- Tuesday/Wednesday
  - 13h15 to 16h
  - 2h lecture + 1h exercise
  - PH H3 31

- Instructors
  - Prof. Andreas Pautz
  - Dr. Mathieu Hursin
  - Tom Mager (TA)
  - Mac Van Rossem (TA)

THIS LESSON …

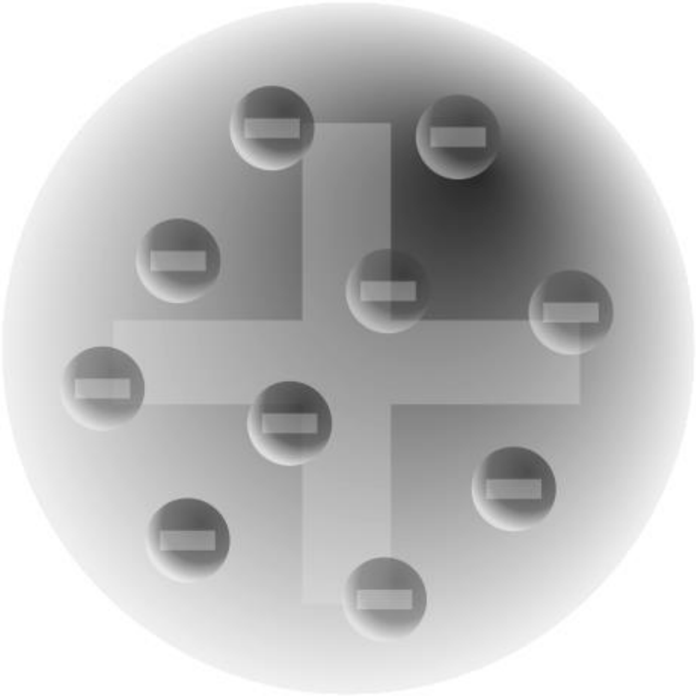
- History
- Why nuclear power?
- Key numbers about nuclear energy
- Object of the course
- Main goals of the course
- Structure of the course

Thompson's model

- In 1898, the British physicist Joseph John Thomson made a bold proposal that "cathode rays" are streams of negatively charged particles which are much smaller than the atom.

- The plum pudding model of the atom proposed by Thomson in 1904 is composed of negatively charged "corpuscles" (electrons) surrounded by a cloud of positive charge to balance the electrons' negative charges, like negatively-charged "plums" surrounded by positively-charged "pudding".

J.J. Thompson (1856-1940)

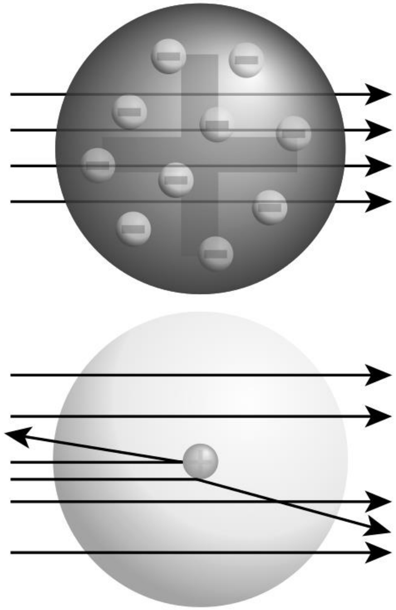


Thompson's plum pudding model

Rutherford's experiment

- In 1911 Thomson's student, Ernest Rutherford, showed that the mass in an atom is not smeared uniformly, but is concentrated in a tiny, inner kernel: the nucleus...
- In the experiment positively charged helium nuclei were directed at a very thin gold foil. The expected result was that the positive particles would be moved just a few degrees from their path as they passed through the sea of positive charge (plum pudding model). In experiment, however, the positive particles were repelled at very high angles, up to 180 degrees, while most of the remaining particles were not deflected at all, but rather, passed through the foil.

E. Rutherford (1871-1937)



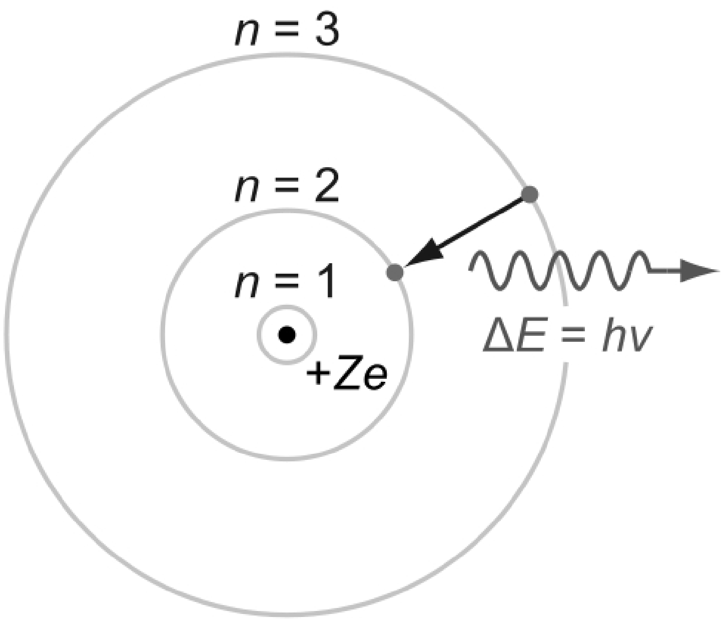
Gold foil experiments

« In order to check what is inside of a pudding with raisins one must put a finger in it »

Rutheford-Bohr's model

- Niels Bohr working with Rutherford in 1911 created a model of the atom called the Rutheford-Bohr model in which nucleus is at the center of the atom with electrons orbiting around it.
- The model of atom, introduced by Niels Bohr in 1913, depicts the atom as a small, positively charged nucleus surrounded by electrons that travel in circular orbits around the nucleus — similar in structure to the solar system, but with electrostatic forces providing attraction, rather than gravity

N. Bohr (1885-1962)

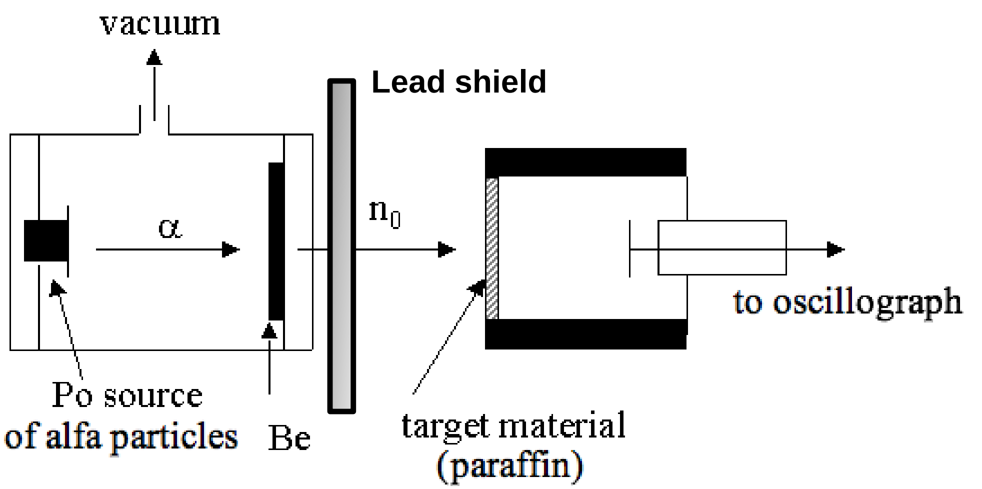


Bohr's model of atom

- In 1932, James Chadwick suggested that the new radiation observed by Bothe and Becker while irradiating beryllium by alpha particles consisted of uncharged particles of approximately the mass of the proton. He performed a series of experiments verifying his suggestion. This was a discovery of neutron.

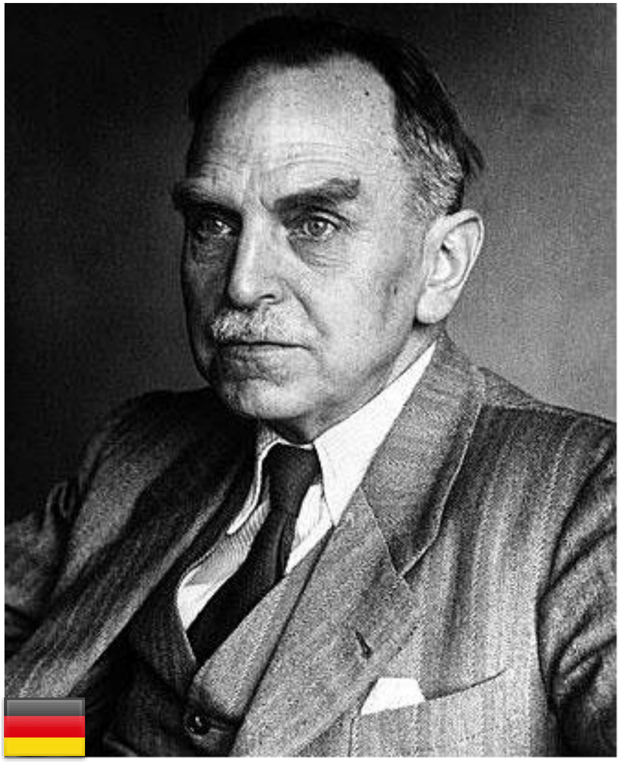
Sir James Chadwick (1891-1974)

$$He_2^4 + Be_4^9 \rightarrow C_6^{12} + n_0^1$$



Chadwick's experiment

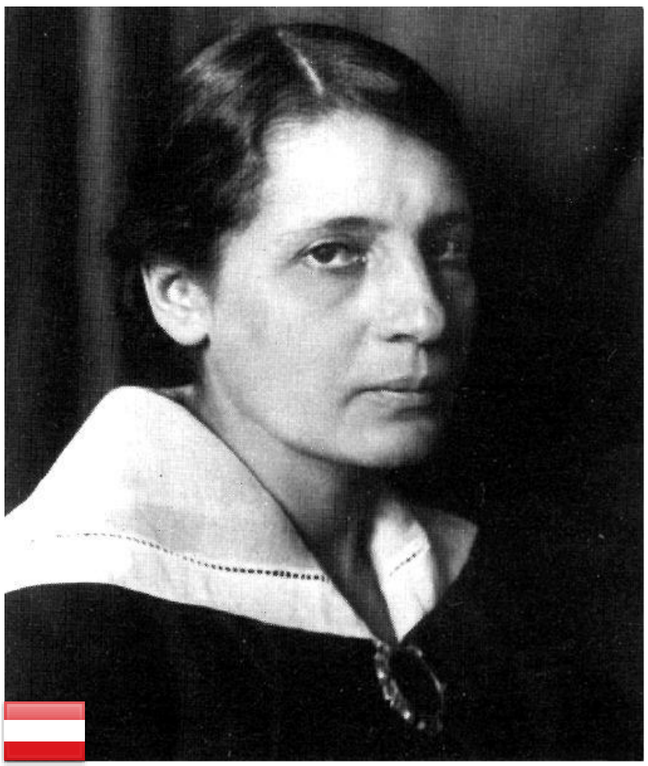
- In 1938, Otto Hahn and Fritz Strassmann were trying to find out what products are formed by bombarding heavy elements with neutrons, hoping to find elements heavier than uranium. However the produced substances looked like radium or barium, much lighter elements...



O. Hahn (1879-1968)

F. Strassmann (1902-1980)

- In December 1938 Lise Meitner and her nephew Otto Frish proposed an explanation of the "strange results" Hahn and Strassmann had found : the uranium nucleus is divided by the neutron into two pieces !

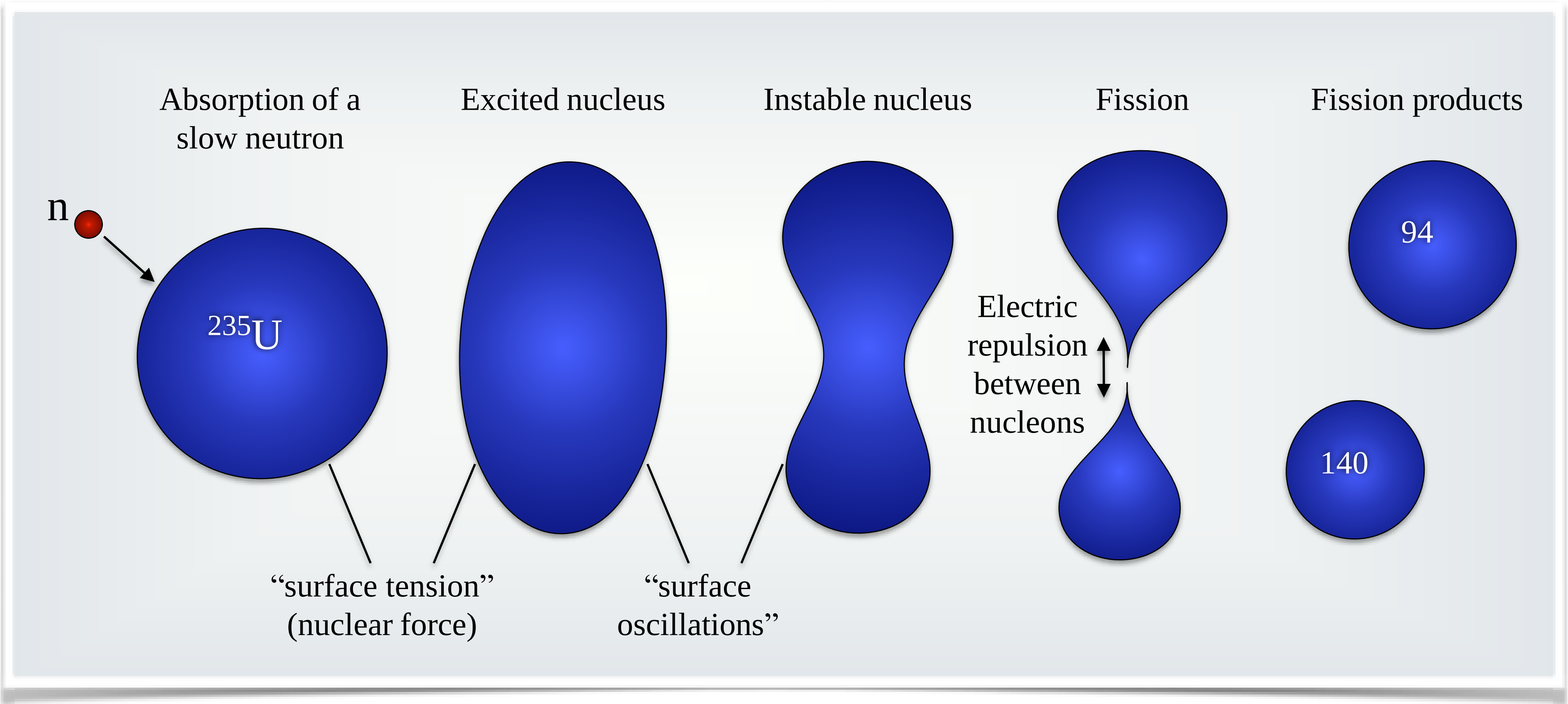


L. Meitner (1878-1968)

O. Frisch (1904-1979)

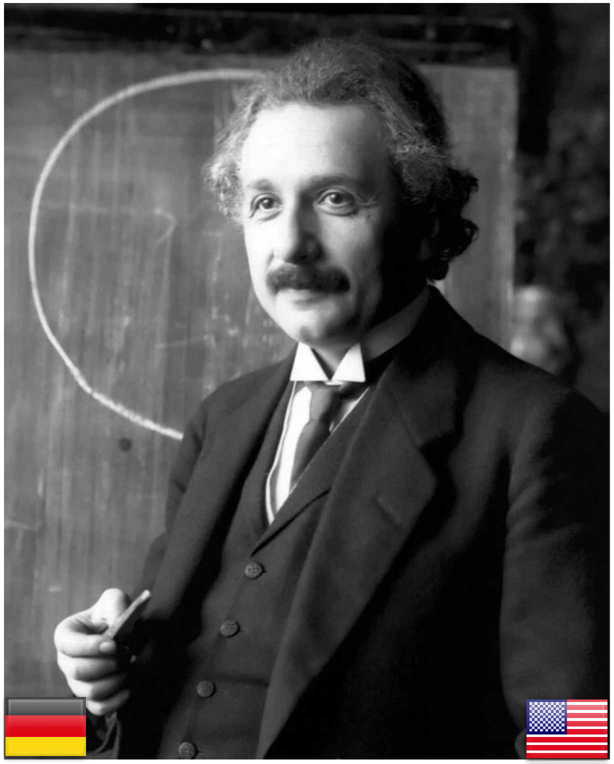
Fission discovery

- According to the theory of Niels Bohr's, a nucleus behaves like a liquid drop, and Meitner with Frisch supposed that if the nucleus (like the liquid drop) is hit hard enough, it might be broken in two.



Nuclear fission according to “liquid drop” model of nucleus

- In 1905 Albert Einstein theorized that energy and mass are equivalent; they can be converted into one another : “The equation $E = mc^2$, in which energy is put equal to mass, multiplied with the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa.”



A. Einstein (1879-1955)

- Applying Einstein’s relation, Meitner calculated that the two fragments of the uranium nucleus should violently move apart one from the other with an energy of around 200 MeV !

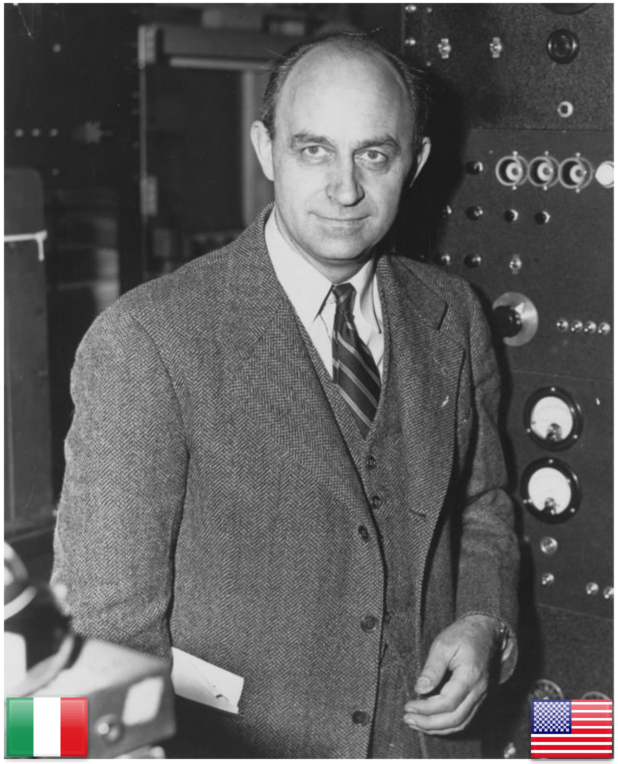
Chain reaction principle

- In 1939 (in parallel to the US team) the French scientists lead by Frederic Joliot and Irene Curie proved that new neutrons come out from split uranium atoms (by observing neutrons of higher energy than original neutrons). The possibility of the chain reaction was demonstrated.

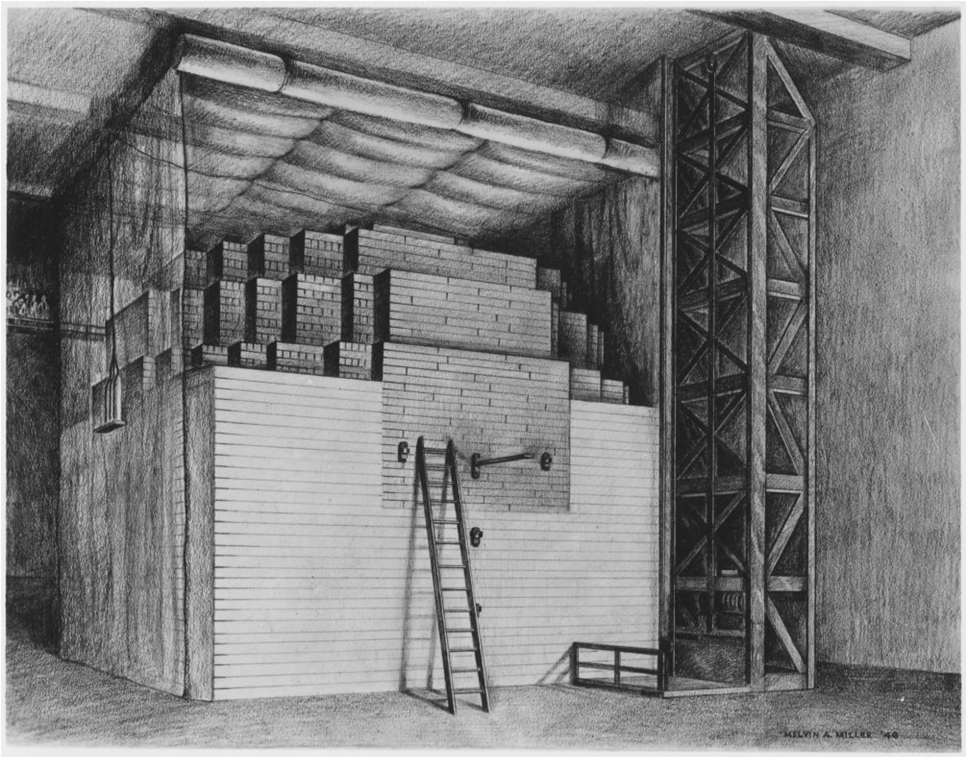
F. Joliot (1900-1958) and I. Curie (1897-1956)

First nuclear reactor

- On December 2, 1942, under the abandoned west stands of the football stadium, at the University of Chicago, a team of physicists led by Enrico Fermi initiated the first self-sustaining chain reaction in the first man-made nuclear reactor called “Chicago Pile-1”.

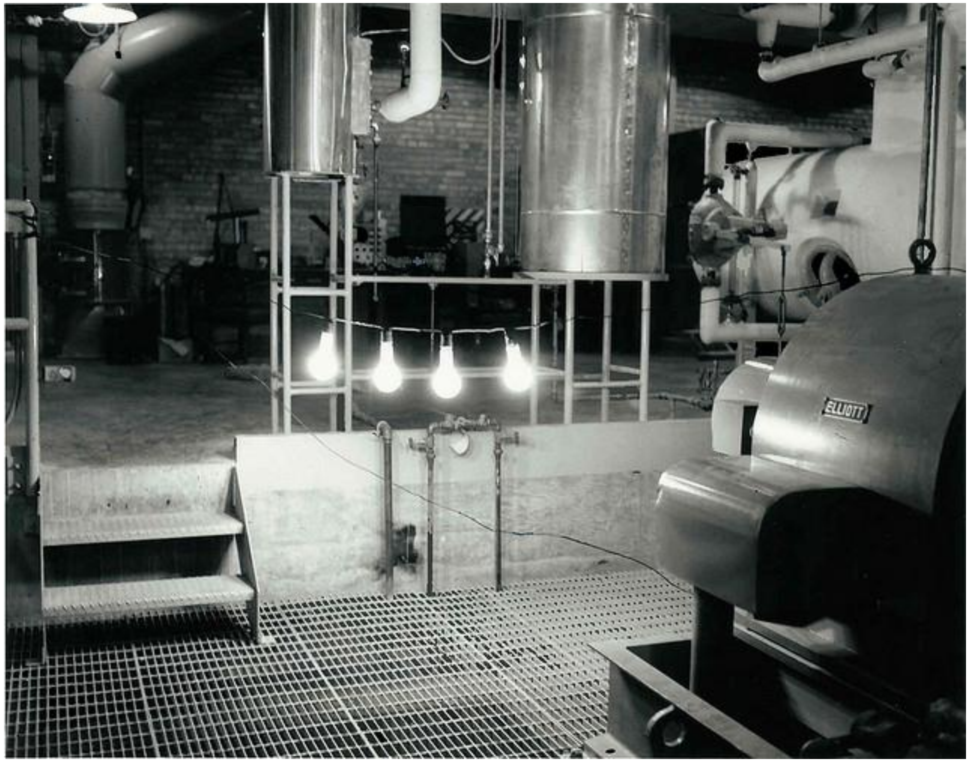


E. Fermi (1901-1954)



Sketch of Pile-1. Courtesy of ANL.

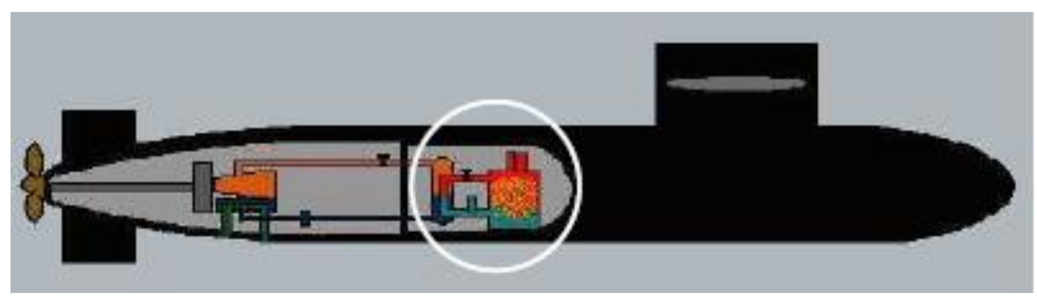
- In 1949 EBR-I – Experimental Breeder Reactor I – was designed at Argonne National Laboratory. In 1951 the world's first electricity was generated from nuclear fission in the fast-spectrum breeder reactor with plutonium fuel cooled by a liquid sodium.



First "nuclear" electricity : four 200-watt light bulbs. Courtesy of ANL.

- In 1954 under supervision of Admiral Hyman G. Rickover the first nuclear-powered submarine USS Nautilus was constructed.
- A limited space determined the reactor core design cooled by pressurized water.

Admiral H. Rickover (1900-1986)



USS Nautilus.

Fossil versus fissile

- Ratio of energy created to the masses of fuel consumed.
- Coal is the most widely used fossil fuel.
  Chemical reaction of combustion: $$C + O_2 \rightarrow CO_2 + 4\,\mathrm{eV}$$
- Uranium-235 is the most widely used fissile fuel.
  Nuclear reaction of fission: $$^{235}\mathrm{U} + \mathrm{n} \rightarrow 2\,\mathrm{FPs} + 200 \cdot 10^6\,\mathrm{eV}$$
- Large 1000 MWe power plant: ~ **10 000 tons** of coal (100-car train) **per day** or
  ~ **20 tons** of uranium fuel **per year**

100-coal car train.

What is 1 kWh?

- As nuclear energy:
  ~ 10 mg of natural uranium
  ~ 10 mg of $^2\mathrm{H}$+$^3\mathrm{H}$
- As chemical energy:
  ~ 0.1 kg of oil / coal / gas
  ~ a meal (860 kcal)
  ~ 25 kg lead-acid battery
- As mechanical energy:
  ~ 10t truck at 100 km/h
  ~ 10t x 40 m fall

Waste

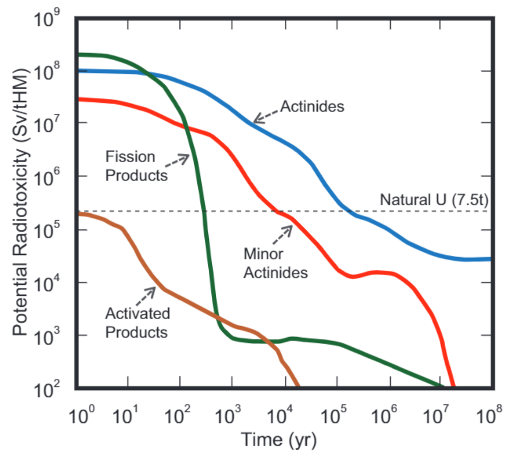
Very high ratio of nuclear energy created to the masses of fuel consumed

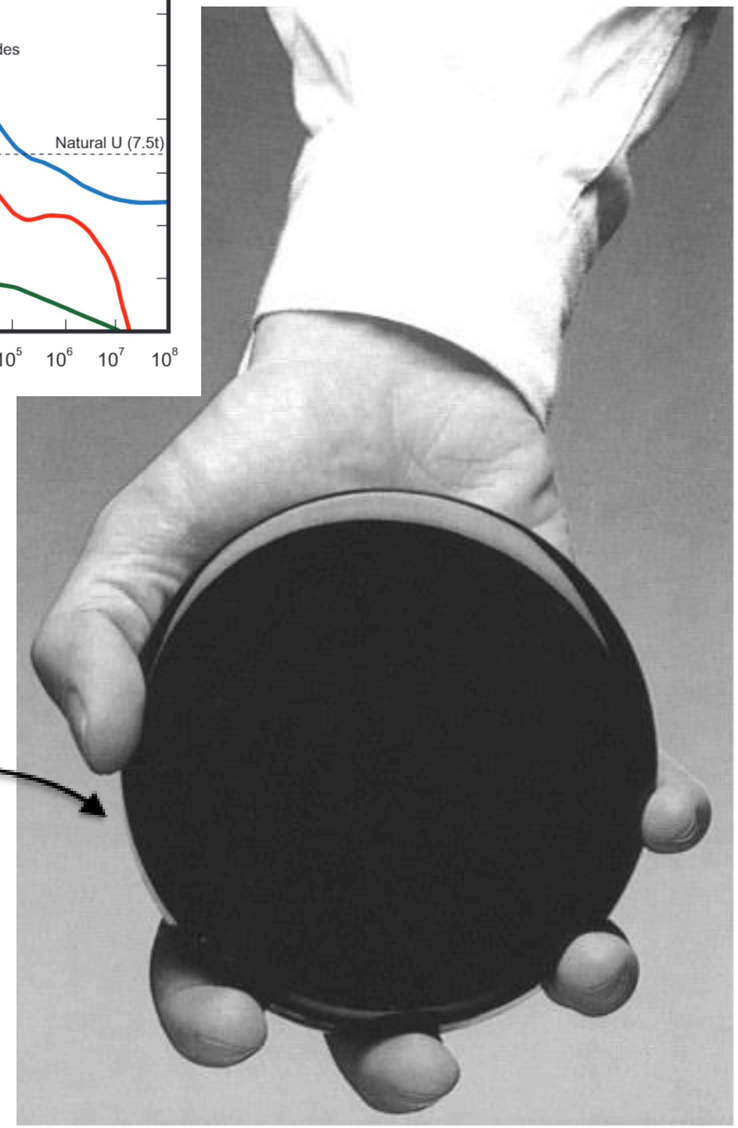
↓

Very limited mass of wastes

↓

Easier to control



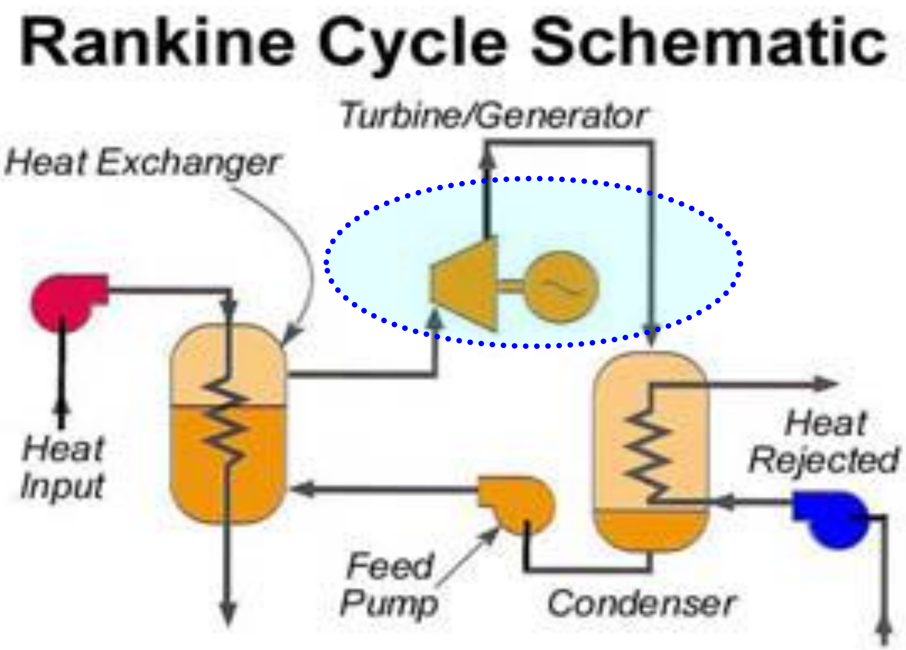


This glass disc simulates the amount of vitrified waste produced by one person in a lifetime if all his/her electricity was produced by nuclear energy.

All of the current operating large power plants operate on a steam cycle (Rankine cycle) in which the heat generated by combustion or nuclear fission is used to convert water into high pressure, high temperature steam

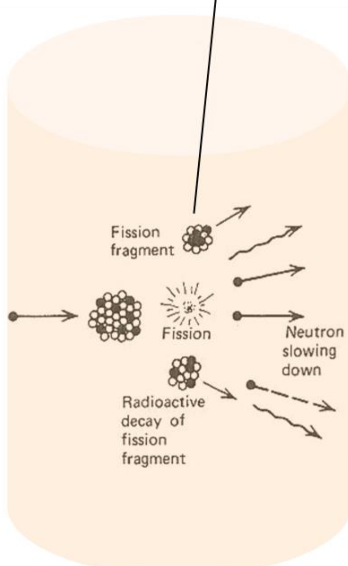
This steam is then allowed to expand against the blades of ***a turbine***

→ the latent energy of the steam is converted into mechanical work by turning the turbine shaft

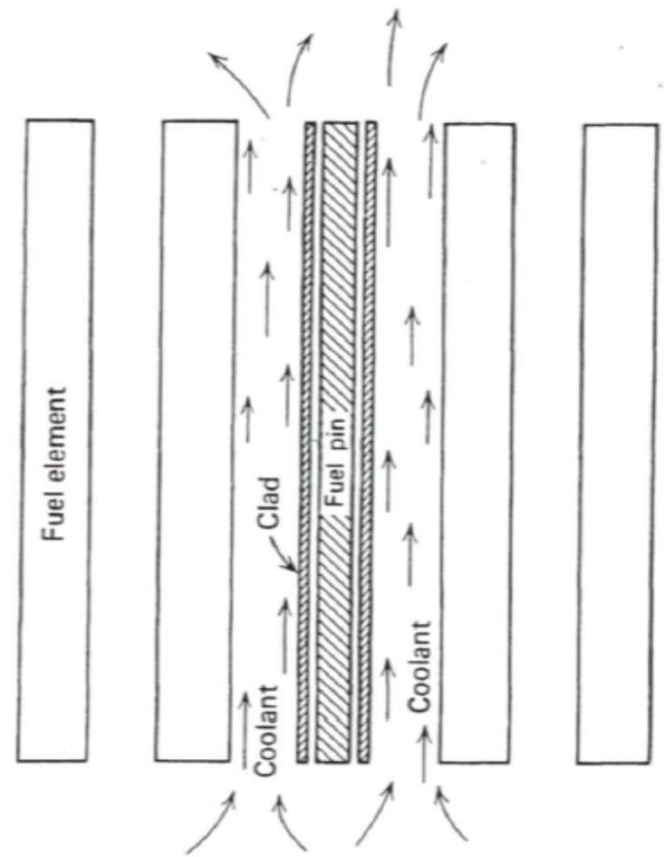


kinetic energy of the fission products is rapidly deposited as heat in the fuel material

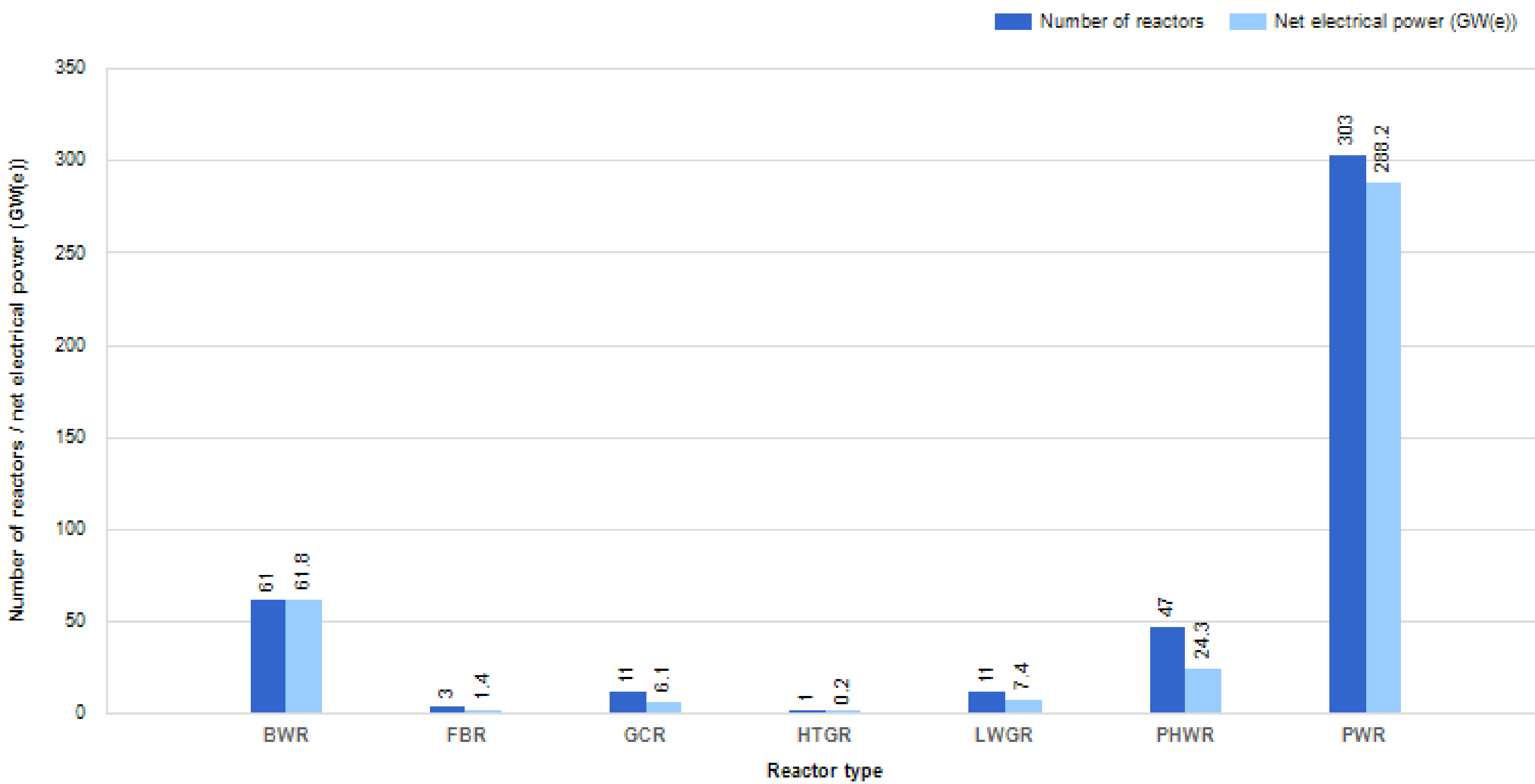
Steam Generator



Fuel pin

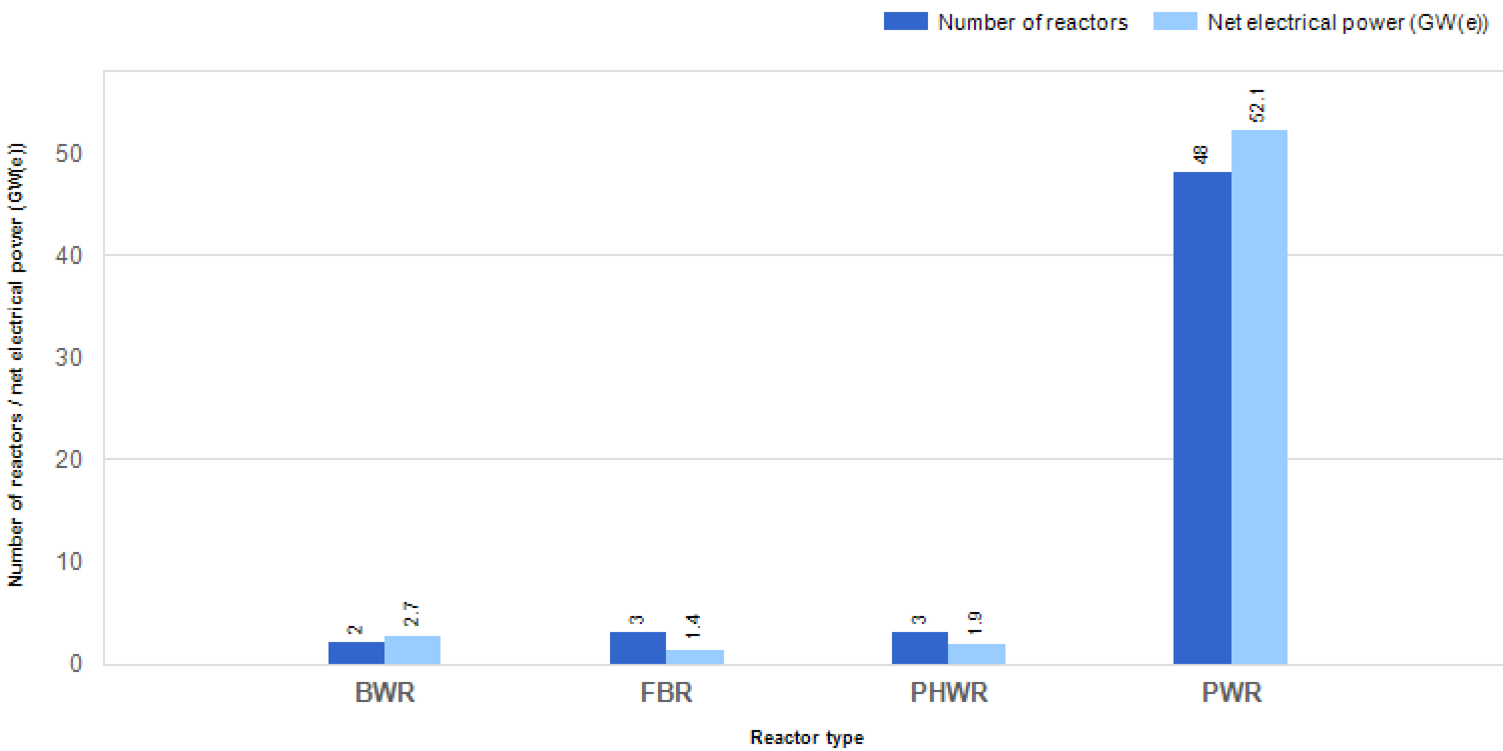


Number of operational reactors



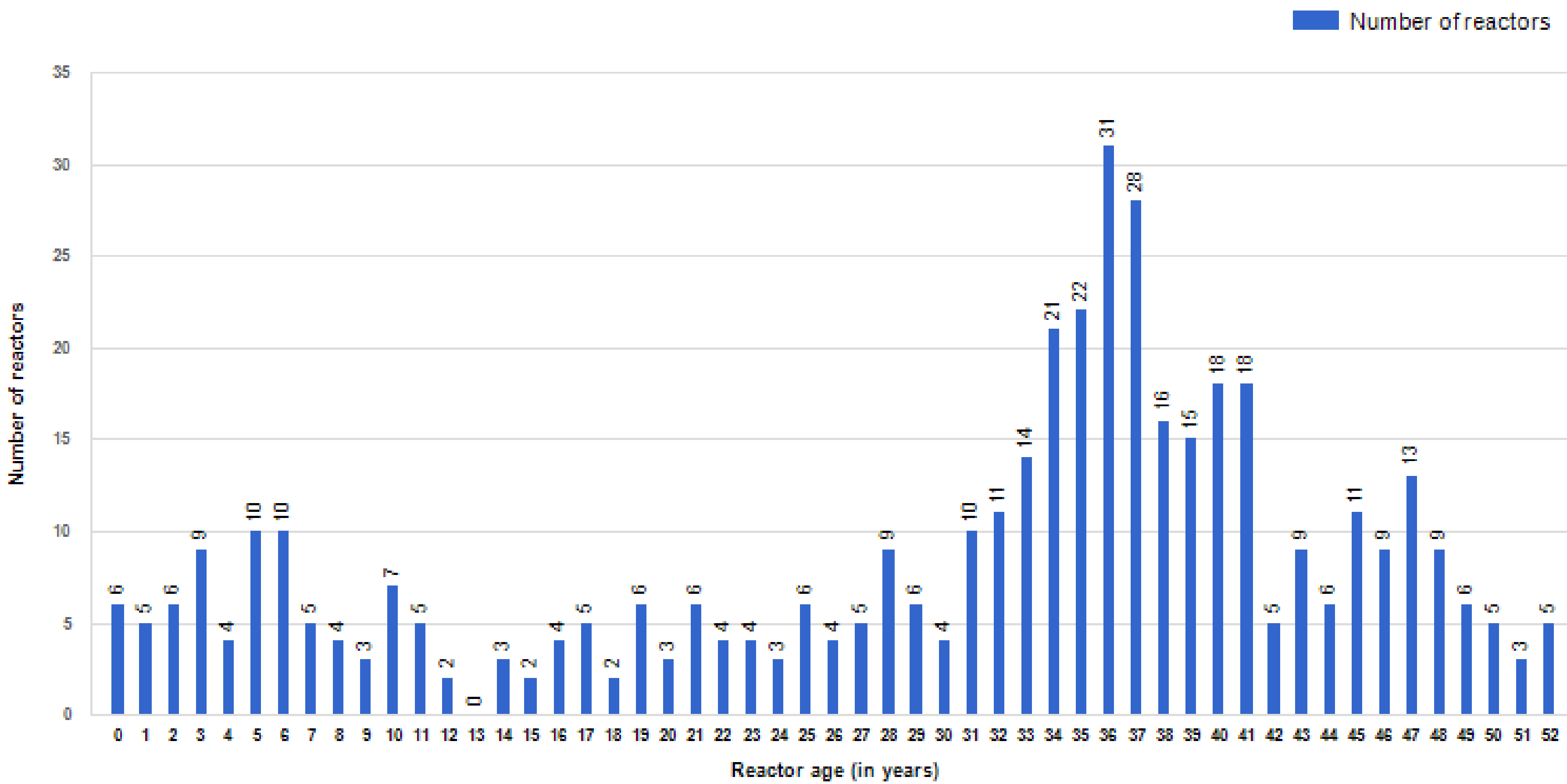
[*Nuclear Power Reactors in the World*, IAEA, 2021]

Reactors under construction



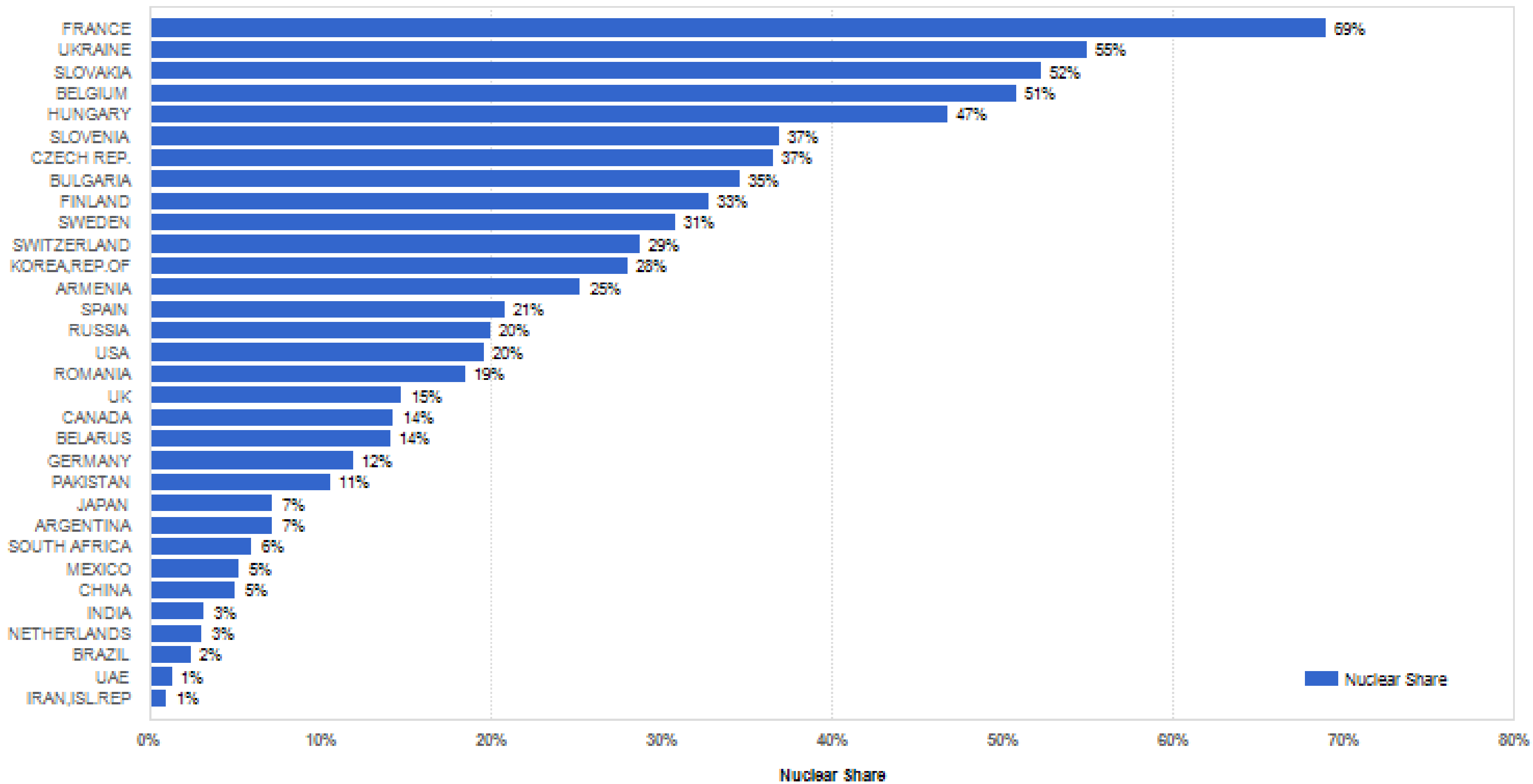
[*Nuclear Power Reactors in the World*, IAEA, 2021]

Operational Reactor by Age



[*Nuclear Power Reactors in the World*, IAEA, 2021]

Nuclear Share of Electricity

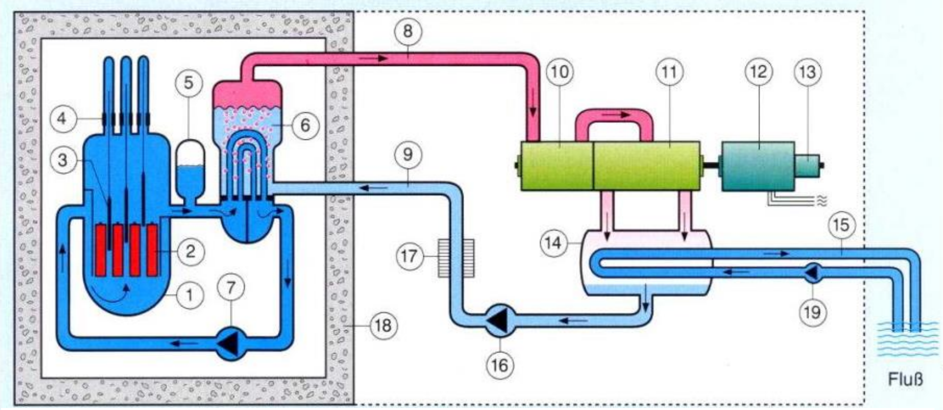


[*Nuclear Power Reactors in the World*, IAEA, 2021]

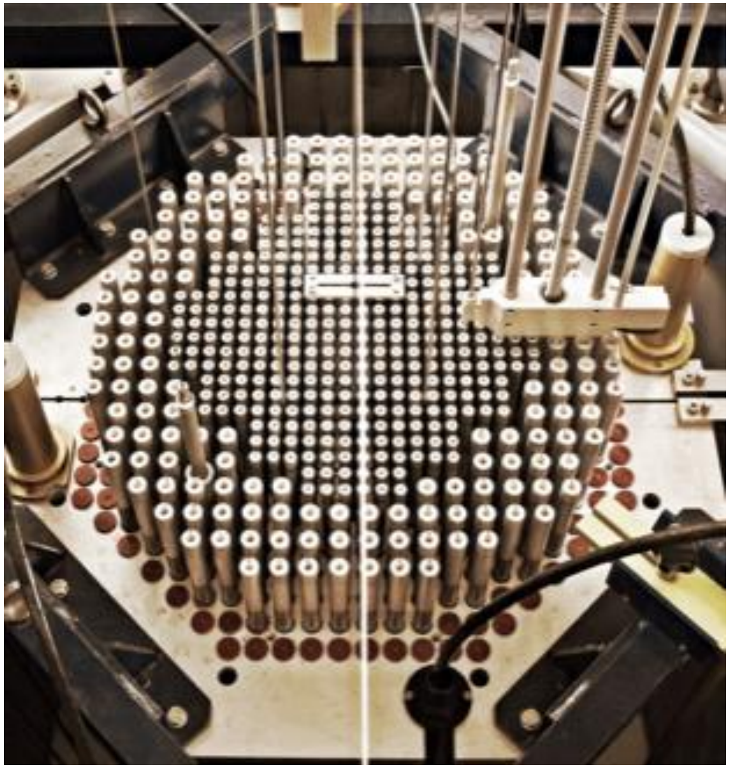
Swiss Reactors

NPP	Type	Shut down	50 yrs	60 yrs	Net Elect. Power
Beznau I	PWR		2019	2029	365 [MWe]
Beznau II	PWR		2021	2031	365 [MWe]
Mühleberg	BWR	2019	-	-	373 [MWe]
Gösgen	PWR		2029	2039	1010 [MWe]
Leibstadt	BWR		2034	2044	1220 [MWe]

- A nuclear reactor core is, on one hand, **a device with complex geometry** and very special material composition and, on the other hand, **a "cloud" of neutrons** being released in nuclear fission, moving around, slowing down, and finally being absorbed inside or outside the core.
- If the neutron is absorbed in a very heavy nucleus (e.g. in uranium), there is a probability that this nucleus is divided in two fragments with emission of several "new-born" neutrons and release of the energy in the form of heat.
- The **nuclear reactor core** as well as the **associated cooling circuit(s)** are the object we are going to study in this course.



PWR Primary and secondary circuits



CROCUS teaching reactor. Courtesy of EPFL.

- The main goal of our course is to understand what the **conditions** (from viewpoint of reactor core material composition and geometry) should be met to have **a self-sustainable fission chain reaction** and therefore stable power generation.

- To find these conditions we will have to answer the following questions:

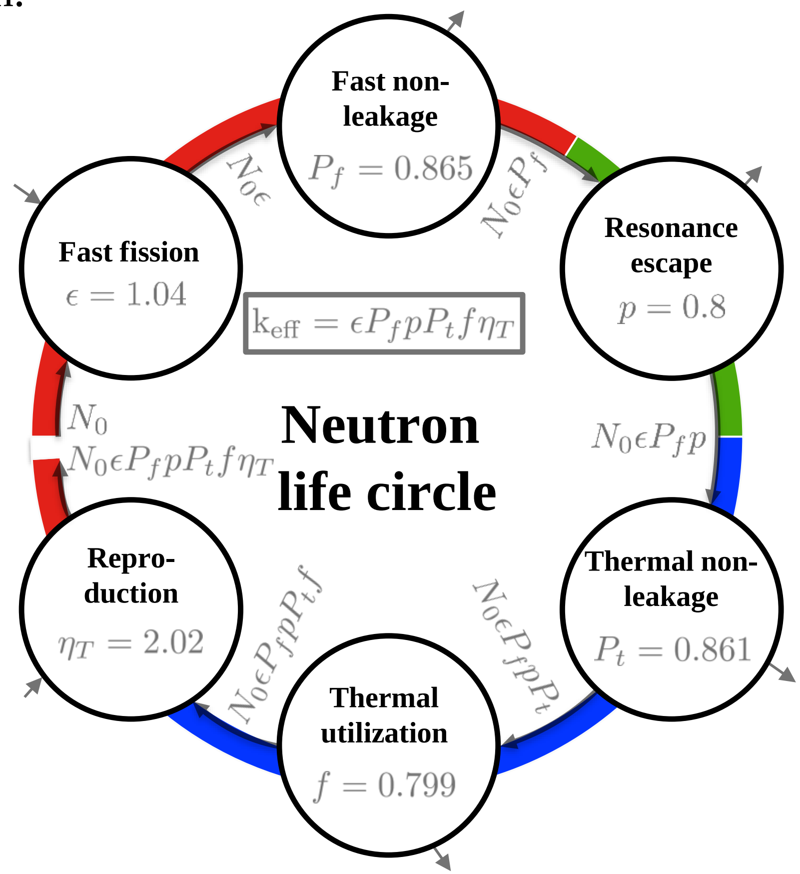
How neutrons interact with the core materials ?

How does a new-born very high-energy neutron changes its energy during its life ?

How neutrons propagate and what is their distribution in space ?

How is the neutron population evolving in time, when there is a deviation from the equilibrium chain reaction conditions ?

How to achieve those conditions practically ?



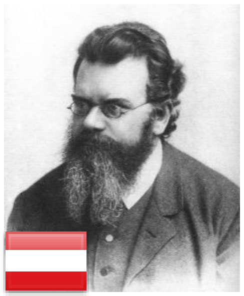
Gas molecules	Neutrons
Move in the container with different velocities	Move in the core with *very* different velocities
Interact *with each other* by exchanging momentum and energy (scattering)	Interact *with nuclei* by exchanging momentum and energy (scattering)
Can diffuse through the container boundary	Can leak from the core
No internal sources and sinks	Can be captured by nuclei (absorption), can be released by nuclei (fission)
Can be described by the Boltzmann equation	Can be described by the Boltzmann equation

[Gas.java (C) 2001 by Paul Falstad, www.falstad.com]

Distribution of neutrons
in **energy**, **time** and **space**

depending on
the core nuclear properties

and described by
Neutron-balance evolution
(Boltzmann) equation



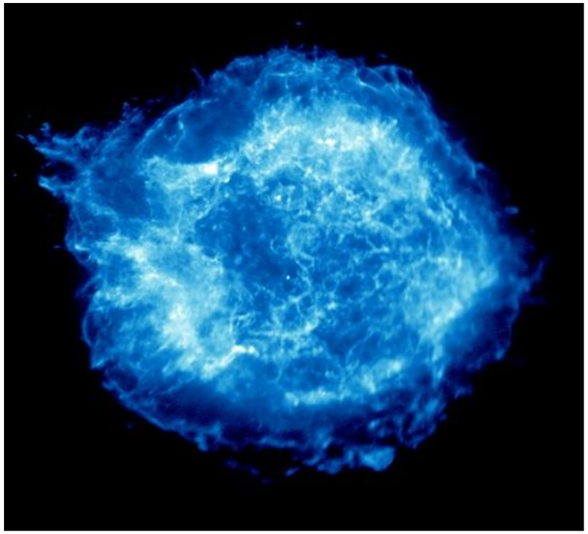
Ludwig Boltzmann
(1844-1906)

Distribution of core nuclear properties
in **time** and **space**

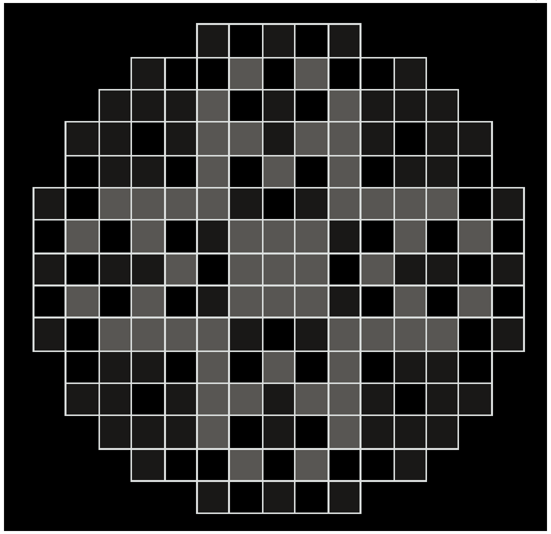
depending on
the neutron distribution

and described by
Material composition evolution
(Bateman) equation

Harry Bateman
(1882-1946)



Caseopeia A, a neutron star;
Courtesy of NASA.



Lewis. Fig.4.3. p. 88.

Boltzmann equation

- If we want to count at a particular point in **space** at a particular **time** moment...
  ... the number of neutrons per cm^3 flying with a particular velocity in a particular direction,
  we need to solve the Boltzmann equation:

$$\frac{1}{v}\frac{\partial\Phi(\vec{r},v,\vec{\Omega},t)}{\partial t} = Q(\vec{r},v,\vec{\Omega},t) - \vec{\Omega}.\vec{\nabla}\Phi(\vec{r},v,\vec{\Omega},t) - \sum_i R_i(\vec{r},v,\vec{\Omega},t)$$

Rate of change of this number =

+ Rate of generation of the “required” neutrons due to
  - arrival of such neutrons from other places;
  - interactions of neutrons with nuclei e.g. fission, scattering;
  - emission of such neutrons in radioactive decay of nuclei;

– Rate of disappearance of the “required” neutrons due to
  - departure of such neutrons to other places;
  - interactions of neutron with nuclei, e.g. absorption, scattering.

Bateman equation

- If we want to count at a particular point in **space** at a particular **time** moment...
  ... *the number of nuclei of a particular isotope per cm*^{3},
  we need to solve the Bateman equation:

$$\frac{\partial N_j(\vec{r},t)}{\partial t} = \sum_{i\neq j}\Big(\lambda_{i\to j}N_i(\vec{r},t) + R_{i\to j}(\vec{r},t)\Big) - \lambda_j N_j(\vec{r},t) - R_j(\vec{r},t)$$

Rate of change of this number =

+ Rate of generation of the “required” nucleus due to
  - interaction of other nuclei with neutrons;
  - radioactive decay of other nuclei;

– Rate of disappearance of the “required” nucleus due to
  - interaction of this isotope with neutrons;
  - radioactive decay of this isotope.

Bateman vs Boltzmann

In this course we

- Only briefly consider the Bateman equation, concentrating on a simplified form of the Boltzmann equation.
- do not distinguish neutrons by the *direction* of their flight, concentrating on distribution of their "smeared" density in space and their velocity (energy) spectrum.

The Bateman equation as well as more accurate solutions of the Boltzmann equation will be considered in the course "Physics of Nuclear Reactors II"

Room: PH-H3-31

Week	Date	Broad topic	Lecture title	Lecture
1	19-Sep	Basic principles of NPP / LWR	L00: Introduction /L01: Review of nuclear physics	A. Pautz
	20-Sep		L02: Interaction of neutrons with matter	M. Hursin
2	26-Sep		L03: Nuclear fission	M. Hursin
	27-Sep		L04: Fundamentals of nuclear reactors	M. Hursin
3	03-Oct		L5: LWR plants	M. Hursin
	04-Oct			M. Hursin
4	10-Oct	Modeling the beast	L06: The diffusion of neutrons - Part 1	M. Hursin
	11-Oct		L07: The diffusion of neutrons - Part 2	M. Hursin
5	17-Oct		Applied problem (1)	M. Hursin
	18-Oct		L08: Neutron moderation without absorption	A. Pautz
6	24-Oct		L09: Neutron moderation with absorption	M. Hursin
	25-Oct		L10: Multigroup theory	A. Pautz
7	31-Oct		L11: Element of lattice physics	A. Pautz
	01-Nov		Applied problem (2)	M. Hursin
8	07-Nov		L12: Neutron kinetics	A. Pautz
	08-Nov			M. Hursin
9	14-Nov		Applied problem (3)	M. Hursin
	15-Nov		L13: Depletion	M. Hursin
10	21-Nov		Applied problem (4)	M. Hursin
	22-Nov	Reactor Concepts Zoo / Practical exercises	L14: Advanced LWR technology	A. Pautz
11	28-Nov		L15: Breeding and LFR	M. Hursin
	29-Nov		Applied problem (5)	M. Hursin
12	05-Dec		L15: Breeding and LFR	A. Pautz
	06-Dec		L16: AGR, HTGR	A. Pautz
13	12-Dec		Applied problem (6)	M. Hursin
	13-Dec		L17: Channels, MSR and thorium fuel	A. Pautz
14	19-Dec			A. Pautz
	20-Dec		**Review session**	A. Pautz

Evaluation based on a project and an oral exam: final grade is the average

Project:

- Numerical solutions of common reactor physics problems (see next slide)

Exam:

- Exams Date: sometimes in January 2023
- Oral – 20 min (+5min to setup) without preparation. Closed book.
- Consists in a course related question and a short exercise

Example:

1. General Question

Diffusion theory for monoenergetic neutrons

(Present the topic, clearly bringing out the principal physical phenomena involved.)

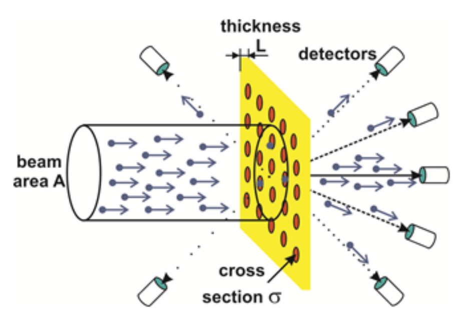
2. Exercise

A beam of 1 MeV neutrons, with an intensity I strikes a gold foil (≈100 % ^{197}Ag, density ρ_{Au}). The thickness of the target is L. The beam has a cross-sectional area A. For 1 MeV neutrons, the total cross-section of ^{197}Ag is σ_t.

(a) What is the interaction rate of the neutrons with the target?

(b) What is the probability that a neutron will suffer a collision while traversing the target?

Assume that the decrease of beam intensity in traversing the target is negligible.



- 6 distinct exercises need to be carried out by each student to produce a portfolio of scripts (and associated write-up < 5 pages each) solving standard reactor physics problems
  1. Attenuation of neutrons from a 1D planar source
  2. 1D/1G reactor slab
  3. 1D/2G reactor slab
  4. 1D/2G reactor slab with a loading pattern
  5. Fuel Evolution with exposure in a homogeneous media
  6. Reactor evolution during a cycle (space and time)

Week	Date
5	17-Oct
7	01-Nov
9	14-Nov
10	21-Nov
11	29-Nov
13	12-Dec

- Each week, the scripts (w/o write-up) are submitted through Moodle and will be checked by the course instructors

- The final portfolio of final scripts and associated write-ups should be delivered by the exam date (tbd)
  - ➢ 50% of the final grade
  - ➢ Evaluation (equal weight) based on
    - ✓ The instructor can run the scripts independently
    - ✓ The script produces accurate results
    - ✓ The quality of the write-up (description of the script - input/algorithm/output - answers to questions)

- Format of the practical session
  - Bring a laptop where coding in MATLAB/Python is possible
  - Brief intro with a succinct presentation of the exercise and expected outcomes ~ 20/30min
  - The remaining time is dedicated to Q&A with respect to practical issues with the problem at hand (as well as the ones of previous weeks)
  - No exercise session / teacher stays in the room until 16h

- Each session dedicated to a problem; the script of previous week exercise (in whatever state) is due the following week to monitor advancement. Milestones are provided each week to check that the scripts are working properly.

- Collaboration between students is highly encouraged but we expect an original script per student, e.g. no copy paste. Questions about the coding exercises will be asked during the oral exam.

Legal information regarding the use of clickers

Goal = to encourage active participation
(not to assess individuals)

You may choose between using the website,
the smartphone app or ~~a hardware clicker~~

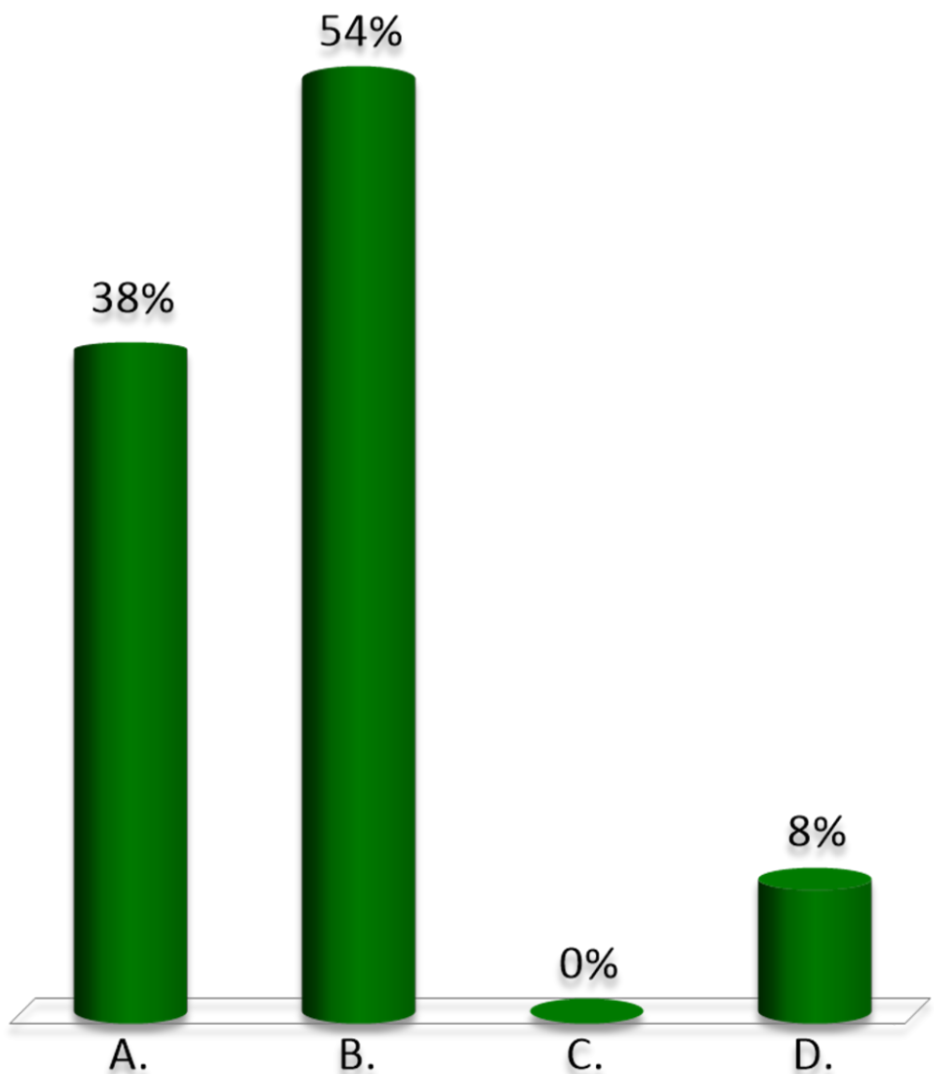
Data protection:

- Data is processed outside Switzerland, which may include the USA or EU countries
- Contract with EPFL = *Turning Technologies will not reuse the data collected for any other purpose*
- Condition = **you must use the website or smartphone app in guest mode** (without entering any personal information)

Website: https://participant.turningtechnologies.eu/en/join

How useful are clickers in a lecture according to my experience?

A. Useful, they keep me awake
B. Very useful, they allow me to check my understanding of the concepts discussed in class
C. Not very useful, a distraction at best
D. I don’t have experience with this



https://moodle.epfl.ch/course/view.php?id=8691