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THE APEX ACCELERATOR CYCLE FOR TRANSMUTATION OF LONG-LIVED FISSION WASTES*†

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INTRODUCTION

Fission waste transmutation concepts generally fall into one of three process categories:

1. Transmutation of fission wastes with no recycling. Residual active wastes are disposed of using some type of geological age storage.

2. Transmutation of fission wastes, with separation and recycling of some or all of the untransmuted active species to the transmutation device.

3. Transmutation of fission wastes, with separation and recycling of some or all of the untransmuted active species to the nuclear fuel cycle. These species blend with fresh fission wastes and eventually return to the transmutation device.

Typically, the first category of processes does not reduce the amounts of active species in the material sent to geologic storage by sufficiently large factors to justify the cost and effort involved in the transmutation process. It is difficult to quantitatively determine what reductions should be achieved if transmutation is to be attractive. These will depend on the biological hazard of the stored waste, societal perceptions of the hazards of the waste (which may not coincide with actual hazards), and the cost and technical difficulty of the transmutation process.

Societal perceptions are probably the most important (and restrictive), and will demand large reductions in the amount of active species in waste to be disposed of. It appears likely that transuranics and the fission products like ^{90}Sr and ^{137}Cs that arouse concern will have to be reduced by several orders of magnitude before opposition to geologic waste disposal will be significantly decreased. Reductions of up to about an order of magnitude could probably be achieved without recycling wastes through the transmutation process, but reductions of several orders of magnitude do not appear feasible.

It thus appears that separation and recycling of fission wastes will be mandatory for an acceptable transmutation process, with the principal distinction being whether the fission wastes are solely retained in the transmutation process, or are put back into the nuclear fuel cycle. In either case, spent nuclear fuel will have to be processed to recover the transuranics and active fission products for transmutation.

There are advantages and disadvantages to either option. Retaining the transuranics and active fission products in a separate transmutation process allows easier handling of fresh fuel and prevents increase of inventories of active species in the nuclear fuel cycle. Incorporating the transuranics and active fission product species in the nuclear fuel cycle, on the other hand, results in additional transmutation and decay in reactors and associated facilities (storage pools, etc.) as well as reducing the storage and handling required for the transmutation process itself.

In either case, in order for nuclear power to play a major long-term role, it will be necessary to have some method of converting fertile material (i.e., ^{238}U and ^{232}Th) to fissile isotopes (^{239}Pu and ^{233}U), since the resources of natural uranium appear insufficient to carry a significant fission power economy based on once-through convertor reactors much past 2000 AD. This necessitates some form of breeding system, based on either breeders (thermal or fast) or external neutron sources (accelerator or hybrid fusion-fission reactors).

Transmutation concepts should thus be viewed in the context of a long-term fission economy and judged as to how well they integrate with various breeding concepts. In our view, the most promising transmutation approach involves accelerator-driven neutron sources, both for breeding fissile fuel to sustain the fission reactor economy, and for transmuting objectionable fission products.

We term this approach APEX (Accelerator Fuel Enricher and Fission Product Exterminator). It has a number of important features and advantages:

- Using an accelerator-driven neutron source, fissile fuel can be bred *in situ* (e.g., ^{238}U is converted to ^{239}Pu by neutron absorption) in reactor fuel assemblies. The rejuvenated fuel is reused in reactors.

- The rejuvenation process is compatible with existing types of reactors and fuel assemblies.

- After several rejuvenation cycles, the fuel is processed. The high burnup between reprocessing operations substantially reduces the unit cost of reprocessing.

- After fuel reprocessing and partitioning, stable and low hazard fission products are disposed of. Transuranics are returned to the nuclear fuel cycle, along with the remaining fissile and fertile fuel. Selected fission products (e.g., ^{90}Sr and ^{137}Cs) can either be recycled along with the nuclear fuel (APEX-1) or transmuted (APEX-2).

- The necessary accelerator and target technologies are relatively well developed and can be applied in a few years. No fundamental breakthroughs (e.g., the development of fusion drivers) are required.

- One accelerator fuel enricher/transmutor can service a substantial number of reactors (e.g., 3 to 10), depending on type of target and nature of fuel cycle. Existing types of reactors (e.g., LWR's, CANDU's, and HTGR's) would continue to form the major part of the fission economy.

- Costs and efficiency penalties associated with the APEX system appear acceptable.

In the rest of this paper, we describe the broad outlines of the APEX concept. On the basis of preliminary studies, APEX appears very promising. More detailed design studies are required, however, to confirm the conclusions drawn from these preliminary studies, particularly with regard to the neutronic and physical behavior of recycled fuel enriched by accelerators, the partitioning processes to recover stable wastes for disposal, and the engineering design of the targets for the accelerator/neutron source.

DESCRIPTION OF ACCELERATOR-BASED ENRICHMENT AND TRANSMUTATION CYCLES

Four cycles have been studied based on the use of accelerator-driven neutron sources for fuel enrichment and waste transmutation. These cycles are summarized in Table 1. The LAFER cycles and the associated accelerator/target system were developed as part of the NASAP study, and are described in detail elsewhere.[1,2] The APEX cycles grew out of the LAFER studies, but were not developed to the same level of detail. Brief descriptions of the APEX cycles are given elsewhere.[3]

The flow sheets for the four basic cycles are shown in Figures 1 through 4. In the LAFER-1 cycle (Figure 1) fuel elements are cycled between the accelerator/rejuvenator and the LWR reactor until a limiting condition, either fuel element damage or excessive reactivity loss due to poisoning by fission product buildup, occurs. Although the LAFER study focused principally on applications to LWR's, the LAFER concept could apply equally to the CANDU reactor system. It could probably also be applied to HTGR's, though this probably was not examined in any detail.

The present burnup limits on LWR fuel elements of 30,000 MWd/ton are set by reactivity loss rather than physical damage. Burnups to ∿60,000 MWd/ton have been achieved in the Zorita reactor.[4] Damage to zircaloy cladding appears to saturate after ∿10,000 MWd/ton, with the ultimate burnup limit probably set by pellet/clad interactions.

In the LAFER-1 cycle, fuel is discarded after radiation damage or reactivity limitations are reached. This resulted from the desire to avoid reprocessing and the possible consequent proliferation of nuclear weapons through the availability of separated plutonium from the spent fuel.

In the detailed fuel cycle worked out, LAFER-1 starts off with a lower ^{235}U enrichment and builds ^{239}Pu into the fuel for the required reactivity. Yellow cake is isotopically enriched to 2.0% ^{235}U and fabricated into oxide fuel clad with zircaloy. The equivalent of 3.2% fissile material is achieved by breeding *in situ* the additional 1.2% ^{239}Pu. The element is then ready for generating power in a LWR. After one burn cycle of 30,000 MWd/ton, the fissile material content has dropped back to 2% and the fuel element is reinserted in the LAFER, where the equivalent fissile material content 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 fuel radiation damage effects. We

have conservatively limited the number of burn cycles to 2, meaning that the element experiences a burnup of 60,000 MWd/ton in the reactor, (with an additional 6000 MWd/ton equivalent burnup in the accelerator). With the LAFER cycle, 1750 tons of natural uranium yellow cake is needed over the three-year life of the 1000 MW(e) LWR, which is a resource gain of 3.6 times over a conventional LWR cycle. Furthermore, it is not necessary to build additional expensive enrichment plants, since the LAFER converts fertile ^{238}U to fissile ^{239}Pu.

LAFER-2 (Figure 2) is similar to LAFER-1, except that a dry reprocess [AIROX[5]] is incorporated into the cycle. In the AIROX process, the fuel is heated and oxidized to U_3O_8 from UO_2. The fuel swells and breaks the cladding, which is separated and discarded. As part of the process, gaseous and volatile fission products are also separated and disposed of. Nonvolatile fission products remain with the fertile/fissile fuel, which is remotely reconstituted and refabricated into fresh fuel elements with new cladding, after which the U_3O_8 is reduced back to UO_2.

The AIROX process appears very promising for the LAFER-2 cycle, since it removes some of the fission products, permitting more recycling before loss-of-reaactivity effects become limiting. The AIROX process is also relatively simple and should be highly proliferation resistant.

The limits to recycling in LAFER-2 have not been established; however, on the basis of reactivity calculations in LAFER-1 recycle, and the degree of fission product removal, it appears that a cumulative burnup of at least 120,000 MWd/ton, and quite possibly much more should be achievable with the LAFER-2 cycle.

The LAFER addresses the front end of the nuclear fuel cycle. Turning to the back end of the fuel cycle and waste management problems, two new concepts have been developed which significantly reduce requirements for long-term geological-age storage. In APEX-1, the long-lived radioactive material is kept in the fuel cycle where it can decay and transmute. In APEX-2, extensive use of accelerator-driven transmutation is made to significantly reduce the total burden of long-lived radioactive material associated with the nuclear fuel cycle.

APEX-1 incorporates the LAFER-1 and LAFER-2 cycles with the addition of a partitioning step to remove nonradioactive stable fission products. The APEX-1 system is shown in Figure 3. Short-term storage (1 to 2 years) of the LWR fuel elements allows short-lived fission products to decay. After the AIROX step, which removes volatile fission products during the high temperature oxidation-reduction steps,[5] the UO_2-U_3O_8 powder is processed to remove nonvolatile stable and decayed fission products, consisting mainly of alkali, alkaline, and rare earth elements. Although no reprocessing scheme for removing stable fission products from uranium and transuranics oxides has been developed through the pilot-plant stage, two candidate processes appear promising: (1) a vapor phase organometallic-chelating (diketonate) process for separation of the alkaline and rare earths from the heavier high valance

uranium and transuranic oxides may be applicable. The physical chemistry of the system is known from the literature.[6] This process would have the advantages of being nonaqueous and operating at relatively low temperature (up to 300°C), and would involve a direct one-step separation from the oxide; (2) if the chelate process is not feasible, an aqueous partial acid leaching of the U oxides could be used followed by drying and calcination. The purpose of the processing steps in APEX-1 is to leave the long-lived Cs, Sr, (LLFP's), and the TU's (Am, Cm, Pu, Np, etc.) in dilute form in the oxide fuel for recycling into the LAFER-LWR fuel circuit. The only waste material taken from APEX-1 is nonradioactive stable or low hazard fission products which can be put back as fill in uranium mines, or disposed of in geologic sites.

The great advantage of APEX-1 is that it eliminates the need for assured long-term (geological-age) storage of fission product waste. The long-lived transuranics are recycled and treated as fertile and fissile material in the fuel cycle. The long-lived fission products, such as Cs and Sr, build up to an equilibrium level in the fuel cycle, and are removed primarily by decay and some small amount of transmutation.

APEX-1 can be applied to the problems of existing stored military waste. The separated Cs and Sr from the existing waste storage tanks could be incorporated into fuel elements in a growing civilian power reactor economy. The long-lived Cs and Sr residual waste from the weapons program would then be folded into the civilian fuel cycle and in effect, would become the long-term storehouse of the long-lived radioactive material. The equilibrium concentration of Cs and Sr in the fuel element resulting from this blending would be higher than the concentration characteristic of the present LWR fuel cycle, but would be acceptable.

APEX-2 involves the LAFER-LWR system with AIROX reprocessing for removal of the volatile fission products. This is followed by partitioning of the long-lived fission products Cs, Sr, and the transuranics (TU's). Cs and Sr are then placed in an accelerator target for transmutation at a high neutron flux. An important advantage of this system over a reactor is that there is no fission heat generated, so that the flux is not limited by power density. The neutrons for this transmutation are generated by spallation reactions between target nuclei and high-energy protons from a linear accelerator. In the case of the cesium FP waste, it will be necessary to make an isotopic separation of the low cross section radioactive ^{137}Cs from the other stable Cs isotopes, ^{133}Cs and ^{135}Cs, to achieve good neutron economy and to keep power requirements for the linear accelerator at reasonable levels. The transuranics would be kept in the regular LAFER/APEX fuel cycle since they are readily fissioned and transmuted in the reactor. The APEX-2 system is shown in Figure 4. Although one single unit is shown for the fuel generator and transmutor, a dedicated FP accelerator/transmutor will probably be needed because of the high flux that is required ($\geq 10^{16}$) if the half-lives of the Cs and Sr are to be significantly reduced (a factor of 10) by transmutation.

The main advantage of APEX-2, compared with APEX-1, is that the total inventory of the long-lived fission products in reactors and in short-term storage is substantially reduced.

LINEAR ACCELERATOR/TARGET SYSTEM

Intense neutron sources can be generated using spallation reactions between a beam of high-energy particles (e.g., protons at ∿1 GeV) and a suitable target. Neutrons are produced by direct reaction, as well as evaporation from excited nuclear states in the target nuclei (particularly for heavy metal targets) and by (n,2n) and (x,n) reactions. In addition, fission reactions, either in the primary target or in a secondary blanket surrounding the primary target, will substantially increase neutron yield. The neutrons produced are used to breed fissile fuel, as in the LAFER and APEX-1 cycles, and for direct transmutation of fission product nuclei, as in the APEX-2 cycle.

Linear accelerators are a well-developed technology. Beams of several hundred milliamps at ∿1 GeV are practical and will have good overall efficiencies (i.e., ∿50%) from input power to output particle beam power.

A practical linear accelerator-target system should have the following characteristics.

1. Good electrical efficiency for production of the particle beam ($\gtrsim$∿50%).

2. High plant factor ($\gtrsim$∿80%).

3. Reasonable cost per unit of beam power ($\lesssim$∿$2000/kW beam).

4. High-neutron yield in the primary target ($\gtrsim$∿30 neutrons/GeV of particle energy).

5. Relatively low power and flux peaking factors in the primary target and blanket, with acceptable power densities.

6. Relatively small neutron leakage from the target-blanket assembly.

7. Minimization of radiation damage effects in the target-blanket assembly.

8. Avoidance of solid windows between the accelerator and primary target.

The last feature appears to be a prerequisite for a practical system. Very high radiation damage rates would be experienced by solid barriers between the accelerator beam transport tube and the primary target. Such windows would have material lifetimes of only a few days. [The accompanying very high power densities of tens of kW/cm^3 in the window material would also cause very severe thermal-hydraulic and stress problems.] As a result, the primary target must be in vacuum of ∿10^{-4} Torr or less. The accelerator vacuum would be considerably better, i.e., ∿10^{-6}, with differential pumping in the beam transport tube between the accelerator and primary target.

In our LAFER/APEX designs,[1,2,3] we employ a proton linear accelerator and a target-blanket assembly with power recovery and generation

equipment. The linear accelerator consists of an Alvarez drift tube followed by a $\pi/2$ mode-coupled-cavity structure operating up to the final energy. An acceleration rate of 1.5 MeV/m appears about optimum. With a length of 1000 m, a 1.5-GeV proton beam is produced. Experience with research machines indicates that continuous wave accelerators can operate with an 80% plant factor and no appreciable beam loss. A 50% efficiency of electric power input to beam power output can be readily achieved with state-of-the-art technology for the system. Improvements in rf conversion equipment appear possible, with ultimate efficiencies in the range of 60 to 70%.

The primary target consists of multiple falling liquid lead columns, i.e., jets. The proton beam interacts with the liquid lead target columns which are spaced in such a manner as to provide an evenly distributed neutron flux. The blanket surrounding the primary lead target contains either fertile material (e.g., LWR fuel assemblies) or fission wastes to be transmuted. An isometric view of the target blanket assembly is shown in Figure 5, and a plan view is shown in Figure 6. The advantages of this configuration are as follows.

1. The liquid lead has a low vapor pressure, 10^{-5} Torr at 400°C. It operates in a vacuum in the containment vessel and is connected to the accelerator via the beam transport tube. No window is required to separate the LINAC from the target and thus there is no concern about window feasibility. Furthermore, the liquid lead target suffers no radiation damage.

2. The assembly is highly subcritical, using He, two-phase steam-water, or D_2O as a coolant, so that there is no nuclear criticality safety problem.

3. The target blanket is separated from the accelerator and the accelerator will not be contaminated by fission products from the fuel elements.

4. Useful power can be recovered from the heat developed in the target and blanket assemblies.

5. Maximum utilization of the neutrons are obtained because the blanket completely surrounds the target.

For the above target-blanket assembly, model neutron code computer calculations were made to determine neutron yields and reaction rates for the LAFER and APEX-1 cycles. The NMTC code was used to calculate evaporation and spallation reactions above 15 MeV by the Monte Carlo method. The TWOTRAN transport code was used to calculate the neutron reactions below 15 MeV. A cross section modified SIZZLE code was used conservatively for burnup calculations and the effect of fission product buildup was estimated by the EPRI Cell Code.

Table 2 shows the initial fissile fuel production rates for eight different target reactor lattices. The calculations indicate that roughly about 1 ton of fissile material (^{239}Pu or ^{233}U) is produced with a

0.3 A, 1.5 GeV proton accelerator. Basically, about 35 neutrons are produced per proton by spallation reactions. This is conservative compared with recent Russian data,[9] which indicate as much as 50% higher production of spallation neutrons. Additional neutrons are produced by fast fission. Figure 7 shows the multiplication factor, K_∞ as a function of burnup, for varying moderator-to-fuel ratio. The highly subcritical condition for the LAFER part of the cycle is shown (the LWR lattice has a volumetric H_2O/UO_2 ratio of 1.67). In the second cycle, if K_∞ drops below 1 shuffling with periodic addition of fresh fuel is needed to smooth out the reactivity decreases experienced toward the end of the cycle. Figure 8 indicates the buildup of ^{239}Pu and decrease of ^{235}U 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 transformed from strongly absorbing isotopes to weaker neutron absorbing species in the process of rejuvenation.

As schematically illustrated in Figure 9, one LAFER of the type described above can support three 1000 MW(e) reactors throughout their 30-year lifetime. 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. Depreciation of the 1.5 billion dollar capital investment (1986 dollars) for the LAFER machine amounts to 11.6 mills/kWh(e), averaged over the system of the power reactors. Table 3 gives the entire fuel cycle cost for the LAFER-LWR system and compares it with that projected for conventional LWR's (1986 dollars). It is interesting to note that yellow cake enrichment and fabrication costs are reduced by substantial factors since the LAFER-LWR system uses much less uranium feed. 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 so that there is no necessity to purchase outside power. Moreover, 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. Also, any cost penalty has to be weighed against the benefits of vastly increasing the uranium fuel resource and reducing the nuclear waste problem while retaining the existing LWR nuclear power economy.

Figure 10 indicates how the LAFER can significantly improve the utilization of the nuclear resource while maintaining a LWR economy. Essentially, we are advocating replacing the isotope enrichment plant with a linear accelerator fuel generator. This can be accomplished in the near-term with state-of-the-art technology. The only nearest competitor is the futuristic fusion-fission hybrid which still requires scientific proof of feasibility, followed by long-term technical demonstration. Linear accelerators are today primarily research tools. They can be converted to fuel production machines with relatively little additional development. The LAFER cycle can be viewed as the missing link that will greatly prolong the LWR nuclear power cycle chain.

LAFER increases the uranium resource base by a factor of ∿4 even within the constraint of no reprocessing. If reprocessing is allowed (which is necessary if radwastes are to be reduced by transmutation), then the LAFER becomes a true breeder, permitting the nuclear economy to operate essentially forever.

PERFORMANCE OF THE APEX AND LAFER SYSTEMS

Buildup of the transuranics and long-lived fission products in the APEX-1 system was analyzed using ORIGEN. The basic cycle diagram, shown in Figure 11, was assumed. A given fuel element first goes through several cycles in a LWR (e.g., 2), with accelerator rejuvenation before reinsertion into the reactor. After reaching fuel/clad damage limits, the element goes through the LAFER-2 AIROX process, with remote decladding and refabrication. It is then rejuvenated in the accelerator blanket and returned to the LWR. This LAFER-2 cycle can continue until the buildup of nonvolatile fission products (volatile fission products are removed in the AIROX process) unduly penalizes reactivity.

For a 27-year cycle (two LAFER-1 cycles and two LAFER-2 cycles with cooling times as indicated in Figure 11) the buildup of TU's (Am, Cm, and Pu) and LLFP's (in g/MT heavy metal) are given in Figures 12 and 13. It can be reduced, however, if desired. This Cs and Sr buildup appears acceptable. If the APEX-1 cycle is increased to 54 years, the concentration of Cs and Sr is reduced to three and four times the values characteristic of the conventional once-through cycle, respectively. This should be quite acceptable in view of the benefit of not having to dispose of radioactive waste material. It should be pointed out that breeders operating at 100,000 MWd/ton burnup will also have three to four times higher long-lived fission product concentration buildup in the reactor core than are now encountered with LWR fuel. Thus, the ^{137}Cs and ^{90}Sr inventories in the APEX-1 cycle appear to be acceptable.

Without isotopic separation, nonradioactive isotopes of Cs and Sr (e.g., ^{136}Cs and ^{88}Sr) will buildup in the reactor/accelerator circuits. Figure 14 shows the total Cs and Sr buildup in g/metric-ton of heavy metal as a function of time for a 27-year APEX-1 cycle. Saturation at ∿1% for total Sr and ∿2% for total Cs will occur in apprixmately 100 years [∿200 years with a 54-year APEX-1 cycle]. These concentrations appear acceptable. They could be reduced, if desired, by isotopic separation of a small purge stream, in which stable Cs and Sr isotopes would be disposed of and ^{137}Cs and ^{90}Sr returned to the APEX-1 circuit.

For the APEX-2 (transmutation system), the concentration of LLFP (Cs and Sr) remains the same, in the reactor, as that for the conventional LWR cycle. However, the out-of-reactor inventory is reduced by an order of magnitude because of transmutation. It is estimated that about 11% of the power generated by the LWR must be fed back to the accelerator for transmutation of the ^{137}Cs and ^{90}Sr produced. Because of the low ^{137}Cs cross section, an isotopic separation will be necessary to maintain a good neutron economy. Isotopic separation will not be needed for ^{88}Sr for hundreds of years because of its low cross section.

Table 4 gives a preliminary comparison of the LAFER and APEX systems. For a nuclear economy consisting of 400 LWR reactors (1000 MW(e) each), the integrated long-term disposal of the once-through LWR cycle operating over a 30-year reactor lifetime amounts to a total of 400,000 MT of waste spent fuel. The APEX-1 and APEX-2 systems essentially eliminate the need for disposal of radioactive transuranics and long-lived fission products (^{137}Cs and ^{90}Sr).

Without reprocessing, the quantity for disposal of spent fuel elements depends on the number of times the fuel element is regenerated. With reprocessing, as indicated in APEX-1, Table 4 indicates that the equilibrium concentration of long-lived fission product ^{137}Cs in the reactor increases six times over that for a conventional LWR system and eight times for ^{90}Sr, while the total inventory in the complete circuit (reactor, processing, and cool-down facilities) remains approximately the same. With a longer APEX-1 cycle, e.g., 54 years, the equilibrium ^{137}Cs and ^{90}Sr inventories in the reactor are reduced by a factor of $\sim$2.

The stored long-lived fission product waste from the military weapons program is on the order of 100 million gallons of liquid waste. Table 5 gives an estimate of the accelerator-target capital cost that would be required to transmute the ^{137}Cs and ^{90}Sr and transuranics in this waste during a period of $\sim$10 years. The military waste could also be incorporated into the recycled commercial waste in the APEX-1 cycle, as shown in Table 5. Additional cost is required for extracting Pu, Cs, and Sr from the waste tanks.

It is interesting to note that by incorporating the Cs and Sr into the LWR fuel elements only 62 reactors would be required to handle a doubling in Cs and Sr concentration over that now in power reactor fuel elements. This is our present operating power reactor capacity, so that they could handle the military waste even now.

Projected costs for the APEX and LAFER systems are shown in Table 6, and compared with the costs of conventional LWR reactors with throw-away fuel. Costs are based on 1986 operation using fuel cycle costs projected by Bechtel.

The LAFER cycles add 10% to the overall cost of power. (The cost projections here incorporate a number of potential improvements over the reference design.) This cost penalty should be judged in the context of the large increase in fuel reserve afforded by the use of accelerator breeders, which in effect allow the nuclear economy to continue for an indefinite period instead of dying shortly after 2000 AD, which would occur if we continue to operate on the present LWR throw-away cycle. If one compared the LWR throw-away cycle on the basis of generating an equal amount of power for the next hundred years, the present LWR cycle would prove to be considerably more expensive than the LAFER cycles, since it would have to use much more costly uranium.

The APEX-1 cycle is slightly more expensive than the LAFER cycles, since reprocessing is required to separate out fission products and recycle the transuranics and fission products. APEX-2 shows a large jump over APEX-1 because of the substantial ($\sim$10%) amount of recycle power required by the accelerators that transmute ^{137}Cs and ^{90}Sr.

CONCLUSIONS

On the basis of the preliminary studies carried out, the following major conclusions can be drawn.

- APEX-1 and APEX-2 systems can destroy TU's, ^{137}Cs, and ^{90}Sr at acceptable cost and efficiency.
  - The principle difference between APEX-1 and APEX-2 is the in-reactor and in-circuit inventory of ^{137}Cs and ^{90}Sr.
  - Stable and low hazard wastes can be disposed of by burial.
- Accelerator breeders can sustain a fission reactor economy effectively indefinitely.
- Military waste can be blended into commercial fuel cycle for transmutation.
- Accelerator and target technologies appear practical and could be developed in a few years.

More detailed studies are needed to better define the technical and economic features of the LAFER and APEX cycles, so that comparative assessments can be made between these cycles, as well as with other transmutation and waste disposal concepts.

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TABLE 1

ACCELERATOR-BASED ENRICHMENT AND TRANSMUTATION CYCLES

Cycle	Characteristics
• LAFER-1	Rejuvenates spent fuel without reprocessing or recladding.
• LAFER-2	Rejuvenates spent fuel without reprocessing but with recladding (AIROX).
• APEX-1	Rejuvenates spent fuel, involves recladding and removal and disposal of stable products, with recycling of transuranics and long-lived fission products.
• APEX-2	Rejuvenates spent fuel, involves recladding and transmutation of long-lived fission products and transuranics.

TABLE 2

INITIAL FISSILE FUEL PRODUCTION RATES FOR Pb-Bi TARGET WITH FUEL ELEMENT BLANKET (0.3 A - 15 GeV PROTON ACCELERATOR)

Density number	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)	D_2O	0.7	53.8	Pu - 1010
2	ThO_2	D_2O	0.7	46.6	^{233}U - 850
3	UO_2(Nat)	H_2O	0.7	74.1	Pu - 1000
4	UO_2	H_2O	0.35	65.8	Pu - 1050
5	UO_2(Nat)	H_2O	0.175	64.9	Pu - 1070
6	ThO_2	H_2O	0.7	46.5	^{233}U - 850
7	ThO_2	H_2O	0.35	48.6	^{233}U - 890
8	ThO_2	H_2O	0.175	49.0	^{233}U - 900

Moderator/fuel volume ratio = 0.8.
Beam power output to electric power input efficiency = 50%.
Plant factor = 80%.

TABLE 3

FUEL CYCLE COST--mills/kWh(e) (ESCALATED TO 1986)

	Unit cost 1977 dollars	Conv. LWR	Reduction factor	2-Cycle LAFER-LWR
Yellow cake	\$ 50/lb U_3O_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 (15%, 80% PF LAFER (15%, 80% PF)	-	-	-	11.63
Electrical power (450 MW(e)) to LAFER at 58.3 mills/kWh(e)	-	-	-	9.45
Operating & Maintenance	-	-	-	2.00
		13.36*		28.06

*Industry Report (1976-77), Bechtel estimate.

TABLE 4

THE APEX LWR NUCLEAR FUEL CYCLE AND WASTE MANAGEMENT SYSTEMS

System	Fuel production system	Fuel burnup MWd/ton	Radioactive[6] material for disposal MT/1000 MW(e)	Equilibrium inventory for 400 LWR's: Long-lived FP's in Reactor conc.-wt% (1) TU	(2) $\frac{^{90}Sr}{Sr_{tot}}$	(3) $\frac{^{137}Cs}{Cs_{tot}}$	Total inventory MT (4) $\frac{TU_{out}}{TU_{in}}$	$\frac{^{90}Sr}{Sr_{tot}}$	$\frac{^{137}Cs}{Cs_{tot}}$
1 Conventional once-through LWR	Low enrich. fuel LEW-3.2% ^{235}U	30,000	1,000	0.9	$\frac{0.055}{0.10}$	$\frac{0.125}{0.25}$	$\frac{3600}{360}$	$\frac{400}{650}$	$\frac{630}{2000}$
2 LAFER-1	LAFER-1.6% ^{235}U 2 cycle 1.6% ^{239}Pu	60,000	500	1.9	$\frac{0.080}{0.15}$	$\frac{0.175}{0.35}$	$\frac{3800}{760}$	$\frac{400}{650}$	$\frac{630}{2000}$
3 LAFER-1	LAFER-5 cycles 3.2% ^{239}Pu	150,000	200	2.2	$\frac{0.130}{0.25}$	$\frac{0.325}{0.65}$	$\frac{1760}{880}$	$\frac{400}{650}$	$\frac{630}{2000}$
4 LAFER-2[a]	LAFER-3 double cycles with AIROX reprocessing	180,000	166	2.2	$\frac{0.140}{0.28}$	$\frac{0.375}{0.75}$	$\frac{1460}{880}$	$\frac{400}{650}$	$\frac{630}{2000}$
5 APEX-1[a,b]	LAFER-2 double cycles with 1st and 2nd stage stable FP reprocessing	120,000	0	2.2	$\frac{0.310}{1.00}$	$\frac{1.000}{2.00}$	$\frac{0}{880}$	$\frac{400}{640}$	$\frac{630}{2000}$
6 APEX-2[a,c]	LAFER-2 double cycles with 1st and 2nd stage FP removal and transmutation	120,000	0	2.2	$\frac{0.055}{0.10}$	$\frac{0.125}{0.25}$	$\frac{0}{880}$	$\frac{40}{65}$	$\frac{63}{200}$

a) AIROX removes volatile FP, I, Xe, Kr, Tc, etc.

b) ORG-MET (Chelate) removes nonvolatile rare earth and stable FP's

c) Cs-Sr separation and transmutation[5] with accelerator.

1) TU's consist of ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu, ^{241}Am and ^{243}Am, and ^{243}Cm.

2) Sr consists of ^{88}Sr and ^{90}Sr.

3) Cs consists of ^{133}Cs, ^{135}Cs, and ^{137}Cs.

4) Out = TU inventory in waste disposal, In = TU inventory in reactor.

5) Isotopic separation of ^{137}Ca required.

6) Mass of radioactive material for long-term disposal, MT for a 1000 MW(e) reactor operating for 30 years, 400 reactors (1000 MW(e) each) will generate 400,000 MT waste for once-through system.

TABLE 5

PRELIMINARY COMPARATIVE COST ESTIMATES FOR CONVENTIONAL AND ACCELERATOR FUEL CYCLES

1986 Cost--mills/kWh(e)

	LWR conventional	LAFER-1	Recycle APEX-1	Transmute APEX-2
Capital charge	26.9	26.9	26.9	26.9
Fuel cycle	13.4	17.3	19.5	27.5
Operating & maintenance	3.3	3.3	3.3	3.3
Power cost, mills/kWh(e)	43.6	47.5	49.7	57.7
Percent increase (over Conv.)	-	10%	14%	32%
LWR fuel resource	Limited	>4 x current	Unlimited	Unlimited
Waste storage	Geological	Geological	In-reactor inventory	Reduced inventory

TABLE 6

MILITARY WASTE--ALTERNATIVE MANAGEMENT

APEX-1 - Incorporates ^{137}Cs and ^{90}Sr into LWR fuel.
Doubling Cs and Sr content in LWR fuel rods adds after 1 burn cycle-
1.0 kg Cs/MT fuel.
Total Cs added per reactor = 100 tons fuel x 1 = 100 kg = 0.1 ton.
Number of reactors required for all waste = 6.2/0.1 = 62 reactors.
We intend to have 280 reactors at least by end of century - 22%
contain military waste
The residual Pu would also be burned out.

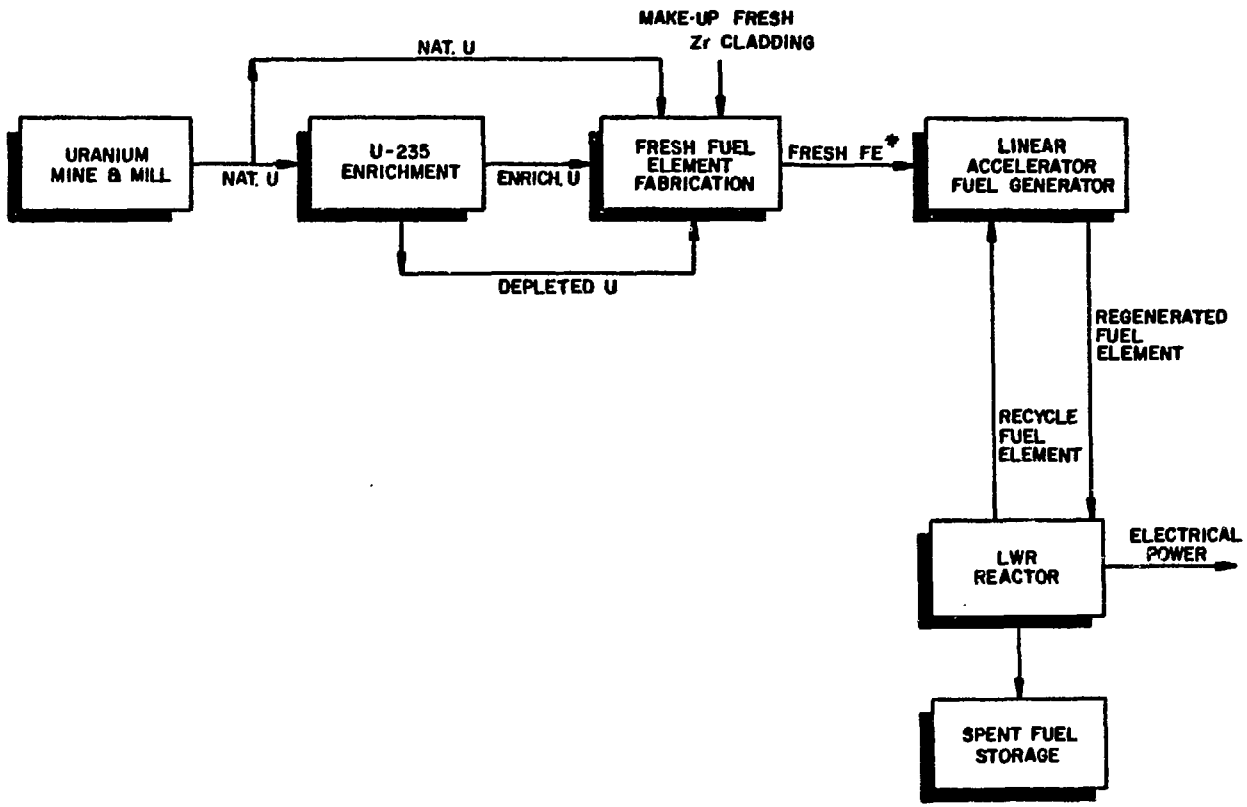
APEX-2 - Transmutation

Approximate volume - 100×10^6 gallons.
Containing ^{137}Cs - 2 tons (6.2 Cs total).
^{90}Sr - 1.3 tons (2.1 Sr total).
Requires - 400 MW accelerator capacity.
^{137}Cs - 0.2 ton/year for 10 years.
^{90}Sr - 0.13 tons/year for 10 years.

Cost

Accelerator	- $2 \times 400 \times 10^3$ kW x \$500/kW	= $\$400 \times 10^6$
Target	- 400×10 x \$200/kW	= 80×10^6
Power cost	- $400 \times 10 \times 10 \times 7000 \times 30$ mils/kWh(e)	= 840×10^6
	Total cost	= $\$1320 \times 10^6$

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

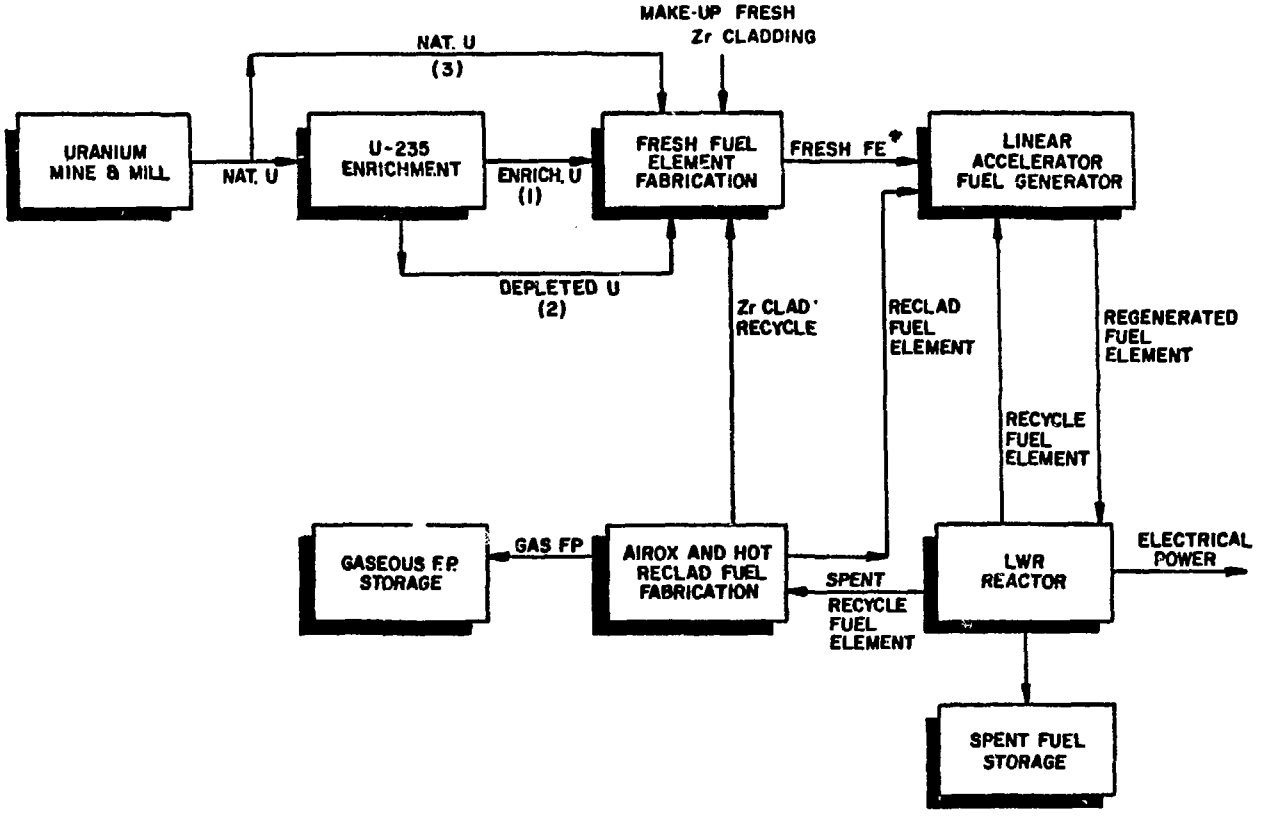


* FRESH FUEL ELEMENTS CAN BE FABRICATED WITH (1) ENR. U : (2) DEPLETED U ; OR (3) NAT. U.

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

FIGURE 1. LAFER-1

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



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

FE - FUEL ELEMENTS
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TU - TRANSURANICS

FIGURE 2. LAFER-2

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

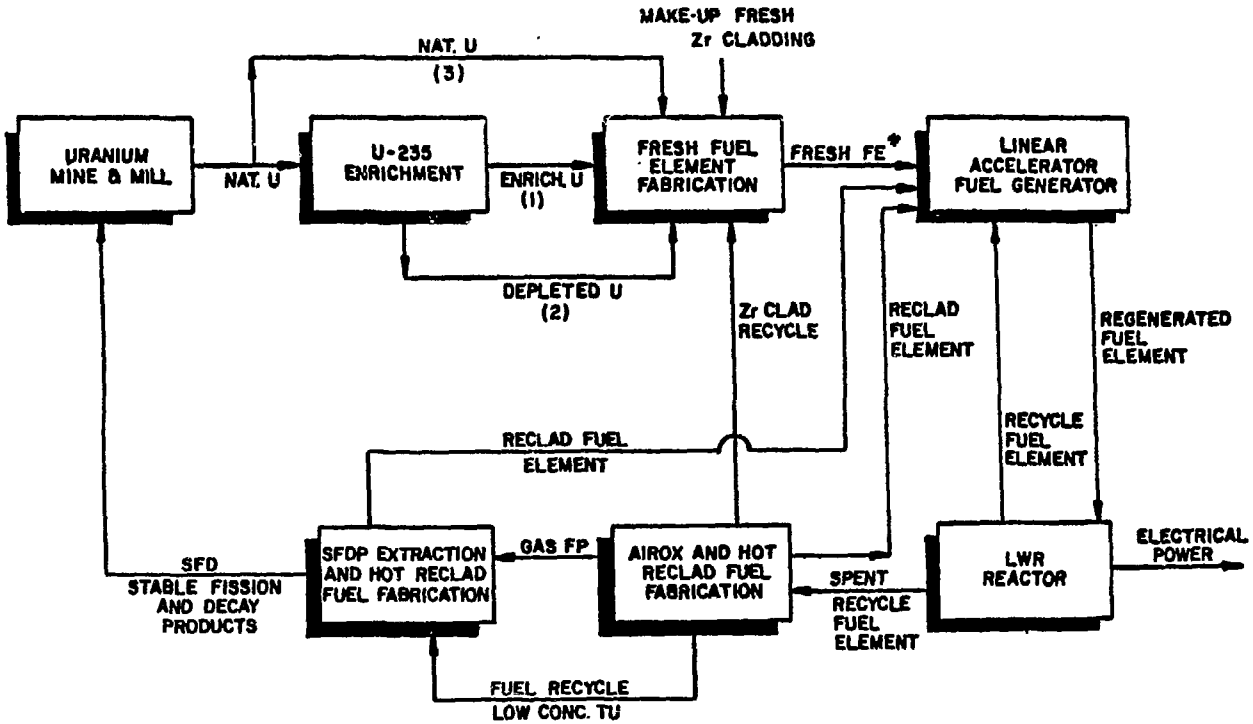

FIGURE 3. APEX-1

* 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

LINEAR ACCELERATOR FUEL ENRICHER REGENERATOR - LWR FUEL CYCLE AND FISSION PRODUCT TRANSMUTOR AT END OF FISSION ECONOMY

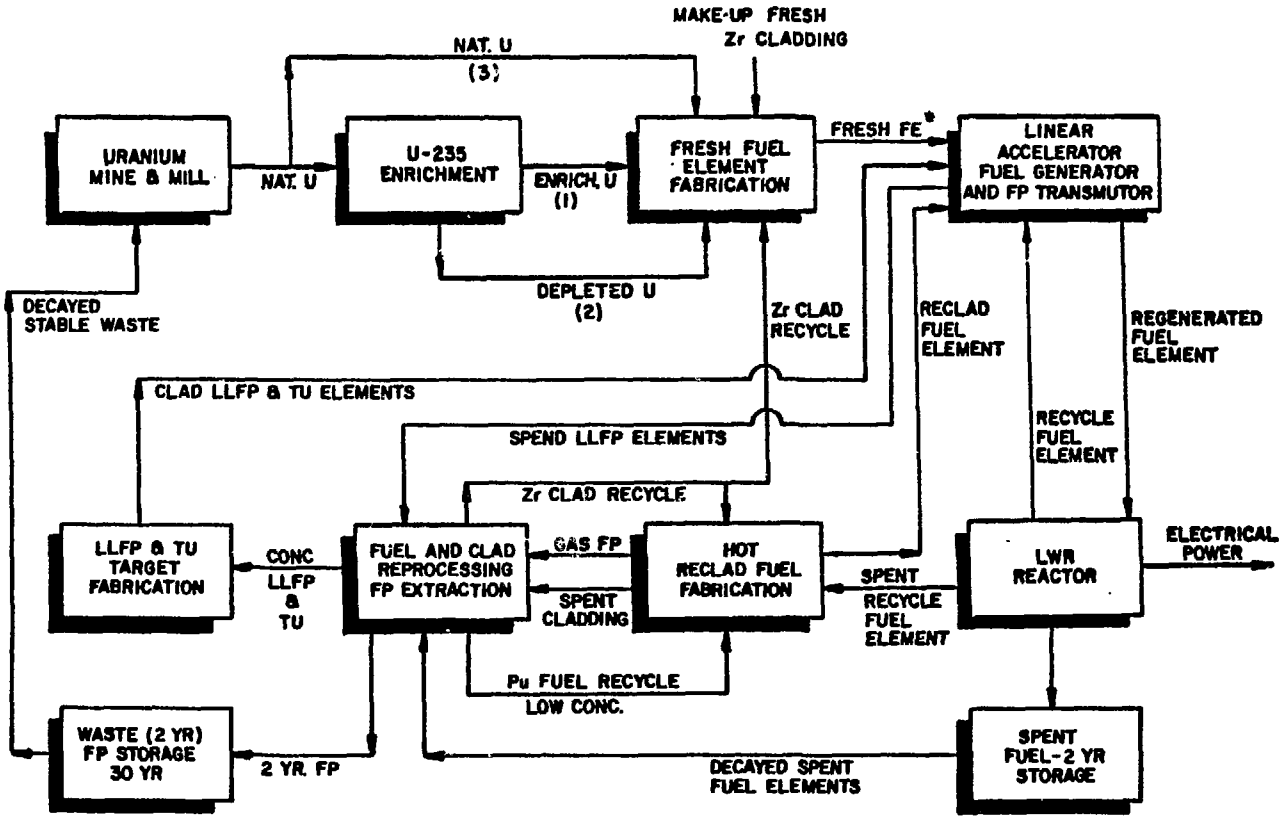

FIGURE 4. APEX-2

* 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

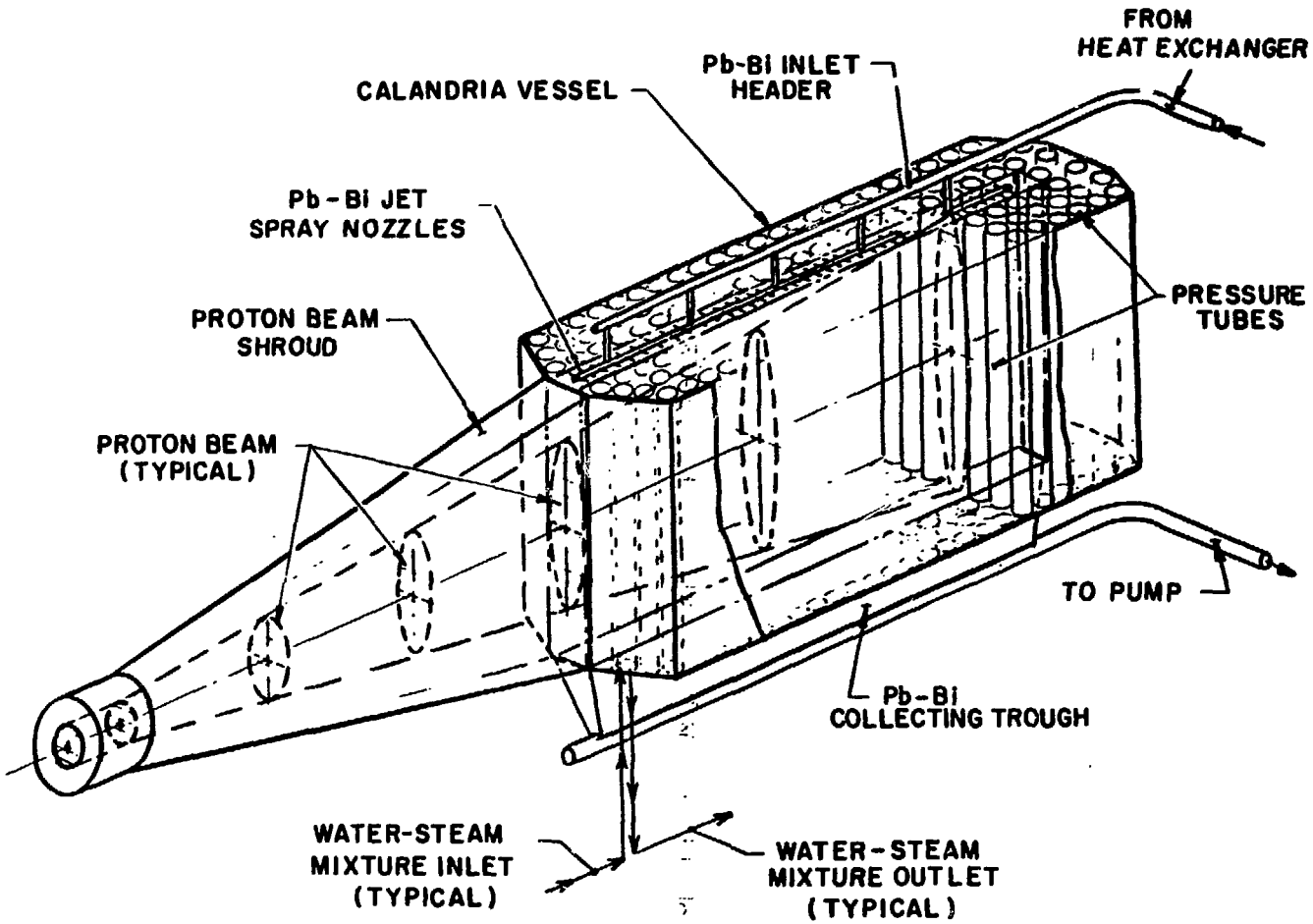

FIGURE 5. PWR TYPE TARGET ASSEMBLY

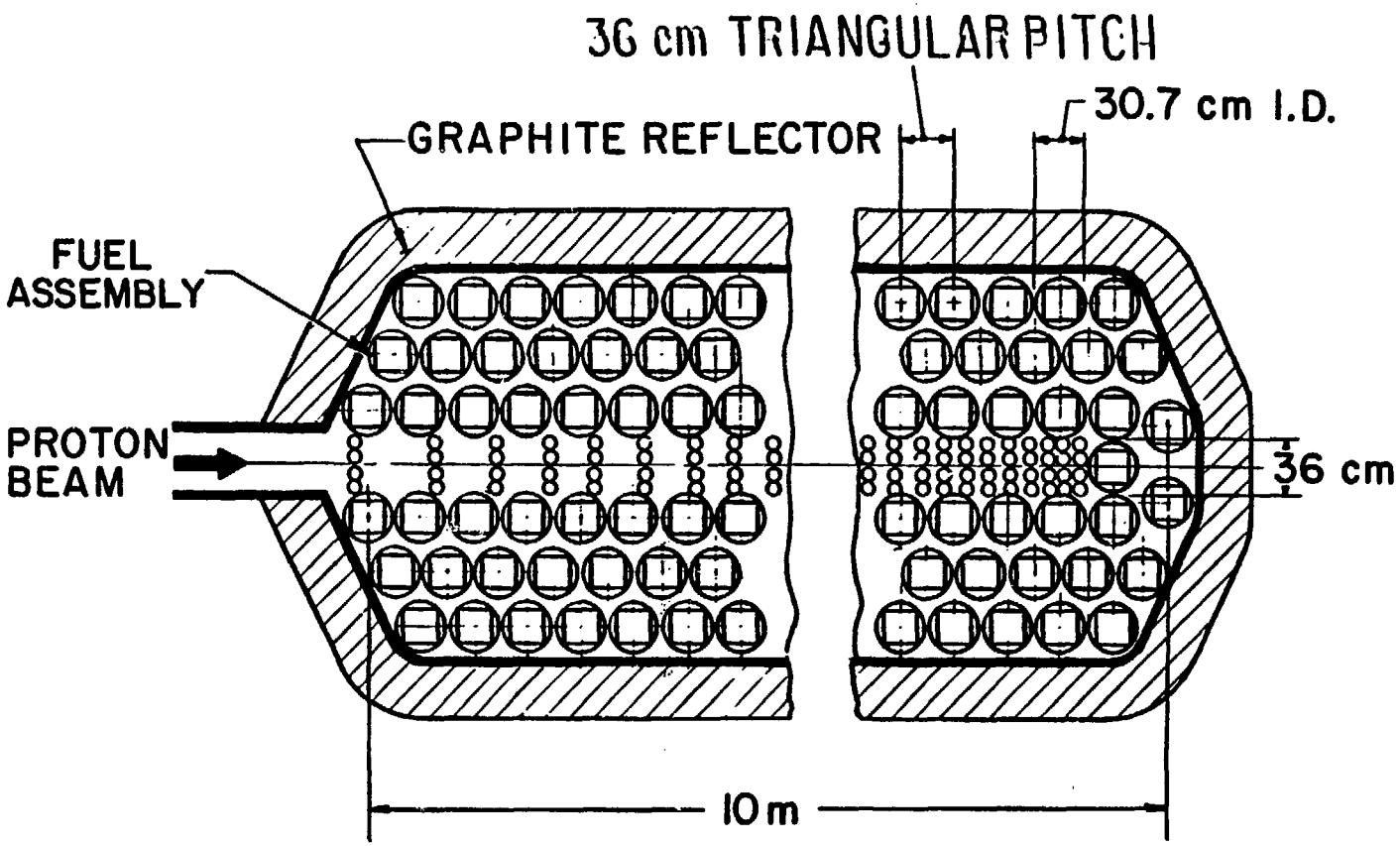

FIGURE 6. PWR TYPE TARGET ASSEMBLY CROSS SECTION

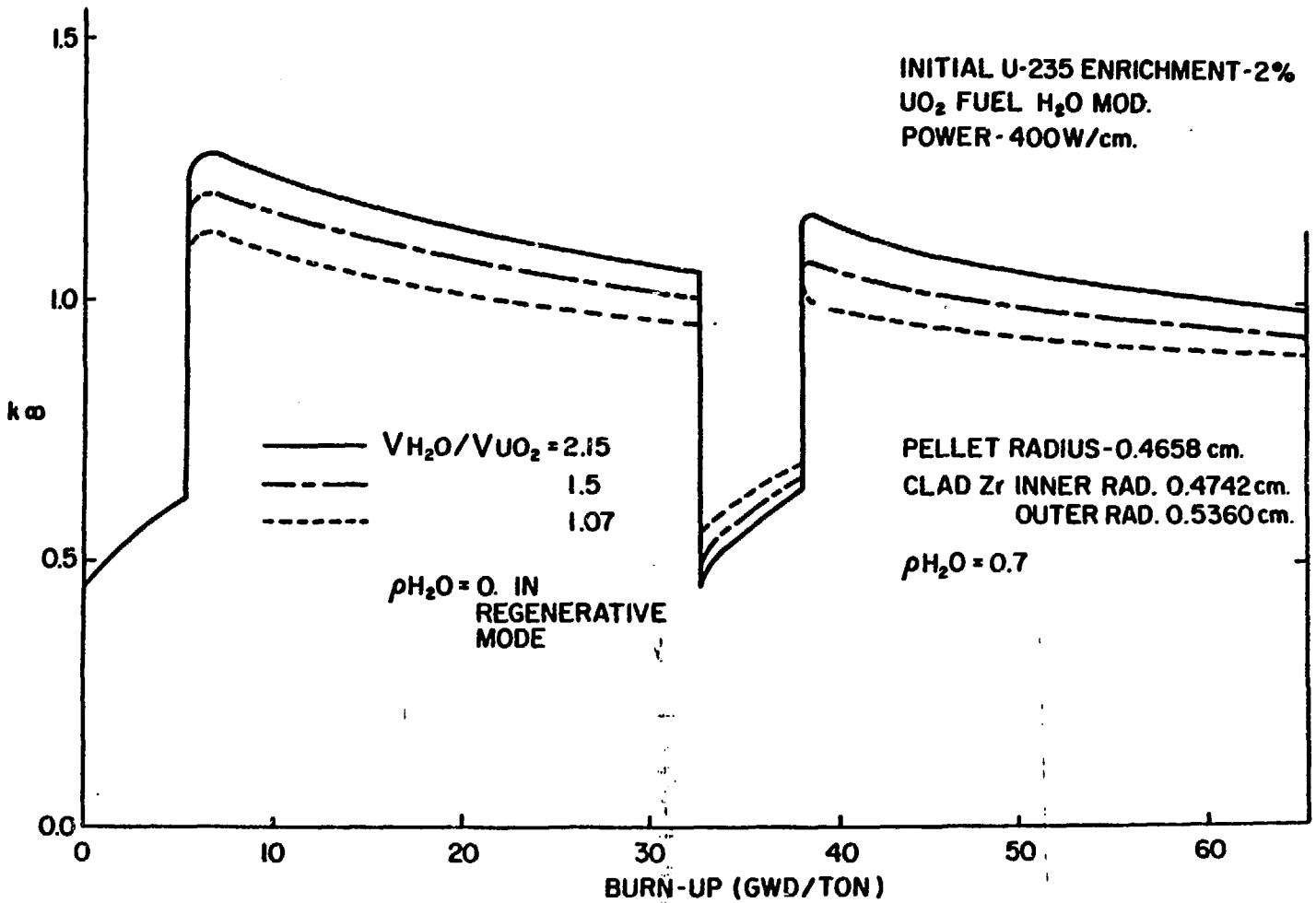

FIGURE 7. MULTIPLICATION FACTOR OF REGENERATIVE AND REACTOR MODES

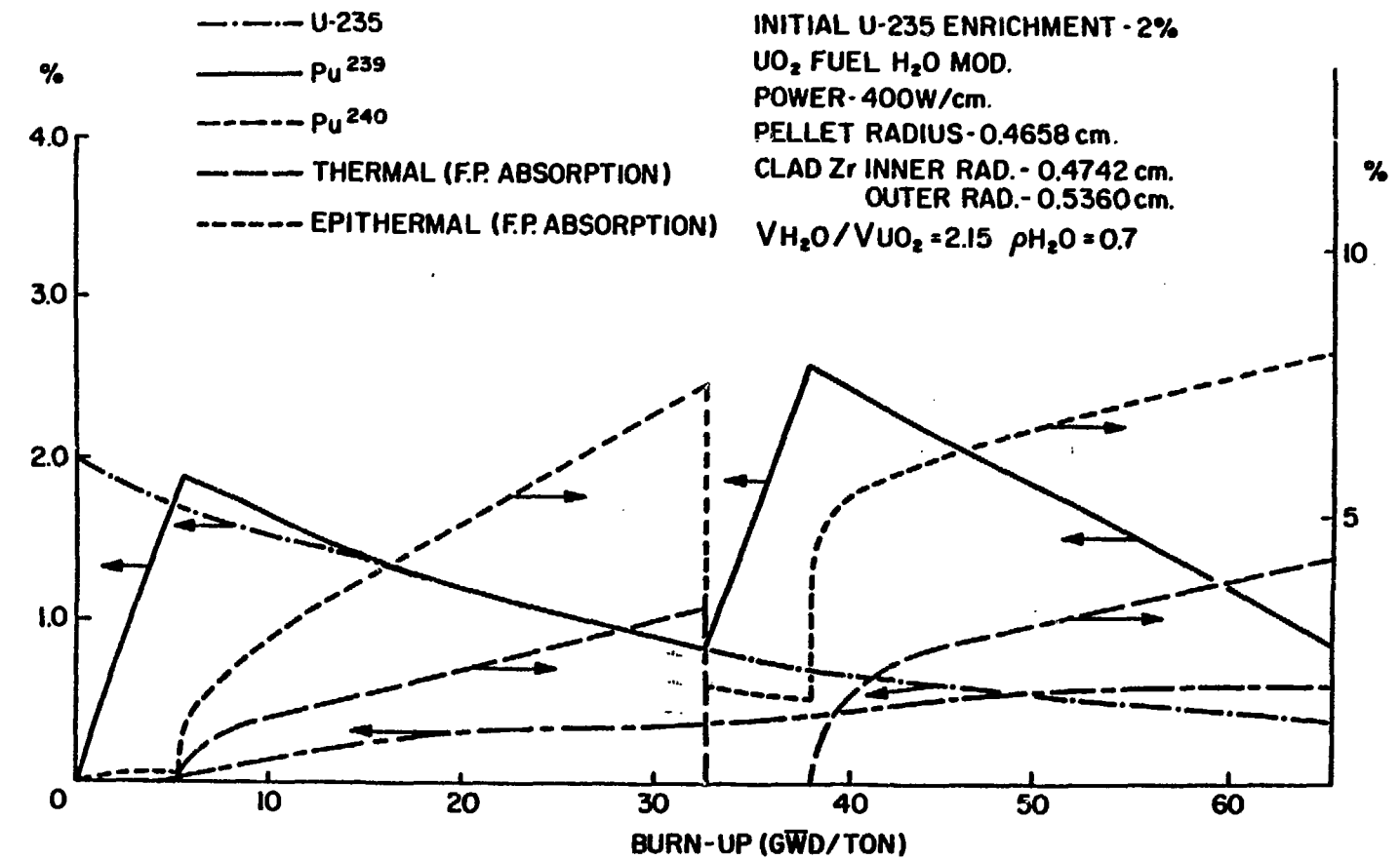

FIGURE 8. CONCENTRATION OF U^{235}, Pu^{239}, AND Pu^{240} NEUTRON ABSORPTION DUE TO FISSION PRODUCTS

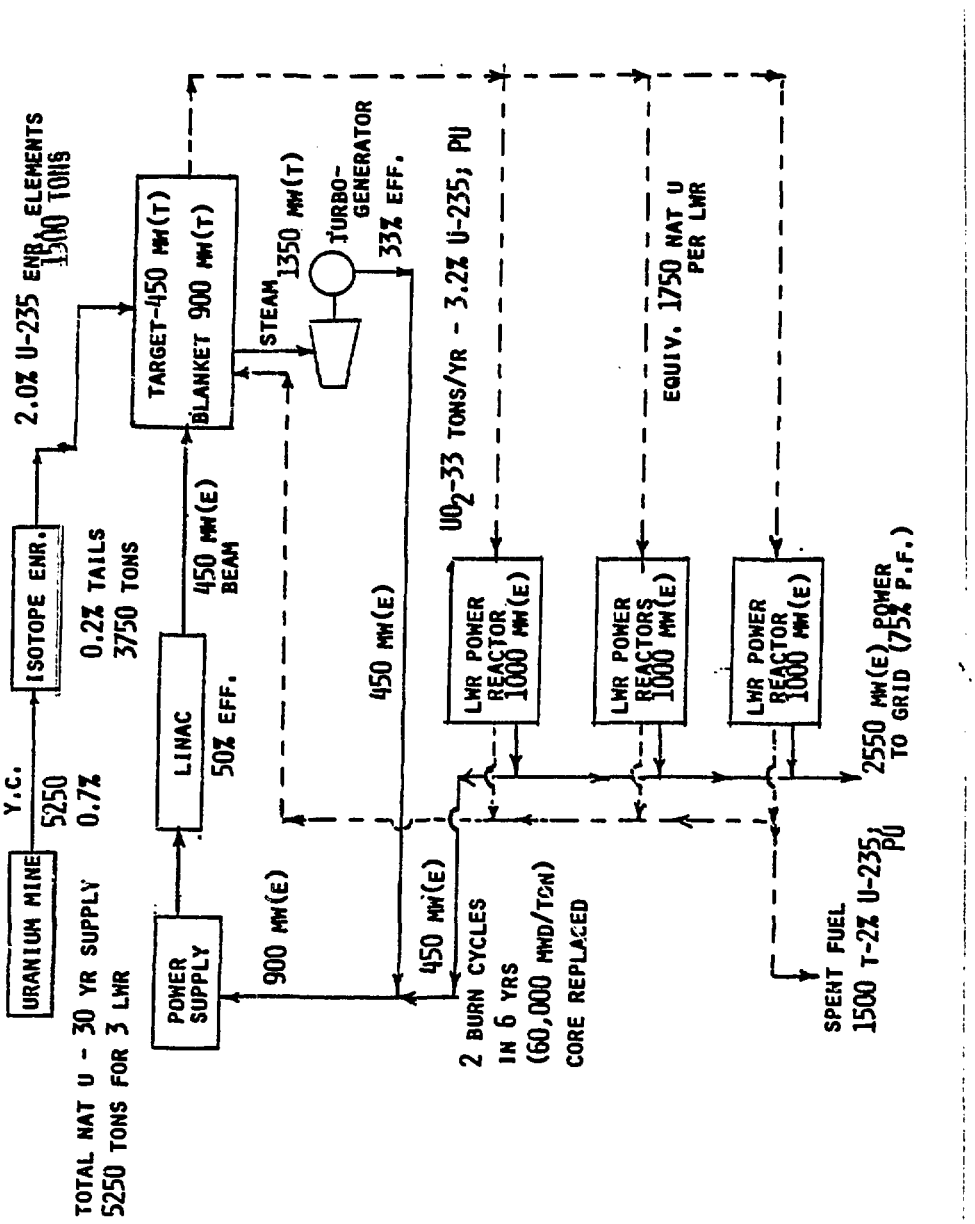

FIGURE 9. LINEAR ACCELERATOR FUEL REGENERATOR WITH LIGHT WATER REACTORS (1 LAFR/3 LWR)

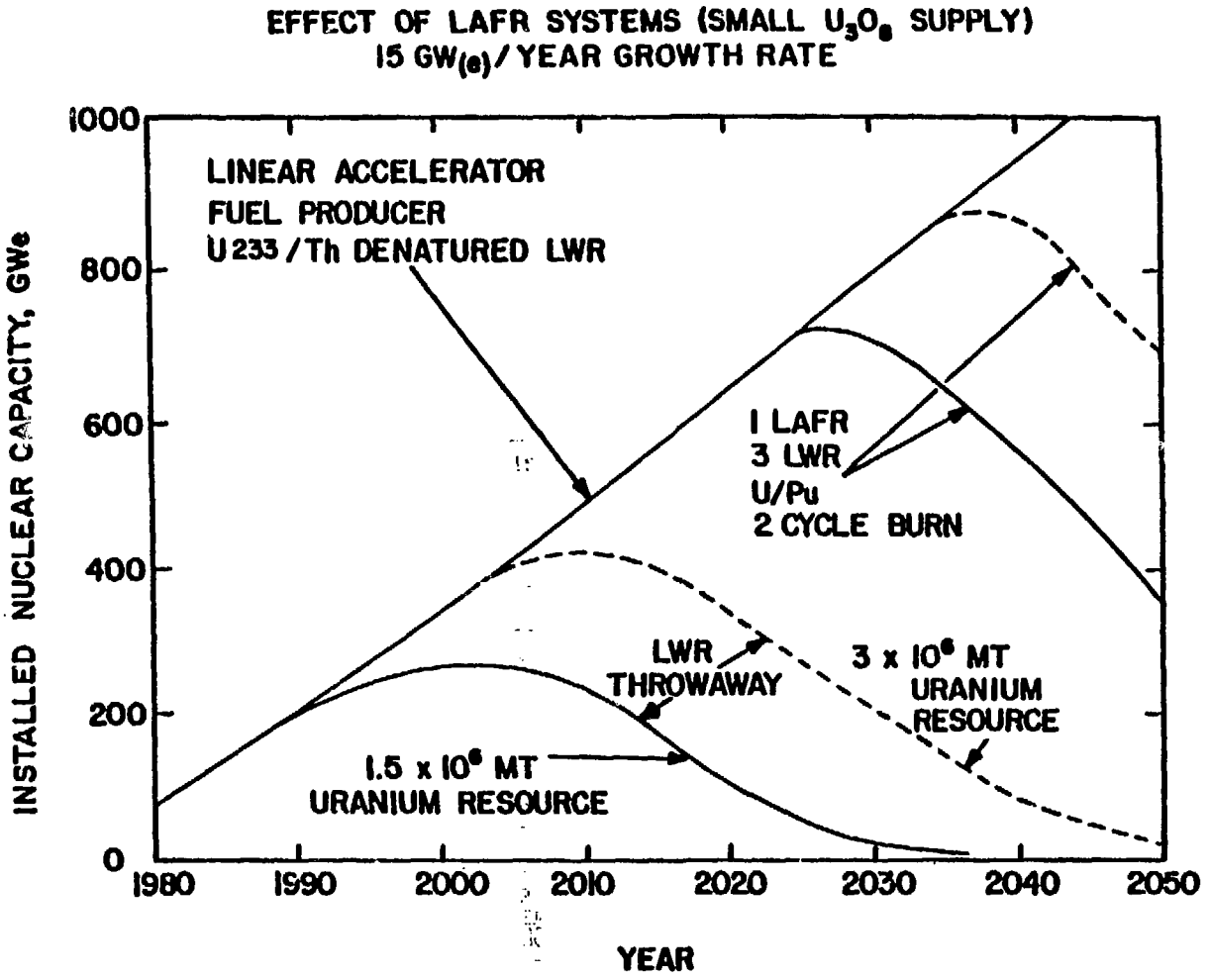

FIGURE 10. NUCLEAR POWER GROWTH PATTERNS

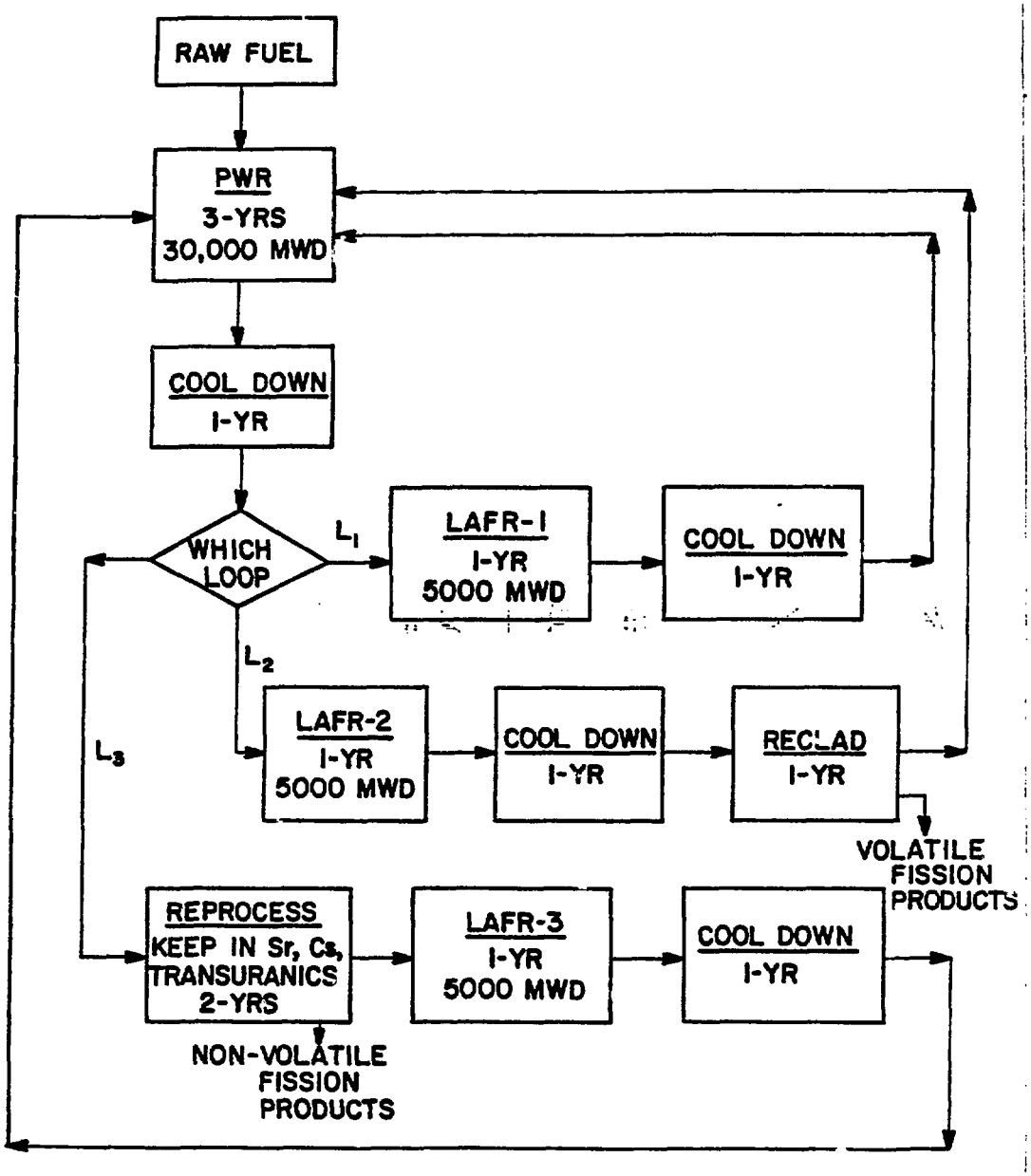

FIGURE 11. APEX-1 SYSTEM

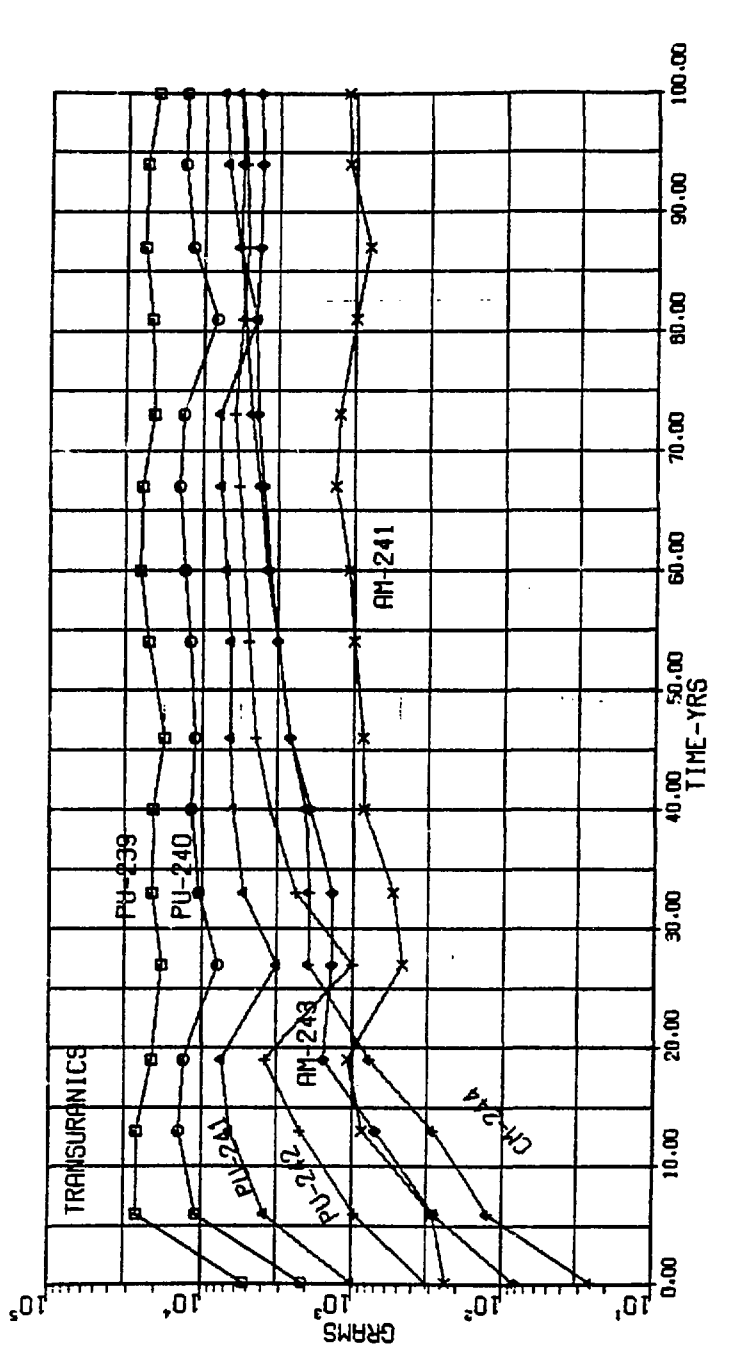

FIGURE 12. TRANSURANIC BUILDUP - gm/atm VS. TIME, APEX-3 - 27 YEAR CYCLE

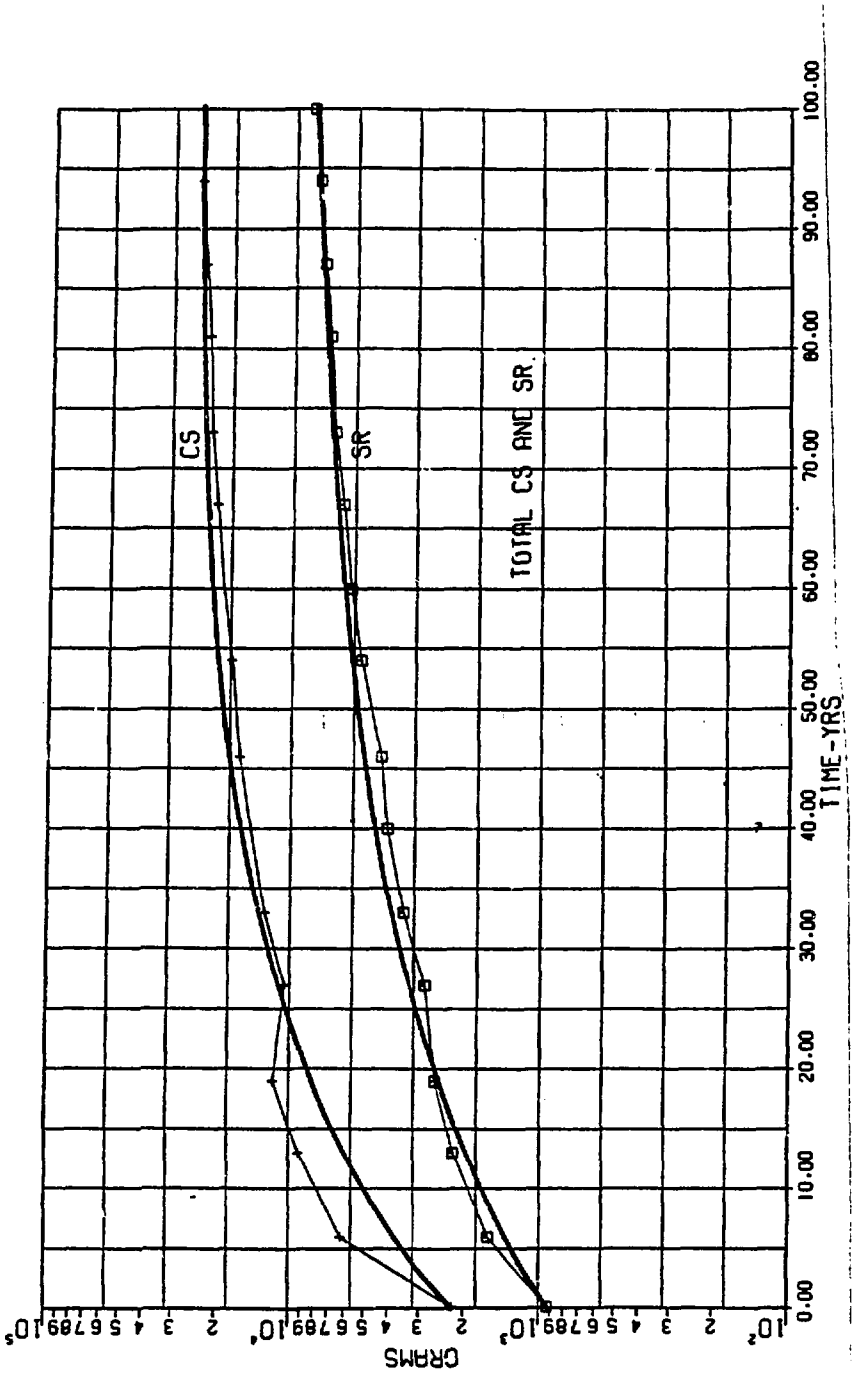

FIGURE 13. Cs AND Sr TOTAL FP BUILDUP - gm/MT HM VS. TIME, APEX-3 27 YEAR CYCLE

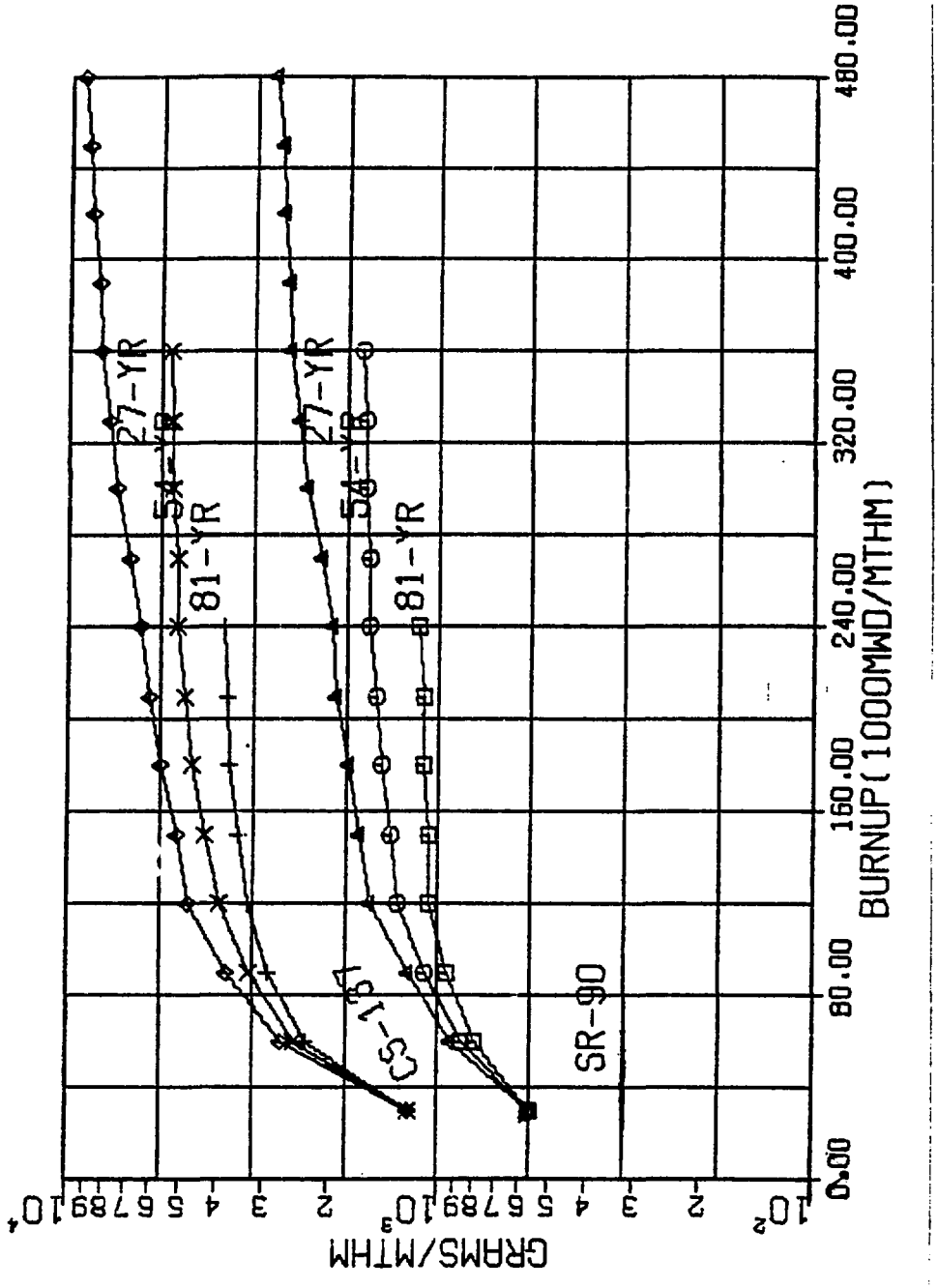

FIGURE 14. ^{90}Sr AND ^{137}Cs BUILDUP - gm/MT HM VS. BURNUP FOR 27, 54, AND 81 YEAR CYCLES