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SCIENTIFIC AND TECHNOLOGICAL OPTIONS ASSESSMENT

STOA

A NUCLEAR AMPLIFIER FOR ENERGY FOR ELECTRICITY PRODUCTION

Final Study

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Author:	**Jean-Pierre Husson & Philippe de Montgolfier,** **Essor Europe, Paris, France**
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A nuclear Energy Amplifier for electricity production

Abstract

The nuclear Energy Amplifier (EA) proposed in 1993 by Professor Carlo Rubbia, Nobel prize, is an original hybrid nuclear reactor made of a fast subcritical nuclear reactor driven by a high energetic and intense proton accelerator which could be at the same time basically a safe electricity producer and could also burn almost completely its own nuclear waste as well as other reactors ones. It found a number of echoes in Europe, in particular in Spain, Italy and France, as well as in the European Commission, in the European Parliament and in the World.

The whole technology of the EA includes several components which are separately well mastered by the nuclear energy industry and the nuclear research community but with a number of innovative improvements which may present implementation and reliability difficulties. Many technological options are still open, and there is a need for more R&D.

Experts largely agree that the EA could not produce electricity at a competitive price, and that the EA technology should not be aimed mainly to electricity production. EA could be an option for burning Actinides and other nuclear fission products, electricity being an interesting by-product of the reactor.

In Europe, Italy, France and Spain have taken a first tripartite- initiative and are open to larger co-operation. Should Europe invest in this domain, and how? Should a research demonstrator be launched in short or medium term? This report addresses these points and propose orientation options to the European Parliament.

Executive summary

Around 6 years ago (1993), the Physics Nobel prize winner and former CERN Director General, Professor Carlo Rubbia, proposed an original hybrid nuclear reactor which could be at the same time basically safe, produce energy and also bum as completely as possible its own nuclear waste as well as other surrounding reactors' ones.
The potentialities of Professor Carlo Rubbia's nuclear Energy Amplifier have been assessed via the analysis of opinions given either by interview and/ or by written detailed contribution by some 40 relevant European personnalities (industrials, nuclear scientists and policy makers); (interviews and/or written answers) and with an extensive analysis of existing reports and publications on the subject,
A detailed questionnaire (1 1 pages, see in annex) was used either as an interview's framework or sent to be answered on general and specific points.

An hybrid nuclear reactor is basically composed of two parts, a neutron generator and a nuclear fuel core where the fission chain reactions, triggered by the neutrons, take place. More generally hybrid reactors are classified as Accelerator Driven Systems (ADS) which seem to be: worldly « popular » these recent years for various reasons, among which:

- their military plutonium destruction capabilities,
- their energy production capacities
- their potentialities to bum and/or transmute nuclear waste elements
- the new impulse given to the associated research by C.Rubbia and his CERN team

After an introduction chapter, we have tried in chapter **2,** to present briefly the basics of nuclear physics needed to understand the principles of the nuclear amplifier. We summarised and describe some nuclear properties, the proton accelerator basics (cyclotron, linear accelerator), the chain reaction, the spallation reaction, the classical reactor's description with the k criticality factor, the nuclear waste elements (Fission products, trans-uranium elements which include major Actinides and Minor Actinides), and the nuclear transmutation's principle.
In chapter 3, we present very schematically the Energy Amplifier's principles and its advantages after its designers.
The Energy Amplifier is composed of:

- a high intensity and high energy proton accelerator unit made of associated cyclotrons which deliver a typical 10mA-1GeV(intensity - kinetic energy) proton beam.
- a thin window between the accelerator and a spallation molten lead target region where neutrons are produced.
- a buffer molten lead region in which neutrons migrate and lose energy before chain reacting on a fuel core region constituted of thorium oxide fuel elements (mixed eventually with minor actinides nuclear waste) and a neutron reflector to avoid losing useful neutrons
- a primary cooling loop made of large quantities (several thousand tons) of molten lead (or lead + bismuth to reduce the temperature)which circulate by natural convection
- a classical secondary water cooling loop with vapour generation and turbine for usual electricity generation

The main originalities of the **EA** are :

- the accelerator proton beam which is electricity driven (switched on-off),
- the use of highly energetic and intense proton beams,
- the same element (molten lead) which is used for spallation reaction target and as a diffusing and cooling fluid,

- the new nuclear fuel proposed namely the thorium oxide,
- the operating reactor (fast neutrons) with a criticality factor **k** strictly < 1, which constitutes a major safety factor,
- the important energy amplification gain obtained,
- and finally the potentialities to burn by fission, actinides elements or to transmute them as well as the classic fission products by neutron capture reactions in more peaceful nuclei even in stable elements.

All these various components are not basically new, and have been studied or experimented in earlier nuclear energy exploration times separately or combined (even the molten lead coolant is still currently used in Russian nuclear submarines); but in the EA, their assembling and the operation of the whole system constitute a new nuclear reactor technology which needs additional R&D, safety evaluations and a number of experimental tests.

In chapter **4,** firstly, we give the summary of personal opinions of the solicited personalities on the various technological points or components considered as specifically advantageous by its promoters or considered to be key or even « killing » points by others.

Even if the EA is considered globally to be very interesting and feasible, serious reserved opinions are emitted about:

- the accelerators reliability, the window's resistance and the relevant consequences on the whole reactor's operations (stops and restarts)
- the utilisation of the same material in large quantities (molten lead) for target and cooling fluid including the corrosive characteristics of molten lead
- the confinement of the nuclear wastes
- the thorium fuel cycle, including the waste chemical extraction process, still at the laboratory scale and which has to be industrially developed, at high costs.
- the safety authorities authorisations for operating and exploiting the reactor
- the reliability of the whole system once connected to the electricity grid(see first indent)
- the economic costs of electricity production

Secondly, we present and put in perspective some elements concerning the needs and the economics for an ADS/EA scientific demonstration facility. Globally, even if a number of key points need to be considered and experimentally checked in details, unanimous opinions are expressed in favour of an European EA scientific demonstrator project. This demonstrator could be partially funded by the EU and operated under **a** specific structure; it could be included in a wide European scientific collaboration, efficiently co-ordinated and which could be led either by the European Commission or by an adequate international framework structure. The total EA construction costs (around 1000 MEURO) which would be annually between **200** and 140 MEURO on **a 5-7** years period, can be considered rather reasonable compared to the fusion project's total costs.

Finally on the major question related to the **EA** potentialities and which motivate the STOA interrogation and this report:

1. Is the EA an option for Europe for electricity production? The answer is **no** in the context of present energy costs competition and the prospective of availability of other primary energy sources up to 2020.
2. Is the **EA** an option to consider by Europe for burning and transmute efficiently the nuclear electricity plants wastes? the global answer is **yes,** even if a number of technological problems have still to be solved.

Taking advantage of these opinions and facts, several options are open for the European Parliament:

1. To recommend, or not, to consider nuclear energy amplifier for addressing the nuclear waste burning issues.
2. If the European Parliament recommend to consider it, then, it may recommend or not to take some initiatives at the European level immediately or in the context of next Framework Programme.
3. If an initiative is taken, several options are open for the linkage with the current tri-partite initiative: independence of both initiatives, joint effort within the tri-partite initiative extended to other Members States and in particular to the European Commission, co-ordinated or integrated initiative led by the European Commission.
4. Some R&D is still necessary in many domains and many technical options are still open. Two options are considered:
   - to encourage co-ordinated R&D in different countries to develop realistic, safe and economically viable technologies and make choices, and then to design and construct a demonstrator;
   - to set up as soon as possible an integrated platform or scientific demonstrator which would be followed later on by a prototype.
5. For a scientific platform or for a demonstrator, will it be useful to consider a structure comparable to the JET and also a way of functioning comparable to CERN? Is it worthwhile to consider a Public Private Partnership as envisaged for the GNSS project (GALILEO)?
6. The question of the level of funding according to the development step is important: should the EC fund different types of activities at 100%, close to 50% or below? This is linked to the above question.
7. Finally, what should be, in the next 6th Framework Programme, the level of priority to attribute to EA related R&D and demonstration? Is it necessary to initiate first significant steps within the current 5th Framework Programme?

1 Introduction

Around 6 years ago (1993), the Physics Nobel prize winner and former CERN Director General, Professor Carlo Rubbia proposed an original hybrid nuclear reactor which could be at the same time basically safe, produce energy and also burn completely its own nuclear waste as well as other reactors ones. This proposal based on numerous publications, conferences and preliminary experiments found some echoes in Europe, in particular in Spain, Italy and France, as well as in the European Commission, in the European Parliament and in the World.

The dream of a «clean» nuclear reactor producing electricity «without» the nuclear waste reprocessing problems could become a reality, provided that, after the authors, additional R&D could be funded on the design and operation of elements of an eventual demonstrator; furthermore, in the context of a future long term European energy policy and the foreseen role of nuclear energy, it will be interesting to put in perspective the potential impact of a socially acceptable renewed nuclear energy.

Before giving a sample of collected ((authorised)) opinions about the nuclear amplifier and its components, let us try to describe the simplest as possible, the necessary nuclear physics elements to understand the argumentation in favour, neutral or opposed to the nuclear amplifier, given by specialised people .

2 Nuclear physics elements from the nucleus up to the reactor

In this section, we shall try to give some basic elements of nuclear physics explanations necessary to understand better the somewhat « hermetic » language of the nuclear energy specialists from the nucleus to the nuclear reactor.

2.1 radioactivity

Radioactivity (discovered in 1896, in Paris by H.Becquerel) is the spontaneous emission of α,or ß, or γ particle by a nucleus.

> ***An*** α particle is an helium nucleus; the α emission transforms a nucleus (A,Z) in a nucleus (A-4,Z-2).
> **A** $ß^+$ particle is **a** positron (electron positively charged), this emission transforms a nucleus (A,Z), in a nucleus (**A,** Z-1). **A** β^- particle is an emission of an electron, this emission transforms a nucleus (A,Z), in a nucleus (**A,** Z+1).
> the y emission is a photon emission (generally more energetic than an X ray), and is a characteristic of the desexcitation of a nucleus;

a and ß emitters are also characterised by their half-life $T^{1/2}$(time to reduce by a factor 2 a population of N nuclei).

2.2 the neutron capture reaction

One nucleus **(A,** Z)* absorbs an incident neutron (nucleon)* and is transmuted in a nucleus (A+1, Z) which **is** generally radioactive.

* **A = mass number = Z protons + N neutrons, nucleon : neutron and proton,**

2.3 the fission reaction

Discovered just before the second world war, the ***fission reaction*** is the basic nuclear energy origin phenomenon; a incident primary neutron (slow or fast) produced by a first reaction (or by a permanent neutron source), is absorbed by a heavy nucleus (nucleus which has a nucleon mass number **A** in the range A= 230 -240) and fission into two nuclei fragments with mass numbers approximately = A/2 (in fact around 100 and 130-140).

The first fission reactions studied were slow neutrons on ^{235} U, a fissile nucleus present in natural uranium (isotopic abundance : ^{235} U: 0.72%, ^{238} U: 99.2745%, ^{234} U: 0.0055%)
Generally the reaction produces two nuclei fragments (fission products (p_F) + a significant number of neutrons (>2); with these last neutrons, new successive fission reactions occur, and continue rapidly to expand : this process is called ***a chain reaction.*** (see fig 1). This ***chain reaction*** multiplies very rapidly and exponentially the number of fission fragments and the associated neutrons; by chance, in particular in ^{235}U, some of the emitted neutrons used for successive fission reactions are time delayed, allowing a control of the number of reactions by neutron absorbers (mainly made in Cadmium and Boron) which can be operated rapidly in order to avoid a nuclear burst.

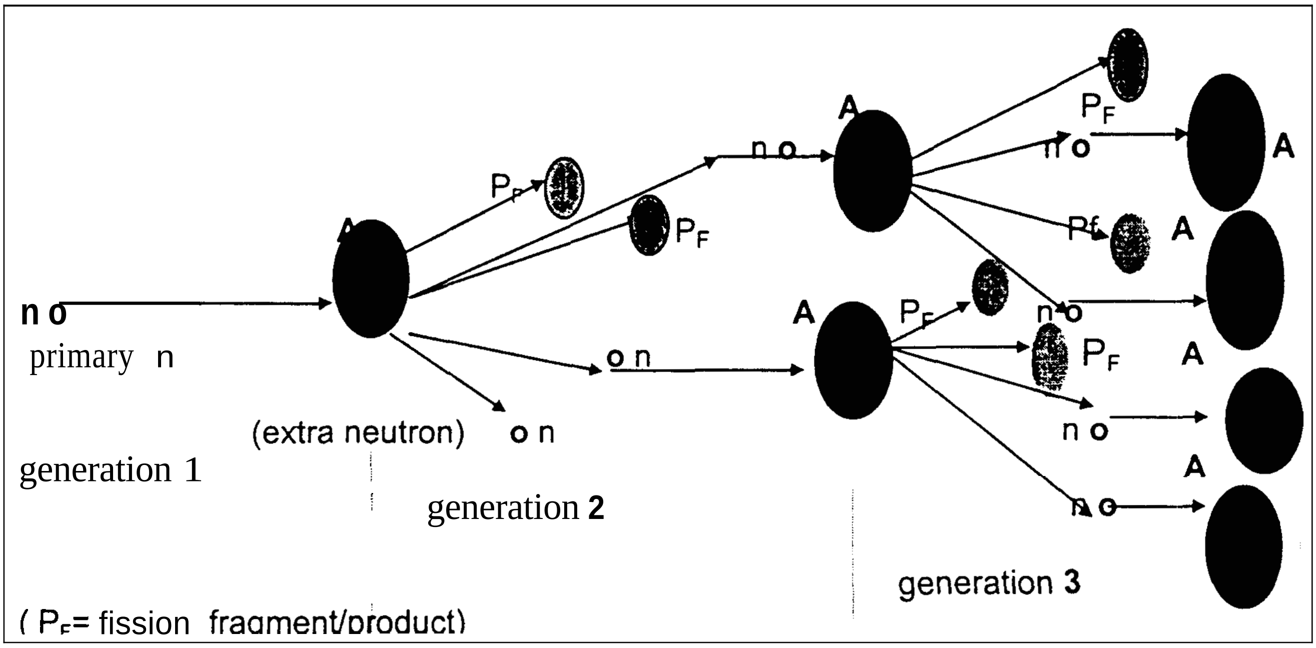

fig 1

The neutrons which trigger the fission reactions are either slow (called thermal, with a very weak kinetic energy after being slowed in an a moderator material) or fast (not slowed, with a significant kinetic energy which can be more than 1MeV[1])

The energy[2] itself comes from the kinetic energy of the fission fragments (positive energy balance between heavy nucleus and fission fragments nucleons binding energies). this kinetic energy dissipates via a thermal process, heats a cooling fluid (water, gas, liquid metal,..) , the resulting heat is then converted classically in water vapour and then in electricity.

Nuclear reactions in general, and fission reactions in particular, are characterised by their occurrence probability, that is to say their cross section σ, function of the kinetic energy of the incident particle and expressed in a historical unit the barn (10^{-28} m^2)[3]; the first fission reactions studied, thermal neutron on uranium, have very high cross sections of several hundreds barns, others like those studied for producing rare particles like e^+e^- --->W^+W^- (in CERN) can be of the **order** of some **picobarns** (10^{-40} m^2)

2.4 primary neutrons

The primary neutrons, kind of first nuclear match which ignite the chain reaction, come in general from **a** permanent neutron source Po^{210}-- Be or Cf^{252}.
The neutrons can also come from another source, namely external nuclear reactions involving energetic charged particles on heavy nuclei targets, like for example the well known spallation

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[1] 1 1MeV: **106 eV= 1.6 10-13 Joules**

[2] 1 g **of ^{235}U totally burned(or fissioned) in one second liberates a power of** 8,2 10^{10} **Watts.**

[3] **a probability expressed in surface units can appear curious, in fact the term ((cross section » traduces the fact that the probability (per sec) dN/N of reaction to occur (N= number of incident particles (per sec), dN number of reactions(per sec)) for a unique target nucleus per** $m2$ **is** : $|dN/N| = \sigma\ Ndx$ **(in which N** dx = 1, **N = number of target nuclei per volume unit,** dx **elementary thickness)**

reactions which «break » the target nuclei in several fragments (n, p and residual nuclei, see fig 2); these reactions imply of course the use of a particle accelerator namely a cyclotron, a synchrocyclotron or a synchrotron depending the energy range wished.

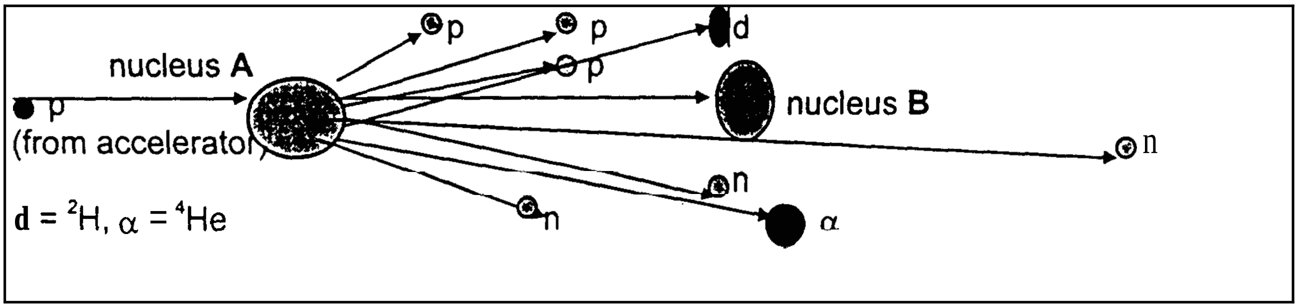

fig 2 : spallation reaction principle

2.5 the cyclotron accelerator:

In a very simplified way the cyclotron principle (fig 3) associates in a vacuum chamber, (10^{-7},10^{-8} Hg mm) injected charged ions (mass m and electric charge q) a magnetic field B perpendicular to the ion beam, which keep the ion trajectory approximately on a circle . The acceleration is obtained by an alternative electric field applied on semi circular electrodes (the Ds), and; charged ions (for ex: hydrogen for protons, helium for a particles,...) are injected in the vacuum chamber), accelerated via the magnetic field B, (following the Laplace law), circulate with a speed v on circular trajectories (radius r = mv/B)

The cyclotrons (synchrocyclotrons, synchrotrons), are to-day standard research equipment in experimental nuclear physics or in medical radio-isotopes production; they are electricity driven which means they can be switched on and off!

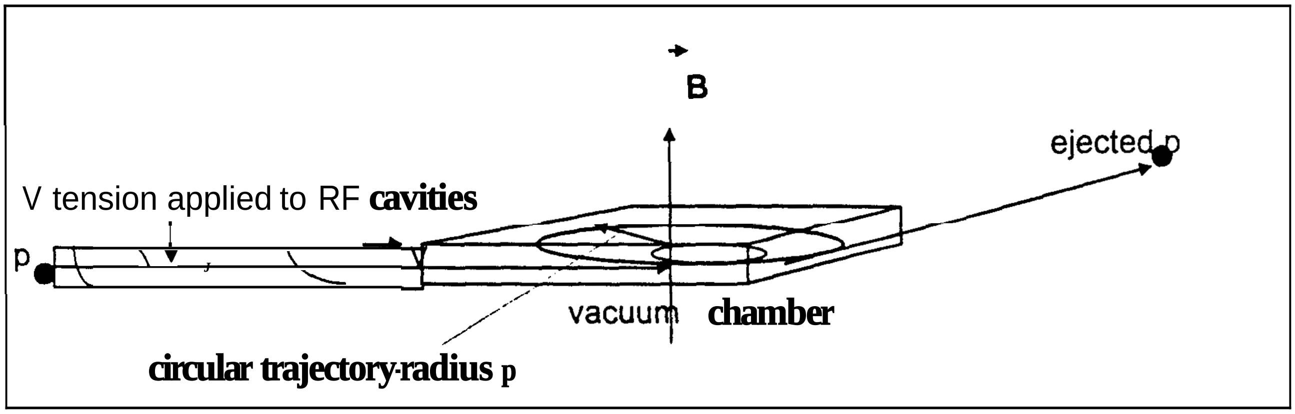

fig 3 : cyclotron’s principle:
if the proton kinetic energy (E,) needed is around or greater than its rest mass energy (M = mc^2), its output impulsion P is : P = 300 Br (where P is expressed in MeV, B in Tessla, and r in meters); then its kinetic energy E, is related to P via the formula (*)P’ = E^2_c + 2Me_c , if B = 1 T, r = 3 m, P = 900 MeV, E, ≅360 MeV

2.6 Secondary neutrons:

After the first fission, the neutrons emitted are called secondary and they can :

- contribute to new fissions and « feed » the chain reaction and then produce a number of radioactive fission products

- be captured simply by some uranium nuclei and follow a radioactive path which leads to heavier radioactive nuclei, also fissile elements (transuranium elements called also actinides) which can eventually fission or not .

2.7 The nuclear reactor heart

The heart of a reactor is constituted of nuclear fuel elements like fissile ^{239}Pu, ^{238}U, enriched ^{235}U oxide, (enriched means that its isotopic natural 0.7% abundance is artificially increased up to several %) assembled in encapsulate samples in a specific geometry arrangement in order to allow a specific neutron multiplicity k_{eff} , (k_{eff} is the neutron multiplication factor after successive chain reactions in a specific heart geometry characteristic):

- if $k_{eff} = 1$ the reactor is said critical (can be controled), normal operation mode
- if $k_{eff} > 1$ the reactor is super-critical, cannot be controled, can fuse, melt and/ or burn
- if $k_{eff} < 1$ the reactor is sub-critical and needs permanent additionnal primary neutrons to produce energy, if the primary neutron source stops, the reactor stops.

It is therefore vital for an operational reactor that this k_{eff} coefficient could be extremely well monitored and be strictiy equal to 1 ; this is realised with the operation of the control neutrons absorbing bars.To cool the reactor's heart, to evacuate the energy (thermic heat) and to transform it and to produce electricity, coolant fluids are necessary; the cooling fluids commonly used are: water, liquid metals (lead, sodium), gases, etc.

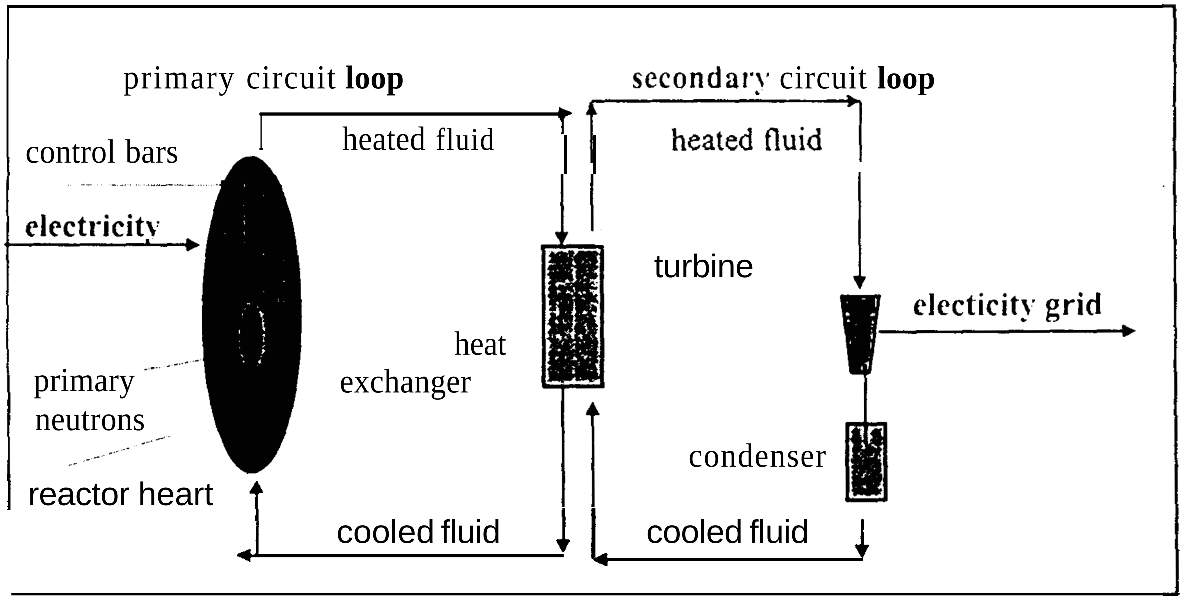

fig 4 : classical nuclear reactor's general principle

The nuclear heart is made of several packs of nuclear fissionable enriched uranium oxide samples sealed in Zircalloy (steel + zirconium) capsules (cylinders of some cms long) constituting the nuclear fuel in which fission occurs. The cooling fluid circulates in a circuit called the primary loop between all these packs, is consequently heated and transfers its heat through a heat exchanger to a more conventional secondary loop, made with condensers and turbines, producing electricity.(see fig 4)

During the reactor's operation, the fission products and the actinides accumulate but are still confined in their capsules. After a certain operation time *(some* years) the reactor is stopped, the nuclear fuel packs are extracted, deposited in rest pools and eventually reprocessed; the nuclear fuel is renewed and reloaded in the heart.

2.8 nuclear waste

After burning, the nuclear fuel is poorer in fissile nuclei and richer in fission products and Actinides: The nuclear wastes are the sum of these different elements (See Annex 3, figure 1):

> The fission products(FP) are radioactive elements(mass number between 90 and 150) with a large range of half-lives (from seconds to millions of years), either solids or volatile; the long lived ones are labelled long lived fission products (LLFP) (the most currently quoted FP, for their half-lives are $^{89,90}Sr$, ^{99}Tc, ^{129}I, ^{131}I, ^{137}Cs, ^{140}Ba - ^{140}La, ^{152}Eu)
>
> The Actinides elements (called also the Trans-uranium elements (TU)) result from successive neutron captures by non fissioned heavy nuclei from nuclear fuel elements; they are radioactive with long half-lives, and include the major Actinides (Uranium 235, 236, 238 and Plutonium 239 mainly) produced in significant quantities, and the Minor Actinides (MA) mainly Americium, Neptunium, and **Curium** produced in much less quantities than the previous ones. The Major Actinides are **re-usable for fission.,** the MA elements, are up to-day, processed, compacted and stored.(the most currently quoted long-lived **MA** are $^{235.238}U$, ^{239}Pu, ^{237}Np, $^{241.242}Am$, ^{244}Cm, ^{252}Cf)

The nuclear wastes are generally separated into three categories: rapidly decaying, medium-time decaying (1-20 years), and long-lived (> 20 years); the nuclear waste are after processing, separation and compaction:

> Either stored (in surface or in deep sites) with associated problems of cooling, waste management and public acceptability of the chosen solutions.
>
> Or reprocessed (with complex chemistry) for specific partitioning (separation) to extract the incompletely burnt fissile Uranium and Plutonium components, and the Actinides, with the associated techniques and problems of compression, vitrification transport, etc...

The "dream" of nuclear operators and safety authorities has always been to eliminate the most completely as possible the nuclear waste; with ADS reactors and the EA in particular, the transmutation of these products appear possible.

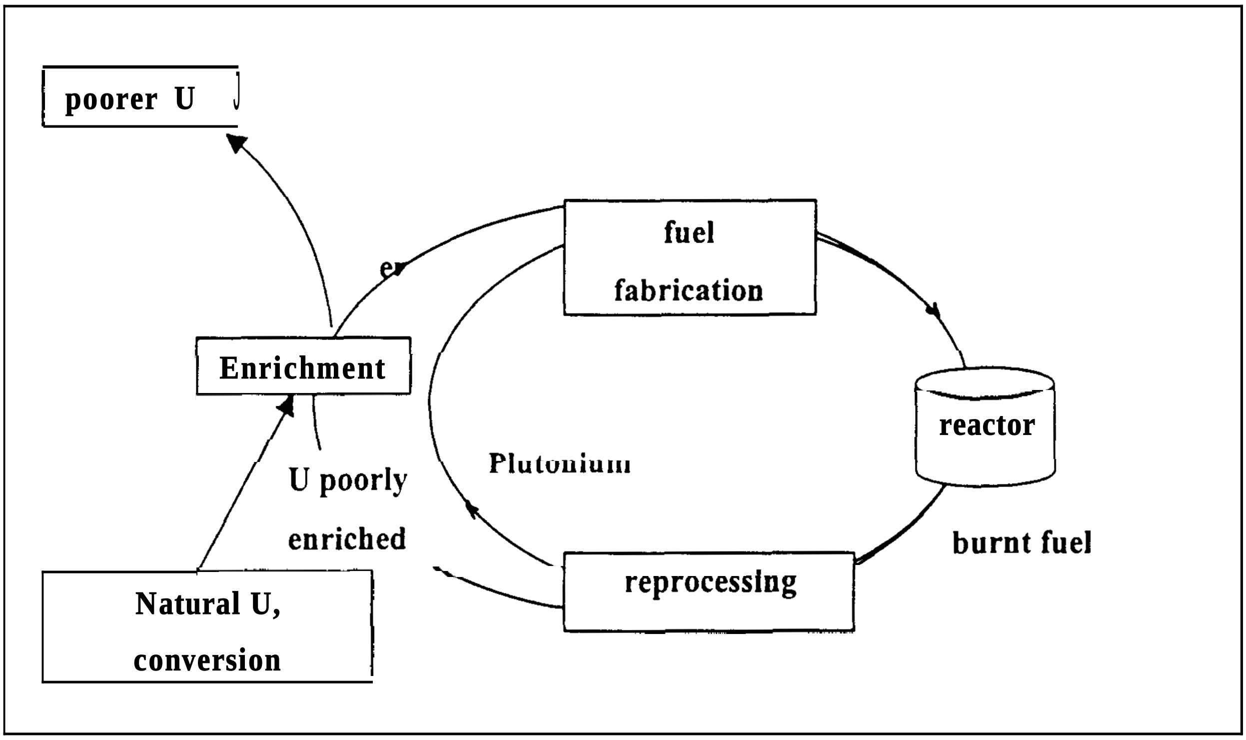

Fig **5**: an example of global process;
French closed cycle.

2.9 nuclear transmutation

Partitioning is the chemical separation of various radioactive elements from the burnt nuclear fuel; it concerns mainly the Iodine, the Lanthanide and the Actinides nuclei, the major Actinides, and the Minor Actinides (MA); the Major Actinides are of interest for reutilization (nuclear fuel or weapons), the Minor Actinides are typical long lived nuclear waste whose separation is of major importance; extensive experimental research studies, which led for example to the PUREX (Plutonium extraction) industrial process, have been done in the past, but this R&D has to be renewed with the Thorium/MA separation process (THOREX) known at laboratory scale but which is not yet industrial, if the Thorium oxide($ThO2$) was used as a fuel in an Energy Amplifier.

Transmutation is the transformation by classical nuclear reactions of radioactive nuclei in shorter lived or even stable and peaceful nuclei; by absorbing incident particles (neutrons or protons, etc...), here the expected abundant neutrons available allow to envisage various and successive neutron captures and in parallel induced fission.

Thermal neutron capture reactions and fast neutron induced fission reactions are of high interest in order to transmute Long Lived Fission Products (LLFP) and the Minor Actinides (MA). as well as to burn (fission) Minor Actinides in mixed fuel, provided that a thermalized neutron region is included around the spallation target. This extremely interesting possibility would allow reducing significantly, (eventually to avoid), the nuclear waste reprocessing and would be particularly useful for solving the nuclear waste management and disposal.
The neutron capture transmutation idea is behind the nuclear amplifier's concept; it has been recently successfully tested in the TARC experiment in CERN (see Re)

As an illustrative example on transmutation, one can quote the case of ^{99}Tc(half-life = $2\ 10^5$ years) which is a medically used isotope but also one of the main component of the LLFP; by absorbing successively thermal neutrons, ^{99}Tc is transmuted in ^{100}Tc, ^{101}Tc, ^{102}Tc which decay respectively to ^{100}Ru, ^{101}Ru and to ^{102}Ru **stable** nuclei (see fig. 6 below, from ref. IAEA p 37).

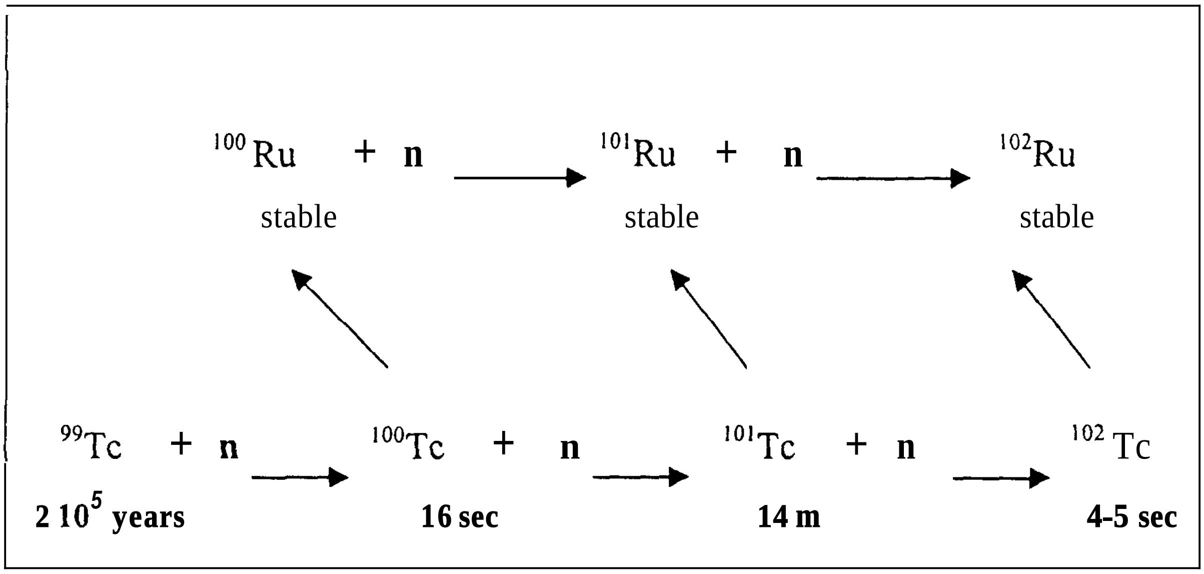

Fig 6

Fission products	Example of neutron capture cross sections for transmutation of some significant fission products		
	σ_{cth} (resonance)	σ_c thermal	$_c$ fast
^{99}Tc	**4000 barns**	**20** b	0.2b
^{129}I		31 b	0.2 b
^{90}Sr		1 b	(0.1) b
^{137}Cs		**0.25 b**	(<<0.01) b

3.The nuclear amplifier

3.1 principle

It is a new type of reactor, (called hybrid or with a more generic term an Accelerator Driven System (ADS)) with a high gain in energy (energy amplifier), with the following new main components which have a specific role in the energy production process :

the cyclotron(s) produces a high current[4] or flux[5] of energetic protons (which « replace » the primary neutron source)

a window between the cyclotron's vacuum chamber($P=10^{-7,-8}$ mm Hg) and the spallation target (at normal pressure), allows the protons to go through it in order to make spallation reactions on the target.

the spallation target itself is constituted of molten metal (lead, or lead +bismuth) which is at the same time the target and the cooling fluid; after spallation reactions, the multiplication of neutrons takes place; the produced neutrons are fast and they trigger fission on the target nuclei.

the fissile material is disposed in the sub-critical nuclear heart (k=0,95 - 0,97) and made of Thorium (^{232}Th oxide) fuel which does not give the same fission products than Uranium in particular no ^{239}Pu; the heart is cooled by large quantities of molten Lead at T =600° C, (or Lead +Bismuth (120-140°C) to decrease the melting temperature) which circulate by natural convection in the system (justifying a vertical geometry for the complete amplifier)

the cooling fluid which circulates in the primary loop, exchanges its heat in classical heat exchangers, vaporising water in the secondary loop which goes to turbines and generate electricity; a fraction (%) of this electricity feeds the nuclear amplifier, the rest goes to the electricity grid.

We present on fig 7 an over-simplified sketch of the nuclear amplifier principle :

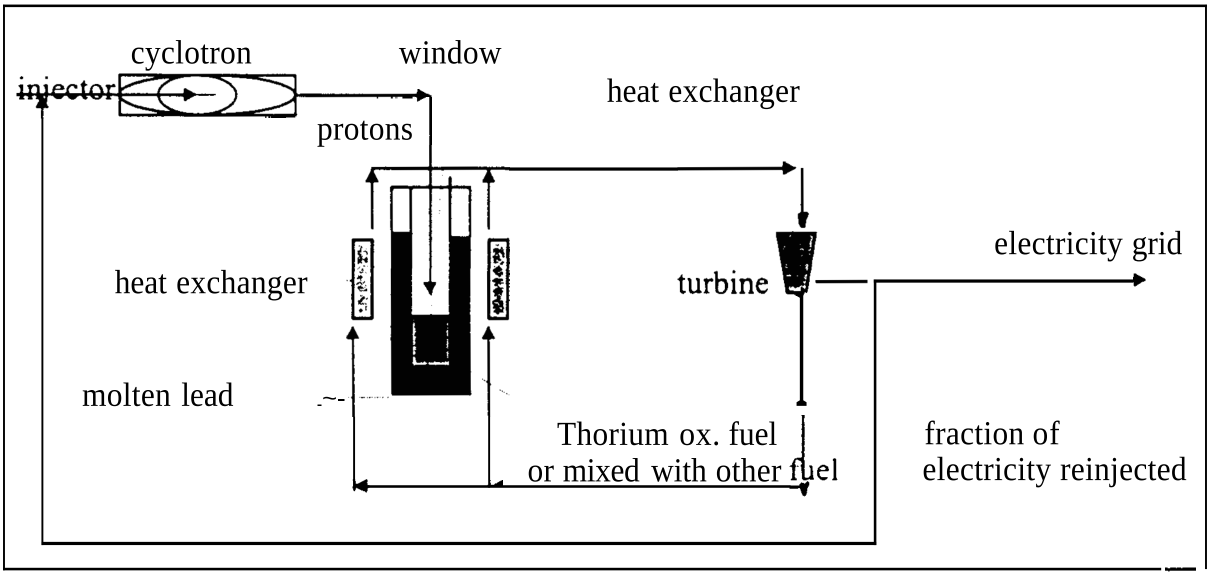

fig 7: the nuclear /energy amplifier principle over-simplified

The original concept drawing(ref) of Prof.C.Rubbia is shown on figure 2 of Annex 3.

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[4] **a proton 's current of 1mA = 6,25 10^{15} $p.s^{-1}$**

[5] **high flux means 10^{15}-10^{16} protons per second, per cm^2 ($p. s^{-1}.cm^{-2}$)**

3.2 Advantages of the nuclear amplifier after its designers:

The nuclear amplifier promoters, when they present the concept and discuss its main components advantages, argue that :

In general:

All the elements constituting the energy amplifier are technically well known, have been or are currently operating; but the required high performances, considered as maxima to-day, can be reached with a reasonable R&D effort in a medium term period.

In particular:

The cyclotron(s) basically delivering the initial nuclear matches proton beam, is switchable; consequently, the delicate stopping procedures for a reactor are avoided and the—system is consequently safe; the necessary high intensity (around or 10mA) of the delivered energetic (800MeV- 1GeV) proton beam is a reachable objective with the to-day available cyclotron technology; the eventual association of a linear accelerator with a cyclotron or the realisation of a multiple stage cyclotron do not present major difficulties, even if additionnal R&D is necessary. Moreover the stability and reliability of the accelerator(s) can be guaranteed, considering the stable conditions of demanded protons energy and intensity.

At this proton energy, proton induced spallation reaction cross section on lead is high and the number of spallation neutrons produced is around 30-40 . A number of experiments (ref) has confirmed the important and more or less constant spallation cross section of high energy protons on lead; systematic cross sections measurements research are going-on, in particular in CERN and in some European countries, and can be easily expanded with existing facilities in Europe.

The window problems (thickness, material, resistance to temperature and pressure differences, proton beam heating, cooling) are solvable with some additionnal research. Even windowless experimental tube could be envisaged playing with the lead vapour density properties.

the new fuel (Thorium oxide (^{232}ThO2) is unique (natural Thorium is a unique. isotope element which is not solvable in water) and relatively abundant on earth **(3-4 x**^{235}U); this fuel can be mixed with other (exterior) nuclear waste fissile elements, reburnt and finally destroyed by fission and/or transmuted in shorter lived or stable elements.

The molten lead (T„, = 328° C) (or mixed with Bismuth to reduce its melting temperature to T„, = 120-140" C), is a well known passive metal, which is in particular neutron transparent, cannot easily capture neutrons (closed shell nucleus), has a number of stable isotopes (which can also spall submitted to an energetic and intense proton beam) and is already used for years as a cooling fluid in Russian submarines nuclear reactors.

4 Assessment of technological advantages claimed for the EA

A set of 32 interviews has been conducted and 20 written answers to a general and specific questionnaire(see in annex) have been received.

The nuclear energy amplifier proposed by Professor RUBBIA for electricity generation and nuclear waste processing is considered to be a very important contribution for renewing interest in nuclear energy research. He gathered some ideas proposed several years ago with a number of many new ideas supported by recent experimental and technological significant progress. In a number of publications all the constituents for an EA have been explored and supporting experiments have been proposed.

The general design of the system associates basically several technical parts which are world-wide rather well developed separately and proposes to push their characteristics to high performances.

A great number of conferences, symposia and projects took place these recent years on the subject more generically labelled under the heading ADS (for Accelerator Driven Systems).
Several European and international laboratories, including CERN, have launched preliminary experiments and studies on the subject and their results show that the concept is right but that a lot of additional R&D work is necessary. In addition a number of opinions have expressed strong doubts about the overall economics in particular for competitive electricity production.

In the next sub-chapters, we will focus on some specific issues, which have been raised. This presentation is quite global and does not address directly at all the scientific background.,which is very substantial and not simple to summarise .

4.1 Accelerator(s) and the associate window

Opinions are unanimous to say that accelerator technologies (separated sector cyclotrons, linacs (linear accelerators), super-conducting magnets, high magnetic fields, ion sources, Radio Frequency (RF) cavities, etc…) are to-day potentially able to deliver 0.8 -1.5 GeV proton beams of 1-10mA intensity (0.6 – 6 10^{16} p.s^{-1}cm$^{-2°}$).
If more intense beams were needed (10- 50mA) answers are more uncertain depending the type of accelerators chosen (cyclotrons or linac, with a preference for linacs where extraction is claimed to be 100% but for which the costs look like the heaviest).

The proton acceleration unit:

It is not clear yet what should be the acceleration unit, considering the energy range, the intensities needed and the demanded beam stability. Current international high power proton accelerators projects (around10) linked to ADS or to neutron spallation research, privilege existing mastered accelerators technologies like.cyclotrons and linacs.

The acceleration unit could consist of either 1 injector + 2 coupled separated sectors cyclotrons or a linac (alone or coupled with a cyclotron with the intrinsic difficulty to adjust exactly the RF frequencies). The energy range does not seem to raise any problem but the demanded high intensities beams and their stability are not so easy to realise. It seems reasonable to foresee that the associated RF cavities technology could meet the 1 to 10 mA range requirements, even if very high performances materials and adequate cooling systems have to be developed; theproton beam stability is still a problem that all the accelerators specialists underline. In a recent article (Ba), G.S.Bauer from the SIN facility, wrote:" even under the assumption that the reliability of future high power accelerators built for industrial applications can be improved by two orders of magnitude over what is routine at current research accelerators , the question still remain as to what the effects of beam trips(seconds to minutes or more) on a driven subcritical reactor would be and how the system could be optimised for maximum service life and economic operation" (the significant beam trips rate in the US Los Alamos ex-LAMPF linac and in the Swiss SIN cyclotron are a good illustration of this issue). Solutions for this problem could lie in multiplexing several accelerators beams to rely on a permanent medium beam and to reduce the temperature stress.

In fact, current accelerators deliver beams with some more or less frequent instabilities tolerable for physics experiments, but not for driving a downstream reactor. These beam trips are considered by the reactors' specialists as a key point for the EA operation and it seems that a lot of technical R&D work is still necessary to improve the accelerators' beam reliability. On the other hand accelerators specialists claim that a set of frozen technical characteristics gives promising hopes to reduce very significantly and even eliminate the beam trips.

Finally if the beam interruption time is longer than several minutes, the reactor's starting protocol would not be so simple and would take time and.. ..safety authorities green lights.

Consequently, R&D is still necessary on: beam's stability, on RF cavities technology (super conducting materials) and their reliability for the high intensity required beam currents. Experiences in this domain of SIN and Los Alamos Nat. Lab.) support the needs for specific accelerator R&D; in addition detailed evaluation of the technical advantages and economic costs of coupled cyclotrons or associations of linac-cyclotron or multiplexing several accelerator beams to reach the required operating characteristics, appear to be still needed.

The window problems :

The intense proton beam produced in the acceleration unit is in a vacuum of $10^{-7,-8}$ Hg mm, and at approximately room temperature; the beam, non focused, has to go through a 2 to 5mm thick «window » of some 100 cm^2 before making nuclear spallation reactions with the molten lead target contained at normal pressure and at a temperature of around 600°C. We have there three combined effects:

- the heating of the window by the intense proton beam going through it
- the important pressure difference(or gradient) between the vacuum chamber and the molten lead vessel
- the temperature difference (or gradient) between the vacuum chamber and the molten lead

Consequently the window issue is considered as a major key problem to be mastered for any operational EA.

The heat resistance of certain materials submitted to charged particle high fluxes is rather well known (for example austenitic steel, or Inconel 718 steel used in Los **Alamos** LAMPF) or tungsten), nevertheless there is a maximum heating threshold for each envisaged window material (maximum power which can be deposited by material cm^2) which has to be carefully measured;

this maximum has been estimated to 0.1mA cm^{-2}, which means by extrapolation, 10 mA for a 100 cm^2 window.

The pressure gradient is manageable, but the associated heat gradient could also present some monitoring difficulties; modelisation and experimental R&D are certainly needed there for all these different combined problems; in addition radiation damage to the window could be very important and should be evaluate. The risk there is the burning of the window, its breakdown and consequently the shutdown of the accelerator; it implies that proper safety emergency techniques should be used to avoid accelerator's damages.

The window location is shown in fig 8 in a very schematic description of the EA core.

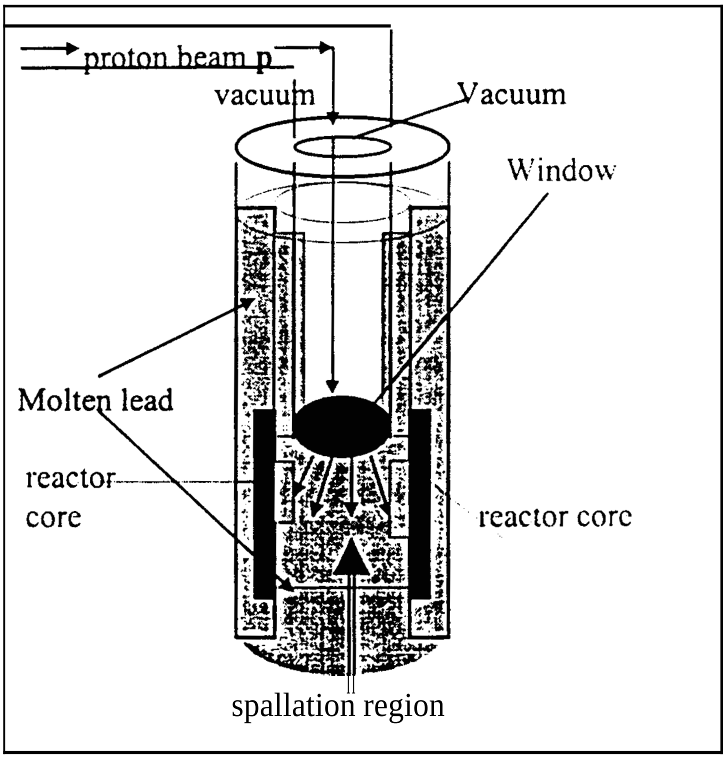


Figure 8

4.2 Spallation source and coolant

Two important issues have there to be considered:

- the coolant and the spallation target are the same (as been proposed by Prof. Rubbia and made of molten lead or lead + bismuth), and the molten metals circulate by convection in the same or in two different circuits.
- The coolant and the target are different: for example molten lead as target and gas for cooling and they circulate obviously in different circuits.

Opinions gathered are in favour of separated target and coolant circuits, the majority of them being in favour of molten lead target, some other opinions prefer target and coolant of different nature, mainly for taking advantage of industrial knowledge experience in some coolants (liquid sodium, or gas).

Spallation

Pr Rubbia has proposed to use molten lead and eventually molten lead/bismuth eutectic for the spallation target. The number of neutron produced by spallation increases with the atomic mass of the target: in this respect several metals appear attractive (Pb, Bi, W, Ta, etc.). The cross section of neutron capture must be as low as possible, and lead appears to be one of the best choice. The melting temperature of lead is 328 "C, which is not very favourable for using lead as a target and a coolant. The lead/bismuth eutectic which has a much lower melting temperature (124°C) and will be more suitable than lead.

Activation of Bismuth produces additional radioactive isotopes in particular more ^{210}Po than activation of lead(factor 100 to 1000).During the rotation time of the lead or lead bismuth target, before purification, many reactions may occur which will produce many different isotopes. Characterisation of neutron multiplication and inventory of radioactivity produced in the spallation process are poor; agreement between experiments and calculations is still not good enough. In particular little is known on some spallation products which may have an impact on corrosion. Production yields can be uncertain by a factor of two to four or even more.

Cooling

Quantity of lead needed in a reactor, if lead is used in the spallation target and as cooling in a single loop, is very high (Ten thousands of tons?). Up to now, nobody has experience with such quantities. Russians have used for many years such a coolant in nuclear submarines, but quantities are much lower. Several type of issues must be considered :

- *Corrosion.* This is a major issue, as historically corrosion has played a major role in failure mechanisms of nuclear reactors. Many physical-chemical processes are involved in the corrosion of solid materials by liquid lead or Pb/Bi. In particular, molten lead has a significant solubility for many metals. Russian experience may be useful in this domain; first experiments have been made in Europe, in particular in CERN and in CEA, but every one agree that much more work is needed. Pb or Pb+Bi are obviously not transparent media, and this will make more difficult inspection and repair of infrastructures.

  High density of Pb and Pb/Bi which will lead to high mechanical constraints, and to sensitivity to thermal shocks.

- ***Thermal convection or mechanically assisted flow of Pb or Pb/Bi.*** There is no doubt that thermal convection would greatly simplify the process and eliminate a **risk** for failure of pumps. However, simulation suggest that natural cooling is not able to effectively remove the heat in strong power transients. Impact of proton beam interruptions depend strongly on their duration: they can lead to thermal shocks.

- ***Design.*** No detailed design has been really made, and practical difficulties are not yet completely identified. Simulation is not yet advanced enough to be used in the design and optimisation of a cooling loop.

Many experts think that much technological research and developments need to be done, but that the options of using Pb or Pb +Bi for cooling should be considered as well as gas cooling, even if, in this last case, high pressure has to be taken into account.

Toxicity

Chemical toxicity of Lead and Lead/bismuth and of by-products will be very high and must be addressed very carefully. Radiotoxicity will be also very high, and continuous purification of Pb or Pb/Bi will have to be implemented. In term of toxicity, pure Lead would preferable to to Pb+Bi, in particular for ^{210}Po production in significant quantities.

Conclusion

Using the same medium for Spallation and cooling is attractive, however, most experts are not sure at this stage, that this solution will comply all requirements. Some industrial companies, would prefer to have different materials for spallation and cooling: molten Pb or Pb+Bi are good candidates for spallation target, but for cooling, other coolants could be considered like high pressure gas or even liquid sodium .

4.3 Burning of Actinides and transmutation of other fission products

The trans-uranium radioactive elements (belong to the Actinides family: Neptunium, Plutonium, Americium, Curium,...), produced in uranium nuclear reactors by successive neutron captures, are well known nuclear waste elements; they are considered as very undesirable because of their radio toxicity and their very long half-lives (thousands, even million years).

To-day they are chemically separated: some like the Plutonium element materials (Pu 239) are extracted and confined because of their military proliferation capacity, the others are reprocessed to extract the non totally burnt uranium and reuse it and finally the remainings are processed, for example vitrified, and stocked (in surface in specific locations or in deep underground sites), with all the safety and public opinion related problems.

The fission products (PF including the Long Lived PF), i.e. the elements resulting from fission of the uranium nuclei, (having a mass number roughly between 80 and 160) are also radioactive and have a large spectrum of half-lives from short (seconds) to very long (millions of years), like the transuranian elements; some are volatile, and must be specially processed to avoid environment problems .

With a Thorium fuel sub-critical **EA** fast reactor delivering high fluxes of fast neutrons (specificity of spallation reactions induced by high energy proton flux), one can envisage, based on favourable results of preliminary experiments :

- to burn (fission) radioactive transuranium elements produced in the nuclear amplifier and produced in other reactors ; (their transmutations, by neutron capture, are possible; it can give shorter lived elements, mainly alpha emitters, which become fissionable heavier nuclei)
  To transmute by fast neutron capture some of the MA

To transmute FPs and LLFPs by thermalising the fast neutrons , taking benefit of the large neutron capture cross sections enhanced if done in the resonance region (typically the ^{99}Tc (see section 2.9)

to transmute, by neutron capture, the radioactive fission products in stable or shorter lived elements.

These technical and physical solutions are considered not only elegant, but potentially extremely useful for the nuclear safety and the nuclear industry future; we give in Annex **2** some examples of both processes which have been, are going to be or will be tested at the laboratory scale (ref CERN, Three countries ADS-Working Group).

An interesting by-product of the nuclear amplifier fast neutrons facility can be the production of medical radio isotopes which are very costly and which constitute to-day a real world market ; introducing (and extracting after neutron) irradiation in the system proper targets (for example ^{98}Mo, or ^{127}I), one can also envisage to produce extensively used medical radio-isotopes like ^{99}Tc via the reaction ($^{98}\mathrm{Mo} + n \text{---->} {}^{99}\mathrm{Tc}$) or ^{128}I ($^{127}\mathrm{I} + n \text{--->} {}^{128}\mathrm{I}$)

All the answers of the different interviews or written contributions received, agree that these opportunities and promising ways opened by the nuclear amplifier concept could operate and consider them as a priority; the energy delivered by the system could be of course usable, does not appear as prior as the nuclear waste new processing. Nevertheless some opinions claim that the same kind of results could be obtained with thermal neutrons of existing Pressurised Water Reactor (PWR), or with fast neutrons reactors existing facilities.

Of course extensive R&D has to performed especially in spallation, neutron capture and fast neutrons fission reactions cross sections; full scale operations are recommended with all the elements assembled justifying a complete R&D scheme. Full scale tests should be realised in existing experimental fast neutron reactors.

4.4 Safety

The Energy Amplifier is considered by its promoters as basically safer than classical PWR reactors for two main reasons and some secondary reasons:

- It operates via a proton accelerator which can be switched on and off
- It is a sub-critical system ($k_{eff} < 1$) where no power excursions can occur and consequently with no risks of explosion or core fusion. The simple secondary reasons are:
  - No pressurised vessel, the lead vessel is at normal pressure
  - With thorium fuel, less plutonium is produced
  - k_{eff} control security margin is enhanced by waste incineration

If the accelerator has problems, everything stops and nothing happens, no pressurised vessels and so no problems linked with pressure leaks or over-pressure, lead is a well known passive metal, cooling the system via natural convection of molten lead is simple, efficient and has been tested in full scale (Russian submarines reactors).Moreover,the promoters have chosen deliberately a determinist safety approach and not a probalistic one.

On these safety aspects, the interviewees and the questionnaire answers are rather careful.

An engineering design of a full scale energy amplifier reactor is not realised yet even if some pre-designs for a Demonstrator are prepared, made by Ansaldo, Framatome and the Spanish Company LAESA; to date no design or pre-design seems to have been submitted to **national** safety authorities, nevertheless it is recognised that the proton controlled operation of the energy amplifier is a great potential safety advantage over other reactors and should be appreciated by safety authorities; however new complexities introduced in the whole system can be pointed out by any safety authority for delaying and made difficult commissioning:

- The accelerator(s) unit itself with RF cavities cooling systems and the proton beam characteristics
- The radio-protection shielding demands, in the accelerator area and in the beam transport lines including the bending magnets
- The sub-criticality control
- The eventual criticality effects while lead is cooling down after proton beam trips
- The window heating and activation
- The target configuration
- The decay heat removal after shut down
- Containment of radioactive wastes and isolation barriers
- Inspection, maintenance and repair difficulties of non-exchangeable structures
- In-service inspection facilities,......

In fact, in the various contributions and comments received and heard, the novel aspects of the Energy Amplifier are said to be probably considered by safety authorities as the addition of a number of problems: all those of a new reactor plus those attached to an innovative accelerator unit delivering high intensity proton beams; safety inspectors could be tempted to demand more than reasonable safety measures which could contribute to a very significant cost increase of the whole reactor.

4.5 Nuclear fuel cycle

Basics

The basic nuclear cycles for Uranium and Thorium are formally analogous.

$$^{238}U + n \longrightarrow {}^{239}U \xrightarrow[\mathbf{23.5\ min}]{P} {}^{239}Np \xrightarrow[\mathbf{2355\ days}]{P} {}^{239}Pu \text{ (fissile)}$$

$$^{232}Th + n \longrightarrow {}^{233}Th \xrightarrow[\mathbf{22.3\ min}]{P} {}^{233}Pa \xrightarrow[\mathbf{27\ days}]{P} {}^{233}U \text{ (fissile)}$$

Fig 9

More detailed routes are given in fig 10, next page.

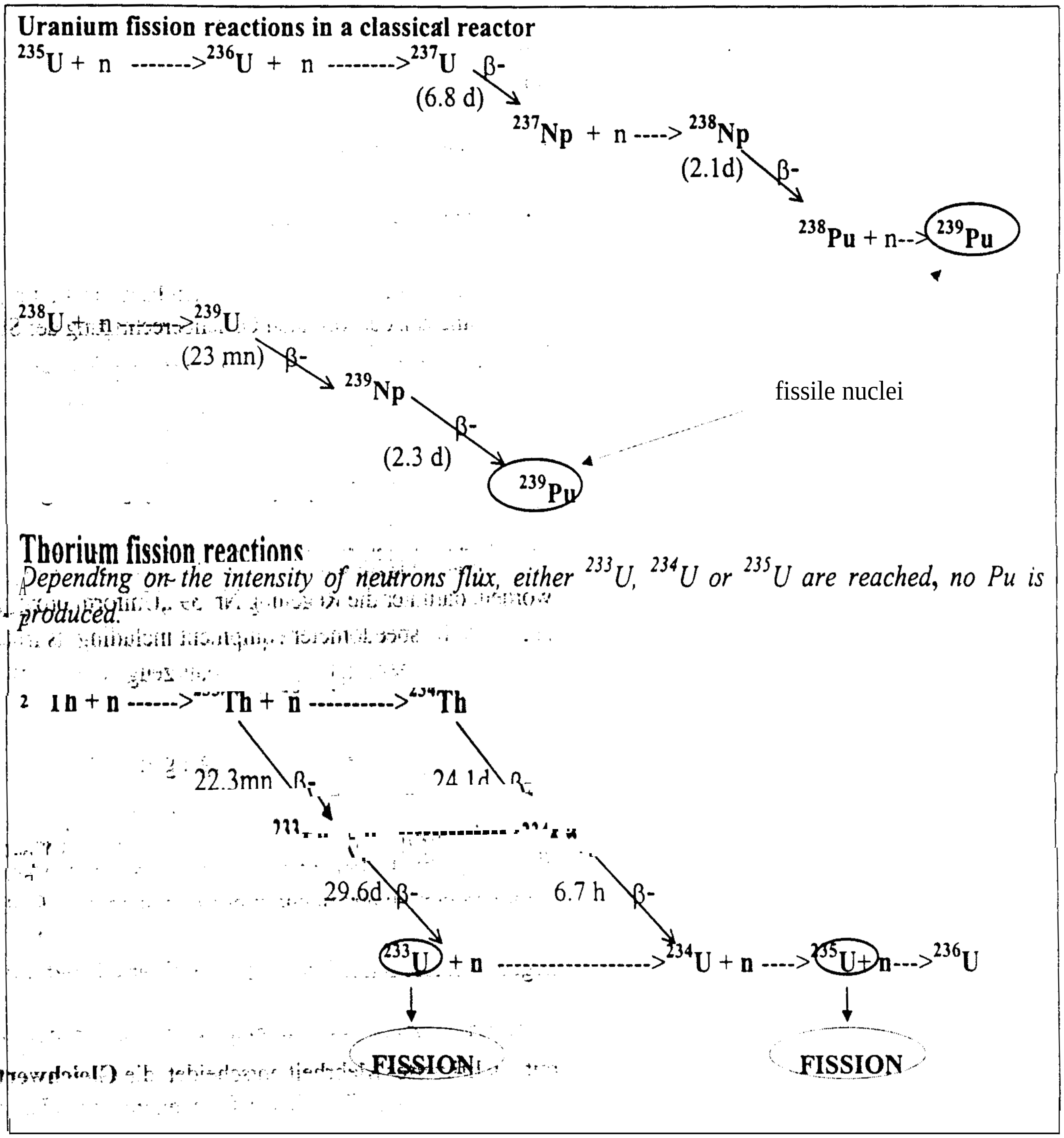


Fig 10: Comparison of successive neutron captures by Uranium 235 & 238 & Thorium 232

In parallel ^{233}**Pa** half-life is long enough to capture a neutron and to produce ^{234}**U** which is non-fissile with the following capture reaction ^{233}**Pa** + **n** -------> ^{234}U (non fissile)

The breeding ratio for thorium is higher than for Uranium, and under favourable conditions may approach or slightly exceed unity, this is an advantage for the Thorium cycle compared to the Uranium-Plutonium cycle.

However, the relatively long life of ^{233} **Pa** favours the slow build-up of the fissile material because of the parallel formation of the non fissile ^{234}**U.In** addition, side reactions lead to α emitters which decay ultimately to Thallium 208 which has an unusually penetrating beta-gamma emission: in these conditions separated Uranium and Thorium reprocessed fuels claddings would require remote handling within a few days after separation.

Another advantage for Thorium (ThO2) is its ability to generate via a continuous neutron capture, much less Major Actinides than MOX (U+Pu) by several orders of magnitude, and no minor Actinide beyond the Neptunium; this has to be confirmed by in-depth experiments. Furthermore the Thorium fuel cycle generates practically no Plutonium which is a very important for obvious reasons of reprocessing and proliferation.

Thorium fuel fabrication and reprocessing

Fuel fabrication will need specific developments, but no major difficulties are expected. One could envisage to adapt existing plants (it could take around one year), but with no return possible to its former production (mainly for safety); there will be a need for a dedicated fabrication plant which could be developed within a five-years time scale.

Fabrication of new mixed fuels including intermediate waste with or without Minor Actinides + Thorium oxide, can be envisaged; :nevertheless, it presents to-day very serious difficult problems linked to the elements separation from the high level nuclear waste (for example lanthanides, potential poison for the system, chemically similar to the higher Actinides such as Americium). The high radioactivity level of these various wastes is another difficulty and will require dedicated installations; it seems nevertheless worth to study it, even if opinions emitted are very pessimistic on the related costs, and the time necessary to master the technology.

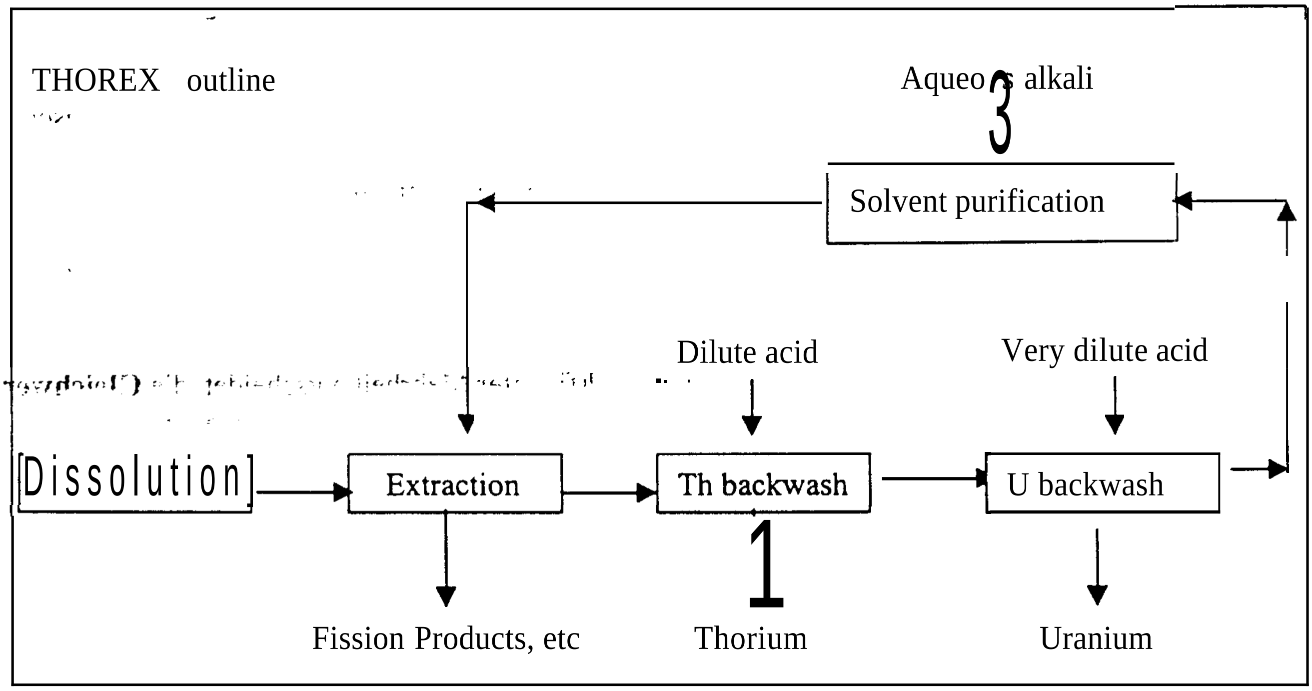


Fig 11: Thorex process (source BNFL)

Reprocessing of the Thorium fuel is not so developed than the PUREX (Plutonium Extraction) process industrially used for the MOX fuel; even if a THOREX process (see above, fig 11) had been studied in earlier times, it is not, at least in the western world, operated industrially (perhaps in India where thorium reactor(s) is (are) in service) The chemistry involved in THOREX is not easy, mainly because Thorium oxide is not solvable in nitric acid (no chemical reduction possible); in addition, Thorium is less extractable than Uranium by a factor **10,** moreover, in this process, the Major Actinides are less extracted than the Minor Actinides. It appears here too, than if the process is finally mastered, a specific reprocessing plant should be built, a reutilization of existing plants does not appear possible unless one is transformed, but definitively.

Another way to reprocess the Thorium fuel could be pyro-processing the burnt fuel: it is a chemical reduction process of fuel oxides associated with a selective electrolytic separation (in molten salts) of several streams of elements: stable ones, medium lived elements (30 years), trans-uranium (can be burnt by fission), and long lived fission products (can be transmuted in stable or shorter lived elements); these techniques are currently studied in the US (Argonne Laboratory), but are not yet at the industrial scale.

Specific concern has been expressed on risks of proliferation which have to be taken into account. Pure ^{233}U is said to be a good candidate for weapon, but is in fact always "contaminated" with ^{232}U which decays in several elements which after few days, make the mixing non-proliferable: (it would be a question of precise days to choose for stealing the product!).

To start an eventual demo, as it is underlined by several experts, it would be preferable to use MOX fuel, and later on to move on Thorium, after detailed experimental R&D on the various issues on the fuel cycle.

Finally one can say that the thorium fuel cycle has advantages and some disadvantages compared at the classic Uranium-Plutonium fuel cycle which can be summarised in fig 12:

^{232}Th - ^{233}U fuel cycle:	^{235}U- ^{239}Pu fuel cycle:
The reactor performance rather well established Minimal production of Pu & Minor Actinides	well developed, including recycle of U & Pu generates more Plutonium than usable
Fission Products practically the same than in a MOX fuel reactor	Fission Products well identified
Problems in reprocessing and recycling No existing industrial infrastructure	Recycling Minor Actinides problematic Industry infrastructure exists

Fig 12

A ^{232}Th – ^{239}Pu fuel cycle would have the advantages of both and in addition a plutonium elimination component which on the long term could contribute to a significant reduction of Pu fuel stocks.

4.6 Potential for energy production and related economics of the ADS

Energy production

Undoubtedly, the original goal for the EA was to present a new nuclear option proposal for Energy production in Europe; in the original EA description (Ru), the obtained significant energy amplification factor, with a sub-critical k factor of 0.98, and a 1 GeV- 12.5 mA proton beam (≡12.5 Mwatts) is 120 which is very attractive for energy production; this means that a 1500 MW thermal power (12.5 x 120) can be delivered at the end of the secondary loop, and transformed, via proper heat exchangers, to around 650 MW electricity power. Even if all the separated EA elements appear to be mastered technologies, the assembly and the operation of all the system appear, for the moment, to the energy sector operators, not responding to all industrial electricity criteria, in particular reliability and operational costs.

On the other hand, the burden problems for nuclear industry of nuclear waste production, processing and storage appear solvable, with a promising new way of partitioning and transmuting, the industry reacts more favourably, and would privilege this latter orientation; the EA promoters have, in fact, realised rapidly , that they had to push in this direction, even if electricity production could be used by the EA system itself, and " marginally" for possible connection with the electricity grid. Furthermore, the nuclear waste partitioning and transmutation potentialities of the EA open the route for installing such a unit inside a nuclear plants site and then the local energy consumption and production could take the whole benefit of extra energy production.

Energy feeding the Energy Amplifier:

A substantial share (>10%) of the energy produced by the EA is foreseen to be re-injected in the electric power feeding of the system, the energy surplus could well be sold to the electricity Utilities and even with a substantial production cost could pay-off for the EA reactor investments.

Plutonium burning and destruction

Another very interesting utilisation of the EA is its ability to burn mixed fuels composed in particular of Plutonium –Thorium oxides; it can thus destroy practically all the Plutonium and so contributes very significantly to the Plutonium stock reduction, with nevertheless the Minor Actinides production to be burnt later on. This was one of the major objectives of the American atomic laboratories working on the ADS subject, these last years.

4.7 Design of an EA Demo and/or prototype, possible timing and related economics and costs

Design of an EA Demo and /or Prototype

Several projects have been or are designed for Energy Amplifiers demos and prototype

- The proposal of C.RUBBIA and J.RUBIO in their 1996 paper for a full-scale prototype of 1500MW(th) - 625 MW(el) **EA** with a super-conducting proton LINAC (1 - (2.7) GeV protons, 30 –(12.5) mA , a 30 MW beam power, molten lead target and cooling, ThO2 + 0.1^{233}

U fuel, a **k** coefficient of 0.95, and an electric power re-injection of 60 MW, could be built and commissioned in 6-7 years.

- ***An*** ANSALDO 80 MW Demo pre-design, within the power range of 10 –100MW(th), with a 400-600 MeV cyclotron (Annex 3, fig 4) **,** and a Demo from Framatome (Annex 3, fig 5 and 6).

- The LAESA Company has designed a prototype project derived from C. RUBBIA's proposal, presented at the ICENES Conference(July 1998), of 100MW(th), 380MeV proton multistage cyclotron, 12.5 mA current, which could be operated in 2003-2004, according to their opinion.

Possible timing

The opinions gathered are rather dispersed but current quoted timing periods mentioned are in the range of **7 -** 10 years for a Demo design, construction and operation with parallel intense R&D on all the various delicate aspects (beam trips, window, etc....) considered as key points by the majority or even "killing points" by others. Some other thinks that more time will be needed, and we think that such a delay is more realistic.

Economics and Costs

Few economic evaluations have been published on the global economy of the Energy amplifier; only R.FERNANDEZ (et al., see (Fe)), and the STC committee(ref. (EU)) have done some interesting assessments: in (Fe) a very detailed cost analysis is presented and in (EU), a comparative economic analysis of current PWR reactors and an EA reactor of same electric powers.

Some other figures circulate here and there, only an on-going study (funded by the EU) will be able to update the 1996 figures (R&D and studies **4**th FWP, see 4.8 section).

Based on a 600 MW,, delivery power, the prototype and a series unit total costs have been assessed in details, assuming that the **EA** lifetime could be **50 years;** in absence of published updated estimations, we can only propose to update the figures published in the above references:

The total costs are classically separated in Direct Investments costs and Indirect ones. The **EA** Unit comprises the following separated costs: the accelerator system, the secondary loop, the Energy generating unit, Auxiliary systems, Mechanical & electrical classic equipment, the general system assembly, Instrumentation & control, structures & civil engineering.

	Costs in Mega US dollars (M$)	
	EA Unit prototype:	EA series unit:
direct investment :	792 **M$**	655 **M$**
indirect investments:	**400 M$**	286 M$
Total Cost:	1192 M$	941 M$
Uncertainty	1000 M$<Cost<1390 M$	670 M$< C <1100 M$

The re-evaluation by the EURATOM- STC working group did not change basic CERN figures; nevertheless it proposes a vendor's price for both units of 1410 MEUROS and in addition **an** estimation of owner's costs and money interest during the construction of 500 MEUROS which leads to a total investment cost of **1910 MEUROS,** which gives a reduced cost per kWh installed of about **3200 EURO/ kWh.**

A classic PWR produces energy at about **2450 EURO/kWh** (actualised 1999 market prices). Therefore, an EA appears to be not competitve for electricity mass production.

However, if an EA is bilt for nuclear waste treatment, energy is a by-product which can be sold at marginal cost, which may be very attractive. Such marginal costing may not comply with competition rules and be criticized by competitors.

4.8 European needs for an EA Demo: opinions

From our enquiry, a large majority supports the need for Europe to design and build an EA Demonstrator for nuclear waste partitioning and transmutation tests. It must be noted however that companies producing electricity or involved in the nuclear fuel retreatment are somehow reluctant to envisage new and heavy investments which could outdate previous investment which is not recovered.

Energy generation is not the main concern of our correspondents even if they recognise to the EA a probable “by-side” energy production capability which is interesting enough; if the Demo realisation and operation are successful, a Prototype could and should be studied and proposed at the European level.

Nevertheless somewhat diverging opinions are emitted when it is asked what preliminary coupled parts would be necessary to test before starting the whole design and construction.
Few answers mention the starting of the whole EA-Demo design and construction, without testing separately a number of assembled components:

- The first delicate coupling test that appears as a priority to a majority of people is the assembled trio accelerator - window - nuclear core, without paying too much attention to the nature of fuel. Complementary R&D on these problems appear to be necessary to a number of experts.

- **A** large consensus is observed for the accelerator’s choice which focuses on proton beam delivered by a multistage cyclotron unit within the mA intensity range required as the original **EA** promoters’ proposal; a number of opinions are very doubtful and womed about the accelerator stability and the proton beam reliability; numerous references are made on existing accelerators beam trips which are considered of weak importance in basic nuclear and particle physics, but in an EA, basically driving the nuclear core burning, could lead to interrupt the reactor’s operation with the associated safety procedures; complementary R&D is then required to solve these basic issues.

- Opinions are balanced between a starting fuel like MOX, and a Thorium oxide fuel mixed or not with Pu; parallel extensive R&D tests on mixed fuels with Minor Actinides is considered to be basically necessary.

- The molten metal(s) coolant is per-se a problem and if specialists would prefer pure lead, even if the melting low temperature advantage of the eutectic Pb-Bi is interesting(125°C), its Polonium (^{210}Po) generation capacity is significantly unattractive.

- The associated substantial R&D necessary for such a project requires common and complementary European efforts and projects .

- The location: either for the Demo or for the prototype, the majority of answers is in favour of a location inside an existing nuclear research centre with all necessary infrastructure and the practice of the safety regulations and relations with safety authorities.

- According to rare opinions about the Demo costs, figures lying in the range **of few** hundreds MEURO are estimated.

4.9 Energy **Amplifier/Accelerator** Driven Systems related research activities in Europe: R&D Member-state activities, the **4th- 5th** E.U. Framework Programme, **STC** Opinion.

Several R&D programmes, projects and initiatives are on - going, have been decided or are planned on the ADS systems in general and on the Energy Amplifier in particular, at the level of CERN, EU member states and the European Union.

- The CERN Group, leaded by Prof. C. Rubbia, continues its pioneer work on the EA and after the successful FEAT and TARC (Transmutation Adiabatic Resonance Crossing) experiments, starts to study and use a spallation driven Time of Flight neutron facility (TOF); this facility will be used within a large range of neutron energies(1eV – 250MeV) to measure precisely neutron fission and capture cross sections.

- In a tri-partite collaboration, associating Italy, France and Spain (1998), a certain number of experiments are and will be undertaken going from molten lead (or Lead+Bismuth) metallurgic studies up to transmutation studies; a 10 years European Demonstration programme has been recommended which would include a partnership implementation, an R&D programme leading to an EA design, and a demonstration facility to be constructed and operated. Accelerator Technical options, the beam window issue, the spallation source, the sub-critical system including the fuel and the primary loop coolant (Pb, Pb +Bi), various coolants options (gas, liquid sodium, molten salts) have been selected as R&D activities very necessary to undertake. Additional R&D subjects on lead, advanced fuels, development of coated particle fuels, Thorium cycle, advanced reprocessing and molten salts have been identified as other important ones. The recommended funding was 10 MEURO per country per year “in order to keep necessary momentum”

- Individual EU member states encourage research on the Energy Amplifier problematic through various organisations, like the French GEDEON group (CEA- CNRS -EDF -Industry), The Italian ENEA Brasimone centre, the Italian **ANSALDO** company and the Spanish LAESA company in Zaragoza are on their side, leading EA related research on complementary subjects.

- EU Commission (DGXII + JRC-ITU of Karlsruhe) fission energy research activities. Several EA related projects and studies (9) were launched and funded during the 4th Framework Programme. These research activities are European Union wide and involve all the major actors (Organisations and Laboratories) in nuclear R&D.

The nine projects were the following:

NEWPART: new partitioning techniques
Extraction and separation of long lived nuclei
Evaluation of possible P&T strategies
Supporting nuclear data for advanced MOX fuels
Joint experiment on Americium transmutation
Thorium cycles as a nuclear waste management option
Transmutation in ADS
Neutron driven nuclear transmutation by adiabatic resonance crossing (TARC)
Physical aspects of lead as a neutron producing target for ADS devices

The EU Commission's contribution for these projects was **5-6** MECU.

- **The 5th Framework programme (key action nuclear fission).** It foresees continuation of the non -completed preceding projects and new subjects titled:

  P&T strategy studies on critical and sub- critical systems
  New efficient and selective separation processes
  Basic nuclear data essential for transmutation and development of ADS
  Fuels and target tests for Actinides and LLFP incineration
  Preliminary study of an ADS with support research work

  Calls for tenders on these subjects will be launched in 1999-2002 and it is envisaged to devote around **40** MEURO to fund (partially) all these projects.

Looking to all these initiatives, programmes and projects, it appears that Europe (all actors included) concentrates its efforts on Partitioning and Transmutation via an ADS-EA type (without excluding other ADS type).

EURATOM- STC Committee has also issued an opinion on Nuclear Energy Amplifier(1996), from which some points are underlined below:

> " The Committee finds the nuclear energy amplifier proposals to contain many interesting **and** thoughtful ideas for improving the way nuclear energy is used for electricity production. The STC does not consider it is realistic to pursue development on the whole system at once. This would involve developing new technologies for almost every aspect of nuclear electricity production
>
> The Committee's judgement is that some of the hoped-for advantages of the proposed system vis a vis LWRs would not be realised, even if full scale development did take place successfully,. .....we believe that the Energy amplifier would be more complex in engineering reality ...and it would not be economically competitive with the: under development EPWR."
>
> ....Commission should encourage further work on su-critical, fast neutron multipliers such as suggested by Professor Rubbia, but primarily at actinide burners , rather than energy producers. .....*'

The STC recommends the Commission to add *two* significant and a third small lines to its proposals for the the 5th Framework Programme namely:

- studies and research on Thorium matrix fuels for Plutonium management and actinide minimisation
- studies and research on accelerator driven fast neutrons reactors for actinide incineration
- an evaluation of lead as a coolant for fast reactors.

4.10 Accelerator Driven Systems international Research-Development activities

These last years in the world, a number of ADS devoted Conferences took place, numerous articles were published mentioning tremendous R&D activities launched to validate the concept. Further tests for other accelerators, other fuels, other coolants, are realised or foreseen; by far the partitioning and transmuting nuclear waste capabilities of the ADS reactor are analysed and feed designs of some interesting projects. The IAEA 1997 report classifies ADS and gives a synthetic panorama of all possible ADS systems (see fig **7,** Annex 3).

United States:

Several R&D initiatives, projects and programmes have been designed, launched and are extensively promoted. Mainly the Los Alamos (LANL), the Argonne (ANL) and the **Oak-**Ridge (ORNL) national laboratories are involved.
In Los Alamos, at least three projects are running at the same time under the umbrella programme LA-ADTTP (Accelerator Driven Transmutation Technology Project):

- The weapon Pu destruction Accelerator Based Conversion (ABC)
- Accelerator Driven Energy Production(ADEP)
- Commercial Waste Transmutation (ATW) (see Annex 3, fig 8)

These projects are based on associating proton LINAC accelerator(5-10 mA), liquid molten lead target, sub-critical (**k** = 0.95), molten Uranium-Thorium-Actinides-FP salts fuel reactor, graphite moderator for delivering thermal neutrons for transmutation. **A** variant has been proposed called TIER 1&2 to design a commercial open cycle Accelerator Transmutation System reactor; a 1000 MW(el) ADS reactor would be deployed, transmute and bum its FP and MA products and could deliver and sale an electric surplus energy of 300 MW; in the context of ADEP the introduction of ADTT systems to bum and transmute nuclear waste could be envisaged in nuclear sites in a proportion of 1 ADDT reactor for 4 nuclear 1300 MW(el) plants to destroy their waste in a 30 years operating time. Figures 9 and 10 of Annex 3 present time scales for development and deployment of a full set of ADDT reactors. *ANL* is focused on pyro-processing separation technology (see in Annex 3, fig 11, a flow diagram of the pyro-metallurgical process) and ORNL has the molten salt reactor facility(MSRE) for complementary research.

The timing for full introduction of the systems in the national electricity grid is studied, with a number of hypothesis; it foresees a 10 years programme for R&D and Demo (5MW) realisation for 2010, a **full** scale prototype (500MW) building in the years 2006-2020; the estimated costs figures are 2-5 M$/yr, for R&D, 10-20 M$/yr for Demo, 20-50M$/yr for engineering Demo.

Japan: The japonese concept of accelerator-driven transmutation system is given in Annex 3, fig 12. At least **two High** power proton accelerators projects are studied, among which a dedicated Engineering Test Accelerator (ETA) ; an ADS oriented programme called OMEGA(see glossary) has been decided, under the responsibility of **JAERI** and CRIEPI organisations (see **glossary**); OMEGA started in 1998 mainly focused on nuclear waste transmutation, two types of ADS are studied :

- a 1.5 GeV, 10 mA(up to 40) LINAC proton beam, a solid tungsten spallation target, cooled by liquid sodium, a sub-critical reactor with actinides fuel; it is a 820 MW (th) fast reactor which can produce 100 MW (el) for the grid.
- a 1.5 GeV, 25 mA intensity (LINAC)proton beam, a liquid molten salts fuel and target (NaCl, Plutonium 239 chloride, Minor Actinides Chlorides), 800 MW(th).

The timing proposed is rather short the R&D phases ending in 2000, the pilot demonstration facilities being constructed after 2000.

Russia For a long time, the Russians operate nuclear submarines cooled by molten Lead and/or Lead-Bismuth; a lot of know-how can be found there and there is still a number of on-going R&D projects currently reported on basics nuclear reactor works, in particular for the liquid Lead, Lead-Bismuth spallation cross sections and cooling properties; furthermore specific collaborations between the Moscow Meson factory at Troisk and USA- LANL are implemented towards an ADS demonstration integrated system experiment is planned.

In the context of IAEA /TEC-DOC 985 Review on ***ADS*** (1997) done by a number of contributors, mostly world nuclear reactor major actors, the following resumed statements were formulated:

"ADS offer a sub-critical mode of operation for nuclear power systems, and make them flexible fi-om the operational point of view.
ADS reduce the long lived waste burden and offer the way to transmute existing nuclear reactor waste.
A well designed ADS can ensure a proliferation-resistant fuel cycle and fuel treatment
ADS offer promising way to utilise Thorium resources for energy production
Ads offer an alternative way to utilise the existing excess of weapons-grade Plutonium for energy production".

"The international co-operation under the auspices of international organisations could be focused on: encouraging and stimulating ADS research in different countries in the fields of :...Accelerators, Transmutation, Utilisation of weapon-grade Pu, Thorium cycle, no-proliferation aspects of ADS, ADS safety, impact of ADS on radio-toxicity of the fuel cycle.....preparing evaluations of possible synergetic nuclear energy systems based on different scenarios e.g. LWR, **FBR,** ADS, etc.. ..
supporting international efforts to organise demonstration experiments on ADS, extending the nuclear data research into reactions and energy regions of interest for ADS,. ......"

4.11 Energy Amplifier: options for Europe?

4.11a The Energy Amplifier: an option for Energy production for Europe?

To this question, from our interviews **and** questionnaire answers, clearly the general expressed opinion is **no.**

The main reasons argued are:

- The delivered energy prospective costs are not and will be not competitive with the current and foreseen evolution (even at long term) in energy market prices.
- The safety authorities regulations, control and various operating constraints, for commissioning would be costly and deter any industrial operator.
- The Thorium cycle is not industrially mastered and the associated investments for the THOREX process (plants, safety, etc...) would be a very long and a heavy financial burden.
- The complexity of the system is important and not yet mastered, and the risks of frequent interruptions are real and the corresponding restarting operations are submitted to tight safety authorities decisions.

In the general context of the energy policy in Europe, it is foreseen up to 2030-50, that the prime energy sources will still be oil and gas, with in particular a tremendous increased gas consumption (by a factor **4).** The renewable energies will still remain at less than **5%** of the total energy consumption and nuclear energy will be maintained in the range of 10-12%; there is no worry, at least for the next decades, about energy sources shortages. So the only "chance" for a new nuclear energy demand would be a combined oil and gas crisis, supposing in addition that the public opinion would be more favourable to nuclear than now: this probability combination seems weak. (ref: Energy scenarios shared analysis, on-going DGXVII study)

4.11b The Energy Amplifier: a nuclear waste management option for Europe?

Clearly from **our** interviews and questionnaire' answers, the general expressed opinion is **yes.**

- The nuclear waste, the Plutonium-Uranium duo, Minor Actinides and Fission products are an extremely sensible problem for safety, and public opinion; any technology which could reduce significantly the waste quantities, their duration, and their toxicity is welcome
- The hopes to apply the new reactor's concept to a dedicated nuclear transmuter industrially developed are clearly expressed
- The necessary complementary R&D is important and would probably be medium and long-term.
- Thanks to Prof.C.RUBBIA, this aspect of its Energy Amplifier proposal has been worldly pushed and promoted; it would be natural, for Europe, to be in this domain, a leading actor.
- The costs aspects are not a "killing point", safety's prices criteria are not the energy market's ones
- European capacities and know-how in the nuclear energy field are important and world wide recognised; it could well be an historical opportunity **for** Europe to open a new promising route in the nuclear energy waste management.

5 Conclusions

The Energy Amplifier proposals from Professor C.RUBBIA has raised a renewed and high interest for ADS reactors, have renewed interest in Nuclear Energy research and mobilised many research teams in Europe and in the world. The ADS reactor is not per se a new concept, but recent technological progress on particle accelerators (cyclotrons, radio-frequency cavities, particle beam intensities) has made possible to envisage the realisation of 500-1000 MW(el) ADS machines.

The novelty of the ADS-EA is its potential ability :

- **to burn** fuels made with a relatively new element, Thorium (reasonably abundant), mixed with undesirable nuclear waste products, namely Plutonium and Major Actinides;
- **to transmute** highly radioactive fission products and actinides in less hazardous or even stable elements, in significant quantities: for example the whole waste of **4** nuclear plants produced in 30 years, if the EA operates nearby (on the same site) during the same period.
- **to produce** extra electricity and to be "self powered" by its own electricity production.

It is clear that the Energy Amplifier can not be considered as a candidate for contributing significantly to solving future energy issues of Europe and of the world. It has however a potential for nuclear waste treatment.

Today, many uncertainties still exist on technologies and many options are open. There is still a need for additional R&D and in-depth economical studies. Most scientists focus their attention on the nuclear reactor itself, but many other issues must be raised. One example is the choice of the nuclear fuel. If Thorium is chosen, a new fuel cycle will be needed, and its economical viability will depend much on the R&D and investments to depreciate and on the volume to be processed. Most of the operational European nuclear plants will be close to their end of life in 2020, and the question of their dismantling and eventually partial replacement will have to be addressed. It is considered that 1 **EA** will be necessary for burning actinides and some other nuclear waste produced by the operation of 4PWR reactors. The number of EAs, and the volume of nuclear fuel to process, will depend strongly on the future of nuclear plants for electricity production. Will it be economically viable to develop a new fuel cycle for burning of the current stock of actinides in 2020? Moreover the nature of the nuclear fuel impacts on the design of the Energy Amplifier.

European R&D co-operation exists in the field of EA: many R&D projects related to the subject are implemented at several levels, national, inter-governmental, CERN, European Union, USA and Japan; even if the main actors are involved in these different programmes within different frameworks, this R&D activity looks like rather dispersed and poorly co-ordinated. Initiatives are taken to open the tri-partite inter-governmental co-operation in the domain to other European nations. If USA' and Japan' ADS programmes *start,* as it looks like, it seems that the time to decide a common action on the ADS-EA issue in Europe has come. The situation is not so uncertain as for fusion research which is still far from application; the European nuclear industry seems ready to co-operate in that context provided that a funded programme **and** projects are set-up. The position of electricity producers and of the nuclear fuel cycle companies appear to be much more careful. It is reasonable to think that a JET-like undertaking could be a good operational instrument to build and operate an EA demonstrator; the adequate article exists in the Amsterdam Treaty.

Finally, several options are open for the European Parliament:

1. To recommend, or not, to consider nuclear energy amplifier for addressing the nuclear waste burning issues. Taking into account the importance of the nuclear waste issue, it may be opportune to examine any potential processing technology: in this context, should EA R&D be given a priority compared to other nuclear research projects?
2. If the European Parliament recommend to consider it, then, it may recommend or not to take some initiatives at the European level. Is it necessary to take such initiatives immediately or is it possible to wait for the next Framework Programme? immediately or in the context of next Framework Programme.
3. If an initiative is taken, several options are open for the linkage with the current tri-partite initiative:
   - independence of both initiatives, joint effort within the tri-partite initiative extended to other Members States and in particular to the European Commission. In such a case, the European Commission would be a member inter alia.
   - co-ordinated or integrated initiative led by the European Commission. What could be the added value of an European Commission co-ordination or leadership?
4. Additional R&D is still necessary in many domains and many technical options remain open. For the European parliament, two options are considered:
   - to encourage co-ordinated R&D in different countries to develop realistic, safe and economically viable technologies to make choices, and then to design and construct a demonstrator. It may be useful to study also assembly of different components and to demonstrate their viability. This could be achieved in different existing European sites.
   - to set up as soon as possible an integrated platform or scientific demonstrator which would be followed later on by a prototype. For a scientific platform, will it be useful to consider an operational structure comparable to the JET one and also a way of operation comparable to CERN? Is it worthwhile to consider a Public Private Partnership as envisaged for the GNSS project (GALILEO)? Actually there will be a need for demonstration not only of the EA itself, but also of other parts of the nuclear cycle (fuel cycle for example).
5. The question of the level of funding according to the development stage is important.: should the EC fund different types of activities at 100%, close to 50% or below? This is linked to the above question. The USA fund similar research through military funding because it is Plutonium oriented (but obviously dual use); if similar R&D and demonstration is funded at low level in Europe, because World Trade Organisation rules strongly limit the level of funding of civil R&D and demonstration, it will place European industry in an unfair competitive position.
6. Finally, what should be, in the next 6th Framework Programme, the level of priority to attribute to EA related R&D and demonstration? Is it necessary to initiate first significant steps within the current 5th Framework Programme?

ANNEX 1

List of persons interviewed and having answered to the questionnaires :

Prof.C.RUBBIA (CERN)
J.P.REVOL (CERN)
R.KLAPISCH (CERN)
P.MANDRILLON (Centre A.LACASSAGNE, CERN)
RADEMACHER
S.BUONO, KHADI
M.HUGON, U.FINZI (European Commission, DG XII)
B.BARRÉ (CEA)
J.B.THOMAS (CEA)
M.SALVATORES (CEA-GEDEON)
L.PATARIN, D.ROBERT, M.TARNEROT (COGEMA)
Mr VIEILLARD-BARON, A.VALLÉE, D.CHAVARDÈS (FRAMATOME)
H.SZTARK (NOVATOME)
Prof.A.PEREZ-NAVARRO GOMEZ, M.LOBON, A.A.VELASCO (Company LAESA–Spain)
Dr W. REITER (Research Ministerium, Austria)
Pr Dr P. HILLE (University of Vienna, Austria)
Pr Dr M. HEINDLER (Energieverwertungsagentur,Austria)
F.JACQ (MENRT, F)
W.JOHO, T.STAMMBACH, G.S.BAUER (SIN, SINQ PSI Institute Villigen, Switzerland)
R.SCHENKEL, Dr MAGILL (JRC-ITU Karlsruhe)
P.M. FASELLA (MURS, Italy)
P.H.REBUT (Fr)

List of persons having answered to the questionnaires:

Prof. VERJSOOIJEN (T.U.Delft NL)
Mr LOCATELLI (ANSALDO, IT)
L.BAETSLE (SCKCEN, B)
Pr. RAVETTO (IT)
J.M.MARTINEZ-VAL PENALOSA (ETSI Industriales, Madrid, SP)
R.BLUE , S. ION, (BNFL, UK),
P.D.WILSON (BNFL, UK)
C BIETH (PANTECHNIK, F)
Prof. TACZANOWSKI (Dept of Nuclear Physics, Mining University, Poland)

ANNEX 2

Specific nuclear wording

Actinides: Major and Minor (all $Z > 89$)

- Major Actinides are Uranium and Plutonium isotopes in a burnt fuel for example, produced in major quantities
- Minor Actinides are Americium, Neptunium, Curium isotopes

Coolant: the cooling fluid inside the cooling loops (primary and secondary circuits) can be of different nature: water, liquid metals or gas

Fast neutron reactor: this is a reactor, which delivers energetic neutrons with a kinetic energy from some keV up to some MeV

Molten salts fuels: the fuel is made of liquid fissionable elements in salts, for example Chloride salts.

Neutron captures:

One of the main route for nuclear transmutation: Nucleus (A,Z)+ n -->(A+1, Z).
in **a** reactor the neutron capture process competes with the radioactive decay and the fission processes

neutron critical factor k_{eff} is a characteristic of a chain reaction inside a reactor:

if **k** is <1 the reactor is said sub-critic

if **k** is = 1, the reactor is said critical, can be controlled and operates around this value

if **k** is > 1, the reactor is over-critic, can fuse and cannot be controlled the (neutron multiplication $= G_0$ W $(1-k)$, G_0 is the characteristic medium multiplication constant)

Partitioning: chemical separation

Radio-active decay: α(He nucleus) ß (electrons +/-) , and γ (photons) emissions from radio active nuclei

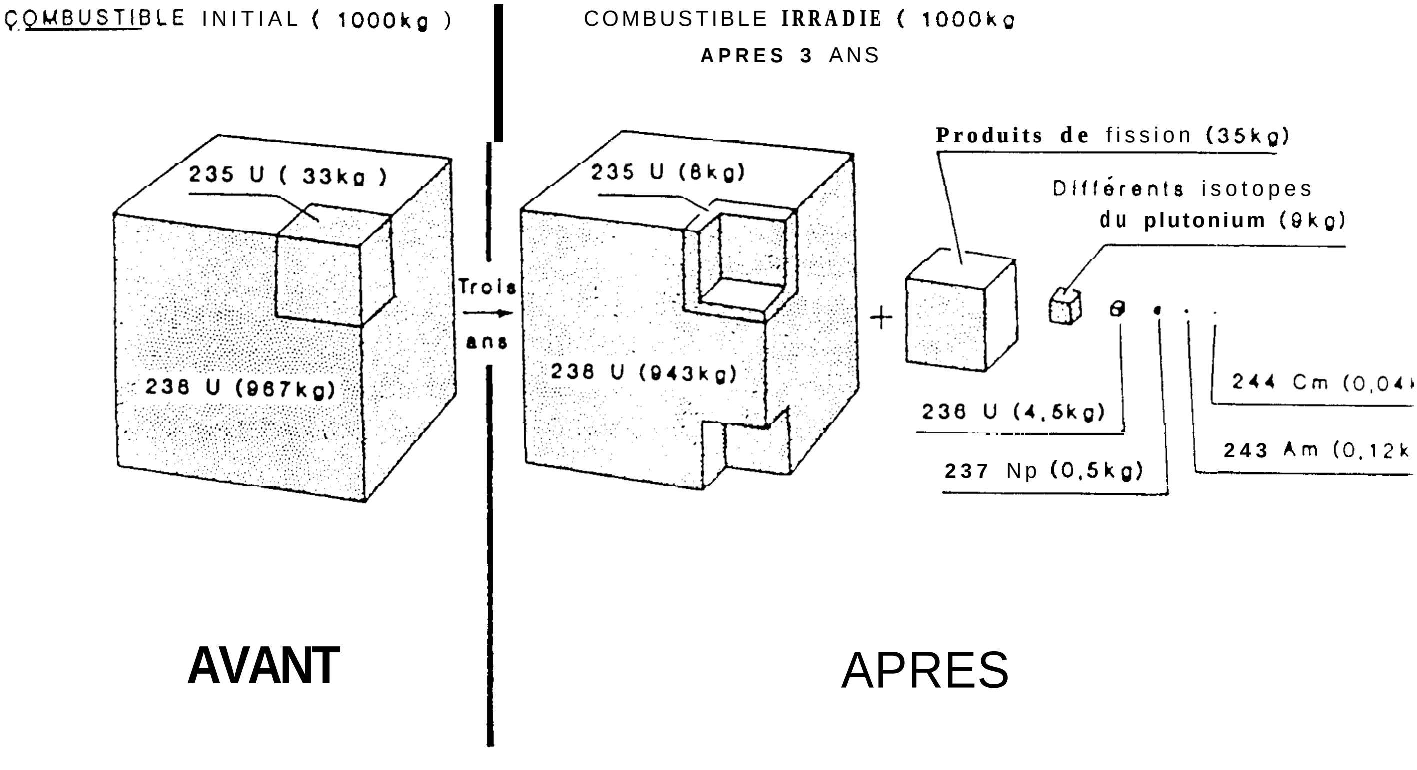
Thermal neutron(s): neutrons which have been slowed down via successive elastic collisions in a moderator material.

Transmutation: nuclear transformation of nuclei by charged or neutron particle absorption: generally used in the nuclear waste context, to transmute a long lived nucleus into a shorter lived or a stable nucleus

ANNEX 3

Figures

Figure 1: Evolution of nuclear fuel in the reactor



- Evolution du combustible dans le réacteur.

Figure 2 : System proposed by Prof. C. Rubbia

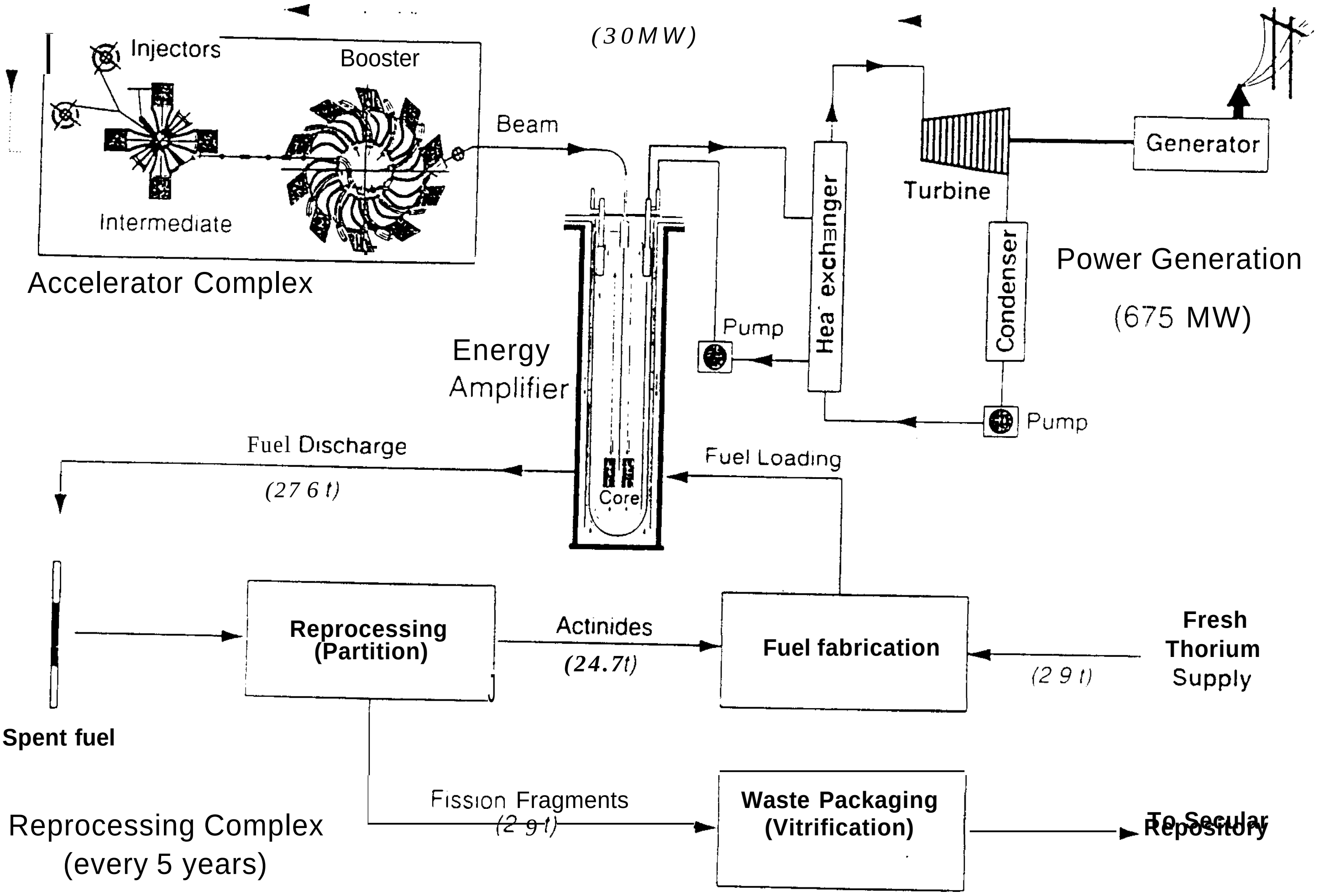


Figure 3: detail of the core of the reactor proposed by Pr Rubbia

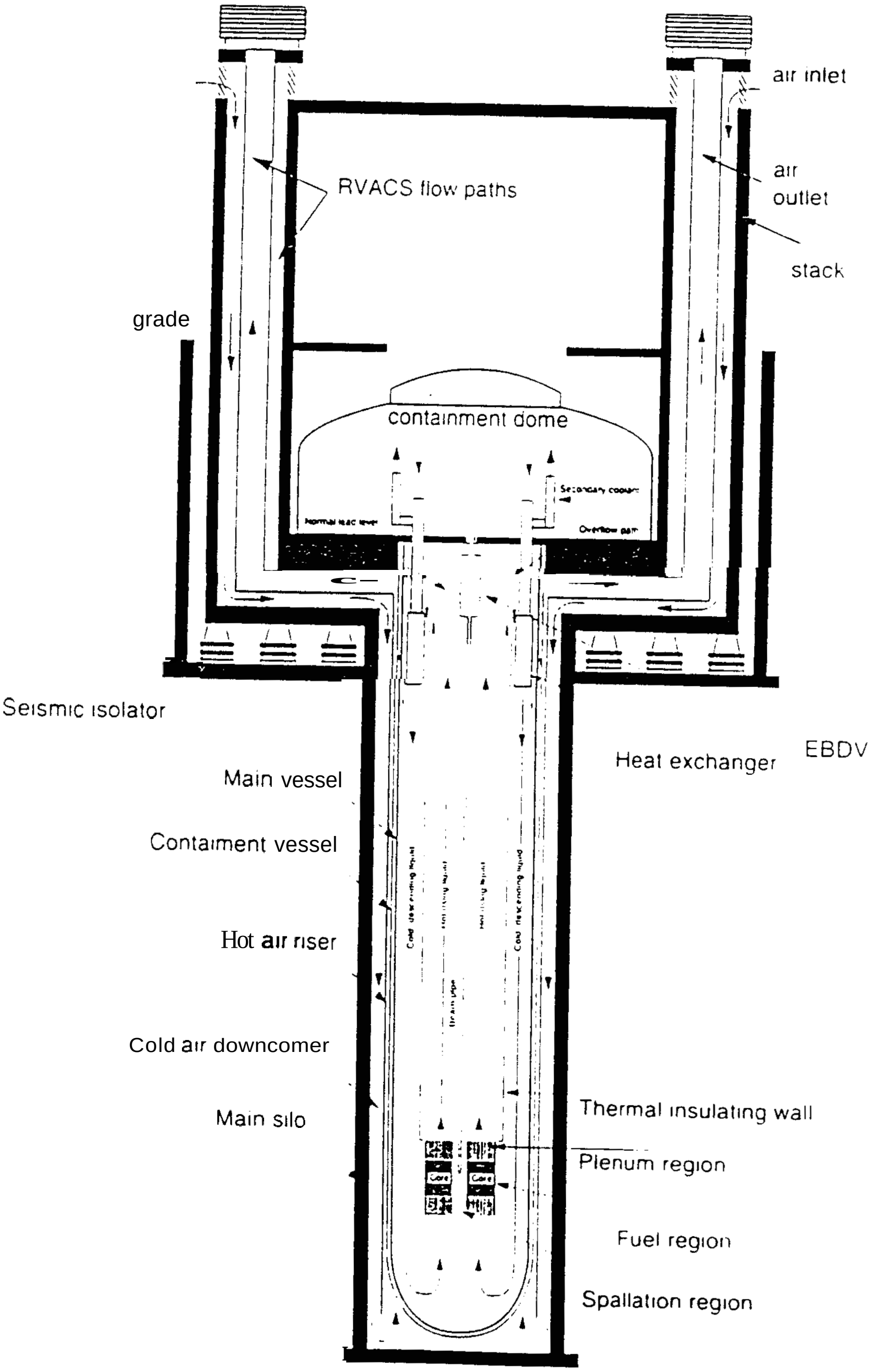


Figure 4: System proposed by ANSALDO

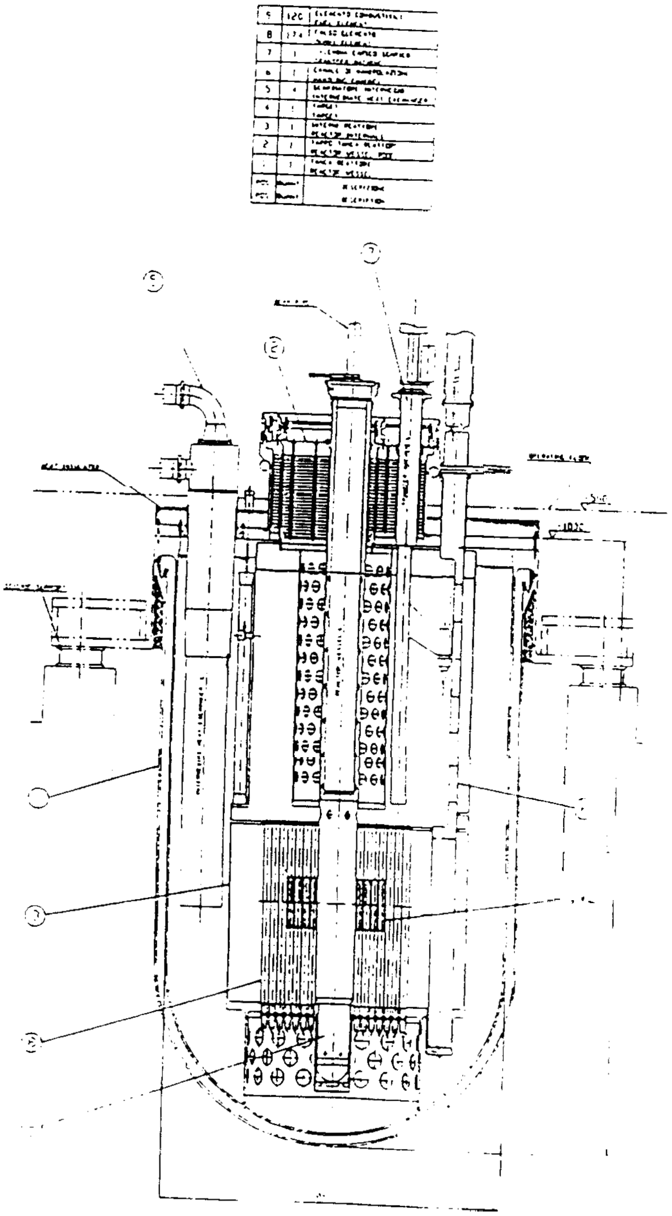


Figure 5: System proposed by Frrmrtome

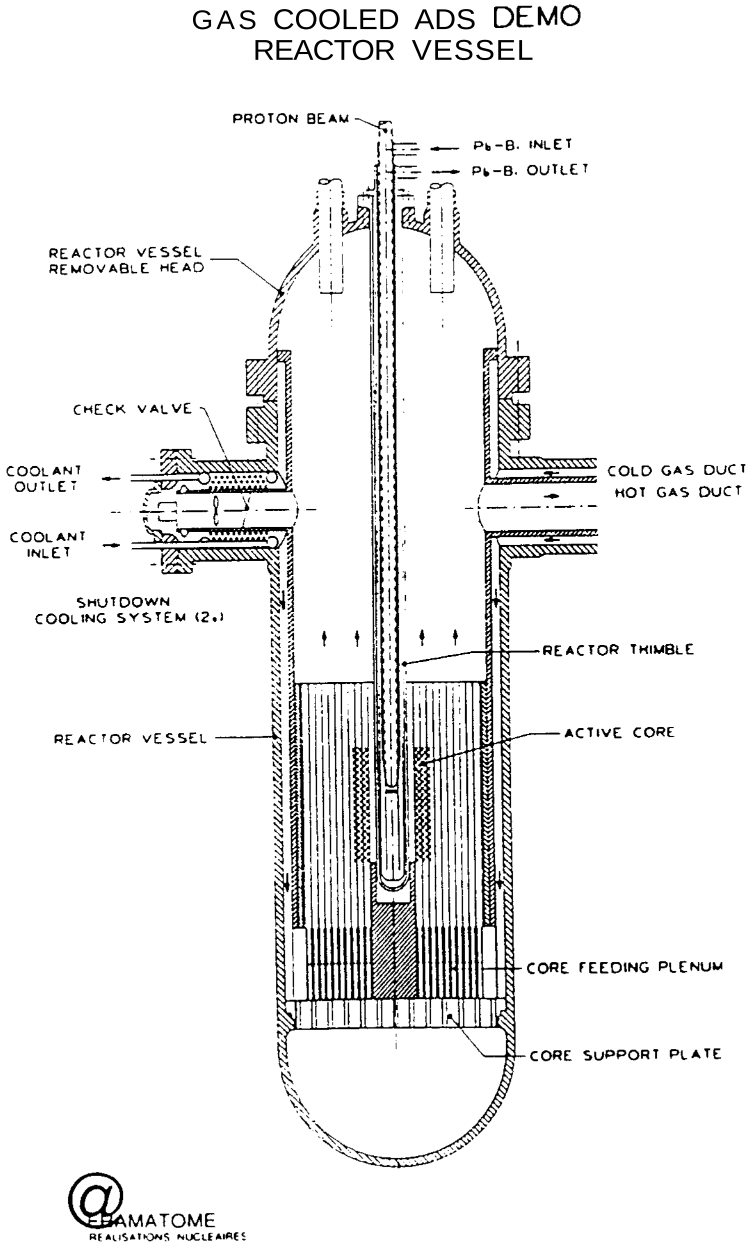


Figure 6: detail of Framatome's system

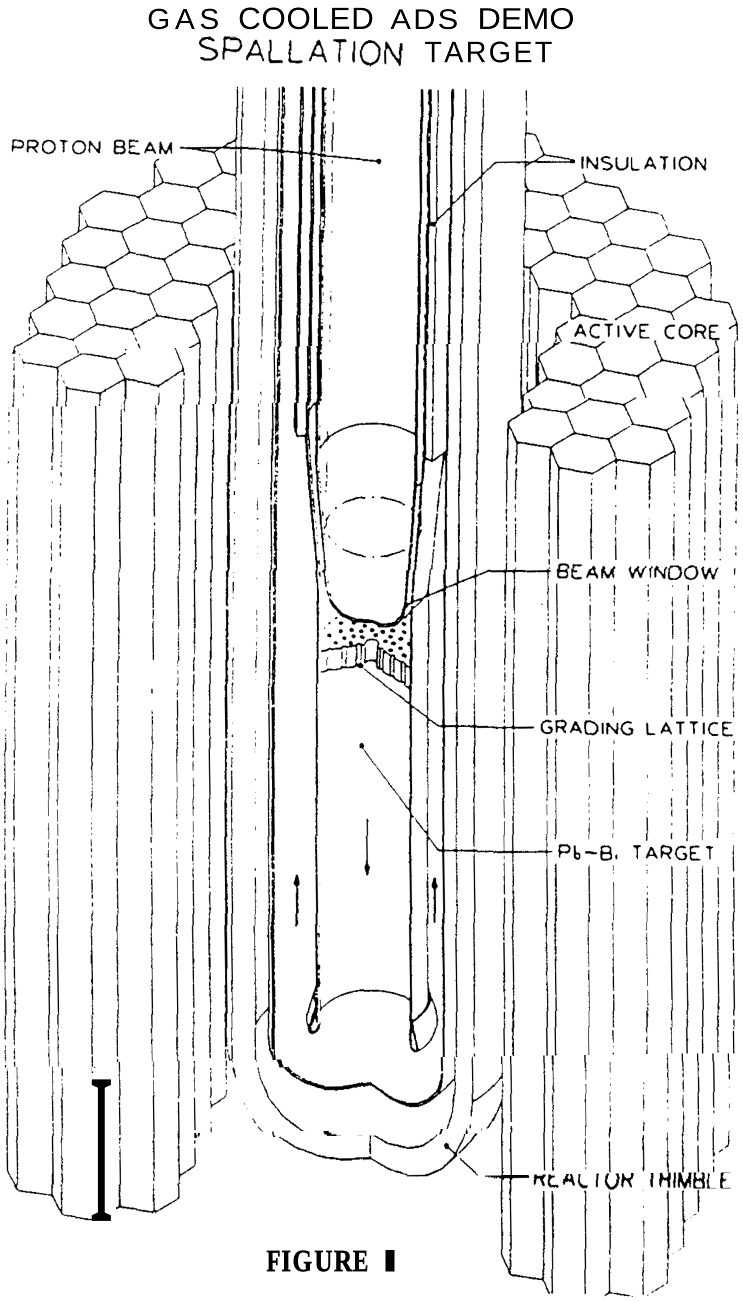


FIGURE I

Figure 7: Accelerator driven Systems proposed in IAEA(ref)

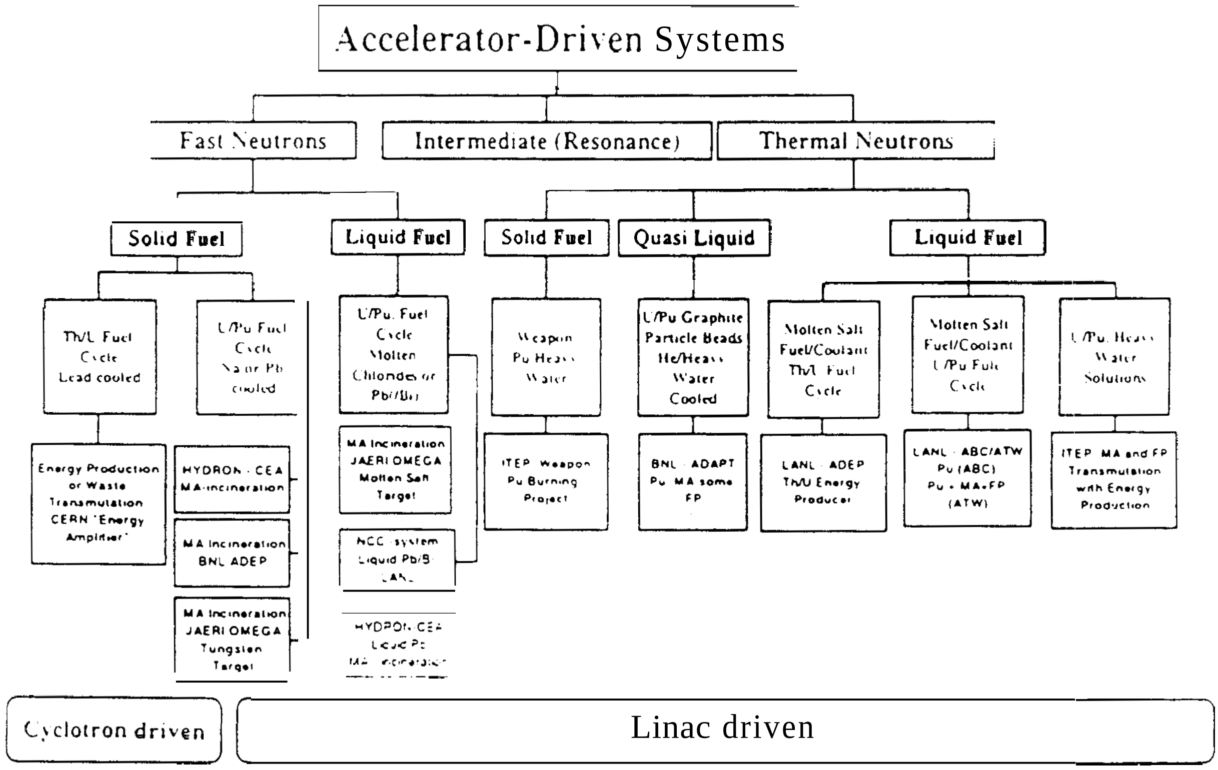


Figure 8: ATW american system

Lead Cooled ATW System

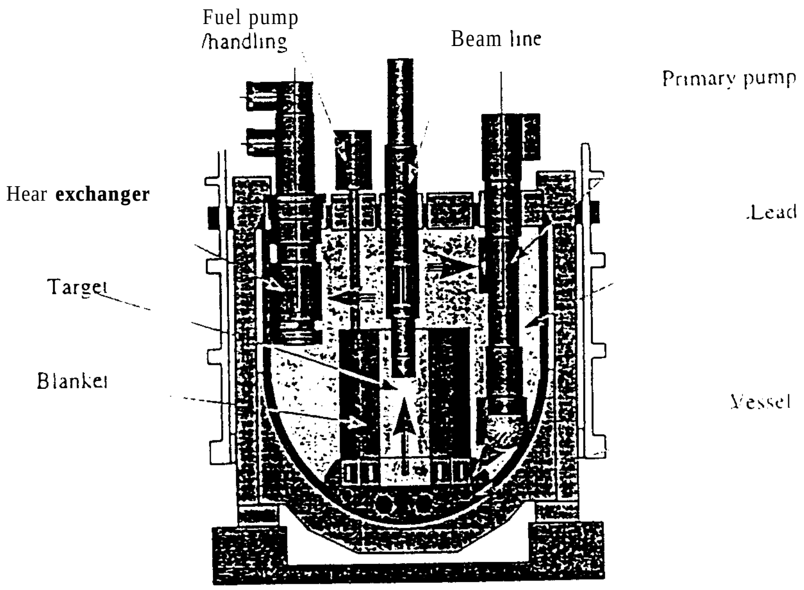


FIG 7 A design concept view of fast. lead-cooled ATW burner

Figure 11: Pyro-metallurgical process

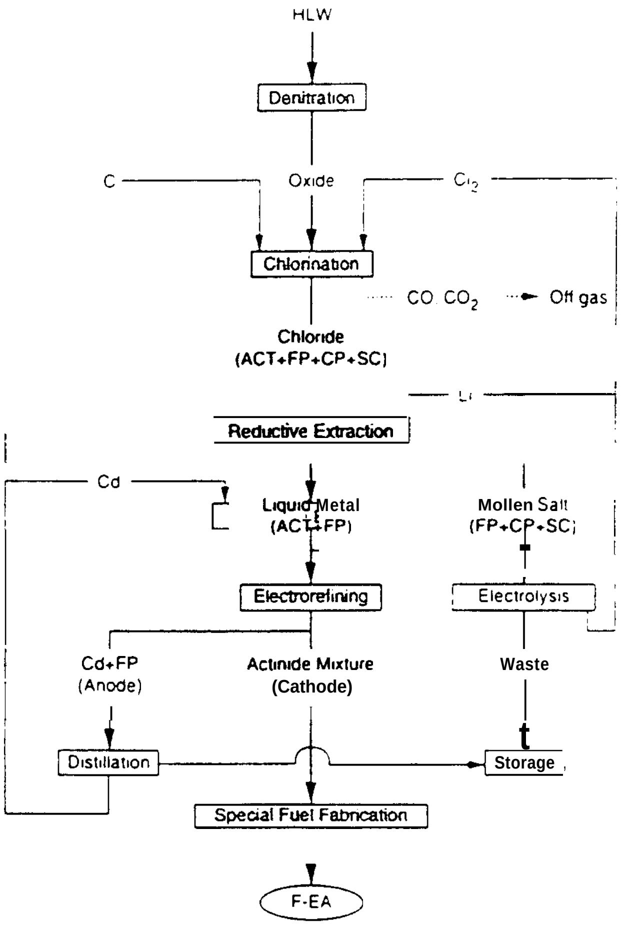
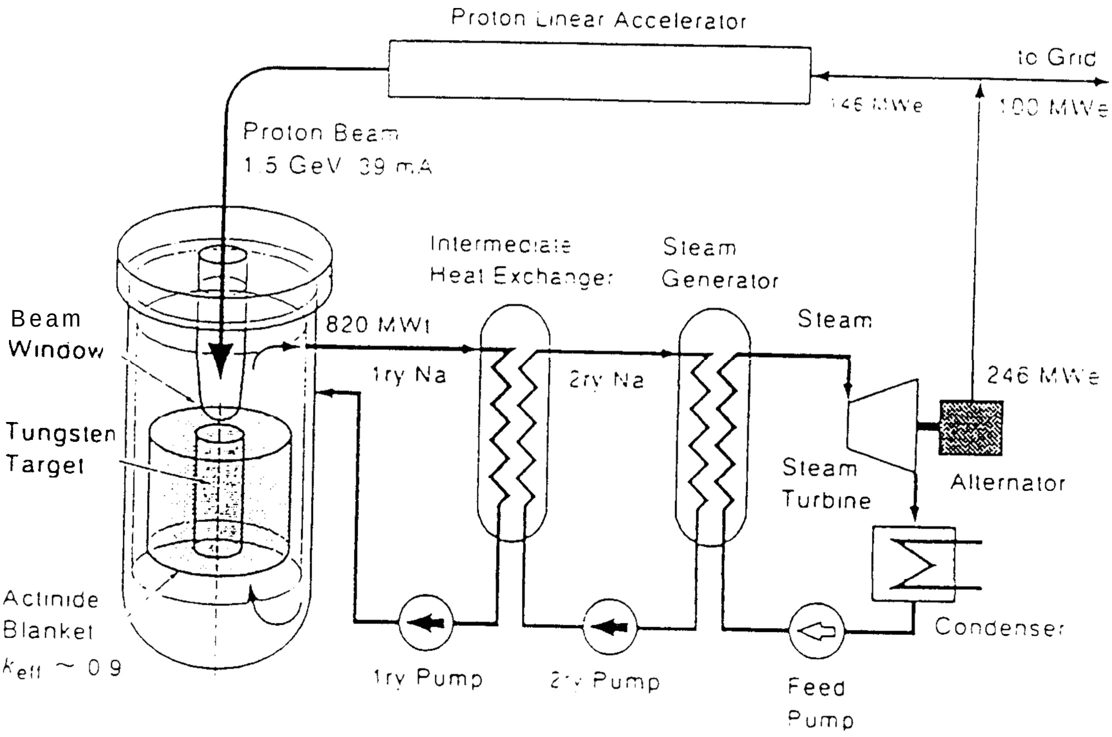


Figure 12: Japonese proposal



Concept of accelerator-driven transmutation system

QUESTIONS ON SOME OF ACCELERATOR DRIVEN SYSTEM (ADS) ISSUES AND IN PARTICULAR THE ENERGY AMPLIFIER (EA)

I - Global questions

I.1 - Accelerators and associated window

- Are proton beam intensities needed for an operational Energy Amplifier **(EA)** (5-50 mA of 800 MeV-1GeV protons) reachable today? If the answer is no, what would be the additional R&D needed.

- What kind of accelerator is more suitable for reliable EA operation: multistage cyclotron or linear accelerator, or both coupled?

- Are the associated window technical problems (interface proton beam/reactor core), solvable, easy to solve or already solved?

1.2 - Molten lead, lead/bismuth

- In your opinion, do molten lead or Pb/Bi present technical difficulties with respect to spallation, cooling and metallurgy/corrosion?

- If yes could you precise?

- Is it a good idea to use the same medium for spallation and heat transfer? Will it be preferable to make use of other heat transfer medium?

1.3 - Burning and transmutation of actinides, transmutation of other fission products

- Is an EA, or more generally an ADS a promising way :
  - to burn or transmute as completely **as** possible actinides (trans-uranium nuclei) ? why ?
  - to transmute fission products in shorter lived or stable nuclei in order to get rid of the nuclear waste reprocessing and stocking? why?

- Why this solution was not proposed and implemented earlier?

- Are the necessary full scale test experiments sufficiently implemented to-day ? if the answer is no, what are the additional tests to launch **and** their time delay?

1.4 - Safety

- Could safety of a « standard » **EA** be significantly lower, equal, higher than the classic reactor's one? why?

- Would safety authorities commission easily, normally or with difficulties this new reactor?

why?

- Compared with a classic reactor what are the new safety key points of EA or ADS which would be considered important by any safety authority

1.5 - The nuclear fuel cycle

- Is the Thorium (^{232}Th) fuel cycle significantly different from the U or Pu cycle? in what terms?
- Is the Thorium cycle be less, equally or more sensible in terms of nuclear «proliferation »?
- Could existing nuclear fuel manufacturing and reprocessing plants be transformed or adapted to thorium fuel manufacturing? if yes how?, if no why?

1.6 - ADS energy amplification potential for energy production

- Is the foreseen energy balance of a «standard» ADS (standard = accelerator delivering several mA of high energy protons, molten lead target and cooling, U235 or Th232 core,) favourable for an electric gnd connection?
- Can a complete ADS system's reliability be compatible with operational electricity grid's conditions?
- Can the ADS be potentially a real technological competitor to the actual PWRs or future European EPR or other designs.

1.7 - Needs for an ADS Demo

- Is an energy amplifier demo needed in Europe? why ? where?
- Is additional R&D needed to demonstrate the complete ADS concept's feasability?
- Is there a need for demonstration on parts of the system before building a full demo? Which one?
- Is there a need for demonstration of coupling of ADS parts before building a full demo? Which ones?
- What would be your criteria for selecting a location for a full demo?
- What should be a realistic financing for such a demo?
- What would be a realistic time scale for all demonstration steps?

1.8 - Economics of the ADS

- Can **EA** potentially be in the near future **an** economical competitor for electricity production to the actual PWRs or to the future **EPR?**

- What could be a realistic EA Kwh's cost ? (all costs included)

- Could the ADS be a smart solution for the best nuclear waste management in the future?

- Is EA, or more generally ADS, a new potential ((zero nuclear waste)) reactor, a physicist's intellectual interesting concept, or an improved solution to reduce significantly the nuclear waste levels?

II - Specific questions related to preceding paragraphs

II.1 - Questions on Accelerators for Accelerator Driven Systems

Pr C. Rubbia has proposed an Energy Amplifier (EA) which is a specific design of an Accelerator Driven Reactor.

Referring to the EA, and more generally to any ADS, designed for energy production and/or nuclear wastes treatment, in your opinion :

1. What are the highest proton beam intensities/energies delivered currently by accelerators, in Europe (CERN, GANIL excepted)?

2. What are the problems encountered in the operation of current high performance (proton beam intensity and energy) accelerators : stability of the proton beam, operation time without any stop, etc.

We have been said that the proton beam intensity and energy needed for an operational Accelerator Driven System (nuclear reactor) should be 5-50 mA and 0.8-1GeV. Let us first concentrate on the accelerator:

3. What kind of accelerator is more suitable for reliable ADS operation: a multi- stage cyclotron or a linear accelerator (Linac), or both coupled ?

4. Are such characteristics reachable to-day, and if not how much time is needed for the design and building of a suitable prototype? How much time in your opinion is needed in total before an operable industrial accelerator adapted to ADS will be available?

5. What is the best energetic yield (energy of the proton beam/energy necessary for running the accelerator) of current accelerators? What could be the energy yield of an accelerator adapted to ADS?

6. Are you aware of any current R&D or demonstration project dedicated to accelerators which may bring useful information for ADS operation ?

7. What new R&D or demonstration projects should be launched for allowing accelerators to fulfil potential requirements for ADS operation ?

Now we consider the coupling of an accelerator with the core of a reactor. An accelerator operates under ultrahigh vacuum and in the reactor core, the proton beam will have to react with a target probably made of Pb or Pb/Bi: the reaction chamber will not be under high vacuum. Two different concepts have been proposed : introduction of the beam into the chamber through windows; introduction without windows.

8. In your opinion, how many mA/cm^2 should go through the window?

9. What are the main foreseeable technical problems linked to windows?

10. Are you aware of current R&D/demonstration projects addressing questions 8 and 9? if yes, can you give us elementary information?

11. What R&D or demonstration projects should be launched on windows associated problems?

General questions:

12. In your opinion, is there in Europe any laboratory which could be adapted to operate an existing accelerator coupled to an experimental nuclear reactor, or vice versa?

13. In a next step would you recommend to build an ADS demo facility in an existing research site or in a new site?

14. Could you mention some names (and addresses) of other European experts we could interview on accelerators operational issues?

II 2 - Lead and Lead/bismuth

We consider successively three points : spallation, cooling and metallurgy/corrosion.

Spallation

1. What is the present status of modelling/experimenting neutron multiplication in lead and lead/bismuth resulting from spallation? Is there a need for further research?

2. Are all residual products well identified and quantified?

3. What could be the quantities of molten Pb or Pb/Bi to consider in the Pb loop? What could be the speed of circulation of this fluid?

4. Are there some specific problems of radioactivity or purification of Pb or Pb/Bi circulating in the loop after spallation? If yes, how often specific operation will be needed?

5. What may happen at the spallation level if for one reason or another Pb or Pb/Bi is no more circulating?

6. What new R&D or demonstration projects should be launched on spallation and Pb, Pb/bi targets?

Cooling

7. What experience has been already made for the circulation of thousands of tons of molten lead or molten lead/bismuth, and what problems have been encountered or are expected?

8. What have been done in terms of primary system modelling? What are the main conclusions?

9. Are you aware of new ideas emerging on mechanically assisted flow of Pb or Pb/Bi?

10. What are the respective advantages/disadvantages/risks of convection flow and of mechanically assisted flow of Pb or Pb/Bi?

11. What may happen on the Pb or Pb/Bi flow if the proton beam is not stable or is interrupted for a while?

12. How do you appreciate potential risk due to Pb-Pb/Bi toxicity (radioactive and chemical)?

13. What new R&D or demonstration projects should be launched on reactor cooling by molten Pb and Pb/bi?

Metallurgy/corrosion

14. What is known about metallurgy/corrosion by lead or lead/Bi? How severe can be the problems encountered? Who is most active in this domain

15. Are there some specific corrosion problems in the spallation zone?

16. What new **R&D** or demonstration projects should be launched on pipes metallurgy/corrosion by lead and lead/bismuth?

Conclusion

17. What are in **your** opinion priority actions to be launched in this context?.

18. Could you mention some names (and address) of other European experts we could interview on Pb and Pb/Bi issues?

11.3 - Burning and transmutation of actinides, transmutation of other fission products

1. Are the neutron transmutation cross section for actinides and fission products to be considered with a nuclear fuel based on Thorium and Uranium known with sufficient precision in the neutron energy range to be considered? If no, what R&D project should be launched, when and for how long?

2. What will be the relative importance of burning and of transmutation for minor actinides in an ADS?

3. How long will it take for burning/transmuting (completely or the best possible) actinides produced in the reactor, and what could be the residual content of the nuclear waste?

4. What are the (minor) actinides and long lifetime fission products which can be efficiently processed by the ADS proposed by Pr C. Rubbia?

5. What could be the quantity of external minor actinides and long lifetime fission products eliminated by a 1000 MW ADS reactor? How does it vary with reactor power?

6. What problems can be expected?

7. What would be the ultimate waste, and how dangerous will it be? How to deal with this ultimate waste?

8. What will be the ratio between nuclear plants and ADS ?

9. *Are* there other specific reactors or machines under consideration for elimination of specific nuclear wastes?

10. If yes, which ones, and how do they compare in your opinion to ADS?

11. Does ADS represents a promising tool for elimination of nuclear wastes?

12. What new R&D or demonstration projects should be launched on burning and transmutation of actinides, transmutation of other fission products?

13. Could you mention some names (and address) of other European experts we could interview on such issues?

11.4 - Safetv

1. Due to any accidental factor (change of geometry of the core due to its melting, etc:.), is there any **risk** for an ADS to become sur-critic? If yes, which factors?

2. Compared to PWR and fast breeder reactors, what parts of an ADS would be less, equally or more sensitive in term of safety?

3. Will any intervention in an ADS be less, equally or more difficult than in a classical PWR?

4. Would safety authorities commission easily, normally or with specific difficulties this new type of reactor? Why?

5. Compared to a classical PWR reactor, what are the new safety key points which would be considered important by any safety authority?

6. Do you consider that the public acceptance of an ADS would be lower, equivalent or higher than for a classical PWR reactor?

7. What new R&D or demonstration projects should be launched on safety issues?

8. Globally, how would you compare the safety of an ADS to the safety of a classical reactor (PWR)?

9. Could you mention some names (and address) of other European experts we could interview on such issues?

11.5 - The nuclear fuel cycle

1. Is Thorium (^{232}Th) fuel cycle technology significantly different from the U or Pu cycle? In what terms?

2. How could be incorporated existing nuclear wastes in the ADS nuclear fuel? Are there specific problems to be solved?

3. What are the advantages of Thorium based fuel compared to existing fuels (MOX...)?

4. Would these advantages/disadvantages be maintained for a mixed Th/U (oxide) fuel?

5. Could existing nuclear fuel manufacturing and reprocessing plants be transformed or adapted to thorium fuel manufacturing and reprocessing? If yes, how and how long could it take? if no why?

6. How long will it take to develop a Th fuel manufacturing facility? A reprocessing facility?

7. Is Th fuel cycle less, equally or more sensitive in terms of "proliferation"?

8. If an ADS demo is to be developed, what type of fuel would you recommend to concentrate on at first? What could be the next steps?

9. What new R&D or demonstration projects should be launched on new fuel cycles?

10. Could you mention some names (and address) of other European experts we could interview on such issues?

11.6 - Design and potential of ADS

1. How many different types of ADS have been proposed for industrial purpose (energy production, nuclear waste treatment, Pu elimination)? Could you characterise them in a simple way?

2. What could be a realistic energy amplification between the energy of the protons beam and of the electricity produced (energy needed for the accelerator excluded)?

3. How does it vary with the quantity and nature of extra wastes in the nuclear fuel? Can it be modelled? Are new R&D projects needed?

4. Would the design of an ADS devoted to energy production be different from an ADS dedicated mainly to nuclear waste treatment?

5. Taking into account the need for energy of the accelerator, what could be the amplification coefficient between the electricity input and the electricity/heat output?

6. How sensitive would be an ADS to fluctuations in protons beam intensity and to accidental switch offs?

7. How difficult would be the monitoring of an ADS?

8. Fuel processing/reprocessing will need energy; globally, all steps of the chain included, do you think that the total energy balance would be positive?

9. In your opinion, should ADS be devoted mainly to electricity/heat production, to waste treatment or to both of them? Why?

10. Up to now, we have have been told that two different sketches of design have been proposed by Ansaldo and Framatome. Do you know some others in Europe?

11. *Are* there any specific needs for new R&D projects on the design side of an ADS reactor?

12. What partial demos are needed before building a full demo?

13. What could be realistically the time needed for each of the following steps:

    1. Additional R&D
    2. Demonstrations of parts of an ADS
    3. Full demonstration of an ADS
    4. Building and testing a full scale industrial ADS
    5. Operating of an industrial ADS

14. Can you place the previous steps on a time scale from 2000 to 2030 (for example)?

15. Could you mention some names (and address) of other European experts we could interview on such issues?

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ACRONYMS

ADS : Accelerator Driven Systems
ADTT : Acceleration Driven Transmutation Technology
CRIEPI: Central Research Institute of Electric Power Industry (Japan)
EA : Energy Amplifier
EPR (or EPWR): European Pressurised(Water) Reactor
FP : Fission Products
F(B)R : Fast (Breeder) Reactor
GEDEON: Gestion des déchets par les options nonvelles
ITU: Joint Research Centre / Institute for Trans-uranium elements
JAERI: Japan Atomic Energy Research Institute
JRC : European Joint Research Centre
LAMPF: ex Los Alamos Meson Physics Facility (now LANSCE
LINAC: Linear Accelerator
LLFP : Long Lived Fission Products
LWR: Light Water Reactor
MA : Minor Actinides (Transuranians elements)
MSRE : Molten Salt Reactor Experiment
MOX : Mixed Uranium – Plutonium Oxide fuel
OMEGA: Options Making Extra Gains from Actinides and fission products
P&T : Partitioning and Transmutation
PUREX: Plutonium Extraction process
PWR: Pressurised Water Reactor
RF : Radio Frequency
TU : Trans-uranium nuclei
STC : EURATOM Scientific and Technical Committee
THOREX : Thorium Extraction process

Exemples of Transmutation and Activation elements obtained by neutron capture

(ref CERN 97-04 C.RUBBIA et al.)

- **Transmutation:**

^{99}**Tc** (Technetium) and ^{129}**I** (Iodine) are typical long lived fission products:

$$^{99}Tc + n \dashrightarrow {}^{100}Tc \xrightarrow{\beta-} {}^{100}Ru$$

half-lives: (2.1 10^5 years) (16 s) **stable**

$$^{129}I + n \dashrightarrow {}^{130}I \xrightarrow{\beta-} {}^{130}Xe$$

half-lives: (1.57 10^7 years) (**12.4**h) **stable**

- **Activation** : **Mo** : Molybdenum, **Te** : Tellurium, **Xe** : Xenon, **Ru** : Ruthenium

$^{127}I + n$ --------->1'S~ $\xrightarrow{\beta-}$ $^{128}Xe^*$ ......> $^{128}Xe + \gamma$ (443keV)

half-lives: (25 min) stable

or

$$^{128}I \overset{\beta+}{>} \quad {}^{28}Te$$

(25 min) stable

$$^{98}Mo + n \dashrightarrow {}^{99}Mo \xrightarrow{\beta-} {}^{99}Tc \xrightarrow{\beta-} {}^{99}Ru^* \dashrightarrow {}^{99}Ru + \gamma$$

half-lives: (66 h) (2.1 10^5 years) stable

Some typical long-lived Fission products and Actinides elements produced in a fission reactor

	FISSION products		**ACTINIDES**	
element	radioactivity type, daughter element	half-life	radioactivity type, daughter element	half-life
^{90}Sr	β- , ^{90}Y (Ytrium)	28.8 years		
^{99}Tc	β-, ^{99}Ru(thenium)	2.1 10^5 years		
^{90}Zr	β-, ^{90}Nb Niobium	1.5 10^6 years		
^{129}I	β-, ^{129}Xe Xenon	1.6 10^7 years		
^{137}Cs	ß-, ^{137}Ba Baryum	30.2 years		
^{151}Sm	β-, ^{151}Eu (ropium)	90 years		
^{238}U			α,γ, ^{234}Th(orium)	4.5 10^9 years
^{236}U			α,γ, ^{232}Th	2.3 10^7 years
^{237}Np			α,γ, ^{233}Pa (Protactinium)	2.1 10^6 years
^{239}Pu			α, y, ^{235}U (Uranium)	2.4 10^4 years
^{243}Am			α, γ, ^{239}Np (Neptunium)	7.4 10^3 years
^{244}Cu			α, γ, ^{240}Pu (Plutonium)	18. 1 years

STOA PROGRAMME
European Parliament
Directorate-General for Research
Directorate A
SCH 4/61

L-2929 Luxembourg

Tel: +352 4300 22511
Fax: +352 4300 22418
rholdsworth@europarl.eu.int

LEO 6 D 46
Rue Wiertz 60
B-1047 Bruxelles

Tel: +32 2 284 3962
Fax: +32 2 284 9059
msosa@europarl.eu.int