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Particle Physics Contribution to the Elimination of Nuclear Waste

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Abstract

Progress in particle accelerator technology makes it possible to use a proton accelerator to eliminate nuclear waste efficiently. The Energy Amplifier (EA) proposed by C. Rubbia and his group is a subcritical system driven by a proton accelerator. It is particularly attractive for destroying, through fission, transuranic elements produced by present nuclear reactors. The EA could also transform efficiently and at minimal cost long-lived fission fragments using the concept of Adiabatic Resonance Crossing (ARC) recently tested at CERN with the TARC experiment. The ARC concept can be extended to several other application domains (radioactive isotopes production for medicine and industry, neutron research applications, etc.).

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1 Introduction

The concept presented here is rather exceptional for a laboratory such as CERN, in principle entirely devoted to fundamental research. However, the Energy Amplifier (EA) [1] is an innovative approach to nuclear energy, and it should not come as a surprise that such an innovation results from fundamental research, since this type of research has always been a main driving engine of innovation. Examples are multiple and well known; let me recall but one of the most recent ones, the World Wide Web, invented at CERN and not by the much more powerful and resourceful computer industry.

Because particle physicists, interested in discovering the ultimate structure of matter, have pushed the particle accelerator technology as far as they did, it is possible today to consider using a proton accelerator to drive a new type of nuclear system with very attractive properties.

Today, the world is facing an extremely difficult challenge, that of producing sufficient energy needed to sustain economical growth without ruining the ecological equilibrium of the planet. The massive use of fossil fuels has allowed the western world to reach an unprecedented level of wealth. Unfortunately, if the rest of the people on Earth were to carry out the same energy policy, the entire planet would be in serious trouble. There is a moral obligation for developed countries to provide new energy sources to the entire world to minimize global warming and other effects of pollution.

If an acceptable solution is found, it will certainly be the result of systematic R&D and in this context, nuclear energy should be part of this R&D. The present nuclear energy programme is meeting growing public opposition world-wide because of three main reasons: (a) the association with military use and the fear of nuclear weapon proliferation; (b) the fear of accidents such as Chernobyl (1986 prompt-supercritical reactivity excursion) and Three Mile Island (loss-of-coolant accident resulting in a core meltdown); (c) the issue of the back-end of the fuel cycle (nuclear waste management).

Obviously, nuclear power, without these drawbacks would be ideal as it releases neither green house gases nor other chemical pollutants (NOx, SOx, etc.) nor dust particles, nor even radioactive particles as coal ashes do. Therefore, the real question facing scientists today is: "Is it possible to transform nuclear energy production in such a way as to make it acceptable to society?". Nuclear energy is a domain that has seen essentially no significant R&D since the 1960's when the first civil power plants were deployed. There were many technological improvements, mainly with the purpose to improve safety. However, we have seen that even this was not sufficient.

The concept of the EA was proposed by C. Rubbia and his group specifically as an answer to the concerns raised by current nuclear energy production. The present EA version is optimized for the elimination of the nuclear waste, as it is considered to be the most pressing issue in the western world. In developing countries such as China and India, where there is virtually no nuclear waste, a version of the EA optimized for energy production, adapted to the detailed needs of the country and with minimization of waste production, is the more appropriate solution.

2 Nuclear waste

Transuranic elements (TRU) and fission fragments (FF) are the two main components of nuclear waste representing respectively 1.1% and 4% of spent nuclear fuel. TRU, which are produced by neutron capture in the fuel eventually followed by decay, can only be destroyed by fission while FF can only be destroyed by neutron capture. Therefore, different methods will have to be used to eliminate them. As the long term radiotoxicity of the waste (Fig. 1) is clearly dominated by TRU, the EA has been designed to destroy them with the highest efficiency.

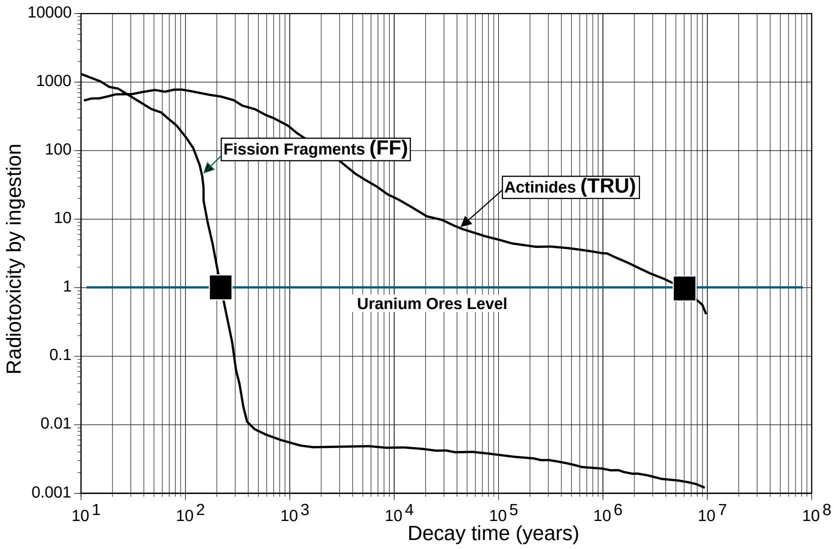

Figure 1: Time evolution of the potential radiotoxicity (relative to uranium ore) of the two main components of nuclear waste for PWR spent fuel (ORIGEN2 code).

3 The Energy Amplifier

The Energy Amplifier is a subcritical system, driven by a proton accelerator and using fast neutrons (Fig. 2). A complete description of all the features of the EA can be found in Ref.[1]. One of the main characteristics is the presence of 10^4 tons of molten lead used as target for the protons to produce neutrons by spallation, as moderator, as coolant to extract heat by natural convection and as radioactivity containment medium.

3.1 Why fast neutrons?

There is a deliberate choice of lead as moderator to obtain the hardest possible energy spectrum for neutrons. This is dictated by the need to maximize the fission probability of TRU. Indeed, in the fast neutron flux provided by the EA all TRU can undergo fission, a

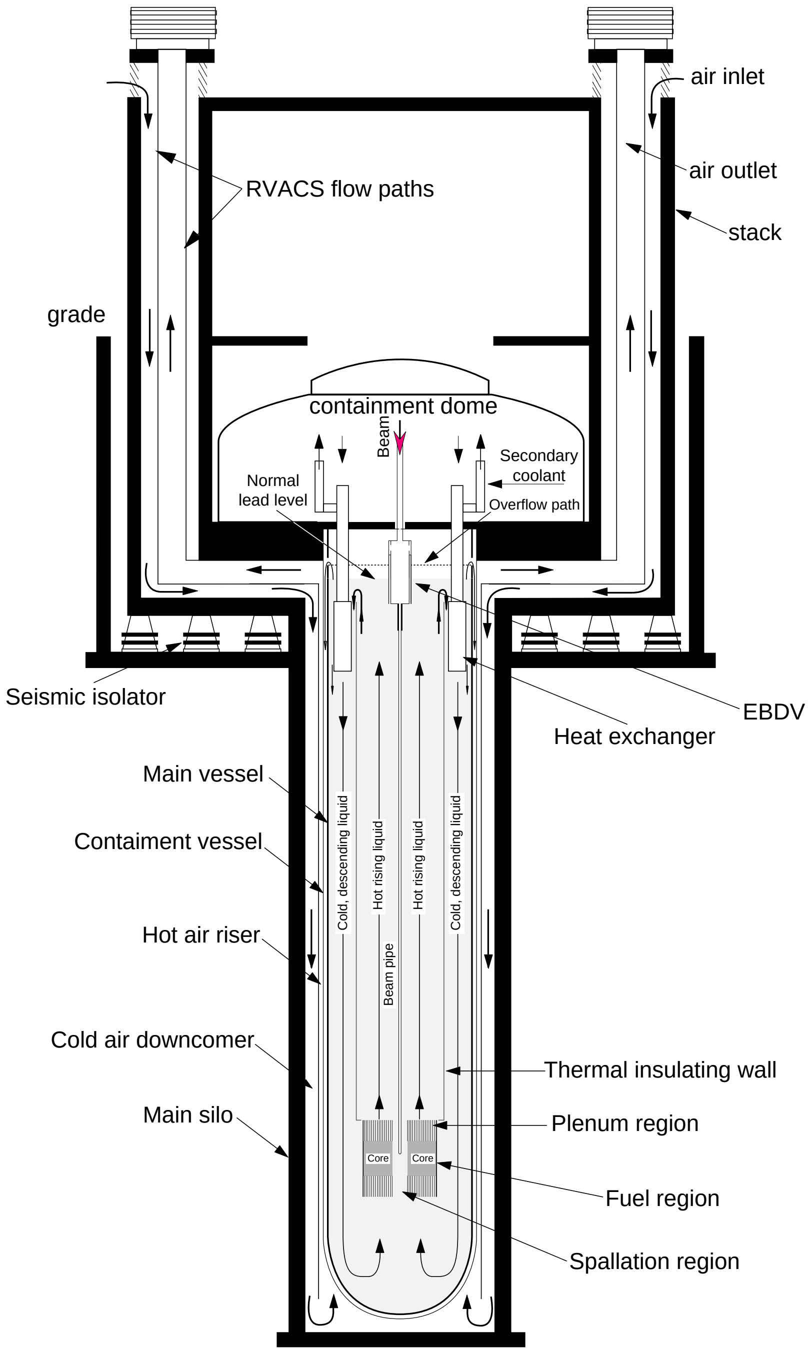

Figure 2: Schematics of the 1500 MW Energy Amplifier standard unit [1]. The main vessel is about 25 m high and 6 m in diameter.

process which eliminates them, while in a PWR thermal neutron flux many TRU do not fission and thus accumulate as waste (Fig. 3).

In addition, as the capture cross section of neutrons on FF is smaller for fast neutrons than for thermal neutrons (Fig. 4), and since neutron capture on FF is the main limitation to long burnups, in a fast neutron system the efficiency with which the fuel can be used will be much higher than in a PWR, typically burnups of 150 GW×day/t could be reached (200 GW×day/t was already achieved in the fast EBR2 system at Argonne).

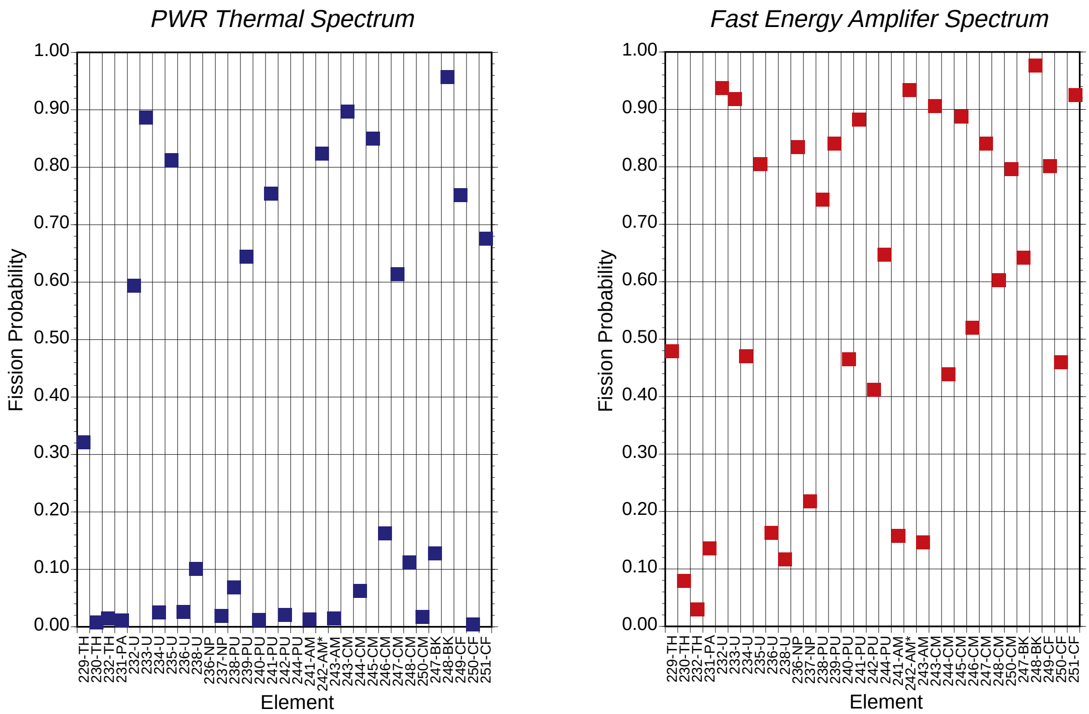

Figure 3: Fission and capture probabilities of actinides for thermal and fast neutron fluxes.

3.2 Subcriticality

The system proposed has a multiplication coefficient (k) of 0.98 for neutrons provided by the beam, which places it far from criticality, and which ensures that it remains subcritical at all times, implying that, by construction, accidents of the Chernobyl type are impossible. The standard k_{eff} of the system is even smaller, of the order of 0.97. The energy amplification in the system, defined as the ratio between the energy produced in the EA and the energy provided by the beam, can be parametrized as $G_0/(1-k)$, with $G_0 \sim 3$. This aspect of the system has been studied in the FEAT experiment [2] where it was shown that this energy gain is well understood and that not only is it independent of the proton beam intensity, but also of the beam kinetic energy above about 900 MeV. This fortunate feature means that the accelerator can be of modest size. All experts agree that the present accelerator technology can provide the required beam power (10 to 20 mA at 1 GeV) with both LINAC and cyclotron solutions [3]. This represents only a reasonable extrapolation of what has already been achieved in research accelerators (1.5

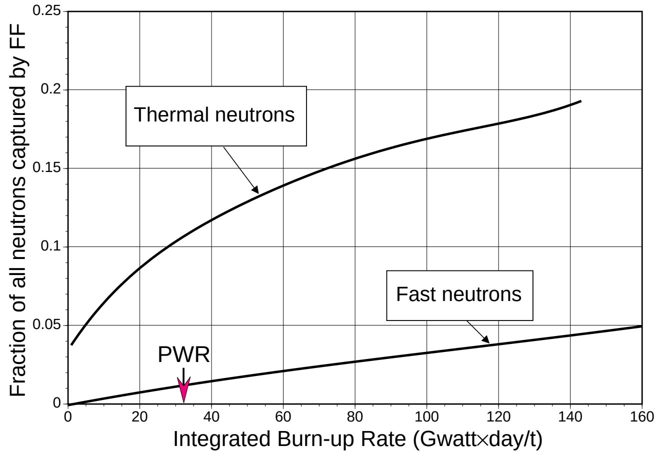

Figure 4: Fraction of neutron captures on fission fragments for thermal and fast neutron fluxes, as a function of burnup. The maximum burnup for a PWR is indicated.

mA at 0.59 GeV at PSI [4]). The preference is given to a cyclotron (Fig. 5) to provide the required beam intensity in a most compact system.

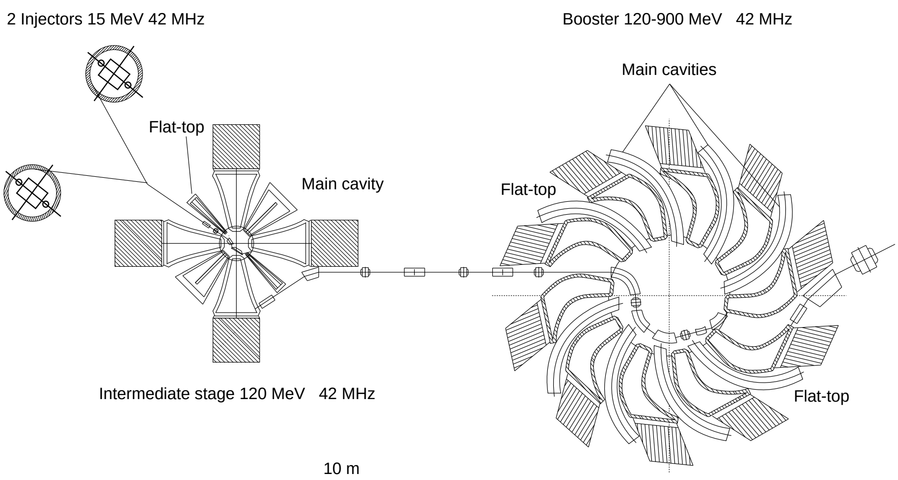

Figure 5: Full cyclotron high intensity accelerator layout proposed for a $k = 0.98$ EA [1].

The FEAT experiment validated the new simulation of energy amplification in accelerator driven subcritical systems and justified the characteristics of a system where less than 5% of the electric power needs to be re–circulated during operation (Fig. 6).

3.3 Destruction of nuclear waste: TRU

The general strategy consists of using as fuel thorium mixed with TRU as opposed to uranium with plutonium as proposed in fast critical reactors, such as SuperPhenix.

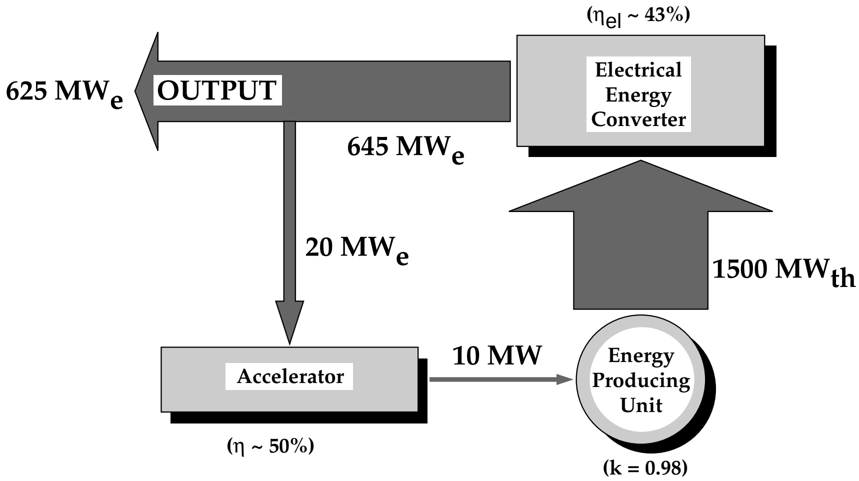

Figure 6: The energy amplification scheme in the standard EA system [1].

The availability of an external neutron source, thanks to the accelerator, and the availability of a fast neutron energy spectrum, thanks to the lead moderator, allows the sustained operation of a subcritical device with a lot of flexibility in the choice of fuel. Pure thorium does not fission, but it is ^{233}U bred from ^{232}Th which can produce energy through fission. In practice, seeds are needed to provide fissions at the startup of the system, and for that purpose any fissionable element will do: ^{233}U from a previous EA fuel load or ^{235}U extracted from natural uranium or military ^{239}Pu or simply TRU, that is precisely the main component of the waste we wish to destroy. Therefore, it is possible, in an Energy Amplifier, to destroy TRU by fission, a process which produces energy and makes the method economically attractive. TRU represent potentially about 40% of the energy that a PWR delivered while producing these TRU.

Thorium is an attractive fuel because it exists in relatively large quantities in the Earth's crust (at least five times more abundant than uranium), it is isotopically pure (no enrichment is needed), it is used entirely as compared to only the 0.7% of ^{235}U in a PWR and it is about 5 neutron captures away from the TRU one wants to destroy, ensuring that it can work in a mode where it destroys more TRU than it produces.

It is easy to see why a thorium system will be much more practical than a uranium system for the destruction of TRU. The high equilibrium concentration (15%) of plutonium in uranium type systems (Fig. 7) forces the use of extremely large plutonium enrichment, which would make these systems extremely dangerous, while in an EA, equilibrium concentrations of the order of 10^{-5} (Fig. 8) ensure naturally a high burning rate for reasonable TRU concentrations.

A study performed for the Spanish Government [6] showed, based on a practical case, that an EA could destroy a net amount of 34 kg of TRU per TW$\times$h$_{th}$ of thermal energy at nominal power of 1500 MW$_{th}$. In comparison, a PWR produces 14 kg of TRU per TW$\times$h$_{th}$.

It is expected that the reprocessing needed to extract TRU from spent fuel should

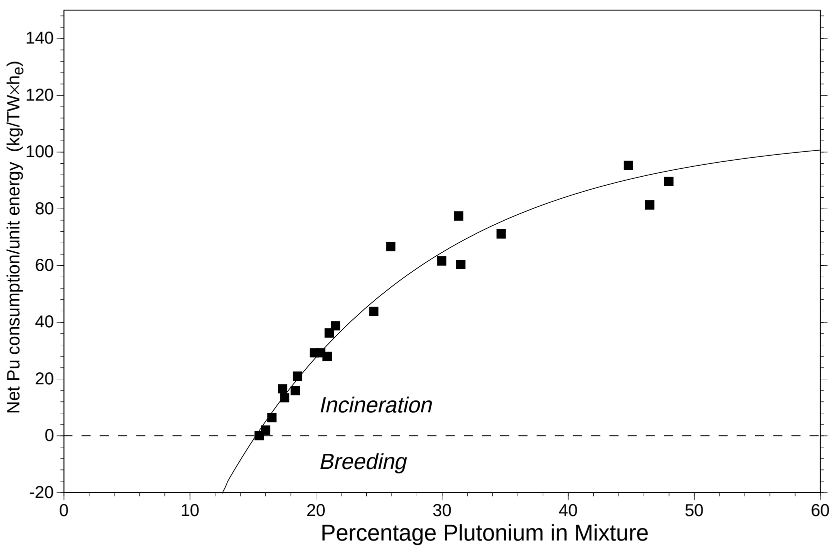

Figure 7: Net plutonium consumption per unit energy in a uranium–plutonium fast breeder (CAPRA [5]) as a function of plutonium concentration. Note that the unit is kg/TW×h electric and not thermal.

be much simpler than what is needed to extract plutonium from spent fuel for MOX, as performed in the La Hague factory (PUREX process). A pyrolectric reprocessing [7] developed at the Argonne Laboratory in the United States collects all TRU on a single electrode; this is sufficient since they all fission and do not need to be separated from one another.

3.4 Destruction of nuclear waste: Long-Lived Fission Fragments (LLFF)

In a system, such as the EA where TRU are destroyed, the long term radiotoxicity of the waste becomes dominated by LLFF (Fig. 9). This residual level of radiotoxicity could perhaps be tolerated, since it is lower than the level of radiotoxicity of coal ashes corresponding to the production of the same quantity of energy. However, since the main LLFF (^{99}Tc and ^{129}I) can be soluble in water and therefore have a non-zero probability over a time scale of millions of years of contaminating the biological chain with long term effects which are hard to predict, it may be wise to also destroy them.

In order to provide such an option, Carlo Rubbia has proposed to use Adiabatic Resonance Crossing (ARC) [9] to enhance the neutron capture probability, turning for instance a 2.1×10^5 year half-life ^{99}Tc into ^{100}Tc decaying quickly ($t_{1/2}$ = 15.8 s) into stable ^{100}Ru. The TARC experiment at CERN [10] has shown that one can indeed use the peculiar (small elastic $\Delta E/E$) kinematic of neutrons in pure lead (the most transparent to neutrons of all heavy elements) to maximize the neutron capture probability, making optimum use of prominent resonances in the neutron capture cross section. Note that ^{129}I

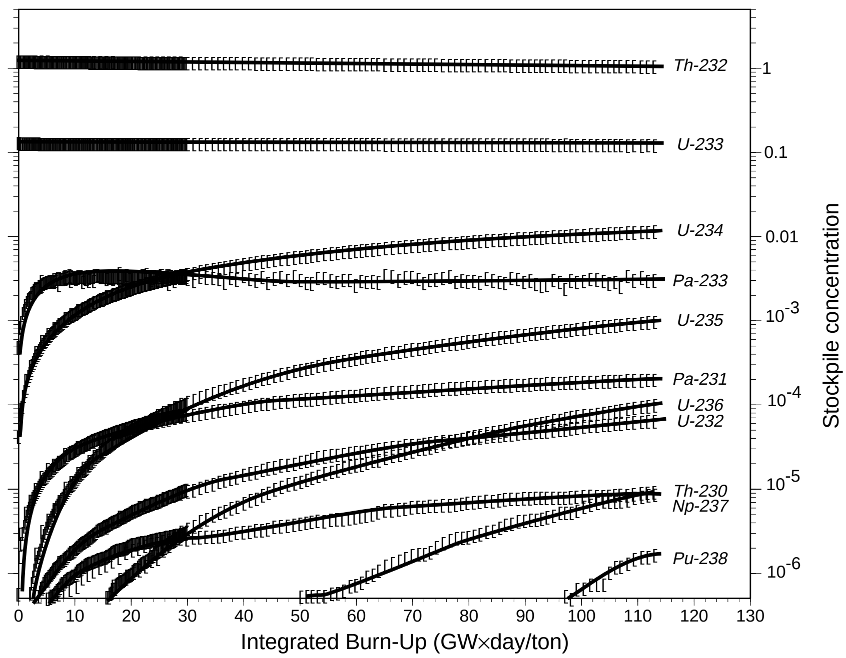

Figure 8: Evolution as a function of burnup of the stockpile of the main elements present in the EA fuel.

and ^{99}Tc which were tested in TARC represent 95% of the LLFF volume. The results from TARC imply that one could actually transmute ^{99}Tc and ^{129}I in the lead in the vicinity of the EA core, where conditions are such that one can destroy about twice as much of these elements as produced during the same time in the EA core. This possibility to transmute LLFF in a parasitic mode in an EA may be an additional incentive to eliminate LLFF, a process which, unlike the elimination of TRU producing energy, does not "pay", and for which the cost must be minimized.

The TARC experiment is a very significant step both for the EA programme, for which it provided precision validation of the simulation and proof of the efficiency of ARC for the destruction of LLFF, and also because it opened up new possibilities in the domain of radioactive medical isotope production (as an alternative to the production with nuclear reactors), in the domain of new research applications (TOF facility [11] in preparation at CERN for the systematic high precision measurement of neutron cross sections) as well as in the domain of space exploration where the TARC effect can be used to provide a practical nuclear engine for deep space travel [12]. Details of these applications can be found in corresponding publications.

4 Conclusion

Fundamental research continues to be a strong driving force in innovation. It can lead to potential solutions of some of the most difficult problems facing our society at the begin-

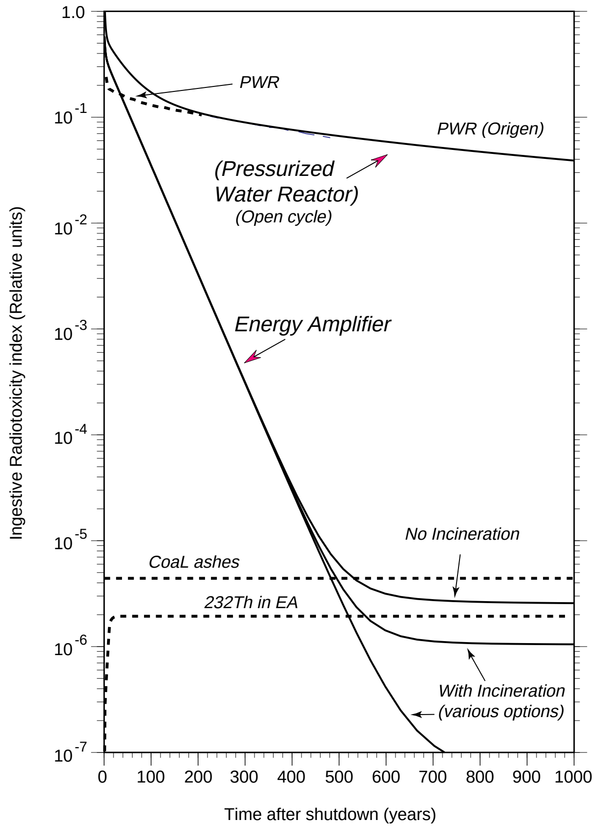

Figure 9: Evolution of the potential radiotoxicity of nuclear waste for PWR, EA and coal burning power station, showing that in the EA, the long term radiotoxicity can be 4 orders of magnitude smaller than in a PWR in open cycle and is dominated by LLFF if no further incineration is performed (adapted from Ref.[8]).

ning of the third millennium. In particular, nuclear energy may represent an acceptable solution of the energy problem and it would be a mistake to exclude it, a priori, from fundamental R&D.

The Energy Amplifier, based on physics principles well established by dedicated experiments at CERN, is the result of an optimization made possible by the use of an innovative simulation code validated in those experiments (FEAT and TARC).

This experimental programme has generated new applications in various fields: medical applications for which CERN has filed a patent, research with the approved TOF facility at CERN and other surprising ideas such as the nuclear space engine. I find all of these extremely rewarding for those who have been involved in this project, and I can only hope that it will also help Governments to recognize the importance of continuing to support strongly fundamental research.

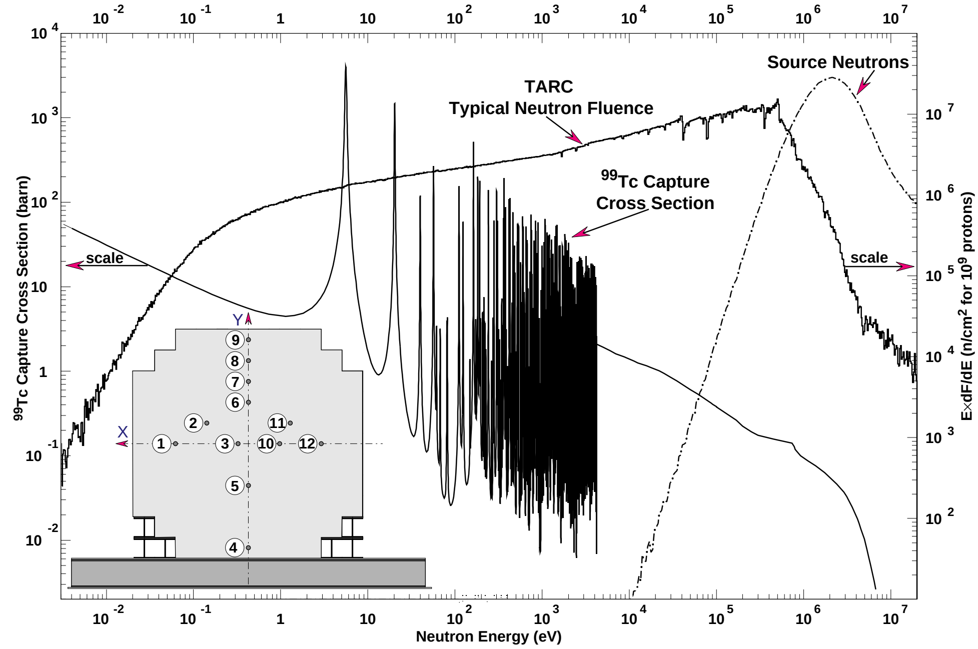

Figure 10: ARC principle: the presence of lead transforms the spallation neutron energy distribution into a flux of slowing down neutrons, with iso-lethargic steps smaller than the width of cross section resonances where they will certainly be captured. A sketch of the 334 ton TARC lead assembly is also shown.

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