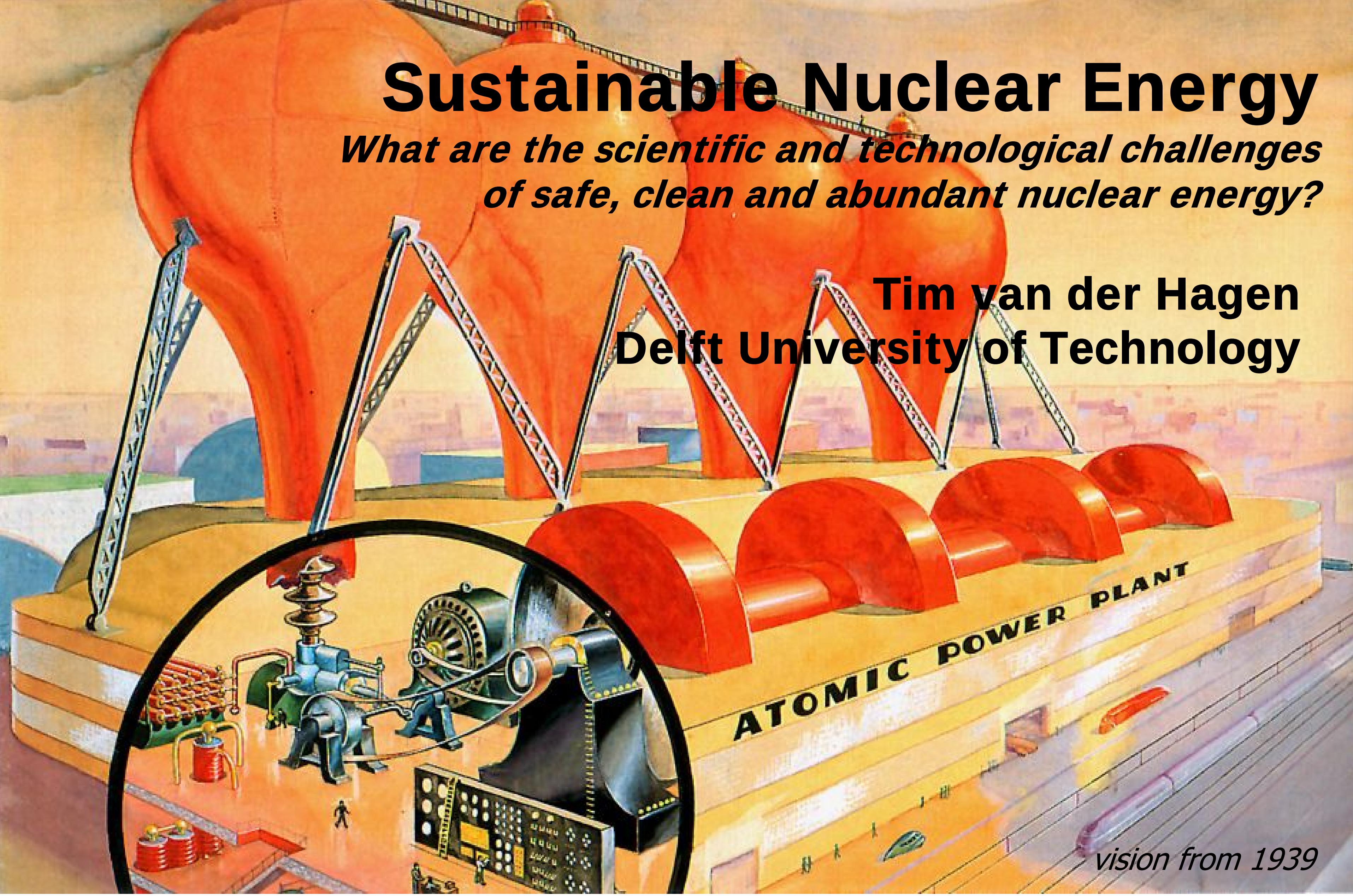
# Sustainable Nuclear Energy

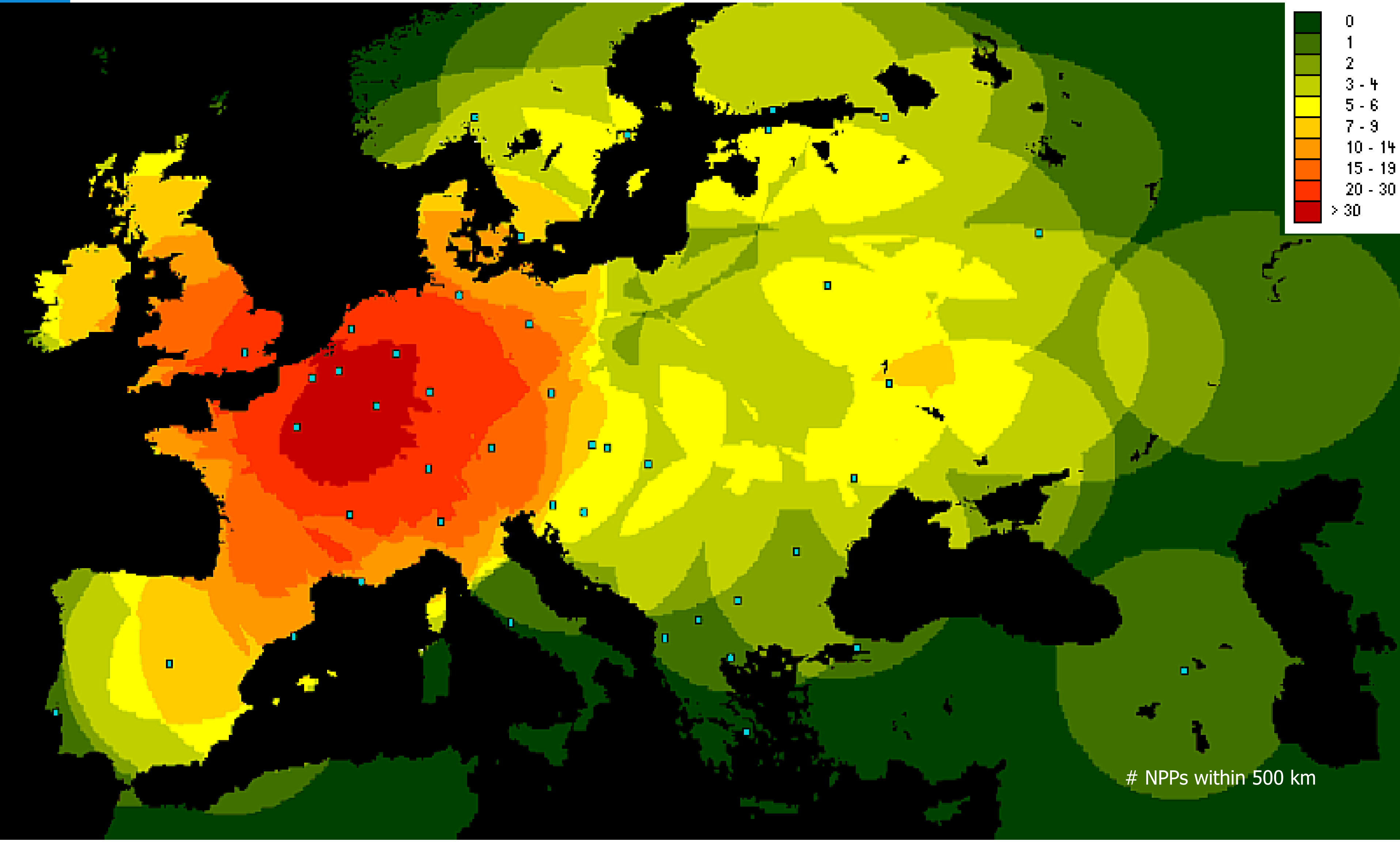
***What are the scientific and technological challenges of safe, clean and abundant nuclear energy?***

**Tim van der Hagen**
**Delft University of Technology**




*vision from 1939*

TU Delft — Delft University of Technology


0
1
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3 - 4
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7 - 9
10 - 14
15 - 19
20 - 30
> 30
# NPPs within 500 km

# IEA Energy Technology Perspectives 2008

June 6, 2008

## ACT Scenarios

- Energy $CO_2$ emissions in 2050 back to the level of 2005

## Blue Scenarios

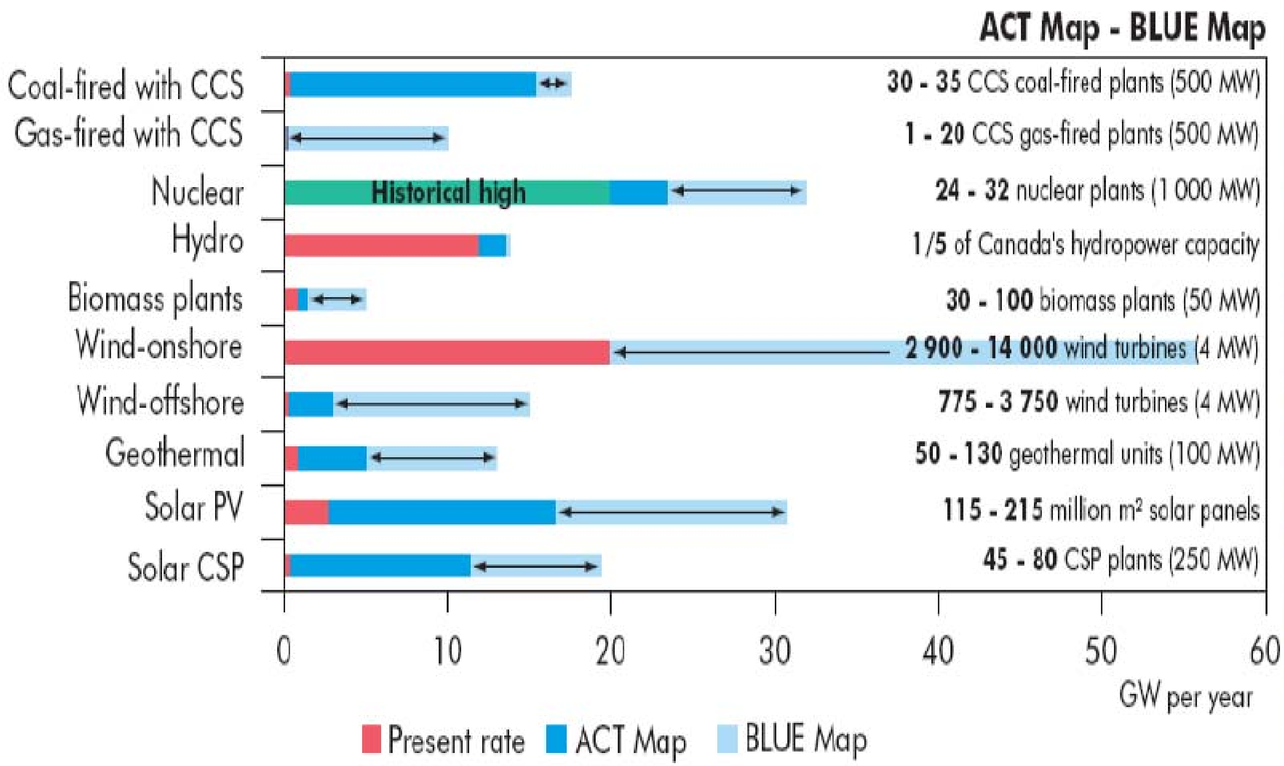
- -50% energy related $CO_2$ in 2050, compared to 2005

# IEA Energy Technology Perspectives 2008

June 6, 2008

## Average Annual Power Generation Capacity Additions, 2010 – 2050

***An Energy Revolution***



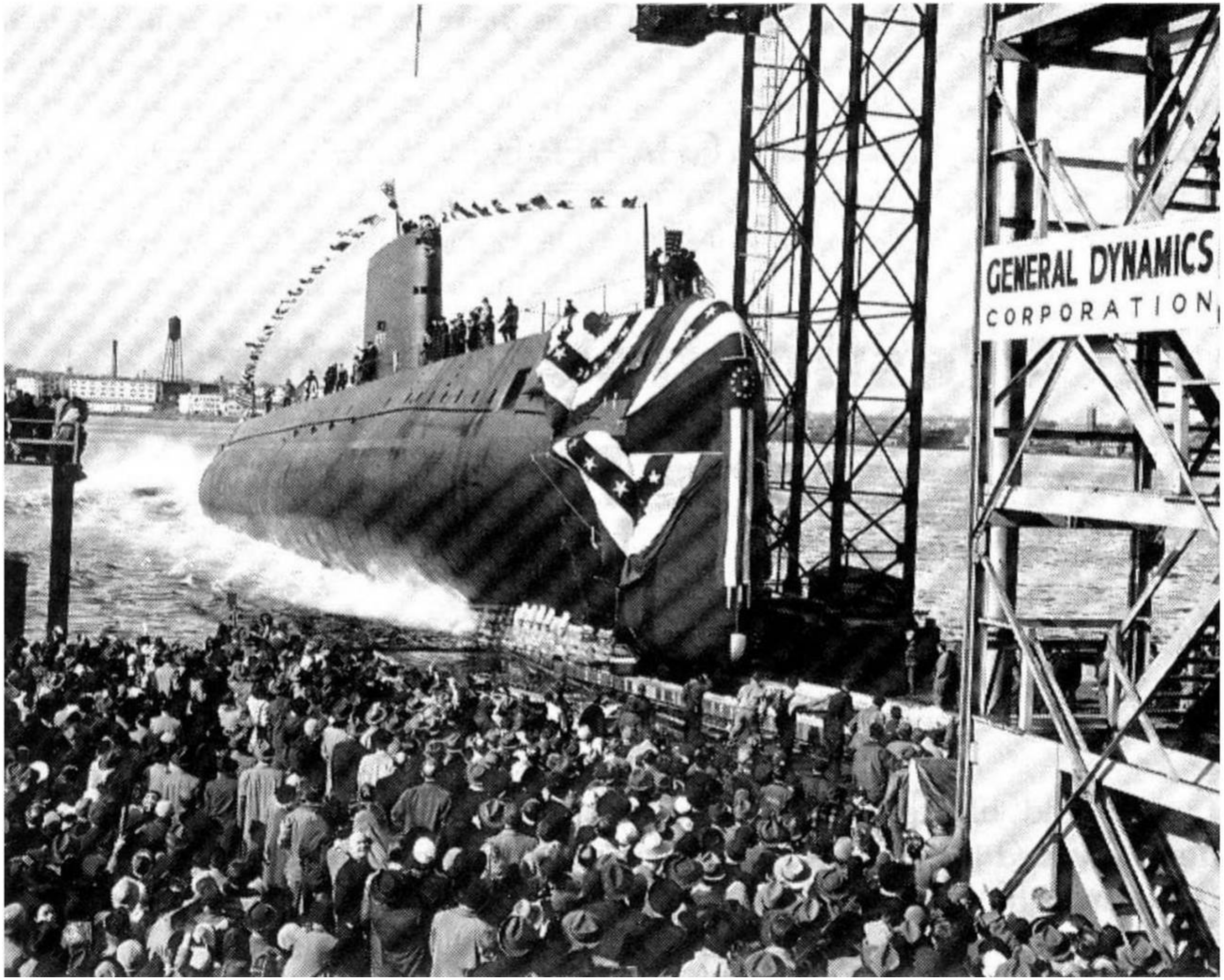


In support of the G8 Plan of Action

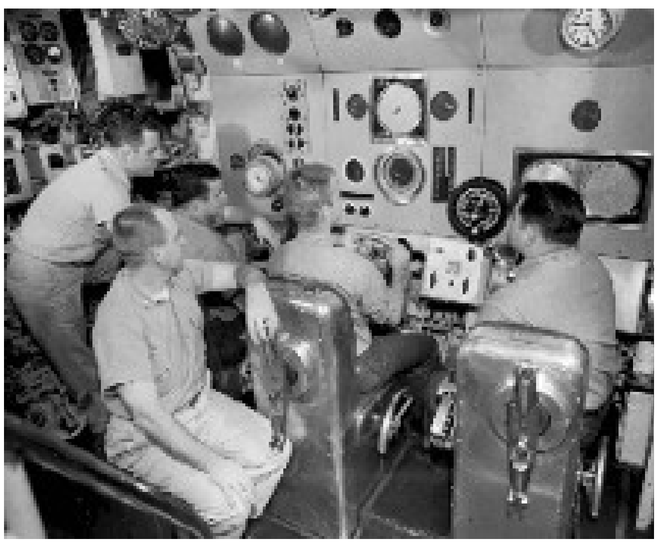
# History

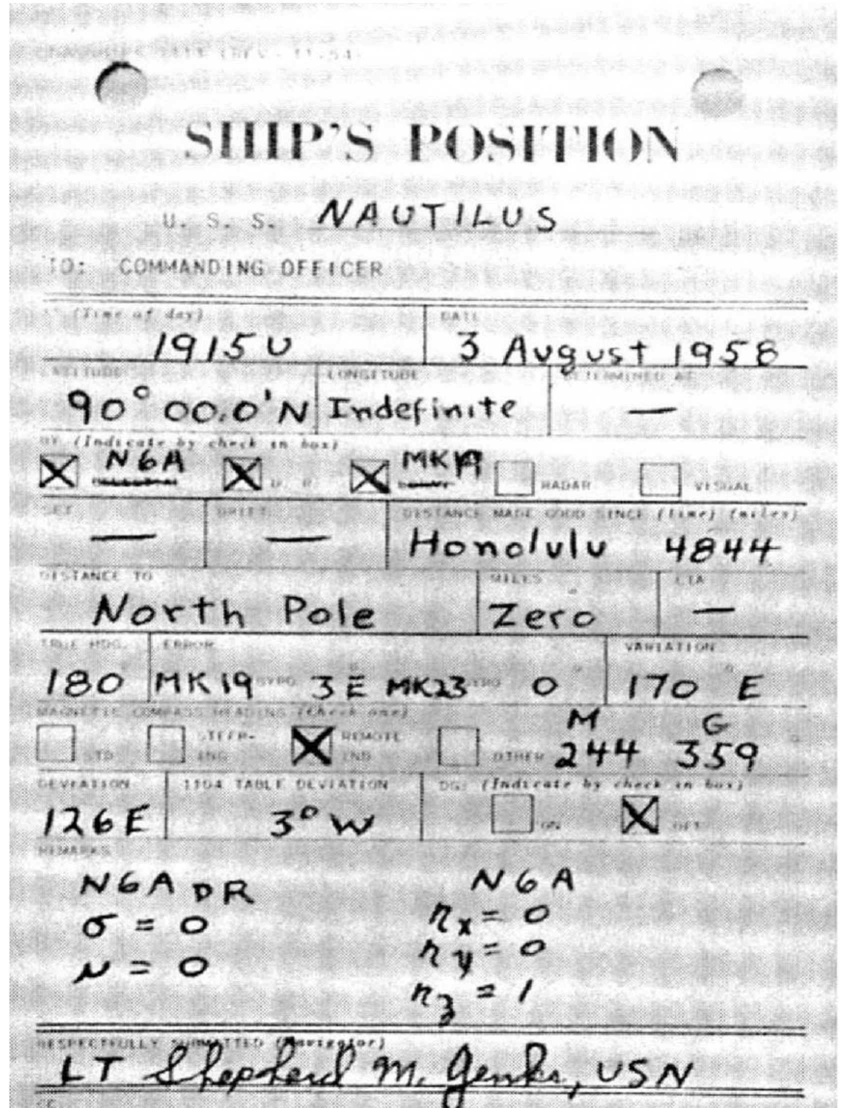
- 1932: Discovery of the neutron (Chadwick)
- 1939: Demonstration of nuclear fission (Meitner, Hahn, Strassman)
- 1942 (Dec. 2): First controlled chain reaction in CP1 (Enrico Fermi)
- 1951 (Dec. 20): First 'nuclear' electricity, *EBR-1,* Idaho
- 1955 (Jan. 17): First nuclear submarine at sea, *Nautilus*
- 1954 (June 26): First NPP, Obninsk, USSR (5 MWe)
- 1956: (Aug. 27): First NPP, Calder Hall, UK (50 MWe)
- 1957 (Dec. 2): First PWR, Shipping Port, USA (60 MWe)

# 1954: Launching of Nautilus



# Nautilus passes the pole





SHIP'S POSITION

U. S. S. NAUTILUS

TO: COMMANDING OFFICER

| (Time of day) | DATE | |
|---|---|---|
| 1915 U | 3 August 1958 | |
| LATITUDE | LONGITUDE | DETERMINED AT |
| 90° 00.0'N | Indefinite | — |

BY (Indicate by check in box): [X] N6A [X] D.R. [X] MK19 [ ] RADAR [ ] VISUAL

| SET | DRIFT | DISTANCE MADE GOOD SINCE (time) (miles) |
|---|---|---|
| — | — | Honolulu 4844 |

| DISTANCE TO | MILES | ETA |
|---|---|---|
| North Pole | Zero | — |

| TRUE HDG. | ERROR | VARIATION |
|---|---|---|
| 180 | MK19 GYRO 3E MK23 GYRO 0 | 170 E |

MAGNETIC COMPASS HEADING (Check one): [ ] STD [ ] STEERING [X] REMOTE IND. [ ] OTHER M 244 G 359

| DEVIATION | 1104 TABLE DEVIATION | DG (Indicate by check in box) |
|---|---|---|
| 126E | 3° W | [ ] ON [X] OFF |

REMARKS

N6A DR
$\sigma = 0$
$\nu = 0$

N6A
$n_x = 0$
$n_y = 0$
$n_z = 1$

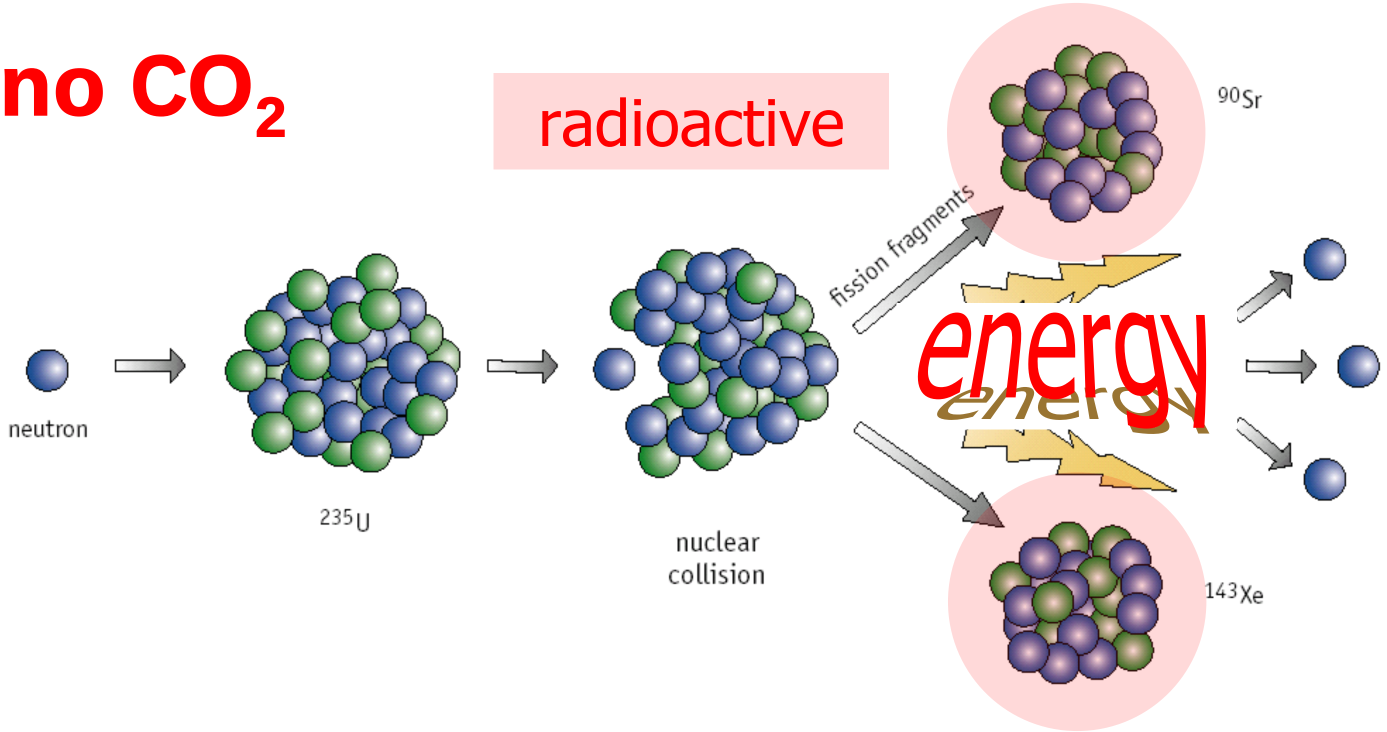
RESPECTFULLY SUBMITTED (Navigator)

LT Shepherd M. Jenks, USN

CC:

# Nuclear fission

**no $CO_2$**



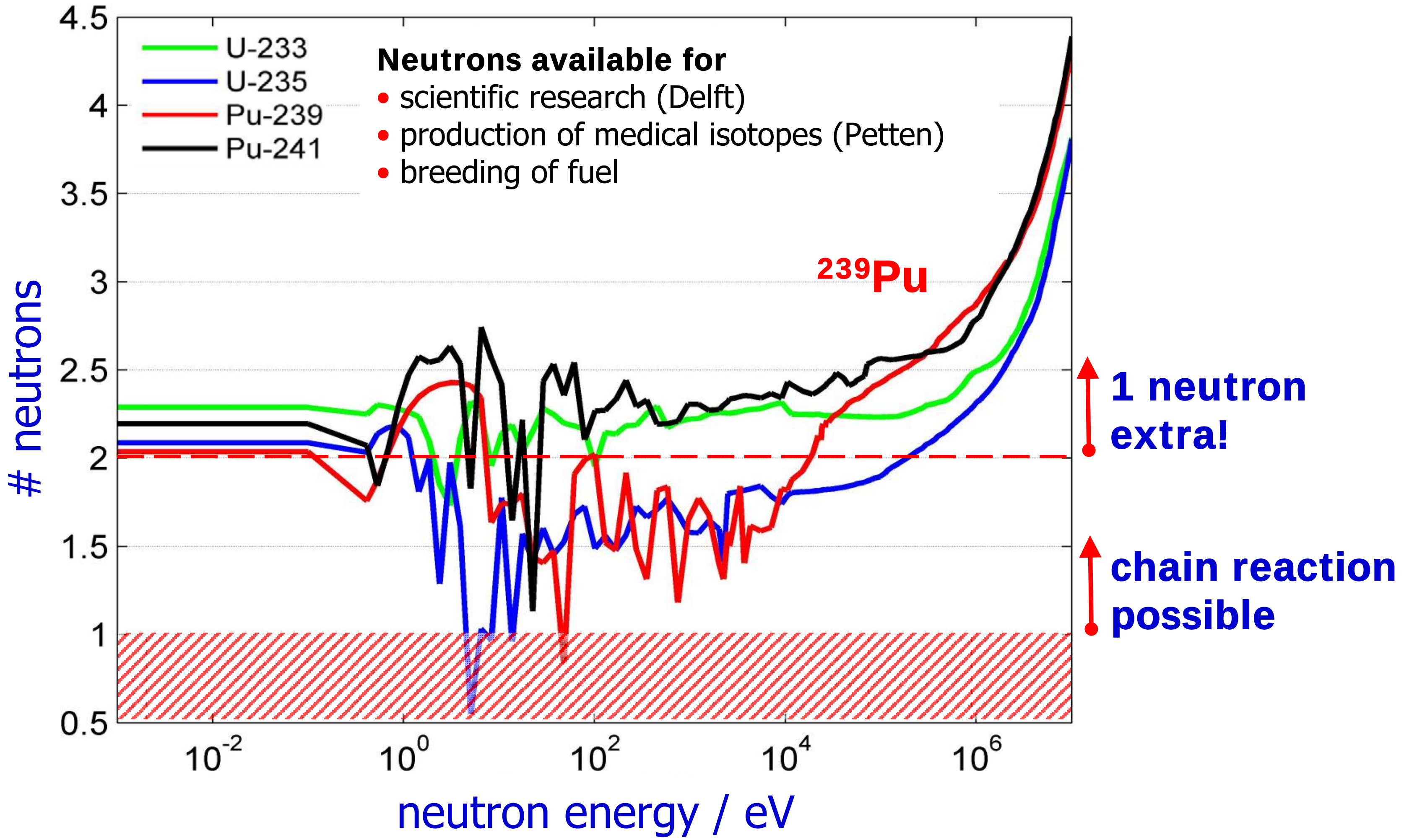

Fissioning of 1 gram uranium yields as much energy as burning 2500 liters petrol or 3000 kilograms coal

# Small volumes of material needed

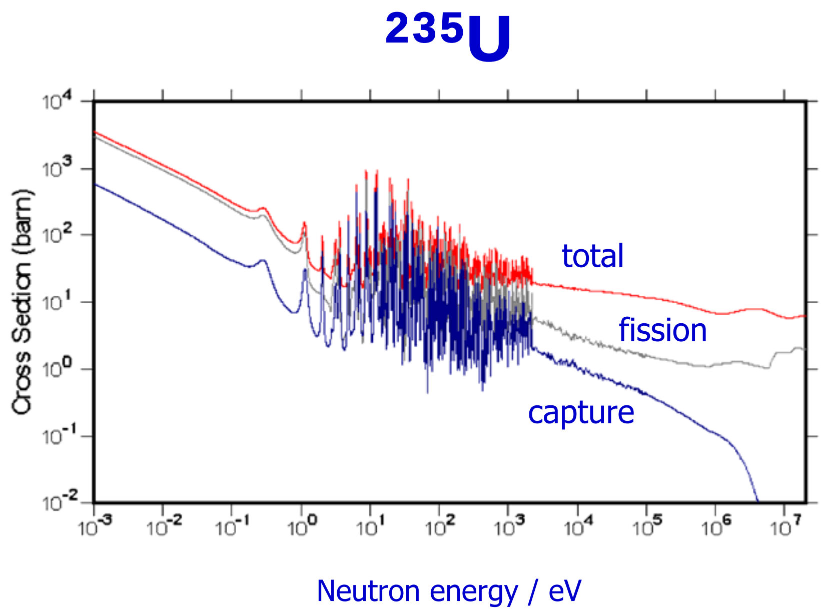
**→ strategic stock possible**
**→ low amounts of waste**

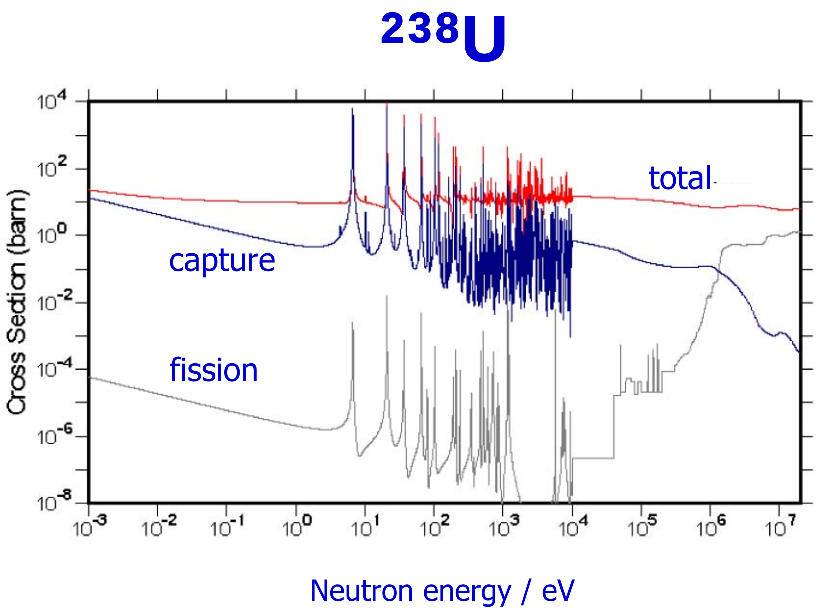
- all electricity in the Netherlands nuclear:
  0.4 gram uranium fissioned (=waste)
  per family per year
- in a human life: a volume of 1 billiard ball
- ‘Borssele’ produces 1.3 $m^3$ highly radioactive waste per year, but ‘prevents’ the emission of 2 billion kilograms $CO_2$ per year
- a radioactive material emits radiation →
  it clears itself (the more radioactive, the quicker)

# # neutrons released per absorption of 1 neutron



# Cross sections (interaction probability)




➡ Neutrons have to be slowed down (*moderated*) to keep the chain reaction going

(moderator: water, graphite)

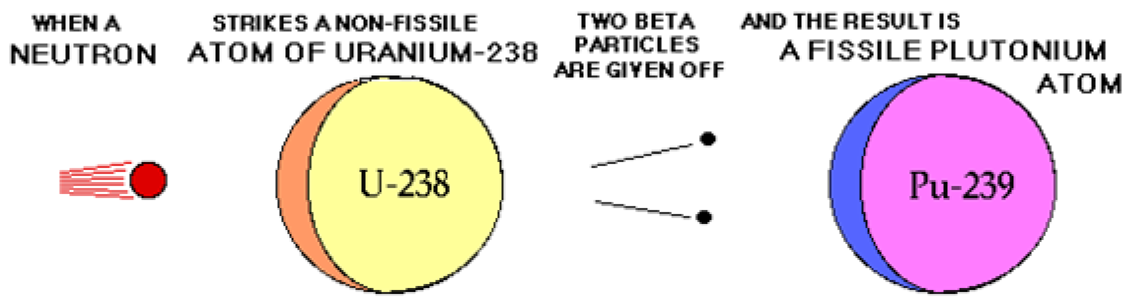
# fissile – fissionable – fertile

- *Fissile* isotopes (can be fissioned by neutron absorption):
  **$^{233}U$, $^{235}U$, $^{239}Pu$, $^{241}Pu$ (rare)**

- *Fissionable* isotopes (threshold in neutron energy):
  **$^{232}Th$, $^{233}Th$, $^{234}U$ , $^{236}U$ , $^{238}U$ , $^{239}U$ , $^{240}Pu$, $^{242}Pu$ ...**

- *Fertile* isotopes (can be turned into a fissile isotope):
  **$^{232}Th$, $^{238}U$**

# Production of fissile isotopes (conversion)

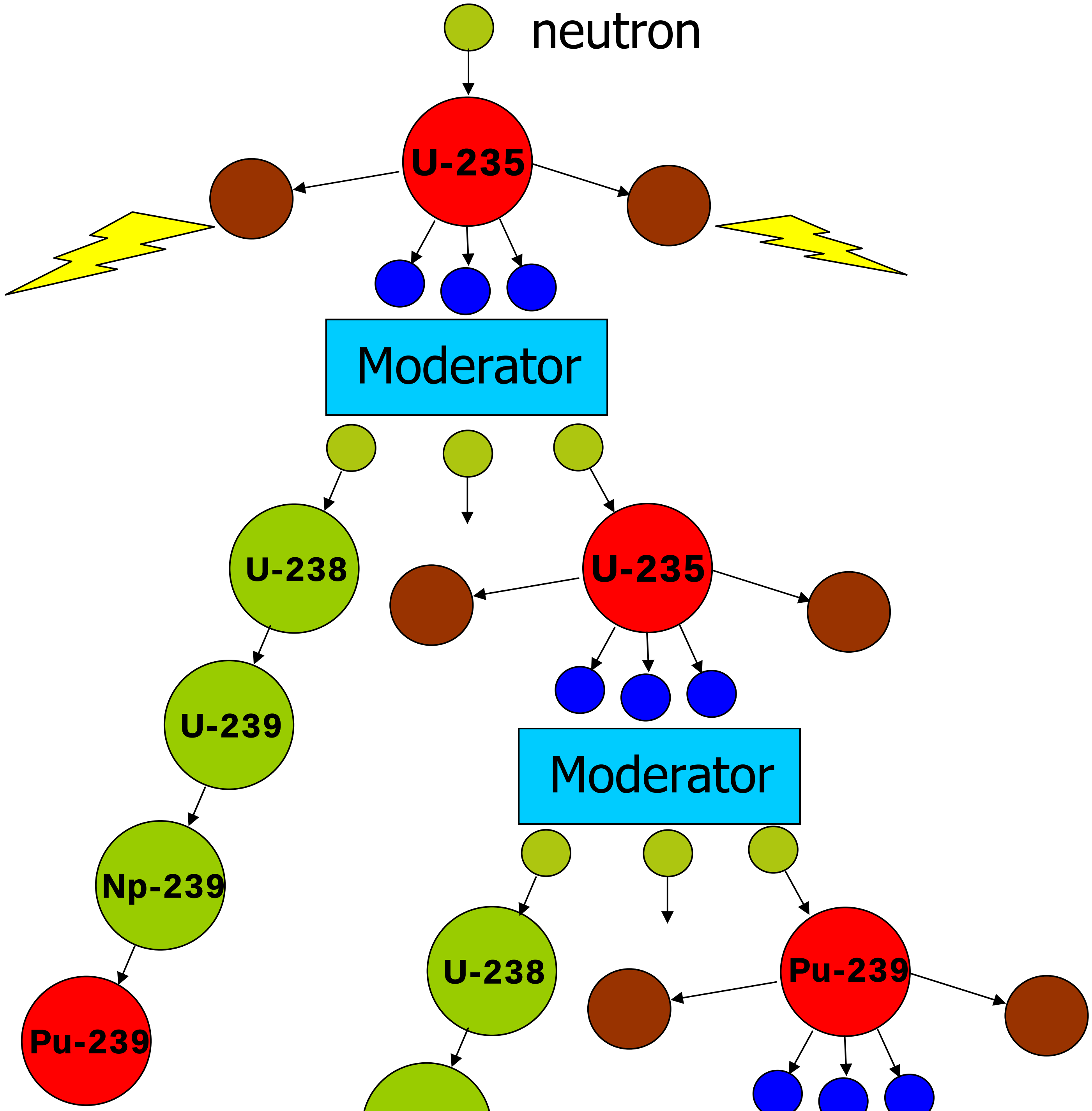



$$^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \xrightarrow[23.5\,\mathrm{min}]{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow[2.3\,\mathrm{d}]{\beta^-} {}^{239}_{94}\mathrm{Pu}$$

extra neutron needed

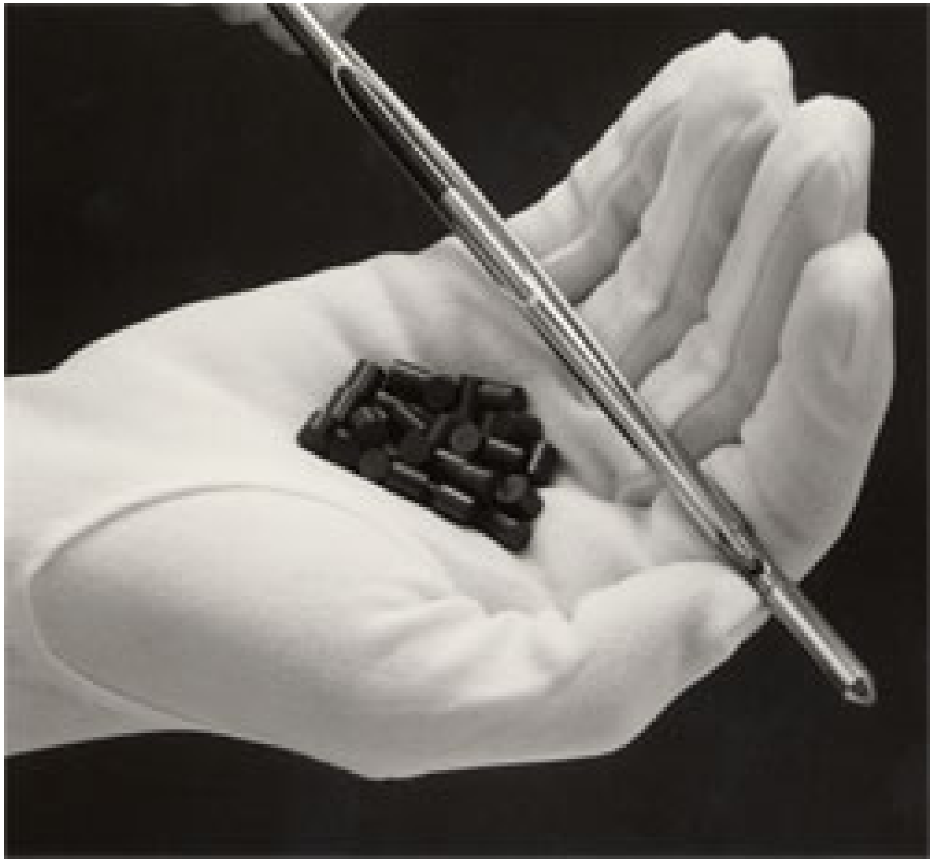
$$^{232}_{90}\mathrm{Th} + \mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow[22.3\,\mathrm{min}]{\beta^-} {}^{233}_{91}\mathrm{Pa} \xrightarrow[27\,\mathrm{d}]{\beta^-} {}^{233}_{92}\mathrm{U}$$

**If more fissile isotopes are produced from fertile isotopes than were destroyed in the chain reaction: breeding**



neutron
U-235
Moderator
U-238
U-235
U-239
Moderator
Np-239
U-238
Pu-239
Pu-239

# Fuel tablets



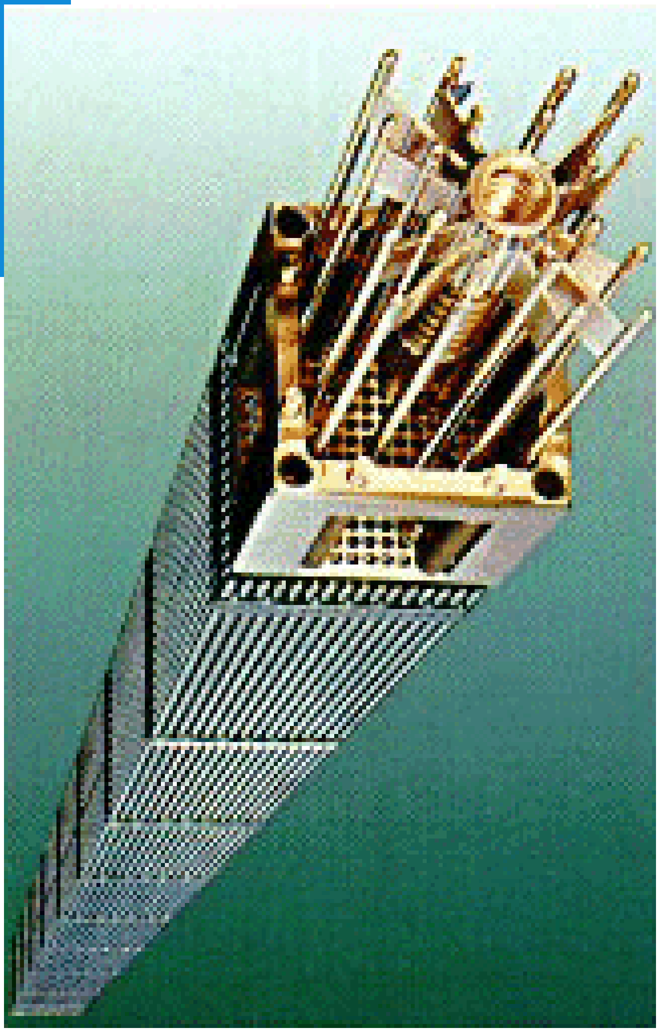
Composition of:

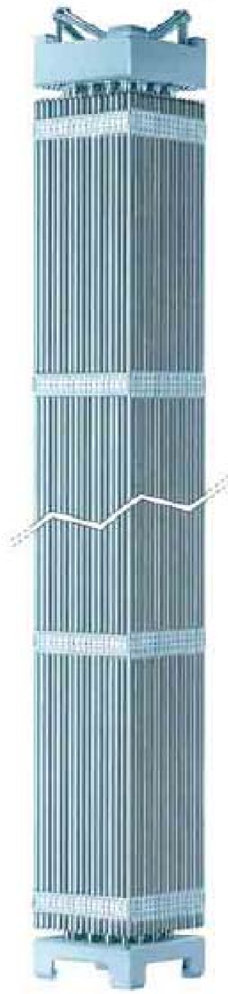
5% $^{235}U$

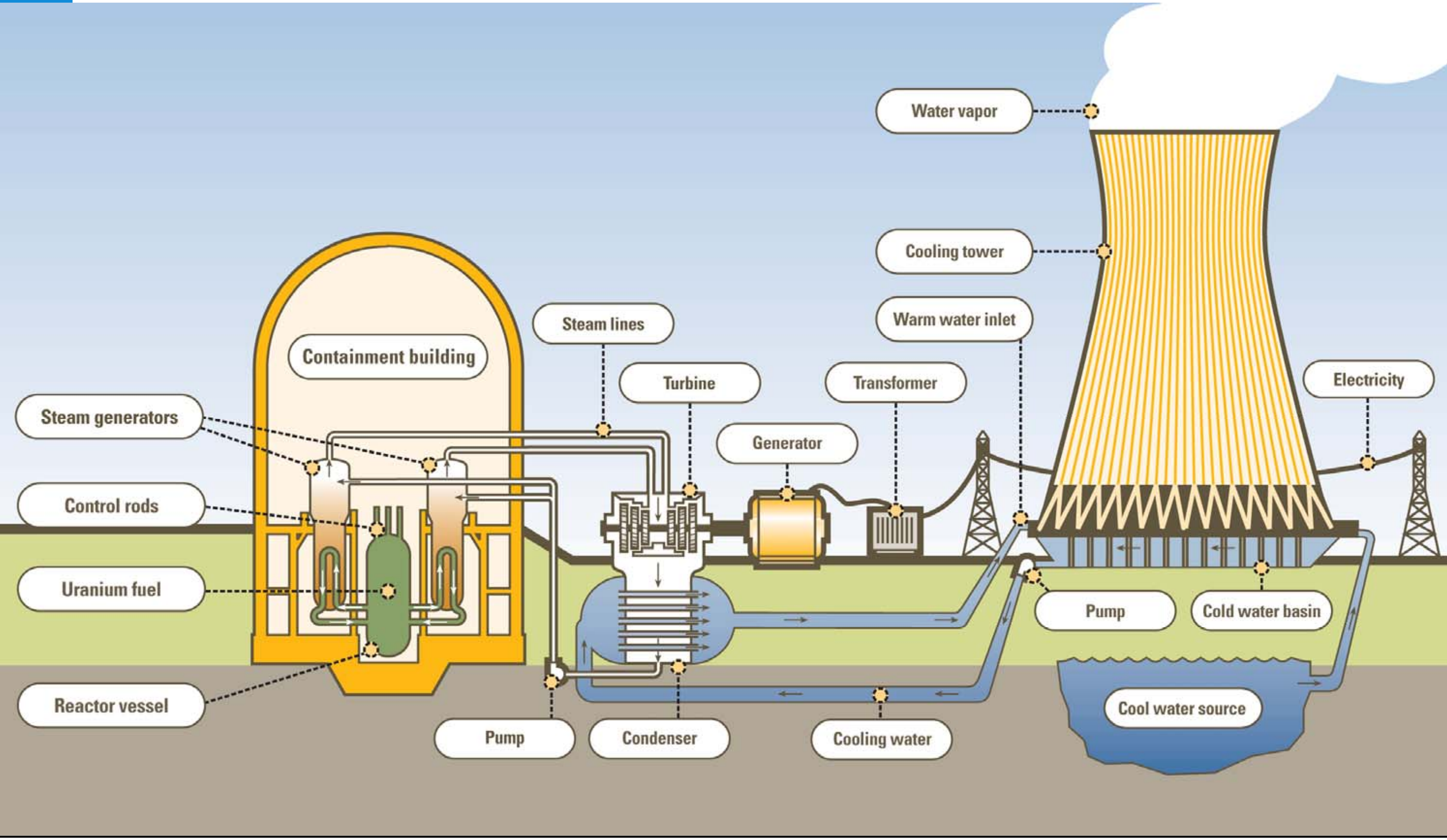
95% $^{238}U$

(0.7% $^{235}U$ in natural ore)

# Fuel assembly of a PWR

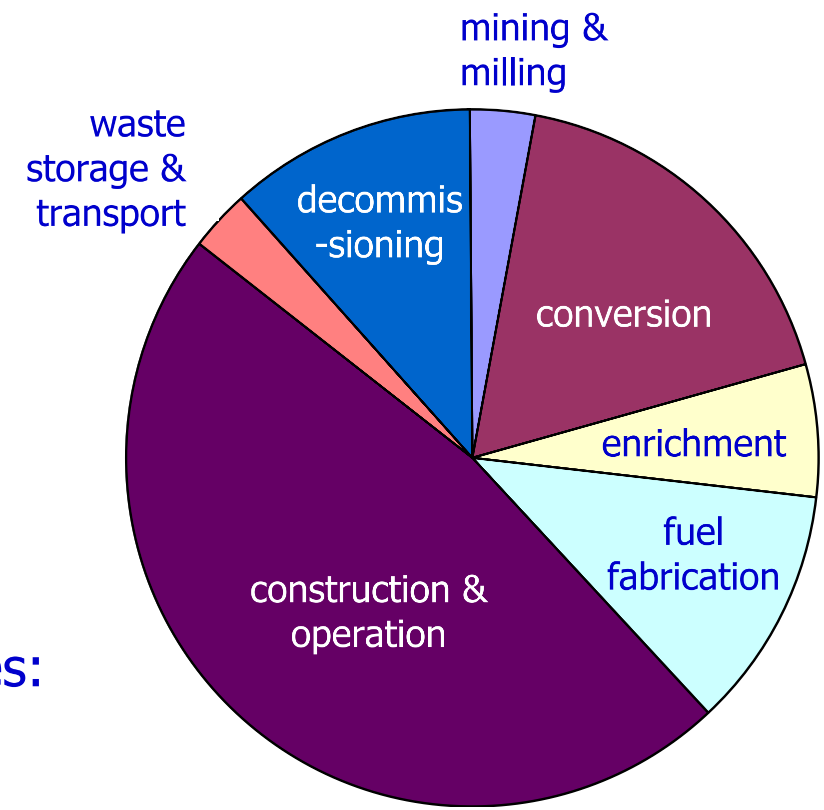





Water vapor
Cooling tower
Warm water inlet
Steam lines
Containment building
Turbine
Transformer
Electricity
Generator
Steam generators
Control rods
Uranium fuel
Pump
Cold water basin
Reactor vessel
Cool water source
Pump
Condenser
Cooling water

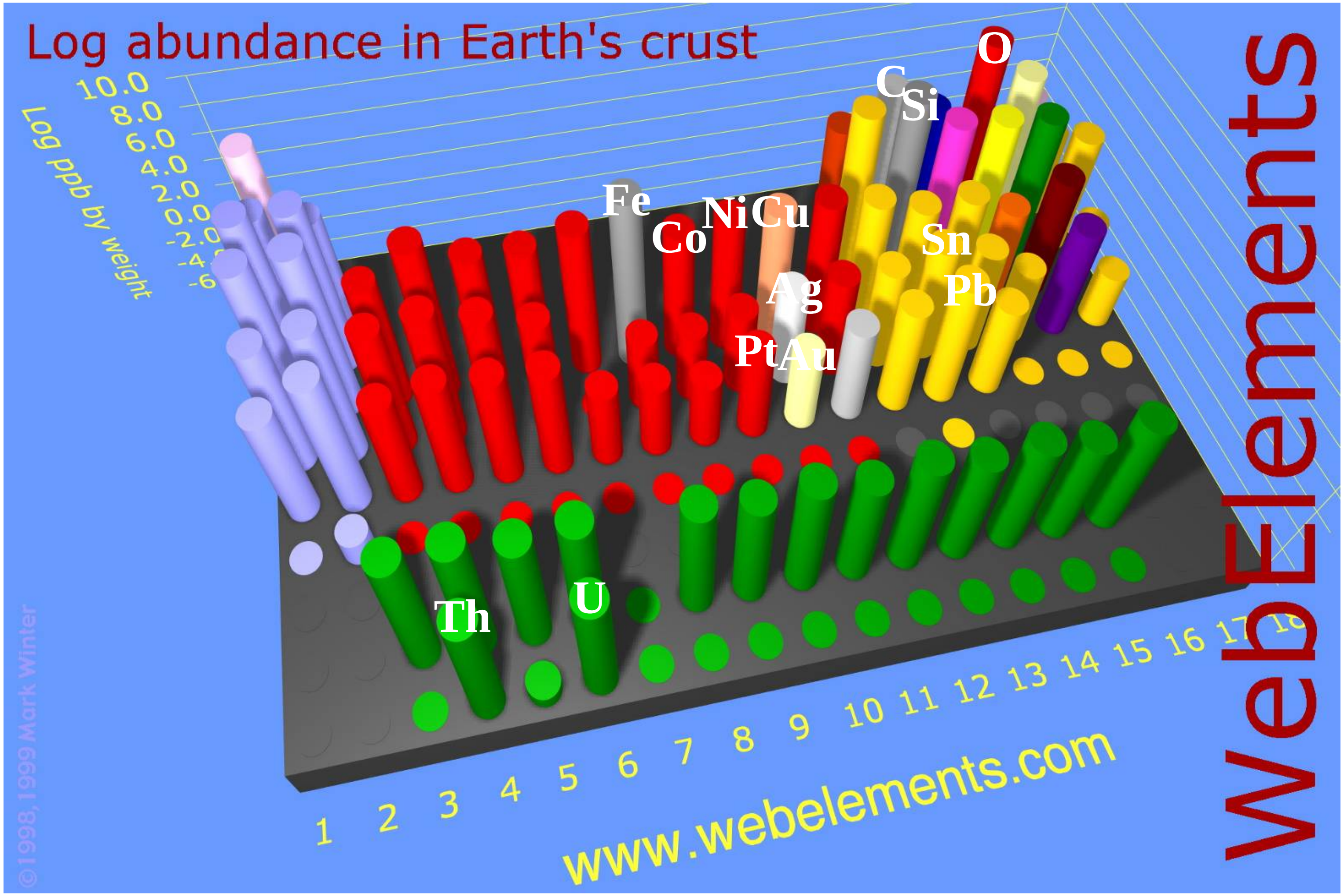
# Energy balance (*Life Cycle Analysis*)

(1000 MWe PWR, 80% availability, 40 years of operation)



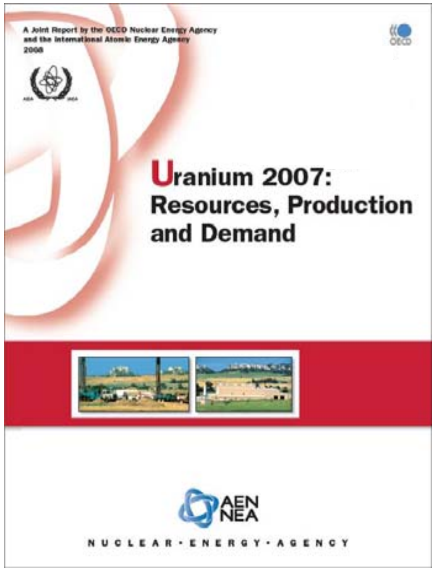

enrichment with centrifuges:
input / output = **1.7 %**

# Element abundance in earth's crust



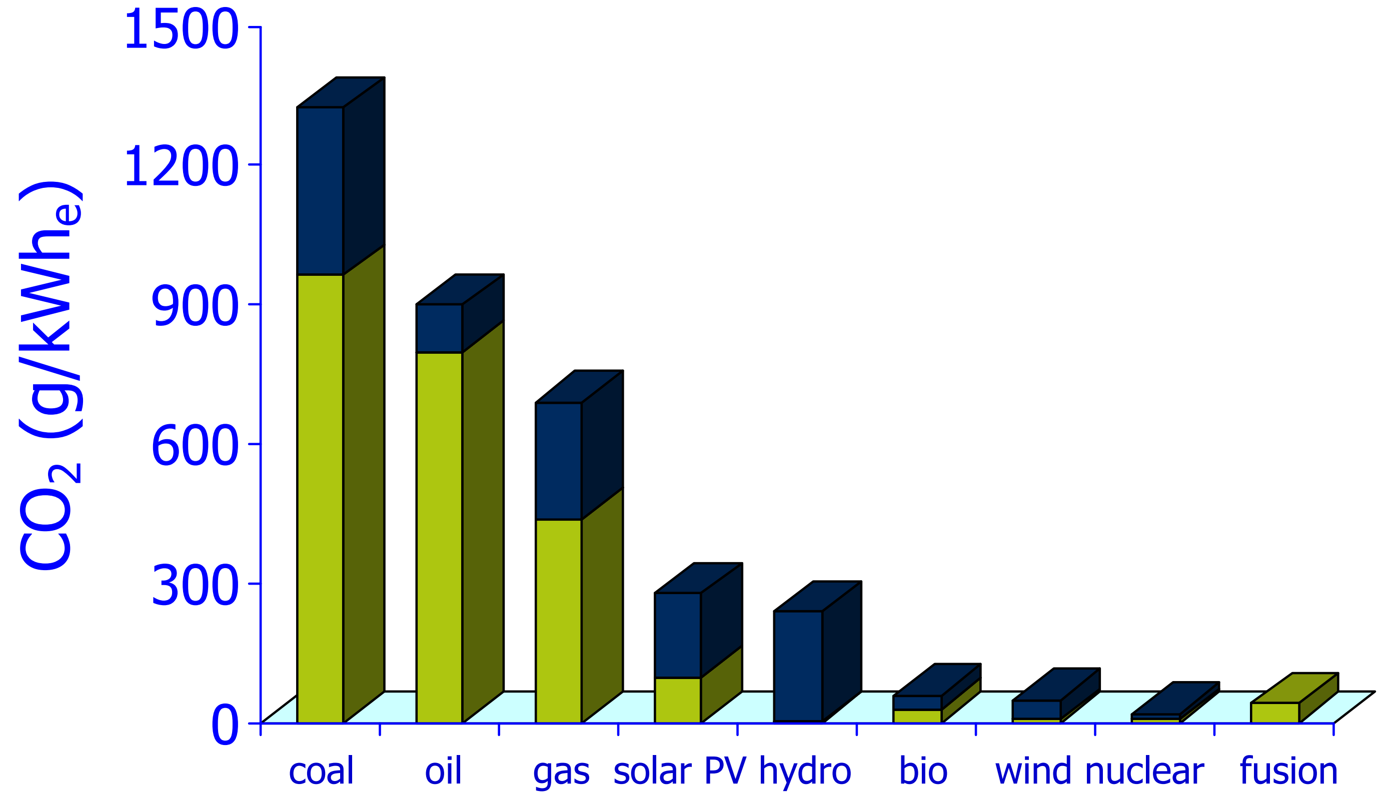
# Uranium resources:

- The earth's crust contains 40 x as much uranium as silver; as much uranium as tin
- Cheap uranium (up to 130$ per kg): 5.5 million tons; enough for 80 years (0.1 ct/kWh)
- For the double price:
  10 times as much; enough for 800 years
  using fast reactors: 80,000 years
- Uranium as byproduct from phosphate deposits (22 Mt recoverable)
- Uranium from seawater (450$ per kg): 4 billion tons; enough for 6,000,000 years



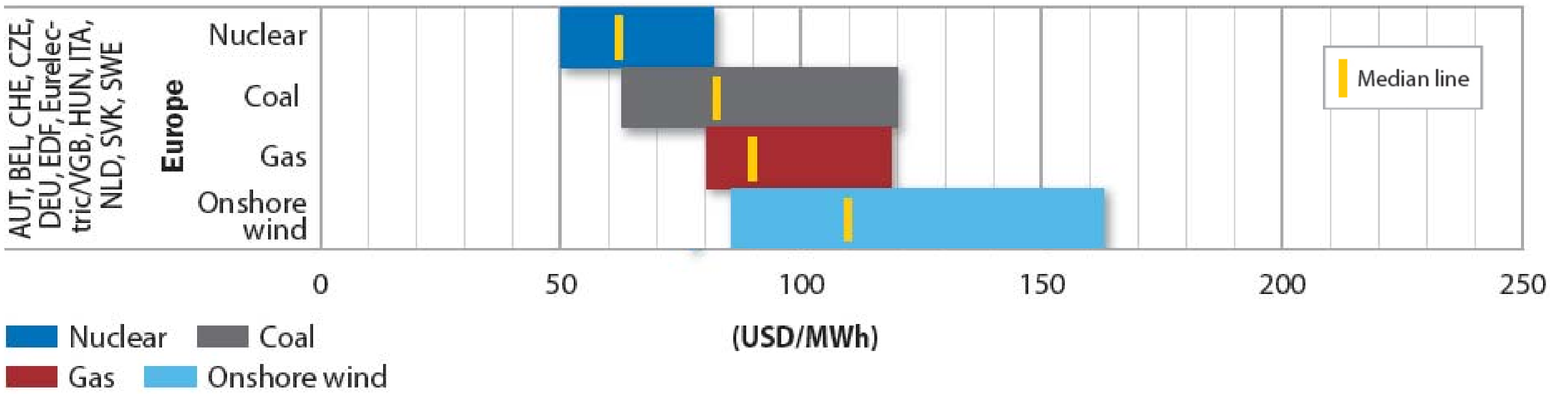

*Source: OECD NEA & IAEA, "Uranium 2007: Resources, Production and Demand" ("Red Book").*

# $CO_2$ production

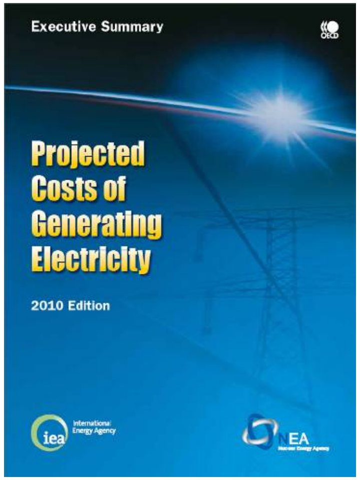



*Source: IAEA (2000)*

# Costs of electricity production

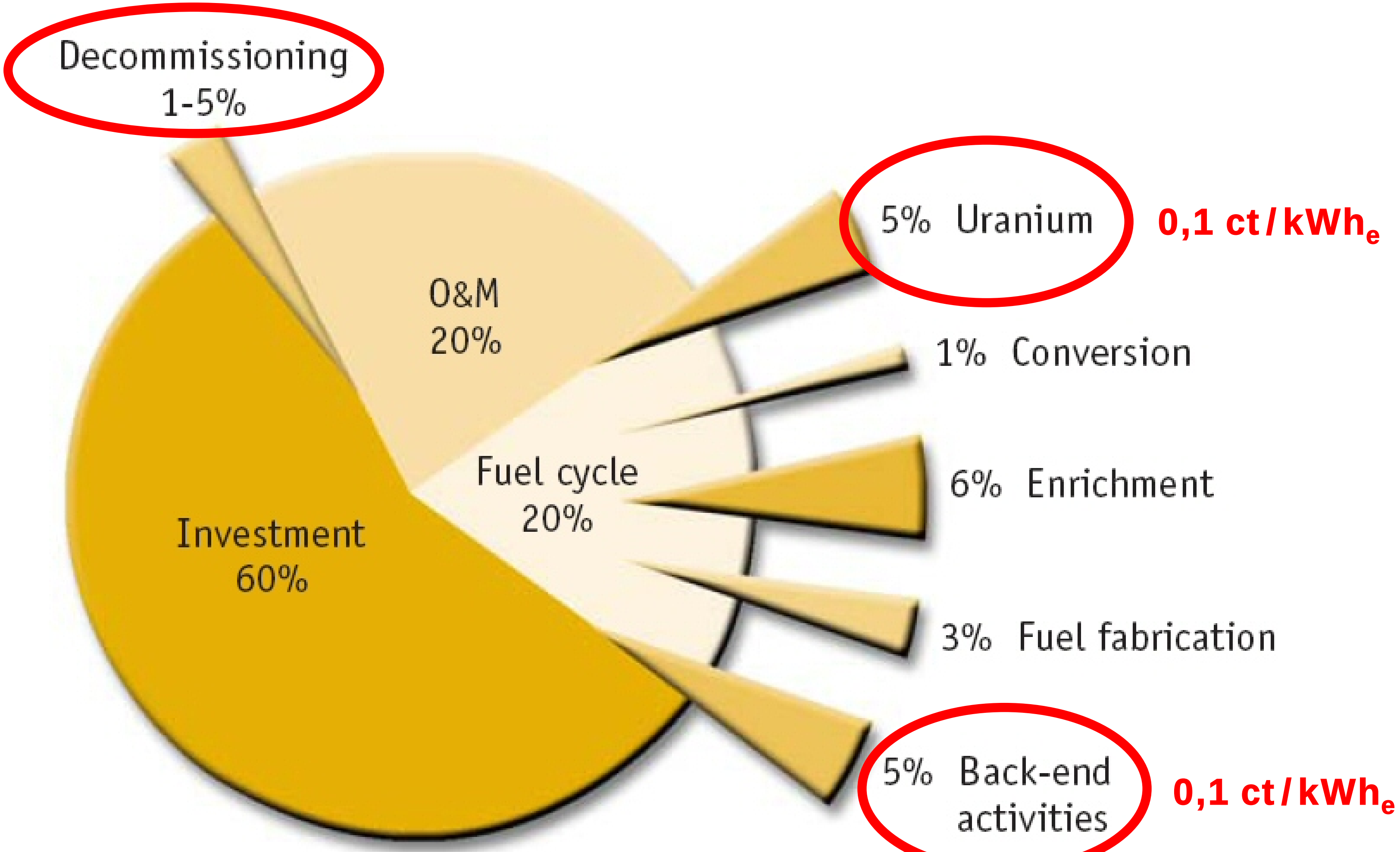



assumptions:
5% discount rate
$CO_2$ price: 30 USD/tonne (plant level, without transport and storage)

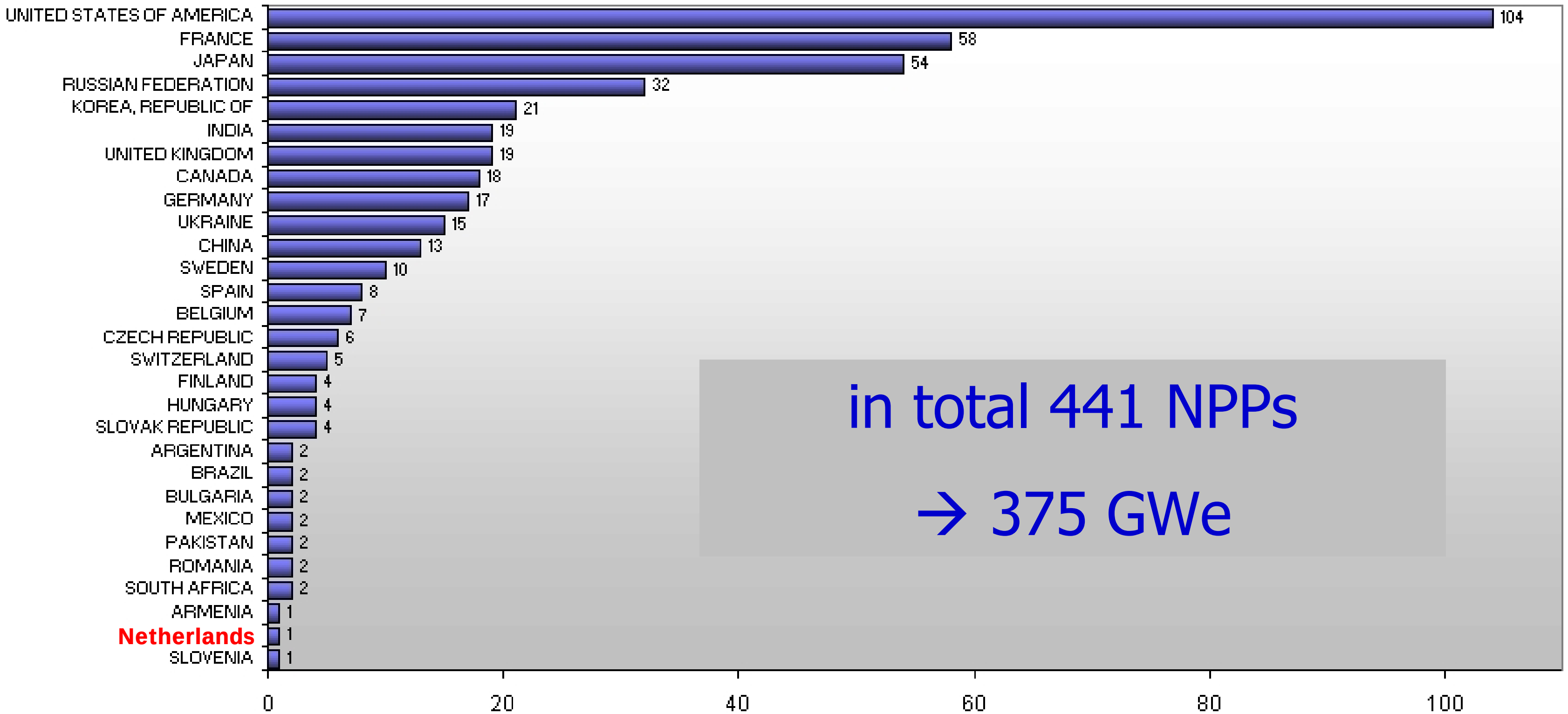



*Source: OECD, "Projected Costs of Generating Electricity", 2010*

# Breakdown of costs of nuclear electricity production

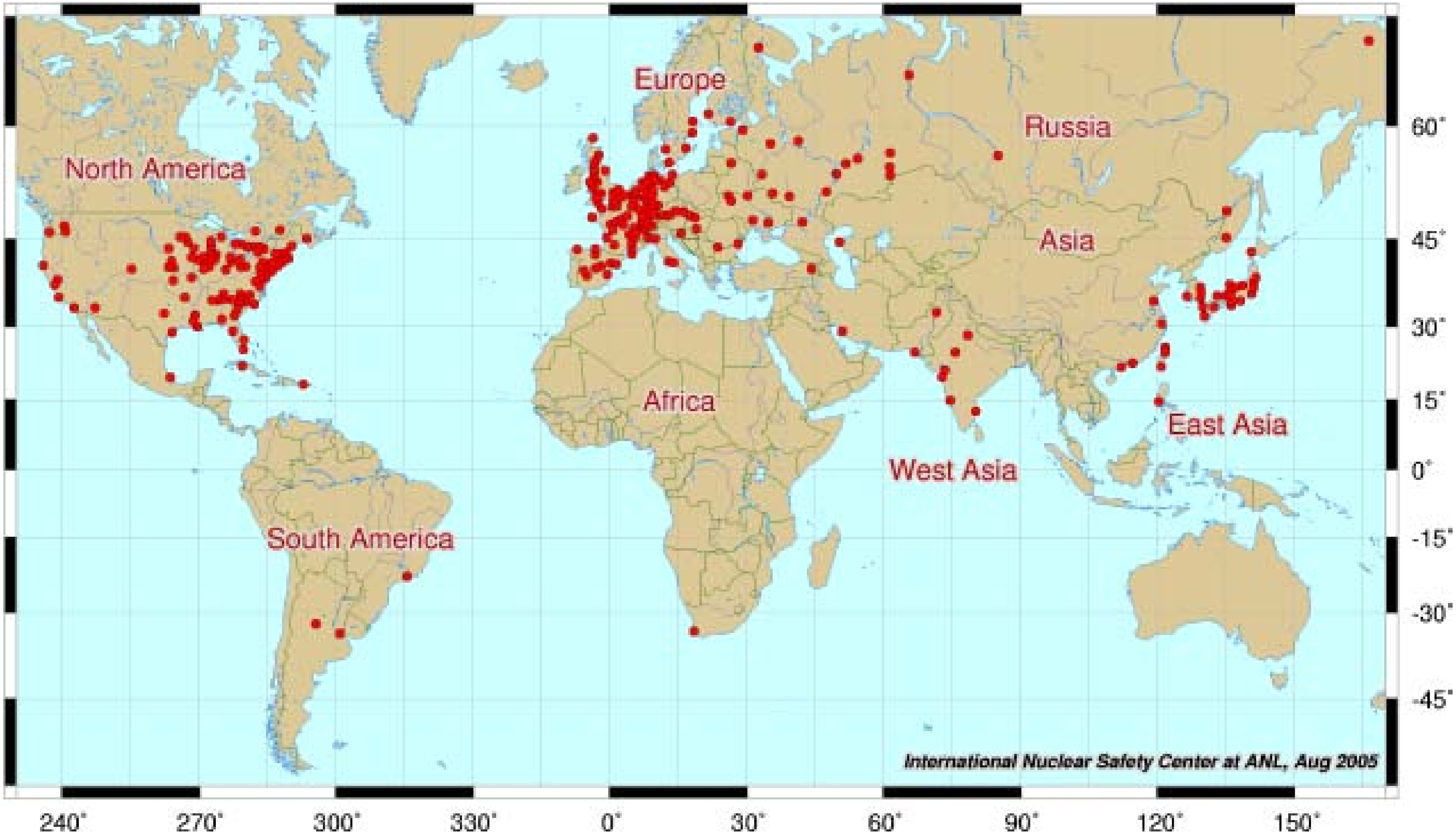


# Nuclear Power Plants in operation



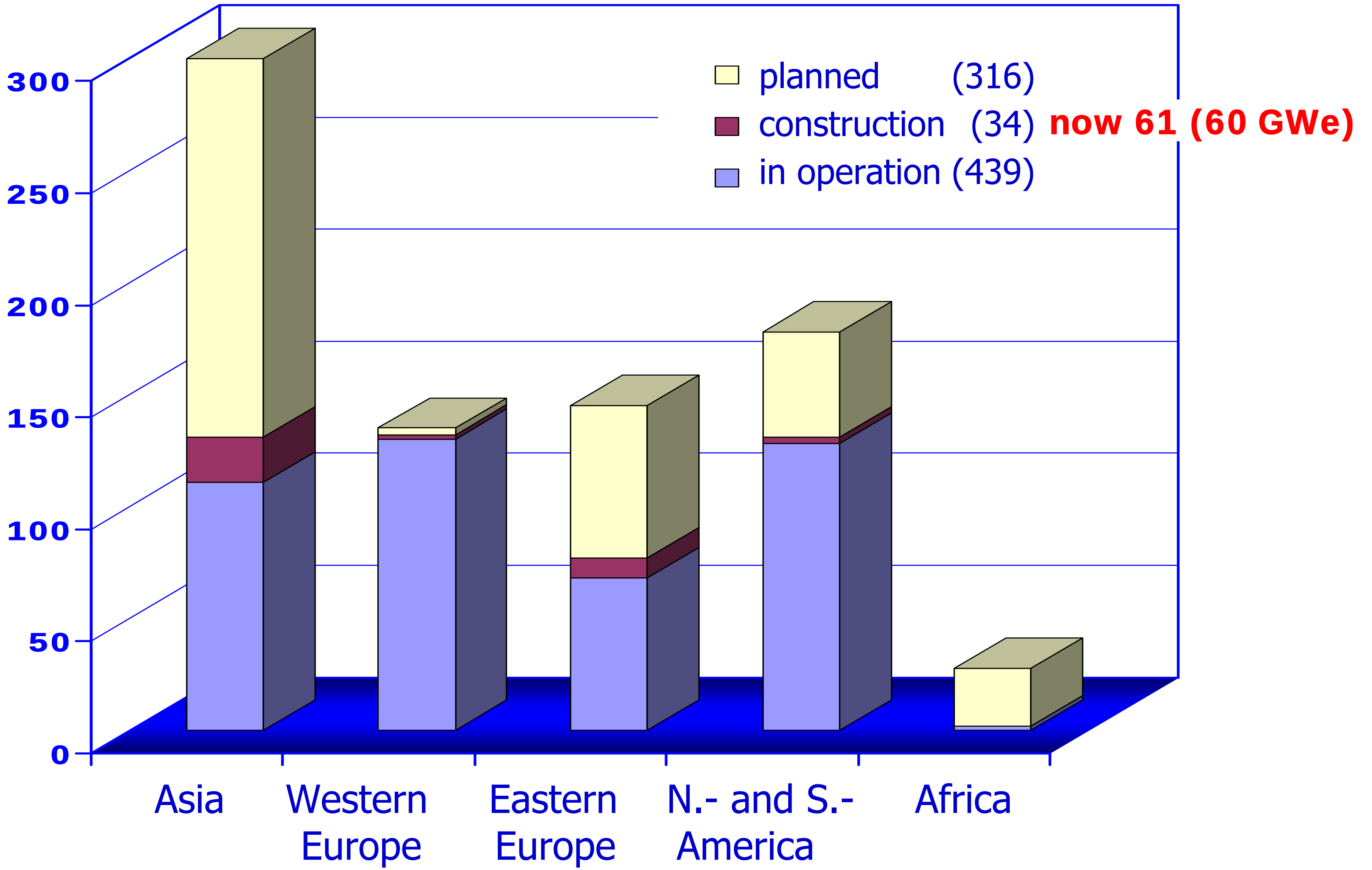

Note:Long-term shutdown units (5) are not counted

# Nuclear Power Plants

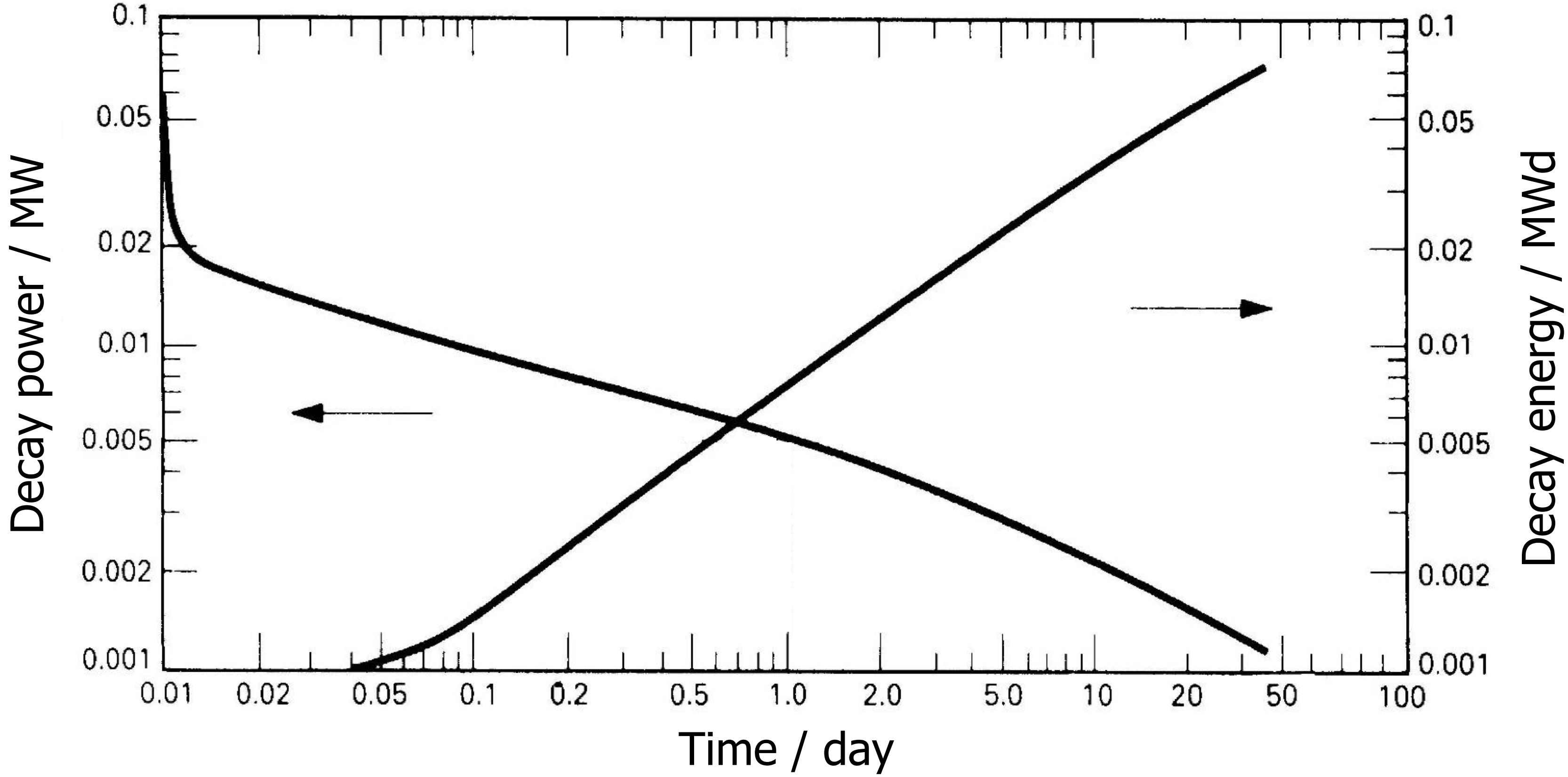


# Status nuclear power plans

## January 2008



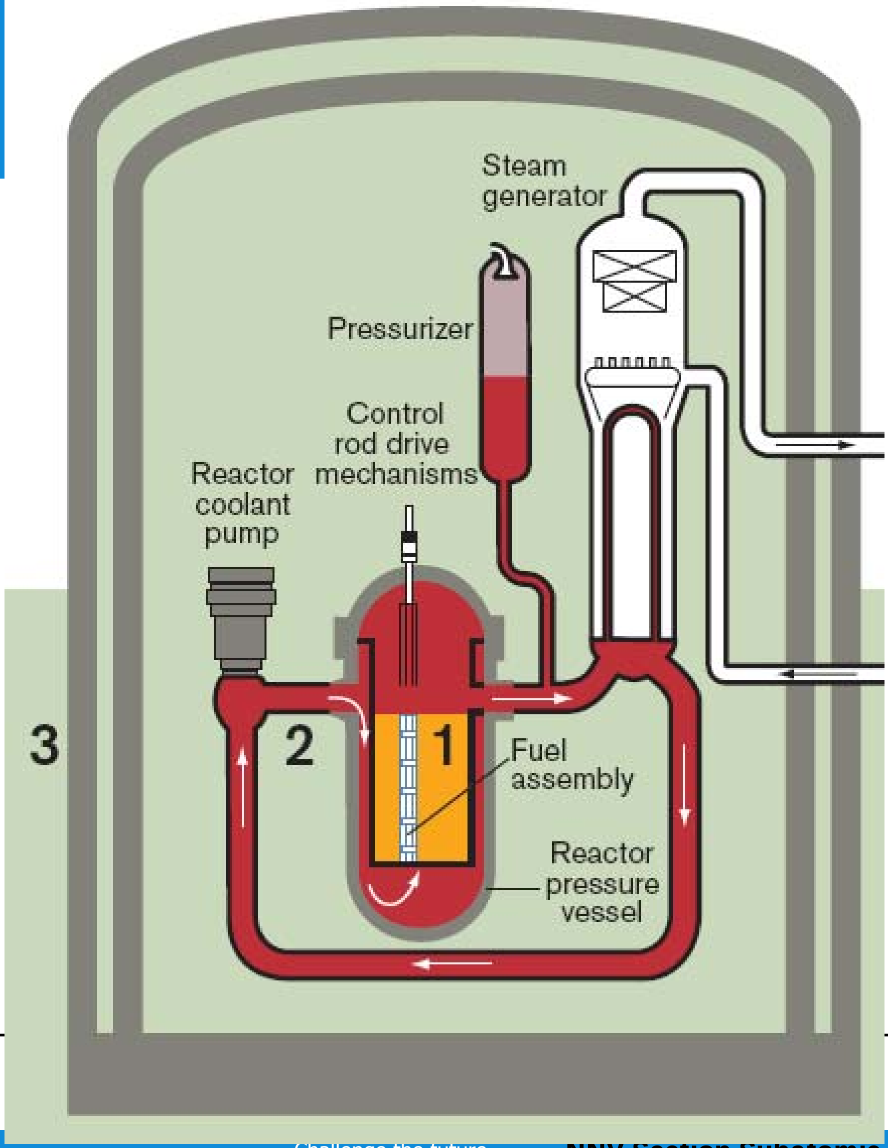
# Safety issue:
## decay heat per MW nominal power

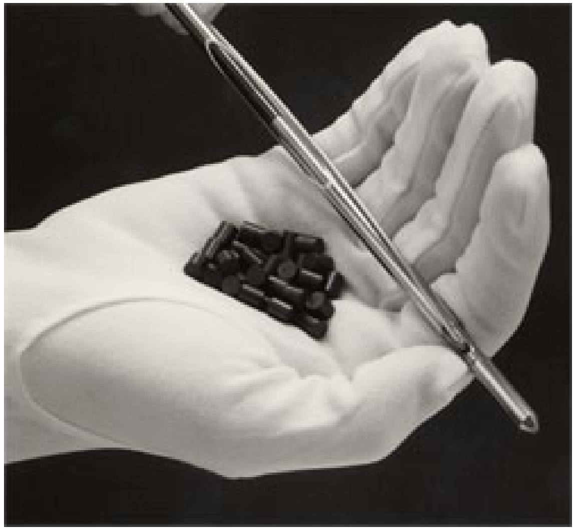



Core cooling is always needed, also after shutdown !

# Safety of nuclear power plants

## multiple barriers to keep radioactive nuclides inside



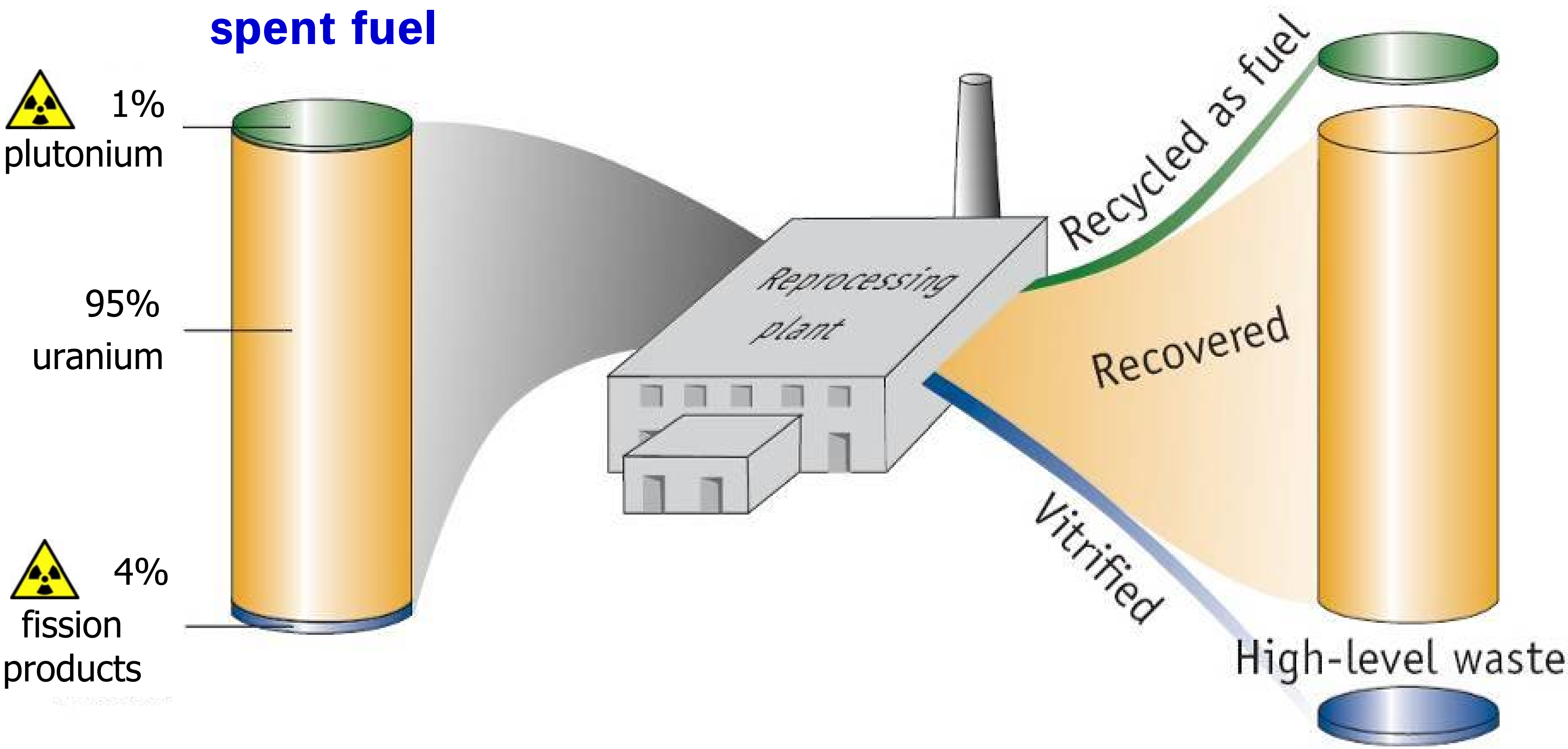



1 Fuel (pellet and cladding)

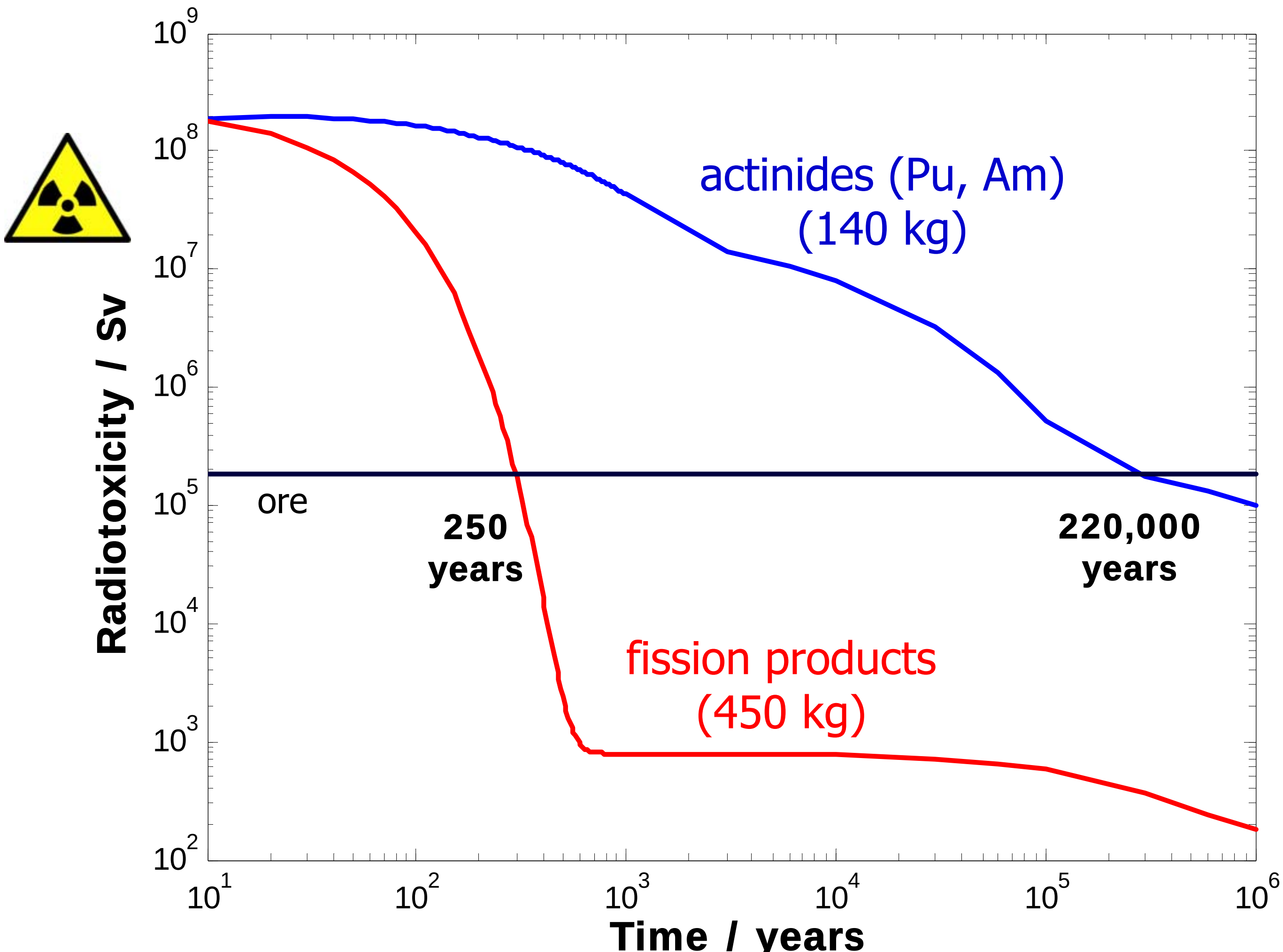
2 Primary system (steel)

3 Containments (2x concrete + steel)

# Spent fuel: only 4% is waste

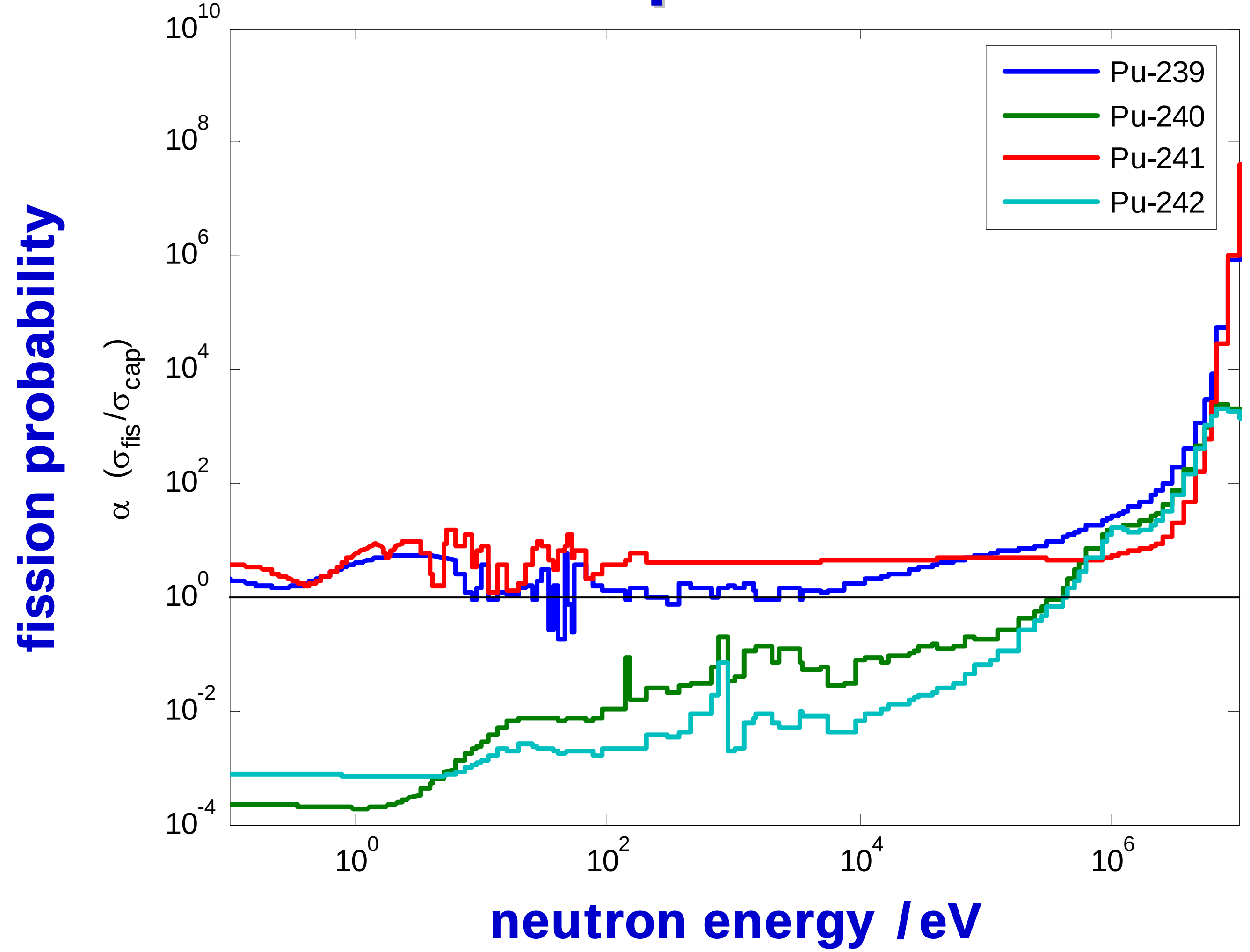


# Two sorts of radioactive products

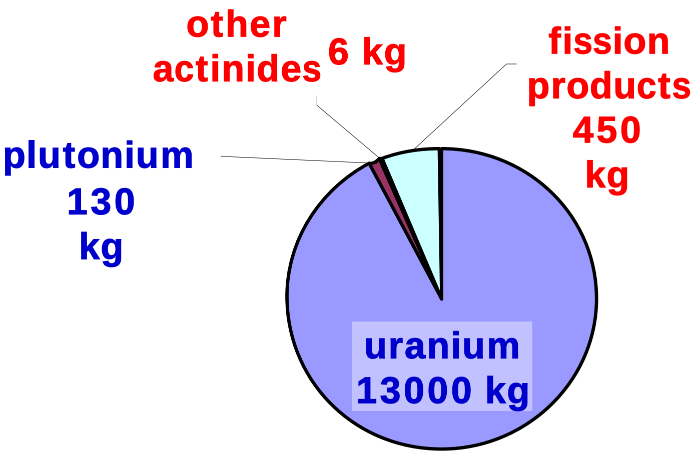



**numbers: yearly production Borssele**

# Fast reactors can fission actinides, like plutonium



# Radioactive waste




numbers: yearly production Borssele

**Two routes possible:**

1) Without reprocessing:
   - 'lifetime' rest products 220,000 year

2) With reprocessing + fast reactors:
   - 'lifetime' waste 500-5,000 years
   - volume reduced to 4%
   - up to 100x better use of base material

# Generations of nuclear reactors

GENERATION IV nuclear power systems

Generation I

Early Prototype Reactors

- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs

- ABWR
- System 80+
- AP600
- EPR

Evolutionary Designs Offering Improved Economics

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

Gen I | Gen II | Gen III | Gen IV

1950 1960 1970 1980 1990 2000 2010 2020 2030

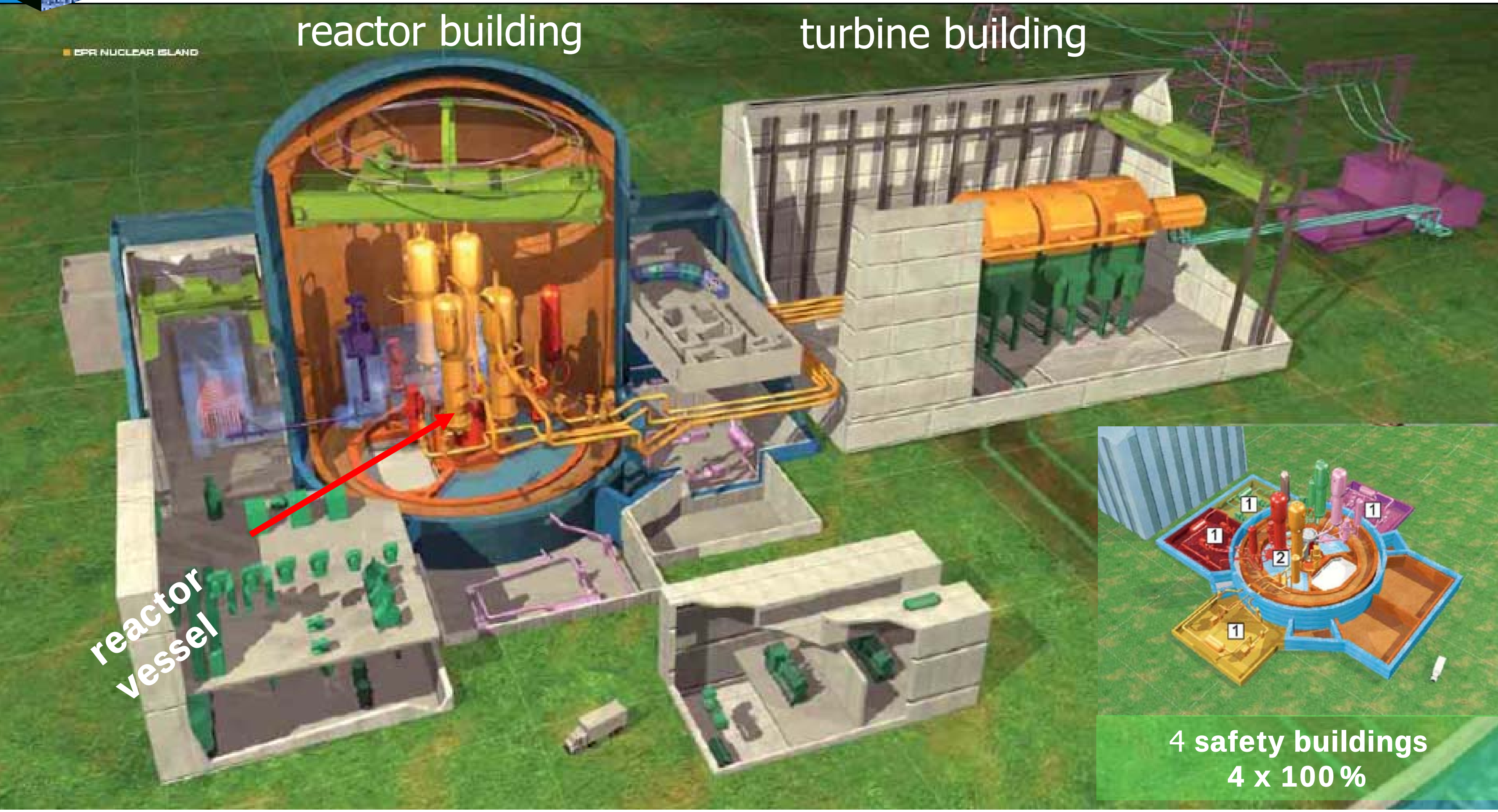
# Advanced reactors, Generation III

reliable and safe due to:

- redundancy
- separation
- diversification
- less and shorter pipelines
- large water volumes

ABWR (in operation since 1995), EPR, ACR1000, System-80$^+$, BWR-90$^+$, KNGR, VVER-91, ...

# European Pressurized Water Reactor
## 4500 MWth

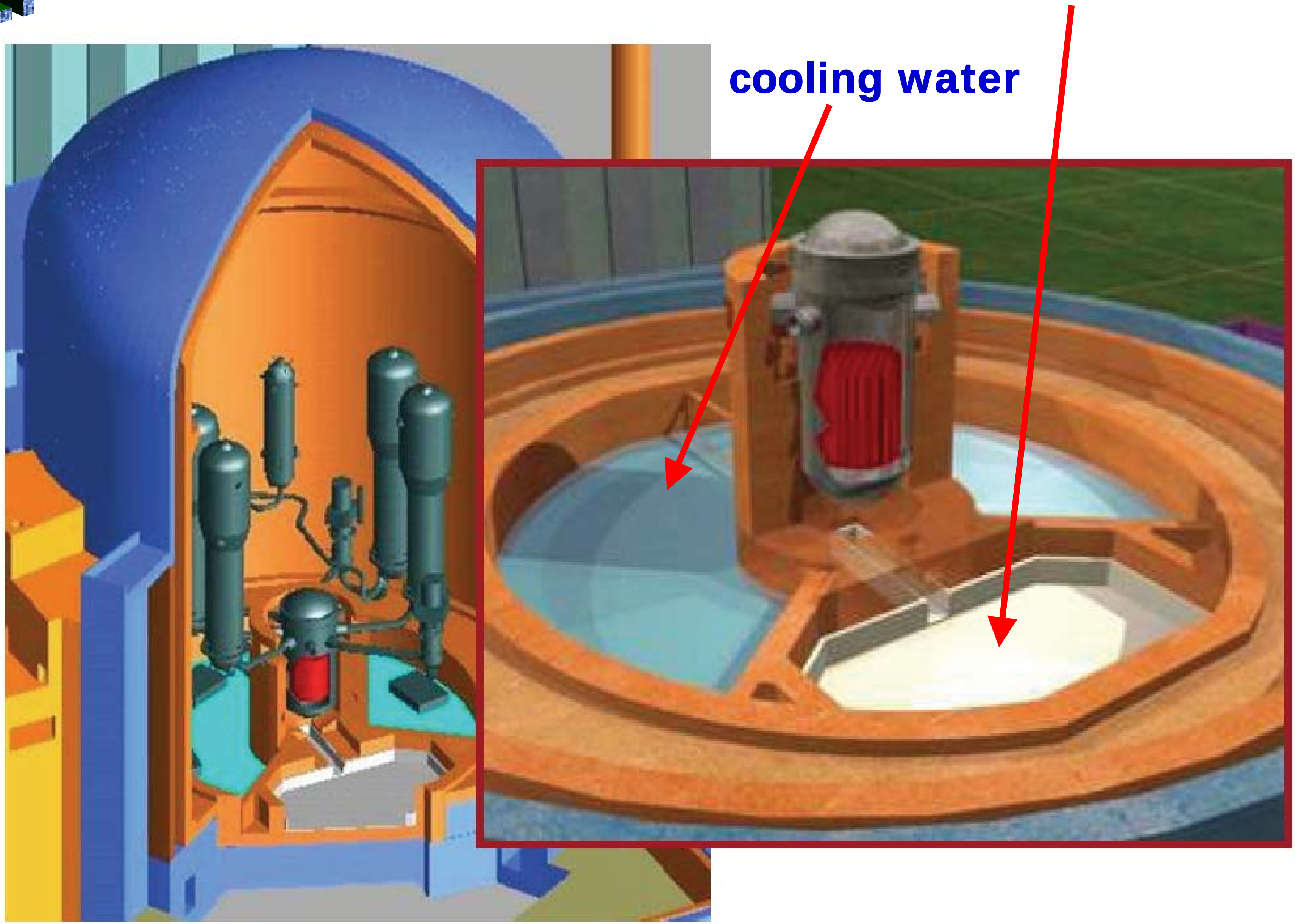


# Double containment

– Concrete –
– Steel –
– Concrete –

**Resistant against the impact of a large airplane**

# Passively cooled 'Core Catcher'



# Advanced, evolutionary designs (Generation III$^{+}$)

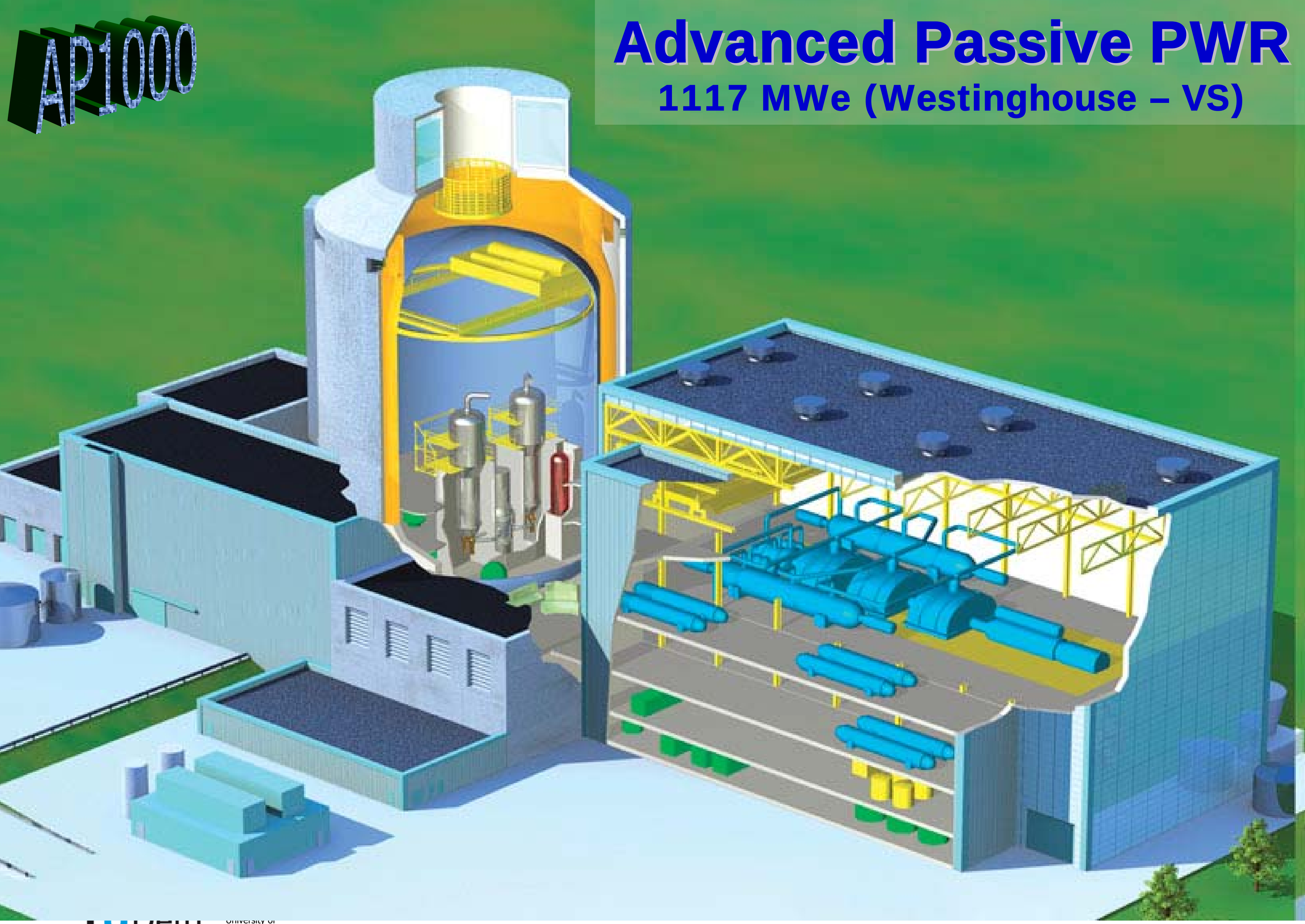
with 'passive' components:

- natural circulation core cooling
- convection cooling of the containment
- heat removal by radiation

AP1000, ESBWR, SWR-1000, PBMR, HTRM, GT-MHR, APWR, EP-1000, AC-600, MS-600, V-407, V-392, JSBWR, JSPWR, HSBWR, CANDU-6, CANDU-9, AHWR, ...

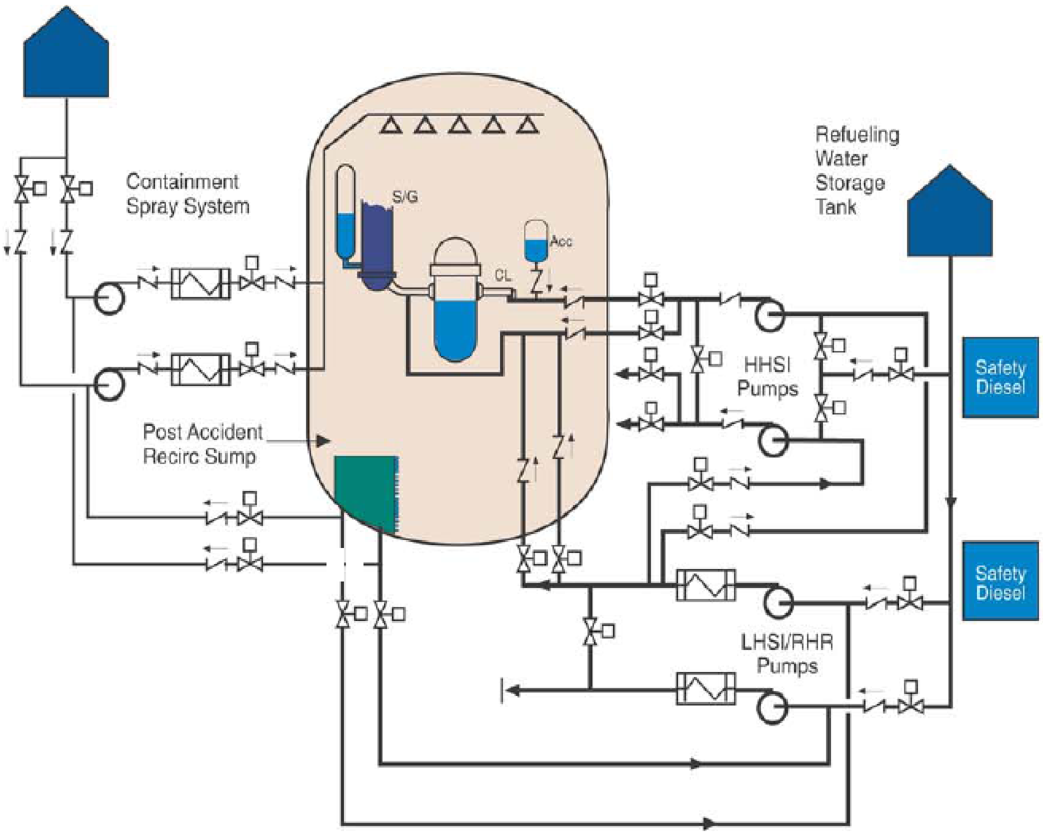
# Advanced Passive PWR

## 1117 MWe (Westinghouse – VS)

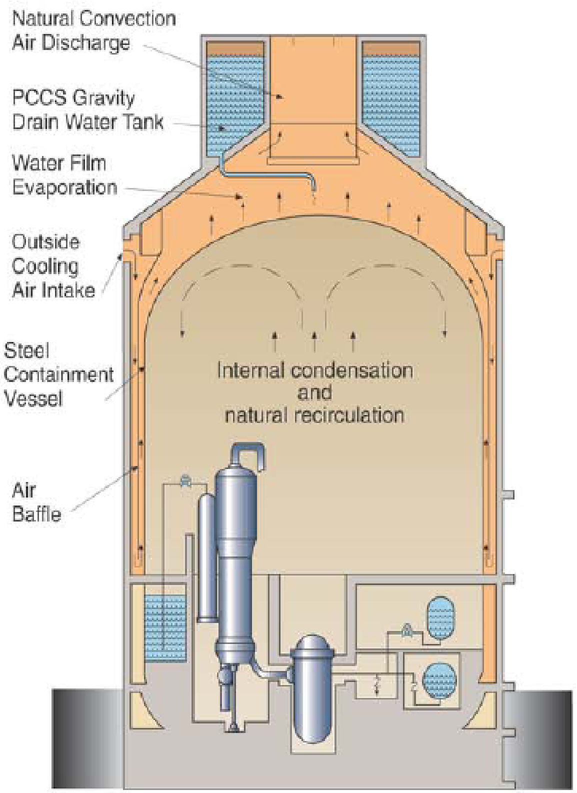


# Passive emergency cooling of the containment

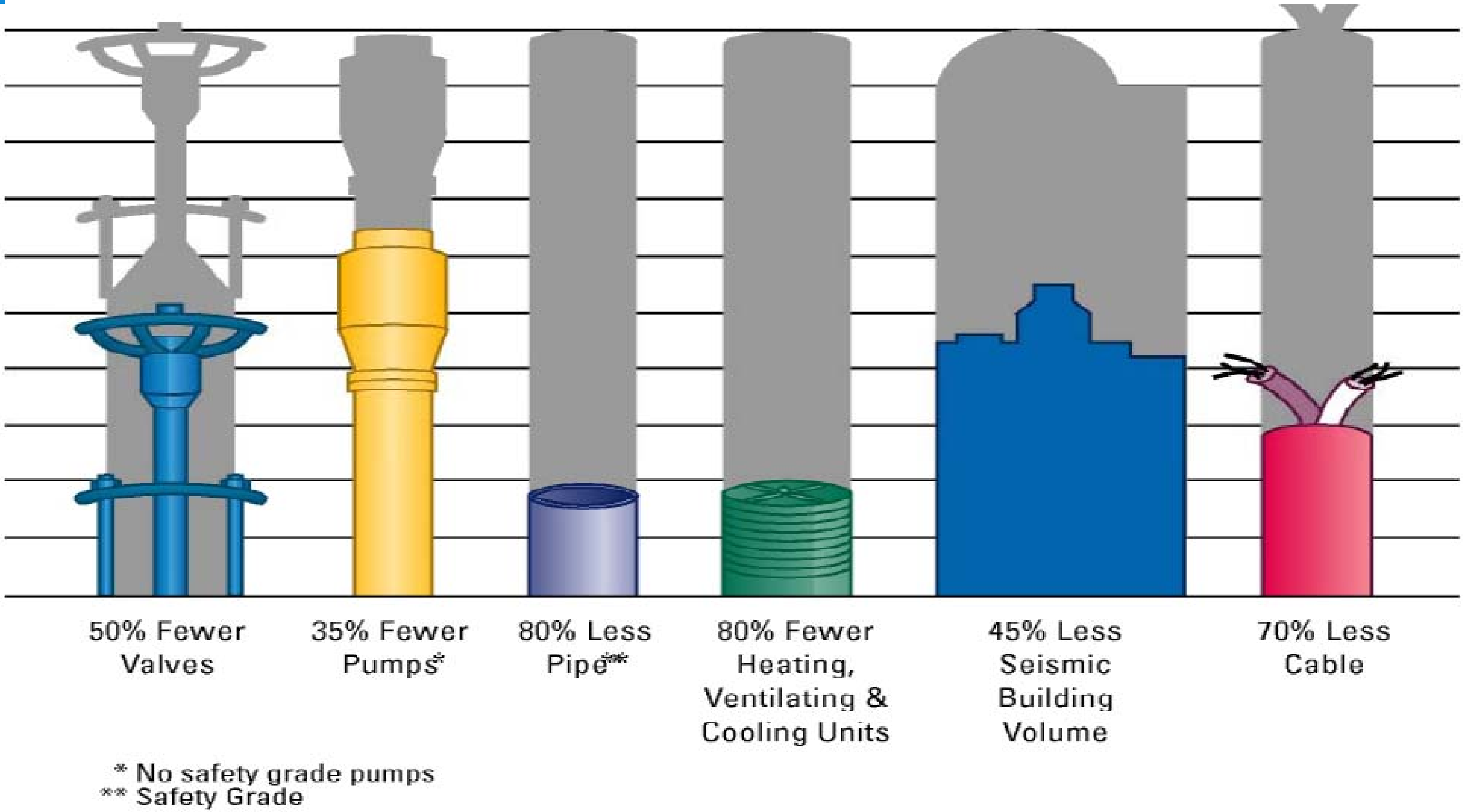
Standard PWR




AP1000



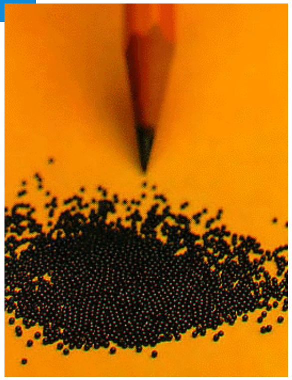
# Passive safety due to fewer components and less piping

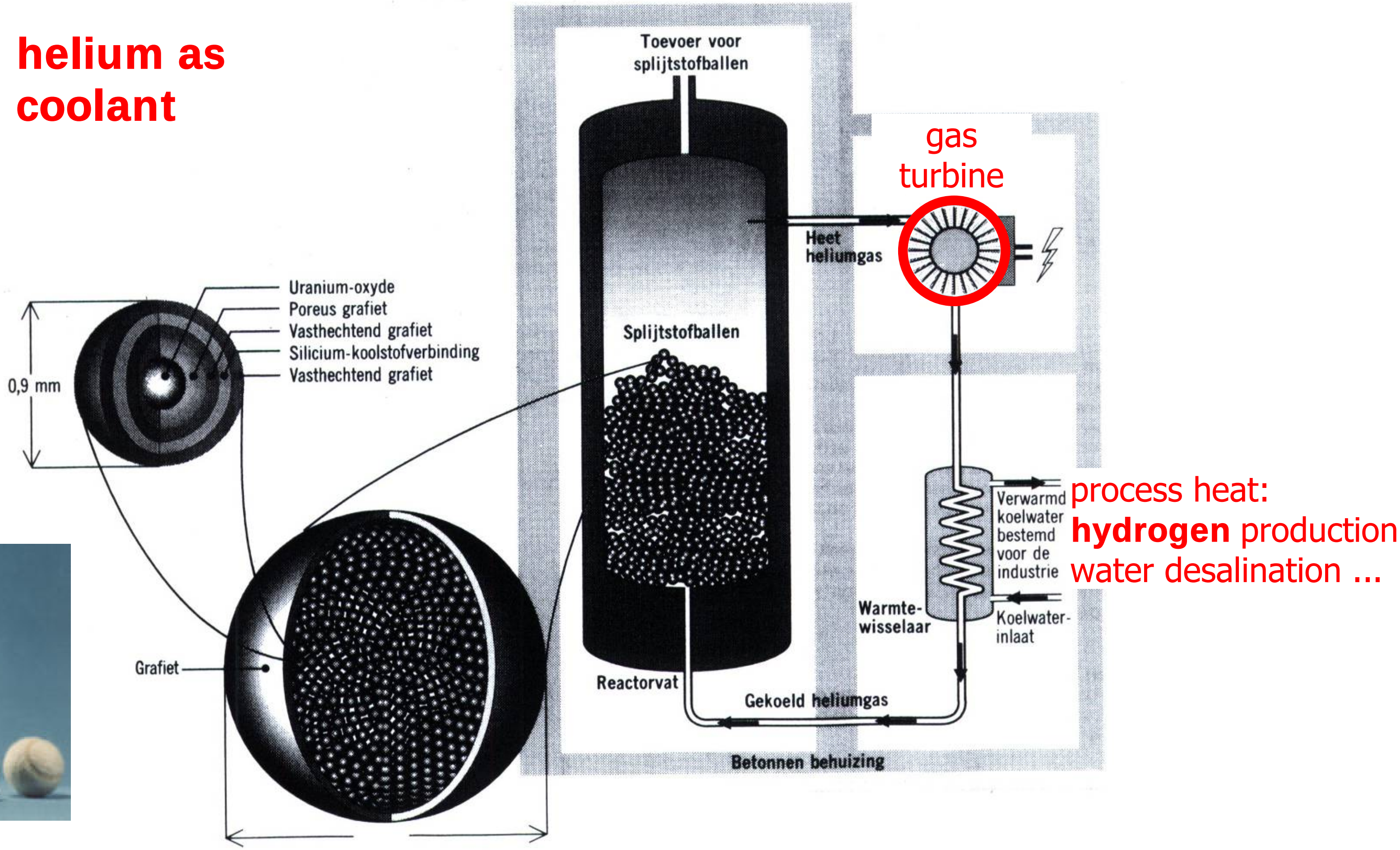


# High Temperature Reactor *generation III+*

AVR (Germany, 1967-1988) – HTTR (Japan, 1999) – HTR10 (China, 2000)

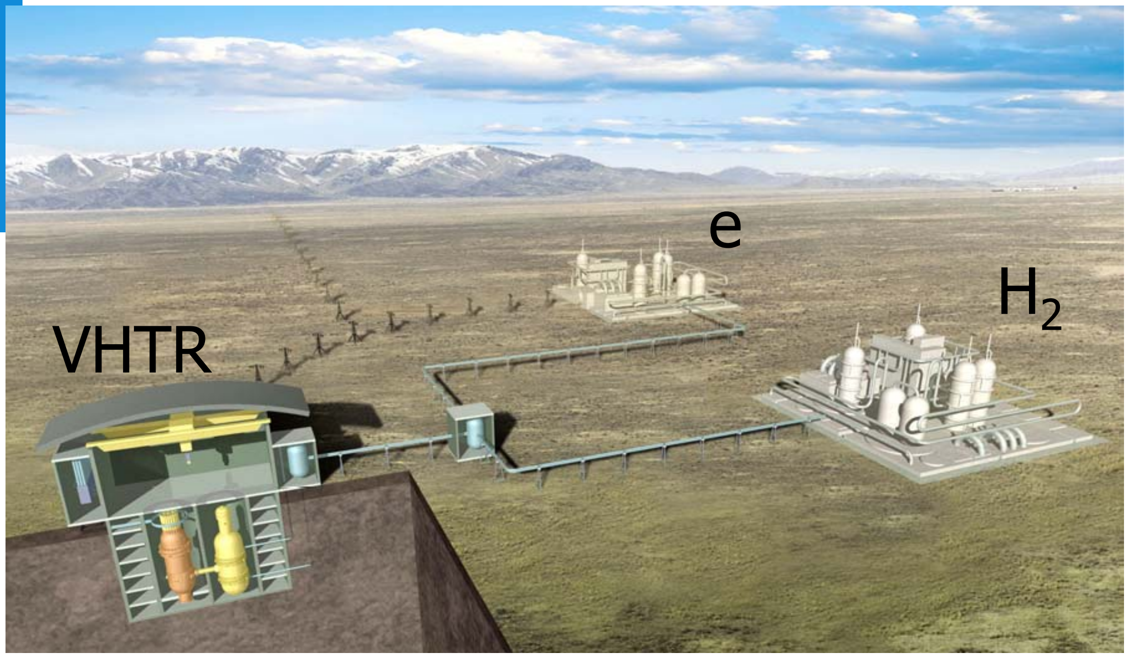
**helium as coolant**



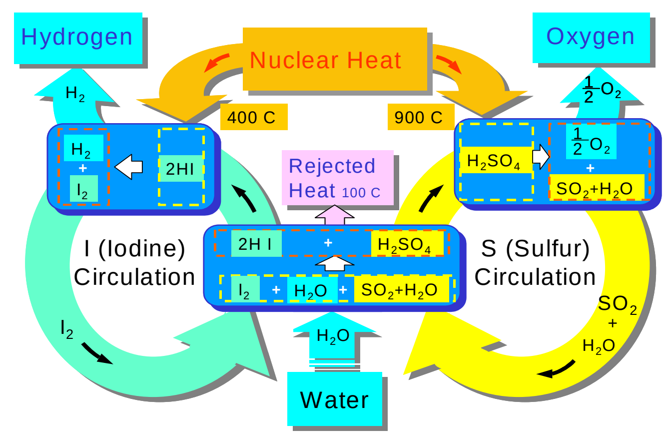



**inherently safe**

# **VHTR**: nuclear e- plus hydrogen production




Idaho 2015 ?




$H_2O$ in,
$O_2$ and $H_2$ out

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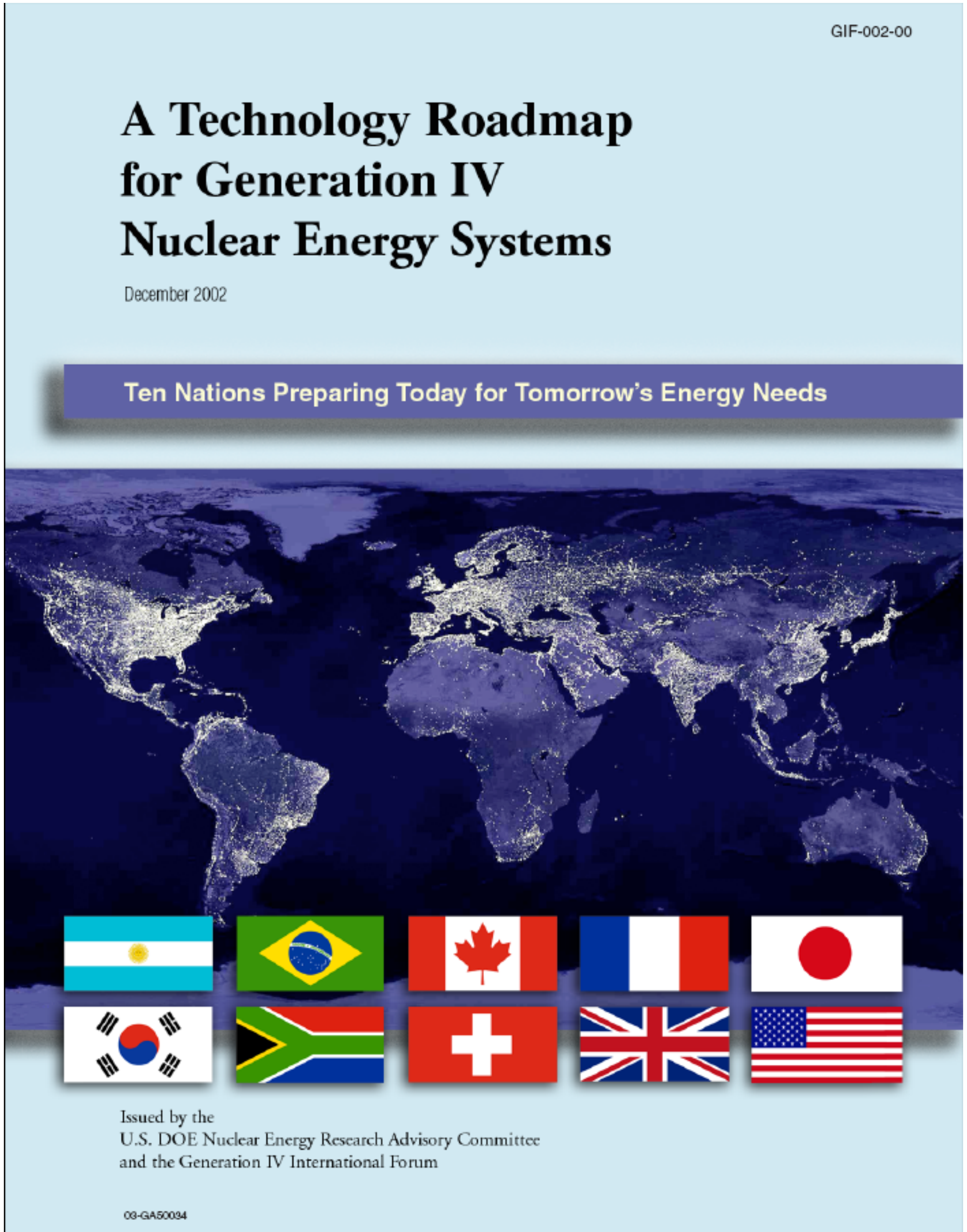
1950 1960 1970 1980 1990 2000 2010 2020 2030



GIF-002-00

# A Technology Roadmap for Generation IV Nuclear Energy Systems

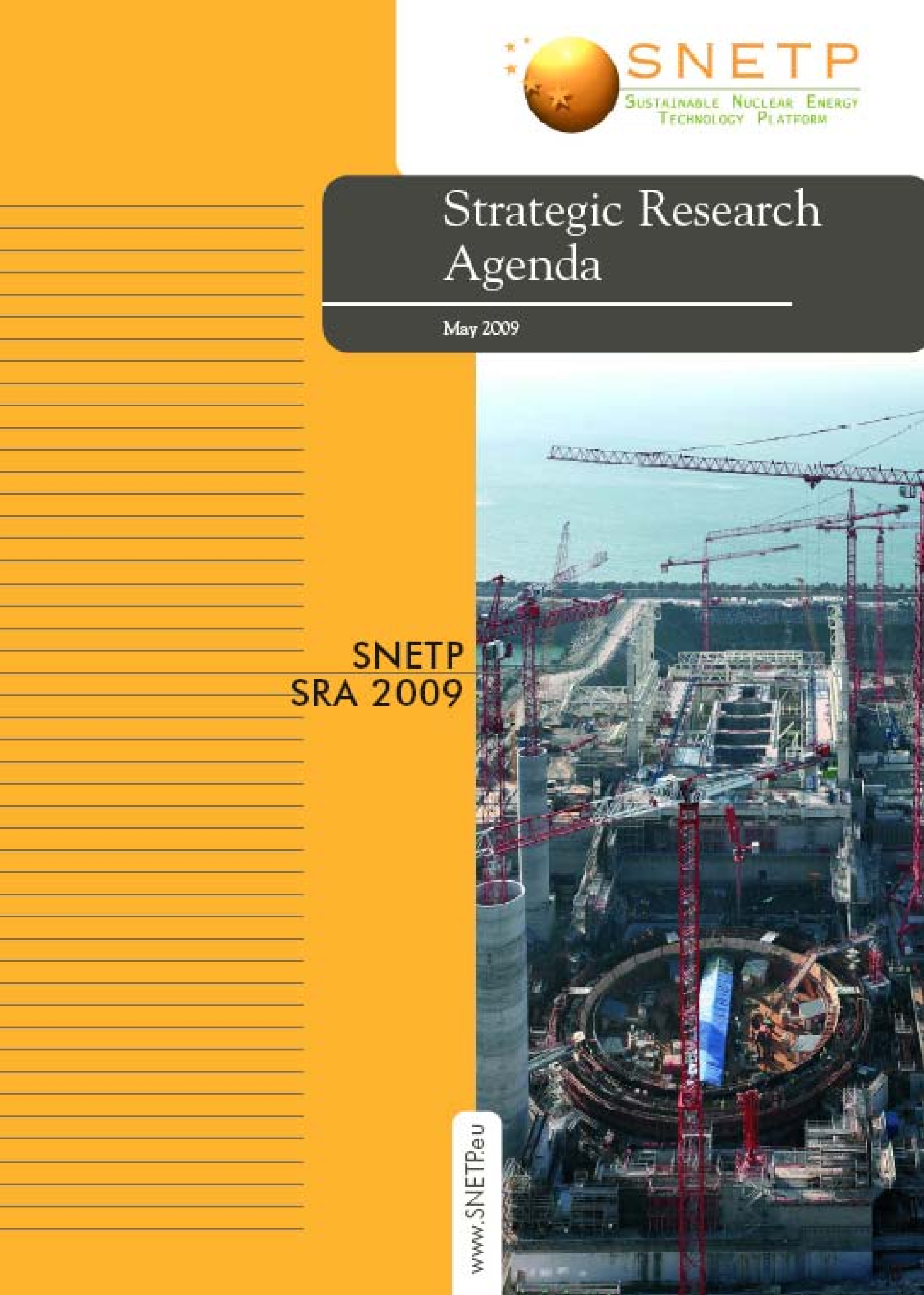
December 2002

Ten Nations Preparing Today for Tomorrow's Energy Needs

Issued by the
U.S. DOE Nuclear Energy Research Advisory Committee
and the Generation IV International Forum

03-GA50034

Gen-IV Roadmap
(2002, 97 pages)


SNETP
Sustainable Nuclear Energy Technology Platform

Strategic Research Agenda

May 2009

SNETP
SRA 2009

www.SNETP.eu

Sustainable Nuclear Energy Technology Platform Strategic Research Agenda (2009, 87 pages)

# The Generation-IV Initiative: *sustainable nuclear energy*

**Argentine, Brazil, Canada, France, Japan, South Africa, South Korea, Switzerland, United Kingdom, United States and the European Union**

## The 6 selected reactor concepts

Hydrogen production:

- Very High Temperature Gas Cooled Reactor

Evolution of Light Water Reactors:

- Supercritical Water Cooled Reactor (thermal/fast)

Waste reduction and high efficiency:

- Gas Cooled Fast Reactor
- Sodium Cooled Fast Reactor
- Lead Cooled Fast Reactor

Very innovative:

- Molten Salt Reactor (epithermal)

} closed fuel cycle

# U.S. DOE initiatives

*Source: US DOE*

## Nuclear Power 2010

- Explore new sites
- Develop business case
- Develop Generation III+ technologies
- Demonstrate new licensing process

## Advanced Fuel Cycle Initiative

- Recovery of energy value from SNF
- Reduce the inventory of civilian Pu
- Reduce the toxicity & heat of waste
- More effective use of the repository

## Nuclear Hydrogen Initiative

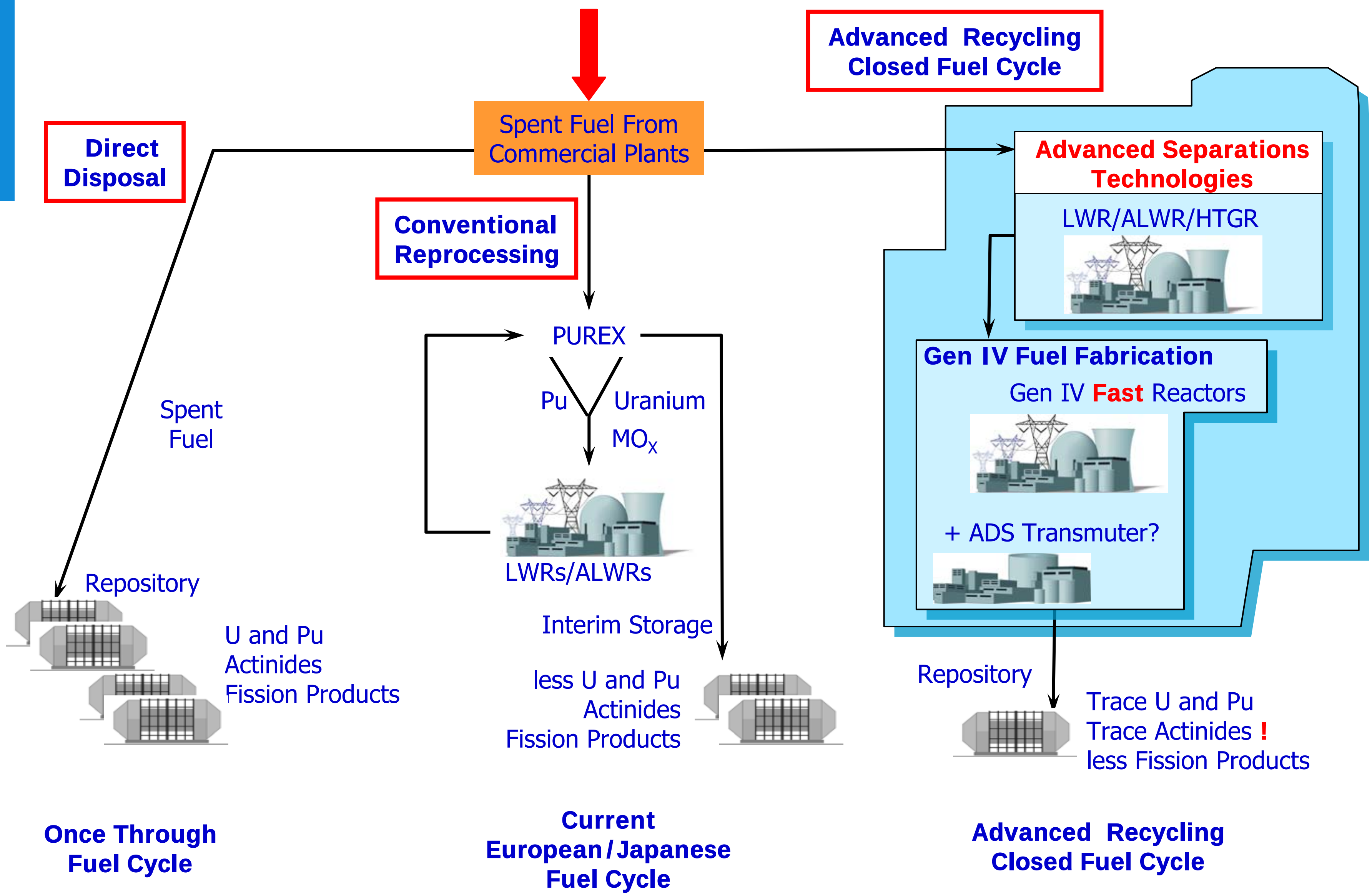
Develop technologies for economic, commercial-scale generation of hydrogen

## Generation IV

Better, safer, more economic nuclear power plants with improvements in

- safety & reliability
- proliferation resistance & physical protection
- economic competitiveness
- sustainability

# AFCI Approach to Spent Fuel Management




*Source: US DOE*

# Research themes Gen-IV

- fuel (fast reactors, transmutation, high burn-up, thorium cycle …)
- materials (corrosion, embrittlement, radiation damage, high temperatures)
- heat transport
- multiphase flows
- neutron data (cross sections of materials)
- chemical treatment of spent fuel
- core design
- system design (safety, efficiency, flexibility, …)
- safety (decay heat removal)
- coupling nuclear heat – process heat (hydrogen production)
- gas turbines

# Resumé nuclear energy

## Positive

- large scale
- no $CO_2$, no air pollution
- security of supply
- economical competitive

## Negative

- radioactive waste
- acceptance (safety)
- large investment
- proliferation

savings, clean fossil and nuclear energy are now necessary to give renewables a chance