THE ENERGY AMPLIFIER

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by

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1. Introduction

In my opinion, the safest approach to the "waste management problem" is the one of producing a minimal amount of waste to start with ! For that matter, the Thorium route is the one of main merit, since: (i) it is far less toxic during its mining stage (ii) it results in much smaller toxicities of Actinides after burnup and (iii) these Actinides can be recycled as seeds for the next fuel load. This has been known for some time, as well as the fact that the neutron inventory is a problem, since the low value of η (2.29) makes it difficult, in fact practically impossible, to operate a standard reactor on a fully sustained ^{232}Th — ^{233}U breeding cycle. This is where particle accelerators can play a crucial role in providing an external supply of neutrons in order to remove the above-mentioned limitation.

Accelerators have since a long time served as dependable, long lasting, routine tools of the research community. Some accelerators at CERN have worked reliably for over 30 years, and the only limit to their lifetime has been the validity of their scientific programrne. As we shall see in § 4, they can now run with a high energetic efficiency ($\eta \approx 1/2$), they can be built as robust devices and their price would be "low", when compared with a large or medium power station.

2. Energy production through nuclear cascades rather than chain reactions

Our inspiration is the "compensated uranium calorimeter", a well known tool of the particle physicist which leads us to propose [ref 1] a concept where neutrons (produced by spallation of a heavy target at a relatively small energetic cost) are further multiplied in a subcritical fuel-moderator configuration. Our calculations indicate that this results in a substantial energy gain relative to the power consumption for running the accelerator.

The first consequence of this is to eliminate the risk of a criticality accident such as the one in Chernobyl. There are other attractive features which, however, are tied to the neutron flux at which one operates. My view is that we should distinguish Incineration from Energy production, since they need entirely different neutron fluxes.

Incineration needs the highest possible flux ($\geq 10^{16} cm^{-2} s^{-1}$), if one is to remove the resilient species which have already been subjected to a reactor flux during ≈ 1 year. On the other hand, in order to breed ^{233}U from ^{233}Pa, the latter must have the time to undergo decay before capturing a neutron to become ^{234}1?a This is at the heart of what we call the "decay dominated regime". At a higher flux, breeding would require quick removal of I?a (e.g. by a liquid circulating fuel), which is the essence of the difference between our approach and the one by the Los Alamos group [ref 2].

3. Main features of "decay dominated" regime

It is easy to show that, in equilibrium conditions: ^{233}U concentration is independent of the neutron flux in steady operation.

$$\frac{N_{U233}}{N_{Th232}} = \frac{\overline{\sigma_{ine}(Th232)}}{\overline{\sigma_{ine}(U233)}} = 0.013 \text{ (for thermal neutrons)}$$

However, the concentration of ^{233}Pa is directly proportional to the neutron flux Φ.

$$\frac{N_{U233}}{N_{Th232}} = \sigma_{ine}(U233)\Phi t_{1/2}(Pa233)$$

Therefore the ^{233}U equilibrium after the system undergoes a flux change is re-established only after a few ^{233}Pa lifetimes (27 days). Fast, daily changes are however averaged out. A new limit to the flux arises since after shut-off, the Amplifier must not become critical when all the ^{233}Pa has decayed into fissile ^{233}U.

A third limitation to the flux arises because of the necessity to avoid bypassing fission of ^{233}U leading directly to ^{234}U. This is costly since we lose fissions and must be kept well under 170>. For small η values, one can write:

$$1 - \eta = \sigma_{ine}(Pa233)\Phi t_{1/e}(Pa233)$$

From which we obtain another limit for the maximum flux. In summary, these three conditions converge in giving a limit for the flux which is $\Phi \leq 10^{14}$ cm^{-2} s^{-1}.

4. The simplest" Conceptual realization" of the Energy Amplifier

The "simplest and safest" Energy Amplifier (EA) in my opinion, should rely upon (i) a proton beam hitting directly the moderator-fuel system (no separate Lead spallation target would be required). Clearly, the number of neutrons produced by interaction with Thorium is adequate and one must only take care to choose the geometry to minimize the interactions with the moderating medium (presumably a light element producing few neutrons by spallation) (ii) pressurized water is to be used both as a cooling medium and as a moderator with the fuel elements being in sealed cladding.

I have already mentioned the crucial fact that the Thorium way produces extremely small quantities of Plutonium, which makes it particularly attractive if one is worried about the issues of nuclear non proliferation. However, one might be concerned about ^{232}U itself becoming a weapons material. The answer is that this is produced in the Amplifier as an isotopic mixture which would require isotopic separation if one wanted to obtain a "weapons grade critical mass". Furthermore, (n,2n) reactions produce ^{232}U which would make the Uranium fraction extremely radioactive, hindering weapons fabrication. In addition, one could consider "denaturation" by adding ^{238}U with the effect of making the critical mass infinite.

All requirements for this "simplest EA conceptual design" can be met with a roughly 50%-50% water and Thorium fuel. The price to pay is under-moderation and a slightly larger equilibrium ^{233}U concentration ($\approx$ 1.5 $\div$1 .60/0).

The amount of energy produced by the cascade and our requirement for setting the flux value at 10^{14} cm^{-2} s^{-1} define a natural size for the energy production of the energy amplifier which is around 300 MWth. It is clear that this does not preclude in any way the possibility of obtaining higher output. This would call for the obvious possibility of building a number of smaller (300 MWth) modular units. It would have the advantage of allowing an easier treatment of the risk of “melt-down”. Depending on the beam intensity available from the accelerator unit, it could either be fed from a unique accelerator with the help of beam splitters or by “stacking” a number of individual accelerators.

Looking at the evolution of the system, and in particular the contamination by fission products, one notices the favorable situation that the EA should permit a longer burn-up (150,000 ÷ 200,000 MWDt) when compared with a PWR, still maintaining a reasonable gain ($k \approx 0.9$).

Which policy should we follow with spent fuel? The approach that we advocate lends itself to a variety of options on which one would have to decide, based on mostly external arguments.

The first is the “once through” option with no reprocessing of the spent fuel elements. This is justified because Thorium is abundant and inexpensive, the burnup is relatively high and actinide toxicity is low (Fig 1).

The second option is to extract from the spent fuel all Actinides (Pa,U, Np, Pu etc.) and use them as seeds for the next load. Actinides are then produced and burnt and their amount is roughly constant over the lifetime of the plant or forever (next plant).

The third option is a variant of the above in which, in addition, one would incinerate the most offending fission products with a different, dedicated device. This is costly and would amount in consuming for that purpose a fraction (around 20%) of the produced electricity.

5. Characteristics of the necessary accelerator

The accelerator should have a power of several megawatts and the necessary proton energy should be around 1 GeV. One is therefore talking of a few mA of current which is within the present state of technology. Furthermore, such a dedicated power should be robust and as simple as possible to construct and operate. New technologies, such as superconductivity should, as far as possible, be avoided. A priori two choices are possible: (i) a Linac (ii) a circular machine, such as a sector focussed fixed frequency cyclotron which we prefer for the time being. Fig 2 shows a schematic of a sector focussed cyclotron which can be considered a reasonable extrapolation of the accelerator presently working at the Paul Scherrer Institute (PSI) near Zurich. The Table shows the striking evolution over time of the efficiency of proton accelerators.

Machine	Energy (GeV)	Power consumption (MW)	Beam Power (kW)	Efficiency
CERN SC	0.5	1	0.62	6.5×10^{-4}
CERN PS	24	12	40	3×10^{-3}
CERN SPS	400	52	360	6.9×10^{-3}
PSI	0.6	2.7	900	0.3
Present design	1.0	13	6000	0.46

6. A strategy for testing these concepts

These are concepts which we believe to be sound but should obviously receive the test of reality. We believe that the basic concepts could be tested quickly and would like to outline two distinct stages for doing that.

Phase 1: a simple experiment (FEAT: First Energy Amplifier Test) will be performed with a very low intensity-proton beam provided by an existing accelerator [ref 3]. There the energy gain G will be measured when the beam interacts with a small, natural Uranium subcritical device ($k \leq 0.90$). In reality, the determination of the gain G aims at measuring the non-trivial gain Go, defined by $G = Go/(1-k)$ on a variety of H.E. targets of interest. With natural Uranium and k= 0.9, one expects a gain around 30. If the result is within expectations, one could consider this as a first validation of the complex simulation procedure, it would then in our view be justified to go for the next step which would test concepts (breeding, burnup etc..) which absolutely need a significant amount of power.

Phase 2: An attractive possibility would be to transform an existing, but so far never used, research reactor (Cirene, Italy) which has a nominal power of 130 MWth. The core could be retrofitted to become an EA with Thorium Oxide fuel and necessary provisions would be made for irradiation by a high intensity proton beam. A dedicated accelerator (1 GeV, 3.25 mA) would have to be built and we believe this to be within present technology. An estimate of the cost is 1OOM$. The reactor would be started with a mix of slightly enriched Uranium and Thorium fuel bars (1 .3: U-2/ 3:Th) and gradually brought up to full Thorium burning.

References

1. CERN/AT/93-47 (ET), An Energy Amplifier for Cleaner and Inexhaustible Nuclear Energy Production Driven by a Particle Beam Accelerator, F. Carminati, R. Klapisch, J. I?. Revel, C. Roche, J.A. Rubio, 1st November 1993

2. Bowman et al., Nuclear Instruments and Methods, A320, 336.

3. Private Communication

Figure captions

Fig. 1 Comparison of relative ingestive toxicity in water of conventional PWR reactors and Energy Amplifier. As is customary, the reference is uranium ores. In the case of the EA, the influence of neutralizing by transmutation the most offending fission fragments and of recycling actinides is shown.

Fig. 2 A Two-Stage Sector Focussed Cyclotron able to feed an Energy Amplifier.

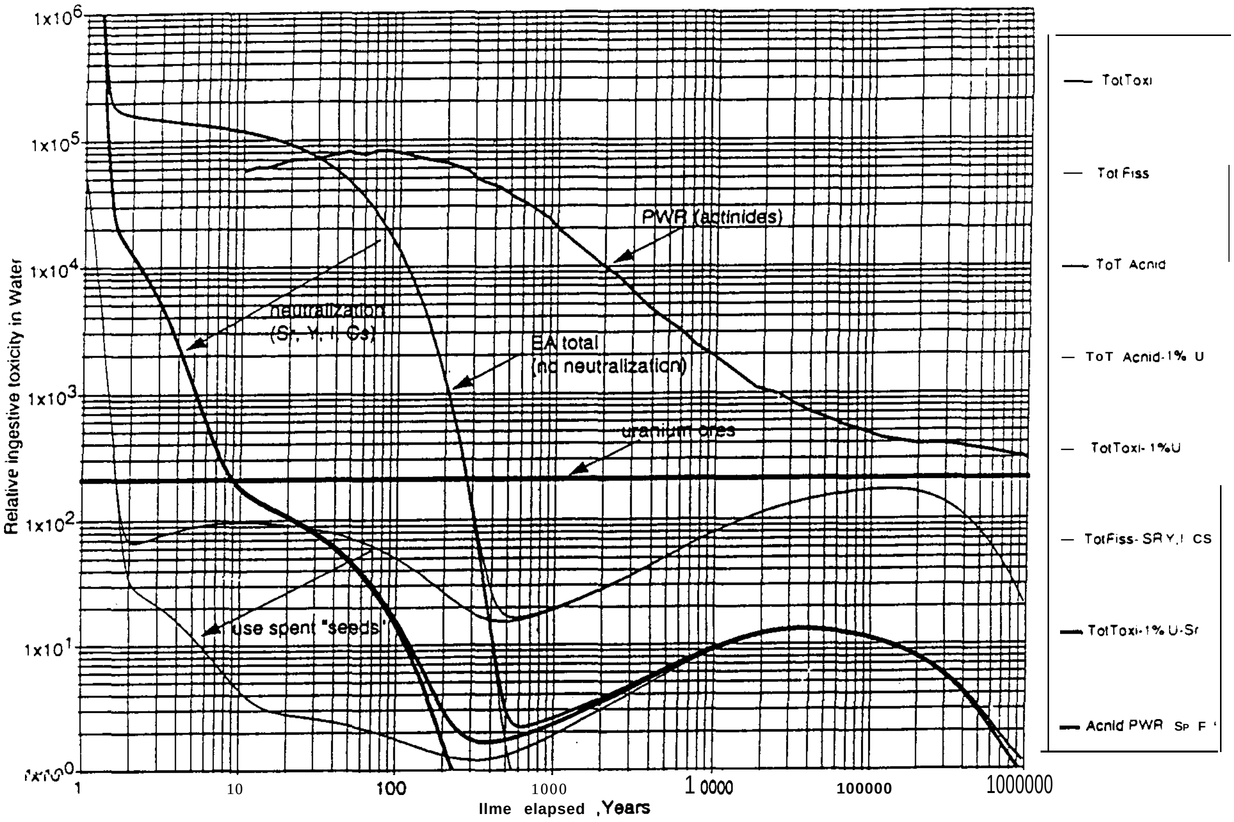

Figure 1

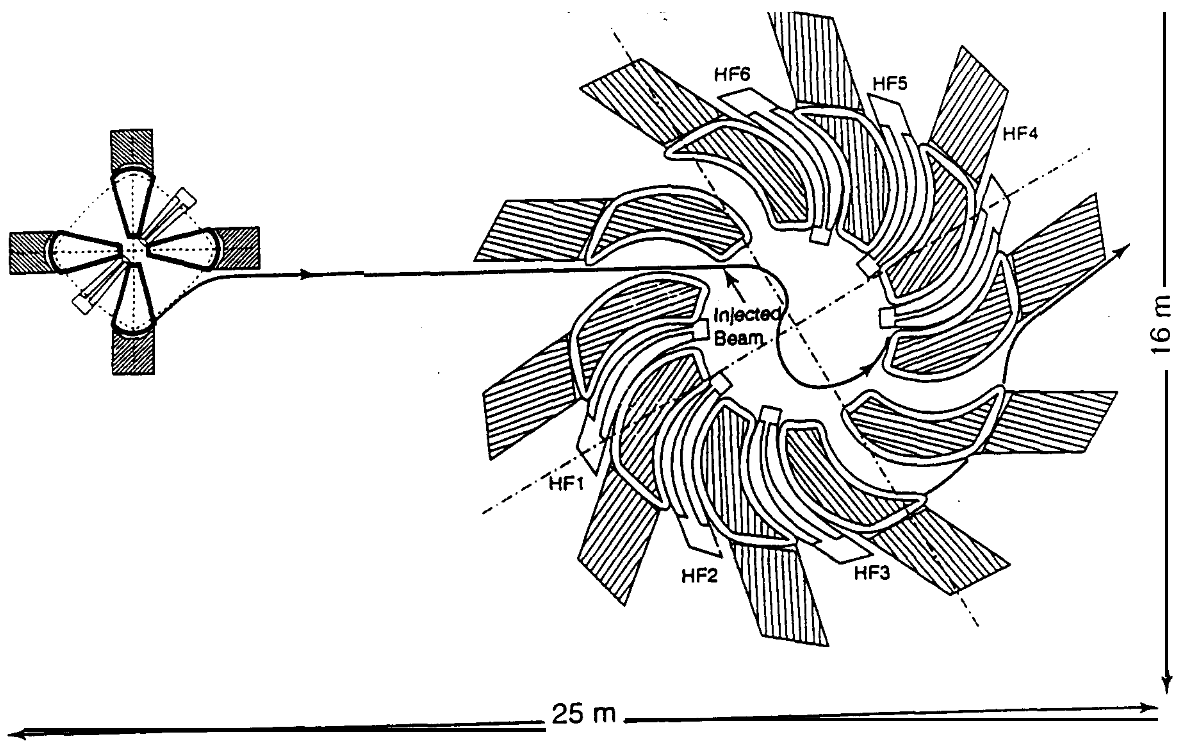

Figure 2