The future of Nuclear Energy

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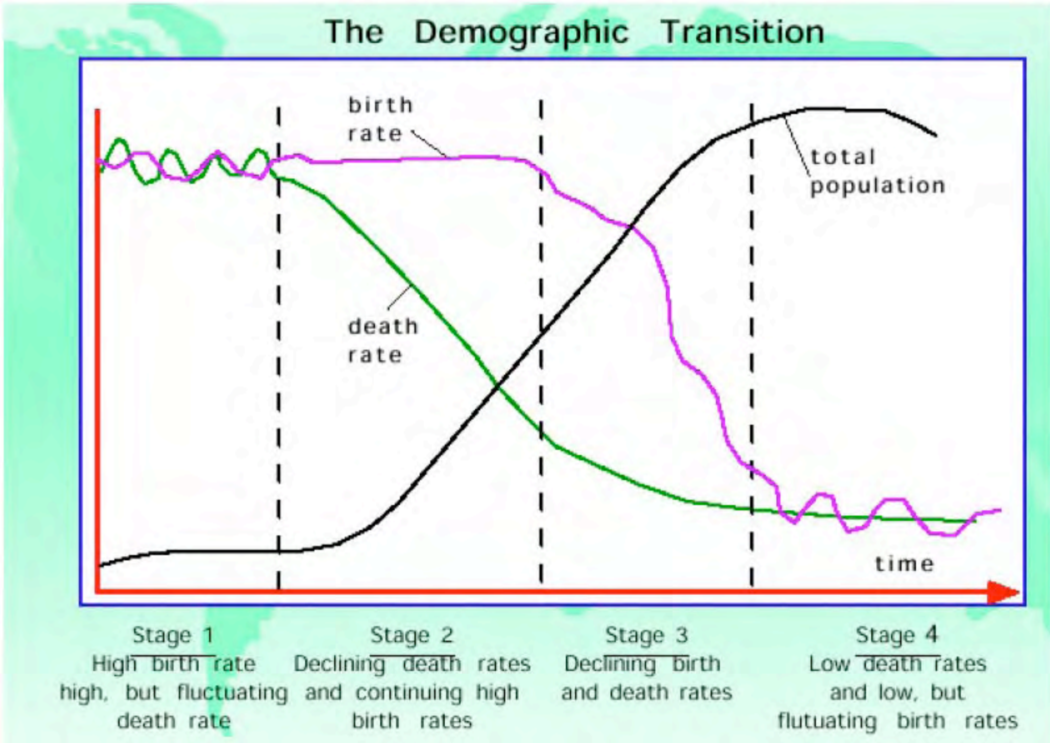
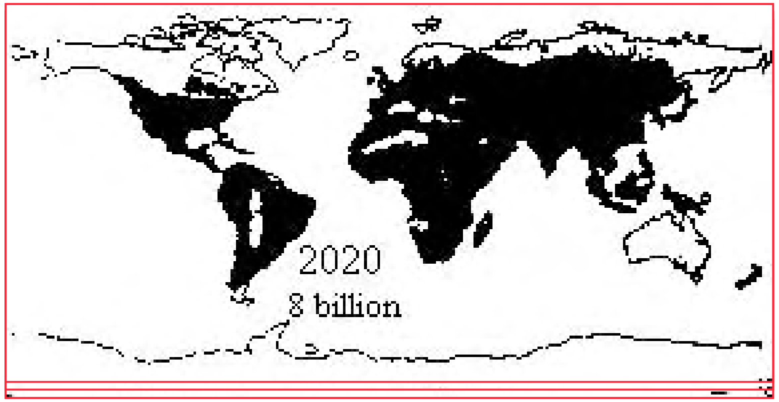
The demographic transition



1 2020; 8 billion



An "explosive" population growth:
90 M/year

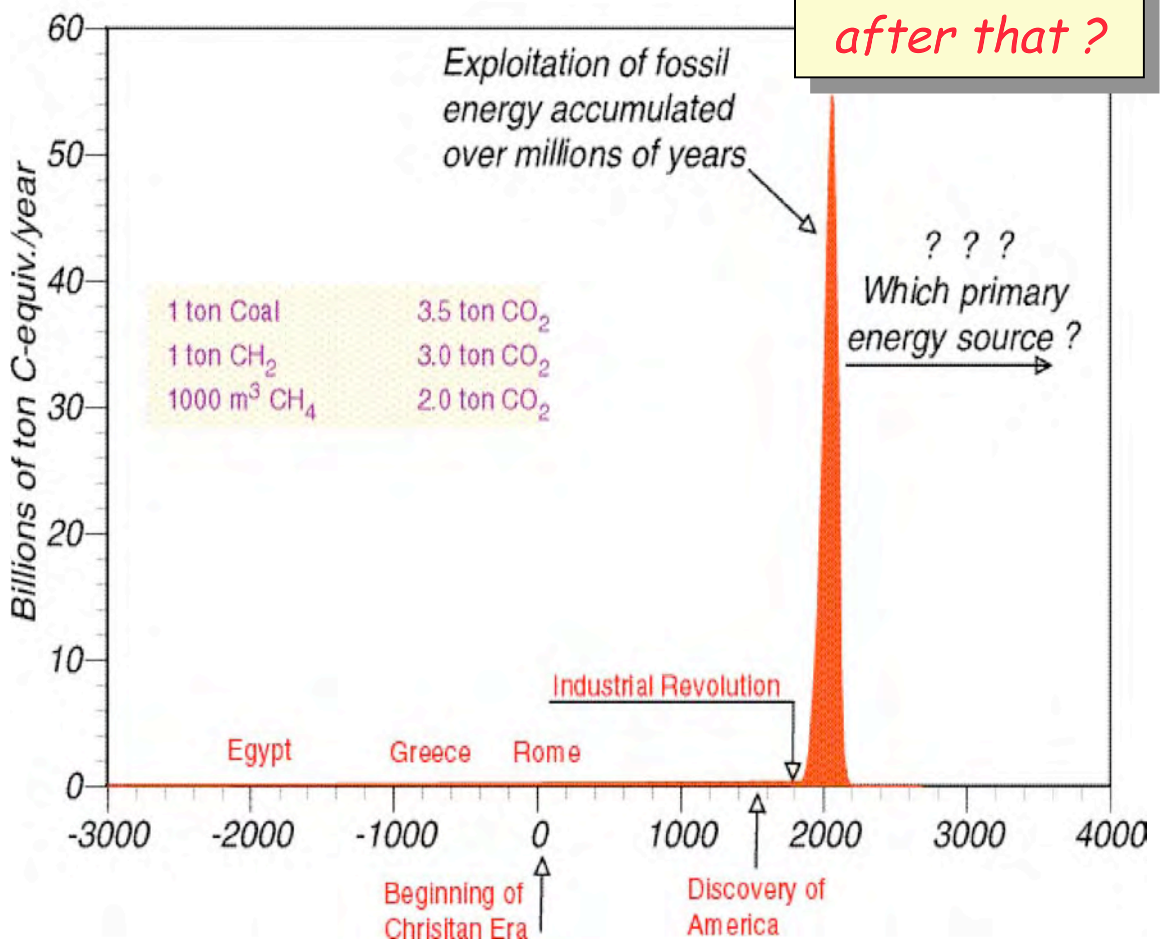
- World's population is rising rapidly .
- It is generally expected that it may grow to some 10÷ 12 Billion people by 2100 and stay relatively stable after that.
- Most of the population will be in what are presently the so-called Developing Countries.
- Everybody will agree on the fact that no future progress of mankind will be possible without substantial amount of of energy, namely

"Energy is necessary" .

Energy growth: it may not be for ever

- The individual energy consumption of the *most advanced part of mankind* has grown about 100 fold from the beginning of history.
- The level is today about
  - ⇨ 0.9 GJ/day /person,
  - ⇨ 32 kg of Coal/day/ person,
  - ⇨ continuous 10.4 kWatt/person.
- The corresponding daily emission rate of CO_2 is about 100 kg

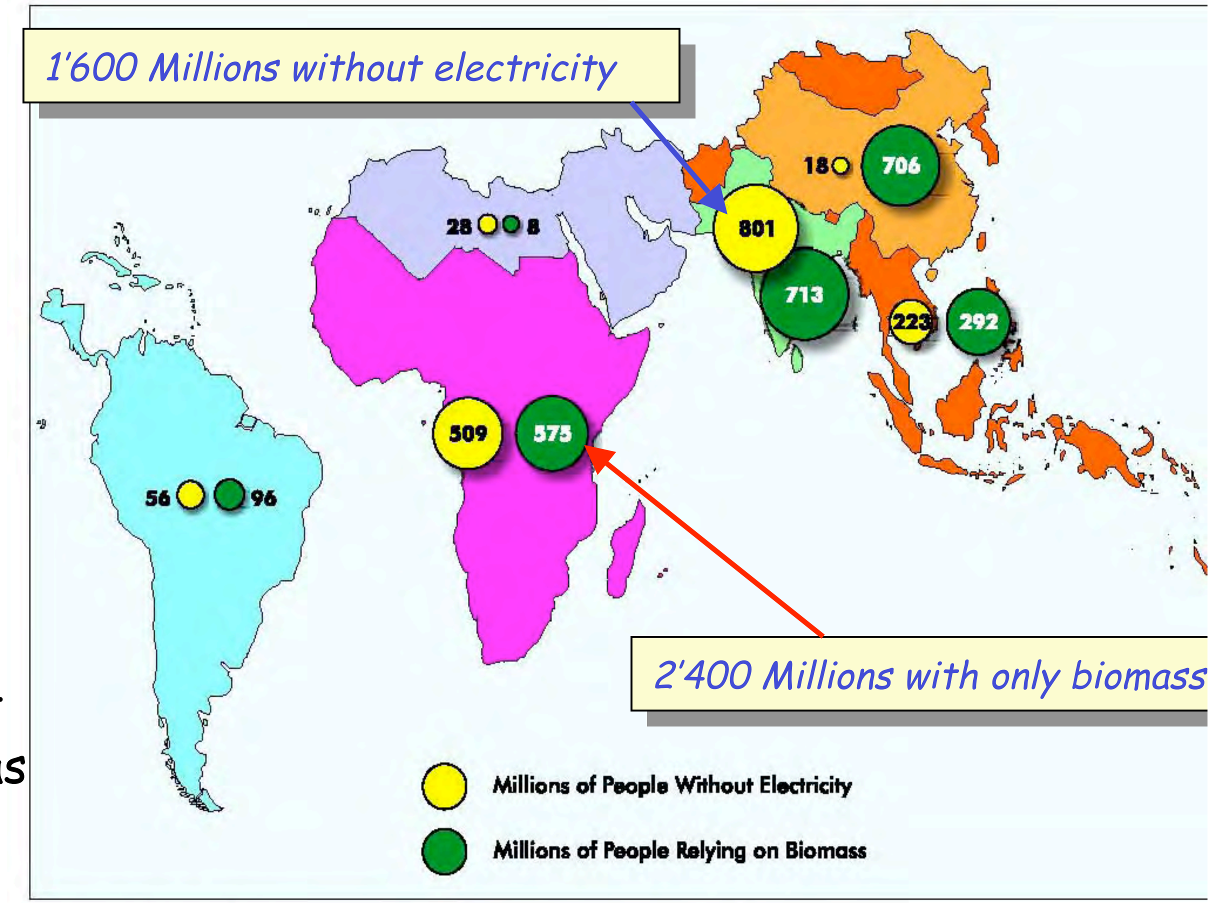
And what after that ?



Energy consumption/person increments by +2 %/y (fossil dominated)

Energy and poverty

- A huge correlation between energy and poverty
  - ⇨Sweden: 15’000 kWh of electricity/ person/year
  - ⇨Tanzania: 100 kWhe /p/y
- 1.6 billion people - a quarter of the current world's population - are without electricity,
- About 2.4 billion people rely almost exclusively on traditional biomass as their principal energy source.
- Of the 6 billion people, about one half live in poverty and at least one fifth are severely under nourished. The rest live in comparative comfort and health.



Source: IEA analysis.

Technologically advanced countries have the responsibility of showing the way to the most needy ones !

New energies: how soon ?

- During this lecture of mine, one hour long, about 10'000 new people have entered the world, at the rate of 3/sec, most of them in the Developing Countries.
- At the present consumption level, known reserves for coal, oil, gas and nuclear correspond to a duration of the order of 230, 45, 63 and 54 years.
- The longevity of the survival of the necessarily limited fossil's era will be affected on the one hand by the discovery of new, exploitable resources, strongly dependent on the price and on the other by the inevitable growth of the world's population and their standard of living.
- Even if these factors are hard to assess, taking into account the long lead time for the massive development of some new energy sources, *the end of the fossil era may be at sight*.

Climatic changes ?

- The consumption of fossils may indeed be prematurely curbed by unacceptable greenhouse related environmental disruptions.
- The climatic effect of the combustion of a given amount of fossil fuel produces one hundred times greater energy capture due to the incremental trapped solar radiation (if we burn 1 with a fossil, the induced, integrated solar heat increment is >100 !)
- Doubling of pre-industrial concentration will occur after *roughly* the extraction of 1000 billion tonnes of fossil carbon. We are presently heading for a greenhouse dominated CO_2 doubling within *roughly* 50-75 years.
- It is generally believed (IPCC, Kyoto…) that a major technology change must occur before then and that *in order to modify drastically the present traditional energy pattern* a formidable new research and development would be necessary.
- New dominant sources are needed in order to reconcile the huge energy demand, growing rapidly especially in the Developing Countries, with an acceptable climatic impact due to the induced earth's warming up.

New energies:

- Only two natural resources have the capability of a long term energetic survival of mankind:

  1. **A new nuclear energy.** Energy is generally produced whenever a light nucleus is undergoing fusion or whenever a heavy nucleus is undergoing fission. Practical examples are *natural Uranium or Thorium (fission) and Lithium (fusion) both adequate for many thousand of years at several times the present energy consumption*.

  2. **Solar energy**. The world's primary energetic consumption is only 1/10000 of the one available on the surface of earth of sunny countries. Solar energy may be either used directly as heat or PV or indirectly through hydro, wind, bio-mass and so on. *If adequately exploited, solar energy may provide enough energy for future mankind.*

- *It is unlikely that any stable, long term development of mankind will be possible without both of them.*

Novel forms of energy from nuclei

Nuclear proliferation and the developing countries

- The most important new energy demands will necessarily come from now fast growing developing countries. *Is there a room for nuclear energy ?*
- 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 of nuclear technology:
  - ⇨ *Uranium enrichment* may be easily extended to a level sufficient to produce a "bomb grade" U-235 (f.i. see the case of Iran);
  - ⇨natural Uranium reactors (CANDU) *generate a considerable amount of Pu*, such as produce easily Pu-239 "bomb grade" (f.i. the case of India).
- The nuclear penetration in the developing countries could become acceptable *only once the umbilical chord between energy and weapons production is severed.*
- ***Some totally different but adequate nuclear technology must be developed***.

Nuclear energy without U-235

- Today's nuclear energy is based on U-335, 0.71 % of the natural Uranium, fissionable both with thermal and 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.

- But, 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 more than one hundred times greater than the one in the case of the classical, U-235 driven nuclear energy*.

- Natural reserves U-238 or Th-232 can become adequate for many tens of centuries at a level several times the today's primary fossil production.

Choosing a nuclear energy without proliferation

- Indeed energy is produced whenever a light nucleus is undergoing fusion or whenever a heavy nucleus is undergoing fission. Particularly interesting are fission reactions in which a natural element is bred into a readily fissionable energy generating process.

$$^{232}Th + n \rightarrow {}^{233}U; \quad {}^{233}U + n \rightarrow fission + 2.3n \quad (Th \;\; cycle) \qquad [1]$$

$$^{238}U + n \rightarrow {}^{239}Pu; \quad {}^{239}Pu + n \rightarrow fission + 2.5n \quad ({}^{238}U \;\; cycle) \qquad [2]$$

- The energies naturally available as ores by [1] and [2] are comparable to the one for the D-T fusion reaction:

$$Li + n \rightarrow T; \quad T + D \rightarrow He + n \quad (Fusion) \qquad [3]$$

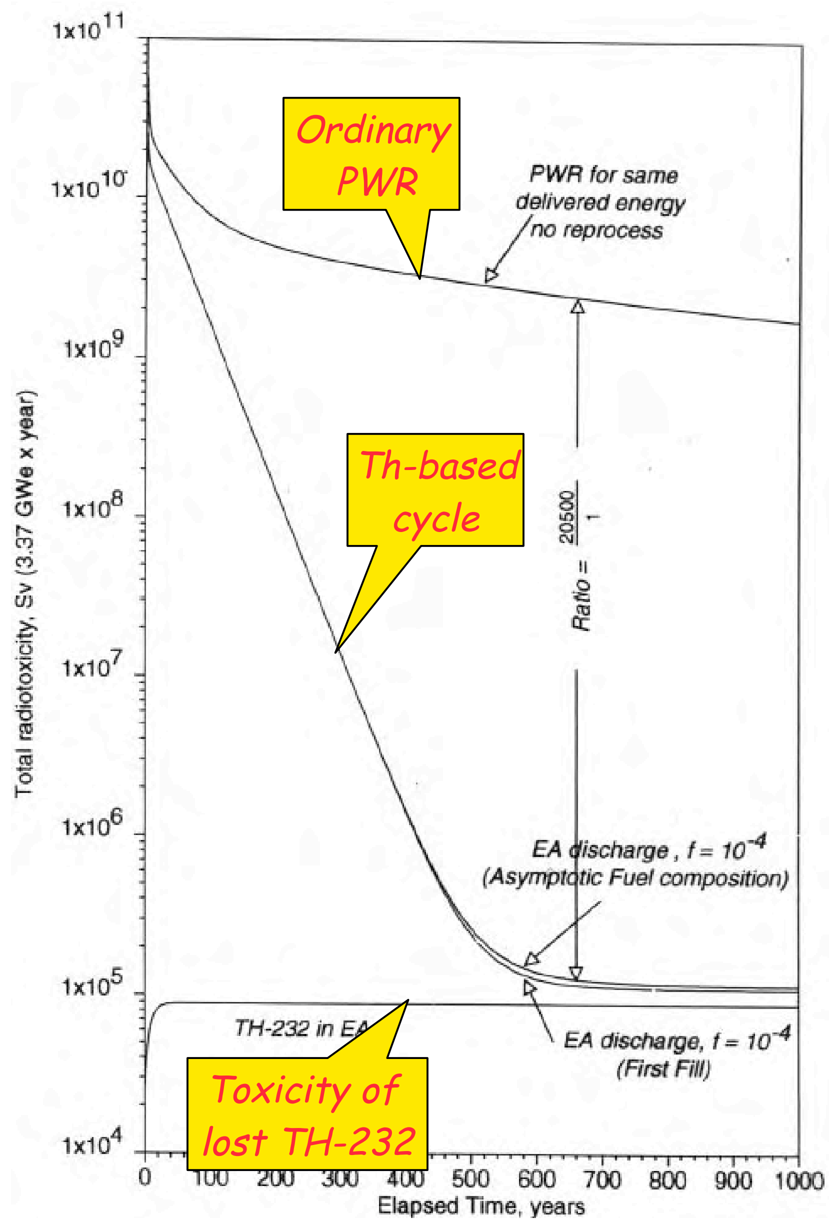
- While reaction [2] is again strongly proliferating, reactions [1] and [3] may be safely exploited in all countries.

Closing the nuclear cycle with Th-232 and U-238

- The fissile element (U-233 or Pu-239) is naturally produced by the bulk natural element progressively converted into fertile element.
- Two neutrons are required within the basic cycle, one for the breeding and the other for the fission, in contrast with the ordinary U-235 process, in which only one neutron is necessary.
- After a time the process has to be recycled since:
  - ⇨ The fraction of the produced fission fragments has affected the operation of the system
  - ⇨ Radiation damage of the fuel elements requires reconstruction of the materials.
- In practical conditions this correspond to the burning of about 10 ÷ 15 % of the metal mass of the natural element (Th-232 or U-238) and to a specific energy generation of 100 ÷ 150 GWatt x day/ ton.
- For practical conditions, this may correspond to some 5 ÷ 10 years of uninterrupted operation.

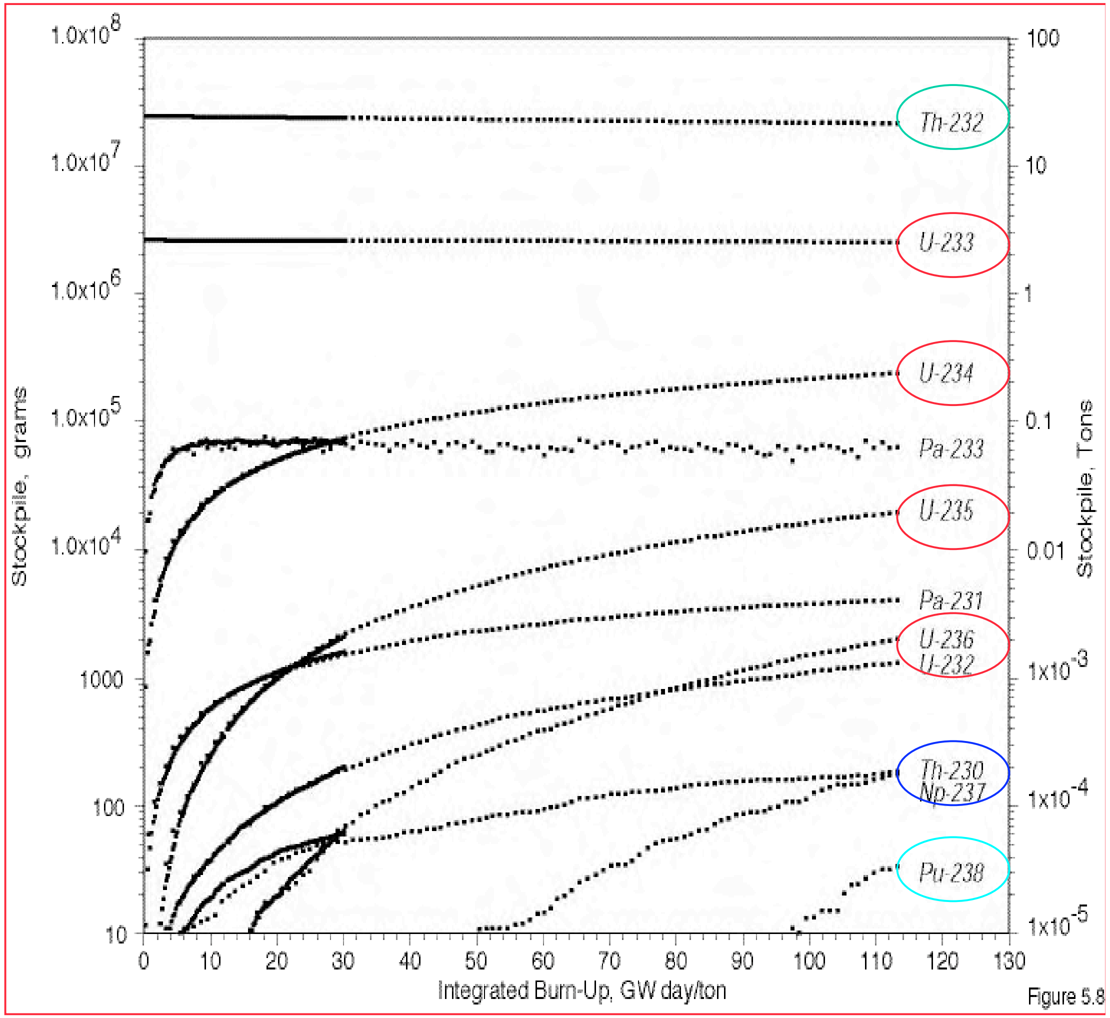
Fuel reprocessing

- At this moment the fuel is reprocessed and
  - 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.*

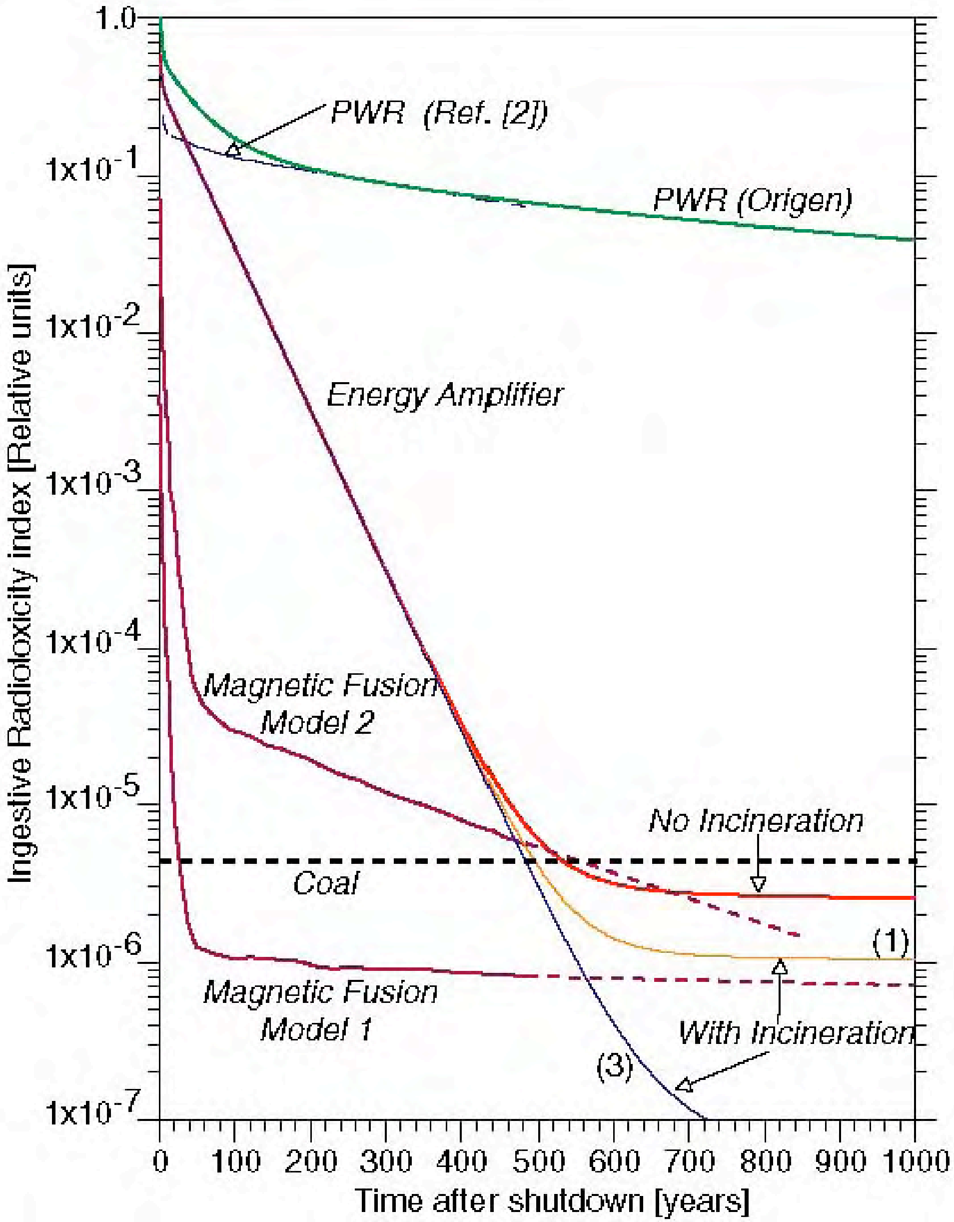


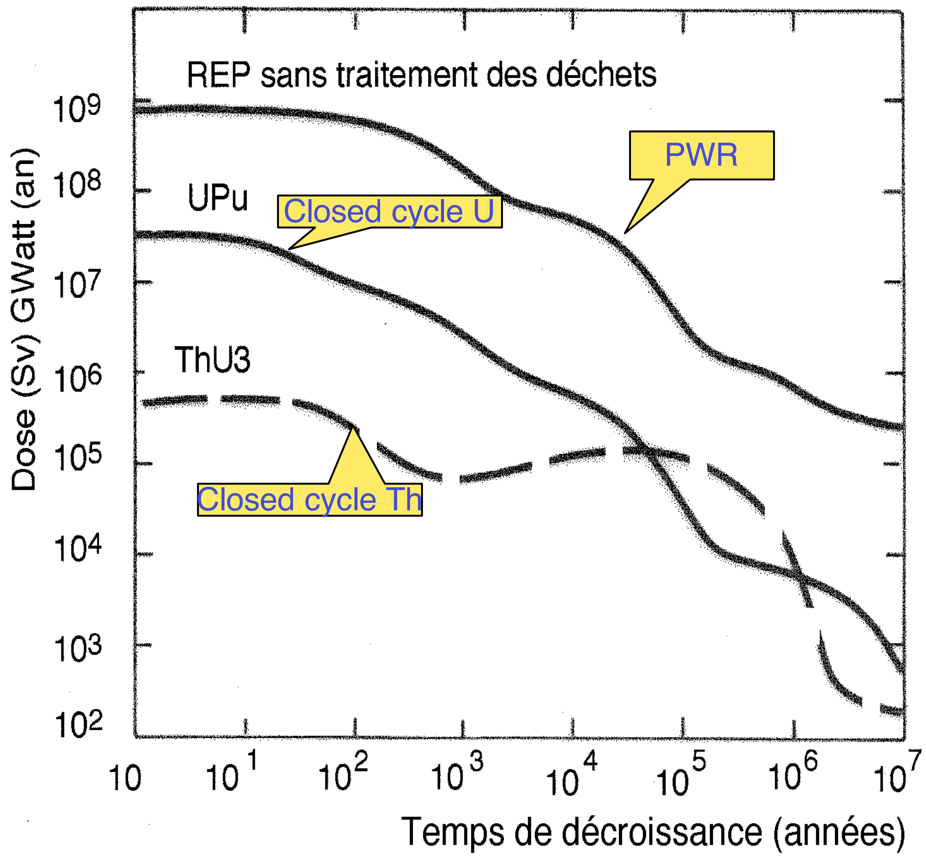
"Breeding" equilibrium

- The process is periodically restarted as an indefinite chain of cycles. The fuel composition progressively tends to a "secular" equilibrium between the many actinides composing the fuel, with rapidly decreasing amounts as a function of the rising of the atomic number.
- In the case of Th-232, the secular mixture is dominated by the various U isotopes with a fast decreasing function of the atomic number.
- Np and Pu (mostly the Pu-238) are at the level of grams/ton !
- Proto-actinium (Pa-233) is the short lived precursory element to U-233 formation.



Residual radio-toxicity of waste as function of time





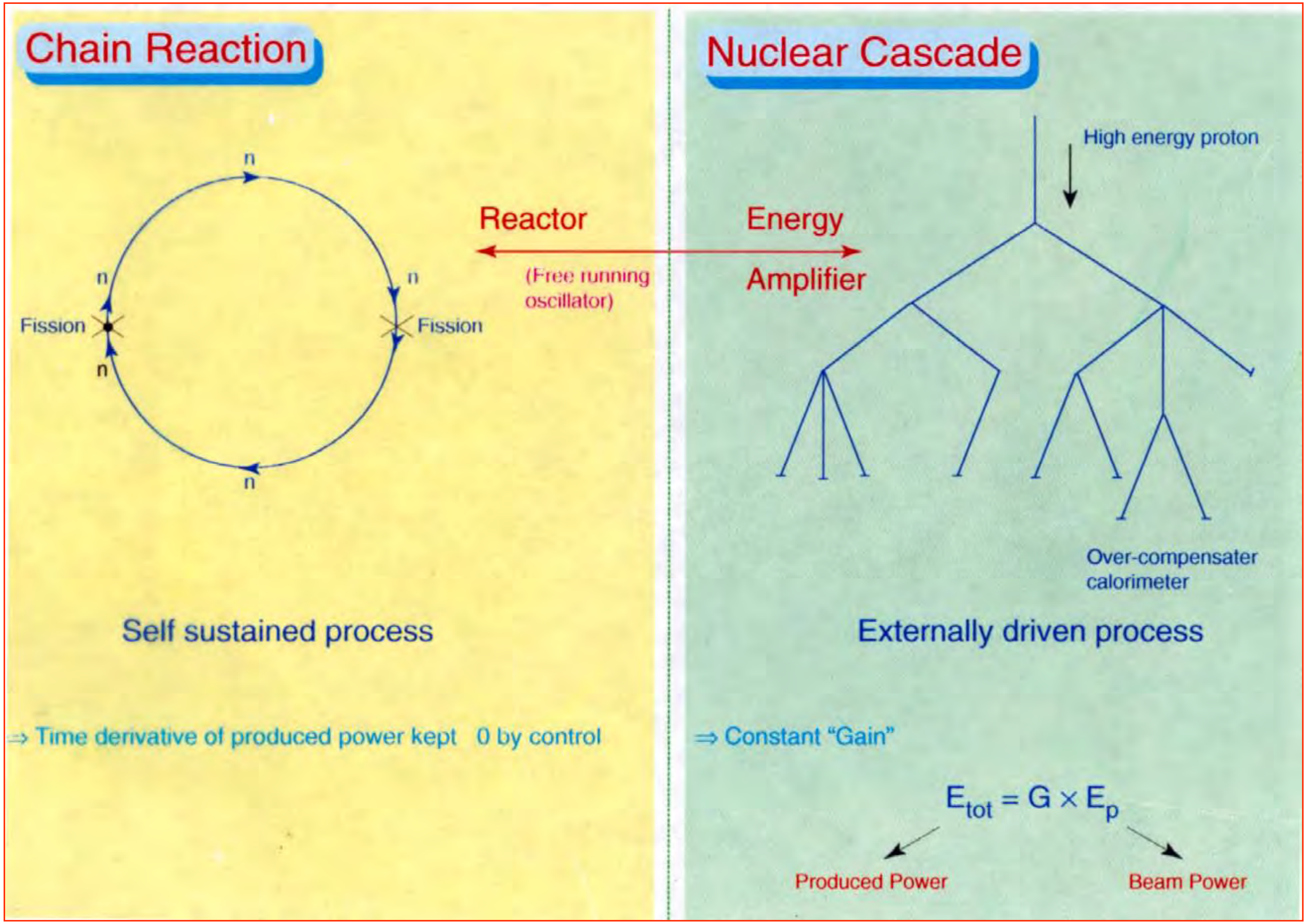
Relative amounts of leaked Actinide waste, excluding fission Fragments. In the case of a closed cycle the rejected fraction is x = 0.1% for U and Pu and of x = 1% for the other actinides

[J.L. Bobin, H. Nifenecker, C. Stéphan : L'énergie dans le monde : bilan et perspectives]

Prompt and delayed neutrons in a reactor

- Operation of a critical reactor is possible only because of the presence of some neutrons delayed up to minutes, which provide enough time to exercise mechanically the multiplication coefficient.
- The fraction of delayed neutrons is for a U=235 PWR, $\beta \approx 0.0070$
- This value of β is particularly favorable: it is only $\beta \approx 0.0020$ for a U-238 breeder and $\beta \approx 0.0025$ for a Th-232 breeder,
- For instance for a Th-232 breeder, an uncontrolled sudden reactivity change $\Delta\beta \approx 0.0036$ implies prompt criticality and a hundred fold power increase in 140 μs.
- Recently the possibility of operating the fission power generation as a sub-critical device with external supply of generating neutrons has been studied.
- These problems can be solved with the help of an external contribution of neutrons produced with a high energy proton beam hitting a spallation target.
- In the case of a sub-critical system with k = 0.99, the corresponding power increase will be a mere +50%.

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



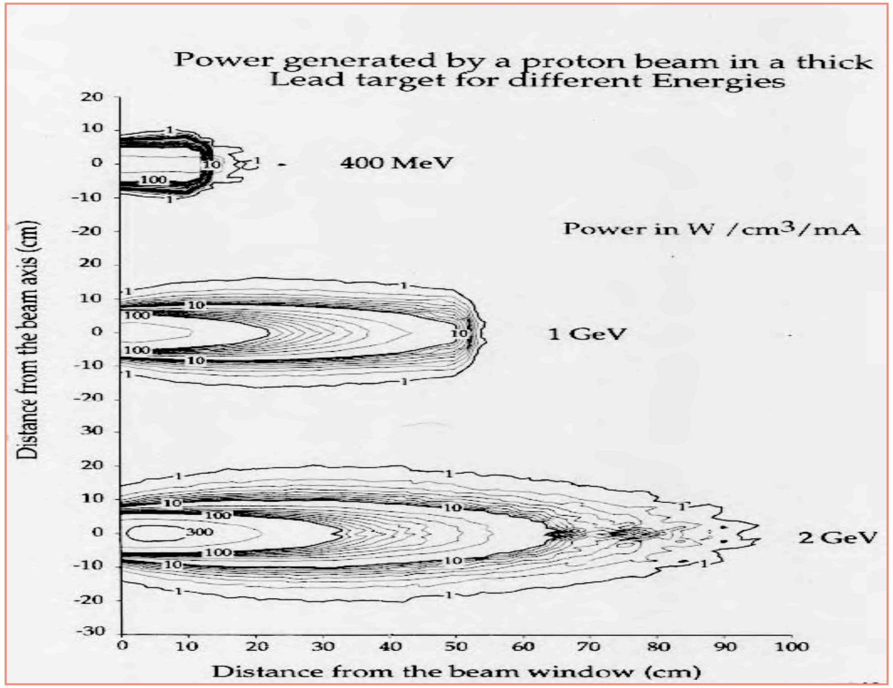
Principle of operation of the Energy Amplifier

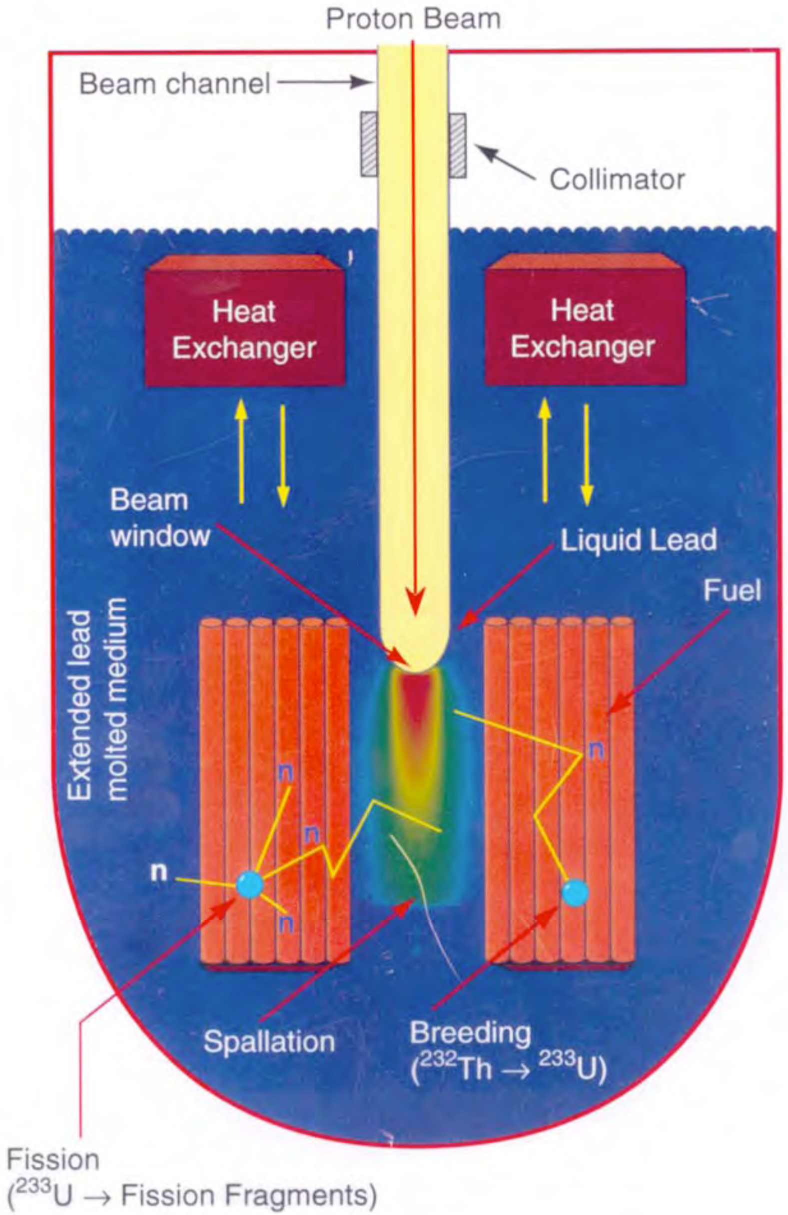
Thorium related Fission

$$^{233}_{92}U + ^{1}_{0}n \rightarrow 2.53[^{1}_{0}n] + 2FF + 200\ MeV$$

$$^{232}_{90}Th + ^{1}_{0}n \rightarrow ^{233}_{91}Pa + \gamma \xrightarrow{\beta-decay\ (27\ days)} ^{233}_{92}U + ^{0}_{-1}e$$

$$^{233}_{92}U + ^{1}_{0}n \rightarrow ^{234}_{92}U + \gamma$$





Sweden, June 2005

Benefits of the sub-critical operation

- A critical reactor operation with U-233 is far more delicate than an ordinary PWR.
- These problems are best solved with the help of an external contribution of neutrons produced with a high energy proton beam hitting a spallation target.
- In absence of the proton beam the assembly is sub-critical with an appropriate criticality parameter $k_{eff}< 1$ and no fission power is produced.
- With the beam on,the nuclear power is directly proportional to the beam power, namely the power gain G = [Fission thermal power]/[beam power] is related to the value of the multiplication coefficient k_{eff} by a simple expression:

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

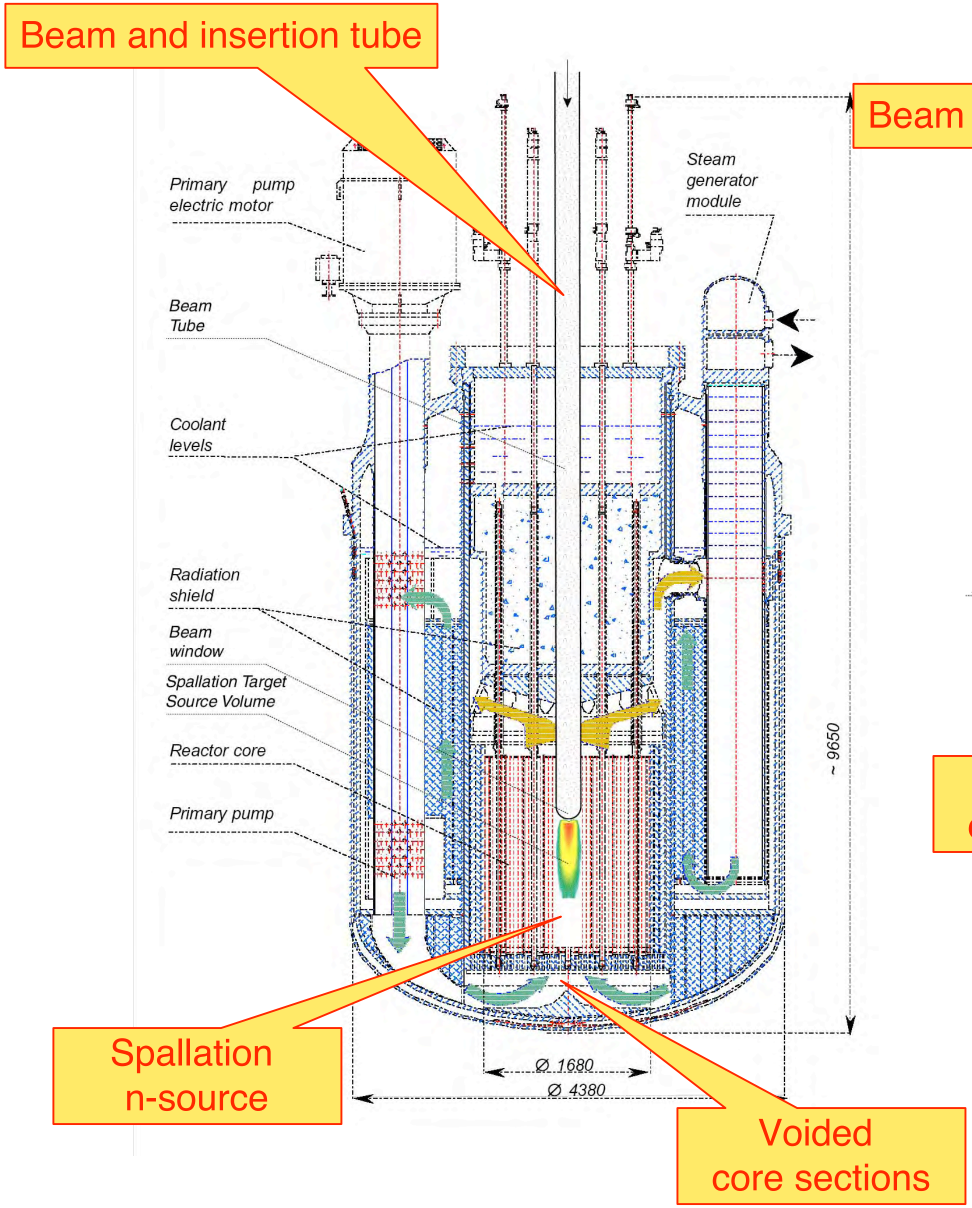
- For instance, in order to correct for the reduction in $\beta \approx 0.007 - 0.002 = 0.005$ of the delayed neutrons, such as to operate with U-233 in the same delayed neutron conditions of ordinary U-235, $k_{eff} \approx 0.995$ and $G \approx 480$, namely the controlling beam power is 2.1 MWatt for each GWatt of thermal power. For $k_{eff} \approx 0.99$, $G \approx 240$.

Basic choices

FUEL	Depleted Uranium (U-238)	Natural Thorium (Th-232)
Fast Neutrons (metal coolant)	Same as Super-Phenix. Pu/U @ equilibrium ≈ 20 % It produces both Plutonium and minor Actinides (Cm, Am, etc). Positive void coeff. <u>Both a critical reactor and sub-critical system (external neutron supply) are possible</u> For critical reactor, very small fraction of delayed neutrons (<0.2 %)-hard to control	Up to 15% mass burn-up but small multiplication coefficient, though very stable (k_o=1.20) U/Th @ equilibrium: ≈10 % Hard to maintain criticality over long burn-up. Not a good reactor. <u>Needs an external neutron supply</u> High power density(≤200MW/m^3) No Plutonium, neg. void coeff. No proliferation (denaturation)
Thermal Neutrons	It does not have an acceptable multiplication coefficient (k_o ≈ 0.7). <u>Not practical</u>	Up to 4% mass burn-up, but small multiplication coefficient, though stable (k_o =1.12) U/Th @ equilibrium: ≈ 1.3 % Hard to maintain criticality <u>Needs an external neutron supply</u> No Plutonium, no Proliferation Low power density (≤ 10 MW/m^3)
	Proliferation risks	**No ploriferation risk**

Operation	Thorium (^{232}Th) cycle	Uranium (^{238}U)cycle
Thermal neutrons	Sub-critical	Not possible
Fast neutrons	Sub-critical	Sub-critical and Critical

Typical Pb-Bi fast sub-critical unit (Russian design)



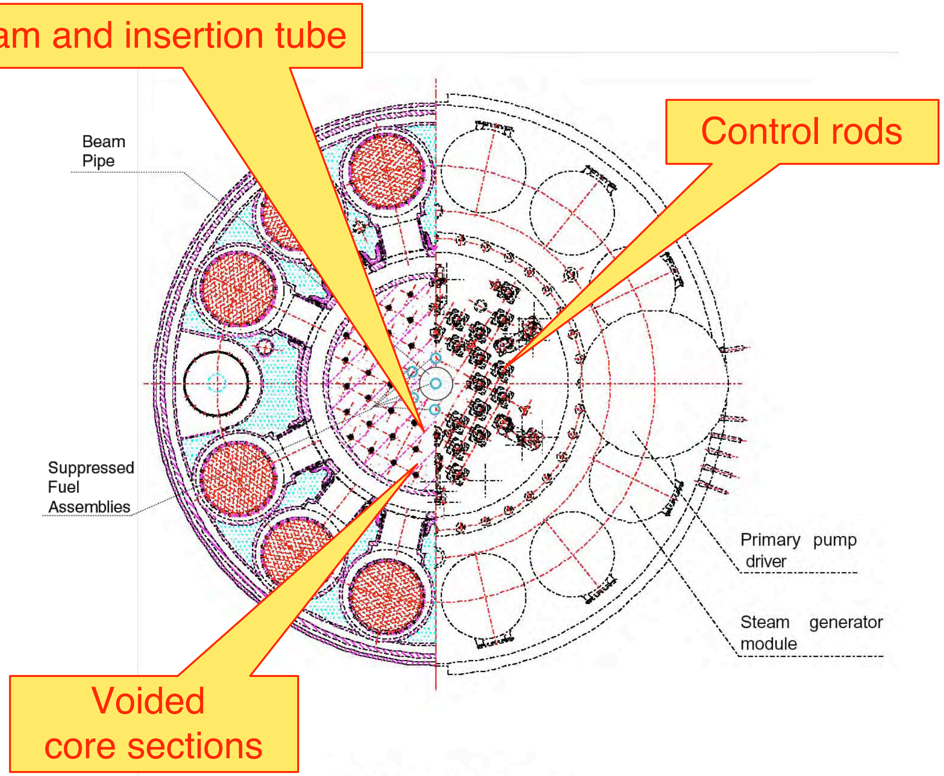


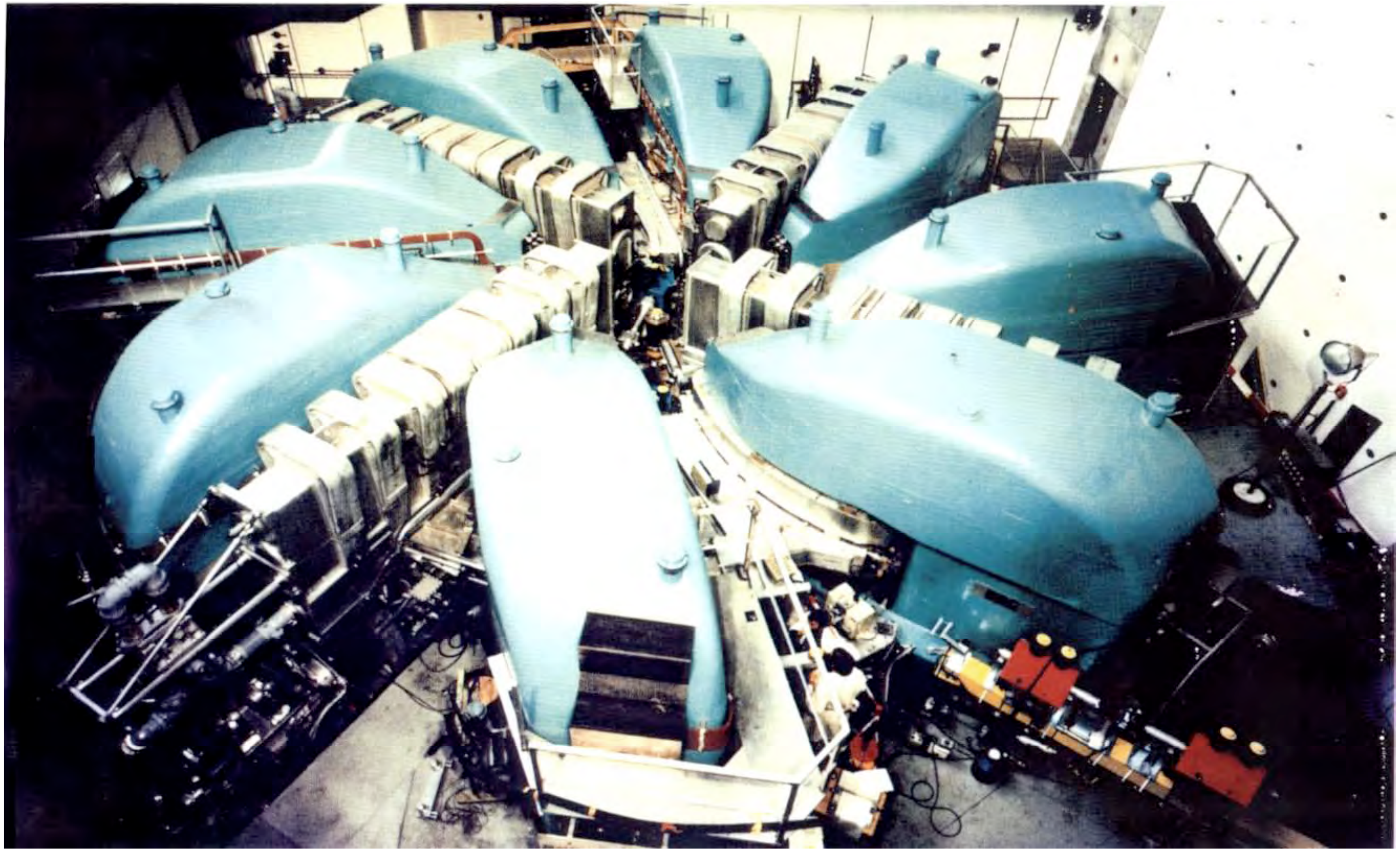
Fig. 2. Reactor Top View

T_p = 600 MeV

I_p = 3.5 mA/GWth for k = 0.995

I_p = 7.0 mA/GWth for k = 0.99

The 600 MeV cyclotron:PSI as a model



Present beam power ≈ 1 MWatt
Upgrade to about 3 × foreseen

Extrapolation at higher currents and energies

10 mA at 1 GeV = 10 MWatt
Efficiency of conversion from AC to beam ≈ 50 %
Injection energy 120 MeV

Potential of Cyclotron based Accelerators for Energy Production and Transmutation

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Abstract. PSI operates a 590 MeV-cyclotron facility for high intensity proton beams for the production of intense beams of pions and muons. The facility, commissioned in 1974, has been partially upgraded and is now operated routinely at a beam current of 1 mA, which corresponds to a beam power of 0.6 MW. At this current, the beam losses in the cyclotron are about 0.02%. By the end of 1995 we expect to have 1.5 mA of protons. Extensive theoretical investigations on beam current limitations in isochronous cyclotrons were undertaken. They show that the longitudinal space charge effects dominate.
Based on our experience we present a preliminary design of a cyclotron scheme that could produce a 10 MW beam as a driver for an "energy amplifier" as proposed by C. Rubbia and his collaborators. The expected efficiency for the conversion of AC into beam power would be about 50% (for the RF-systems only). The beam losses in the cyclotron are expected to be a few μA, leading to a tolerable activation level.

A PSI study

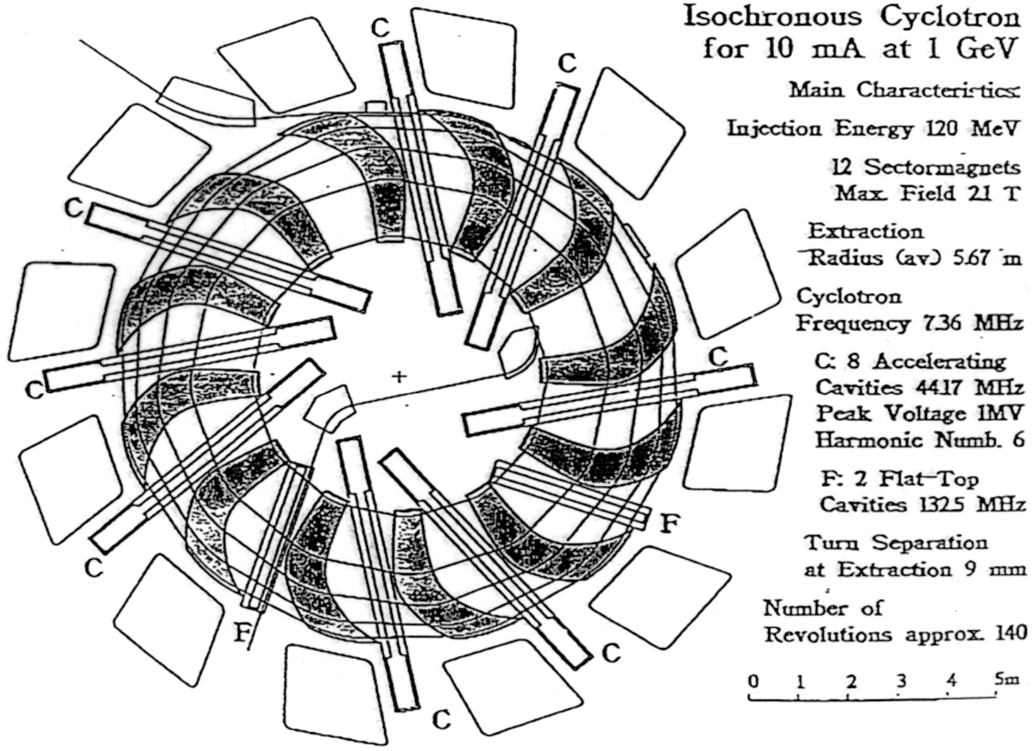


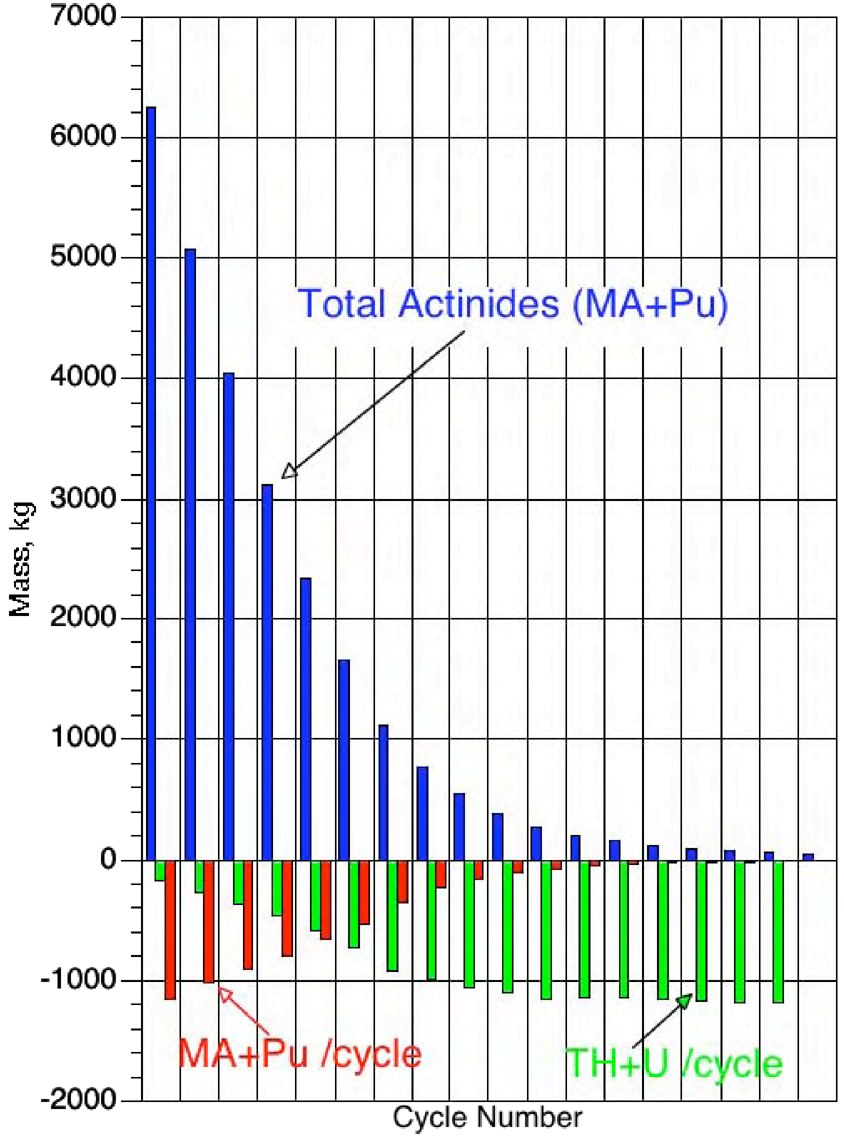
Fig. 4. Layout of the proposed high power cyclotron.

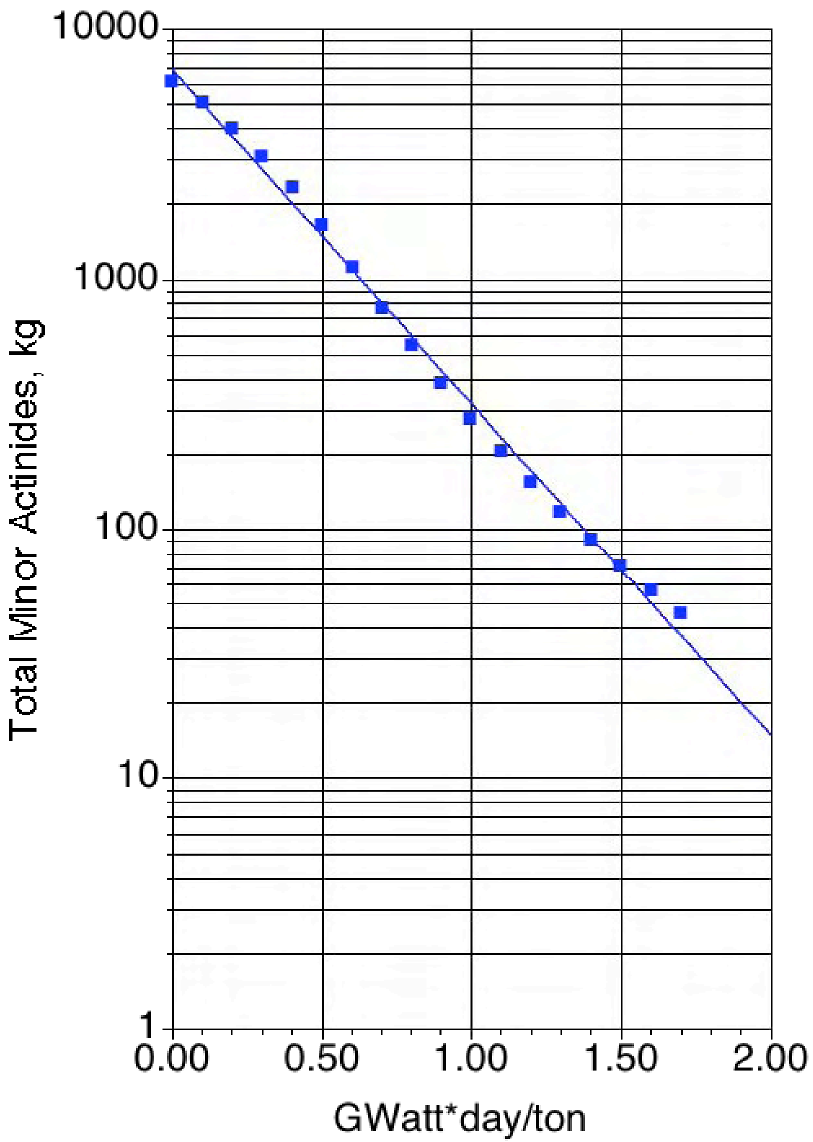
Maximum fission driving power: 2.4 GWth for k_{eff} = 0.99

The initiation of the breeding process.

- The Th fuel is not directly fissile: an adequate amount of U-233 must be in equilibrium with Th in order to produce fissions and energy.
- Several methods are considered in order to start-up the breeding process with the addition to Thorium of a provisional fissile element recovered from an ordinary reactor which has no appreciable proliferating risks.:
  - ⇨ An adequate mixture of Plutonium, with an advanced isotopic composition. (fast and/or thermal)
  - ⇨ An adequate mixture of Minor Actinides (Am,Cm,Np…), only with fast breeders.
- Another more advanced method is the so-called electro-production, in which a Th target is directly bread into U-233 by a high energy proton beam and a very strong current. As an example, a powerful accelerator with 2 GeV and 150 mA (300 MWatt) can bread and extract about 1-1.5 ton of U-235 every year.
- Once the initial U-233 has been produced, the breeding process will continue indefinitely in an equilibrium condition between production and fission, slowly tending to the asymptotic mixture and with a remarkably constant multiplication value k.

Transition from initial MA to Th-U





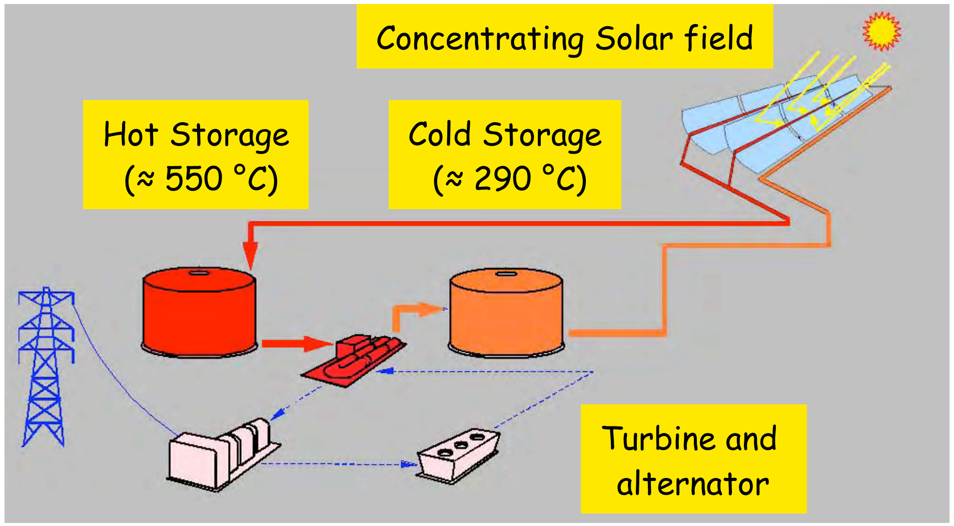
In short:

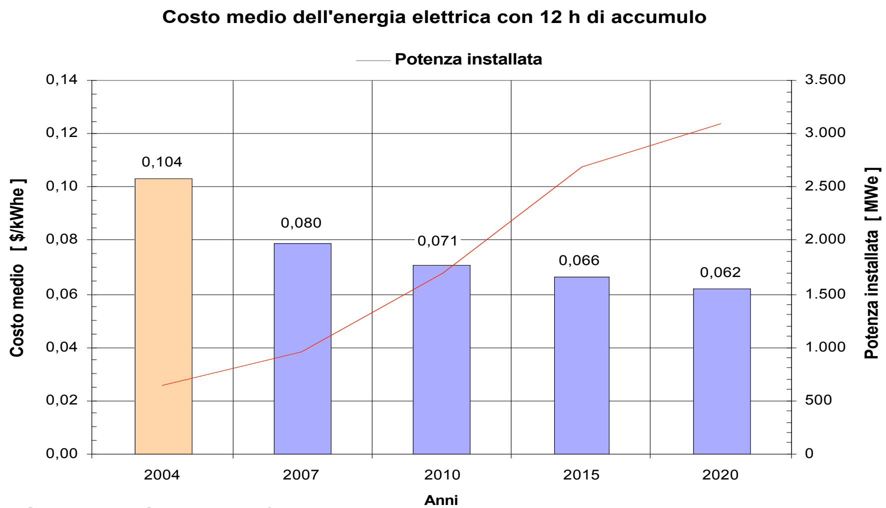
Item	Energy Amplifier
Safety	Not critical, no meltdown
Credibility	Proven at zero power
Fuel	Natural Thorium
Fuel Availability	Practically unlimited
Chemistry of Fuel	Regenerated every 5 years
Waste Disposal	Coal like ashes after 600 y
Operation	Extrapolated from reactors
Technology	No major barrier
Proliferating resistance	Excellent, Sealed fuel tank
Cost of Energy	Competitive with fossils

Novel forms of energy from the sun

New solar energies

- *On 1 m^2 in a good location (sun belt), it "rains" yearly the equivalent of ≈ 25 cm of oil.*
- Produced energy can either be directly collected, eventually with concentrating mirrors or alternatively converted, although with a lower efficiency, into wind, bio-mass,hydro or photovoltaic.
- With the exception of hydro and of biomass, today's renewable wind and photovoltaic have so far reached a modest penetration and this for two main reasons:
  1. The cost of the produced energy is generally higher than the one from fossils.
  2. The energy is produced only when the source is available and not whenever needed.
- In order to overcome these limitations, new technological developments are vigorously pursued in several countries in order to (1) reduce the cost to an acceptable level and (2) to introduce a thermal storage between the solar source and the application.

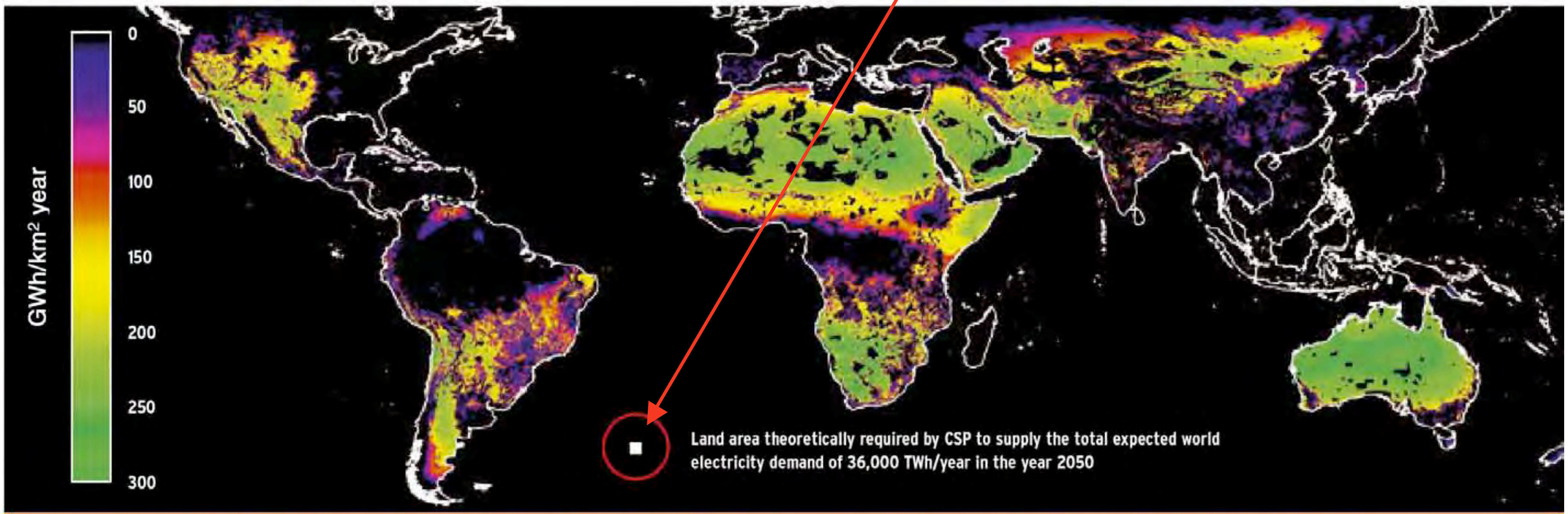




Source: Sargent & Lundy,

Concentrating solar power

Land area theoretically required by CSP to supply the total expected world's electricity demand of 35'000 TWh/year in2050



World wide potential of solar electricity generation by CSP in GWh/km² year (based on radiation data from G. Czisch, ISET).

Conclusions

Conclusions

- The future of mankind is crucially dependent on continued availability of cheap and abundant energy. *Should energy supply breakdown, mankind may collapse*.
- Energy from fossils is not for ever: furthermore it is likely to be prematurely curbed by *the emergence of serious and uncontrollable climatic changes*.
- Time has come to seriously consider other sources of energy, without which mankind may be heading for a disaster. *Nuclear and solar are the only candidates*.
- A serious alternative is a new nuclear energy without U-235 and without proliferation : Thorium fission and D-T fusion are likely candidates, capable of supplying energy for millennia to come— the difference between renewable and non renewable becoming academic.
- Depleted Uranium is also possible, but not for everybody, since it has strong links to military deviations.
- The other alternative is solar energy: particularly promising is the direct use of concentrated solar radiation in the wide regions of the "sun belt".
- These methods are likely to be successful in the long run: however *a vast, urgent and innovative R&D is necessary.*
- Although innovative energies may eventually more essential to developing countries, *only our technically developed society can realistically foster such a change.*