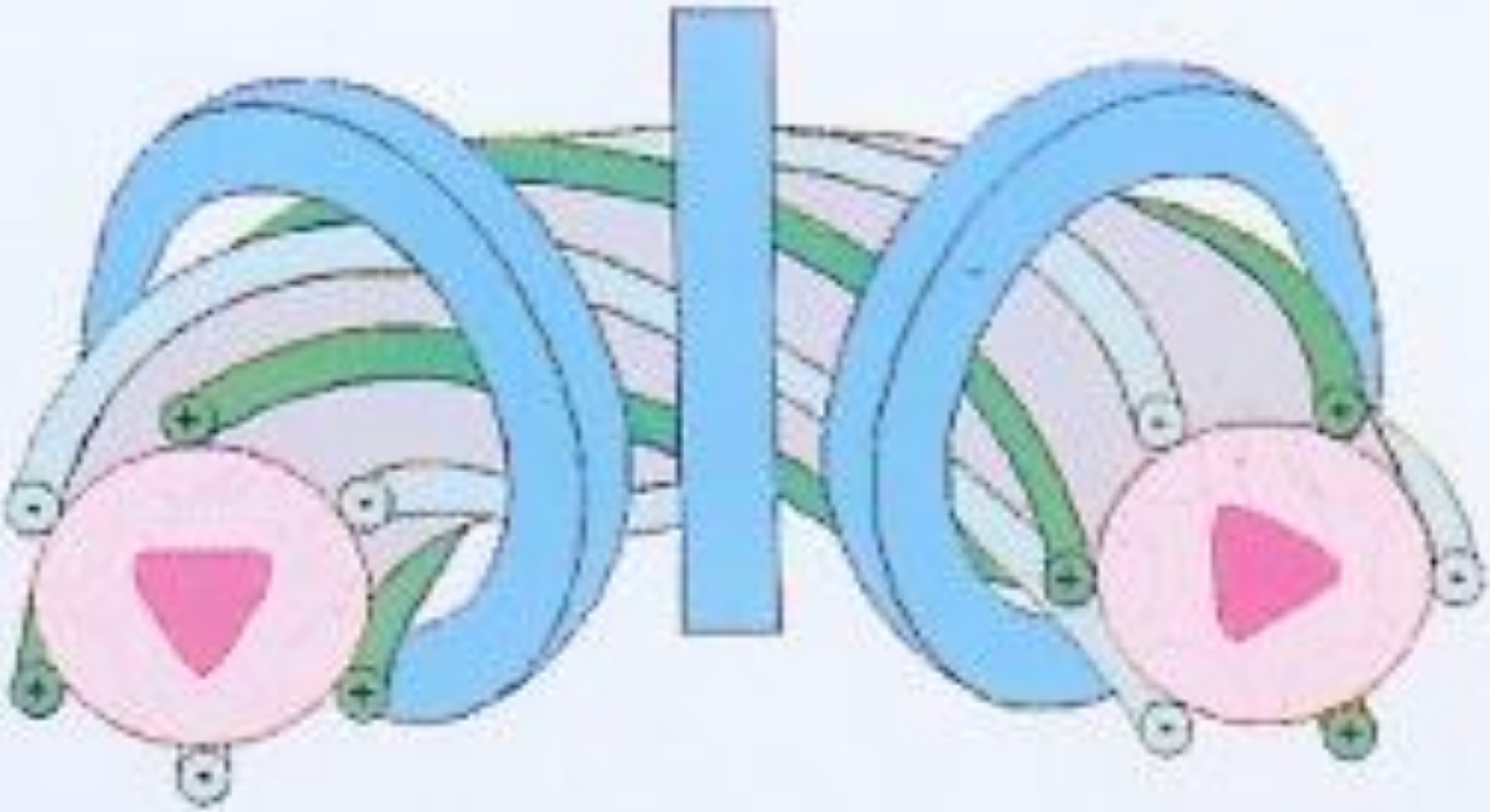


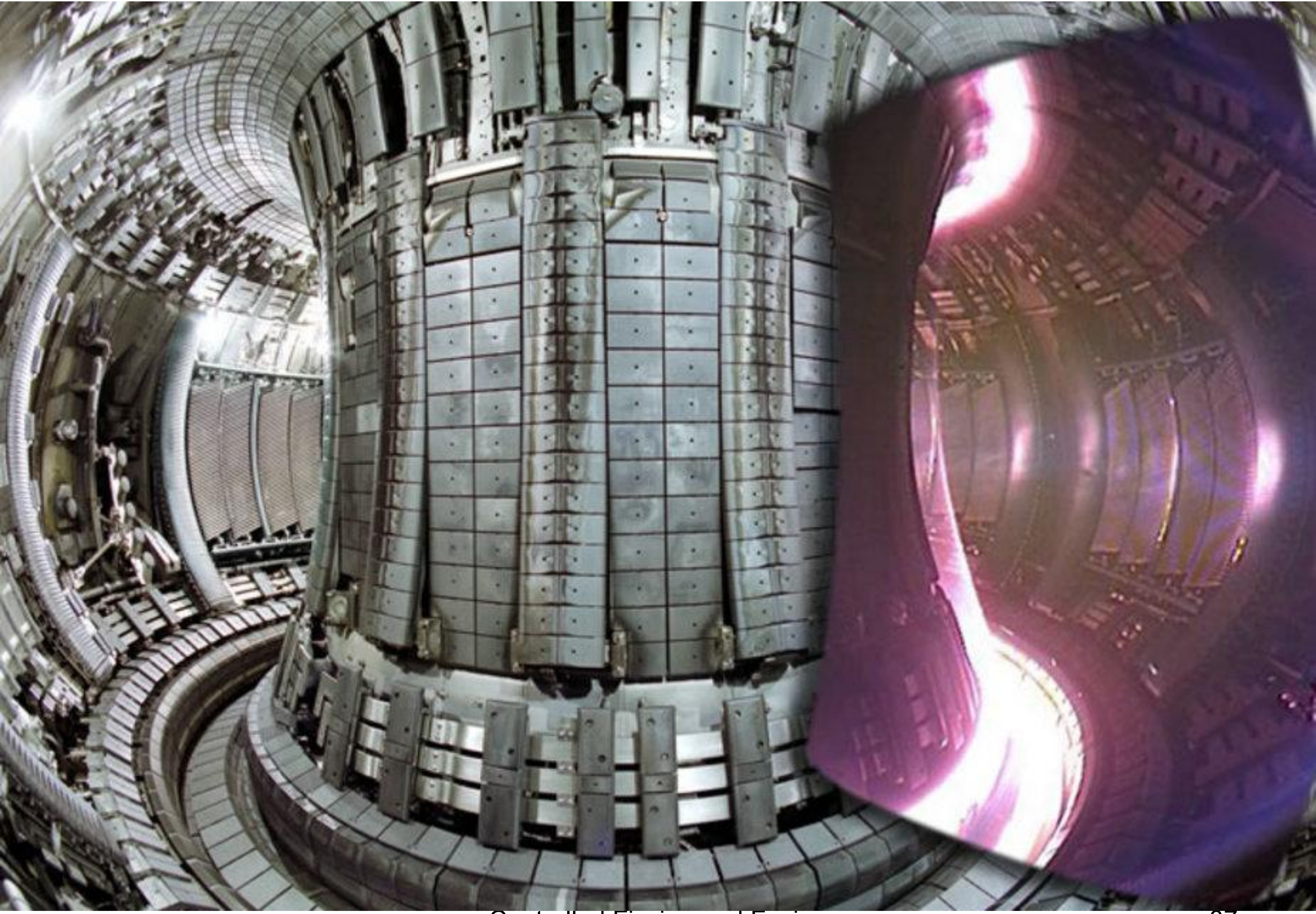
Nova Laser Bay

Magnetic confinement: Tokamak (Stellerator)

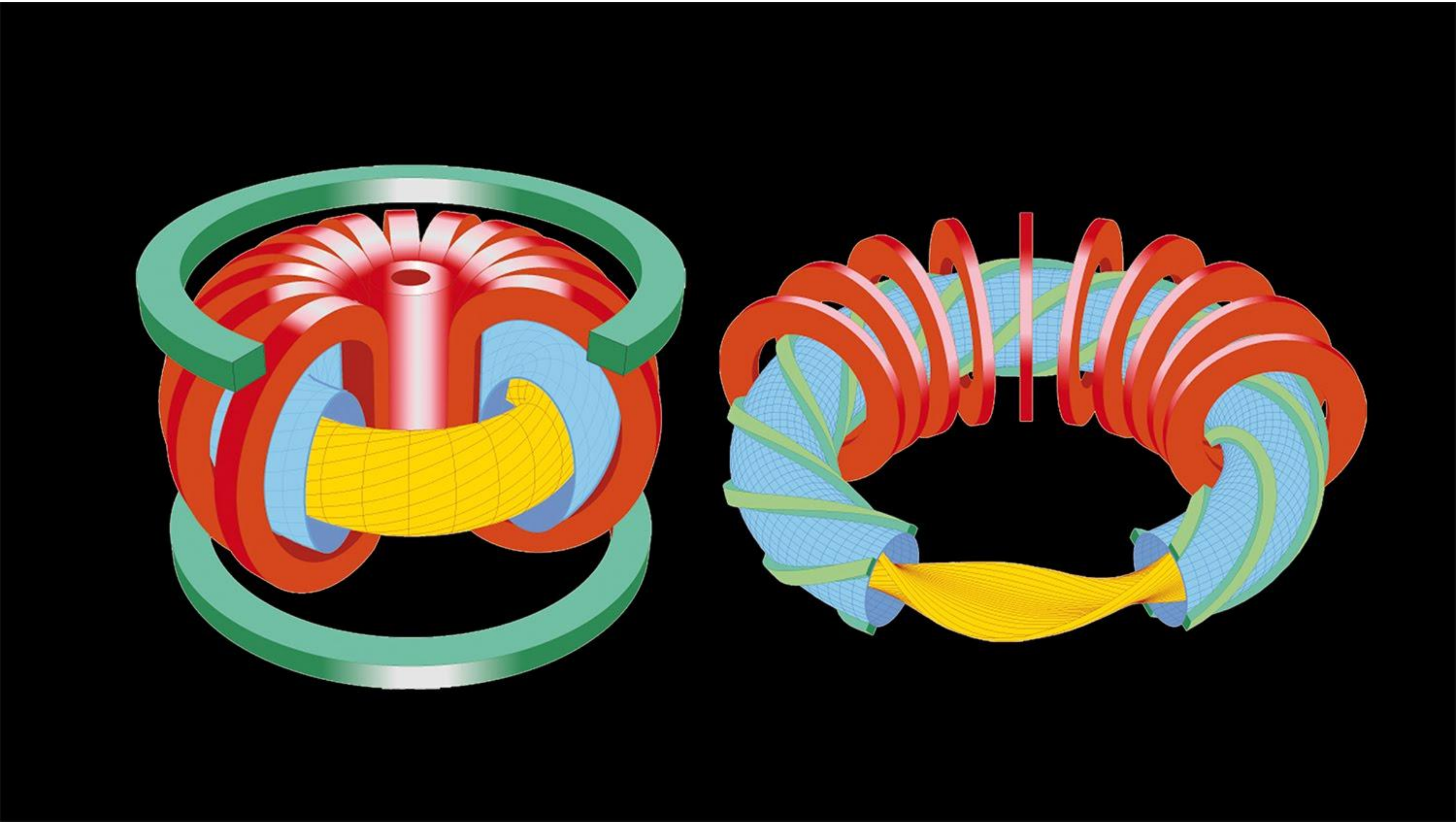


Alcator (MIT)





Magnetic confinement



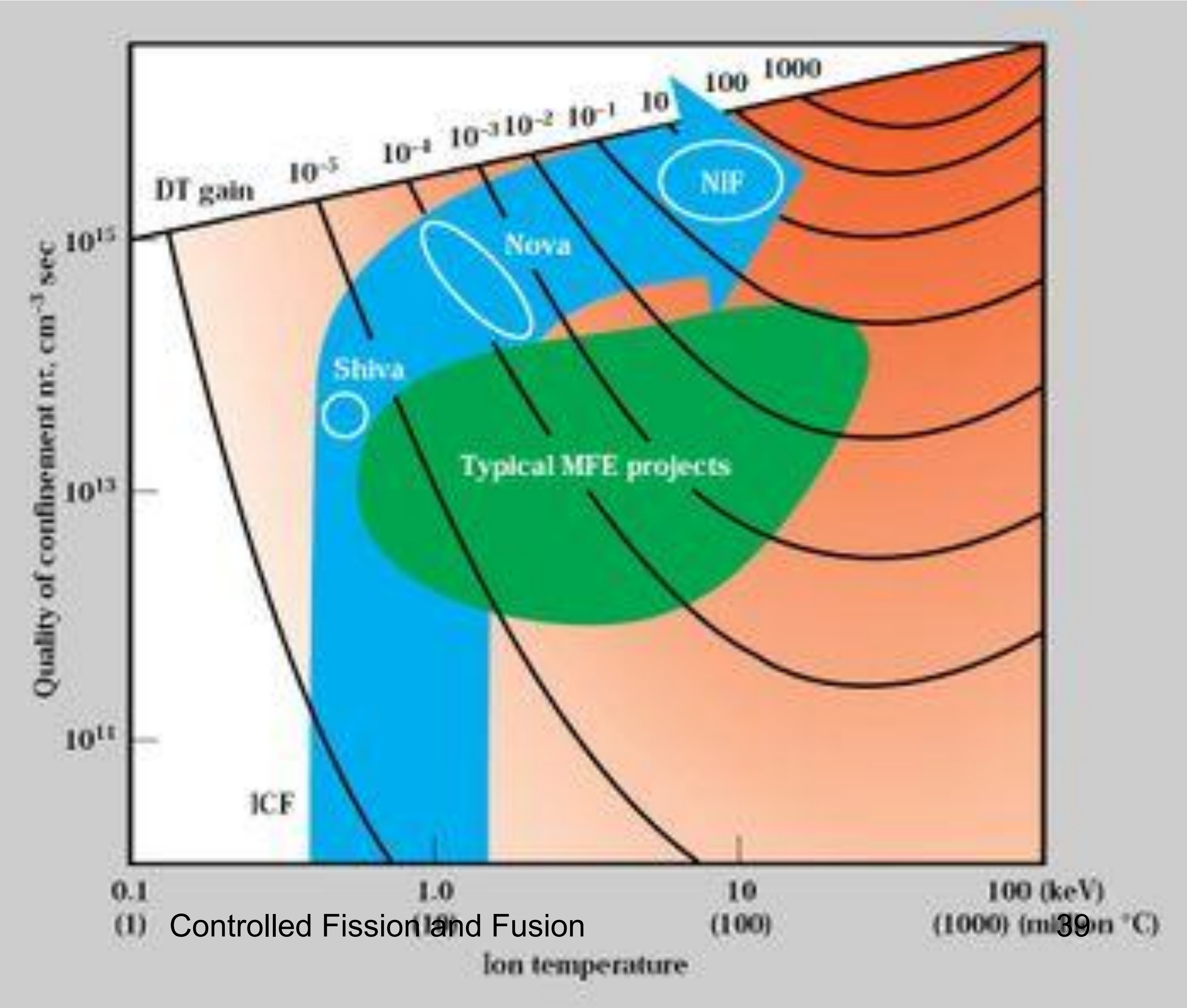
Parameter Space occupied by Inertial/Magnetic Fusion Energy Devices

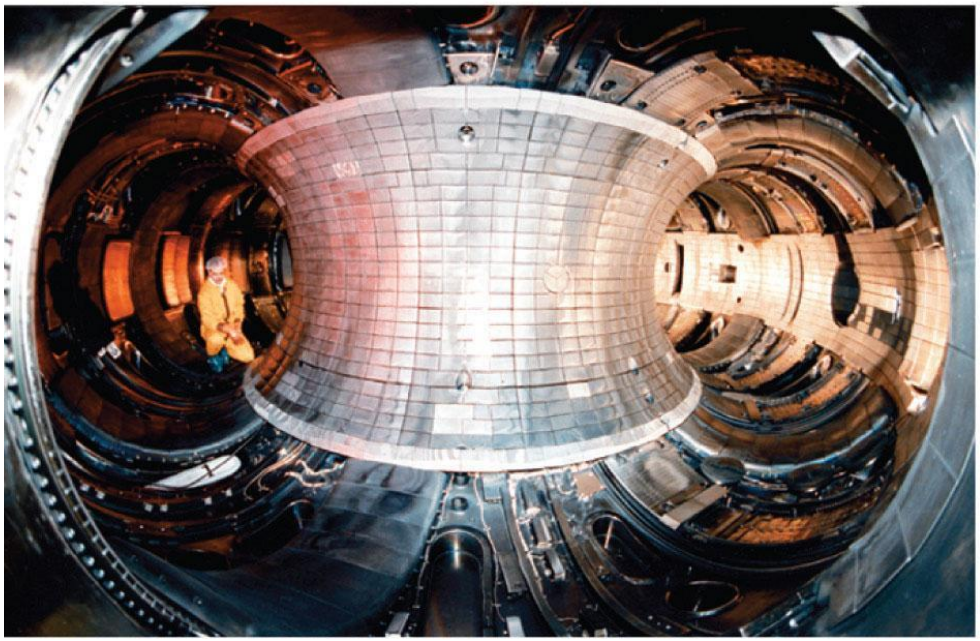
$n\tau > 10^{14}$

Lawson criterion.

n - plasma (electron) density

τ – confinement time





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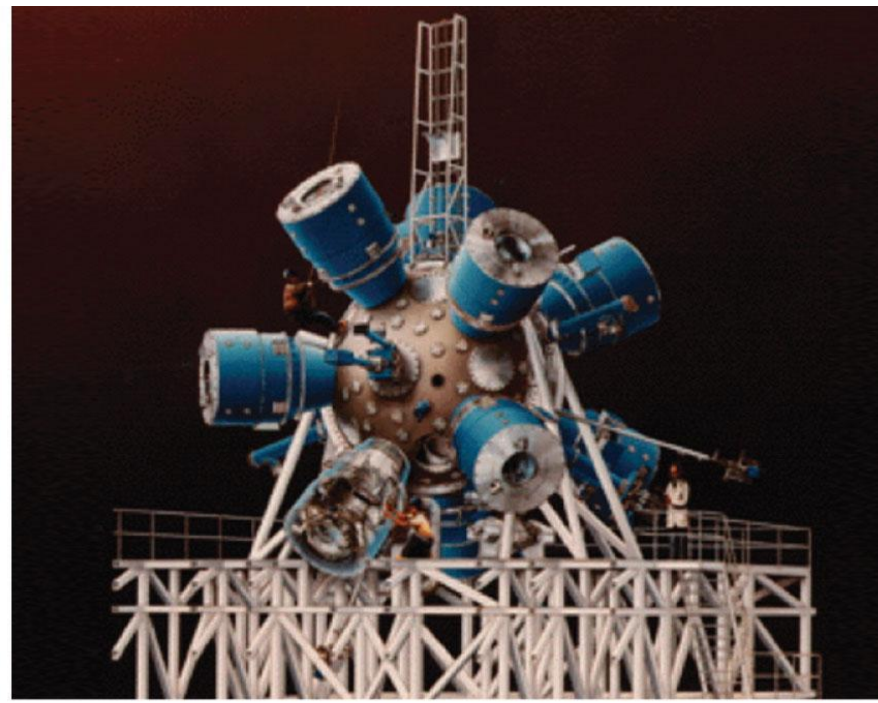


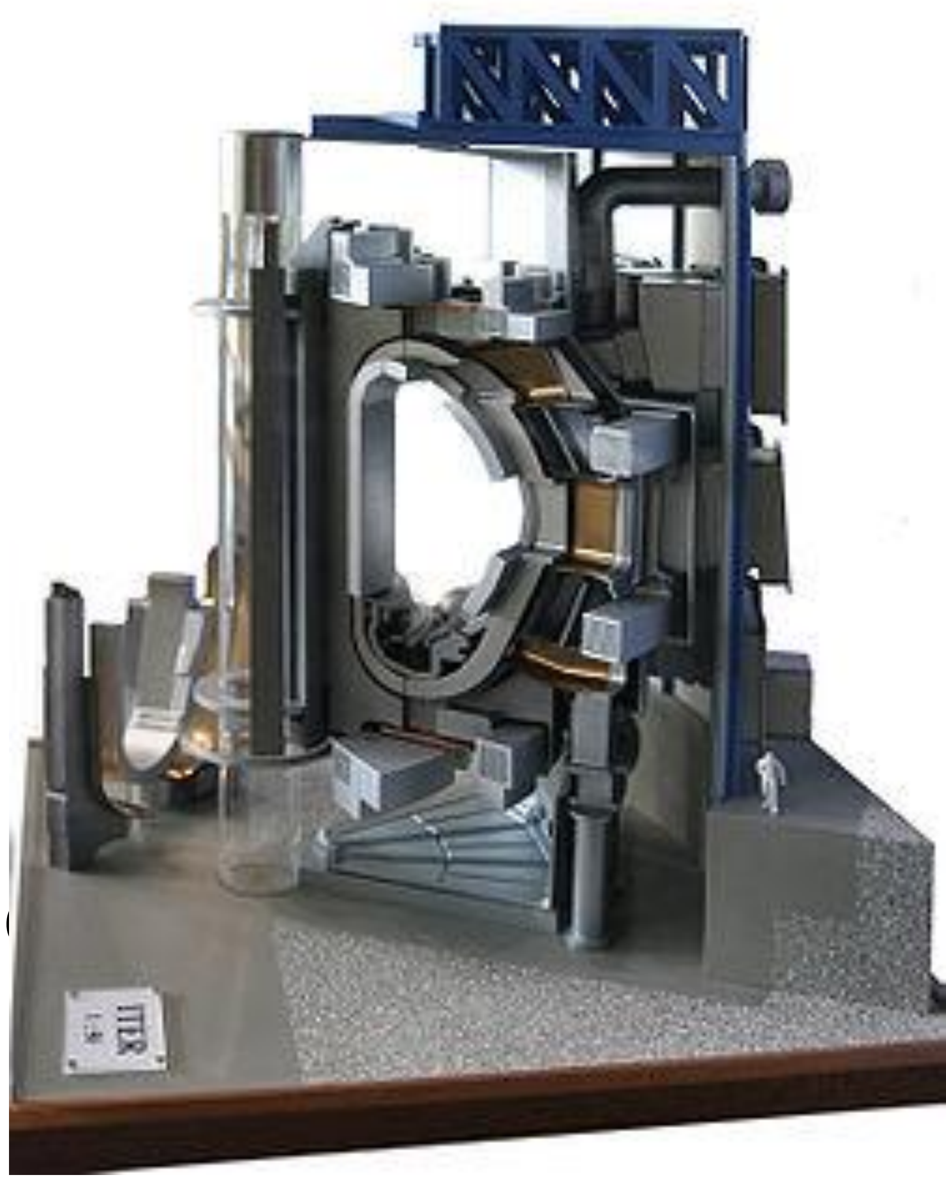
(b)

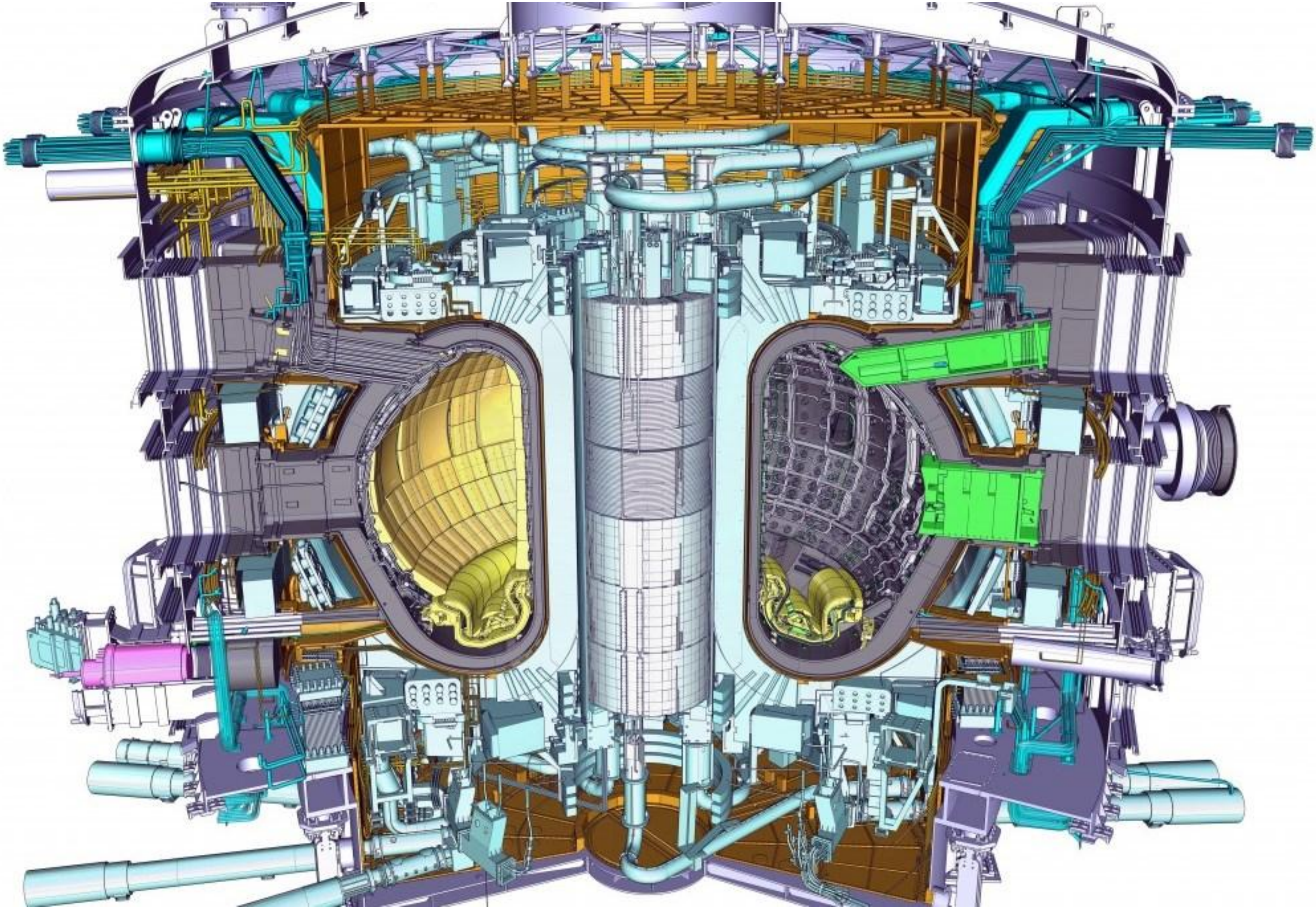
Confinement Concepts

- **Equilibrium:** There must be no net forces on any part of the plasma, otherwise it will rapidly disassemble. The exception, of course, is inertial confinement, where the relevant physics must occur faster than the disassembly time.
- **Stability:** The plasma must be so constructed that small deviations are restored to the initial state, otherwise some unavoidable disturbance will occur and grow exponentially until the plasma is destroyed.
- **Transport:** The loss of particles and heat in all channels must be sufficiently slow. The word “confinement” is often used in the restricted sense of “energy confinement”.

ITER

- **International Thermonuclear Experimental Reactor**, and is also Latin for "the way")
- Cadarache facility in Saint-Paul-lès-Duran e, south of France





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