# Week 7 Lecture 1 – Nuclear Reactions & Waste

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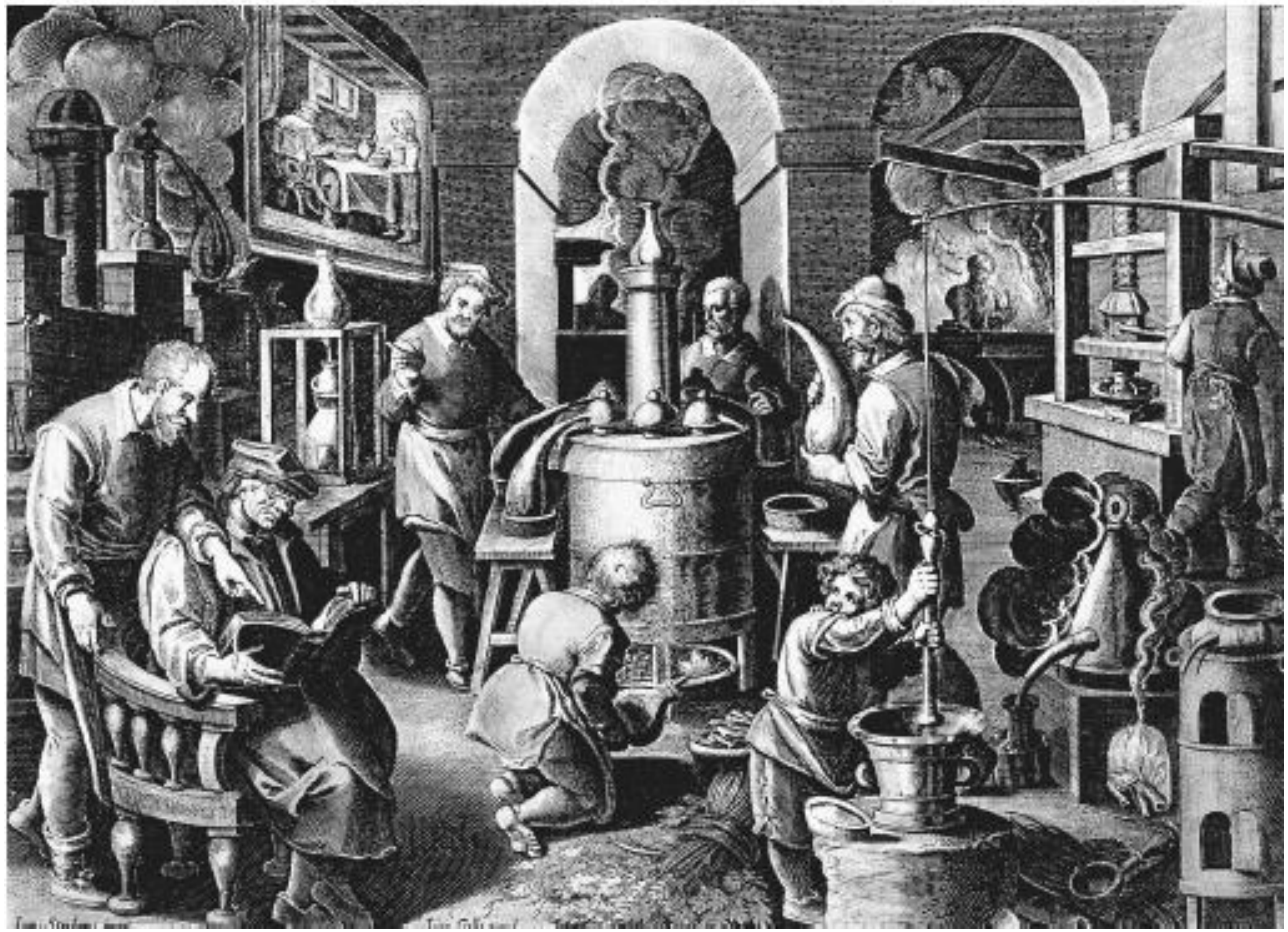
**Nuclear Reactions**

-- Nuclear Reactions & Waste

-- Transmutation

-- Nuclear Reactions

5th Homework
due today



The Alchemists Workshop

# Nuclear Power – Reaction Overview

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The most common nuclear reactions being run on earth this days are:

$$^{1}n + {}^{235}_{92}U_{143} \rightarrow \left({}^{236}_{92}U_{144}\right)^{*} \rightarrow Fission + \approx 2.4\ {}^{1}n$$

$$\sim 10\% \quad {}^{236}_{92}U_{144} + {}^{1}n \rightarrow {}^{237}_{92}U_{145}$$

α, 24,000 yr

$$^{1}n + {}^{238}_{92}U_{146} \rightarrow \left({}^{239}_{92}U_{147}\right)^{*} \rightarrow {}^{239}_{92}U_{147}$$

$$\xrightarrow{\beta-\ 23m} {}^{239}_{93}Np_{146}$$

$$\xrightarrow{\beta-\ 2.4d} {}^{239}_{94}Pu_{145}$$

$$^{1}n + {}^{239}_{94}Pu_{145} \rightarrow \left({}^{240}_{94}Pu_{146}\right)^{*} \rightarrow Fission + \approx 2.5\ {}^{1}n$$

$$\sim 10\% \quad {}^{240}_{94}Pu_{146} + {}^{1}n \rightarrow {}^{241}_{94}Pu_{147}$$

$$\xrightarrow{\beta-\ 14yr} {}^{241}_{95}Am_{146}$$

The typical reactor fuel in (light) water-moderated reactors is:
~3% $^{235}$U (compared to a natural enrichment of 0.27%) and the rest of the fuel is $^{238}$U.

The spent fuel on discharge contains:
The left over uranium with plutonium, neptunium, americium, and curium,
and
the fission products (iodine, technetium, neodymium, zirconium, molybdenum, cerium, cesium, ruthenium, palladium, etc.) that constitute about 2.9% by weight.

# Neutron Capture in "Minor Actinides"

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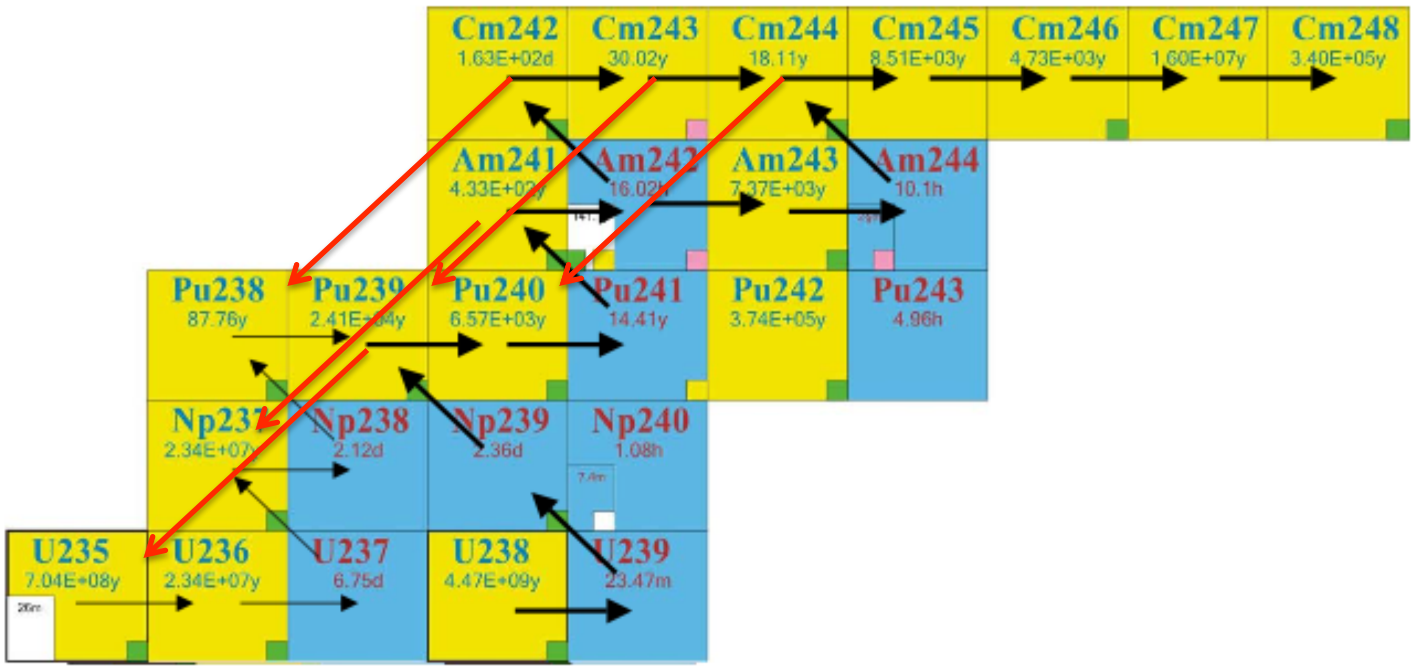
Inside the reactor *a slow neutron capture* process takes place where β- decay competes with neutron capture to produce heavier nuclei.  Every once in a while the process falls back by an alpha decay, and ends in spontaneous fission decay of the heaviest elements.




After use in the reactor the discharged fuel is:

~ 0.90% enriched in $^{235}$U,

~1% of the weight is plutonium (mostly $^{239}$Pu)

~0.1% "minor actinides" by weight (which is divided into 50% $^{237}$Np, 47% Am and 3% Cm)

Leaving ~ 95% $^{238}$U plus ~3% Fission products

# Nuclear Power – Fission Product Overview

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Imagine the simplest picture of nuclear fission with an equal division of mass and charge:

$$^{1}n + {}^{235}_{92}U_{143} \rightarrow \left({}^{236}_{92}U_{144}\right)^{*} \rightarrow Fission + \approx 2\ {}^{1}n$$

$$\rightarrow 2\ {}^{(236-2)/2}_{92/2}Pd$$

Recall from early in the course, the stable atomic number (Z) for this set of isobars (A=117) is:

$$Z_A \approx \left(\frac{A}{2}\right)\frac{81}{80+0.6A^{2/3}} = \left(\frac{117}{2}\right)\frac{81}{80+0.6(117)^{2/3}} = 50.2$$

thus, these fission fragments will have to undergo 4 or 5 β- decays to reach a stable nucleus. In this particular example the chain would be:

$$^{117}_{46}Pd \xrightarrow{\beta-4.3s} {}^{117}_{47}Ag \xrightarrow{\beta-73s} {}^{117}_{48}Cd \xrightarrow{\beta-2.5h} {}^{117}_{49}In \xrightarrow{\beta-43m} {}^{117}_{50}Sn$$

The fission product distribution runs from Z~30 to Z~70 and is sensitive to the underlying nuclear structure and the most probable mass split produces other chains of decaying nuclei:

$$^{138}_{53}I \xrightarrow{\beta-6.2s} {}^{138}_{54}Xe \xrightarrow{\beta-14m} {}^{138}_{55}Cs \xrightarrow{\beta-33m} {}^{138}_{56}Ba$$

$$^{98}_{39}Y \xrightarrow{\beta-0.5s} {}^{98}_{40}Zr \xrightarrow{\beta-30s} {}^{98}_{41}Nb \xrightarrow{\beta-2.9s} {}^{98}_{42}Mo$$

# What to do with this stuff?

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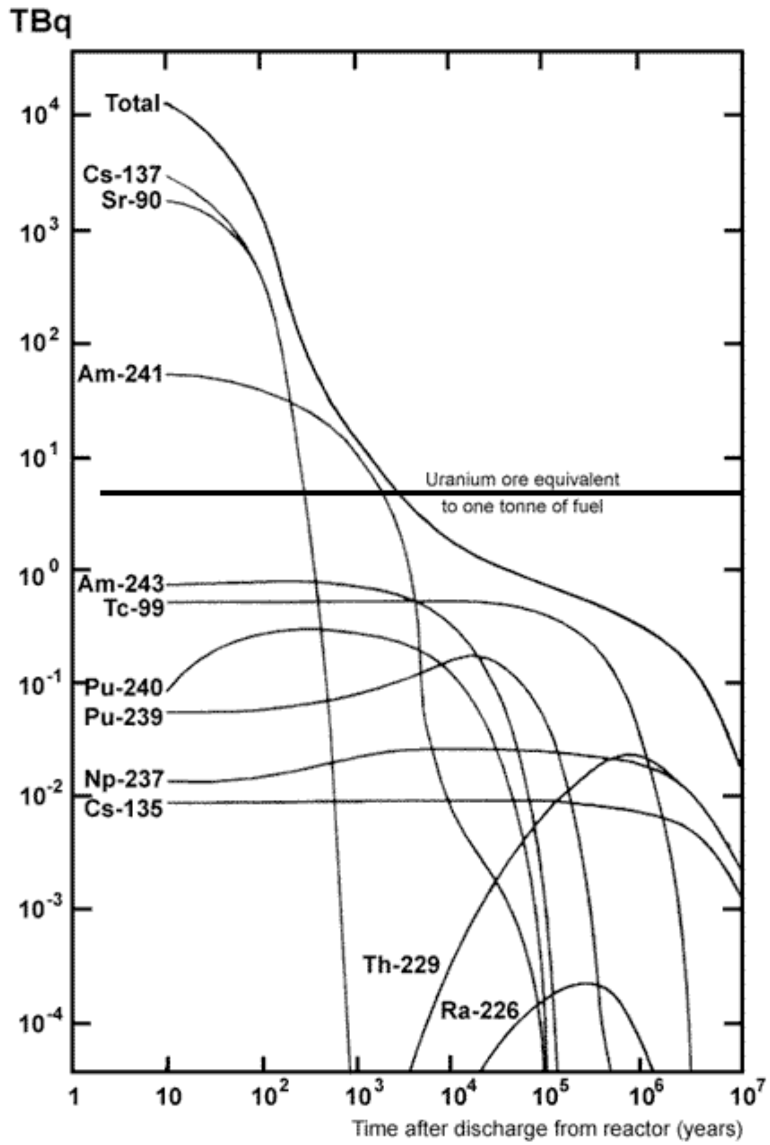


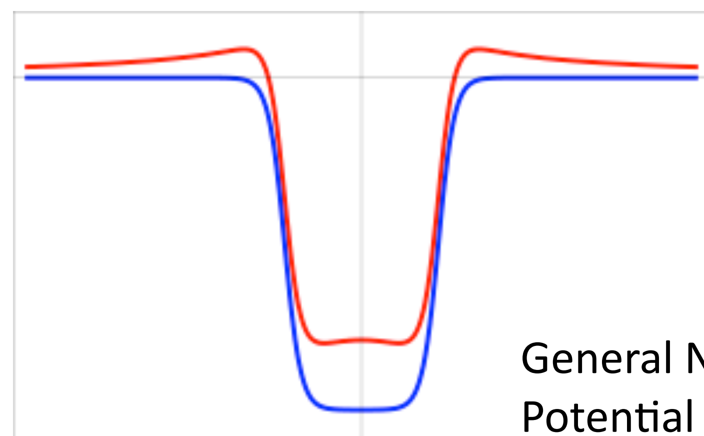

**Activity of high-level waste from one tonne of spent fuel**

*Source:* IAEA, 1992 - radioactive waste management.

1) Wait

2) Separate out valuable isotopes, recycle into Mixed Oxide (MOX) fuel

3) Burn it up …
 (transmutation via nuclear reactions)



General Nuclear Potential Energy

Force = -dV /dr

# Transmutation Facility make Neutrons

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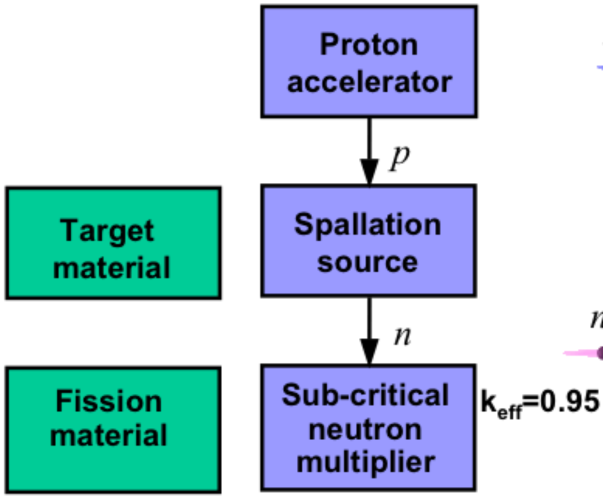
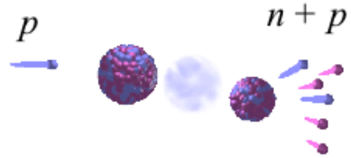
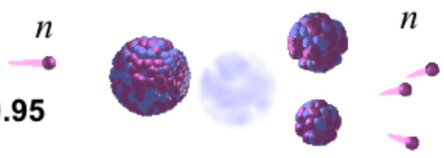



Spallation




Fission

SCK-CEN Center, Mol, Belgium

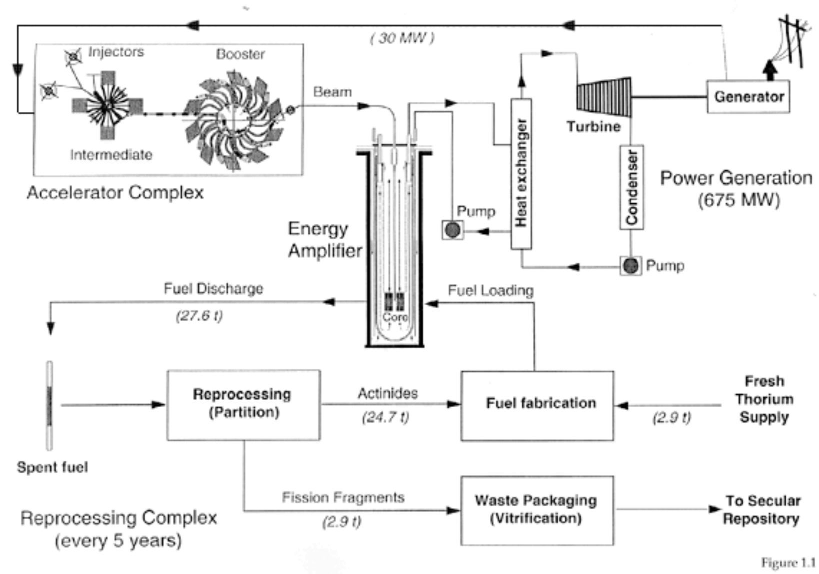



Figure 1. Rubbias Fast Energy Amplifier.

Carlo Rubbia,
Nobel Prize in Physics, 1984,
Understanding of the Weak Interaction ($\beta$ decay)