

NUCLEAR POWER IN SHORT

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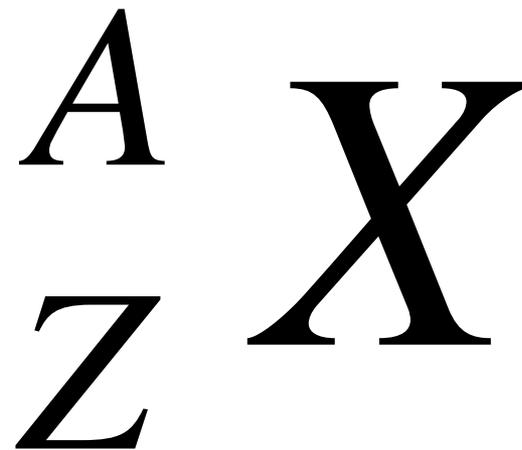
WHERE DOES THE ENERGY COME FROM?

$$E = mc^2$$



ATOMIC NUCLEUS

- Z protons
- N neutrons
- $A = Z + N$



HOW MUCH DOES THE NUCLEUS WEIGH?

- Z protons
- N neutrons

$$M = N \cdot m_n + Z \cdot m_p$$

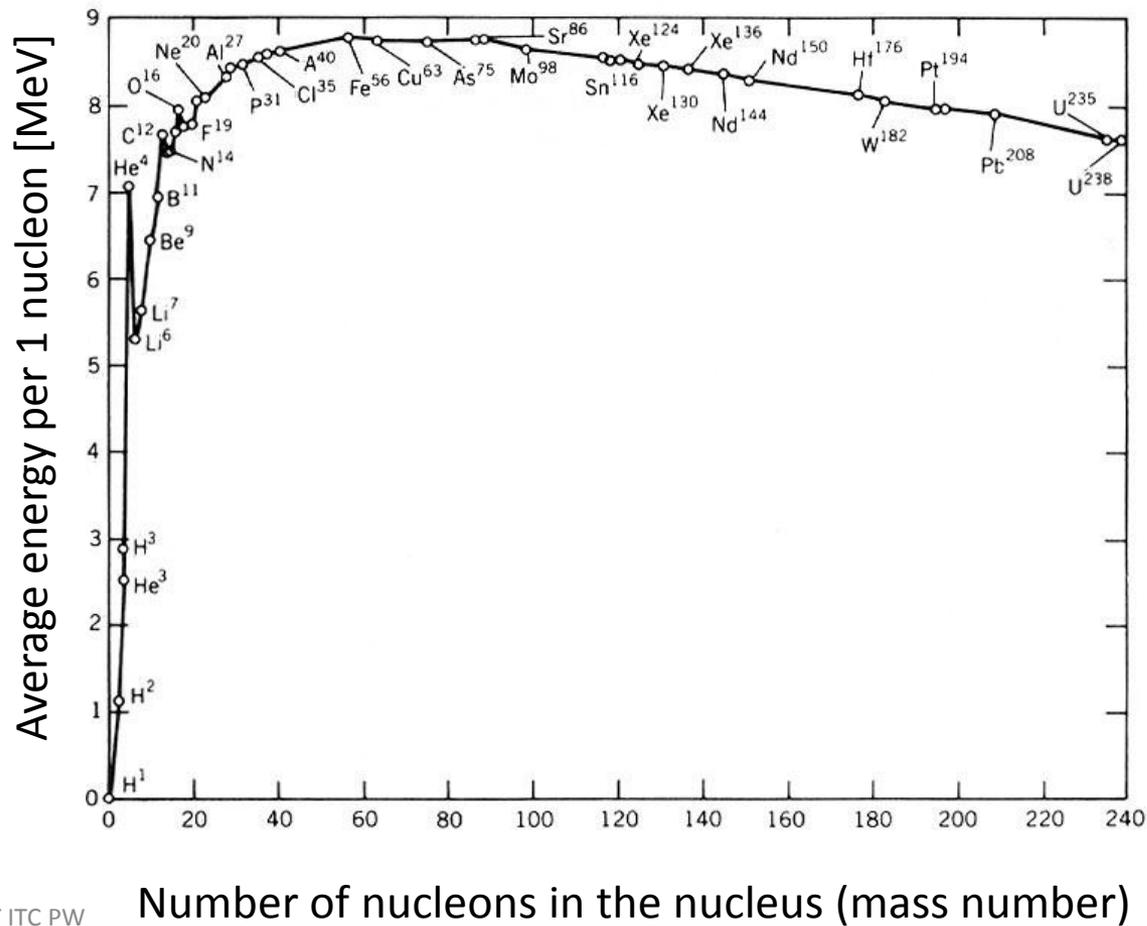
$$M < N \cdot m_n + Z \cdot m_p$$

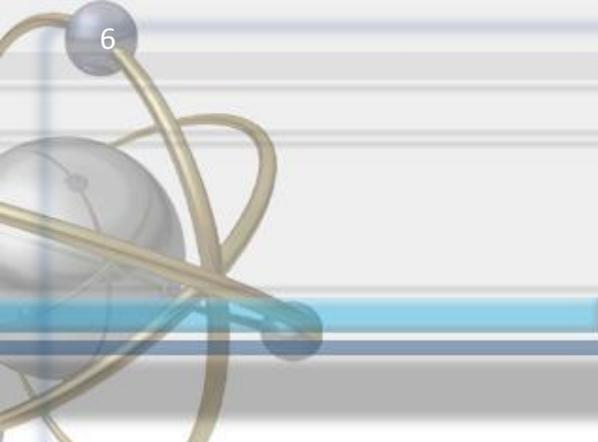
**Mass
Defect**

$$\Delta m = \frac{E_w}{c^2}$$

Binding energy

BINDING ENERGY





FISSILE ISOTOPES

U-233

U-235

Pu-239

Pu-241

FERTILE ISOTOPES

Th-232 → U-233

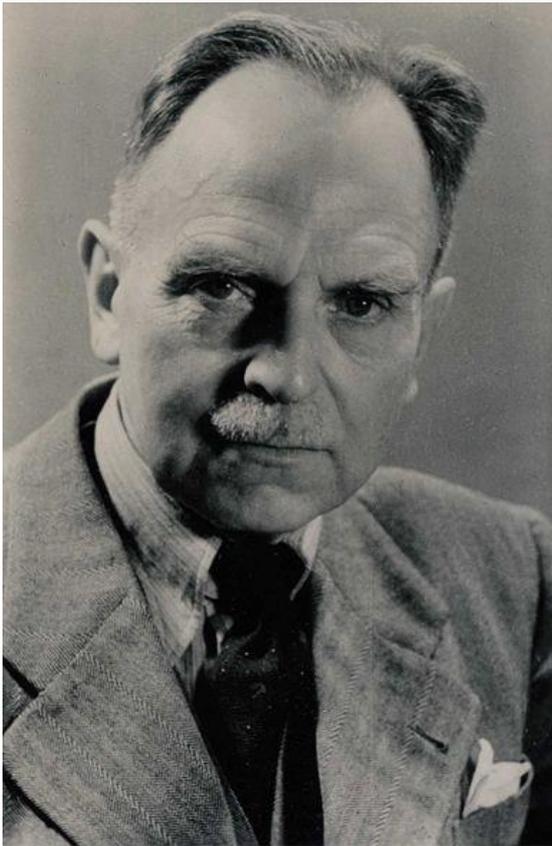
U-234 → U-235

U-238 → Pu-239

Pu-238 → Pu-239

Pu-240 → Pu-241

HOW TO BREAK A NUCLEUS?



- Otto Hahn (1879-1968)
- 17 December 1938 – first confirmed uranium fission
- 15 November 1945 – Nobel Prize in chemistry

NUCLEAR REACTIONS WITH NEUTRONS (MOST IMPORTANT)

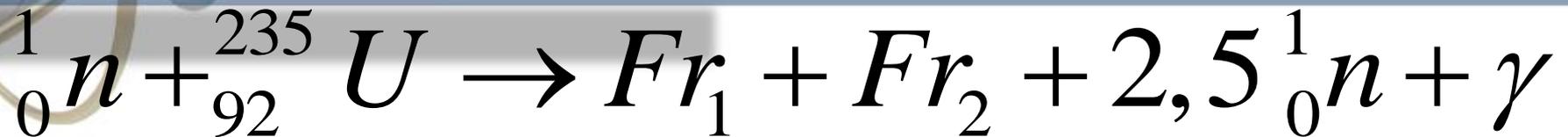
Absorption

- Fission(n,f)
- Radiative capture (n, γ)

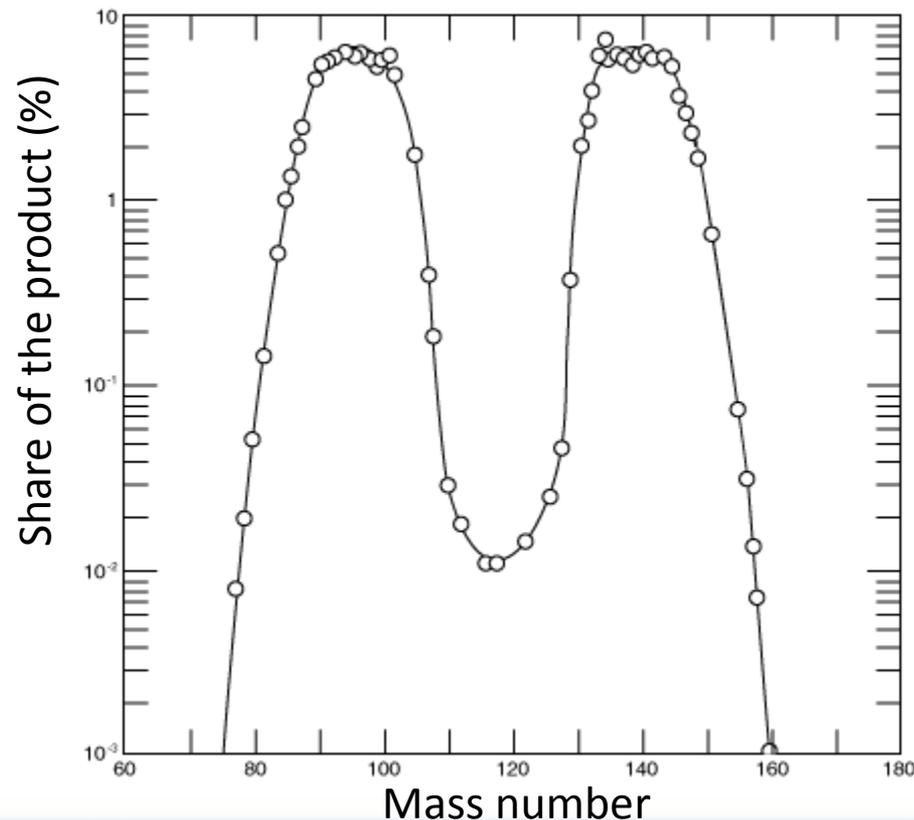
Scattering

- Elastic (n,n)
- Inelastic (n,n')

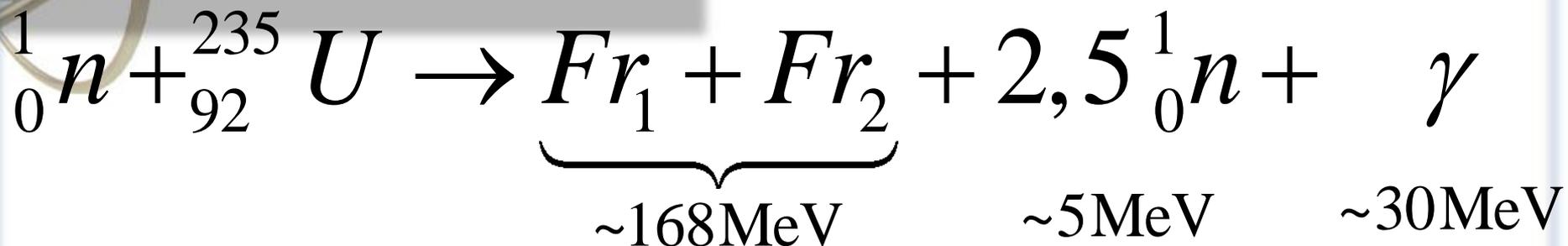
URANIUM FISSION



U-235 fission with thermal neutrons



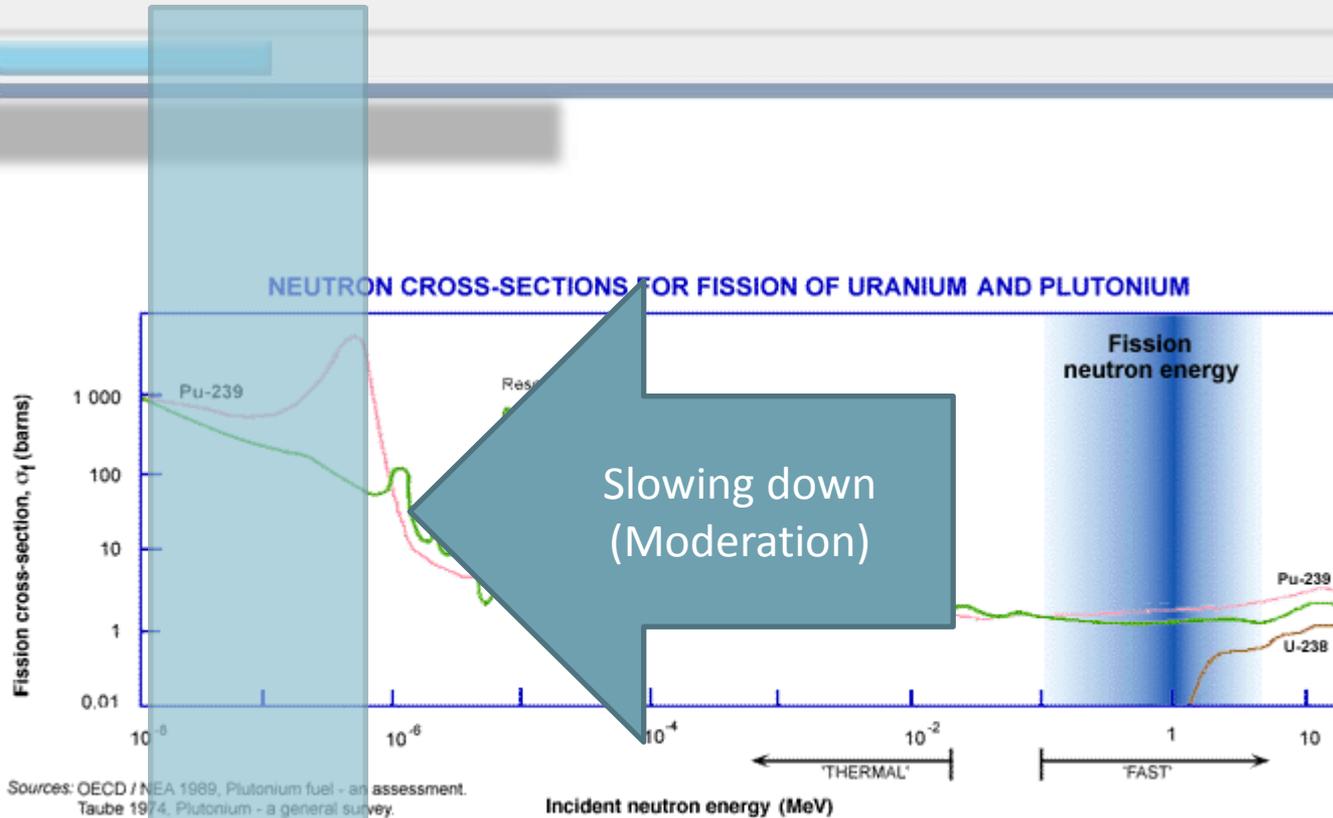
WHERE DOES THE ENERGY GO?



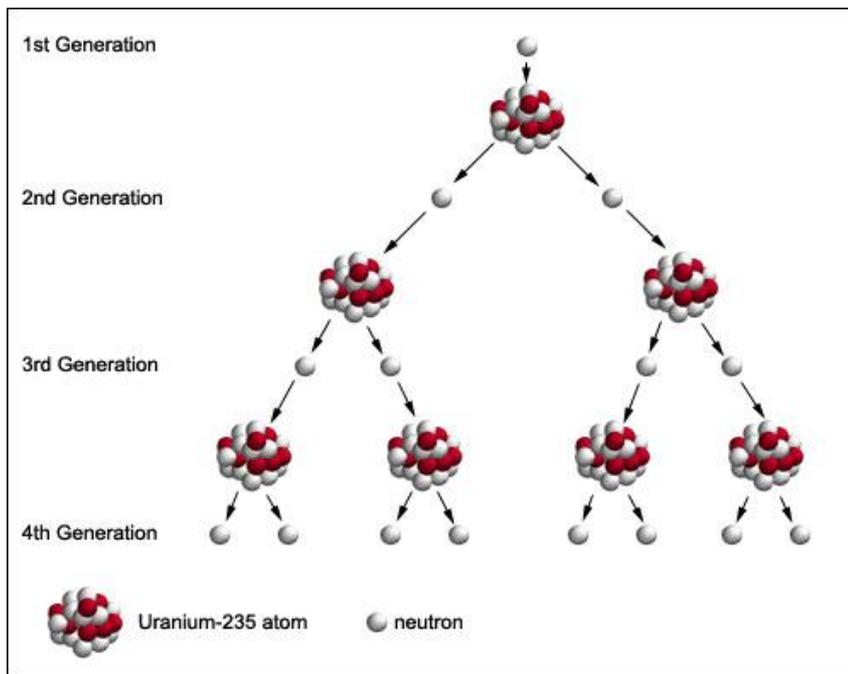
„A single atom is such a small thing that to talk about its energy in joules would be inconvenient. But instead of taking a definite unit in the same system, like 10^{-20} J, [physicists] have unfortunately chosen, arbitrarily, a funny unit called an electronvolt (eV) ... I am sorry that we do that, but that's the way it is for the physicists.”

R. Feynman (1961)

NEUTRON ENERGY



CHAIN REACTION



- Critical mass
- Neutron management
 - Slowing down (moderator)
 - Turning back (reflector)

WHAT DO WE USE TO SLOW DOWN?

- A perfect moderator:
 - Low atomic mass
 - Well reflects neutrons
 - Does not absorb neutrons

USED MODERATORS

Hydrogen(^1H)

- In form of water
- Absorbs neutrons – requires fuel enrichment

Deuterium (^2H , ^2D)

- As heavy water (D_2O)
- Allows to use natural uranium
- Expensive

Carbon

- Usually in form of graphite
- Can allow natural uranium usage

Beryllium

- Expensive
- Toxic

Lithium(^7Li)

- Lithium fluoride

ENERGY CONVERSION

- In micro-scale: kinetic energy
- In macro-scale: heat
- Recovering energy = reactor cooling
- Good coolant:
 - High specific heat
 - Low chemical activity
 - No neutron absorption

USED COOLANTS

Air

- Early research reactors, low output

Water

- Cheap and easy
- Can be simultaneously a moderator
- Can be directly used in power-generation circuit
- Absorbs neutrons

Carbon dioxide

Helium

- Expensive
- Inactive
- Can be used in high temperatures
- Może pracować w obiegu roboczym elektrowni

COMBINATIONS

H_2O

- PWR, BWR, VVER
- The same volume of water is coolant and moderator

$D_2O + D_2O$ or $D_2O + H_2O$

- CANDU reactors (Canada)

Graphite + CO_2

- GCR, AGR – no longer produced

Graphite + H_2O

- RBMK – including Charnobyl-4



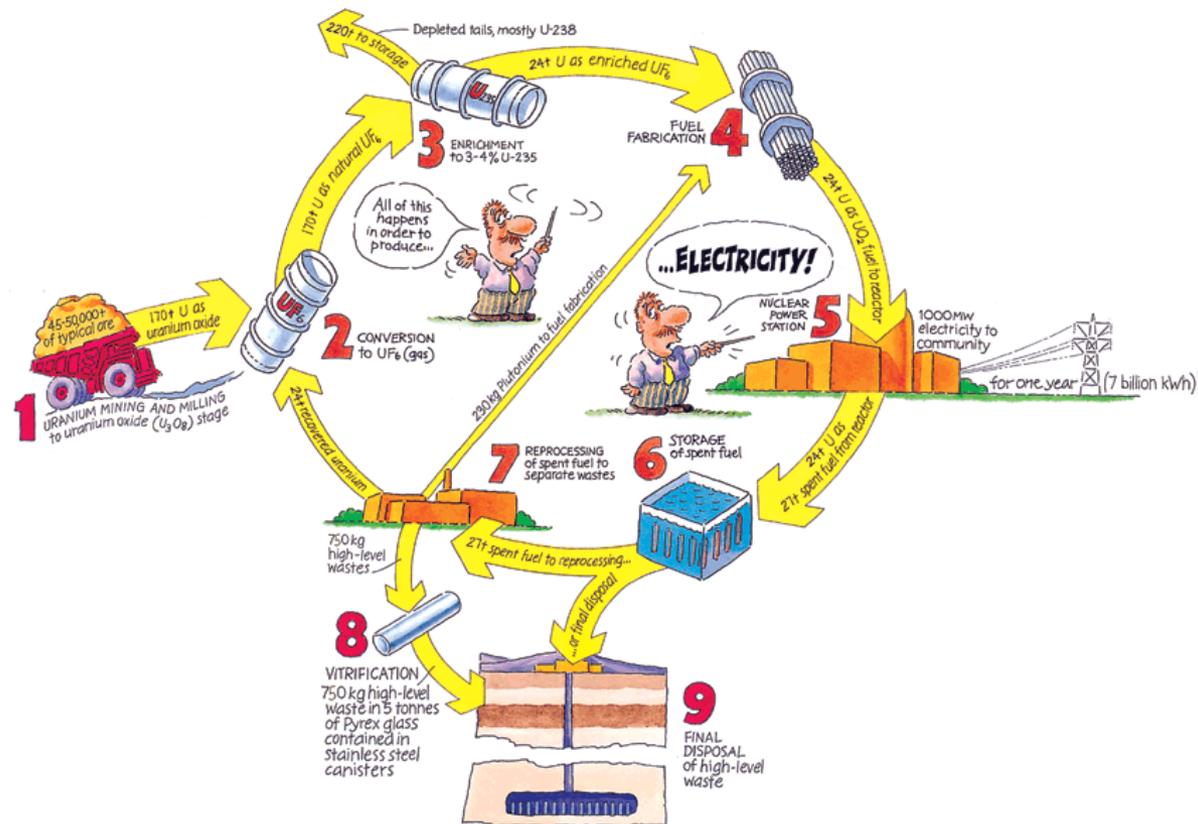
REACTION CONTROL

- Control rods
 - Sliding into the core
 - Made of a good neutron absorber (e.g. boron)
- Adding boric acid to the coolant (PWR)
- Adjustments of the water (moderator) flow through the core (BWR)

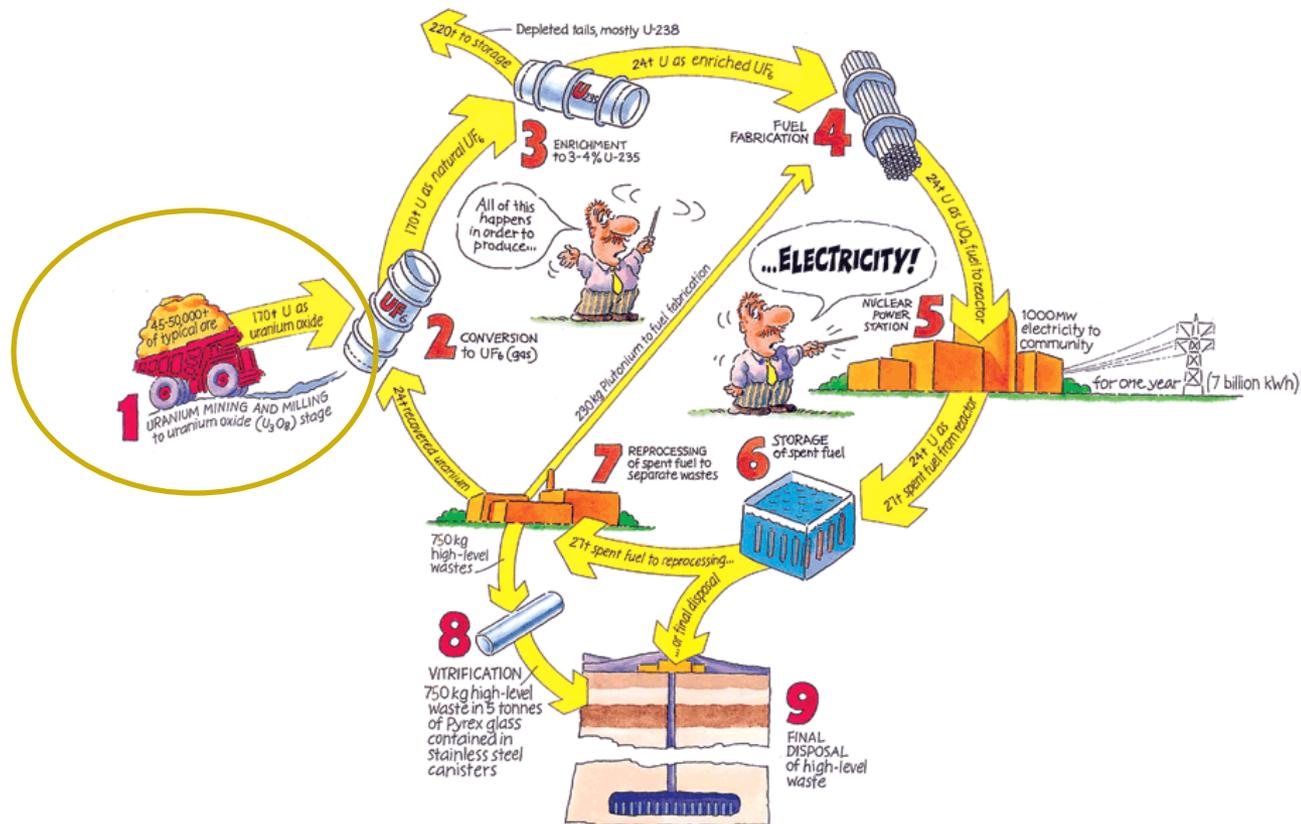
USED FUELS

- Uranium-235
 - Usually as uranium dioxide (UO_2)
 - Mined from natural deposits
 - Usually enriched to 4-5% U-235
- MOX – Mixed Oxide Fuel
 - Mixture of UO_2 and PuO_2
 - Plutonium recycled from spent fuel elements
 - Plutonium from dismantled nuclear warheads

FUEL CYCLE



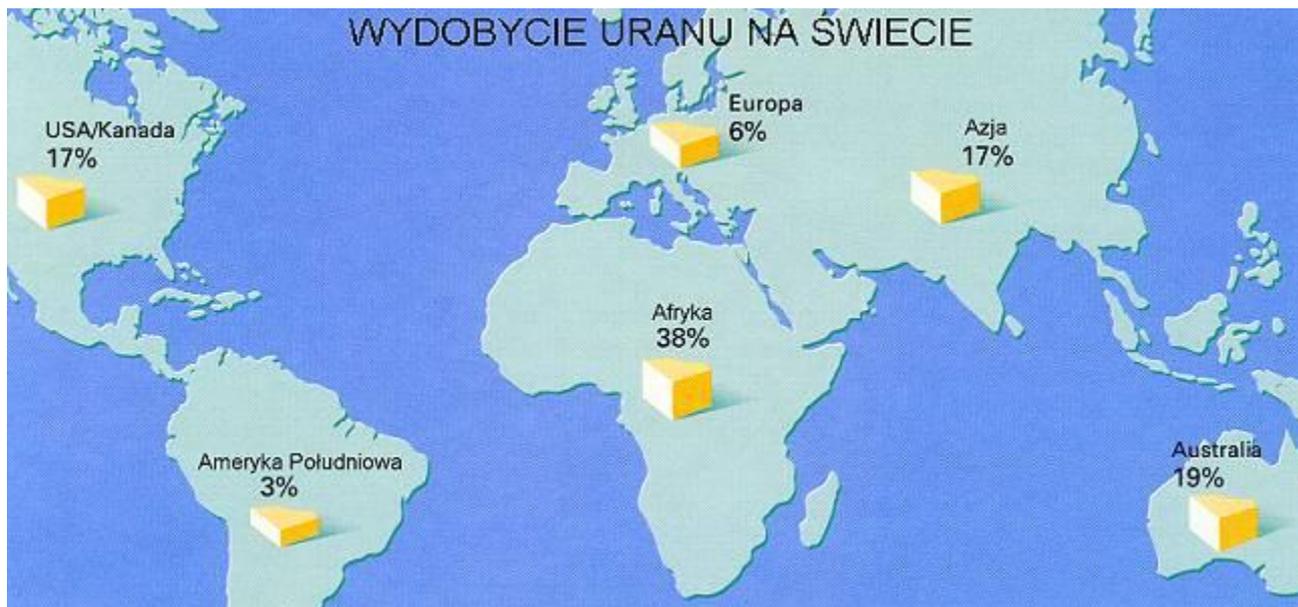
URANIUM ORE MINING



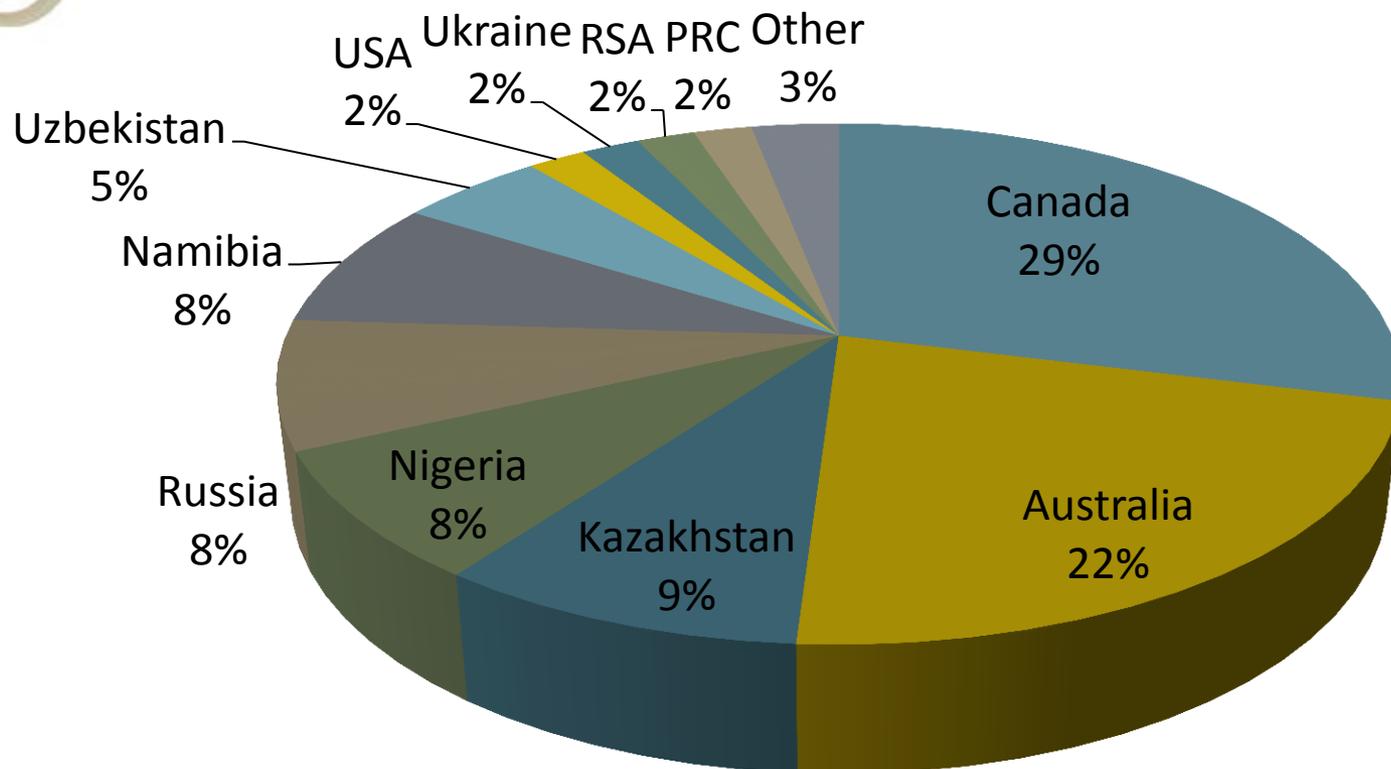
URANIUM ORE MINING



URANIUM ORE MINING



URANIUM ORE MINING



URANIUM MINERALS



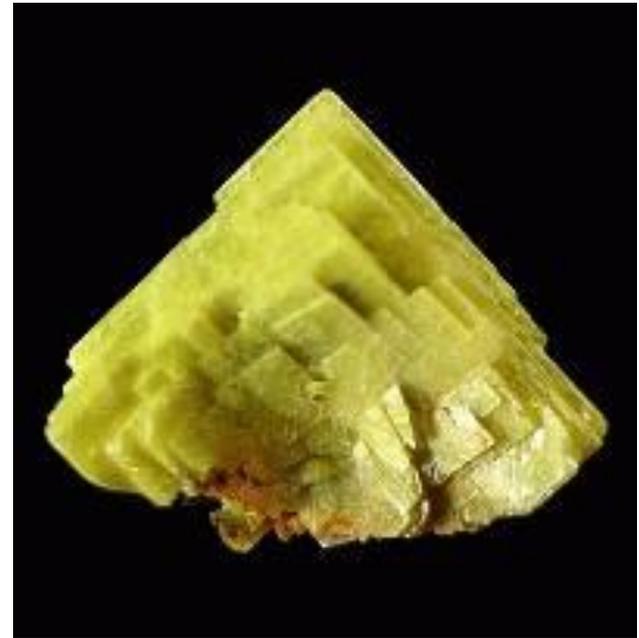
Uraninite – UO_2



Sklodowskite – $\text{Mg}(\text{UO}_2)_2(\text{HSiO}_4)_2 \cdot 5\text{H}_2\text{O}$



Carnotite – $\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 4\text{H}_2\text{O}$



Autunite – $\text{CaO}(\text{UO}_3)_2\text{P}_2\text{O}_5 \cdot 12\text{H}_2\text{O}$

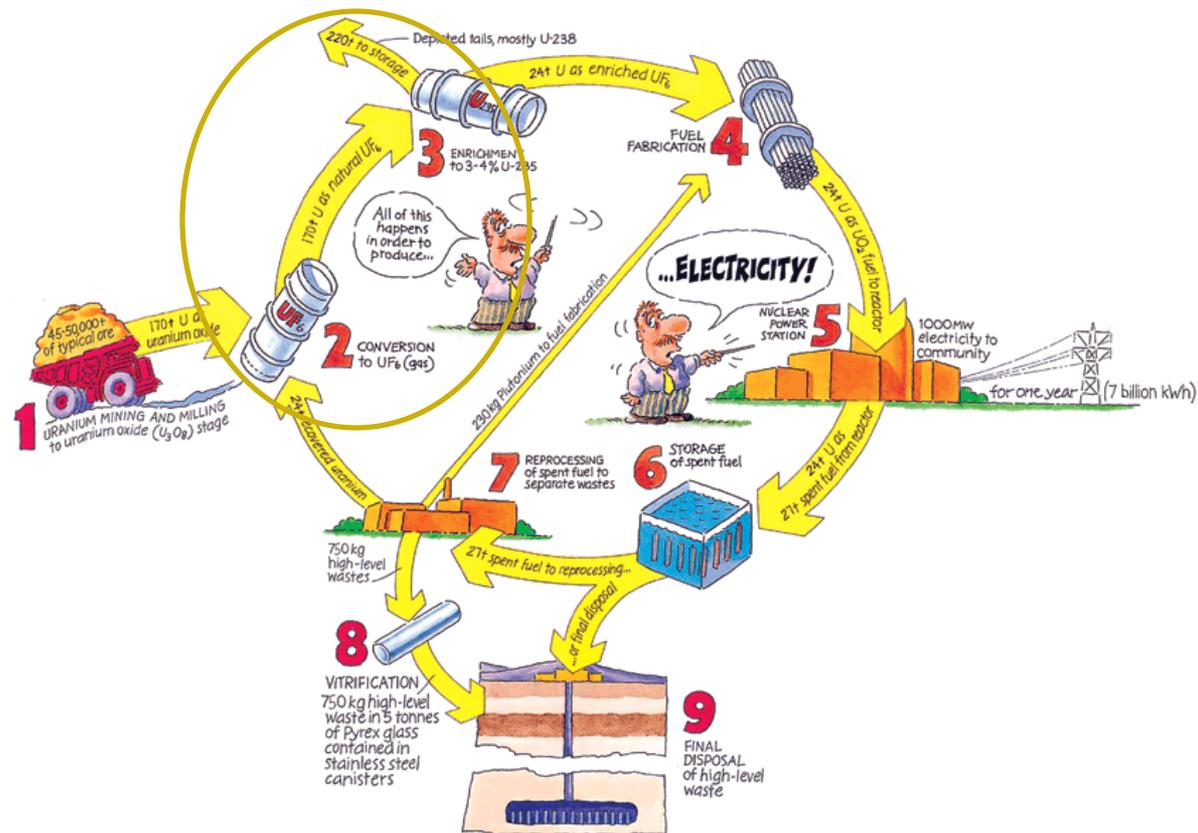
Exemplary uranium minerals

YELLOWCAKE



- Uranium concentrate
- ~80% U_3O_8
- Chemically stable

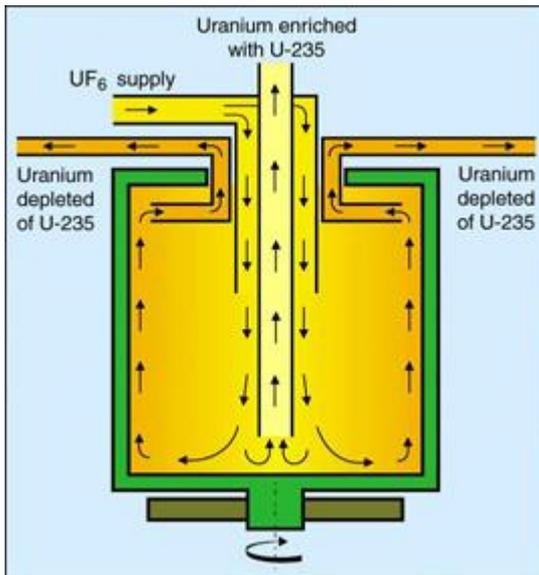
URANIUM ENRICHMENT



URANIUM ENRICHMENT

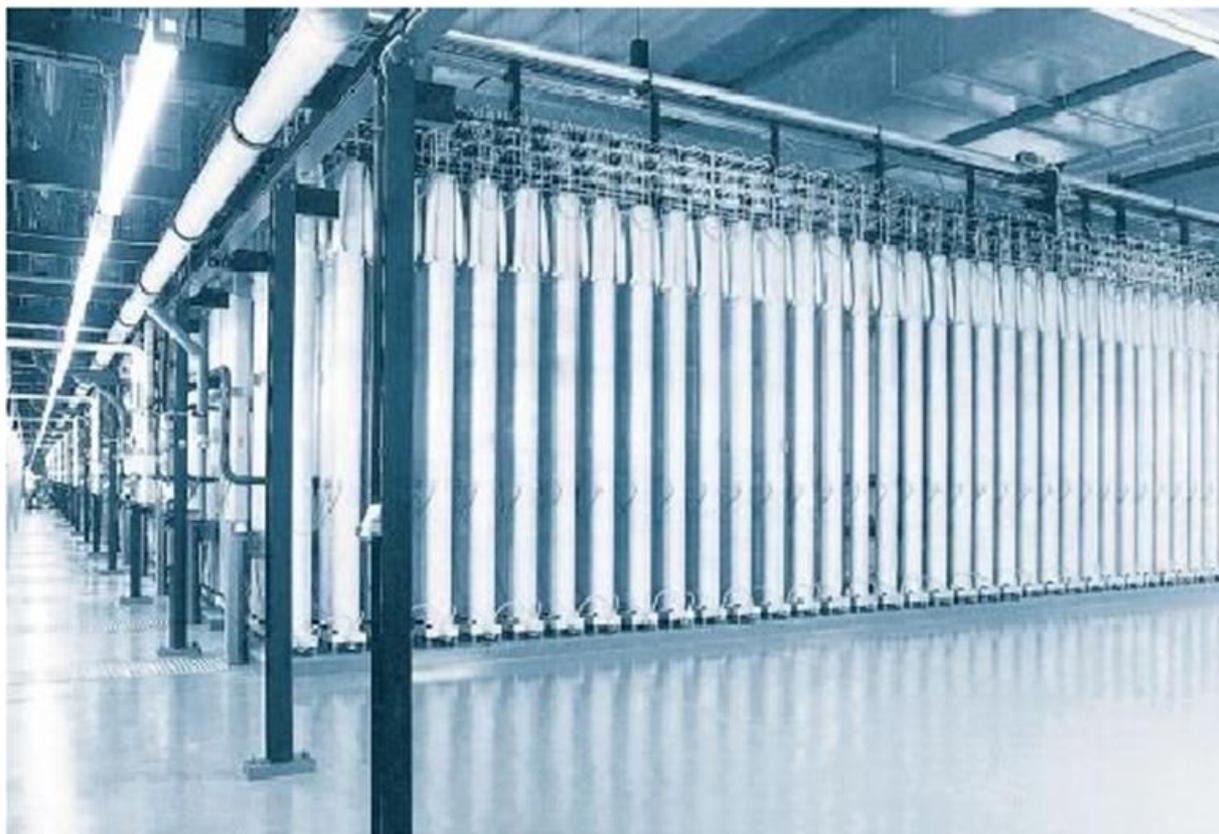
- There is only 0.72% U-235 in natural uranium
- Most power reactors need 3-4% U-235
- Enrichment = increasing U-235 content in uranium mass
- Physical methods – based on mass difference
- Enrichment carried out in UF_6 gas

ENRICHMENT CENTRIFUGES



- Using mass difference
- Lighter U-235 concentrates near the axis
- Centrifuge cascade needed to obtain proper enrichment level

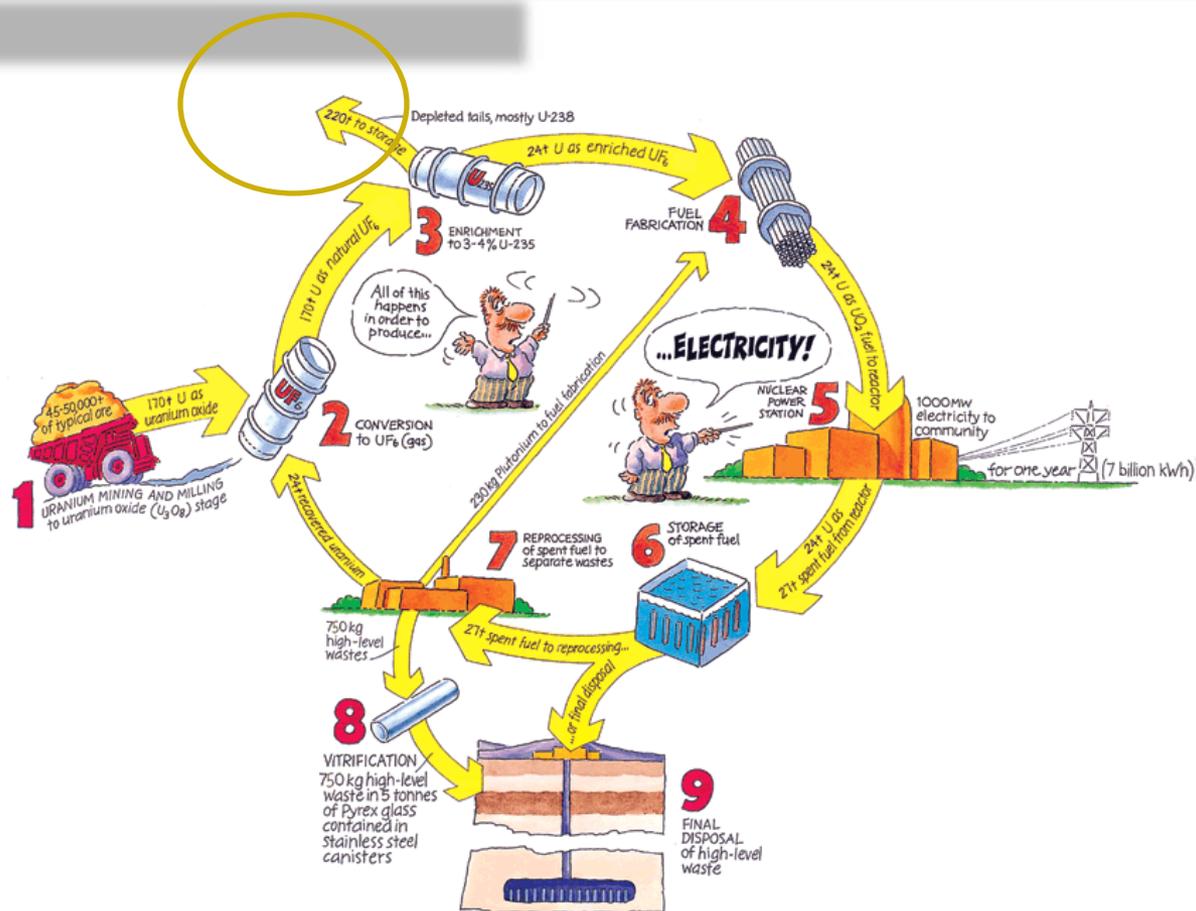
CENTRIFUGE CASCADE



CENTRIFUGE CASCADE

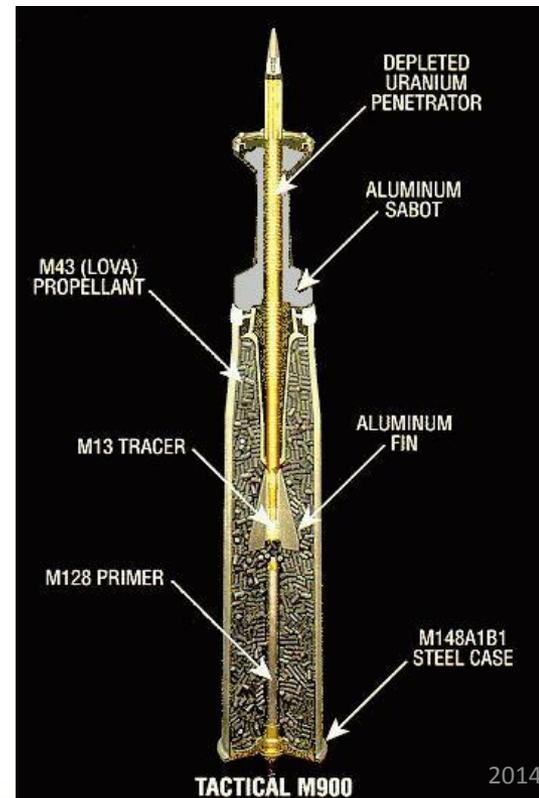


WHAT ABOUT THE REST?

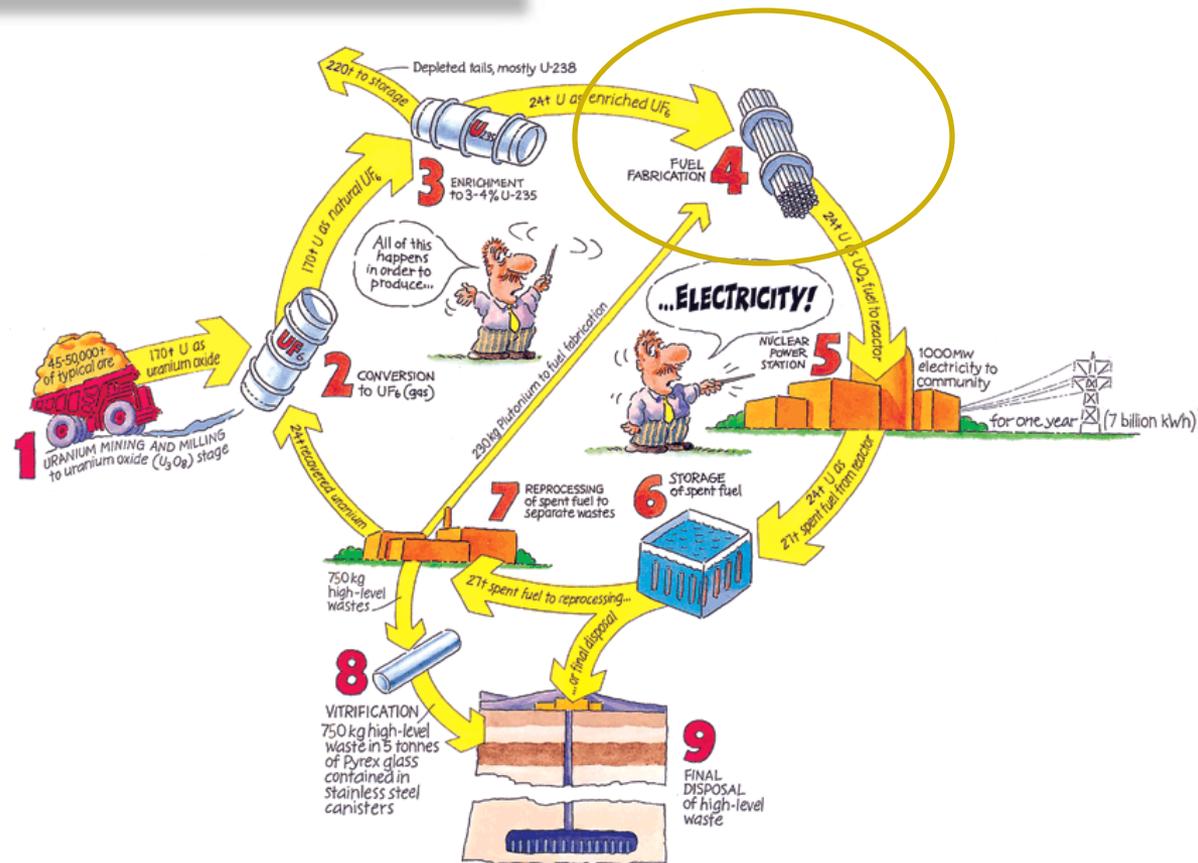


USAGE OF DEPLETED URANIUM

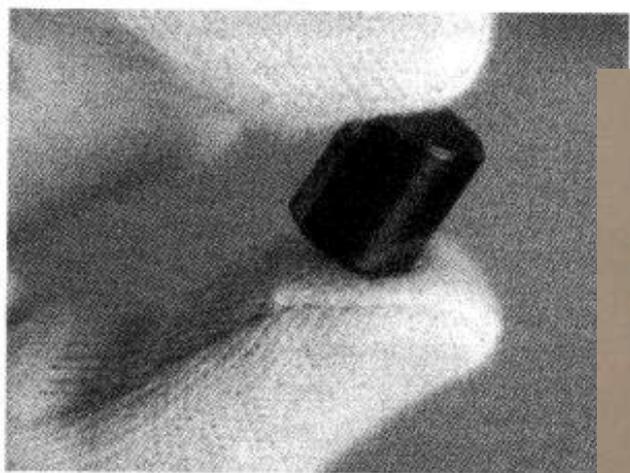
- Biological shields (medical diagnostics)
- Dyes
- Aircraft counterweights
- Armour plates
- Armour-piercing projectiles



FUEL PRODUCTION



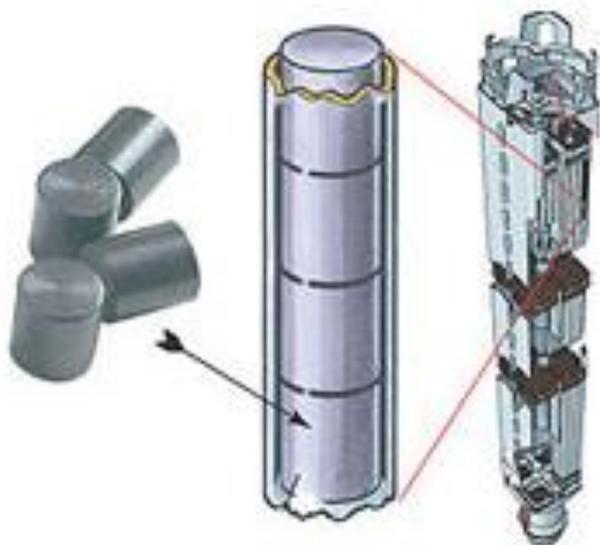
NUCLEAR FUEL - UO₂ PELLETS



One pellet of **10g** can be used to generate **600 kWh** of electricity

It is ca. $\frac{1}{4}$ of annual electricity consumption by one Polish household.

NUCLEAR FUEL



Uranium
dioxide

Fuel
pellets

Fuel rods

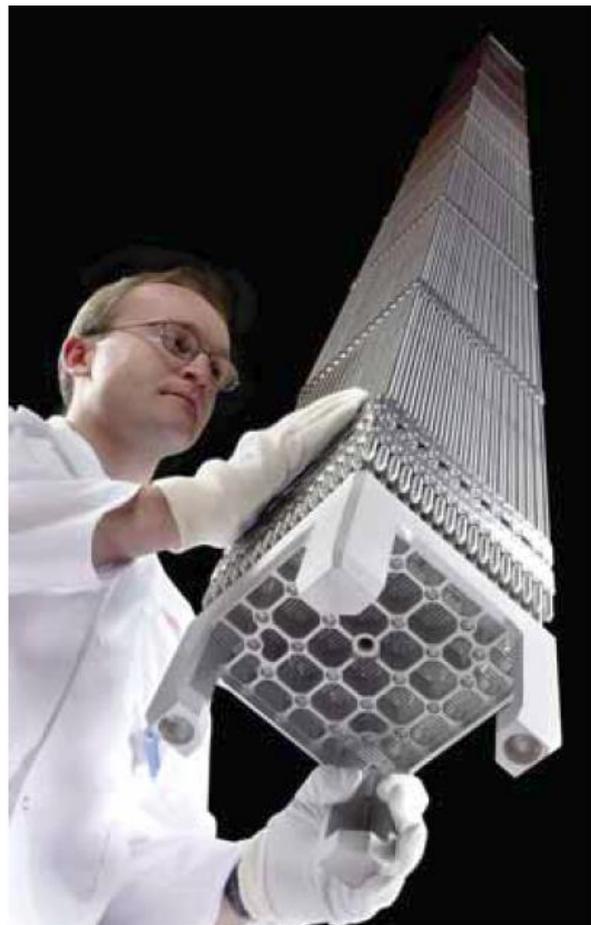
Fuel
bundles



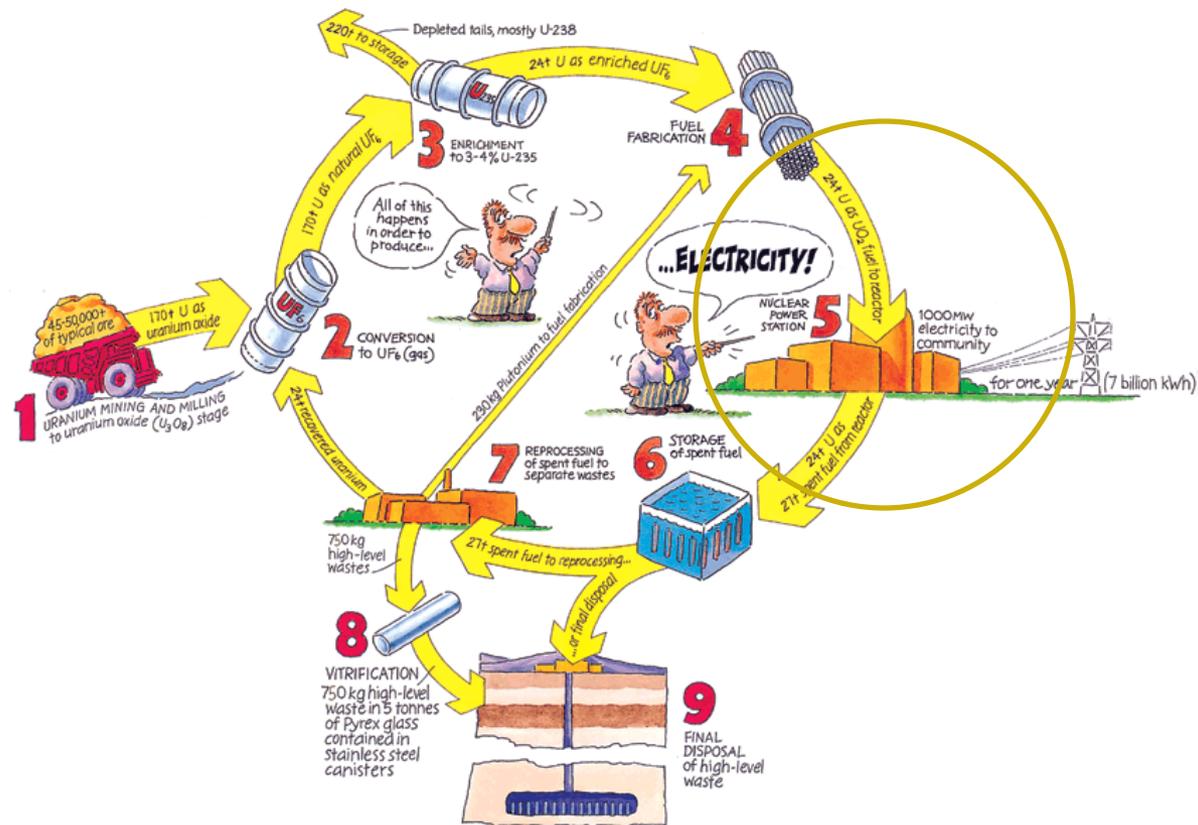
FUEL ASSEMBLY



Source: Babcock and Wilcox Company



FUEL CONSUMPTION

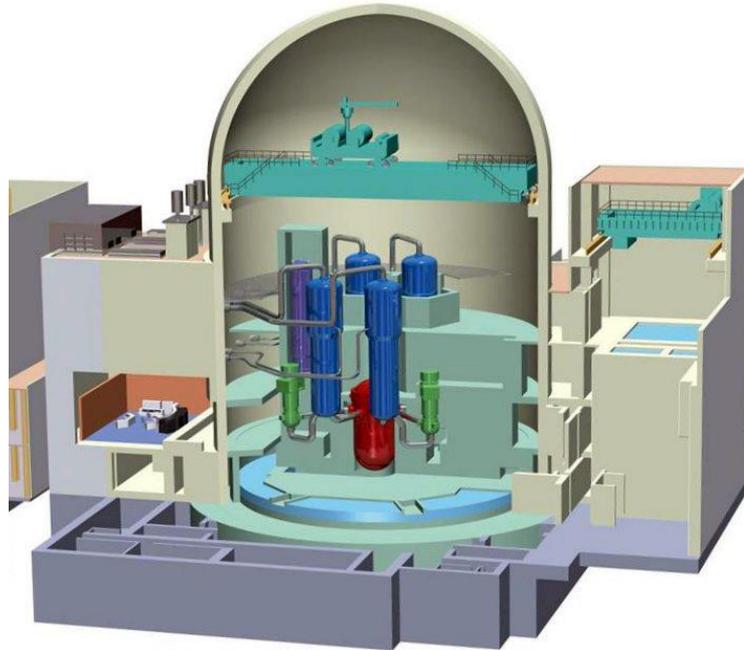


NUCLEAR REACTOR

- Device where controlled chain nuclear reaction occurs
- Needs appropriate control systems
- Needs proper cooling

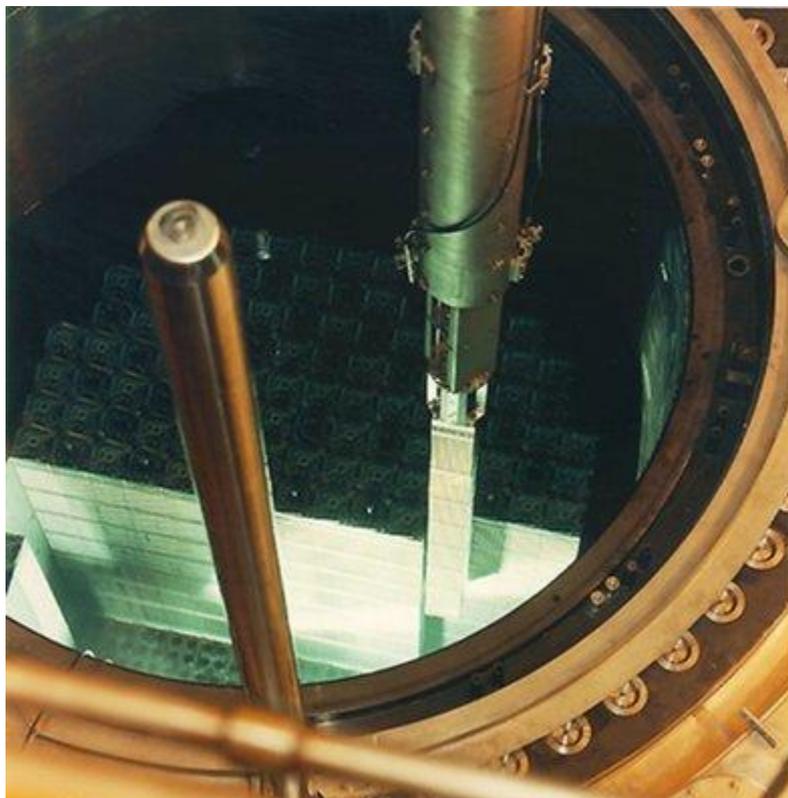
NUCLEAR REACTOR

Typical Pressurized Water Reactor

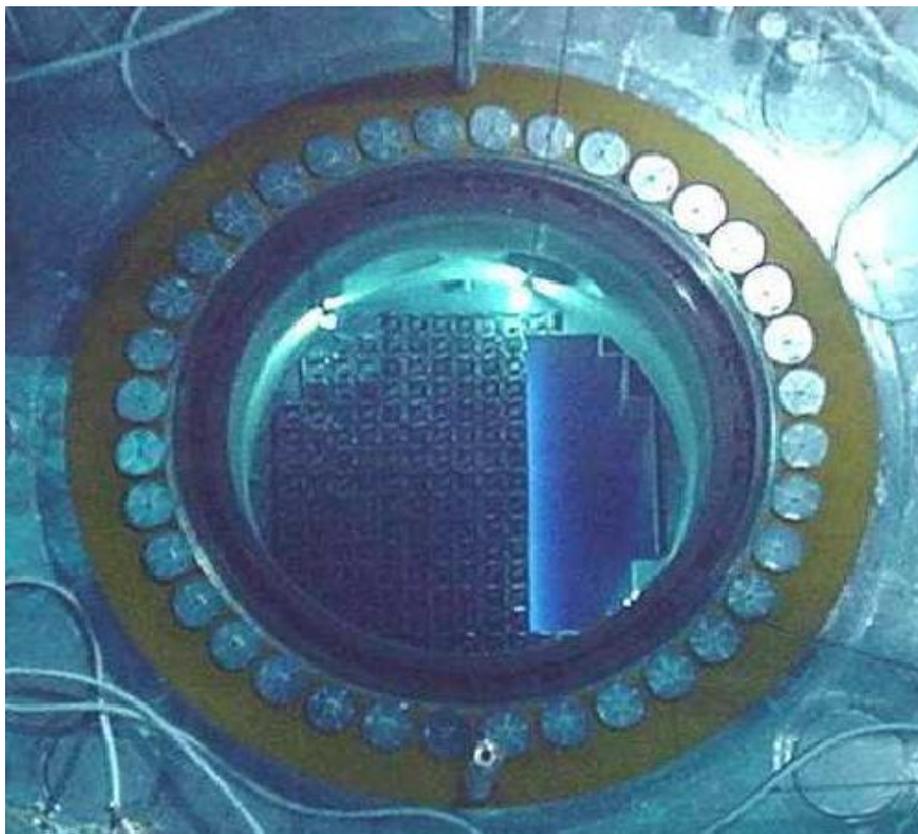


Source: U.S. Nuclear Regulatory Commission

NUCLEAR REACTOR



NUCLEAR REACTOR



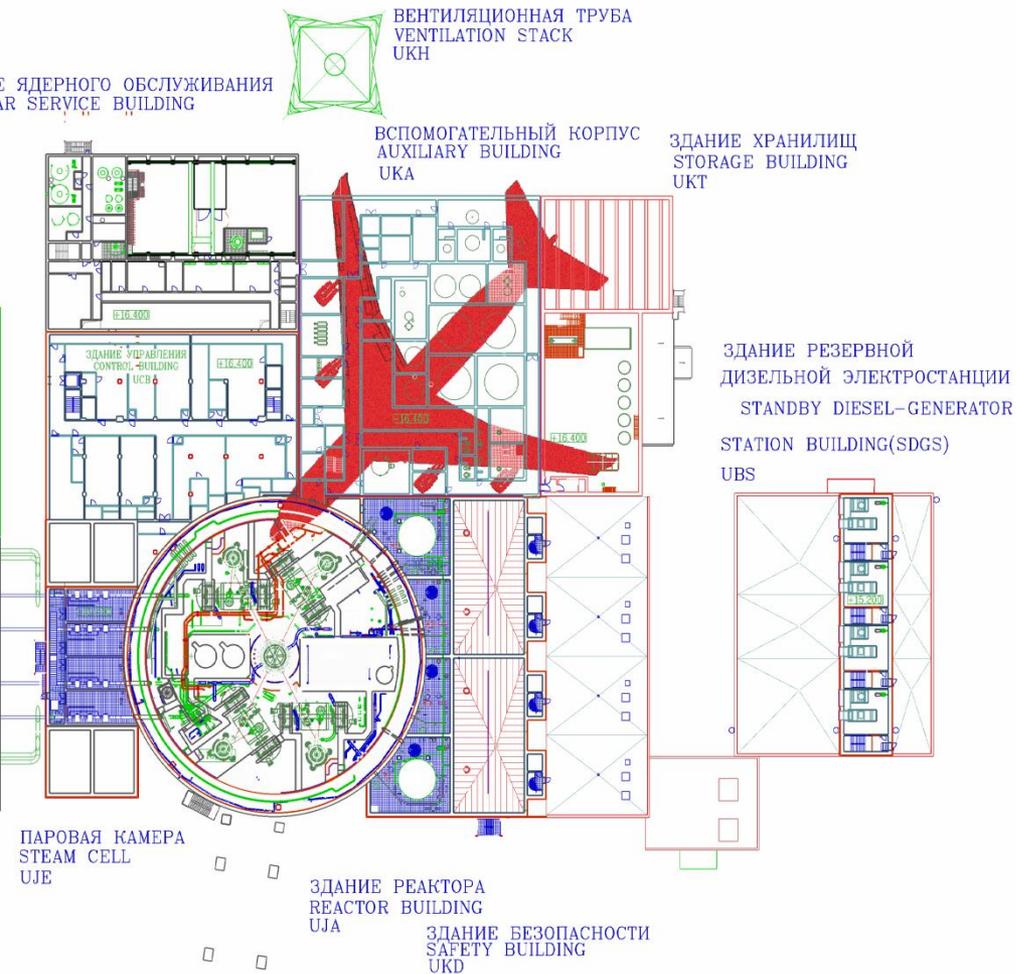
NUCLEAR REACTOR



REACTOR OPERATION

- Fission is carried out within the fuel pellets
- Radioactive fission products are contained within the fuel elements
- Safety barriers:
 - Pellet structure (for solids)
 - Fuel element cladding
 - Integral coolant (primary) circuit
 - Biological shield (concrete, water)
 - Containment (concrete)
- Heat is transferred through the cladding into coolant

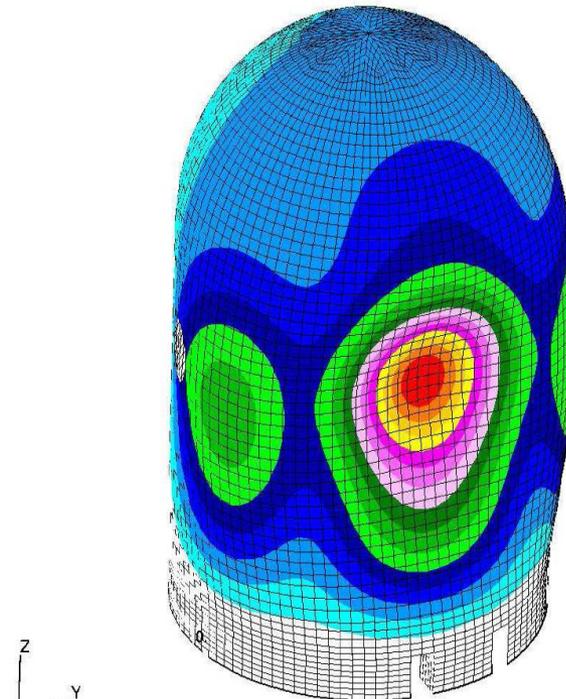
REACTOR CONTAINMENT



MSC/PATRAN Version 7.6

Fringe: AIRCRAFT_3, Time=0.206: Displacements, Translational-(NON-LAYERED) (MAG)

Deform: AIRCRAFT_3, Time=0.206: Displacements, Translational-(NON-LAYERED)



3.40-02

3.18-02

2.95-02

2.72-02

2.49-02

2.27-02

2.04-02

1.81-02

1.59-02

1.36-02

1.13-02

9.07-03

6.80-03

4.54-03

2.27-03

5.12-09

default Fringe:

Max 3.40-02 @ Nd 3458

Min 0. @Nd 2

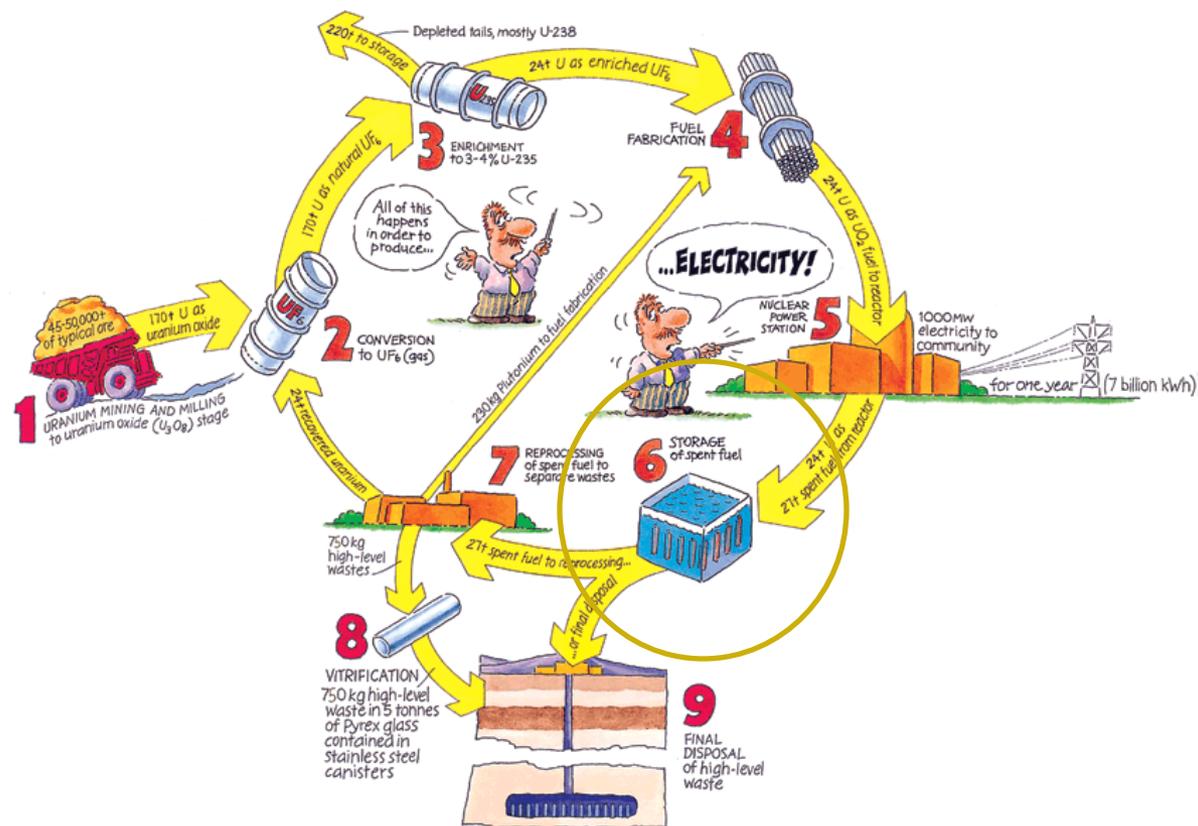
default Deformation:

Max 3.40-02 @ Nd 3458

REACTOR CONTAINMENT

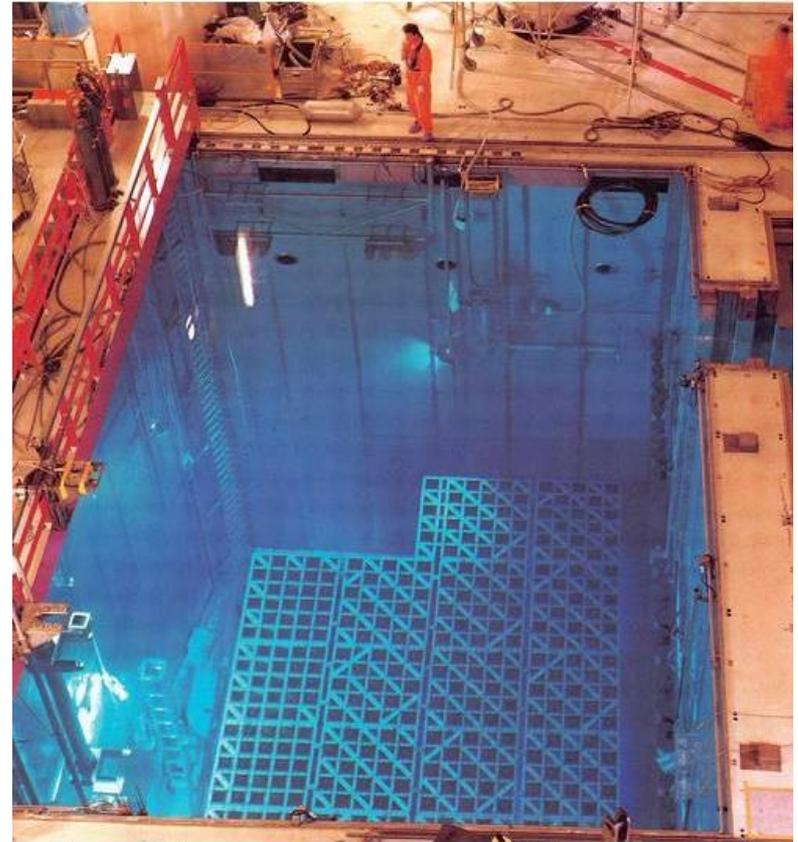


SPENT NUCLEAR FUEL

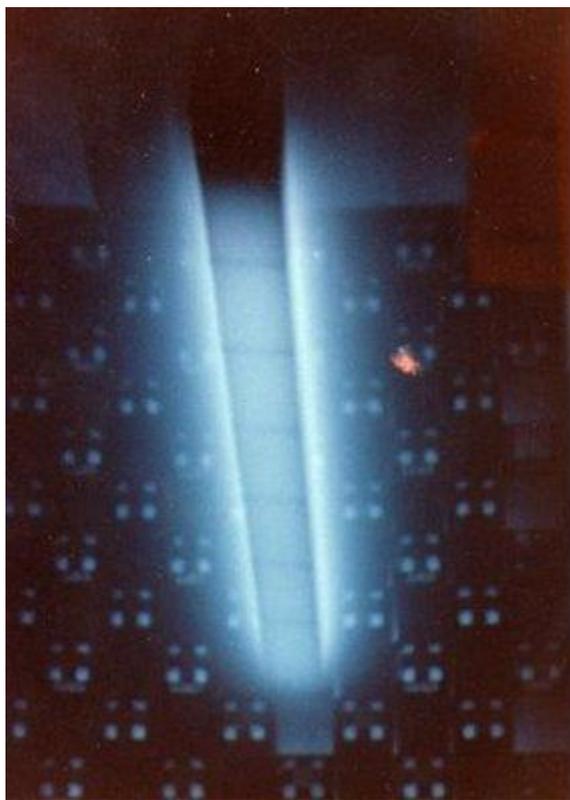


SPENT NUCLEAR FUEL

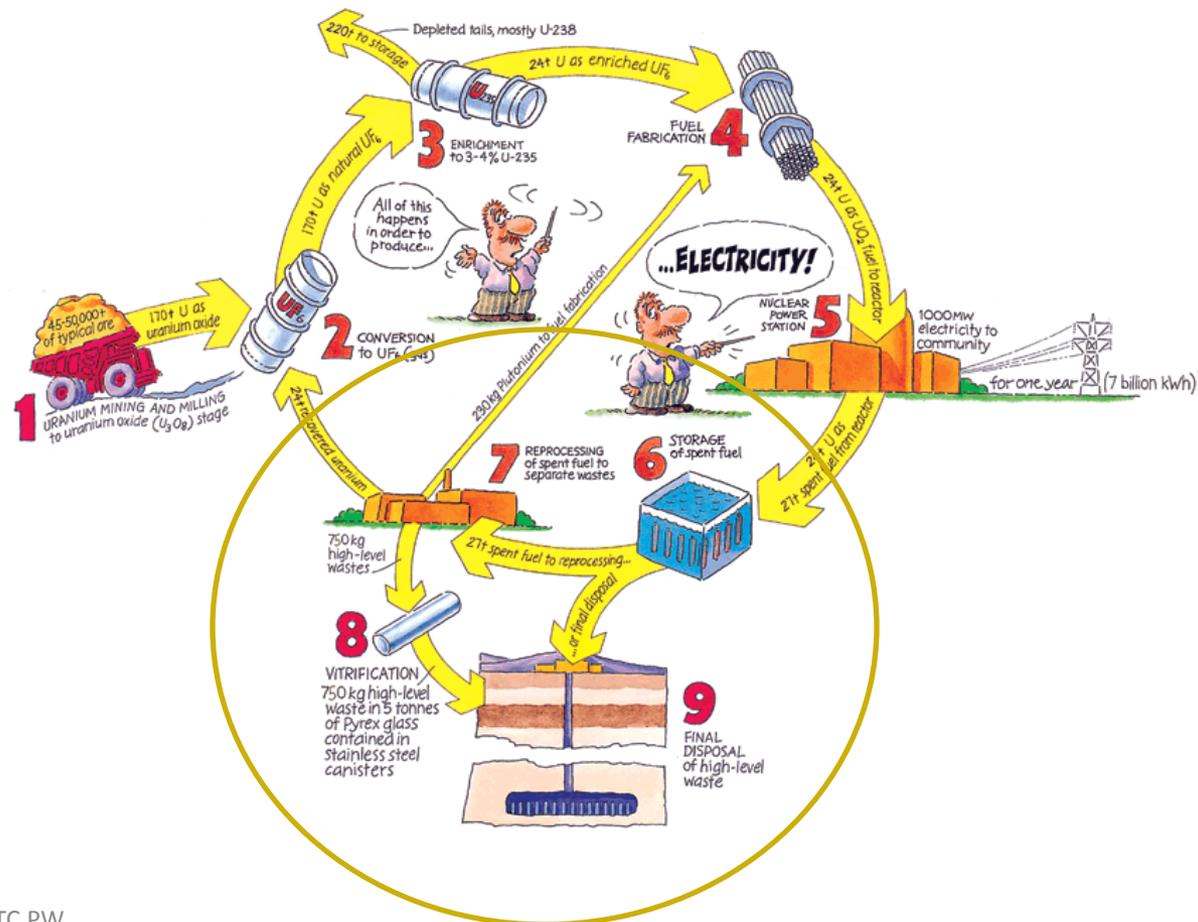
- Spent fuel elements hold short and medium-lived fission products which keep decaying
- They have to be cooled until the activity drops (after several years)
- Initial storage na pool next to the reactor



SPENT NUCLEAR FUEL



SPENT NUCLEAR FUEL



SPENT FUEL TRANSPORT



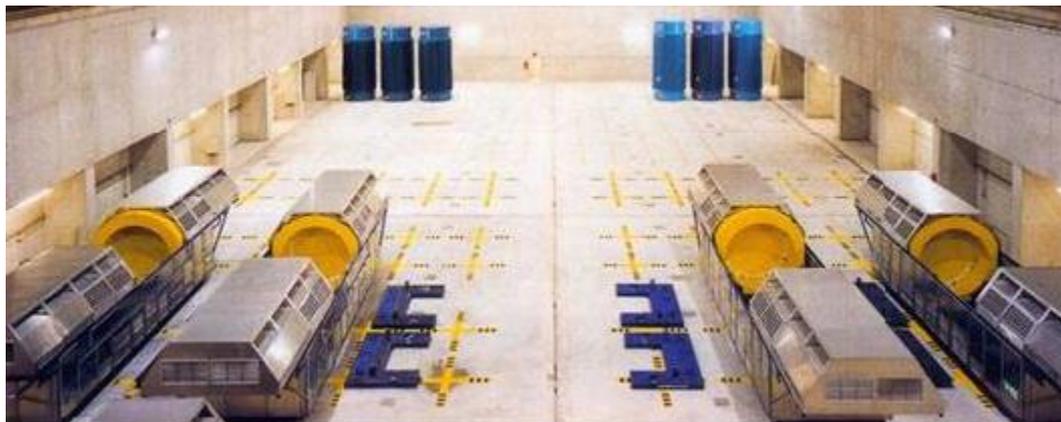
SPENT FUEL TRANSPORT



SPENT FUEL TRANSPORT



SPENT FUEL TRANSPORT

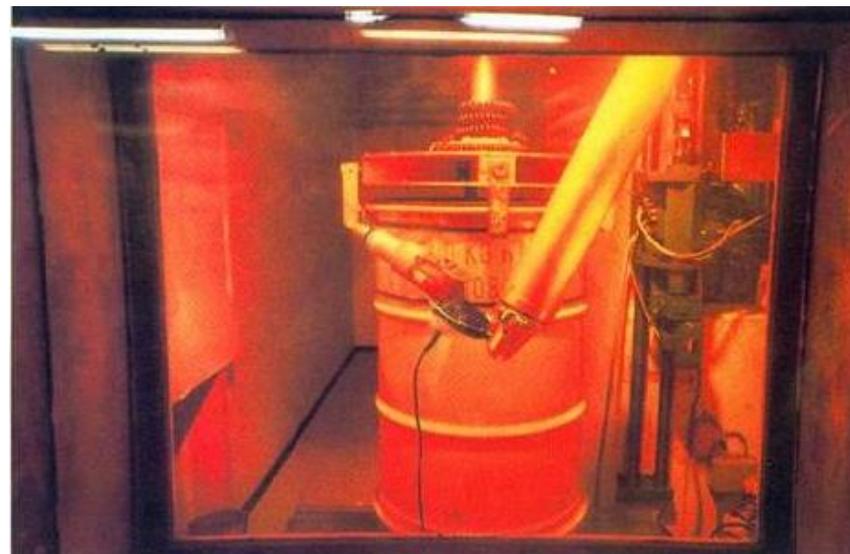


„Spent nuclear fuel cask test” →
youtube.com

SPENT FUEL TRANSPORT

- There is a certain amount of unused U-235 in spent fuel elements
- Fissile Pu-239 is formed in the fuel elements
- Those isotopes can be recycled into fresh fuel elements

NUCLEAR FUEL RECYCLING



RADIOACTIVE WASTE

Low-activity

- Compressed, concentrated or combusted
- Cemented in barrels

Medium-activity

- Grinded down
- Cemented in barrels

High-activity

- Melted into glass blocks (vitrified)

HOW MUCH WASTE?

Lignite-fired PP

- 290 kg/s lignite
1040 Mg/h
25,000 Mg/d
9 mi. Mg/a
- ~3 mi. Mg/a of ash

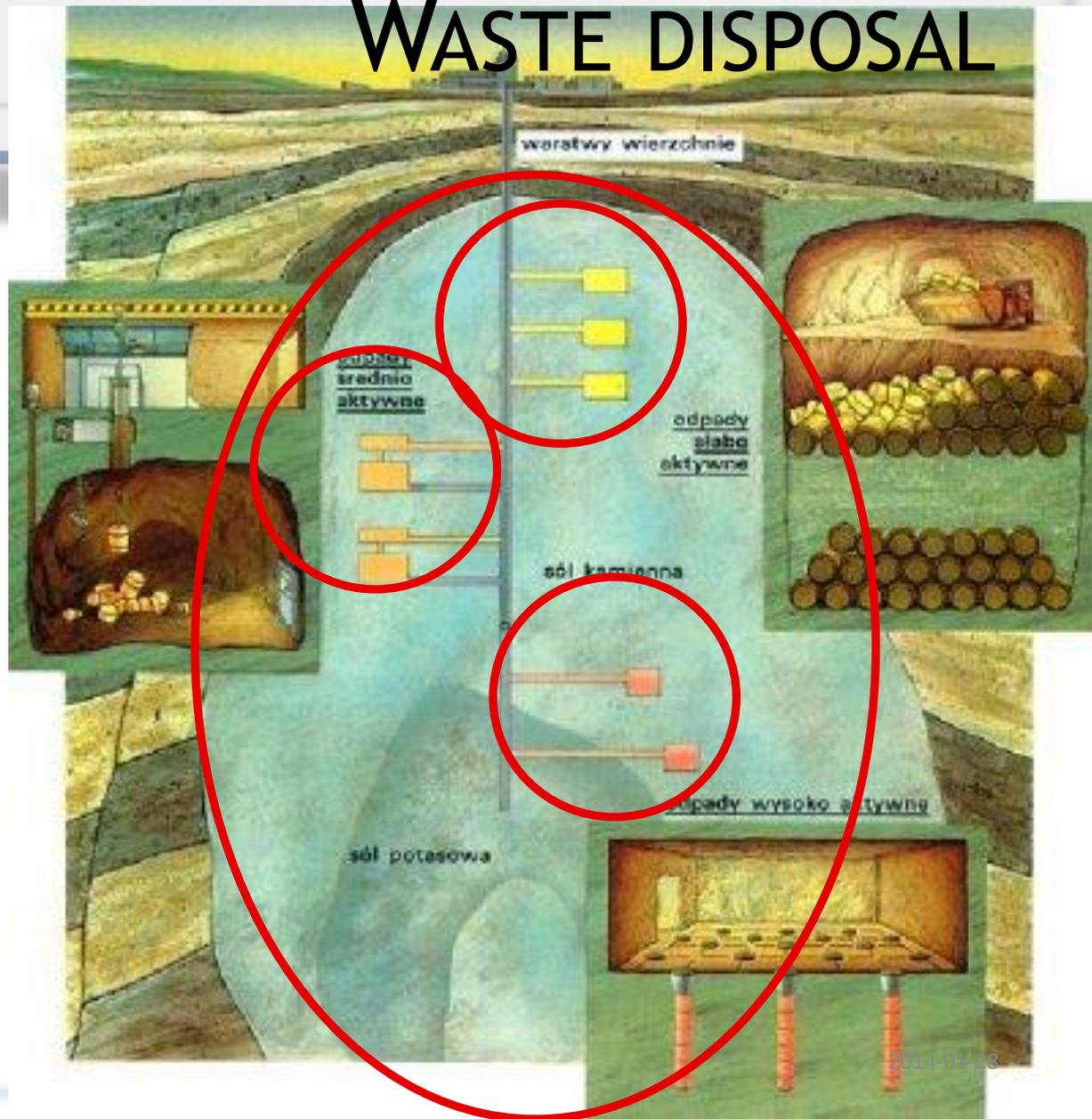
Nuclear Power Plant, 1300 MWe

- 30 Mg/a of fuel
- 55,000 Mg/a of uranium ore

- 30 Mg/a of spent fuel
- 4 m³ high-activity waste
- 60 m³ medium-activity waste
- 180 m³ low-activity waste



WASTE DISPOSAL



NUCLEAR SAFETY

Extreme design requirements

- Design has to deal with all physically possible malfunctions
- Safety from aircraft impact, unauthorized access etc.

Nuclear explosion is physically impossible

- Too low enrichment level
- Too small neutron energy (reaction cannot develop fast enough)

“Idiot-proofness”

- Safety systems independent from human operators
- Safety systems based on laws of physics not on automation prone to failures

ENVIRONMENTAL FOOTPRINT

Radiation

Noise

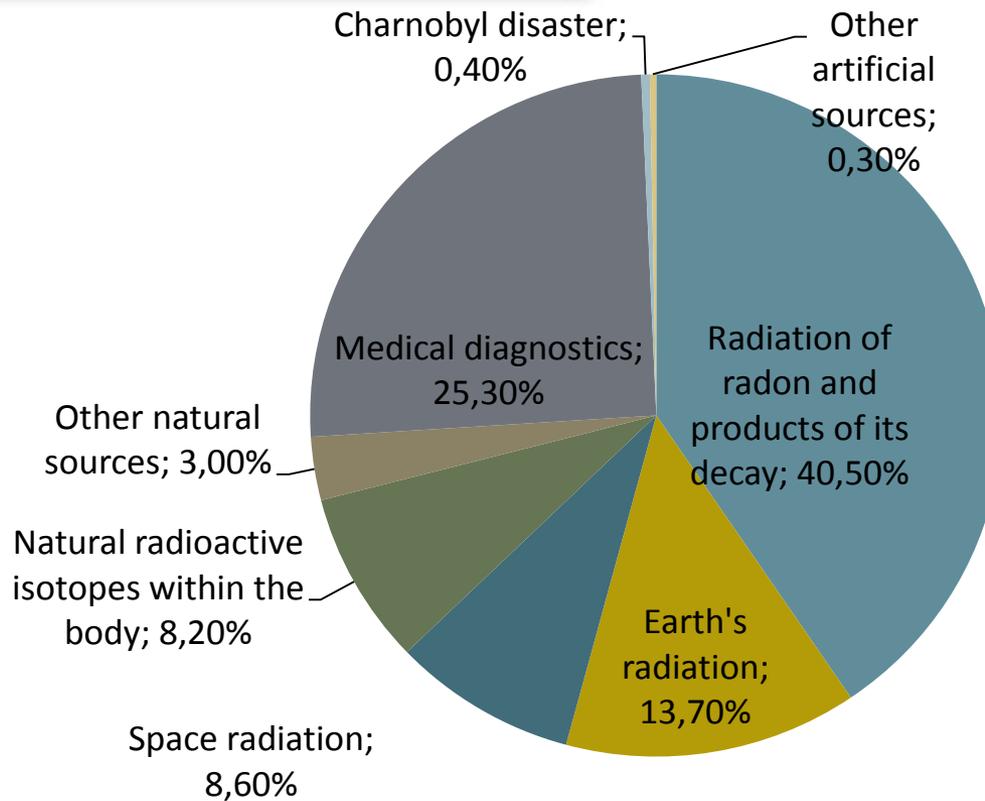
Cooling water

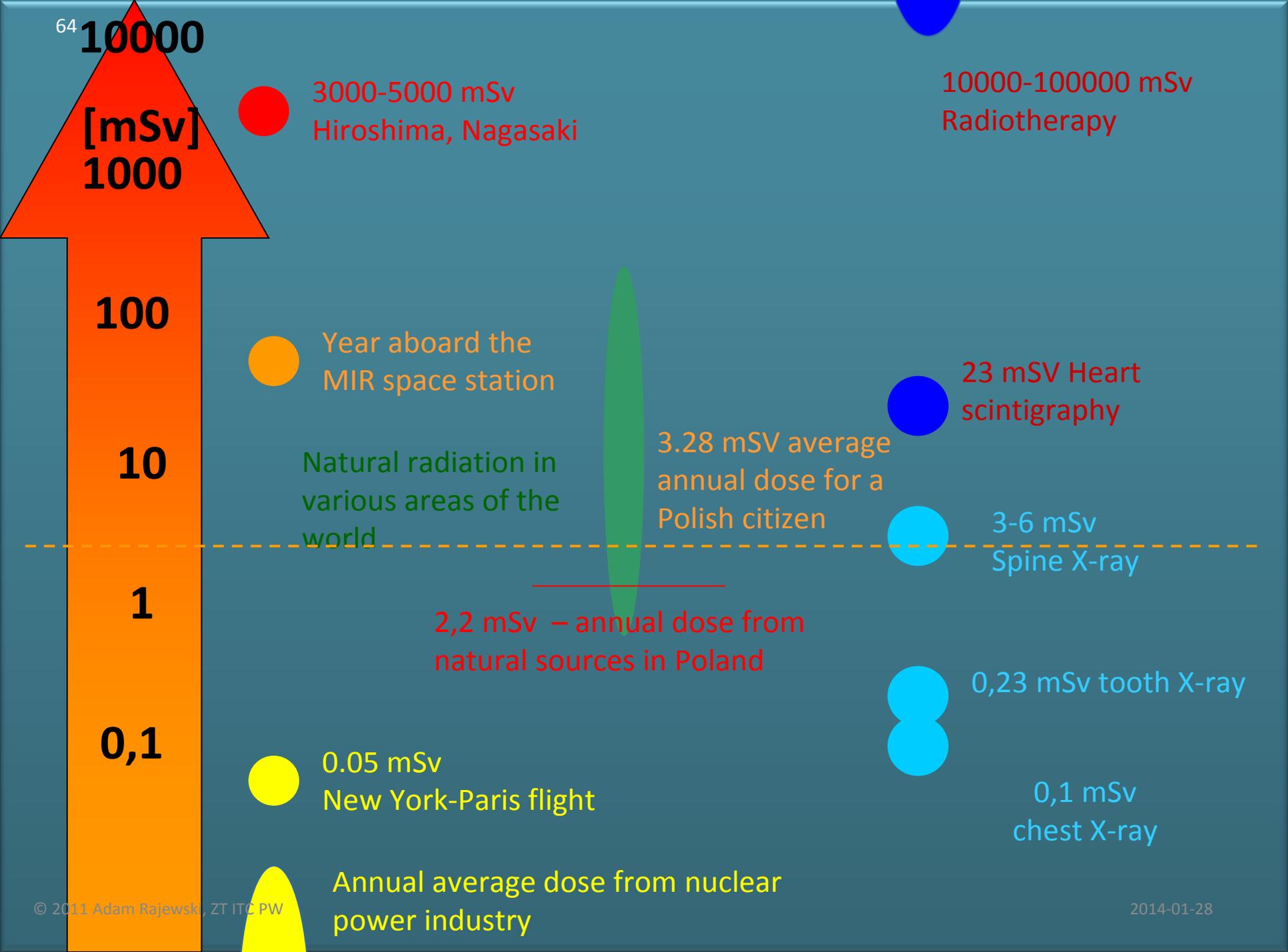
Fuel

Radioactive waste



ANNUAL RADIATION DOSE (POL)





64
10000
[mSv]
1000

● 3000-5000 mSv
 Hiroshima, Nagasaki

10000-100000 mSv
 Radiotherapy

100

● Year aboard the
 MIR space station

● 23 mSv Heart
 scintigraphy

10

Natural radiation in
 various areas of the
 world

3.28 mSv average
 annual dose for a
 Polish citizen

● 3-6 mSv
 Spine X-ray

1

2,2 mSv – annual dose from
 natural sources in Poland

0,1

● 0.05 mSv
 New York-Paris flight

● 0,23 mSv tooth X-ray

● 0,1 mSv
 chest X-ray

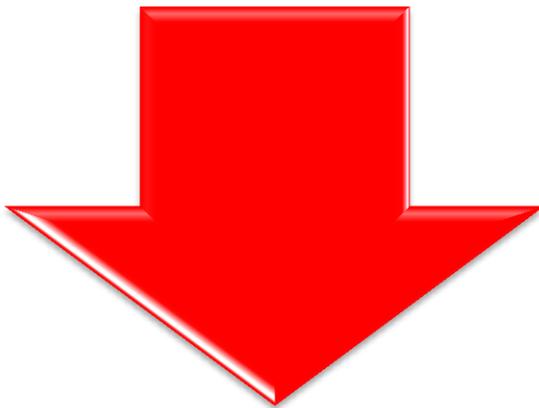
● Annual average dose from nuclear
 power industry

SUMMARY - ADVANTAGES AND DISADVANTAGES OF NUCLEAR POWER



Advantages:

- Low share of variable cost in operation (low sensitiveness to fuel cost)
- Very limited environmental footprint, no harmful gas emissions
- Fuel can be purchased at stable countries
- High reliability



Disadvantages:

- High investment cost
- Expensive and cumbersome decommissioning
- Social problems
- Low flexibility (not suitable for peaking operation)
- Waste issue not fully resolved



THANK YOU!