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ACCELERATOR DRIVEN SYSTEM (ADS): AN INNOVATIVE REACTOR TO BE USED AS DEDICATED WASTE BURNER AND A MULTIPURPOSE NEUTRON SOURCE. THE STATUS OF THE ART

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ABSTRACT

This paper describes the main concepts of Accelerator Driven System (ADS) under development, Lead and Lead-Bismuth; Molten Salt, Gas Cooled etc. Zero Power Sub Critical Facilities, such as FEAT, YALINA , MUSE etc, will also be described. The potential utilization of ADS as dedicated waste burner reactor in a double strata fuel cycle will be discussed. Also, the utilization of ADS as a multipurpose neutron source as in development in Belgium will be presented. Finally, a proposal of program for ADS in Brazil will be presented.

1. INTRODUCTION

The Accelerator Driven System (ADS), is an innovative reactor which is being developed as a dedicated burner in a Double Strata Fuel Cycle to incinerate nuclear waste, aiming to reduce the requirements in the geological repository as illustrated in figure 1, where almost all possibilities of fuel cycles are illustrated, with an emphasis in Partition and Transmutation (P&T)[1]

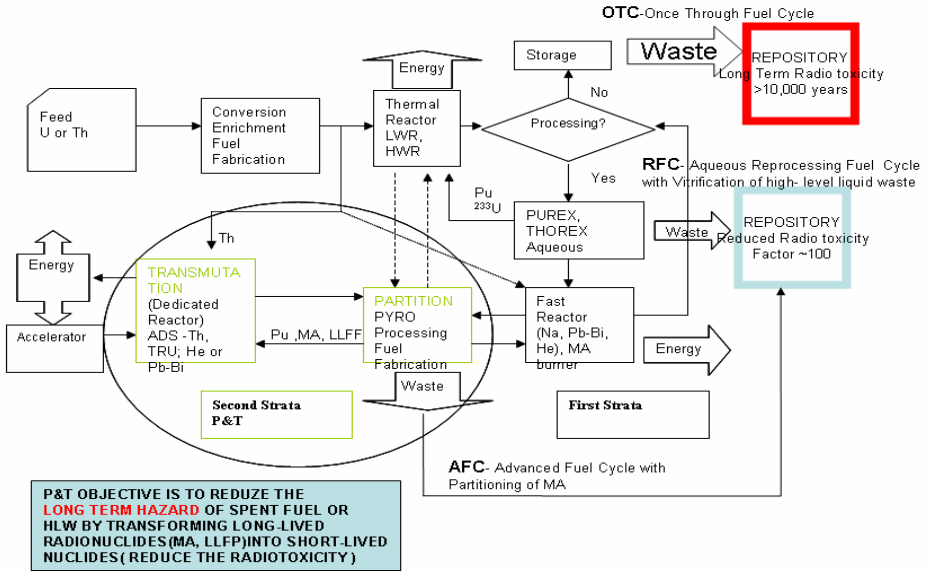

Figure 1: General Fuel Cycles with Partition and Transmutation Option using an ADS[1]

The ADS system consists of a fast sub-critical assembly driven by an external source of neutrons. Figure 2. illustrates the basic concept of an ADS, which in short consist of 1) Accelerator(Cyclotron or Linac), which accelerates the proton beam(1 GeV, few mA), 2) the target(window or windowless), where neutrons are produced by spallation, 3) Coolant(loop or pool), Sodium, lead, or lead-bismuth eutectic(LBE) melted, or gas(helium), 4) The sub critical core(k_{eff} ~0.95-0.97), consisting of an array of fuel in metallic, oxide or nitride form with nuclear fissile material (U, Th, Pu, minor actinides(MA), such as Am, Np, Cu,etc.) where energy is generated with a positive energy gain(G= energy generated/energy to drive the accelerator),and incineration of the TRU(Pu and MA), or Long Lived Fission Products(LLFP), is possible, and with breeding(U/Pu or Th/U).

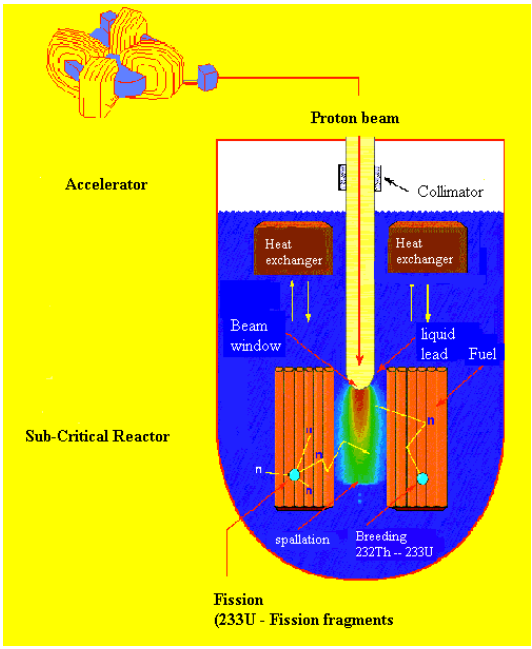

Figure 2: Basic Concept of ADS

2. ADS CONCEPTS

The innovative features of ADS have motivated an international effort in R&D, in several countries and different concepts of ADS. The status of the art has been reported by several authors [2,3,4]. However, it is important to notice that the interest for ADS and its utilization as dedicated HLW burner reactor has been impulse by the Rubbia´s proposal in 1995[5] when the concept of a fast energy amplifier was introduced. In this concept, a modular three stage cyclotron (1 GeV, 12.5 mA) accelerates protons to induce spallation in melted lead. The secondary neutrons produced in the target(~30n/p) are the source in a sub critical(k_{eff}~0.95) surrounding media containing as fuel Th, Pu, U, TRU in metallic or oxide form in a hexagonal array of pins. Melted lead in natural convection is the coolant. The Rubbia´s concept was proposed with a nominal power of 1500 MW(th), or 600 MW(e), an energy gain of 120, an extraction burn up of 150 GWD/t HM and reprocessing each five years. In the initial concept, although transmutation was considered, the energy generation and thorium utilization were the important issue. Later on, Rubbia et al.[6], with slight modification developed a concept with emphasis in transmutation, and demonstrated theoretically the capability to eliminate the HLW from the installed nuclear park in Spain(9 PWR).

After Rubbia´s proposal several countries were involved with P&T and ADS. The European Community developed a road map [7], defining joint R&D in all technical aspects of ADS and having as goal an eXperimental ADS (XADS)[8], in short range(~10 years).
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2.1 The XADS Concept[8]

The mission of XADS is to demonstrate the safe and efficient operation of ADS concept dedicated to the transmutation of long lived HLW. Since the most efficient transmutation of MA requires a fast neutron spectrum, for which the ratio between fission and capture is the highest, XADS is a fast sub-critical reactor, and the following concepts are being studied:

- Two lead-bismuth(LBE)-cooled concepts(a 80 MW concept; a 50 MW, MYRRHA concept)
- A gas cooled concept(80 MW)

2.1.1. Gas Cooled Concept

This concept is being developed leader by Framatome ANP, and in short it has the following characteristics:

- Reactor Power: 80 MW_{th}
- First sub critical core: classical FR fuel U-PuO_2(Pu<35%)
- Accelerator: Linac type, E=600 MeV, I<6 mA
- Target Liquid LBE window concept; inlet/outlet Temperature: 250/400 ^{0}C; Alternative: Helium Cooled Solid Tungsten Target
- Primary Coolant Fluid: Pressurized helium at about 6 MP_a; Helium inlet/ outlet temperature: 200/450 ^{o}C; He flow rate 61.6 Kg/s core pressure drop <0.1 MP_a, primary He containment is a metallic vessel, and the power conversion system is a heat exchanger and circulator.
- Core Design: power density: 47.5 MW/m^3, fissile length: 1.5 m, maximum neutron flux: 10^{15} n/cm^2s, k_{eff} in the range of 0.95-0.97, triangular lattice, 37 pins per element

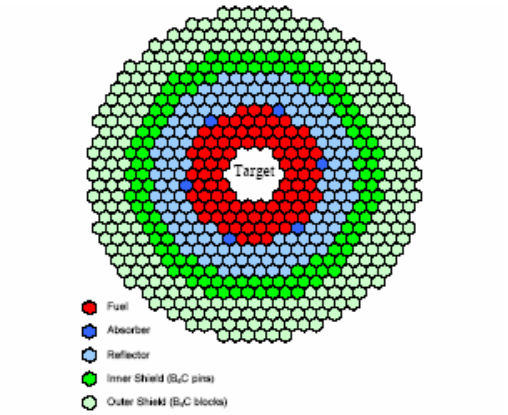
Figure 3 illustrate the core and the reactor vessel for the gas cooled XADS concept.

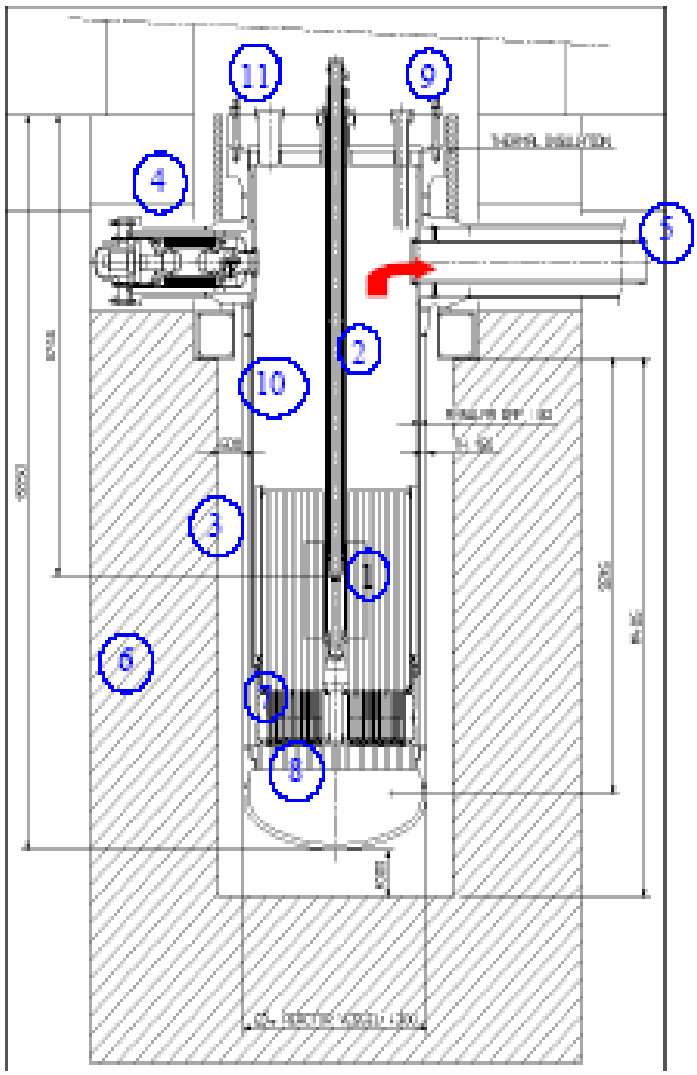
2.1.2. LBE Concept

The LBE XADS design is being conducted leader by Ansaldo. The power, accelerator and the first sub-critical fuel,(U-Pu)O_2 are the same as for the gas cooled concept. The other characteristics are:

- Target: Window less LBE
- Primary System: pool type LBE, Reactor Vessel, Core inlet/outlet temperature: 300/400^{o}C, Coolant Flow Rate: 5471 kg/s, LBE inventory: ~1700 t.
- Core Design: 120 hexagonal fuel assemblies, 90 pins/assembly, k_{eff}=0.97(BOL)-093(EOL), MOX hexagonal lattice

Figure 4, illustrates the general view of the LBE concept.





1 - Sub-critical core

2 - Target unit

3 - Reactor Pressure Vessel

4 - SCS

5 - Cross duct

6 - Vault pit

7 - Diagrid

8 - Strongback

9 - Roof Slab

10 - Inner vessel

11 - Pantograph penetration

Figure 3: Core and Reactor Vessel for the gas cooled XADS.

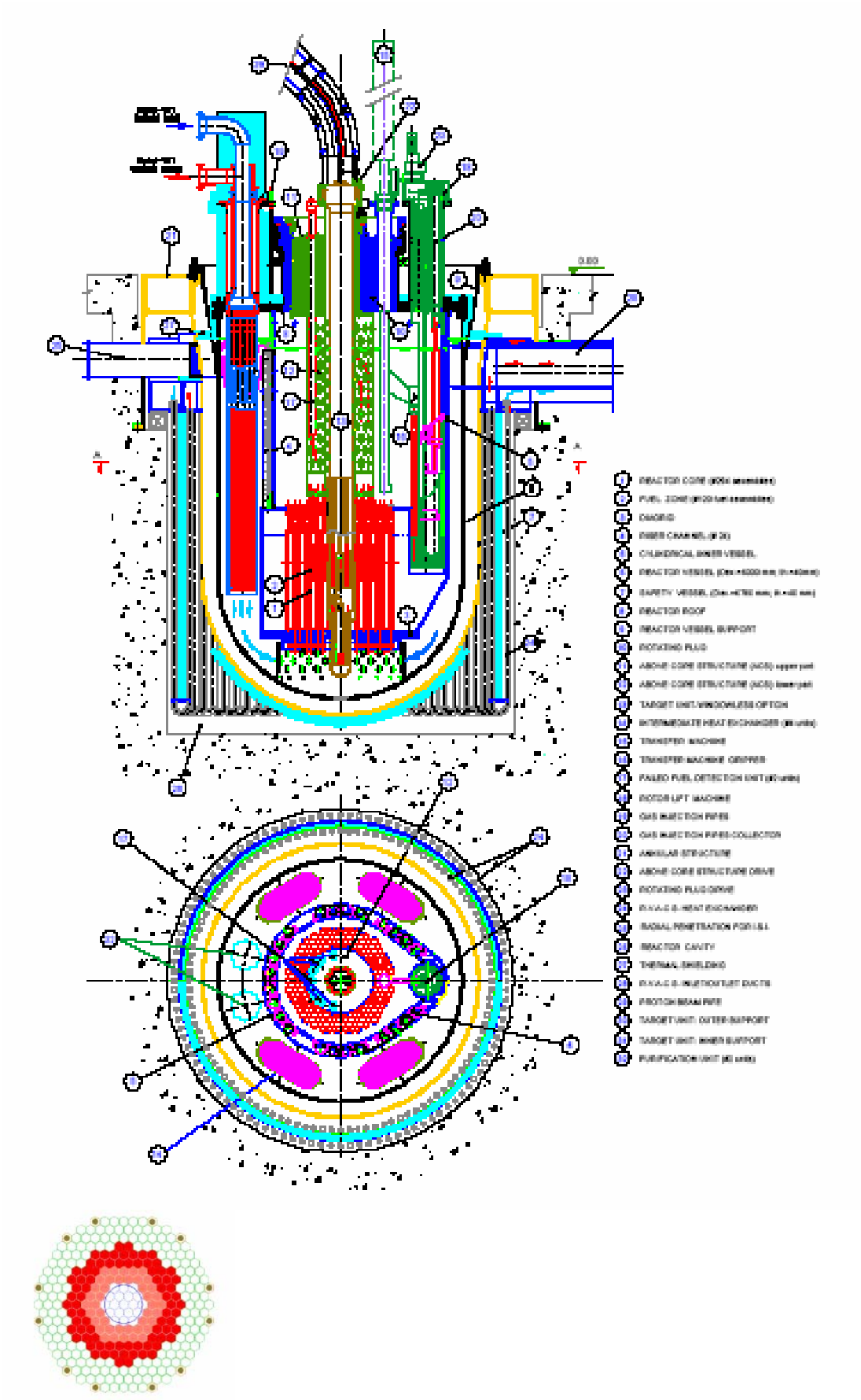


Figure 4: LBE XADS Primary System and Core

2.1.3. MYHRRA ADS

Since 1998, under leadership of SCK-CEN at Mol in Belgium a multipurpose ADS for R&D application (MYHRRA) is being developed. Besides to serve as a basis for XADS demonstration facility (nuclear waste transmutation), the devise will also be dedicated to research on structural materials, radioisotope production, nuclear fuel, liquid metal technology etc. It consist of a proton accelerator (cyclotron or Linac) delivering a 350 MeV, 5 mA proton beam to a windowless liquid Pb-Bi spallation target coupled with a LBE sub-critical core A general view of MYHRRA is illustrated in figure 5.

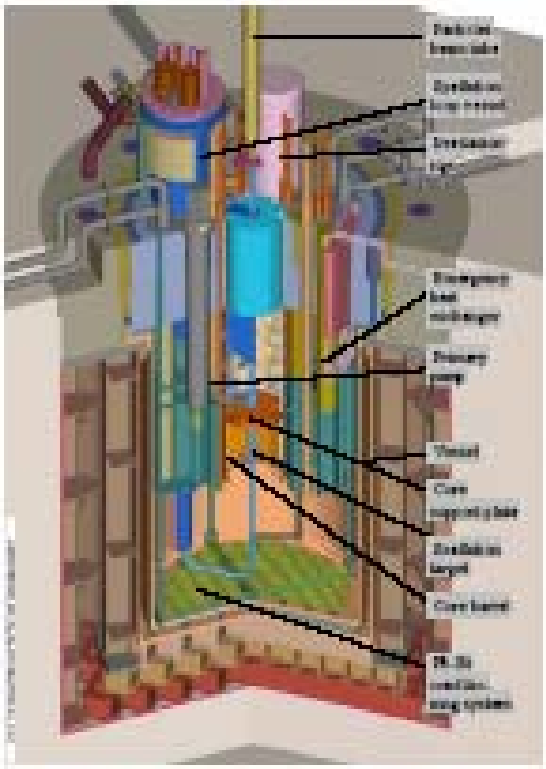


Figure 5: General View of MYHRRA

The primary system is a pool type LBE. The core is fueled with (U-Pu)O_2 fuel pins, in an hexagonal array(D=1m, H=60 cm), with 127 pins/ assembly. The k_{eff} is 0.95, and the fast flux is ~10^{15}n/cm^2.s. The core has "Thermal Island" to produce radioisotopes or LLFP incineration with thermal fluxes of ~$2x10^{15}$n/cm^2.s.

2.2. Low Power or Zero Power ADS[10,11,12,13,14]

Facilities at Zero Power or Low Power are being constructed or planning to provide data, mainly Reactor Physics parameters, using fast neutrons from neutrons generators or low energy spallation. Among several facilities, here we will describe the MUSE experiment at MAZURCA facility at Cadarache(CEA-France), TRADE(Italy), YALINA(Belarus), SAD(Russia), and FEAT(CERN). Other Zero Power ADS being planned are the SAD(Russia), a sub-critical driven by spallation, the TEP-P(JAERI, Japan), a split table sub critical driven by spallation, and a thermal sub critical driven by a neutron generator in India(BARC), as part of a ADS program to use thorium- based system.

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2.2.1. TRADE

TRADE("**TR**iga **A**ccelerator **D**riven **E**xperiment")[9] is an small ADS, being developed by a consortium of countries leader by the Italian ENEA(CEA, FZK-Germany, ANL-USA, CIEMAT-Spain), and was proposed by C.Rubbia as an intermediate experiment between the Zero Power ADS, and the XADS. Basically, the TRADE experiment will couple a cyclotron(140MeV), which accelerate protons into a solid tantalium target(spallation source) in a sub critical existing TRIGA reactor at ENEA Casaccia Center(1 MW).

2.2.2. MUSE

Since 1996, experiments to study Reactor Physics of ADS is being conducted at MAZURCA facility at Cadararache, which is a very flexible zero power facility(5kW) for different types of fuel, coolant, .From 1996-1999 neutronic studies, within the European framework of transmutation and incineration in fast system, had been carried out using a ^{252}Cf sources, or commercial neutron generators(14 Mev neutrons, 3 x10^8 n/s). After 2000, the MUSE program used as an external source the GENEPI accelerator specially designed for ADS studies. The GENEPI is a neutron generator which accelerates deuterium(140-240 keV) to produce pulsed neutrons(<1 μs) through D-T, or D-D reaction, with intensities up to 1.2x10^{10} n/s. The MUSE-4 sub-critical core was a MOX fuel imbibed in a lead/ sodium media. Several Reactor Physics parameters were measured, such as reaction rate (flux) distribution, neutron spectrum, sub criticality and kinetics measurements. MUSE is in the ADS European Road Map, as a basis for code qualification, kinetics parameters etc. for ADS Reactor Physics.

2.2.3. FEAT, TARC and n-TOFL[10]

FEAT (First Energy Amplifier Test) was a sub critical(k_{eff}~0.92) facility(1 W) driven by a CERN Proton Synchroton (10^8n/s), constructed to demonstrate the Energy Gain of the Rubbia's ADS concept, and to qualify the CERN codes(FLUKA-EA-MC). Besides FEAT, an experiment, TARC (Transmutation by Adiabatic Resonance Crossing) was conducted at CERN , which is an external source induced by CERN accelerators(3.5 GeV) in a lead block to study transmutation of LLFP. Finally, a huge facility (accelerator) was constructed at CERN (n-TOFL-ND-ADS) for Neutron Cross Section Measurements relevant for Nuclear Waste Transmutation. All these facilities were in the European Road Map R&D program.

2.2.4. YALINA

The YALINA facility is a zero power ADS, operating since 2000 in Belarus. The present sub-critical (k_{eff}= 0.97)core is a fast-thermal assembly(fast Zone: U_{met},99w/o, UO_2 36w/o imbibed in lead; thermal zone: UO_2, 10w/o imbibed in polyethylene), reflected by Graphite and Driven by a pulsed 100-250 kV Neutron Generator NG-12-1(D-T; D-D, 1.5x10^{12} n/s). Also it provides data for ADS Reactor Physics

2.3. Other ADS Concepts and Projects[10, 11, 12,13,14]

2.3.1. HYPER

Korean Atomic Energy Research (KAERI) is developing the project HYPER, which is a 1000 MW_{th} LBE ADS. The basic features of HYPER are :k_{eff}= 0.98; Proton Bean: 1 GeV,

10.6/16.4 mA(BOL/EOL); Fuel Type: TRU- Zr Metal Alloy; Coolant/Target: Pb-Bi/Windowless, Transmutation: TRU, ^{99}Tc, ^{129}I, TRU Transmutation Rate: 282 kg/yr, LLFP Transmutation Rate: 27 kg/yr(^{99}Tc); 7 kg/yr(^{129}I), Coolant inlet/out let temperature: 340/490 ^{o}C.

2.3.2. ATW (Accelerator Transmutation of Waste)

In 1999 the USA established a road map for ATW, as ADS is know in the USA, in a program denominated AAA(Advanced Accelerator Application). In this program under development at Los Alamos and Argonne National Laboratories, it was proposed two proton Linear Accelerators(1GeV, 45 Ma), each providing beam to four targets, in 8 LBE ADS(840 MW_{th} each). The accelerator and burner architecture is illustrated in figure 6.

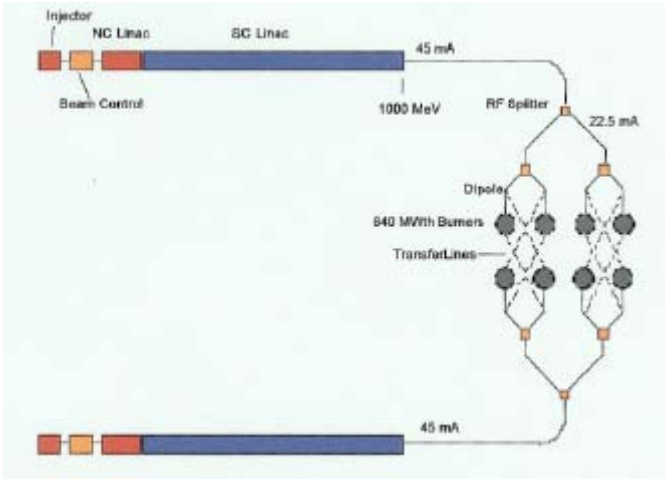

Figure 6: The accelerator and burner architecture for the reference ATW plant

The AAA program had been included in a program related with Fast Systems Transmutation technology, in the Advanced Fuel Cycle Initiative (AFCI), and presently the DOE are integrate this program together with Generation IV R&D(G-IV), and Nuclear Hydrogen Initiative(NHI) in a integrated nuclear energy development program(AFCI, G-IV, NHI).

2.3.3. Molten Salt ADS (MSB)

Russian Institutes leader by Kurchatov Institute are involved in a project(ISTC): " Experimental study of molten salt technology for safe and low waste treatment of plutonium and minor actinides in accelerator driven and critical systems". The MSB concept utilizes fluorides salts of Uranium, Plutonium and MA.

3 CONCLUSION AND FINAL REMARKS

This paper has presented the status of the art related with ADS development for transmutation of HLW. We notice that there are great international efforts of R&D for the development of such system. Zero Power Sub-Critical facilities are being constructed or planned and providing benchmarks for ADS Reactor Physics. The experimental demonstrator (XADS), is

an advanced stage of development in the European Community. The MYHRRA, once built could be a replacement for the present time Research Reactors (neutron source). Brazil cannot be out of these developments. In fact, a proposal of a national program or net work of R&D on the utilization of medium size accelerator (300 MeV, 1-2 Ma) to be used in basic and applied research, products and services(Radio isotopes, proton therapy etc.), and to drive a small power ADS for R&D, similar to the MYHRRA, was made[4]. Feasibilities studies to utilize small existing accelerators (CV-28, VG) to drive a Zero Power Fast ADS were made[15, 16]. Conceptual studies of a modified fast energy amplifier, using helium as coolant and three points of spallation were realized[17,18]. Finally, a proposal of a research line in the Millennium Institute for Advanced and Innovative Reactors, was submitted to the MCT-CNPq, involving several Brazilian Research Institution(IPEN, IEN, CDTN, CBPF, IFUSP, CTM-SP), to consolidate all the ADS neutronic methodology(Spallation, static, burn up and transmutation, kinetics and dynamics) in Brazil, and to participate in International Coordinated Research Projects.

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