The role of neutrons in nuclear technology and neutron beam experiments (I)

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Introduction: It is all about energy

The average energy consumption of a (rich) human being is about 2500 kcal/day, which is equivalent to a power of ~120 W.

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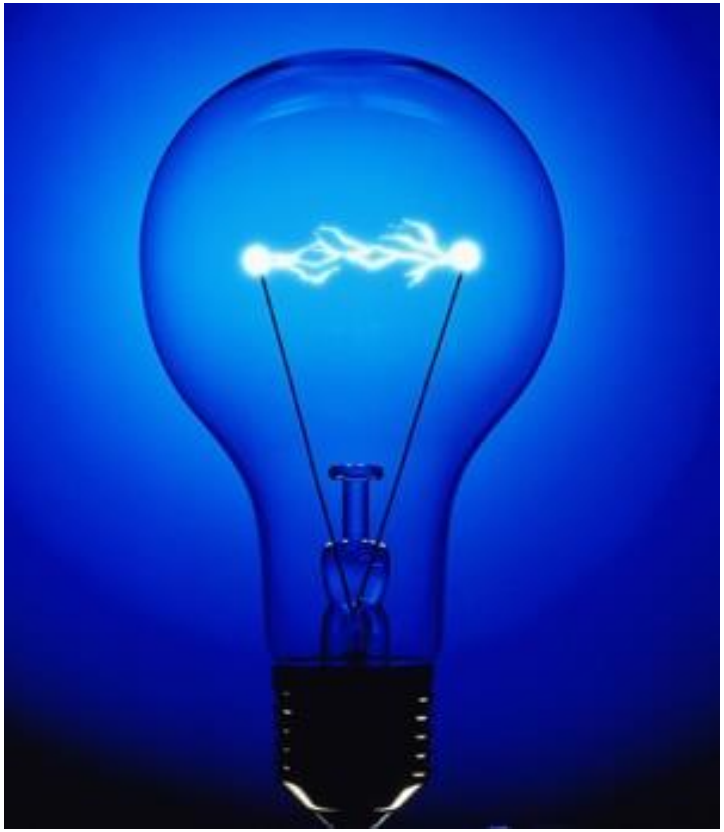
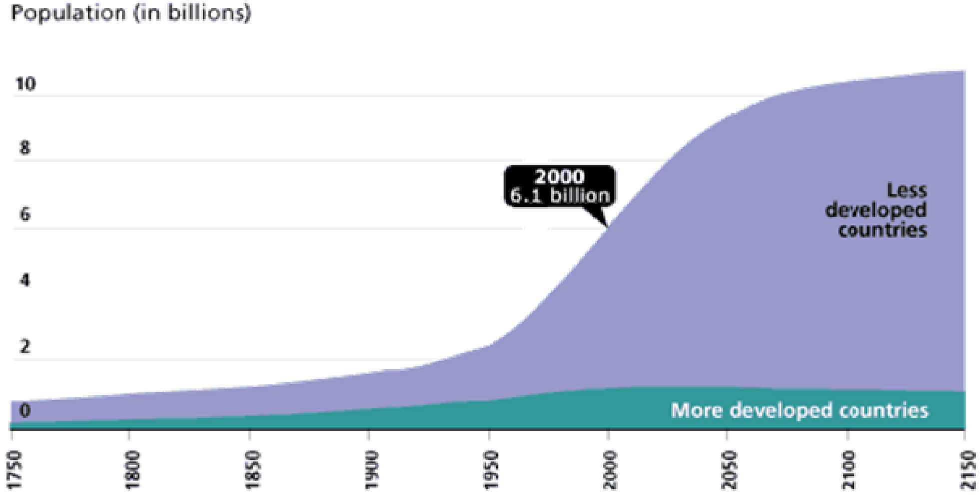
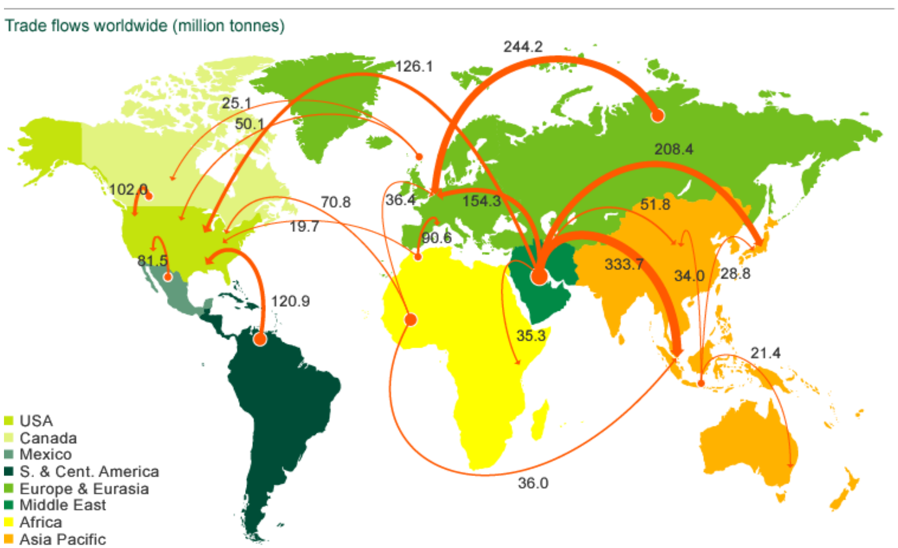




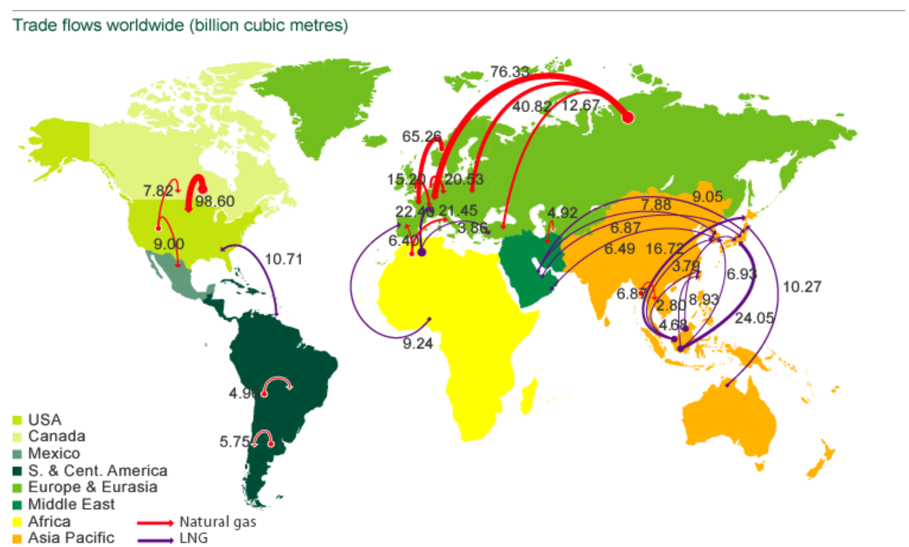
Energy, a necessary evil

Currently, around an 80% of the primary energy comes from a fossil source. This dependency in fossil fuels creates important problems:

- Greenhouse effect due to CO_2 and other gases
- Acid rain and similar phenomena
- Strong political tensions because of the dependencies between consumer and supplier countries
- Location of the production in a few countries and in unstable geopolitical zones
- Strong oscillations in energy cost

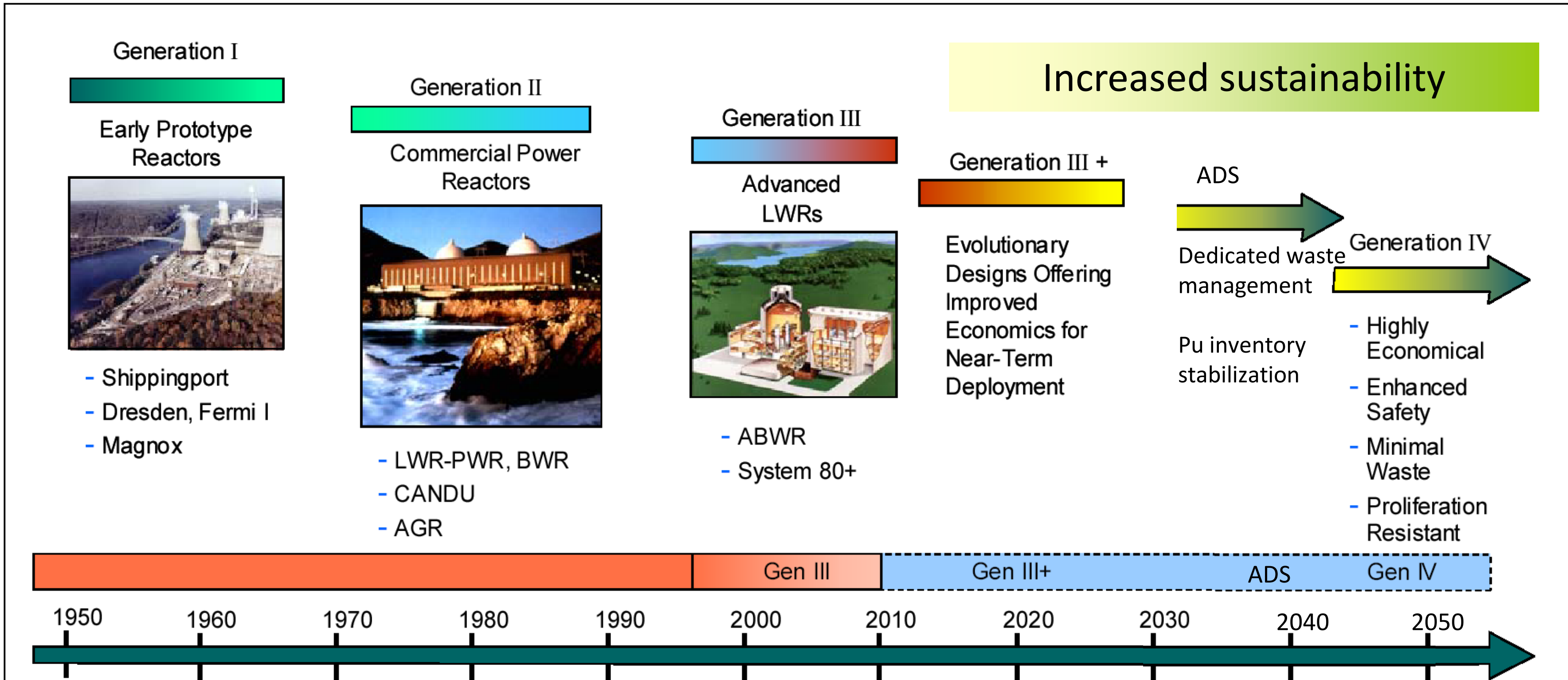


Fuel oil commercial fluxes



Gas commercial fluxes

Nuclear energy timeline

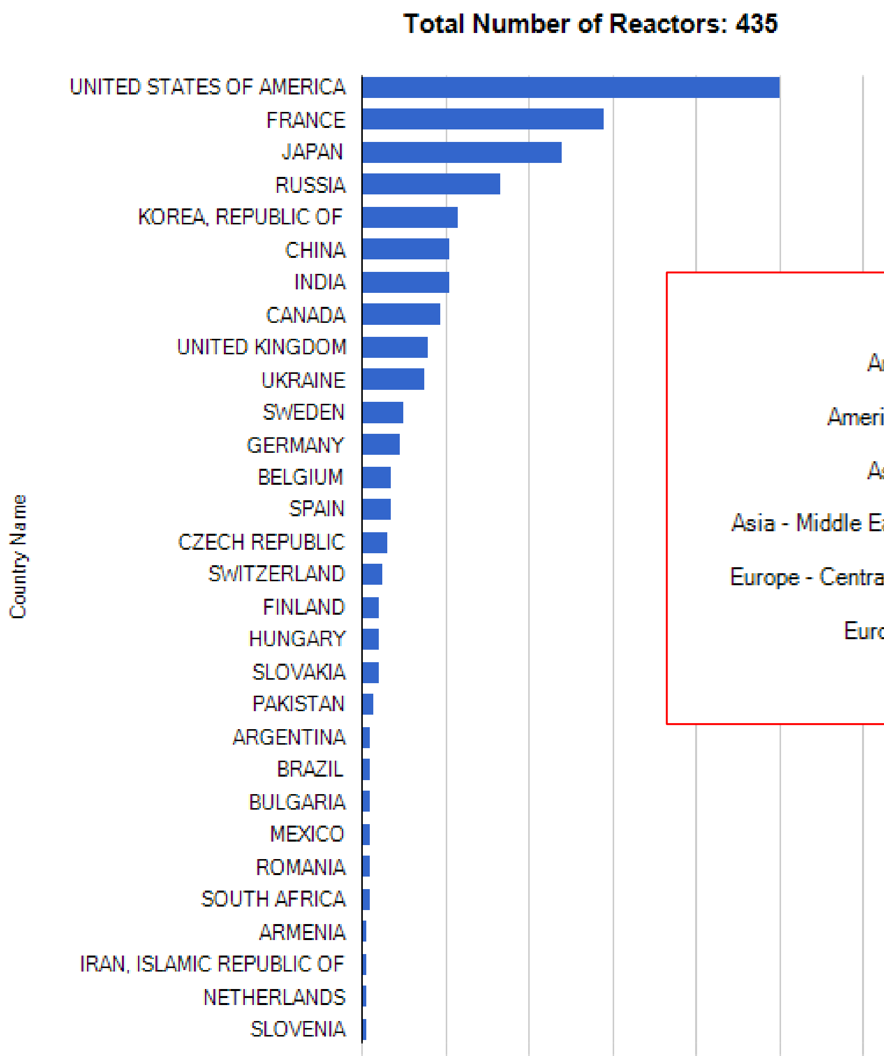


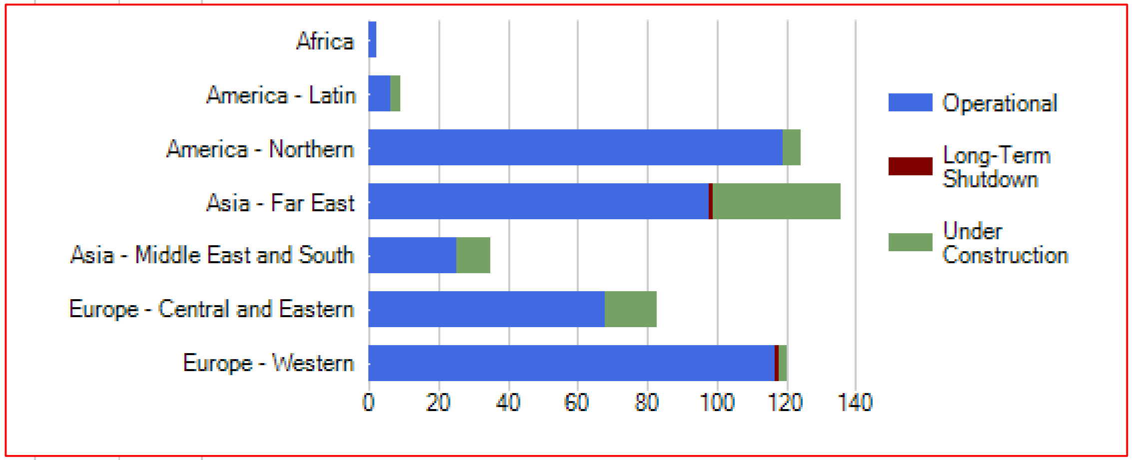
Improved:
- safety,
- efficiency
- economy

\+ reduction of the high level waste

\+ better use of the natural resources (U,Th)

Nuclear reactors in the world





Already in construction or planned:
~400 more reactors!

Data from:
http://www.iaea.org/PRIS/home.aspx
http://www-pub.iaea.org/books/IAEABooks/10593/Nuclear-Power-Reactors-in-the-World-2013-Edition

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- Other applications

Neutrons

The neutron was discovered by **James Chadwick** in 1932 in the reaction:

$$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$$

A free neutron has mass: 939.56 MeV. One mole of neutrons weights ~1 g.

Neutrons are electrically neutral (no charge)

Electric dipole moment = $q_n < 0.29 \times 10^{-25}$ ecm

Magnetic moment = -1.9130427 + 0.0000005 mN

Free neutrons decay with a half life of 885.7 +- 0.8 s.

In practice, most studies neglect decay and magnetic moment.

So, free neutrons move in a straight line between two collisions with the material nuclei without modifying its own energy.

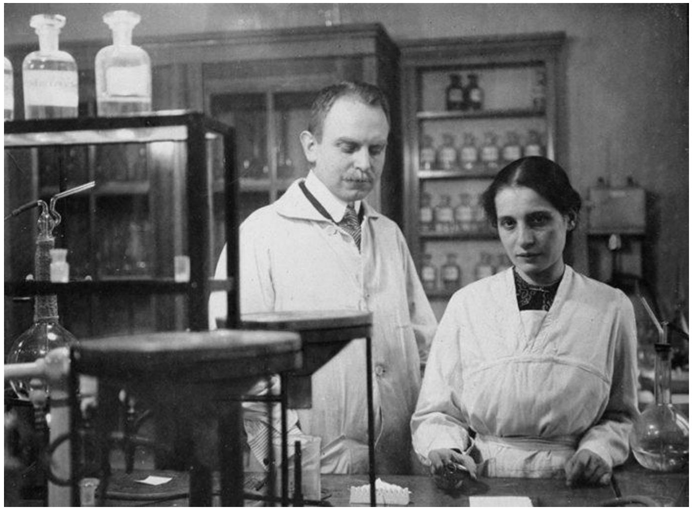
Excepting in special experiments, the neutron density is so low that the probability of neutron-neutron interaction is negligible.

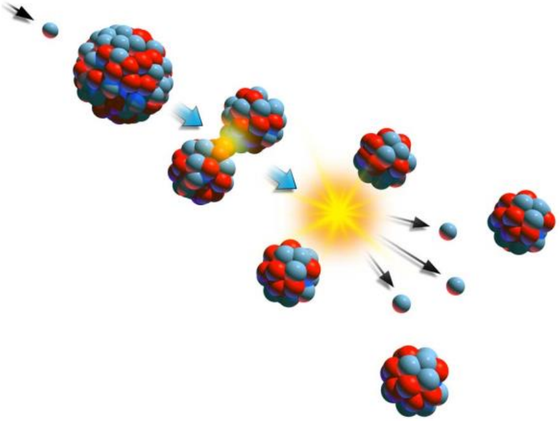
The discovery of nuclear fission

A brief nuclear fission was first experimentally achieved by **Enrico Fermi in 1934** when his team bombarded uranium with neutrons.

In 1938, German chemists **Otto Hahn** and Fritz Strassmann (along with Austrian physicists **Lise Meitner** and Meitner's nephew, Otto Robert Frisch) conducted experiments (interpreted correctly the results) with the products of neutron-bombarded uranium.

They determined that the relatively tiny neutron **split the nucleus of the massive uranium atoms into two roughly equal pieces**.



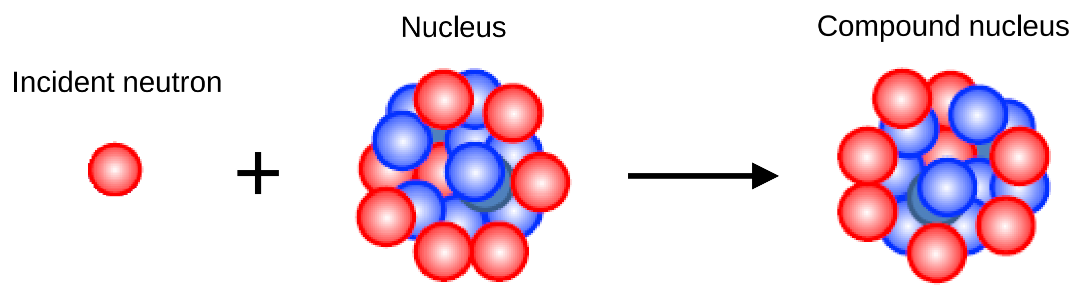


Otto Hahn and Lise Meitner in Berlin, 1909. Source: Churchill College, Cambridge

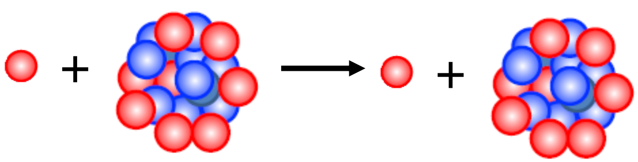
Different nuclear reactions

As already mentioned, neutron are usually found in the interior of a nucleus but sometimes they exist in a free state.

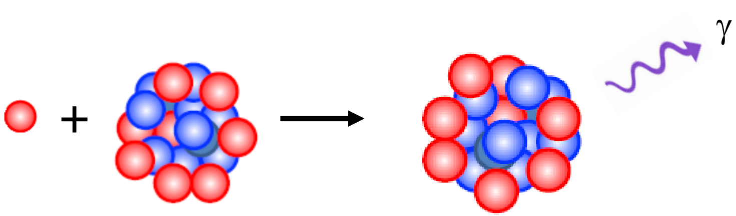
In these interactions or *collisions*, the nucleus most often absorbs the neutron and takes its binding energy, leading to an unstable excited state of the compound nucleus.



Each nuclear reaction is defined by the way in which the compound nucleus emits the excess energy provided by the neutron.

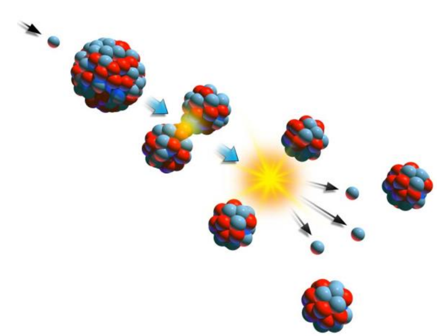


Elastic/inelastic



Radiative capture

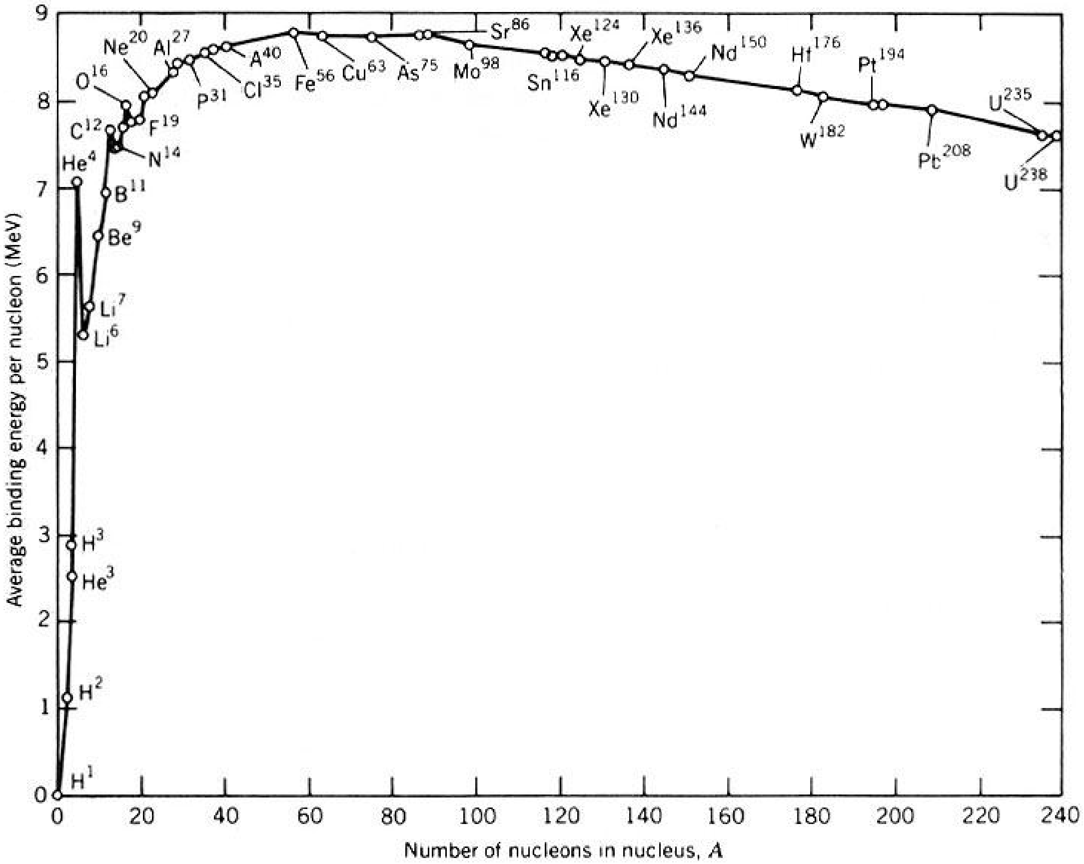
Fission



Different nuclear reactions

Interaction without formation of a compound nucleus		
Potential scattering (elastic)	$n + A \Rightarrow n + A$	Always possible
Interactions occurring via formation of a compound nucleus		
Elastic resonant scattering	$n + A \Rightarrow n + A$	Always possible
Inelastic resonant scattering	$n + A \Rightarrow n + A^*$ $A^* \Rightarrow A + \gamma$	Threshold: first level of A
Reaction (n,2n)	$n + A \Rightarrow n + n + (A - 1)$	Threshold: separation energy of a neutron from A
Radiative capture	$n + A \Rightarrow \gamma + (A + 1)$	Always possible
Reaction (neutron, charged particle)	$n + A \Rightarrow p + B$ $n + A \Rightarrow \alpha + C$ etc.	Usually with threshold; sometimes without threshold
Fission	$n + A \Rightarrow$ $PF_1 + PF_2$ + a few neutrons (On average, ν, from 2 to 3)	Heavy nuclei: without threshold for odd N, with threshold for even N; tunnel effect.

Binding energy



The stable nuclides have a mass defect:

$$\Delta = \left[Zm_p + (A-Z)m_n\right] - {}^{A}m_n$$

The Binding Energy is the energy necessary to disasemble the nucleus into its separate nucleons:

$$BE = \Delta c^2$$

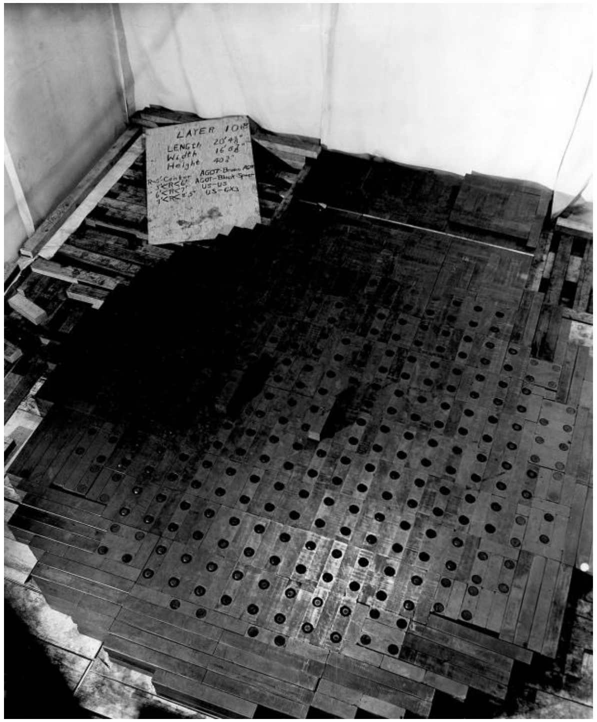
Any process that results in nuclides being converted to other nuclides with more binding energy per nucleon (BE/A) will result in the conversion of mass into energy.

The Manhattan Project

Leo Szilard recognized that if fission reactions released additional neutrons, a **self-sustaining nuclear chain reaction** could result.

In the United States, where **Enrico Fermi and Szilard** had both emigrated, this led to the creation of the first man-made reactor, known as **Chicago Pile-1**, which achieved criticality on December 2, **1942**.

This work became part of the **Manhattan Project**.



Chicago Pile-1

Fission energy balance

Emitted energy

• Fission fragments:	166.2
• Prompt photons:	8.0
• Neutrons:	4.8
• β radiation (electrons):	7.0
• Antineutrinos from β radiation:	9.6
• Photons from β radiation:	7.2
Total:	202.8 MeV

^{233}U:	190.0 ± 0.5 MeV/f
^{235}U:	192.9 ± 0.5 MeV/f
^{239}Pu:	198.5 ± 0.8 MeV/f
^{241}Pu:	200.3 ± 0.8 MeV/f

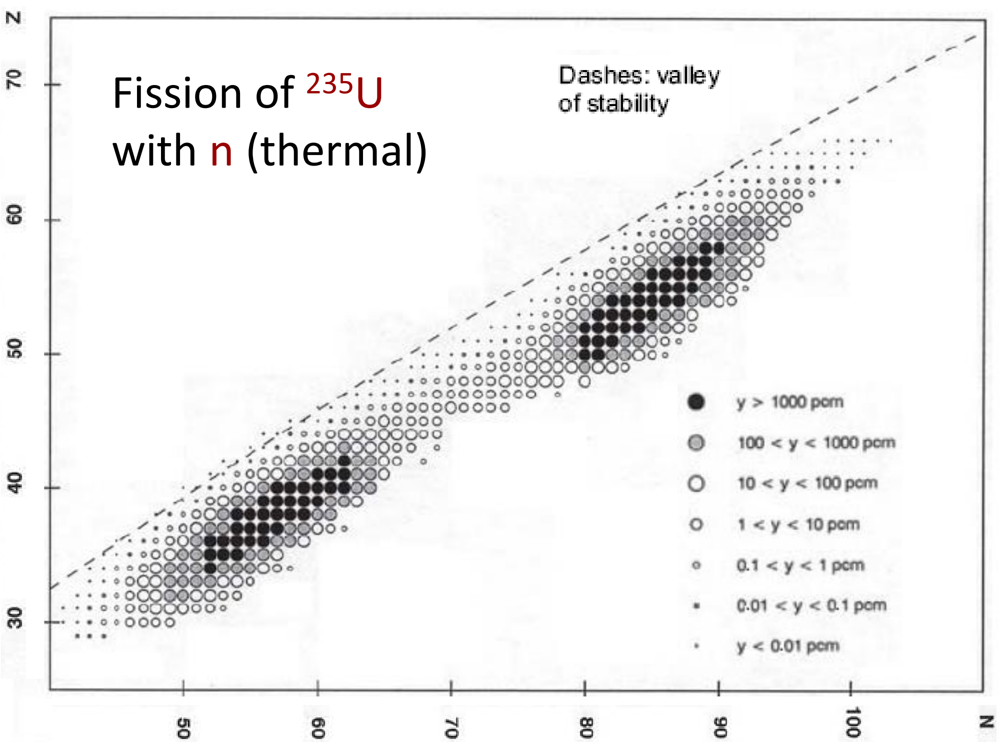
Recovered energy

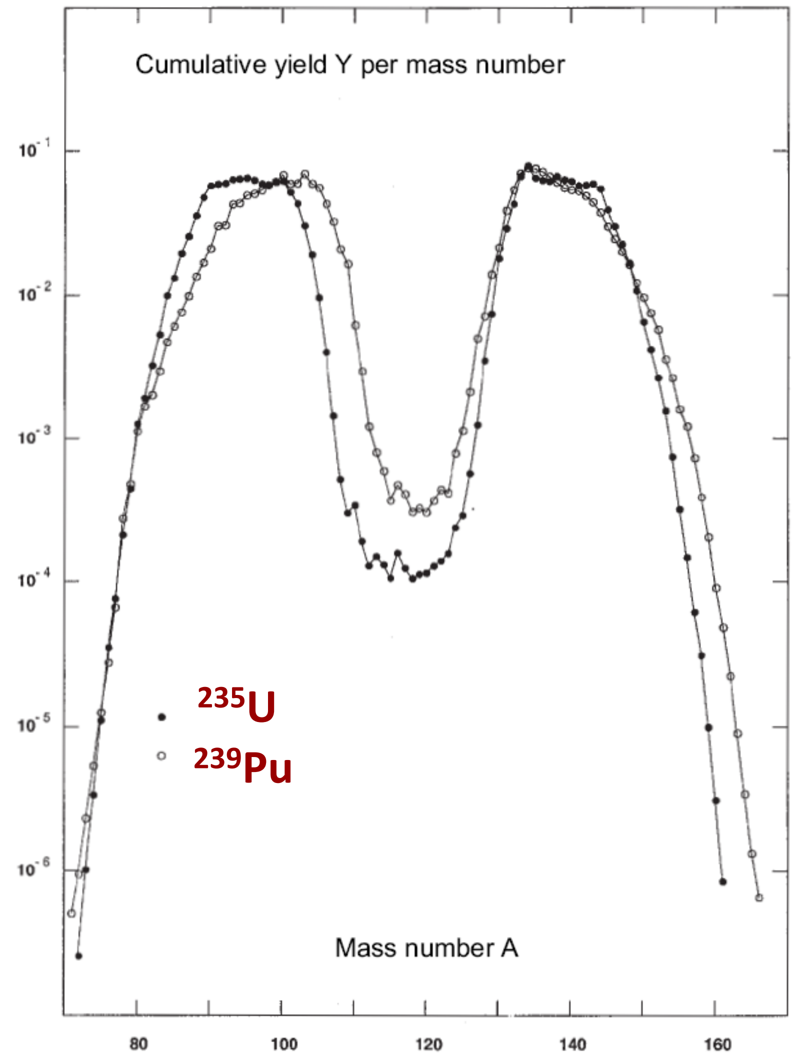
• Emitted energy:	202.8
• Antineutrinos from β radiation:	-9.6
• Photons from neutron capture:	+8.4
Total:	201.7 MeV

In short, about 200 MeV per fission can be recovered, to be compared with the energy of chemical combustion: a factor larger tan 1 million

Fission fragments

No symmetry!





Delayed neutrons

$$^{87}\mathrm{Br} \Rightarrow {}^{87}\mathrm{Kr}^* \Rightarrow {}^{86}\mathrm{Kr} + {}^{1}\mathrm{n}$$

(54.5 s)

$$^{137}\mathrm{I} \Rightarrow {}^{137}\mathrm{Xe} \Rightarrow {}^{136}\mathrm{Xe} + {}^{1}\mathrm{n}$$

(21.8 s)

Group	β (pcm)	*T* (s)	τ (s)
1	24	54.5	78.6
2	123	21.8	31.5
3	117	5.98	8.62
4	262	2.23	3.22
5	108	0.495	0.714
6	45	0.179	0.258
Average	679	7.84	11.31

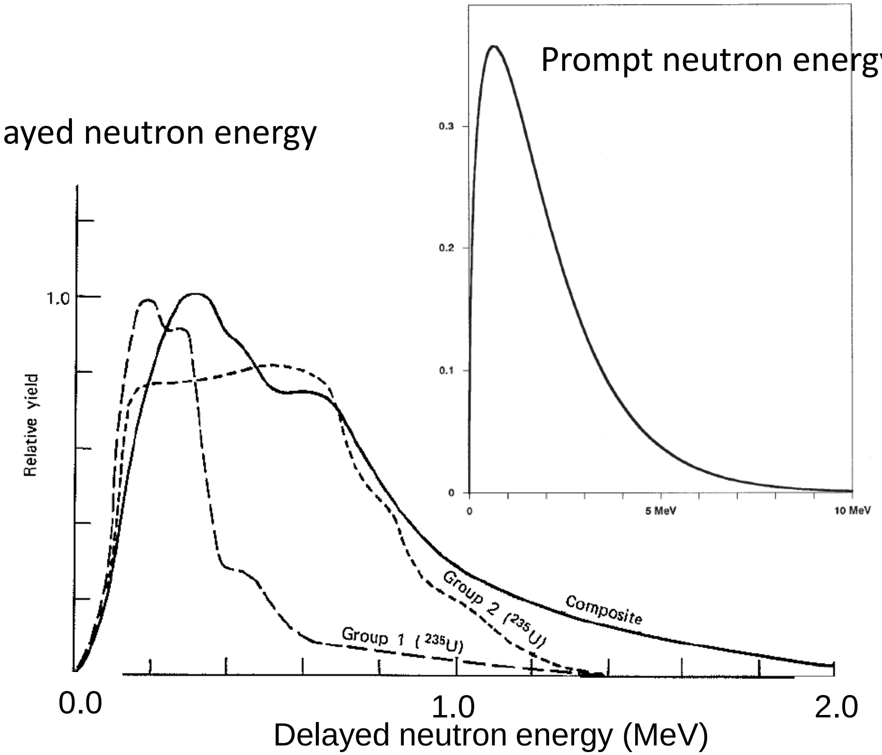
1 pcm = part per hundred thousand

^{232}Th	**F**	**2433**
^{233}U	**Th**	**296**
^{235}U	**Th**	**679**
^{238}U	**F**	**1828**
^{239}Pu	**Th**	**224**
^{240}Pu	**F**	**292**
^{241}Pu	**Th**	**535**

F=fast spectrum
Th=thermal spectrum

Fraction of delayed neutrons (β)

Delayed neutron energy



Delayed neutrons have a softer spectrum with average energies between 0.2 and 0.6 MeV

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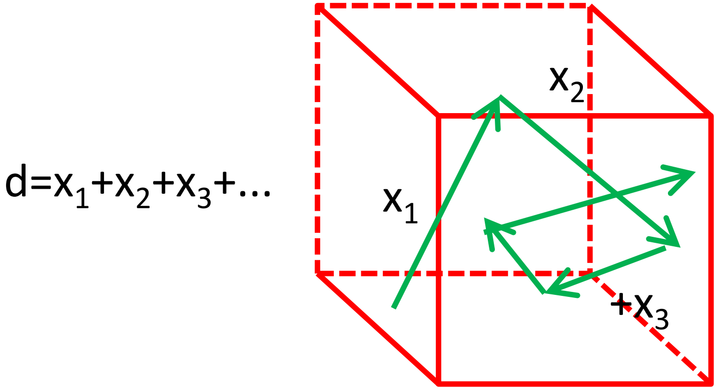
The concept of flux

$$\Phi(\vec{r},t) \equiv vN(\vec{r},t)d^3r \equiv \text{neutron flux } [\text{cm}^{-2} \cdot \text{s}^{-1}]$$

The definition of flux in reactor physics is misleading. Here **flux** is a **scalar quantity** where in other contexts (i.e. electromagnetism or heat theory) flux is a **vectorial quantity**. The concept of **neutron current** (to be defined) corresponds more closely to the conventional interpretation of **flux**.



$$\Phi \equiv \frac{d/t}{V} [\text{cm}^{-2} \cdot \text{s}^{-1}]$$

Neutron transport equation

The objective of neutron transport is the development of an equation which rigorously describes the behavior of the neutron collective in absorbing and fissioning materials.

The equation is a balance between the creation and loss rate of neutrons and it is called the Boltzmann equation.

$$\frac{d}{dt}\left[\frac{1}{v}\varphi(\vec{r},\vec{\Omega},E,t)\right] = Gains - Losses$$

$$\frac{d}{dt}\left[\frac{1}{v}\varphi(\vec{r},\vec{\Omega},E,t)\right] = S(\vec{r},\vec{\Omega},E,t) - \Sigma_T(\vec{r},E,t)\varphi(\vec{r},\vec{\Omega},E,t) +$$

$$\int_{4\pi}\int_0^\infty \Sigma_s(\vec{r},E',t')f(\vec{r},\vec{\Omega}'\to\vec{\Omega},E'\to E,t)\varphi(\vec{r},\vec{\Omega}',E',t)dE'd\vec{\Omega}' +$$

$$\int_{4\pi}\int_0^\infty s(E')\Sigma_f(\vec{r},E',t')\nu(\vec{\Omega},E',t)\varphi(\vec{r},\vec{\Omega}',E',t)dE'd\vec{\Omega}'$$

Reactor physics: criticality constant k_{eff}

Simplifying →

$$\frac{1}{v}\frac{\partial \phi}{\partial t} = D\nabla^2\phi(\vec{r},t) - \Sigma_a\phi(\vec{r},t) + \frac{\nu\Sigma_f}{k_{eff}}\phi(\vec{r},t)$$

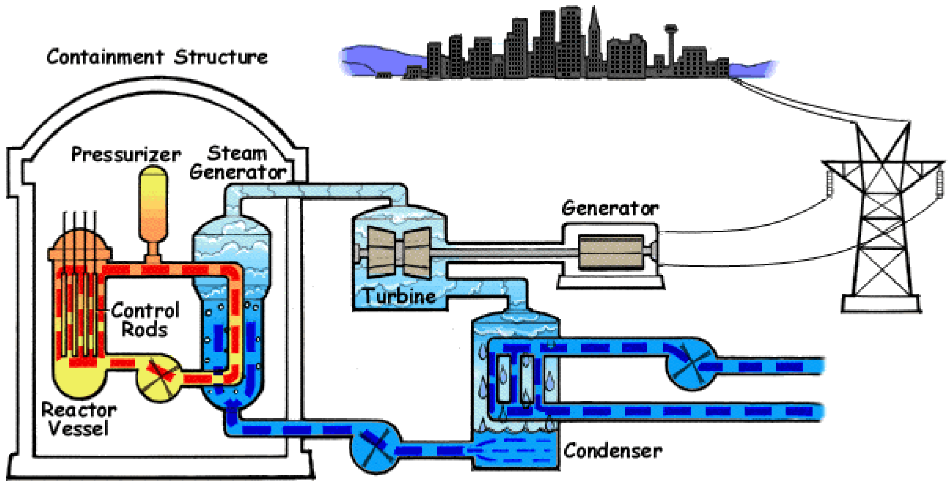
k_{eff} is introduced in the equations to study how far the nuclear system is from critical (ability to sustain the chain reaction). It is defined as the amount of neutrons in one generation over the amount of neutrons in the previous generation.

Concept of reactivity:

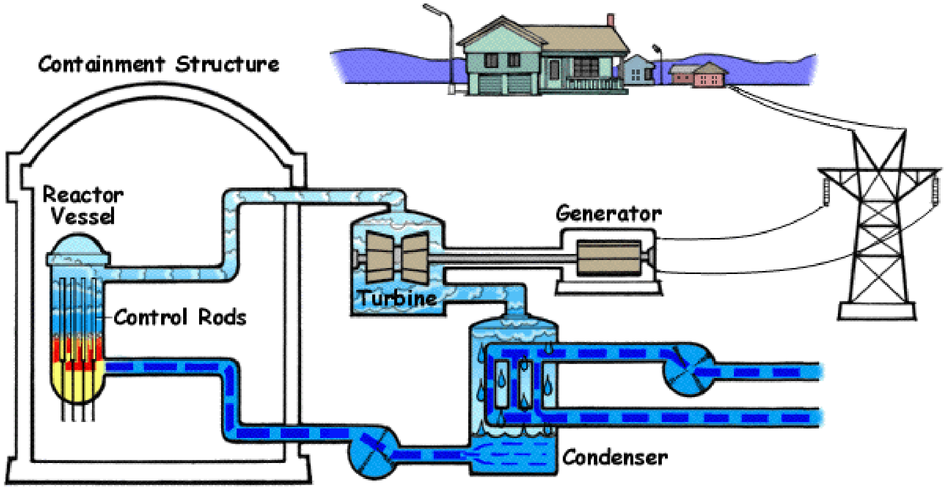
$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

- **Supercritical: $k_{eff} > 1$; $\rho > 0$**
- **Critical: $k_{eff} = 1$; $\rho = 0$**
- **Subcritical: $k_{eff} < 1$; $\rho < 0$**

Nuclear reactor



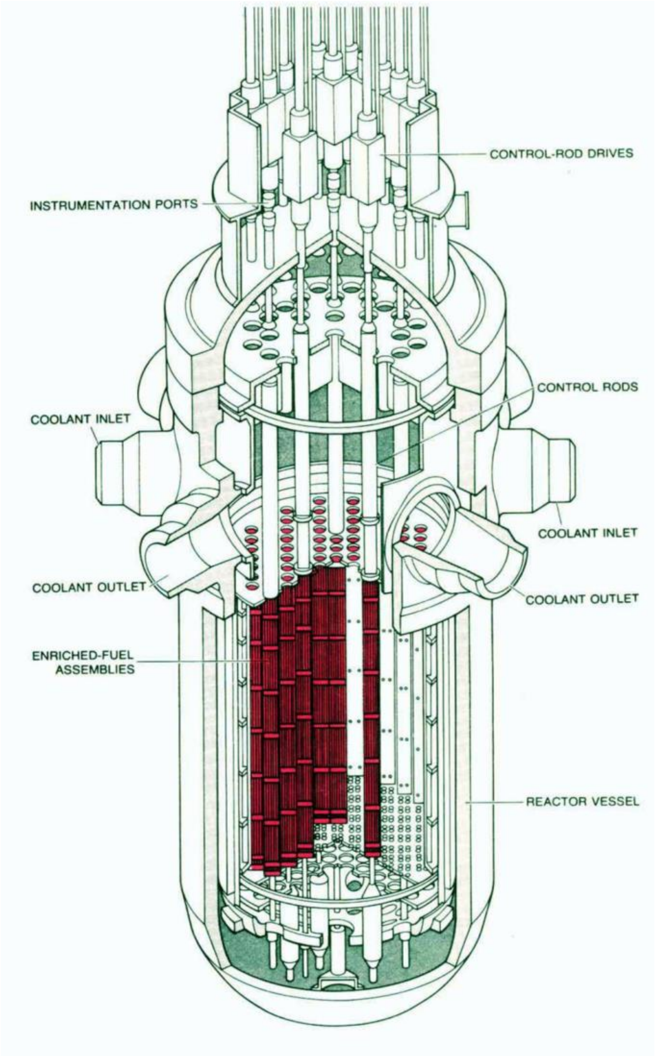
Pressurized water reactor



Boiling water reactor

Nuclear reactor

- The nuclear power plant generates energy in the same way as other power plants.
- The idea is to heat water to create steam.
- The steam moves a turbine and electricity is then generated.
- The nuclear power plant heats water by means of nuclear fission reactions.
- A chain reaction is maintained in a controlled manner.
- The reactor core is formed by fuel elements assembled in fuel assemblies containing a number of fuel rods.



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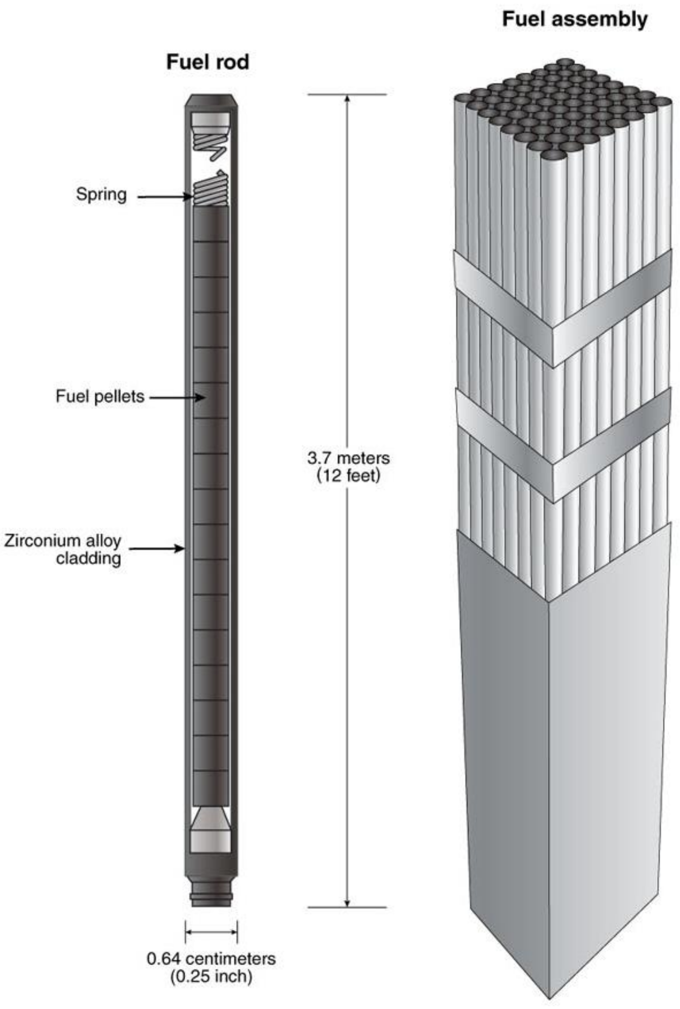
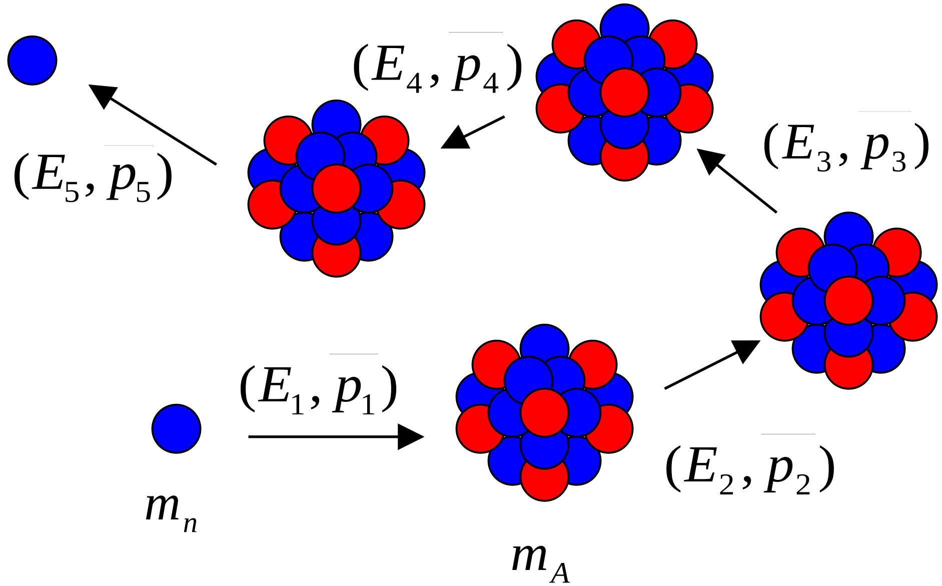


The moderation process

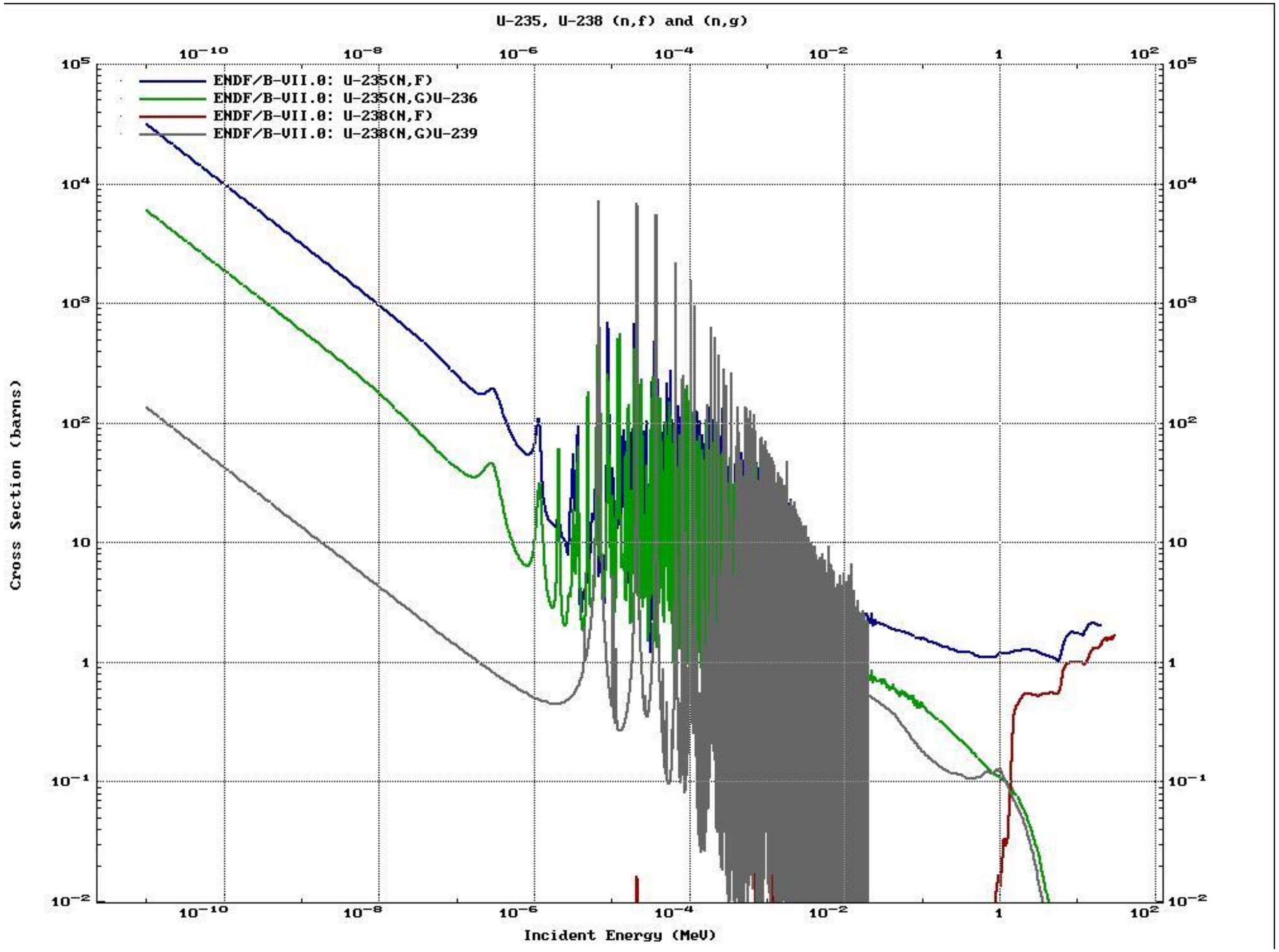
Neutron do lose energy in a logarithmic way:



$$\frac{E_2}{E_1} = \frac{m_n^2 + m_A^2}{(m_n + m_A)^2} + \frac{2 m_n m_A \cos\theta}{(m_n + m_A)^2} \approx \frac{A^2 + 1 + 2A\cos\theta}{(A+1)^2}$$

The thermalization process

In order to sustain the chain reaction, one of the neutrons out of the 2-3 produced in the previous fission process needs to survive to the resonant absorption.



Neutron energy dependence during lifetime

MeV neutrons from previous fission

Scattering with light nuclei

Resonance absorption

Thermal absorption
or leakage

Fission

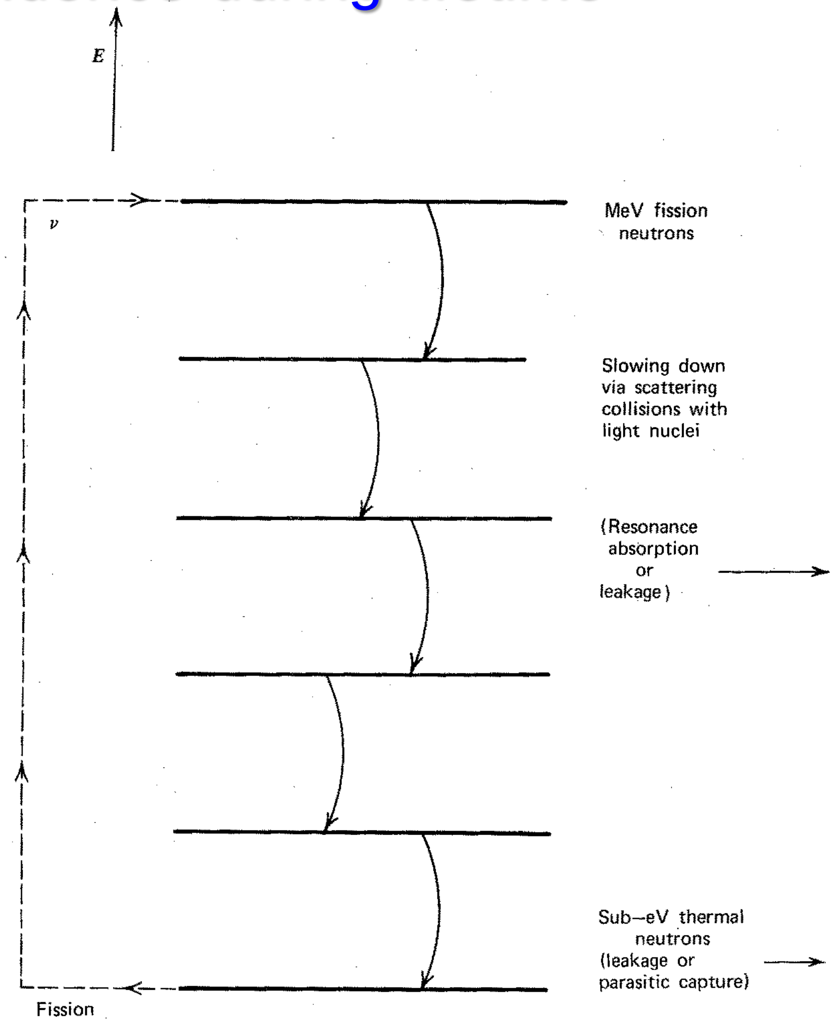
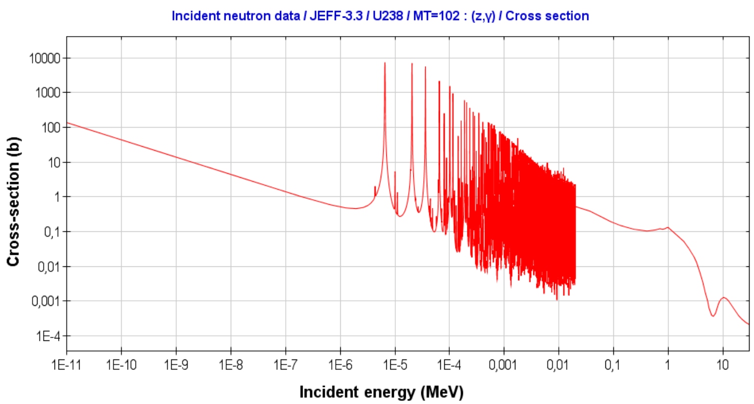


FIGURE 3-3. Processes characterizing a neutron generation in a thermal reactor.



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The Nuclear Data Cycle

Defining nuclear data needs

Experimental data (EXFOR)

Evaluated Nuclear Data Files (ENDF)

App. libraries (e.g. ACE format)

Measurement (differential exp.) → **Evaluation** → **Processing** → **Validation (integral exp.)** → **Applications**

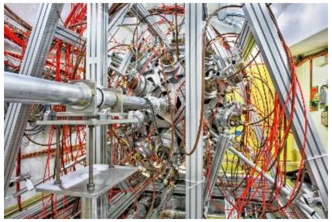
- n_TOF (CERN)
- GELINA (JRC)
- ORELA (ORNL)

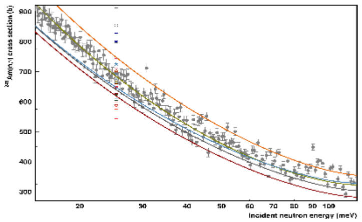
- ENDF
- JEFF
- JENDL
- …

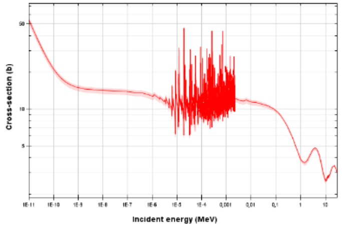
- NJOY
- AMPX (SCALE)
- FRENDY

- ICSBEP
- IRPhE
- SFCOMPO
- SIMBAD

- Reactor physics
- Nucl. fuel cycle
- Rad. shielding
- Nucl.medicine…



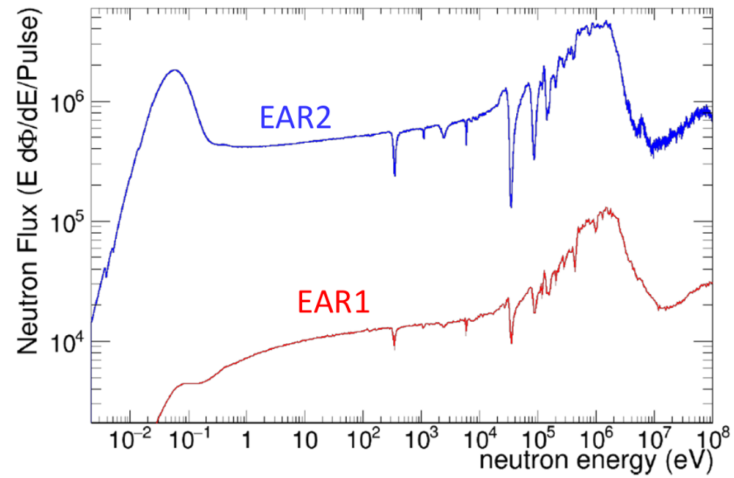




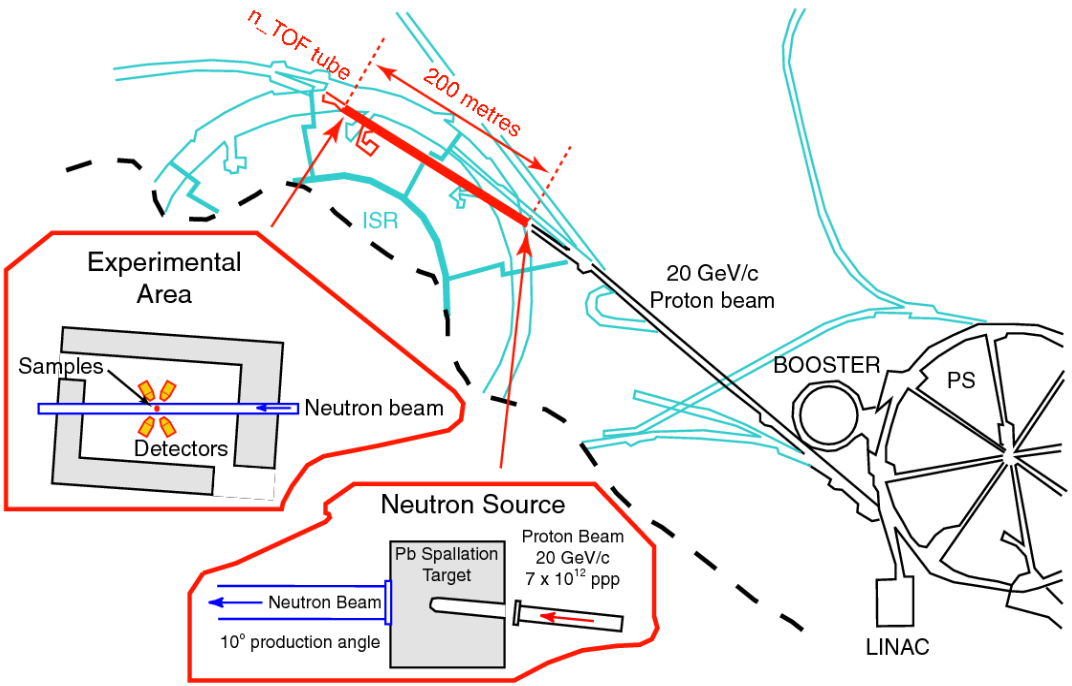
The n_TOF facility at CERN

The n_TOF facility is a high instantaneous intensity spallation neutron source driven by the CERN PS synchrotron (20 GeV/c with up to $8x10^{17}$ protons per pulse).

There are two experimental areas: EAR1 and EAR2 located at 185 m and at 20 m, respectively, from the spallation target.



Experimental neutron fluence per 7 $10^{12}p^{+}$



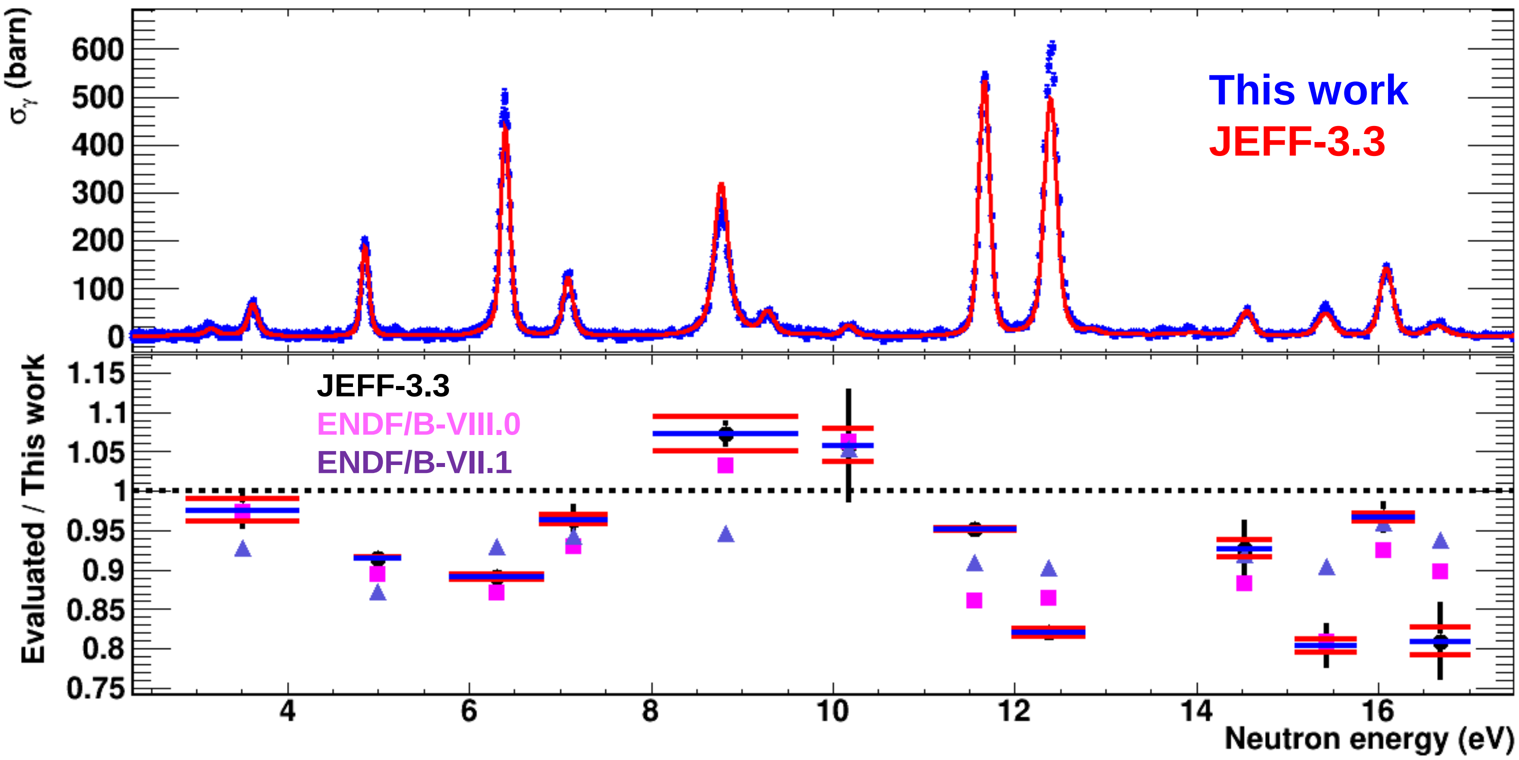
The energy of the neutrons is obtained from the time-of-flight method:

$$E = \frac{1}{2} m \left(\frac{L}{t}\right)^2$$

The neutron energy range extends from thermal energies up to a few GeV.

Measurement of the ^{235}U (n,γ) cross section

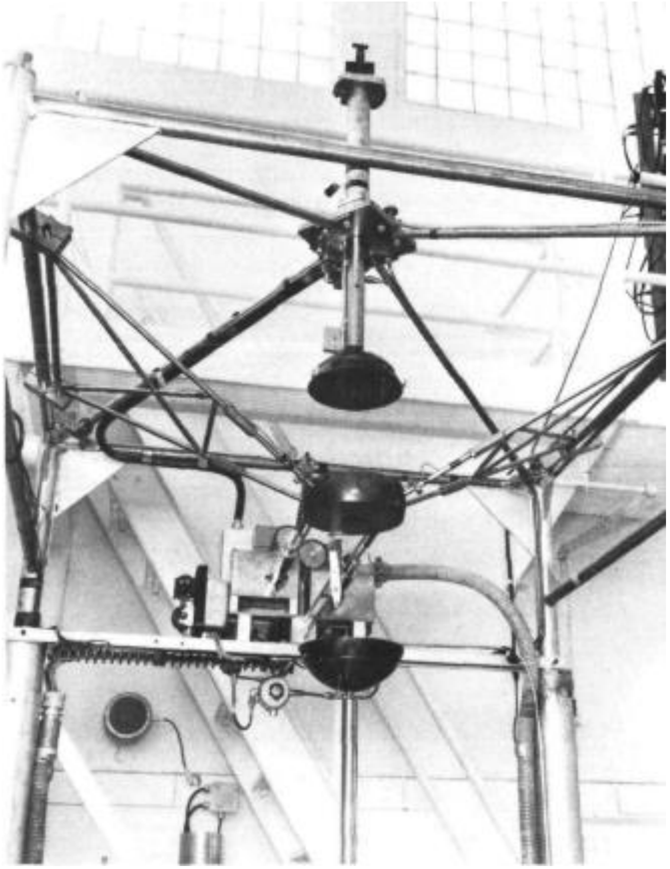
The ^{235}U(n,γ) was measured using the Total Absorption Calorimeter (TAC), made of 40 BaF_2 crystals, for detecting the γ-ray cascades emitted after the neutron capture, and *micromegas* fission detectors for detecting, in coincidence, the fission reactions in ^{235}U.



J. Balibrea-Correa *et al.,* Phys. Rev. C 102, 044615 (2020)

Integral experiments

- Calculation results (e.g. critical masses, reactor parameters, shielding attenuation lengths…) obtained using measured nuclear data need to be validated in systems representative of the intended applications → *integral vs. TOF experiments*.
- For reactor physics applications, integral experiments are usually conducted in simple, very low ("zero") power, well characterized reactors → (sub)critical assemblies, reactor mock-ups.
- In the past, integral experiments constituted the main source of nuclear data.
- Example: Godiva reactor.
  - Los Alamos National Lab (USA).
  - First assembled in 1951.
  - Bare Highly Enriched Uranium (HEU) sphere (1.02% ^{234}U, 93.71% ^{235}U, 5.27% ^{238}U).
  - k_{eff} = 1.000 ± 0.001.



Integral experiments

- Databases of integral experimental data:
  - International Criticality Safety Benchmark Evaluation Project (ICSBEP)

    https://www.oecd-nea.org/jcms/pl_24498/international-criticality-safety-benchmark-evaluation-project-icsbep
  - International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhE)

    https://www.oecd-nea.org/jcms/pl_20279/international-handbook-of-evaluated-reactor-physics-benchmark-experiments-irphe
  - Spent Fuel Isotopic Composition (SFCOMPO)

    https://www.oecd-nea.org/jcms/pl_21515/sfcompo-2-0-spent-fuel-isotopic-composition
  - Shielding Integral Benchmark Archive and Database (SINBAD)

    https://www.oecd-nea.org/jcms/pl_32139/shielding-integral-benchmark-archive-and-database-sinbad
- Distributed free of charge by OECD-NEA (under request)
- Suggested readings:
  - H. C. Paxton (1983). *A History of Critical Experiments at Pajarito Site*. Los Alamos National Laboratory Report LA-9685-H.
  - J. Goda *et al.*, *A New Era of Nuclear Criticality Experiments: The First 10 Years of Godiva IV Operations at NCERC*. Nuclear Science and Engineering 195 (2021) S75-S79.

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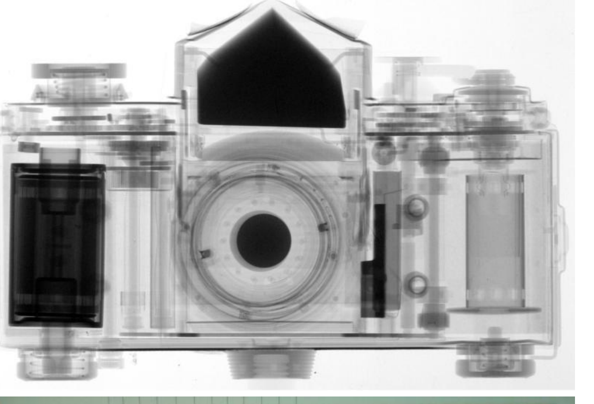
Other scientific and technological applications of neutrons

- Neutron activation analysis
  - Neutrons can activate stable isotopes within samples and the gamma-rays from its decay can be used to determine its concentration (non-destructive analysis).
  - These techniques can be applied with low neutron fluxes produced by sealed sources (AmBe, ^{252}Cf) or compact neutron generators (DD, DT) and are widely used in the oil & gas or cement industries.
- Isotope production (mainly for medical uses)
  - Many radioactive isotopes produced by neutron reactions in nuclear reactors can be used as radiotracers.
  - ^{99}Mo (which decays in ^{99m}Tc) is the most important medical isotope (80% of nuclear medicine imaging procedures).
- Solid state physics & material science
  - The particle-wave duality and high penetrating power of neutrons can be exploited for neutron imaging and scattering experiments.
  - These techniques usually require high-flux research reactors (e.g. HFR at ILL or FRM-II) or spallation sources (e.g. ESS).



Thank you for your attention