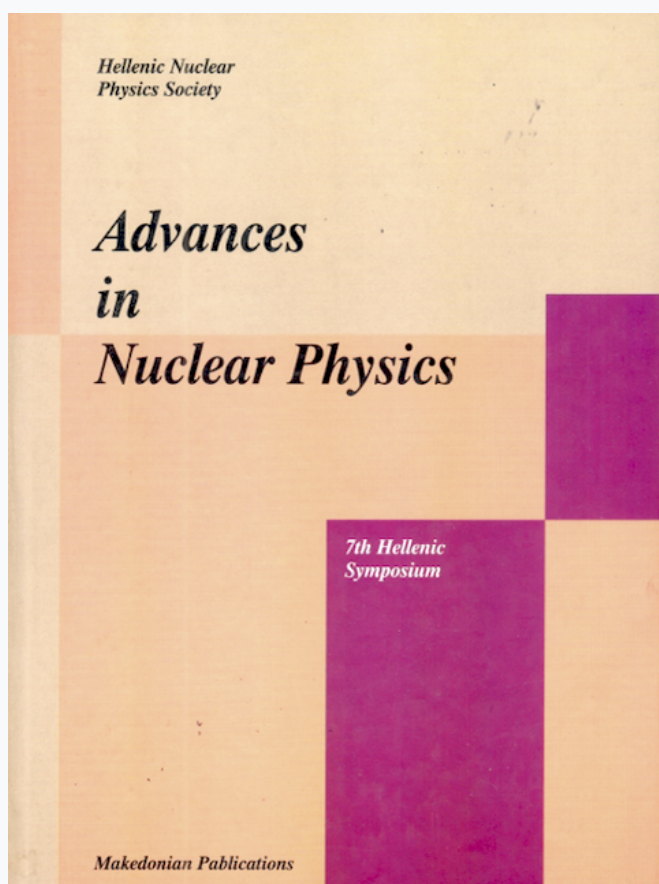


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# The Energy Amplifier, an “Ecological” Reactor

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## Abstract

*The main ideas for the Energy Amplifier (EA) are presented, as they have been developed at CERN [1]. The discussion concerns with the safety and environmental features of this new kind of reactor which are far more better than the ones of the conventional reactors. A comparison is also given with fusion reactors and other non-nuclear methods for energy production, such as coal burning.*

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## 1. Introduction

It is more than certain that the role of safety and environmental features will be of major importance in any decision concerning large scale human activities, such as energy production. All the methods have an undesired impact on the environment, the nature of this impact being dependent on the specific method in use. For instance, all the methods based on carbon burning, that is release of chemical energy from coal or oil, add on the CO<sub>2</sub> in the atmosphere and, consequently, on the Greenhouse effect. Natural gas is better in this sense, due to its high hydrogen content. Moreover, sulphur oxides coming from burning already proved to be a serious problem for the environment.

Nuclear fission reactors do not contribute to the Greenhouse effect and relevant problems, since they do not produce CO<sub>2</sub>, sulphur oxides etc. On the other hand they exhibit a number of negative points, first of all the potential danger for a large scale accident, such as the one in Chernobyl. This danger is common in all power reactors, since they all operate at the critical point. The second point has to do with the nuclear waste management, which is a problem continuously growing, since the amount of nuclear waste grows in parallel with the energy production from fission reactors. These dangers are taken into account more seriously after the Chernobyl accident and this is reflected from the decline in the installation of new nuclear reactors during the last decade.

## 2. The Energy Amplifier

In contrast to the conventional reactors, the EA remains always a subcritical device under any conditions. Thus, the possibility of a criticality accident is completely excluded. On the other hand, the subcriticality sets the need for an external source of neutrons. This is achieved by using an accelerator providing protons with an energy of the order of 1 GeV. The current of the beam depends on the criticality factor (which anyway is chosen to be between 0.95 and 0.98) and the thermal power to be produced. To give an example, for a module of 1.5 GWatt thermal power and  $k=0.98$ , the proton current needed is 12 mA. A thorough discussion on the EA concept, as it has been developed at CERN by C.Rubbia et al, can be found in ref.1.

The protons are shot on a heavy target with high neutron excess, such as lead. Through a spallation reaction, they liberate a large number of neutrons depending on the proton energy. Some 30 neutrons are expected to be produced in average, when an 1 GeV proton shots a lead nucleus. Further multiplication takes place due to  $(n,2n)$  reactions. These neutrons "drive" the reactor, keeping the heat production at a level depending on the proton current. Part of the energy produced is used to run the accelerator [2,3]. The fraction of energy needed to run the accelerator ranges between 5% and 10%, depending on the criticality factor. Evidently the reactor produces far more energy than the one needed for the accelerator. The idea of energy amplification has been experimentally verified at CERN, using protons shot on a heavy target in a subcritical device [4].

An EA module is shown in fig.1. The vessel is 6 meters in diameter and 30 meters in height. It is housed in underground silo made of thick concrete and put on proper seismic absorbers to be efficiently protected against earthquakes. The core is divided in three radial regions, namely the Inner Core (IC), the Outer Core (OC) and finally the Breeder. The fuel in the core is a mixture of thorium and an element fissionable by thermal neutrons, that could be  $U^{233}$  or  $Pu^{239}$ . The breeding material is pure thorium, which gives  $U^{233}$  after a neutron capture and two subsequent  $\beta^-$  decays. The criticality factor remains always below 1, if the start-up value is up to  $k=0.98$ . For the various configurations proposed, the start-up  $k$  value ranges between 0.95 and 0.98. The energetic gain  $G$  of the EA increases with the  $k$  value, it is for instance equal to  $G=120$  for  $k=0.98$ . The energetic gain is defined as the thermal energy produced by the EA divided by the energy deposited by the proton beam.

During start-up, energy in the form of heat is produced through  $U^{233}$  fissions, whereas at the same time this element is created in the breeder region. In the above way, the fissionable material is regenerated in the breeder and there is a counterbalance against burning of  $U^{233}$  and poisoning due to the created fission fragments. During a period of five years no need appears for fuel reprocessing or shuffling. The module is a closed passive device producing thermal energy with no human interventions in the fuel, thus strongly reducing the probability for small scale nuclear accidents.

The coolant medium surrounding the core in the form of a swimming pool is molten lead. The mass of lead is around ten thousand tones. The unique

properties supporting the choice of lead are the large dilatation coefficient and the large heat capacity. Lead enters the core region with a temperature of  $400^{\circ}\text{C}$  and removes the excess heat from the cladding surrounding the fuel. The fuel temperature is supposed to remain below  $2500^{\circ}\text{C}$  and that of the cladding less than  $700^{\circ}\text{C}$ . The lead temperature in the outlet of the core is expected to be about  $600^{\circ}\text{C}$ .

The heat produced inside the core of the EA due to fissions and nuclear cascades is removed by the molten lead, as it moves upwards acting as the coolant medium. Liquid lead is driven by natural convection, as a consequence of the temperature difference between the core region and the upper part of the vessel, where four heat exchangers are located. In this way the need for pumps ceases to exist thus simplifying considerably the primary cooling loop. At the same time the operation becomes much more safe since convection cooling is nearly self-regulated and maintenance free.

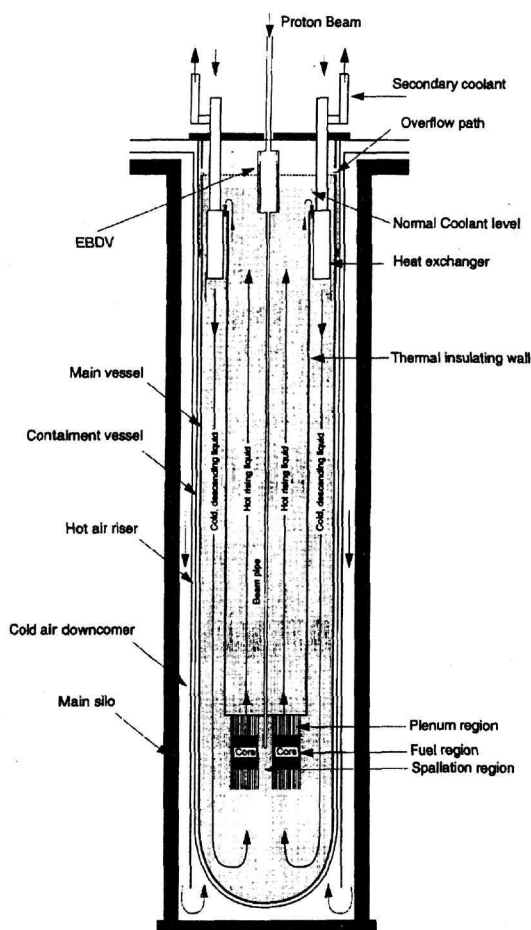


Fig.1. A layout of the Energy Amplifier (from ref.1.)

Due to the very small lethargy of the neutrons in lead and, also, the small absorption cross section, the EA is a fast neutron reactor. Thus it can burn actinides not fissionable by thermal neutrons, producing energy and at the same time reducing the amount of nuclear waste.

The use of thorium as fuel has considerable advantages compared to the ordinary enriched uranium. To start, thorium is three times more abundant in earth's crust than uranium. Further, the energy produced in the EA by burning 1 Kg of thorium equals the one produced in a Pressurized Water Reactor (PWR) from about 250 Kg uranium. Considering the energy consumption world-wide, thorium constitutes a practically unlimited energy source. Also the total amount of nuclear waste is strongly reduced since the fuel is used much more efficiently.

A major problem arising from operation of PWRs is the production of plutonium. It can be produced also in breeder reactors from  $U^{238}$  with one neutron capture and two  $\beta^-$  decays, for subsequent use as a fuel. Considering that plutonium is a highly radiotoxic element, not to mention its potential use for nuclear weapons, its presence should be considered as undesirable. The EA produces essentially no plutonium since, starting from thorium, a nucleus needs 7 neutron captures and 4  $\beta^-$  decays to become plutonium and the probability for this to happen is very small. As a matter of fact all the problems associated with plutonium, in the EA simply do not exist.

Moreover, it has to be mentioned here that existing 'dirty' plutonium, as it comes from conventional reactors, can be used as start-up fuel in the EA [5]. This plutonium contains a lot of other actinide isotopes. However, no need appears to separate them since they are burned all together in the EA. Nuclear weapon grade plutonium can be burned also. The EA starts its operation with a thorium-plutonium mixture and as plutonium is burned,  $U^{233}$  is created from the breeder ensuring that the module will continue to operate after plutonium elimination. This possibility is environmentally acceptable and, at the same time, economically profitable. Evidently in the forthcoming years a plutonium elimination scheme has to be launched and EA seems to be the most promising solution.

### 3. Incineration of Nuclear Waste

Among the fission fragments, the long lived ones constitute the major problem of the nuclear waste. Up to now the solution used is their storage in the so-called geological repositories. In such a case, one cannot exclude the potential dangers when radiocative materials are stored for thousands of years. This is the reason there have been various proposals to transform the unwanted long-lived isotopes into either stable or short-lived ones. Most of these proposals are based on thermal neutron capture by these nuclei and subsequent  $\beta^-$  decay. The neutron

excess needed is supposed to be provided by a reactor or by a accelerator driven subcritical device [6].

In the EA the approach to the problem of incineration is somehow different, in the sense that instead of thermal neutrons, the utilisation of the resonance region is considered, where the peak cross sections for neutron captures take much higher values [7]. For instance,  $^{99}\text{Tc}$  absorbs thermal neutrons with a cross section of 20 barns, whereas at the resonance at 5 eV the peak cross section is 4000 barns.. In order to access the resonance region, one needs a medium with a very small lethargy and also very small neutron absorption cross section, that could be lead or bismuth. Thus, the EA offers this possibility since its coolant medium is liquid lead. Bismuth is not appropriate since long-lived isotopes could be formed in the presence of a high neutron flux. Neutrons in lead are moving with a mean free path of about 2-3 cm and undergo more than one thousand elastic scatterings before absorption. Their energy decreases with small steps and eventually they pass through the resonance region. The above method, that is Transmutation by Adiabatic Resonance Crossing (TARC) [7], is under study at CERN, experiment PS211.

#### **4. Comparison with Coal Burning and Magnetic Confinement Fusion**

The EA has unique safety features not only during operation, but also concerning its nuclear waste. Even if compared with non-nuclear methods for energy production it exhibits clear advantages. For instance, coal burning releases radioactivity in the environment through fume, dust and the ashes. The impact of this radioactivity on the population is about ten times the respective one when the same amount of energy is produced by the EA. That is, even concerning the impact of radioactivity, the EA seems to be in much better position from a classic non-nuclear method, not to mention the presence of sulphur oxides,  $\text{CO}_2$  etc the impact of which should be considered as much more serious.

The Magnetic Fusion, as it is the case for the EA, has a lot of advantages when compared to conventional reactors [8]. The availability of resources is practically unlimited in the case of Magnetic Fusion too. The radioactive waste produced reaches, after a cool-down period and for the same energy production, a level of radiotoxicity which is lower than the one of the ashes of Coal burning. The same holds for the EA, but this cool down period is longer for the EA, namely some 500 years. On the other hand, considering simplicity of operation and reliability, the EA has an advantage over Magnetic Fusion. Moreover, the EA is a very realistic prospect within the next decade, whereas for Magnetic Fusion there is still need for intense research and development for at least the next three decades to come, as well as considerable money investment.

The conclusion is that EA deserves consideration as a very promising method for energy production in a clean, safe and environmentally acceptable way.

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