PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments
Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

The utilization of a small accelerators to drive a zero power sub critical ADS

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This paper describes a feasibility study to design a fast lead sub critical zero power reactor driven by existing small accelerators, a Cyclotron and a Van de Graff. The Zero Power Facility is being designed for future reactor physics experimental validation of a fast lead ADS He Cooled Concept under study. The paper review the conceptual ADS under study and the results obtained for BOL. The feasibility study to use small available accelerator to drive a zero power sub critical ADS was performed by changing the neutron source (accelerator), changing the type of fuel (oxide and metallic), pitch, fuel diameter and geometry.

KEYWORDS: Accelerator Driven Systems, Zero Power Sub Critical, Lead, and Fast Systems, helium cooled, cyclotron, Van de Graff

1. Introduction

The feasibility of using the Rubbia's Fast Energy Amplifier to generate energy, eliminate Pu, the utilization of different fuel cycles (U/Th/Pu), and the incineration of Minor Actinides (MA) and Long Lived Fission Products as an alternative to geological storage had been extensively studied during the 90´[1,2]. After that several other concepts of Accelerator Driven Systems (ADS) were proposed and R&D programs were initiated all around the world [3,4]. A conceptual proposal of an alternative concept for the Rubbia´s Fast Energy Amplifier was suggested by us[5, 6]. The main points which we considered in the Modified Energy Amplifier concept (MEA), was the introduction of more than one point of spallation, in order to reduce the requirements in the accelerator and to obtain a more uniform fast neutrons distribution besides increasing the amount of regions more close to the fast neutrons improving the possibility of incineration of TRU, as well long lived FF. The other change in the modified concept was the substitution of the coolant, melted lead in natural circulation, by Helium. The reason for this change is that there is little technological experience with liquid coolant with lead whereas helium coolant has been used successfully in the High Temperature Reactor, as well as proposed in fast system like the Gas Cooled Fast Breeder Reactor. Besides, using He 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 EA. Finally, the fuel cycle proposed by Rubbia assumes that the fuel stays in a fixed position during 5 years, with a high burn up (150 MWD/t), and a reprocessing in batch each five years. In the modified concept we propose to use the same idea of the CANDU Reactor of fuel channels containing fuel bundles,

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which are shuffling or refueled on line. Then the MEA proposed consist of a horizontal cylinder (CALANDRIA) of lead with tubes containing the fuel elements.

The spallation regions are consisted of circulating liquid lead. In these regions, the accelerator proton beans induce the spallation reaction in symmetric points. The second region is a buffer consisting of solid lead cooled by He and isolated from the spallation region by a thermal isolator, which has also the function of softening the energetic spallation neutron. 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. The He flows through the channels which are thermal isolated from the lead, allowing the heat generated to be transferred mostly to the coolant, although due the high temperatures heat will be transferred by radiation. The fourth is the blanket, which 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 (Th-232) from the blanket can be moved to the seed region after a equilibrium has been reached, and there is enough fissile material (U-233). 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 and fissile material (U-233 in Th/U cycle), which are sent to a fuel fabrication and returns to the core. A feed of fresh Thorium, and waste (TRU) from existing thermal reactors will allow using the natural Th resource, as well as to couple the MEA with the thermal reactors and open the possibility to reduce the requirement of secular final storage.

Results for BOL had been obtained using several spallation sources [7] and demonstrated the feasibility of the MEA concept. Studies to utilize the MEA concept as a waste burner are underway. Besides a proposal to lunch a program on P&T coupled with the utilization of accelerators in Basic and Applied Physics and a low power ADS as a neutron source was realized [8], and a road map to achieve such goal is underway. As first milestone of such road map, a fast lead zero power sub critical driven by small existing accelerators was proposed. This paper will describe the neutronics feasibility study performed to design such Zero Power ADS.

2. The Zero Power ADS

Power and Waste Burner ADS are still on the stage of development, and although several concepts are underway, none of them have been built. R&D activities are being developed in several fields, such as in Reactor Physics, Nuclear Data, Target, Fuels, Thermal Hydraulics, Spallation Physics, Transmutation, etc [9].

For Reactor Physics and Nuclear Data, experimental facilities operating at zero power (few watts) are being operating, or on planning, with the purpose to provide experimental benchmark on calculation methodology and nuclear data. Given the conceptual modified fast energy ADS under study [6], it is proposed a solid lead zero power ADS, using U/Th fuel and using as neutron source proton or deuterium from the CV-28 in a Be or Li targets, or 14 MeV neutron from a D-T reaction from a 400 KV existing Van de Graff. The proposed conceptual sub critical is illustrated in Figure 1, and in short it consist of lead blocks supported by a SS structure, containing holes in which the fuel elements are inserted. Given the low power, it is cooled by air natural convection.

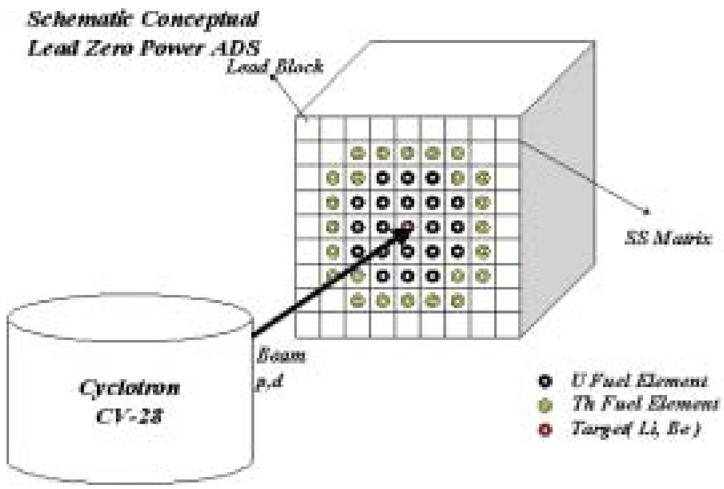

Figure 1. Conceptual design of a Sub critical lead zero power ADS.

IPEN operates 2 cyclotrons; the CYCLONE 30, from Ion Beam, dedicated exclusively to RI production (e.g. ^{18}F, ^{123}I, ^{67}Ga, ^{201}Tl, ^{111}In), and CV-28, from USA Cyclotron Co., which is a compact, isochronous, multi particle radiation source where protons, deuterons, 3He++ and alpha particles can be accelerated with variable energies (current) up to 24 (40-60 μA), 14 (50-100 μA), 365 (5-50 μA) and 28 MeV (6-40 μA), respectively. Besides, IPEN also operates a 400 KV Van de Graff (VG) accelerator, which accelerates deuterons. The CV-28 or VG accelerators could be used as an external neutron source to drive a zero power ADS. Using the CV-28, fast neutrons (5-6 MeV) could be produced from the nuclear reactions of protons or deuterons with Beryllium or Lithium targets [10], with integrated intensities between $10^{11} – 10^{12}$ n/s and the VG can produce fast neutrons (14 and 2 MeV) from the D-T and D-D reactions with intensities 10^{8} –10^{9} n/s. Although both accelerators needs some refurbishing in order to reach full operational condition.

Given the availability of these accelerators, a feasibility study to use them to drive a zero sub critical ADS was realized, and a conceptual project is underway. The zero power sub critical reactor would be used to simulate the conceptual ADS described before and provide experimental support for it.

3. Neutron Source Term

The external neutron source to drive the Zero Power ADS, using CV-28, could be induced by nuclear reaction of protons or deuterons with targets of Beryllium or Lithium to produce fast neutrons. Experimental results of the neutron yield, angular and spectral distribution was obtained by Lone [10]. From these data, for thick Be target, the CV-28 (E_P = 24 MeV, I = 50μA), can provide neutrons with intensities 10^{11}-10^{12} n/s, and average energy 5.1 MeV ($E_n \sim 1.14E_p^{1.13}$).

Also the Lone experimental results were reproduced by LAHET [11], and the results obtained were in good agreement. Therefore in the simulations, the source term was calculated by LAHET with appropriate corrections.

To simulate the neutron source emerging from the Van de Graff we use the MCNP-4C Monte Carlo code. The source was modeled using the experimental data obtained at IPEN [12], which gives the information of spatial and energetic distribution of the D-T reactions neutron source.

4. Calculation Methodology

The methodology employed in this work is based in the LAHET [11] and MCNP-4C [13] code systems. LAHET is the LANL version of the HETC Monte Carlo for the transport of protons. Its geometric transport capability is that of LANL's continuous energy neutron-photon Monte Carlo code MCNP-4C. The calculation methodology is made of two parts. In the first part LAHET performs the transport of protons and the subsequent characterization of the neutron and gamma sources arising from the nuclear reactions in the target. For this purpose, LAHET employees a Monte Carlo approaches for the transport of protons through the lead target. The sources are writing in special files denominated as NEUTP for neutrons and GAMTP for gamma for subsequent MCNP-4C utilization. Beyond that, LAHET has also the capability to calculate the energy deposited in the target as well as the reaction products. The second part of the calculation methodology concerns the k_{eff} determination and the transport of neutrons and gamma through the fuel core and its surroundings. This task is accomplished by the continuous energy neutron-photon Monte Carlo code MCNP-4C. The nuclear data needed for MCNP-4C are generated by NJOY [14] accessing the ENDF/B-VI nuclear data file.

A computer code, MCMC/MCEF [15,16,17] is under development in IFUSP to calculate the intra nuclear cascade properties and the nuclear evaporation process, present in all nuclear reactions with energies above few tens of MeV, using Monte Carlo techniques. Some new reaction channels were included in the code, resulting in a more realistic representation of the process involved in reactor physics studies and in the future with additional work could improve the results of the LAHET for the neutron multiplicity.

5. Cases Simulated

There are some options that were taken into account. Basically there are two ways to define the fuel pin distribution: square lattice and hexagonal lattice. In the first one were designed two configurations, where the basic difference is the fuel pin diameter. The diameter varies from 2.5 cm to 10.0 cm, and the reason is purely due to manufacturing capability at IPEN. The cases simulated are illustrated in Figure 2 and its characteristics are shown in Table 1.

The first idea was to use natural Uranium, but due to the restricted space that is available (1 m^3), the multiplication factor obtained for these configuration were to small (~ 0.36), too far from the desired value 0.95. The adopted solution was to use enriched fuel.

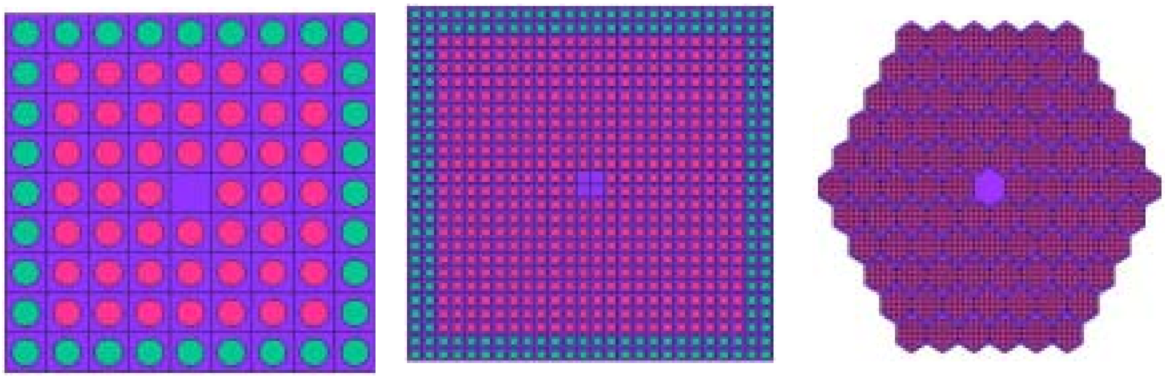

Figure 2. Schematic configuration of the three cases simulated. Square lattice are the first and second cases and a hexagonal lattice is the third case.

Table 1. Detailed characteristics and Results of the simulated configurations.

	Lattice	**k_{eff}**		**Fuel mass (ton.)**		**Enrichment (%)**		**Power (W/µA)**	
		Umet	***UO_2***	***Umet***	***UO_2***	***Umet***	***UO_2***	***Umet***	***UO_2***
Case 1	square	0.95	0.93	7.2	3.8	9	20	0,1	0.02
Case 2	square	0.96	0.95	10	5.3	8,5	19	50	18
Case 3	hexagonal	0.95	0.71	6.5	3.4	13.5	20	2732	164

6. Results

For the zero power ADS, some cases had been simulated for sub critical core varying the pin diameter and pitch, for hexagonal and square arrays, as well as the enrichment and the radial power distribution. Table 1 shows the results obtained, the Figures 3 and 4 shows the variation of the multiplication factor as function of the enrichment for the hexagonal and square lattice configuration, and the Figure 5 shows the radial power distribution for case 2. As an example of one of these simulation for a metallic uranium fuel, 8.5 w/o enrichment, 2.5 cm pin diameter, 3 cm pitch, in a square array imbibed in a lead cubic matrix of 1 m^3 gives k_{eff} = 0.96.. Using as external neutron source the one coming from 24 MeV, 3 µA proton beam in a thick target of Be, located in the center of the cubic lead matrix, gives for the example a power of 150 watts.

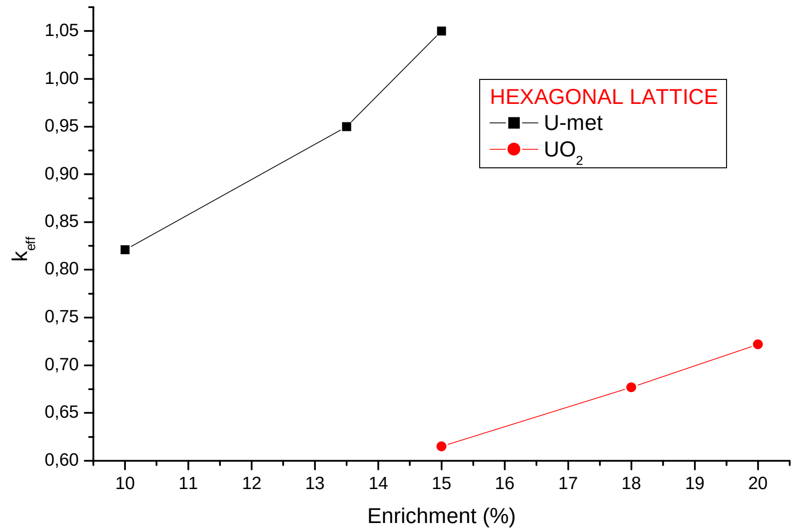

Figure 3. The graphic shows the variation of the multiplication factor as function of the enrichment for the hexagonal lattice configuration.

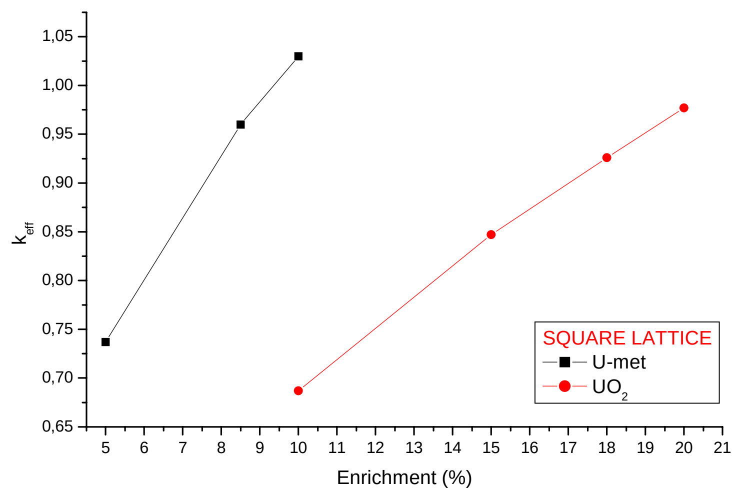

Figure 4. The graphic shows the variation of the multiplication factor as function of the enrichment for the square lattice configuration.

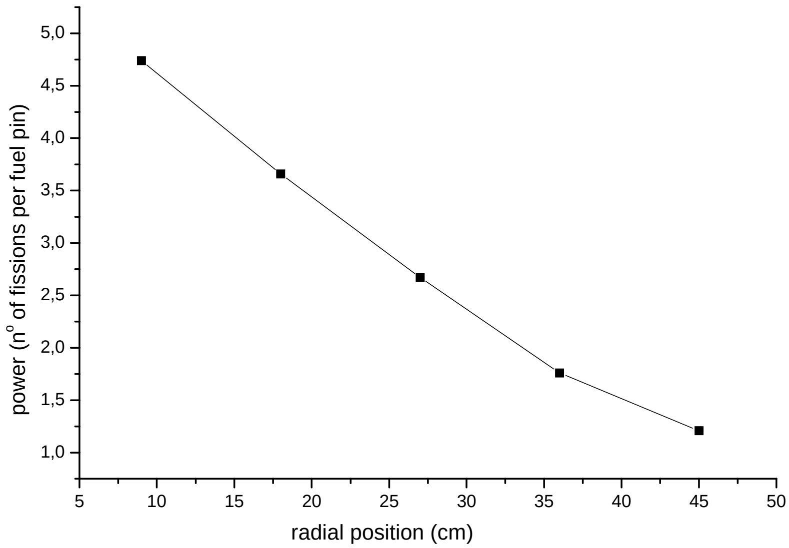

Figure 5. Radial power distribution simulated for Case 2.

7. Conclusions

The feasibility to design a zero power lead ADS using the existing accelerators (CV-28 and VG) is being demonstrated. The conceptual design will detail the facility, and will allow having a clear idea of the needed investment to build it, and to look for financial support.

The results obtained show that using metallic U, or UO_2 is possible to utilize Low Enriched Uranium (20 w/o), with ~10 w/o for metallic, and ~20 w/o for oxide. The case which is more attractive is a square configuration with < 10 w/o enrichment for metallic fuel, and 20 w/o for oxide fuel (Case 2), given a k_{eff} ~0.95, and a power ~50 watts/μA, with an advantage for oxide fuel due to the reduced weight of Uranium.

Finally, although the activities on ADS in Brazil are just beginning, the routes being followed will allow that the motivation to start the R&D is achieved, and in a near future it becomes a National Program. Of course due to human power, knowledge available, and financial limitation in a developing country like Brazil, International Cooperation will be a key issue for the success of the ADS program.

References

1. C. Rubbia et al., "Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier", European Organization for Nuclear Research, CERN/AT/95-44-ET (1995).
2. C. Rubbia et al, “Fast Neutron Incineration in the Energy Amplifier as Alternative to Geologic Storage: the Case of Spain”, CERN/LHC/97-01 (1997).
3. IAEA, Review of National Accelerator Driven System Programs for Partitioning and Transmutation, IAEA TECDOC 1365, August 2003
4. A European Roadmap for Developing Accelerator Driven System (ADS) for Nuclear Waste Incineration, The European Technical Working Group on ADS, April 2001
5. J. R. Maiorino et al., "Alternative Concept for a Fast Energy Amplifier Accelerator Driven Reactor", Research and Development Brazilian Journal, 3,1, p.13 (2001).
6. J. R. Maiorino et al., " A New Proposal for the Fast Energy Amplifier", Radiation Physics and Chemistry, 61,3-6, p. 789(2001).
7. S. Anéfalos, An Alternative Concept of a Hybrid Reactor (A Sub Critical Assembly Coupled with an Accelerator), Ph.D. Thesis- IPEN-USP (in Portuguese) 2002.
8. J. R Maiorino et al., " The Utilization of Accelerators in Sub Critical Systems for Energy Generation and Nuclear Waste Transmutation-The World Status and a Proposal of a National R&D Program ", Brazilian Journal of Physics, 33, 2, p.267 (2003).
9. W. Haeck et al, Ed, International Workshop on P&T and ADS Development 2003, SCK CEN, Belgium, October 6-8 2003.
10. M.A Lone et al., "Characteristic of Neutrons from Be Targets Bombarded with Protons, Deuterons, and Alpha Particles, Nuclear Instruments and Methods, 189, p. 515(1981).
11. R. E. Prael and H. Linchtentein, "User Guide to LCS: The Lahet Code System", LA-UR-89-3014, Los Alamos National Laboratory, USA (1989).
12. P.R.P.Coelho,” Experimental Benchmark in Fast Neutron Spectrometry from D-T Reaction Neutrons”, Ph. D. Thesis at IPEN-USP (in Portuguese), 1993.
13. J. F. Briesmeiter, "MCNP-4C- A General Monte Carlo N-Particle Transport Code-Version 4C", Los Alamos National Laboratory, LA-13709-M (2000).
14. R. E. MacFarlane et al., "The N-JOY Nuclear Data Processing System: Users Manual", Los Alamos National Laboratory, LA-9303-M, Vol. I, ENDF-324 (1982).
15. A. Deppman et al.," The MCEF Code for Nuclear Evaporation and Fission Calculation", Computer Physics Communication, 145, p. 385(2002).
16. S. Anéfalos et al., " Development of MCMC/MCEF Codes for Spallation Reaction Studies and its Utilization for ADS Studies", presented at the V Latin American Symposium on Nuclear Physics, 1-6 September, Santos, Brazil (2003).
17. S. Anéfalos, A. Deppman and A. dos Santos, “Development of CRISP package for spallation studies and ADS (Accelerator Driven System), to be presented in this conference.