

History of Nuclear Power Development

Prof. Christophe Demazière

28 January 2026



Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens



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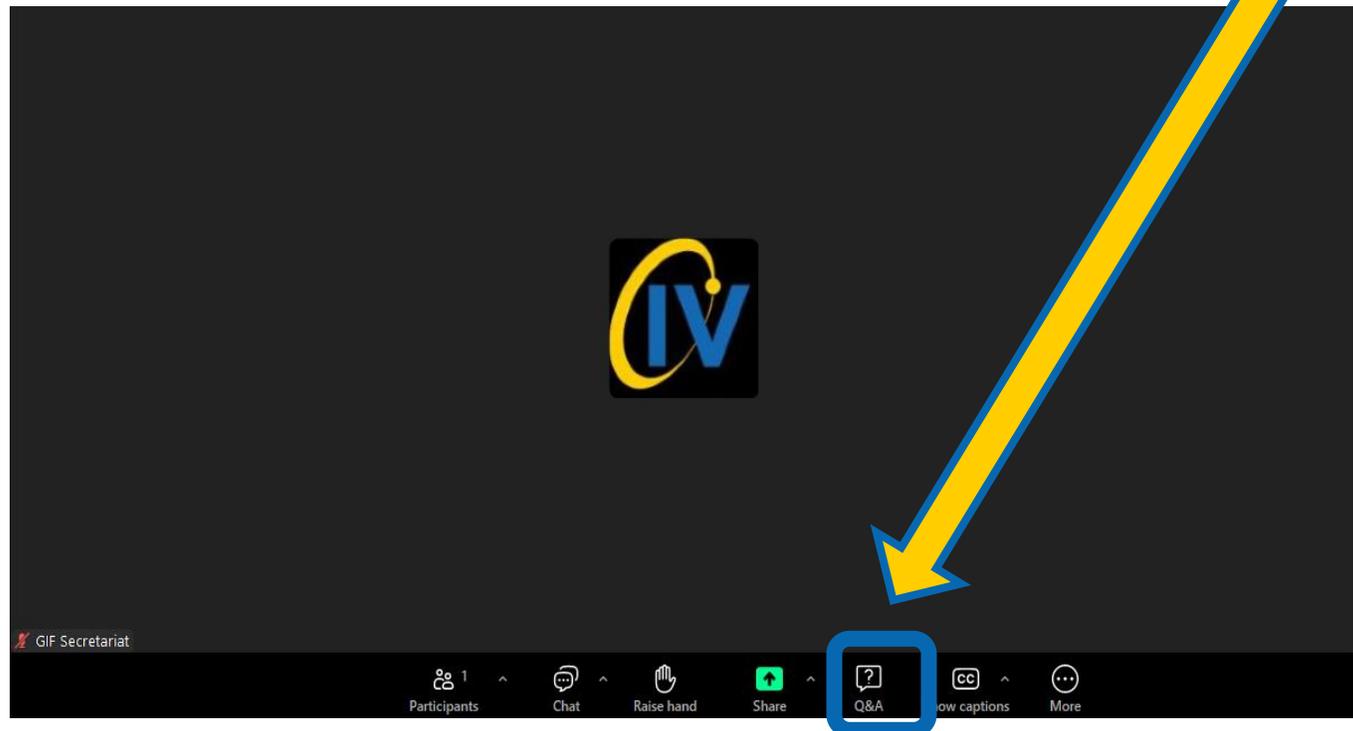
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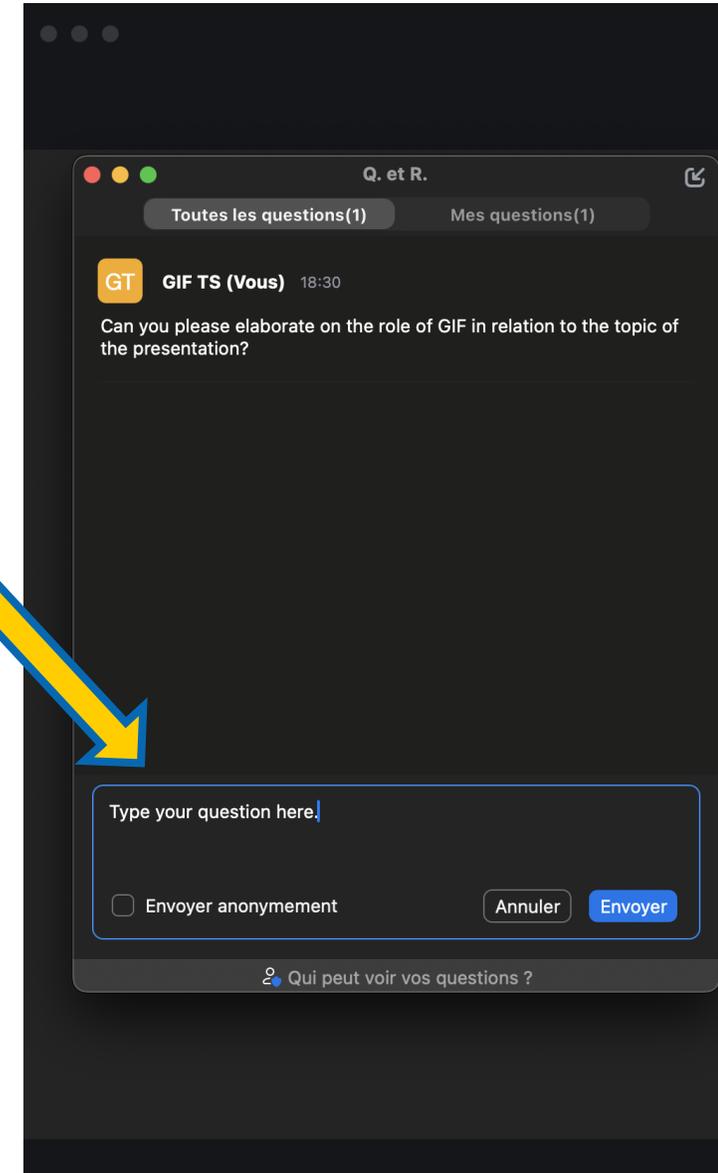
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History of Nuclear Power Development

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Meet the Presenter

Prof. Christophe Demazière earned his PhD in reactor physics in 2002 from Chalmers University of Technology, Gothenburg, Sweden, where he is now Full Professor. He is responsible for research and education in nuclear engineering. His expertise and research interests are in reactor physics, reactor dynamics, neutron noise, reactor multiphysics and reactor modelling.

He is the author of a book on the “[Modelling of nuclear reactor multi-physics – From local balance equations to macroscopic models in neutronics and thermal-hydraulics](#)” and has published more than 70 peer-reviewed journal articles and more than 130 peer-reviewed conference contributions.

Prof. Demazière is the former coordinator of the EU-funded [CORTEX project](#) and currently coordinates the [GRE@T-PIONEeR Alliance](#), which provides advanced education in reactor physics, modelling and safety, worldwide. He is also a member of the American Nuclear Society.





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HISTORY OF NUCLEAR POWER DEVELOPMENT

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DREAM

TASK FORCE ON
DETERMINISTIC REACTOR MODELLING

Structure of the presentation

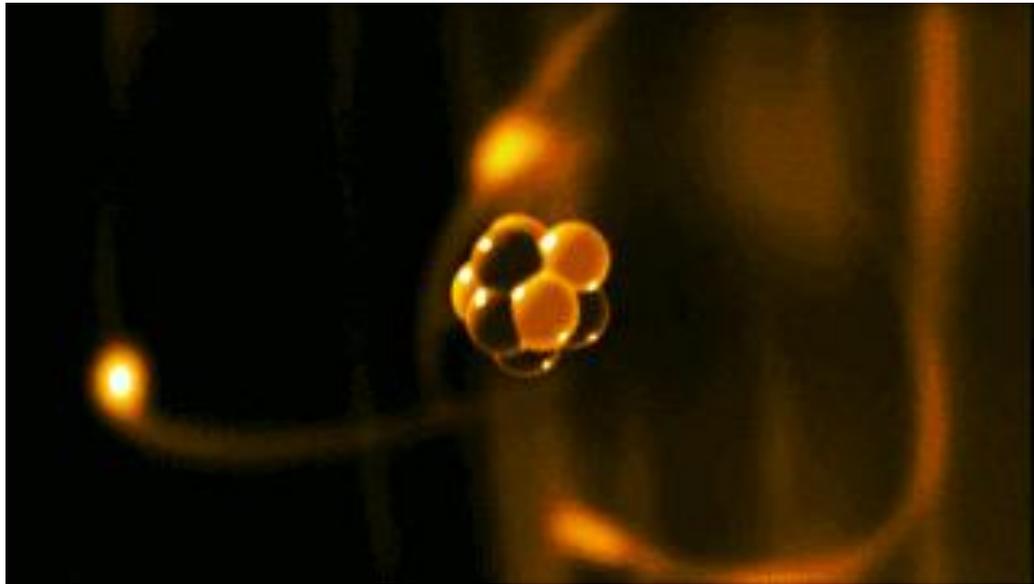
- Elementary concepts in nuclear physics
- Working principle of nuclear reactors
- History of world nuclear power development
- Fuel utilization
- Nuclear waste
- Uranium resources
- Dependence on the fuel cycle strategy
- Proliferation risk
- Take-aways
- Prospects
- SMRs
- Conclusions

Elementary concepts in nuclear physics

How to better understand the physical principles of nuclear reactors

Elementary concepts in nuclear physics

- Matter made of **atoms**:

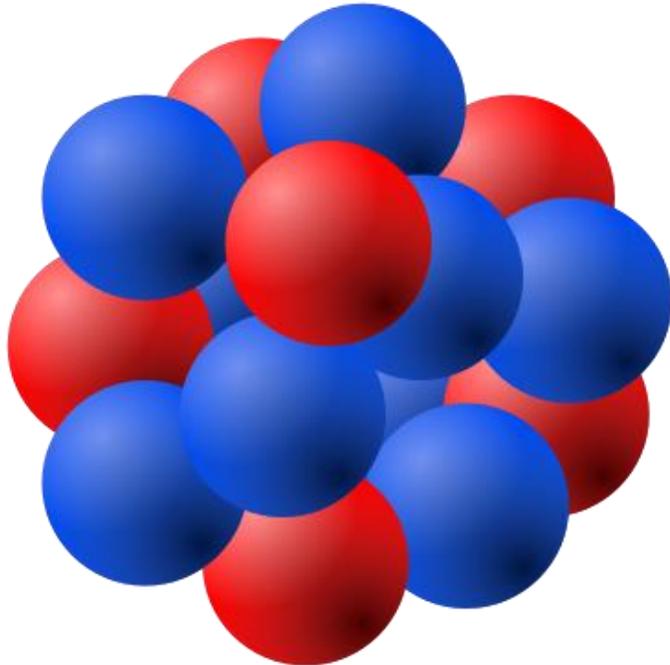


- Typical size:
ca. $1 \text{ \AA} \equiv 10^{-10} \text{ m}$
- Made of:
 - **Electrons** (negatively charge)
 - **Nucleus** (positively charge)

Figure credit: Galarza Creador (https://commons.wikimedia.org/wiki/File:Átomo_de_Oro.gif), „Átomo de Oro“, <https://creativecommons.org/licenses/by/3.0/legalcode>

Elementary concepts in nuclear physics

- **Nucleus:**



- Typical size:
ca. $10 \text{ fm} \equiv 10^{-14} \text{ m}$
- Made of **nucleons**:
 - **Protons** (positively charge)
 - **Neutrons** (no charge)

Figure credit: Marekich (https://commons.wikimedia.org/wiki/File:Nucleus_drawing.svg), „Nucleus drawing“, <https://creativecommons.org/licenses/by-sa/3.0/legalcode>

Elementary concepts in nuclear physics

- Different nuclear reactions can be induced by **neutrons**:
 - **Scattering**
 - Radiative **capture**
 - **Fission**

Elementary concepts in nuclear physics

- **Fission** = some nuclei can be **split** when **bombarded** with **neutrons**:
 - **Fission** = neutron absorption followed by a splitting of the formed nucleus – example of U-235

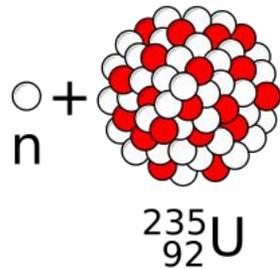


Figure credit: MikeRun (https://commons.wikimedia.org/wiki/File:Nuclear_fission_reaction.svg),
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Elementary concepts in nuclear physics

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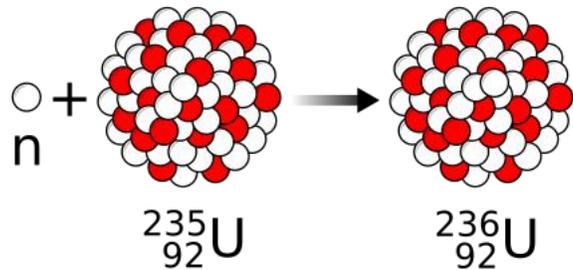
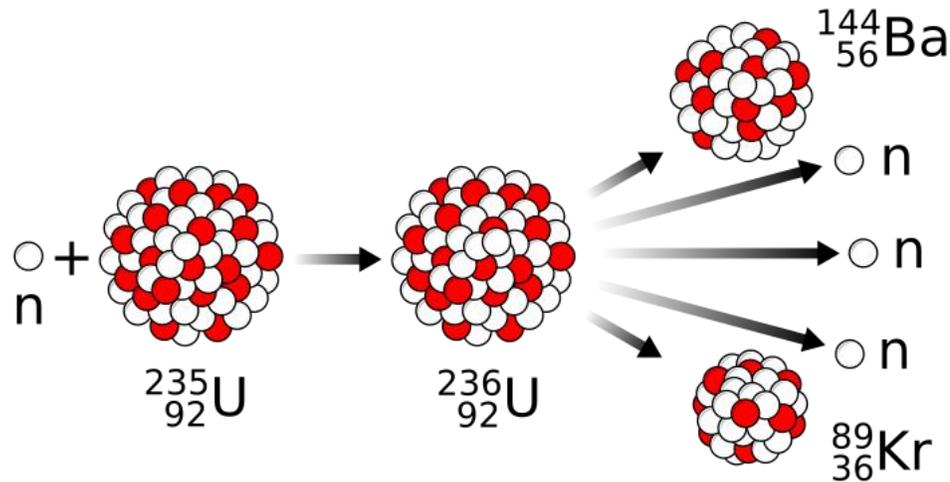


Figure credit: MikeRun (https://commons.wikimedia.org/wiki/File:Nuclear_fission_reaction.svg),
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Elementary concepts in nuclear physics

- **Fission** = some nuclei can be **split** when **bombarded** with **neutrons**:
 - **Fission** = neutron absorption followed by a splitting of the formed nucleus – example of U-235



Properties:

- Release of extreme amounts of energy
- Release of radiations of various types
- Release of new neutrons
- Production of radioactive fission products

Figure credit: MikeRun (https://commons.wikimedia.org/wiki/File:Nuclear_fission_reaction.svg),
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Elementary concepts in nuclear physics

- **Likelihood** of neutron interaction given by **microscopic cross-section** denoted $\sigma_{a,X}$ (for reaction a on species X)
= Area of possible interaction “seen” by the neutron
Unit: barn, with $1 \text{ barn} = 10^{-24} \text{ cm}^2$

Elementary concepts in nuclear physics

- Beyond **neutron emissions**, other types of **radiations** are typically associated to nuclear reactions:
 - **β^- decay**: neutron transformed into a proton and emission of an electron
 - **β^+ decay**: proton transformed into a neutron and emission of a positron
 - **α decay**: emission of a helion
 - **Gamma radiation**: electromagnetic wave at very high frequency
- **Ionizing radiations**
Sufficient energy to affect the atoms in living cells and thereby damage their genetic material (DNA)

Elementary concepts in nuclear physics

- How **hazardous** “radiation” is depends on:
 - The **intensity** of the radiation (measured in Becquerel, with 1 Bq = 1 disintegration/second)
 - The **type** of radiation: penetration, energy absorbed, biological effect (depends on type of radiation and type of organ)
- Hazard measured in **Sievert**
- **Background radiation** typically around **3-4 mSv/year** (in Sweden)

Working principle of nuclear reactors

On what physical principles are nuclear reactors based?

Working principle of nuclear reactors

- Basic principles: **chain reaction**

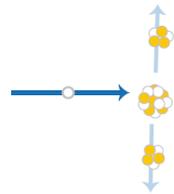
Working principle of nuclear reactors

- Basic principles: **chain reaction**



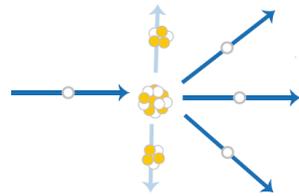
Working principle of nuclear reactors

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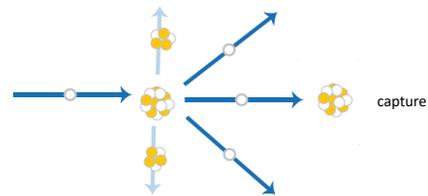
Working principle of nuclear reactors

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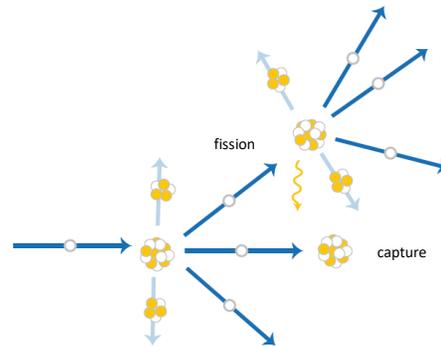
Working principle of nuclear reactors

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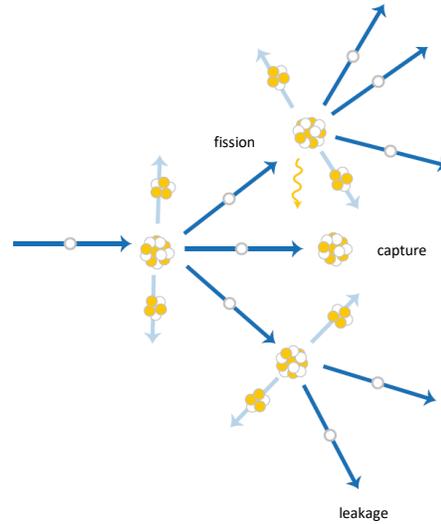
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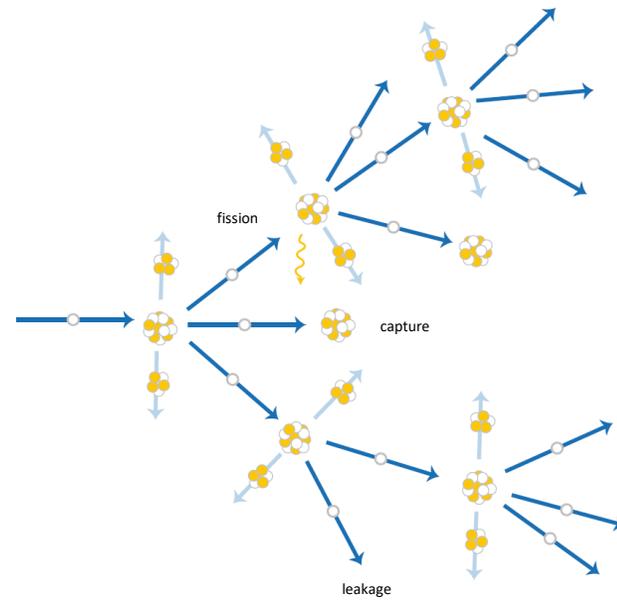
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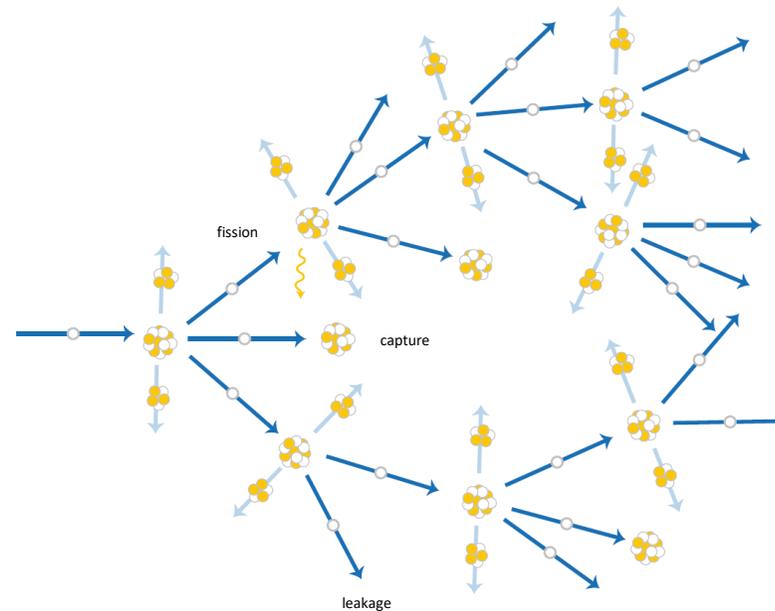
Working principle of nuclear reactors

- Basic principles: **chain reaction**



Working principle of nuclear reactors

- Basic principles: **chain reaction**



Another nuclear reaction will play an essential role in thermal nuclear reactors: **scattering**

Working principle of nuclear reactors

- **Uranium isotopes:**

- **Isotopes** = nuclei with same number of protons but a different number of neutrons

- Examples for Uranium: ${}_{92}^{235}\text{U}$ and ${}_{92}^{238}\text{U}$

- Not all isotopes of Uranium can “easily” undergo fission:

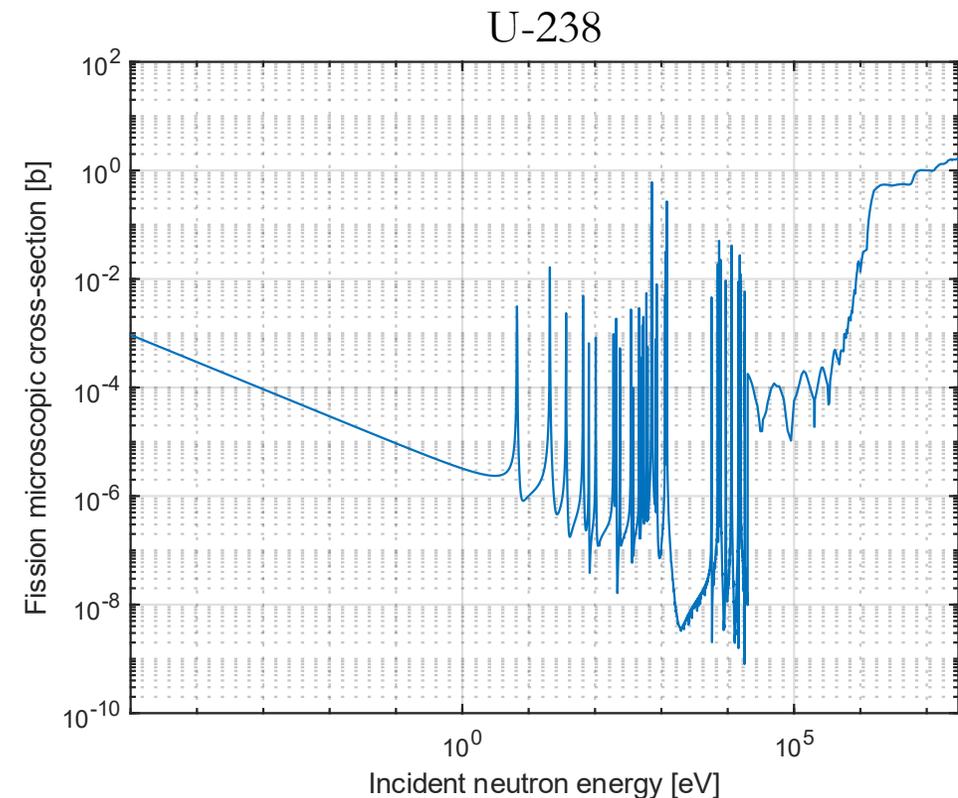
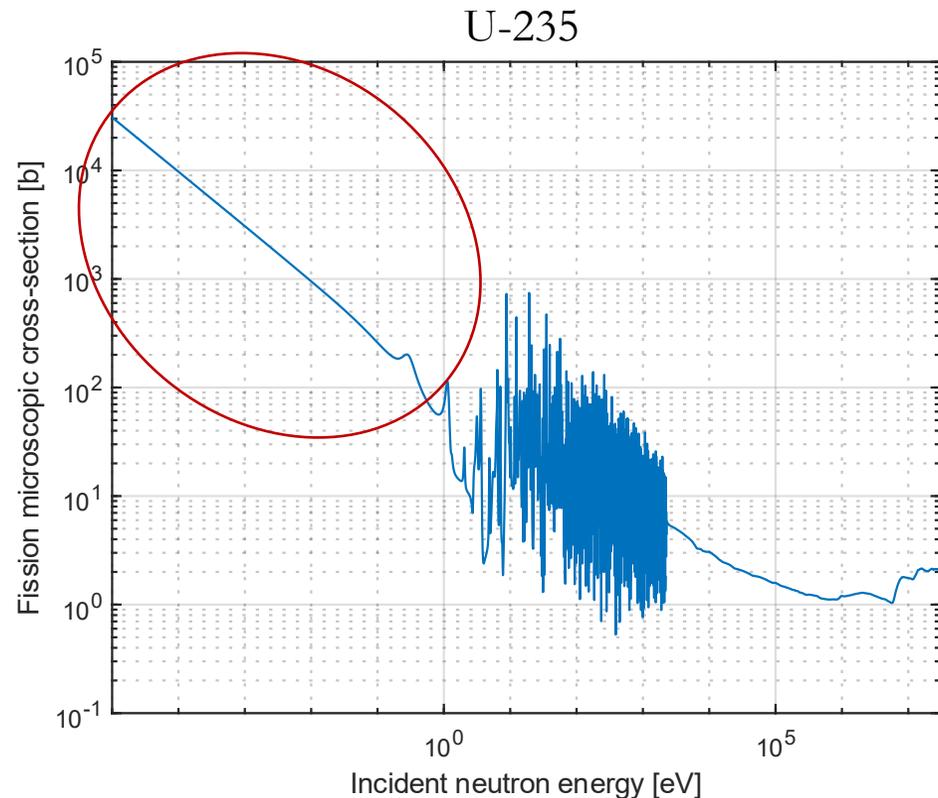
- U-238 undergoes fission only with high energy neutrons (**fissionable**)

- U-235 undergoes fission even with very low energy neutrons (**fissile**)

- Natural Uranium: 99.3% of U-238 and 0.7% of U-235

Working principle of nuclear reactors

- Uranium isotopes:



➤ Easier to induce fission reactions on U-235 and at low energies of the incident neutron

Working principle of nuclear reactors

- **Reactor systems:**

- Two possible paths:

- **Fast reactor systems:** Fissions induced primarily by **fast** (and/or epithermal) neutrons:

- Typically requires an enrichment of about 15-20% in U-235 and/or use other fissile species (Pu-239 and Pu-241)

- **Thermal reactor systems:** Fissions induced primarily by **thermal** neutrons:

- Typically requires an enrichment of about 3-5% in U-235

- But...

- Need to **slow-down** or **moderate** neutrons by **collisions** on other nuclei

- Most efficient species for moderation: light species, e.g., H

Working principle of nuclear reactors

➤ Neutron cycle for thermal reactors:

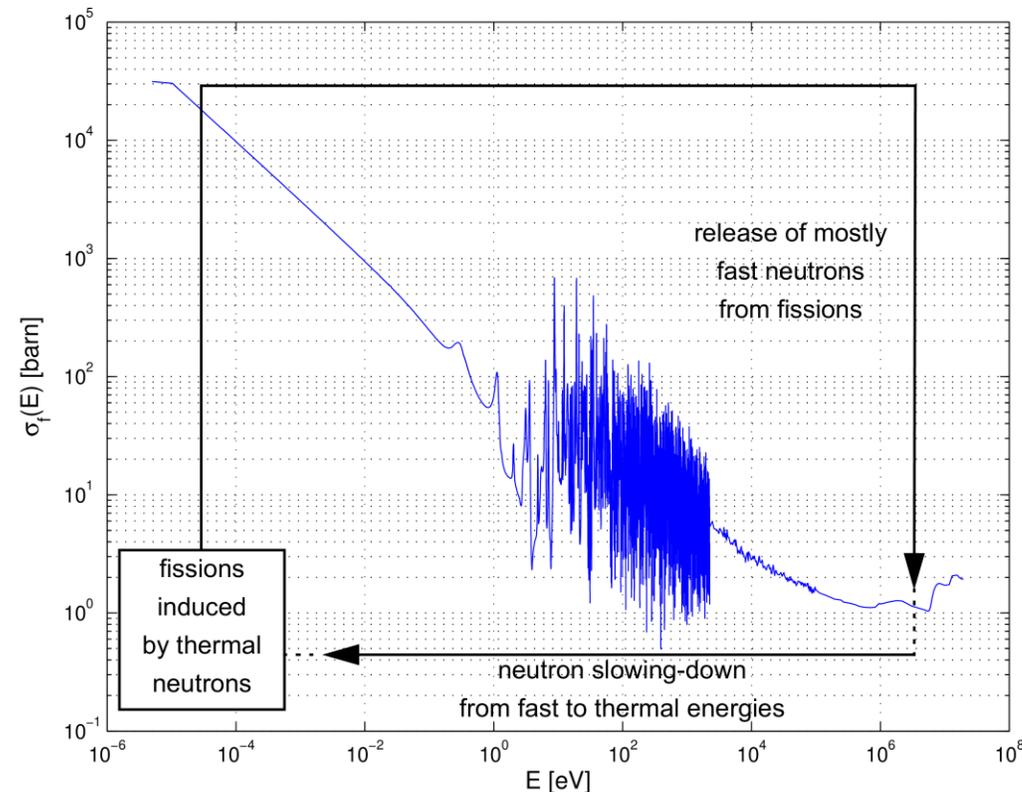


Figure credit: Reproduced from Modelling of Nuclear Reactor Multi-physics – From Local Balance Equations to Macroscopic Models in Neutronics and Thermal-Hydraulics, Demazière C., Neutron transport calculations at the core level, Page 17, 2020





History of world nuclear power development

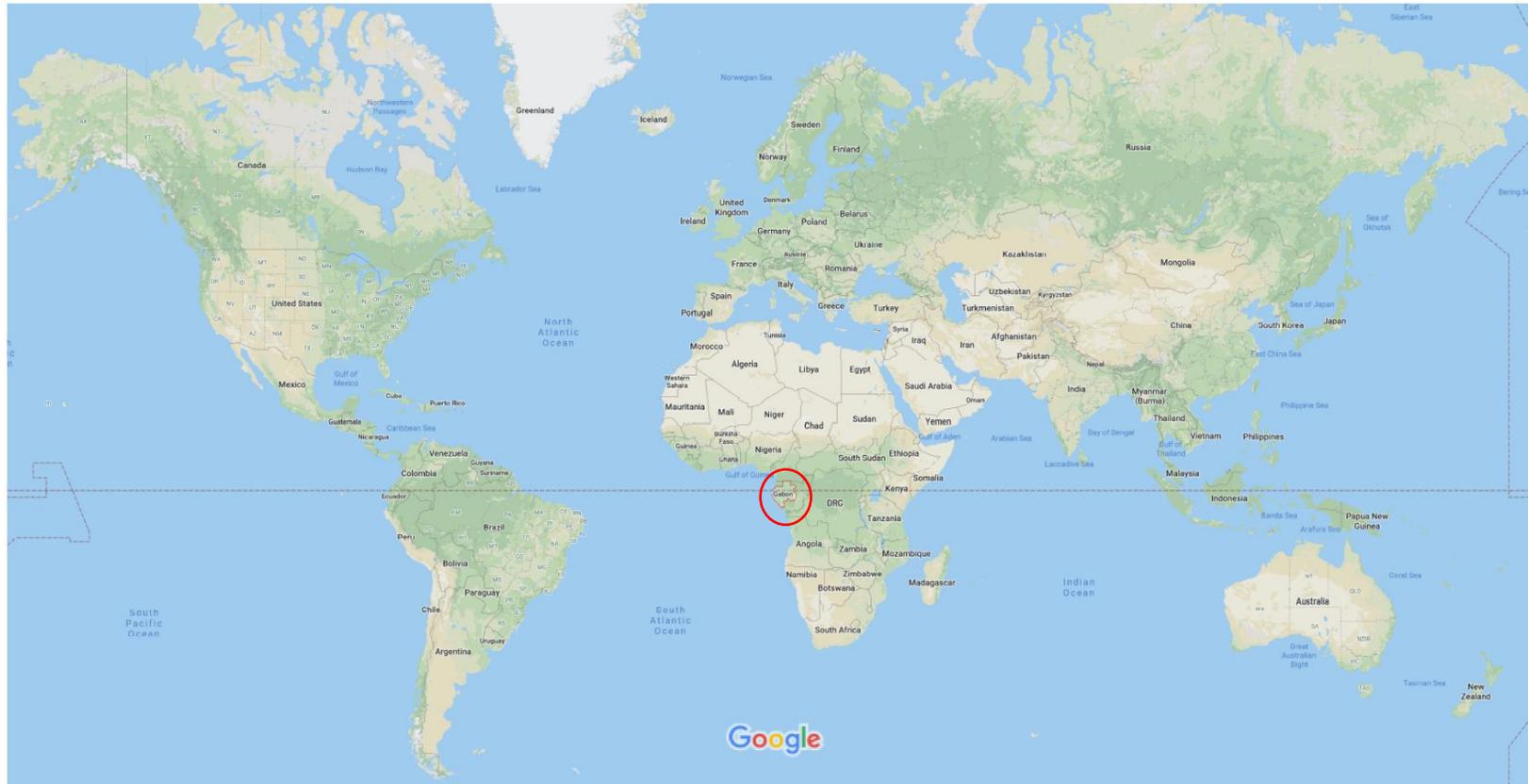
How did we end up with the current fleet of reactors?

History of world nuclear power development

- Everything started much earlier than one thinks...

History of world nuclear power development

- Uranium mine in Oklo, Gabon:



History of world nuclear power development

- Uranium mine in Oklo, Gabon:
 - **Fission products** also found

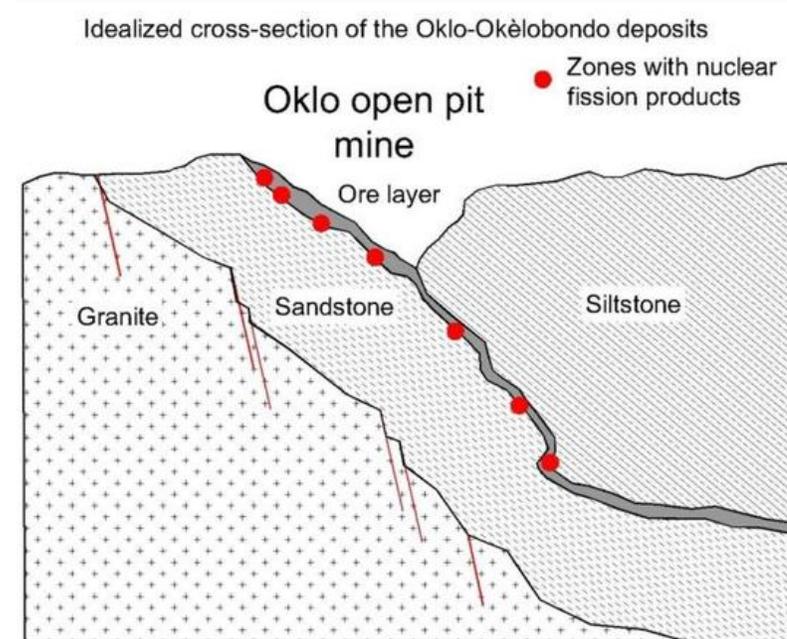
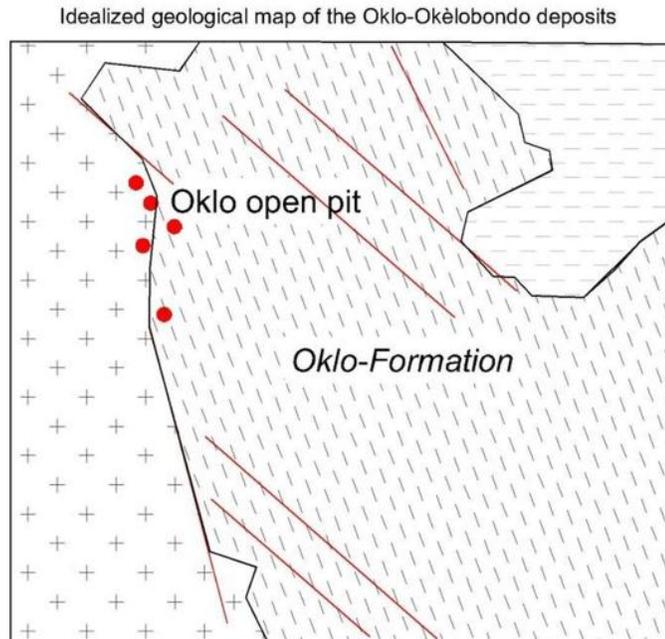


Figure credit: David Bressan, “This Two Billion Year-Old Natural Reactor May Hold The Key To Safe Nuclear Waste Disposal.” Forbes, Editors’ Pick, August 14, 2018

History of world nuclear power development

- Uranium mine in Oklo, Gabon:
 - Fission products mean that **fission reactions** had occurred
 - How come, when the present concentration in U-235 is only 0.7%?
- Uranium isotopes decay by **radioactive decay**
 - U-235: half-life of 704 million years
 - U-238: half-life of 4.46 billion years

(Half-life = time at which the amount of a radioactive species has decayed by its half)

History of world nuclear power development

- Uranium mine in Oklo, Gabon:
 - Long ago, the proportion of U-235 in relation to U-238 was much higher than 0.7% / 99.3% as of today
 - Groundwater in Oklo acted as a neutron moderator, thus making a fission chain reaction possible
- Oklo = the **first natural nuclear reactor** (about 1.7 billion years ago)

History of world nuclear power development

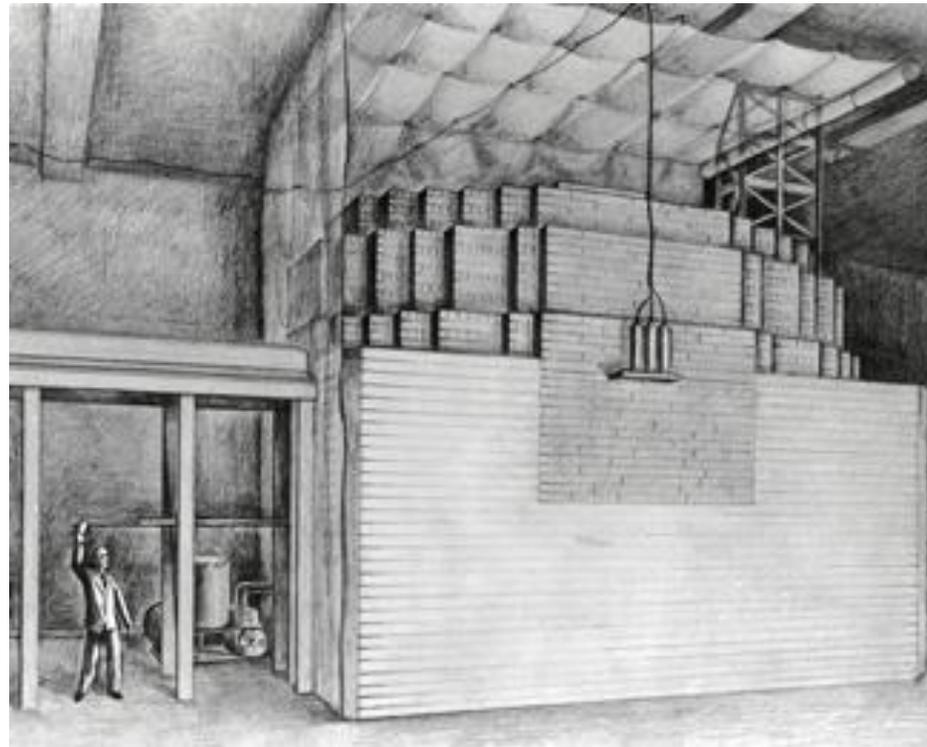
- History of world nuclear power development (mankind's perspective):
 - 1896: Henri Becquerel discovers radioactivity
 - 1898: Marie and Pierre Curie discover two new (radioactive) elements, radium and polonium, more radioactive than uranium
 - 1919: Ernest Rutherford observed the nuclear reaction
$$^{14}\text{N} + \alpha \rightarrow ^{17}\text{O} + \text{p}$$
 - 1925: Albert Einstein formulates relativity's theory
 - 1932: James Chadwick discovers neutrons

History of world nuclear power development

- History of world nuclear power development (mankind's perspective):
 - 1938: Lise Meitner and Otto Frisch explain fission (experiments made by Otto Hahn)
 - 1939: Niels Bohr and Enrico Fermi were able to confirm that nuclear fission occurred and that large amounts of energy were released
 - 1939: Frédéric Joliot-Curie discovers secondary fission neutrons (confirmed by Szilard)

History of world nuclear power development

- History of world nuclear power development (mankind's perspective):
 - 1942: First research reactor CP1 (Chicago Pile, Chicago, USA)

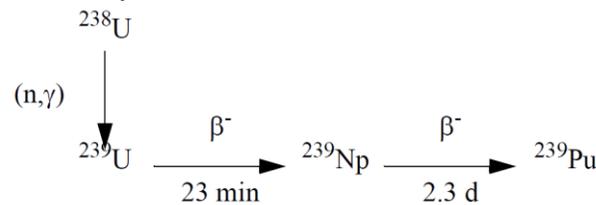


- Graphite-moderated thermal reactor using natural uranium

Figure credit: Argonne National Laboratory, IL, USA

History of world nuclear power development

- History of world nuclear power development (mankind's perspective):
 - 1942-1946: Manhattan Project (USA)
 - Aimed at developing **nuclear weapons**
 - Nuclear weapons require an **extremely high enrichment in U-235** (>90%)
 - Two paths followed:
 - Enrichment in U-235 by **isotope separation**
(different techniques developed: centrifugation, electromagnetic separation, gaseous diffusion and thermal diffusion)
 - Production of fissile species by **nuclear reactions on U-238** and **chemical separation**



➤ Can be done in a **nuclear reactor**

History of world nuclear power development

- History of world nuclear power development (mankind's perspective):
 - 1942-1946: Manhattan Project (USA)
 - Production of fissile species by **nuclear reactions on U-238** and **chemical separation** performed in **two nuclear reactors** (the first of their kind)

Clinton Pile

X-10 Pile

X-10 Graphite Reactor
(ORNL, TN, USA)

- Graphite-moderated and air-cooled thermal reactor using natural uranium



Figure credit: Oak Ridge National Laboratory, TN, USA

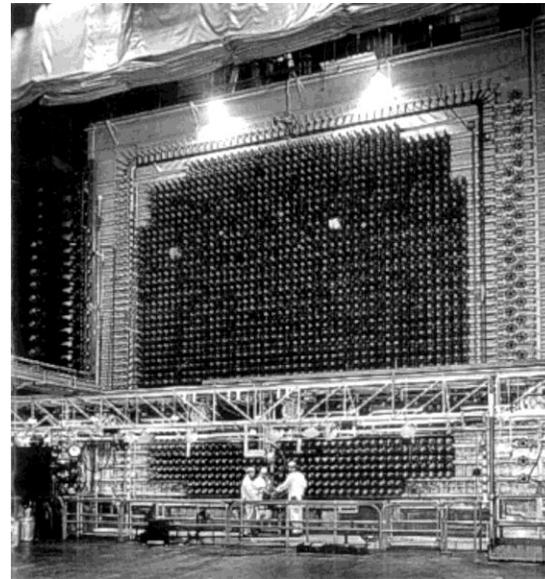


Figure credit: unknown source

B Reactor

(Handford site, WA, USA)

- Graphite-moderated and water-cooled thermal reactor using natural uranium

History of world nuclear power development

- History of world nuclear power development (mankind's perspective):
 - 1945: Atom bombs in Hiroshima and Nagasaki, Japan
 - 1955: First nuclear-powered submarine (Nautilus, USA) with a reactor from Westinghouse Electric Corporation

USS Nautilus (SSN-571)
in New York harbour in
1958

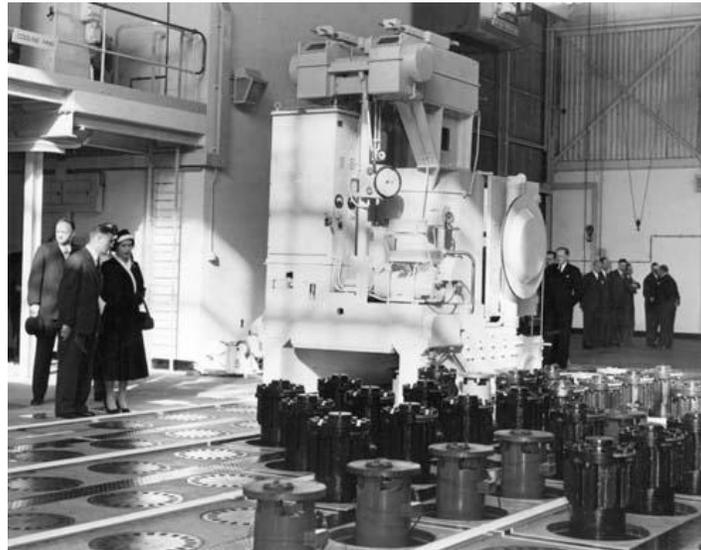


Water used for cooling and
moderation
➤ Very compact reactor

Figure credit: Official U.S. Navy photo

History of world nuclear power development

- History of world nuclear power development (mankind's perspective):
 - 1954: First nuclear power station for electricity production (Obninsk, USSR, 5 MWe)
 - 1956: First commercial nuclear power station for electricity production (Calder Hall, England, 50 MWe)



Queen Elizabeth II for
the inauguration of
Calder Hall

Figure credit: Hulton Archive/Getty Images

History of world nuclear power development

- History of world nuclear power development (mankind's perspective):
 - 1950s-1960s: development of **Generation-I reactors** (early prototype reactors)

Spectrum	Moderator	Coolant	Fuel
Thermal	Graphite	CO2 gas	Nat. U
Thermal	Heavy water	Heavy water	Nat. U
Thermal	Water	Water	Enriched U

➤ Note on moderators:

- Graphite: does not absorb neutrons very much, but does not moderate neutrons efficiently
- Heavy water (D_2O): does not absorb neutrons very much, and moderates neutrons efficiently, but expensive
- Water (H_2O): moderates neutrons efficiently and cheap, but absorbs neutrons to some extent

History of world nuclear power development

- History of world nuclear power development (mankind's perspective):
 - 1960s-1990s: massive deployment of **Generation-II reactors**

Spectrum	Moderator	Coolant	Fuel
Thermal	Water	Water	Enriched U
Thermal	Heavy water	Heavy water	Enriched U

- Note on moderators: Heavy water-based designs now using enriched U to make the reactor inherently safe

History of world nuclear power development

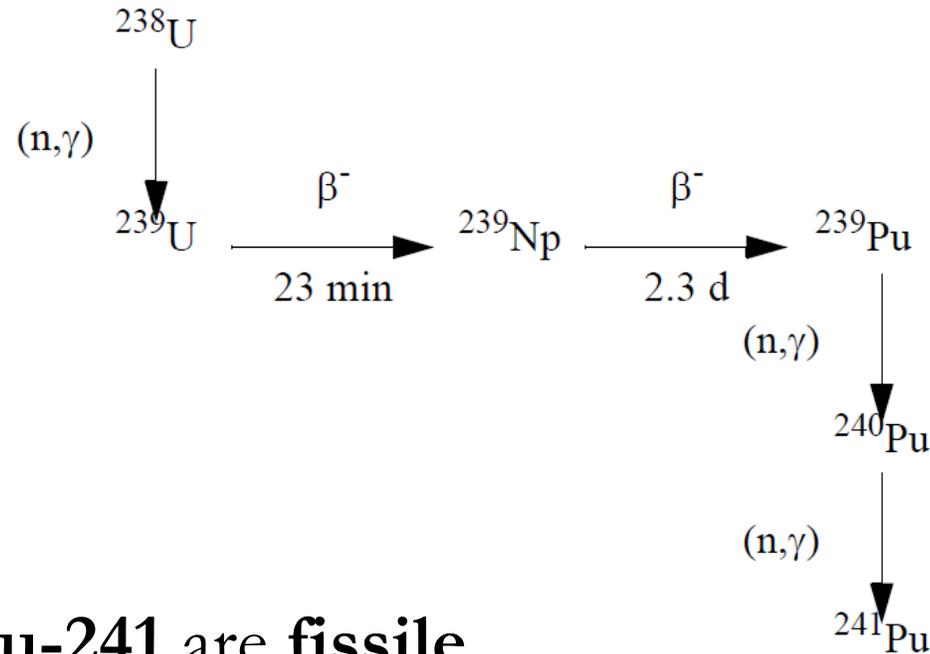
- History of world nuclear power development (mankind's perspective):
 - 1990s-2020s: limited deployment of **Generation-III and III+ reactors**:
 - Reactors using the same principles as Generation-II reactors
 - Main differences with Generation-II reactors: advanced safety features (III) and passive safety features (III+)
 - Today:
 - More than 400 nuclear reactors in operation
 - More than 50 reactors under construction
 - Actual data can be consulted at: <https://pris.iaea.org/>

Fuel utilization

How much fuel is actually used in a thermal reactor?

Fuel utilization

- Whereas **U-235** is **consumed** by neutron irradiation, **Pu-239** and **Pu-241** are **produced**:

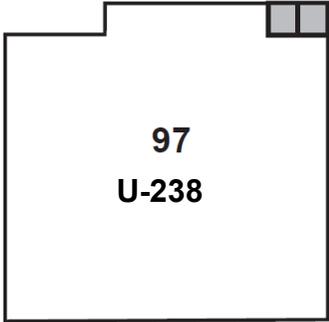


- Both **Pu-239** and **Pu-241** are **fissile**

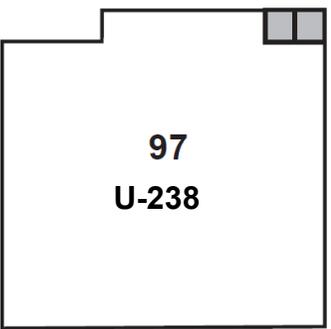
Fuel utilization

- Assuming a 3% enrichment in U-235 for a fresh fuel:

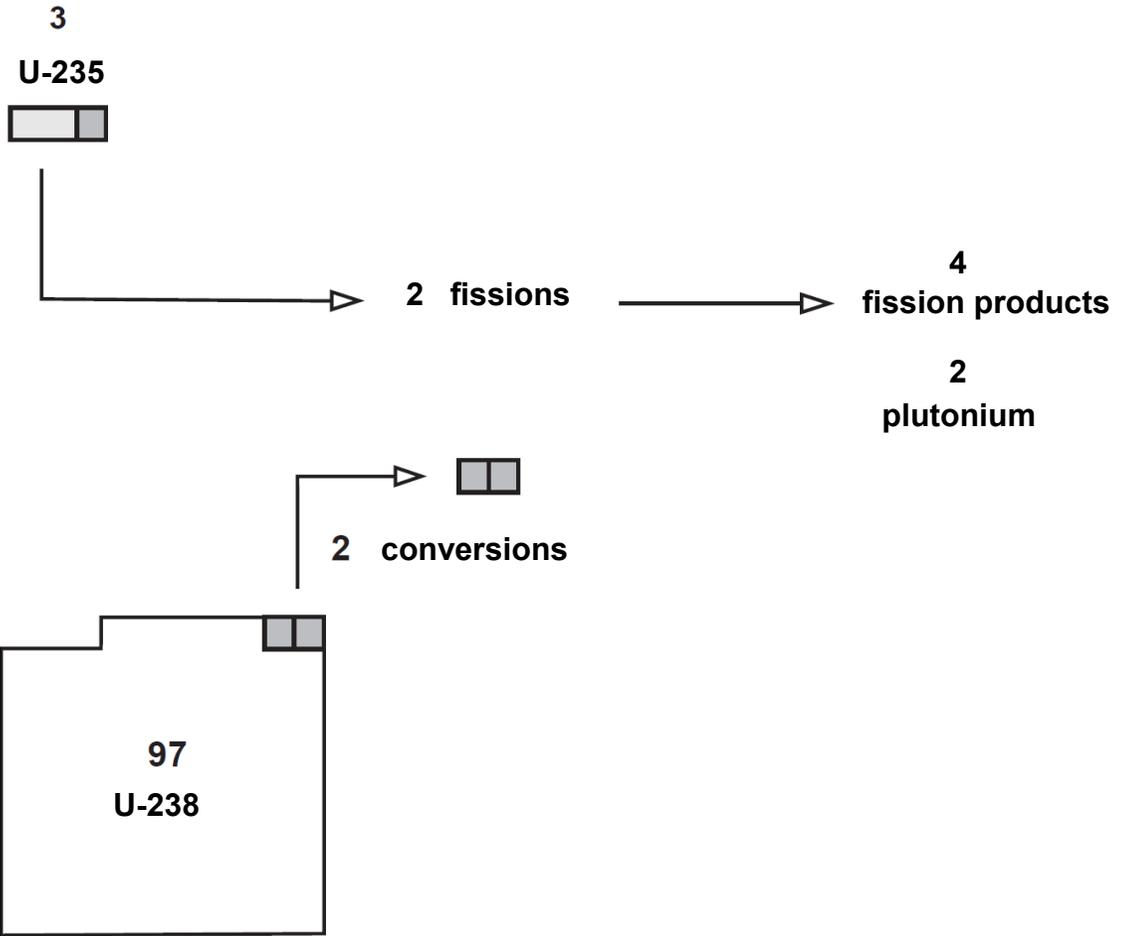
Fuel utilization



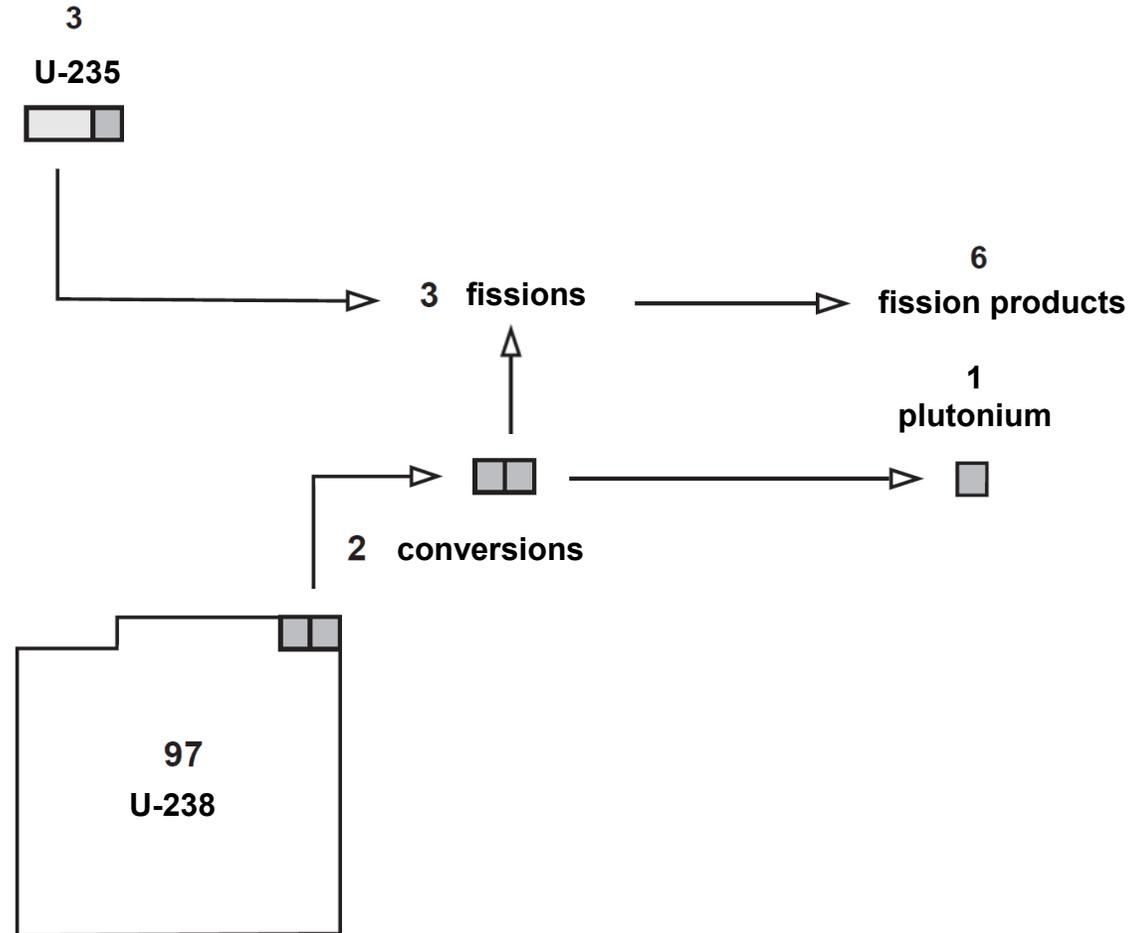
Fuel utilization



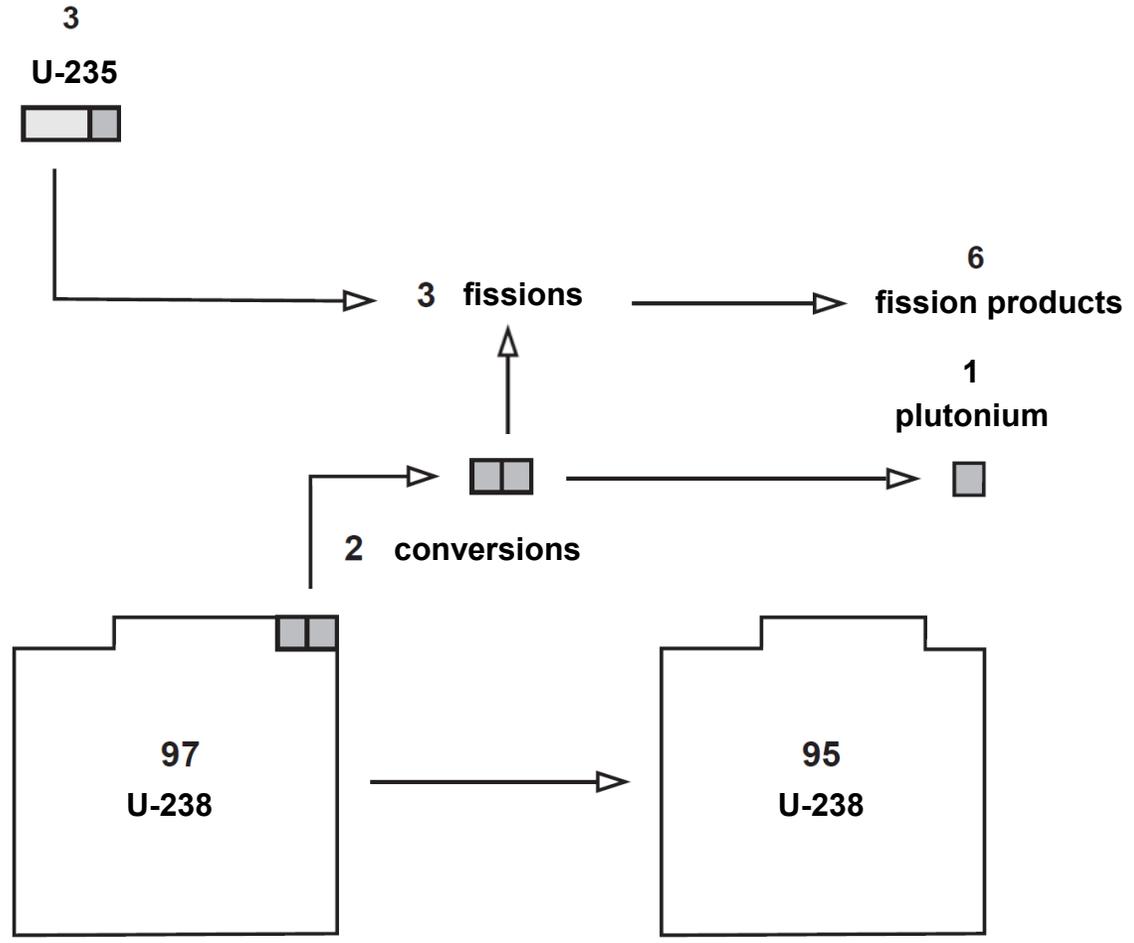
Fuel utilization



Fuel utilization



Fuel utilization



Fuel utilization

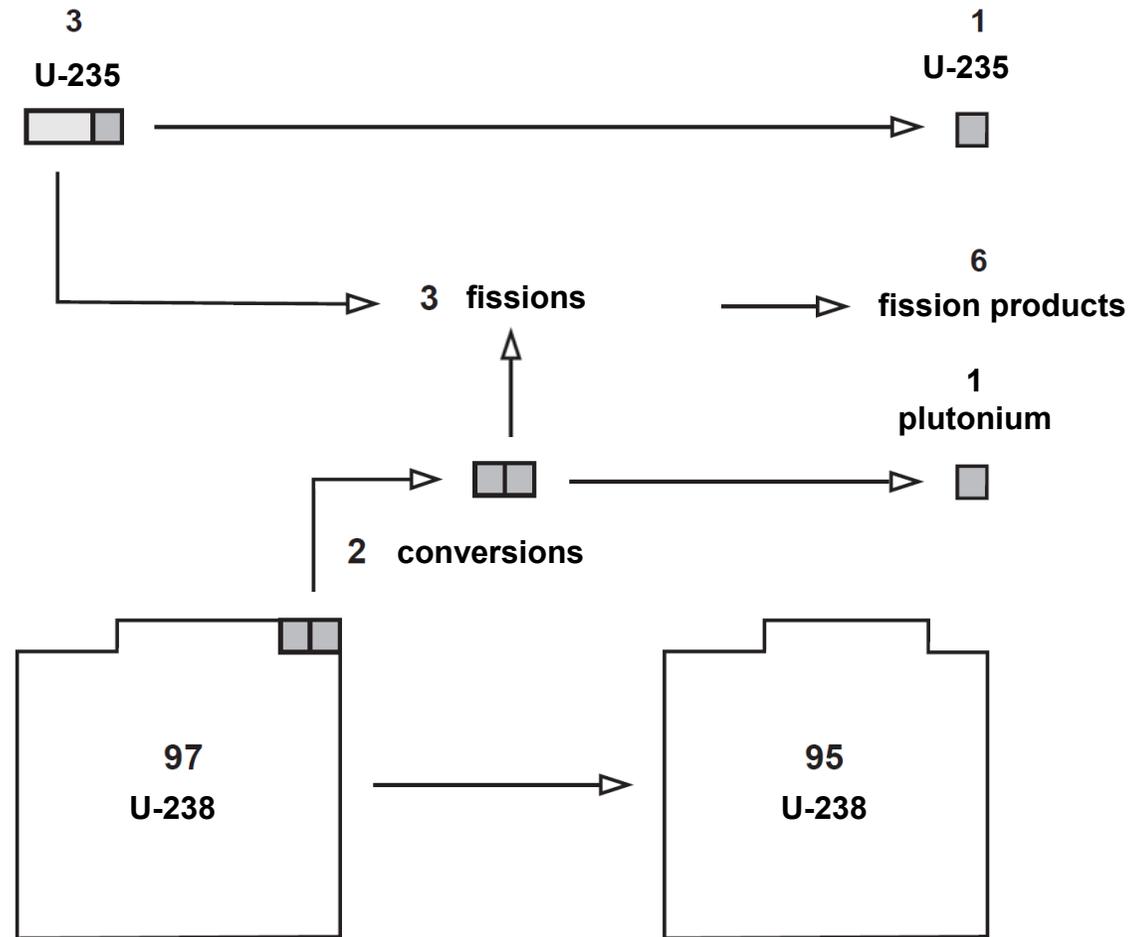


Figure credit: Figure derived from Paul Reuss' lecture notes on reactor physics (1996)

Fuel utilization

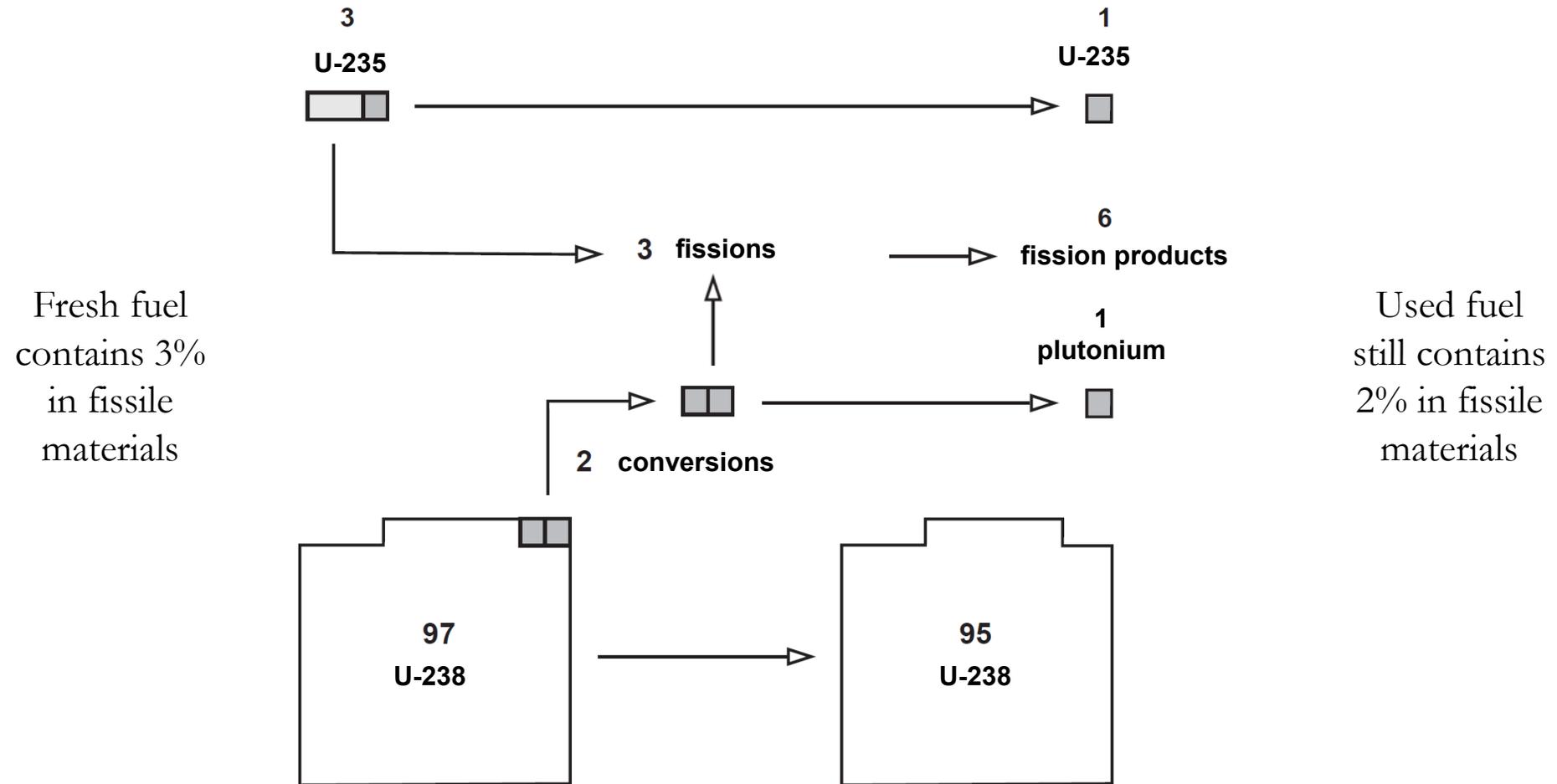


Figure credit: Figure derived from Paul Reuss' lecture notes on reactor physics (1996)

Fuel utilization

- Very large amounts of **useful** (i.e., fissile) materials in the **irradiated** fuel
- Two possible options:
 - **Disposal**
 - **Reprocessing**

Nuclear waste

How much nuclear waste do we produce and how hazardous is it?

Nuclear waste

- Nuclear waste emits **radiations**

Nuclear waste

Nuclear waste

Evolution of the isotopic mass fraction of a nuclear fuel assembly [1]

time = 0 days

¹ H																	² He
³ Li	⁴ Be											⁵ B	⁶ C	⁷ N	⁸ O 1.2e-01	⁹ F	¹⁰ Ne
¹¹ Na	¹² Mg											¹³ Al	¹⁴ Si	¹⁵ P	¹⁶ S	¹⁷ Cl	¹⁸ Ar
¹⁹ K	²⁰ Ca	²¹ Sc	²² Ti	²³ V	²⁴ Cr	²⁵ Mn	²⁶ Fe	²⁷ Co	²⁸ Ni	²⁹ Cu	³⁰ Zn	³¹ Ga	³² Ge	³³ As	³⁴ Se	³⁵ Br	³⁶ Kr
³⁷ Rb	³⁸ Sr	³⁹ Y	⁴⁰ Zr	⁴¹ Nb	⁴² Mo	⁴³ Tc	⁴⁴ Ru	⁴⁵ Rh	⁴⁶ Pd	⁴⁷ Ag	⁴⁸ Cd	⁴⁹ In	⁵⁰ Sn	⁵¹ Sb	⁵² Te	⁵³ I	⁵⁴ Xe
⁵⁵ Cs	⁵⁶ Ba	⁵⁷⁻⁷¹	⁷² Hf	⁷³ Ta	⁷⁴ W	⁷⁵ Re	⁷⁶ Os	⁷⁷ Ir	⁷⁸ Pt	⁷⁹ Au	⁸⁰ Hg	⁸¹ Tl	⁸² Pb	⁸³ Bi	⁸⁴ Po	⁸⁵ At	⁸⁶ Rn
⁸⁷ Fr	⁸⁸ Ra	⁸⁹⁻¹⁰³															

Lanthanides	⁵⁷ La	⁵⁸ Ce	⁵⁹ Pr	⁶⁰ Nd	⁶¹ Pm	⁶² Sm	⁶³ Eu	⁶⁴ Gd	⁶⁵ Tb	⁶⁶ Dy	⁶⁷ Ho	⁶⁸ Er	⁶⁹ Tm	⁷⁰ Yb	⁷¹ Lu
Actinides	⁸⁹ Ac	⁹⁰ Th	⁹¹ Pa	⁹² U 8.8e-01	⁹³ Np	⁹⁴ Pu	⁹⁵ Am	⁹⁶ Cm	⁹⁷ Bk	⁹⁸ Cf	⁹⁹ Es	¹⁰⁰ Fm	¹⁰¹ Md	¹⁰² No	¹⁰³ Lr

Graphics by Carl Hellesen
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Nuclear waste

Evolution of the isotopic mass fraction of a nuclear fuel assembly [1]

time = 0 days

¹ H																	² He
³ Li	⁴ Be											⁵ B	⁶ C	⁷ N	⁸ O 1.2e-01	⁹ F	¹⁰ Ne
¹¹ Na	¹² Mg											¹³ Al	¹⁴ Si	¹⁵ P	¹⁶ S	¹⁷ Cl	¹⁸ Ar
¹⁹ K	²⁰ Ca	²¹ Sc	²² Ti	²³ V	²⁴ Cr	²⁵ Mn	²⁶ Fe	²⁷ Co	²⁸ Ni	²⁹ Cu	³⁰ Zn	³¹ Ga	³² Ge	³³ As	³⁴ Se	³⁵ Br	³⁶ Kr
³⁷ Rb	³⁸ Sr	³⁹ Y	⁴⁰ Zr	⁴¹ Nb	⁴² Mo	⁴³ Tc	⁴⁴ Ru	⁴⁵ Rh	⁴⁶ Pd	⁴⁷ Ag	⁴⁸ Cd	⁴⁹ In	⁵⁰ Sn	⁵¹ Sb	⁵² Te	⁵³ I	⁵⁴ Xe
⁵⁵ Cs	⁵⁶ Ba	⁵⁷⁻⁷¹	⁷² Hf	⁷³ Ta	⁷⁴ W	⁷⁵ Re	⁷⁶ Os	⁷⁷ Ir	⁷⁸ Pt	⁷⁹ Au	⁸⁰ Hg	⁸¹ Tl	⁸² Pb	⁸³ Bi	⁸⁴ Po	⁸⁵ At	⁸⁶ Rn
⁸⁷ Fr	⁸⁸ Ra	⁸⁹⁻¹⁰³															

Lanthanides	⁵⁷ La	⁵⁸ Ce	⁵⁹ Pr	⁶⁰ Nd	⁶¹ Pm	⁶² Sm	⁶³ Eu	⁶⁴ Gd	⁶⁵ Tb	⁶⁶ Dy	⁶⁷ Ho	⁶⁸ Er	⁶⁹ Tm	⁷⁰ Yb	⁷¹ Lu
Actinides	⁸⁹ Ac	⁹⁰ Th	⁹¹ Pa	⁹² U 8.8e-01	⁹³ Np	⁹⁴ Pu	⁹⁵ Am	⁹⁶ Cm	⁹⁷ Bk	⁹⁸ Cf	⁹⁹ Es	¹⁰⁰ Fm	¹⁰¹ Md	¹⁰² No	¹⁰³ Lr

Graphics by Carl Hellesen
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Nuclear waste

Evolution of the isotopic mass fraction of a nuclear fuel assembly [1]

time = 5.0 years

¹ H 4.2e-09																	² He 5.3e-06
³ Li 4.8e-17	⁴ Be 6.9e-13											⁵ B 2.9e-15	⁶ C 1.4e-05	⁷ N 6.6e-09	⁸ O 1.2e-01	⁹ F	¹⁰ Ne
¹¹ Na	¹² Mg											¹³ Al	¹⁴ Si	¹⁵ P	¹⁶ S	¹⁷ Cl	¹⁸ Ar
¹⁹ K	²⁰ Ca	²¹ Sc	²² Ti	²³ V	²⁴ Cr 5.0e-14	²⁵ Mn 1.1e-11	²⁶ Fe 3.1e-10	²⁷ Co 2.0e-09	²⁸ Ni 6.2e-09	²⁹ Cu 3.7e-09	³⁰ Zn 2.4e-10	³¹ Ga 3.0e-09	³² Ge 5.9e-07	³³ As 1.8e-07	³⁴ Se 7.1e-05	³⁵ Br 2.7e-05	³⁶ Kr 4.2e-04
³⁷ Rb 4.0e-04	³⁸ Sr 1.1e-03	³⁹ Y 5.9e-04	⁴⁰ Zr 4.6e-03	⁴¹ Nb 2.6e-05	⁴² Mo 4.1e-03	⁴³ Tc 1.0e-03	⁴⁴ Ru 3.3e-03	⁴⁵ Rh 5.4e-04	⁴⁶ Pd 1.9e-03	⁴⁷ Ag 1.2e-04	⁴⁸ Cd 1.3e-04	⁴⁹ In 2.5e-06	⁵⁰ Sn 9.1e-05	⁵¹ Sb 2.8e-05	⁵² Te 6.4e-04	⁵³ I 2.8e-04	⁵⁴ Xe 7.0e-03
⁵⁵ Cs 3.7e-03	⁵⁶ Ba 2.0e-03	⁵⁷⁻⁷¹	⁷² Hf 1.8e-19	⁷³ Ta	⁷⁴ W	⁷⁵ Re	⁷⁶ Os	⁷⁷ Ir	⁷⁸ Pt	⁷⁹ Au	⁸⁰ Hg	⁸¹ Tl 2.9e-20	⁸² Pb 8.4e-15	⁸³ Bi 4.6e-18	⁸⁴ Po	⁸⁵ At	⁸⁶ Rn 2.7e-20
⁸⁷ Fr	⁸⁸ Ra 4.8e-16	⁸⁹⁻¹⁰³															

- Fission products
- Actinides

Lanthanides	⁵⁷ La 1.6e-03	⁵⁸ Ce 3.4e-03	⁵⁹ Pr 1.4e-03	⁶⁰ Nd 5.0e-03	⁶¹ Pm 1.8e-04	⁶² Sm 8.9e-04	⁶³ Eu 2.0e-04	⁶⁴ Gd 1.9e-04	⁶⁵ Tb 3.7e-06	⁶⁶ Dy 1.6e-06	⁶⁷ Ho 1.5e-07	⁶⁸ Er 4.1e-08	⁶⁹ Tm 4.0e-12	⁷⁰ Yb 8.2e-14	⁷¹ Lu 1.6e-16
Actinides	⁸⁹ Ac 5.1e-15	⁹⁰ Th 4.8e-10	⁹¹ Pa 1.0e-10	⁹² U 8.3e-01	⁹³ Np 6.6e-04	⁹⁴ Pu 9.8e-03	⁹⁵ Am 2.5e-04	⁹⁶ Cm 1.1e-04	⁹⁷ Bk 1.7e-11	⁹⁸ Cf 5.6e-12	⁹⁹ Es	¹⁰⁰ Fm	¹⁰¹ Md	¹⁰² No	¹⁰³ Lr

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Nuclear waste

Evolution of the activity of a nuclear fuel assembly [Bq/g]

time = 0 days

¹ H																	² He
³ Li	⁴ Be											⁵ B	⁶ C	⁷ N	⁸ O	⁹ F	¹⁰ Ne
¹¹ Na	¹² Mg											¹³ Al	¹⁴ Si	¹⁵ P	¹⁶ S	¹⁷ Cl	¹⁸ Ar
¹⁹ K	²⁰ Ca	²¹ Sc	²² Ti	²³ V	²⁴ Cr	²⁵ Mn	²⁶ Fe	²⁷ Co	²⁸ Ni	²⁹ Cu	³⁰ Zn	³¹ Ga	³² Ge	³³ As	³⁴ Se	³⁵ Br	³⁶ Kr 4.3e+08
³⁷ Rb 6.8e+07	³⁸ Sr 3.1e+10	³⁹ Y 4.1e+10	⁴⁰ Zr 5.4e+10	⁴¹ Nb 5.4e+10	⁴² Mo 6.4e+10	⁴³ Tc 9.2e+05	⁴⁴ Ru 8.9e+10	⁴⁵ Rh 4.4e+10	⁴⁶ Pd	⁴⁷ Ag 3.2e+09	⁴⁸ Cd 5.2e+08	⁴⁹ In	⁵⁰ Sn 4.7e+08	⁵¹ Sb 7.0e+08	⁵² Te 5.0e+10	⁵³ I 3.6e+10	⁵⁴ Xe 7.0e+10
⁵⁵ Cs 2.3e+10	⁵⁶ Ba 5.8e+10	⁵⁷⁻⁷¹	⁷² Hf	⁷³ Ta	⁷⁴ W	⁷⁵ Re	⁷⁶ Os	⁷⁷ Ir	⁷⁸ Pt	⁷⁹ Au	⁸⁰ Hg	⁸¹ Tl	⁸² Pb	⁸³ Bi	⁸⁴ Po	⁸⁵ At	⁸⁶ Rn
⁸⁷ Fr	⁸⁸ Ra	⁸⁹⁻¹⁰³															

Lanthanides	⁵⁷ La 6.1e+10	⁵⁸ Ce 1.5e+11	⁵⁹ Pr 5.0e+10	⁶⁰ Nd 2.2e+10	⁶¹ Pm 4.2e+10	⁶² Sm 2.0e+10	⁶³ Eu 1.5e+10	⁶⁴ Gd	⁶⁵ Tb 5.7e+07	⁶⁶ Dy	⁶⁷ Ho	⁶⁸ Er	⁶⁹ Tm	⁷⁰ Yb	⁷¹ Lu
Actinides	⁸⁰ Ac	⁹⁰ Th	⁹¹ Pa	⁹² U 3.5e+10	⁹³ Np 8.1e+11	⁹⁴ Pu 8.0e+09	⁹⁵ Am 1.2e+07	⁹⁶ Cm 4.4e+09	⁹⁷ Bk	⁹⁸ Cf	⁹⁹ Es	¹⁰⁰ Fm	¹⁰¹ Md	¹⁰² No	¹⁰³ Lr

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Cut-off at 10⁴ Bq/g

Nuclear waste

Evolution of the activity of a nuclear fuel assembly [Bq/g]

time = 0 days

¹ H																	² He
³ Li	⁴ Be											⁵ B	⁶ C	⁷ N	⁸ O	⁹ F	¹⁰ Ne
¹¹ Na	¹² Mg											¹³ Al	¹⁴ Si	¹⁵ P	¹⁶ S	¹⁷ Cl	¹⁸ Ar
¹⁹ K	²⁰ Ca	²¹ Sc	²² Ti	²³ V	²⁴ Cr	²⁵ Mn	²⁶ Fe	²⁷ Co	²⁸ Ni	²⁹ Cu	³⁰ Zn	³¹ Ga	³² Ge	³³ As	³⁴ Se	³⁵ Br	³⁶ Kr 4.3e+08
³⁷ Rb 6.8e+07	³⁸ Sr 3.1e+10	³⁹ Y 4.1e+10	⁴⁰ Zr 5.4e+10	⁴¹ Nb 5.4e+10	⁴² Mo 6.4e+10	⁴³ Tc 9.2e+05	⁴⁴ Ru 8.9e+10	⁴⁵ Rh 4.4e+10	⁴⁶ Pd	⁴⁷ Ag 3.2e+09	⁴⁸ Cd 5.2e+08	⁴⁹ In	⁵⁰ Sn 4.7e+08	⁵¹ Sb 7.0e+08	⁵² Te 5.0e+10	⁵³ I 3.6e+10	⁵⁴ Xe 7.0e+10
⁵⁵ Cs 2.3e+10	⁵⁶ Ba 5.8e+10	⁵⁷⁻⁷¹	⁷² Hf	⁷³ Ta	⁷⁴ W	⁷⁵ Re	⁷⁶ Os	⁷⁷ Ir	⁷⁸ Pt	⁷⁹ Au	⁸⁰ Hg	⁸¹ Tl	⁸² Pb	⁸³ Bi	⁸⁴ Po	⁸⁵ At	⁸⁶ Rn
⁸⁷ Fr	⁸⁸ Ra	⁸⁹⁻¹⁰³															

Lanthanides	⁵⁷ La 6.1e+10	⁵⁸ Ce 1.5e+11	⁵⁹ Pr 5.0e+10	⁶⁰ Nd 2.2e+10	⁶¹ Pm 4.2e+10	⁶² Sm 2.0e+10	⁶³ Eu 1.5e+10	⁶⁴ Gd	⁶⁵ Tb 5.7e+07	⁶⁶ Dy	⁶⁷ Ho	⁶⁸ Er	⁶⁹ Tm	⁷⁰ Yb	⁷¹ Lu
Actinides	⁸⁰ Ac	⁹⁰ Th	⁹¹ Pa	⁹² U 3.5e+10	⁹³ Np 8.1e+11	⁹⁴ Pu 8.0e+09	⁹⁵ Am 1.2e+07	⁹⁶ Cm 4.4e+09	⁹⁷ Bk	⁹⁸ Cf	⁹⁹ Es	¹⁰⁰ Fm	¹⁰¹ Md	¹⁰² No	¹⁰³ Lr

Graphics by Carl Hellesen
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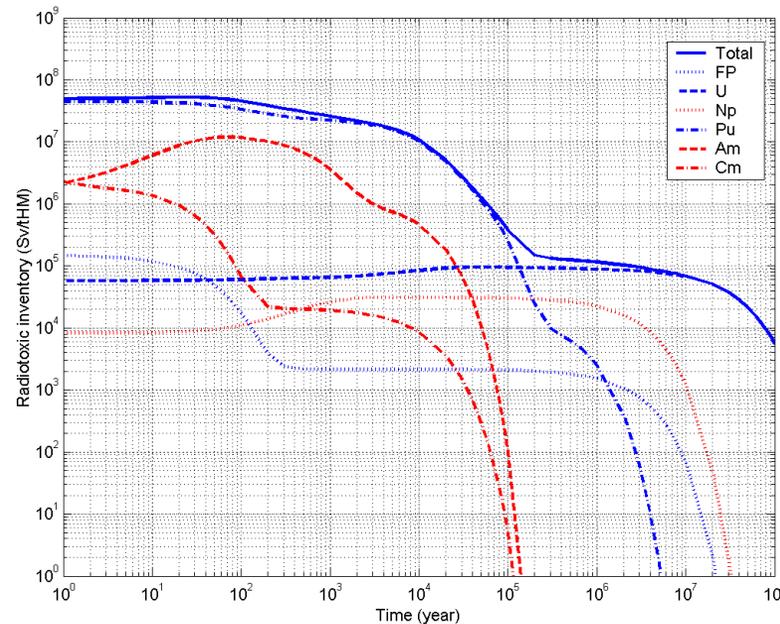
Cut-off at 10⁴ Bq/g

Nuclear waste

- **Fission products:**
 - Highly radioactive
 - Short-lived
 - Relatively small activity after 500 y
- **Actinides:**
 - Not as highly radioactive
 - Long-lived
 - Non negligible activity during at least 100 000 y

Nuclear waste

- Radiotoxicity of nuclear fuel assemblies:



- Radiotoxicity of used fuel comparable to natural uranium after ca. 100 000 years

Nuclear waste

- **Volume of waste:**

Example of the entire Swedish nuclear power program

The Stockholm Avicii
Arena
600,000 m³

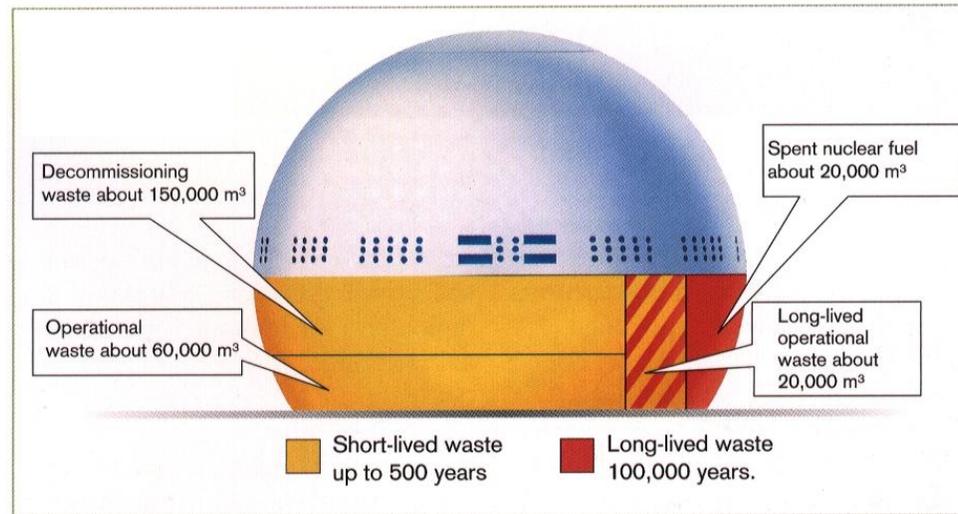


Nuclear waste

- **Volume of waste:**

Example of the entire Swedish nuclear power program

The Stockholm Avicii
Arena
600,000 m³



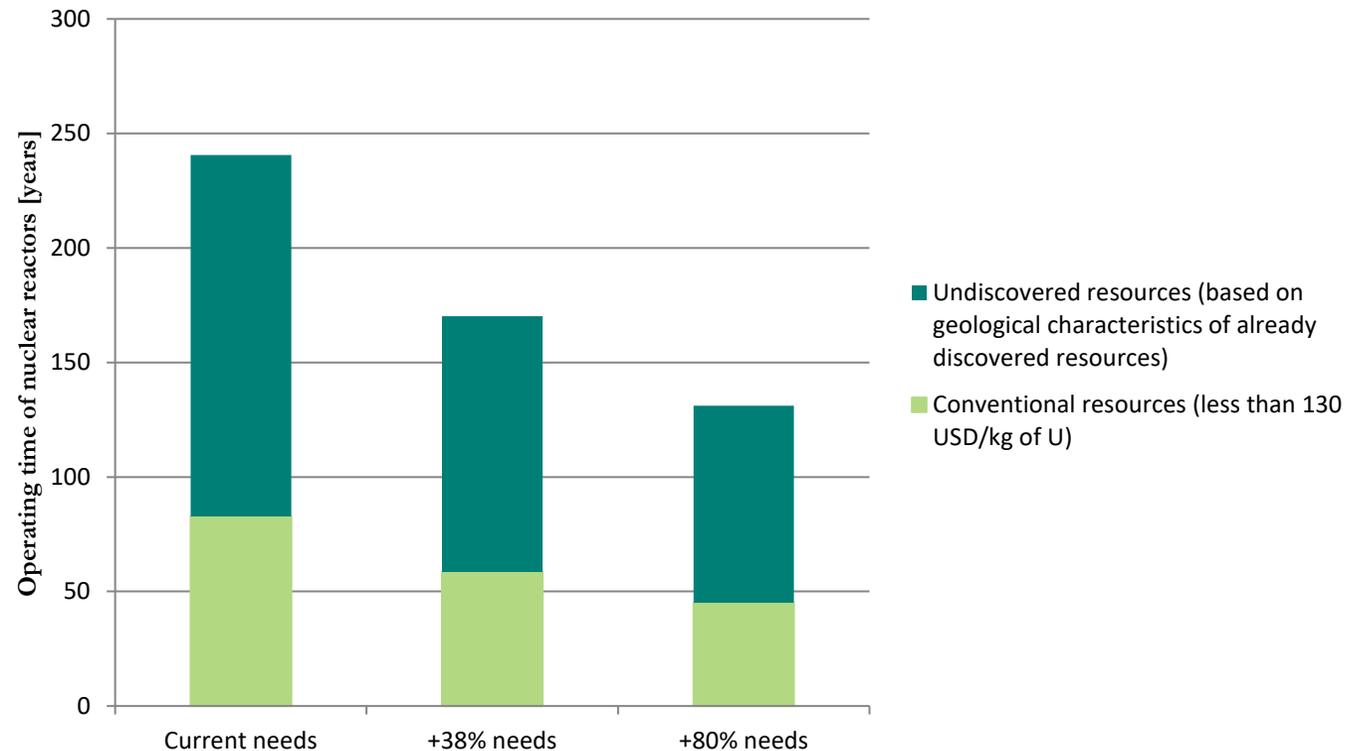
➤ Small volumes of long-lived waste

Uranium resources

How much uranium resources do we have and where are those located?

Uranium resources

- **Uranium resources:**



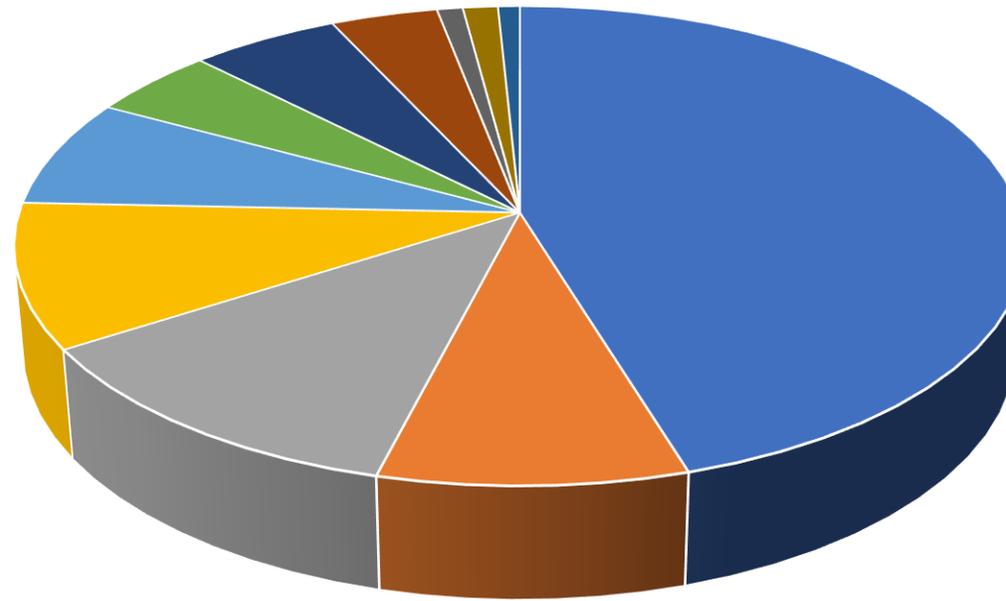
➤ Sufficient resources in Uranium for the next couple of generations but not more

Figure derived from: Uranium 2007: Resources, production and demand. OECD and International Atomic Energy Agency

Uranium resources

- **Security of supply of uranium:**

Share of the top 11 producers of Uranium from mines in 2021
(representing 99.6% of the total production)



- Kazakhstan
- Australia
- Namibia
- Canada
- Uzbekistan (est.)
- Niger
- Russia
- China (est.)
- Ukraine
- India (est.)
- South Africa (est.)

Figure derived from: World Nuclear Association
(accessed on November 18th, 2022)

Uranium resources

- Uranium reserves:

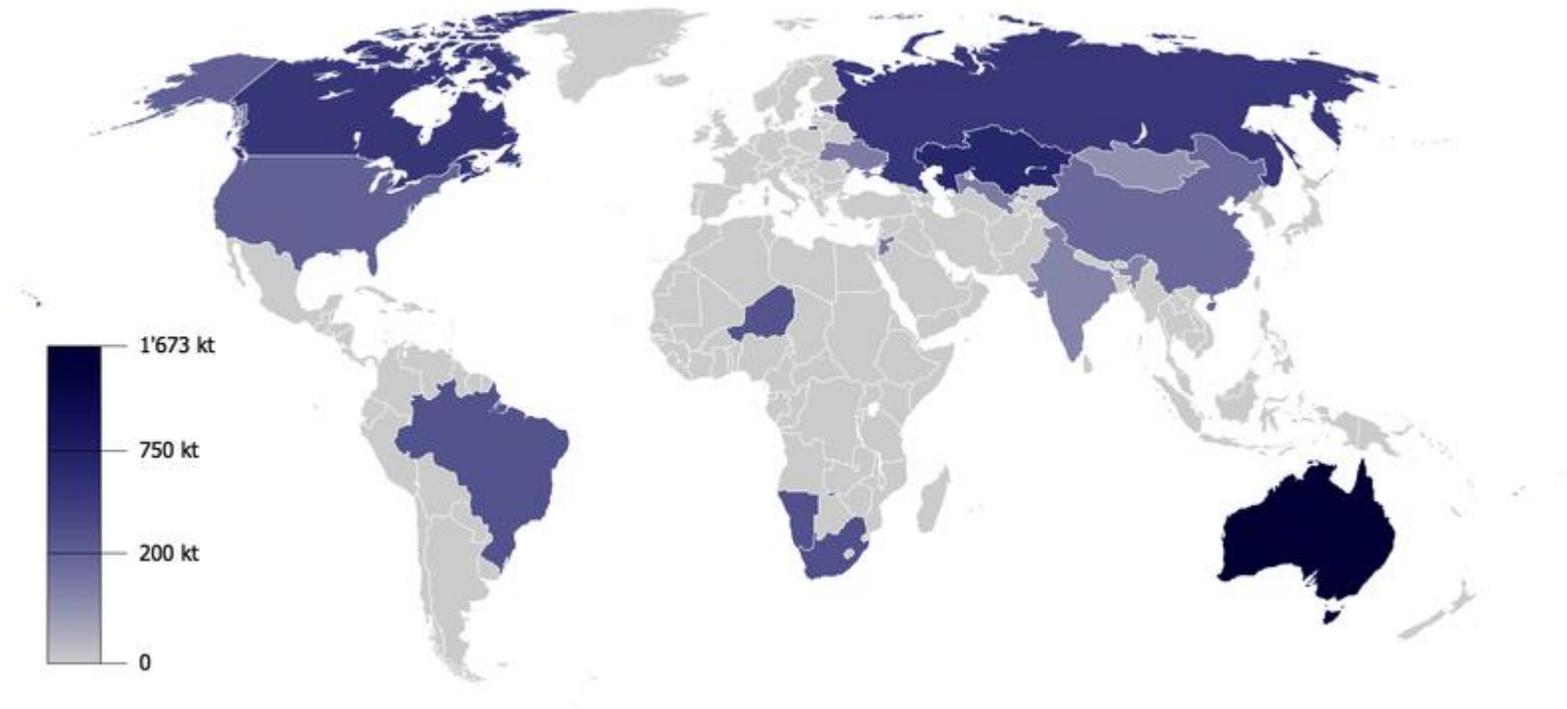


Figure credits: Emilfaro (https://commons.wikimedia.org/wiki/File:Uranium_Reserves.png), „Uranium Reserves“, marked as public domain, more details on Wikimedia Commons: <https://commons.wikimedia.org/wiki/Template:PD-user>

Dependence on the fuel cycle strategy

Can fuel resources be maximized and nuclear waste “reduced” using other fuel cycle strategies?

Dependence on the fuel cycle strategy

- Most countries use an “open fuel cycle”:

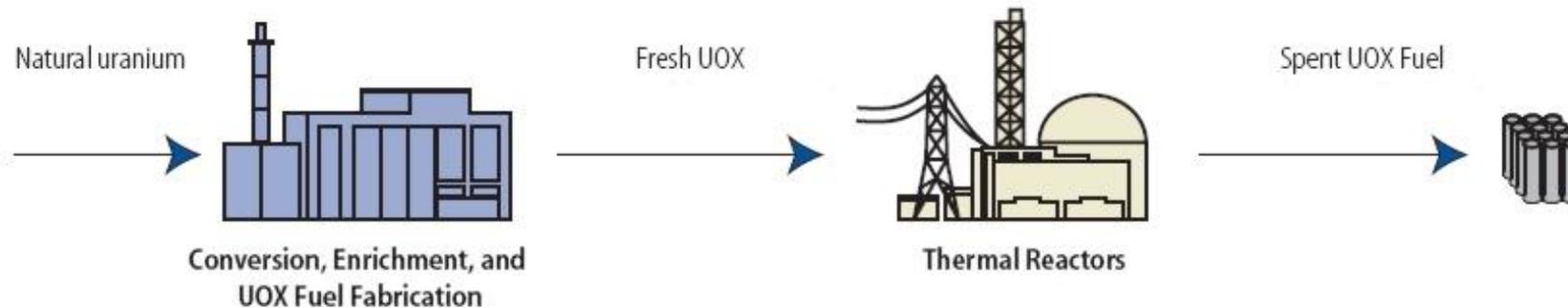


Figure derived from: “The future of nuclear power –An interdisciplinary MIT study” (2003)

- In heavy metals, used fuel still contains 2% in fissile materials and 95% of fissionable materials

Dependence on the fuel cycle strategy

- Some countries **reprocess** the fuel:

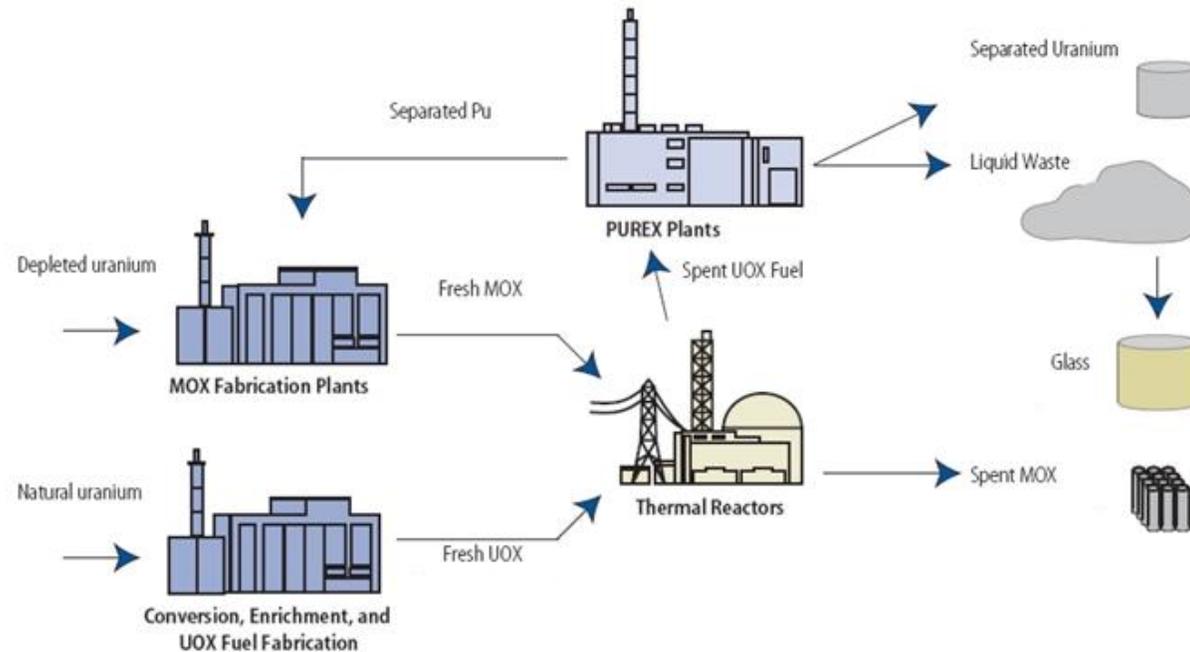
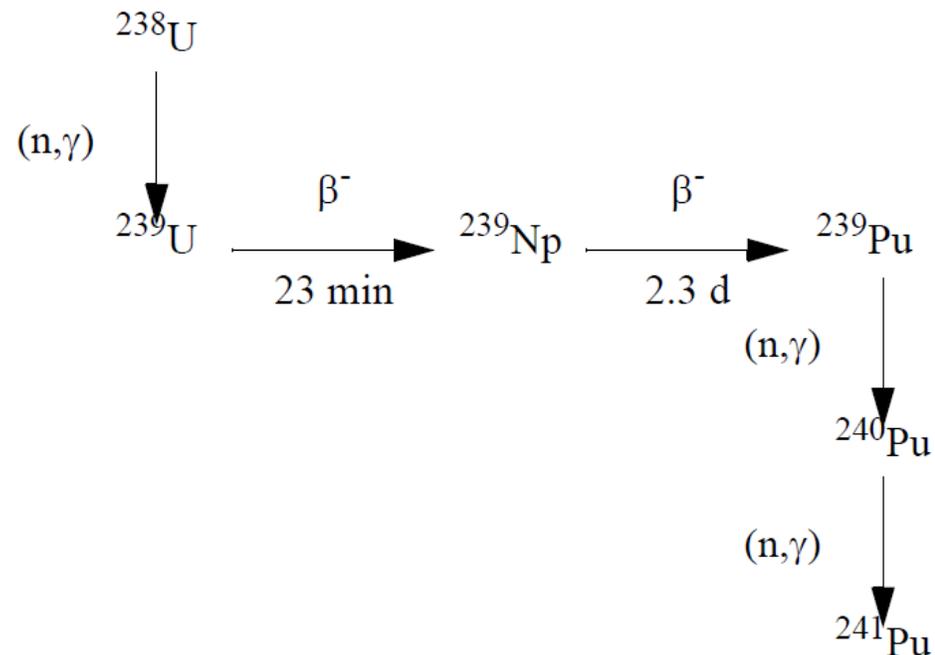


Figure derived from: “The future of nuclear power –An interdisciplinary MIT study” (2003)

Dependence on the fuel cycle strategy

- The fuel cycle could also be “**closed**” in the future:



➤ **U-238** (very abundant) can be **converted** into **Pu-239** and **Pu-241** (both fissile)

Dependence on the fuel cycle strategy

- The fuel cycle could also be “**closed**” in the future:
 - **Breeding** = fabrication of as much new fissile species as the ones consumed

$$\text{breeding ratio} = \frac{\text{number of fissile species gained}}{\text{number of fissile species consumed by fission and capture}}$$

- Reaching a breeding ratio of at least 1 is only possible in a fast neutron spectrum with, e.g., Pu-239

Dependence on the fuel cycle strategy

- The fuel cycle could also be “closed” in the future:

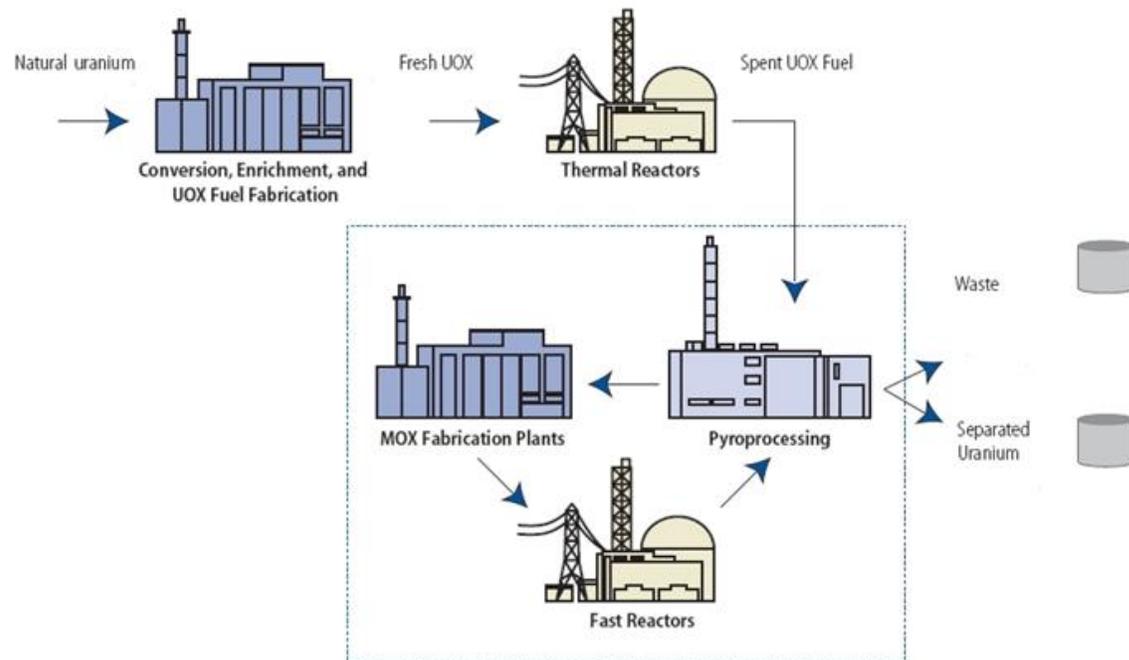


Figure derived from: “The future of nuclear power –An interdisciplinary MIT study” (2003)

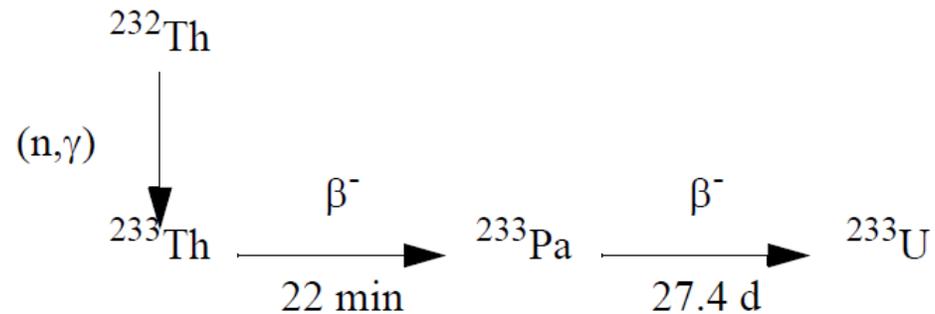
Dependence on the fuel cycle strategy

- The fuel cycle could also be “**closed**” in the future:
 - In one converts U-238 into Pu-239 (and Pu-241), resources estimated to last for 10 000 – 250 000 years

(R. Price, J. R. Blaise, ”Nuclear fuel resources: Enough to last?”, NEA Updates NEA News, 20 (2), 2002)

Dependence on the fuel cycle strategy

- Uranium could also be produced from **Thorium** (very abundant):



- In one converts Th-232 into U-233, resources estimated to last for 17 000 – 35 500 years

(R. Price, J. R. Blaise, "Nuclear fuel resources: Enough to last?", NEA Updates NEA News, 20 (2), 2002)

Dependence on the fuel cycle strategy

- Fast reactor systems, if not used as breeders, can also be used to **transmute** long-lived nuclear waste into shorter-lived nuclear waste
 - Time at which radiotoxicity of used fuel is comparable to natural uranium could be reduced from ca. 100 000 years to ca. 100 years
 - **Fast reactors** are key to **close** the fuel cycle and “**incinerate**” current waste

Proliferation risk

What are the risks of proliferation for the current fuel cycle strategies and future ones, respectively?

Proliferation risk

- Fissile materials could be used for **nuclear weapon fabrication**:
 - **Atomic bombs** (relying on fission, initiated by a conventional explosive)
 - **Hydrogen bombs** (relying on fusion, initiated by fission bomb)
- **Critical mass** of fissile material necessary
- Can be created by:
 - U-235 enrichment or
 - Pu-239/U-233 produced artificially in dedicated nuclear reactors and separated



Figure credits: United States Department of Energy
(https://commons.wikimedia.org/wiki/File:Castle_Romeo.jpg),
„Castle Romeo“, marked as public domain, more details on Wikimedia
Commons: <https://commons.wikimedia.org/wiki/Template:PD-US>

Proliferation risk

- Radioactive materials could be dispersed with conventional explosives: radiological dispersal devices (“**dirty**” **bombs**)

Proliferation risk

- Nuclear weapons require an extremely high enrichment in fissile materials:

Enrichment in U-235 for non-military and military applications

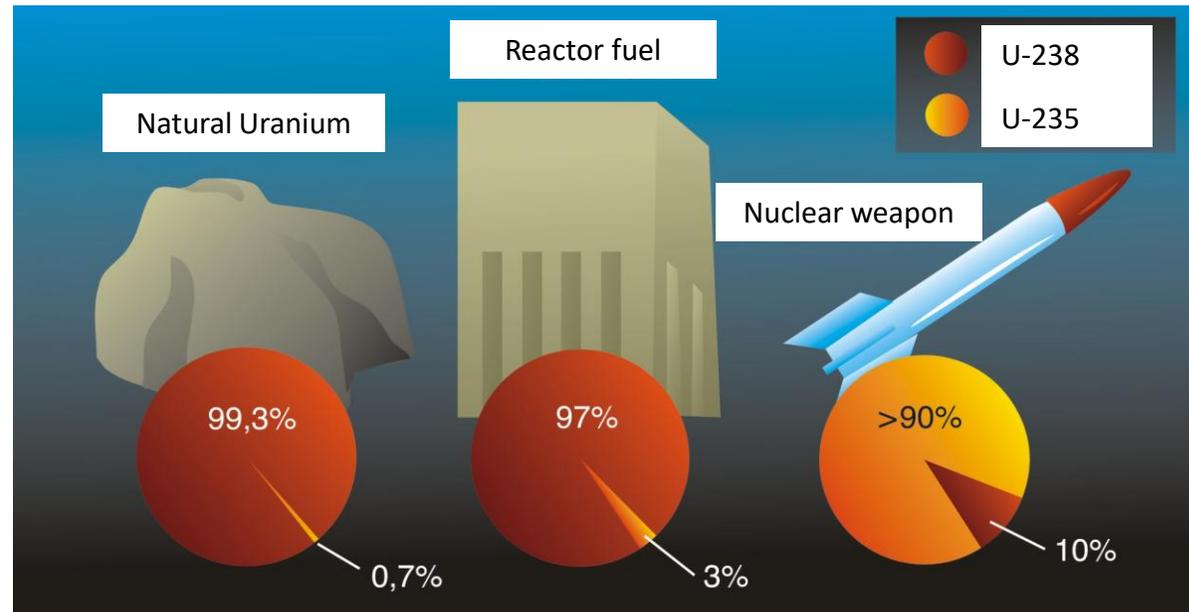


Figure derived from: L. Widlund, Analysgruppen vid KSU

Proliferation risk

- In case of **open fuel cycle**:

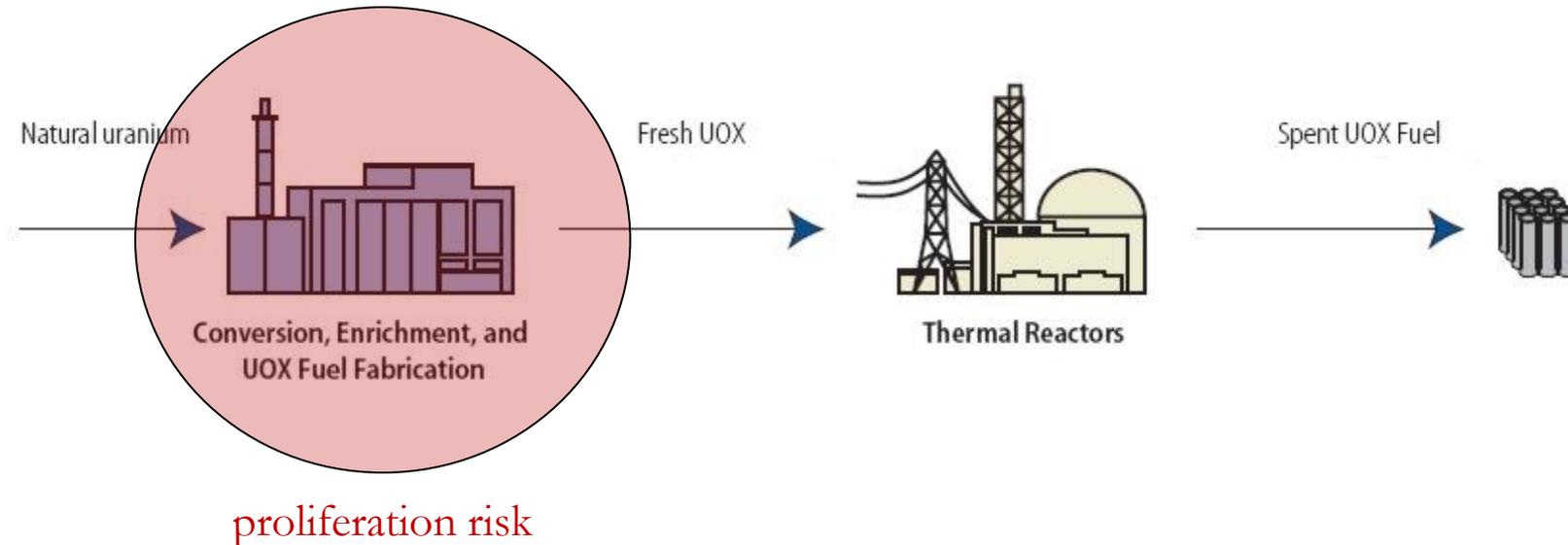


Figure derived from: “The future of nuclear power –An interdisciplinary MIT study” (2003)

- **Additional proliferation risk** in case of **reprocessing**



Take-aways

Take-aways

- **Advantages** of nuclear power:
 - Reliable and safe base load generation means
 - “Manageable” waste
 - Very small environmental impact
- **Disadvantages** of nuclear power:
 - Lifetime of nuclear waste
 - Proliferation risk
 - Technology-intensive industry
 - Many aspects of nuclear power specific risks and costs externalized
 - Public acceptance necessary

Prospects

- Can nuclear power solve our **climate challenges**?
 - Can be part of the solution (combined with other energy sources not releasing CO₂)

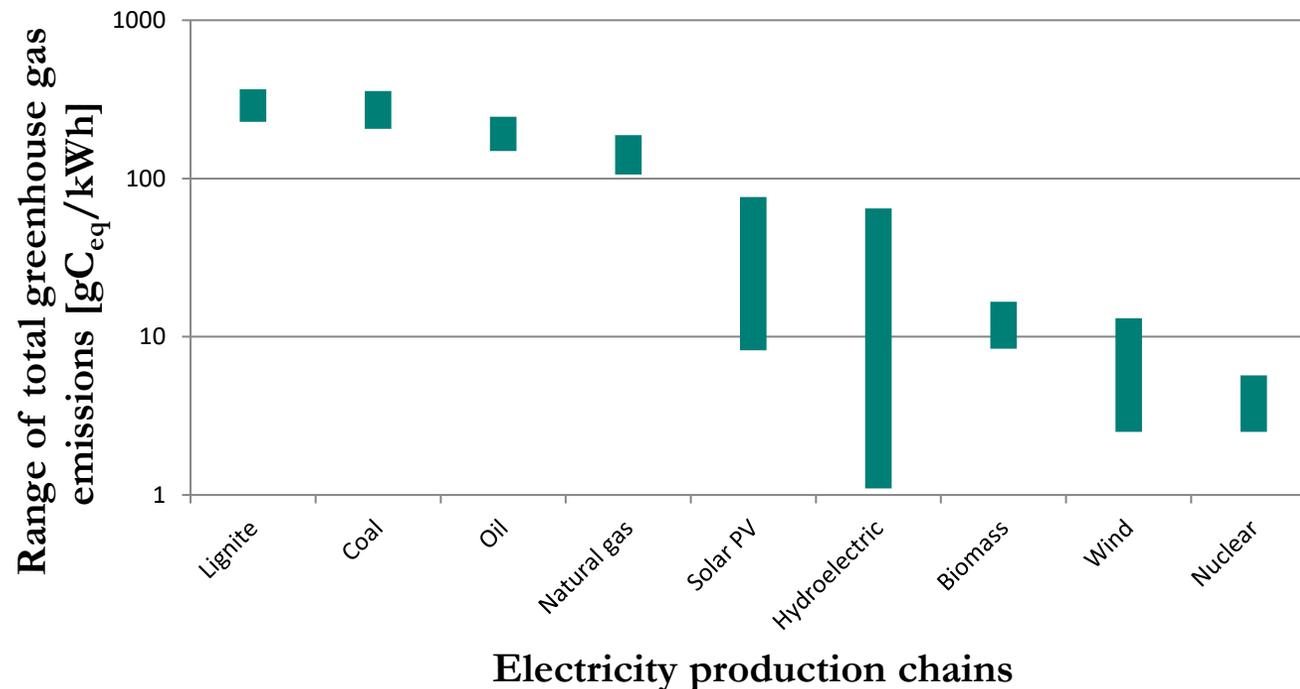


Figure derived from: J. V. Spadaro, L. Langlois, and B. Hamilton, "Greenhouse gas emissions of electricity generation chains – Assessing the difference". IAEA (International Atomic Energy Agency) Bulletin, 42 (2), 2000

Prospects

- Can nuclear power solve our **climate challenges**?
 - **Large scale deployment** beyond today 10% **very unlikely** to occur...

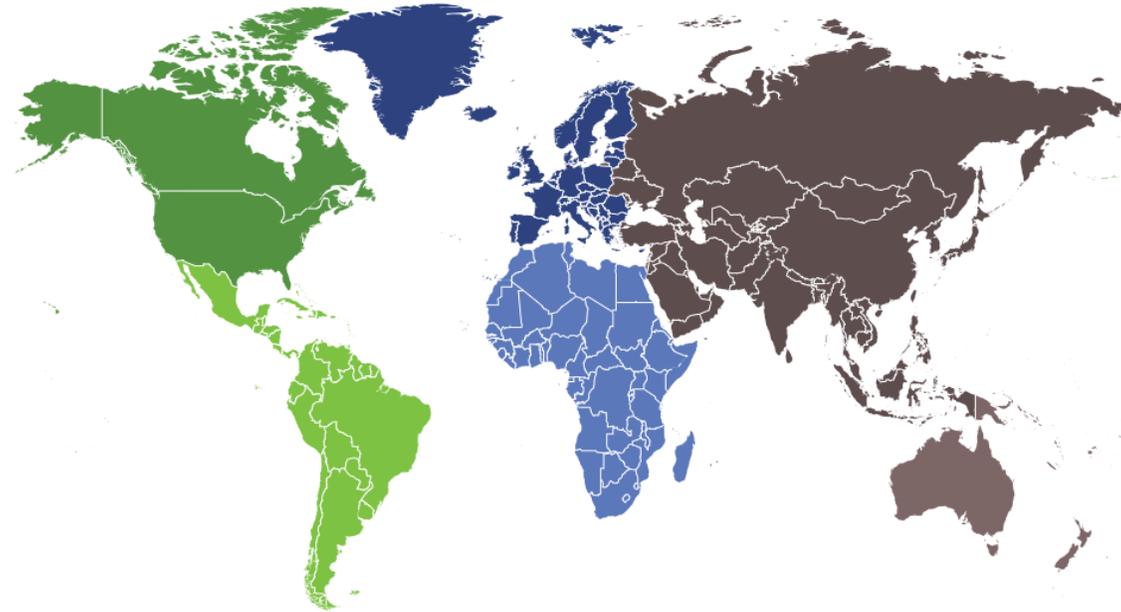


Figure credit: www.bouncymaps.com

Prospects

- Can nuclear power solve our **climate challenges**?
 - **Large scale deployment** beyond today 10% **very unlikely** to occur...

Number of nuclear reactors in operation in 2019



Figure credit: www.bouncymaps.com

Prospects

- Can nuclear power solve our **climate challenges**?
 - **Large scale deployment** beyond today 10% **very unlikely** to occur...

Number of inhabitants in 2019

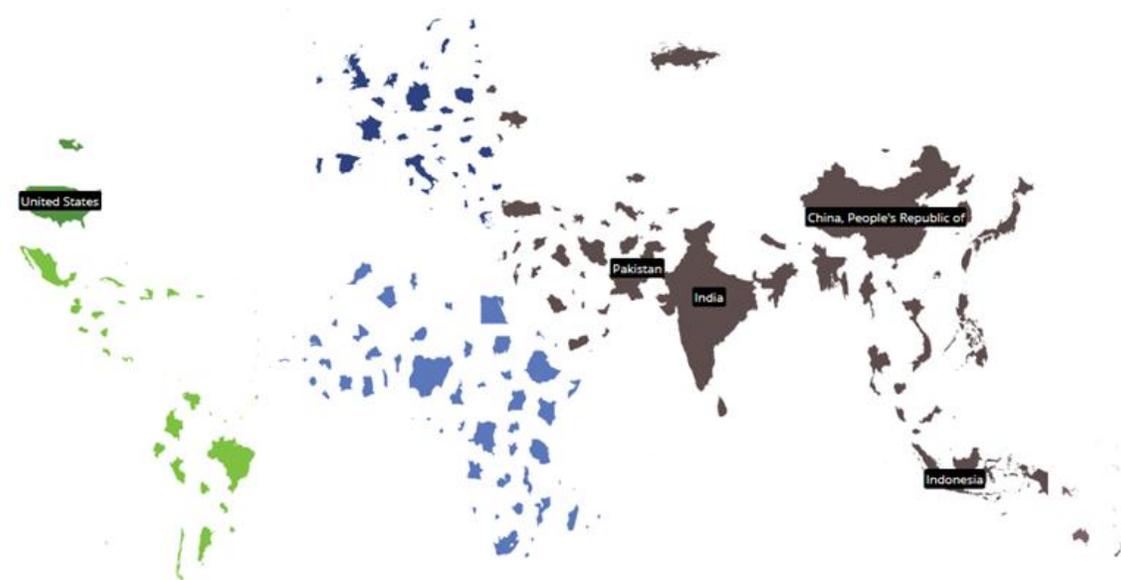


Figure credit: www.bouncymaps.com

Prospects

- Can nuclear power solve our **climate challenges**?
 - **Inadequacy** between **current installation** of nuclear power and **current needs**
 - **Deployment** of nuclear power where energy most needed **difficult** as technology-intensive industry
 - Unless new reactor types simplifying the entire chain are introduced

SMRs

SMRs

- **Small Modular Reactors (SMRs):**
 - Smaller thermal output
 - Could be of Gen-II/III/IV designs
 - Pre-fabricated modules
 - Expected lower construction costs
 - Typically, passive safety designs

➤ 56 designs under active development

Overview of the reactor building in the NuScale design



SMRs

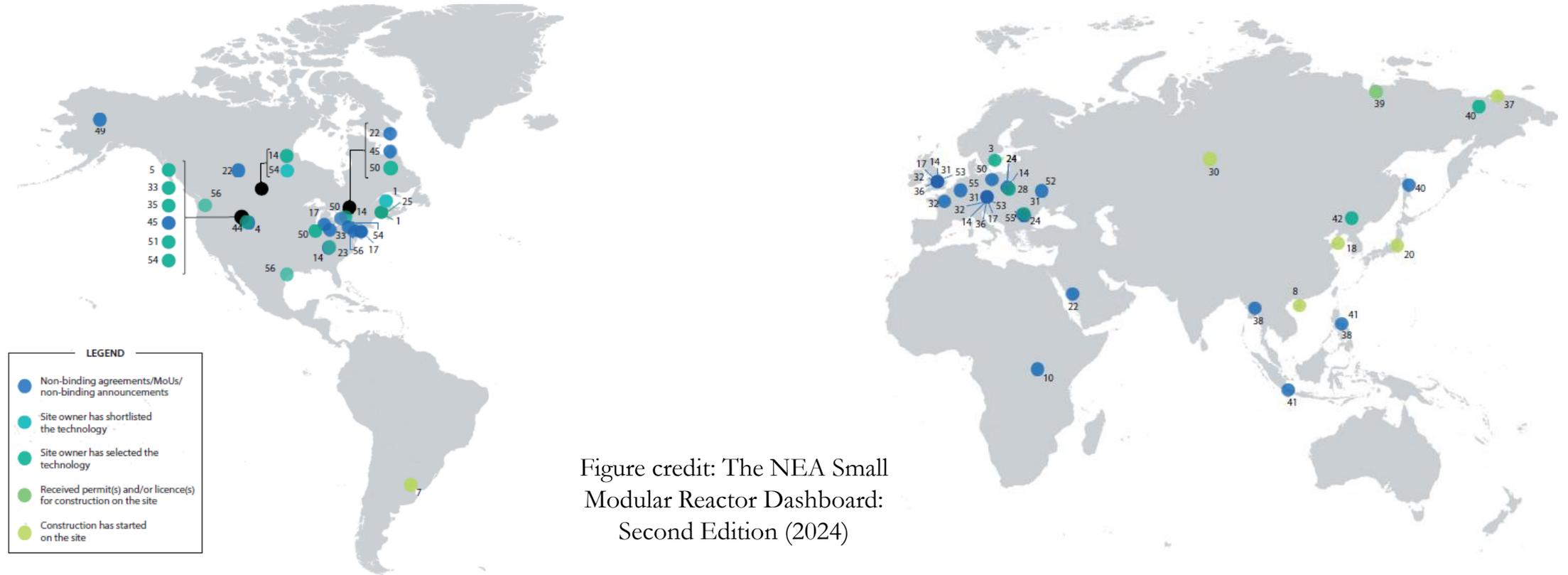


Figure credit: The NEA Small Modular Reactor Dashboard: Second Edition (2024)

1	ARC-100	ARC Clean Technology	15	Calogena	Gorgé
2	Blue Capsule	Blue Capsule Technology	16	HEXANA	Hexana
3	SEALER-55	Blykalla	17	SMR-300	Holtec International
4	BANR	BWXT	18	HTR-PM	INET
5	Project Pele	BWXT	19	GTHTR300	JAEA
6	ACPR505	CGN	20	HTTR	JAEA
7	CAREM	CNEA	21	Jimmy SMR	Jimmy
8	ACP100	CNNC	22	SMART	KAERI
9	Energy Well	CVR	23	Hermes	Kairos Power
10	DF300	Dual Fluid Energy	24	PWR-20	Last Energy
11	A-HTR-100	Eskom	25	SSR-W	Moltex Energy
12	LFTR	Flibe Energy	26	FLEX	MoltexFLEX
13	SC-HTGR	Framatome	27	XAMR	NAAREA
14	BWRX-300	GE Hitachi Nuclear Energy	28	HTGR-POLA	NCBJ

29	LFR-AS-200	newcleo	43	HTMR-100	Stratek Global
30	BREST-OD-300	NIKIET	44	Natrium Reactor Plant	TerraPower
31	VOYGR	NuScale Power	45	IMSR	Terrestrial Energy
32	NUWARD SMR	NUWARD	46	ThorCon 500	ThorCon International
33	Aurora Powerhouse	Oklo	47	Thorizon One	Thorizon
34	Otrera 300	Otrera Nuclear Energy	48	MoveluX	Toshiba Energy Systems & Solutions Corporation
35	Kaleidos	Radiant Industries	49	4S	Toshiba Energy Systems & Solutions Corporation
36	RR SMR	Rolls-Royce SMR	50	MMR	USNC
37	KLT-40S	ROSATOM	51	Pylon D1	USNC
38	RITM-200M	ROSATOM	52	TEPLATOR	UWB and CIIRC CTU
39	RITM-200N	ROSATOM	53	AP300™ SMR	Westinghouse Electric Company
40	RITM-200S	ROSATOM	54	eVinci microreactor	Westinghouse Electric Company
41	CMSR	Seaborg Technologies	55	Westinghouse LFR	Westinghouse Electric Company
42	HAPPY200	SPIC	56	Xe-100	X-energy

Conclusions

Conclusions

- Nuclear “**renaissance**”:
 - **New builds in Europe:**
 - **New builds planned** in UK, Poland, Czech Republic, Hungary, Romania (planned = approvals, funding or commitment in place)
 - **New reactors under construction** in Slovakia, Turkey, UK
 - **New builds worldwide:** 62 units under construction, 86 units planned (and 344 units proposed)
 - Plenty of **new designs** being considered:
 - Gen-III/III+/IV reactors
 - SMRs
 - Micro-reactors
 - **End of ban** by the **World Bank** on funding nuclear energy projects

Conclusions

- But also **new challenges**:
 - **Security** of the entire **supply chain**
 - **Costs** of nuclear versus other production means
 - **Resilience** of nuclear infrastructures in case of **war/conflict**



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HISTORY OF NUCLEAR POWER DEVELOPMENT

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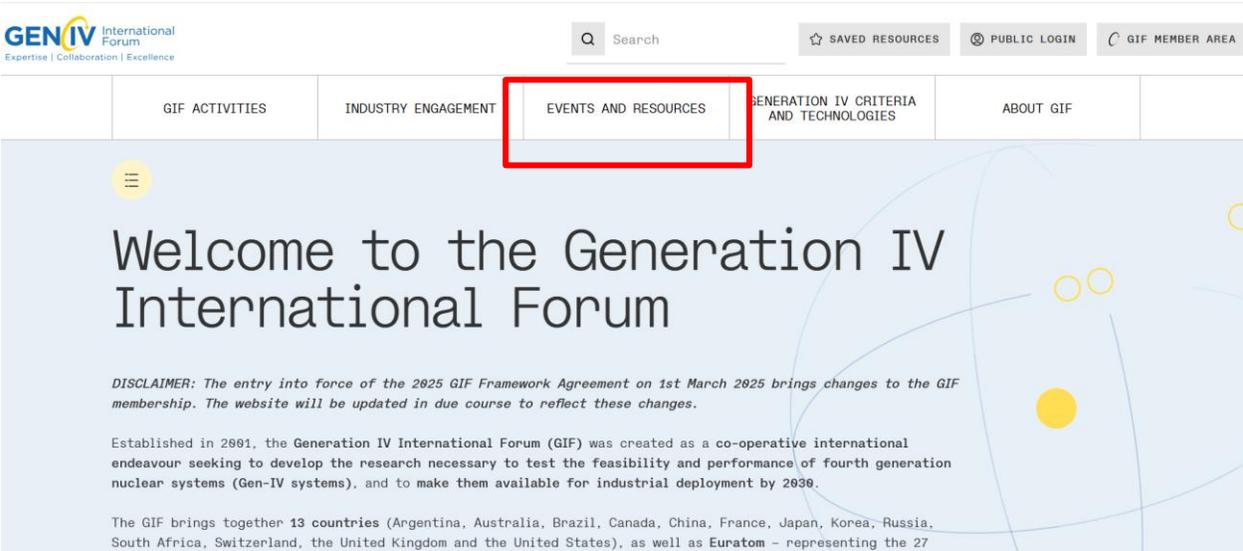
DREAM

TASK FORCE ON
DETERMINISTIC REACTOR MODELLING

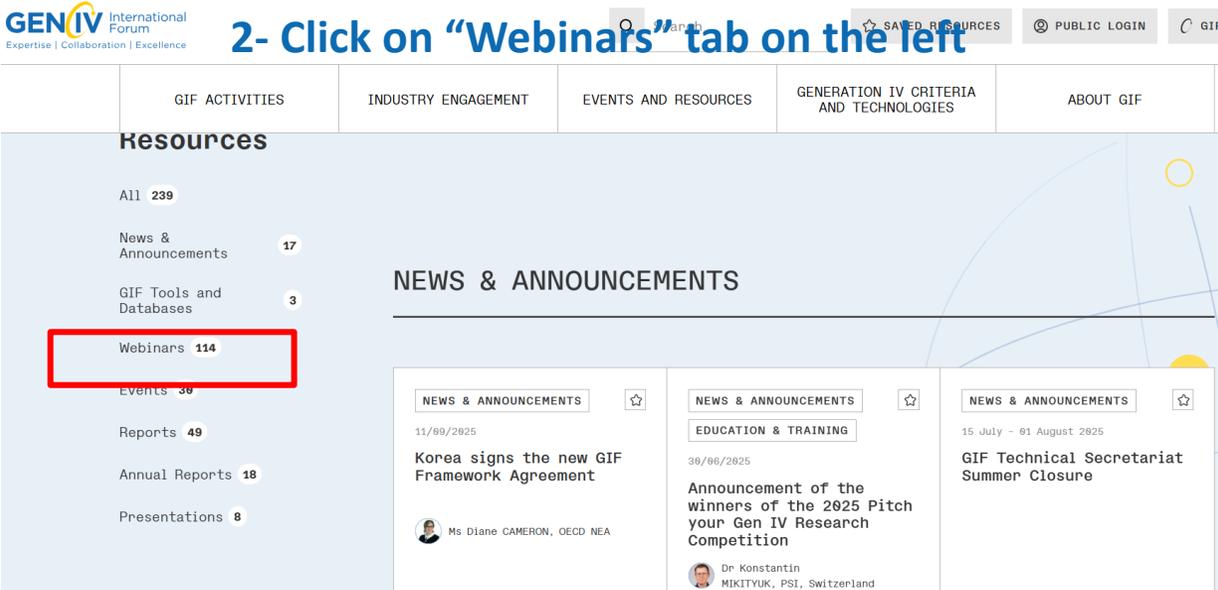
Upcoming Webinars

Date	Title	Presenter
18 February 2026	Approach to Waste Characterisation as well as the Use of Synroc Technology for Advanced Fuel Cycle	Dr. Dan Gregg and Dr. Anton Peristy, ANSTO, Australia
18 March 2026	Overview of the various UK NNL activities supporting advanced reactor systems and their related fuel cycles	Dr. Mike Edmonson, Dr. Seddon Atkinson, Dr. Nassia Tzelepi, UK National Nuclear Laboratory, United Kingdom
29 April 2026	Advances in Monitoring Techniques for Molten Salt Reactor and Fuel Cycle	Prof. Sungyeol Choi, Seoul National University, Republic of Korea

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