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**ACCELERATOR SPALLATION REACTORS
FOR BREEDING OF FISSILE FUEL AND TRANSMUTING FISSION PRODUCTS**

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I. Introduction

This report constitutes a summary review of the status and prospects of the development of accelerator spallation reactors for breeding fissile fuel and for transmuting fission products.

The concept of utilizing a high energy particle accelerator in conjunction with a target to generate neutrons for use in converting U-238 to Pu-239 dates back to 1947 when E.O. Lawrence recommended this method for the US weapons program.⁽¹⁾ A project called MTA was established and studies were made on producing Pu-239 with the use of a 500 Mev deuteron beam and 320 ma current on a primary beryllium target and secondary uranium target surrounded by a uranium lattice blanket. Liquid NaK coolant was used for primary and secondary targets and water for the uranium blanket. The incentive for the project was the lack of natural uranium resources (U-235) for the nuclear weapons program. Upon discovery of ample supplies of uranium in the US and development of reactor technology, the MTA project was terminated in 1953.

The technical feasibility was established and it is interesting that even at that early stage of development the design efficiency of the linear accelerator was as high as 50% of power into the machine to beam power out.

The next development was a detailed design study by Wilson et al of AECL for an Intense Neutron Generator (ING) in the early 1960's⁽²⁾. The design was based on measurements of spallation neutrons performed at the BNL Cosmotron ⁽³⁾ in a joint project between AEC and ORNL. The ING was a 65 MW linear accelerator (65 ma and 1000 MeV beam) machine with a Pb-Bi liquid metal target and coolant to generate high energy neutrons for basic research purposes. However, Wilson always had in mind that this could also be of value as a suitable fissile materials production machine as well.

In 1967, work at BNL⁽⁴⁾ first proposed the use of an accelerator spallation reactor for transmuting the long-lived Cs-137 and Sr-90 fission product waste. This was proposed because it was determined that thermal fission reactor cores could not produce the high neutron flux necessary to effectively shorten the half-lives of these long-lived radioactive products by neutron transmutation. A study was again undertaken in 1976 ⁽⁵⁾ using a ThO₂ target with helium gas cooling. It was shortly thereafter (6,15) that studies were undertaken at BNL on a Linear Accelerator Breeder for producing nuclear fissile fuel material from fertile material as a possible backup to the Liquid Metal Fast Breeder Reactor (LMFBR). The concept of the Linear Accelerator Driven Reactor (LADR) and the Linear Accelerator Fuel Producer (LAFF) was developed at that time. Oakridge (ORNL), Los Alamos (LASL) and Livermore (LLL) then undertook studies on their own. A conference on Accelerator Breeding was convened at BNL in 1977 which reviewed a number of the concepts⁽¹⁾ concerned with producing fissile material with spallation induced neutrons.

In April 1977 the Carter administration in the U.S. established a non-proliferation policy which forbade the reprocessing of nuclear fuel because of the risk of nuclear weapons proliferation. This policy for all practical purposes tended to retard the progress towards commercialization of the fast breeder reactor in the U.S. The U.S. Department of Energy set up studies for developing a Nonproliferation Alternative Systems Assessment Program (NASAP). A number of nuclear alternative reactor and system candidates were proposed and investigated.⁽⁸⁾ Several linear accelerator fissile fuel production concepts were studied and one particular concept the Linear Accelerator Fuel Enricher Regenerator (LAFER) was studied in depth⁽⁷⁾ by Brookhaven National Laboratory.

The LAFER study was presented at the First International Meeting in Graz, Austria on "Advanced Nuclear Reactor Concepts" in April 1978. The Accelerator Spallation Breeder was included in the International Nuclear Fuel Cycle Evaluation (INFCE) studies only as an advanced concept because the system was not considered as a demonstrated technology.

In addition to the above, several waste management concepts ^(12,13,14) based on transmutation and decay using accelerator spallation neutrons were studied by BNL and presented at the Second International Meeting in Lucerne, Switzerland on "Advanced Nuclear Reactor Concepts" in April 1980 and in Austin, Texas at an International Meeting on "Waste Transmutation" in July 1980. ^(11,13)

Neutron Spallation-Evaporation Characteristics and Yields

The basis for an accelerator spallation reactor is the neutron multiplication obtained when a high energy particle having energies greater than approximately 50 Mev interacts with a target atom. The principal types of interactions with atoms are electron ionization-excitation and inelastic

collisions. These interactions are called spallation-evaporation or intra-nuclear cascade evaporation processes. Some experimental measurements of the yield of neutrons produced in the spallation-evaporation process by energetic protons have been made. Fig. 1 shows the results of experiments conducted with the 3 GeV Cosmotron at Brookhaven. It is noted that the neutron yield for U-238 is twice that obtained for Pb. The difference is due to fast high energy neutron (>2 MeV) fission occurring in U-238.

Fig. 2 shows the calculated energy spectra of neutrons produced by 800 MeV protons incident on solid targets of Pb and U-238. Here again the difference introduced by fission neutrons is clearly indicated. The yields and energy spectrum resulting from the intra-nuclear cascade alone (>5 MeV) are about the same for both materials.

The neutron yields have been modelled and calculated from models using the Monte Carlo method with the Nuclear Meson Transport Code (NMTC). Table 1 indicates the calculated neutron yield when 1 GeV protons are injected into the center of an infinite medium of different types of material of interest for a target assembly. It is noted that the neutron yield does not vary greatly even for H_2O/UO_2 lattices of widely varying ratios. This calculation only includes neutron induced reactions of ≥ 15 MeV. The interactions for <15 MeV neutrons are included in the target-blanket calculations using neutron transport codes with neutrons crosssection libraries.

Experimental studies have indicated that for interaction of 660 MeV protons with a metallic uranium lattice, the total neutron yield amounts to about 50 neutrons/proton⁽¹⁶⁾. Calculations by Boroshenkov⁽¹⁷⁾ indicate a neutron yield for 1 GeV protons of 100 neutrons. Further neutron yield experiments are needed to confirm these results which includes the fast fissioning of U-238.

It is also of interest to note that in the 1-Gev region, deuterons give a 20% increase in neutron yield compared to protons. Although this indicates that accelerating deuterons might be advantageous, the higher cost and design constraints of a deuteron accelerator tend to negate the higher neutron yield advantage.

Calculations have been made for the production of fissile material and the generation of thermal power in various target blanket assemblies. Table 2 shows the production rate of fissile material for a number of arrays based on a 1.5 Gev proton with 0.3 amp current. The target is Pb surrounded by various fertile material-coolant blankets. Table 3 gives the initial and final calculated blanket thermal power (after 1 year) irradiations for different values of fissile fuel enrichment in the blanket. This thermal power and the direct target thermal power deposited by the proton beam is recoverable for generating electrical power for use by the accelerator in making the system power self-sufficient. The neutron yield and thermal power calculations are considered conservative. A prime experimental effort for developing the accelerator spallation reactor should be the actual measurement of the neutron yield and the heat released in a real lattice structure.

III. Accelerator Development

The reason that spallation reactors can be seriously considered as a production tool today is because the linear accelerator has been developed and engineered to a high degree over the past 30 years for high energy physics basic research purposes. Linear Accelerator technology is at the point where a continuous wave (CW) high capacity machine can be designed and built with great deal of confidence and that it can be made to operate with a high degree of reliability.

Protons and heavier particles can be accelerated to energies >1 Gev most economically in synchrotrons. These accelerators are limited, however, to pulsed operation and very low average intensity. A continuously operating high current beam accelerator is required for fissile fuel production. The linear accelerator is the only type of accelerator available today capable of accelerating a steady, continuous beam current of protons of over 100 mA. With linear accelerators, proton currents of 300 mA have been accelerated, and the possibility is available of accelerating even higher currents, if necessary. Table 4 lists a number of relevant accelerators (most of them operating) with their characteristics. Storage rings are listed to show that very large currents (large for accelerators) can be circulated and contained for very long time periods essentially without beam loss.

Besides its unique capability of accelerating high currents, the linear accelerator has the added advantage of: (a) providing the most efficient means of energy conversion (electrical energy to beam energy), and (b) having the lowest beam loss factor (particles lost during the acceleration process).

Minimization of beam loss is an important criterion for this application. In all circular accelerators a certain amount of beam loss is inevitable at injection and extraction, which makes all equipment located in these areas highly radioactive. For the very high beam power application considered here, even the lowest fractional beam loss that has been achieved is still several orders of magnitude higher than that which is acceptable. With a linac, there is no extraction loss, and since the injection energy is typically less than 1 MeV, injection losses are manageable. In addition, because the beam travels in a natural straight line, the loss during the acceleration is much lower than in all other types of accelerators. These

simple considerations lead directly to the conclusion that the linac is the optimum choice for a production type facility.

The charged particles are produced in an ion source. They are first accelerated to an energy which is typically about 750 keV in a dc electrostatic accelerator. The 750-keV beam is then injected into the linac and accelerated to the final energy by the rf field in the cavities. New developments in linear accelerators indicate that the injection energy required for high beam currents might be relaxed. In particular, work carried out in the USSR shows that 100-keV injection might be possible. Many different linac cavity designs are available, each having its own merits for special applications. The choice of specific structure and rate of acceleration per unit length is based on cost, beam-loading efficiency, and other construction and operating features.

Above the lower limit of beam energy set by ionization loss, the neutron yield in the target is roughly proportional to the beam power, which is in turn proportional to the rf power for a given beam loading. A major part of the cost of the linac roughly about 70% of the total cost of the accelerator is in rf supply. This cost is proportional to the beam power, hence the fuel yield. Thus for a given fuel yield the total accelerator cost is primarily affected by the cost of the radio-frequency system. The remaining costs, such as those of the cavity structure, the control and monitoring system, the linac housing, etc., amount to about 30% of the total. The costs of these components are generally proportional to the length, hence the energy, of the linac. Therefore, for a given neutron yield, the total cost of the linac is somewhat lower for lower energy and higher current.

A beam current of 300 mA has been obtained at Fermilab, though only in a pulsed mode. However, during the pulse, a steady state is reached insofar as

the transfer of power from the rf supply to the beam is concerned. The pulse length is limited only by the size of the rf supply. Hence, a 300-mA continuous wave (cw) beam current is considered a realistic goal attainable with high confidence. At LASL a particle energy of 0.8 GeV has been achieved in a linac, and further acceleration will require only iteration of stages that are now in use. This demonstrates the total practicality of attaining energies >1 GeV. One reference design is based on an accelerator that will provide a beam of 1.5-GeV protons at 300 mA to produce, conservatively, more than 1 ton of fissile fuel per year. This is enough fissile material to support three reactors. These parameters are not optimized, and it is likely that optimization will result in somewhat different design characteristics.

Higher beam energies are well within the expectations of linac technology. A higher energy, with the same beam current, will yield a correspondingly higher fuel production rate with little or no reduction in certainty of success. However, the unit cost of fuel produced will not be significantly lower.

It is to be noted here that linear accelerators at BNL, CERN, Fermilab, and LASL have impressive records for operational reliability ($>90\%$ of scheduled time with an overall plant factor of better than 80%). It is expected that the linac part of the fuel regenerator facility will at least match this performance.

A discussion of the linear accelerator design and development needs can be found in ref 7. The major parts of the accelerator can be categorized as follows: (1) the injection system, (2) the low β -linac section, (3) the high β -linac section, (4) the radio-frequency systems, and (5) the control and diagnostic section. Improvement in efficiency and cost must necessarily come from development in the rf supply. If a Russian development of an rf

system called the Gyrocon materializes, this could increase the overall conversion efficiency of dc to rf power to over 90% and would greatly reduce cost of the linac.

It is generally agreed that a 50% efficiency of electrical power input to beam power output can be readily achieved with state-of-the-art linac technology. Improvements could ultimately bring efficiencies to 70% or more.

III. Target-Reactor Development

The target-reactor design generally depends on a combination of the following four factors.

1. The primary target material.
2. The coolant of the primary target.
3. The blanket configuration.
4. The coolant of the blanket.

If the primary target is a fertile material such as uranium or thorium, the neutron yield due to fast fission will be considerably higher than if it were lead. On the other hand, much greater thermal power and radiation damage will occur in a solid U or Th target than in a liquid Pb target. The primary target and coolant properties will determine whether a window or barrier between the electron machine and the primary target is necessary. If a gas coolant such as helium, steam or a liquid coolants such as light or heavy water is used, a window or thin walled barrier between the vacuum of the linac beam tube and the primary target becomes necessary. A beam window becomes a design problem in balancing beam energy losses with thermal and structural stability. Besides high strength to weight ratio materials such as steel, aluminum, and titanium, graphite has also been suggested as a window material. Liquid coolants such as molten lead, sodium or salts, because of their low vapor pressure normally do not require a window.

The bred fuel can be produced in the primary target or in a surrounding blanket in which fertile material is placed. The blanket is subject mainly to a neutron flux. A contained or uncontained coolant surrounding the blanket fertile material may be used.

An example of a workable target-blanket design developed at Brookhaven National Laboratory is given in Figure 3. The assembly is designed to generate fuel in-situ in a PWR-type fuel assembly bundle. This configuration is also useful for production of fissile fuel from fertile uranium or thorium. The bundles are placed into pressure tubes which surround a central slot through which jets of liquid Pb-Bi metal are projected down along the length of the calandria assembly of pressure tubes. The proton beam spreads elliptically from the beam transport tube entering the side of the calandria vessel with no interfering walls and interacts with the jets or columns of falling liquid lead. Neutrons are spalled and evaporated isotropically from the lead by the high energy protons and the high energy spallation and evaporation neutrons enter through the walls of the pressure tubes and are absorbed by the PWR-type fuel element rods (Zr clad UO_2) forming fissile Pu-239 from U-238 in-situ within the element. The purpose of the jets is to disperse the dense Pb-Bi target so as to allow a longer penetration path in the target for the purpose of distributing the neutron flux to a level which will be tolerable from a power density point of view. The Pb-Bi has a vapor pressure of 10^{-4} torr at the expected temperature of 300°C , thus maintaining an adequate low vacuum condition for the proton beam. The Pb-Bi is collected at the bottom of the vessel and cooled in a separate circuit. In order to prevent loss of neutrons, the outside area of the calandria vessel is covered with a neutron reflector (i.e. graphite) including top and bottom sections.

The assembly should be long enough to accommodate a full length PWR bundle (8 ft long).

For cooling purposes, because it is necessary to provide a hard spectrum, steam is used, but since a high heat flux is also expected, wet steam or two-phase evaporative cooling is used. The calandria tubes are made of zircaloy as is the cladding of the PWR elements. Wet steam prevents corrosion of the zircaloy. Liquid heavy water coolant is also an adequate coolant which would not require two-phase cooling. The thermal hydraulics of the system has been analyzed(7). Recovery of power can be obtained from the primary lead target as well as the secondary coolant. Pumping power would be less than 5% of the power required by the accelerator.

Another HWR-type target assembly arrangement is shown in Fig 4. This is of the horizontal pressure tube-type assembly similar in concept to the CANDU reactors. The Pb-Bi jets are in the center slot with the pressure tubes surrounding. The fuel elements are inserted horizontally through the pressure tubes. Shorter elements can be used in this arrangement for fissile fuel production with reprocessing.

IV. System Applications

The accelerator spallation reactor can be applied in several basic modes.

The Linear Accelerator Driven Reactor (LADR) uses a sub-critical reactor assembly in which the neutrons generated by the spallation reaction causes fission multiplication and a net production of power. This configuration is shown in Fig 5. The LADR becomes economically viable when the power produced in the target is 5 times that required by the accelerator.

The advantage of the LADR are (1) the fuel elements can be put through the reactor once without reprocessing, (2) power can be obtained from

natural uranium in light or heavy water-moderated sub-critical assemblies, (3) a sub-critical assembly has numerous reactor safety advantages, (4) the uranium resource can be stretched, and (5) the assembly does not require enriched fuel.

The disadvantages include (1) each power reactor requires an accelerator, (2) construction and operation is more complex than conventional power reactors, and (3) longer burnup may be limited by radiation damage to cladding and structural material.

The Linear Accelerator Fuel Enricher Regenerator (LAFER) produces fissile material in a fuel element designed for use in a conventional LWR power reactor. After burnup in the LWR reactor, the fuel is regenerated in the LAFER target-blanket assembly to build back the concentration of fissile material in the element to LWR feed criticality values. A schematic of the concept is given in Fig 6. A number of advantages accrue with this concept. (1) There is no departure from existing LWR power reactor practice. The utility operator does not have to learn a new technology as would be needed with the liquid metal fast breeder (LMFBR); (2) no reprocessing is required, reprocessing would only be limited by radiation damage to the fuel element with an increasing number of enriching-burning cycles; (3) one accelerator-spallation reactor can supply several LWR power reactors; (4) the LAFER stretches the natural uranium fuel resource by a considerable amount; (5) the accelerator is kept separate from the power reactor, this makes for a higher reliability of each part of the system, (6) enrichment capacity can be considerably reduced; no new enrichment facilities would be required; (7) substantially reduces reprocessing requirements when reprocessing is allowable; (8) There are no new scientific principles or technologies that have to be developed or demonstrated.

The only disadvantage of the LAFER is the limitation of the durability of the element on long term burnup, either due to fission product buildup or radiation damage to cladding.

The third concept is the Linear Accelerator Fuel Producer (LAFP). This Accelerator Spallation Reactor is used to produce fissile material from fertile material in conjunction with reprocessing and fabrication operations. The fissile material is incorporated into fuel elements for use in power reactors. After burnup, the spent fuel from the power reactors are returned to the reprocessing plant to recover the fissile material remaining and to remove the fission products which are sent to waste storage. A schematic of this system is shown in Fig 7. The advantages of the LAFP are as follows. (1) The fuel cycle comes closest to conventional; (2) eliminates the need for enrichment; (3) makes full use of fuel resource and is therefore a true breeder; (4) one accelerator can supply fissile fuel to several power reactors; (5) the LAFP can produce U-233 from thorium for use in high convertors. The main disadvantage of the system is that it depends on reprocessing the fuel elements.

V. Linear Accelerator Fuel Enricher-Regenerator System Analysis

A system analysis of the LAFER concept illustrates some of the advantages and economics of the LAFER fuel cycle.

The conventional LWR nuclear fuel cycle is shown in Fig 8. Natural uranium feed is isotopically enriched to 3.2% U-235 in a gaseous diffusion plant, fabricated into zirconium clad uranium oxide fuel, and then burned in the LWR. If reprocessing is allowed, the Pu is extracted or recycled and the separated radwaste fission products sent to long term storage. If reprocessing is prohibited, which is the present U.S. non-proliferation policy, the spent fuel elements must be stored in pools. For a 1000 MW(e)

reactor, over a 30 year life, 6300 tons of natural yellow cake is required to produce 1050 tons of enriched fuel, which ends up in spent fuel elements containing about 1.0% Pu-239 and 1.0% U-235. The net burnup is equivalent to 5000 MWD/ton of natural U. By comparison, heavy water cooled reactors (CANDU type) exhibit a fuel utilization of about 8000 MWD/ton and require no enrichment. The isotope enrichment plant wastes a great deal of the uranium resource, requiring 6 tons of raw natural uranium material to produce 1 ton of fuel; 5 tons are waste tailings.

The proposed Linear Accelerator Fuel Enricher Regenerator Cycle (LAFER) starts off with either no enrichment or a lower U-235 enrichment and builds into the fuel the required Pu-239 reactivity. One illustrative cycle is shown in Fig 9. Yellow cake is isotopically enriched to 2.0% U-235, fabricated into zirconium clad oxide fuel, and placed into the LAFER target where the fissile content is brought up to 3.2% fissile material by breeding in-situ the additional 1.2% Pu-239. The element is then ready for generating power in an LWR. After one burn cycle of 30,000 MWD/ton, the fissile material is reduced back to 2% and the fuel element is reinserted into the LAFER where fissile material is once again increased from 2 to 3.2%. Without reprocessing, the net fuel to storage is 500 tons or half that for a conventional cycle. The number of allowable fuel regeneration cycles depends primarily on the radiation damage to the cladding. Conservatively, the number of burn cycles has been limited to 2, meaning that the element experiences a burnup of 60,000 MWD/ton in the reactor with another 6000 MWD/ton burnup in the accelerator. Figure 10 indicates the buildup of Pu-239 and decrease of U-235 in the LAFER, followed by buildup of fission products and burnup of the fissile material in the reactor. It is interesting to note

that the thermal and epithermal neutron absorption due to fission products is decreased in the LAFER irradiation cycle. This indicates that some of the fission products are transmuted from strongly absorbing isotopes to weaker neutron absorbing species in the process.

There has been much successful operation of conventional LWR elements to burnups of 60,000 MWD/ton in LWR power reactors. Present projected burnup designs for the liquid metal fast breeder (LMFBR) reactors call for 100,000 MWD/ton of fuel. The total natural uranium (yellow cake) needed for the LAFER cycle is 1750 tons over the 3 year life of the 1000 MW(e) LWR. Thus, the resource gain is 3.6 times the conventional cycle. Furthermore, no additional capacity of expensive enrichment plants are necessary. The LAFER is a positive enrichment machine because it converts fertile U-238 to fissile Pu-239. The isotope enrichment plant is actually a depletion plant since it only utilizes the very limited natural U-235 resource and throws away the bulk of the natural fertile material.

Based on the above concept, a system was devised as shown in Fig 11 where 3-1000 MW(3) reactors are supplied throughout their 30 year lifetime with fuel from one LAFER. The 450 MW beam from the accelerator is produced using a 900 MW(e) power supply, 450 MW(e) of which are obtained by recovery of the heat developed in the target. A comparative cost estimate of the LAFER systems has been made. Table 5 shows the LAFER capital investment using 1978 dollars and escalating to 1986 using industry cost accounting. In terms of depreciation of the 1.5 billion dollar capital investment for the LAFER machine, the charge to electrical energy production amounts to 11.6 mills/KWh(e) delivered by the power reactors. Table 6 gives the entire fuel cycle cost and compares it to the conventional LWR cost. It is interesting

to note that yellow cake enrichment and fabrication costs are reduced by substantial factors. The cost of make up LINAC power charged at the full production cost rate and the amortization charges increases the fuel cycle cost to the point where the LAFER fuel cycle cost is twice that of the conventional LWR cycle cost. An optimization study should bring these values down especially if the LAFER can be made self-sufficient in power by generating sufficient heat in the target to produce enough power to supply the LINAC. Even with the increased fuel cycle cost as shown in Table 7, the total production cost for power is only 35% higher than the conventional fuel cycle. This is about the same incremental estimate that is projected for the LMFBF breeder. However, this cost differential could easily disappear in the next 20 years depending on the growth of the nuclear industry and the availability of natural uranium. Moreover, this potential cost penalty has to be weighed against the enormous cost/benefit of more than tripling the uranium fuel resource and reducing the amount of radioactive waste by half all within the context of supplying the well established and accepted conventional LWR nuclear power reactor economy.

It should be noted that the LAFER cycle is a general one in that the initial content of fissile material can vary from 0% (natural thorium) to 0.2% (depleted uranium) to 0.7% (natural uranium) to any amount of enriched fuel that makes economic sense. The amount of makeup fissile fuel needed to supply different types of convertors decreases with increasing conversion ratios. Fig 12 indicates that the number of 1000 MW(e) reactors that can be supported by fuel supplied by one 300 MW beam power accelerator increases from 3 for a 0.6 conversion ratio conventional LWR to 5 for an advanced (0.73 conversion ratio) reactor to 14 for a high conversion (0.9 conversion ratio; reactor.

The above LAFER and LAFP are based on a conservative design using a neutron yield of 35 neutron/Gev proton with a Pb target. A more recent accelerator spallation reactor design and analysis has been made for fuel production based on a uranium metal target yielding approximately 100 neutron/Gev proton. The U-metal target is surrounded by Zr clad UO_2 fuel elements. The design characteristics are listed in Table 8. This analysis indicates that 3.7 metric tons of fissile material can be produced with a 2 Gev-300 ma proton beam and sufficient energy is developed in the target due to fast fission to supply the electrical power to the front end, thus making the system entirely power self-sufficient. This system could supply fuel for 12 LWRs at an economically attractive rate.

Figure 13 indicates how the LAFER and the LAFP significantly improves the utilization of the nuclear fuel resource while maintaining an LWR economy. The data is based on the conservative value of 3 LWRs/accelerator. Assuming various nuclear power growth rates and quantities of uranium resource, a peaking in fuel availability will occur at a higher capacity and at a later date with the accelerator fuel producer than without it. The more recent design, indicating 12 LWRs/accelerator, makes the supply picture even look much better. The accelerator fuel generator essentially replaces the isotopic enrichment plants. Allowing reprocessing of spent fuel, the accelerator fuel producer acts as a true breeder while maintaining a long term LWR power reactor economy. The LAFP can act as a backup to the fast breeders or indeed it can be a strong competitor or even a supplier to the fast breeder. The only other nearest competitor is the futuristic fusion-fission hybrid which still requires scientific proof of feasibility followed by long term technical development. Linear accelerators are here today in the form

of research tools. They can be converted to fuel production machines with relatively little additional development investment. Countries that desire to become self-sufficient in nuclear fuel and want to maintain the LWR reactors now universally accepted for power production, need only to install an accelerator spallation reactor fuel producer for maintaining a continuous assured fuel supply. The LAFER and LAFF cycles appear to be the missing link in the long term usage of an LWR nuclear power reactor technology.

Transmutation and Waste Management Cycles

The accelerator spallation reactor can also be used to burnup transuranic materials and to transmute fission product wastes. Several concepts have been investigated. In the APEX concepts, after several LAFER cycles, the fuel is reprocessed and partitioned. The stable and low hazard short half-life (<2 yr) materials are disposed of and the transuranics are returned to the nuclear fuel cycle, along with the remaining fissile and fertile fuel. Selected fission products such as Sr-90 and Cs-137 can either be recycled along with nuclear fuel (APEX-1) or transmuted separately (APEX-2). A composite schematic of the APEX waste management fuel cycles is shown in Fig 14. The Airox process indicated in the diagram involves a dry partial reprocessing by hydrogen reduction followed by oxidation of the uranium oxide fuel pellets. In this system, the volatile fission products are removed and the remaining fuel can be refabricated and burned further in the LWR. In this fuel cycle the high neutron crosssection transuranics are fissioned and the low crosssection fission products are allowed to buildup and decay within the fuel cycle so that only stable fission products are sent to storage. Computer calculations indicate that an accelerator fuel enriching transuranics burnup and fission product transmutation and decay fuel cycle can be designed so that the equilibrium transuranics and long-lived fission

product concentrations would be about the same as that anticipated in the 100,000 MWD/con burnup cycle planned for the LMFBR fuel.

In the direct transmutation of the long lived fission product cesium and strontium, it may be necessary to isotopically separate Cs-137 to maintain a high neutron economy. This would not be necessary for the Sr-90.

It has also been suggested that the military waste be disposed of by incorporating the residual Pu, transuranics and long-lived fission products into the growing LWR fuel cycle. The APEX concepts depend on reprocessing the wastes with a high degree of decontamination to minimize the loss of long-lived fission products to the waste stream. Fissile material and fission products do not have to be concentrated; only losses need to be minimized. The APEX concepts then provide an alternative to the long-term geological-age-disposal of long-lived radioactive nuclear waste. Additional studies are needed to thoroughly evaluate the tradeoffs and economics of each of the alternative APEX cycles to establish the optimum system.

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TABLE 1
 MONTE CARLO CALCULATIONS
 FOR Pb AND UO₂
 NEUTRONS PRODUCED BY REACTIONS OF GREATER THAN
 OR EQUAL TO 15 MeV EXCITATION ENERGY
 NEUTRONS/1 GEV PROTON

TARGET MAT.	AVER. YIELD*
Pb	35
UO ₂	35
1.4 H ₂ O/UO ₂ EFFECTIVE VOL. RATIO	28
0.7 H ₂ O "	29
0.17 " "	30

INFINITE MEDIUM, 1 GEV PROTON INJECTED INTO CENTER

*DOES NOT INCLUDE FISSION NEUTRONS < 15 MEV.

Table 2

Initial Fissile Fuel Production Rates for
Pb-Bi Target - Fuel Elements Blanket
(0.3-A 1.5-GeV Proton Accelerator)

Design No.	Fertile material	Coolant	Density of coolant, g/cc	Initial neutron yield Y_n (includes fission reaction)	Initial production rate of fuel material, kg/yr
1	UO ₂ (Nat. U)	D ₂ O	0.7	53.8	Pu 1010
2	ThO ₂	D ₂ O	0.7	46.6	233U 850
3	UO ₂ (Nat. U)	H ₂ O	0.7	74.1	Pu 1000
4	UO ₂ (Nat. U)	H ₂ O	0.35	65.8	Pu 1050
5	UO ₂ (Nat. U)	H ₂ O	0.175	64.9	Pu 1070
6	ThO ₂	H ₂ O	0.7	46.5	233U 850
7	ThO ₂	H ₂ O	0.35	48.6	233U 890
8	ThO ₂	H ₂ O	0.175	49.0	233U 900

moderator/fuel volume rates = 0.8

beam power output to electric power input efficiency = 50%

plant factor = 80%

Table 3

Initial and Final Blanket Thermal Power
for a 1-yr Irradiation Period
Starting with Different Enrichment Values

Pb-Bi target, fuel elements blanket
(0.3-A, 1.5-GeV proton accelerator).

Case No.	Initial enrichment, %			
	0	0.7	2	3
1	-	300 460	430 620	570 780
2	55 220	-	420 610	850 1040
3	-	380 530	530 660	620 740
4		380 540	530 680	650 810
5	-	450 620	640 830	810 1030
6	50 500	-	750 1000	1030 1260
7	60 310	-	550 710	770 940
8	80 260	-	560 730	820 1040

moderator/fuel volume ratio - 0.8

beam power output to electric power input efficiency = 50%

plant factor = 80%

TABLE 4

PARAMETERS OF EXISTING RELEVANT ACCELERATORS

ACCELERATOR LABORATORY	TYPE	ION TYPE	EMAX MEV	IMAX AMPS.	DUTY FACTOR	STATUS
LASL - LAMPF	LINAC	PROTON	800	0.020	12.0%	OP
LLL - MTA	LINAC	DEUT.	500	0.320	100.0%	PROP
BNL - AGS	LINAC	PROTON	200	0.2	0.5%	OP
FNAL	LINAC	PROTON	200	0.3	0.2%	OP
HEDL - HFNS	LINAC	DEUT.	35	0.1	100.0%	PROP
CERN - ISR	STORAGE RINGS	PROTON	3×10^4	40.0	-	OP
BNL - ISA	STORAGE ACCELERTOR	PROTON	4×10^5	6.0	-	PROP

Table 5.

LAFER FUEL CAPITAL COST
(1978 dollars escalated to 1986)

Linac Cost (0.3A - 1.5 GeV)	=	\$ 500 x 10 ⁶
Target Reactor Cost, 450 MW(e) x 1000 x $\frac{\$ 700}{\text{KW(e)}}$	=	<u>315 x 10⁶</u>
LAFER Cost (1978 Dollars)	=	\$ 815 x 10 ⁶
Escalation and Interest Charges (7% and 9%)	=	<u>675 x 10⁶</u>
LAFER Cost (1986 Dollars)	=	\$1490 x 10 ⁶
Amortization (15%)	=	\$ 223 x 10 ⁶
Energy from 3 x 1000 MW(e) Reactors (75% PF.)	=	19.2 x 10 ⁹ KWH(e)/Year
LAFER Fuel Capital Cost	=	11.63 Mills/KWH(e)

TABLE 6
FUEL CYCLE COST - MILLS/KWH(e) (ESCALATED TO 1986)

	<u>Unit Cost Dollars*</u>	<u>Conv. LWR*</u>	<u>Reduction Factor</u>	<u>2-Cycle LA FER-LWR</u>
Yellow Cake	\$50/Lb U ₃ O ₈	3.94	3.62	1.09
Conversion	\$11/Kg	0.29	3.62	0.08
Enrichment	\$100/SWU	2.90	4.33	0.67
Fabrication	\$200/Kg	2.05	2.0	1.03
Storage and Carrying Charge	\$400/Kg HM	3.87	2.0	1.94
Transportation	\$30/Kg HM	0.31	2.0	0.16
Amortization of LA FER (15%, 80% PF)		-		11.63
Electrical Power (450 MW(e)) to LA FER at 58.3 Mills/KWH(e)		-		9.46
Oper. and Maintenance		-		<u>2.00</u>
		13.36*		28.06

*ANS - US Industry Report (1976-7).

TABLE 7

COMPARATIVE ECONOMICS OF LINEAR ACCELERATOR FUEL REGENERATOR (LAFER)
WITH LIGHT WATER REACTORS (LWR)

	<u>Conv. LWR*</u>	<u>LAFER-LWR</u>
<u>Capital Cost</u>		
Base Capital Cost \$/KW (Gross)	\$ 600	\$ 600
Completion Cost \$/KW (Escalated for 1986 Operation) (Gross)	1100	1100
<u>Resource</u>		
Fuel Requirement over 30 years, Tons Nat. U	6300	1750
<u>Power Generation Cost (Average 1st - 10 yrs.)</u>	<u>Mills/KWH(e)</u>	
Capital Charges (15% and 70% P.F.)	26.9	26.9
Fuel (5% Escalation/Yr)	13.4	28.1
Op. and Maint.	<u>3.3</u>	<u>3.3</u>
Total	43.6	58.3

(*) ANS - US Industry Report (1976-7).

TABLE 8
 CHARACTERISTICS OF
 ACCELERATOR SPALLATION REACTOR
 (ASR)
 FOR SUPPORTING LWR POWER ECONOMY

p-ENERGY	-	2 GeV
CURRENT	-	300 mA
BEAM POWER	-	600 MW
MACHINE EFFICIENCY	-	50%
POWER TO ACCELERATOR	-	1200 MW (e)
POWER GENERATED IN TARGET	-	3600 MW(t) (self-sufficient)
PLANT FACTOR	-	80%
Pu ²³⁹ FISSILE FUEL PRODUCTION	-	3700 kg/yr
FUEL FOR 1 - 1000 MW(e) LWR	-	300 kg/yr
NO. of LWRs SUPPORTED	-	12

EXPERIMENT YIELD OF NEUTRONS BY BOMBARDMENT OF
A HEAVY METAL TARGET WITH HIGH ENERGY PROTONS

Figure 1

NEUTRON ENERGY SPECTRA FROM 800 MeV PROTONS
INCIDENT ON Pb AND U_{238} TARGETS

Figure 2

PWR TARGET ASSEMBLY

FIGURE 3

HWR TYPE TARGET ASSEMBLY .

Figure 4

LINEAR ACCELERATOR DRIVEN REACTOR (LADR)

Figure 5

LINEAR ACCELERATOR FUEL REGENERATOR (LAFR)

-35-

Figure 6

LINEAR ACCELERATOR FUEL PRODUCER (LAFP)

Figure 7

CONVENTIONAL NUCLEAR FUEL CYCLE - LWR

FIGURE 8

LAFR FUEL CYCLE - NO REPROCESSING

NATURAL URANIUM REQUIREMENT FOR
1000 MW(E) (75% P.F.)

LAFR-LWR OVER 30 YR PRODUCTION = 1750 TONS

BURNUP IN POWER REACTOR, 2 BURN CYCLES AT 30,000 MWD/TON

EXPOSURE IN LAFR = 3,000 MWD/TON MAX. PER CYCLE

NET RESOURCE GAIN = 3.6x

FIGURE 9

FIGURE 10

FIGURE 11

LINEAR ACCELERATOR FUEL REGENERATOR WITH LIGHT WATER REACTORS (1 LAFR/3 LWR)

-14-

Figure 12

NUCLEAR POWER GROWTH PATTERNS

EFFECT OF LAFR SYSTEMS (SMALL U_3O_8 SUPPLY)
15 $GW_{(e)}$ / YEAR GROWTH RATE

FIGURE 13

LINEAR ACCELERATOR FUEL ENRICHER REGENERATOR-LWR FUEL CYCLE AND WASTE MANAGEMENT (SPENT FUEL STORAGE)

FIGURE 14

* FRESH FUEL ELEMENTS CAN BE FABRICATED WITH (1) ENR. U; (2) DEPLETED U; OR (3) NAT. U.

FE - FUEL ELEMENTS
SFPD - STABLE FISSION AND DECAY PRODUCTS
TU - TRANSURANICS