Nuclear Fuel Cycle.
Types of Commercial Nuclear Reactors.

SPG course MJ2405

Miro Petrov

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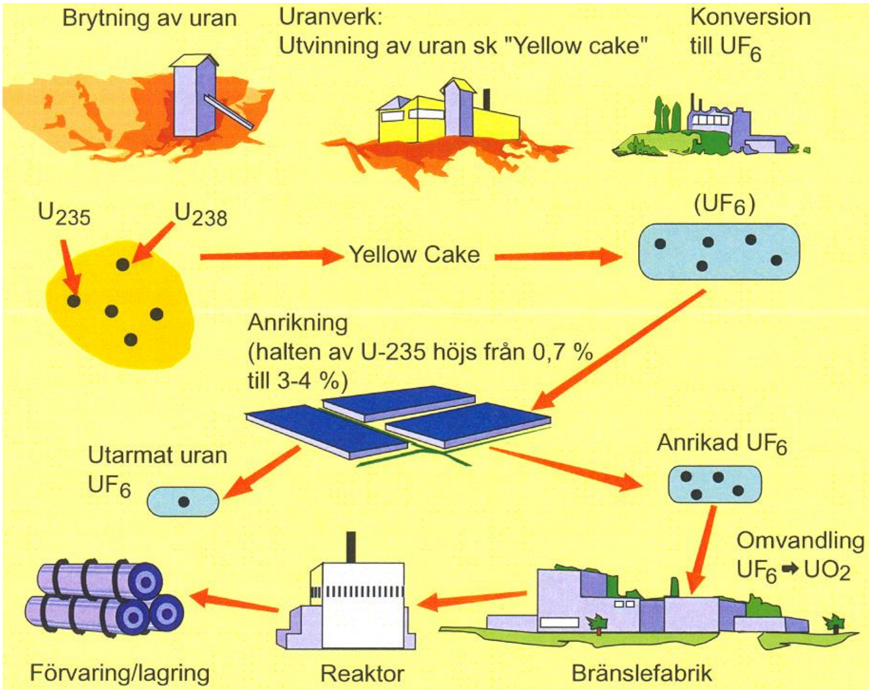

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Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.01																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.30											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 30.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (97.91)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (208.98)	85 At (209.99)	86 Rn (222.02)
87 Fr (223.02)	88 Ra (226.03)	89 Ac (227.03)	104 Rf (261.11)	105 Ha (262.11)	106 Sg (263.12)												

Rare Earth Elements:

Lanthanides →	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (144.91)	62 Sm 150.36	63 Eu 151.97	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinides →	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237.05)	94 Pu (244.06)	95 Am (243.06)	96 Cm (247.07)	97 Bk (247.07)	98 Cf (251.08)	99 Es (252.08)	100 Fm (257.10)	101 Md (258.10)	102 No (259.10)	103 Lr (262.11)

Uranium atom

Existing in nature in several isotopes, some of them more fissile than the others

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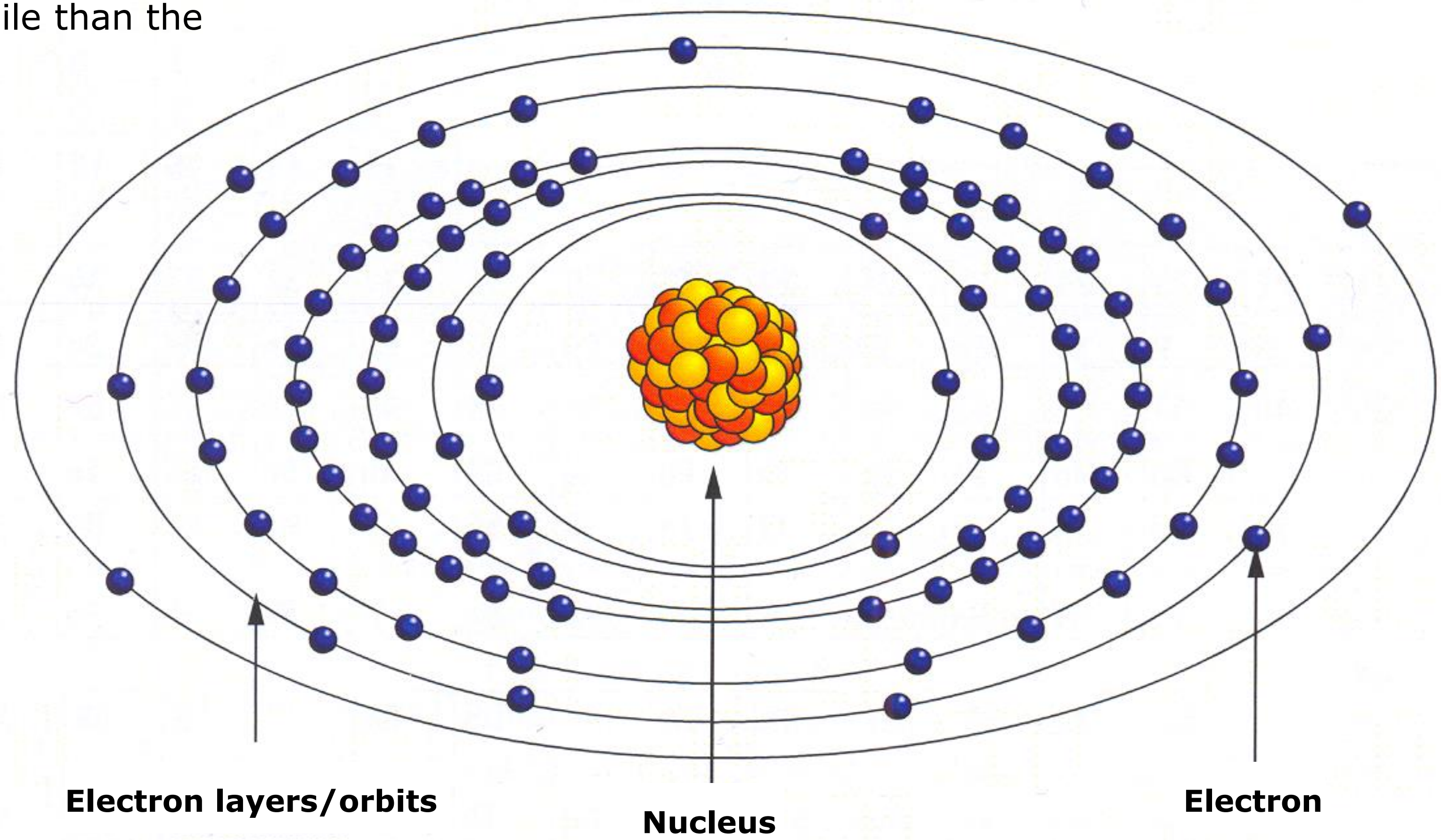

Uranium element

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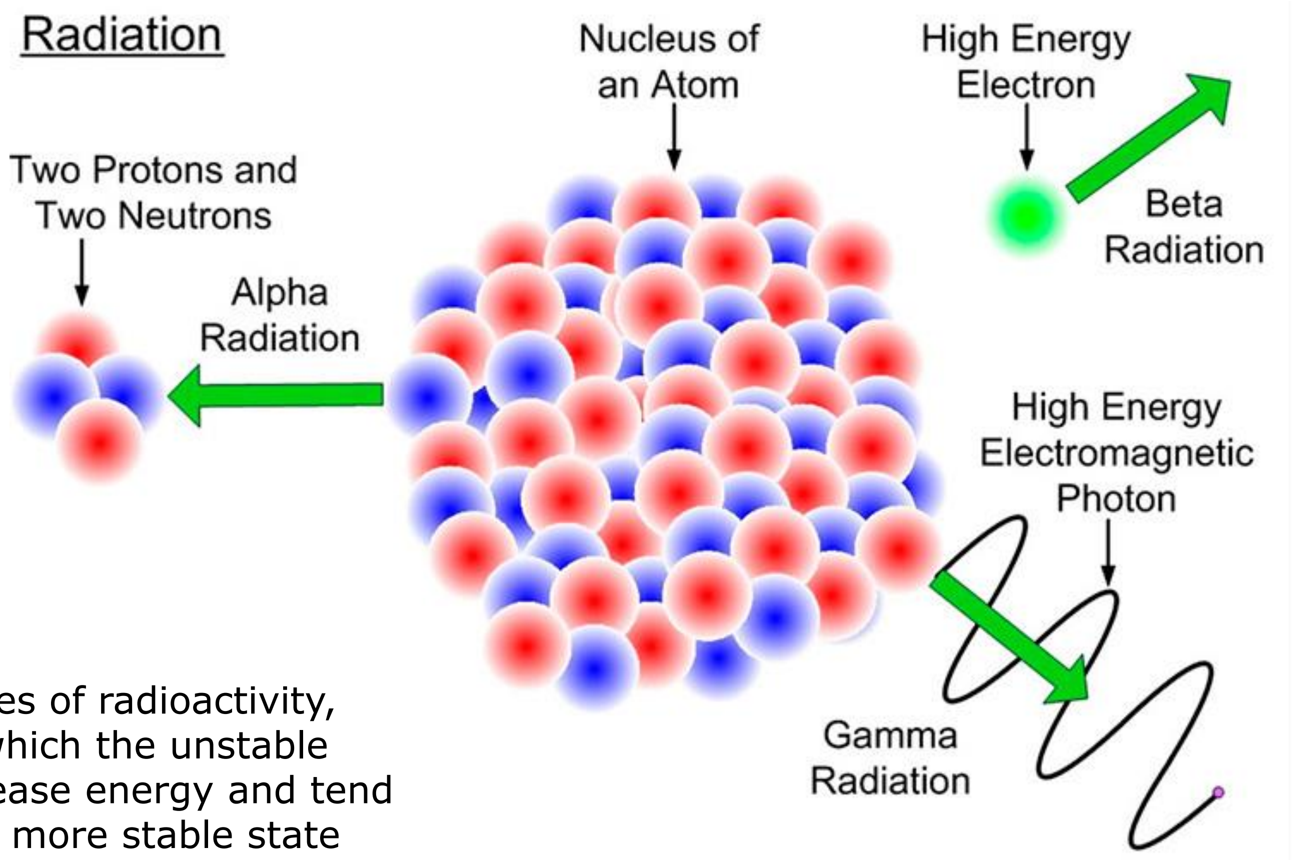
- $_{92}U^{238}$
- Found as a mixture of U-238 (99.29%) and U-235 (0.71%), with very small amounts also of U-234.
- Available more or less everywhere on our planet, both in crystalline rocks (Earth's crust) and in the ocean.
- About 500 times more common than gold!
- Melting point for pure Uranium: 1132 ^{o}C
- Silvery-white metallic appearance
- U-238 has a half-life of $4.51*10^{9}$ years
- Not particularly radioactive on its own, but a source of natural radioactivity via its decay products' chain (e.g. radon)

Radioactive Decay



Three types of radioactivity, through which the unstable nuclei release energy and tend towards a more stable state

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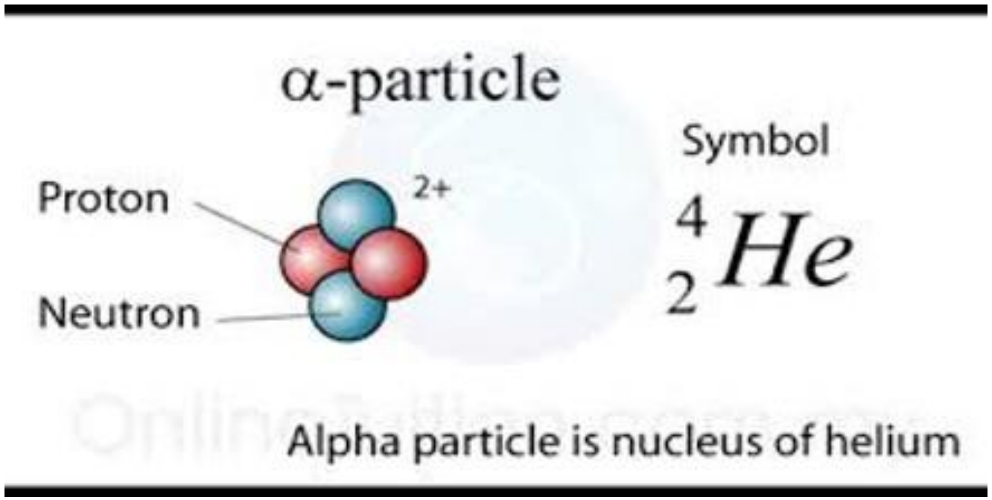
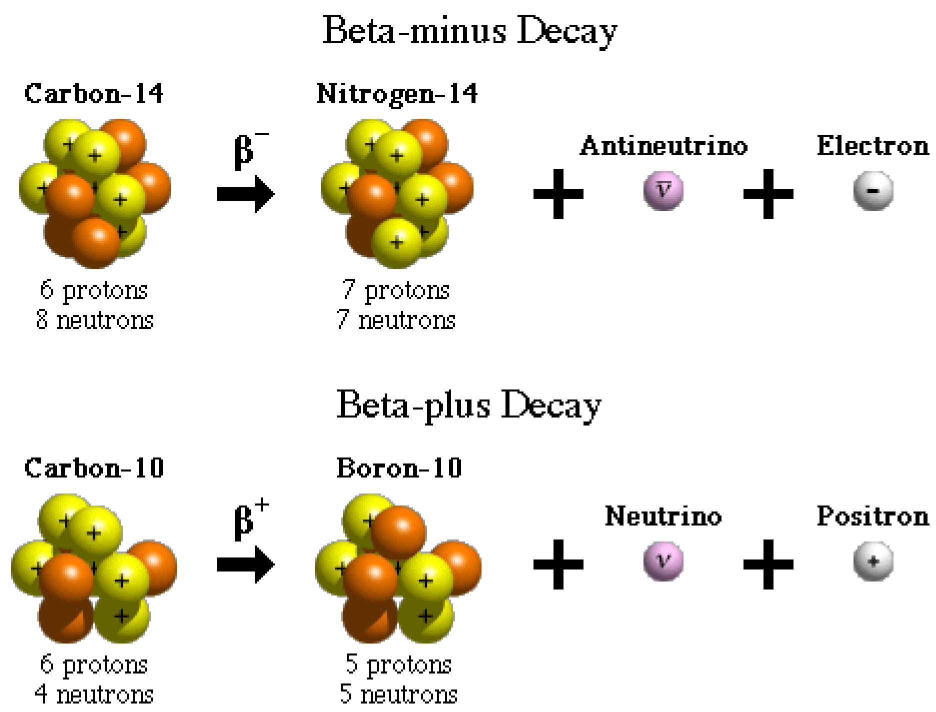
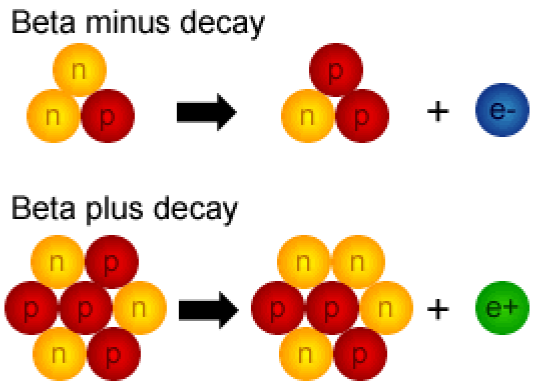
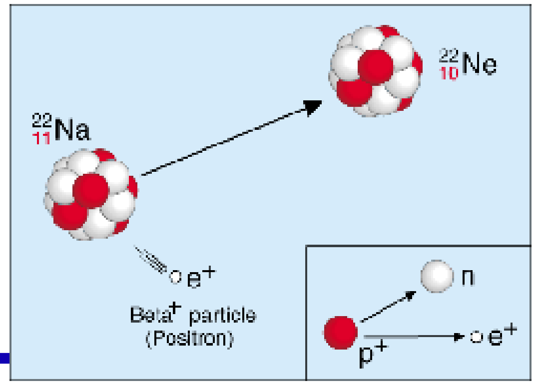
Alpha and Beta particles



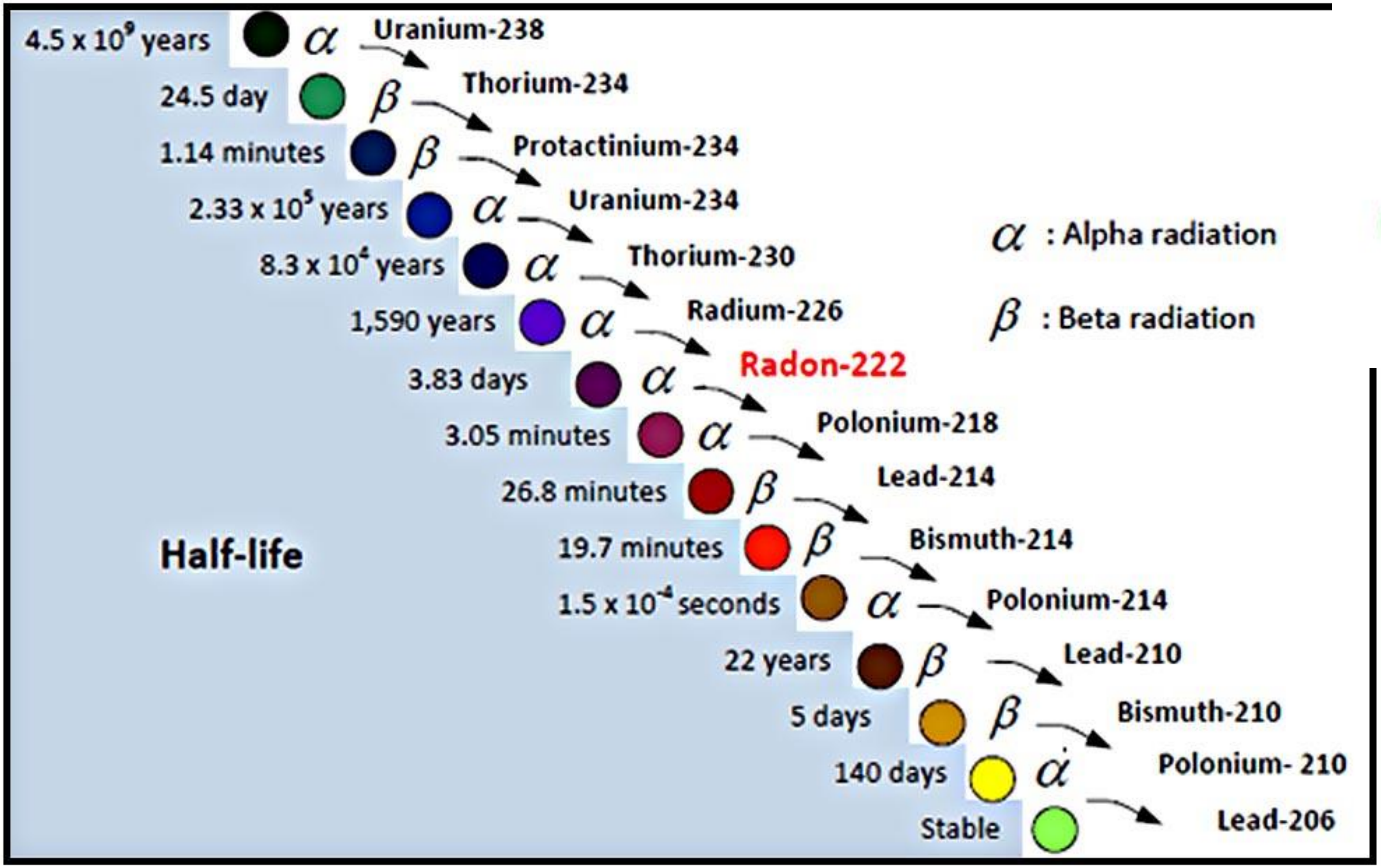


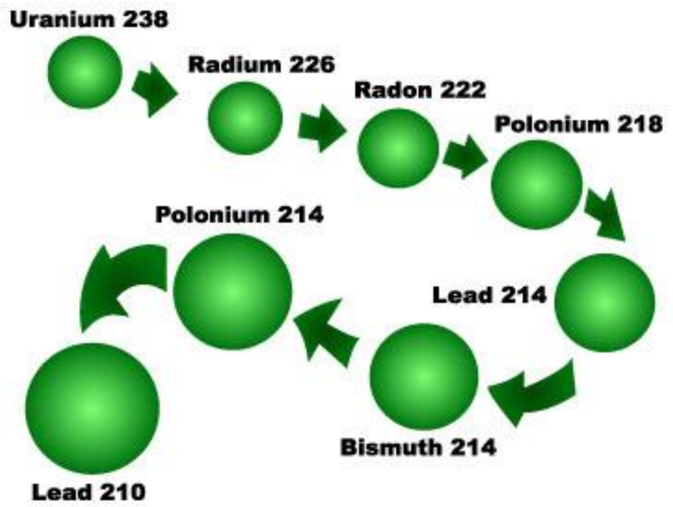


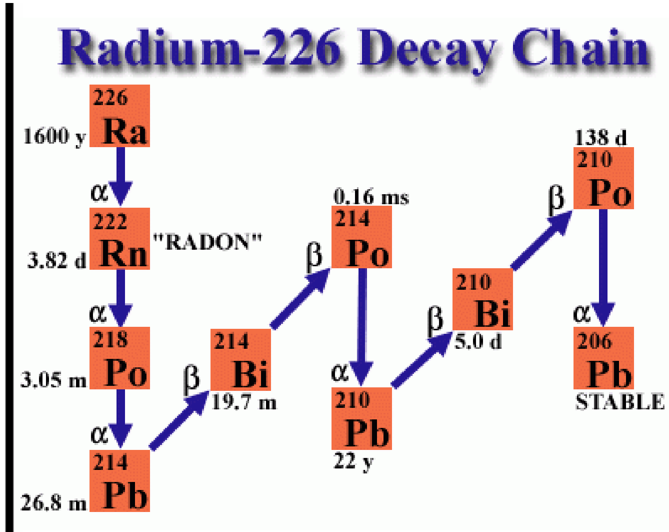


Radioactive decay product chain

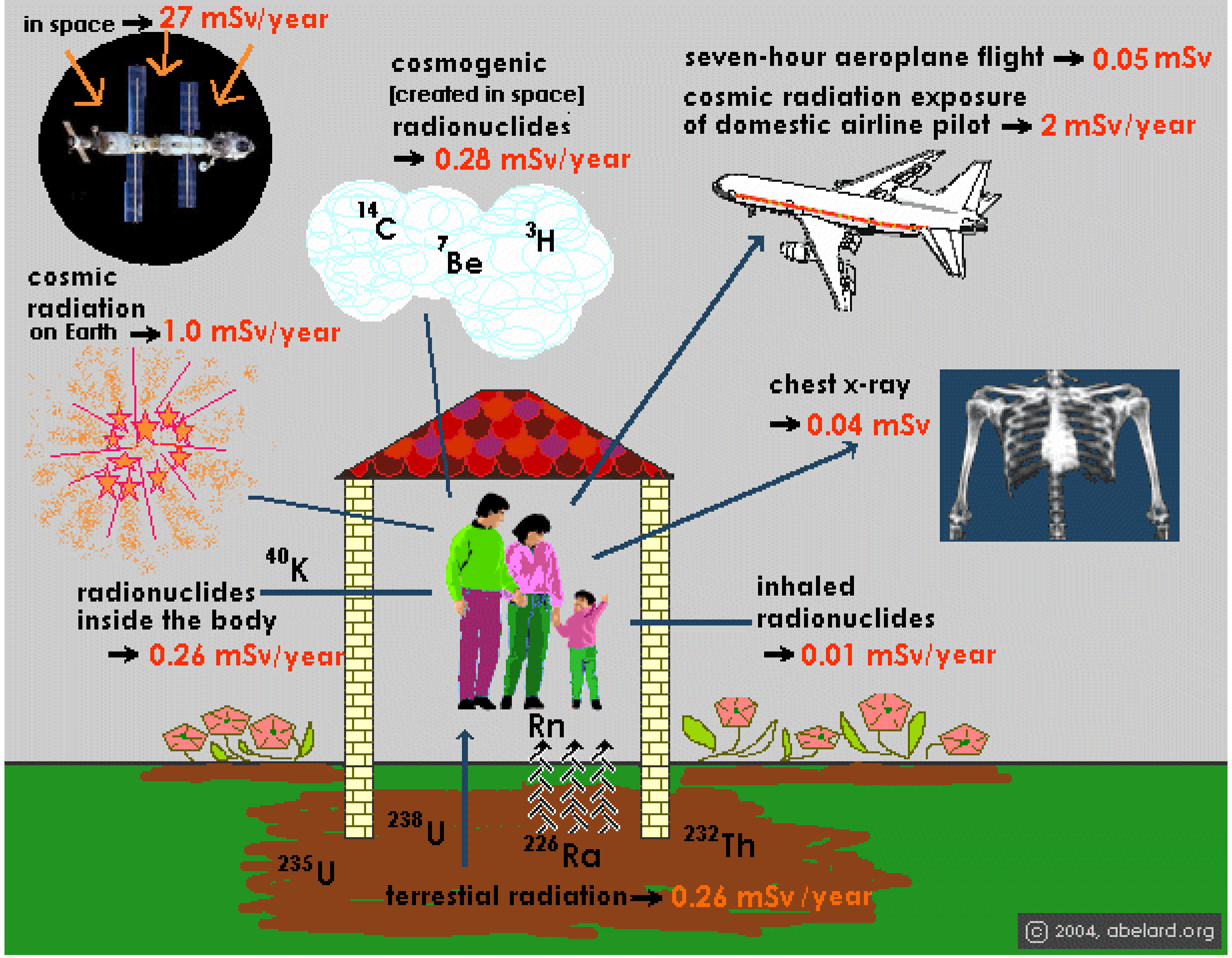
A source of natural radioactivity and background radiation, all around us!
Radon-222 is an intermediary product, but being a gas it easily spreads with the air and is inhaled by humans

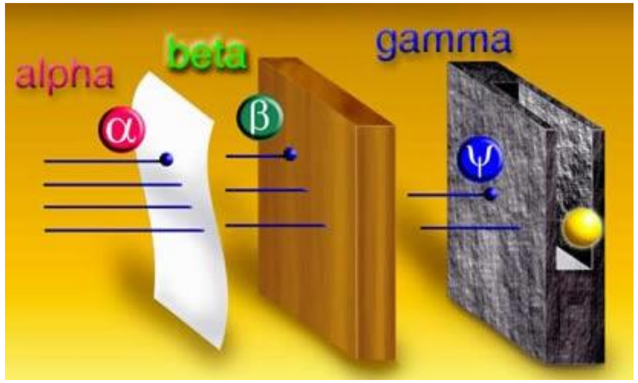


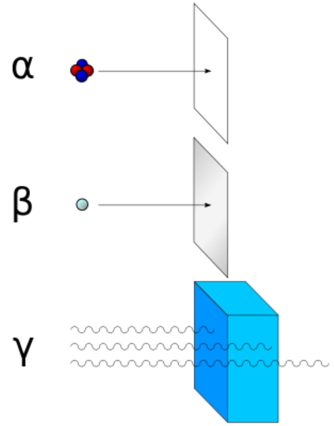


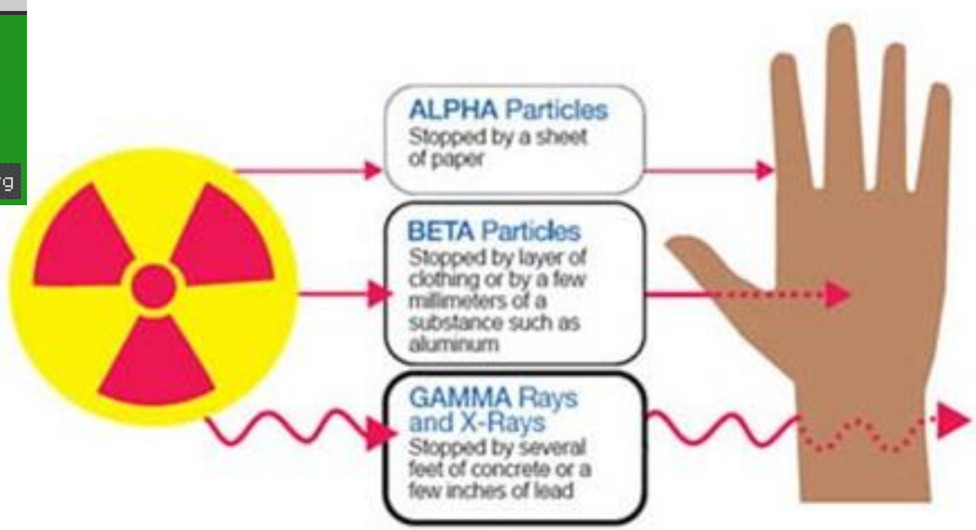


Radiation Safety





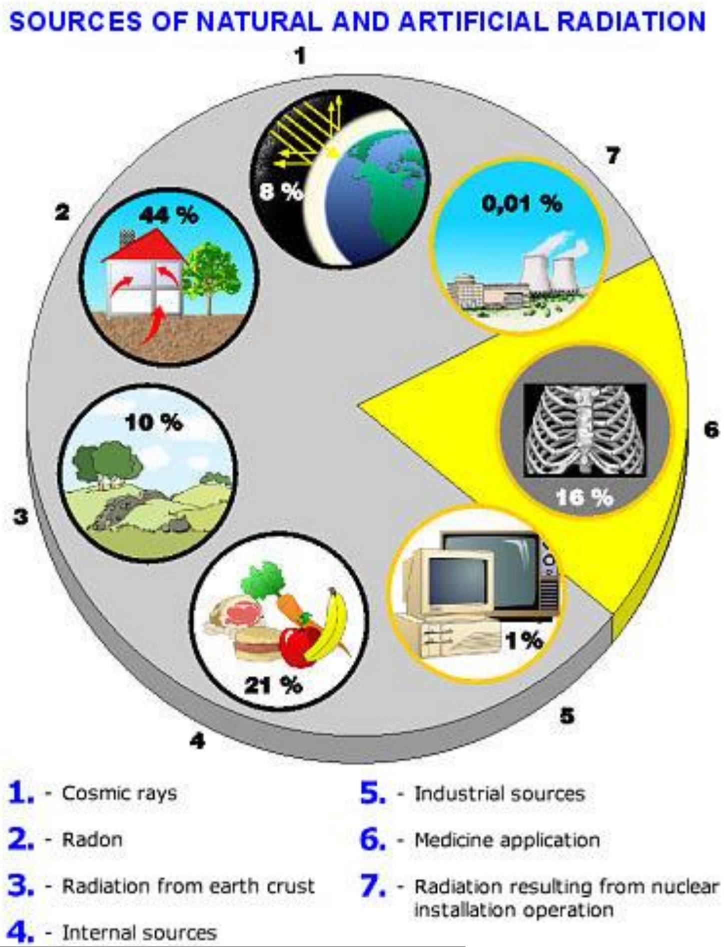


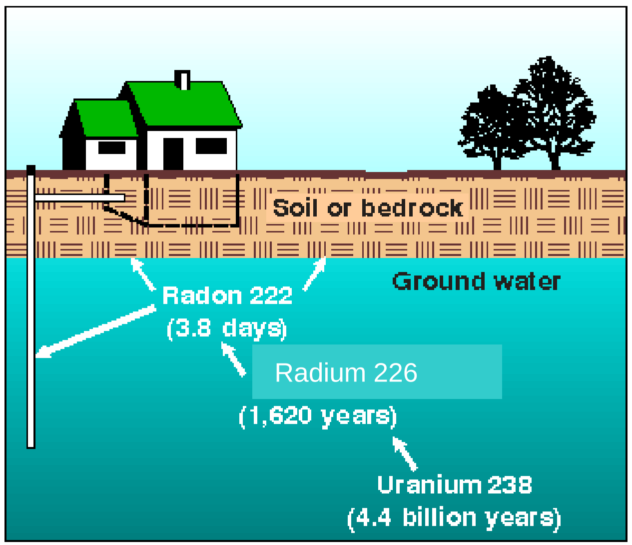


Natural radioactivity

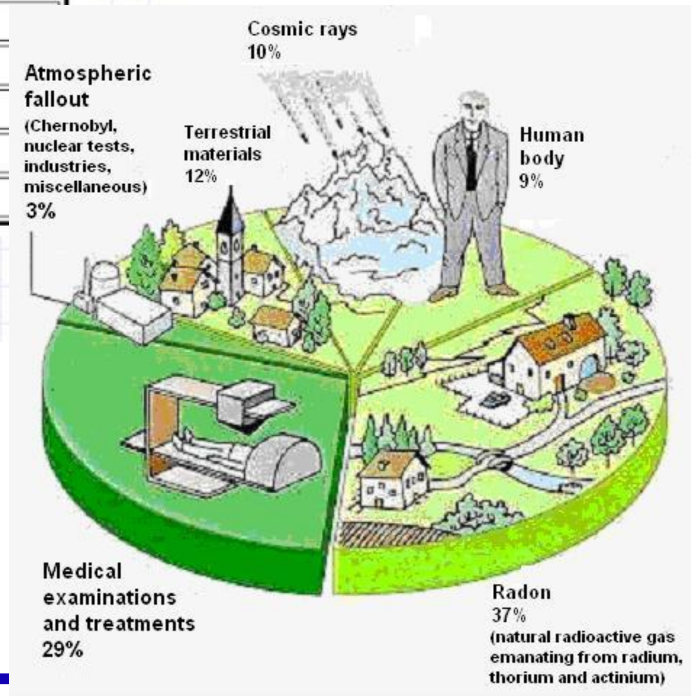
Annual estimated average effective dose equivalent received by a member of the population of the United States.

Source	Average annual effective dose equivalent	
	(µSv)	(mrem)
Inhaled (Radon and Decay Products)	2000	200
Other Internally Deposited Radionuclides	390	39
Terrestrial Radiation	280	28
Cosmic Radiation	270	27
Cosmogenic Radioactivity	10	1
Rounded total from natural source	3000	300
Rounded total from artificial Sources	600	60
Total	3600	360

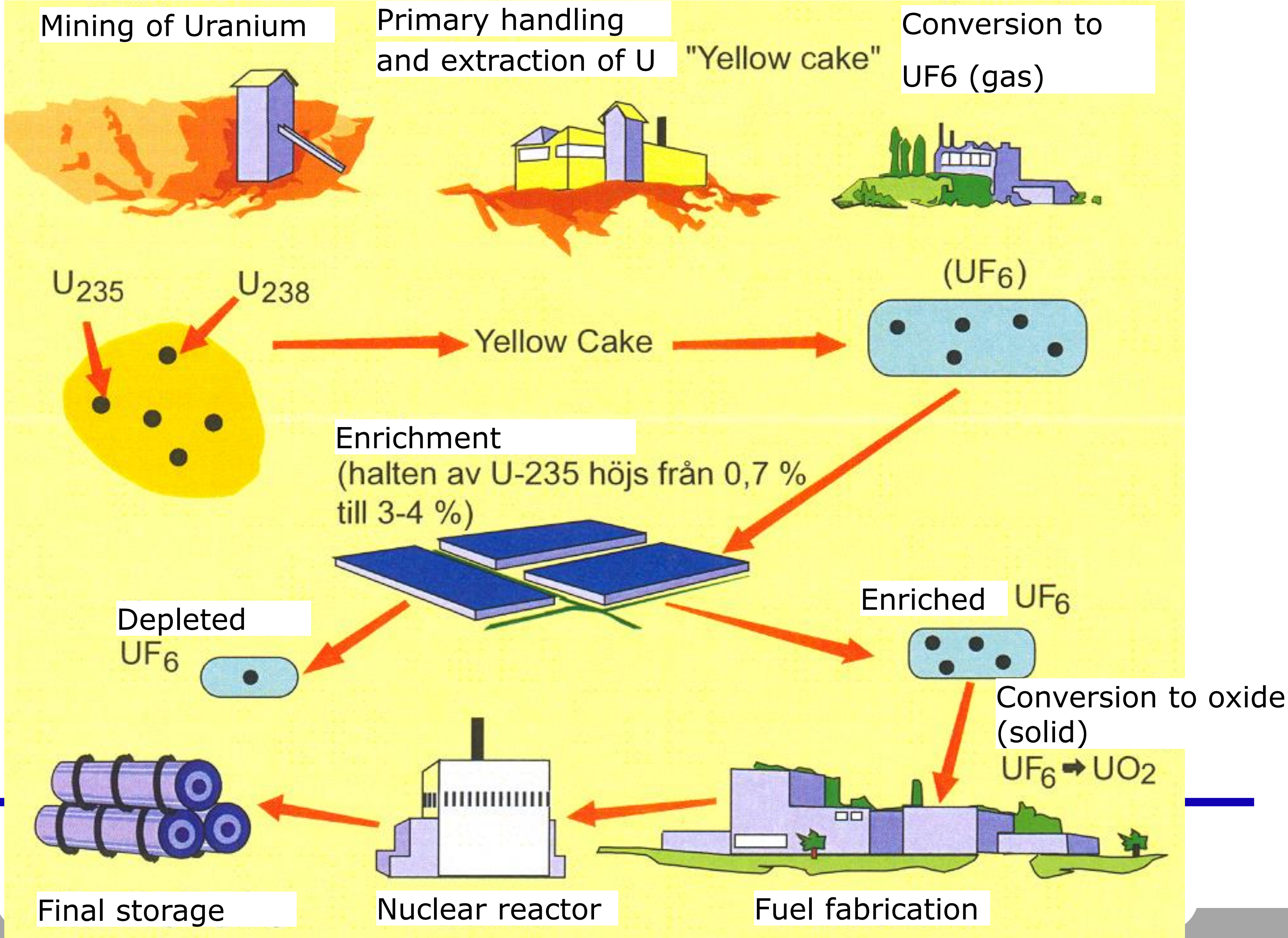




Modified from Clark and Briar, 1993



Uranium as a nuclear fuel



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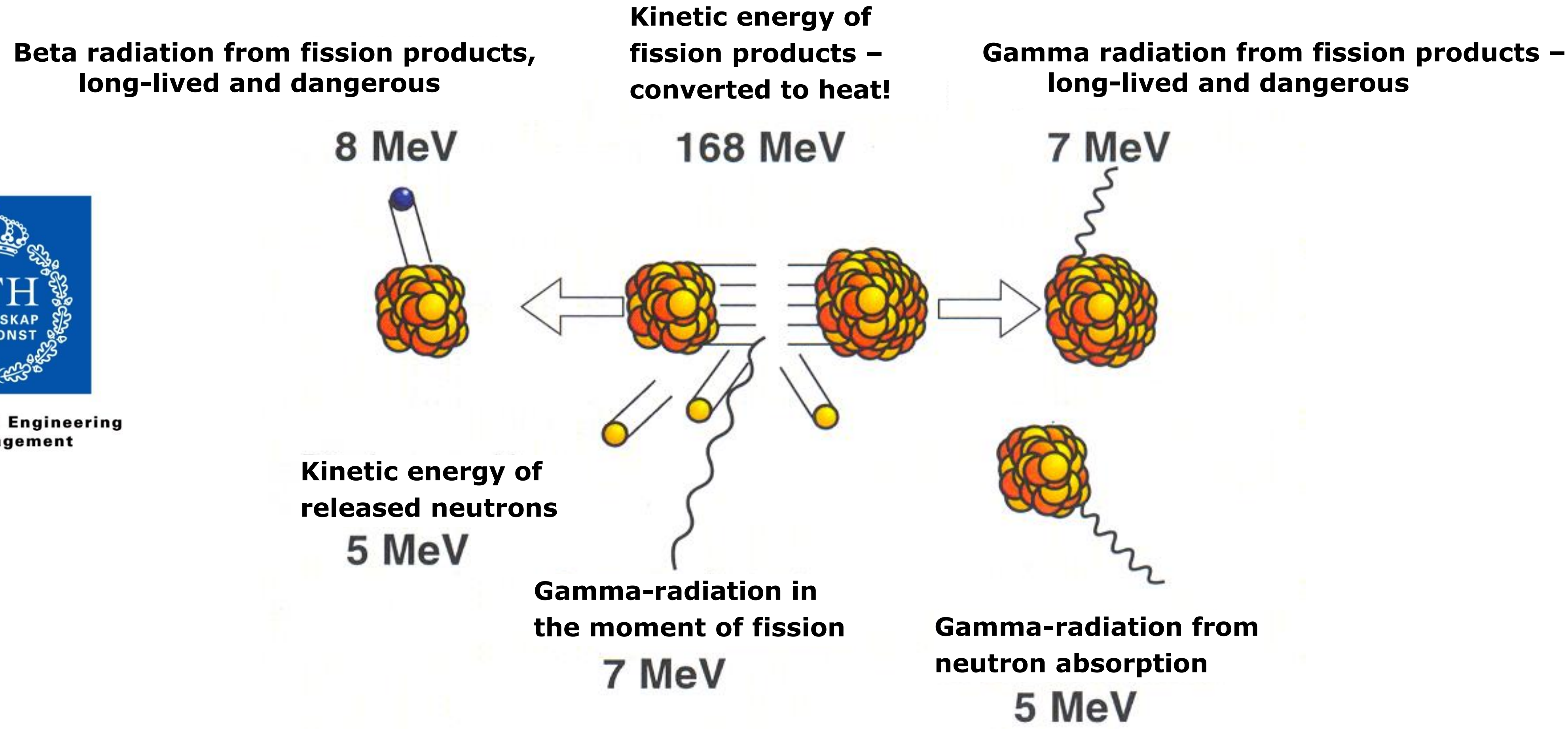
Fission Energy



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Fission of Uranium

- U-238 fissile only by fast neutrons
- U-235 fissile only by thermal (slow) neutrons
- U-238 can absorb a neutron and convert to fissile Pu-239

- Typical nuclear fission reactions for U-235:

$_{92}U^{235} + n^1 \rightarrow {}_{54}Xe^{140} + {}_{38}Sr^{94} + 2n^1 + \sim 200$ MeV

$_{92}U^{235} + n^1 \rightarrow {}_{56}Ba^{137} + {}_{36}Kr^{97} + 2n^1 + \sim 200$ MeV

$_{92}U^{235} + n^1 \rightarrow {}_{57}La^{147} + {}_{35}Br^{87} + 2n^1 + \sim 200$ MeV

$_{92}U^{235} + n^1 \rightarrow {}_{55}Cs^{140} + {}_{37}Rb^{93} + 3n^1 + \sim 200$ MeV

$$^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U \xrightarrow{\beta^-} {}^{239}_{93}Np \xrightarrow{\beta^-} {}^{239}_{94}Pu$$

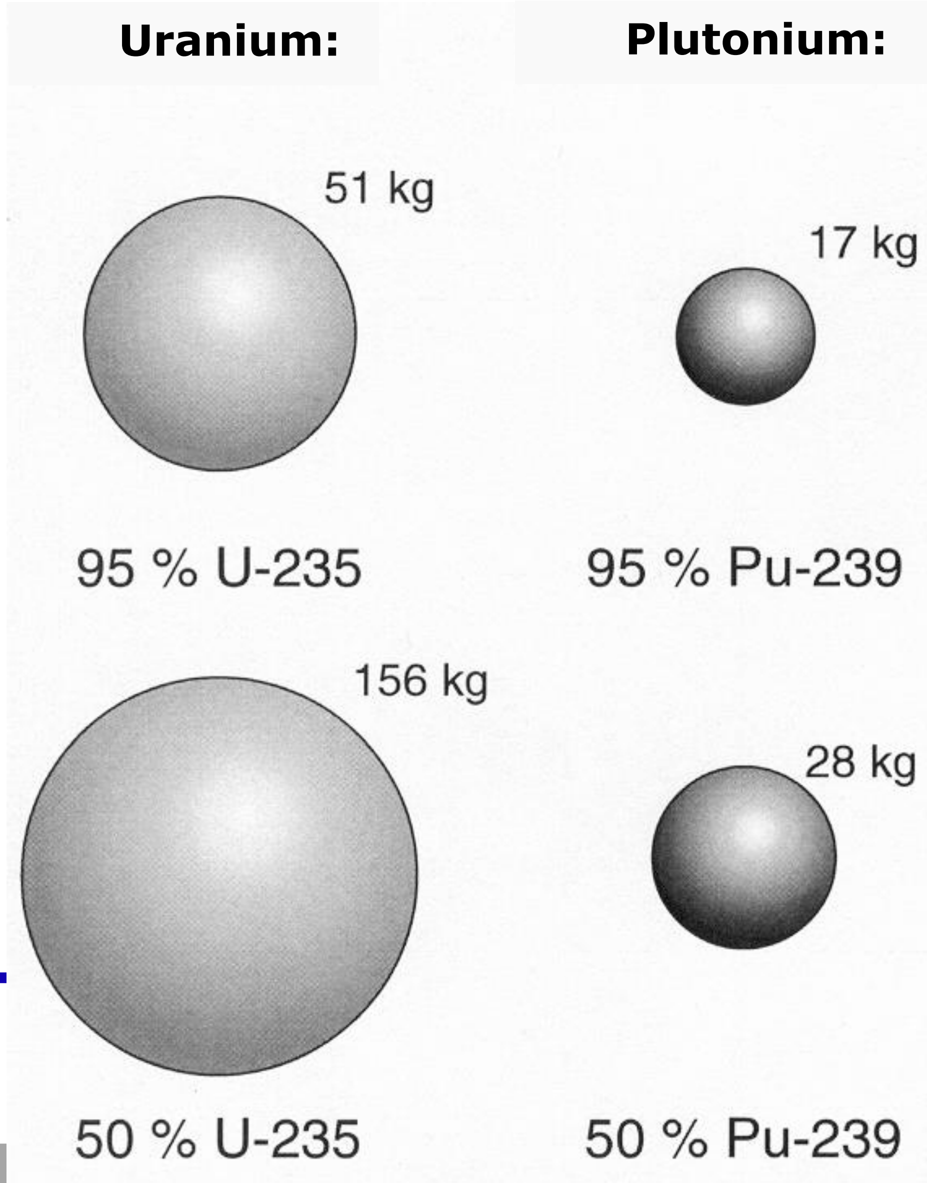
Neutron Life

Possible events for a neutron in a fission reactor:

- Initiates fission when hitting a fissile nucleus
- Be absorbed by a nucleus without fission
- Collides with a nucleus and loses energy (slows down)
- Leaves the reactor zone (leaks out)

Chain Reactions & Critical Mass

The statistical probability for a neutron to ”find and hit” a fissile nucleus decreases quickly with the decreased space occupied by the nuclei (higher probability to leak out) and with the decreased number of fissile nuclei in that confined space. Below a certain minimum volume or confined mass, a chain reaction is not possible, thus the concept of ”critical mass”.



Nuclear Fission Reactors

Performing a sustained and contained (controlled) chain-reaction delivering a steady and continuous release of energy (heat).

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For that purpose, the following main reactor components are necessary:

- The **fuel** with enough fissile nuclei for sustained operation (U-235);
- The means to control neutron life and alter neutron energy level so that continuous fission reactions would be possible – the **containment** to prevent leakage, and the **moderator**;
- The means to quickly shut down the fission reaction – the **inhibitor** in the form of neutron absorbing elements;
- The **heat sink**, that is the reactor cooling medium.

Moderator

- **It is necessary to slow down the fast neutrons in order to make sure that they meet a U-235 nucleus and initiate a controllable fission reaction.**
- Achieved by using a moderator. The neutrons collide with moderator's nuclei and lose energy.
- **The moderator shouldn't enter fission reactions or absorb the neutrons, but only slow them down.**
- *Good moderators are:*

- Light water (H_2 nucleus)
- Heavy water (D_2 nucleus)
- Beryllium
- Graphite (carbon)
- Oxygen

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Fission Inhibitors

- **Nuclear reactions can be stopped (or flex-controlled) by absorbing all neutrons, thus safely decreasing the possibility to initiate new fission reactions.**
- *Good neutron absorber materials are:*

- Boron **B**
- Silver **Ag**
- Indium **In**
- Cadmium **Cd**

- Certain fission products are also good neutron absorbers (Xe, Sm), which act as undesired inhibitors by ”poisoning” the nuclear reactor.

Neutron Generations (continuous operation)

Some neutrons are absorbed by the moderator or by inhibitors, and therefore lost ⑤

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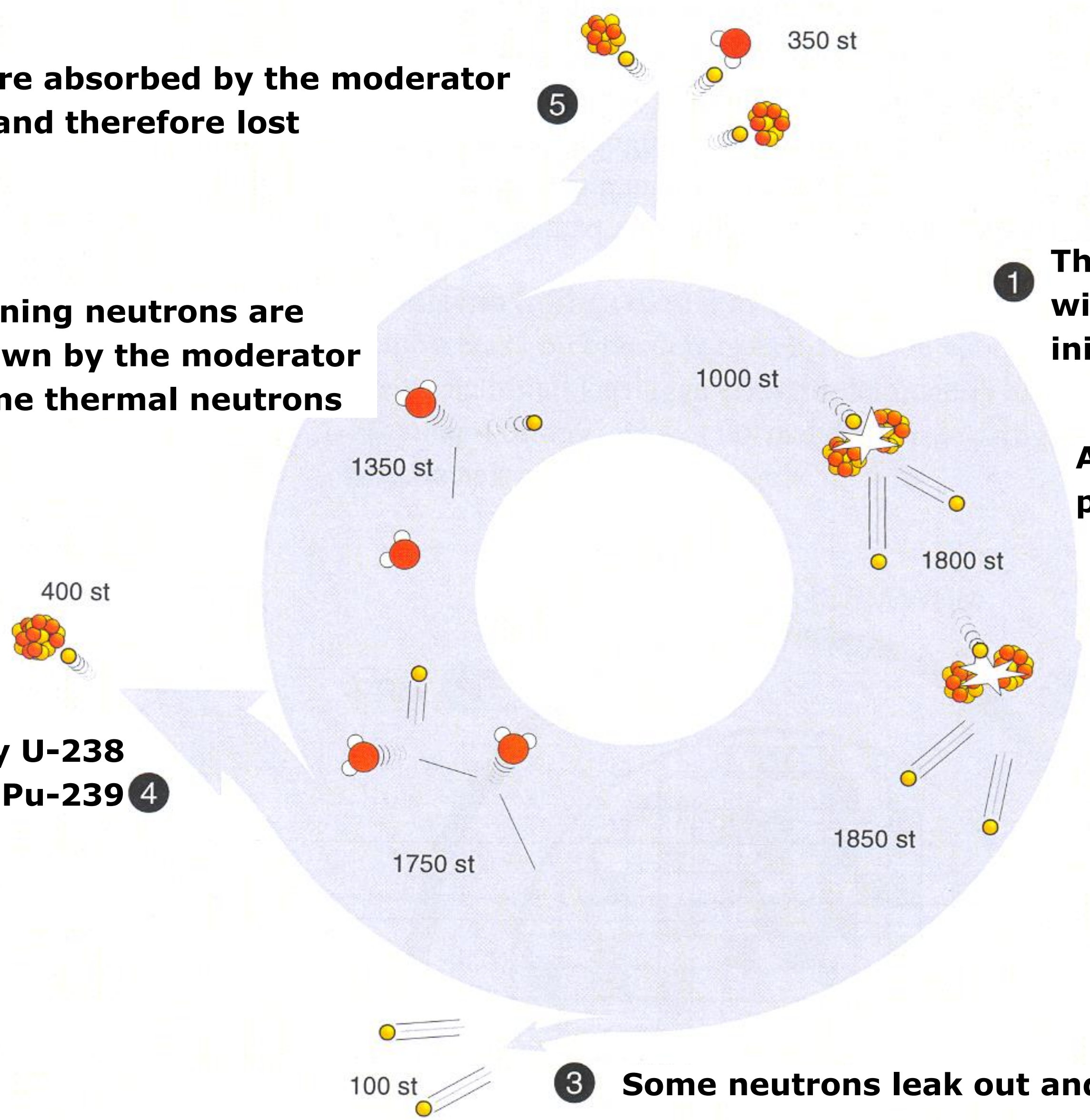
The remaining neutrons are slowed down by the moderator and become thermal neutrons

① Thermal neutrons collide with fuel atoms and initiate fission

Average of 1.8 neutrons are produced per one fission

A small number of fast neutrons manage to initiate fission of U-238

Some neutrons are captured by U-238 which transforms into Pu-239 ④



③ Some neutrons leak out and leave the fuel space

The BWR as an example

Fuel rods (black) and regulation rods (white) situated in the reactor core

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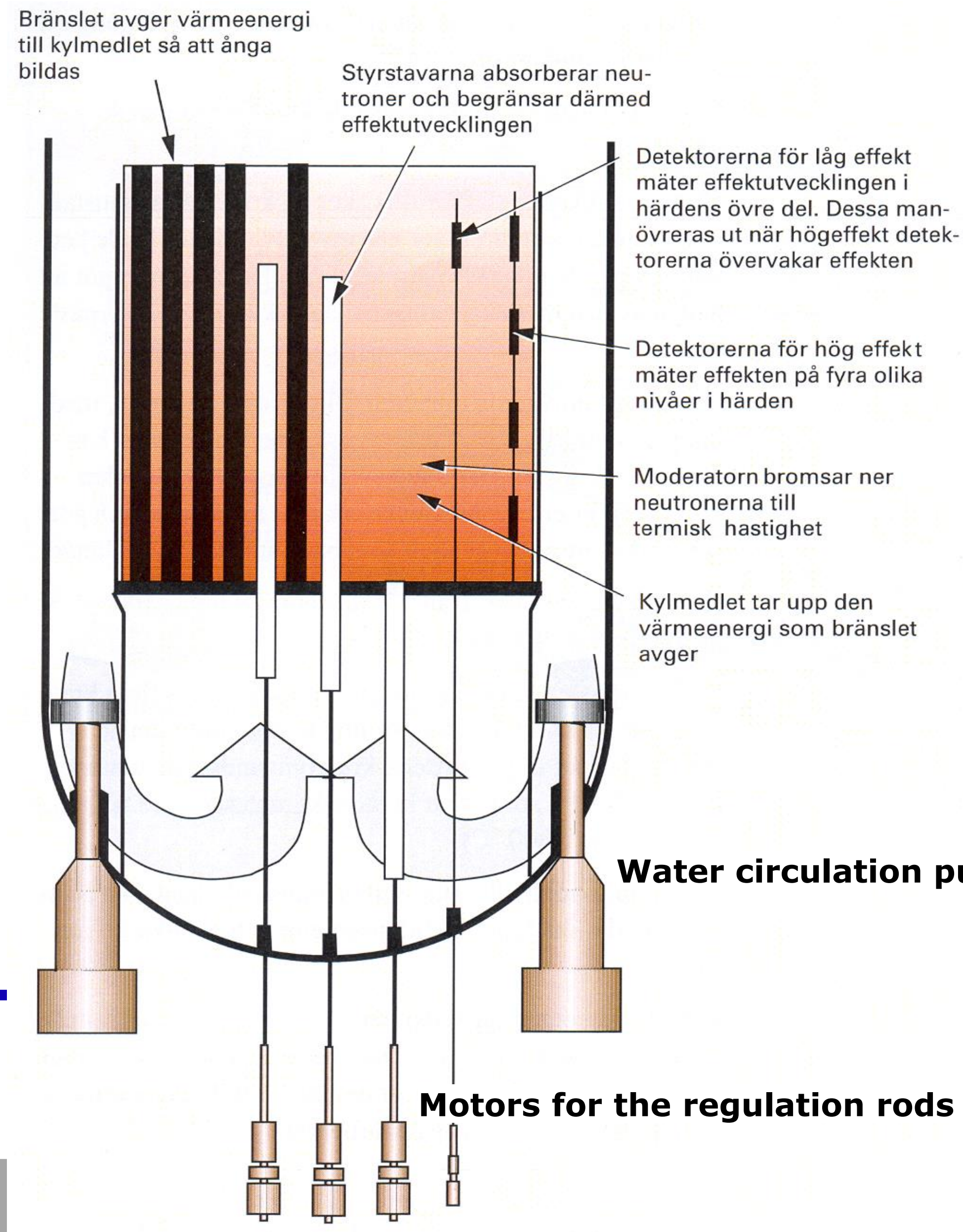

Various detectors at different positions measuring temperature, neutron flow, etc.

Light water serves both as moderator and as cooling medium, and also as working medium for the power generation cycle!

Water circulation pumps

Motors for the regulation rods

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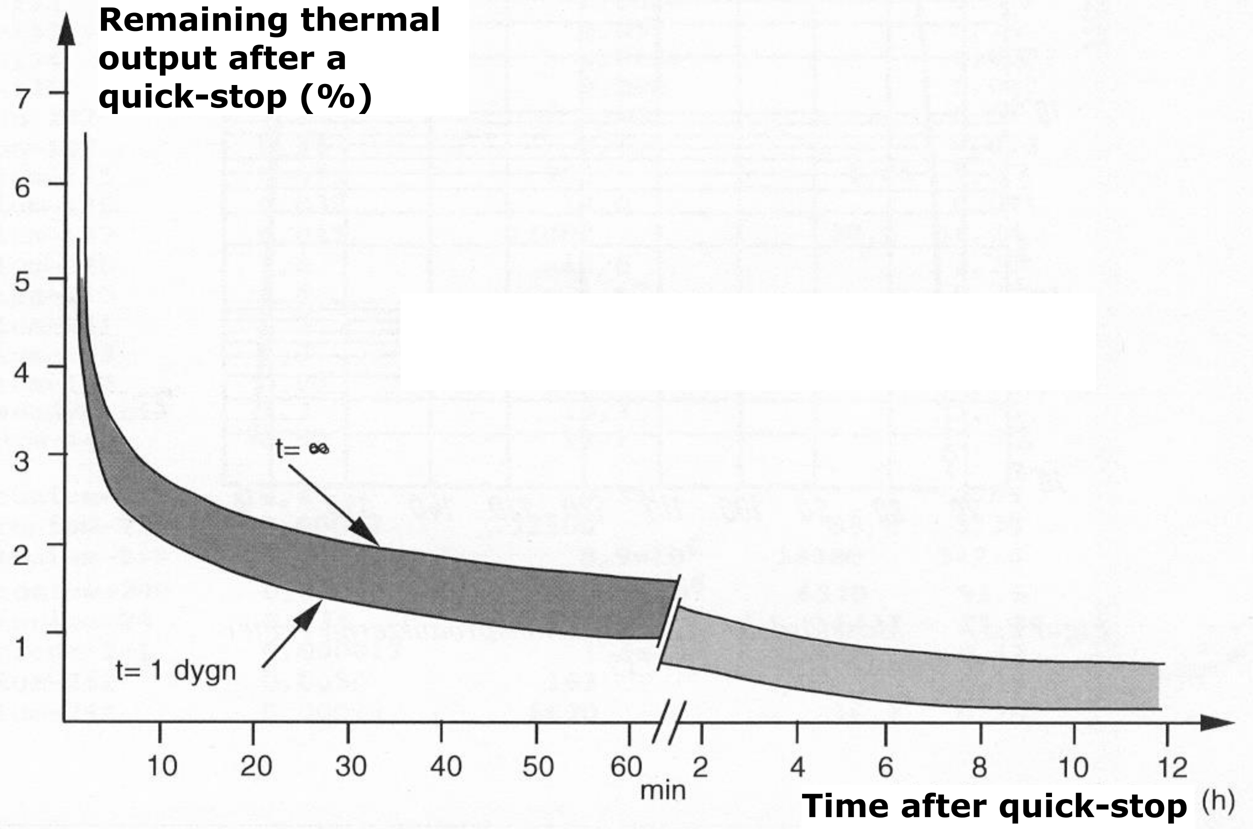
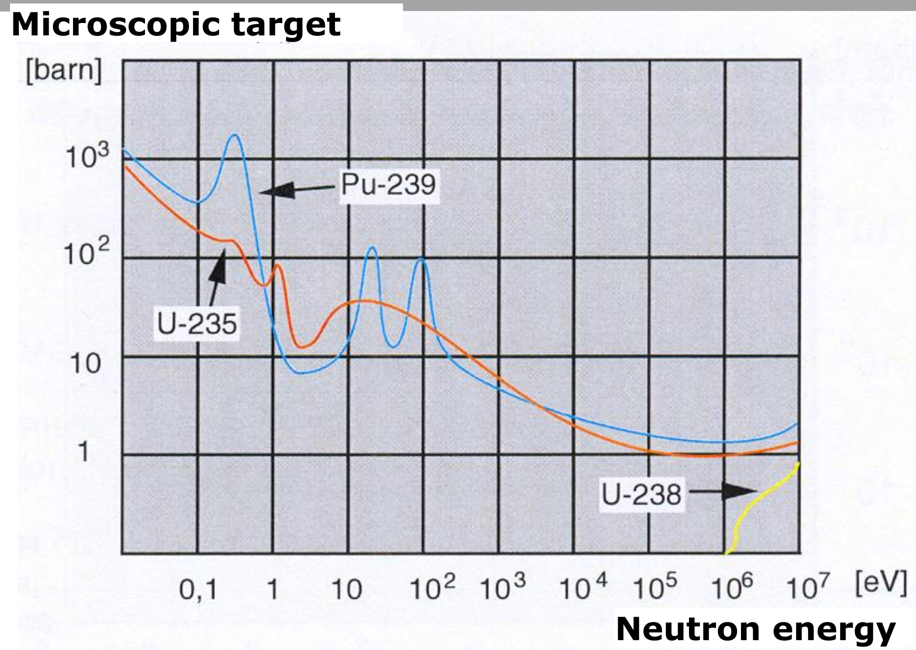
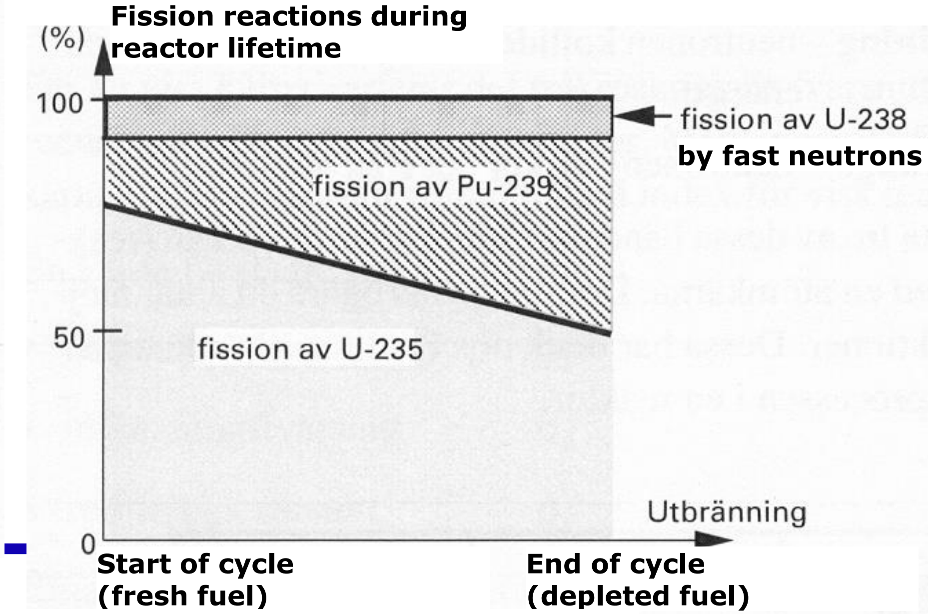
Neutron economy & thermal inertia







Boiling Water Reactor (BWR)

Fuel: **enriched U ~3.5%**
Moderator: **Light Water**
Cooling: **Light Water**
El. Efficiency: **~33%**

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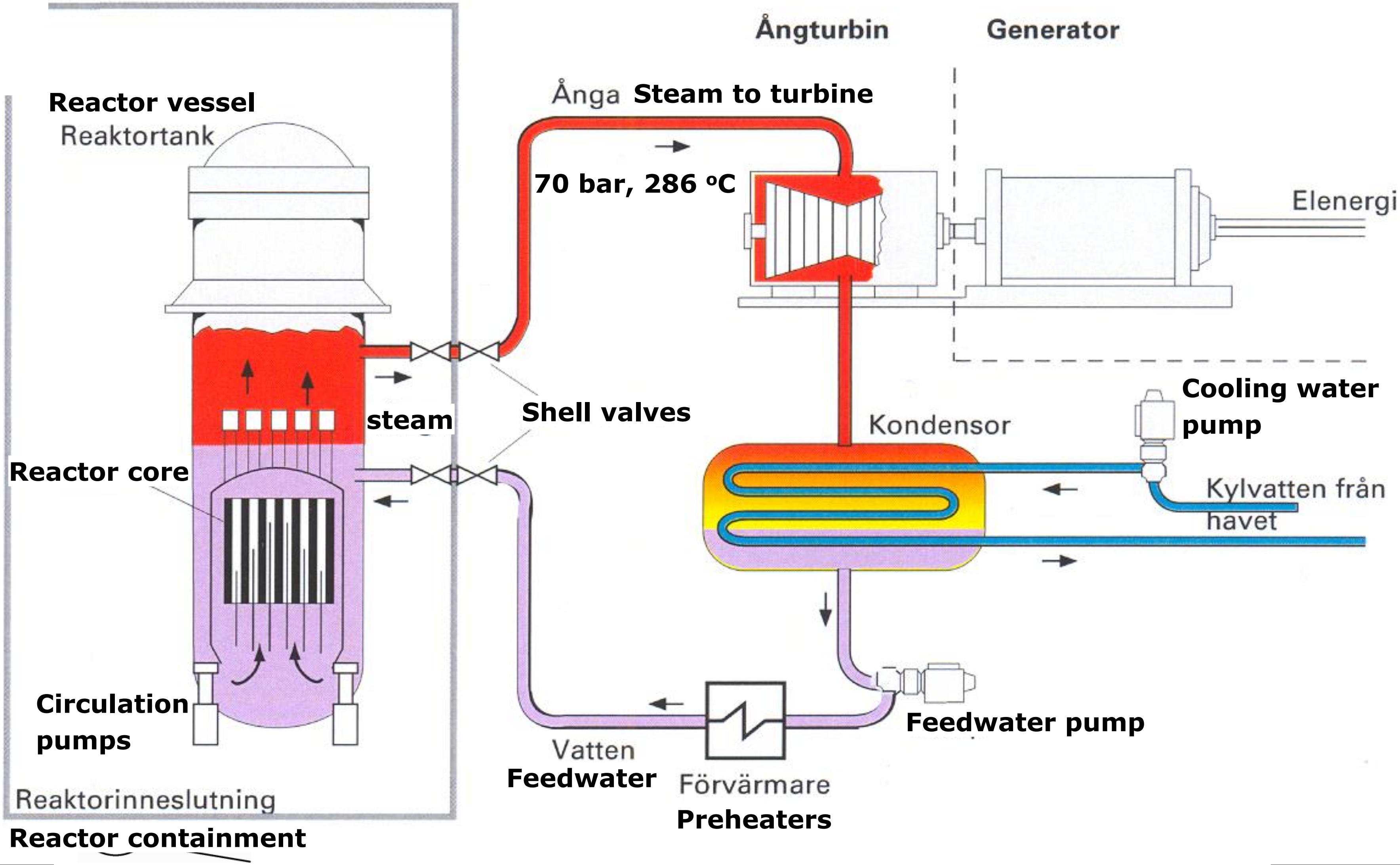

Pressurised Water Reactor (PWR)

Fuel: **enriched U ~3.5%**
Moderator: **Light Water**
Cooling: **Light Water**
El. Efficiency: **~32%**

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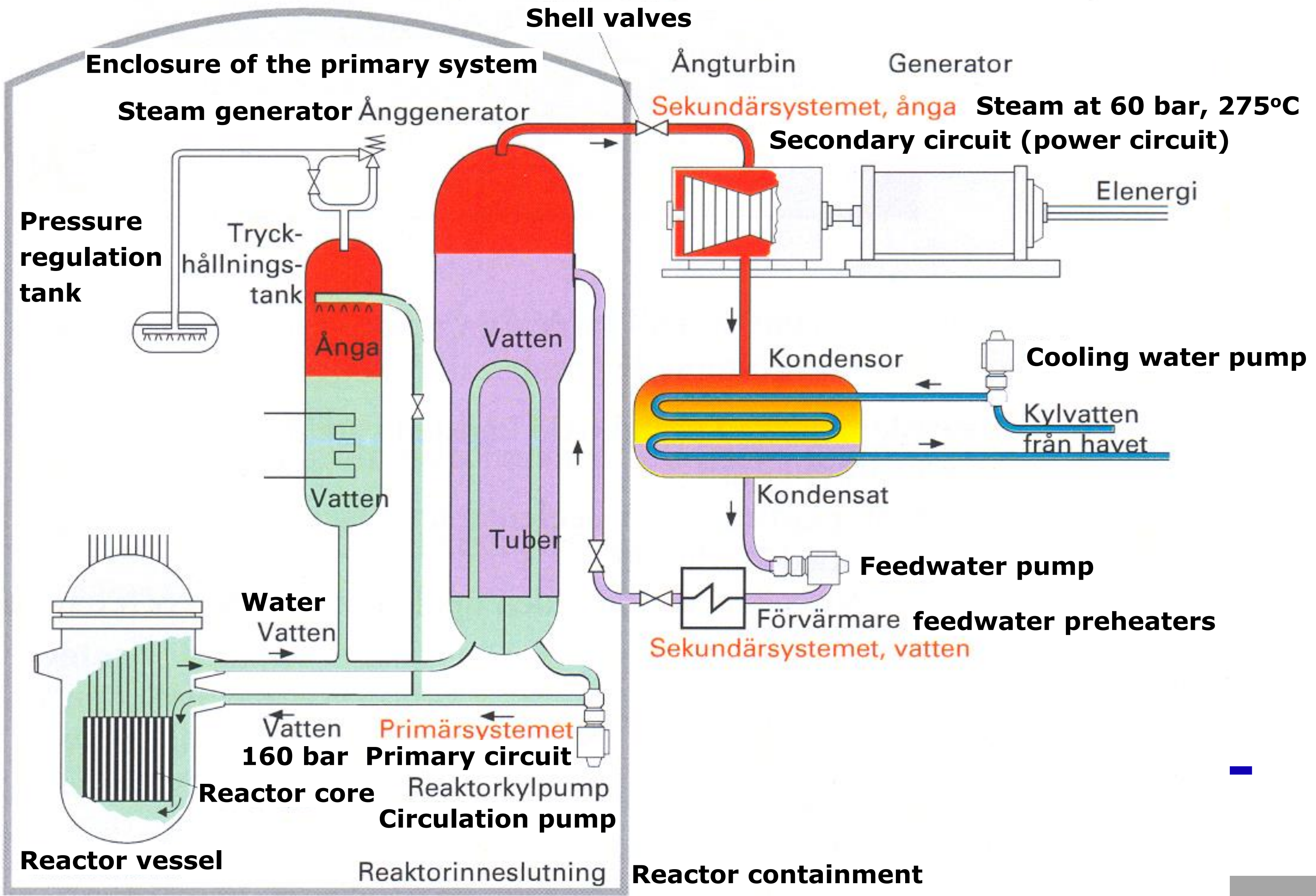
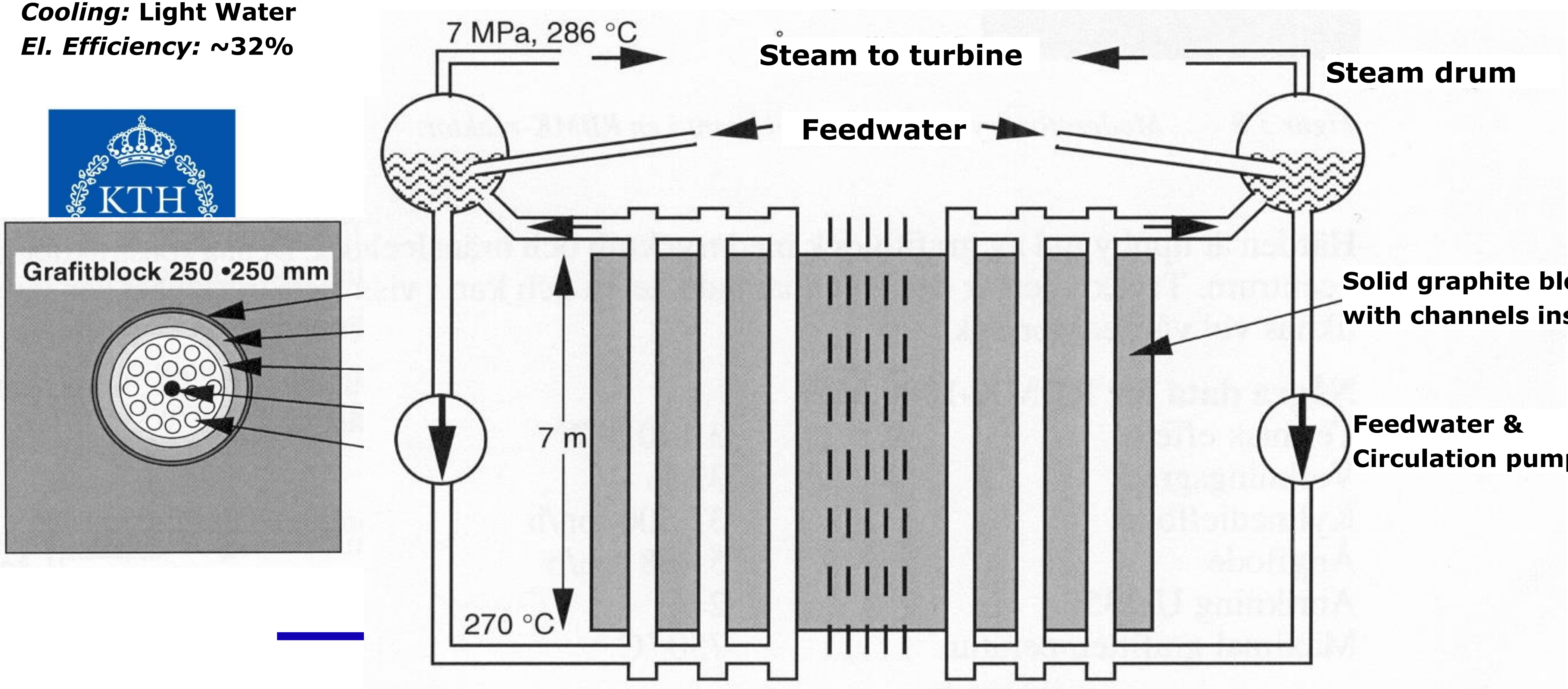


Channel-type Graphite Reactor (RBMK)

Fuel: **low-rich U ~2%**
Moderator: **Graphite,**
max 750 C graphite temp.
Cooling: **Light Water**
El. Efficiency: **~32%**

Russian version of a boiling water reactor, graphite moderated, able to use fuel with lower enrichment



Tubes with fuel in each pressurised water channel. Regulation rods in neighbouring channel. Modular construction. More graphite blocks with tubes can easily be added.

Magnox Reactor (gas cooled)

Fuel: **natural U**
Moderator: **Graphite**
Cooling: **CO2 at 400 C**
El. Efficiency: **~31%**

CO_2-cooled graphite moderated reactor, old design

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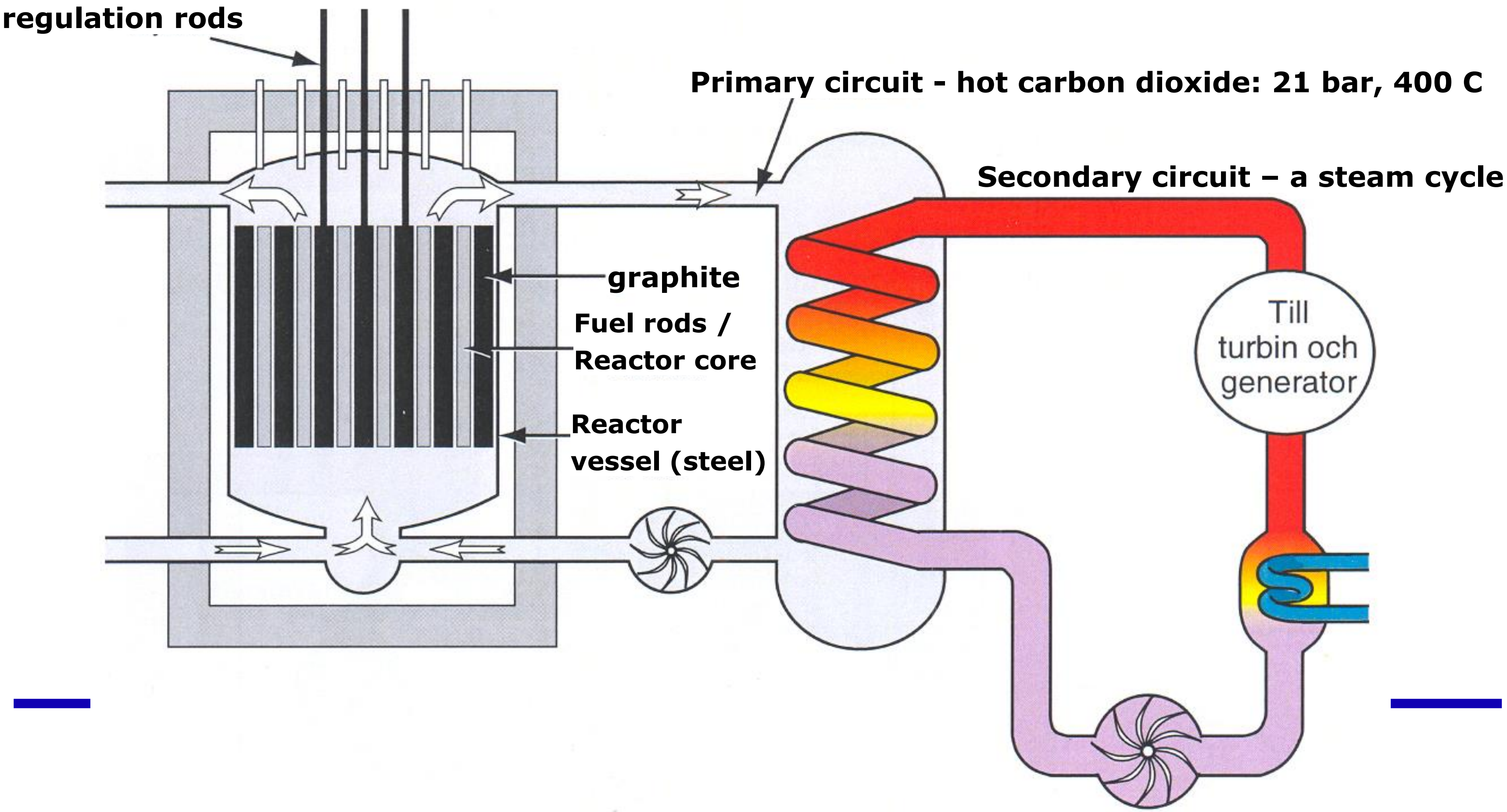

Advanced Gas-cooled Reactor (AGR)

Fuel: **enriched U ~2.3%**
Moderator: **Graphite**
Cooling: **CO_2 at 650 C**
El. Efficiency: **~42%**

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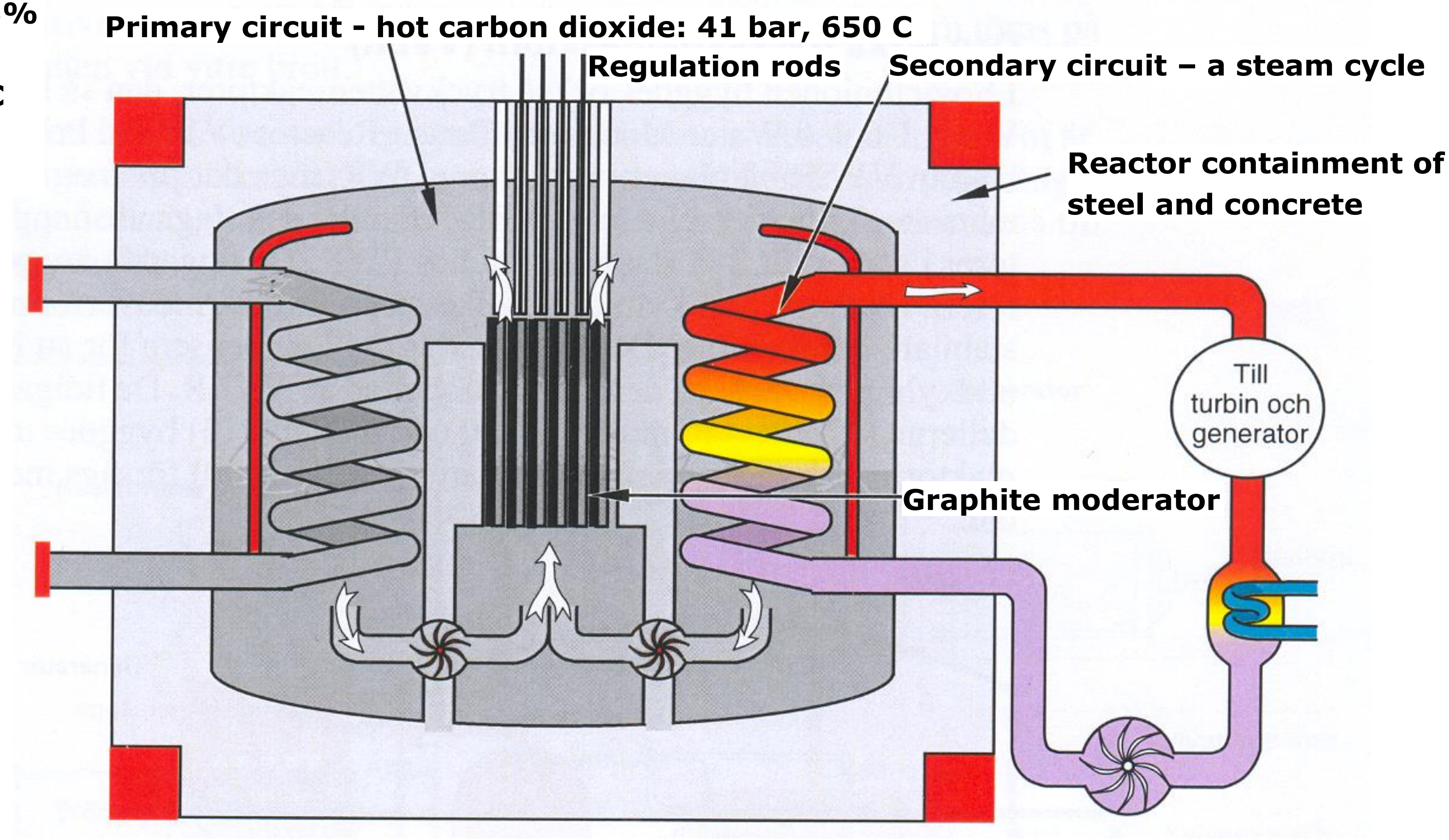

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Heavy-Water Reactor (CANDU)

Fuel: **natural U**
Moderator: **Heavy Water**
Cooling: **Heavy Water**
El. Efficiency: **~31%**

A Canadian design, heavy-water cooled and moderated reactor, with a light-water/steam secondary circuit for power production

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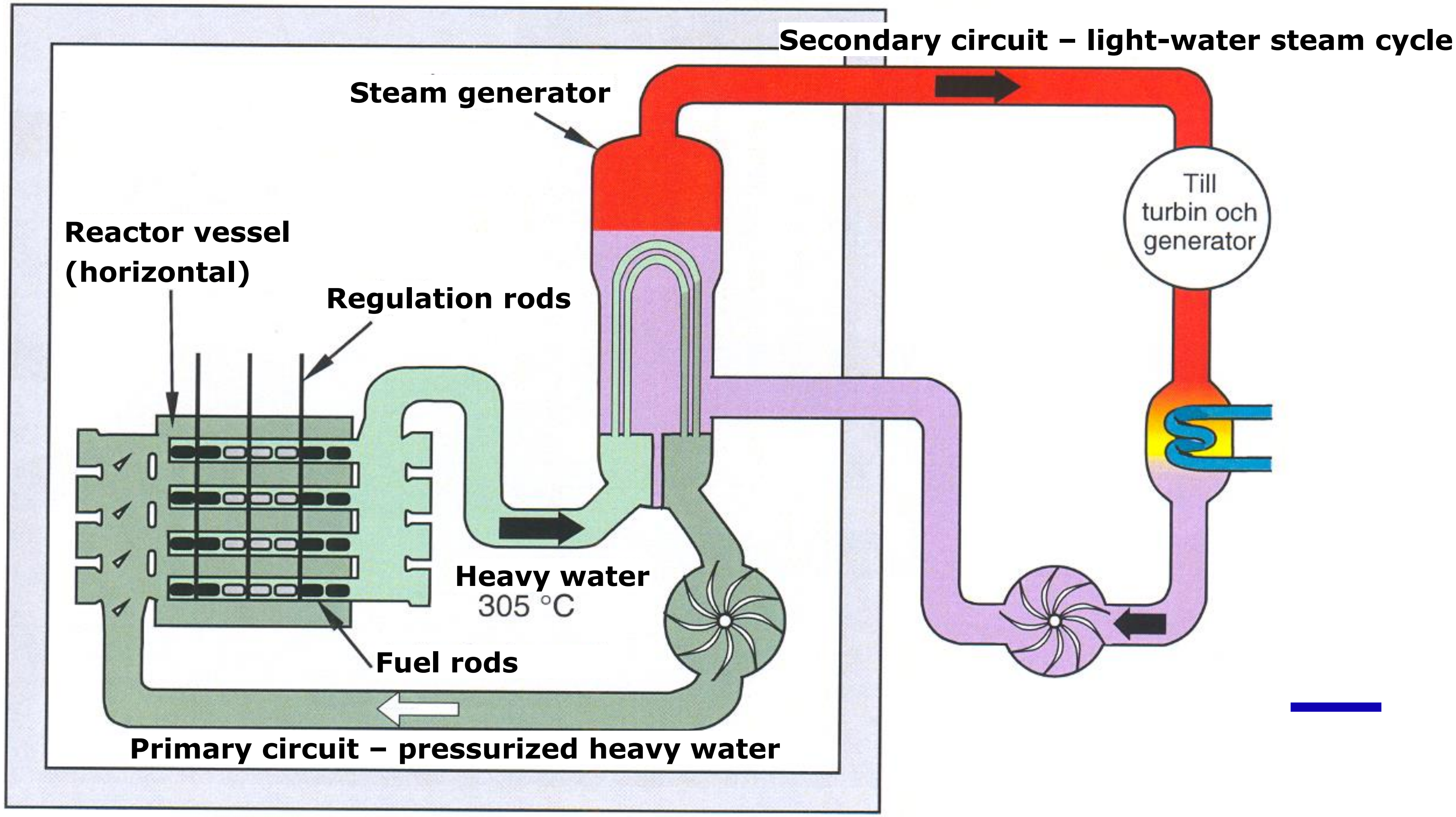

Fast Breeder

Works with fast neutrons,
without a moderator.
Can convert U-238 into fissile fuel.

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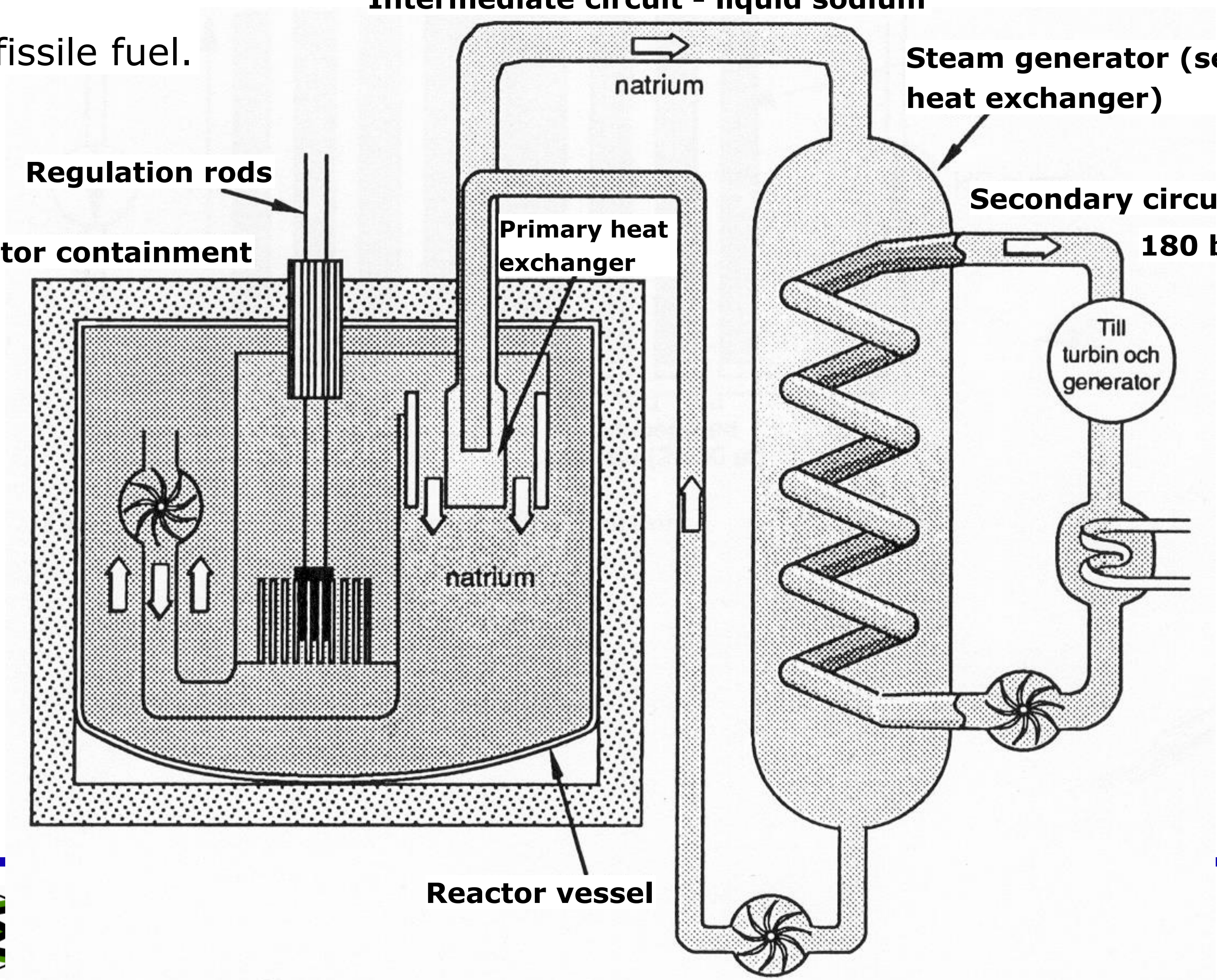

Fuel: **highly rich U ~20%**
Converts U-238 to Pu
Moderator: **None!**
Cooling: **liquid sodium (Na)**
0.3 bar, 620 C
El. Efficiency: **~42%**

Summary of Operable Reactors worldwide, per type (year 2014)

Type:	*number~:*	*fuel:*	*cooling:*	*moderator:*
PWR	263	enriched U	water	water
BWR	92	enriched U	water	water
Gas-cooled	26	low-rich U	CO_2	graphite
CANDU	38	natural U	heavywater	heavywater
RBMK	17	low-rich U	water	graphite
Fast breeder	3	high-rich U, Pu	liquid Na	none

Future Nuclear Fuel?

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- **Large economically-available Uranium resources:**
  Australia, Kazachstan, Canada, South Africa, Namibia, Brasilia, Russia, USA, Uzbekistan…
- Total for the world: $3.6*10^6$ tons

- Possible to utilize more U-238 in innovative reactor designs or in fast-breeders.

- Recycling of ~30 ton nuclear weapons into conventional reactor fuel would feed ~14% of today's nuclear power capacity!

- **Thorium as fuel?**

Th-232 can be transformed into fissile U-233 by neutron absorption.

Th is about 3 times more commonly available than **U**!

Thorium reactors would operate with different neutron economy:

$$\mathrm{n} + {}^{232}_{90}\mathrm{Th} \rightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow{\beta^-} {}^{233}_{91}\mathrm{Pa} \xrightarrow{\beta^-} {}^{233}_{92}\mathrm{U}$$

Small Modular Reactors (SMR)

Nowadays, new nuclear plants have become far too expensive to build. Instead of economy-of-scale by enlargement of modern designs beyond 1000 MW_{el} per unit, it might be better to go for small prefabricated units of 50-300 MW, much easier to mass-manufacture and deliver. The SMR concept focuses on this option, by virtue of various possible designs and modifications. It is a fuzzy concept that still lacks the necessary support and investment, but might turn out to be very promising for the future.