MANCHESTER
1824

The University of Manchester

Issues in Accelerator-Driven Systems

Hywel Owen

Cockcroft Institute/University of Manchester

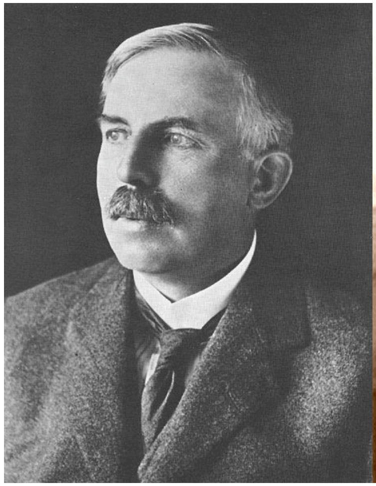
source:
Government Energy Support Unit
(confirmed by OECD)

Energy source	Grammes of carbon per KWh of electricity
Nuclear	4
Wind	8
Hydro electric	8
Energy crops	17
Geothermal	79
Solar	133
Gas	430
Diesel	772
Oil	828
Coal	955

500x less land area than windmills

Leó Szilárd, Ernest Rutherford and the Chain Reaction

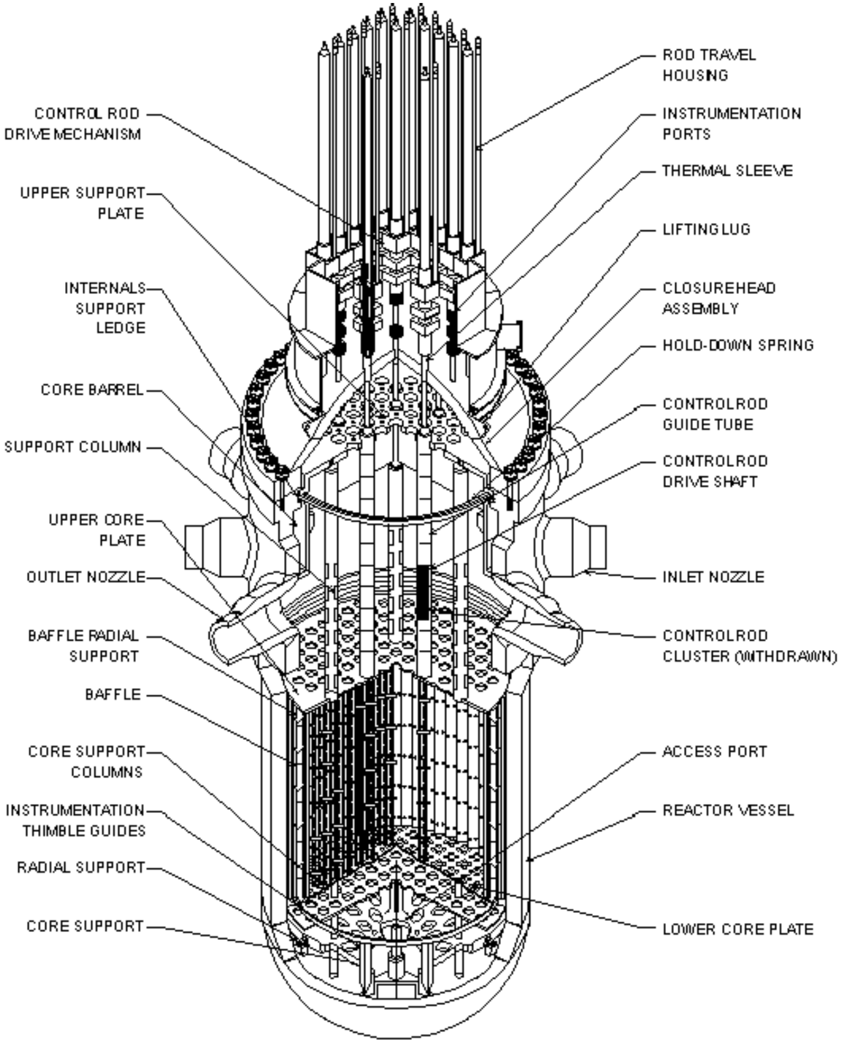
- In a Times article on March 6th 1933, Ernest Rutherford asserted:
  - ‘The energy produced by the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine’
- Leó Szilárd was apparently annoyed by this, and conceived of the nuclear chain reaction while waiting for traffic lights to changed in Bloomsbury , London, in 1933!

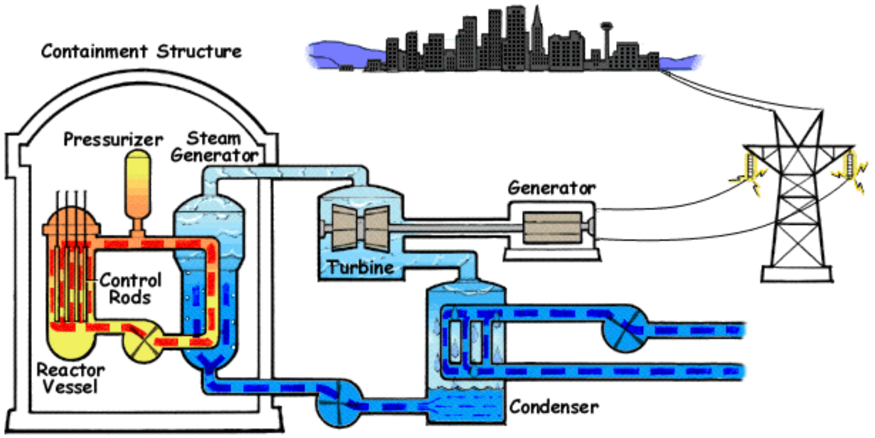


A Little History…

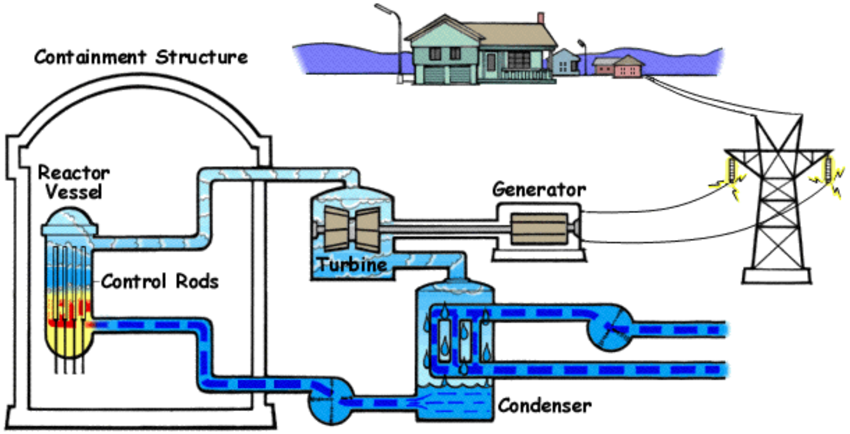
- 1932 – Chadwick discovers neutron
- 1932 – Lawrence invents cyclotron (or was it Szilard?)
- 1933 – Rutherford article/Szilard conceives chain reaction
- 1933 - Curie and Joliot produce first artificial radioactivity
- 1937 – Segre discovers first artificially-created element - Technetium
- 1941 – Glenn Seaborg makes 239Pu using d on 238U (ugm)
- 1942 – Chicago Pile 1 (criticality)
- 1945 – Trinity Test, Oppenheimer et al.
- 1949 – Goeckermann and Perlman carry out high energy spallation (high multiplicity)
- 1950 – Lawrence 'Material Testing Accelerator' project approved
- 1951 – EBR-1 (Idaho) – first electricity
- 1952 – W B Lewis proposes accelerator breeding of 233U
- 1956 – Calder Hall – first nuclear power plant (PIPPA)
- 1957 – Shippingport – first commercial plant & LWR & Th breeding

LWRs: PWRs and BWRs

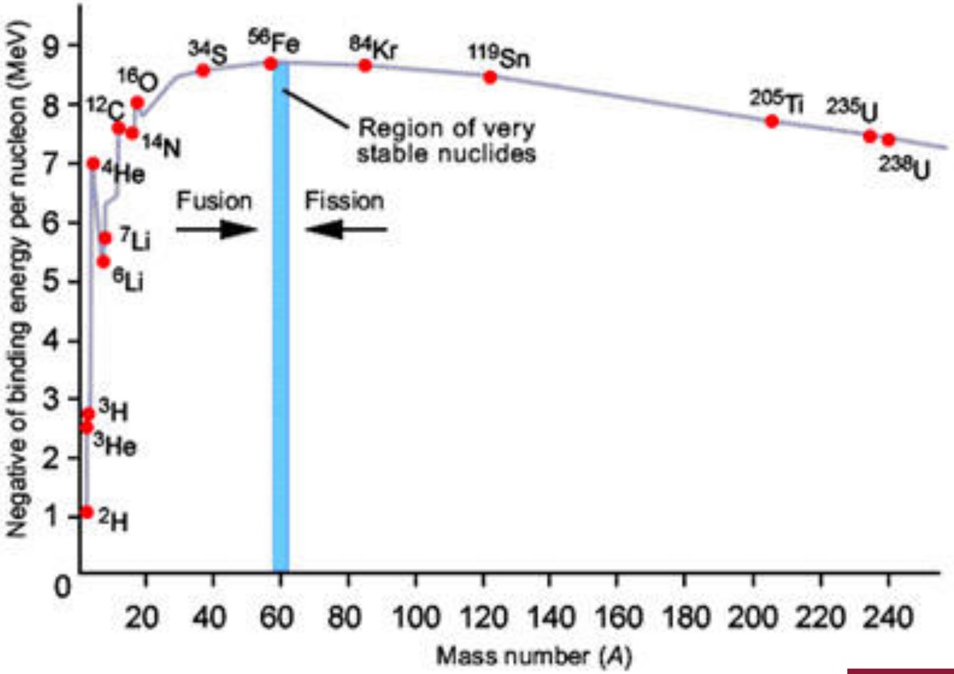


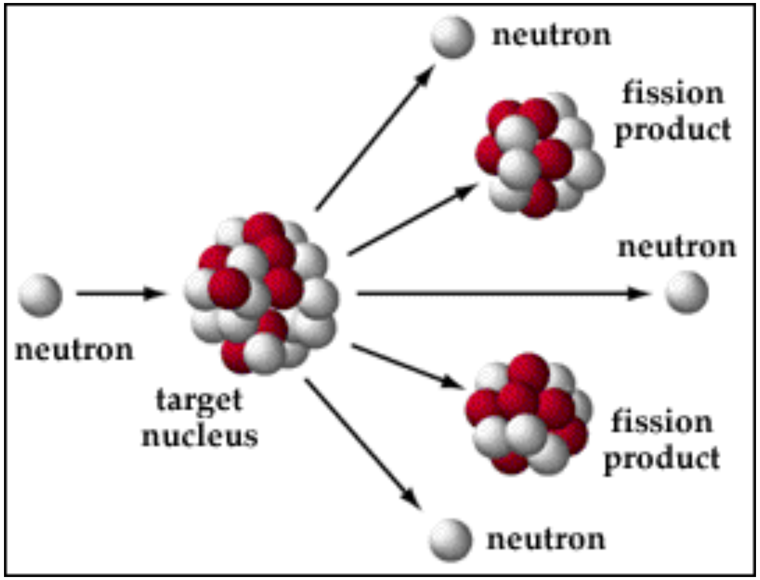


Pressurised Water Reactor



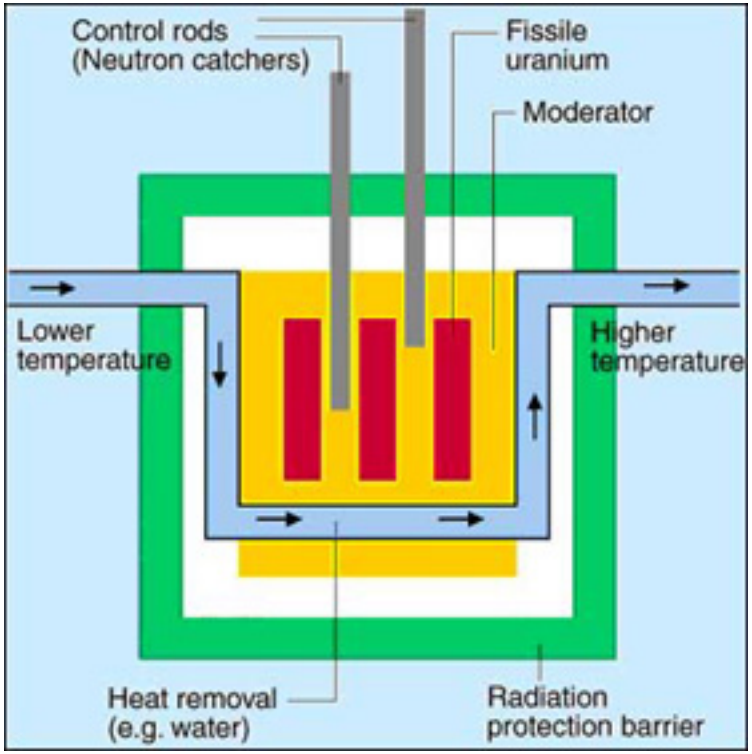
Boiling Water Reactor





Action	Energy (MeV)
FPs	168
Fission n	5
Prompt gamma	7
Decay beta	8
Decay gamma	7
Neutrinos	12
Capture gamma	5
Total available	200

Isotope	ν Thermal	ν Fast
235U	2.44	2.50
239Pu	2.87	3.02
233U	2.48	2.55



Fissile Fuel

Moderator

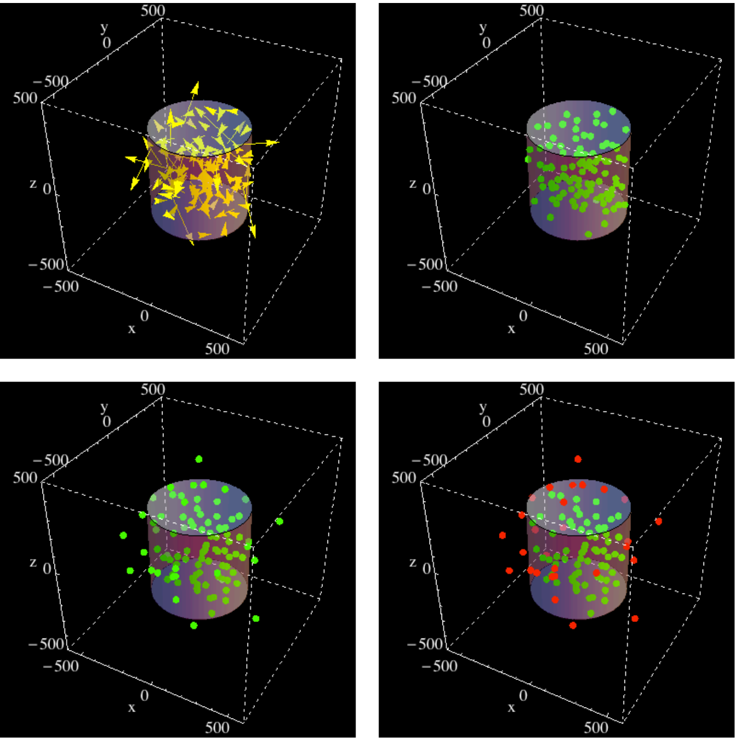
Coolant

Control

As fissile atoms consumed, fission products and actinides are produced. Other materials (burnable poisons) may also be consumed.

Comparison of Moderators and Coolants

- LWR
  - Abundant
  - Liquid at RTP
  - Transparent
  - High Pressure required at working T (370K)
  - Requires Enriched Fuel
- HWR
  - v. Low absorption – can use natU
  - Transparent
  - Abundant, but v. expensive
  - High pressure required
- AGR
  - No phase changes
  - Very high temperatures possible
  - Future limit in He supply?
- SFR
  - Low melting temperature
  - Atmospheric pressure (pool-type)
  - Reasonable experience
  - Flammable with water/air
- LFR
  - Transparent to neutrons: fast spectrum
  - Atmospheric pressure (pool-type)
  - PbBi gives lower temp, but 210Po production



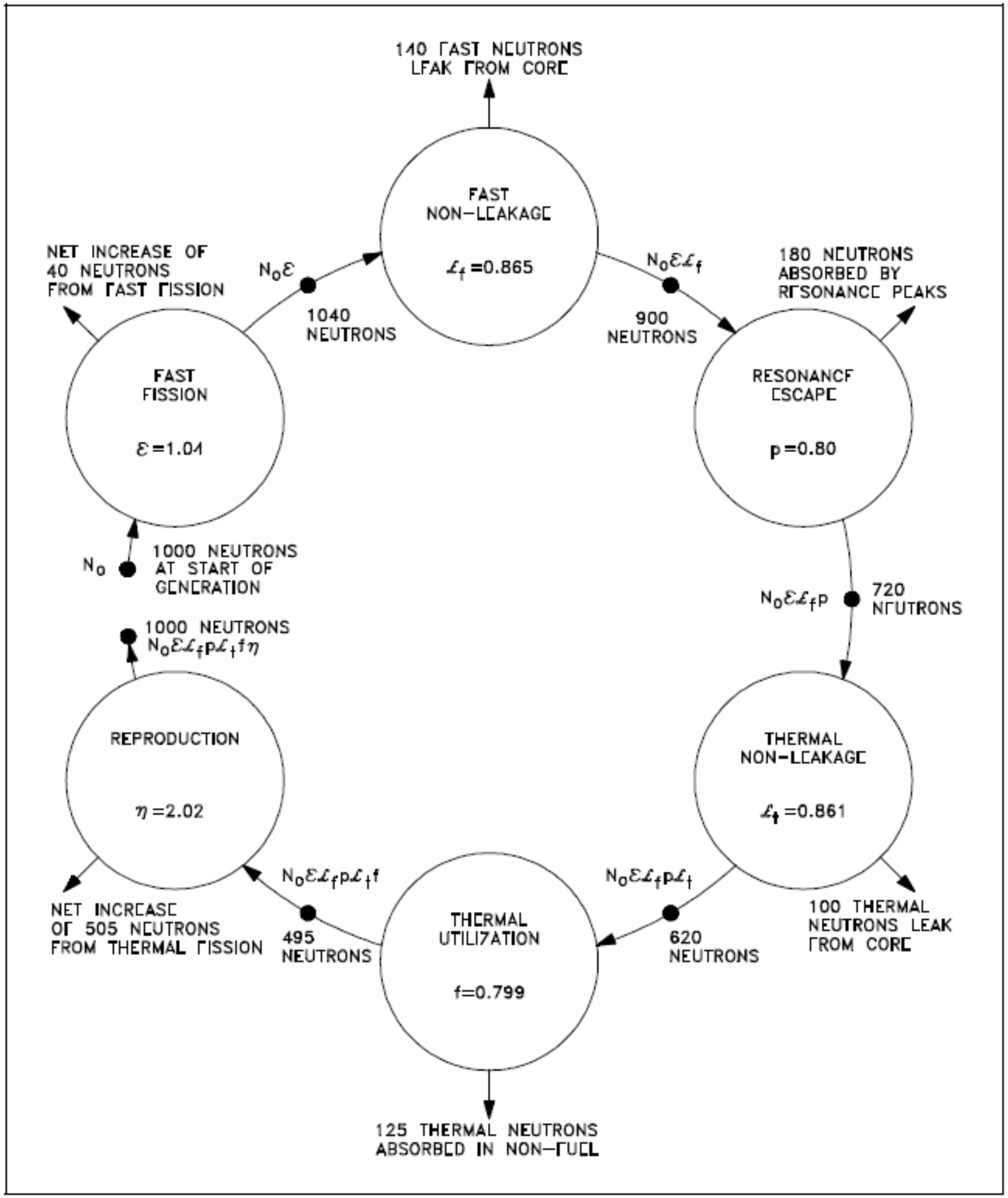


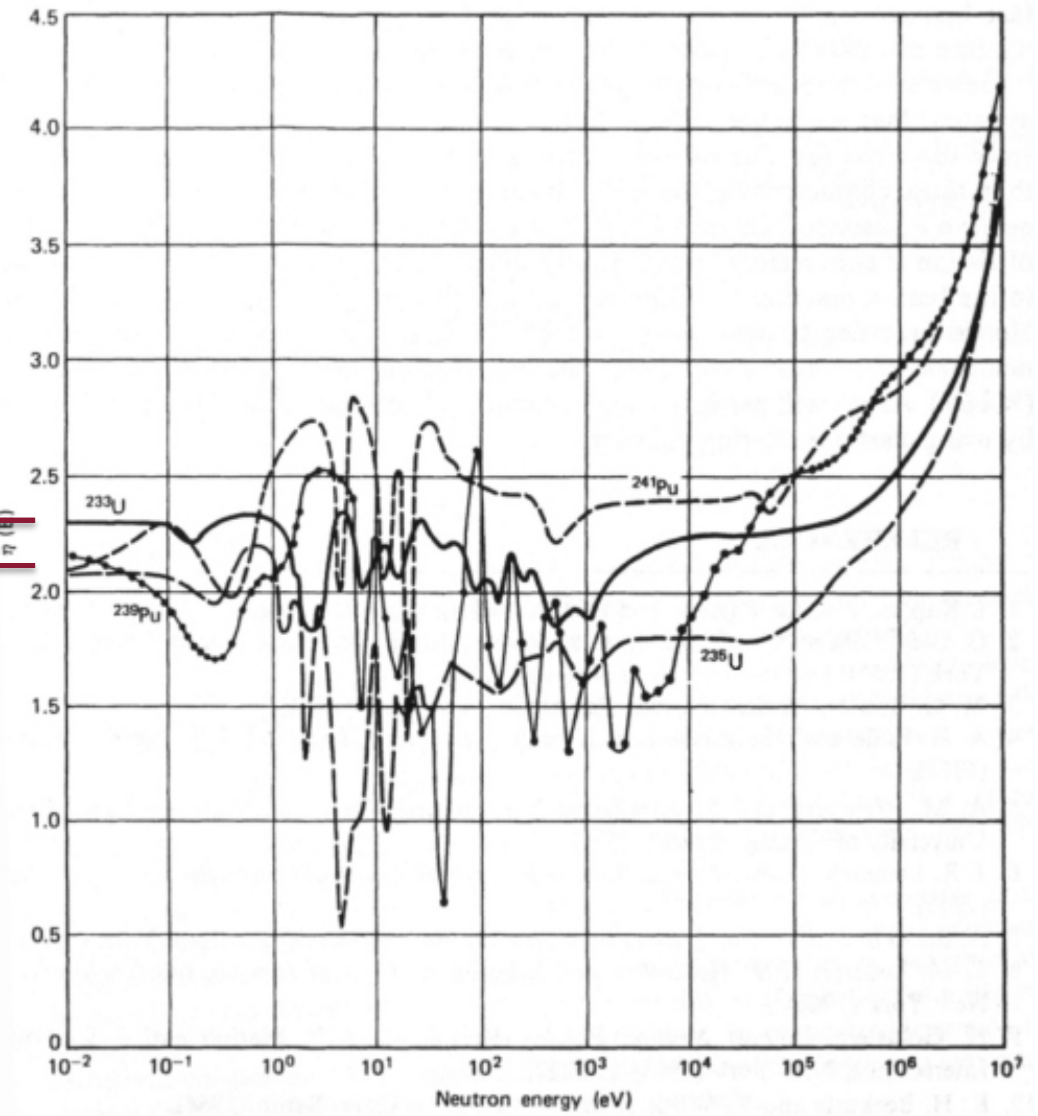
Figure 1 Neutron Life Cycle with $k_{eff} = 1$

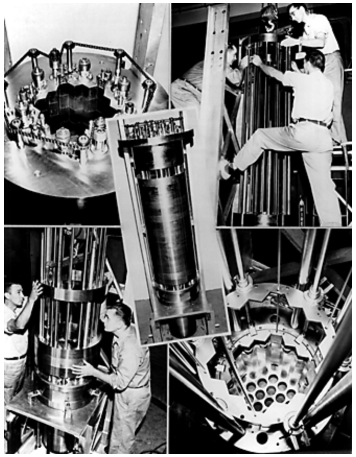
Breeding New Fuel

$$B = \eta_f - 1 - (C + L)$$

Isotope	Thermal	Fast
235U	2.08	2.09
239Pu	2.12	2.53
233U	2.28	2.35

has to be bigger than ~2.2





This little difference is really important!

Reactor Control

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

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

$$N_0 \rightarrow (1+\rho)^n N_0$$

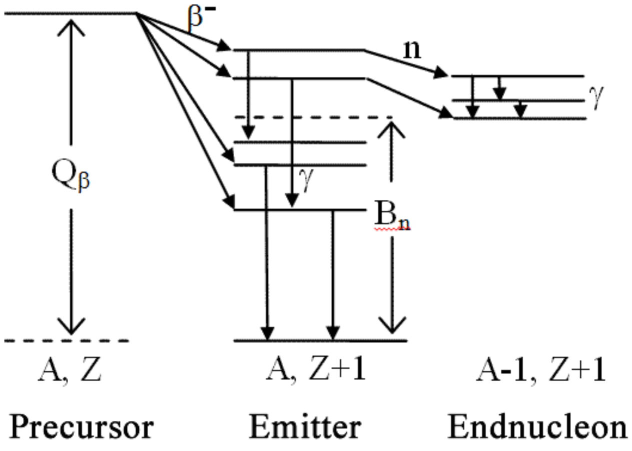
$$n(t) = n_0 \exp(\frac{\rho t}{\tau_n})$$

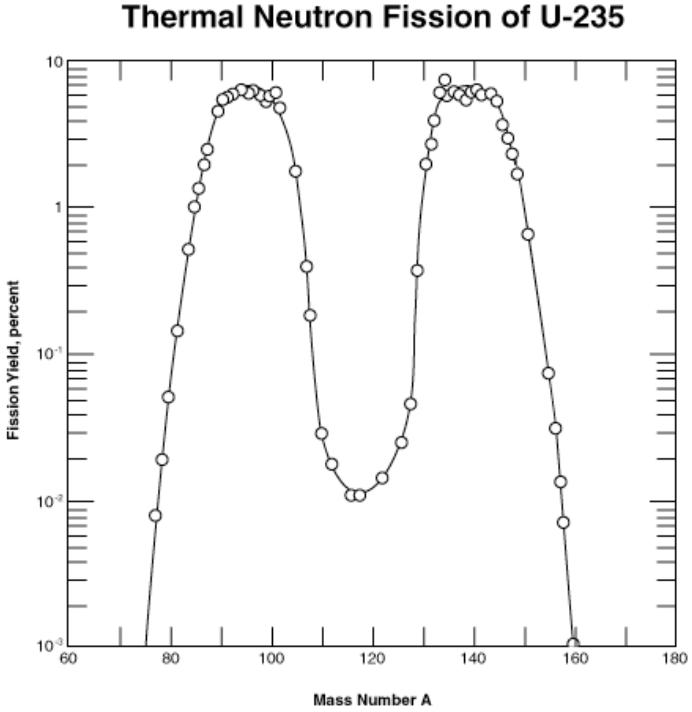
$$W(t) = W_0 \exp(\frac{\rho t}{\tau_n})$$

τ_n
Thermal reactor: 10^{-4} s
Fast reactor: 10^{-7} s

Delayed neutrons fix everything!

	β	T_d(sec.)	τ_d(sec.)	N/A
^{232}Th	0.0203	6.98	0.141	0.612
^{233}U	0.0026	12.40	0.032	0.605
^{235}U	0.00640	8.82	0.056	0.608
^{238}U	0.0148	5.32	0.079	0.613
^{239}Pu	0.002	7.81	0.020	0.607
^{241}Pu	0.0054	10^9	0.054	0.609
^{241}Am	0.0013	10	0.013	0.606
^{243}Am	0.0024	10	0.024	0.609
^{242}Cm	0.0004	10	0.004	0.603





Delay neutron production

$$\begin{tikzcd} {}^{93}_{36}\mathrm{Kr} \arrow[r, "1.3\ \text{sec}", "\beta^-"'] & {}^{93}_{37}\mathrm{Rb} \arrow[r, "6\ \text{sec}", "\beta^-"'] & {}^{93}_{38}\mathrm{Sr} \arrow[r, "7.5\ \text{min}", "\beta^-"'] & {}^{93}_{39}\mathrm{Y} \arrow[r, "10\ \text{hr}", "\beta^-"'] & {}^{93}_{40}\mathrm{Zr} \arrow[r, "1.5\times10^{6}\ \text{yr}"] \arrow[dr, dashed, "\beta^-"'] & {}^{93m}_{41}\mathrm{Nb} \arrow[d, "13\ \text{yr}"] \\ & & & & & {}^{93}_{41}\mathrm{Nb}\ \text{(stable)} \end{tikzcd}$$

$$ {}^{141}_{54}\mathrm{Xe} \xrightarrow[\beta^-]{1.7\ \text{sec}} {}^{141}_{55}\mathrm{Cs} \xrightarrow[\beta^-]{25\ \text{sec}} {}^{141}_{56}\mathrm{Ba} \xrightarrow[\beta^-]{18\ \text{min}} {}^{141}_{57}\mathrm{La} \xrightarrow[\beta^-]{3.9\ \text{hr}} {}^{141}_{58}\mathrm{Ce} \xrightarrow[\beta^-]{32.5\ \text{d}} {}^{141}_{59}\mathrm{Pr}\ \text{(stable)} $$

But also need either control rod movement, or negative coefficients of reactivity

PWR Fissile, MA and FP Inventories

Inventories at loading and discharge of a 1 GWe PWR [19]

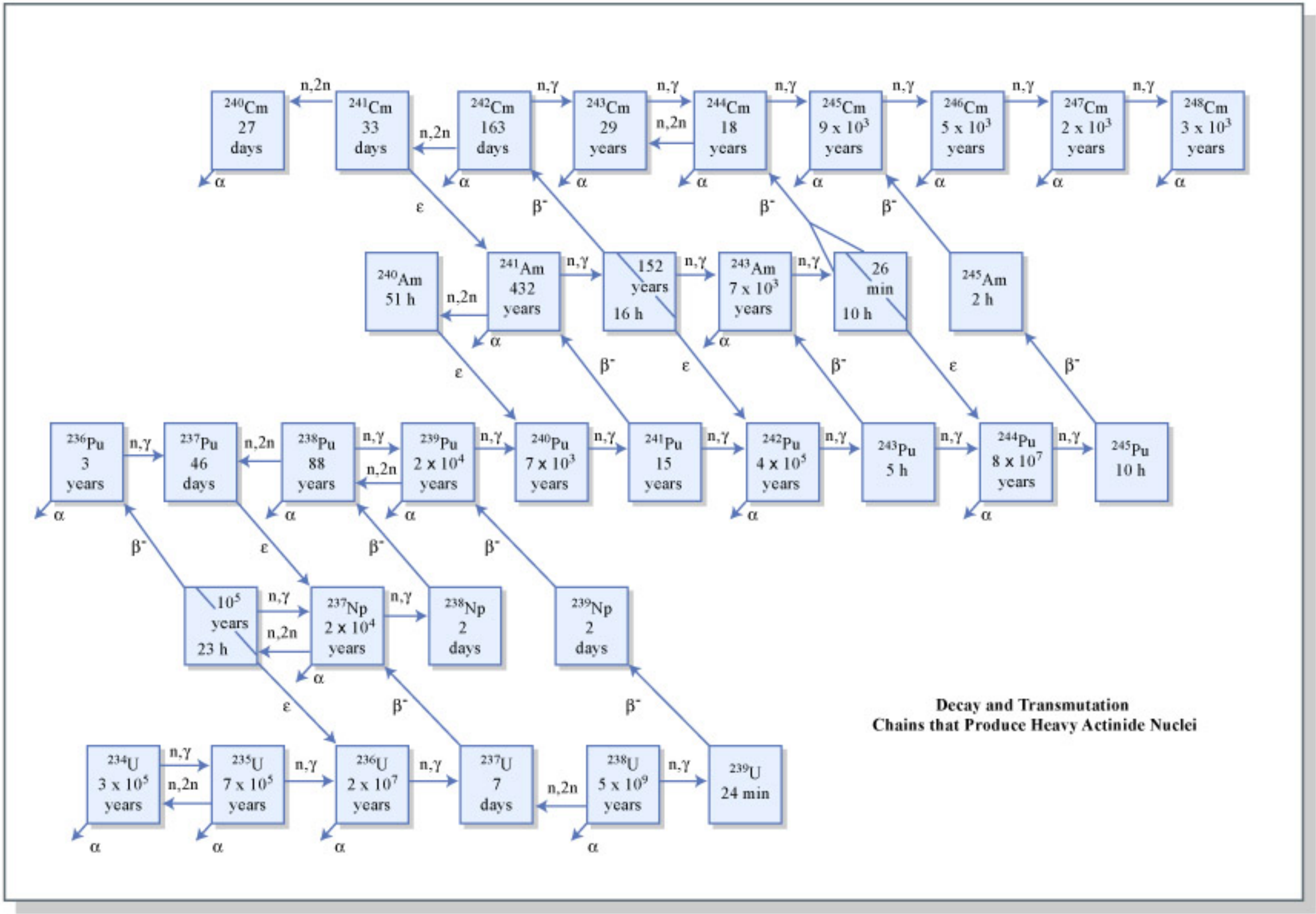
Nuclides	Initial load (kg)	Discharge inventory (kg)
^{235}U	954.0	280.0
^{236}U		111.0
^{238}U	26 328.0	25 655.0
U total	27 282.0	26 047.0
^{239}Pu		56.0
Pu total		266.0
Minor actinides		20.0
^{90}Sr		13.0
^{137}Cs		30.0
Long-lived PF		63.0
PF total		946.0
Total mass	27 282.0	27 279.0

- 4.5% of world energy is nuclear
  - 350 Gwe
  - ~440 reactors
  - Most PWR or BWR
- Yearly rates:
- Spent fuel: 8,000 t
- Each 1 GWe reactor:
  - 80,000t U ore (cf. 2M toe)
  - 200t natU
- Yucca Mountain capacity: 70,000 t

Long-lived fission fragments with their half-lives and production rates

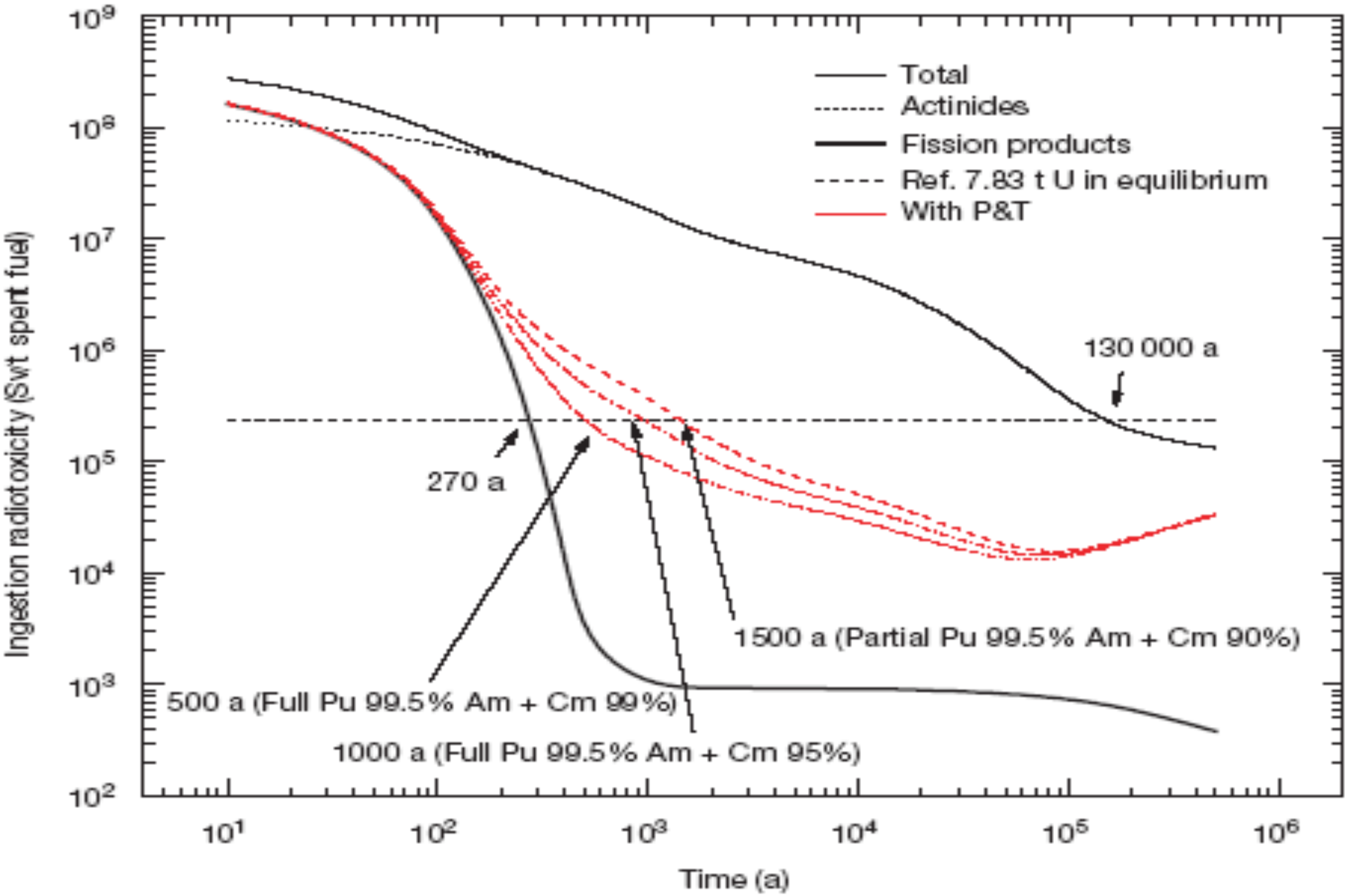
Nuclide	^{79}Se	^{90}Zr	^{99}Tc	^{107}Pd	^{126}Sn	^{129}I	^{135}Cs
$T_{1/2}$ years	70 000	1.5×10^6	2.1×10^5	6.5×10^6	10^5	1.57×10^7	2×10^6
Production kg/yr	0.11	15.5	17.7	4.4	0.44	3.9	7.7

U/Pu Cycle and Waste

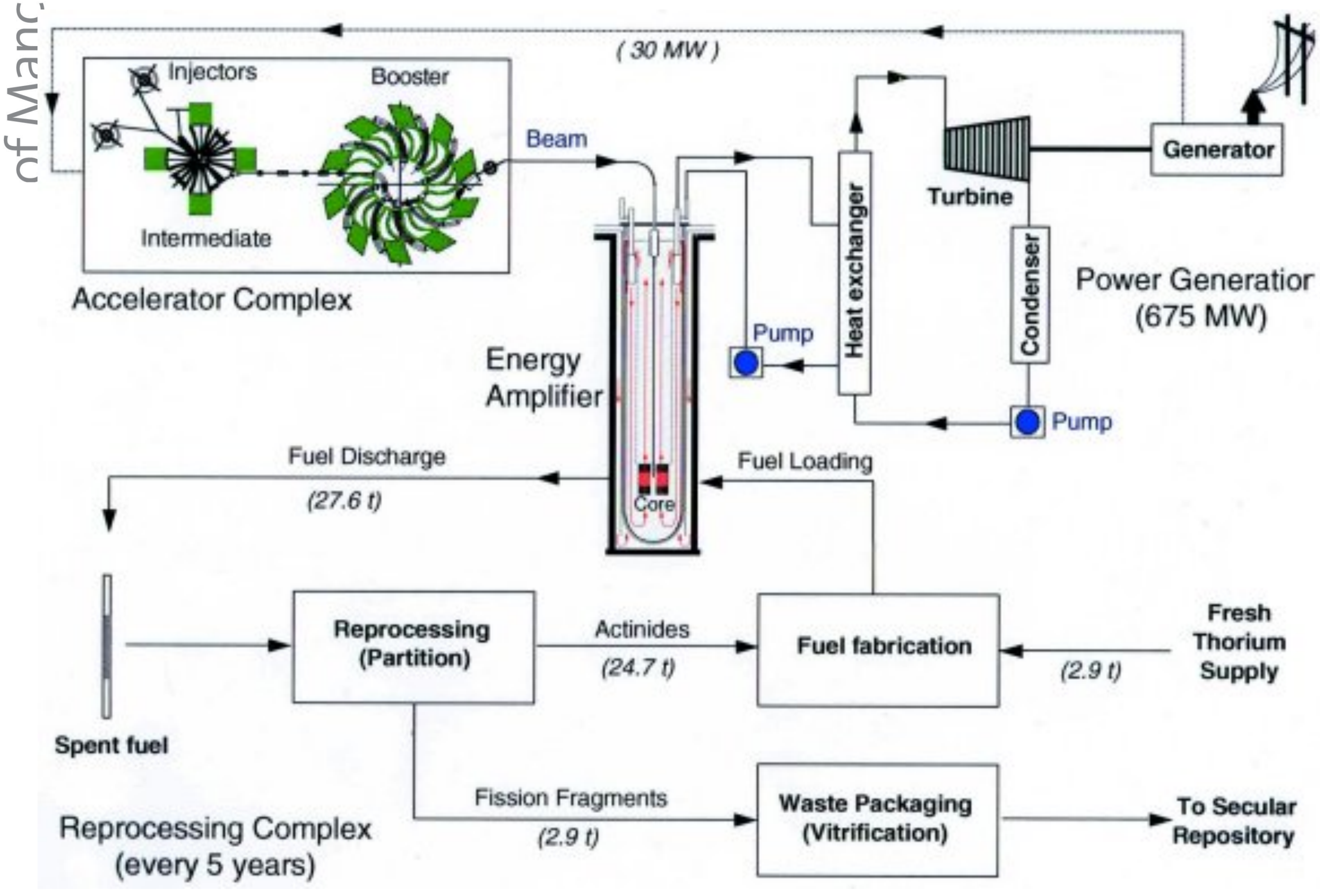


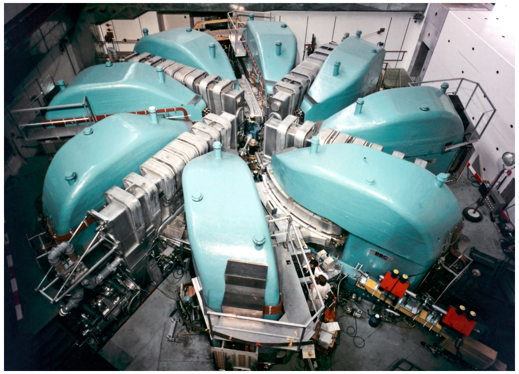
Decay and Transmutation
Chains that Produce Heavy Actinide Nuclei

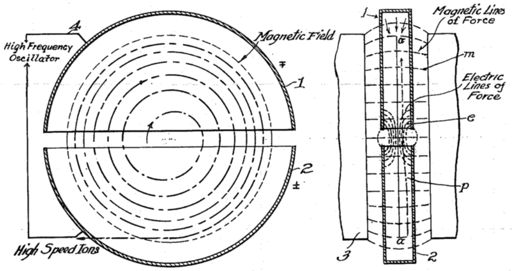
The Motivation for Transmutation

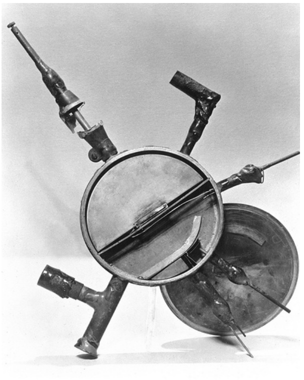


‘Energy Amplifier’ (Rubbia)



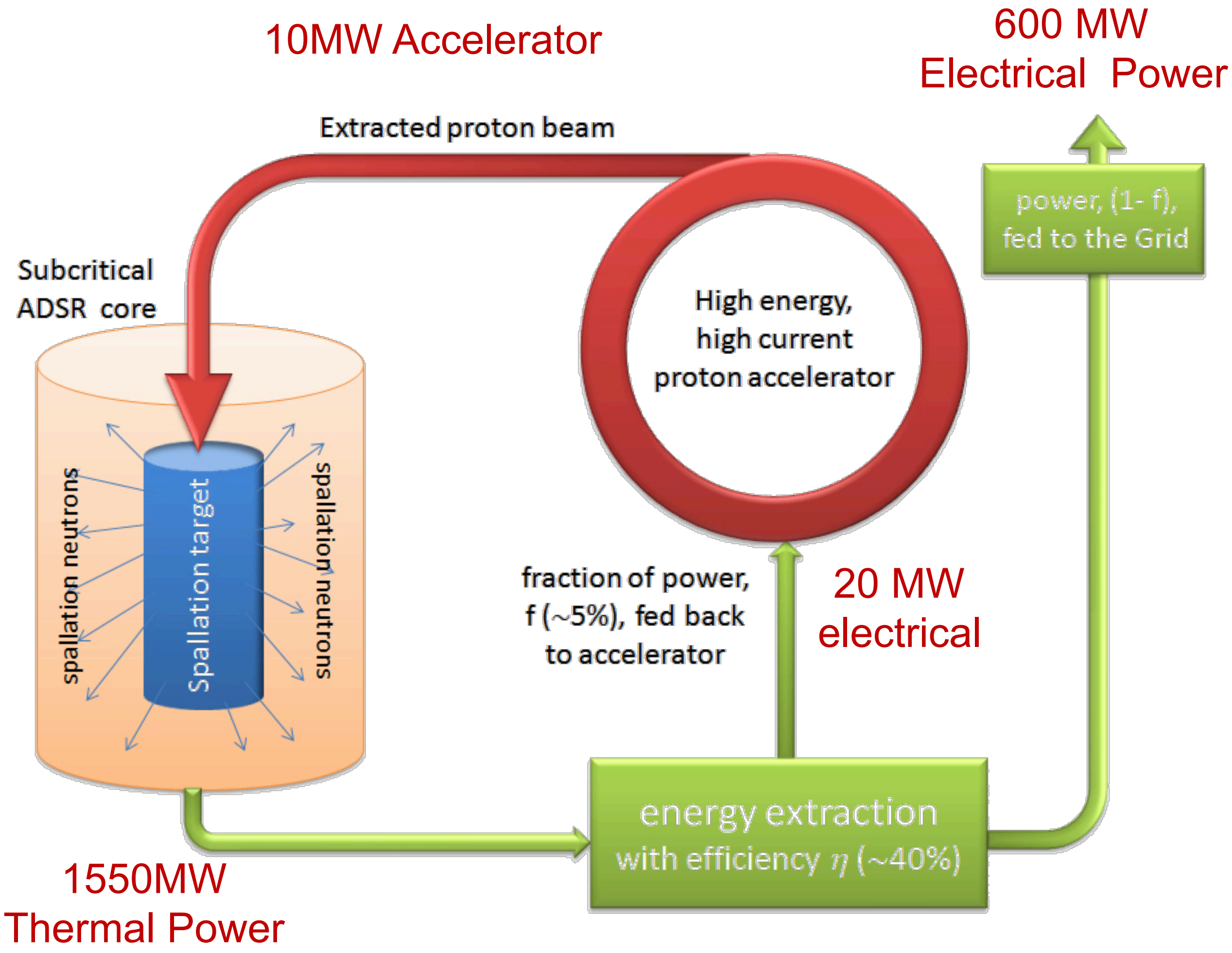






Rubbia et al., CERN/AT/93-47 (ET), CERN/AT/95-44 (ET)
Phys Rev C73, 054610 (2006)
also MSR option: C.D.Bowman, NIM A320, 336 (1992)

ADSR as an 'Energy Amplifier'



Reactor part costs about ~2-3 billion to construct
Fuel is 'sort-of' free

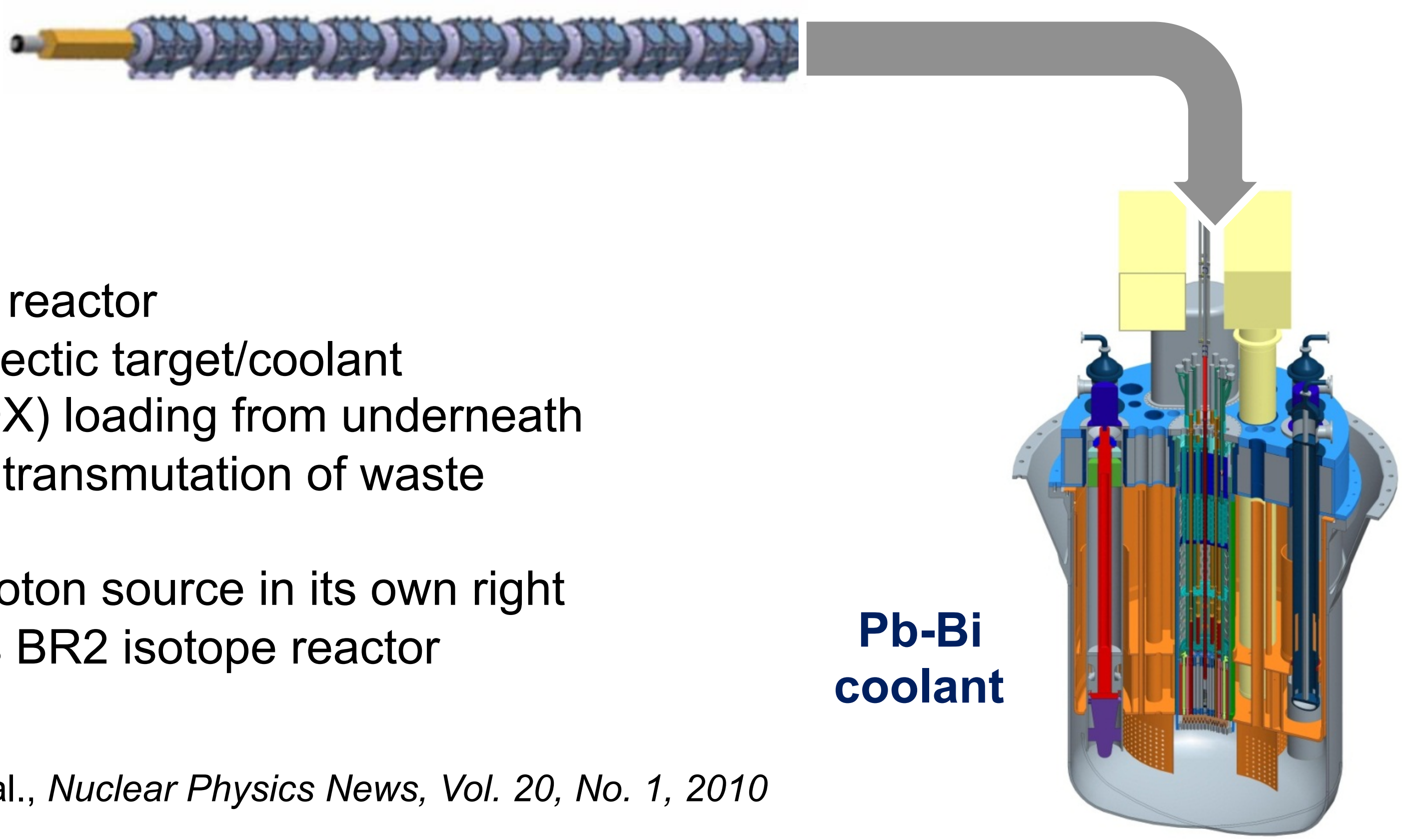
MYRRHA - Accelerator Driven System

Accelerator

(600 MeV - 4 mA proton)

Reactor

- Subcritical and Critical modes
- 65 to 100 MW_{th}



SC Linac
57 MWth reactor
Pb-Bi eutectic target/coolant
Fuel (MOX) loading from underneath
Examine transmutation of waste

Useful proton source in its own right
Replaces BR2 isotope reactor

Abderrahim et al., *Nuclear Physics News, Vol. 20, No. 1, 2010*

http://myrrha.sckcen.be/

MYRRHA Core Layout

$k_{eff} \approx 0.95$

183 hexagonal macro-cells

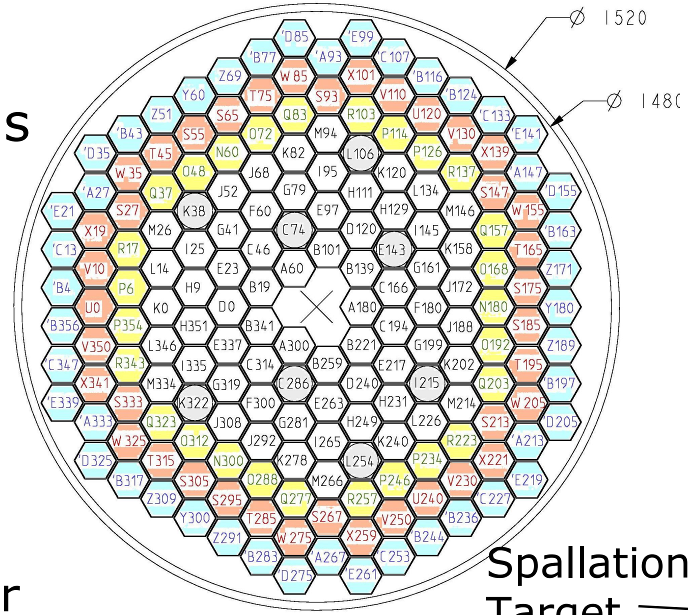
Target-block hole :
3 FA removed

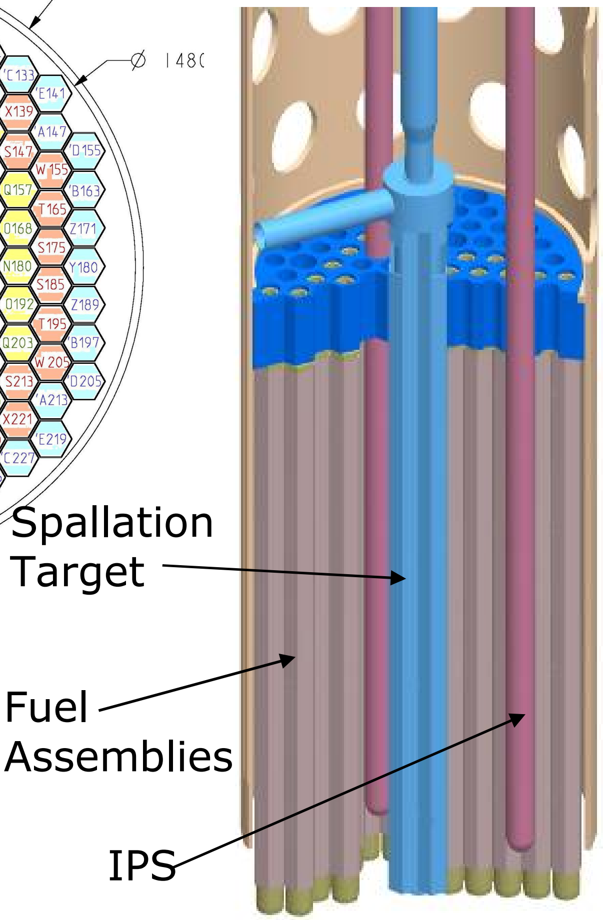
72 positions for fuel assemblies
(8 IPS positions included)

- ≈30 % MOX fuel

27 positions for fuel assies or dummy assies (filled with LBE) (yellow)

84 additional cells for core reconfiguration





Neutron multiplication in a sub-critical system

- In an accelerator driven, sub-critical system the "primary" (or "source") neutrons produced via spallation initiate a cascade process. The « source » neutrons are multiplied by fissions and (n,xn) reactions through the multiplication factor M :

$$M = 1 + k + k^2 + k^3 + \ldots + k^n = \frac{k^{n+1} - 1}{k - 1} \xrightarrow{n \to \infty} \frac{1}{1 - k} \quad for\ k < 1$$

- If we assume that all generations in the cascade are equivalent, we can define an average criticality factor k (ratio between the neutron population in two subsequent generations), such that :

$$k = \frac{M - 1}{M} = 1 - \frac{1}{M} < 1$$

- This **k ≠ k_{eff}**. k_{src} *is* the value of k calculated from the net multiplication factor M in the presence of an external source.

$$k_{src} = \frac{M - 1}{M}$$

Proton beam requirements for EA/ADSR

The (thermal) power output of an ADSR is given by

$$P_{th} = \frac{N \times E_f}{\nu} \cdot \frac{k_{eff}}{1 - k_{eff}}$$

with N = number of spallation neutrons/sec
E_f = energy released/fission (~200MeV)
ν = mean number of neutrons released per fission (~2.4)
k_{eff} = criticality factor (<1 for ADSR)

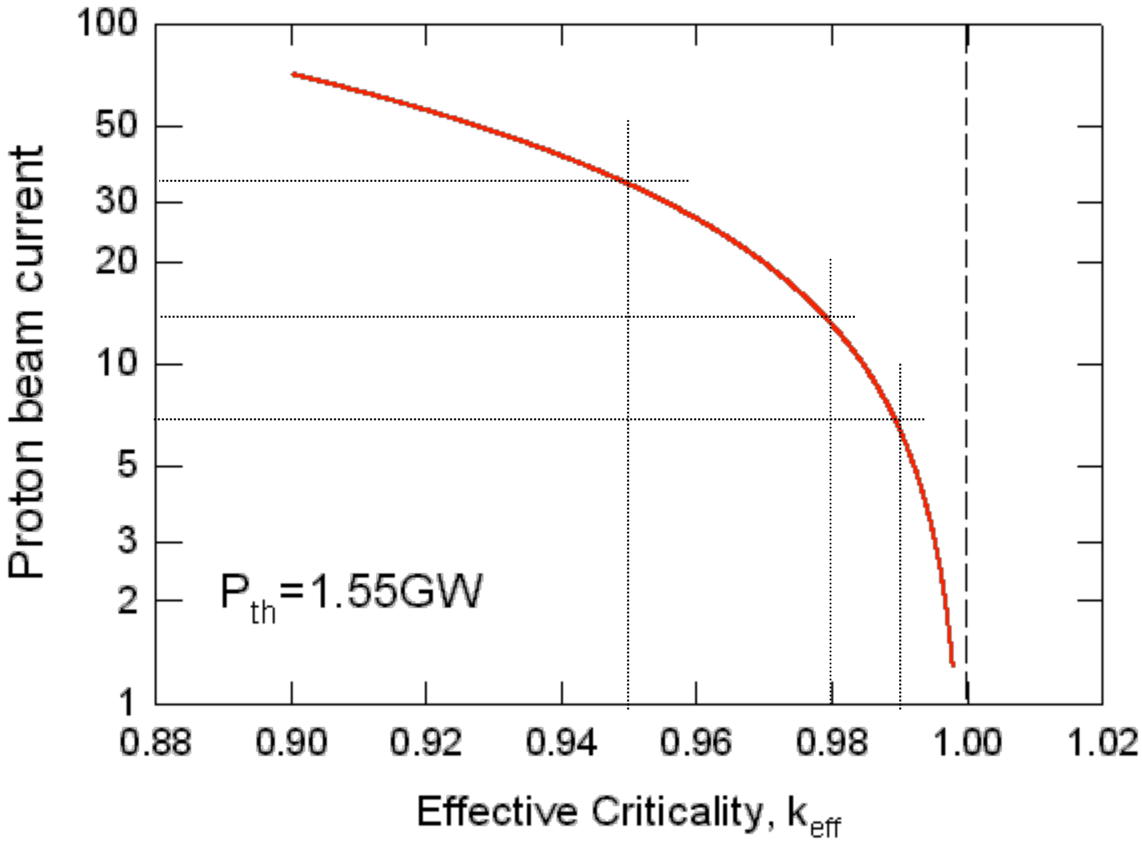
So, for a thermal power of 1550MW we require

$$N = 9.6 \times 10^{19} \times \frac{1 - k_{eff}}{k_{eff}} \quad \text{neutrons.s}^{-1}$$

Given that a 1 GeV proton produces, say, 24 neutrons (in a lead target) this corresponds to a proton current of

$$I = \frac{9.6 \times 10^{19}}{24} \times 1.6 \times 10^{-19} \times \frac{1 - k_{eff}}{k_{eff}} \; Amps = 640 \times \frac{1 - k_{eff}}{k_{eff}} \; mA$$

Proton Beam Requirements



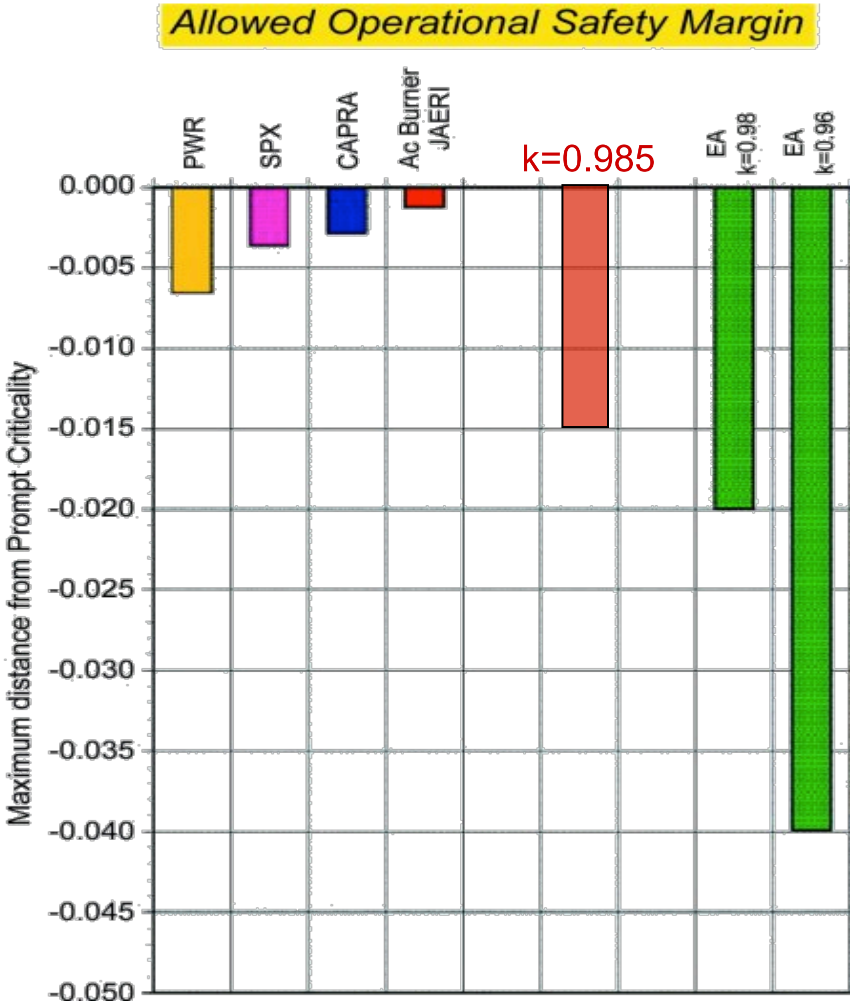
k_{eff}=0.95, i=33.7mA

k_{eff}=0.98, i=13.1mA

k_{eff}=0.99, i=6.5mA

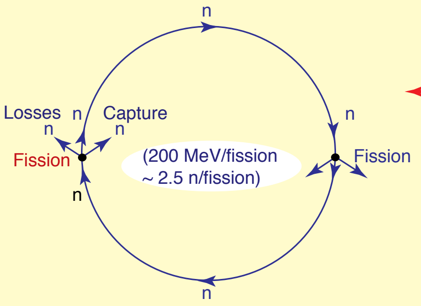
To meet a constraint of a 10MW proton accelerator we need k_{eff}*=0.985*

Safety margins



Subcritical vs Critical

Chain Reaction



Critical Reactor ⟷ **Energy Amplifier**

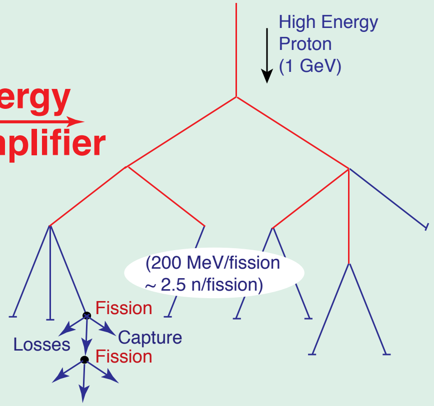
Effective neutron multiplication factor

$$k = \frac{\text{Production}}{\text{Absorption + Losses}}$$

Self-sustained process:
k = 1
(if k < 1 the Reactor stops
if k > 1 the Reactor is supercritical)

⇒ The time derivative of the power kept equal to zero by control

Nuclear Cascade



Externally driven process:
k < 1 (k = 0.98)

$$E_{tot} = G \times E_p$$

Energy Produced ↙ ↘ Beam Energy

⇒ Constant Energy Gain

❶ EAs operate in a non self-sustained chain reaction mode
- ⇨ minimises criticality and power excursions

❷ EAs are operated in a sub-critical mode
- ⇨ stays sub-critical whether accelerator is on or off
- ⇨ extra level of safety against criticality accidents

❸ The accelerator provides a control mechanism for sub-critical systems
- ⇨ more convenient than control rods in critical reactor
- ⇨ safety concerns, neutron economy

❹ EAs provide a decoupling of the neutron source (spallation source) from the fissile fuel (fission neutrons)

❺ EAs accept fuels that would not be acceptable in critical reactors
- ⇨ Minor Actinides
- ⇨ High Pu content
- ⇨ LLFF...

There is a spectacular difference between a critical reactor and an EA (reactivity in $\$ = \rho/\beta$; $\rho = (k-1)/k$) :

- Figure extracted from C. Rubbia et al., CERN/AT/95-53 9 (ET) showing the effect of a rapid reactivity insertion in the Energy Amplifier for two values of subcriticality (0.98 and 0.96), compared with a Fast Breeder Critical Reactor.
- 2.5 \$ ($\Delta k/k \sim 6.5\times10^{-3}$) of reactivity change corresponds to the sudden extraction of all control rods from the reactor.

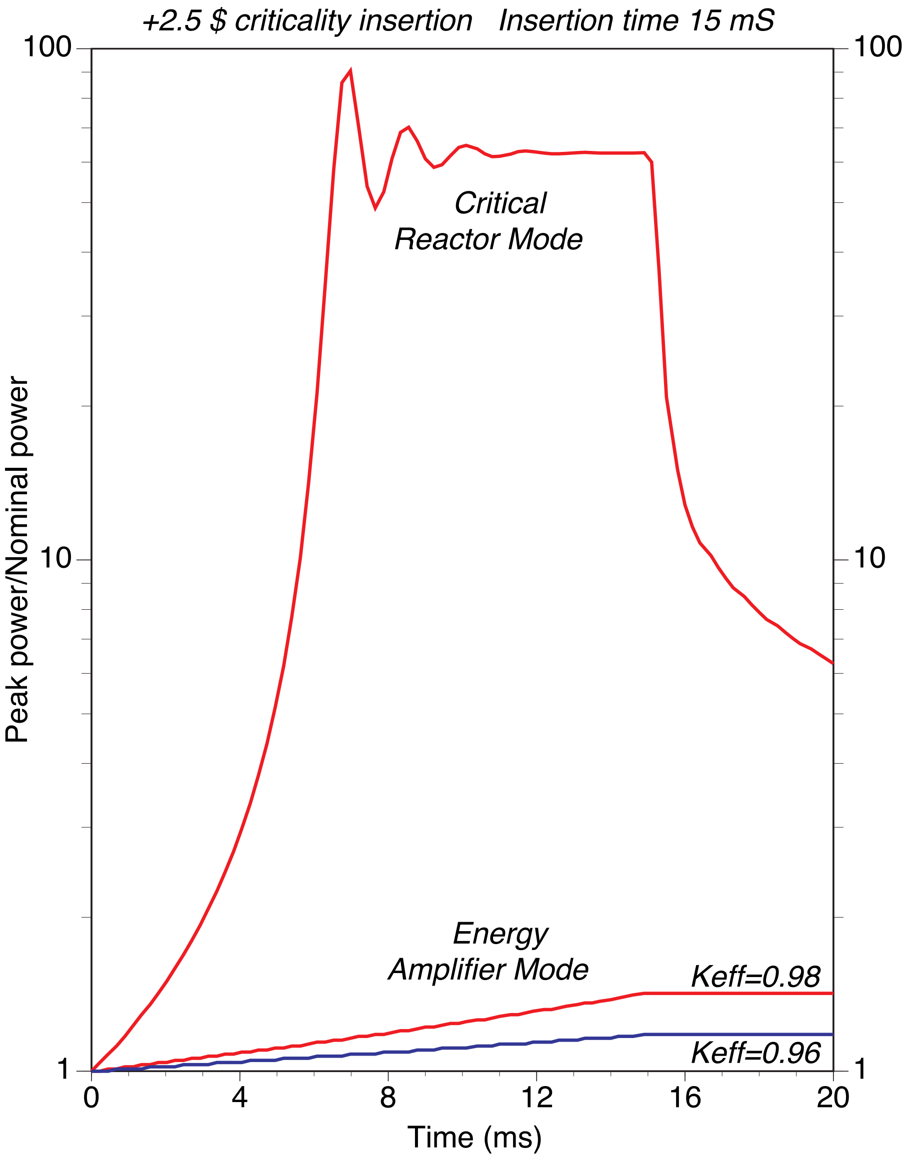


Figure 1.3

The Thorium Fuel Cycle

Advantages

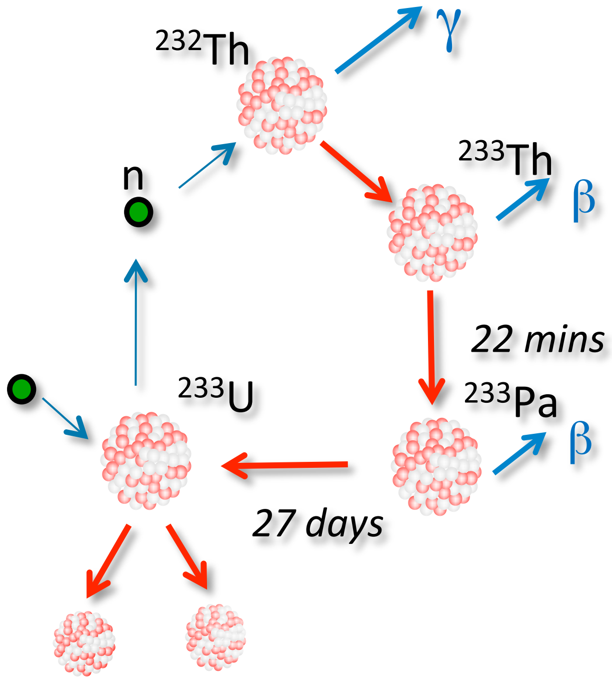
Thorium supplies plentiful

Robust fuel and waste form

Generates no Pu and fewer higher actinides

^{233}U has superior fissile properties

Proliferation *resistant*



Disadvantages

No fission until ^{233}U is produced

^{233}U is weapon grade unless denatured

Parasitic ^{232}U production results in high gamma activity

Thorex processing of waste needs substantial development

It is generally considered that the neutrons necessary to produce ^{233}U from ^{232}Th must be introduced by seeding the Th fuel with ^{235}U or Pu

Benefits of the Thorium ADS Reactor

"No plutonium is bred in the reactor"
COSMOS magazine , "New age nuclear" Issue 8, April 2006

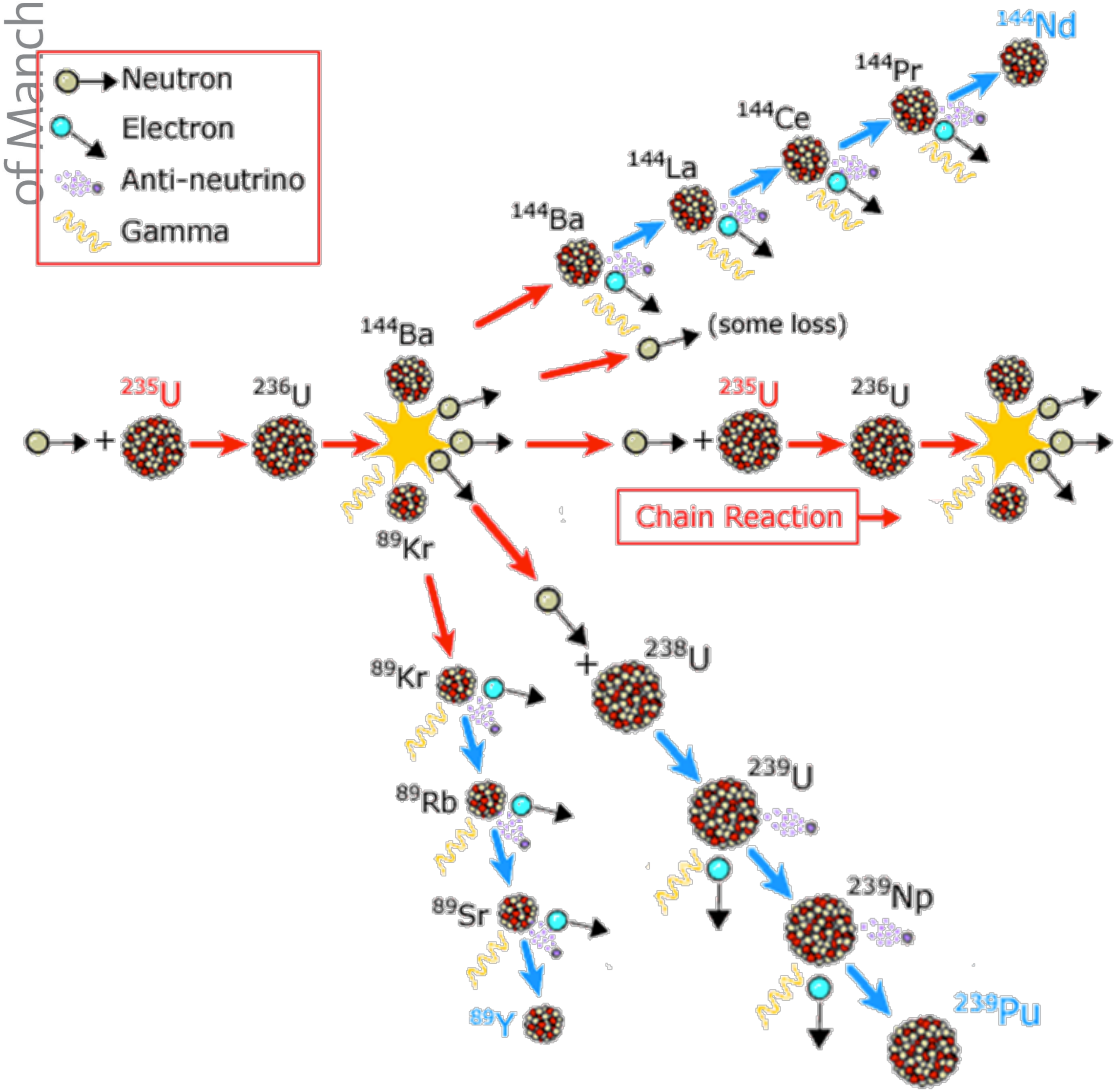
"$(Th, Pu)O_2$ fuel is more attractive, as compared to $(U, Pu)O_2$, since plutonium is not bred in the former"
IAEA-TECDOC-1450 "Thorium fuel cycle- Potential benefits and challenges", 2005.

"The advantages of the thorium fuel cycle are that it does not produce plutonium"
Thorenco LLC website

"Examination of claimed advantages, (a) Producing no plutonium, This is true of the pure thorium cycle"
IAEA-TECDOC-1319 ,"Potential advantages and drawbacks of the Thorium fuel cycle in relation to current practice: a BNFL view" 2002.

"The fuel cycle can also be proliferation resistant, stopping a reactor from producing nuclear weapons-usable plutonium"
Power Technology website

Fission/Breeding Cycles



^{238}U + 1 Neutron

^{239}Np (2.3 Days) Beta Decay

^{239}Pu + 1 Neutron
65% Fission
35% Capture

^{240}Pu + 1 Neutron

^{241}Pu + 1 Neutron
75% Fission
25% Capture

^{242}Pu + 1 Neutron

^{243}Am
Chemically Separable

^{232}Th + 1 Neutron

^{233}Pa (27.4 Days) Beta Decay

^{233}U + 1 Neutron
90% Fission
10% Capture

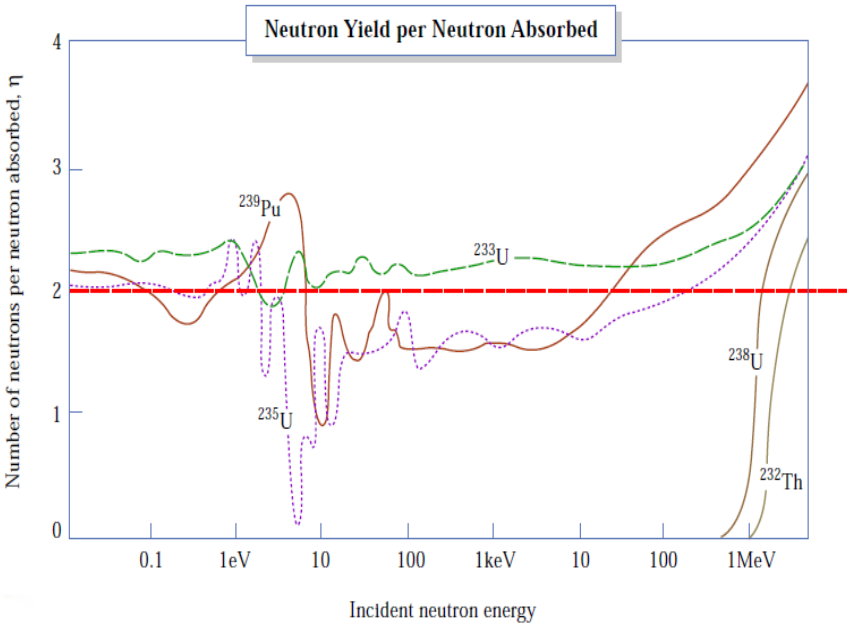
^{234}U + 1 Neutron

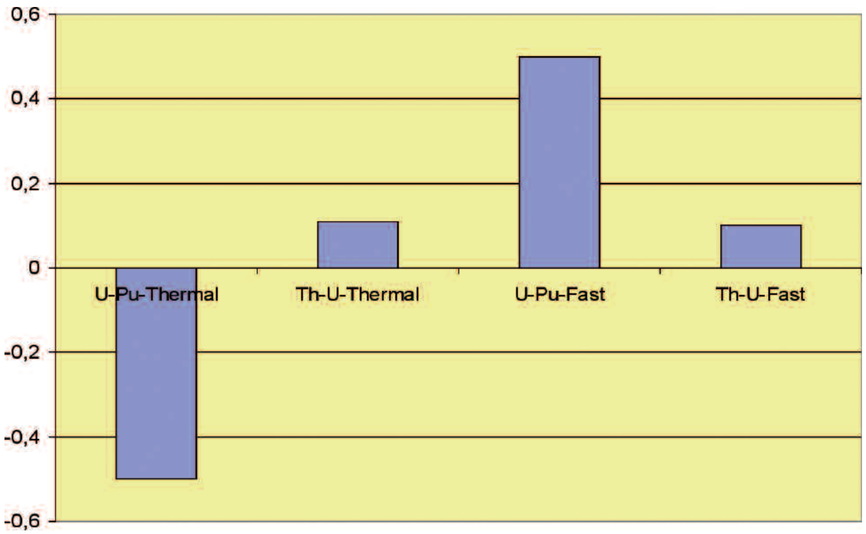
^{235}U + 1 Neutron
80% Fission
20% Capture

^{236}U + 1 Neutron

^{237}Np
Chemically Separable

Breeding and Reactor Types





Advantages

^{233}U has superior fissile properties

Robust fuel and waste form

Generates no Pu and fewer higher actinides

Proliferation *resistant*

Disadvantages

Requires introduction of fissile seed (^{235}U or Pu)

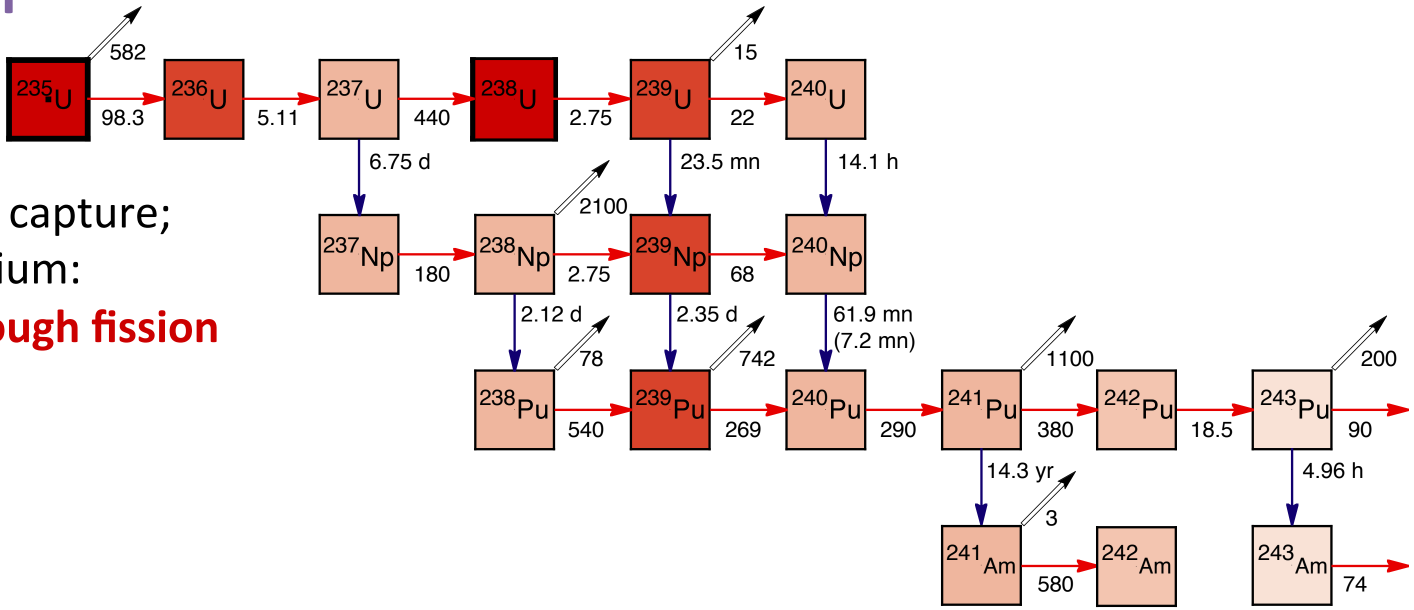
^{233}U is weapon grade unless denatured

Parasitic ^{232}U production results in high gamma activity.

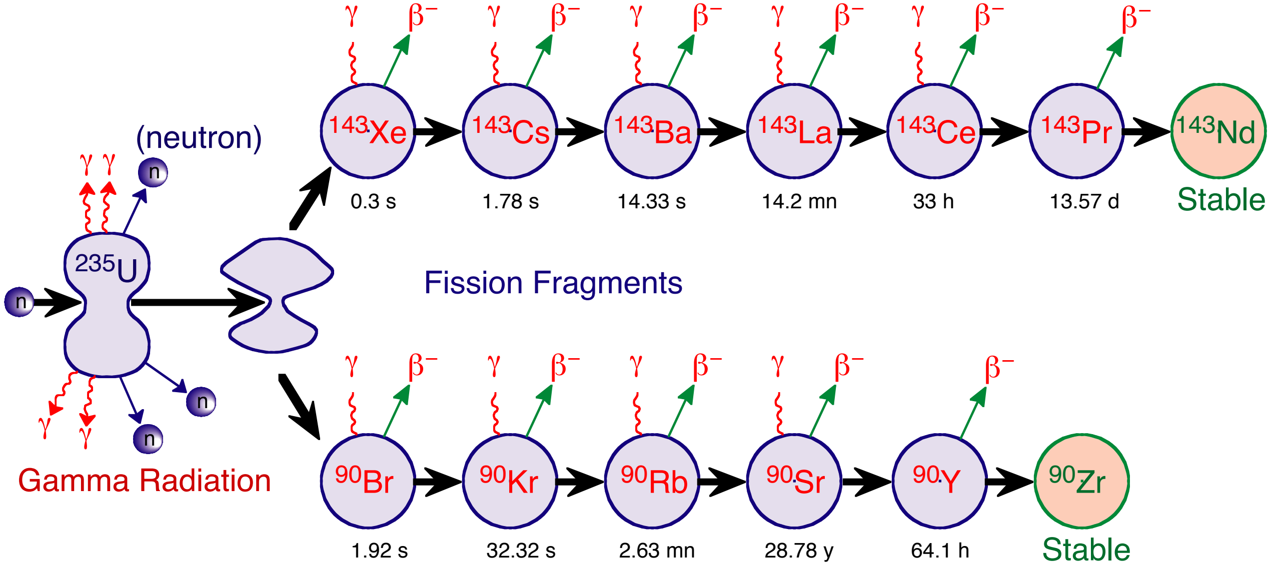
Thorex processing of waste needs substantial development

Transmutation

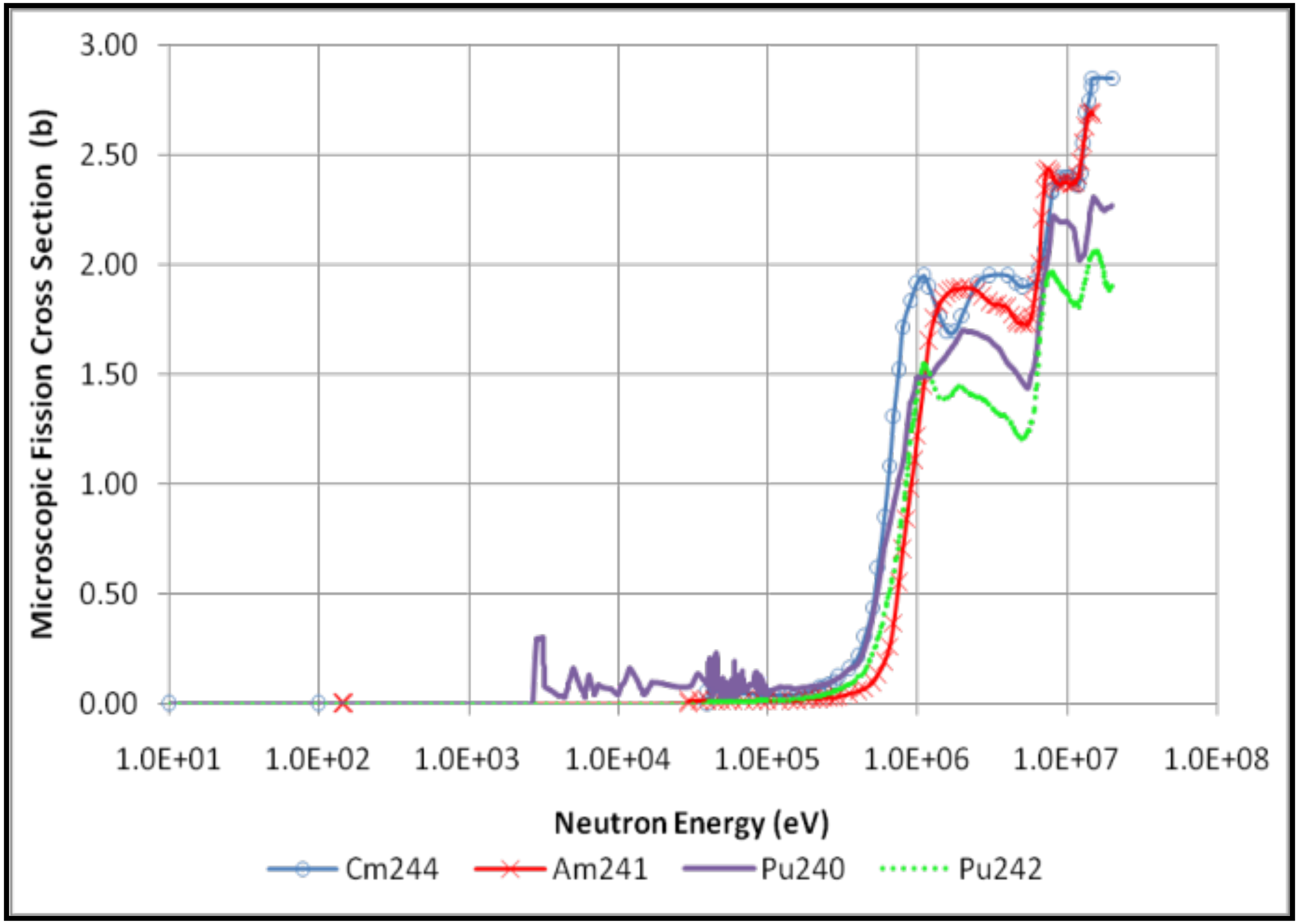
- **MAs:**
  (1.1%)
  produced by neutron capture;
  dominated by plutonium:
  ⇒ destroy them through fission



- **Fission Fragments:**
  (4%)
  the results of fissions
  ⇒ transform them into stable elements through neutron capture



Variations in Fission Cross-sections



Justification for ADS (from E. Gonzalez)

Efficient transmutation	• High (fast) neutron flux	⇒ Nuclear (Fast) Reactor	***ADS***
	• High burnup	⇒ Flexible	
	• High Pu+MA and low U content but very high safety standards	⇒ Subcritical	

The most efficient transmutation would be a reactor of significant power (nx100 or 1000 MW), of fast neutron spectrum, with a fuel with very low Uranium content and high concentration of Pu and MA.

A reactor with these characteristics shows an important lack of intrinsic safety:

Low delay neutron fraction
Small Doppler effect
Bad void coefficient

In addition the reactor needs a large operation flexibility, to be able to handle:

Very high burn-up levels in each irradiation cycle
Large reactivity evolution within one irradiation cycle

Very difficult for critical reactors and strong limitation on their transuranium elements load.

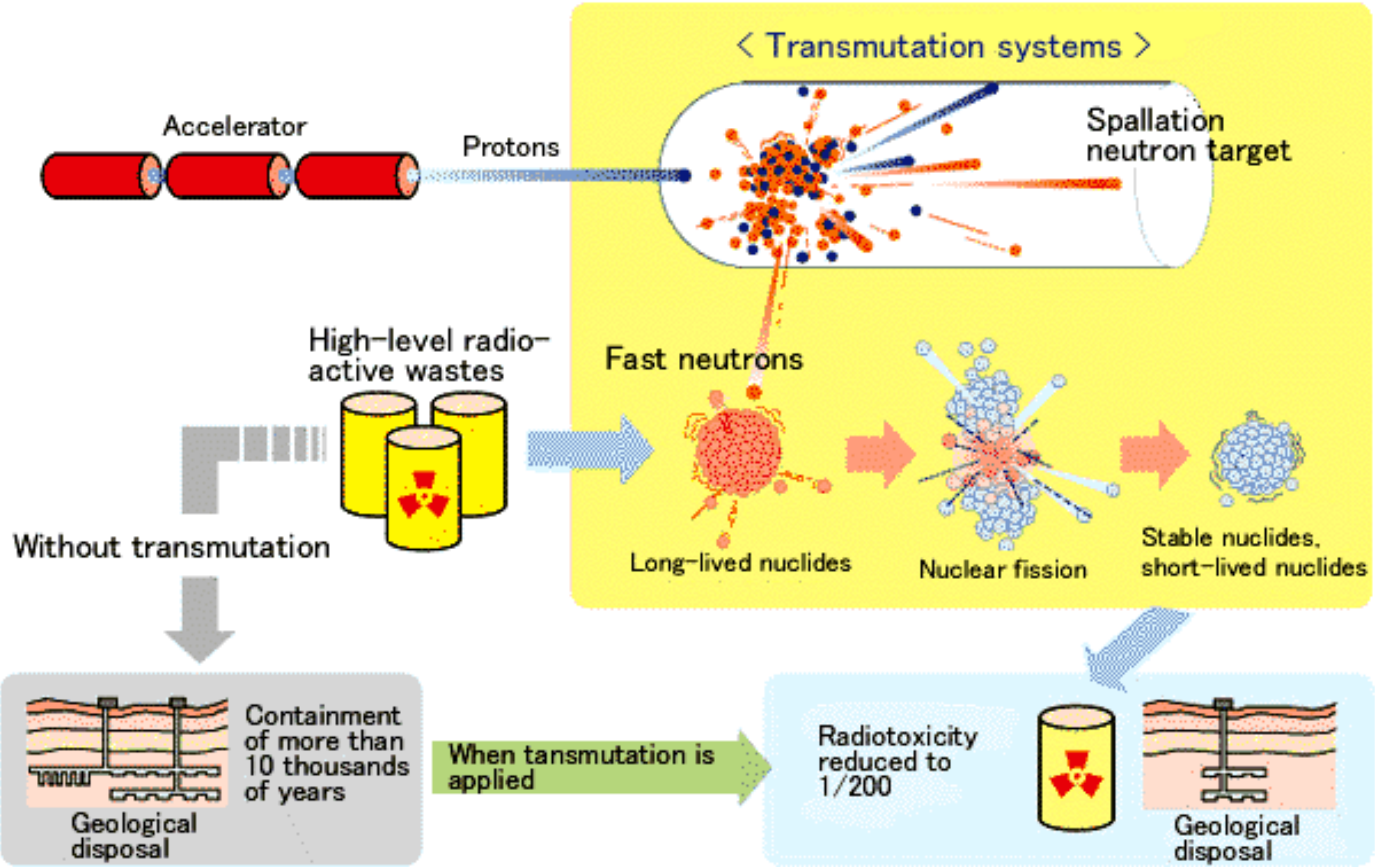
Two types of solutions:

A large number of fast reactors with small regions dedicated to transmutation (countries with large park of nuclear power plants)

A small number of subcritical accelerator driven systems, ADS, dedicated to transmutation.

ADS For Transmutation

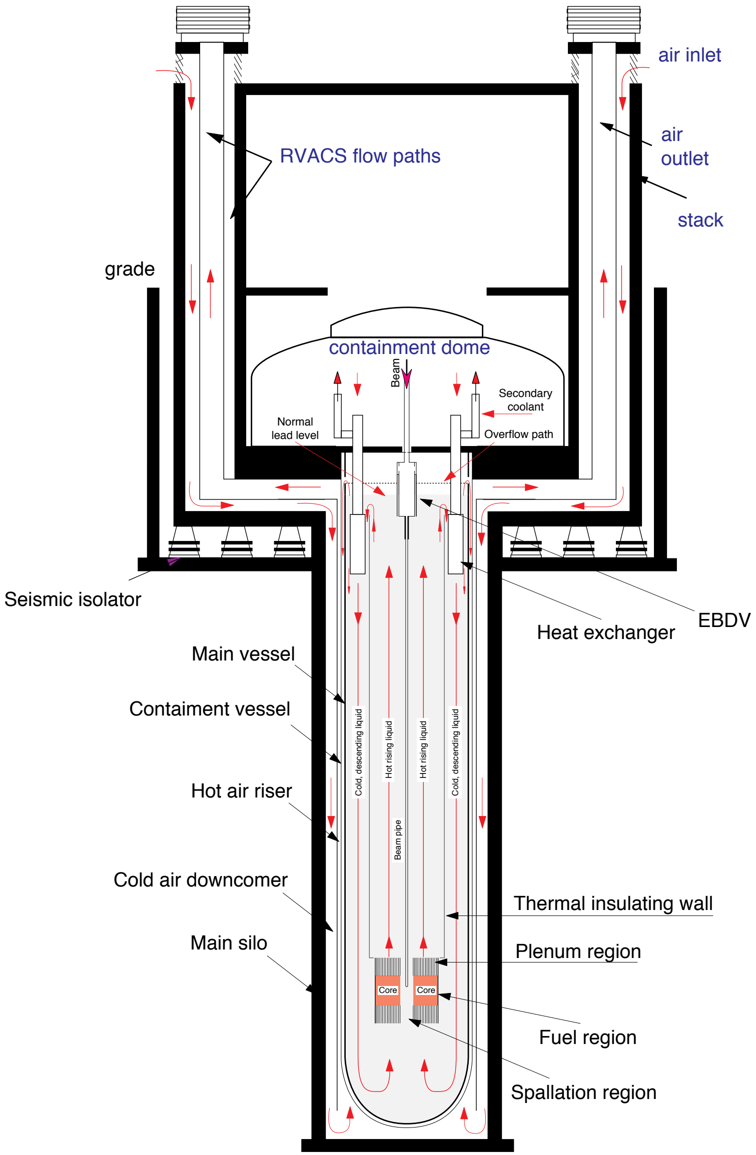
"For Christ's sake, Soddy, don't call it transmutation. They'll have our heads off as alchemists."
Ernest Rutherford, to his colleague Frederick Soddy on the discovery of transmutation of thorium, 1901.



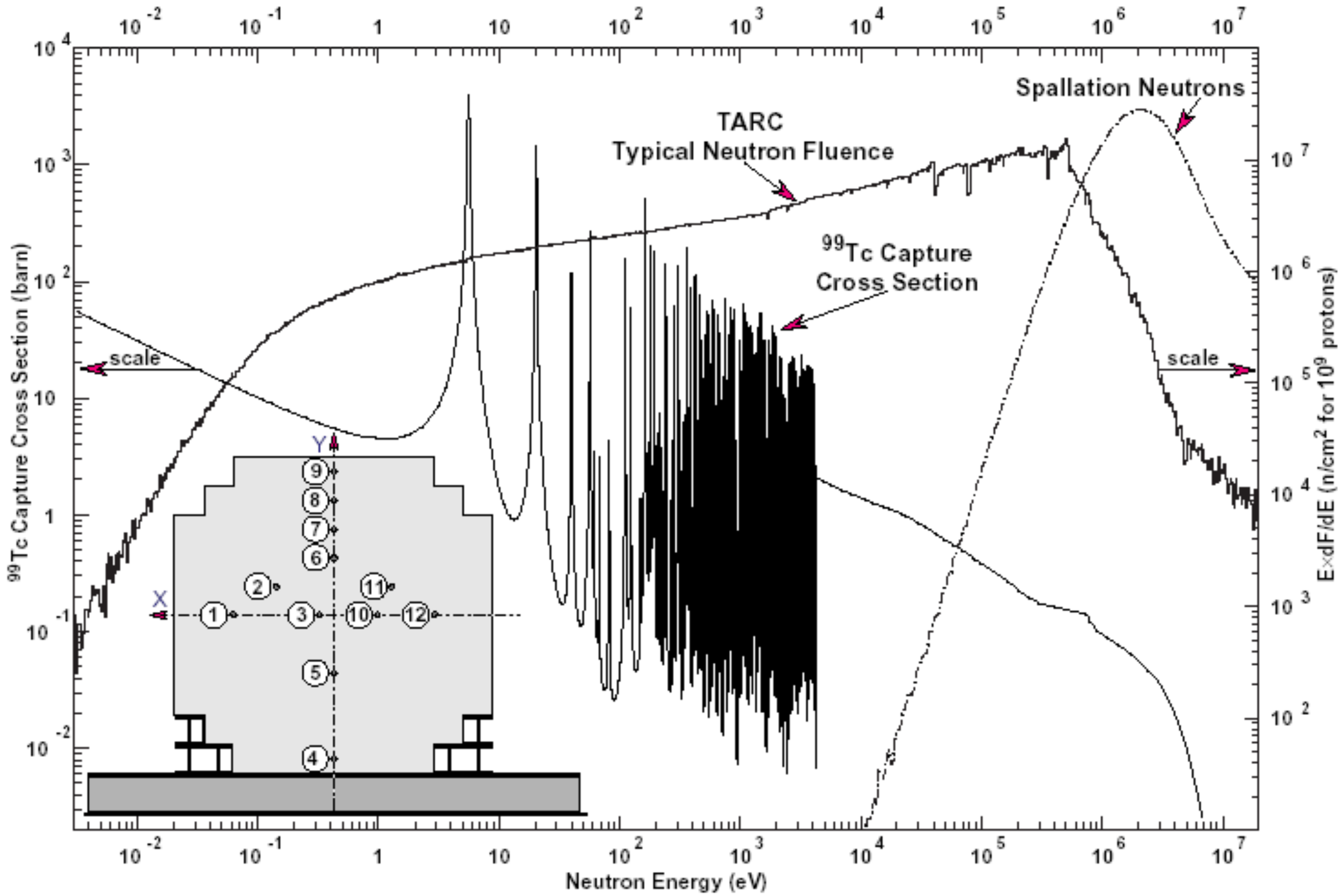
The Lead-Cooled ADS

Subcritical system driven by a proton accelerator:

- **Fast neutrons** (to fission all transuranic elements)
- Fuel cycle based on **thorium** (minimisation of nuclear waste)
- **Lead** as target to produce neutrons through spallation, as neutron moderator and as heat carrier
- **Deterministic safety** with passive safety elements (protection against core melt down and beam window failure)



Resonant Neutron Capture



Resonant Neutron Capture

Medium lived elements

$^{137}_{55}Cs\ (\tau = 30.1\ y) + n \Rightarrow\ ^{138}_{55}Cs \xrightarrow{\beta^-\ (33.2\ m)}\ ^{138}_{56}Ba$ (stable)

$^{134}_{55}Cs\ (\tau = 2.06\ y) + n \Rightarrow\ ^{135}_{55}Cs\ (\tau = 2.6 \times 10^6\ y)$

$^{90}_{38}Sr\ (\tau = 29.1\ y) + n \Rightarrow\ ^{91}_{38}Sr \xrightarrow{\beta^-\ (6.63\ h)}\ ^{91}_{39}Y \xrightarrow{\beta^-\ (58.51\ d)}\ ^{91}_{40}Zr$ (stable)

$^{90}_{39}Y\ (\tau = 64.1\ h) + n \Rightarrow\ ^{91}_{39}Y \xrightarrow{\beta^-\ (58.51\ d)}\ ^{91}_{40}Zr$ (stable)

Long lived elements

$^{135}_{55}Cs\ (\tau = 2.6 \times 10^6\ y) + n \Rightarrow\ ^{136}_{55}Cs \xrightarrow{\beta^-\ (13.16\ d)}\ ^{136}_{56}Ba$ (stable)

$^{129}_{53}I\ (\tau = 6.6 \times 10^7\ y) + n \Rightarrow\ ^{130}_{53}I \xrightarrow{\beta^-\ (12.36\ h)}\ ^{130}_{54}Xe$ (stable)

$^{126}_{50}Sn\ (\tau = 1.0 \times 10^5\ y) + n \Rightarrow\ ^{127}_{50}Sn \xrightarrow{\beta^-\ (12.4\ m)}\ ^{127}_{51}Sb \xrightarrow{\beta^-\ (3.85\ d)}\ ^{127}_{52}Te \xrightarrow{\beta^-\ (9.35\ h)}\ ^{127}_{53}I$ (s

$^{99}_{43}Tc\ (\tau = 2.1 \times 10^5\ y) + n \Rightarrow\ ^{100}_{43}Tc \xrightarrow{\beta^-\ (15.8\ s)}\ ^{100}_{44}Ru$ (stable)

$^{93}_{40}Zr\ (\tau = 1.5 \times 10^6\ y) + n \Rightarrow\ ^{94}_{40}Zr$ (stable)

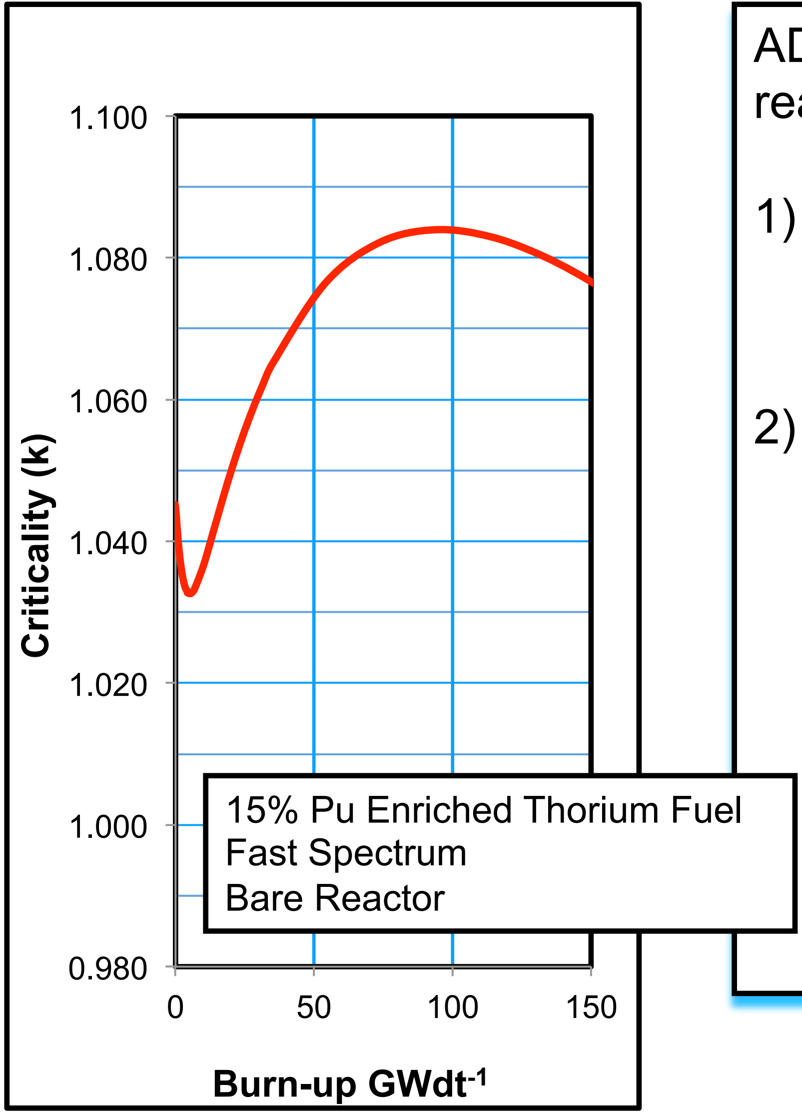
$^{79}_{34}Se\ (\tau = 6.5 \times 10^4\ y) + n \Rightarrow\ ^{80}_{34}Se$ (stable)

The Fission Reaction Dies Out When The Accelerator Stops ?

“ An ADS drives nuclear reactions that will stop if the proton beam from the accelerator stops”
Nuclearinfo.net

“If the particle beam is switched off, it is impossible for the fuel to enter a chain reaction and cause a meltdown. Instead, the rate of fission will immediately begin to slow and the fuel will eventually cool down and die out” ”
COSMOS magazine

Courtesy of David Coates, Cambridge



ADS operating modes to compensate for reactivity variations:

1) Use rods to continually flatten the reactivity variations and maintain fixed k_{eff}
2) Use fixed rods to set maximum k_{eff} and use the accelerator to compensate for reactivity movements

Note: The bare reactor is critical and requires rods to achieve sub-critical operation

Critical and ADS Shut-down

Critical – Control Rod Insertion

1)Has an inherent reduction in the reactivity of the system as a direct consequence of the action
2)Intrusive – requires a clear path

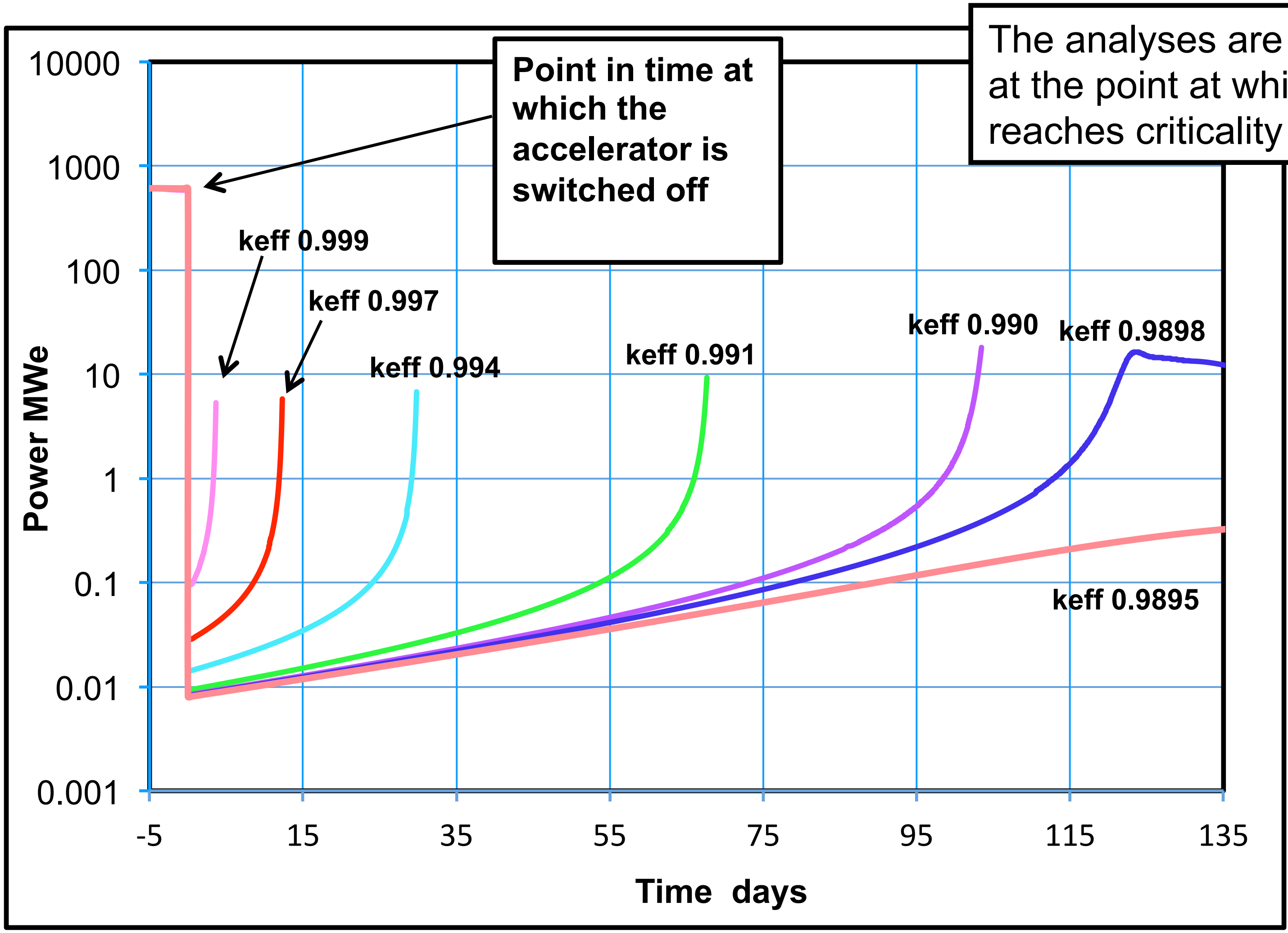
ADS- Accelerator Trip

1) No associated inherent reduction in the reactivity of the system
2) Non intrusive
3) The system must be sub-critical for this to work

The ADS trip requires the reactor to be sub-critical and remain sub-critical to be effective

Courtesy of David Coates, Cambridge

Thorium Reactor – Post Shutdown Power Increase



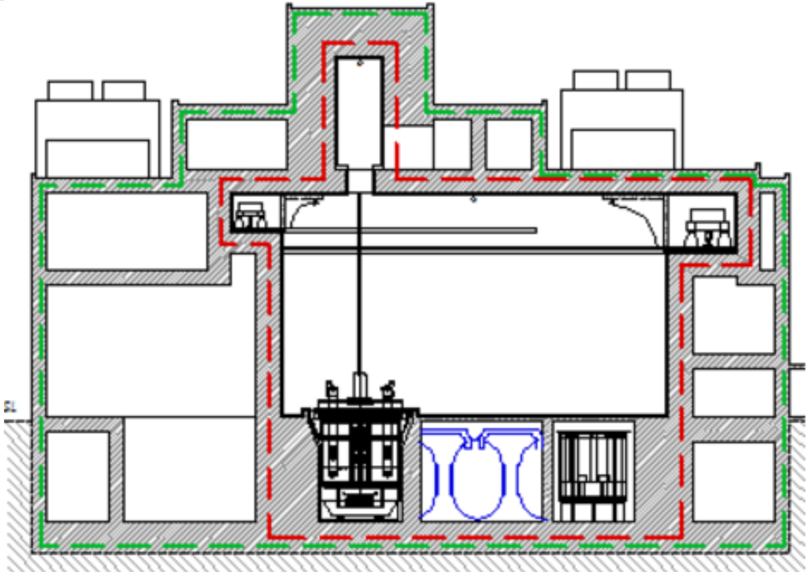
Point in time at which the accelerator is switched off

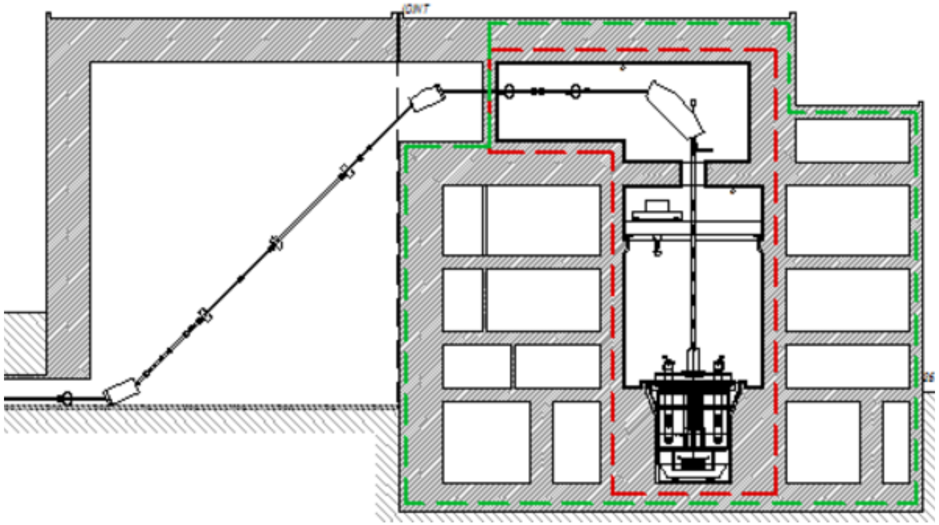
The analyses are discontinued at the point at which the reactor reaches criticality

MYRRHA: EXPERIMENTAL ACCELERATOR DRIVEN SYSTEM

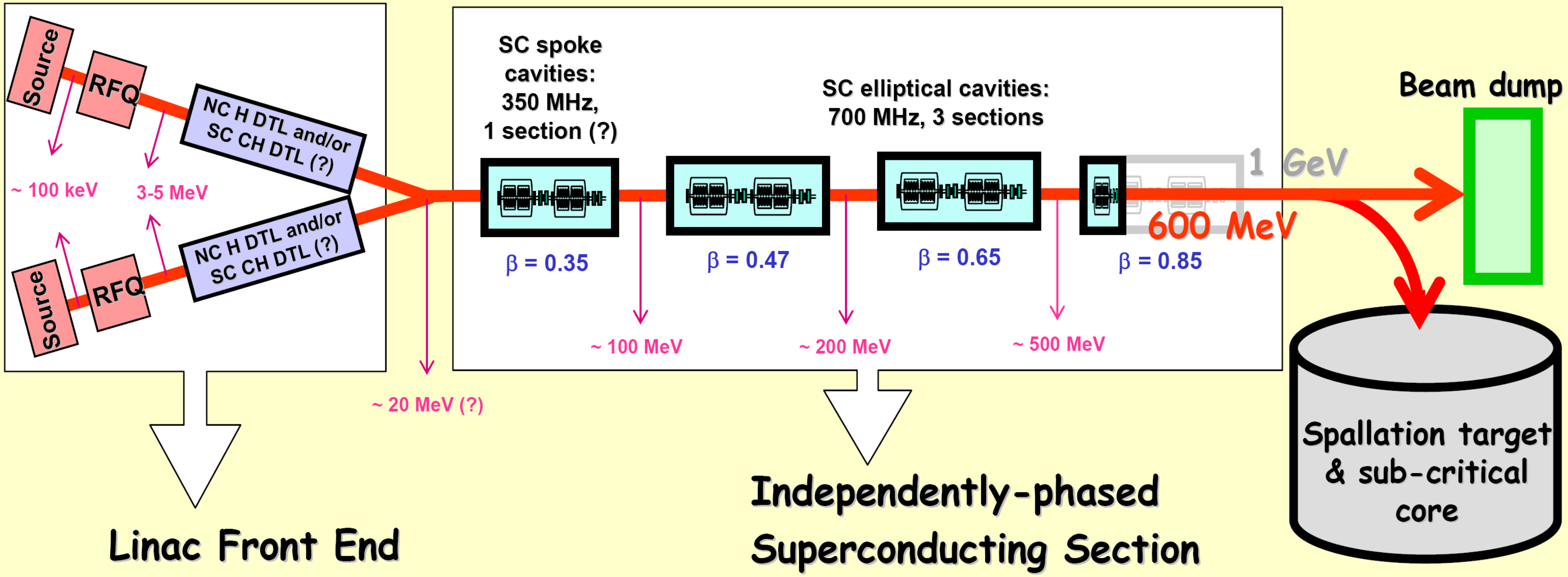
A pan-European, innovative and unique facility

MYRRHA: Integration into building





MYRRHA Proton Driver



Source
RFQ
NC H DTL and/or SC CH DTL (?)
~ 100 keV
3-5 MeV
Source
RFQ
NC H DTL and/or SC CH DTL (?)
~ 20 MeV (?)

SC spoke cavities: 350 MHz, 1 section (?)
β = 0.35
~ 100 MeV

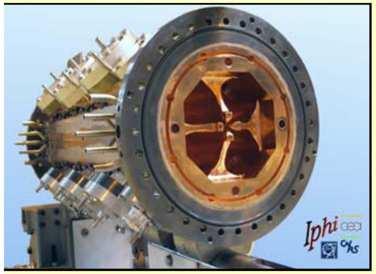
SC elliptical cavities: 700 MHz, 3 sections
β = 0.47
~ 200 MeV
β = 0.65
~ 500 MeV
β = 0.85
1 GeV
600 MeV

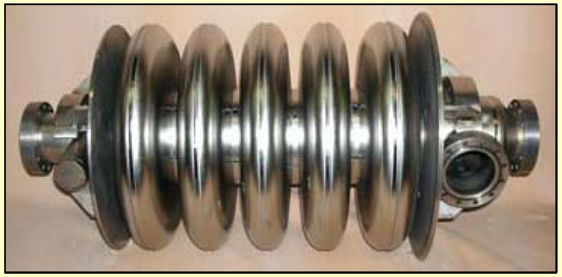
Beam dump

Spallation target & sub-critical core

Linac Front End

Independently-phased Superconducting Section



Proton Driver Alternatives

- Cyclotron
  - Energy limited in classical cyclotron
  - Power perhaps achievable, but difficult
  - Reliability not good enough
- Linac
  - Can meet power requirements (e.g. 2x ESS)
  - May be reliable enough (loss of module okay)
  - But too expensive for commercial use

(JAEA and MYRRHA demonstrators propose linac)

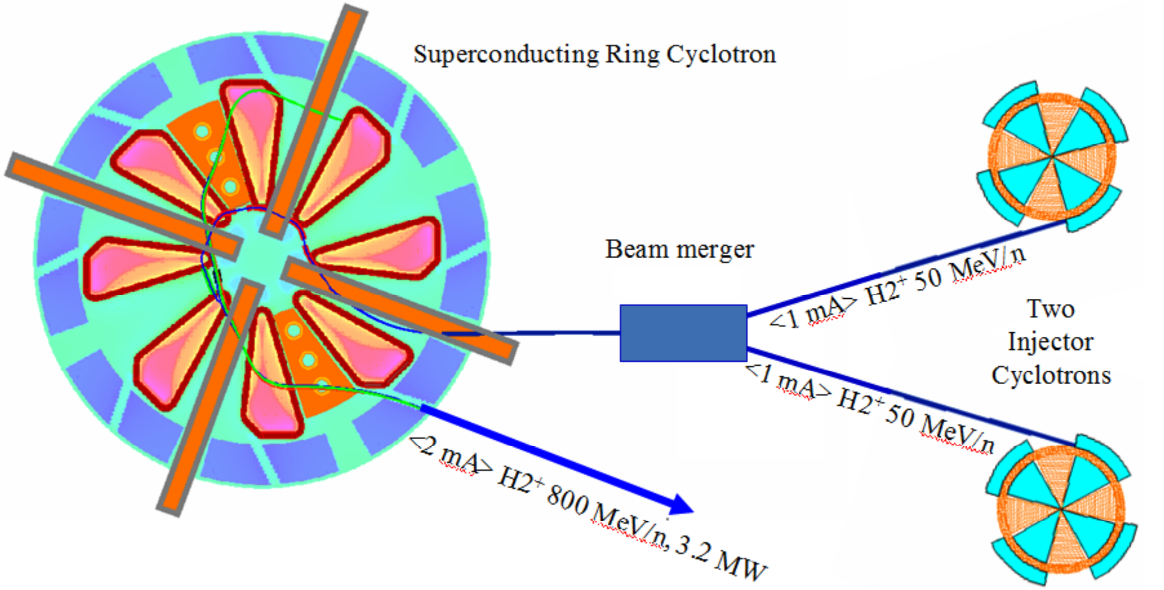
- Synchrotron
  - Can't yet achieve currents (RCS?)
  - More complicated (ramping magnets), therefore reliability probably low
- FFAG
  - Can deliver currents in principle
  - Still quite large
  - Simpler than synchrotron
  - First proton FFAGs only built recently at KEK

High-Power Cyclotron Options

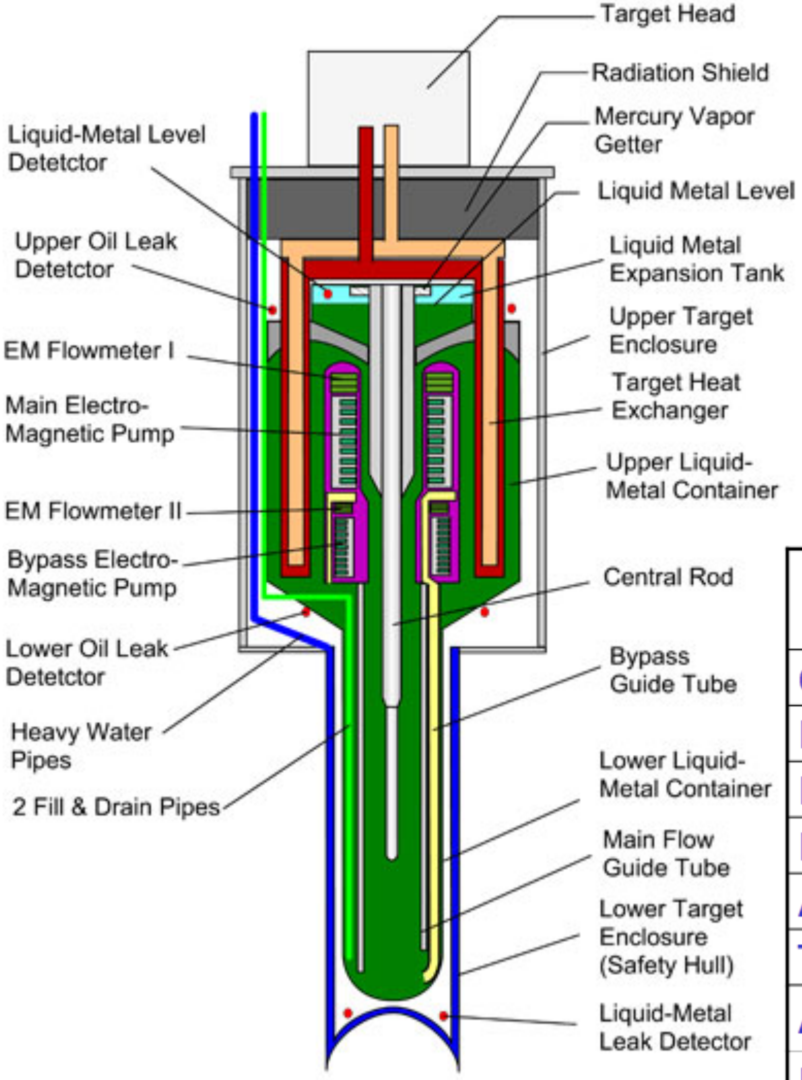
Accelerated Species	Advantages	Disadvantages
H+	Simpler ion source	Poor extraction efficiency Auto-extraction limited to 85%?
H-	Stripping extraction	Lorentz stripping Gas stripping
H2+	Stripping extraction	Lorentz stripping Gas stripping Complex extraction path

Favoured option: H2+
Calabretta et al., INFN-Catania
arxiv:1107.0652

Rext	4.9m
<B>ext	1.88T
Bmax	< 6.3 T
V	0.5-1 MV/turn
dE	3.6 MeV/turn



MEGAPIE (SINQ Facility, PSI)



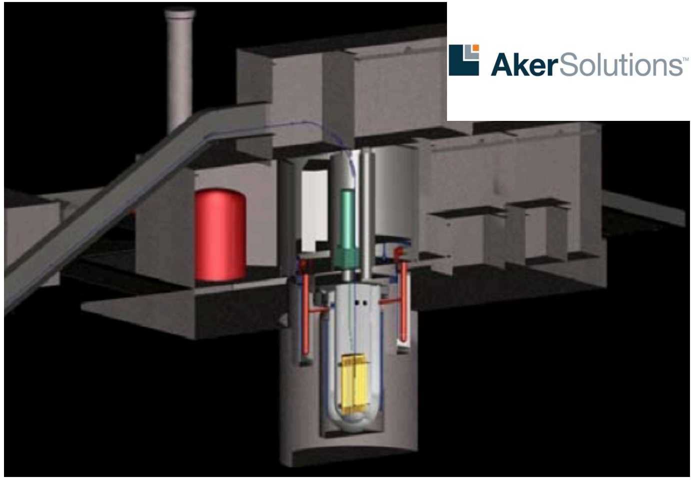
Ran successfully for 4 months in 2006

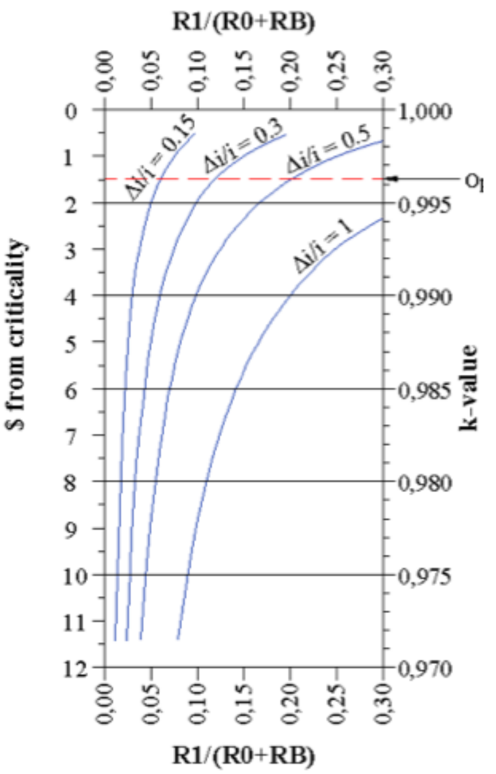
700 kW, CW, liquid Pb-Bi
First Pb-Bi spallation target

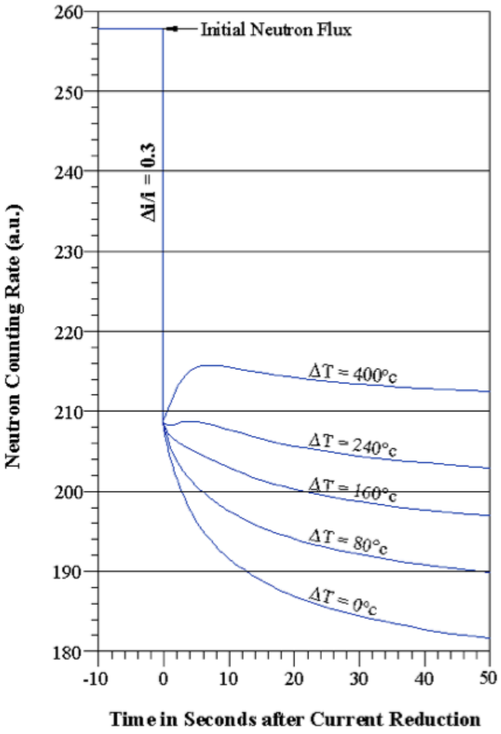
	Megapie	XT-ADS target
Coolant / target	liquid Pb-Bi	liquid Pb-Bi
Beam energy	595 MeV	600 MeV
Beam current	1.4 mA max	3 mA
Lifetime	4 months	9 months
Accumulated charge	2.8Ah	20Ah
Target diameter	Ø20 cm	Ø10 cm
Accumulated charge / m²	90 Ah/m²	2500 Ah/m²
Beam interface	window	windowless

ADTR

- 1^{st} demonstration of ADSR
- Reactor kinetic studies (load-following)
- Source-jerk k_{eff} measurement (ADTR concept)
- Fuel irradiation measurements

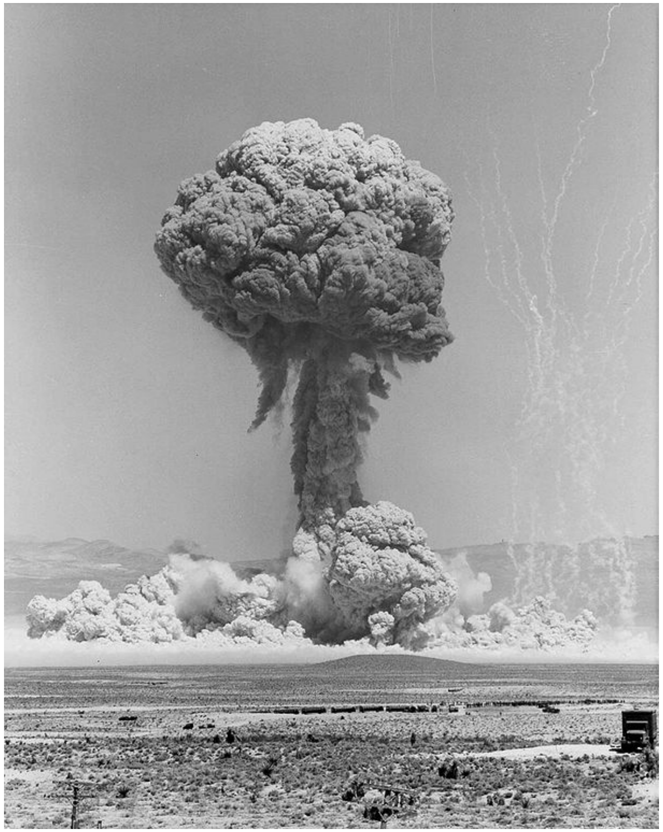






Thermal Power (P_{th})	1500 MW $_{th}$
Electric Power (P_{el})	600 MW $_{el}$
Fuel	ThO_2 /PuO_2 84.5%/15.5% (first cycle)
Total fuel mass	59 tonne
Target fuel dwell time	8 – 10 years
Neutron multiplication coefficient (k_{eff})	0.995
Power density ρ	55 W/g oxide
Energetic Gain G	402 to 532
Coolant	natural lead
Spallation target	natural lead
Coolant temperature at core inlet	400˚C
Coolant temperature at core outlet	540˚C
Four off single loop lead to water/steam heat exchangers rated at 375 MW per unit	
Water temperature (feed to system steam generators)	340˚C
Steam temperature	450˚C
Steam pressure	183 bara
Coolant pumps	4 off axial flow
Sub-critical configuration, accelerator driven	

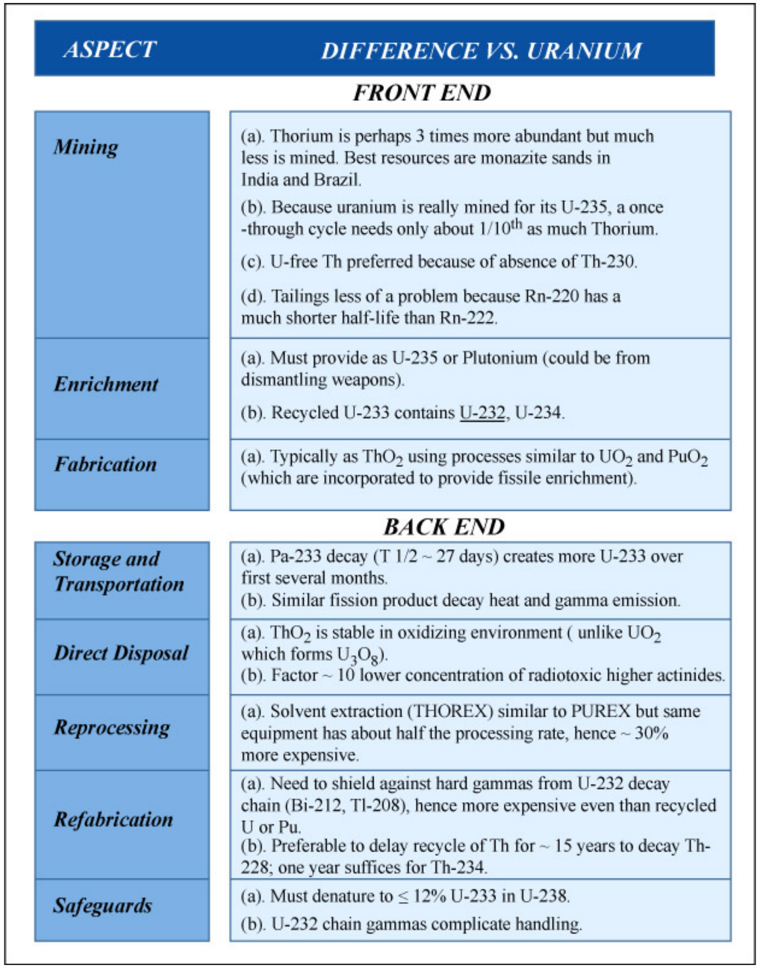
Proliferation



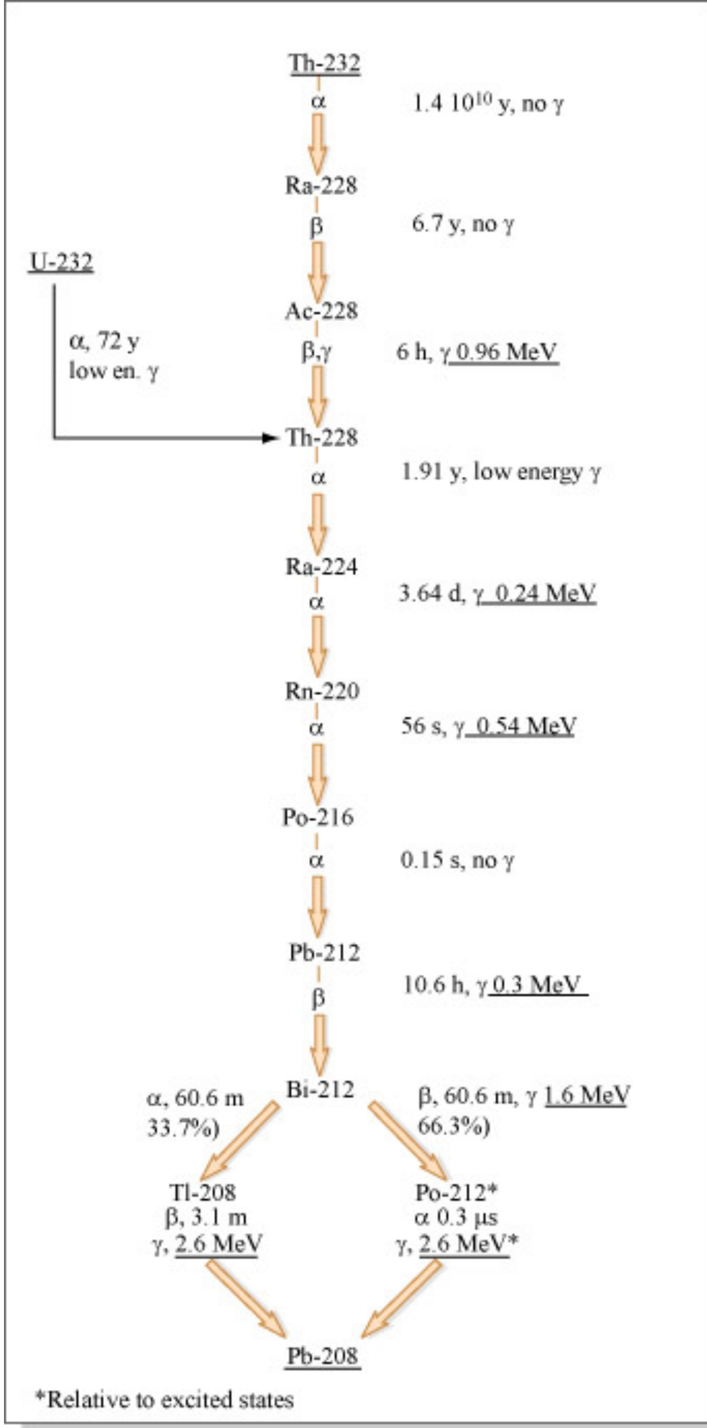
- Operation Teapot
  - 233U test
  - So you can make a bomb from it
- IAEA enrichment limit is somewhere around 12%
  - Depends on the amount of 235U
- Can be protected by denaturing with 238U
  - (requires enrichment, i.e. won’t be done)

Proliferation and Cost

$$^{230}\text{Th} \xrightarrow{n,\gamma} {}^{231}\text{Th} \xrightarrow[25.52\ \text{h}]{\beta^-} {}^{231}\text{Pa} \xrightarrow{n,\gamma} {}^{232}\text{Pa} \xrightarrow[1.31\ \text{days}]{\beta^-} {}^{232}\text{U}$$



ASPECT	*DIFFERENCE VS. URANIUM*
	FRONT END
Mining	(a). Thorium is perhaps 3 times more abundant but much less is mined. Best resources are monazite sands in India and Brazil. (b). Because uranium is really mined for its U-235, a once -through cycle needs only about 1/10th as much Thorium. (c). U-free Th preferred because of absence of Th-230. (d). Tailings less of a problem because Rn-220 has a much shorter half-life than Rn-222.
Enrichment	(a). Must provide as U-235 or Plutonium (could be from dismantling weapons). (b). Recycled U-233 contains U-232, U-234.
Fabrication	(a). Typically as ThO_2 using processes similar to UO_2 and PuO_2 (which are incorporated to provide fissile enrichment).
	BACK END
Storage and Transportation	(a). Pa-233 decay (T 1/2 ~ 27 days) creates more U-233 over first several months. (b). Similar fission product decay heat and gamma emission.
Direct Disposal	(a). ThO_2 is stable in oxidizing environment (unlike UO_2 which forms U_3O_8). (b). Factor ~ 10 lower concentration of radiotoxic higher actinides.
Reprocessing	(a). Solvent extraction (THOREX) similar to PUREX but same equipment has about half the processing rate, hence ~ 30% more expensive.
Refabrication	(a). Need to shield against hard gammas from U-232 decay chain (Bi-212, Tl-208), hence more expensive even than recycled U or Pu. (b). Preferable to delay recycle of Th for ~ 15 years to decay Th-228; one year suffices for Th-234.
Safeguards	(a). Must denature to ≤ 12% U-233 in U-238. (b). U-232 chain gammas complicate handling.



*Relative to excited states

Key Papers and Books

- Michael Dittmar, ‘The Future of Nuclear Energy’ Vols 1-4, arXiv (2009)
- R. R. Wilson, ‘Very Big Accelerators as Energy Producers’, FERMILAB-FN-0298
- Nifenecker et al.: ‘Hybrid Nuclear Reactors’
  Progress in Particle and Nuclear Physics 43 (1999) 683-827
- Nifenecker et al.: ‘Basics of accelerator driven subcritical reactors’ Nuclear Instruments and Methods in Physics Research A 463 (2001) 428–467
- IAEA-TECDOC-985 ‘ Accelerator Driven Systems: Energy Generation and Transmutation of Nuclear Waste’
- Leipunskii et al., ‘Development of Nuclear Power with Fast-Neutron Reactors in the USSR’, Atomnaya Energiya, 25 (1968), 380-387
- Rubbia et al., CERN/AT/94-47 & CERN/AT/95-44, Phys Rev C73, 054610 (2006)
- S. Andriamonje et al. Physics Letters B 348 (1995) 697–709,
- J. Calero et al. Nuclear Instruments and Methods A 376 (1996) 89–103;