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A PRELIMINARY ESTIMATE OF THE ECONOMIC IMPACT OF THE ENERGY AMPLIFIER

R. Fernández, P. Mandrillon[1], C. Rubbia and J.A. Rubio

Abstract

The basic concept and the applicability of the Energy Amplifier (EA) have been exhaustively described elsewhere (Refs. [1] to [4]). The EA is essentially a source of high quality heat, produced by the nuclear cascades induced by a high intensity proton beam inside an appropriate "beam dump" arrangement. A fraction of such "heat" has to be transformed into electricity to run the accelerator, the rest being available for a number of different industrial applications, and in particular commercial electricity production.

In this paper the economic aspects are further explored and we attempt a first order estimate of the cost of such an energy source, comparing it critically with more conventional sources. In this task we have been greatly helped by a number of people[2] who have specific competence in the industrial aspects of the application.

We conclude that in agreement to our previous estimates, the practical cost of high quality heat is about $0.77^{+0.12}_{-0.12}$ US $/ GJ, namely $3.0^{+1.5}_{-0.9}$ and $4.8^{+2.7}_{-1.4}$ times lower than the one of Coal and Natural Gas for the prevailing net interest rate of 5%. The cost of electricity produced with our method is estimated of the order of ≈ 2 ¢ / kWh, again highly competitive (about half of the cost) with all other traditional sources. In spite of the significant uncertainties in the evaluation, we evidence a strikingly lower cost for our method, direct consequence of the basic simplicity of the design and of its high level of intrinsic safety. Figures are for a 600 MW_e stand alone power station.

We recall that the EA is also an environmentally more acceptable form of energy from nuclei of virtually unlimited supply. The integrated collective dose for the same energy has been estimated [3] of the order of ≈ 2 man Sv / [GWe × year], 1 / 10 of the average dose due to radionuclide emission from Coal burning and comparable to Oil and Geothermal. The radioactive waste reaches the activity of coal ashes after about 500 years of "cool-down". Environmentally, the EA performance is comparable to the one of Magnetic Fusion [9], which has, no doubt, a higher cost.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ALMR	American Liquid Metal Reactor
AT	Accelerator Technologies
BME	Extraction Bending Magnet
BMI	Injection Bending Magnet
BMN	Russian Fast Breeder Reactor
BSSC	Booster Separated Sector Cyclotron
BNL	Brookhaven National Laboratory
CERN	European Laboratory for Particle Physics
CIC	Compact Isochronous Cyclotron
DGXII	Direction Générale XII (Union Européen)
EA	Energy Amplifier
EBDV	Emergency Beam Dump Volume
EET	Emerging Energy Technologies
EFR	European Fast Reactor
EGU	Energy Generating Unit
EM	Electromagnetic (pumps)
EMDE	Electromagnetic Deflector
EMDI	Electromagnetic Channel
EPAC	European Particle Accelerator Conference
ESDE	Electrostatic Deflector
ET	Emerging Technologies
GJ	Joules x 10^9
GW	Watts x 10^9
HF	High Frequency
HGA	Heat Generating Assembly
HT	High Tension
HVAC	Heating, Ventilating and Air Conditioning
HVACS	Heating, Ventilating and Air Conditioning System
IEA	International Energy Agency
IEPE	Institut d'Economie et de Politique de l'Energie (Grenoble)
ILW	Intermediate Level Waste
ISSC	Intermediate Separated-Sector Cyclotron
LHC	Large Hadron Collider
LLW	Low Level Waste
LMFBR	Liquid Metal Fast Breeder Reactor
MHz	MegaHertz

MLAS	Molten Lead Activated Scram
MONJOU	Japanese Fast Breeder Reactor
MOX	Mixed Oxide fuel
MW	Watts x 10^6
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-Operation and Development
O&M	Operation and Maintenance
PUREX	Fuel reprocessing method based on TBP extraction
PWR	Pressurized Water Reactor
RF	Radiofrequency
RVACS	Reactor Ventilating Air Convection System
SERCOBE	Asociacion Nacional de Fabricantes de Bienes de Equipo (Spanish Association of Heavy Equipment Enterprises - Madrid)
SWU	Separating Work Unit
THOREX	Thorium based PUREX
VHLW	Vitrified High Level Waste

1.— INTRODUCTION

Some preliminary considerations on the economical issues of the Energy Amplifier (EA) have shown that, within the range of significant uncertainties in these calculations, the upper limit to the cost of the electrical kWh produced with the EA is generally smaller to that from more conventional energy sources [5]. The basic assumptions and calculations of Ref. [5] were independently confirmed by the IEPE (Institut d'Economie et de Politique de l'Energie de Grenoble) [6] and by several other experts.

An exact evaluation of the financial envelope of the EA requires the complete engineering design of the plant, largely premature at this stage. Nevertheless, the conceptual design presented in Ref. [3] allows a further step in the economical calculations since it provides a first definition of the principal components and in most cases, of their main characteristics. Essential details relative to the operation of the plant and the fuel cycle are also given. Therefore we have all the basic ingredients to afford a first, *analytical* estimate of the costs. The width of the uncertainty margins affecting our present estimate may be progressively reduced in the future, following the progress of the engineering design of the EA.

The cost of unit energy produced depends significantly on the size of the plant. The optimal size of an EA is evidently application dependent. Usually significant cost reductions can be introduced by clustering several units or by building bigger units. In Ref. [3] we have chosen the approach of a modular design made of units of 1500 MWatt thermal power, each driven by a separate Accelerator. This corresponds to about 675 MWatt of primary electrical power with “state of the art” turbines and an outlet temperature of the order of 550 ÷ 600 ^{o}C. The thermodynamical efficiency of ≈ 45% is substantially higher than the one of a PWR and it is primarily due to the present higher temperature of operation. The size of each module is determined by three main considerations: (1) transportability of the main tank which can be factory assembled (2) optimum current and therefore power which can be produced by the type of accelerator we have chosen and (3) safety in the decay heat removal which suggests to limit the maximum power to be dissipated by the passive cooling system.

The modular approach has been preferred in several recent conceptual designs of Sodium cooled fast reactors in the US (ALMR, American Liquid Metal Reactor), Japan (MONJOU) and in Russia (BMN-170), for reasons of cost, speed of construction and licensing. Such modularity permits the use of the devices in relatively isolated areas. The power plant can be built in a well developed country and transported to the target area. Decommissioning of the device is also simplified.

Each EA module is therefore about half the size of a standard PWR (Pressurised Water Reactor) and clustering of several units is likely at least for massive electricity production. Nevertheless we have evaluated here the cost of a single stand alone unit. We believe that for instance the three unit cluster discussed in Ref. [5] for the energy production of some 1900 MW of useful electric power will further reduce the unitary electricity cost by some 15 ÷ 20%. We note finally that the chosen, smaller size is in accordance with the general policy followed with Coal and Natural Gas driven power generating units. A simpler technology, as is the case of the EA when compared to a PWR, pushes the optimisation towards smaller, more flexible single units.

Cost estimates given here are for a “commercially oriented” plant, not for a research prototype. It is assumed that the prior phases of R&D and of a demonstration plant has been completed and independently financed. However the engineering costs related to the specific project are obviously included (see item: other costs) and evaluated from the experience with conventional power generating installations.

Several years may be needed to build a plant and the corresponding yearly investments are immobilised until the plant is ready to generate energy. During this period the capital interest has to be considered in the total investment cost estimate. The utility financing is with 100% debt. We have chosen US$ as monetary unit and made no assumption on inflation (constant US-dollars): therefore the assumed capital interest rates are above inflation (net discount rate).

As usual, costs may be divided into several chapters, which have been identified as follows:

i) The direct *investment costs* are derived from the technical descriptions of the EA components, based on the unit costs of similar equipment available in the industrial market. In some cases several options satisfy our technical requirements and the optimal choice requires further engineering studies. In others, the equipment has to be developed on the basis of the existing ones. Both effects are translated in larger uncertainty margins of the cost estimate. Assembly costs are included throughout.

ii) The *fuel cost* includes all operations affecting the fuel. It will rely on the market price for the row fuel material and on the subsequent steps belonging to both the front and to the back-end of the fuel cycle, for which a large experience exists from the PWR fuel cycle.

iii) *Indirect costs*, affect investments and the fuel cycle costs. Capital interest is particularly important in our case since investments are large compared to other contributing items and the construction period extends over several years. The net discount rate is the determining parameter. It affects also the operations prior to the fuel use, the waste reprocessing and/or disposal and the fuel immobilisation period inside the plant. The time distribution of investments allows to calculate the indirect costs for a realistic range of the net discount rate taken as an input parameter.

iv) *Other investment costs* relate to the design and architect engineering of the particular project, the supervision and coordination of the site work and commissioning, the administrative matters, etc. In their evaluation previous experience with the PWR, properly adapted to the EA, is taken as a basis for a global estimate of the cost. A particular item generally considered in this category is the dismantling of the plant, once its useful life comes to an end. For the Nuclear Power plants currently the existing experience is modest and the requirements are affected by increasingly strict conditions. Nevertheless, since its contribution to the total investment costs is small, mainly due to its projection to the time of the plant start-up and it is premature to assume a policy for the EAs, we will neglect its contribution to the cost estimate.

v) The evaluation of the *Operation and Maintenance (O&M) costs* will be based on the working requirements of the plant subsystems and the foreseen plant operating conditions. To this purpose the experience with installations of similar characteristics will be the main asset of the estimate.

In what follows the above defined ingredients of the EA energy cost are evaluated, based on generally accepted assumptions [7] [8], and a total cost derived. The results are shown to be compatible with previous estimates [5] [6]. Also, by comparing the costs, both at the electricity and heat levels, with those from other energy sources [7] we confirm the EA expectations to be an economically competitive energy source.

Anticipating the conclusions of the paper, the economic impact of the EA is best identified by looking at the cost of high temperature heat (steam), the initial ingredient of all possible uses. In Fig. 1 we have compared the costs from Natural Gas burning, Coal burning and Thorium burning in the EA. In the quoted cost we have singled out the differentials for the three possible energy sources, including the direct and indirect costs of the energy generating units well as the Fuel and related O&M costs. Presumably the additional costs which are application dependent are largely independent on the choice of the initial energy source and are an additive term in the total cost. The uncertainty bands for coal- and gas- fired plants reflects mainly the differences in cost and availability of fuels, while the uncertainties in the EA are related to the preliminary nature of our design. Since the EA is capital investment intensive, the energy cost is strongly dependent on the cost of money.

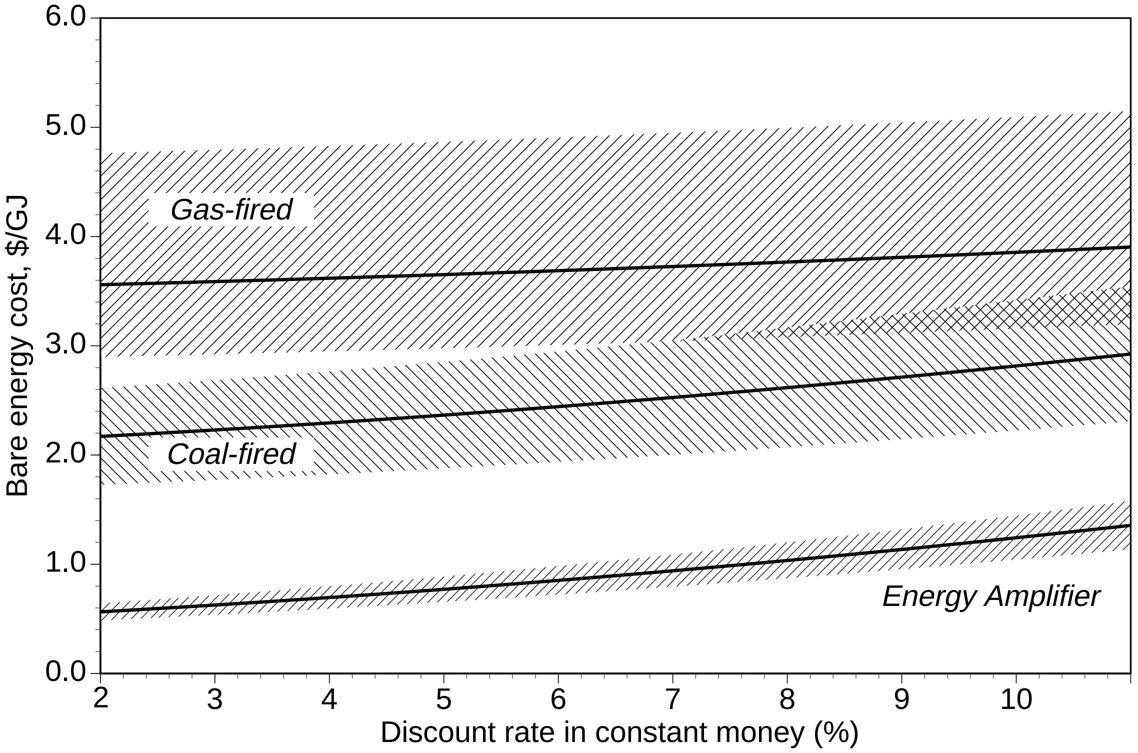

Figure 1. *Comparative costs of high quality heat produced by conventional methods and with the Energy Amplifier, as a function of the net discount rate.*

In spite of the significant uncertainties in the evaluation of the cost of energy from the EA, Fig. 1 evidences a strikingly lower cost of our method, which is a direct consequence of the basic simplicity of the design and of its high level of intrinsic safety. This reflects itself in about a factor two in the cost of electric energy production, which is of the order of as little as 2 ¢ / kWh.

The EA is also an environmentally more acceptable form of energy from nuclei of virtually unlimited supply. In particular the integrated collective dose (both local & regional and global) has been [3] estimated to be of the order of ≈ 2 man Sv / [GWe × year], which is one order of magnitude smaller than the radionuclide emission from Coal burning and comparable to the one due to the use of Oil and Geothermal [3]. Finally we recall that the EA radioactive waste reaches the activity of coal ashes after about 500 years of "cool-down" time. In these respects, the EA performance is comparable to the one of Magnetic Fusion [9], which has however no doubt a higher energy cost.

The main fuel to be used by the EA is natural Thorium, in which the necessary fissionable ^{233}U isotope is continuously bred. However, as pointed out in Ref. [3], a variety of different fuels can be used extending the application of the EA from pure energy *amplification* (production) to the one of the *incineration* of unwanted actinide "waste" from Nuclear Power Reactors (PWR) and from the disassembly of Military Weapons.

The key idea is the one of using a Thorium-Plutonium mixture which is much more effective in eliminating Plutonium at acceptable concentrations ($\leq$ 20%) than the conventional mixture of Uranium-Plutonium. The EA operates as an effective Plutonium to ^{233}U converter. The latter can be later mixed with ordinary or depleted Uranium and it constitutes an excellent fuel for the PWRs.

Plutonium complete elimination through fissions produces a very large amount of energy, namely 940 MW × day for 1 kilogram. In practice the energy yield is higher since fissions occur in the Thorium matrix and in the ^{233}U bred in the Thorium. The energy produced by the incineration of 1 kg of unwanted Actinides is about 1200 MW × day. A 1.0 GW-electric PWR produces about 900 GW × day of thermal energy yearly and a total "Dirty Plutonium" waste (Np, Pu, etc.) of 271 kg. Hence "incineration" of such a waste will inevitably lead to the production of some 325.2 GW × day, 36.13 % of the power produced by the initial PWR, close to the "theoretical" limit in which only Pu is burnt, i.e. 28.30 % of the PWR power. The energy accumulated in the Actinide "waste" and which can be recovered with our method is therefore very large, since it amounts to about 1/3 of all the nuclear power produced by the PWR. In particular an EA-incinerator will eliminate the Actinide waste at the rate produced by a PWR with only about 1/3 of the installed power.

A cluster of EAs operated in conjunction with existing PWRs is a very effective and realistic solution to the ultimately complete elimination of the accumulated Plutonium and Minor Actinide stockpiles and it greatly alleviates the problem of definitive geologic disposal. The economics of this combined EA-PWR operation is analysed. We find that (1) the cost of the substitution (^{233}U) fuel is comparable to the one of the ordinary enriched ^{235}U fuel and (2) the cost of energy from the EA is very close to the one of ordinary operation.

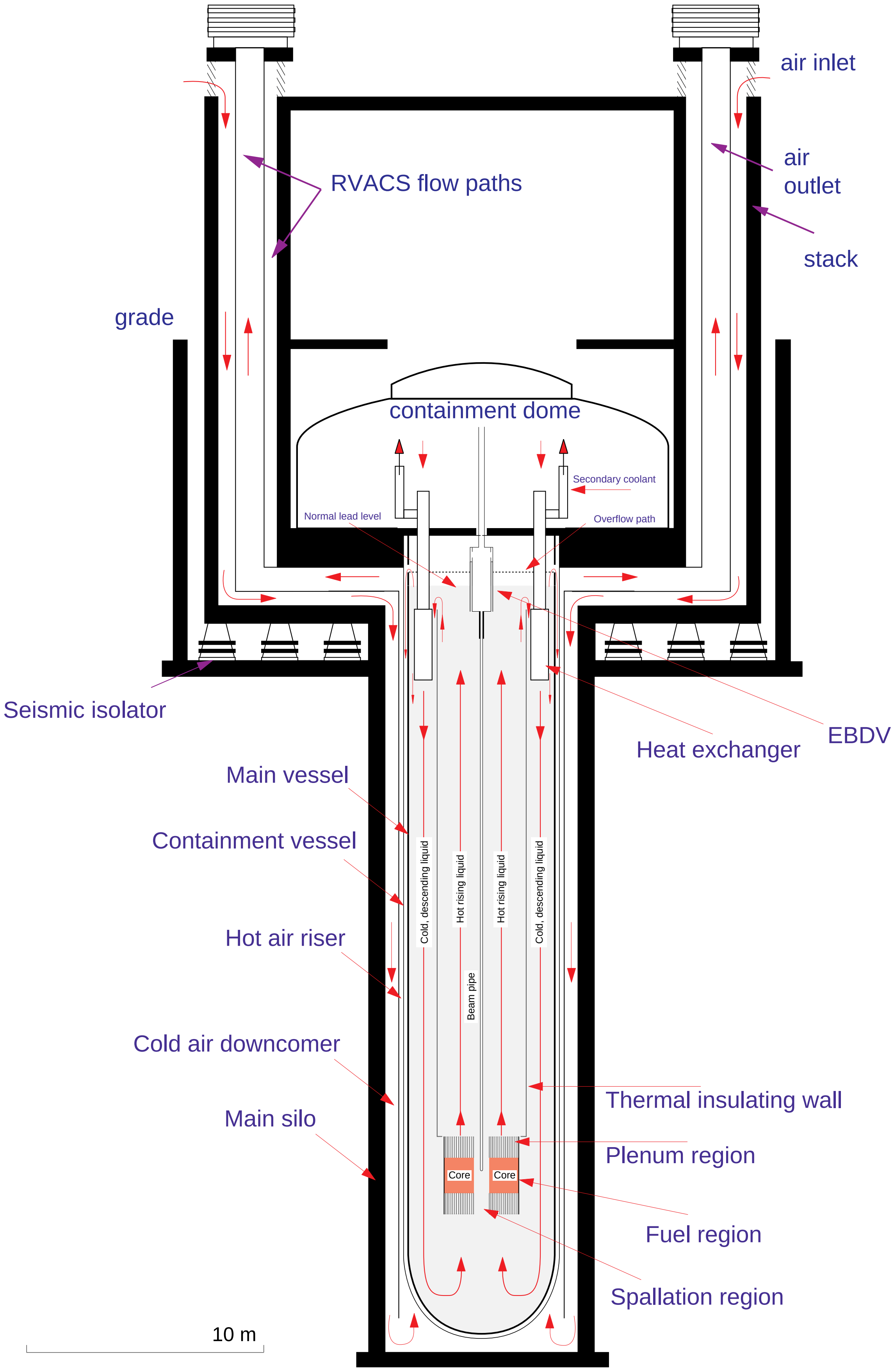

Figure 2. *General layout of the Energy Amplifier/Beam Dump.*

2.— BRIEF DESCRIPTION OF THE REFERENCE DESIGN

The EA reference design is the one described in Ref. [3] and it is shown in Fig. 2. It is based on a convection driven molten Pb swimming pool of roughly 10^4 tons. The choice of fast rather than thermal neutrons is motivated by the higher attainable power density and the larger burning efficiency for the higher Actinides. For more details we refer to Ref. [3]. The nominal thermal power has been set to 1500 MW. As already pointed out, several modules could be clustered in a power installation. The coolant medium is molten natural Lead operated in analogy with Fast Breeders (Sodium cooled) at a maximum temperature of $600 \div 700$ °C. In view of the high boiling temperature of Lead (1743 °C at n.p.t.) and the negative void coefficient of the EA, even higher temperatures may be considered, provided the fuel and the rest of the hardware are adequately designed.

A most relevant feature of our design is the possibility of using natural convection alone to remove all the heat produced inside the Core. Convection cooling has been widely used in "swimming pool" reactors at small power levels. It has been shown in Ref. [3] that an extension of this very safe method to the very large power of the EA is possible because of the unique properties of Lead, namely high density, large dilatation coefficient and large heat capacity. Convection is spontaneously and inevitably driven by (any) temperature difference. Elimination of all pumps in the Primary loop is an important simplification and a contribution towards lower costs and safety, since unlike pumps, convection cannot fail. In the convective mode, a very large mass of liquid Lead ($\approx$ 10,000 tons), with an associated exceedingly large heat capacity[1] moves very slowly (≤ 2.0 m/s inside the core, about 1/3 of such speed elsewhere) transferring the heat from the top of the core to the heat exchangers located some 20 metres above and returning at a lower temperature ($\Delta T \approx -200$ °C) from the Heat Exchangers to the bottom of the Core.

The geometry of the EA Main Vessel is therefore relatively slim (6.0 m diameter) and very tall (30 m). The vessels, head enclosure and permanent internal structures are fabricated in a factory and shipped as an assembled unit to the site. The relatively slender geometry enhances the uniformity of the flow of the liquid Lead

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[1] The heat capacity of liquid Lead at constant pressure is about 0.14 Joule/gram/°C. For an effective mass of $\approx 10^4$ tons = 10^{10} grams and a power of 1.5 GWatt (full EA power), the temperature rise is of the order of 1.0 °C/s. The mass flowing through the core for $\Delta T \approx$ 200 °C is 53.6 tons/sec, corresponding to some 1.5 minutes of full power to heat up the half of the coolant in the "cold" loop, in case the heat exchangers were to fail completely.

and of the natural circulation for heat removal. The structure of the Vessel must withstand the large weight of the liquid Lead.

There are four 375 MW_{th} heat Exchangers to transfer the heat from the primary Lead to the intermediate heat transport system. They are located above the Core in an annular region between the support cylinder and the walls of the Vessel.

The Vessel is housed below floor level in an extraordinarily robust cylindrical silo geometry lined with thick concrete which acts also as ultimate container for the liquid Lead in case of the highly hypothetical rupture of the Main Vessel. In the space between the Main Vessel and the concrete wall the Reactor Vessel Air Cooling System (RVACS) is inserted. This system [10] largely inspired from the ALMR design, is completely passive and based on convection and radiation heat transfer. In case of a thermal overheating, the significant dilatation of the molten Lead will raise the level of the liquid which (see Fig. 2) activates (1) the RVACS cooling, (2) stops the proton beam by flooding an appropriate emergency beam stopper (EBDV) and (3) scrams the EA at a lower multiplication coefficient $k \leq 0.90$. The whole Vessel is supported at the top by anti-seismic absorbers. Even in the case of an intense earthquake the large mass of the EA will remain essentially still and the movement taken up by the absorbers.

The fuel is made of mixed oxides, for which considerable experience exists. More advanced designs have suggested the use of metallic fuels or of carbides [11]. These fuels are obviously possible also for an EA. We remark that the use of Zirconium alloys is not recommended since irradiation leads to transmutations into the isotope ^{93}Zr, which has a long half-life and which is impossible to incinerate without separating it isotopically from the bulk of the Zirconium metal. The choice of the chemical composition of the fuel is strongly related to the one of the fuel reprocessing method.

A relative novelty of our machine when compared to ordinary Pressurised Water Reactors (PWRs) is the large concentration of ThO_2 in the fuel and the corresponding production of a small but relevant amount of Protactinium. A liquid separation method called THOREX has been developed and tested on small irradiated ThO_2 fuel samples [12]. The extrapolation from the widely used PUREX process to THOREX is rather straightforward and this is why it has been chosen [3] at least at this stage, as a “proof of existence”. Methods based on pyro-electric techniques [13] are most interesting and probably the way to go, though they still require substantial research and development work.

Since the destination of the Actinides is now well defined i.e. to be finally burnt in the EA, the leakage of Actinides in the Fission Fragment stream must be more carefully controlled, since they are the only Actinides in the "Waste". We have assumed that a "leaked" fraction of $f = 10^{-4}$ is possible for Uranium. The recycled fuel has a significant radio-activity. We have checked that the dose at contact is similar to the one of MOX fuels made of Uranium and Plutonium, already used in the Nuclear Industry.

The average power density in the fuel has been conservatively set to be $\rho = 55$ Watt/gr-oxide, namely about 1/2 the customary level of LMFBR[2] (ALMR, MONJOU, and EFR). The nominal power of 1500 MW_{th} requires then 27.3 tons of mixed fuel oxide. The fuel dwelling time is set to be 5 years equivalent at full power. The average fuel burn-up is then 100 GWatt day/ton-oxide. Since the fissile fuel is internally regenerated inside the bulk of the Thorium fuel, the properties of the fuel are far more constant than in the case of a PWR. As shown in Ref. [3], one can compensate to a first order the captures due to fission fragments, operating initially with a breeding ratio below equilibrium. All along the burn-up, the growth of the fissile fuel concentration counterbalances the poisoning due to fission fragments. *Therefore neither re-fuelling nor fuel shuffling appear necessary for the specified duration of the burn-up.*

No scheduled intervention is therefore foreseen on the fuel during the five years of operation, at the end of which it is fully replaced and reprocessed. Likewise in the "all-convective" approach there are no moving parts which require maintenance or surveillance. In short the *EA is a large, passive device in which a proton beam is dumped and the generated heat is extracted, without other major elements of variability.*

Normally the EA is well away from criticality at all times ($0.95 \le k \le 0.98$), there are no control bars (except the scram devices) and the power produced P_{EA} is directly controlled by the injected beam current. The accelerator [14] is a synchronous cyclotron with an accelerated continuous current of 10 ÷ 20 mA and kinetic energy of 1.0 GeV (Fig. 3). It makes use of warm magnets ($B_{max} = 1.8$ Tesla over 5 cm magnet gap) and RF-cavities. Experience with these machines has shown that the beam losses can be made sufficiently small so that no remote handling of the machine components is necessary. In particular the accelerator can be housed outside the containment region. The nominal external power provided by the beam is $P_{ext} = 12.5$ MW, corresponding to a gain $G = P_{EA}/P_{ext} = 120$. The heat flux extracted

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[2] This choice is motivated by the relative novelty of the "all-convective" approach and the relative scarce experience with ThO_2 , when compared with UO_2.

by the Lead coolant from the fuel pins is on the average 100 W/cm^2 = 1 MW/m^2. The peak power density in the beam window is of comparable magnitude, namely 113 W/cm^2 = 1.13 MW/m^2.

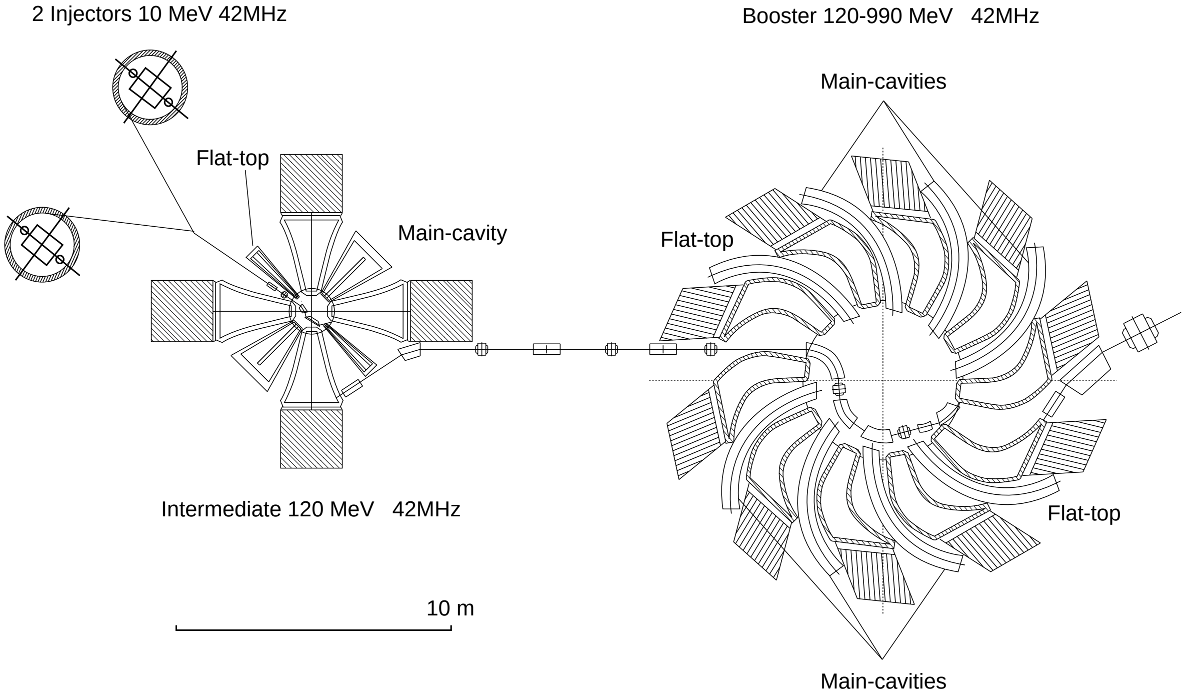

Figure 3. *General layout of the particle Accelerator.*

3.— INVESTMENT COSTS

3.1-The Energy Generating Unit (EGU) Its main function is the one of producing thermal energy by fission of the breaded fissile material in the Core. The energy is extracted by natural convection in molten Lead. There are two Lead columns, the hot rising and the cold down coming ones, with a Separator-Insulator in the middle which also acts in its inner part as support for the Spent Fuel Storage. Energy is extracted from the EGU with the help of 4 Heat Exchangers, placed at the top of the down coming Lead column. The Secondary loop is filled with an eutectic mixture of Lead-Bismuth. The high energy proton beam is brought through a beam channel to the spallation region located in the centre of the Core.

There are several ultimate passive safety systems which allow to stop the energy generation by fission and to extract the residual heat in the unlikely event of a failure of the normal control systems: the EBDV system, the MLAS and the RVACS.

The whole EGU is insulated at the top by the supporting anti seismic absorbers in order to ensure little or no damage even in the eventuality of very strong earthquakes. The conceptual design parameters of the EGU can be found in [3].

The overall approximate dimensions of the EGU are 8 m diameter and 36 m height (including the RVACS but without the four 30 m tall exhaust chimneys for the decay heat). Its total weight is about 10500 tons. The best cost estimate of the EGU is 58.98 M$. The uncertainty limits are 45.61 M$ and 67.51 M$ respectively. This figure is relevant to the sum of its various elements, which are analysed in detail next.

3.1.1-The Main Vessel. The Main Vessel houses most of the elements of the EGU. It also provides the first barrier for the liquid Lead coolant and supports the weights of the internal equipment and the coolant Lead. It can be subdivided in three parts, namely the Vessel, the Spool and the Cover. Its total weight is 405 tons and its best estimated cost is 13.77 M$, with an uncertainty range between 10.53 M$ and 15.39 M$.

1)The <u>Vessel</u> supports the weight of Lead and other internal equipment. It is approximately a cylinder of 6 m diameter, 30 m height and 7 cm thickness[3], with a hemispherical lower closure and an upper flange, made of high temperature resistant steel. It will have a ring of holes at the upper part to allow Lead overflow in case of Lead temperature transient. The Main Vessel operates at nearly atmospheric pressure and must withstand the following weights:

- Lead: 9350 tons nominal.
- Fuel: about 30 tons of fuel and 5 tons of breeder.
- Fuel pin claddings: 14 tons.
- Upper and lower core fixtures: 1 ton.
- Internals (upper & lower support structures): 40 tons.
- Thermal Insulating Wall (Separator): 33 tons.
- Spent Fuel Storage system: 66 tons.
- Refuelling Machine System (Pantograph): not yet estimated.

The weight of the Vessel itself is estimated to be 358 tons. Loads supported by the Vessel are transferred to the structural concrete by the upper flange (Fig. 4). The requirements on the Vessel are not so strict as those in the case of a PWR since it is not a pressurised vessel (except for the natural weight of molten Lead) and the radiation damage is negligible because of the larger distance from the

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[3] This thickness includes a large safety margin since 3 cm thickness is already sufficient to hold the Lead weight.

Core and the excellent shielding properties of Lead. The Spool and the Cover are thermally insulated since their operating temperatures must be close to the one of the Vessel. The regions of the Vessel without Lead are filled with a inert gas (Helium) at a small static over-pressure, slightly lower than the Lead-Bismuth pressure of the Primary Heat Exchangers. In this way, any leak will go in the sense Heat Exchanger-Main Vessel. The Vessel, the Spool and the Cover must be heated[4] before filling with Molten Lead in order to avoid thermal shocks. A unitary price of 34 $/Kg has been used for the Vessel, with a range between 26 $/Kg and 38 $/Kg. Therefore the total cost of the Vessel is 12.17 M$, with an uncertainty ranging from 9.31 M$ to 13.60 M$.

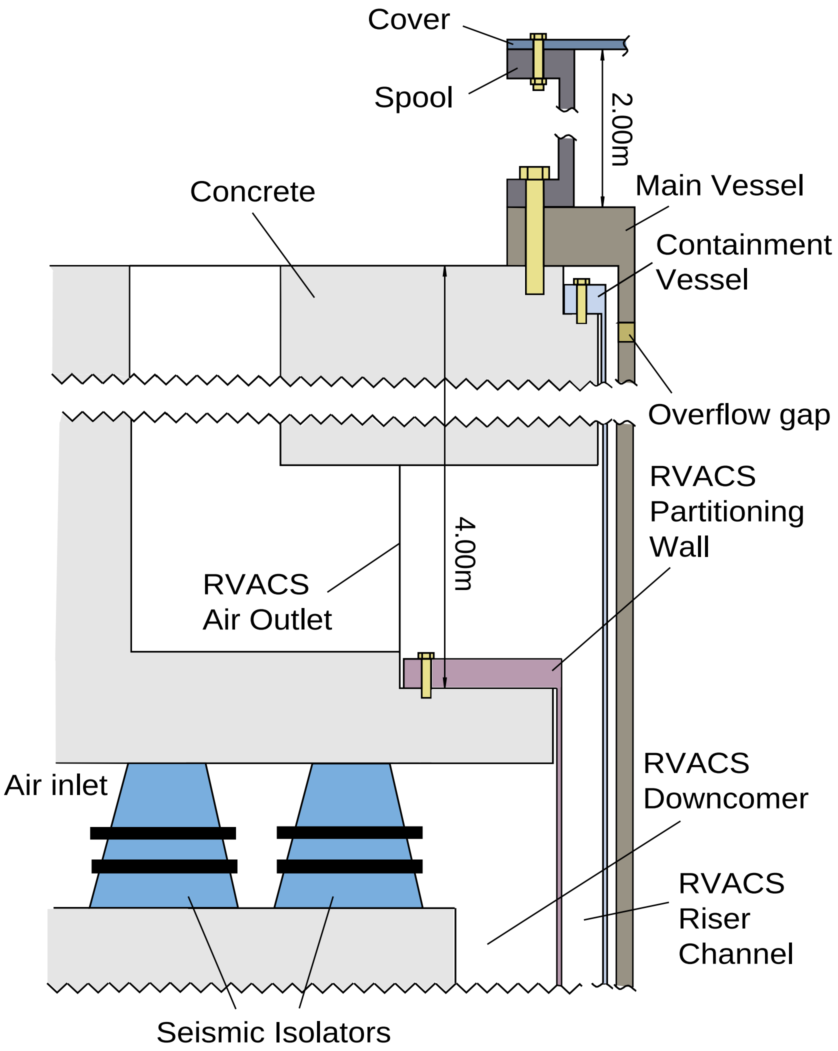

Figure 4. *Scheme of the Main Vessel, Containment Vessel and RVACS support structures.*

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[4] The initial warming up of the Vessel can be easily done either with the help of recirculating Helium gas or by other appropriate means.

2) The Spool holds the weight of the Main Heat Exchangers and provides inlet and outlet connections to the Secondary Coolant loop. It also connects the Helium gas filling to its purification system and provides the appropriate penetration paths for safety devices and instrumentation (presumably less than 50 penetrations, a typical number for a PWR vessel). It is a cylinder of 6.6 m diameter, 2 m height and 7 cm thickness. It has two flanges, one at the upper part joined to the Cover and another at the lower part joined to the Vessel (Fig. 4). It will carry eight nozzles (2 per Primary Heat Exchanger) with an approximate diameter of 1 m. It will have to support a maximum weight of 658 tons (162 tons per Primary Heat Exchanger filled with Lead-Bismuth) and a lifting force of 96 tons (24 tons per Heat Exchanger in the Lead submerged position). The Spool weights 32 tons. The unitary cost and cost range are considered to be similar as for the Vessel. The estimated Spool cost ranges between 0.83 M$ and 1.22 M$, with a best estimate of 1.09 M$.

3) The Cover ensures the tightness of the Main Vessel. It holds the Beam Channel which includes the Emergency Beam Dump Volume System (EBDV) and eventually the refuelling machine. It is a flat plate cover with an approximate thickness of 5 cm. It has at its centre the porthole for the beam channel and several viewing ports allowing visual inspection and/or sampling. Eventually it may also provide space to anchor the Fuel Transfer Machine (Pantograph), in which case its parameters might have to be appreciably redefined in order to accommodate for the extra weight. The Cover weighs 15 tons. The previously indicated unitary cost and uncertainties have been used, leading to a best estimate of 0.51 M$ (0.39 - 0.57 M$).

3.1.2 - The Containment Vessel. It acts as a secondary barrier for Lead leaks from the Main Vessel and in case of a temperature transient causing a Main Vessel Lead overflow, it activates the RVACS system to extract the residual heat. It consists of a cylindrical vessel (6.26 m internal diameter, 32.2 m height and 3 cm thickness) with a hemispherical bottom closure of 3.13 m internal radius. It has a flange in the upper part to anchor the Vessel to the concrete structure (Fig. 4). The requirements of the Containment Vessel are similar to those of the Vessel, although somewhat less strict. The gap adopted between the Main and Containment Vessels takes into account the standard working conditions (400 °C in the Vessel walls) and the fact that the RVACS system is fully operational with a Lead temperature increase of approximately 200 °C above the initial overflow temperature (which is 50 °C over the nominal operating temperature). The Containment Vessel weights 157 tons.

The unit cost value for the Containment Vessel has been aligned to the one of the Vessel, although it might be slightly cheaper because of the less demanding requirements. Hence the upper cost limit has been maintained and the lower cost limit slightly decreased (22 $/Kg). Therefore the best estimate of the cost is 5.34 M$ (3.45 - 5.87 M$).

3.1.3 - Core and Core Support Structure. The Core generates heat mostly by fissions of the fissile material. The Core is made of 120 fuel bundles and 42 breeder bundles disposed in an hexagonal array [3]. The nominal amount of fuel, made of a mixture Thorium-Uranium Oxide, is 28.41 tons. The Thorium Oxide in the breeder is 5.6 tons. The Core Support Structure holds the Core in the upper and lower positions, with and without buoyancy. It also locks accurately in position the fuel elements and allows the locking-unlocking operations by the Fuel Transfer Machine (Pantograph). It ensures an accurate location to the MLAS system and to the Core instrumentation.

A detailed engineering design of the Core Support Structure is still pending. At this stage, the Core Support Structure has been modelled as a disk 15 cm thick, made of 60% of steel, the remaining 40% being holes for various purposes. From these dimensions, its weight has been estimated to be 40 tons. The total weight of the assembly including the fuel elements is about 92 tons and the lifting force in Lead (because of its buoyancy) of the order of 37 tons.

The unit cost of the EA fuel is about 20.31 $/Kg. The cost of a fuel is about 0.58 M$. The cost of the breeder is 0.06 M$ and the total cost is about 0.64 M$. Costs include fuel fabrication and all the necessary steps in the front-end as well as in the back-end of the fuel cycle. The cost of the fuel is not counted as an investment cost and its contribution to the energy cost is calculated separately under the item “Fuel Cycle Cost”.

In the absence of a detailed design we have adopted for the Core Support Structure an unit cost estimate similar to that valid for a PWR, namely 108 $/Kg. Therefore the cost and cost range of the Core Support Structure is 4.32 and 3.46 - 5.18 M$ respectively.

3.1.4 - Separator and Fuel Storage. It provides a barrier between both the hot and cold legs of the main natural circulation loop and a temporary storage of the spent fuel elements. It consists of a cylindrical barrel (3.65 m external diameter, 26.5 m height) incorporating a thermal barrier. The solution adopted consists of a reinforced double wall barrel with vacuum in between (Fig. 5). Both walls and the vacuum region are 1 cm thick. The spent fuel will be placed in four rings along the perimeter, requiring a vertical allowance of 15 m. The total weight is 56 tons, and 108 tons including the spent fuel.

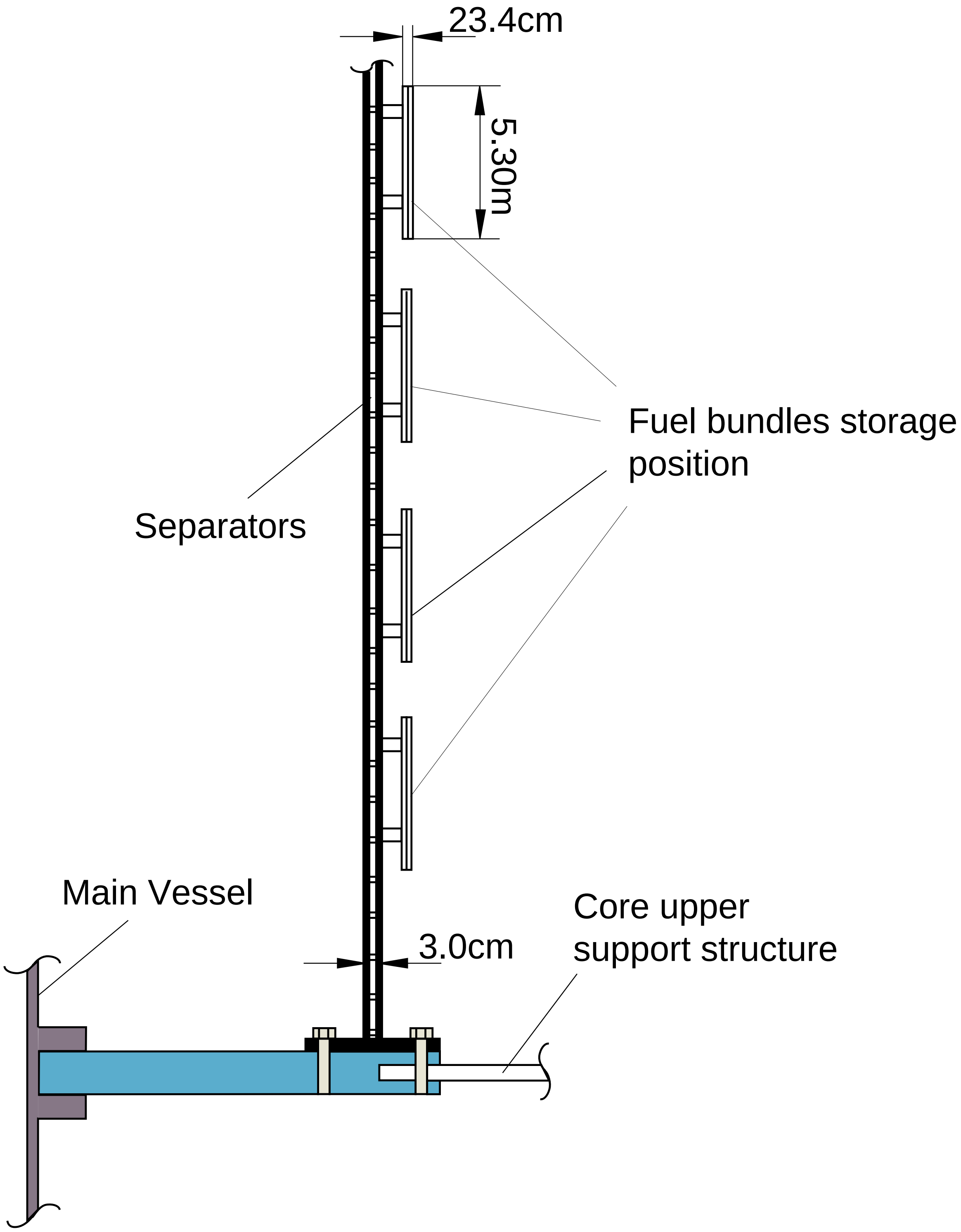

***Figure 5**. Layout of the Separator and Fuel Storage.*

The Lead lifting force of the Separator is 108 tons and, including the fuel, the total force is approximately 134 tons. The Separator has straightening studs to ensure its positioning in the Vessel.

Its unitary cost has been assumed equal to the one of the Core Support Structure (108$/Kg), although it might be somewhat lower (cost range 75.6 - 130 $/Kg). The corresponding best estimated cost is 6.05 M$ and within the bracket 4.23 - 7.26 M$.

3.1.5 - Main Coolant (Molten Lead). It is used in the Main loop of the EGU as spallation target material, Core coolant and neutron reflector. As explained in Ref. [3] its choice is optimal because of its high atomic number, low capture neutron cross section, good chemical stability at high temperatures and its thermodynamical properties which allow an effective natural convection. It also a very effective shield, thus reducing the radiation damage to the Vessel and other key elements of the Main Vessel.

The Lead passes through the Core extracting the nuclear produced heat and moves up to the top part of the Lead column, where it is cooled by the Lead-Bismuth Secondary loop in the Primary Heat Exchangers. The difference of density between the cold and hot Lead columns produce the necessary driving force to maintain the natural convection at the required velocity to extract the heat of the Core and transfer it to the Primary Heat Exchangers.

The total Main Coolant Lead volume is estimated to be 905 m^3 (9350 tons). The unit cost used is 0.84 $/Kg, the current quote when bought in small amounts and adequate purity. It may become lower because of the large amount needed, but the saving might be offset because of unforeseen purity requirements. Therefore we have adopted the quoted unit cost with an uncertainty of 10%. The corresponding total cost is 7.85 M$ (7.10 - 8.60 M$).

3.1.6 - Beam Window and EBDV system. The Beam Window is located at the end of the beam inlet channel, bringing the high energy proton beam near the centre of the Core where the neutron production by nuclear cascades occur. The EBDV system makes use of the expansion properties of Lead with rising temperature in order to fill with Molten Lead a normally empty volume at the top of the Main Vessel, thus preventing the access of the Fuel Core to the beam (beam stopper).

The Beam Channel is a long, evacuated[5] cylindrical pipe 29 m in height and 20 cm diameter. It ends in a hemispherical window of 20 cm diameter. The cylinder

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[5] In reality the level of the vacuum is of the order of 10^{-3} Torr and it is determined by the residual

thickness is 6 mm and its material is an appropriate steel (HT9 characteristics have been used). The Beam Window through which the beam is passing is made of Tungsten with a variable thickness of 1.5 mm minimum and 3 mm maximum [3]. The Beam Channel is guided by the upper part of the Core Support Structure.

The EBDV device is a double cylinder with a gap in between, partially filled with Lead during normal operation [3]. The cylinders communicate in the top part and the gap between both cylinders is opened, as Lead inlet from the Vessel, in its lower part. Inside the inner cylinder there is a passive valve which closes the Beam Channel when the Lead enters due to the expansion caused by a temperature increase. The valve can be of a float type. Both cylinders can be made of steel, their height and thickness can be 2 m and 0.3 cm respectively, and the inner diameters 50 cm for the outer cylinder and 40 cm for the inner one. The total weight is then 1 tons (0.85 tons due to the Beam tube and 0.15 to the EBDV). The buoyancy force will be about 11.7 tons (7.0 tons for the Beam tube and 3.9 tons for the EBDV). The cost of the Beam Window and EBDV system is 0.05 M$ (0.03 - 0.07 M$).

3.1.7 - Primary Heat Exchangers. There are four Heat Exchangers which serve to remove the heat produced in the Core, using the natural convection in the Main Coolant loop. There are different options for the design of the Heat Exchangers, with a final choice depending on the detailed engineering design.

One option is of the type 1-2 shell and tube (Fig. 6). The shell is reduced to an upper and lower plenum chamber with Primary Coolant Lead flowing freely outside the tube bundle. The heat load of each Heat Exchanger is 378 MW. The Primary Coolant Lead inlet and outlet design temperatures are 600° C and 400° C respectively. The Secondary coolant inlet and outlet design

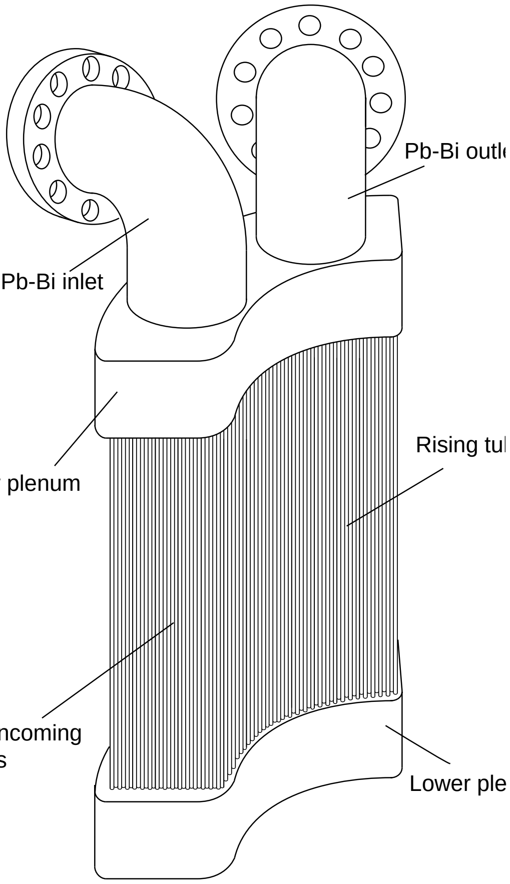

Figure 6. *Layout of the 1-2 shell and tube Heat Exchanger model.*

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vapour pressure of Lead at the operating temperature. For more details see Ref. [3].

temperatures are 200° C and 550° C. The total heat exchange surface is 1924 m^2. The plenums can be 20 cm high with a wall thickness of 3 cm, except in the two plates where the tubes are attached, for which the wall thickness should be higher, 5 cm. There are 6861 tubes, 23 mm outer diameter, 0.5 mm thick (which might have to be better optimised by an engineering design) and 4 m length. The tubes are arranged in a triangular type of array with 25 mm pitch.

The flow surface requirement imposes an occupation of about 85% of the total surface available between the Main Pressure Vessel and the Separator (15 m^2 over a total surface of 17.7 m^2). Therefore, each of the four Primary Heat Exchangers occupy an arc of about 90° between the two concentric cylinders (Fig. 7).

The inlet and outlet connections to the Secondary Coolant Loop are in the upper plenum and the corresponding pipes can also serve as structural to support the Heat Exchanger weight. In this option there are one inlet and another outlet Lead-Bismuth pipes having 1 m inner diameter and 2 cm thickness, depending on the Lead-Bismuth working speed. Their shape is toroidal. The pipes are attached to the Spool to which they transfer the Heat Exchanger load.

Details about this Heat Exchangers option and Lead-Bismuth connecting pipes are given in Fig. 7. Including the plenums, tubes, thermal protections, pipes, etc., each Heat Exchanger will have an approximate weight of 30 tons. When filled with Lead-Bismuth the total weight will be about 162 tons. The lifting force in Lead of each Heat Exchanger is about 24 tons.

The above design is well matched to our requirements [15]. It is of relatively novel design with regards to the shape and the overall arrangement of headers and tubes. The diameter of the connecting pipes is relatively large (1 m), matched to the slow coolant speed of the order of 0.9 m/s. The diameter and corresponding Lead-Bismuth speed may vary according to design optimisations.

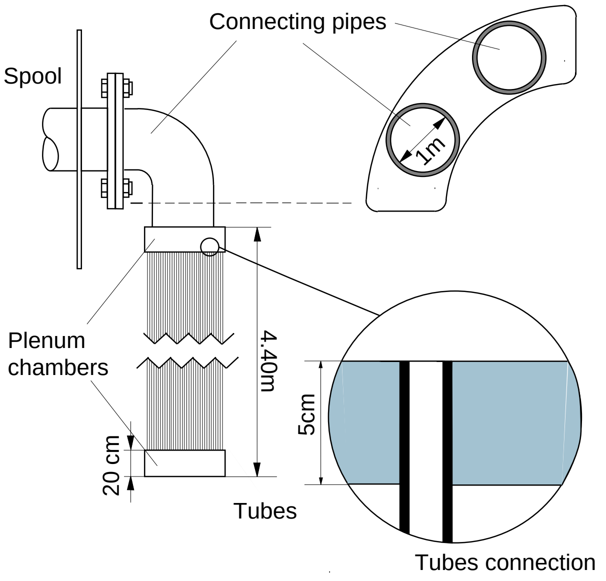


Figure 7. *1-2 shell and tube Heat Exchanger model with the inlet and outlet connecting pipes.*

The possible leaks of the Secondary Lead-Bismuth loop should be continuously monitored for instance taking samples of coolant and eventually using activation methods.

Extrapolation from existing equipment gives a cost estimate for one Heat Exchanger of 3.10 M$. An estimate of the cost range is 2.48 - 3.41 M$. Therefore the total cost and cost range of the four Heat Exchangers will be 12.4 M$ and 9.92 - 13.64 M$ respectively.

There are other alternative options for the Heat Exchanges, like the 1-1 shell and tube (Fig. 8) with only one Lead-Bismuth passing and three connecting pipes (one inlet and two outlets), or by using U-shape tubes. The main general characteristics are similar and the cost estimate will not differ significantly from the adopted figure.

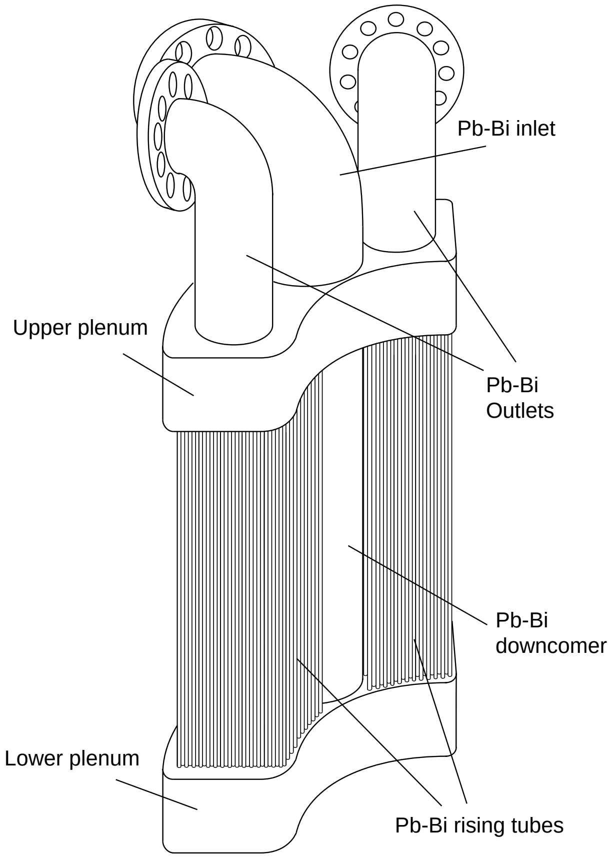


***Figure 8**. Layout of the 1-1 shell and tube Heat Exchanger model.*

3.1.8 - The RVACS system. It removes the decay heat through passive, natural convection air cooling in the unlikely event that all active cooling systems fail. It consists of two annular regions (channels), the down comer and the raiser, which allow a natural air circulation around the Containment Vessel. The design width of the channels are 57 and 18 cm respectively. For a Containment Vessel temperature of 500°C the air flow rate is 53 m^3/s [3]. At the top of the Containment Vessel the natural air circulation is enhanced with the help of a 30 m tall chimney. The thickness of the partition wall is about 2 cm and, if made of steel, it weighs 184 tons.

The inlet connections to the down comer channel are made with short pipes in the seismic elastometers area close to the ground surface level. The outlet connections to the raiser pass through pipes embedded in the concrete. The required [3] air flow of 53 m^3/s is attained with four 1 m diameter pipes and an average air speed of 8.5 m/s.

Here we include only the partition wall since all other components are included in the Civil Work section. The unitary cost is 15 $/Kg with a range 13 - 17 $/Kg. The best estimate of the cost is 2.76 M$ and the cost range 2.39 - 3.13 M$.

3.1.9 - Fuel Transfer Machine. The system allows the extraction of the fuel elements from the Core, their transport to the Fuel Storage area and their unloading in the appropriate storage positions. It is also needed to position the fresh fuel elements in the Core. Finally it has to take the spent fuel elements out from the storage region and make them accessible for extraction.

The Pantograph will have to operate in hot, molten Lead. The lifting (buoyancy) force of a fuel element is about 160 kg. To facilitate the refuelling process it might be convenient to compensate the lifting force with an additional weight made with a denser material, f. i. Tungsten.

Table 1. *Main components of the Fuel Transfer Machine (Pantograph)*

Item	*Million US $*
Precision positioning system	3.10
Hydraulic precision system	0.40
Core reference positioning system	0.24
Bundle extraction system	0.24
Control system	0.40
Mechanisation and fabrication	1.50
Assembly	0.40
Others	0.16

The Pantograph is a component for which a complete design has to be developed, although similar devices are in use in Sodium cooled Fast Breeders. The described functions could be fulfilled by the following systems:

- A two axis positioning system similar to those of a machine tool but able to give an accuracy of about 1 mm in 5 m distance.
- An extensive telescopic boom using a hydraulic or pneumatic system.
- A Core reference positioning system for interlocking in the Core Support Structure and later positioning of the telescopic boom.
- An extraction system using an appropriate linkage device.
- An adequate chart and control system.

Indicative costs of the components are shown in Table 1. Based on such a cost estimate, the total cost is 6. 44 M$ and the range 4.50 - 8.37 M$.

3.2 - Secondary loop

It transports heat from the Primary Heat Exchangers to the steam feeding the turbine. In the design of Ref. [3] it is operated with a Lead-Bismuth eutectic mixture (56.1 % Bi) although other coolants might be considered. This choice is determined by the low melting point temperature of the eutectic system (125 °C), close to the one of molten Sodium (98 °C) for which ample experience exist as a heat exchanger fluid. The circuit will be operated by convection boosted by additional pumping. The nominal temperatures in the Primary Heat Exchangers have already been given in the previous paragraph. The steam production and re-heating equipment has not yet been defined, though it is entirely conventional. It could be done with two separate units:

– One steam Boiler.
– One steam Reheater.

or, as it is done, for instance, in SuperPhenix, with a single Boiler-Reheater unit. There are also several options for the whole Secondary loop set-up, the decision being the result of a detailed engineering design: four secondary loops each one with a Boiler-Reheater, or two loops with two Boiler-Reheaters, or even one single loop. Approximate value of the main parameters are given in Table 2. Since the total pumping power and steam characteristics are independent of such a choice, the cost estimate is not expected to be significantly different for the various options.

Table 2. *Nominal working conditions of the Boiler-Reheater*

Item	*Temperature* °C	*Pressure* *bar*
Lead - Bismuth inlet	550	
Lead - Bismuth outlet	200	
Reheated steam outlet	475	175
Feed water	180	200

The overall flow rate per Primary Heat Exchanger is about 2500 m^3/h. At this rate, electromagnetic pumps are considered adequate, although it may require some development. The connecting pipes between the Primary Heat Exchangers and the Boiler-Reheater Unit/s can be made of steel. The dimensions for the one loop option, 1 m internal diameter and 2 cm thickness correspond to a Lead-Bismuth speed of 0.9 m/s. The diameter can be reduced easily by increasing the speed. The average distance travelled from the EGU to the Boiler-Reheater is estimated to be about 10 m. In these conditions the inventory of Lead Bismuth required is about 1950 tons, distributed as shown in Table 3.

***Table 3**. Lead-Bismuth inventory in the Secondary Loop*

Item	*Inventory (ton)*
Primary Heat Exchangers & Main Vessel pipes	520
Pipes out of the Main Vessel	628
Boiler-Reheater	800

The complete circuit is then made of the EM pumps, the Boiler-Reheater, a Lead-Bismuth Expansion Tank and the connecting pipes. The Expansion Tank is required in order to detect steam leaks in the Boiler-Reheater causing a steady pressure increase in the Tank gas phase. It also represents an expansion tank in order to absorb the volume changes during normal operation. Its dimensions are 2 m internal diameter and 3 m height, allowing a level increase of 1 cm/30°C. The pumping flow rate is 2500 m^3/h with a pressure difference slightly larger than 1 atm, to which one has to add the pressure drop of the whole circuit. A "Reservoir" is required for the initial heating and dumping of the Lead-Bismuth. The Tank should be capable of storing 2000 tons of Lead-Bismuth (250 m^3).

EM pumps for Lead are commercially available. However, the flow rate of these pumps is currently limited to about 100 m^3/h. The cost estimate, probably largely overestimated since based on the cost of the current pumps linearly scaled to higher flow rates, is 17.30 M$ (13.84 - 22.49 M$).

The cost estimate of the steam Boiler-Reheater Unit (for instance of helical type) is derived from existing equipment, namely 29.5 M$ (23.6 - 35.4 M$). Pipes and support structures are estimated at 3 M$ (2.4 - 3.6 M$).

The unit cost of the eutectic Lead-Bismuth is currently high since the lack of Bismuth demand has originated in the closure of Bismuth mines, particularly in Bolivia. We use the current unit cost of the eutectic 5 $/Kg and a range of 3 $ - 5.5 $/Kg). The total cost of the Lead-Bismuth inventory is then 9.75 M$ (5.85 - 10.72 M$).

The cost of the Expansion Tank is considered negligible compared to the cost of the other components of the circuit. Including the Boiler-Reheater, the EM pumps, the Expansion Tank and the pipes, the cost of the Secondary loop is 59.55 M$ (45.69 -72.21 M$).

3.3 - Accelerating system.

It is designed to produce a proton beam of 1 GeV kinetic energy with a nominal intensity of 12.5 mA. The expected over-all efficiency, namely the beam power over the mains load is of the order of 40% [3]. The Accelerator scheme is based on three stages of cyclotron accelerators (Fig. 3), namely in succession: (1) the Injector, made of two 10 MeV Compact Isochronous Cyclotrons (CIC), where beams are merged with the help of negative ion stripping; (2) the intermediate stage (ISSC) bringing the beam up to 120 MeV; (3) the final booster (BSSC) rising the kinetic energy up to 1 GeV.

The cost estimate and cost range of the three stage cyclotron accelerator is 170.87 M$ (153.22 - 202.17 M$). The necessary shielding is estimated at 7.95 M$ (0.38 M$, 1.9 M$ and 5.67 M$ for the Injector, the ISSC and the BSSC respectively). The 15 MW cooling station adds 5.63 M$. The electrical power system for the accelerator complex is included in the general switchyard of the installation. The total cost best estimate is 184.45 M$ (165.45 - 217.10 M$).

Such total cost has been calculated from the cost of each component of the four main subsystems, namely 1) the CIC, 2) the ISSC, 3) the BSSC and 4) the Beam Transport. In all cases the estimates are based on the existing experience as well as on the information requested from potential suppliers.

The large pole pieces of the ISSC and BSSC magnets require tight tolerances in machining and a good reproducibility of the main coils, which requires a precision of the order of 0.2 mm over 2 m distances. Magnetic measurements are needed for each magnet and consequently some appropriate tooling. The row material for the pole pieces is low carbon steel in the form of laminated or cast iron depending on the size.

The HF Cavities of the BSSC are composed of three main parts: 1) the accelerating electrode made of Copper supported by precise Stainless Steel (316 LN) structures, 2) The liner to which the cooling circuit is welded, also made of copper, having a total surface of 55 m^2 and a weight of 3 tons for a thickness of 5 mm, and 3) the vacuum chamber support made of Stainless Steel and having a weight of about 25 tons per cavity. The machining is the most critical issue and accounts for 70% of the cost. Three RF feedthroughs and one movable tuning panel per cavity has been considered. In the case of the ISSC the total surface of the liner is 25 m^2 and the total weight of the vacuum chamber 10 tons.

The HF Amplifiers generate 800 kW of RF power for each cavity of the ISSC and 2 MW for each cavity of the BSSC. The same value of the fundamental accelerating frequency is used for all the accelerators. Cost includes the power tubes, drivers, RF cabinets, transmission lines, power supplies, low level controls, etc.

3.3.1 - Injection system. It generates a continuous external beam of the order of 6 mA at 10 MeV. Beams from two such injectors, one accelerating protons (H^+), the other negatively ionised hydrogen atoms (H^-) are combined to produce a single beam in the intermediate ring. The two injectors are synchronised and the bunches are combined in a straight section of the second stage (ISSC) injection line. Merged H^+ and H^- beams have much smaller repulsive, electrostatic space-charge effects. A stripper is installed at the end of the injection line, before the beam enters the ISSC magnetic field in order to get a “pure” H^+ beam. Each injector cyclotron is composed of:

a) A four sector magnet excited by a single cylindrical coil.

b) An axial injection system with the following characteristics :
- A high voltage platform at about 100 kV.
- An external multicusp ion source for the production of H^- ions.
- A buncher to slightly increase the intensity while avoiding too strong longitudinal space charge effects.
- 3 focusing lenses.
- Diagnostic stations.
- A spiral inflector to bend the beam in the median plane.
- Pumping system.

c) The RF system, which consists of two accelerating and two auxiliary cavities. A classical $\lambda/2$ coaxial-type accelerating cavity with a single circular stem has been selected breaking through the return yoke. The auxiliary cavities operate according to a coax-like fundamental mode. Long stem extension along the electrode is necessary in order to meet the requirement frequency and voltage.

d) An electromagnetic channel with a septum in order to extract the beam.

e) Internal destructive and non destructive diagnostics probes remotely controlled.

Cost estimates for one CIC are detailed in Table 4.

***Table 4**. CIC Mechanics and Electronics*

	Item	*Million US $*
a) Mechanics		
	Magnet (iron + coils + lifting system + ass. tools)	0.80
	RF cavities	0.68
	Vacuum chamber + pumping	0.46
	Injection line	0.38
	Extraction channel (electromagnetic channel)	0.23
	Diagnostics	0.17
	Cooling	0.13
b) Electronics		
	Power supplies	0.34
	RF amplifiers	1.20
	Controls	0.10
	Injection line	0.19
	Diagnostics	0.10

The total cost of one CIC is 4.78 M$ and hence the cost of the injector system is 9.54 M$ (8.58 - 10.49 M$).

3.3.2 - Intermediate Separated-Sector Cyclotron (ISSC). It raises the kinetic energy of the injected beam (10 MeV) to 120 MeV. A four-separated sector cyclotron has been chosen because of the following features :

- It has good focusing properties.
- The acceleration can be achieved in about 200 turns due to the possibility to install between the sectors cavities providing a high accelerating voltage and a good turn separation at extraction.
- The cavities can be easily inserted in the valleys.
- An efficient extraction channel can be located in the field-free valleys.

The main components are:

a) Four separated sector magnets weighing in total 1000 tons.

b) RF cavities: Double-gap cavities for both acceleration and flat-topping purposes have been selected thus leaving space in the centre of the machine for the bending and injection magnets, as well as the beam diagnostics. Losses in each accelerating cavity are estimated to be 220 kW for 170 and 340 kV accelerating voltage at injection and extraction orbits.

c) Injection channel: At the end of the combined beam line from the injectors, a stripper produces a pure proton beam, which is injected in the cyclotron through a valley along a flat-topping RF cavity in order to avoid the effect of the fringe field of the magnet sectors. The beam is deflected by two bending magnets BMI1 and BMI2 before entering the electromagnetic channel EMDI, located in one of the cyclotron sector gaps and reaches the first RF cavity gap where acceleration begins. An electrostatic deflector (located in one of the valleys where a flat-topping cavity is installed) is used to steer radially the beam position in order to ensure that the first internal orbit is sufficiently separated from the injected orbit and more generally that the injection conditions in the ISSC are optimised.

d) Extraction channel: A simple system is used to extract the beam with a very high efficiency, consisting of an electrostatic deflector ESDE, an electromagnetic deflector EMDE and a bending magnet. The three channel components are

Table 5. *ISSC subsystems cost estimate and cost range*

	Item	*Best Estimate Million US$*	*Range Million US$*
a) Mechanics			
	Magnet (iron + coils + ass. tools)	9.50	8.55 - 11.40
	RF cavities (+Flat-top cavities)	6.65	6.00 - 7.61
	Vacuum chamber + pumping	6.65	6.00 - 7.33
	Injection channel	2.85	2.57 - 3.14
	Extraction channel	2.85	2.57 - 3.14
	Diagnostics	1.14	1.03 - 1.25
	Misc.	1.90	1.71 - 3.80
b) Electronics			
	Power supplies	1.90	1.71 - 2.09
	RF amplifiers	2.85	2.58 - 3.15
	Controls	0.76	0.68 - 0.84
	Injection channel	0.76	0.68 - 0.84
	Extraction channel	0.67	0.60 - 0.73
	Diagnostics	0.95	0.86 - 1.05
	Misc.	0.95	0.86 - 1.90

located in two successive valleys. After the beam is kicked out from the last internal orbit by the ESDE, located at the exit of a main RF cavity, it passes through a magnet sector and is further deflected by the EMDI to the entrance of the next valley. The last section is a conventional bending magnet, which is located in the valley behind a RF flat-topping cavity.

e) Internal destructive and non-destructive diagnostics probes remotely controlled.

Relevant costs are summarised in Table 5. The total cost is 40.38 M$ (36.34 - 48.21 M$).

3.3.3 - Booster Separated-Sector Cyclotron (BSSC). It serves to boost the energy of the beam coming out of the ISSC up to the requested final kinetic energy. It is a 10 sectors-6 cavities machine. In order to obtain sufficient vertical focusing at high energies, a spiral is needed on the edges of the magnet sectors. The sector angular width and magnetic field level (1.8 T) have been selected to get the required focusing strengths. It has the following main components:

a) 10 or 12 sector magnets.

b) RF cavities: Acceleration of the beam is provided by 6(8) main resonators located in the valleys. Two flat-topping cavities are needed at the fifth harmonic of the main cavities, i. e. 210 MHz. The main cavities accelerating voltages are 550 kV at injection and 1100 kV at extraction. The shape of the cavities is being optimised in order to reduce the losses to less than 400 kW. Cavities handle about 1.7 MW of beam power and the RF power transmitted to each cavity is about 2.1 MW. A single RF window can safely handle only up to 600 ÷ 700 kW. Therefore a minimum of three windows are needed in each cavity.

c) Injection channel: The beam is injected through one of the empty valleys and deflected clockwise towards the machine centre by the first bending element BMI1. After a straight section, it is successively bent counter-clockwise by the four following bending magnets BMI2 to BMI5, of which location and magnetic field has been adjusted to clear out both the neighbouring cavity and the sector magnet. An additional electromagnetic deflector is used in the subsequent sector nose in order to bring the beam in the first RF cavity gap in the appropriate conditions for an efficient beam acceleration and transport in the cyclotron.

d) Extraction channel: An electrostatic deflector ESDE located in the free valley deflects the beam in order to get sufficient separation from the last internal orbit, such as not to interfere with the electromagnetic deflector (EMDE) structure. The last element of the extraction system, the bending magnet BME, is located far enough from the magnet yoke to provide room for the injection beam line passing between the yoke and the bending magnet itself. Additional elements between EMDE and BME are radially focusing the beam which experiences the strong effects of the sector fringe field.

e) Remotely controlled internal destructive and non-destructive diagnostics probes.

Costs are given in Table 6. The total cost is 115.33 M$ (103.78 - 136.73 M$).

***Table 6**. BSSC subsystems*

	Item	*Best Estimate Million US$*	*Range Million US$*
a) Mechanics			
	Magnet (iron + coils + ass. tools)	35.15	31.62 - 43.70
	RF cavities (+Flat-top cavities)	18.05	16.25 - 19.95
	Vacuum chamber + pumping	19.00	17.10 - 20.90
	Injection channel	3.99	3.59 - 4.39
	Extraction channel	6.65	5.98 - 7.32
	Diagnostics	1.90	1.71 - 2.09
	Misc.	3.42	3.08 - 4.75
b) Electronics			
	Power supplies	5.70	5.13 - 6.27
	RF amplifiers	14.82	13.32 - 19.00
	Controls	1.90	1.71 - 2.09
	Injection channel	1.33	1.20 - 1.52
	Extraction channel	1.52	1.37 - 1.90
	Diagnostics	0.95	0.86 - 1.52
	Misc.	0.95	0.86 - 1.33

3.3.4 - Beam Transport. It is required in order to transport the beam from each unit of the Accelerating System to the next and from the whole Accelerator complex into the EGU. It has three parts:

- From the Injector to the ISSC,
- From the ISSC to the BSSC and
- From the BSSC to the EGU.

The cost of the beam transport Injector-ISSC is the following:

- 1 steering magnet, 2 quadrupole triplets, 3 quadrupole doublets, 4 pumping stations, cross, turbo molecular pump, converter, primary pump, pipes, valves, bellows and vacuum gauges - 0.39 M$.
- 5 CIC emittance measuring stations, 6 bending magnets, 7 diagnostic stations, 8 combining magnets and a buncher 42 MHz - 0.26 M$.
- Power supplies - 0.48 M$.

The total cost is 1.13 M$ (1.02 - 1.24 M$). In the absence of detailed designs and on the basis of current practices we estimate the cost of the beam transfers ISSC-BSSC and BSSC-EGU to 2.0 (1.5 - 2.5 M$) and 2.5 M$ (2.0 - 3.0 M$) respectively. The total cost estimate and cost range are 5.63 M$ and 4.52 - 6.74 M$.

3.4 - *Assembly*

This item refers to the assembly of the EGU, the Accelerating system and the Secondary loop. As already mentioned, the basic engineering of a standard design of an EA Unit is part of a previous special R&D programme and its cost is not included in this evaluation. According to common practice, the cost of the assembly of an already defined system is about 12.5% of the cost of its components, within a relative uncertainty margin of roughly ± 20%, depending on complexity and experience in assembling similar systems. In our case, most components are simple and their number is relatively modest. In addition there are no critical subsystems which may require special or delicate adjustments. Nevertheless we retain the figure of 12.5%, which includes the costs of tooling. The cost of the assembly of the EGU, the Secondary loop and the Accelerating system is then 37.88 M$ (30.30 - 45.45 M$) respectively.

3.5 - Instrumentation and Control

The control of the main parameters of each component of the EGU and the Secondary Loop include the EGU protection and control systems, the control room, the monitoring and diagnostic (including radiation protection), the fire protection, sensors, transmitters, impulse pipes and valves as well as the necessary cables. It does not include the Balance of Power Instrumentation and Control since it will be considered in the Mechanical and Electrical classical equipment. The protection system has the following functions:

- To scram the EGU when safety set points are exceeded.
- To process all Class 1E post accident monitoring sensors.
- To close the RVACS louvers at low Lead temperature.
- To isolate the Secondary loop from the Water Steam loop in case of an Steam Generator failure.

The protection system will process the following input parameters:

- Cover gas radiation level.
- Lead level.
- Bismuth inventory in the Vessel.
- Core outlet and inlet temperatures, including the high fuel element outlet temperature.
- Neutronic flux measurements.
- Secondary loop pressure.
- Fuel failure detection.
- Loss of station service power.
- Earthquake acceleration.

Pending an engineering design, the evaluation is based on the following assumptions:

- The instrumentation needed for the primary system is strongly reduced in comparison to a conventional fast reactor. About 500 primary instruments are assumed to be installed in the primary system.
- The Scram actuation system is strongly simplified.
- The Instrumentation and Control required for the Secondary loop is less than for a conventional Fast Reactor.
- The Control Room is significantly simpler than for a conventional Fast Reactor. However, its cost is supposed to be similar since it contains the overall Accelerating System control.

Our best estimate is 35 M$ with an uncertainty margin of 28 - 42 M$, distributed according to the following percentages: 65% for the Primary system including processing signals to and from the Accelerating system, 15% for the Secondary loop and 20% for the Control Room.

3.6 - Auxiliary systems

They provide the Lead heating and dumping, Lead-Bismuth heating and dumping and the He heating and compression. The Lead Heating and Dumping Tank can be visualised as an insulated steel vessel of 150 m^3, with comparable diameter and height and dished heads, placed underground in a location where the highest point of the Tank remains below the lowest point of the Main Vessel. The Tank can be equipped with a compression He system in order to push the Lead into the Main Vessel (40 Kg/cm^2 is enough). It can also include the heating system to melt and heat up the Lead (Fig. 9).

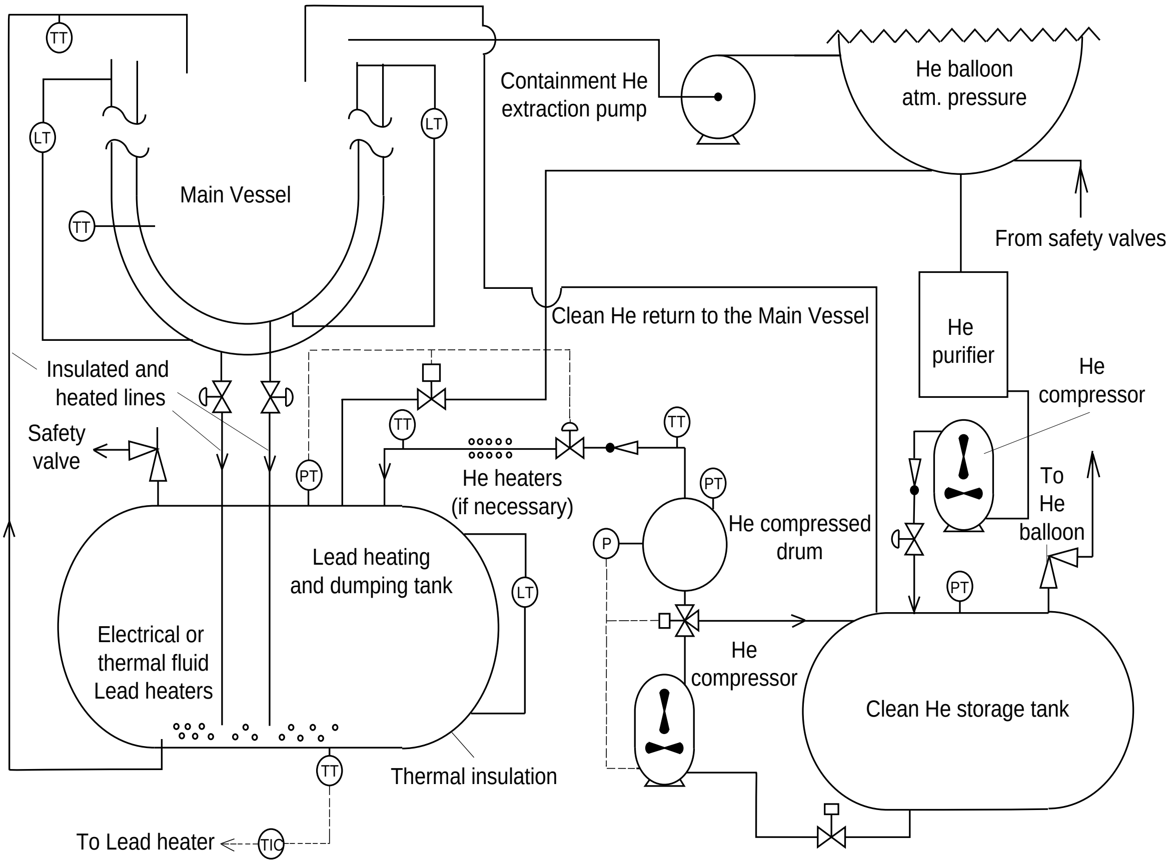


Figure 9. *Scheme of the Lead heating and dumping and the He compression and heating systems.*

An installed power of 350 kW allows to melt the full 10000 tons of Lead and to bring it to 400 °C in about one month. The He system may also be used to maintain the He atmosphere over the Lead in the Main Vessel during normal operation and to warm up the Main Vessel before its initial filling with hot Lead (in order to avoid localised thermal shocks).

The Lead-Bismuth Tank is an insulated steel vessel of 250 m^3, with equal diameter and height values, which may be placed at ground level close to the

Secondary loop. A power of 40 kW is enough to melt and heat the Lead-Bismuth, in about one month, until it reaches a temperature of 200 °C.

Table 7. *Main components of the Lead and Lead-Bismuth Heating and Dumping.*

Item	*Lead Tank Million US $*	*Lead-Bismuth Million US $*
Tank	0.83	1.60
Heating system	2.00	0.80
Helium pumping and heating	0.24	0.08
Assembly	0.35	0.30
Instrumentation and miscellanea	0.79	0.70

Costs have been estimated with the help of potential suppliers and they are listed in Table 7. The cost of the Lead Heating and Dumping Tank is 4.21 M$ and the Lead-Bismuth Tank is 3.48 M$. The total cost of this auxiliary equipment is 7.69 M$ (6.15- 9.23 M$).

3.7 - Mechanical and Electrical classical equipment It converts the heat carried by the steam into electricity with the help of a turbine. It also transforms the electrical power to the appropriate voltage of the external electrical grid. A typical Steam Heat Balance adapted for an EA Power Plant of 1500 MW_{th} is shown in Fig. 10, as a first approach to a complete engineering design, in which all the thermodynamical parameters of the Primary loop, Secondary loop and Water-Steam cycle will be revised. The cycle is based on existing water-steam cycles of coal-fired power plants, since the high working temperatures of the Primary and Secondary loops allows to produce reheated steam at high pressure and hence to increase the thermodynamical efficiency to well above 40%, the typical figure in the case of coal-fired electricity production. This is a notable advantage of the EA when compared to current PWRs.

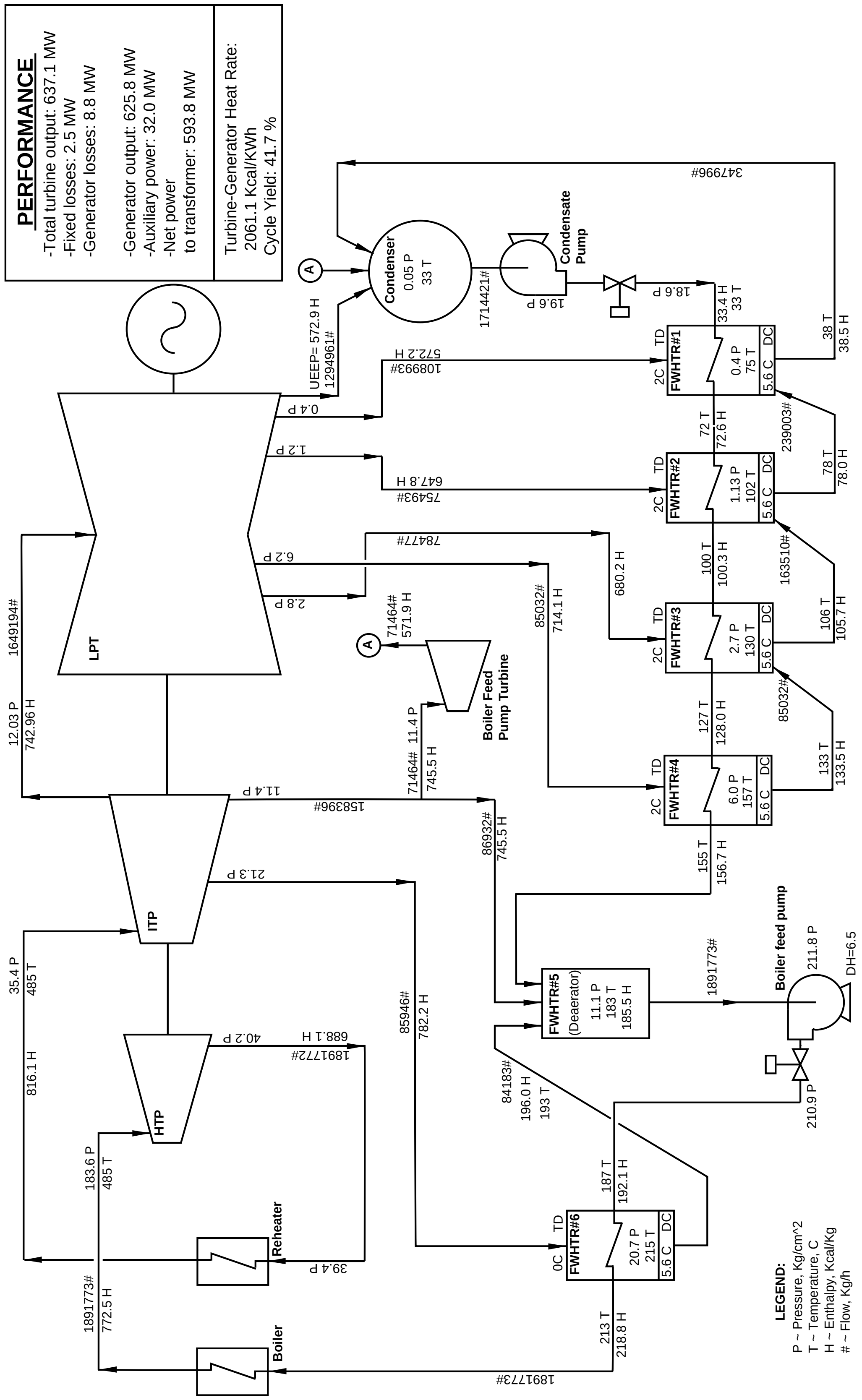


***Figure 10**. Steam heat balance diagram of the EA unit.*

The steam temperature and pressure at the high pressure turbine inlet were set to 485 °C and 180 bar. As a first approach we have calculated a re-heating and regenerative cycle with 6 low pressure extraction, 5 of them feeding closed heaters and one for a de-aerator. The turbine characteristic curves are taken to be the ones typical for 625 MW of electric power. Also the feed water heater parameters, pressure losses in pipes, pumping yields and condenser conditions are standard for this kind of application.

The inventory consists of the Turbine-Generator System, the H_2 plant for the Turbine-Generator, the Distributed Control System, the feed and condensed water treatment, the water-steam piping, the Electrical and Engines System, the support structures and pipe-racks. The Switchyard has a capacity of 945 MWe. It is composed of three sub-stations of 315 MWe each, two of them operating and the third as a stand-by at a given time.

The total cost estimate based on similar systems of the same power as the EA (625 MWe) is 233.5 M$ (210.15 - 256.85 M$) including assembly. It is subdivided as shown in Table 8. If necessary two Refrigeration Towers will be included. Their cost estimate is 11.5 M$ (11 - 12 M$).

Table 8. *Mechanical and electrical subsystems*

Item	*Best Estimate Million US$*
Turbine-Generator System	72.6
H_2 plant for the Turbine-Generator	6.6
Distributed Control System	22.0
Feed and condensed water treatment	22.0
Water-steam piping	22.0
Electrical and Engines System	33.0
Support structures and pipe-racks	41.8
Switchyard	13.5

3.8 - Structures and Civil Work

They house all the components of the Energy Amplifier with the required safety, as well as the necessary services to operate the Power Plant. Several structures are necessary:

1. *Main Pit and Small Auxiliary Pit.* They hold the Main Vessel, Internals, some auxiliary equipment, the conduits of the RVACS as well as the access to the Lead Storage Cavern.

2. *Lead Storage Cavern.* Placed at slightly lower level than the lowest point of the Main Vessel. The Cavern will hold the Lead Heating and Dumping Tank.

3. *Containment Building.* It is the third barrier of containment for any radioactive leak.

4. *RVACS and Steam Building.* It holds the steam Boiler-Reheater and the Secondary loop components external to the Main Pit: the EM pumping, the Expansion Tank and the Main pumping. It also holds part of the Beam Transport, the RVACS components, including the chimneys and the HVAC (Heating, Ventilating and Air Conditioning) of the Containment Building.

5. *Fuel Building.* It will hold the fresh fuel storage and the handling of both the fresh and spent fuel.

6. *Waste Treatment Building.* It contains the systems for the treatment of radioactive wastes generated during the operation of the Plant.

7. *Turbine-Generator Building.* It holds the complete Turbine-Generator system and all the water-steam conditioning systems.

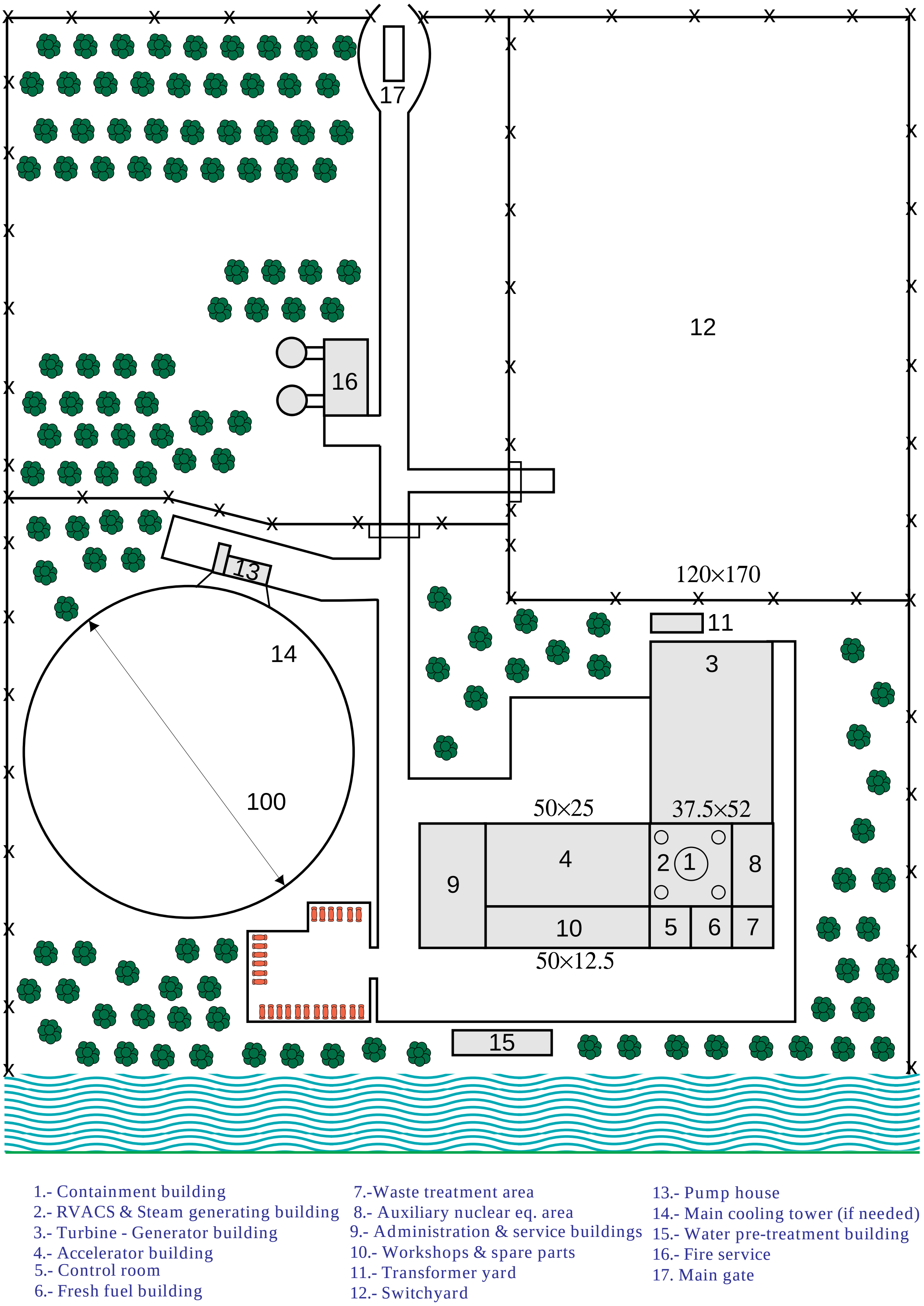
8. *Control Room.* It will hold all the main control systems of the EGU and the Accelerating System control.

9. *Accelerator and Beam Transport Building.* It will hold the complete Accelerating System: the Injectors, the ISCC and the BSSC, as well a part of the Beam Transport.

10. *Auxiliary Nuclear Equipment Building.* It houses miscellaneous auxiliary nuclear equipment such as the Lead-Bismuth Tank, demineralizers, filters, etc.

11. *Administration and General Services Building.* It houses service shops, equipment rooms, laboratories, etc., as well as general offices and conference rooms.

12. *Workshops and Spare Parts Building.* It will hold the workshops and it will serve as storage for spare parts ready for replacement.



1.- Containment building
2.- RVACS & Steam generating building
3.- Turbine - Generator building
4.- Accelerator building
5.- Control room
6.- Fresh fuel building
7.-Waste treatment area
8.- Auxiliary nuclear eq. area
9.- Administration & service buildings
10.- Workshops & spare parts
11.- Transformer yard
12.- Switchyard
13.- Pump house
14.- Main cooling tower (if needed)
15.- Water pre-treatment building
16.- Fire service
17. Main gate

Figure 11 *- General layout of the 600 MWe EA power plant.*

In addition there will be a Pump building, a Water pre-treatment and a Fire service building, as well as a transformer and a Switchyard. An overview is given in Fig. 11.

In order to make an estimate of the cost, a specific site and detailed engineering are required. Considering the dimensions of the Nuclear Island (50% smaller than for a PWR of the same power), an optimisation of the Turbine characteristics affecting the usual Turbine Building dimensions, the overall simplicity in the operation and maintenance of the Energy Amplifier and the lower number of staff required, one should expect significant savings with respect to the current cost estimate for an equivalent PWR plant, in spite of the cost increase due to the pits. An estimate of the cost is 175 M$ with a cost range of 140 - 210 M$, including the HVACS of the Nuclear Island (about 15 M$ cost).

3.9 - Summary of direct investment costs

The total direct investment cost is calculated simply by adding the costs of the separate EA components (Table 9). The entire installation has a direct investment cost of 792.05 M$, (671.35 - 920.35 M$). The corresponding direct investment cost per kWe installed is 1331 $/kWe (1128 - 1547 $/kWe).

Table 9. *Total Direct investment costs.*

Item	*Best Estimate Million US$*	*Lower limit Million US$*	*Upper limit Million US$*
EGU	58.98	45.61	67.51
Secondary Loop	59.55	45.69	72.21
Auxiliary Systems	7.69	6.15	9.23
Accelerator System	184.45	165.45	217.10
Mech. & Electrical Classical Eq.	233.50	210.15	256.85
General Assembly	37.88	30.30	45.45
Instrumentation & Control	35.00	28.00	42.00
Structures & Civil Work	175.00	140.00	210.00
Total	792.05	671.35	920.35

For purpose of comparison with other energy sources we have calculated the corresponding costs in 1991 $ values, on the basis of 2.5% annual inflation. The results are 700.05 M$ (593.38 - 813.46 M$) respectively, which correspond to 1177 $/kWe installed (997 - 1367 $/kWe).

We define as the Heat Generating Assembly (HGA) the hardware required to produce the high quality heat, namely the EGU, the Secondary Loop, the Auxiliary Systems, the Accelerator System, Instrumentation & Control and the corresponding Assembly. The direct investment of the HGA without the Structures & Civil Work, ranges between 321.20 M$ and 453.50 M$ with 383.55 M$ as best estimate (Table 10).

It is important to remark that the above estimates can significantly decrease, either because a higher power Energy Amplifier Unit is installed, by using several (three is a typical number) Accelerating Units, and/or because there is a series production of EAs. According to what is usual when an installation is industrialised there is a cost reduction from the prototype to the head of series (industrial prototype) and another reduction from this to the series production. The scenario considered as pessimistic in [6] makes the assumption of a 15% cost decrease between the industrial prototype and the series production, both for the Accelerator and for the EGU. Between the first and the industrial prototypes it considers a cost reduction of 45% in the Accelerating System since it is of novel nature and nothing in the EGU, given the simplicity and "classical" nature of its design. If those assumptions are used the direct investment cost and range will become 655.13 M$ and 552.82 - 758.68 M$, respectively (579.04 M$ and 488.61 - 670.56 M$, in 1991 $). Therefore, the estimates for kWe installed will be 1101 and 929 - 1275 $/kWe (973 and 821 - 1127 $/kWe, in 1991 $). Also, the direct investments of the HGA becomes 246.63 M$ and 202.67 - 291.83 M$ for the best estimate and cost range respectively.

Table 10. *HGA Direct Investment cost*

Item	*Best Estimate Million US$*	*Lower limit Million US$*	*Upper limit Million US$*
EGU	58.98	45.61	67.51
Secondary Loop	59.55	45.69	72.21
Auxiliary Systems	7.69	6.15	9.23
Accelerator System	184.45	165.45	217.10
Assembly	37.88	30.30	45.45
Instrumentation & Control	35	28	42
Total	383.55	321.20	453.50

3.10 - The indirect and other investment costs

The indirect investment cost is the capital interest accumulated during the lead times from when the investment is made and when the installation starts to operate and it depends on the total investment and its distribution in time, as well as the net discount rate value. We remark that we have not included inflation (essentially unknown) and used instead 1996 US $. <u>Therefore the relevant interest rate is the one above inflation</u>, i.e. the net discount rate.

The construction time of an Unit is at this stage widely unknown. Nevertheless the time of construction of the components, Assembly and Civil Work could be completed in a few years. The specific safety aspects of an EA, once properly tested and generally admitted, will undoubtedly facilitate the necessary permission from the Nuclear Regulatory Agencies. Therefore the EA construction time is expected to be not longer than the corresponding time for a PWR plant. As a conservative reference we have made two options, namely a construction time of 5 and of 7 years. The former applies to the series production. The latter should be relevant for the construction of a first prototype.

We have also assumed that the schedule of investment is similar to the case of PWR, eventually adjusted to the chosen time scale. With the help of Ref. [7] we arrive at the distribution of Fig. 12. The yearly investments referred to start-up are given in Table 11.

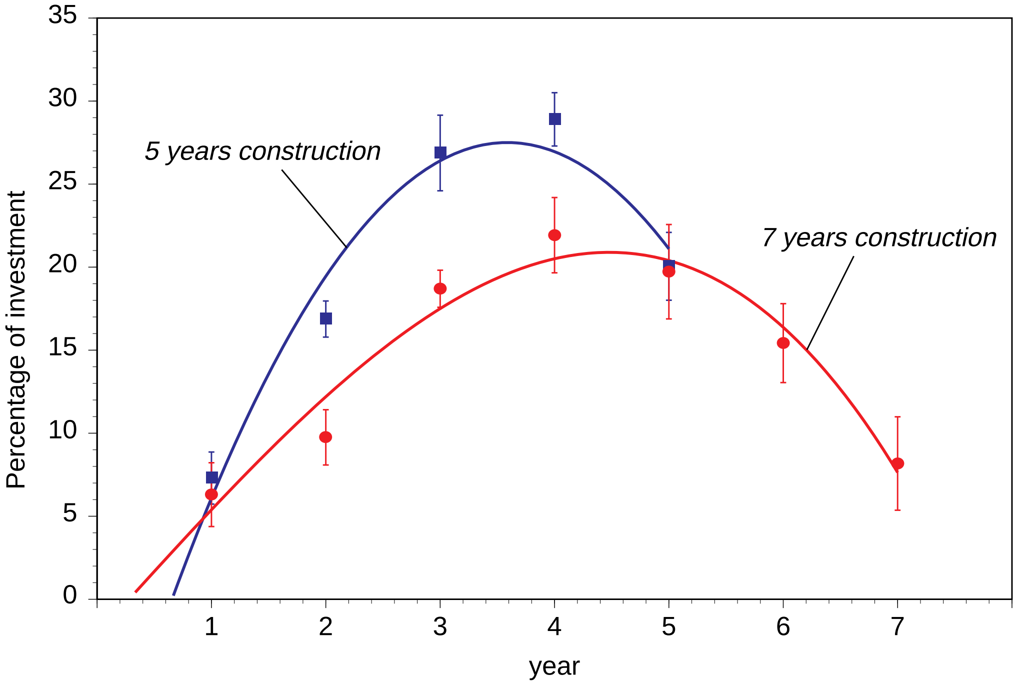


Figure 12. *Time distribution of investments during construction.*

Table 11. *Fractional distribution of investments (5/7 years options)*

Years	-7	-6	-5	-4	-3	-2	-1
5 years schedule Fractional investment (%)			7	18	26	29	20
7 years schedule Fractional investment (%)	6	10	19	22	20	15	8

Table 12. *Indirect cost as a fraction of direct cost*

Net discount rate above inflation	Construction time 5 years	7 years
5%	0.11	0.18
10%	0.23	0.38

The net discount rate above inflation is an essential parameter to evaluate indirect costs. Two cases are generally considered: a 5% net discount rate above inflation, usual for most of the OECD countries, and a 10% net discount for the others. Indirect costs as a fraction of the direct investment cost for the 5 and 7 years options are given in Fig. 13. Independently from the net discount rate, the construction time is a critical term affecting the indirect cost (the average ratio between the two options is about 1.6). Also, the ratio of indirect/ direct costs is strongly dependent on the net discount rate. For the 10% and 5% net discount cases it varies by a factor of about 2.1. Table 12 gives the indirect costs as a fraction of the direct investment, for the reference cases.

Figure 13 *-Indirect/Direct cost ratio as a function of the net discount rate for both 5 and 7 years of construction period.*

Assuming 5% net discount rate and 7 and 5 years construction period for the prototype and the series respectively, the indirect costs are 142.65 M$ (120.91 - 165.75 M$) and 72.98 M$ (61.58 - 84.51) M$)[6]. The indirect costs for HGA alone are 69.04 M$ (57.82 - 81.63 M$) and 27.13 M$ (22.29 - 32.10 M$) for the prototype and series respectively.

The item "Other costs" is very dependent on its particular characteristics, site, country, etc. Nevertheless, for a reasonable construction time (of the order of 7 years) a reasonable figure based on current practice is about 30% [6] of the direct investment costs, distributed as follows:

- 10% for the design and architectural engineering of the particular project (the general design of a standard EA Unit, as mentioned above, being part of a previous R&D programme).
- 16% for the surveillance and manufacture of work (1%), the supervision and coordination of site work and commissioning (10%), as well as the setting up and running the site (3%) and pre-operational expenses (2%).
- 4% for the administrative matters (general administrative expenses, planning and management of the project, negotiation and management of contracts, insurance, etc.).

The confidence level of this estimate is of the order of 20% (6% of the direct investments cost).

Table 13. *Other costs .*[7]

Item	*Best Estimate Million US$*	*Lower limit Million US$*	*Upper limit Million US$*
EA- Unit			
prototype	237.61	190.09	285.14
series unit	196.54	157.23	235.85
Heat Generating Unit			
prototype	115.06	92.05	138.08
series unit	73.99	59.19	88.79

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[6] For the purpose of comparison, the prototype and series production indirect costs evaluated in 1991 $, are 126.08 M$ (106.87 - 146.50 M$) and 64.50 M$ (54.43 - 74.70 M$) respectively.

[7] 1991-dollars are calculated multiplying table entries by 0.881.

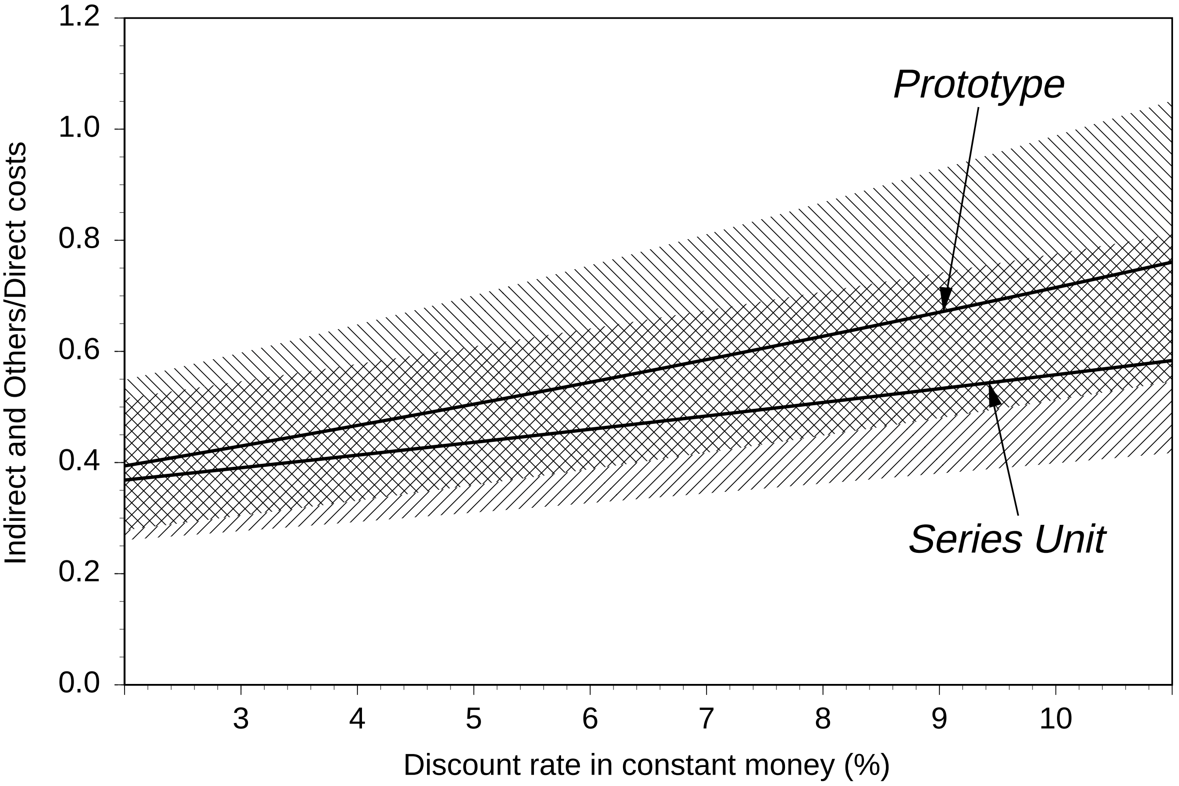

Figure 14 *- Indirect and Others/Direct cost ratio (best estimate and range) as a function of the net discount rate, for the EA prototype and the Series Units.*

This figure can decrease by a significant factor from the prototype to the series production. We assume 20% in the case of the series production (which agrees with the total estimate from Ref. [6]), with a 20% level of accuracy, distributed as 6%, 11% and 3% among the three items listed above. Values relevant to the EA Unit and the HGA are given in Table 13.

As already mentioned, no provision has been included for the final decommissioning of an EA Unit since the policy has to be defined. We remark that after several decades of the EA operation, the Lead inside a pit (sealed with concrete) might become an appropriate secular repository. The present experience of decommissioning PWRs is limited and the current estimate of the cost when compared with the total investment cost is relatively minor, at this level of approximation and if projected to the time of the plant start-up.

The total Indirect and Other Costs for the prototype and series, including an additional 2.5% provision for spare parts are given in Table 14. The ratio Indirect and Other/Direct Costs, is shown in Fig. 14 as a function of the net discount rate. These costs amount to about 50% and 44% of the direct costs for the prototype and series respectively, within large uncertainty margins (15%).

Table 14. *Total indirect costs*

Item	*Best Estimate Million US$*	*Lower limit Million US$*	*Upper limit Million US$*
EA- Unit			
prototype	400.06	330.80	470.69
series unit	285.89	235.19	336.74
Heat Generating Unit			
prototype	193.73	159.49	229.34
series unit	107.63	87.93	127.46

Table 15. *EA Unit total investments*

Item	*Best Estimate Million US$*	*Lower limit Million US$*	*Upper limit Million US$*
Prototype			
Direct investment	792.05	671.35	920.35
Indirect and others	400.06	330.80	470.69
Total	1192.11	1002.15	1391.04
Unit of series			
Direct investment	655.13	330.80	758.68
Indirect and others	285.89	235.19	336.74
Total	941.02		1095.42

Total Investment /kWe installed	*Best Estimate $/kWe installed*	*Lower limit $/kWe installed*	*Upper limit $/kWe installed*
Prototype	2003	1684	2338
Unit of Series	1582	1324	1841

3.11 - Total investment cost

The total investment cost is the sum of the Direct and Indirect and of the Other investment costs (Table 15 and Table 16) As can be seen the total current cost of an EA prototype is estimated in 1192 M$, with an upper limit of 1391 M$. It decreases by about 20% for the series production. In the case of the prototype, the current cost of the kWe installed is estimated in 2003 $/kWe and has lower and upper limits of 1684 and 2338 $/kWe (- 20% for the series production).

The total investment cost distribution is shown in Fig. 15. The heat generating and directly associated equipment (HGA) requires an investment slightly larger than 25% of the total. The equipment for electricity generation amounts to about another 25%. Civil Works add another 20% and the remaining is due to indirect and other costs.

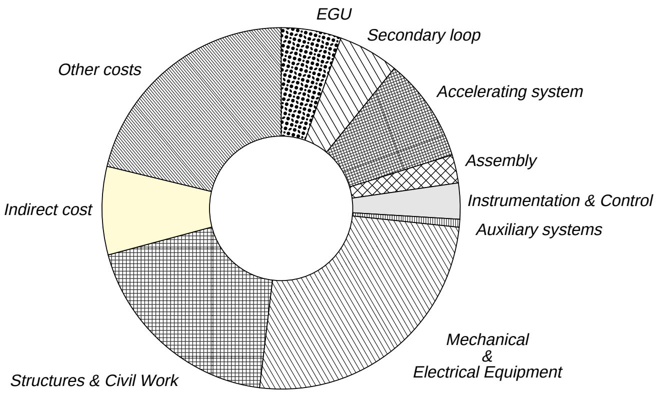

Figure 15 . *Total investment cost distribution for the EA series unit.*

The total investment and kWe installed costs dependence with the net discount rate are shown in Fig. 16. Variations of about 10% for the series and nearly 20% for the prototype are apparent for net discount rate above inflation from 5% to 10%.

Table 16. *HGA total investments ($ 1996)*

Item	*Best Estimate Million US$*	*Lower limit Million US$*	*Upper limit Million US$*
Prototype			
Direct investment	383.55	321.20	453.50
Indirect and others	193.73	159.49	229.34
Total	577.28	480.69	682.84
Unit of series			
Direct investment	246.63	202.67	291.83
Indirect and others	107.63	87.93	127.46
Total	354.26	290.60	419.29

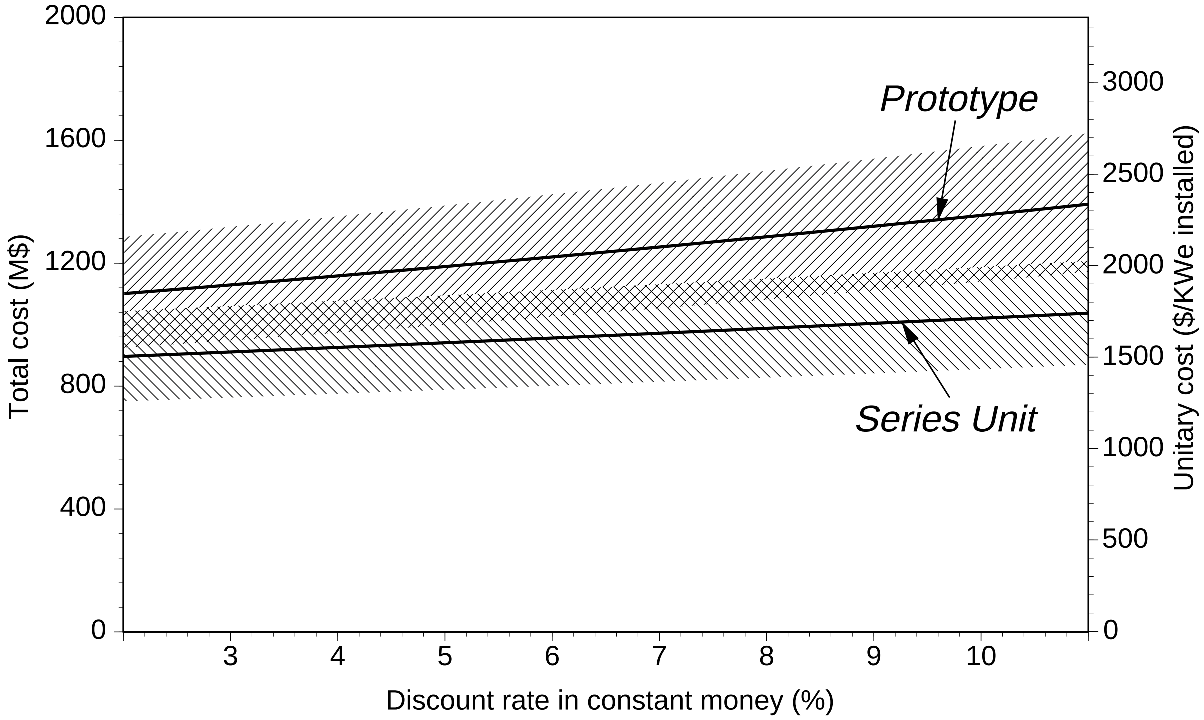

Figure 16. *EA total cost and costs for unitary installed electrical power (best estimate and range) as a function of the net discount rate for both the EA prototype and series unit.*

4.— THE FUEL CYCLE

This Section presents an evaluation of the fuel cycle cost for the standard EA Unit of Ref. [3]. For completeness it will be compared with the corresponding cost estimate for a PWR plant and for an EA coupled with a PWR which has been proposed in [16] as a method to incinerate the PWR residual Actinides.

As is well known [8] the total unit cost of the usual nuclear fuel has several ingredients, either coming from the front-end or from the back-end of the fuel cycle. The front-end cost includes:

1) The direct cost of the natural Uranium concentrate (U_3O_8) produced in the ore processing plant.
2) The direct cost of the conversion to Uranium hexafluoride (UF_6), used in the enrichment process.
3) The enrichment direct cost.
4) The fuel fabrication direct cost, which includes the conversion to Uranium dioxide, the pellets production, the ceramic fuel sintering and the sealing and fabrication of the fuel elements.

The corresponding front-end indirect cost comes from the lead times since the Uranium is obtained or the services (conversion, enrichment and fuel fabrication) are performed before the fuel is loaded into the reactor. An additional indirect cost is due to the delayed time of the energy production relative to the fuel load. Typically, for a PWR, the total front-end cost (direct plus indirect) amounts to nearly 2/3 of the total expenses.

The back-end integrates two main operations which are different depending on the option selected for the spent fuel. In the case of the reprocessing option the operations are:

1) transport of the spent fuel and reprocessing & vitrification,
2) waste disposal.

In the direct disposal option the activities are:

1) transport & storage of the spent fuel,
2) encapsulation & disposal.

The amount of waste for final disposal and their medium and long-term radioactive levels is strongly option dependent. The back-end of the fuel cycle has also indirect associated costs (or savings), which comes from the lag times at which the back-end phases occur relative to the discharge of the fuel from the nuclear power plant. In addition, the reprocessing option allows to recuperate Uranium and Plutonium instead of classifying it as waste. In a PWR plant these materials may be recycled as fuel, but normally through only a single recycling stage. Hence, the closed cycle allows to partially replace the fresh enriched fuel by MOX, thus decreasing the total fuel cost significantly.

Table 17- *Fuel cycle unitary prices*

Component	*Reference unitary price*
Uranium purchase	$ 50/kg (in 1991)
Thorium purchase	$ 28.6/kg (in 1991) (escalation: 1.2% p.a.)
Conversion	$ 9/kg U
Enrichment	$ 124/SWU
Fabrication	$ 311/kg U
MOX fuel fabrication	$ 1244/kg U
Reprocessing option:	
Spent fuel transport	$ 56/kg U
Reprocessing (including disposal of LLW & ILW & vitrification & storage of VHLW)	$ 815/kg U
VHLW disposal	$ 102/kg U
Direct disposal option:	
Spent fuel transport & storage	$ 260/kg U
Encapsulation & disposal	$ 690/kg U

In our estimates all figures are based on the unitary costs which appear in Table 17, Ref. [8], which are projected costs for the year 2000. These costs are scaled up from 1991 to 1996 money value (2.5% yearly inflation) and payable at the time in which the corresponding operation takes place. The enrichment prices are expressed in terms of the number of separative work units (SWU) needed to obtain enriched Uranium in the form of UF_6.

The total direct cost of natural Uranium purchase is obtained as the product of its unitary cost by the amount needed to produce one unit of enriched Uranium, which is given by:

$$(X_e - X_t)/(X_n - X_t)$$

where X_n, X_e and X_t are the corresponding ^{235}U content in natural, enriched Uranium and tails respectively. The number of SWU units required for the enrichment *(S)* are given by:

$$S = C_e + C_t(X_e - X_n)/(X_n - X_t) - C_n(X_e - X_t)/(X_n - X_t)$$

and $C_i = (2X_i - 1)ln(X_i/(1 - X_i))$, where *i* holds for *e*, *n* or *t*.

Table 18. *- EA parameters*

Thermal output	1500 MW
Net electric output	595 MW
Load factor	90%
Fuel irradiation time	5.5 years
Fuel burn-up	100 GWd/t
Total fuel mass	30 tons

Table 19. *- PWR parameters*

Thermal output	2900 MW
Net electric output	1000 MW
Load factor	75%
Fuel burn-up	33 GWd/t
Fuel irradiation time	2.8 years
Total fuel mass	90 tons
Fuel enrichment	3.3%

The assumed parameters of the EA and PWR power plants are given in Table 18 and Table 19 respectively. The loading factor for a PWR plant is a typical value. The loading factor for the EA is significantly higher since the EGU is completely passive, the accelerator components can be replaced "on line" and the refuelling only takes place every five years. Also power plants with several EA units sharing one spare accelerator are foreseen. The value chosen in Table 18 is a conservative value which takes care of contingencies.

Table 20. *- Fuel cycle data*[8]

Item	*Reference*
Tails assay for enrichment	0.25%
Lead time[9]	
Uranium purchase	2 years
Enrichment	1 year
Fabrication	0.5 year
Fuel storage time at the plant	5 years
Lag time[10]	
Reprocessing	5 years
Disposal	35 years

Fuel cycle data is displayed in Table 20. The delay between the fuel load and energy

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[8] All the data is applicable to the PWR fuel cycle. For the EA fuel cycle only fabrication and back-end items are applicable.

[9] relative to the fuel loading date

[10] relative to spend fuel discharge date

production has been chosen as the half of the fuel irradiation time in the plant. Material losses in the different operations are usually very small and have been considered negligible. The cost estimates are made based on a financial appraisal method in which the net discount and interest rates in constant money have been fixed to 5 and 2% respectively. The first corresponds to the interest on the money spent on the front-end of the cycle, ahead of the energy generation, and the second is the return assumed on the money put aside to meet the back-end fuel cycle cash outflow.

It is important to stress the uncertainties of the projected unitary costs. In the case of the front-end of the fuel cycle uncertainties are of the order of 20%. This is also true for the reprocessing operation. However, uncertainties in the case of the waste disposal are larger, in particular because of the long time scale involved in repository estimates. In addition, there might be many unforeseen technical parameters affecting the waste disposal which may affect the evaluation. Nevertheless, in a relative comparison between the EA, the PWR with reprocessing option or in a combined cycle EA-PWR, such estimates can be used as a fair approximation.

Table 21. - *Unitary fuel cost ($/kg U) and cost of the fuel cycle (¢ /kWh)*

Component	EA
Thorium purchase	3.4
Fuel MOX Fabrication	1244.0
Transport of spent fuel	56.6
Reprocessing	814.6
Disposal	101.8
Indirect costs	76.5
Total	2296.9
Fuel cycle contribution to the energy cost (¢ /kWh)	*0.268*

Table 21 shows the fuel cost for the EA. In normal operation the EA requires a kind of MOX fuel, since it uses either the ^{233}U bred from previous cycles in the independent operation or the “dirty Pu” in the EA-PWR combined cycle, in addition to the other Actinides produced in the EA discharge.

Table 22 shows the evaluation of the fuel cost for a PWR plant when operating alone or in a combined cycle with an EA. As can be seen, the results are similar, although the combined PWR-EA fuel cycle presents a slightly lower cost (≈ 4%). This reflects the fact that the natural Uranium cost, plus its concentration, enrichment and fuel fabrication is slightly higher than the MOX fuel fabrication cost using the Uranium recuperated from the EA and the Uranium tails from previous Uranium enrichment.

Table 22. *- Unitary fuel costs ($/kg U) and cost of the fuel cycle (¢/kWh)*

Component	PWR alone	PWR-EA[11]
Uranium purchase	422.3	0.0
Enrichment	549.3	0.0
Fabrication	311.1	1244.5
Transport of spent fuel	56.6	55.6
Reprocessing	814.6	814.6
Disposal	101.8	101.8
Indirect costs	36.3	-14.1
Total	2292.0[12]	2203.4
Fuel cycle contribution to the energy cost (¢ /kWh)	*1.119*	*1.076*

The unitary cost of the Energy Amplifier fuel is similar to the ones obtained for the PWR. (In these calculations zero cost was given to the “dirty Pu” and the Uranium recuperated from the PWR and EA discharges respectively). When translating the fuel cost to the energy cost, the EA and the PWR show an important difference, a factor of the order of 4. The main reason is the differences in the reference burn-ups and, to a smaller extent, the quoted performance of the plants.

The sensitivity of the fuel cycle cost to price variations shown in Figs. 17 and 18 for the EA and PWR respectively. As can be seen the cost of the EA cycle is mainly sensitive to the fuel fabrication cost, while for the PWR cycle cost, the reprocessing is the most relevant operation. Fig. 19 shows the sensitivity in the cost ratio PWR/EA. The ratio increases when the Uranium price increases, it is practically insensitive to cost variations of reprocessing and it decreases for larger fuel fabrication cost.

We have also evaluated in Fig. 20 the effect of the net discount rate ranging from 5% to 10%, and taking for each calculation an interest rate three points below the net discount rate in constant money. The fuel contribution to the energy cost is nearly independent of the rate variation for the three studied cases: the EA, the PWR

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[11] PWR-EA combined cycle.

[12] This cost slightly decreases by recuperating Uranium and Plutonium from the reprocessing phase (15 - 20% core loading of MOX).

with reprocessing option, and the combined cycle EA-PWR [16]. The effect is due to the balance between the front-end indirect cost increase and the back-end savings.

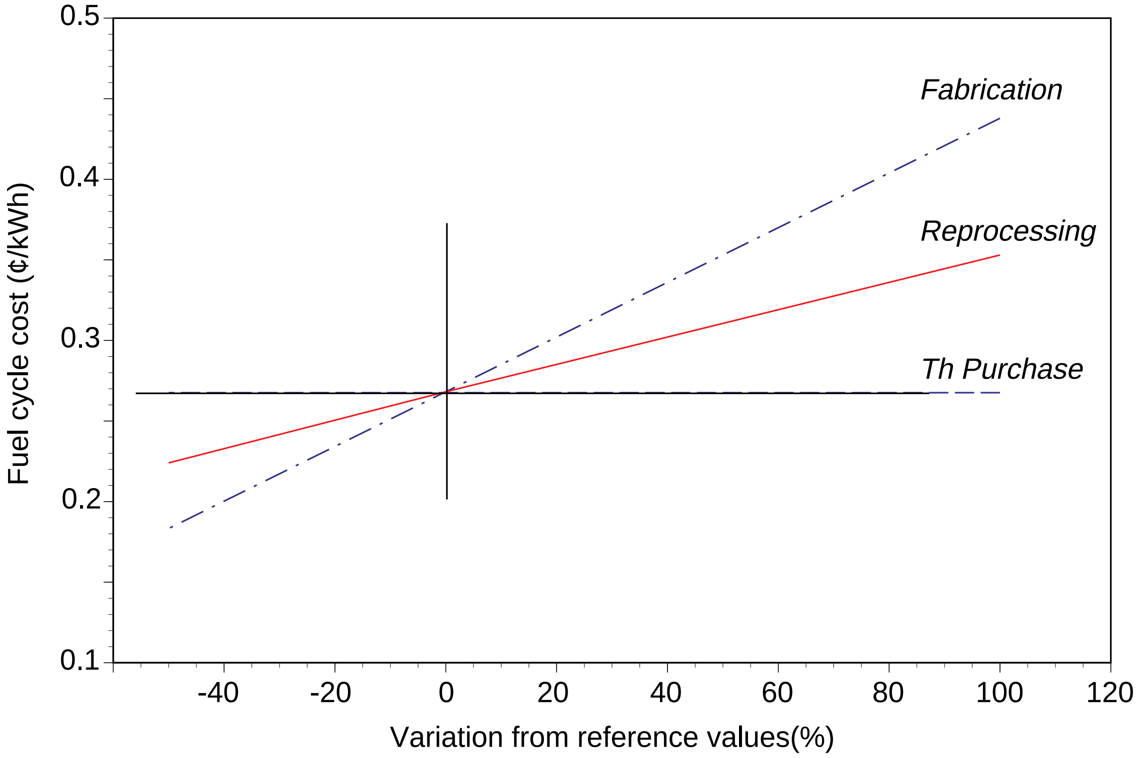

Figure 17. *- Sensitivity plot of the EA fuel cycle cost.*

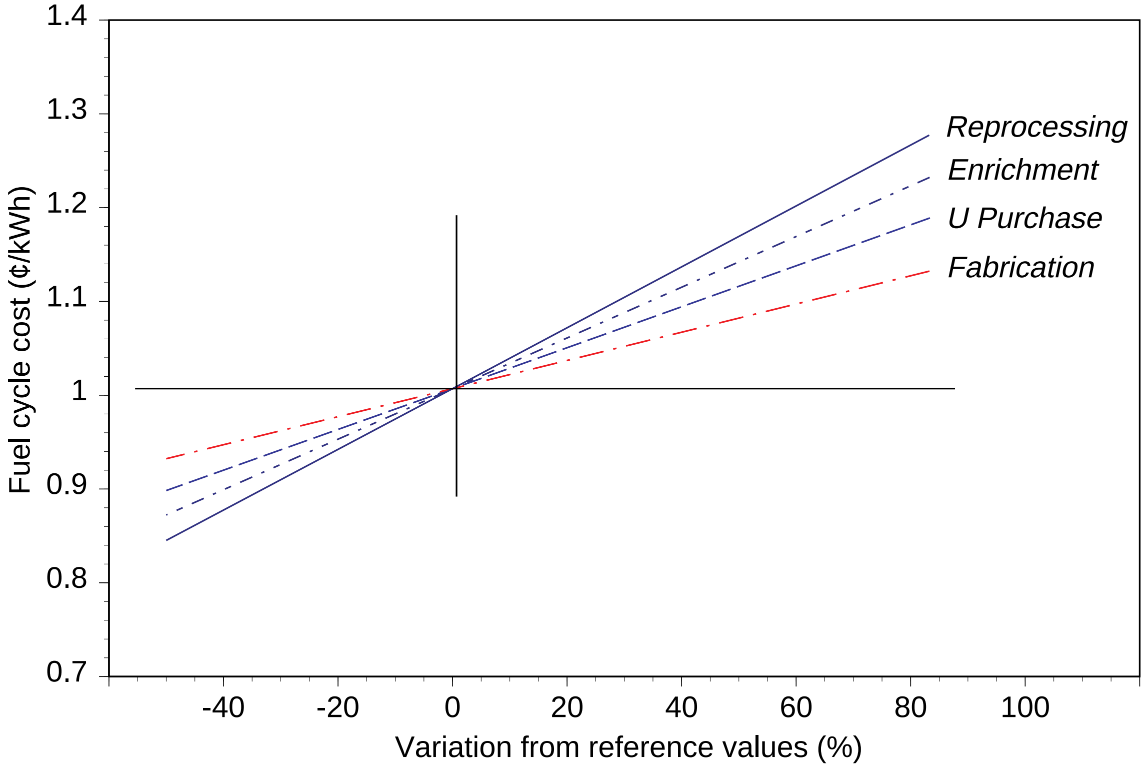

Figure 18 *- Sensitivity plot of the PWR fuel cycle cost.*

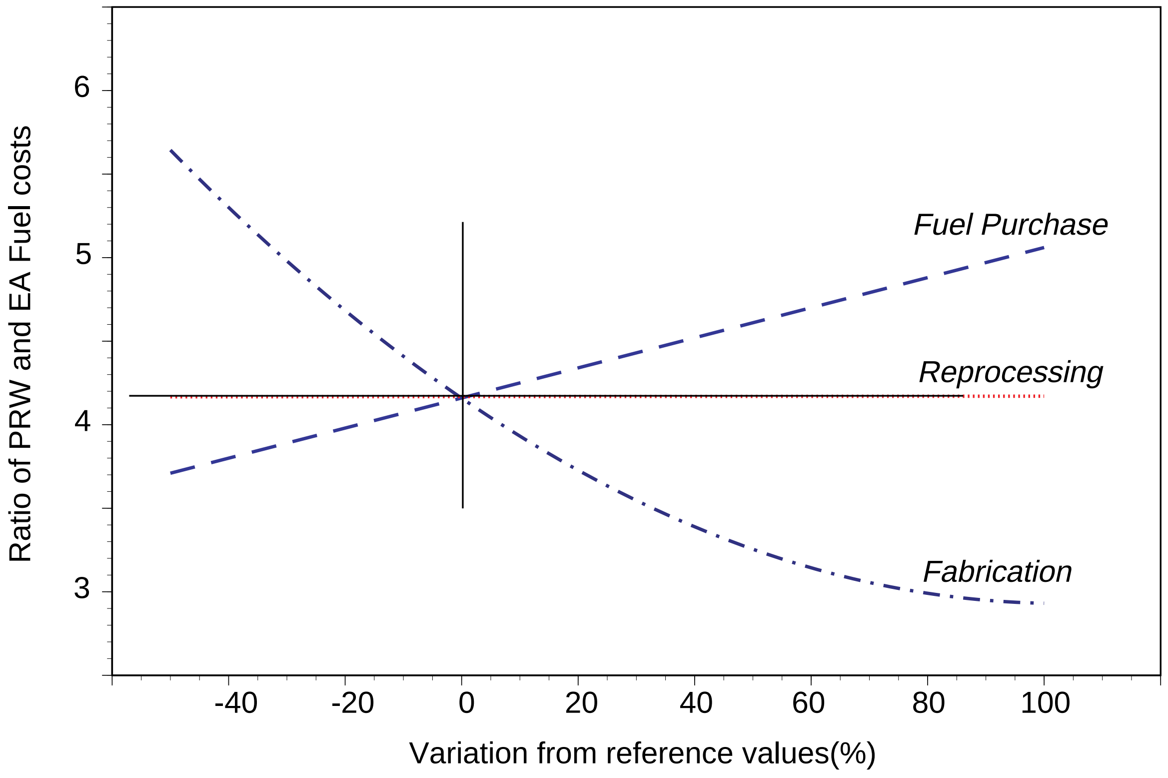

Figure 19 - *Sensitivity plot of the ratio between the PWR and EA fuel cycle costs.*

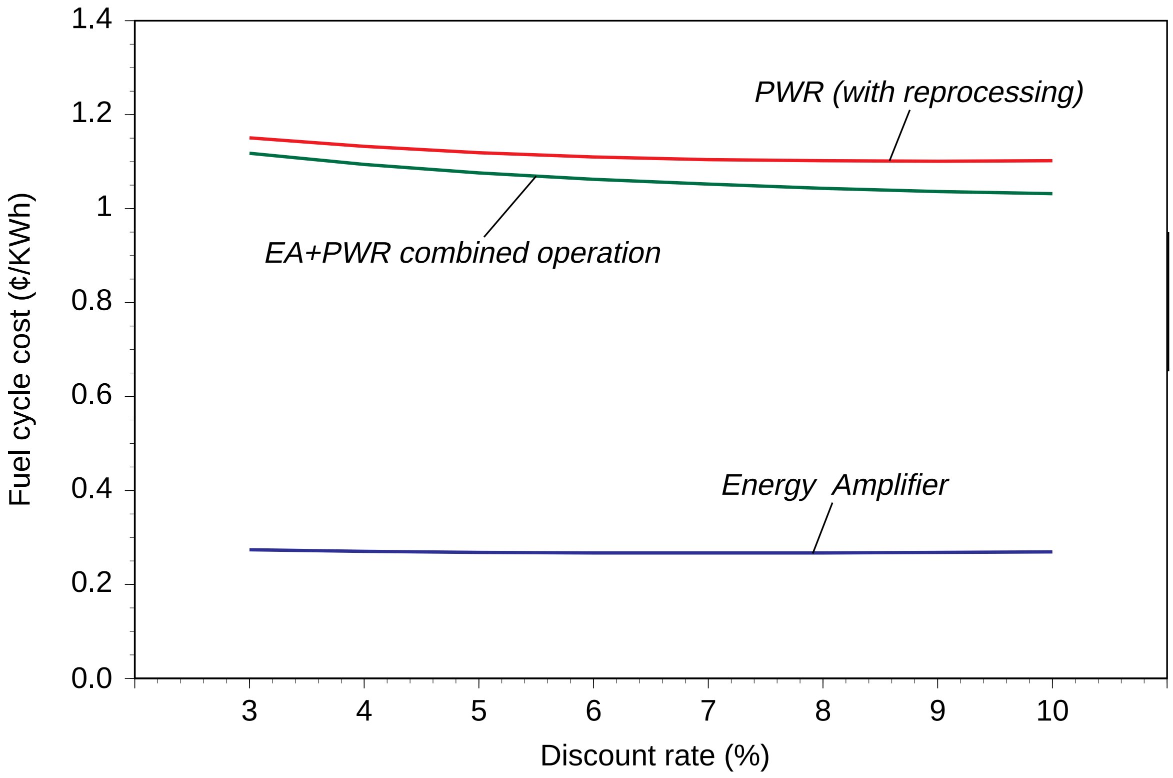

Figure 20 - *EA, PWR-reprocessing option and EA-PWR combined cycle fuel contributions to the energy cost, as a function of the discount rate in constant money*

Another relevant estimate is the cost of the fuel PWR cycle in the case of direct disposal option for the wastes. Since the reference data was taken from [8] our estimate gives a similar result for the cost ratio between the two options with about 10% in favour of the direct disposal with respect to the reprocessing. However, as stated above, this factor has to be taken cautiously since it has large uncertainties due to the unknowns in the disposal option. In addition, since direct disposal services are not currently available on the market each country follows its own approach and, as shown in Ref. [8], it varies significantly from country to country.

In summary, the EA fuel contribution to the energy cost is 0.27 ¢/kWh, namely about 4 times lower than in a PWR. Also, by using the combined cycle EA-PWR, the fuel contribution to the EA and PWR energy cost are essentially the same than operating independently. Based on the sensitivity analysis and the cost of the basic fuel cycle operations the uncertainty margin is of the order of 10%.

5.— OPERATION AND MAINTENANCE COSTS

Expenses due to operation and maintenance cover the consumable and other maintenance costs, as well as the personnel salaries. Consumables and other maintenance costs could be divided into three categories: those affecting the Accelerating system, those derived from the Energy Generating Unit (EGU) and those coming from the Secondary loop and the classical Mechanical and Electrical equipment. Concerning the Accelerating system, an extended experience exists from the Research Sector on their reliability during long periods, 30 years and even longer. A safe figure for the consumable expenses is about 5% of the total cost of the series, which corresponds to a complete replacement every 20 years, amounting to 4.31 M$.

The EGU is a passive sealed Beam Dump which will be opened every 5 years for refuelling, with the exception of the Beam Window (0.05 M$ cost), which will be replaced every year. An estimate of the yearly EGU consumable expenses is 3.1 M$, considering the maintenance of the Heat Exchangers and Auxiliary systems as well as the Instrumentation and Control. For the Secondary loop and the conventional Mechanical & Electrical systems an estimate of 14 M$ per year matches with the experience coming from nuclear, coal or gas power plants. Adding 1 M$ for general services a figure of 22.41 M$ is reached.

Relative to the Personnel expenses, a total of 100 staff is enough to run the Energy Amplifier, equivalent to about 7 M$ per year. Therefore the O&M yearly costs of an EA is 29.41 M$, within an uncertainty of the order of 20%.

The O&M cost for the HGA can be obtained by considering only the relevant expenses. It is estimated at 14.05 M$ per year, also within an uncertainty range of 20%.

6.— GENERAL CONCLUSIONS

6.1 - Total energy cost

An essential parameter in order to evaluate the EA energy cost is the useful life of the installation. As explained above, in the assumption that Lead corrosion is mastered, the Energy Generating Unit can last for many decades, since the Main Vessel is not pressurised and its radiation damage is negligible. Also, the operations are minimal because the refuelling takes place every 5 years and the installation operates "sealed" during this period. There is also a large experience on the long useful lifetime of accelerators, 40 or 50 years, for which, however, a complete replacement every 20 years has been foreseen in the O&M cost. In our view a 50 years lifetime for the EA is realistic and could be even longer.

For the purpose of energy cost estimate we will consider the operation conditions displayed in Table 18, an EA lifetime of t =50 years and net discount rate r in constant money varying between 5% and 10%, The reference value is the usual OECD value of 5%. The reduced lifetime S of the installation in years (corresponding to a yearly cost of 1/S) is given by the well known formula:

$$S = \frac{1-(1+r)^{-t}}{r}$$

In our conditions, for a net discount rate r = 0.05 , S = 18.3 years and the annual investment cost (1/S) is 5.4% of the total investment cost.

The total cost of the kWh is displayed in Table 23 for the prototype and series, as well as its three components: investment, fuel and O&M expenses. For comparison, Table 24 shows the cost of the GJ, calculated on the basis of the total cost of the HGA (without considering the Structures and Civil Work costs).

Table 23. *Cost of kWh, in ¢ for the 5% net discount option.*

Item	*Best Estimate ¢ /kWh*	*Lower limit ¢ /kWh*	*Upper limit ¢ /kWh*
Prototype			
Investment	1.39	1.17	1.62
O&M	0.63	0.50	0.75
Fuel	0.27	0.24	0.29
Total	**2.29**	**1.91**	**2.67**
Unit of Series			
Investment	1.10	0.92	1.28
O&M	0.63	0.50	0.75
Fuel	0.27	0.24	0.29
Total	**1.99**	**1.66**	**2.33**

Table 24 *Cost of GJ in ¢ for the 5% net discount option.*

Item	*Best Estimate ¢ /GJ*	*Lower limit ¢ /GJ*	*Upper limit ¢ /GJ*
Prototype			
Investment	74.2	61.8	87.9
O&M	1.8	1.5	2.2
Fuel	29.6	26.6	32.5
Total	**105.6**	**89.9**	**122.5**
Unit of Series			
Investment	45.5	37.4	53.9
O&M	1.8	1.5	2.2
Fuel	29.6	26.6	32.5
Total	**76.9**	**65.4**	**88.6**

Figs. 21 and 22 show the energy cost distribution among its three components, as a function of the net discount rate, for both the prototype and the series. As can be seen the investment costs are of the order of 60% (5 % discount rate) and increases when the net discount rate increases. The O&M expenses amount to nearly 30% of the total cost and the fuel contribution slightly higher than 10%, both decreasing with increasing values of the net discount rate.

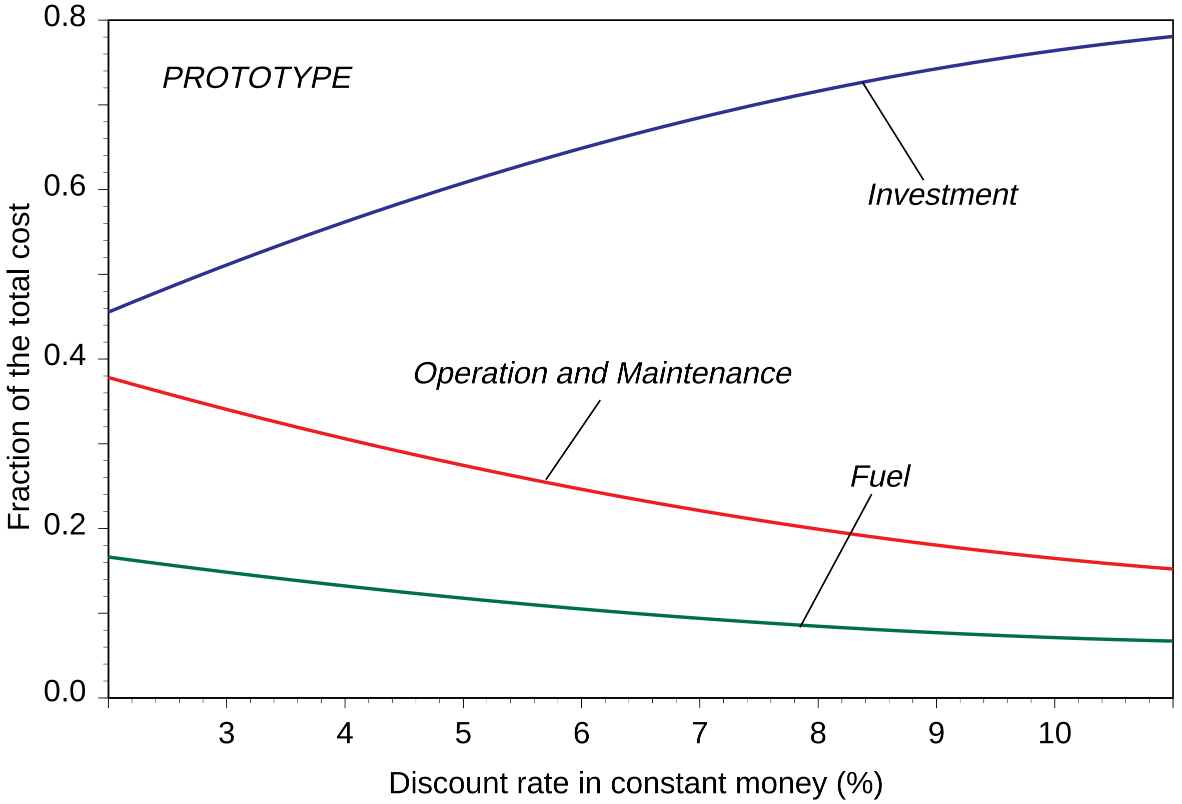

Figure 21 *- Investments, Operation and Maintenance and Fuel fractional contributions to the total energy cost of an EA prototype, as a function of the net discount rate.*

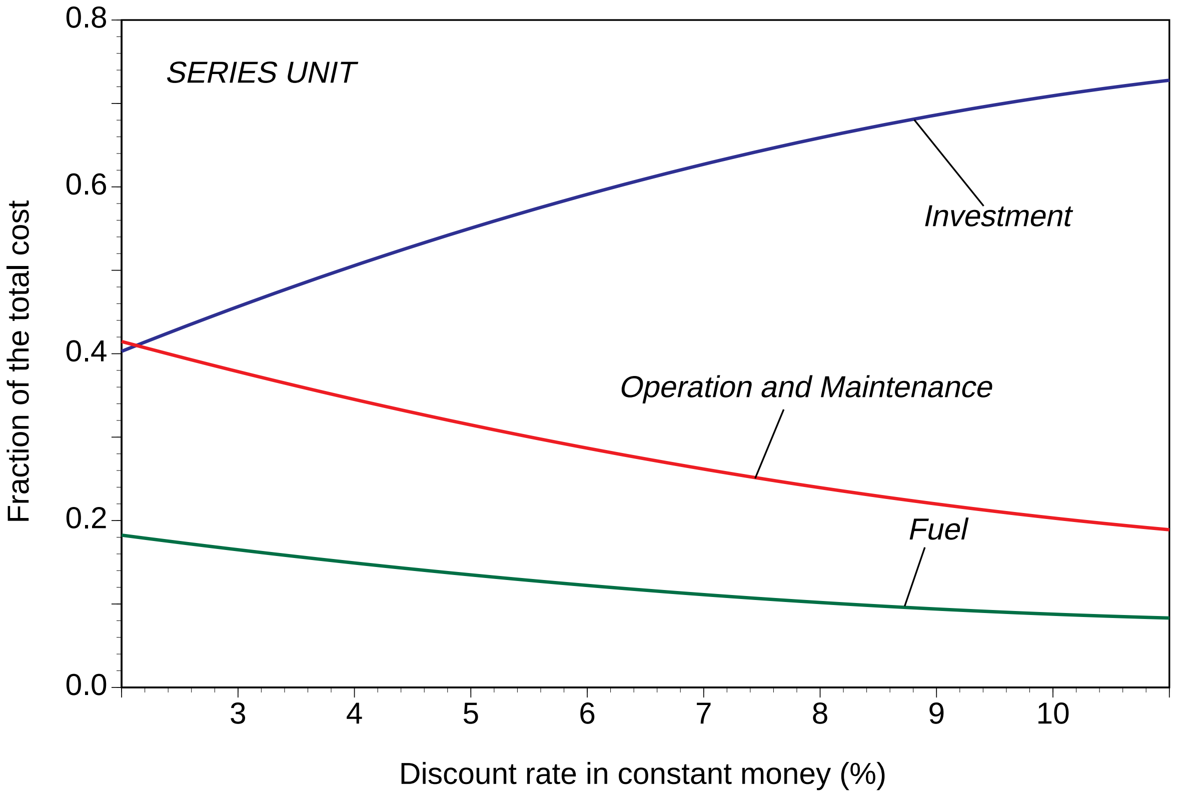

Figure 22 *- Investments, Operation and Maintenance and Fuel fractional contributions to the total energy cost of an EA series unit, as a function of the net discount rate.*

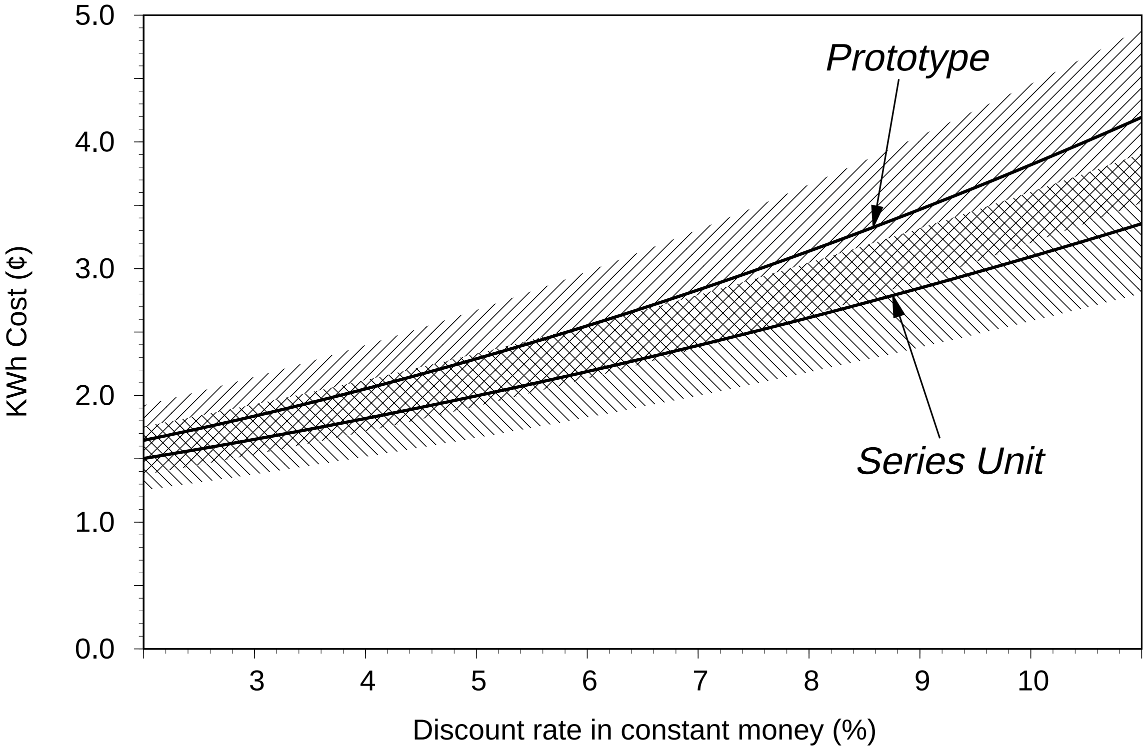

Figure 23 - *Cost of the kWh as a function of the net discount rate for both the EA prototype and series unit, assuming 50 years plant lifetime.*

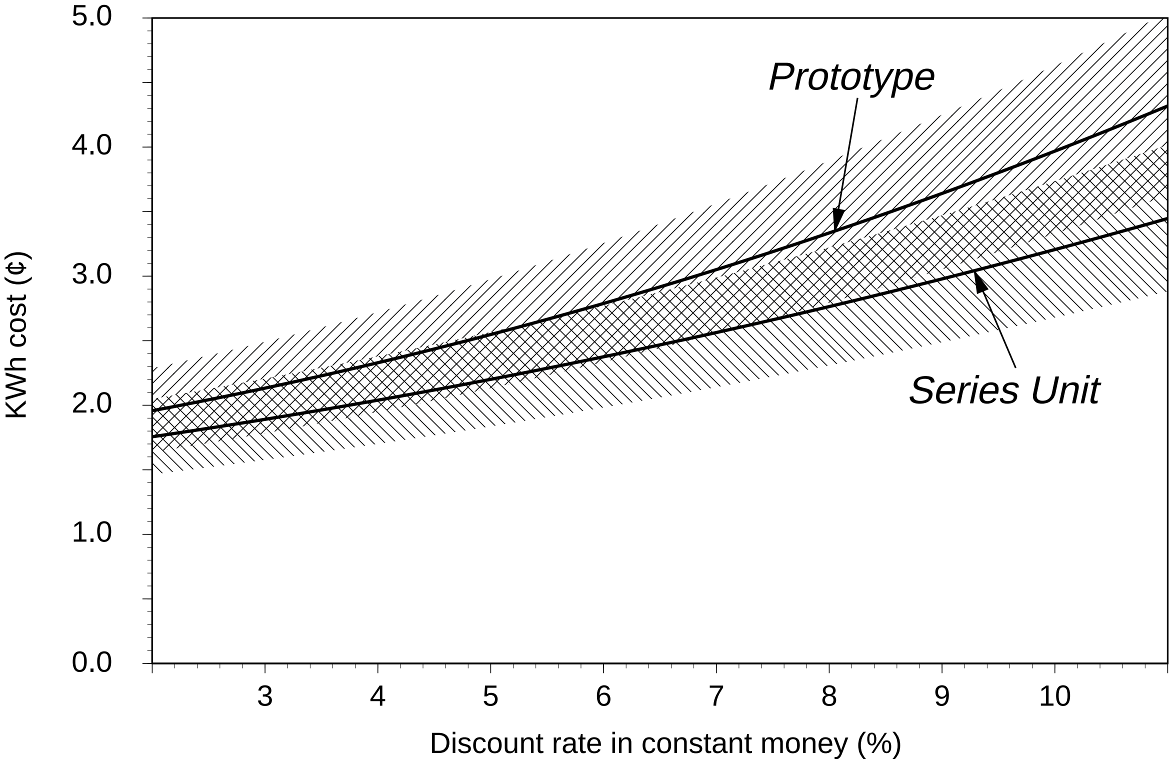

Figure 24 - *Cost of the kWh as a function of the net discount rate for both the EA prototype and series unit, assuming 30 years plant lifetime.*

In general the fractions behaviour is similar to the standard Nuclear Power plants, and different from the one shown by other energy sources (The investments are between 20 and 40 % for coal-fired plants and between 10 and 25 % for gas fired plants).

The kWh cost has an important dependence on the net discount rate affecting the investments. A change in the net discount rate from 5% to 10% implies an increase in the cost by nearly 60%, Fig. 23. Also, since the EA lifetime is expected to be significantly longer than for PWRs we have analysed its influence in the energy cost. To this purpose we have estimated the kWh cost for a 30 years EA. The results are shown in Fig. 24. As can be seen a change from 30 to 50 years in the lifetime of the installation implies an overall reduction in the energy cost of about 11%.

6.2 - Comparison with the energy cost from other energy sources

The electric energy economics of an EA prototype can be summarised as:

- An Unit cost varying between 1002 and 1391 M$ with a best estimate value of 1192 M$.
- An investment cost ranging between 1684 and 2338 $ per kWe installed, with a typical value of 2003 $/kWe.
- An energy cost range of 1.91 - 2,67 ¢ per kWh with a best estimate of 2.29 ¢/kWh.
- A typical energy cost distribution of 61%, 27% and 12 % among the investments, O&M and fuel costs respectively.

The electric energy economics of an EA series Unit, under the above described assumptions, is defined by:

- An Unit cost of 941 M$ within a range of 788 - 1095 M$.
- An investment cost of 1582 $ per kWe installed with 1324 and 1841 $ per kWe as lower and upper limits.
- An energy cost of 1.99 ¢ per kWh within 1.66 - 2.33 ¢ range.
- A fractional cost distribution among investments, O&M and fuel cost of 0.55, 0.31 and 0.14 respectively.

The quoted values correspond to the 5% net discount rate usually considered in the evaluations for OECD countries. For a 10% net discount rate the Unit and Investment costs increase by a factor of the order of 1.1. However, the energy cost increases by a factor close to 1.6 due to the strong influence of the net discount rate in the reduced lifetime of the installation.

To compare the prospective performances of the EA with those from the Nuclear Power Plants we used the data from Ref. [7], given in 1991 $, which summarises data presented from several OECD and a few non OECD countries on the projected energy cost of Nuclear, coal-fired and gas-fired Power Plants commercially available for the year 2000. Some data on renewable energy sources is also presented. As shown in [7] there are significant fluctuations from country to country, due to their specific conditions, and it is difficult to extract general conclusions. Nevertheless, at 5% net discount rate the Nuclear Power is projected to be the cheapest option for electricity production in most of the countries (thirteen from a total of fifteen countries). In those regions with direct access to cheap Coal or Gas, the nuclear option may no longer be the cheapest. The situation changes if the net discount rate is 10%. In slightly less than 50% of the countries nuclear energy turns out still to be the cheapest option. The projected average cost of the electricity from standard Nuclear Power plants is 3.77¢ (1991)/kWh which is 1.87 times the EA prototype prospective energy cost and slightly higher than twice (2.14) the cost for a series Unit. Also, the lowest projected energy cost for a particular plant is 1.7 times more expensive than the prospective cost with an EA series Unit. These ratios decrease slightly (by about 15%) for a net discount rate variation from 5% to 10 %.

The overall factor 2 can be split into the factors corresponding to the investments, O&M expenses and fuel cycle contributions to the energy cost. The average values quoted in [7] are 2.03, 1.01 and 0.74 ¢ (1991) whereas for the EA the corresponding estimates are 1.10, 0.55 and 0.24 ¢ (1991) respectively. As can be seen there is a factor around 2 both for the investment and O&M contributions to the energy cost, while for the fuel contribution the factor is slightly higher than 3.

In comparing the energy cost from Nuclear, Coal and Gas, Ref. [7] shows that, at 5% net discount level, nuclear electricity is about 20% cheaper than Coal or Gas while at 10% net discount level the costs become comparable. Therefore the electricity cost from the EA is expected to be slightly less than a factor two cheaper than Coal or Gas, at 10% net discount rate, and 2.6 times cheaper if the net discount rate is 5%.

Relative to the renewable energies, firstly they are not adequate for an energy base supply and second, according to [7], the energy cost is significantly higher than coal or gas-fired sources.

The above comparison of the energy costs has been done in terms of electricity. However, it can be more direct in terms of "heat cost", since the steam quality from the EA is, due to the high working temperatures, close to that from Coal or Gas. To that purpose we will evaluate the Investment, O&M and Fuel costs for the Heat Generating Assemblies (HGA) of coal and gas Power Plants of similar thermal power. The total cost of a GJ will be then estimated and compared with that from an EA Unit.

***Table 25**. Analytical cost of an HGA for a coal-fired power plant, in M$*

Item	*Best Estimate Million US$*	*Lower limit Million US$*	*Upper limit Million US$*
Boiler	143.99	116.62	171.36
Coal Storage Park	83.30	59.50	107.10
Ashes Extraction	10.00	5.00	15.00
Total	**237.29**	**181.12**	**293.46**

The Cost of thermal energy from coal-fired varies considerably depending on the quality of the fuel, since the fuel characteristics are very different for anthracite, ordinary coal, lignite or bituminous shales. Also, the environmental impact differs strongly according to the fuel used.

As a reference we will consider the most usual fuel types like ordinary coal, or anthracites mixed with bituminous elements to allow lower ignition temperatures. In this case, for a 600 MWe coal-fired plant, an estimate of the cost of the main components and the total direct cost of the HGA appears in Table 25 [17], where the cost for a fuel storage park has been included since it is a necessary and singular component of a coal-fired plant.

The indirect cost has been calculated on the basis of 5% net discount rate, a 5 years construction period and the fractional investment distribution given in Table 26, which corresponds, with the appropriate time scaling, to the data from Ref. [7].

***Table 26** Fractional distribution of investments for a coal-fired power plant*

Year	-5	-4	-3	-2	-1
Fractional Investment (%)	9	20	27	30	14

The other costs have been estimated in 20% (with 4% of accuracy) of the direct investment costs and 2.5% for the spare parts, the same values used for an EA series Unit.

The total investment cost estimate and range are 326.14 and 252.09 - 400.20 M$ respectively. The selected power plant parameters are 30 years lifetime, a load factor of 75% and a thermodynamical yield of 36% which gives a heat power of 1650 MWth. Therefore, the total cost of the investment, in terms of $/GJ is 0.543 and the cost range 0.420 - 0.666 $/GJ.

The O&M cost has been estimated on the basis of a complete replacement of the boiler after 30 years and is 0.010 within a range of 0.008 - 0.012 $/GJ. The fuel contribution has been estimated in 1.81 $/GJ (which corresponds to a cost of 2.08 $/GJ by the year 2000 considering 2.5% yearly inflation [7])[13].

The total energy cost and cost range in current money is presented in Table 27, together with the contribution from the three items.

Table 27. *Investment, O&M, Fuel and Total Energy Cost for a 600 MW_e coal-fired power plant (in $/GJ)*

Item	*Best Estimate $/GJ*	*Lower limit $/GJ*	*Upper limit $/GJ*
Investment	0.543	0.420	0.660
O&M	0.010	0.008	0.012
Fuel	1.812	1.449	2.174
Total	**2.36**	**1.88**	**2.85**

The dependence of the energy cost on the net discount rate is shown in Fig. 25. As can be seen the energy cost increases by 19% when the net discount rate varies from 5 to 10%.

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[13] The values quoted correspond to the current cost derived from the projected cost from Ref. [7]. We adopted this estimate because an EA Unit will not be operational before the beginning of the next century, as considered in [7].

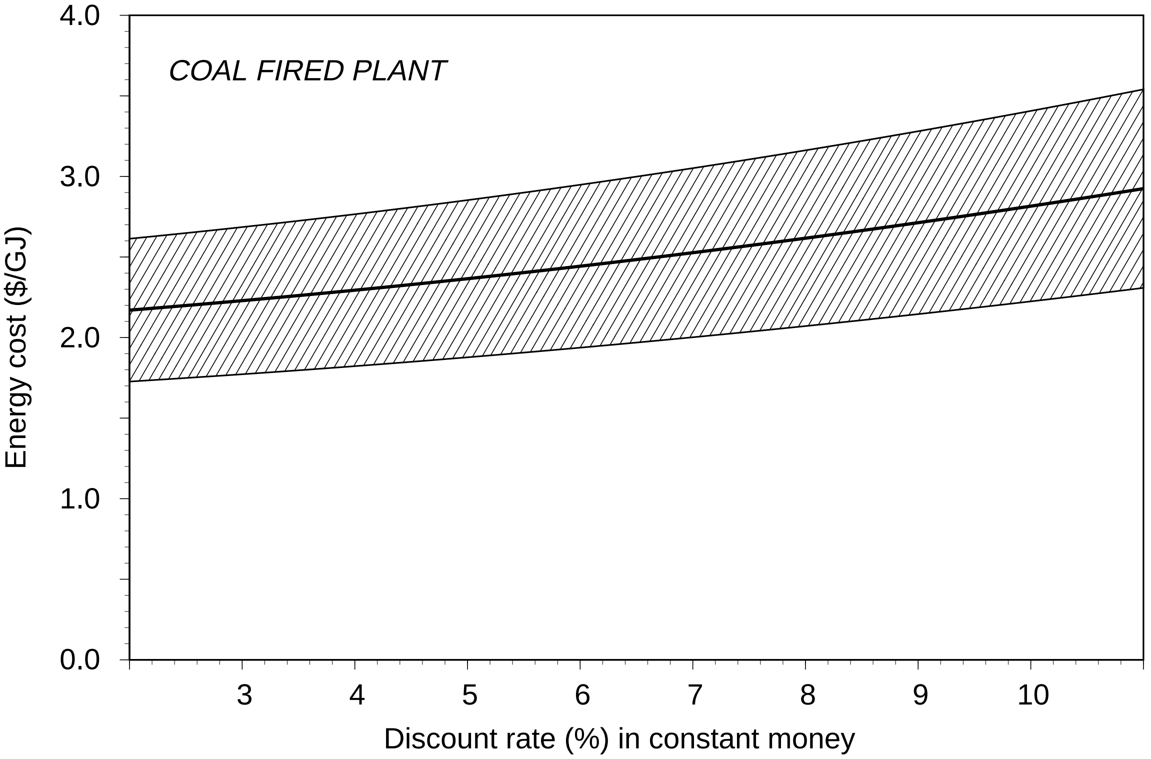

Figure 25 - *Thermal energy cost (best estimate and range) for a typical 600 MWe coal-fired power plant, as a function of the net discount rate.*

The cost of thermal energy from a gas-fired plant has been estimated with a similar methodology than for a coal-fired plant. The cost range of a boiler for a 600 MWe Unit is 84 - 104 M$ with a typical value of 94.5 M$ [17]. The indirect cost has been estimated on the basis of 5% net discount rate, a 4 years construction period and the fractional distribution of investments given in Table 28.

Table 28. *Fractional distribution of investments for a gas-fired power plant*

Years	-4	-3	-2	-1
Fractional investment (%)	10	26	40	24

In estimating the other costs we also took 20% (with a 4% accuracy) of the direct investment cost and an additional 2.5% for spare parts.

Therefore the total investment cost and cost range are 126.70 and 110.08 - 142.20 M$. The selected power plant parameters are 25 years lifetime, a load factor of 75% and a cycle yield of 47% which gives a heat production of 1300 MWth. The total investment cost and range, in terms of $/GJ are 0.292 and 0.254 - 0328 respectively. The O&M expenses and range have been estimated in 0.009 and 0.007 - 0.010, corresponding to a yearly costs of 4% of the total direct cost of the boiler. The fuel cost estimate and range are 3.35 M$ and 2.72 - 4.53 $/GJ, which gives as total energy cost the values given in Table 29.

***Table 29.** Investment, O&M, Fuel and Total Energy Cost for a 600 MW_e gas-fired power plant.*

Item	*Best Estimate $/GJ*	*Lower limit $/GJ*	*Upper limit $/GJ*
Investment	0.292	0.254	0.328
O&M	0.009	0.007	0.010
Fuel	3.35	2.72	4.53
Total	3.65	2.98	4.87

The dependence of the energy cost on the net discount rate is given in Fig. 26. As can be seen the energy cost increases by 6% when the net discount rate varies from 5 to 10%. The cost of thermal energy from an EA Unit is given in Table 24 and its dependence with the net discount rate shown in Fig. 27 for the prototype and series Unit.

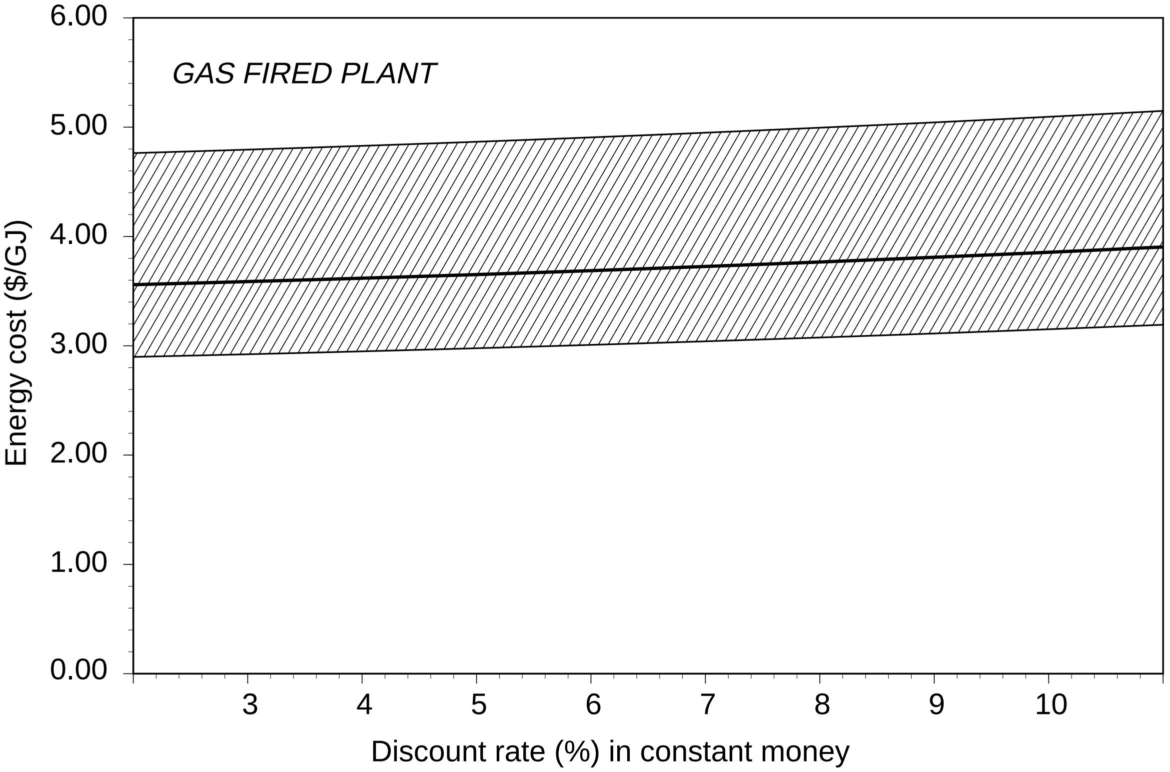

***Figure 26** - Thermal energy cost (best estimate and range) for a typical 600 MWe gas-fired power plant, as a function of the net discount rate.*

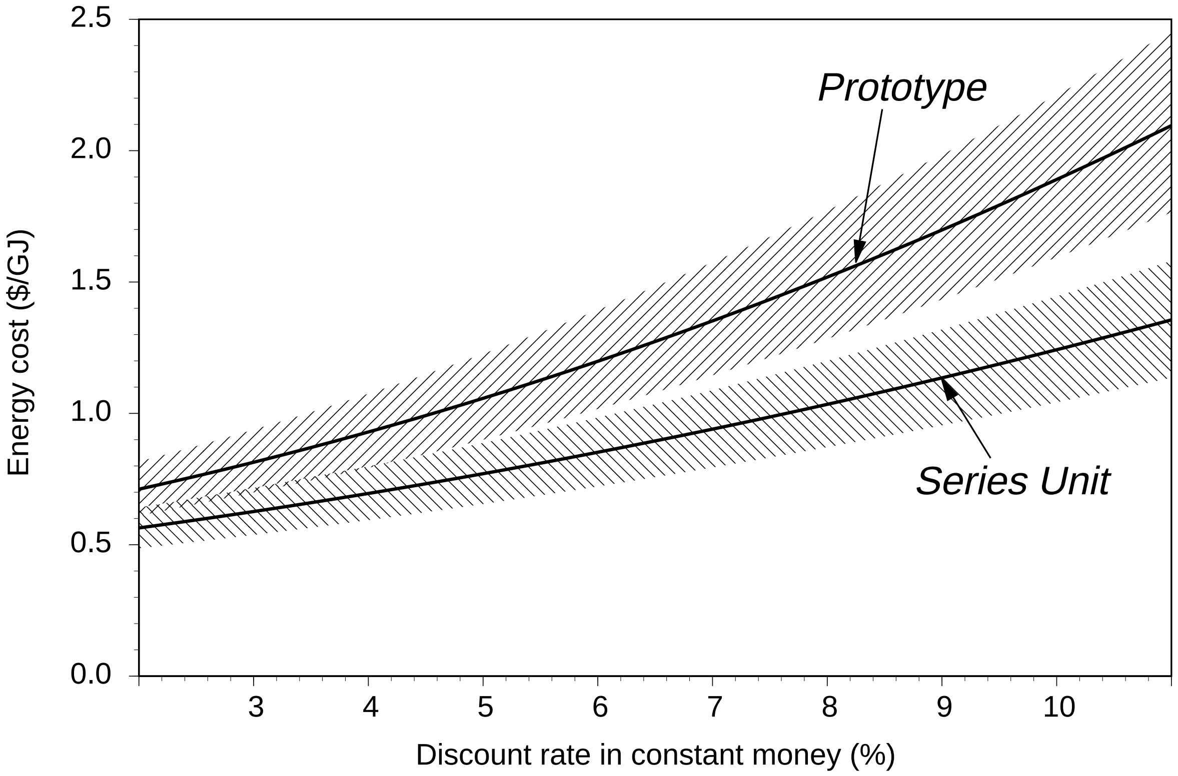

Figure 27 - *Thermal energy cost (best estimate and range) for both the EA prototype and series unit, as a function of the net discount rate.*

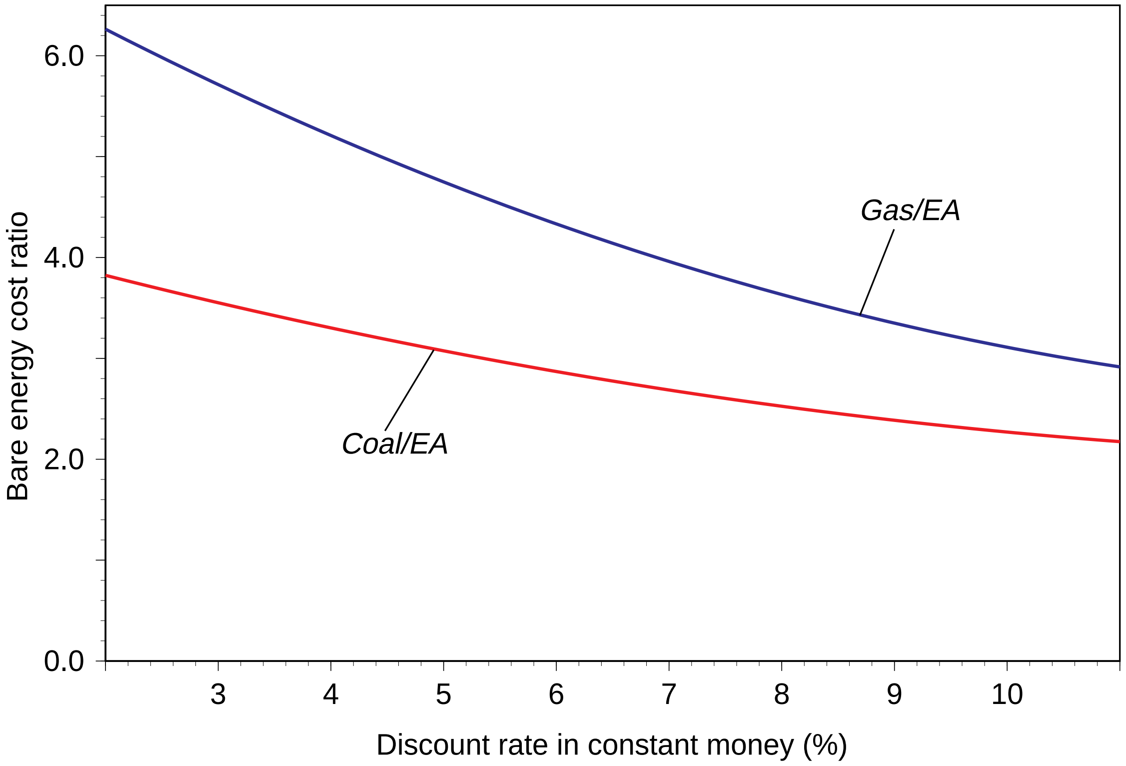

Figure 28 - *Thermal energy cost comparison between the EA and typical 600 MWe gas-fired and coal-fired power plants. The uncertainties in the ratios are of the order of 30%.*

Comparing the heat produced cost from the three sources, EA, coal-fired and gas-fired, the following conclusions can be reached:

- For a 5% net discount rate and the other assumptions already described in the text the "heat" cost from an EA Unit is 3.07 times lower than its corresponding cost from coal-fired (within an accuracy range of 2.12 - 4.37 times). When comparing with the "heat" cost from gas-fired the energy from the EA Unit is 4.75 times cheaper (within an accuracy range of 3.36 - 7.44). The large accuracy margins include the fluctuations from country to country, in addition to the intrinsic accuracy of the estimate.
- An increase of the net discount rate implies a reduction of the cost ratios. However, as shown in Fig. 28, for a 10% net discount rate the factors are still very significant, 2.3 and 3.2, with respect to the coal-fired and gas- fired cost respectively.

6.3 - Conclusions

An analytical estimate of the EA Unit energy cost shows that, in terms of electricity, the energy will be about twice as cheap as the current nuclear energy, nearly independent of the net discount rate value. With respect to the coal and gas-fired it will also be cheaper, the cost ratio varying from 2.6 at 5% net discount rate to about 2.0 at 10% net discount rate, as it is shown in Table 30.

When comparing the heat production cost from the EA and that from coal and gas-fired their ratios are, at 5% net discount rate, close to than 3 and 5 respectively. These values decrease with increasing net discount rate, but still remain larger than 2 and 3 for a value of 10%, as it can be seen in Table 31.

We stress the robustness of our cost estimate, in spite of the relative novelty of the method. Indeed, the only truly innovative elements are the EGU and the Accelerator. Since their relative contribution to cost are modest (approximately 5 % for the EGU and 10% for the Accelerator, see Fig. 15) even large variations in their cost will produce effects which are generally within the quoted uncertainties for the total cost.

In all cases the EA prospective economics is clearly competitive.

Table 30. *Cost estimate of kWh*[14]*, cost ratios and limits.*

Energy source	***Costs in ¢/kWh***			***Ratio to EA***		
	Best estimate	*Lower limit*	*Upper Limit*	*Best estimate*	*Lower limit*	*Upper Limit*
Net disc. rate 5%						
Nuclear	4.3	4.0	4.6	2.1	1.6	2.9
Coal	5.2	4.9	5.5	2.6	2.0	3.4
Gas	5.3	5.0	5.6	2.6	2.0	3.5
EA	2.0	1.7	2.3	—	—	—
Net disc. rate 10%						
Nuclear	6.3	6.0	6.6	2.0	1.6	2.6
Coal	6.6	6.9	6.3	2.1	1.7	2.8
Gas	5.8	5.5	6.1	1.9	1.4	2.5
EA	3.1	2.6	3.6	—	—	—

Table 31 *Cost estimate of GJ, cost ratios and limits.*

Energy source	***Costs in $/GJ***			***Ratio to EA***		
	Best estimate	*Lower limit*	*Upper Limit*	*Best estimate*	*Lower limit*	*Upper Limit*
Net disc. rate 5%						
Coal	2.3	1.9	2.9	3.0	2.1	4.5
Gas	3.7	3.0	4.9	4.8	3.4	7.5
EA	0.77	0.65	0.89	—	—	—
Net disc. rate 10%						
Coal	2.8	2.2	3.4	2.3	1.6	3.4
Gas	3.9	3.1	5.1	3.3	2.2	5.1
EA	1.2	1.0	1.4	—	—	—

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[14] The values quoted for nuclear, coal-fired and gas-fired energy cost are the updating to 1996 $ (2.5% yearly inflation rate) of the averages and statistical errors calculated with Ref. [7] data.

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