The role of Research for a sustainable development of Nuclear Energy

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Nuclear Energy

- About fifty years ago, the idea of ***"Atoms for peace"*** was greeted with the greatest enthusiasm, as a way of providing a new form of cheap, abundantly available and inexhaustible energy for all people on Earth.
- During the subsequent half century the position on Nuclear Energy has been profoundly modified: nuclear power is today definitely no longer viewed as it was 50 years ago.
- In spite of the Chernobyl accident, nuclear energy consumption during the period 1990-1999 has grown by + 25.9%, namely to 650.8 MTep. During the year 1999, 436 nuclear power stations have contributed to 16% of the world's production of electricity.

Role of Nuclear Energy

- Nuclear energy is contributing today with a reduction of 5.6 % to the world's emissions of greenhouse gases, which however is voided by the actual increases of fossil energies in just 2.5 years.
- This means that substituting ideally all nuclear energy with fossils (coal + NG mix) would represent a mere anticipation of 2 1/2 years of the level of the greenhouse concentration.
- BUT, a further substantial growth of the nuclear energy production, up to a level such as to significantly curb gas emissions coming from fossils, is not without problems.
- This is particularly relevant in the case of the Developing Countries, for which however a rapid growth in the energy demand is a primary goal related to economic progress.

Problems to a uncurbed development of Nuclear Energy

- The present nuclear power technology, essentially based on Light Water Reactors (LWR) operated mostly on enriched Uranium and thermal neutrons has a number of problems which hamper its unconstrained free use:
  - ⇨Accidents, though with very small probability, like Chernobyl and TMI, which have so far doubled the radioactivity dose to the population due to nuclear energy.
  - ⇨Emissions due to radioactive isotopes during reactor operation, fuel transport and fuel storage which extend to a very long duration (millions of years)
  - ⇨Links to military and eventually terrorist-related applications of nuclear weapons.
- In order to harness on a vast scale the immense potential of nuclear energy, very solid conditions must be satisfied, which, in turn, will inevitably demand new methods and new ideas.

Operational Safety

- There is no doubt that the environmental and safety features will govern any new development in the field of energy from nuclei.
- Most of nuclear related accidental phenomena are of *probabilistic* origin, i.e. proportional to the number of reactors in operation, but with their occurrence acceptably low, typically by a redundant repetition of a cascade of correcting devices.
- Introduction of deterministic rather than probabilistic conditions may forbid *a priori* the happening of extreme events, and for instance:
  - ⇨ *Criticality accidents (Chernobyl)* can be eliminated operating the reactor in a sub-critical mode, with the help of a substantial neutron contribution by an outside source (accelerator) rather than stabilizing the reactor's power with the help of delayed neutrons.
  - ⇨ *Melt-down accidents, due to residual decay heat (TMI)* may be eliminated with the help of automatic, passive heat extraction to the environment, occurring naturally and inevitably. Typical events are for instance loss of a pressurized coolant or loss of electric power.

The choice of Fuel

- The benefits attributed somewhat naively to nuclear energy, when compared to fossil fuels, are (1) potentially zero emissions and (2) an extremely parsimonious use of the fuel.
- For instance 1 ton of Actinides — if fissioned completely —produces an energy equivalent to 3 Million tons of Coal (TEC). Today's full primary world's demand could be ideally exhausted with about 4000 ton/year.
- BUT, at least with the present nuclear power technology based on Water Reactors operated on Uranium and thermal neutrons, the energy extracted in practice is far from such an idealised expectation.
- Of natural Uranium, only the ^{235}U (0.71%) is directly fissile. Typically, only about 0.4% of the energy potentially contained in the natural U is used.
- In this way, in spite of the tremendous potentials of nuclear energy, there will be no more future energy from Uranium than from Oil and NG, unless U could be extracted directly from the water of the ocean (few ppb) .

Nuclear breeding with a closed fuel cycle

- In these schemes, a not readily fissile element is converted first into another readily fissionable element, which in turn constitutes the main energy producer (breeding).
- For each fission two neutrons (rather than one) are therefore required, one for the production of the fissile element and another in order to initiate fission. Therefore:
  - ⇨ No fuel enrichment is required, since naturally dominant isotopes ^{238}U or ^{232}Th are excellent breeders of easily fissionable nuclei, ^{239}Pu or ^{233}U.
  - ⇨ At the end of the cycle, the remaining actinides are recovered as "seed" for the next cycle, and entirely recycled. The fuel waste products are mainly fission fragments, strongly radio-active but with a shorter lifetime (β or γ with $t_{1/2} \leq 30$ y).
- In these conditions, the totality of the fuel is burnt and the energy extracted from a given supply of natural element could be about two hundred times larger than the one presently in use.

The ^{238}U closed cycle

- A large amount of surplus depleted uranium is today available (> 500'000 ton) as the result of previous enrichment and reprocessing activities.
- If recycled with breeding and in a Pu dominated closed cycle, the newly produced energy would be enormous, equivalent to the total planetary primary energy consumption during more than 100 years!
- At breeding equilibrium of the Actinide chain (Pu,Am, Cm …) the n-multiplication coefficient is too low for thermal neutrons, but sufficient for very fast neutrons, with a typical stationary ratio Pu/U ≈ 20 %.
- Each fuel cycle between reprocessing corresponds to the burning of ≥ 15 % of the actinides, which is replaced with fresh fuel. Hence the externally supplied initial fuel is effectively bred and burnt in about 7 cycles.
- Reactor criticalities may be caused by a positive void coefficient and a too small fraction of delayed neutrons (0.2 ÷ 0.4 %, vs. 0.7 % for a PWR).
- These problems could evidently be eliminated operating below criticality (k<1) with the help of an external accelerator.

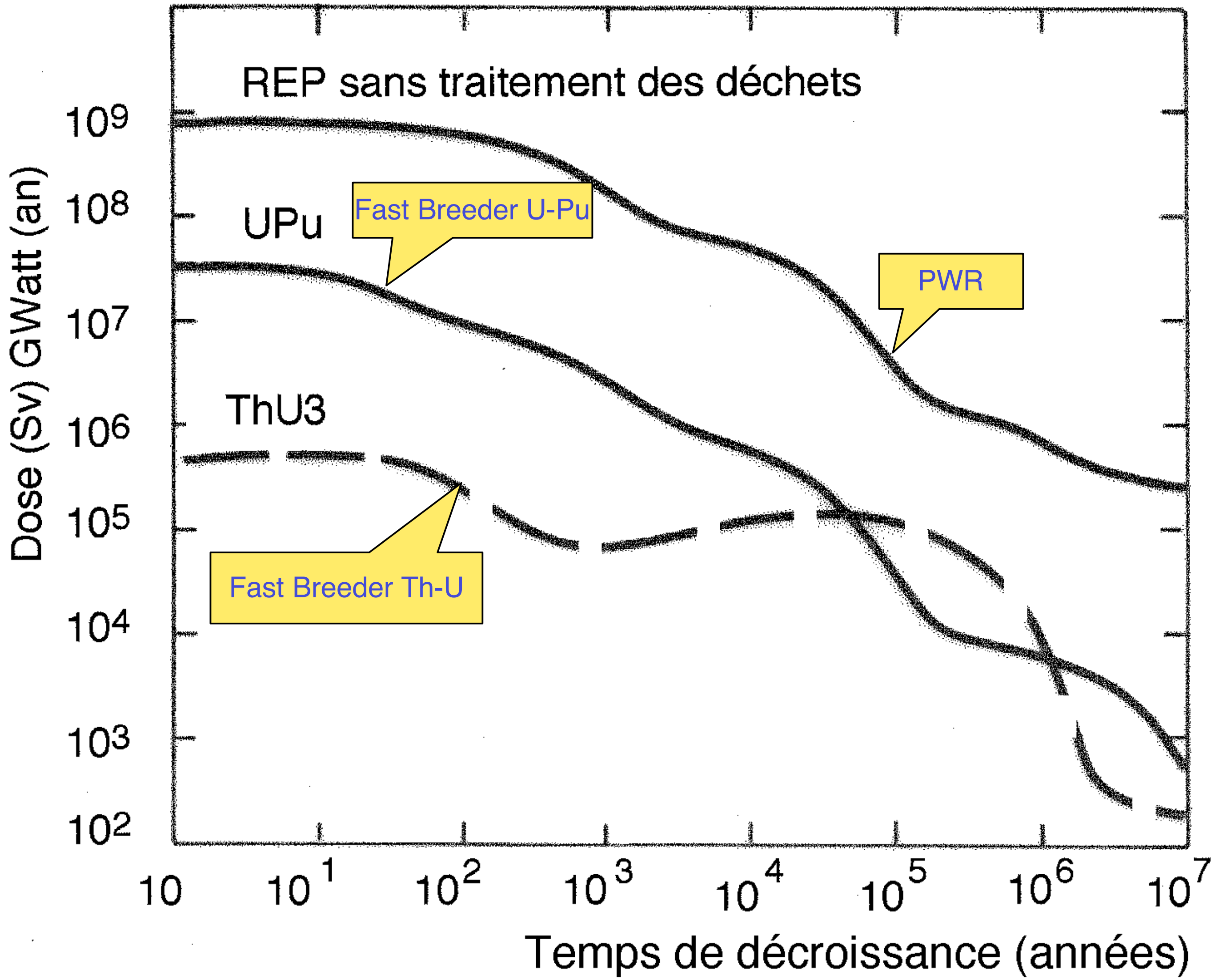
Such a huge amount of plutonium world-wide may introduce major concerns, in view of its potential risks of military or terrorist deviations

The Thorium Cycle:

- Particularly interesting is the breeding closed cycle starting from natural Thorium (a pure isotope ^{232}Th). The totality of the primary energy of today could be ideally burnt with 5000 tons/y of Th !
- In equilibrium conditions of a continuously recycled burning, the principal fissionable elements are various isotopes of U. The production of trans-uranic actinides, including Pu and Np, is absolutely negligible.
- Chemically extracted Actinides (U) from the Th cycle cannot be used for military purposes, since they do not allow contact handling, due to their very intense intrinsic radioactivity.
- In contrast with the ^{238}U cycle which is dominated by Pu, the conversion to the Th cycle permits to reduce strongly the links to potential military weapons applications.
- The radio-toxicity of the waste for unit power production, excluding fission products, is far smaller than the one of a standard PWR and of the one of a closed cycle.

Evolution of waste

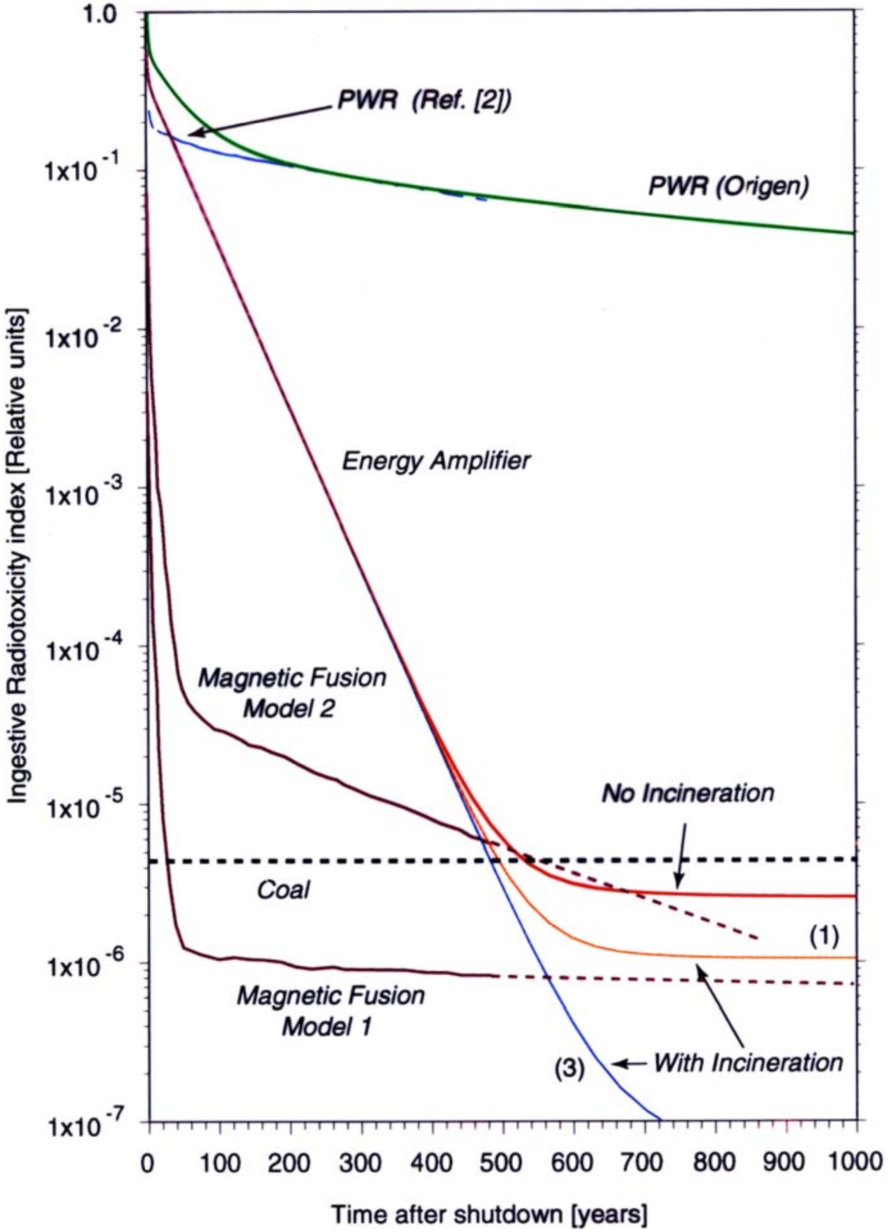
Evolution of radio-toxicity of waste (excluding FF). In the case of reprocessing, the fraction escaping into the waste is 0.1% for U and Pu and 1% for the other Actinides.



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

Comparing advanced Fission with Fusion

- In its simplest form magnetic containment Fusion is based on a breeding of Lithium into Tritium which is "fused" with Deuterium to produce Helium and a neutron, which supplies breeding.
- A considerable activation of the surrounding structures of the reactor is due to neutron activation.
- From the environmental point of view it is worth comparing for the same produced energy
  1. A standard PWR
  2. The Th based sub-critical fission
  3. Two models for Magnetic fusion



The ultimate kind of Fusion ?

- Radioactivity is one of the main shortcoming of nuclear energy. In the case of Fission this is inevitably related to the fission products. In the case of Fusion many different possibilities exist.
- There are several exothermic reactions which produce no neutrons, neither directly, nor indirectly through secondary reactions. Since neutrons are the primary sources of activation, their absence will be a tremendous asset, making the process inherently "clean".
- It is probably in this way that an ultimate nuclear energy will be eventually exploited in a very far fetched future.
- The simplest reaction of this kind is $^{1}_{1}p + ^{11}_{5}B \rightarrow 3\left[^{4}_{2}He\right] + 8.78\ MeV$
- The 3 α-particles which are emitted could be slowed down with direct electricity production (no thermo-dynamical cycle)
- Unfortunately it is known not to "ignite" in a magnetically confined device (Tokamak) and most likely also with inertially confined Fusion.
- Both Hydrogen and ^{11}B (81 % of natural Boron) are extremely abundant and easily obtained. So far unknown methods are needed in order to exploit such a formidable asset,

A long term renovated nuclear scenario

- The main motivations for the Research of new sources of energy from nuclei is that of reconciling the inherent advantages of such powerful and virtually unlimited energy sources with an environmentally acceptable and safe new technology.
- There is no doubt that the environmental and safety features will govern any new development in the field of energy from nuclei.
- We must use, far more efficiently, a naturally abundant fuel, in order to secure its wiser use and practically unlimited resources.
- A renewed nuclear approach could be, for instance, based on full breeding of a natural element, either through Fusion or Fission.
- In both options, the potentially available energy, though not strictly renewable, can realistically last for many tens of centuries at a few times the present consumption.