

THE LINEAR ACCELERATOR FUEL ENRICHER REGENERATOR (LAFER)
AND FISSION PRODUCT TRANSMUTOR (APEX) *

MASTER

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ABSTRACT

In addition to safety, two other major problems face the nuclear industry today; first is the long-term supply of fissile material and second is the disposal of long-lived fission product waste. The higher energy proton linear accelerator can assist in the solution of each of these problems.

High energy protons from the linear accelerator interact with a molten lead target to produce spallation and evaporation neutrons. The neutrons are absorbed in a surrounding blanket of light water power reactor (LWR) fuel elements to produce fissile Pu-239 or U-233 fuel from natural fertile U-238 or Th-232 contained in the elements. The fissile enriched fuel element is used in the LWR power reactor until its reactivity is reduced after which the element is regenerated in the linear accelerator target/blanket assembly and then the element is once again burned (fissioned) in the power LWR. In this manner the natural uranium fuel resource can supply an expanding nuclear power reactor economy without the need for fuel reprocessing, thus satisfying the U.S. policy of non-proliferation. In addition, the quantity of spent fuel elements for long-term disposal is reduced in proportion to the number of fuel regeneration cycles through the accelerator. The limiting factor for in-situ regeneration is the burnup damage to the fuel cladding material. A 300 ma-1.5 GeV (450 MW) proton linear accelerator can produce approximately one ton of fissile (Pu-239) material annually which is enough to supply fuel to three 1000 MW(e) LWR power reactors. With two cycles of enriching and regenerating, the nuclear fuel natural resource can be stretched by a factor of 3.6 compared to present fuel cycle practice without the need for reprocessing. Furthermore, the need for isotopic enrichment facilities is drastically reduced. The U-235 enrichment separative work requirements are reduced by a factor of 4 and the volume of spent fuel to be stored is reduced by a factor of 2. Current estimates indicate that the LAFER fuel cycle would increase the cost of power by about 35% compared to present LWR power costs. This increment is in the range of cost increases projected for the breeder reactor (LMFBR). As the natural uranium fuel resource becomes depleted, the LAFER becomes more competitive. The LAFER, on the one hand, is an alternative to the breeder reactor and on the other hand, it is also an alternative to isotope enrichment, i.e., U-235 separation, either by gaseous diffusion, by gas centrifugation or by laser separation. The LAFER is based on achievable near term technology and does not require a scientific proof of principle experiment.

The fuel cycle can be designed so that only stable fission products are removed from the fuel while the long-lived fission products remain contained

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in the fuel cycle thus eliminating the need for long term (geological age) waste management (the APEX cycle). The transuranics and fission products are fissioned, decayed, and transmuted within the LAFER-APEX fuel cycle. The reactor itself can be the repository for the long lived fission product waste. This cycle appears to be the missing link in assuring a long-term LWR power economy.

INTRODUCTION

Nuclear energy is an important factor in our total energy system. For it to become even more acceptable in the future, several major issues must be resolved. The industry must improve the safe operation of light water reactors (LWRs) so that another three Mile Island (TMI) incident does not occur. Experience with LWRs throughout the world show them to be highly safe and that even under adverse conditions such as that at TMI, injury and exposure to the public is minimal. It is a psychological factor which requires reactor operation to be of the highest reliability and with practically zero reactor malfunction to prove wide acceptance by the public. A continuing increasing safe operational experience with LWRs will eventually achieve this goal.

Two other major problems face a growing nuclear industry. One is the long-term supply of fissile material and the other is the disposal of long-lived fission product waste. The present directions in addressing these problems are (1) the development of fast breeders and (2) the long term geological-age storage of fission product waste. However, the development of liquid metal fast breeder (LMFBR) has proved to be slower and costlier than first estimated. In addition, because the reprocessing facilities required for the LMFBR are now seen as augmenting the risk of nuclear weapons proliferation we have seen a change of U.S. policy which has, for all practical purposes, halted progress towards commercialization of fast breeder reactors in the country. Another option is possible to meet these nuclear policies.

This alternative is based on the use of spallation neutrons produced by the interaction of high energy protons from a linear accelerator on a heavy metal target. The neutrons are then used to produce fissile (Pu-239 and U-233) material from fertile material (natural uranium and thorium). An extensive study⁽¹⁾ conducted over the past two years has indicated a number of attractive features for the concept of accelerator assisted fuel and waste management cycle.

THE LINEAR ACCELERATOR FUEL ENRICHER AND REGENERATOR CYCLE (LAFER)

The conventional LWR nuclear fuel cycle is shown in Figure 1. 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

CONVENTIONAL NUCLEAR FUEL CYCLE - LWR

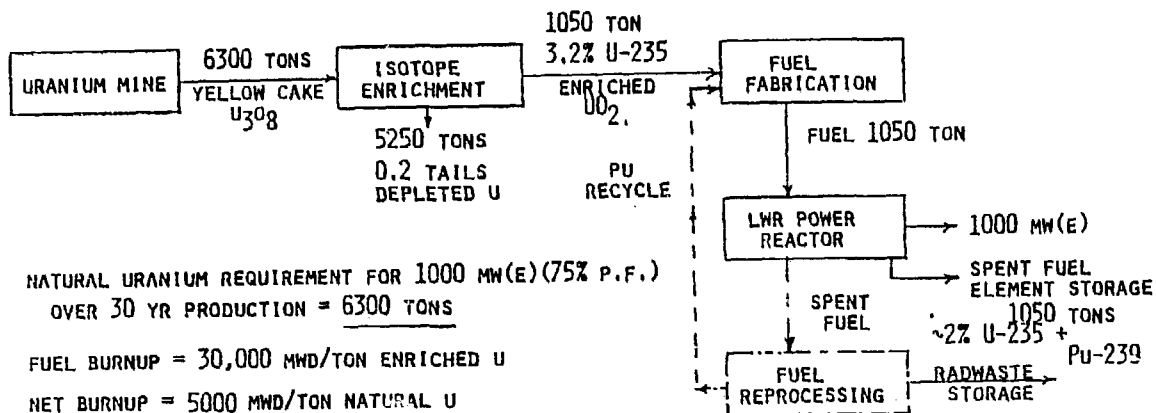


FIGURE 1

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 a lower U-235 enrichment and builds into the fuel the required Pu-239 reactivity. The cycle is shown in Figure 2. 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 in 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. 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 another 6000 MWD/ton burnup in the accelerator. There has been much successful operation of conventional LWR elements to burnups of 60,000 MWD/ton in LWR power reactors.⁽²⁾ Present burnup designs for the fast LMFBR reactors are 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

LAFR FUEL CYCLE - NO REPROCESSING

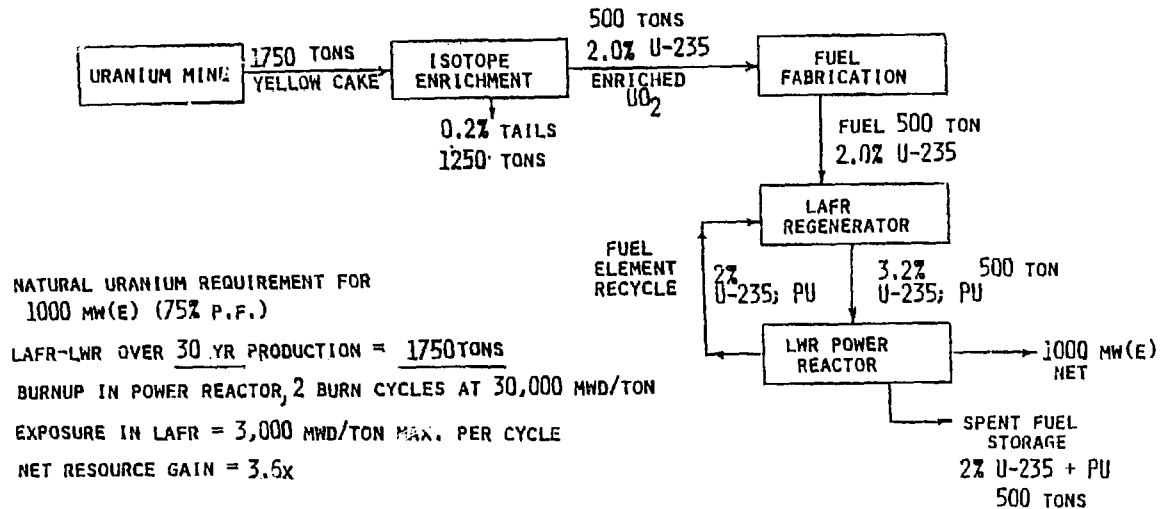


FIGURE 2

Pu-239. The isotope enrichment plant is actually a depletion device since it only utilizes the very limited natural U-235 resource and throws away the bulk of the natural fertile material.

LINEAR ACCELERATOR (LINAC)

The heart of the cycle is the LAFER which consists of a proton linear accelerator and a target-blanket assembly with power recovery and generation equipment. The linear accelerator consists of an Alvarez drift-tube operating at 200 MHz up to an energy of 150 MeV. The Alvarez structure is followed by a $\pi/2$ mode coupled cavity structure up to the final energy. An acceleration rate of 1.5 MeV/meter appears about optimum. With a length of 1000 meters, a 1.5 GeV proton beam is produced. Experience with research machines, indicate that continuous wave accelerators can operate with an 80% plant factor and without 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.

TARGET DESIGN

We have made real advances in the design of the target-blanket assembly.⁽¹⁾ The primary target consists of multiple falling liquid lead or lead-bismuth columns or 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 fertile material in the blanket consisting of LWR fuel assemblies are located in pressure tubes surrounding the liquid lead target. An isometric view of the target blanket assembly is shown in Figure 3, and a plan view is shown in Figure 4. The advantages of these configuration are as follows:

1. The liquid lead having a low vapor pressure 10^{-5} torr at 400°C , 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 interference with the beam. Furthermore, a liquid lead target suffers no radiation damage.
2. The pressure tubes are heavy water cooled in a highly subcritical assembly so that there is no nuclear criticality safety problem.
3. The target blanket is separated from the accelerator so that the accelerator will be essentially contamination free.
4. Power can be recovered from the heat developed in the target and blanket assemblies because of the liquid circulation systems.
5. Maximum utilization of the neutrons are obtained because the blanket completely surrounds the target and the reflector contains the neutrons.

LAFER TARGET - BLANKET ASSEMBLY

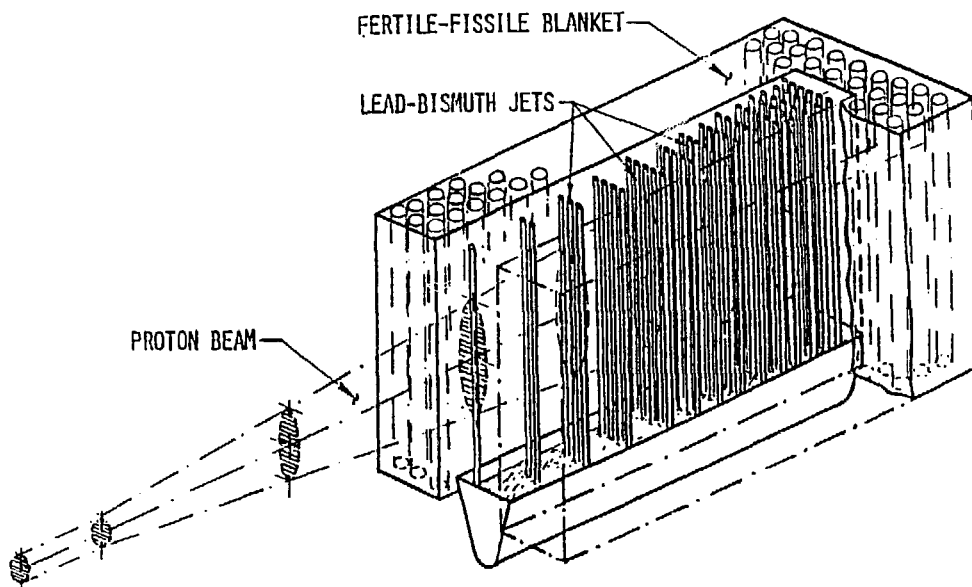
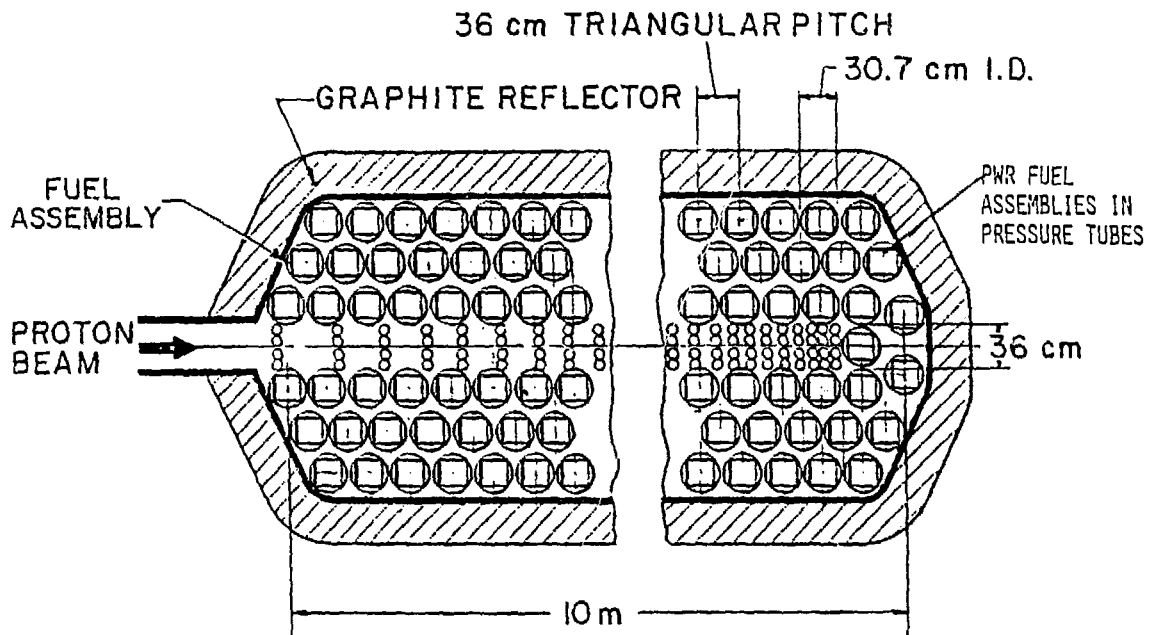


FIGURE 3



PWR TYPE TARGET ASSEMBLY
CROSS SECTION

FIGURE 4

Based on the target-blanket assembly shown, model neutron code computer calculations were made for the neutron physics estimates. An NMTC code is used to calculate the 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 crosssection modified SIZZLE code was used conservatively, for burnup calculations and the effect of fission product buildup was estimated by the EPRI Cell Code⁽¹⁾.

Table 1 shows the initial fissile fuel production rates for 8 different target reactor lattices. The data indicate that roughly about 1 ton of fissile material Pu-239 or U-233 is produced with a 0.3 Amp-1.5 GeV proton accelerator. Basically about 35 neutrons are produced per proton by direct spallation, about 15 MeV. This is conservative compared to recent Russian data⁽³⁾ which indicate as much as a 50% higher production of spallation neutrons. Additional neutrons are produced by fast fission. Figure 5 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, so that 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 6 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 transformed from strongly absorbing isotopes to weaker neutron absorbing species in the process.

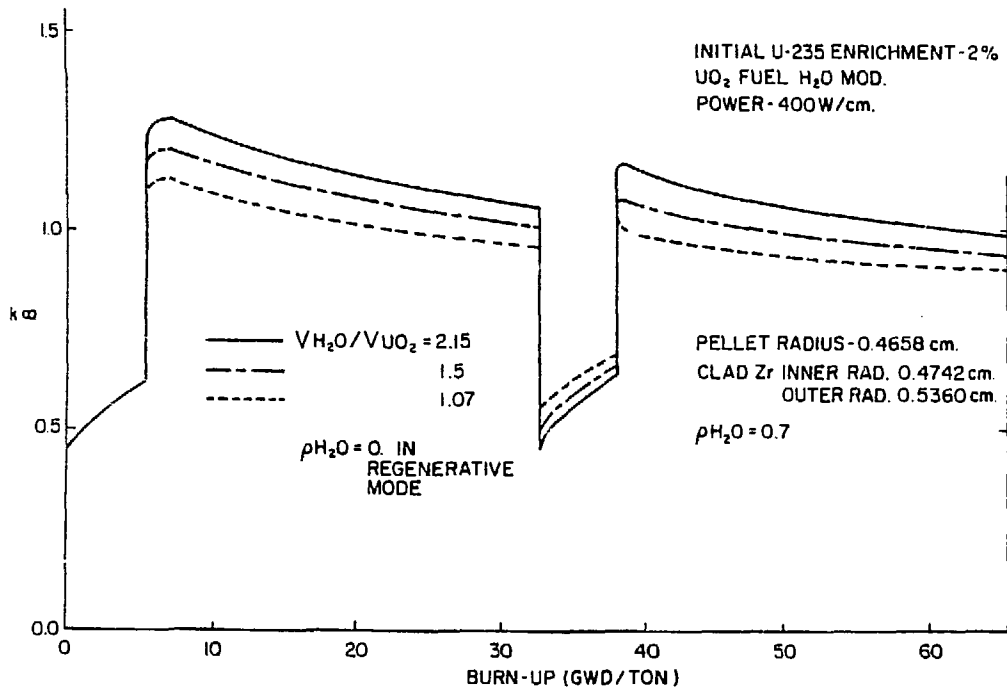
Table 1. INITIAL FISSILE FUEL PRODUCTION RATES FOR Pb-Bi TARGET WITH FUEL ELEMENT BLANKET (0.3A - 15 GeV PROTON ACCELERATOR)

Design 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 ₂ O	0.7	53.8	Pu - 1010
2	ThO ₂	D ₂ O	0.7	46.6	U ²³³ - 850
3	UO ₂ (NAT)	H ₂ O	0.7	74.1	Pu - 1000
4	UO ₂	H ₂ O	0.35	65.8	Pu - 1050
5	UO ₂ (NAT)	H ₂ O	0.175	64.9	Pu - 1070
6	ThO ₂	H ₂ O	0.7	46.5	U ²³³ - 850
7	ThO ₂	H ₂ O	0.35	48.6	U ²³³ - 890
8	ThO ₂	H ₂ O	0.175	49.0	U ²³³ - 900

Moderator/Fuel Volume Ratio = 0.8

Beam Power Output to Electric Power Input Efficiency = 50%

Plant Factor = 80%



MULTIPLICATION FACTOR OF REGENERATIVE AND REACTOR MODES

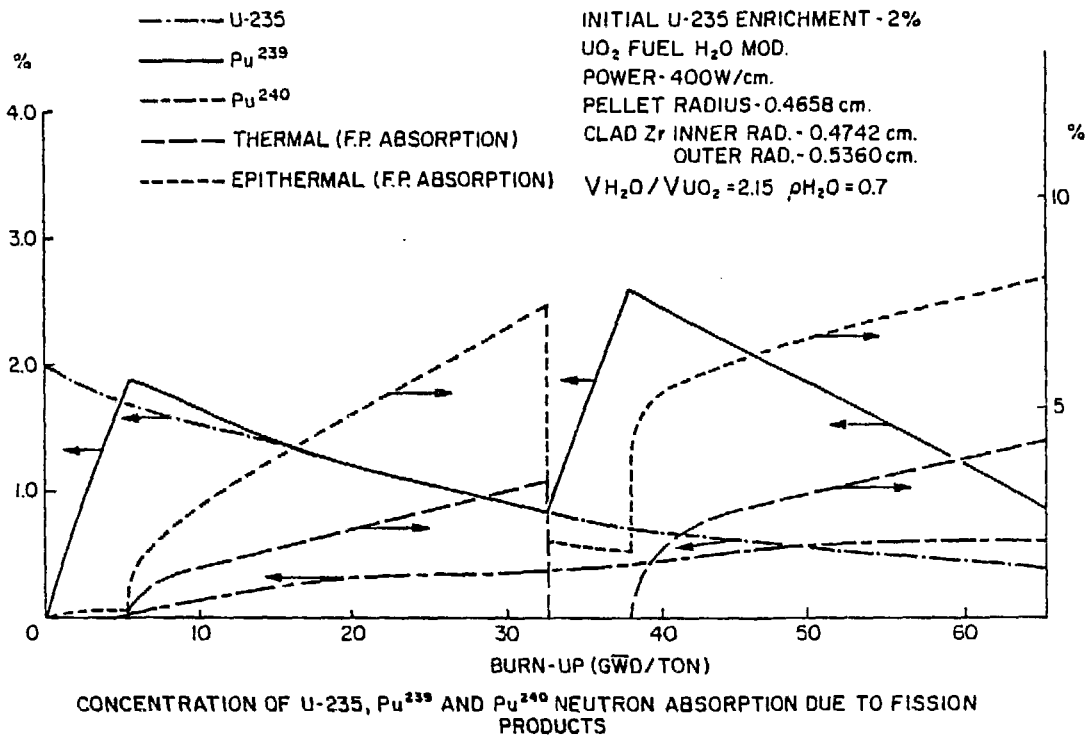


FIGURE 6

ECONOMICS

Based on the above concepts a system was devised as shown in Figure 7 where 3-1000 MW(e) 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. Table 2 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 energy production amounts to 11.6 mills/KWh(e) delivered by the power reactors. Table 3 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 so that there is no necessity to purchase outside power. Even with the increased fuel cycle cost as shown in Table 4, the total production cost for power is only 35% higher than conventional fuel cycle. This is about the same incremental estimate for the LMFBR 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 an existing LWR nuclear power economy.

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

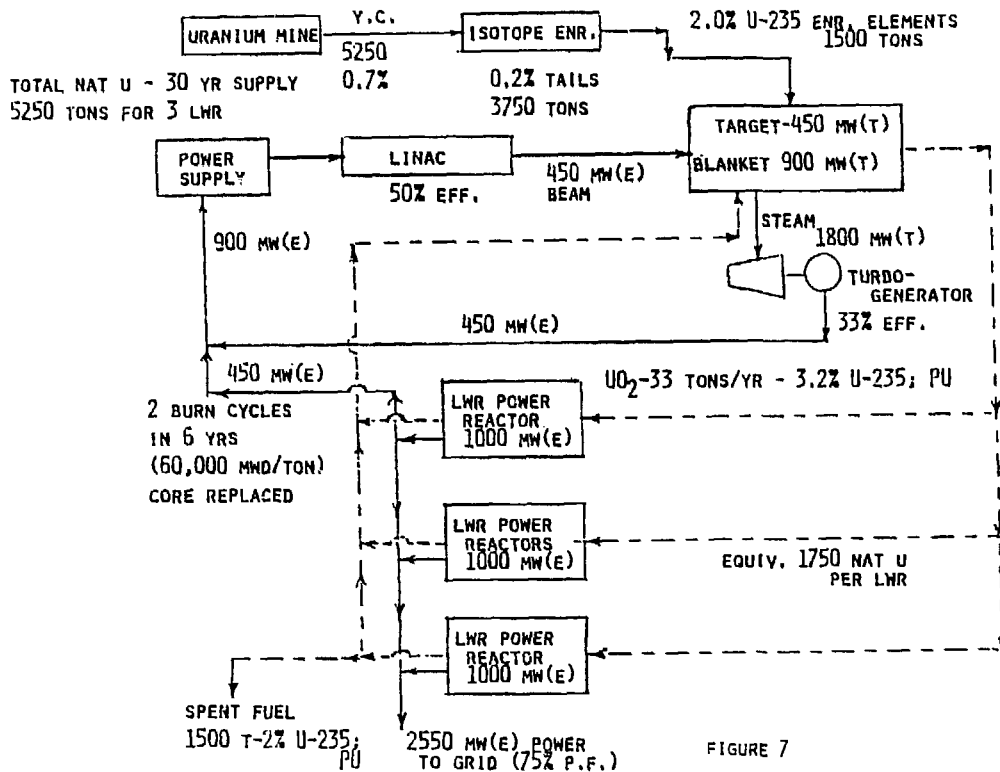


FIGURE 7

Table 2. LAFER FUEL CAPITAL COST

Linac Cost (0.3A - 1.5 GeV)	= \$ 500 x 10 ⁶
Target Reactor Cost, 450 MW(e) x 1000 x $\frac{\$700}{\text{KW(e)}}$	= 315 x 10 ⁶
LAFER Cost (1978 Dollar.)	= \$ 815 x 10 ⁶
Escalation and Interest Charges (7% and 9%)	= 675 x 10 ⁶
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 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 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 (15%, 80% PF) LAFER (15%, 80% PF)		-		11.63
Electrical Power (450 MW(e)) to LAFER at 58.3 Mills/KWH(e)		-		9.46
Oper. & Maintenance		-		2.00
		13.36*		28.06

(*)Industry Report (1976-7) - Bechtel Estimate

Table 4. COMPARATIVE ECONOMICS OF LINEAR ACCELERATOR FUEL REGENERATOR (LAFER) WITH LIGHT WATER REACTORS (LWR)

	Conv. LWR*	LAFER-LWR
<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. & Maint.	3.3	3.3
Total	43.6*	58.3

(*)ANS Industry Report (1976-7) - Bechtel Estimate
Conclusion - LAFER/3 LWR Reasonably Competitive with LWR

Figure 8 indicates how the LAFER can significantly improve the utilization of the nuclear resource while maintaining an 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 here today in the form of research tools. They can be converted to fuel production machines with relatively little additional development investment. The LAFER cycle appears to be the missing link in the LWR nuclear power cycle chain.

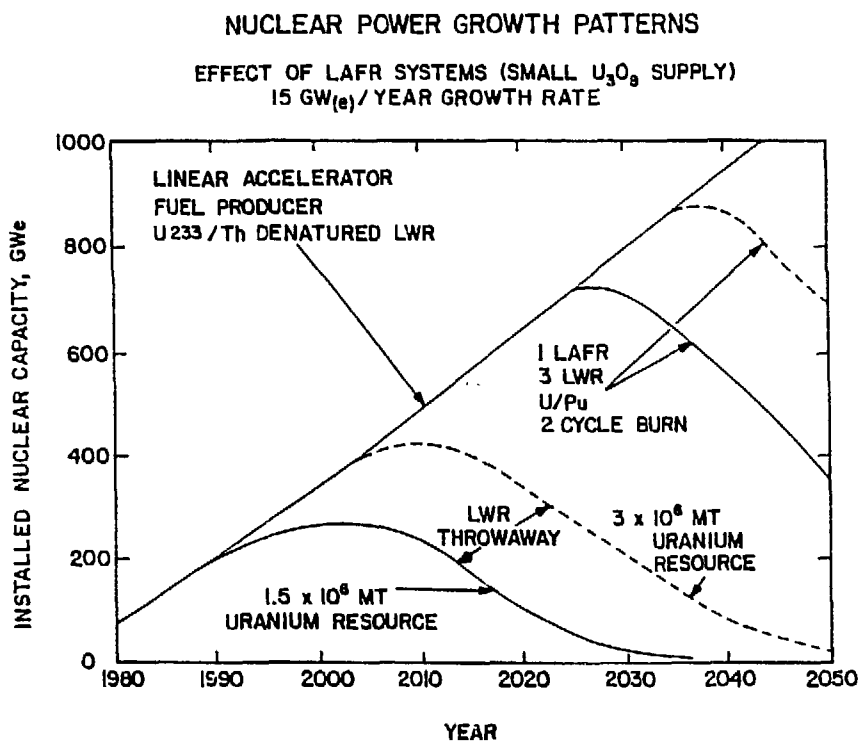


FIGURE 8

ACCELERATOR FUEL PRODUCER AND FISSION PRODUCT EXTERMINATOR - (APEX)

The LAFER addresses the front end of the nuclear fuel cycle. Turning to the back end of the fuel cycle for considering waste management, two new concepts have been developed which appear to significantly reduce requirements for long-term geological-age storage. APEX-1 involves keeping the long-lived radioactive material in the fuel cycle where it can decay and transmute. APEX-2 makes extensive use of accelerator-driven transmutation to significantly reduce the total burden of long-lived radioactive material associated with the nuclear fuel cycle. The acronym APEX is derived from Accelerator Fuel Producer and Fission Product Exterminator.

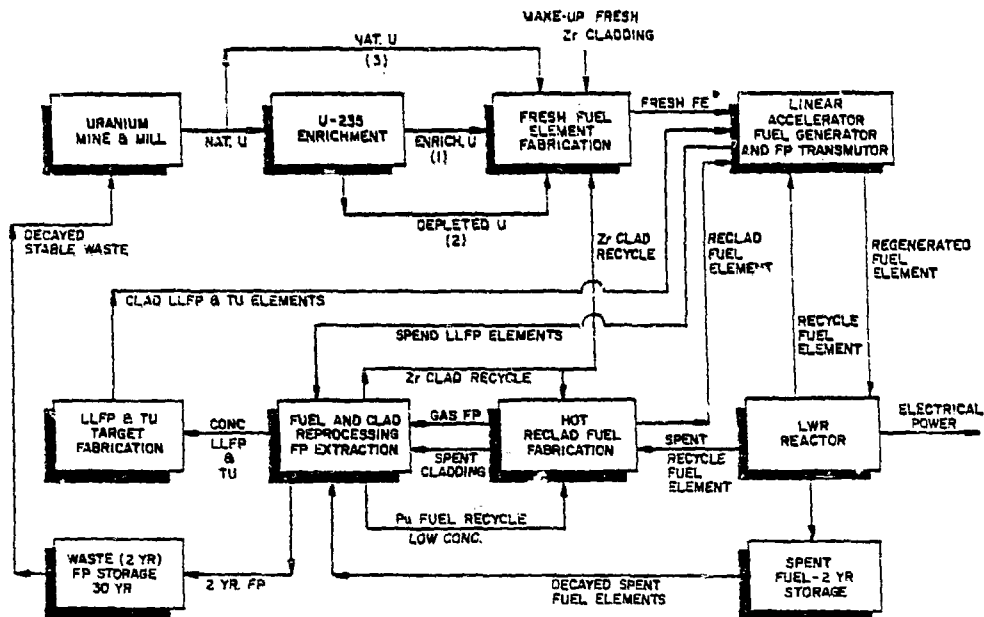
APEX-1

APEX-1 incorporates the LAFER-1 and LAFER-2 cycles with the further addition of a non-radioactive stable fission product partitioning step. The APEX-1 system is shown in Figure 9. Short-term (1 to 2 year storage) of the LWR fuel elements allows the short-lived fission products to decay. After the AIROX step, which removes the volatile fission products by alternating oxidation-reduction steps⁽⁴⁾, the $UO_2-U_3O_8$ powder is processed for removal of the non-volatile stable and decayed fission products, consisting mainly of alkali, alkaline, and rare earth (Cs, Sr, Ba, La, Gd, etc.) 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 heavy higher valent uranium and transuranic oxides may be applicable. The physical chemistry of the system is known from the literature.⁽⁵⁾ This process would have the advantages of being non-aqueous 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 non-radioactive stable fission products which can either be utilized for special commercial purposes or can be put back as fill in the uranium source mines.

The great advantage of APEX-1 is that it eliminates the need for 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 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 problem 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 not be significantly higher than the concentration characteristic of the present LWR fuel cycle.

APEX-2
LINEAR ACCELERATOR FUEL ENRICHER REGENERATOR-LWR FUEL CYCLE
AND FISSION PRODUCT TRANSMUTOR



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

FIGURE 10

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

There are other possible applications of the transmutation process beside the APEX-2 described above. One could, for example, transmute the long-lived fission product waste from the military weapons program, which is estimated to be stored to the extent of a 100 million gallons of liquid waste. Table 5 gives an estimate of the accelerator-target capital cost. Additional cost is required for extracting Pu, Cs and Sr from the waste tanks. A demonstration of transmutation might be conducted at the Nuclear Fuel Services (NFS) West Valley Plant in New York State where 600,000 gallons of reprocessed fuel waste is presently stored. Another possibility is to apply transmutation to the remaining inventory of long-lived fission products at the end of a fission reactor nuclear power economy.

Table 5. MILITARY WASTE - ALTERNATIVE MANAGEMENT

APEX-2 - Transmutation

Approximately Vol. - 100 x 10⁶ gallons
 Containing Cs¹³⁷ - 2 tons (6.2 Cs total)
 Sr⁹⁰ - 1.3 tons (2.1 Sr total)

Capacity 400 MW accelerator beam capacity
 Cs¹³⁷ 0.2 ton/yr for 10 years
 Sr⁹⁰ 0.13 tons/yr for 10 years

Capital Cost

Accelerator	2 x 400 x 10 ³ Kw x \$500/Kw	= \$ 400 x 10 ⁶
Target	400 x 10 ³ x \$200/Kw	= 80 x 10 ⁶
Power Cost	400 x 10 ³ x 10 x 7000 x 30 Mills/Kwh(e)	= 840 x 10 ⁶

Total Cost = \$1,320 x 10⁶

APEX-1 - Incorporates Cs¹³⁷ and Sr⁹⁰ 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
 No. of reactors required for all waste = 6.2/0.1 = 62 reactors

We intend to have 280 reactors at least by end of century or 22% of them would contain M waste. The residual Pu would also be burned out.

It appears that as far as public perception and acceptance is concerned, the public regards the waste disposal problem just as great an issue, if not more so, than the safety of light water power reactors. Since many millions of curies of activity exist in operating fission power reactor cores, recycling the long-lived fission products and transuranics adds less than 1% to the overall radioactive inventory to operating LWR reactor cores. Recycling long-lived fission products should be highly acceptable by the public, if it eliminates the need to bury or store long-lived radioactive material for long periods of time. 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 in the power reactor fuel elements. This number of reactors equals our present operating power reactor capacity and thus could handle the military waste even now.

COMPARISON OF LAFER AND APEX SYSTEMS

Table 6 gives a preliminary comparison of the LAFER and APEX systems.

Table 6. THE APEX-LWR NUCLEAR FUEL CYCLE AND WASTE MANAGEMENT SYSTEMS

System	Fuel Production System	Fuel Burnup MWd/ton	First Stage Processing	Second Stage Processing	Radioactive Material for Disposal MT/1000 MW(e)(6)	Equilibrium Inventory for 400 LWR's Long-lived FP's in Reactor conv.-wt % Total Inventory MT					
						Reactor conv.-wt %			Total Inventory		
						(1) TU	(2) Sr ⁹⁰	(3) Cs ¹³⁷	(4) TU _{out}	Sr ⁹⁰ _{in}	Cs ¹³⁷ _{out}
1. Conventional once-through LWR	Low enrich. fuel LEU-3.2% U-235	30,000	—	—	1,000	0.9	0.055 0.10	0.125 0.25	3600 360	400 650	630 2000
2. LAFER-1	LAFER-1.6% U-235 2 cycle 1.6% Pu-239	60,000	—	—	500	1.9	0.080 0.15	0.175 0.35	3800 760	400 650	630 2000
3. LAFER-1	LAFER-5 cycles 3.2% Pu-239	150,000	—	—	200	2.2	0.130 0.25	0.325 0.65	1760 880	400 650	630 2000
4. LAFER-2	LAFER-3 double cycles with AIBOX reprocessing	180,000	AIBOX Removes vol. FP, I, Xe, Kr, Tc, etc.	—	166	2.2	0.140 0.28	0.375 0.75	1460 880	400 650	630 2000
5. APEX-1	LAFER-2 double cycles with 1st and 2nd stage stable FP reprocessing	120,000	AIBOX Removes vol. FP, I, Xe, Kr, Tc, etc.	CMC-MET(Chelate) Removes non-vol. rare earth and stable FP's	0	2.2	0.310 1.00	1.000 2.00	0 880	400 640	630 2000
6. APEX-2	LAFER-2 double cycles with 1st and 2nd stage FP removal and transmutation	120,000	AIBOX Removes vol. FP, I, Xe, Kr, Tc, etc.	Ca-Sr separation and transmutation(5) with accelerator	0	2.2	0.055 0.10	0.125 0.25	0 880	40 65	63 200

Notes:
 1) TU's consist of Pu-239, 240, 241, and 242, Am-241 and 242 and Cm-243. 2) Sr consists of Sr-88 and 90.
 3) Cs consists of Cs-131, 135, and 137. 4) Out = TU inventory in waste disposal, In = TU inventory in reactor
 5) Isotopic separation of Cs-137 required. 6) Mass of radioactive material for long-term disposal, MT for a 1000 MW(e) reactor operating for 30 years. 400-1000 MW(e) will generate 400,000 MT waste for once-through systems.

For a nuclear economy consisting of 400-1000 MW(e) LWRs, long term disposal of a 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 eliminates the need for disposal of radioactive waste.

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 6 indicates that the equilibrium concentration of long-lived fission product Cs¹³⁷ in the reactor increases six times over that for a conventional LWR system and eight times for Sr⁹⁰, while the total inventory remains approximately the same.

The APEX-1 cycle was studied for LLFP and TU buildup using the ORIGIN computer code. The cycle diagram for a 27 year cycle is shown in Figure 11.

APEX 1 SYSTEM - 27 YR. FUEL CYCLE

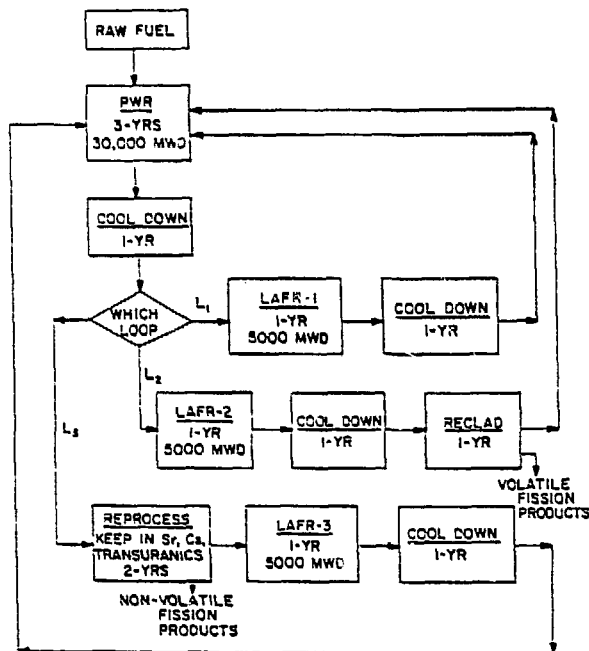


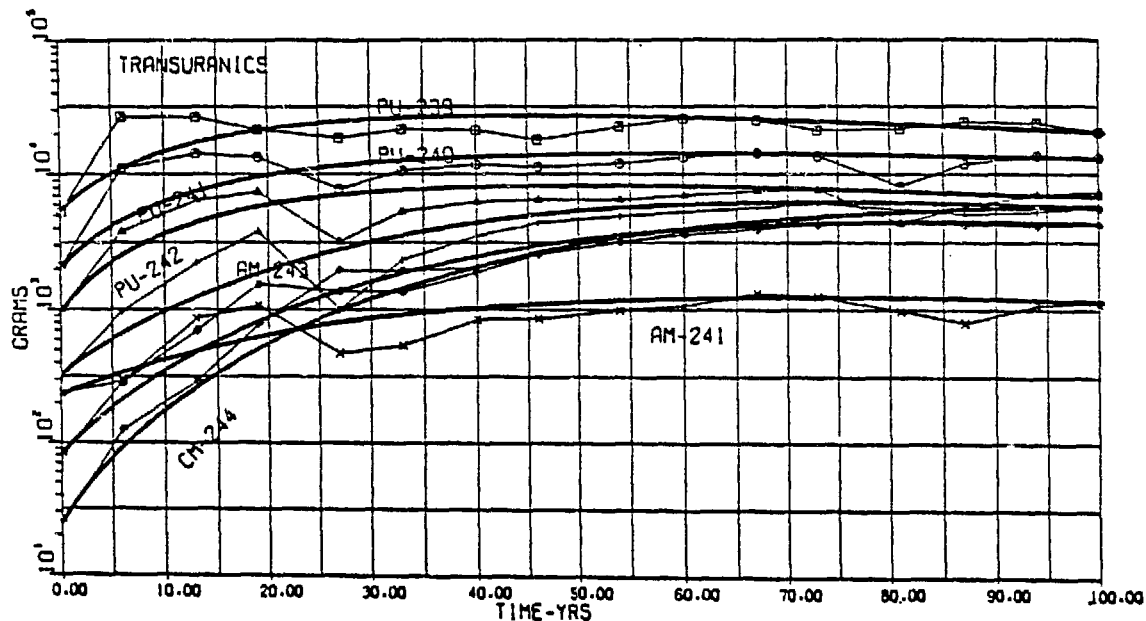
FIGURE 11

The buildup of TU's (Am, Cm, and Pu) and LLFP's (in gms/MT heavy metal) are given in Figures 12 and 13 respectively for the 27 year APEX-1 cycle shown in Figure 11. Although this Cs and Sr buildup appears acceptable compared to alternate high burnup schemes, if the APEX-1 cycle is increased to 54 years, as shown in Figure 14, the concentration of Cs and Sr is reduced to 3 and 4 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.

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 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 Cs¹³⁷ and the Sr produced. Because of the low Cs¹³⁷ cross section, an isotopic separation will be necessary to maintain a good neutron economy. Isotopic separation will not be necessary for Sr⁹⁰ (at least not for hundreds of years) because of the lower cross section of the stable Sr⁸⁸ isotope.

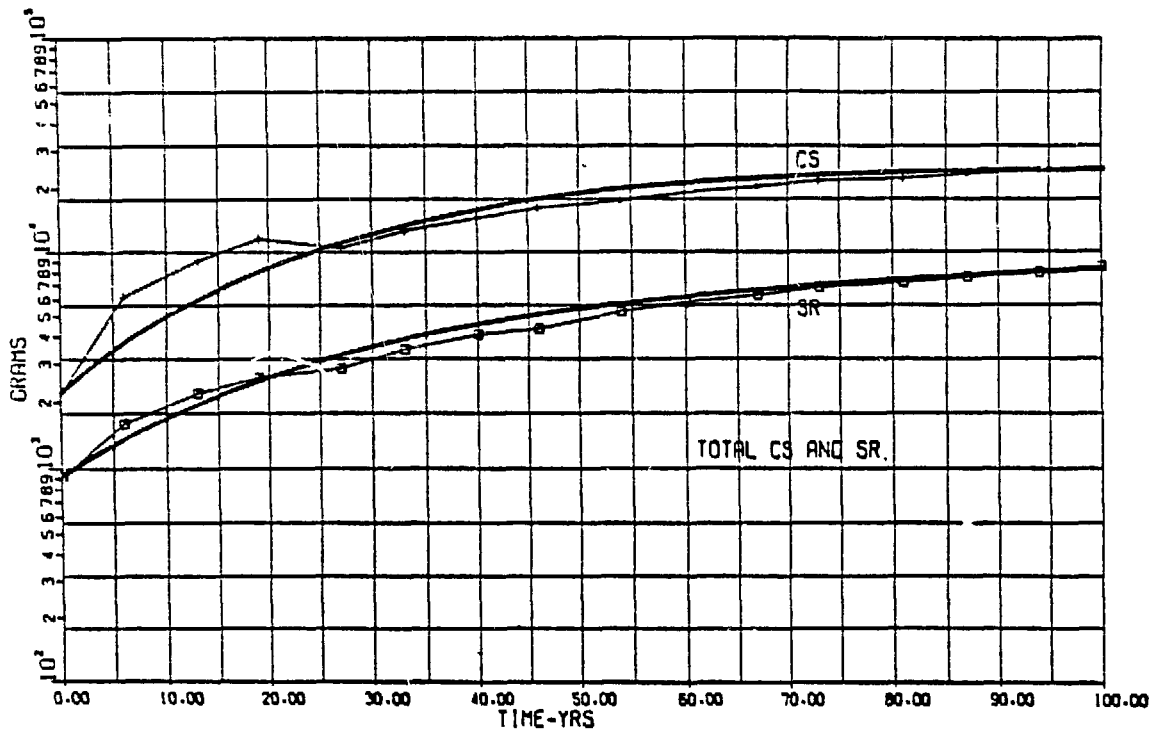
APEX processing and waste management schemes could be applied to alternative reactor fuel cycles without accelerator breeding; enriched fuel could be added to reprocessed fuel, however, a closer approach to non-proliferation policy, i.e. (1) eliminating Pu recycle through Purex reprocessing, (2) stretching the fuel supply by in-situ breeding and regeneration, and (3) keeping fissile material concentrations low at all times in the fuel cycle can be accomplished only by employing the accelerator in which fuel is produced or regenerated in-situ.

The APEX concepts provide a long-term non-geological-age storage solution to the nuclear waste management program. It is recommended that a thorough evaluation be made to determine the tradeoffs and economics of each of the APEX concepts and if found attractive in comparison with long-term geological-age storage, a program plan should be developed for implementing the optimum system.



TRANSURANIC BUILDUP - gm/MT VS. TIME
APEX-1 - 27 YR. CYCLE

FIGURE 12



Cs AND Sr TOTAL FP BUILDUP - gm/MT HM VS. TIME
APEX-1 - 27 YR. CYCLE

FIGURE 13

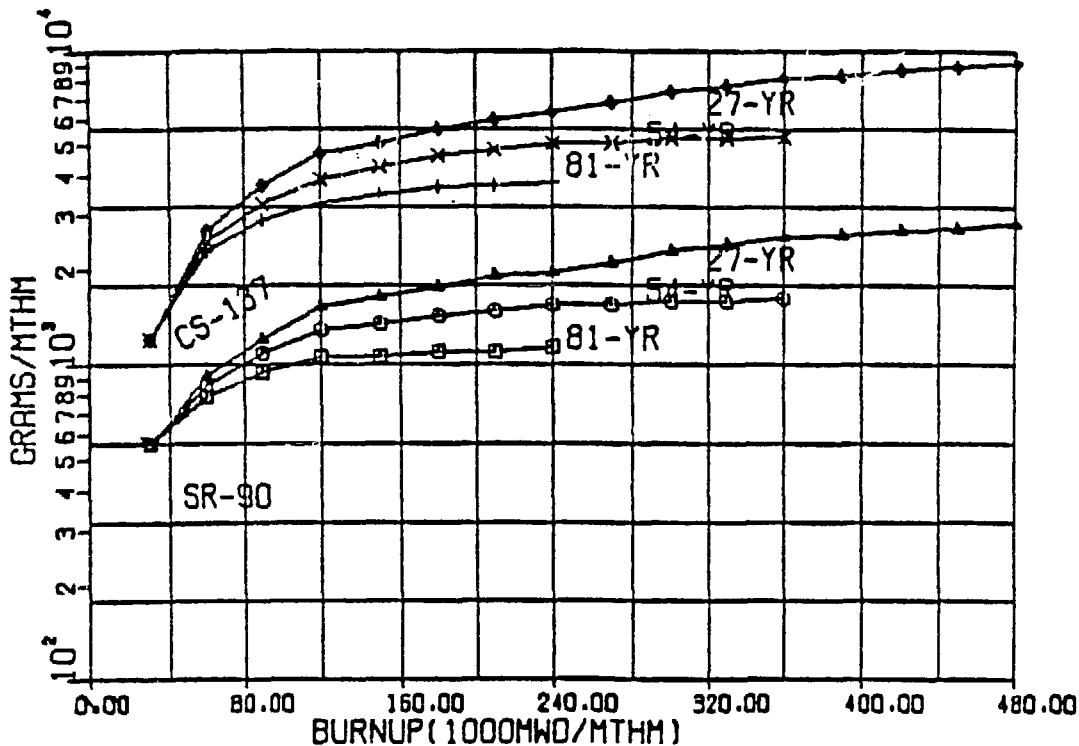


FIGURE 14
⁹⁰Sr and ¹³⁷Cs BUILDUP - gm/MT HM VS. BURNUP FOR 27, 54, and 81 YR. CYCLES.
APEX-1

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