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ALTERNATIVE CONCEPT FOR A FAST ENERGY AMPLIFIER ACCELERATOR DRIVEN REACTOR

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ABSTRACT

Recently Rubbia et alii introduced a conceptual design of a Fast Energy Amplifier (FEA) as an advanced innovative reactor, which, besides being breeder and waste burner, generates energy. The FEA utilizes a neutron spallation source induced by a proton beam of a three-stage cyclotron accelerator to induce fission in a subcritical core imbibed in a molten lead coolant. This paper introduces some qualitative changes in the Rubbia's concept. The novel element of our concept is the introduction of more than one point of spallation (at least two), in order to make the neutron distribution more uniform and reduce the requirements (current, and energy) of the accelerator. Also, the subcritical core that in Rubbia's concept is a hexagonal array of fuel pins imbibed in molten lead is replaced in our concept by a solid lead calandria with the fuel elements in channels cooled by Helium. This concept will allow fuel refueling and shuffling on line, which we believe will be more efficient in waste incineration, since a fuel element can circulate in different reactor positions before discharge.

Key Words: Energy Amplifier, Spallation Source, Thorium, Accelerator Driven, Waste Transmutation, and Helium Coolant.

RESUMO

Recentemente, Rubbia e colaboradores introduziram o projeto conceptual de um Amplificador de Energia Rápido (FEA) como um reator avançado e inovativo, o qual, além de regenerador e incinerador de rejeitos, gera energia. O FEA utiliza uma fonte de nêutrons de "spallation" induzida por um feixe de prótons de um acelerador em três estágios tipo ciclotron para induzir fissão em um núcleo subcrítico imerso em um refrigerante de chumbo líquido. Este trabalho introduz algumas modificações qualitativas na concepção de Rubbia e colaboradores. O elemento inovador da nossa concepção é a introdução de mais de um ponto de "spallation" (pelo menos dois), a fim de se obter uma distribuição neutrônica mais uniforme e reduzir os requisitos do acelerador (corrente e energia). Além disso, o núcleo subcrítico, que na concepção de Rubbia e colaboradores é um arranjo hexagonal de varetas combustíveis imersas em chumbo, é substituído em nossa concepção por uma calandria cilíndrica de chumbo sólido contendo elementos combustíveis em canais refrigerados por Hélio. Esta concepção permitirá o recarregamento e o remanejamento do combustível "on line", o qual acreditamos será mais eficiente na incineração de rejeitos, desde que um elemento combustível poderá circular em diferentes posições do reator antes da descarga.

Descritores: Amplificador de Energia, Fontes de "spallation", Tório, Aceleradores, Transmutação de Rejeitos e Refrigerante Hélio.

INTRODUCTION

The present time commercial thermal reactors (**LWR** and **CANDU**) operate in a once through fuel cycle and are producing a large stockpile of radioactive waste, mainly long lived transuranics (**TRU**) elements and fission fragments (**FF**) (**Table 1**), requiring the construction of final underground geological storage. The buildup of radioactive stock piles, besides the concern related to waste disposal, also brings the issue of proliferation, mainly due plutonium isotopes. To overcome the need of final storage and to burn plutonium, incineration of TRU elements are being considered by using ultra fast neutrons from spallation source[1]. Incineration is possible taking in account that the fission cross section for most TRU elements is higher than capture cross section at these energies, transmuting long lived TRU elements in medium or short lived waste. Transmutation of long lived FF, such as technetium (^{99}Tc) and Iodine (^{129}I), into stable, harmless isotopes, are also being considered[2].

Table 1 - Projected amount of radioactive waste from 400 GWe Nuclear Reactors in the world (2010)[3].

Total Spent Fuel	300,000 tons
Plutonium Isotopes	3,000 tons
TRU (Np, Am, Cf , etc.)	260 tons
Long Lived FF(^{99}Tc,^{135}Cs,^{129}I)	400 tons

Besides incineration of TRU elements and FF, a coupled system consisting of spallation source and a subcritical array of fuels may have a positive energy gain (net energy/energy to operate the accelerator). This fact has motivated innovative concepts of accelerator driven reactors in which thorium is being considered as fuel, such the one proposed by C. D. Bowman et alii[4] from Los Alamos. In this concept a proton accelerator (1.6 GeV, 25-250 mA) induces spallation in molten lead (50 n/p). This external source is surrounded by heavy water to moderate high energetic spallation neutrons, producing high thermal fluxes (10^{16} n/cm^2.s). The fissionable material (Th/Pu; Th/U) and TRU elements circulate in a closed loop with reprocessing on line, as in the Molten Salten Breeder Reactor. This concept is a Thermal Energy Amplifier. Later, Rubbia et alii[5] proposed a Fast Energy Amplifier (FEA) using a modular three stage cyclotron of 1 GeV, 12.5 mA, to induce spallation with protons in molten metal lead. The fuel (Th, Pu, U, TRU in oxide or in ternary alloy of Zr) in a hexagonal array of fuel pins forms the subcritical core surrounding the spallation source, and imbibed in molten lead that circulates in natural convection. The conceptual design of Rubbia et alli was proposed with a nominal power of 1500 MWth (670 MWe), a energy gain of 120, a high burnup (150 GWD/ t), and one reprocessing each 5 years, as illustrated in Figure 1.

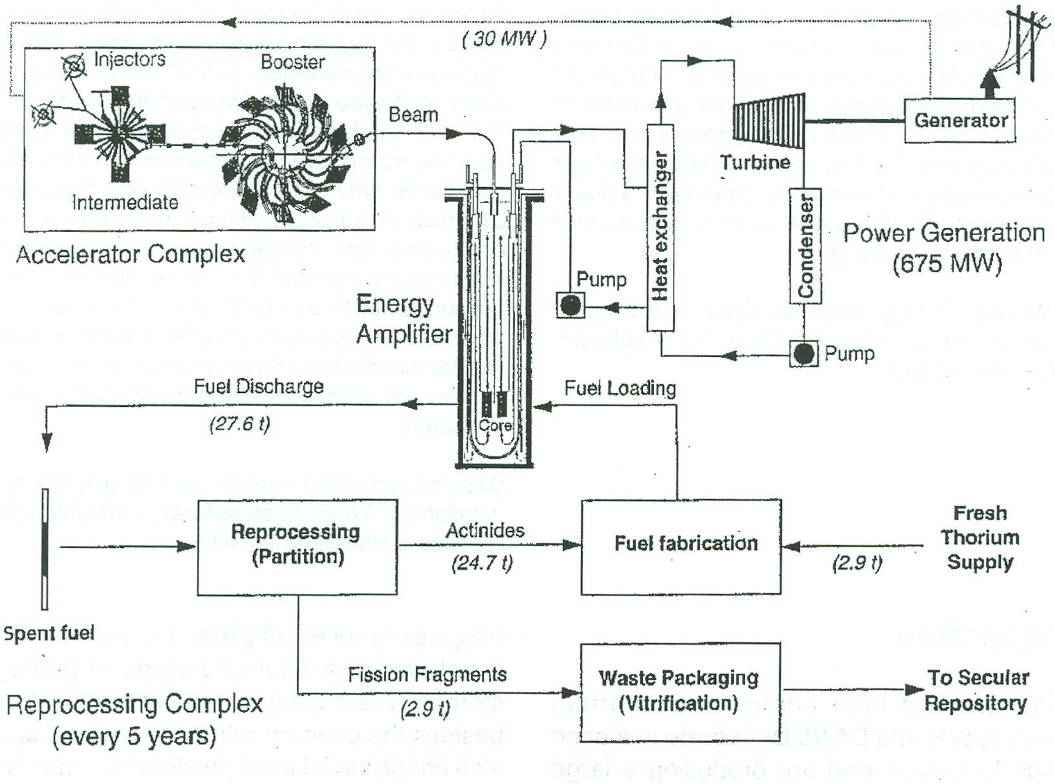

Figure 1: Rubbia's Fast Energy Amplifier[5].

In this paper an alternative concept to Rubbia's FEA is presented. The main modification is the introduction of more than one point of spallation (at least two), in order to make the neutron distribution more uniform and reduce the requirement (current, and energy) of the accelerator. Also, instead of molten lead as coolant, Helium gas is used allowing the utilization of Brayton cycle gas turbine with high efficiency (47%). The Helium coolant will circulate in channels of a cylindrical calandria of solid lead containing fuel elements in the same concept as the Canadian reactor CANDU. This concept will allow fuel refueling and shuffling on line that we believe will be more efficient in waste incineration, since a fuel element can circulate in different reactor positions before discharge. Although the calculations to demonstrate the feasibility of the FEA alternative concept are underway, and since the basic physics is almost the same as Rubbia's FEA, we do not see any reasons for the concept do not work out in the same way, and even with advantages as it will shown in this paper.

CONCEPTUAL BASES

The basic idea of the FEA is bombarding a subcritical mixture of fuel (Th, U, Pu) and waste (TRU, FF) with fast neutrons coming from a spallation source.

Spallation is a well-known nuclear reaction in which energetic particles (e.g. protons) interact with the atomic nucleus. Given the energy of the incident particles they interact in a first stage with the individual nucleons instead of the formation of a compound nucleus as in low energy nuclear reaction. The initial collision leads to an ejection of nucleons and pions, which still have enough energy to a cascade reaction (intranuclear cascades). After this point, the nucleus is left in an excited state and goes to a ground state by evaporation of nucleons (mostly neutrons). Fragmentation (fission) of the nucleus may occur, as well as (n,xn) reaction in secondary stages. In short, the spallation reaction produces high energy secondary particles (neutrons, protons, mesons, gamma), which, besides deposing a large amount of energy in the target and generating spallation product, when escaping from the target, mainly neutrons, are the external source in the subcritical media. The most common used targets are Pb and Bi.

The theory of spallation had already been developed and incorporated in codes, such as FLUKA[5] and LAHET[6]. In the FEA concept the protons have 1GeV and produces an external source of the order of 30 n/p. Since in our modified concept one of the aims is to reduce the requirements of the accelerator (energy and current), we have run LAHET code for an incident proton beam with energies in the range of 250-350 MeV in a bare cylindrical Pb target of H = 55 cm (this height can be considered as infinite). The net leakage per proton versus the cylinder diameter is illustrated in Figure 2. From these data we notice that the net leakage saturates for diameters greater than 60 cm, being this value the order of the magnitude of the spallation region.

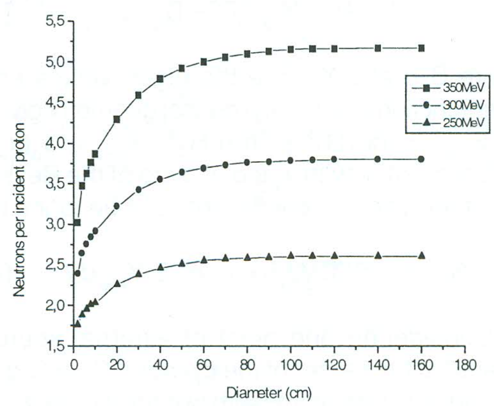

Figure 2. Total leakage production.

In order to analyze the possibility of reducing the requirements in the external source, let us make a simplified analysis of the system, considering a homogeneous subcritical cylinder driven by one or two external source, as illustrated in Figure 3.

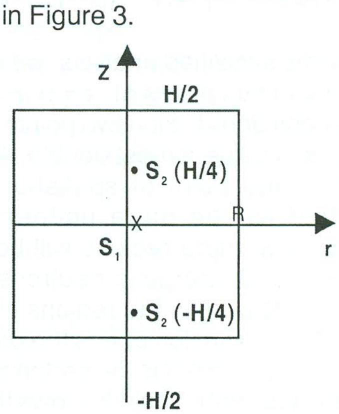

Figure 3 : Schematic subcritical homogeneous media driven by external source (S_1; S_2).

Assuming that the fast system can be described by one group diffusion theory, i.e.

$$D\nabla^2 f - S_a f = -S \qquad (1)$$

where, S = k¥S_af + S_e, with S_e the external spallation neutron source, and the others symbols with their usual meaning. For a fast system k¥ = h = nS_f/S_a and Equation(1) can be written as

$$\tilde{N}^2 f + B^2 f = -S_e/D \qquad (2)$$

with B^2 = (k¥ - 1)/L^2; L^2 = D/Sa. The general solution of Equation (2) can be easily obtained as

$$f = åS_{n,m}Y_{n,m}/(B^2 - B_{n,m}{}^2) \qquad (3)$$

where $B_{n,m}$ and $Y_{n,m}$ are the eigen values and eigenfunctions, and in cylindrical geometry given by $B_{n,m}{}^2 = (x_n/R)^2 + (mp/H)^2$, $Y_{n,m} = J_0(x_n r/R)\cos(mpz/H)$, with x_n the n^{th} zero of the Bessel Function. The $S_{n,m}$ coefficients can be found by

$$S_{n,m} = -[2/(DVJ_1{}^2(x_n))]\ ò_V\ S_e Y_{n,m}\,dV \qquad (4)$$

Considering one point of external source located at the center of the cylinder ($S_{e1} = S_1$d(r) d(z)/pr), and comparing with two point of external source located each one at ± H/4{$S_E = S_2$d(r)[d(z-H/4) + d(z+H/4)]/pr}, then the flux distribution is given by

$$f^1 = (2S_1/DV)åY_{n,m}/(B^2 - B_{n,m}{}^2)J_1{}^2(x_n) \qquad (5)$$

and

$$f^2 = (4S_2/DV)å\cos(mp/4)Y_{n,m}/(B^2 - B_{n,m}{}^2)J_1{}^2(x_n) \qquad (6)$$

From this simplified analysis, we notice that the maximum flux peaks at r = 0, z = 0, and in the case considered using two points compared with one, this value almost double. Also, using more than one point of spallation, the flux distribution will be more uniform, with an advantage that more regions will be closer of high fluxes and energetic neutrons, favoring TRU elements burn in the regions close to the source. This conclusion opens the possibility to reduce the requirement in the proton energy and its intensity (current). Table 2 shows the neutron yield for spallation process induced by high-energy protons calculated by LAHET code and also compared with those reported by Rubbia (FLUKA code). Therefore even using low energy protons, if more than one point of spallation is used, a reduced source intensity may be used. Of course this result was based in a very simplified analysis. However, it indicates that accelerators in the range of 300-500 MeV and currents of few mA may be used with at least two points of spallation, as proposed in the modified concept.

Table 2. Neutron yield for spallation process induced by high-energy protons calculated by LAHET and FLUKA.

Proton Energy (MeV)	Multiplicity n_0, (n/p) FLUKA	LCS	Integrated Yield S_0, (n/sec.mA) FLUKA	LCS
100	0,399	0,321	2,49E+15	2,00E+15
150	0,898	0,835	5,61E+15	5,21E+15
200	1,788	1,627	1,12E+16	1,02E+16
250	2,763	2,664	1,73E+16	1,66E+16
300	4,156	3,883	2,60E+16	2,42E+16
350	5,291	5,272	3,31E+16	3,29E+16
400	6,939	6,784	4,34E+16	4,23E+16
1000	----	28,76	----	1,79E+17

Also it is interesting to make a simplified analysis of the neutronics of the FEA. First of all, we notice that whereas $B^2_{n,m}$ is related to geometry, B^2 is related to materials. Also, the criticality condition can be defined as $S_{n,m}$®0, and therefore one of the $B^2 - B^2_{n,m}$®0. The smallest value of $B^2_{n,m}$ (m=1, n=0) gives the classical critical condition ($B^2 = B^2_{0,1}$, or material buckling equal to geometrical buckling). Also it can be expressed as k¥/(1+ $B_{0,0}{}^2L^2$) = 1. The others eigenvalues can be expressed as the mode multiplication factor, i.e., $k_{n,m}$ = k¥ - $B_{n,m}{}^2L^2$, and represents that the FEA will excite a large number of different modes, each with a different criticality coefficient, $k_{n,m}$. The flux distribution can be calculated by Equation 3, for a given source distribution, and as shown by Rubbia it has an approximately exponentially rather than cosine shape.

Finally it is also interesting analyze a ^{232}Th/^{233}U pure cycle. In this cycle the equilibrium condition is given by

$$N_{232}s^{232}g = N_{233}(s^{233}g + s^{233}{}_f), \qquad (7)$$

or

$$e = N_{233}/N_{232} = s^{232}g/(s^{233}g + s^{233}_{f}), \quad (8)$$

and using data from Table 3, e = 0.11. Also, the multiplication factor of the subcritical array can be written by

$$k_{eff}=\{[ns^{233}_{f}e+ns^{232}_{f}(1-e)]/[s^{233}_{a}e+(1-e)s^{232}_{a}]\}F \quad (9)$$

with F being the sum of fractional losses (absorbed in structures, FF poisons, leakage). Then using the data from Table 3 and assuming F = 0.8, k_{eff} = 0.93. This value can be assumed as the working k_{eff} in the same way as in the CANDU. The similar analysis could be made for U/Pu cycle.

Table 3: Fast Cross Section for ^{233}U, ^{232}Th[7].

Isotope	σ_γ barns	σ_f barns	σ_a barns	ν
Th-232	0.34	0.0075	0.35	2.30
U-233	0.26	2.74	3.00	2.52

Also in order to analyze the possibility of incineration of TRU elements, we notice from reference 2, that the fission probability of TRU elements is large for all of them, mainly because of the hard spectrum, and, as consequence, incineration becomes an efficient process.
Thus from all the simplified analysis presented, a FEA can be designed to be breeder and waste incinerator.

THE MODIFIED FEA CONCEPT

Rubbia's concept of FEA was well described in several papers, which demonstrated its physical feasibility. Also the feasibility of using the FEA to eliminate Pu, utilization of different fuel cycles (U/Th/Pu), incineration as an alternative way to geological storage, and economy of the FEA had been studied. Even so we believe that some improvements in the Rubbia's concept can be made. The main points which we wish to consider in our Modified Energy Amplifier (MEA) concept, is a tentative to introduce more than one point of spallation, in order to reduce the requirements in the accelerator, and mainly through a more uniform fast neutrons distribution (obtained by using more than one point of spallation and increasing the amount of regions more close to the fast neutrons) improve the possibility of incineration of TRU elements, as well long lived FF. The other change in our modified concept is the substitution of the coolant, which in Rubbia's concept is molten lead in natural circulation, by Helium. The reason for this change is that there is few technological experience with molten lead coolant whereas Helium coolant has been used successfully in the High Temperature Reactor, as well proposed in fast system like the Gas Cooled Fast Breeder Reactor. Besides using Helium as coolant will allow the use of direct thermodynamic cycle (Brayton) with gas turbines, which are more efficient than the thermodynamic cycle proposed in the FEA. Finally, the fuel cycle proposed by Rubbia assumes that the fuel stays in a fixed position during 5 years, with a high burnup (150 MWD/t), and a reprocessing in batch each five years. In the modified concept we use the same idea of the CANDU reactor of fuel channels containing fuel bundles, which will be shuffled or refueled on line.

Then the MEA proposed consist of a horizontal cylinder (CALANDRIA) of lead, with 5 regions, as shown in Figure 4.

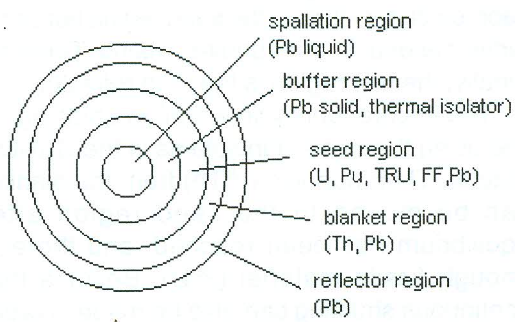

Figure 4. Schematic regions for the MEA.

The central region is the spallation region, consisting of circulating molten lead. In this region the accelerator proton beam induces the spallation reaction in 1 or 2 symmetric points (in a variant of 4 spallation points these regions will be located at the fuel region). The second region is a buffer consisting of solid lead cooled by Helium and isolated from the spallation region by a thermal isolator, which has the function of softening the energetic spallation neutrons. The third region is the seed region consisting of solid lead with channels where the fuel bundles are located, and is the region where the fission occurs as well as the incineration of TRU elements. The Helium flows through the channels, which are thermal isolated from the lead, allowing the heat generated be transferred mostly to the coolant, although due the high temperatures heat will be transferred by radiation. Also to keep the lead solid, coolant channels will be necessary. Figure 5 illustrates a typical cell of the seed region.

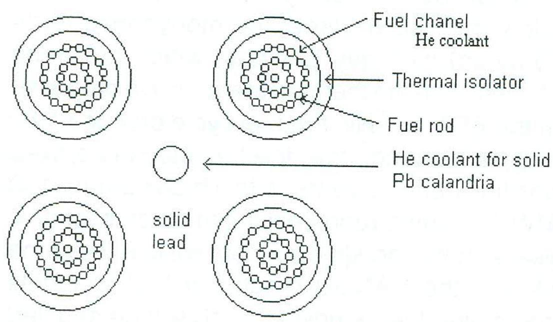

Figure 5. Schematic cell of a seed region.

The fourth region is the blanket that is geometrically similar to the seed region but using fertile material in the bundles, mainly Thorium. Finally, the last region is the lead reflector.

The in-core fuel cycle will allow shuffling on line using the same principle as in the CANDU reactor. Then bundles (^{232}Th) from the blanket can be moved to the seed region after equilibrium has been reached, and there is enough fissile material (^{233}U). Besides that continuous shuffling can also be made in order to optimize the fuel utilization and waste incineration. A continuous refueling can be made extracting burned bundles and reprocessing it on line to extract TRU, Pu, and fissile material (^{233}U in Th/U cycle) which are sent to a fuel fabrication and returns to the core. A feed of fresh Thorium, and waste (TRU/FF) from existing thermal reactors will allow to use the natural Th resource, as well as to couple the MEA with the thermal reactors and open the possibility to avoid secular final storage. Figure 6 illustrates the possible fuel cycle for the MEA.

Finally it is of interest to discuss on the accelerator and the thermodynamic cycle. In the accelerator side the Rubbia's FEA proposed to use 2 injectors, an intermediate, and a booster cyclotrons, or a CERN linear 1 GeV accelerator. We will try to analyze the possibility to reduce the requirement of the accelerator complex,

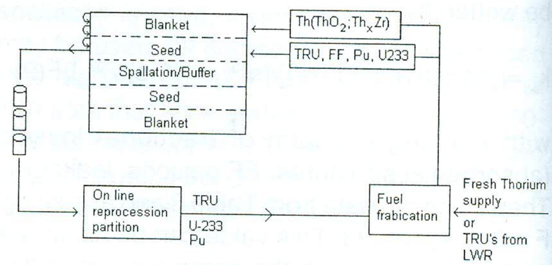

Fig. 6: Fuel Cycle for the MEA.

or eliminating the booster, or using the Belgium developments in the Myrrha project[8], in which there are technical possibilities to upgrade their reference design to 250-350 MeV, 5-10 mA, as well as multiple exit ports. From the thermodynamics point of view, our modified concept will analyze to lower the power of the FEA (1500 MWth) to 600 MWth, and use the same concept of the modular Helium HTR. We expect that with these modifications an accelerator complex can share as source driven at least 4 modular units. Besides, the utilization of Helium as coolant will provide the use of a Brayton cycle Helium gas turbine, which provides electricity generation capacity of about 47% of efficiency, a level that can be obtained by no other nuclear reactor.

A schematic flow diagram of system is illustrated in Figure 7.

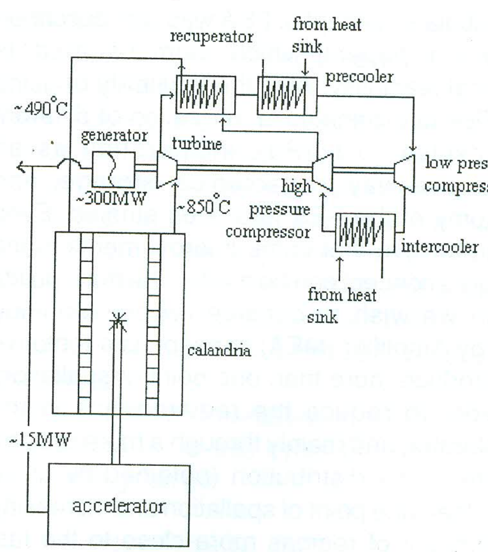

Figure 7. Schematic flow diagram of a Brayton Cycle for the MEA.

CONCLUSION

Although the calculations to demonstrate the feasibility of the FEA alternative concept are underway and not yet finished, these ideas do not violate the basic physics of the FEA, with evident advantages in the fuel cycle (on line refueling); reduced requirements in the accelerator complex, which is more realistic and economical in today accelerator technology, and finally the utilization of Helium as coolant. Compared with molten lead it is more closed to the proved technology given the know-how of gas cooled reactors and more efficient from the thermodynamic point of view, allowing simplification and utilization in other process, besides electricity generation, as hydrogen generation.

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Assuming that the fast system can be described by one group diffusion theory, i.e.

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$$\nabla^2\phi + B^2\phi = -S_e/D \qquad (2)$$

with $B^2 = (k\infty - 1)/L^2$; $L^2 = D/\Sigma a$. The general solution of Equation (2) can be easily obtained as

$$\phi = \Sigma S_{n,m}\Psi_{n,m}/(B^2 - B_{n,m}{}^2) \qquad (3)$$

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or

$$\varepsilon = N_{233}/N_{232} = \sigma^{232}{}_\gamma/(\sigma^{233}{}_\gamma + \sigma^{233}{}_f),$$

and using data from Table 3, $\varepsilon = 0.11$. the multiplication factor of the subcritical can be written by

$$k_{eff} = \{[\nu\sigma^{233}{}_f\varepsilon + \nu\sigma^{232}{}_f(1-\varepsilon)]/[\sigma^{233}{}_a\varepsilon + (1-\varepsilon)\sigma^{232}{}_a]\}$$

with F being the sum of fractional lo (absorbed in structures, FF poisons, leak Then using the data from Table 3 assuming $F = 0.8$, $k_{eff} = 0.93$. This value be assumed as the working k_{eff} in the s way as in the CANDU. The similar ana could be made for U/Pu cycle.

Table 3: Fast Cross Section for ^{233}U, ^{232}Th

Isotope	σ_γ barns	σ_f barns	σ_a barns	ν
Th-232	0.34	0.0075	0.35	2.30
U-233	0.26	2.74	3.00	2.52

Also in order to analyze the possi of incineration of TRU elements, we n from reference 2, that the fission probabil TRU elements is large for all of them, m because of the hard spectrum, and consequence, incineration becomes efficient process.

Thus from all the simplified ana presented, a FEA can be designed t breeder and waste incinerator.

THE MODIFIED FEA CONCEPT

Rubbia's concept of FEA was described in several papers, demonstrated its physical feasibility. Als feasibility of using the FEA to eliminat utilization of different fuel cycles (U/T incineration as an alternative wa geological storage, and economy of the had been studied. Even so we believe some improvements in the Rubbia's co can be made. The main points which we to consider in our Modified Energy Am (MEA) concept, is a tentative to intr more than one point of spallation, in on reduce the requirements in the accele and mainly through a more uniform neutrons distribution (obtained by using than one point of spallation and increasi amount of regions more close to th neutrons) improve the possibility incineration of TRU elements, as well

$$\varepsilon = N_{233}/N_{232} = \sigma^{232}_{\gamma}/(\sigma^{233}_{\gamma} + \sigma^{233}_{f}). \quad (8)$$

and using data from Table 3, $\varepsilon = 0.11$. Also, the multiplication factor of the subcritical array can be written by

$$k_{eff}=\{[\nu\sigma^{233}_{f}\varepsilon+\nu\sigma^{232}_{f}(1-\varepsilon)]/[\sigma^{233}_{a}\varepsilon+(1-\varepsilon)\sigma^{232}_{a}]\}F \quad (9)$$

with F being the sum of fractional losses (absorbed in structures, FF poisons, leakage). Then using the data from Table 3 and assuming $F = 0.8$, $k_{eff} = 0.93$. This value can be assumed as the working k_{eff} in the same way as in the CANDU. The similar analysis could be made for U/Pu cycle.

Table 3: Fast Cross Section for ^{233}U, ^{232}Th[7].

Isotope	σ_{γ} barns	σ_{f} barns	σ_{a} barns	ν
Th-232	0.34	0.0075	0.35	2.30
U-233	0.26	2.74	3.00	2.52

Also in order to analyze the possibility of incineration of TRU elements, we notice from reference 2, that the fission probability of TRU elements is large for all of them, mainly because of the hard spectrum, and, as consequence, incineration becomes an efficient process.

Thus from all the simplified analysis presented, a FEA can be designed to be breeder and waste incinerator.

THE MODIFIED FEA CONCEPT

Rubbia's concept of FEA was well described in several papers, which demonstrated its physical feasibility. Also the feasibility of using the FEA to eliminate Pu, utilization of different fuel cycles (U/Th/Pu), incineration as an alternative way to geological storage, and economy of the FEA had been studied. Even so we believe that some improvements in the Rubbia's concept can be made. The main points which we wish to consider in our Modified Energy Amplifier (MEA) concept, is a tentative to introduce more than one point of spallation, in order to reduce the requirements in the accelerator, and mainly through a more uniform fast neutrons distribution (obtained by using more than one point of spallation and increasing the amount of regions more close to the fast neutrons) improve the possibility of incineration of TRU elements, as well long lived FF. The other change in our modified concept is the substitution of the coolant, which in Rubbia's concept is molten lead in natural circulation, by Helium. The reason for this change is that there is few technological experience with molten lead coolant whereas Helium coolant has been used successfully in the High Temperature Reactor, as well proposed in fast system like the Gas Cooled Fast Breeder Reactor. Besides using Helium as coolant will allow the use of direct thermodynamic cycle (Brayton) with gas turbines, which are more efficient than the thermodynamic cycle proposed in the FEA. Finally, the fuel cycle proposed by Rubbia assumes that the fuel stays in a fixed position during 5 years, with a high burnup (150 MWD/t), and a reprocessing in batch each five years. In the modified concept we use the same idea of the CANDU reactor of fuel channels containing fuel bundles, which will be shuffled or refueled on line.

Then the MEA proposed consist of a horizontal cylinder (CALANDRIA) of lead, with 5 regions, as shown in Figure 4.

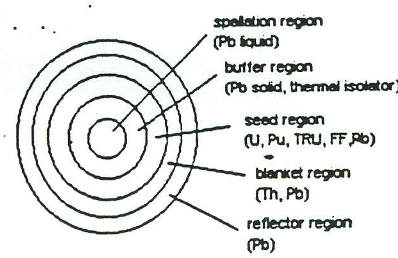

Figure 4. Schematic regions for the MEA.

The central region is the spallation region, consisting of circulating molten lead. In this region the accelerator proton beam induces the spallation reaction in 1 or 2 symmetric points (in a variant of 4 spallation points these regions will be located at the fuel region). The second region is a buffer consisting of solid lead cooled by Helium and isolated from the spallation region by a thermal isolator, which has the function of softening the energetic spallation neutrons. The third region is the seed region consisting of solid lead with channels where the fuel bundles are located, and is the region where the fission occurs as well as the incineration of TRU elements. The Helium