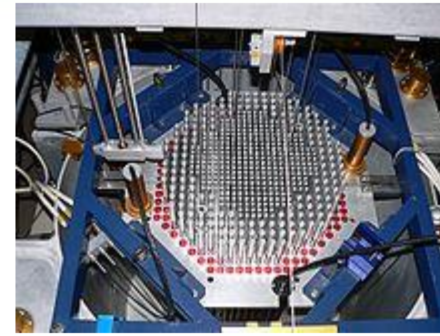


# NUCLEAR POWER IN SHORT

Adam Rajewski
Division of Thermodynamics
Institute of Heat Engineering

# Where does the energy come from?

$$E = mc^2$$

# Atomic nucleus

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

$$^{A}_{Z}X$$

# How much does the nucleus weigh?

- Z protons
- N neutrons

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

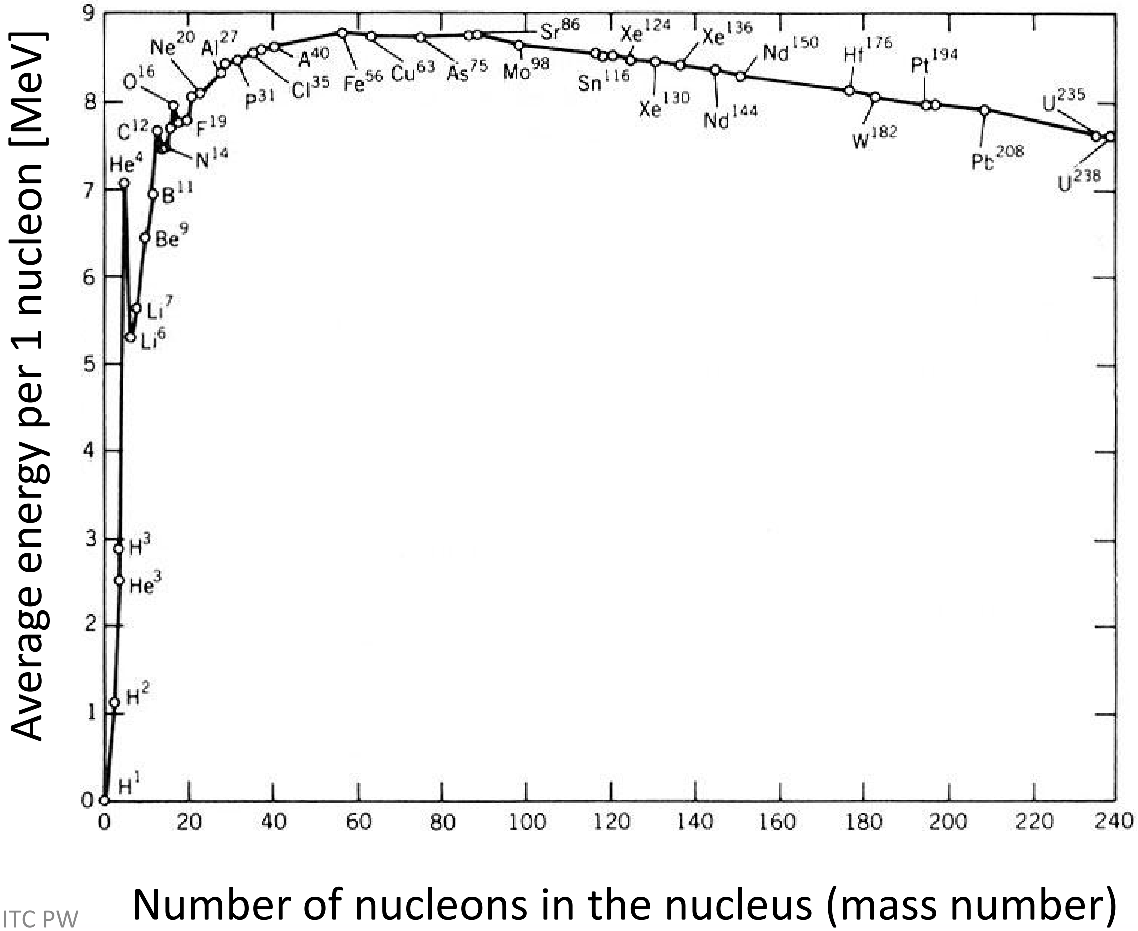
$$M < N \cdot m_n + Z \cdot m_p$$

**Mass Defect**

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

**Binding energy**

# Binding energy



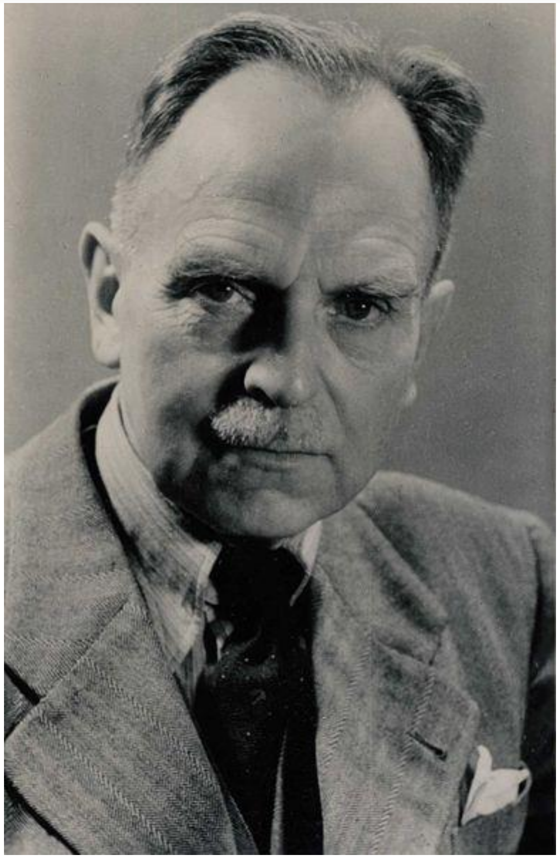
# Fissile isotopes

- 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 November1945 – Noble Prize in chemistry

# Nuclear reactions with neutrons (most important)

## Absorption

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

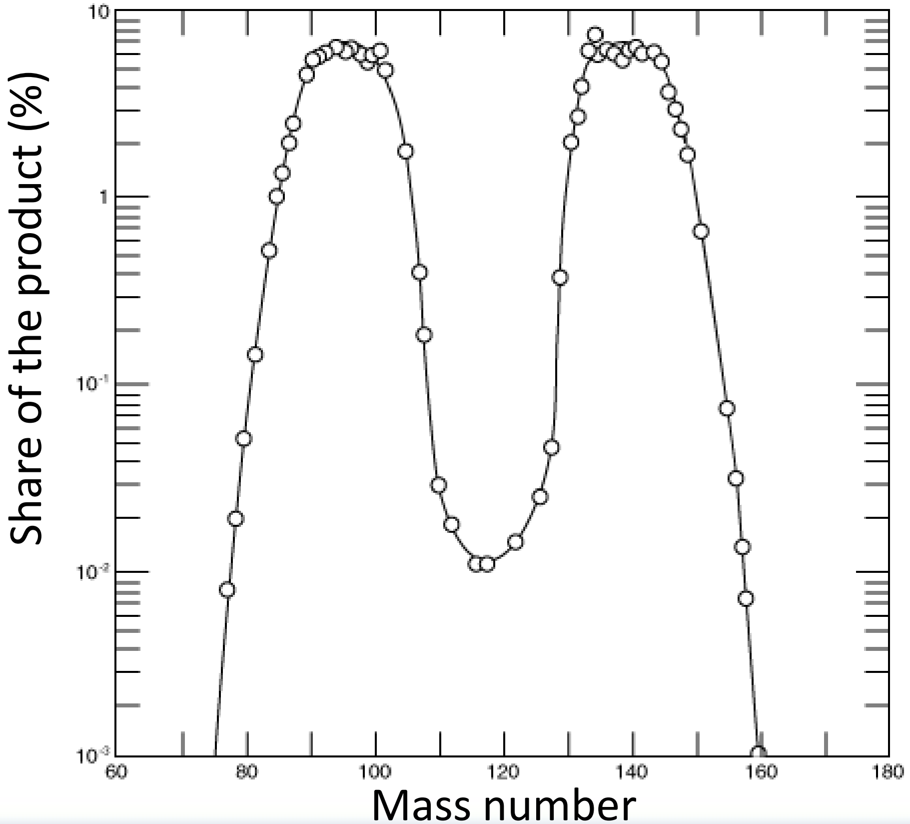
## Scattering

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

# Uranium fission

$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow Fr_1 + Fr_2 + 2,5\,{}_{0}^{1}n + \gamma $$

U-235 fission with thermal neutrons



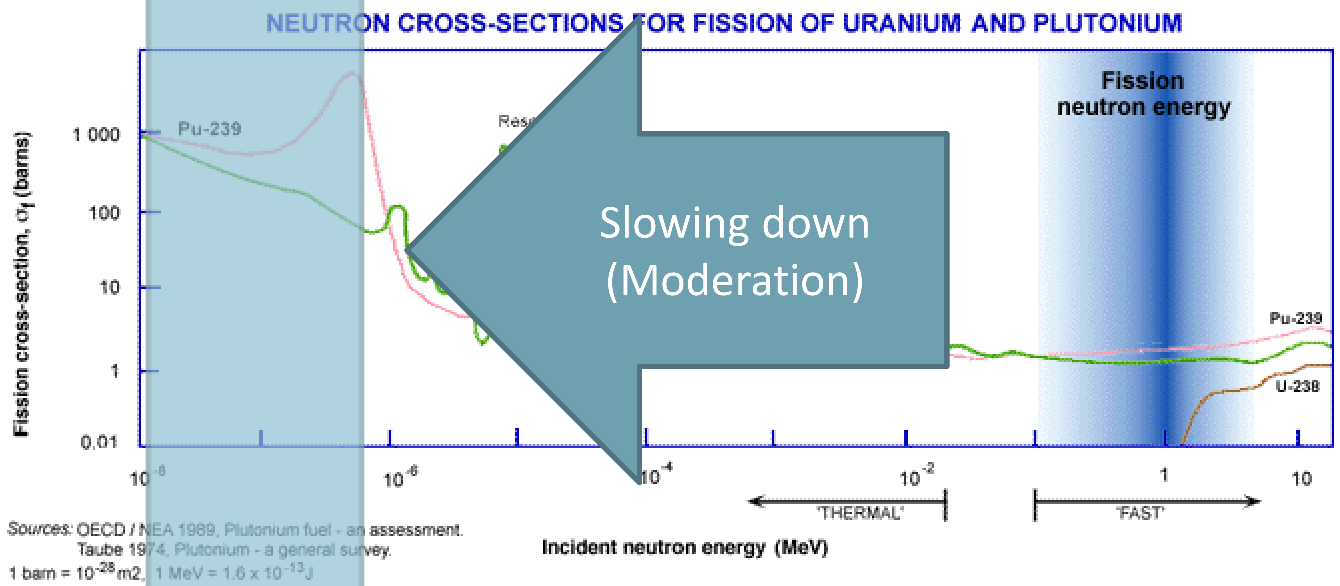
# Where does the energy go?

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow \underbrace{Fr_1 + Fr_2}_{\sim 168\,\mathrm{MeV}} + \underbrace{2{,}5\,{}^{1}_{0}n}_{\sim 5\,\mathrm{MeV}} + \underbrace{\gamma}_{\sim 30\,\mathrm{MeV}} $$

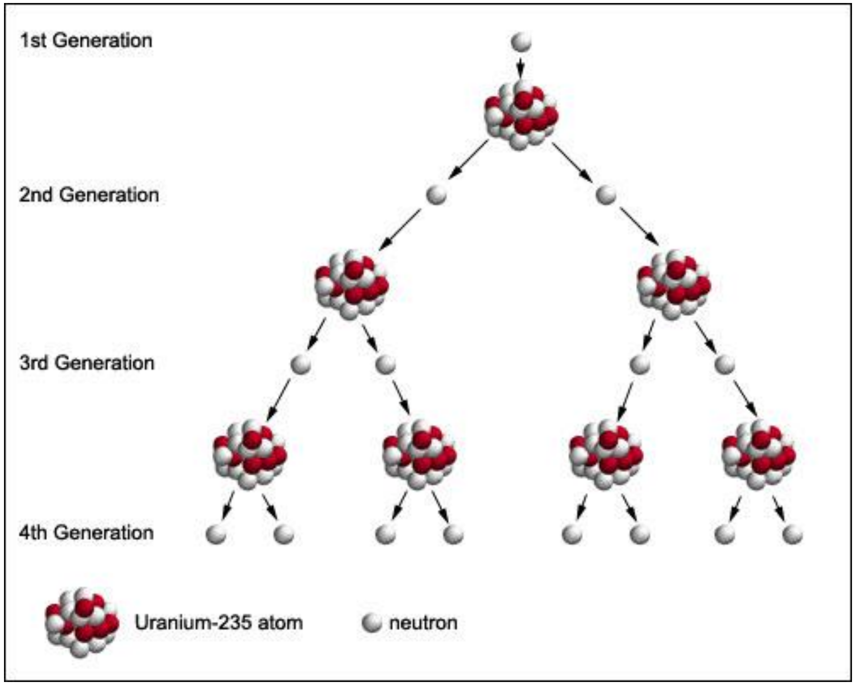
„A single atom is such a small thing that to talk about its energy in joules would be inconvenient. But instead of taking a definite unit in the same system, like $10^{-20}$ J, [physicists] have unfortunately chosen, arbitrarily, a funny unit called an electronvolt (eV) ... I am sorry that we do that,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

# 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

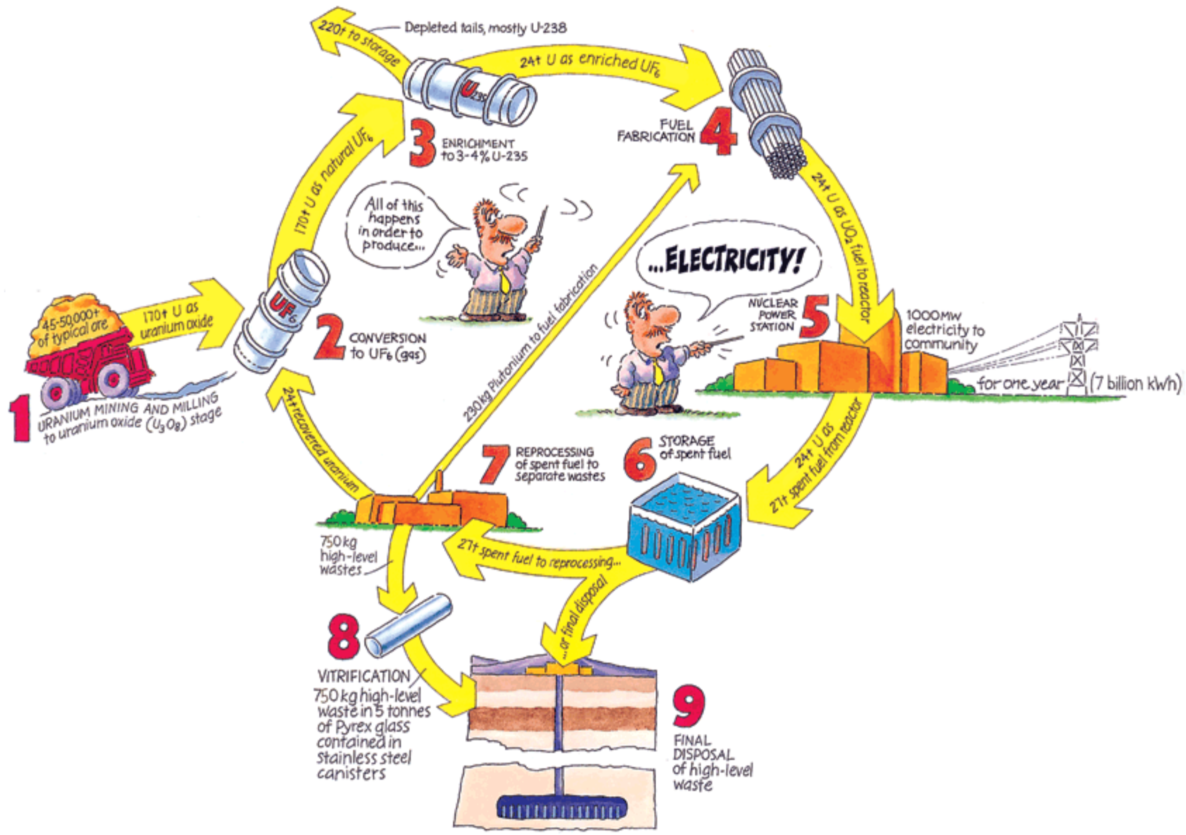
# Reaction control

- 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 thorugh the core (BWR)

# Used fuels

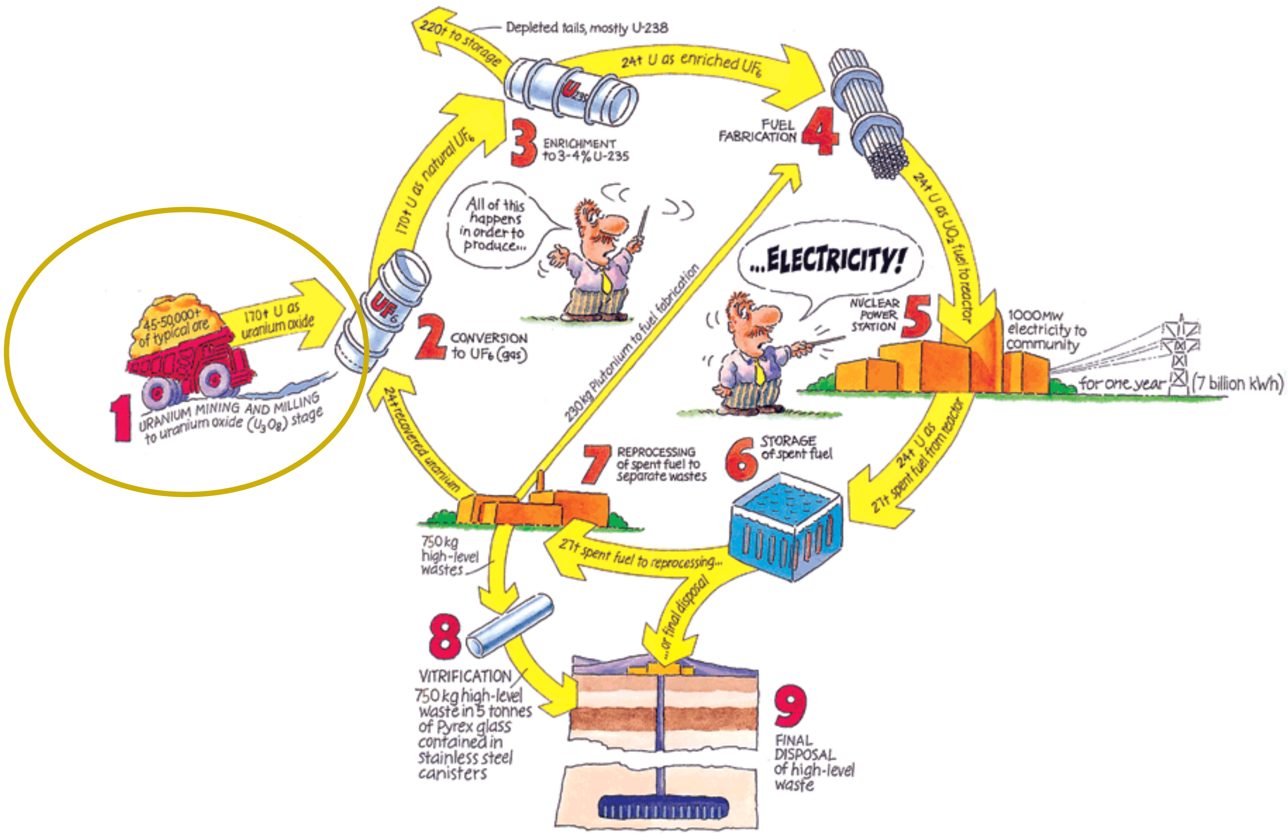
- Uranium-235
  - Usually as uranium dioxide ($UO_2$)
  - Mined from natural deposits
  - Usually enriched to 4-5% U-235
- MOX – Mixed Oxide Fuel
  - Mixture of $UO_2$ and $PuO_2$
  - Plutonium recycled from spent fuel elements
  - Plutonium from dismantled nuclear warheads

# Fuel cycle



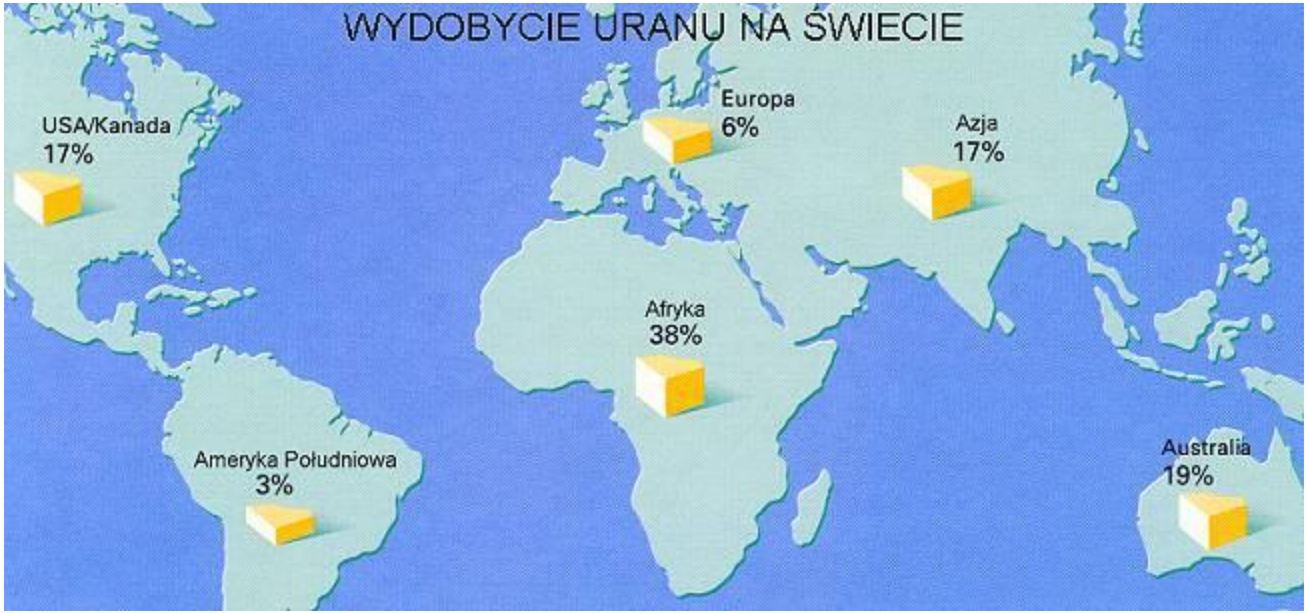
Depleted tails, mostly U-238
220t to storage
24t U as enriched UF6
3 ENRICHMENT to 3-4% U-235
FUEL FABRICATION 4
170t U as natural UF6
All of this happens in order to produce...
...ELECTRICITY!
24t U as UO2 fuel to reactor
NUCLEAR POWER STATION 5
1000MW electricity to community
for one year (7 billion kWh)
45-50,000t of typical ore
170t U as uranium oxide
2 CONVERSION to UF6 (gas)
1 URANIUM MINING AND MILLING to uranium oxide (U3O8) stage
230kg Plutonium to fuel fabrication
24t recovered uranium
7 REPROCESSING of spent fuel to separate wastes
6 STORAGE of spent fuel
24t U as 27t spent fuel from reactor
750kg high-level wastes
27t spent fuel to reprocessing...
...or final disposal
8 VITRIFICATION 750kg high-level waste in 5 tonnes of Pyrex glass contained in stainless steel canisters
9 FINAL DISPOSAL of high-level waste

# Uranium ore mining

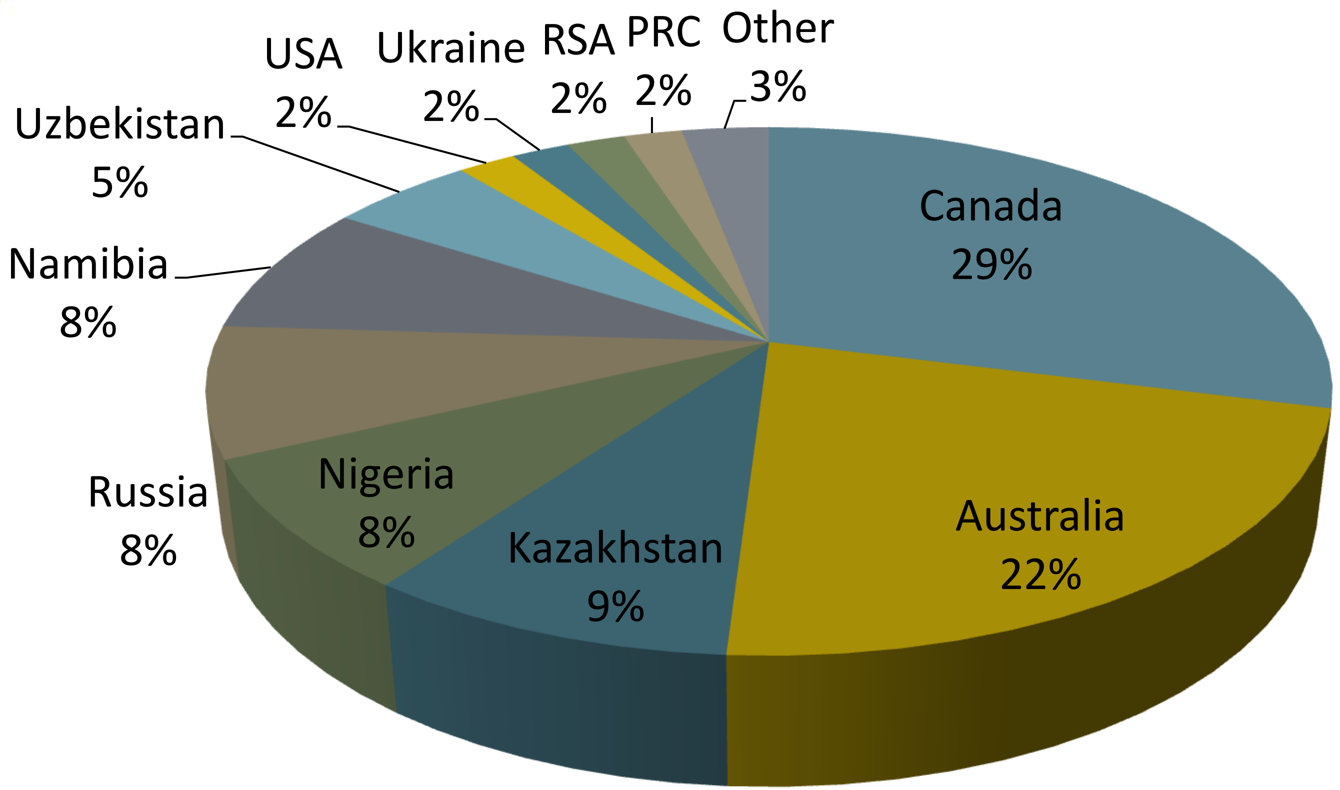


# Uranium ore mining

# Uranium ore mining



# Uranium ore mining

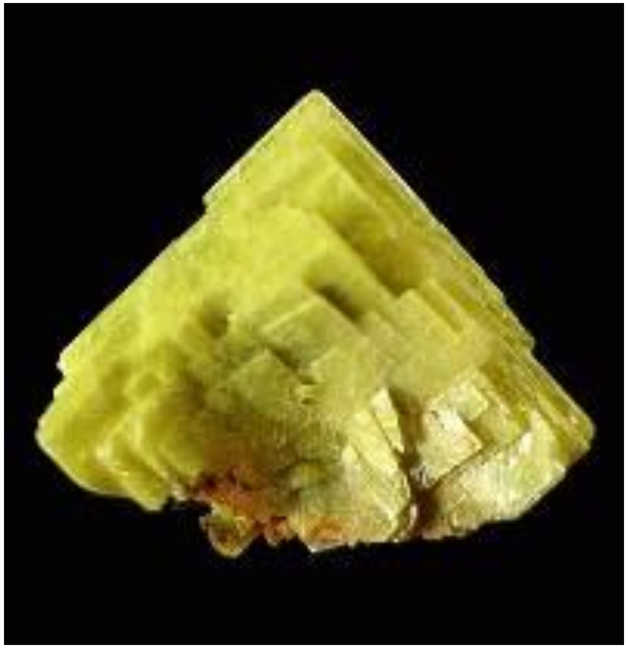


# Uranium minerals

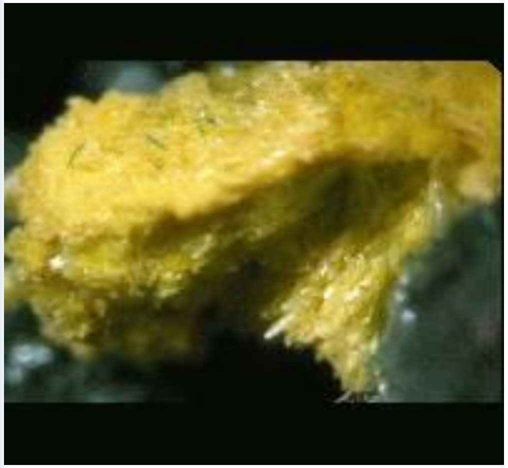
Uraninite – $UO_2$



Carnotite – $K_2(UO_2)_2(VO_4)_2 \cdot 4H_2O$



Autunite – $CaO(UO_3)_2P_2O_5 \cdot 12H_2O$



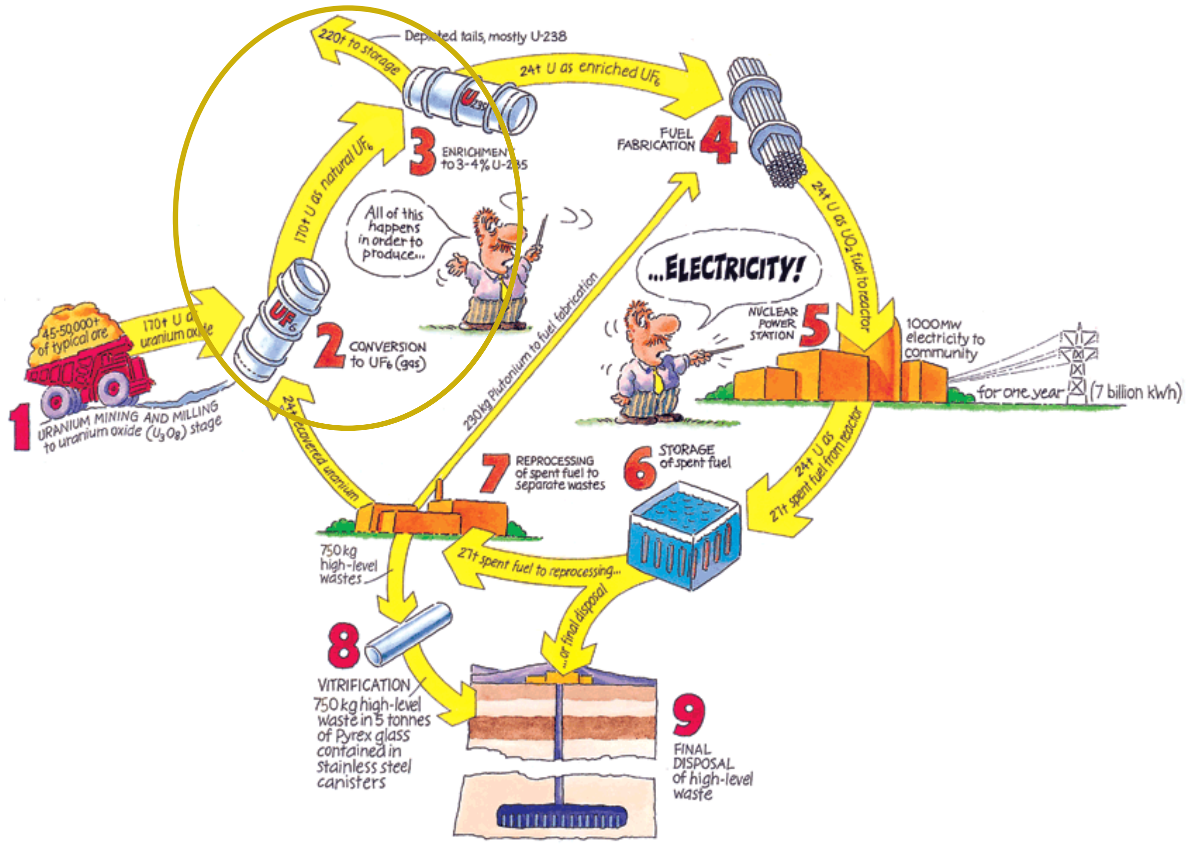
Sklodowskite – $Mg(UO_2)_2(HSiO_4)_2 \cdot 5H_2O$

*Exemplary uranium minerals*

# Yellowcake


- Uranium concentrate
- ~80% $U_3O_8$
- Chemically stable

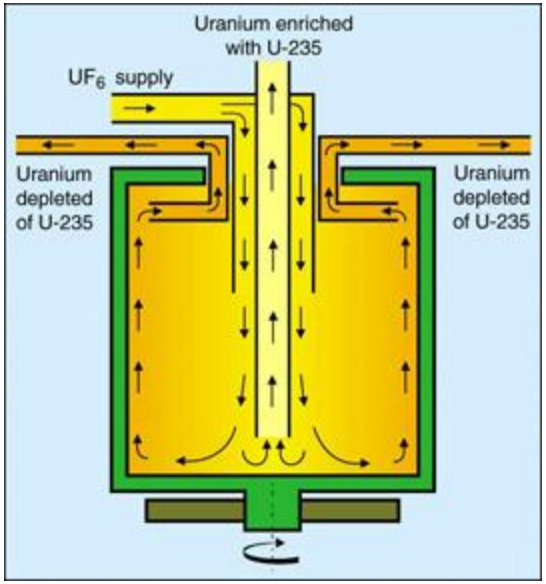
# Uranium enrichment



# Uranium enrichment

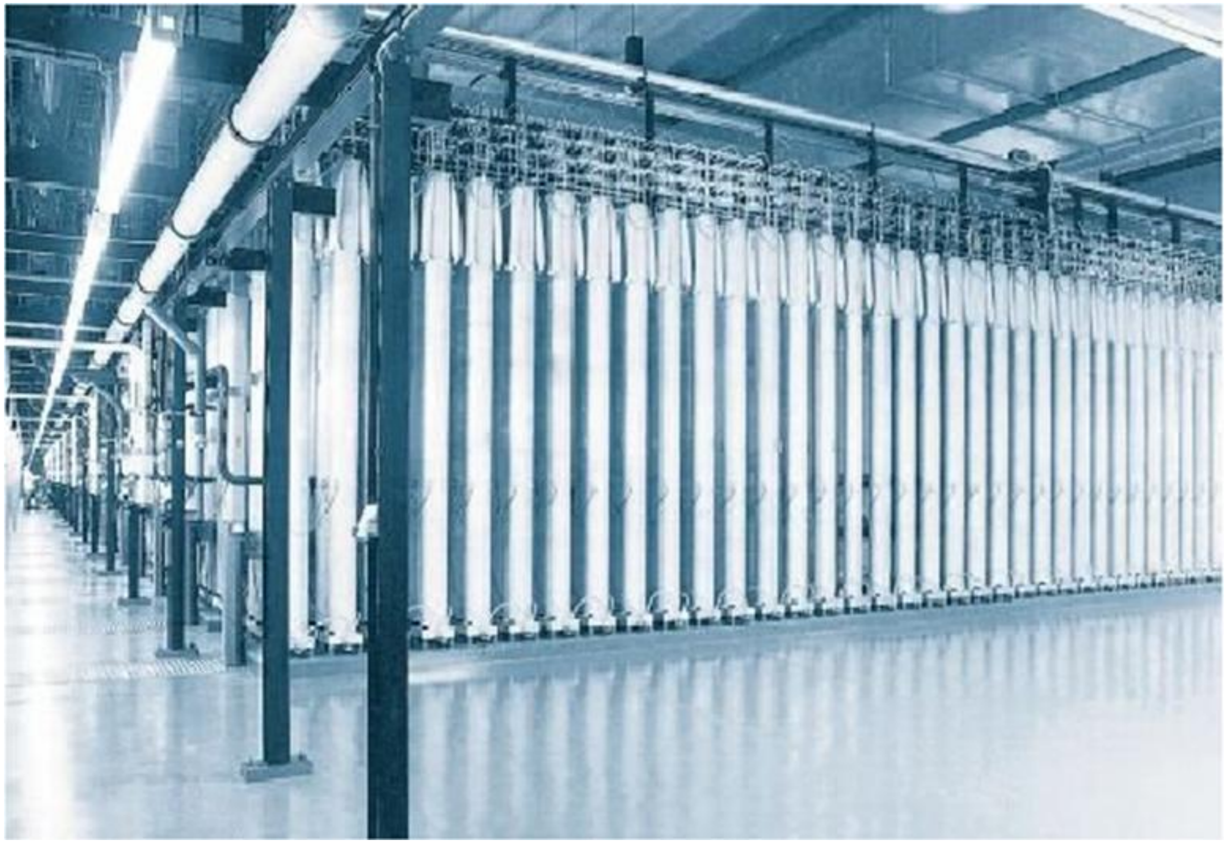
- There is only 0.72% U-235 in natural uranium
- Most power reactors need 3-4% U-235
- Enrichment = increasing U-235 content in uranium mass
- Physical methods – based on mass difference
- Enrichment carried out in $UF_6$ gas

# Enrichment centrifuges

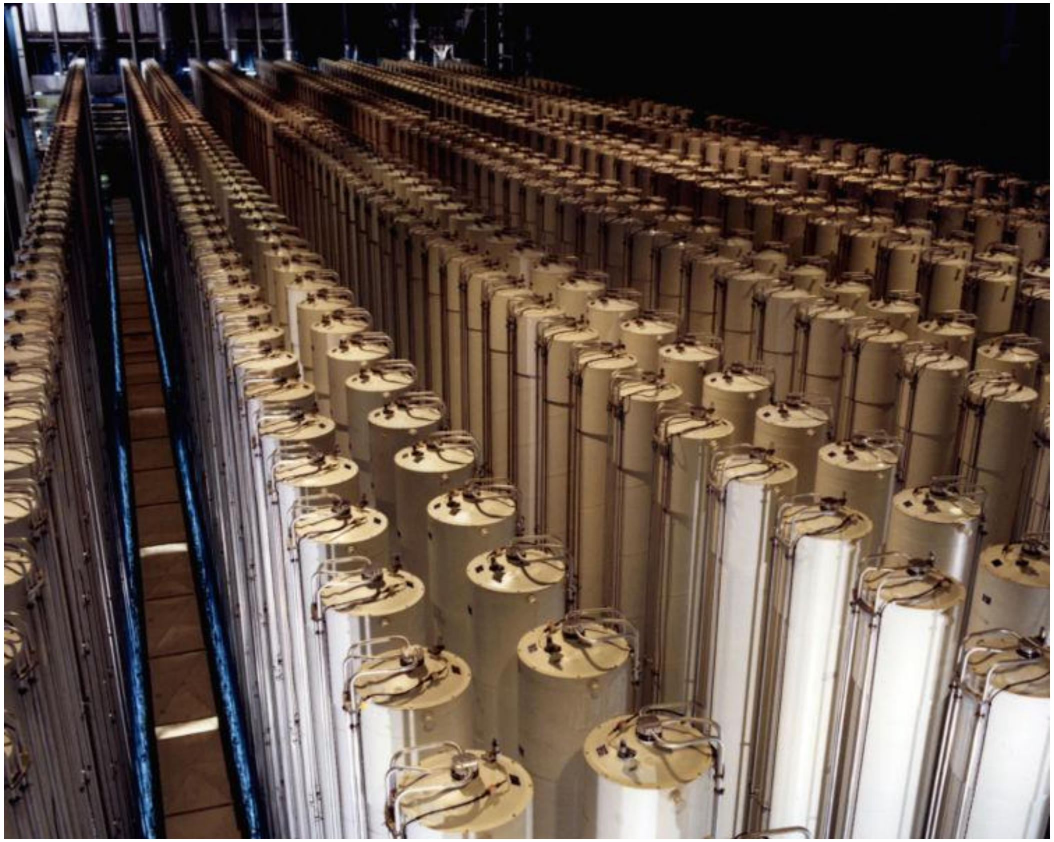



- Using mass difference
- Lighter U-235 concentrates near the axis
- Centrifuge cascade needed to obtain proper enrichment level

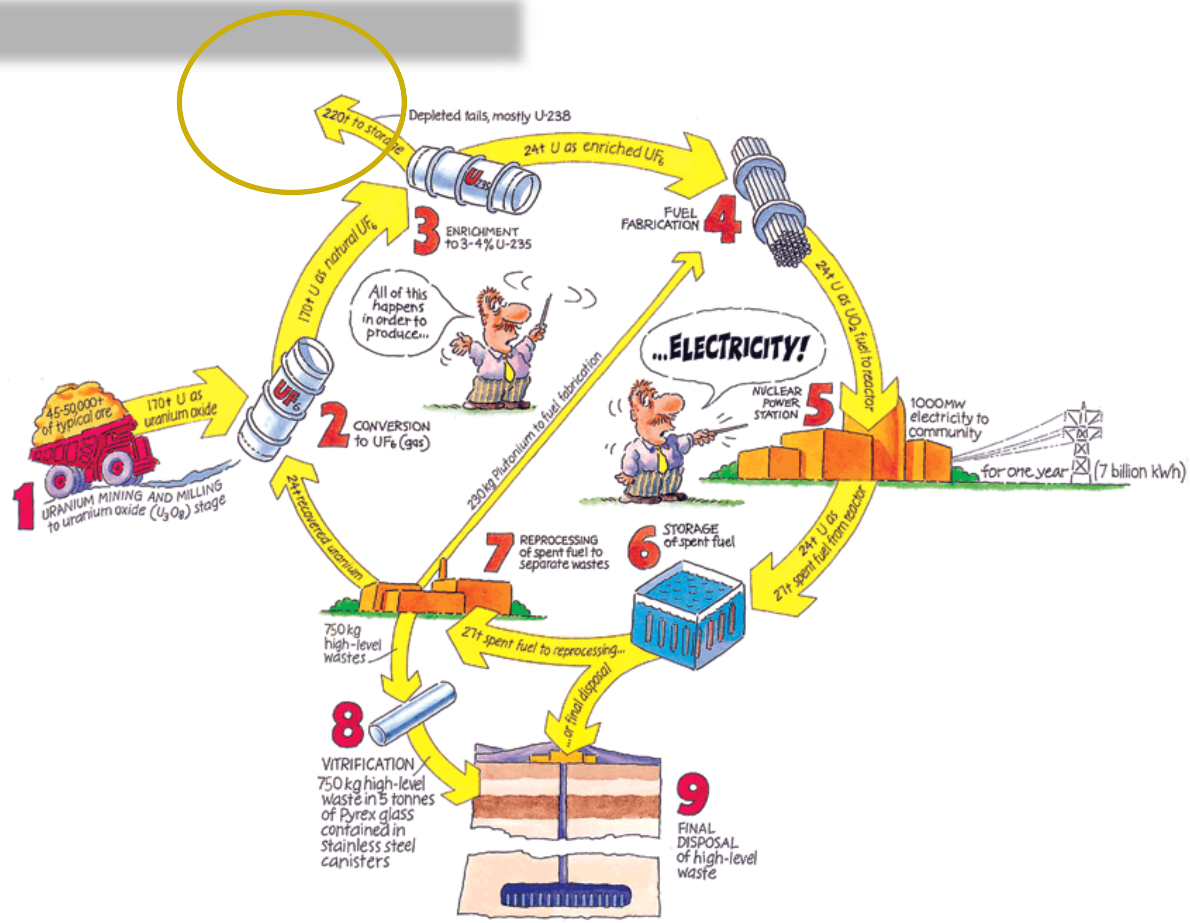
# Centrifuge cascade



# Centrifuge cascade

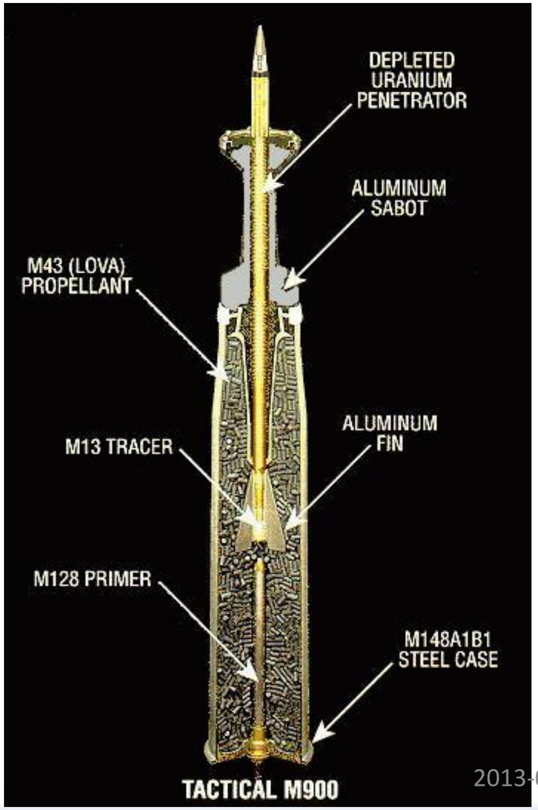


# WHAT ABOUT THE REST?

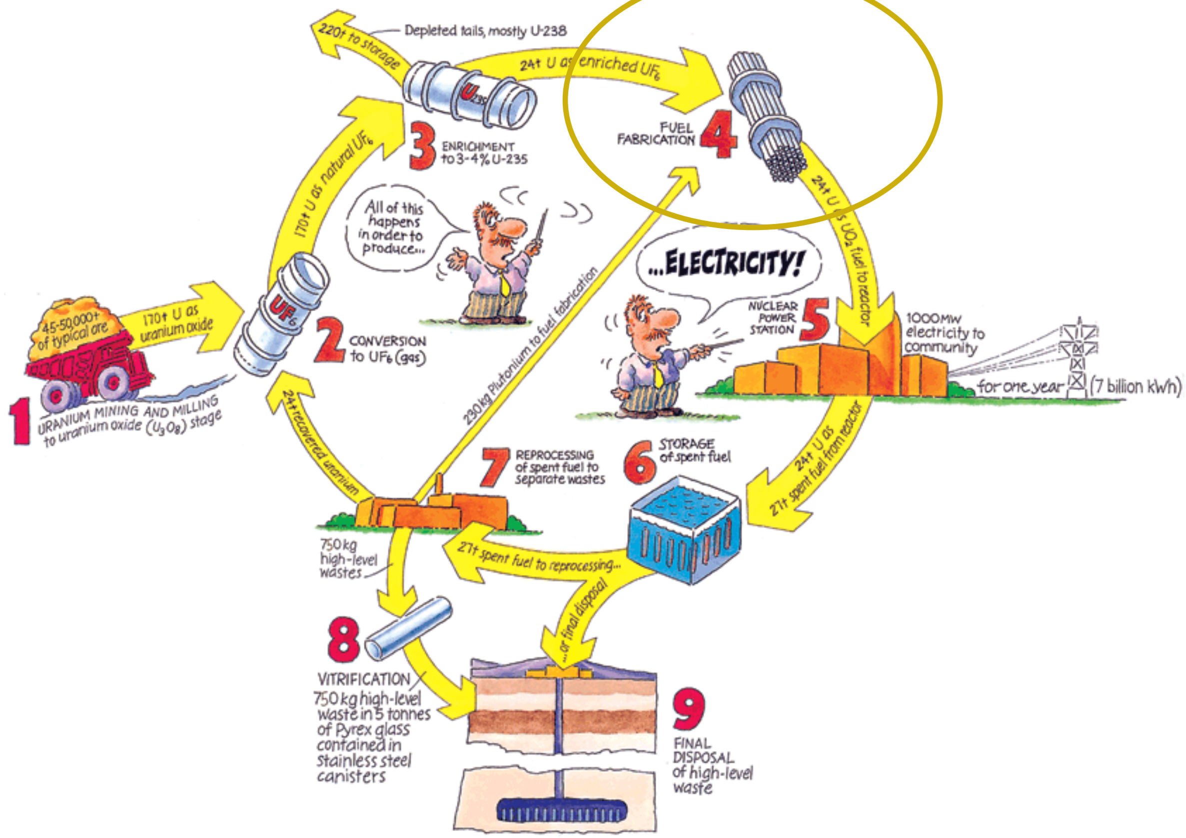


# Usage of depleted uranium

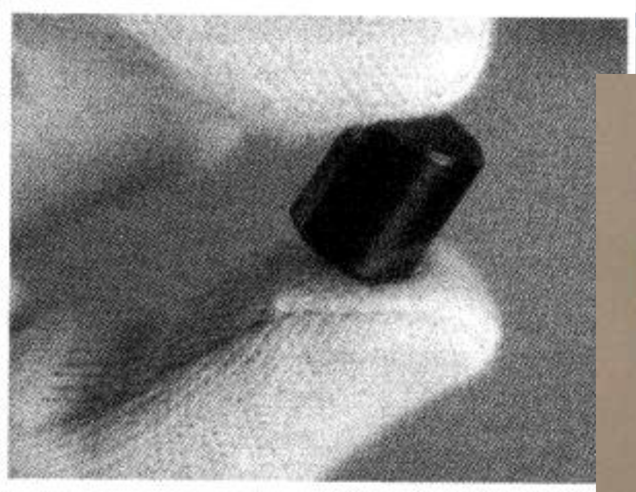
- Biological shields (medical diagnostics)
- Dyes
- Aircraft counterweights
- Armour plates
- Armour-piercing projectiles



# Fuel production



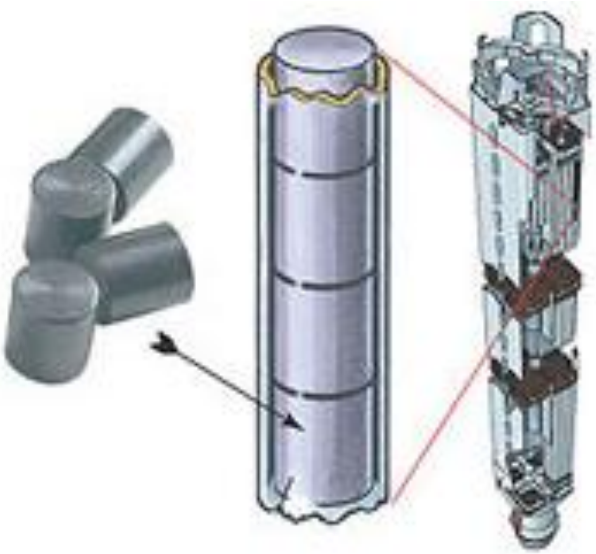
# Nuclear fuel – UO2 pellets



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

It is ca. ¼ of annual electricity consumption by one Polish household.

# NUCLEAR FUEL



Uraniium dioxide

↓

Fuel pellets

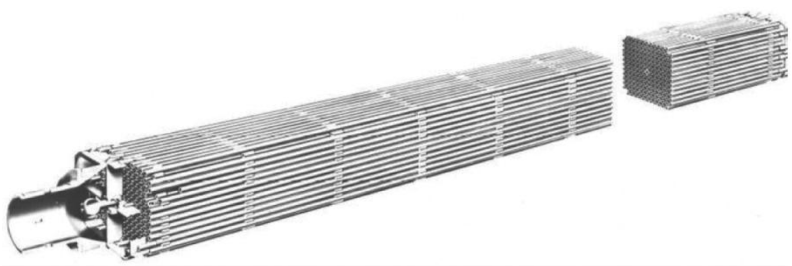
↓

Fuel rods

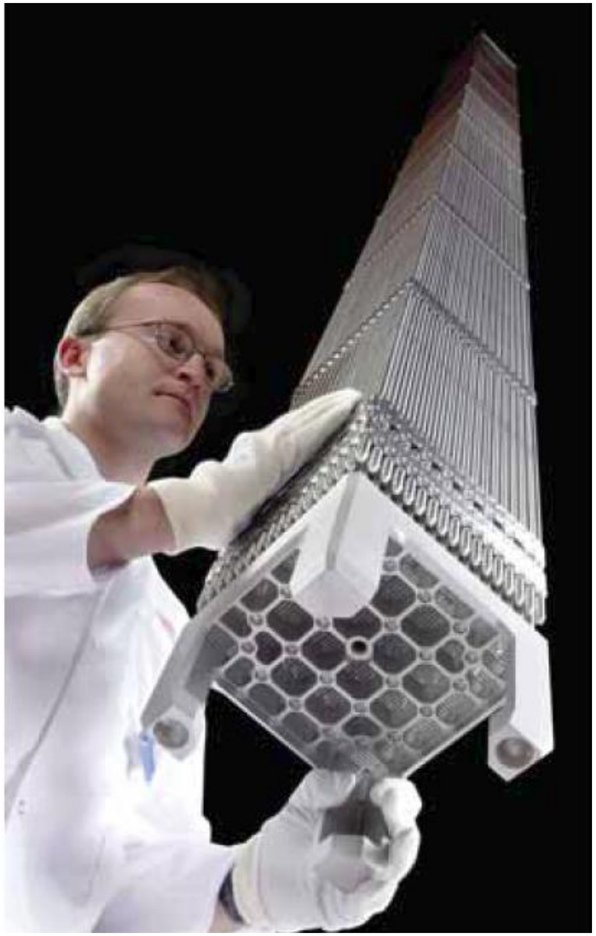
↓

Fuel bundles

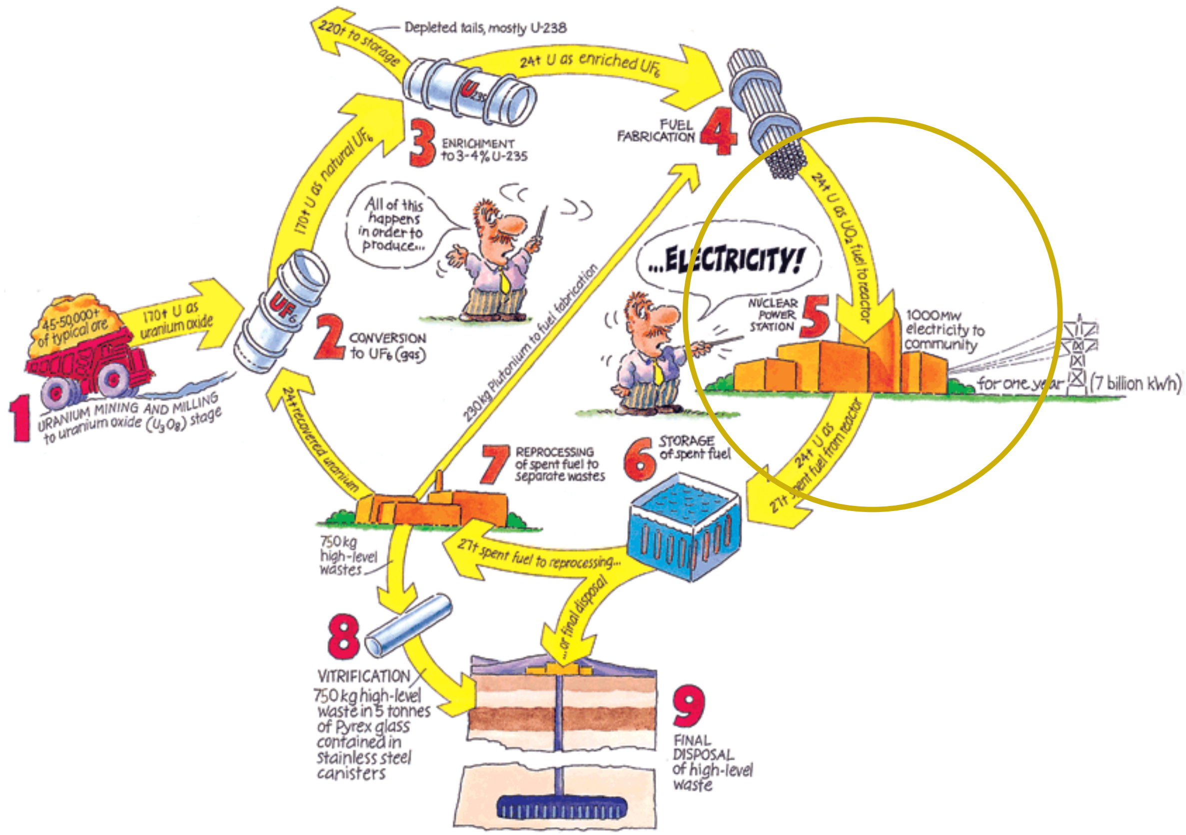
# Fuel assembly



**Source:** Babcock and Wilcox Company



# FUEL CONSUMPTION



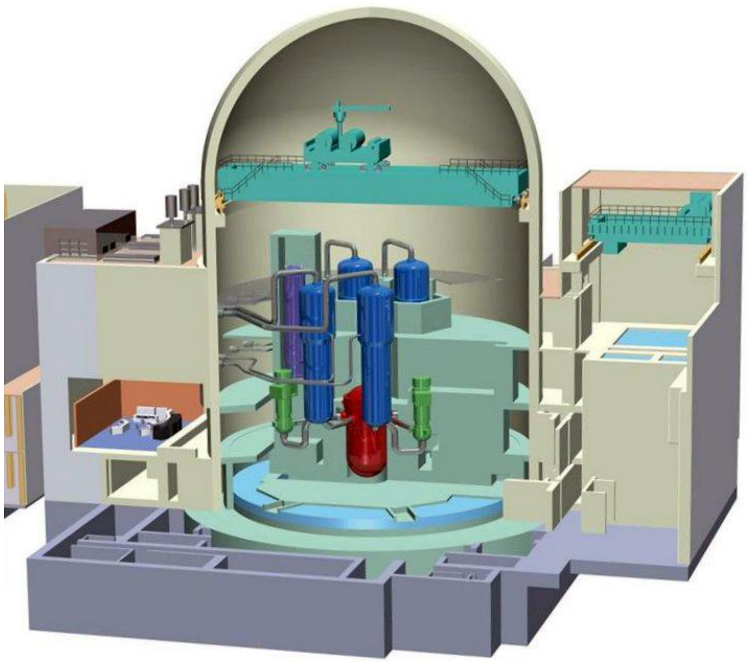

 

# Nuclear reactor

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

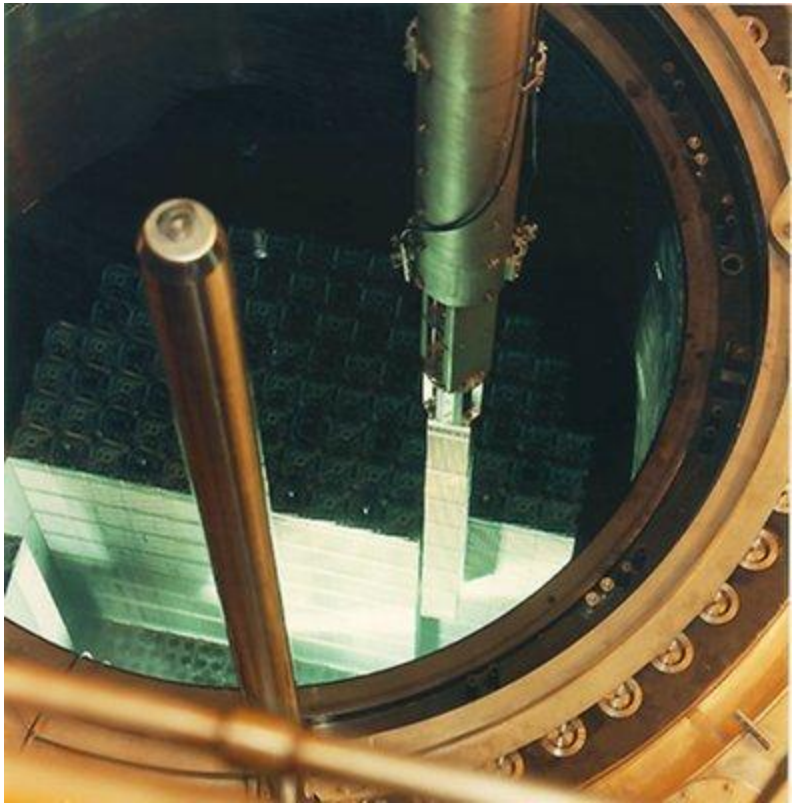
# Nuclear reactor

Typical Pressurized Water Reactor

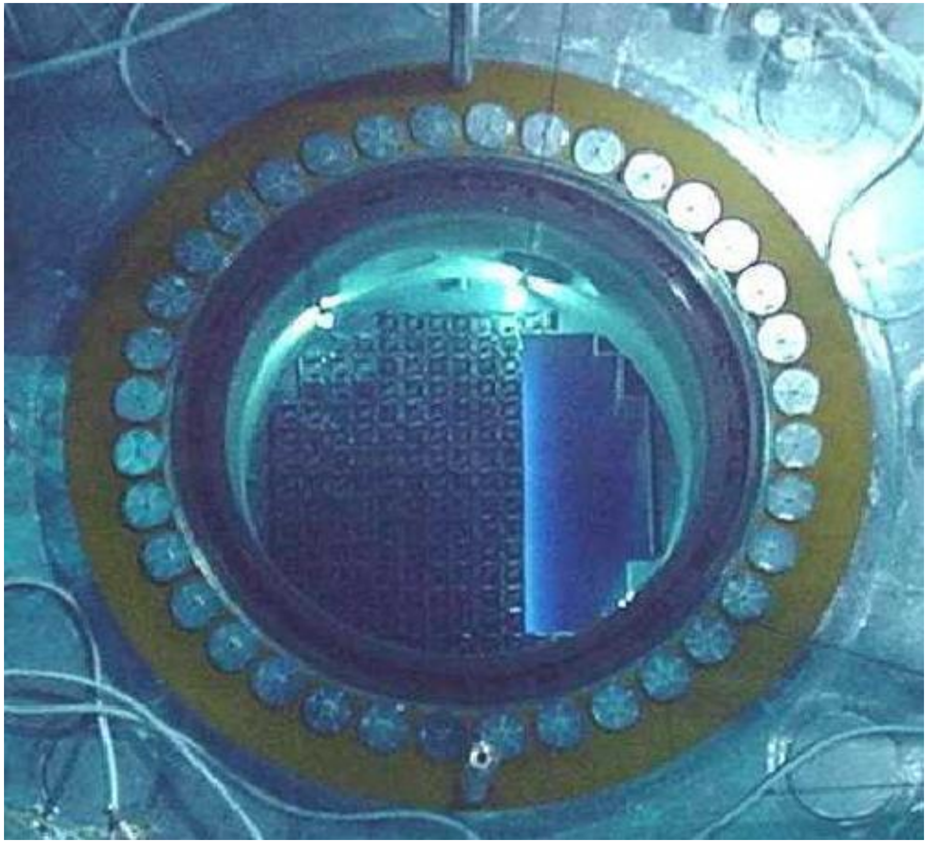


Source: U.S. Nuclear Regulatory Commission

# Nuclear reactor



# Nuclear reactor

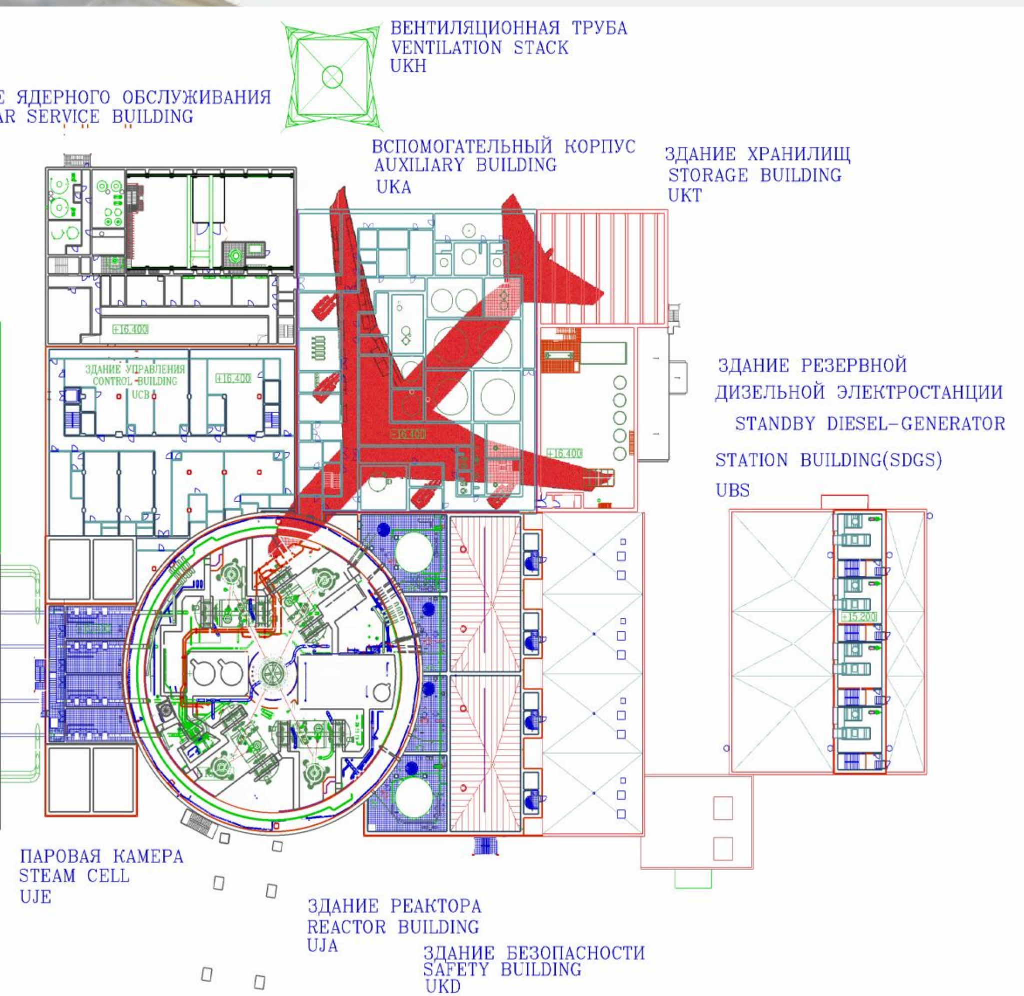


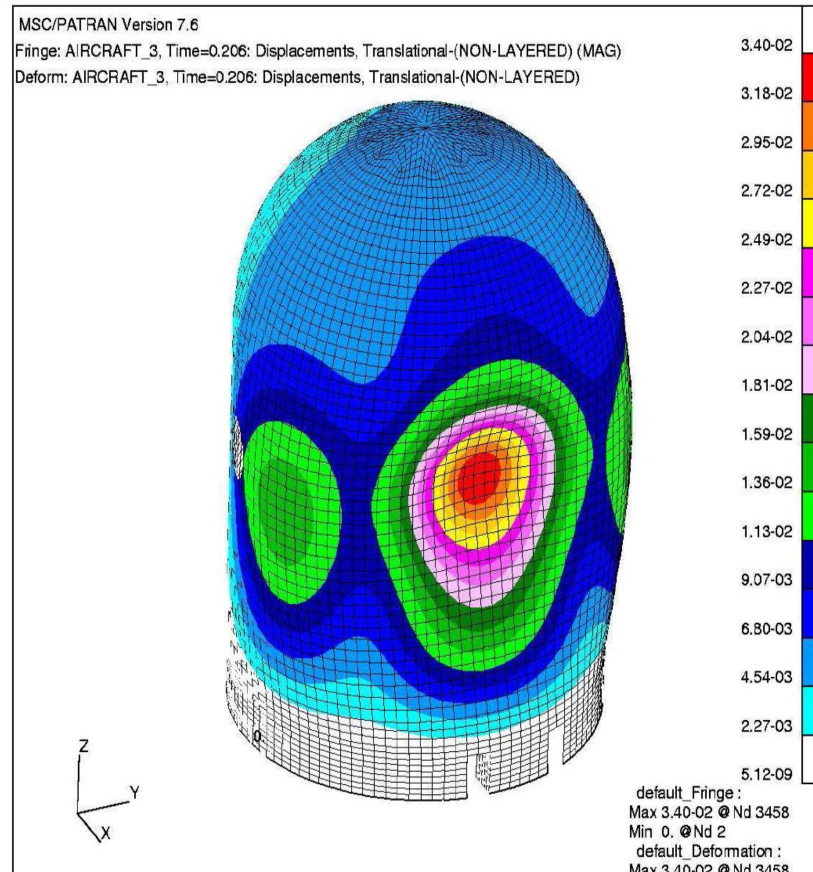
# Nuclear reactor

# 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

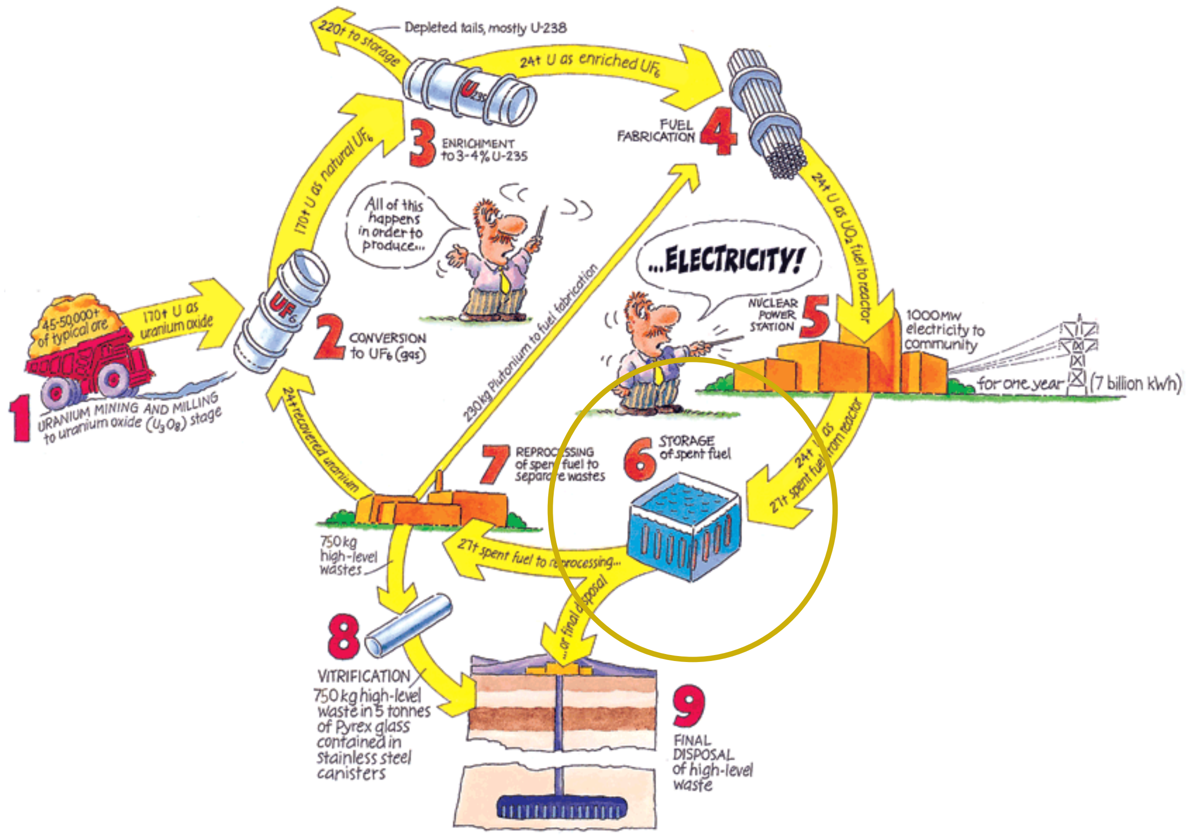
# Reactor containment



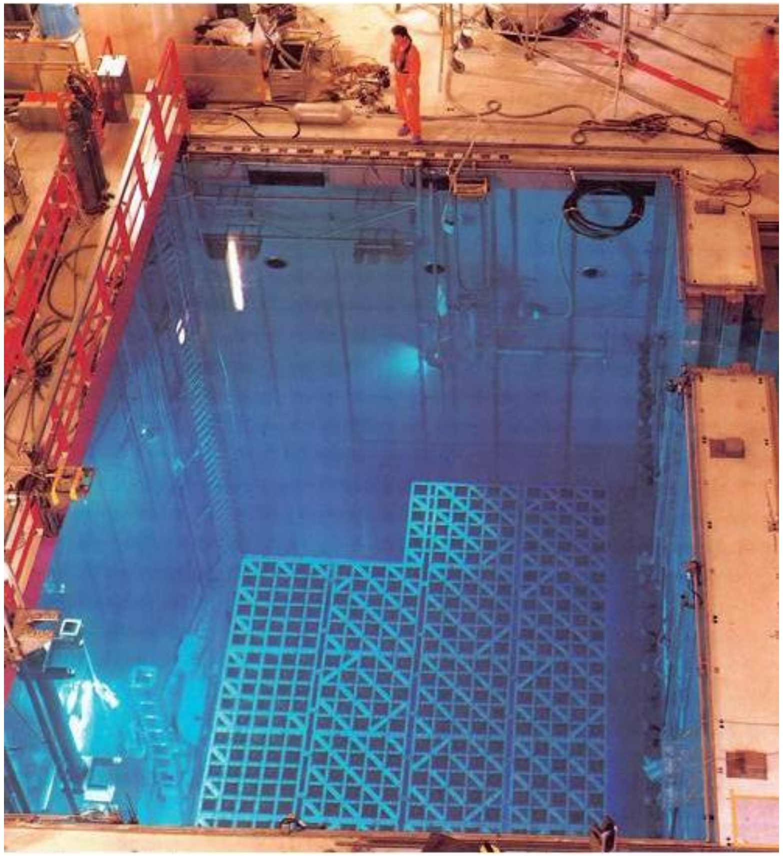
# Reactor containment

# Spent nuclear fuel

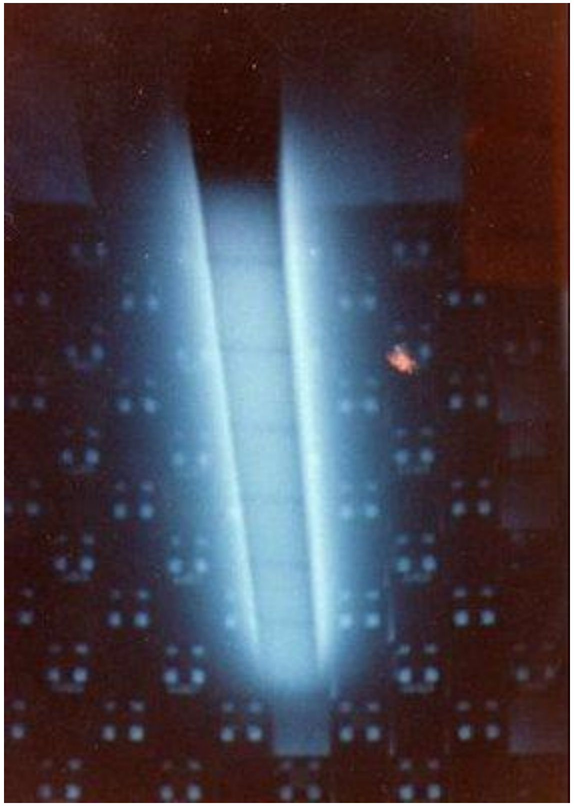


# Spent nuclear fuel

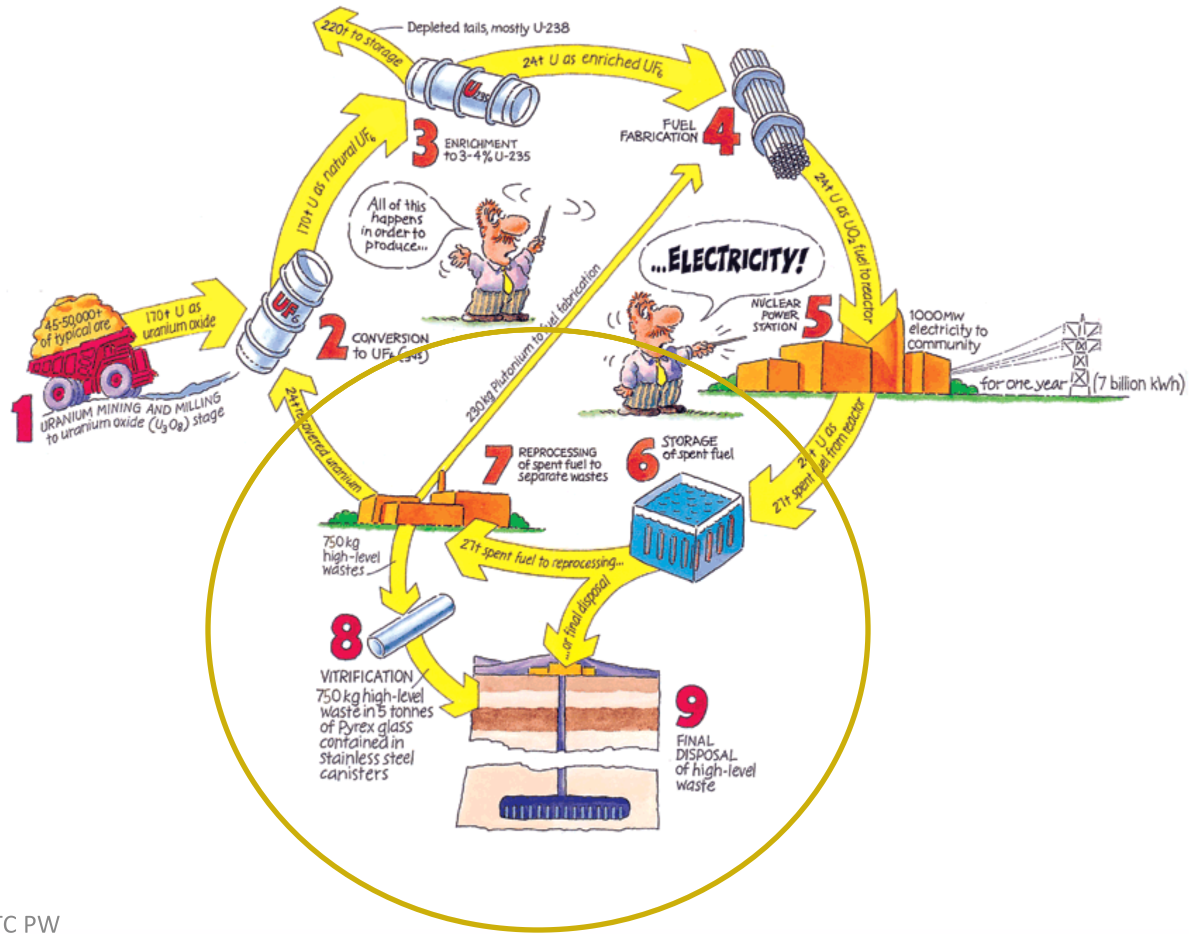
- Spent fuel elements hold short and medium-lived fission products which keep decaying
- They have to be cooled until the activity drops (after several years)
- Initial storage na  pool next to the reactor



# Spent nuclear fuel



# Spent nuclear fuel

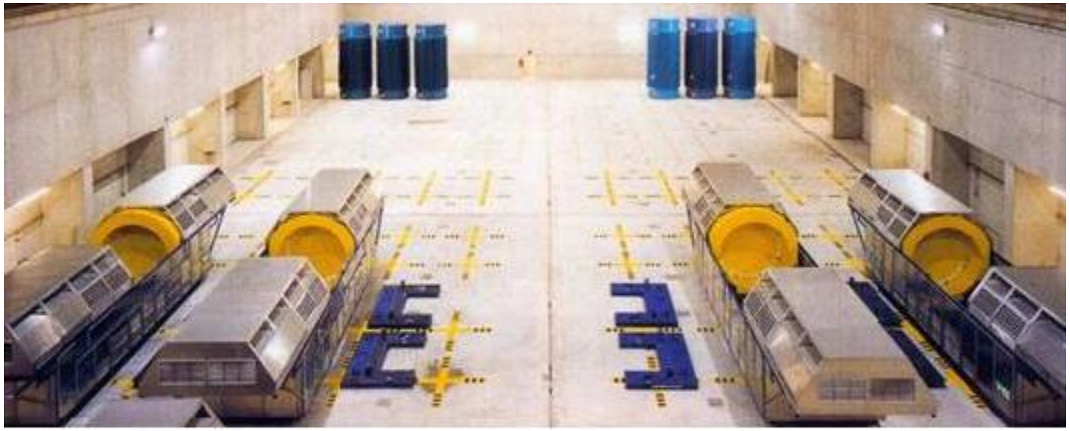


# Spent fuel transport

# Spent fuel transport

# Spent fuel transport

# SPENT FUEL TRANSPORT

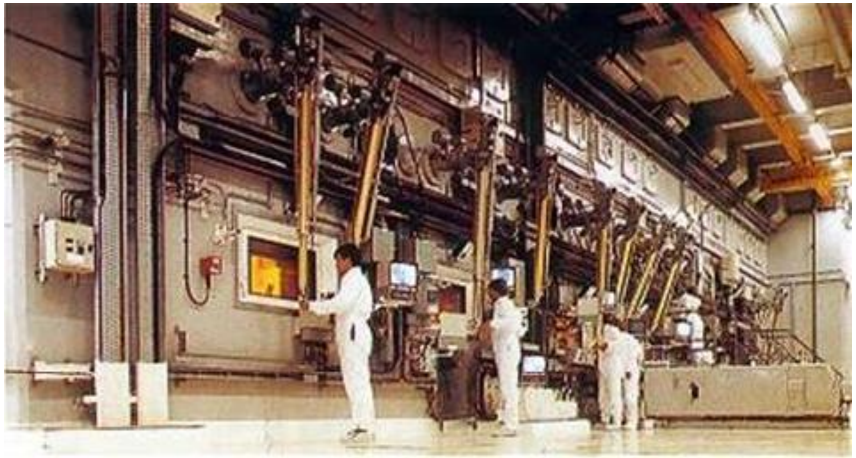


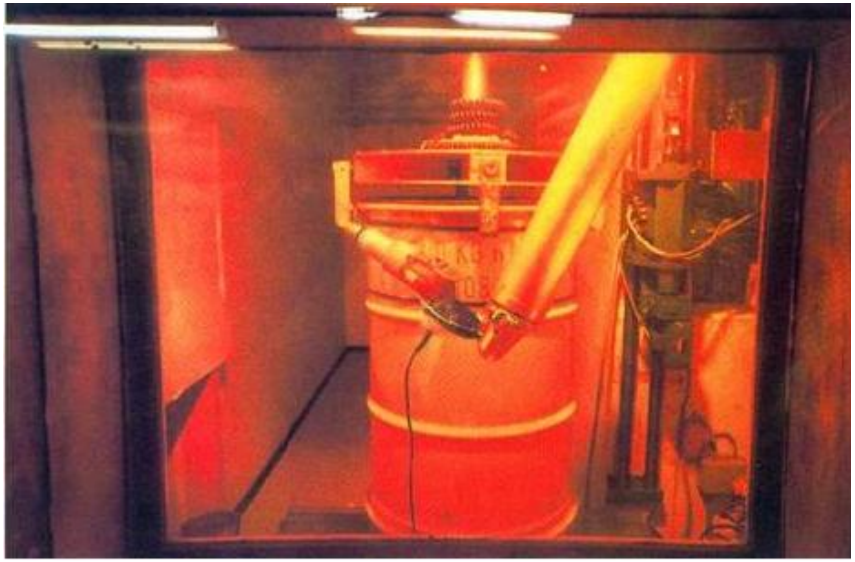
*„Spent nuclear fuel cask test” ➔ youtube.com*

# 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<br>• Cemented in barrels |
| Medium-activity | • Grinded down<br>• Cemented in barrels |
| High-activity | • Melted into glass blocks (vitrified) |

# How much waste?

**Lignite-fired PP**

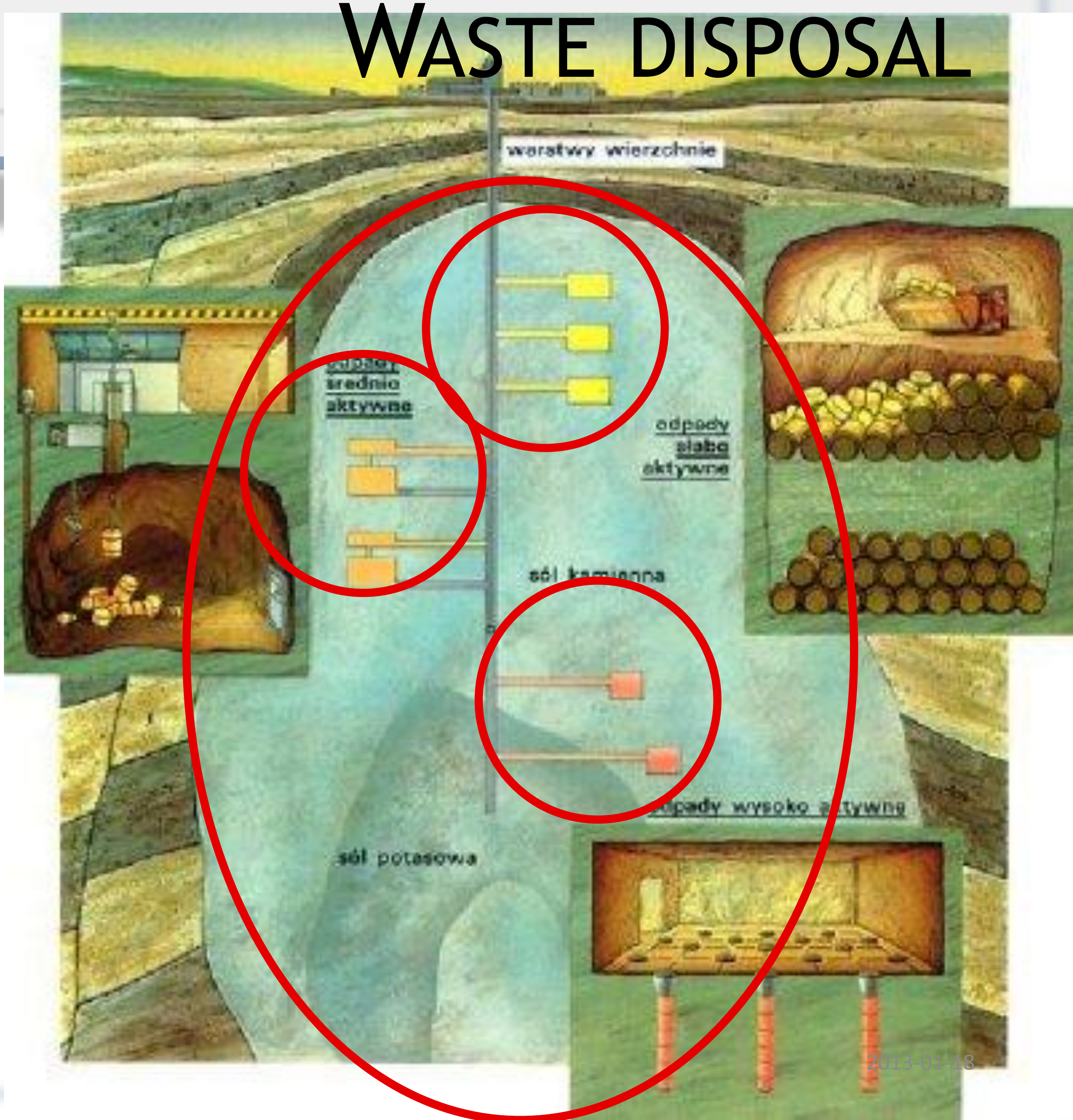
- 290 kg/s lignite
  1040 Mg/h
  25,000 Mg/d
  9 mi. Mg/a
- ~3 mi. Mg/a of ash

**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 reqirements

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

## Nuclear explosion is physically impossible

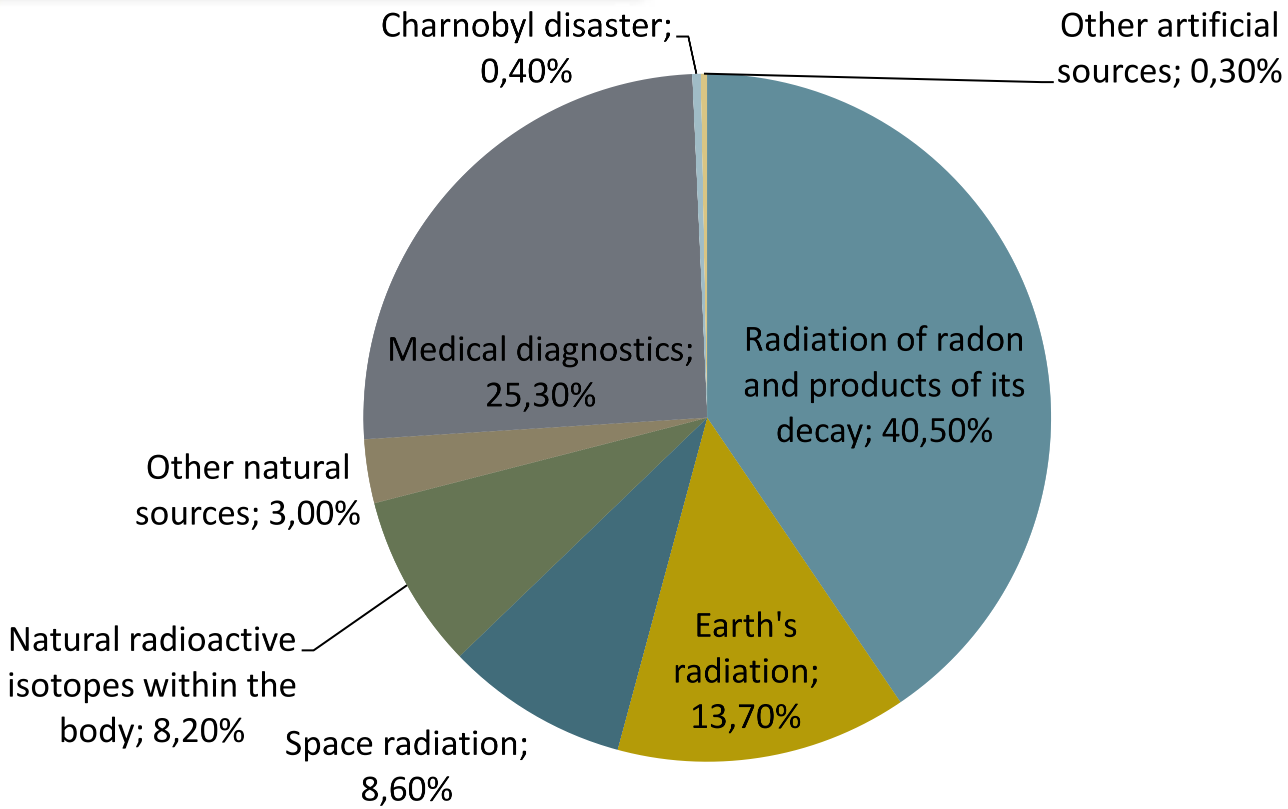
- Too low enrichment level
- Too small neutron energy (reaction cannot develop fast enough)

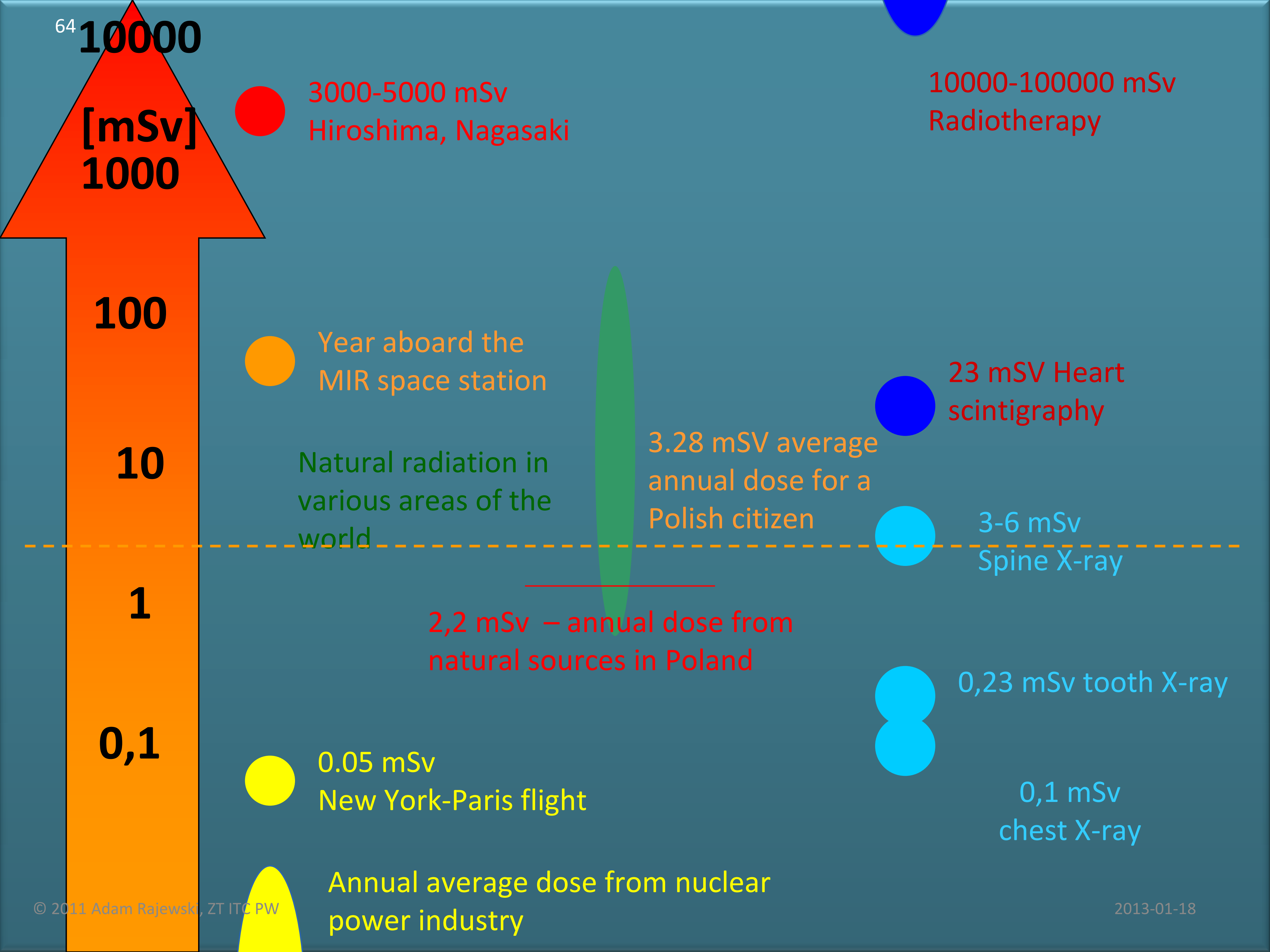
## “Idiot-proofness”

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

# Environmental footprint

# ANNUAL RADIATION DOSE (POL)




10000
[mSv]
1000
100
10
1
0,1
3000-5000 mSv
Hiroshima, Nagasaki
10000-100000 mSv
Radiotherapy
Year aboard the
MIR space station
23 mSV Heart
scintigraphy
3.28 mSV average
annual dose for a
Polish citizen
Natural radiation in
various areas of the
world
3-6 mSv
Spine X-ray
2,2 mSv – annual dose from
natural sources in Poland
0,23 mSv tooth X-ray
0.05 mSv
New York-Paris flight
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 decomissioning
- Social problems
- Low flexibility (not suitable for peaking operation)
- Waste issue not fully resolved

# Thank you!