Earth, Environment and Energy

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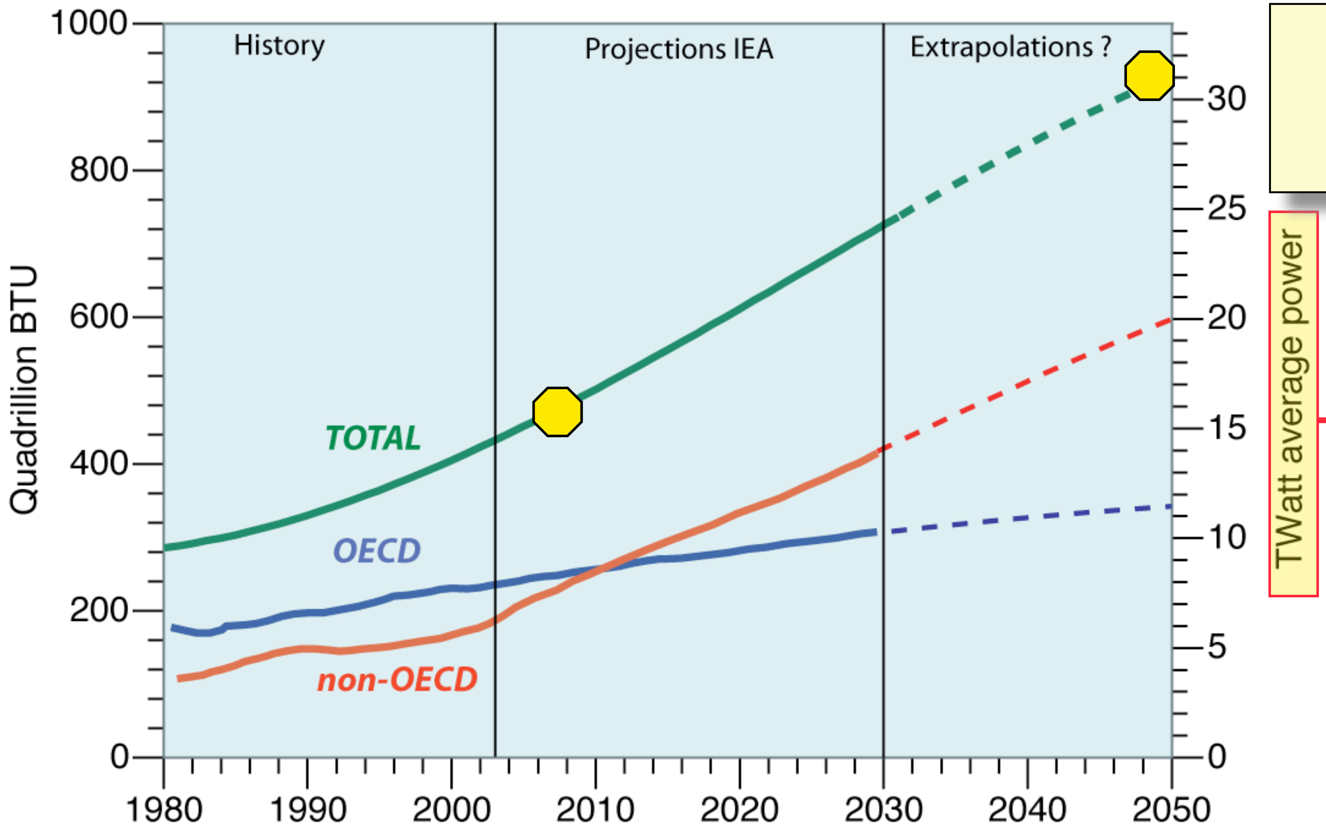
Primary total world's Energy



These are the requirements

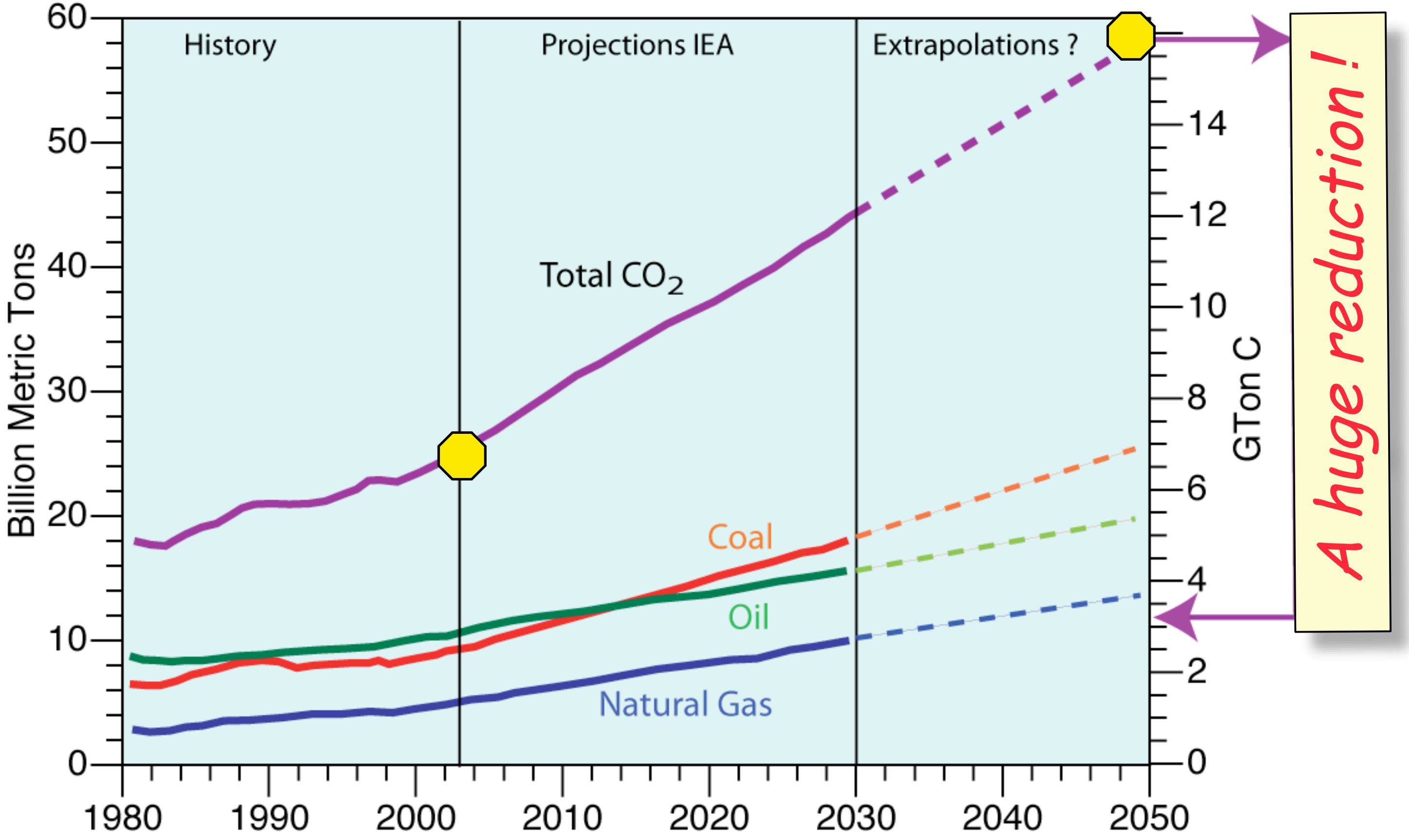
The question is: with which kinds of resources ?

- Today the energy consumption is equivalent to the one of an "engine" with an average power of 15 TWatt
- Predictions of "business as usual" indicate that energy may increase to as much as 30-35 TWatt by 2050

A new "political" determination…

- The realization of the risks related to Climate Change has generated especially in the in the EU -but also elsewhere- the political determination (based on well founded scientific considerations) for a quick and dramatic reduction of the present emissions from fossils.
- Global warming and pollution are inevitable consequences of our growing population and economies. Investing in devices which conserve energy is worthwhile, but also **new alternatives** must be vigorously pursued with an appropriate level of investment.
- It is generally believed that by 2050, or even earlier, a progressive reduction to at least 1/2 the present CO_2 emissions from fossils is needed, namely to 6 TWatt, leading to 24-29 TWatt of "carbon free" supplies, or if possible, of more.
- *WARNING: Reversing an **un-interrupted fossil dominance** lasted for over three centuries may not be accomplished **without fierce oppositions**.*

Curbing the CO2 emissions: the magnitude of the problem



- Today about 80% of the energy produced is due to fossils, with about 6.5 GTonC emitted every year.
- Predictions of "business as usual" indicate that that it may continue to increase to as much as 15 GTonC/year by 2050.

Present nuclear energy

- Today's nuclear energy is based on U-235, 0.71 % of the natural Uranium, fissionable both with thermal and with fast neutrons.
- A massive increase of this technology (5 ÷ 10 fold), such as to counterbalance effectively global warming is facing serious problems of accumulated waste and of scarcity of Uranium ores.
- In the sixties,"atoms for peace" promised a cheap, abundant and universally available nuclear power, where the few "nuclear" countries would ensure the necessary know-how to the many others which have renounced to nuclear weaponry.
- Today, the situation is far from being acceptable: the link between peaceful and military applications has been shortened by the inevitable developments and the corresponding widening of the know-how of nuclear technologies.
- For the nuclear penetration to become freely and abundantly available in all countries, some totally different but adequate nuclear technologies must be developed.

A few numbers on nuclear power ….

- By 2050, to produce 12 TWatt i.e. 1/3 of the “carbon free” primary energy with *ordinary reactors*, we would need to use for instance about 5000 nuclear reactors each of 1 Gwatt(e),
- At≈ 80% efficiency and a nominal lifetime of 40 years this would mean to build about one new 1 GWatt reactor every three days.
- A serious evaluation of the fuel availability and critical issues related to proliferation especially in the developing countries and the security of long-term waste disposal should be carried out when facing these much larger numbers in a long-time perspective.
- *A New Nuclear*, but on a longer timetable and with due consideration for its problems will necessarily require different fuel, “breeding”, incineration of the long lived waste and a new reprocessing with a “closed” fuel cycle.

The need of new nuclear reactions

- The huge increment of nuclear energy eventually needed to combat global warming excludes an exclusive use of U-235

$$^{232}Th + n \rightarrow {}^{233}U; \quad {}^{233}U + n \rightarrow fission + 2.3n \quad (Th \;\; cycle)$$

Non Proliferating

$$^{238}U + n \rightarrow {}^{239}Pu; \quad {}^{239}Pu + n \rightarrow fission + 2.5n \quad ({}^{238}U \;\; cycle)$$

Proliferating

- The amounts of energy available in nature as ores are comparable to the one for the D-T fusion reaction:

$$Li + n \rightarrow T; \quad T + D \rightarrow He + n \quad (Fusion)$$

Non Proliferating

- While reaction from U-238 is again strongly proliferating, reactions on Th-232 and on Lithium may be safely exploited in all countries.

Fission energy without U-235 ?

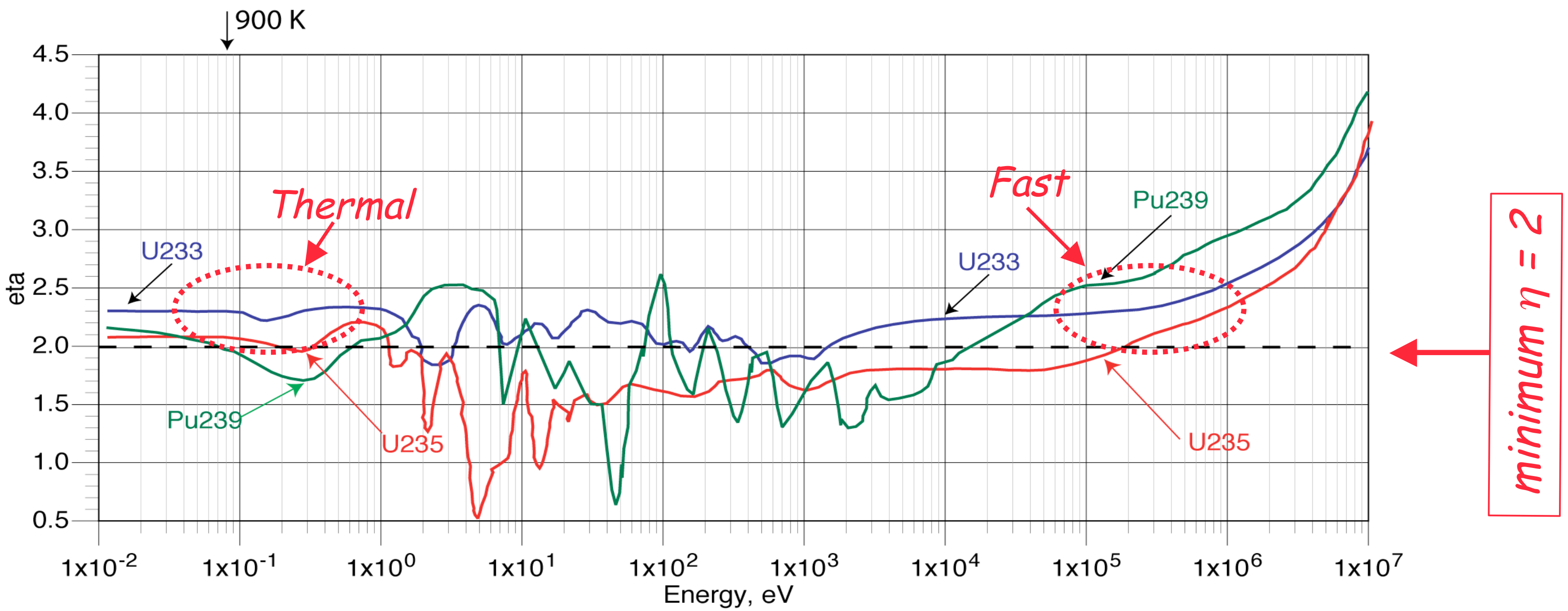
- New, more powerful nuclear reactions are possible. Particularly interesting are fission reactions on U-238 or Th-232 in which
  - the natural element is progressively converted into a readily fissionable energy generating daughter element
  - the totality of the initial fuel is eventually burnt
  - the released energy for a given quantity of natural element *is about two hundred times greater than the one in the case of the classical, U-235 driven nuclear energy.* (F.I. 1 GWe x year = 200 ton of U and ≈ 1 ton of Th)
- Th-232 average abundance on the crust (10^{-5}) is 4 x U, near to the one of Lead. Th energy yield is about 3 x 10^{6} times the one of Coal
- U-238 or Th-232 are adequate for many tens of centuries at a level several x the today's primary fossil production

Fission Breeders

- A neutron capture in the very abundant 232-Th and 238-U which cannot themselves sustain a neutron chain reaction, is followed by fission of the fertile element, U-233 or Pu-239.
- In the steady process of a fission driven chain of the daughter element derived from the initial supply of a non-fissile element, *a minimal number η of two neutrons must be produced, one to maintain the chain reaction and the other absorbed by the fertile material.*
- In practice the actual number η of neutrons necessary in the fuel for each neutron absorbed in the fissile isotope must be >2 in order to allow for the inevitable losses in the process due to captures in the other materials, escapes and so on.
- This is a new situation which requires major new developments of the reactor technology. An ordinary reactor will not operate without the presence of abundant U-235.

Thermal and fast options

- Most of the present day reactors operate with thermal(ized) neutrons, for which a well established technology exists.
  - ⇨ A Uranium (U-238) breeder will not operate with thermal neutrons, since there Pu-239 has η <2. Very fast neutrons are mandatory.
  - ⇨ A Thorium (Th-232) breeder can instead operate both with thermal and fast neutrons.



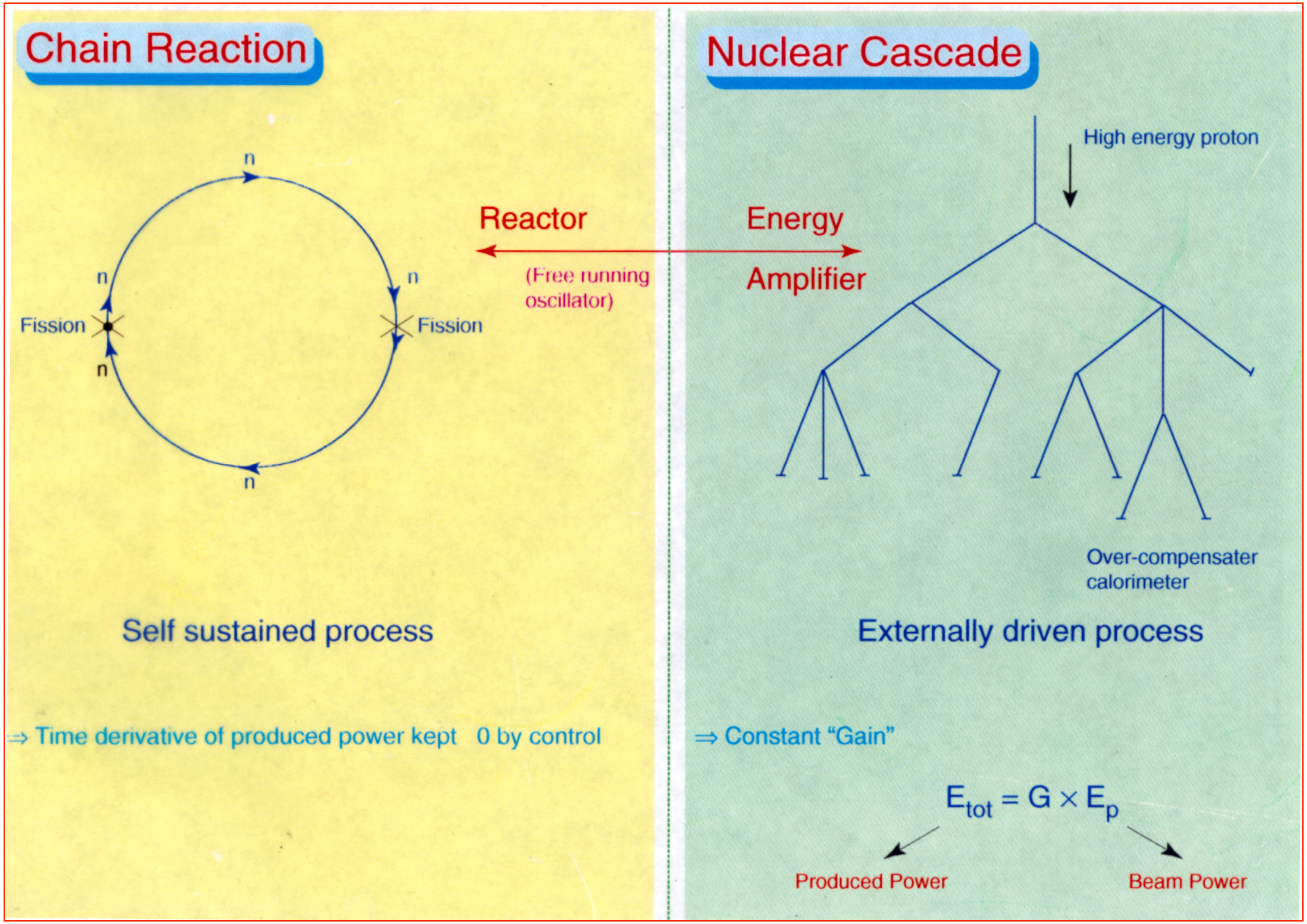
The need for a new concept: an Accelerator driven system

- This very small neutron excess is essentially incompatible with the requirements of any critical reactor without U-235. An external neutron source must be added to ensure the neutron inventory balance. This is both true for Fission (Th and/or Depleted U) and D-T Fusion starting from Lithium.
- The development of modern accelerators has permitted the production of a substantial complementary neutron flux with a proton driven high energy spallation source (ADS).
- Let k_{eff} be the neutron multiplication coefficient of an ADS (k_{eff} =1 for a critical reactor). In a "sub-critical" mode, k_{eff} <1 neutrons are produced by a spallation driven proton beam source and multiplied by fissions. The nuclear power is then directly proportional to the proton beam power with a gain G:

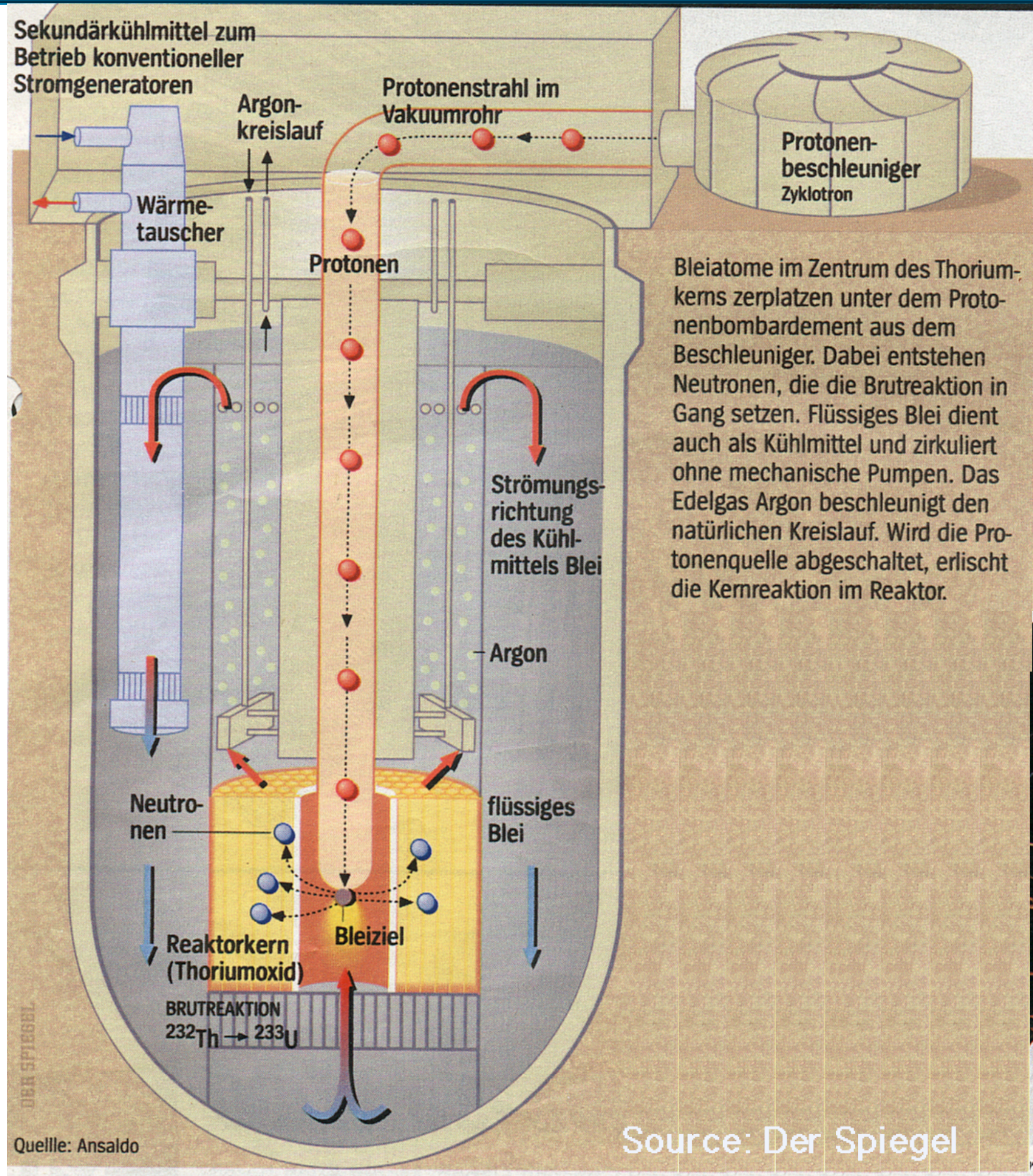
$$G = \frac{\chi}{1 - k_{eff}} \quad ;\chi \approx 2.1 \div 2.4 \;\; for \;\; Pb - p \; coll. > 0.5 \;\; GeV$$

G = 70-80 for K_{eff}=0.97 and G = 700-800 for K_{eff} = 0.997 (very large)

Critical(reactor) and sub-critical (energy amplifier) operation

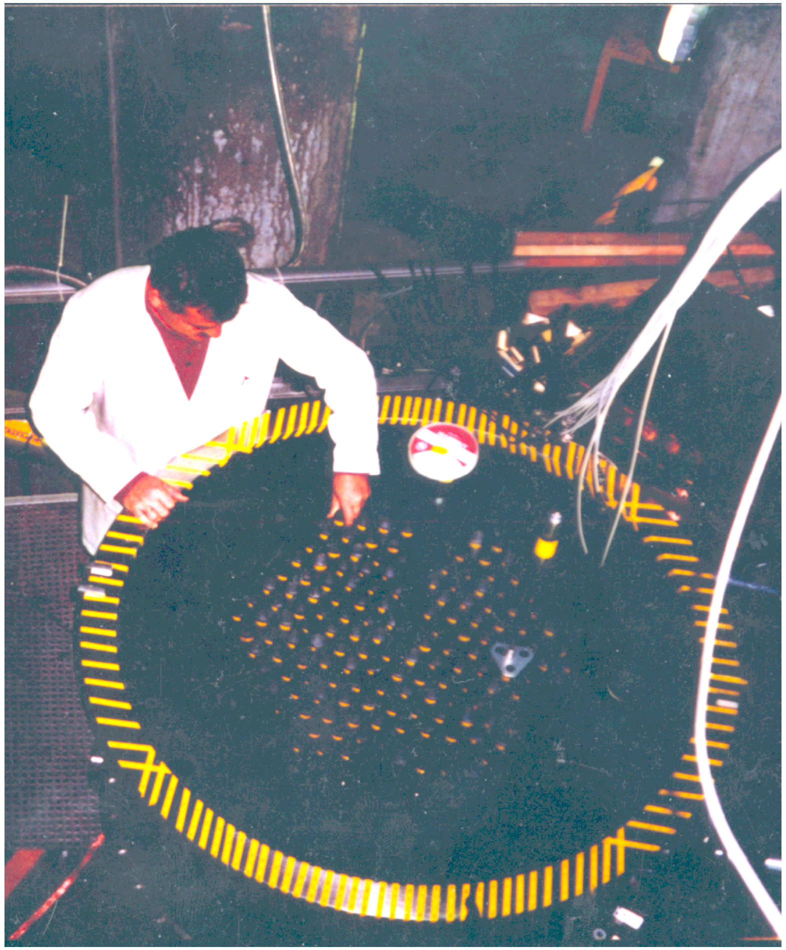


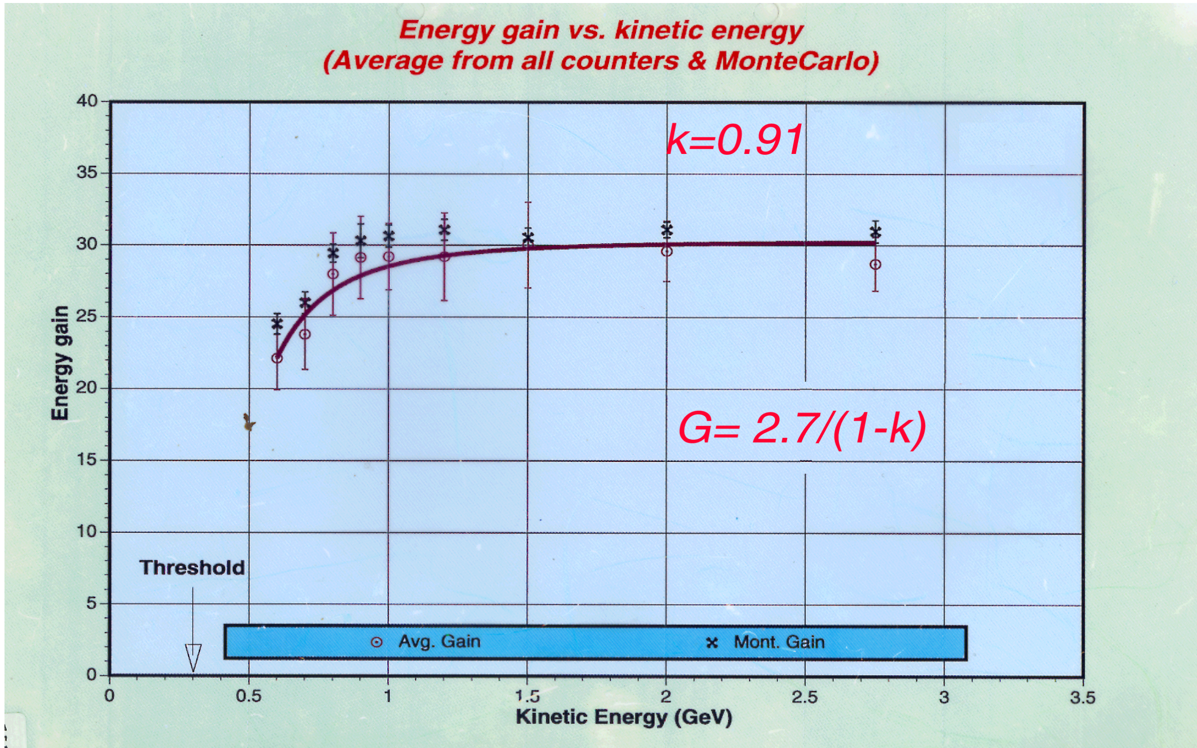
Spiegel's picture



The FEAT Experiment

A proton beam between 0.5 to 3 GeV kinetic energy from the CERN-PS on a Natural Uranium-Water sub-critical target of 2.5 tons and k = 0.91





Sub-critical unit with natural U in water
Temperature rise is measured

Excellent agreement between calculations and experiment

The thorium driven fast EA

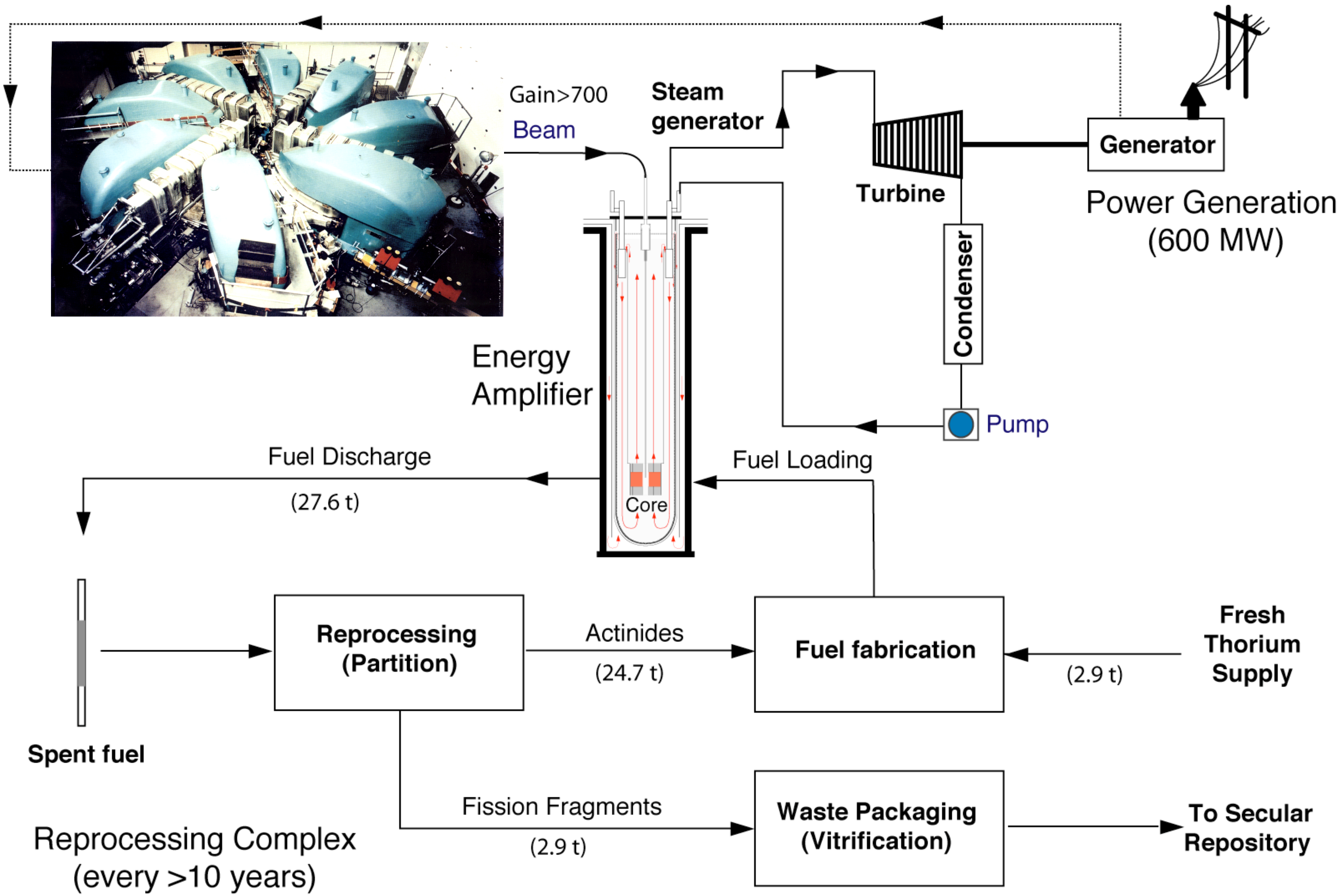


Figure 1

The energy Amplifier

- **Closed cycle**: all actinides are recycled indefinitely unmixed. The only "waste" are fission fragments and structural materials which are relatively short-lived
- **Fast neutrons** and fuel cycle based on **Thorium**
- **Lead** as target both as neutron moderator and as heat carrier
- **Subcritical system** driven by a proton accelerator
- **Deterministic safety** with passive elements to eliminate
  - ⇨ Prompt criticality
  - ⇨ Meltdown
  - ⇨ Decay heat
  - ⇨ Seismic protection

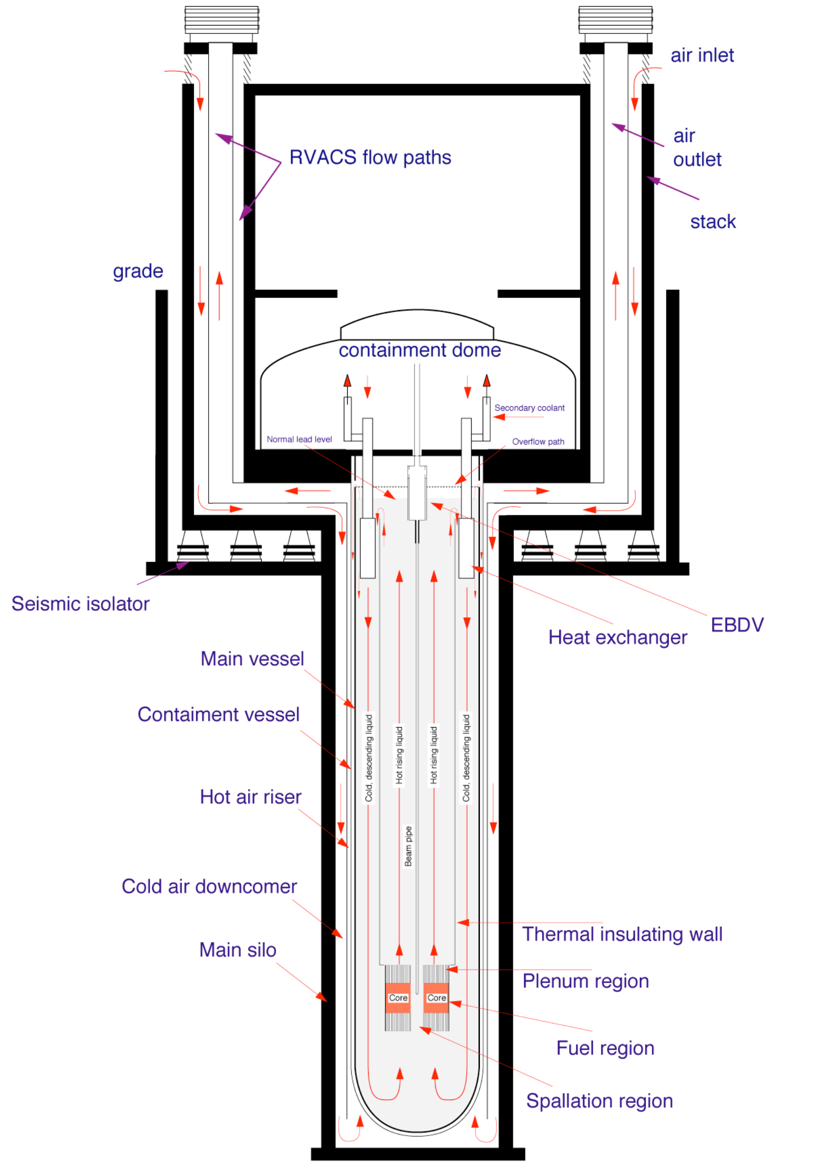


Figure 4.1a

Main parameters of the EA according to CERN/AT/95-44 Rev.

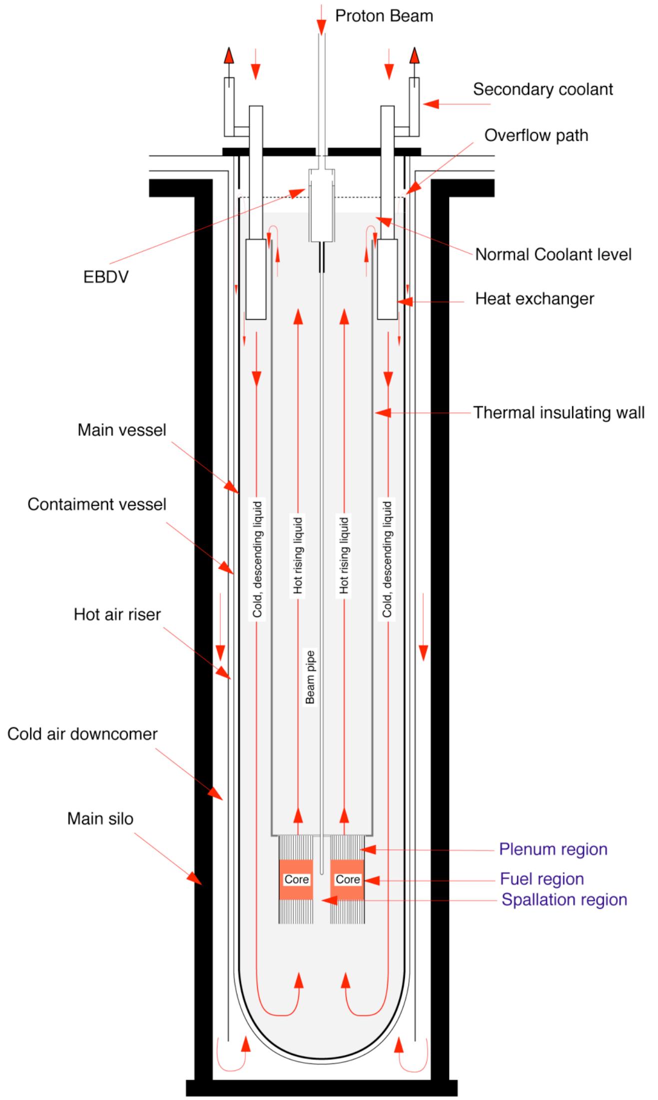


Figure 4.1b

Gross Thermal Power/unit	1500	MW
Electric conversion efficiency	40	%
Primary Electric Power	600	MW
Type of plant	Pool	
Coolant	Molten Lead	
Sub-criticality factor k, (nominal)	0.997	
Doppler Reactivity Coefficient, (Dk/DT)	– 1.37 ¥ 10-5	
Void coefficient (coolant) Dk/(Dr /r)	+ 0.010	
Nominal energetic EA gain	800	
Scram systems, Control Bars	CB4 rods	
Seismic Platform	yes	
Proton Accelerator		
Type of Accelerator	cyclotron	
Accelerator circulating Power	1.875	MW
Fraction Electric Power recirculated by beam	3.125 x 10-3	
Kinetic energy	600	MeV
Average current	3.125	mA
Spallation neutrons/proton	19.2	
Target geometry	windowless	
Main Vessel		
Gross height	30	m
Diameter	6 m	m
Material	HT-9	
Walls thickness	70	mm
Weight (excluding cover plug)	2000	ton
Double Liner	yes	
Fuel Core		
Initial fuel mixture	0. 845ThO2 +0.155PuO2	
Initial fuel mass (oxide)	27.85	ton
Cladding material	low act. HT-9	
Specific power	57.4	W/g
Dwelling time (aver. @ 0.7 peak power)	12	years
Average Burn-up (oxide)	120.0	GW d/t
Primary cooling system		
Approximate weight of the coolant	10,000	ton
Pumping method	Nat. Convection	
Height convection column	25	m
Convection generated primary pressure	0.637	bar
Heat exchangers,(located in main vessel)	4 ¥ 375	MW
Secondary Coolant	H2O vapour	
Decay Heat Passive Cooling to Air	RVACS	

The breeding equilibrium

- Assume for simplicity the main breeding process $n + {}^{232}Th \xrightarrow{\beta-} {}^{233}Pa \xrightarrow{\beta-} {}^{233}U$
- In steady neutron flux conditions, the chain will tend to an equilibrium, namely to a condition in which each fissioned nucleus is replaced by a newly bred fuel nucleus. To a first approximation, the spectrum averaged equilibrium is

$$\phi\left\langle \sigma_{\gamma}^{232Th} \right\rangle N\left({}^{232}Th\right) = \frac{N\left({}^{233}Pa\right)}{\tau\left({}^{233}Pa \rightarrow {}^{233}U\right)} = \phi\left\langle \sigma_{\gamma}^{233U} + \sigma_{fiss}^{233U} \right\rangle N\left({}^{233}U\right)$$

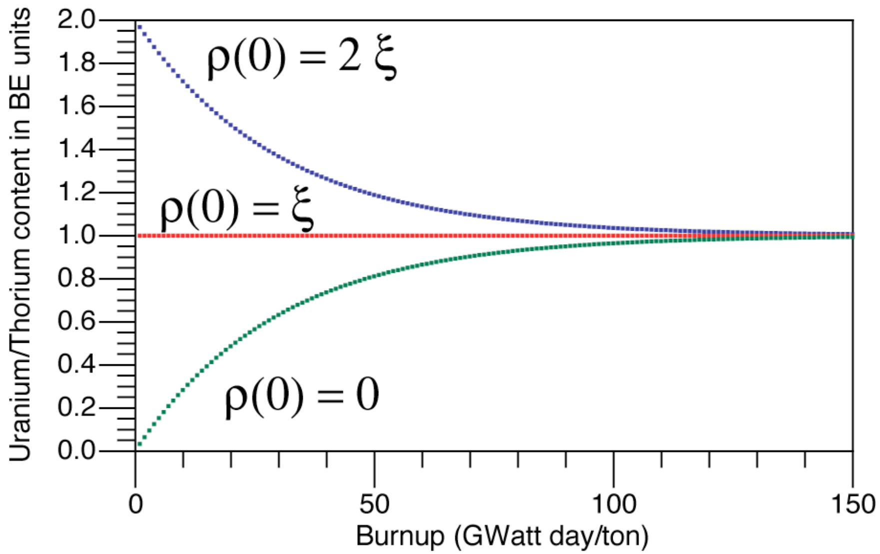
- The breeding equilibrium is then a pure function of the averaged cross sections

$$\xi = N\left({}^{233}U\right) / N\left({}^{232}Th\right) = \left\langle \sigma_{\gamma}^{233U} + \sigma_{fiss}^{233U} \right\rangle / \left\langle \sigma_{\gamma}^{232Th} \right\rangle$$

- Ratio ρ = N(U233)/N(Th232) as a function of burn up for 3 typical initial U233 configurations:

1. At the breeding equilibrium, ρ = ξ
2. For an initial excess of U233, ρ = 2ξ
3. For an initially pure Th232, ρ = 0

- All configurations tend to approach progressively the breeding equilibrium, for which the ratio is ρ = ξ

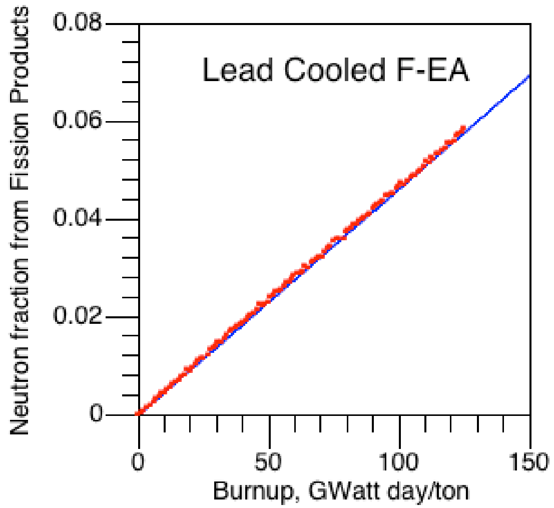


- For thermal neutrons (T-EA): ξ = 0.0135, for fast neutrons (F-EA): ξ = 0.125

Breeding equilibrium

- In contrast with the majority of the Thorium driven reactors, the EA is bound to operate steadily at the breeding equilibrium, namely without the frequent and continuous addition of other fissile materials.
- Consequently the fission driven coefficient is given by $k = \varepsilon\eta(1-L)/2$, where
  - ⇨ L is the sum of fractional losses, due to structures and coolant, early captures of Pa233, fission products, diffusion outside the EA and so on
  - ⇨ η is the spectrum averaged number of neutrons produced by the fissile U-233
  - ⇨ ε is a factor ≥ 1 representing other (small) neutron sources like (n-2n), etc.
- The criticality k = 1 value, an important reference, is then given by $L_{critic}=1 - 2/\varepsilon\eta$ and it is L_{critic}= 0.167-0.200 for a F-EA, but smaller for a T-EA.
- For the F-EA of CERN/AT/95-44 the values for L are material wise as follows:
  - ⇨ Lead coolant: L = 0.0626
  - ⇨ Cladding: L = 0.0378
  - ⇨ Beam window L = 0.0004
  - ⇨ Main Vessel L = 0.0071
  - ⇨ Leakage L = 0.0012

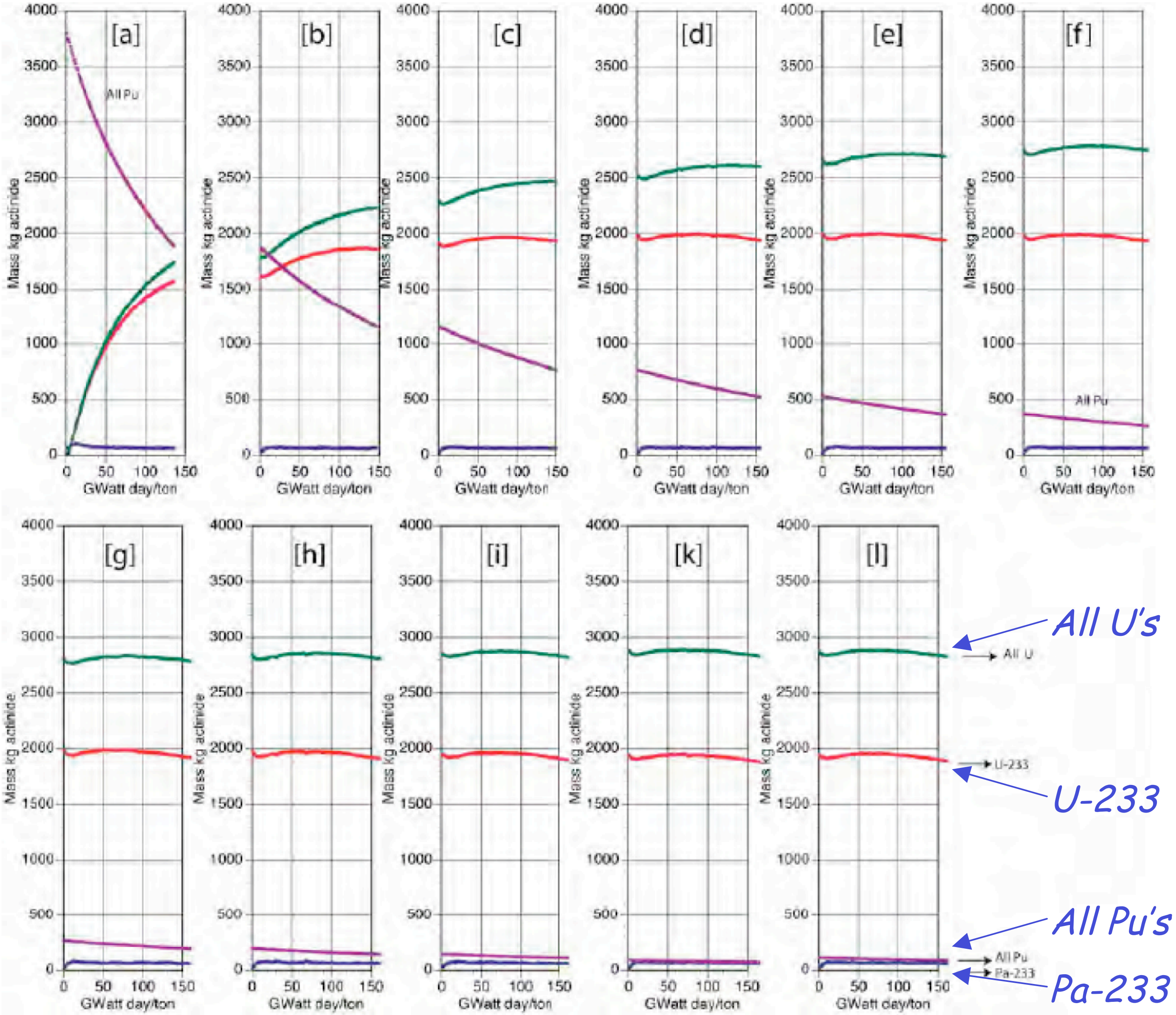
  L = 0.1091



- To these values of L, contributions due to the Fission Products must be added, linearly growing with burnup.

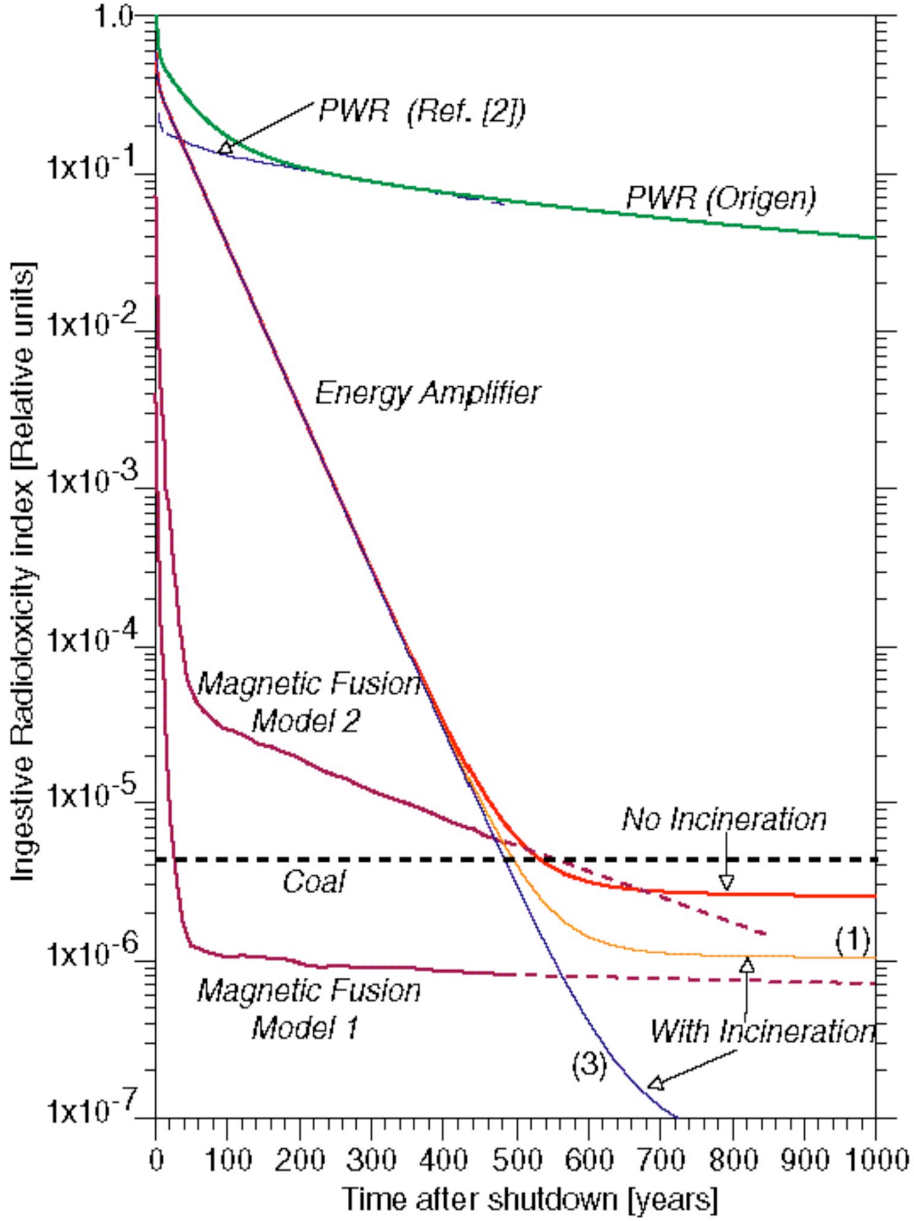
Plutonium elimination and Uranium Fissile buildup

- Metal content of Plutonium, U-233, all Uranium isotopes and Pa-233 as a function of the burn-up for 11 successive cycles.
- The initial fuel is a MOX mixture with of 84.5 % of *ThO2* and 15.5% of *PuO2* .
- At the end of each cycle, all Actinides are reprocessed and burnt Th-232 is refilled with fresh Th-232 .



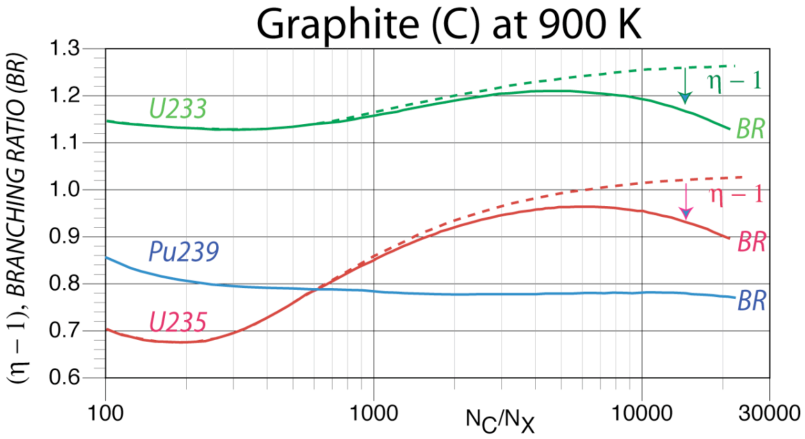
Short duration of nuclear waste and Fuel reprocessing

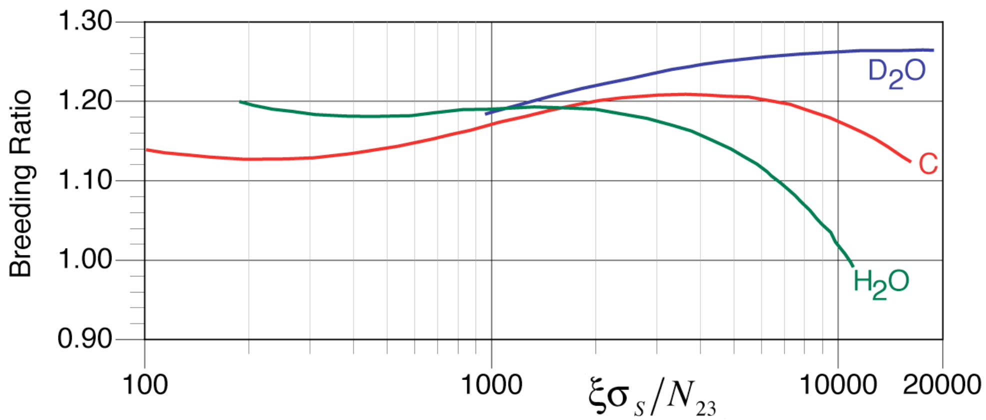
- An uninterrupted operation of about 10 years, in which
  - ⇨the only waste are Fission fragments Their radio-activity of the material is intense, but limited to some hundreds of years.
  - ⇨Actinides are recovered without separation and are the "seeds" of the next load, after being topped with about 10 ÷ 15 % of fresh breeding element (Th or U-238) in order to compensate for the losses of element.
  - ⇨A small fraction of Actinides is not recovered and ends with the "waste"
- *The cycle is "closed" in the sense that the only material inflow is the natural element and the only "outflow" are fission fragments.*



Thermal breeders:T-EA

- The main advantage of a T-EA is that the reactor technology is well known.
- Only Th-U233 may be acceptable. The branching ratio includes the effects of the (infinite) moderator. Water, heavy water and graphite are considered.
- The breeding ratio is given as the function of the slowing down power per fuel atom, $\xi\sigma_s$, where σ_s is the free atom cross section in the moderator and ξ is the mean logarithmic energy loss of neutrons in the moderator atoms (lethargy).





- Two effects,depending on specific power S(MW(t)/kg fissile fuel) in addition to FP:
- The Xenon poison fraction P = 0.037 (0.047)for S = 1, (3) MW(t)/kg, a reduction of about 0.04 in breeding ratio at equilibrium
- It is 0.01, 0.07 for S = 1, 3 MW(t)/kg, 10-12 hours after shut down
- Captures in Pa233, intermediate to the breeding reaction, with loss in breeding ratio approximately of 0.03, 0.09 for S = 1, 3 MW(t)/kg

$$P(Xe) \approx \frac{0.054S}{(0.44 + S)}$$

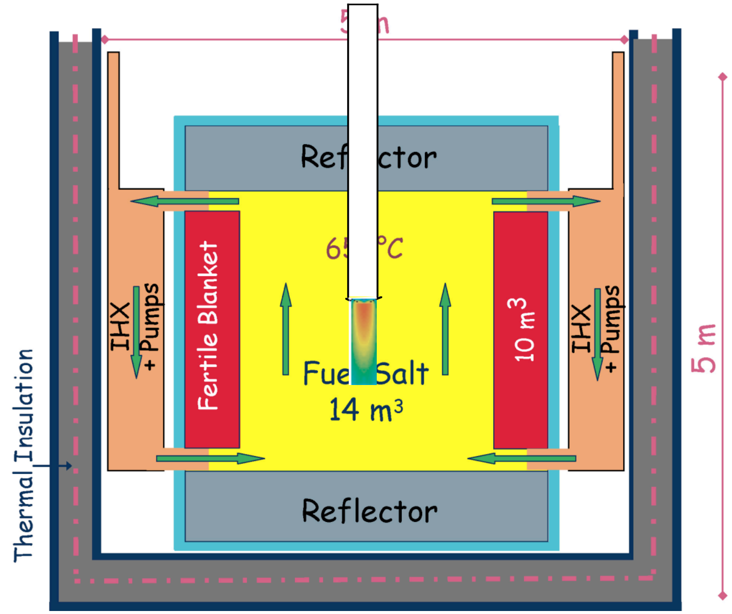
$$\delta BR = \frac{2S}{(64 + S)}$$

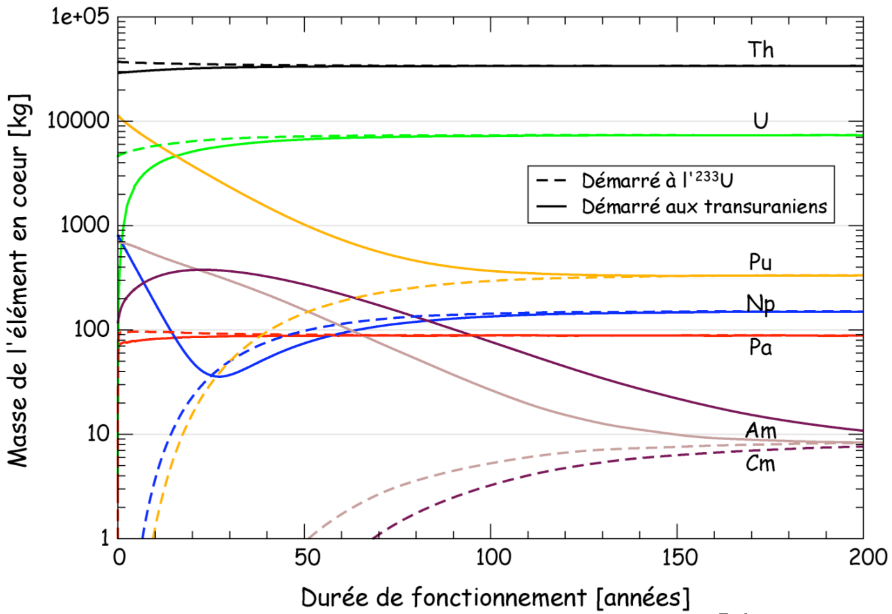
Thermal breeders: the most conservative approach?

- It is always possible to operate a critical thermal system with Thorium, but well above the breeding value ξ = 0.0135, with frequent and continuous additions of fissile fuel, like for instance U-235, Pu or other.
- At the breeding equilibrium, several inevitable neutron losses reduce the maximum value of k and require sub-critical operation.
- Some losses are growing with power density. Typical operation is at about S ≈ 1 (MW(t)/kg fissile fuel or ≈ 10 W/g of Thorium metal with a n-flux of the order of 2. 10^{13} cm^{-2} s^{-1}. Such losses include ΔL ≈ -0.04 for Xe poisoning and ΔL ≈ - 0.03 for Pa-233 intermediate absorption.
- In addition, captures due to cladding, structures and Fission Products further contribute to ΔL, but are density independent.
- A typical operating condition may be k ≈ 0.95, G = 2.3/(1-k) ≈ 45 (Lead spallation target). Taking into account a electric conversion of 0.3 and an accelerator efficiency of 0.5, the re-circulated thermal power is 1/(45 x 0.3 x 0.5) = 0.15. (DT-Fusion has similar expectations !).
- The only novelty left is the large superconducting LINAC which must provide a required high power for big installations. Economically viable?

Thermal (Molten salt) Thorium breeder (Alvin Weinberg)

- Liquid Fuel: LiF, $(NL)F_4$, BeF:
- NL from 6,5% to 20 %.
- Volume : 20 m³, Temp.: 630°C,
- Power : 2.5 GW_{th} = 1 Gw_{ele}
- A molten salt reactor's fuel is continuously reprocessed by an adjacent chemical plant on line. *All the salt has to be reprocessed every 10 days*. Reprocessing is based on fluorination:
  - ⇨Fluorine removes U233 from the salt.
  - ⇨A molten bismuth column separates Pa-233 from the salt before decay
  - ⇨A fluoride-salt system distills the salts. Each salt has a distinct temperature of vaporization
  - ⇨The light carrier salts evaporate at low temperatures, and form the bulk of salt.
  - ⇨The thorium salts must be separated from the FP which become "waste"
- The amounts recovered are about 800 kg of waste per year per GW generated.





Thorium molten salt reactors (TMSR)

- In 2002 a 1000 MWe Thorium MSR was designed in France with a fissile zone where most power would be produced and a surrounding fertile zone where most conversion of Th-232 to U-233 would occur.
- The FUJI MSR is a 100 MWe design operating as a breeder and being developed internationally by a Japanese, Russian and US consortium.
- It is not a fast neutron reactor, but epithermal (intermediate neutrons). The value of η is small and closer to 2.
- A major fraction of Xe and of Pa-233 to U-233 conversion must be recovered by the on-line purification plant, (not clearly shown as yet).
- A possible but exotic sub-critical scenario is also shown.

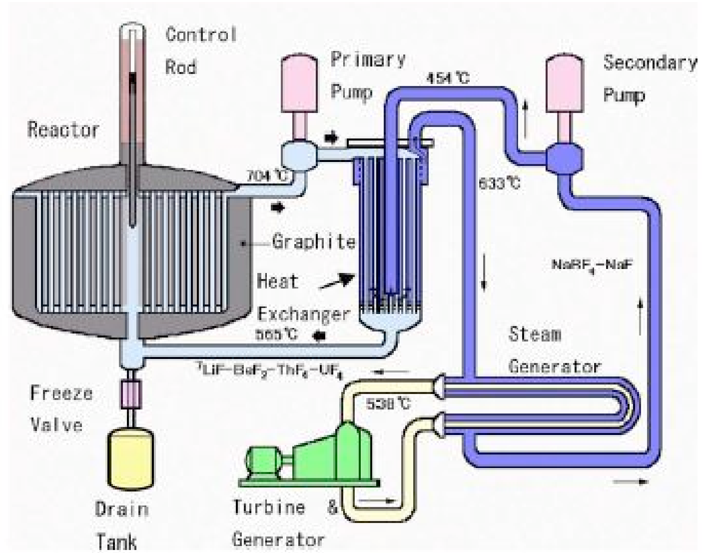
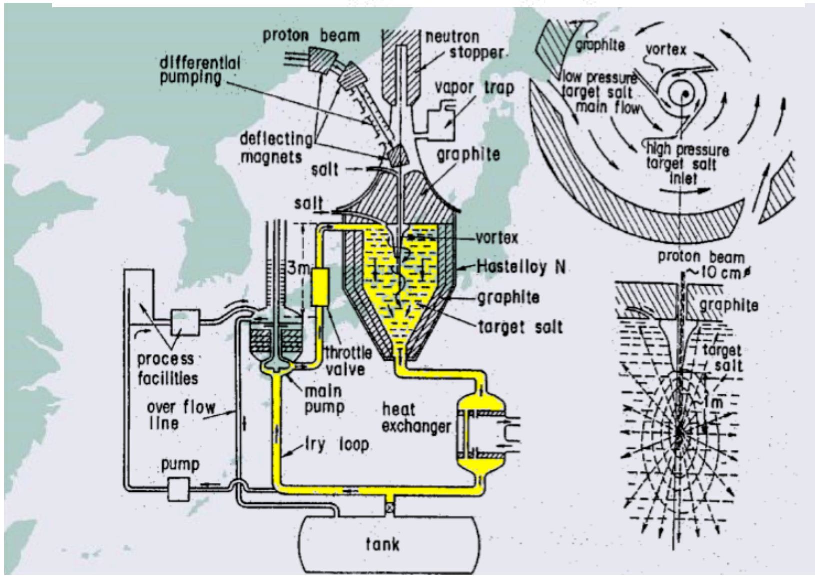
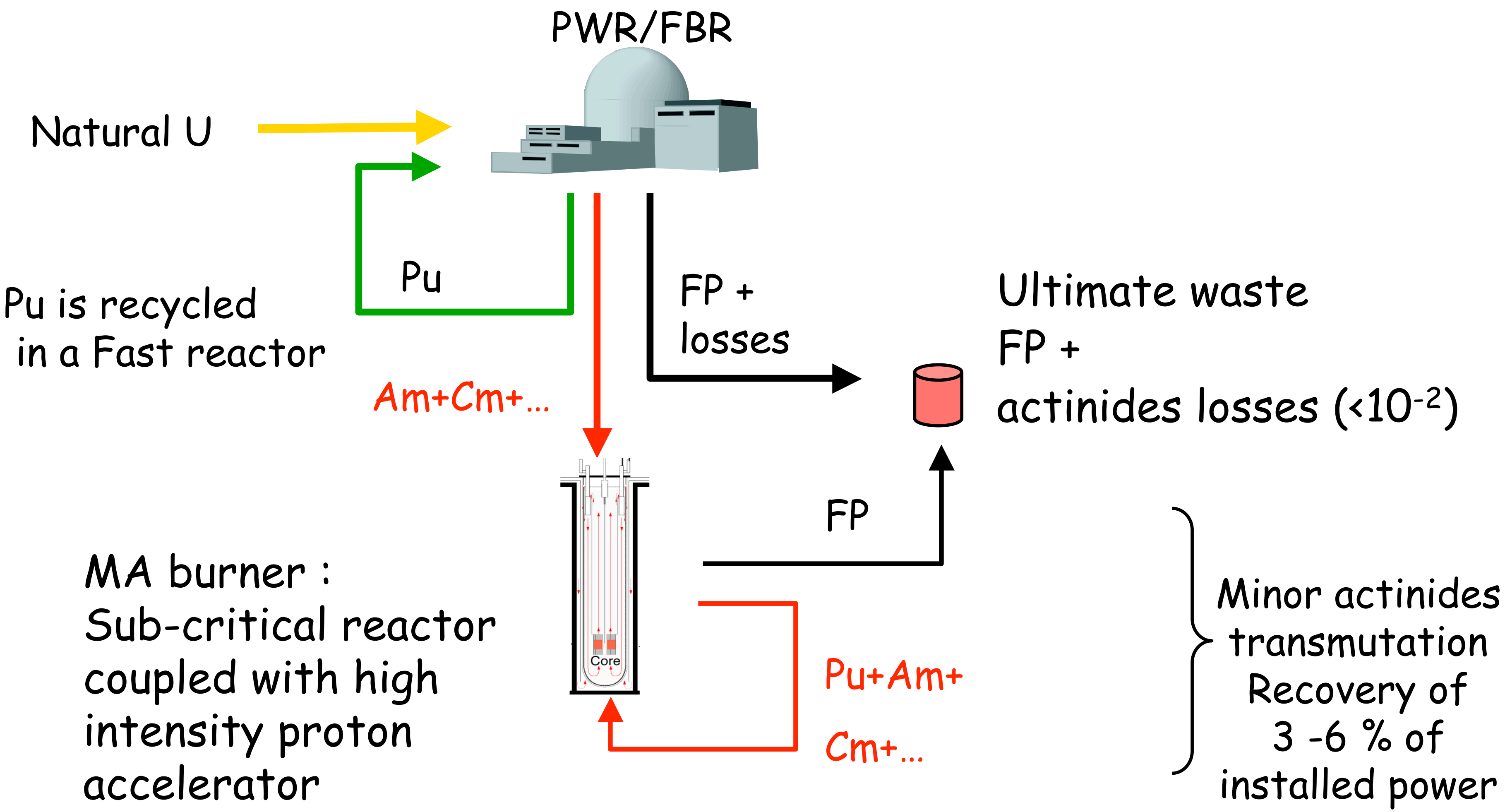


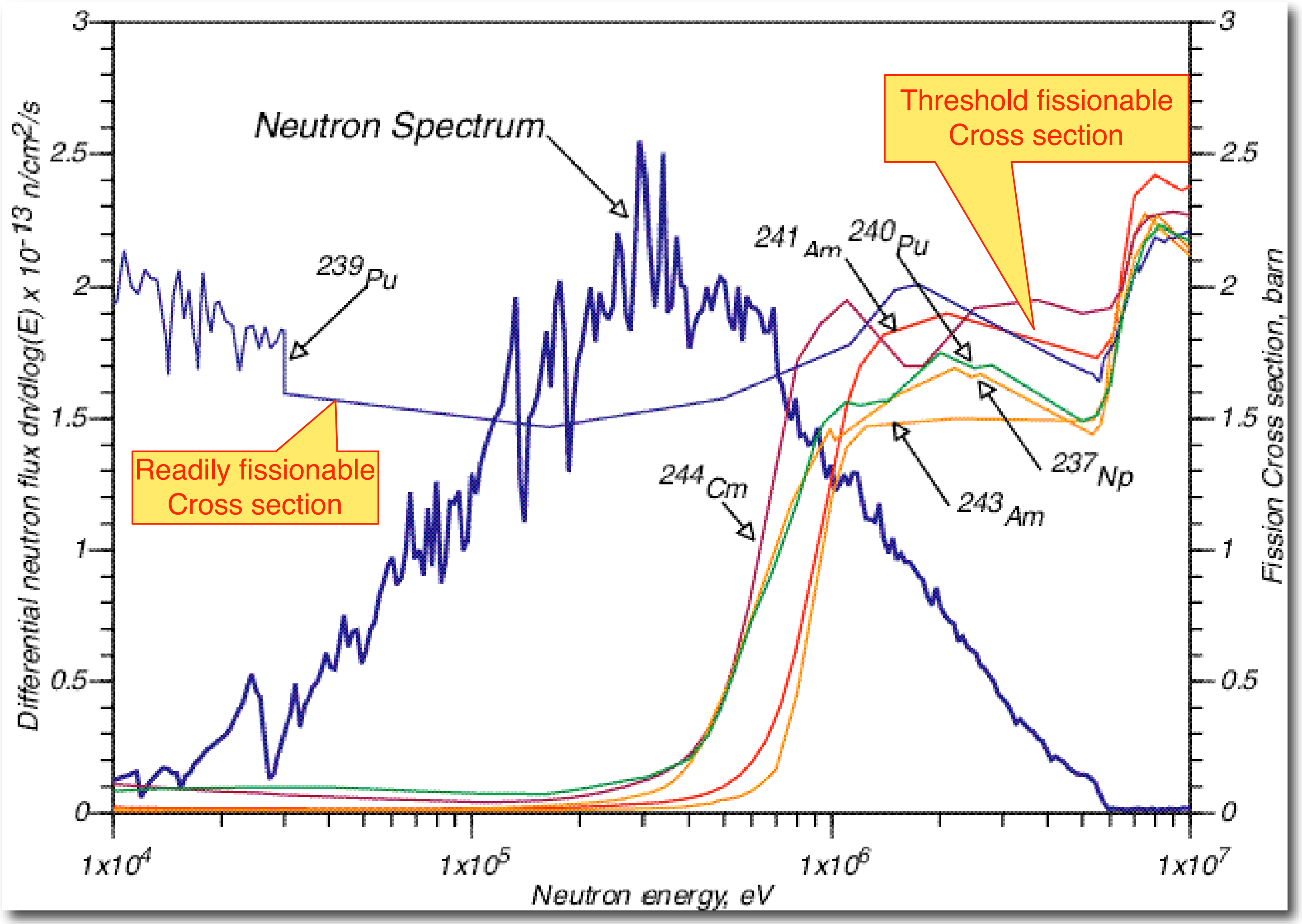
FIG XXX-1. Simplified schematic diagram of FUJI



Transmutation of waste of minor actinides

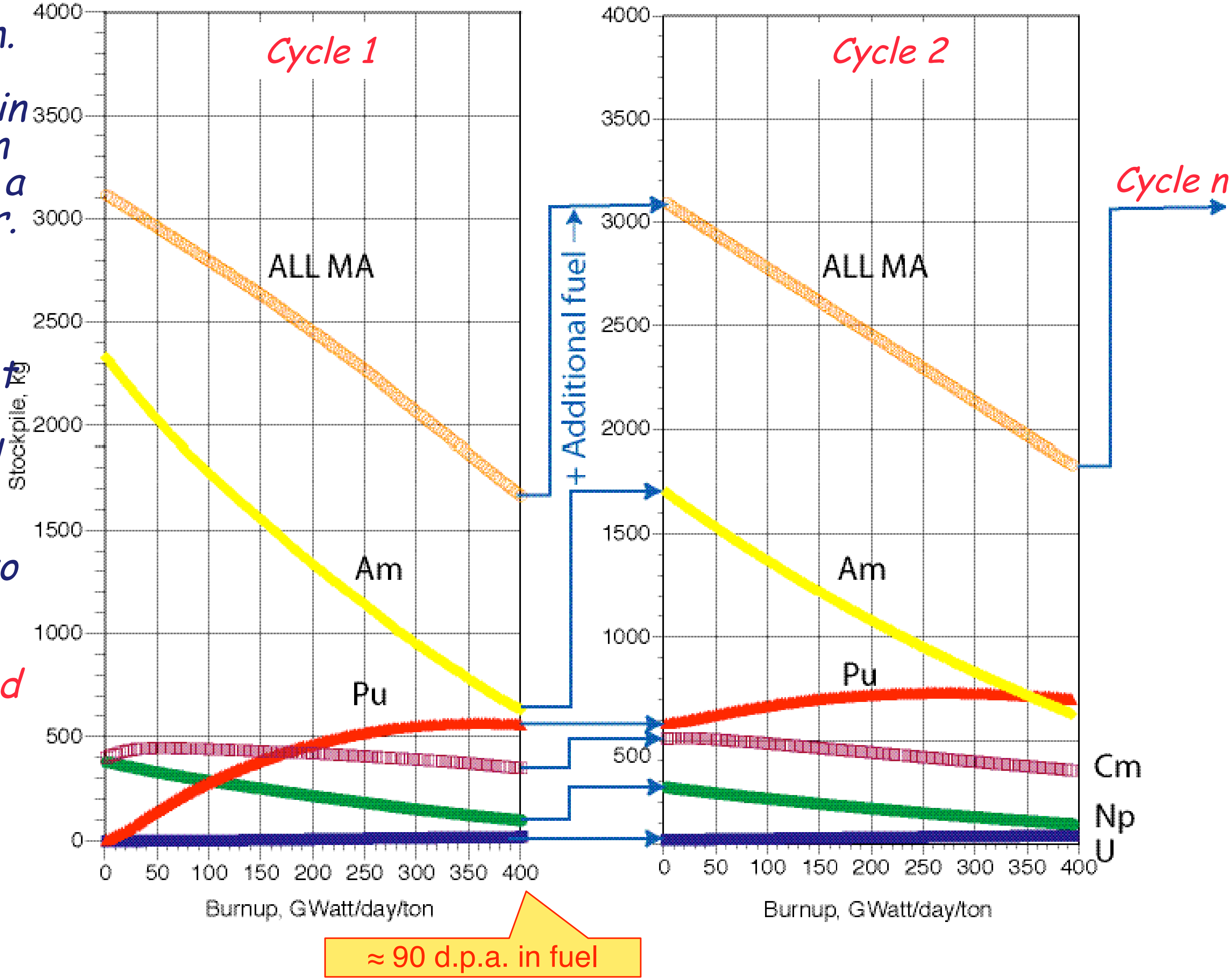


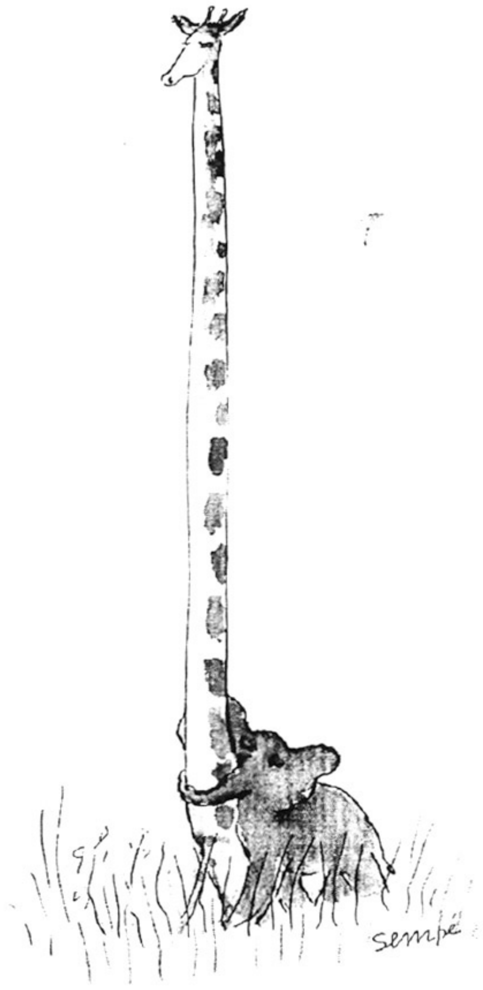
Energy spectrum for efficient incineration



Cyclic time evolution of the MA's stockpile in a EA

- *About 3.1 ton of h.m. MA's are burnt for about 400 GW d/t, in a sub-critical molten Pb fast reactor and a neutral matrix of Zr.*
- *The burnup is normalized to the MA h.m. The final MA h.m. mass is 1.7 t.*
- *At each subsequent cycle additional fuel is added to the surviving MA's, topping each cycle to 3.1 ton of h.m.*
- *The cycle is indefinitely repeated*
- *Secondary Pu and U are generated and incinerated during the cycles.*
- *No appreciable Bk, Cf, Es etc. are produced*





Le couplage d'un accélérateur et d'un réacteur nucléaire :
un accouplement contre nature ou l'avenir
de l'énergie nucléaire ?

The coupling of an accelerator and of a nuclear reactor:
a mating against nature or the future of the nuclear energy ?

Thank you !

The St James's Palace Nobel Laureate Symposium
London, 26 – 28 May 2009

The St James's Palace Memorandum calls for a global deal on climate change that matches the scale and urgency of the human, ecological and economic crises facing the world today. It urges governments at all levels, as well as the scientific community, to join with business and civil society to seize hold of this historic opportunity to transform our carbon-intensive economies into sustainable and equitable systems. We must recognize the fierce urgency of now.

- **Milestones of the Great Transformation** Building on the Potsdam Memorandum and the recent advances in the scientific understanding of climate change, the participants of the St James‟s Symposium identified as key requirements **an effective and just global agreement on climate change**, **low-carbon energy infrastructure** and **tropical forest protection, conservation and restoration.**
- The solutions to the extraordinary environmental, economic and human crises of this century will not be found in the political arena alone. Stimulated by the manifesto of Bertrand Russell and Albert Einstein, the first Pugwash gathering of 1957 united scientists of all political persuasions to discuss the threat posed to civilization by the advent of thermonuclear weapons. Global climate change represents a threat of similar proportions, and should be addressed in a similar manner. There should be an acceleration and integration of global sustainability studies, to encourage the active involvement of all scientists in these matters, championing the process of robust scientific study. All scientists should be urged to contribute to raising levels of public knowledge on these threats to civilization and engage in a massive education effort to popularize the principles in this Memorandum.