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APEX NUCLEAR FUEL CYCLE FOR PRODUCTION OF LWR FUEL AND ELIMINATION OF RADIOACTIVE WASTE

MASTER

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ABSTRACT

The development of a nuclear fission fuel cycle is proposed which eliminates all the radioactive fission product waste effluent and the need for geological-age high level waste storage and provides a long term supply of fissile fuel for an LWR power reactor economy. The fuel cycle consists of reprocessing LWR spent fuel (1 to 2 years old) to remove the stable non-radioactive (NRFP, e.g. lanthanides, etc.) and short-lived fission products (SLFP e.g. half-lives of <1 to 2 years) and returning, in dilute form, the long-lived fission products, ((LLFPs, e.g. 30 yr half-life Cs, Sr, and 10 yr Kr, and 16×10^6 yr I) and the transuranics (TUs, e.g. Pu, Am, Cm and Np) to be refabricated into fresh fuel elements. Makeup fertile and fissile fuel are to be supplied through the use of a Spallator (linear accelerator spallation-target fuel-producer). The reprocessing of LWR fuel elements is to be performed by means of the Chelox process which consists of Airox treatment (air oxidation and hydrogen reduction) followed by chelation with an organic reagent (β-diketonate) and vapor distillation of the organometallic compounds for separation and partitioning of the fission products. The stable and short-lived fission products (NRFP and SLFP) are allowed to decay to background in 1 to 2 years for final disposal to the environment. The fertile material (FM, e.g. U-238) and transuranics (TUs) are returned to be reincorporated into LWR fuel elements. The even mass-numbered TUs are efficiently converted to odd mass-numbered fissile fuel (FF) in the reactor which then fission to produce power and fission products in the LWR. The TUs have high thermal neutron crossections and are therefore efficiently converted in the thermal LWR. The long-lived fission products (LLFPs, e.g. Cs, Sr, Kr and I) are recycled in the fuel cycle to decay and become transmuted both in the Spallator and the LWR to short-lived (SLFP) and stable (NRFP) products. Decay is the major mode of transmutation of the LLFPs because of their small thermal neutron crossections. Some neutron transmutation does occur and shortens the storage times for the LLFPs. In this manner, long term geological-age storage of fission product waste is avoided and the need for a new fast breeder reactor economy is no longer a necessity by the utility power industry. APEX can be beneficially applied to the thorium/U-233 cycle as well as the described uranium/Pu-239 cycle.

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INTRODUCTION

It is well known that Purex nuclear fuel reprocessing for the civilian power program was primarily derived from the need to produce weapons grade plutonium. Thus Pu-239 is solvent extracted with tributyl phosphate (TBP) from an aqueous nitrate solution of spent fission fuel and the Pu-239 is then recovered and concentrated for mixing with fresh uranium oxide to make up the fuel in a thermal nuclear power reactor. Actually no fuel reprocessing has been performed for the civilian power economy since deferment of reprocessing was instituted by the Non-proliferation Act of 1976. Thus, most of the reprocessing that has occurred was for the weapons program. The effluent high level waste from these production plants contain up to about 2% of the Pu-239 originally present in the spent fuel from the convertor reactor together with the fission products. The high-level waste from the fuel reprocessing plants have been stored to date, on-site in large engineered storage tanks. Much work is now being conducted to solidify this high level waste for placement in underground excavations for geological-age storage in so-called waste isolation facilities. Because of the Pu-239 content, which has a 26,000 year half-life, this waste requires storage for a quarter of a million years (~10 half-lives) to decay to biologically acceptable background level, along with other long-lived transuranics (Pu, Am, Cm, Np, etc.). The longest-lived and biologically most hazardous fission products are Cs-137 and Sr-90, both of which have half-lives of approximately 30 years, require at least 300 years to decay to background. Actually the bulk of the present waste consists of 80 million gallons stored at the weapons materials production plants. The main radioactive products, in this aged waste consists of Pu, and Cs and Sr fission products. The civilian fuel as mentioned above is not being reprocessed presently, but is being stored in pools at the power reactor sites. Eventually these elements will either have to be reprocessed or disposed of.

Weapons materials require high concentrations (>20%) of high grade-high purity fissile material (Pu 239, U-235 or U-233). For the thermal fission nuclear burner power reactors, for example, the light water reactors (LWRs), one does not need to concentrate fissile U-235 (natural) or Pu-239 (made from uranium 238) or even U-233 (made from thorium) to these higher levels for use in the power reactor fuel elements. The fissile fuel concentration in the fuel elements need only be in the order of 2% to 4% to be able to function in a light water power reactor (LWR).

APEX FUEL CYCLE

We are proposing an alternate new fuel cycle which eliminates the radioactive fission product waste effluent and thus avoids long-lived geological-age radioactive waste storage(1,3) and supplies fissile fuel for the LWR power reactor. For all intensive purposes this fuel cycle does not have any radioactive waste effluent. Only non-radioactive stable waste which does not have to be stored in a waste isolation facility but which can be disposed of in a normal fashion to the environment is produced by the system.

The fuel cycle consists of chemically reprocessing LWR spent fuel which has been aged for 1 to 2 years. The reprocessing removes the stable non-radioactive (NRFP,e.g. the lanthanides, etc.) and short-lived fission products (SLFP) with half-lives of <1 to 2 years and returns in dilute form, the long-lived transuranics (TU's, e.g., Pu, Am, Cm, Np, etc) and long-lived fission products (LLFP's e.g. mainly the 30 year half-life Cs, Sr, and 10 year Kr and $16x10^6$ yr I, etc.) to be refabricated into fresh LWR fuel elements. The fissile transuranics (the odd mass-numbered) will fission and the fertile transuranics (the even mass-numbered) will be converted to fissile transuranics in the thermal nuclear power reactor. The TU's have large thermal neutron crossections and can either be readily fissioned or converted from fertile material (FM) to fissile fuel (FF) in the LWRs. Equilibrium concentrations of these materials are achieved in the fuel cycle within a relatively short period of time. Recycling the transuranics, which actually act as fuel, adds to the power capacity of the LWRs and does not detract from the neutron economy of the reactor. Because of their much lower cross-sections, the long-lived fission products (LLFPs) Cs-137 and Sr-90 fission products are not readily transmuted in the LWRs. For these waste products we would be mainly relying on the decay process by storage within the fuel cycle. Some transmutation will occur in the Spallator and the LWRs which will shorten the recycle storage times for decay of the LLFPs to non-radioactive stable isotopes (NRFP). It is interesting to note that the main long-lived radioactive fission products formed in the fission process are the 30 yr half-life Cs-137 and Sr-90 isotopes so that no other hazardous long-lived (nuclides) are expected to be formed on recycling. Over the longer period of time the total inventory of Cs and Sr thus reaches asymptotic equilibrium values.

In order to implement the above fuel cycle, it may be possible to use conventional Purex reprocessing, however, we are proposing to improve and design the reprocessing chemistry to accomplish the goal set forth. A fundamental consideration is that the purpose of Purex was to produce pure Pu for weapons. Purex was therefore operated to allow Pu to spill over into the waste in order to prevent contamination of the Pu metal with fission products. In the concept proposed herein the reverse is allowed for the civilian reactor fuel. Fission products are allowed to contaminate the fissile Pu but Pu is not allowed to contaminate the waste. The purpose of this new reprocessing system is to extract the stable non-radioactive (NRFP) and shorter-lived fission products (SLFPs with <2 years half-life) and to allow the transuranics and long-lived fission products to remain in the fuel. Furthermore, in order to produce make-up fissile fuel (FF) for fabricating fresh fuel elements for use in the thermal burner LWR power reactors, it is proposed to use the Spallator (linear accelerator spallation-neutron target reactor) to produce fissile material.(1) Isotopic enrichment of U-235 from natural uranium is not needed and the cycle functions in the same sense as a breeder.

CHELOX REPROCESSING

The new reprocessing chemistry which we call "Chelox" first involves the use of the Airox process(4) followed by extraction with a chelating agent. The Airox process breaks open the zircaloy cladding of the LWR fuel element by air oxidation and hydrogen reduction processes and removes the uranium. This is followed by treatment of the UO_2 with a chelating atent (β-diketonate) to extract and separate the stable alkali and rare earth fission products from the higher valent uranium and transuranic oxides.(2) The Airox process consists of air oxidation of a mechanically punctured LWR fuel element at ~400°C, thus converting the UO_2 to U_3O_8 which swells and cracks open the zircaloy cladding. The U_3O_8 powder falls out and separates from the cladding. The U_3O_8 is then reduced back to UO_2 with hydrogen at about the same temperature. This process has been tested through pilot plant scale(4) with irradiated LWR fuel elements. The chemistry of the Airox process is as follows:

Airox Process

$$3UO_2 + O_2 = U_3O_8$$

$$U_3O_8 + 2H_2 = 3UO_2 + 2H_2O$$

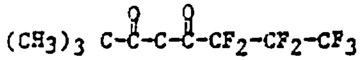
In the Airox process the volatile fission products (Xe, Kr, I) and some of the Cs are volatilized and recovered by trapping, filtering and absorption processes with short-term storage (1 to 2 year) of the spent LWR fuel. Prior to reprocessing most of the short-lived (<1 to 2 months) fission products will have been decayed so that, as far as the volatile fission products are concerned, these will mainly consist of Kr-85 (10 year half-life), I-129 (16 million yr half life) and Cs-137 and Sr-90 (30 year half-life) and will be recovered by well-known techniques mentioned above. The volatile I and Cs fission products will returned to the fuel cycle because they can be readily solidified in chemical compound formations. The Kr-85 gas can be captured either in a clathrate form or preferably concentrated as a gas in storage tanks which can then be condensed into the free space of the zircaloy clad LWR fuel elements for return to the spallator and reactor for transmutation and decay. The reprocessing system be designed to totally recycle the longer-lived fission products. The black UO_2 powder is then chemically treated with a β-diketonate chelating agent. The zircaloy cladding will also be returned to hot refabricating for reuse in fresh fuel elements.

An alternate mechanical method of decladding can be used by chopping and leaching with the chelating agent. The chop-leach operation has been highly developed in the Purex system so it is well known. The advantages of chop-leach may be that contamination due to escape of dry particulates and volatiles will be less. This would eliminate the need for Airox and could be a distinct advantage in simplifying the process.

The β-diketonate chelating chemistry has been tried out in the laboratory for complexing and separating transuranics but has never been developed into a fuel processing scheme. The basic physical chemistry of the process is available in the literature and has been extensively used as an analytical procedure.(2) At present, it is visualized that the UO_2 powder from the Airox process will be contacted with the organic β-diketonate chelating agent at temperatures in the order of 100-200°C to extract most of the fission products and some transuranics, leaving the bulk of the uranium and plutonium undissolved. The metal complexing chelating agents have been successfully used in extraction of metallic ore bodies and analyzed by gas phase chematography.(2) It is proposed to develop this basic analytical procedure into a process which can extract and partition the TUs and FPs. The type of diketonate and the reaction conditions will be one of the major objectives of the proposed research and development task. This R and D will determine the feasibility and the process conditions necessary to obtain the optimum desired separation and partitioning of the non-radioactive (NRFP) stable and short-lived isotopes (SLFP) from the long-lived transuranics (TUs) and fission products (LLFPs). Once the organometallic compounds of the stable and short-lived fission products (SLFPs) are formed these compounds will be further separated and refined by distillation. Distillation is possible because of the widely differing vapor pressures and volatilities between the TUs and FP chelates.(2)

β-diketonate Chelating Process

One of the possible Chelating Agents (briefly referred to as fod) has the following structure:



$$(CH_3)_3\ C-\overset{O}{\overset{\|}{C}}-C-\overset{O}{\overset{\|}{C}}-CF_2-CF_2-CF_3$$

and is organically 6,6,7,7,8,8,8-heptafluoro-2,2-dimethyl-3,5-octanedione (briefly referred to as fod).

Thus, the chelating reaction of spent UO_2 fuel can be represented as follows:

$$UO_2 + FPs + TUs = UO_2 + TU(fod) + FP(fod)$$

Fod is a stable organic liquid which can be readily handled in the atmosphere. For process purposes, closed reaction vessels are preferred since elevated temperatures will be necessary. By extraction of the UO_2 and distillation of the organo-metallic chelate a separation and partitioning will be obtained, whereby stable (NRFP) and short-lived products (SLFPs) and the long-lived fission products (LLFPs) will be distilled out from the transuranics (TUs). The vapor pressures of the lanthanide chelates have values of over 10 mm Hg at 200°C while that of the uranium and plutonium chelates are as low as 10^{-3} mm Hg, thus the relative volatility is large ($\sim 10^4$) and a very large separation factor becomes possible. The fod reagent may be recovered by either extraction with another solvent or by hydrogen reduction. If these are not efficient, the chelated organo-metallic compound can be roasted back to oxide and the fluorine gas will be recovered for remaking the fod chelating agent. The detailed process chemistry has yet to be worked out in an R and D program. Even though the fod reagent may be expensive to make, because we are handling relatively small quantities of fission products, the cost per unit of power produced in the total fuel cycle is negligible. Actually fod is made from cheap organic materials, e.g. acetone, and propionic acid, and fluorine. The conversion of the fission products to the oxide can be presented by air-oxidation as follows:

$$\text{SLFP}(\underline{\text{fod}}) + O_2 = \text{SLFP} + O_2 + CO_2 + F_2$$

It is important to note that the organic chelating agent is stable in the presence of air and water to temperatures of more than 100°C. However, the radiation stability of the chelating agent must be determined. Some decomposition can be tolerated because of the relative low cost of the reagent in the total fuel cycle cost. It should be noted that fluorine substitution in the organic structure of the chelating agent increases the chemical and radiation stability of the compound. It must also be emphasized that fod is only one of a number of reagents of the β-diketonate class which can be used, so that there can be a large degree of flexibility in process design with this class of compounds.

The recovered uranium, plutonium, transuranic and long-lived fission products (Cs and Sr) are mixed together and fabricated back into a fuel pellet. In this fabrication procedure, makeup fertile and if desired, fissile fuel is added to the mixed oxide and then made into an LWR zircaloy clad fuel element. If U-235 from an enrichment plant is available this can be used to makeup fissile fuel. However, this would eventually deplete all the natural U-235 and the nuclear industry would then come to a halt unless a breeder reactor becomes available. It is preferred to have a Spallator makeup the fissile material inventory for assuring long-term fuel supply for an LWR power reactor economy. The Chelox process can also be applied to the breeder cycle, however, because of the advantageous LWR economics and safety considerations, a spallator supplying fuel to a number of LWRs is preferred.

THE SPALLATOR FOR FISSILE FUEL PRODUCTION

The Spallator employs a linear accelerator (LINAC) to generate a high energy proton (1 to 2 GeV) which impinges on a UO_2 target which produces spallation neutrons which can be absorbed in fertile material to produce fissile Pu-239.(1,5) The neutron yield is sufficient so that one 600 MW(e) beam Spallator can supply eight 1000 MW(e) LWRs with fuel throughout the life of the LWR power reactors. High energy and fast fission produce heat in the target which can be converted to steam to generate the electrical energy necessary to drive the accelerator. The Spallator is a self-standing machine. In contrast to the breeder, it neither producers nor does it consume power. It only produces fissile fuel for power burner reactors. The breeder is a dual purpose machine, whereas the Spallator is a single purpose machine.

The spallator consists of two major parts: a linear accelerator (LINAC) and a spallation target. Over the past 50 years the LINAC has been developed into a highly reliable and efficient research tool. Figure 1 shows the main features of the accelerator. There is little doubt that a high current (300 ma at 2 GeV proton) continuous wave (CW) production accelerator can be constructed at a reasonable cost.(5) The target is essentially a subcritical assembly resembling a power reactor without control rods. Figure 2 shows the target reactor design for the Spallator, and Table 1, the design characteristics and the production capacity of the Spallator. The basic neutron yield for a UO_2 target from spallation, and high energy and fast fission, has been assumed to be 70 neutrons per GeV-proton and is backed up by experiment and model calculations.(6) Table 2 gives an estimate of the Spallator cost and Table 3 shows a comparative cost analysis for 1) a Spallator providing fuel for 8 LWRs, 2) a conventional LWR economy without Pu recycle, 3) an LWR economy with Pu recycle, and 4) 5 breeders with 3 supported LWRs to provide a total equalized power generation of 8000 MW(e). The breeder has a doubling time of approximately 30 years. The Spallator/LWR economy indicates a 20% lower total lifetime capital investment than the breeder/LWR economy mainly because each breeder costs 70% more than each LWR and the inventory of fissile material for the breeder is considerably higher (2 times) than for the LWRs. It also appears that under todays cost assumptions the Spallator is even competitive with todays U-235 fed LWRs even with reprocessing. Besides being more economical, the Spallator allows the utilities to continue using LWR technology which has become well known, is safe and is licensable. The fast breeder reactor is a far cry from this position.

A flow sheet of the entire APEX process concept is given in the attached Figure 3. The Chelox fuel reprocessing scheme is shown in Figure 4.

A possible disadvantage that might be cited against the APEX system is that radioactively hot elements would have to be handled for loading into the reactor. However, this should not be so difficult since radioactive elements are handled when they are taken out of a reactor, so why can they not be handled when they are put into a reactor? Moreover, this would be an advantage from a proliferation point of view, because it would make diversion of hot elements much more difficult. It should also be noted that the non-radioactive (NRFP) and short-lived fission products (SLFP of <1 to 2 years half-life) are stored in tanks for periods in the order of 20 years to decay these isotope to background before disposing of them to the environment or placing them back into the U mines as stable non-radioactive waste (NRFP). These may be also uused for new stable isotope sources which are not available in nature.

Figures 5 and 6 show preliminary computer code calculations for recycling the transuranics and the Cs and Sr in accordance with the flowsheet shown in Figure 2. As can be seen, the TUs quickly reach equilibrium on recycling and also add fissile fuel in the normal way that a thermal reactor converts fertile to fissile fuel which then fissions and produces power. With internal fuel cycle storage of the Cs and Sr, these are decayed and reach near asymptotic values in the fuel cycle as given by a computer calculation shown in Figure 5. The neutron economy penalty in the LWR is small because of the small thermal neutron cross sections and limiting the concentration through decay in intermediate process storage vessels. Most of the conversion of the Cs and Sr is by means of the decay mechanism and a smaller portion is by transmutation through neutron absorption in the Spallator and LWRs. Any transumation will hasten the approach to an equilibrium concentration value for the LLFPs.

The above process concept can also be applied very advantageously to a thorium/U-233 fuel cycle. The Spallator would produce the U-233 inventory from natural thorium. Furthermore, since the conversion ratio in the U-233 LWR cycle is higher than in the U/Pu-239 LWR cycle, more LWRs can be supplied from each Spallator. There is also an advantage of the Th/U-233 fuel cycle in that no long-lived transuranics such as Pu-239 are formed.

The advantages of the APEX fuel cycle with Chelox reprocessing are several-fold as follows:

1. A non-aqueous fuel reprocessing system is proposed in contrast to that of the aqueous Purex process with all its difficulties of handling highly corrosive reagents.

2. We can afford to leave a small amount of stable fission products in the low concentration fissile fuel recycled so that high decontamination factors required of the discard stable waste product is more easily obtained. This is in contrast to the conventional Purex waste, which has to be sharply separated from the plutonium in order to maintain high Pu purity (a hold-over from weapons production). As a result, residual Pu-239 remains in the effluent waste. Additional decontamination of the waste by going through a second TBP extraction cycle is possible with Purex, but evidently, has not been found worthwhile for the weapons program or even for further cleanup of the waste for the civilian power program.

3. The temperature of the Chelox process is not very high reaching a maximum in the order of 400°C in the Airox process and probably not more than 250°C in the chelate process. As mentioned earlier, a chop and leach with the chelating agent may be a more advantageous alternate because of less particulate contamination and lower temperature reprocessing.

4. In conjunction with the Airox process, the bulk of the UO_2 does not have to be dissolved or chemically reacted with corrosive acids. In the complexing metal chelate system it also may be possible to leach out the stable and short lived fission products sufficiently without completely reacting the bulk of the UO_2 which mass-wise constitutes over 90% of the spent fuel material.

5. The handling of radioactively hot recycled fuel elements can be a deterrant to fissile fuel diversion for weapons. Additionally, remote handling of non-aqueous concentrated fissile material is easily accomplished versus remote handling of corrosive liquids and gases.

6. The entire process scheme supports a long term LWR economy so that, the electrical utilities do not have to learn a new technology or license a new type and more expensive reactor technology, e.g., the liquid metal fast breeder reactor (LMFBR).

7. The process system concept can be equally applied to uranium or thorium in an LWR fuel cycle economy, through the production of either Pu-239 from uranium or U-233 from thorium in the Spallator. A long term supply of fuel is available without the utilities worrying about developing a new type of reactor such as the liquid metal fast breeder reactor (LMFBR).

8. Only stable fission products are discarded as a waste so the public does not have to be concerned about long-term terrestrial geological-age storage of waste. There simply isn't any radioactive waste issuing from this system for any one to worry about.

Tables 2 and 3 list additional advantages of the APEX fuel cycle with Spallator fuel production and Chelox reprocessing. The system solves the problem of fuel supply and waste management for a long-term LWR power reactor economy. It is recommended that a research and development program be initiated to (1) develop the reprocessing chemistry of the organic chelating process, (2) develop in detail the entire APEX fuel cycle flowsheet design, and (3) make a realistic economic assessment.

It is realized that we are recommending a new approach for the nuclear industry which may take a good deal of development funds and a number of years to reach commercialization, however, it should take much less than the almost 40 years it took the US to get to the present position of the same unsolved problems of fuel and waste still facing us. Unless the nuclear industry takes a new approach and solves the problems the public perceives and recognizes indirectly, we may not have a nuclear industry to be concerned about. There is still some means and time for the country and industry to take a path divergent from the well-known path. We may find it to be a short-cut to establishing a firm nuclear industry. The APEX system with Spallator and Chelox appears technically sound and economically viable.

A final note of paramount concern. Establishment of a firm and expanding LWR economy will allow us someday to reduce the stockpiles of nuclear weapons by burning up the Pu in LWR burner power reactors. The LWR is the only device which can implement nuclear disarmament by burning up the plutonium now existing in nuclear weapons. A mutual US-USSR SALT III agreement to convert weapons Pu to civilian power fuel would be needed much like the Nuclear Test Ban Treaty. Fabricating LWR reactor fuel containing Pu weapons material fits in well with the APEX fuel cycle. This should help the world become a safer and saner place in which to live.

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TABLE 1

THE SPALLATOR

Accelerator Spallation Reactor

Production Capacity and Design Characteristics

P-Energy	2 GeV
UO$_2$/Zr Target, Neutron Yield	70 n/GeV-p
Current CW	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	75%
Pu^{239} Fissile Fuel Production Rate	2475 Kg/Yr
Fissile Fuel Needed for 1-1000 MW(e) LWR	300 Kg/Yr
No. of 1000 MW(e) LWRs Supported	8

TABLE 2

THE SPALLATOR

Accelerator Spallation Reactor

Capital Investment
1980 Dollars

Linear Accelerator = \$1000/KW(e) x 600 MW	=	\$600 x 10^6
Target = 1200 MW(e) x \$1000/KW(e)	=	1,200 x 10^6
Total Cost		\$1,800 x 10^6

TABLE 3

NUCLEAR ENERGY ALTERNATIVE SYSTEMS COMPARISON

Lifetime Capital Investment 1980 Dollars

		Spallator 1 S/8 LWRs	LWR No Recycle	LWR With Recycle	Breeder (LMFBR) 5 Breeder/3 LWR
No. of Reactors (1000 MW(e))		8	8	8	8
Capital Cost ($1000/KW(e))	LWRs	$\$8.0 \times 10^9$	$\$8.0 \times 10^9$	$\$8.0 \times 10^9$	$\$3.0 \times 10^9$
	Breeders	————	————	————	$\$8.5 \times 10^9$*
Capital Cost of Spallator		$\$1.8 \times 10^9$	————	————	————
Nat. U Feed (30 Yrs)		Negligible	48,000 MT	16,000 MT	Negligible
Enriched Fuel - MT U-235		————	216 MT (3.0%)	72 MT (33%)	————
Total Cost of Nat. U Feed at $40/lb		————	$\$3.8 \times 10^9$	$\$2.6 \times 10^9$	————
Cost of Enrichment		————	$\$2.6 \times 10^9$	$\$1.4 \times 10^9$	————
Fissile Material Inventory***		44 MT	42 MT	42 MT	66 MT
Fissile Inventory Cost at $40/gm		$\$1.8 \times 10^9$	$\$1.7 \times 10^9$	$\$1.7 \times 10^9$	$\$2.6 \times 10^9$
Cost of Reprocessing Plant**		$\$0.3 \times 10^9$	————	$\$0.3 \times 10^9$	$\$0.3 \times 10^9$
Cost of Fuel Fabrication Plant**		$\$0.3 \times 10^9$	Negligible	Negligible	$\$0.3 \times 10^9$
Cost of Waste Storage		Negligible	$\$1.2 \times 10^9$	Negligible	Negligible
Total Cost		$\$12.2 \times 10^9$	$\$17.3 \times 10^9$	$\$12.7 \times 10^9$	$\$14.7 \times 10^9$

* There is a projected 70% cost differential between a 1000 MW(e) LWR ($\$1 \times 10^9$) and a 1000 MW(e) LMFBR ($\$1.7 \times 10^9$);

** Estimated total cost of reprocessing plant is $\$1.5 \times 10^9$ for reprocessing fuel from 60 LWRs. Hot Fuel Fabrication Estimated to be Equal to Reprocessing.

***Fissile Material Inventory for 1 S/8 LWRs = 44 Kg (22 in core and 22 out-of-core) for 5 Breeder/3 LWRs 66 Kg (33 in-core and 33 out-of-core) - (1 LWR core contains 2.7 Kg; 1 LMFB core contains 5.2 Kg).

TABLE 4

ADVANTAGES OF APEX NUCLEAR FUEL CYCLE

- Produces long-term supply of nuclear fuel for the LWR power reactor economy.
- Produces initial reactor inventory for fuel cycle; either fissile Pu-239 from natural U-238 or fissile U-233 from natural Th-232.
- Eliminates need for long-term geological-age storage of radioactive fission product and transuranic waste.
- Eliminates need for enrichment plant.
- More economical than a fast breeder reactor (FBR) power and fuel cycle.
- Utilities need no new power reactor technology.
- The conventional LWR power reactor technology is sustained. No new licensing and safety procedures are required.
- Relatively low temperature, non-aqueous, non-corrosive, non-mechanical, reprocessing (Chelox) of fuel is employed.
- APEX uses near term technology. No need to demonstrate a scientific principal (e.g. fusion).

TABLE 5

APEX IS A SAFER ECONOMICAL AND MORE PROLIFERATION RESISTANT FUEL CYCLE

- ALL FISSILE MATERIAL IS MAINTAINED IN DILUTE FORM (<4%).
- INVENTORY IS THE LOWEST OF ANY FUEL CYCLE (LESS THAN BREEDER).
- THERMAL REACTORS ARE A KNOWN TECHNOLOGY WITH AN EXCELLENT SAFETY RECORD.
- SPALLATOR TARGET IS A SUBCRITICAL REACTOR.
- SPALLATOR PRODUCES FUEL ONLY ON DEMAND - IT IS A SINGLE PURPOSE MACHINE. LMFBR WHICH IS A DUAL PURPOSE MACHINE DELIVERS POWER AS WELL AS FUEL.
- THE SPALLATOR IS AN INDEPENDENT MACHINE - DECOUPLED FROM ANY POWER GRID UNLIKE LMFBR AND ENRICHMENT PLANT WHICH DEPEND ON THE POWER GRID.
- FISSION PRODUCT CONTAMINATION OF FISSILE MATERIAL IS ALLOWABLE IN CIVILIAN FUEL CYCLE. Pu FOR WEAPONS REQUIRES HIGH PURITY; CONTAMINATION OF Pu IS NOT ALLOWABLE RESULTING IN Pu CONTAMINATION OF FISSION PRODUCT WASTE.
- FUEL ELEMENTS IN AND OUT OF REACTOR ARE RADIOACTIVE, MAKING THEM MORE DIFFICULT TO DIVERT FOR PRODUCING WEAPONS MATERIAL - ALSO Pu IS ISOTOPICALLY CONTAMINATED MAKING IT A POOR WEAPONS GRADE MATERIAL.
- SPALLATOR IS A HIGHLY FLEXIBLE MACHINE.

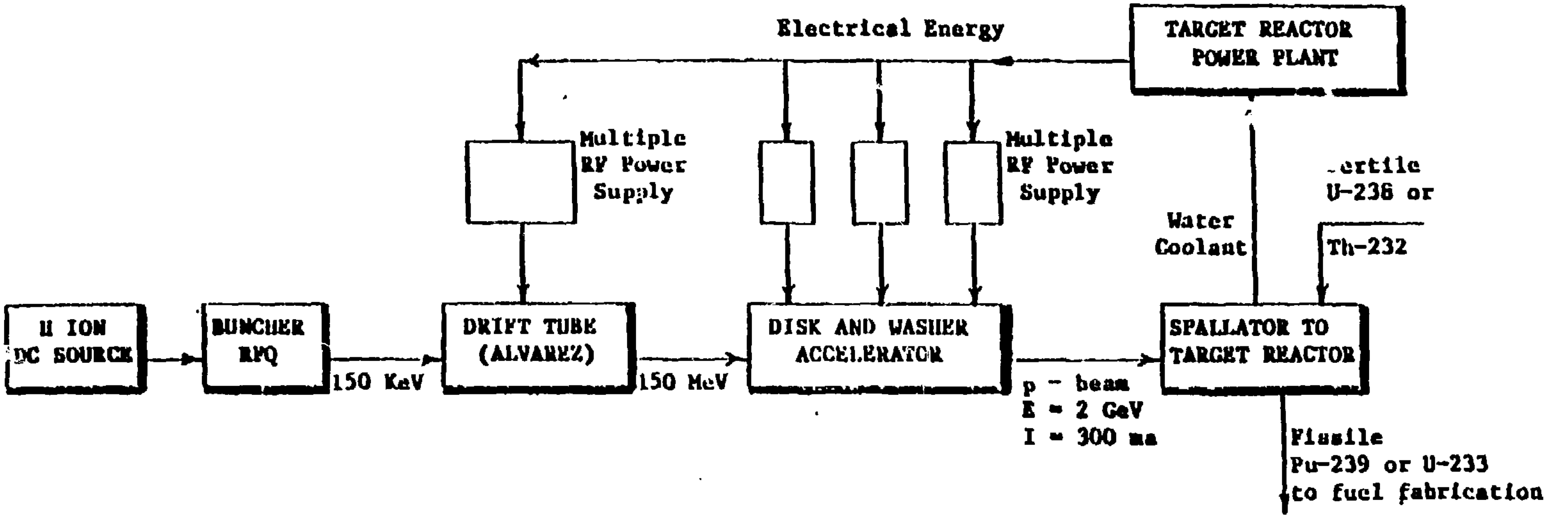
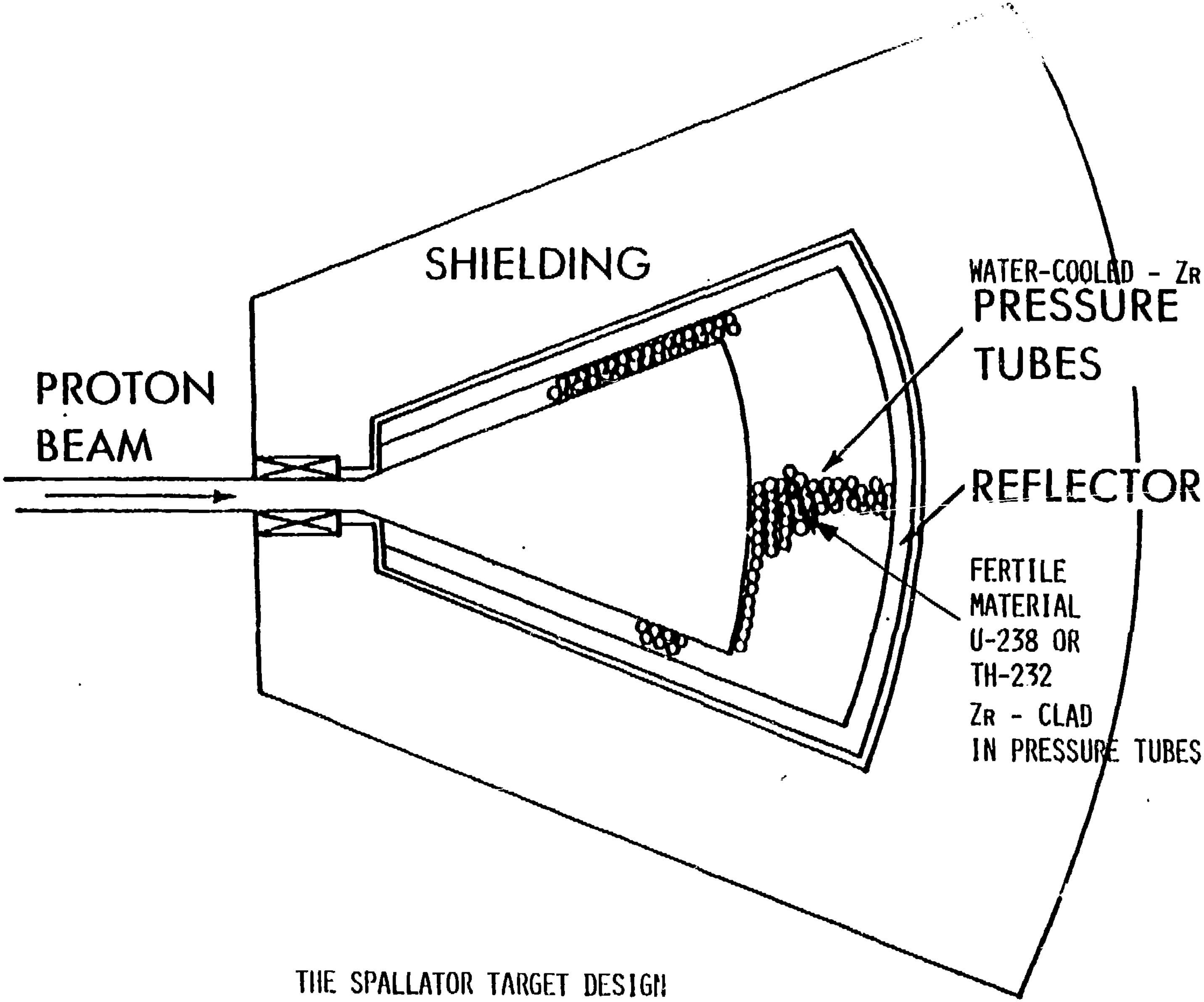
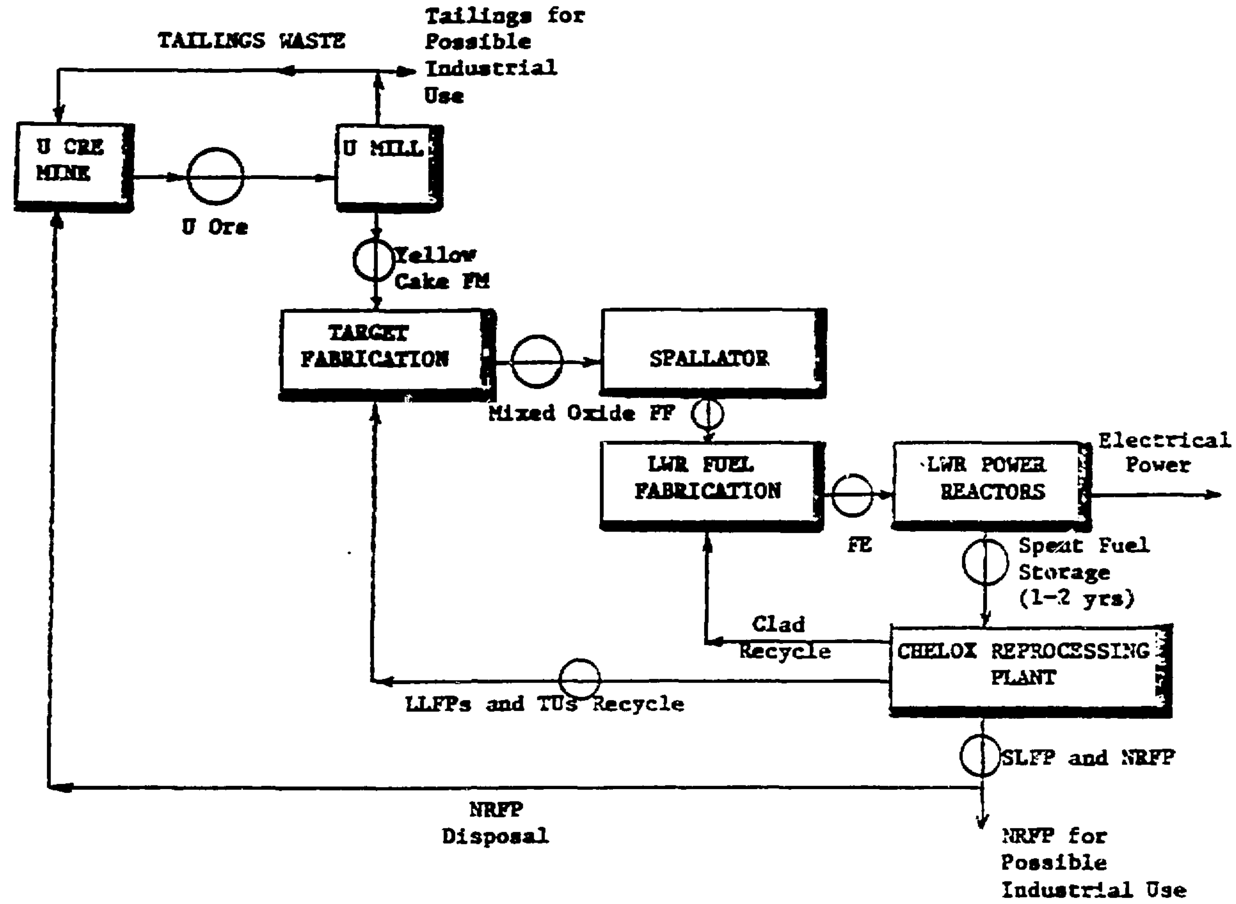


FIGURE 1

LINEAR ACCELERATOR (LINAC) FOR SPALLATOR



THE SPALLATOR TARGET DESIGN
FIGURE 2



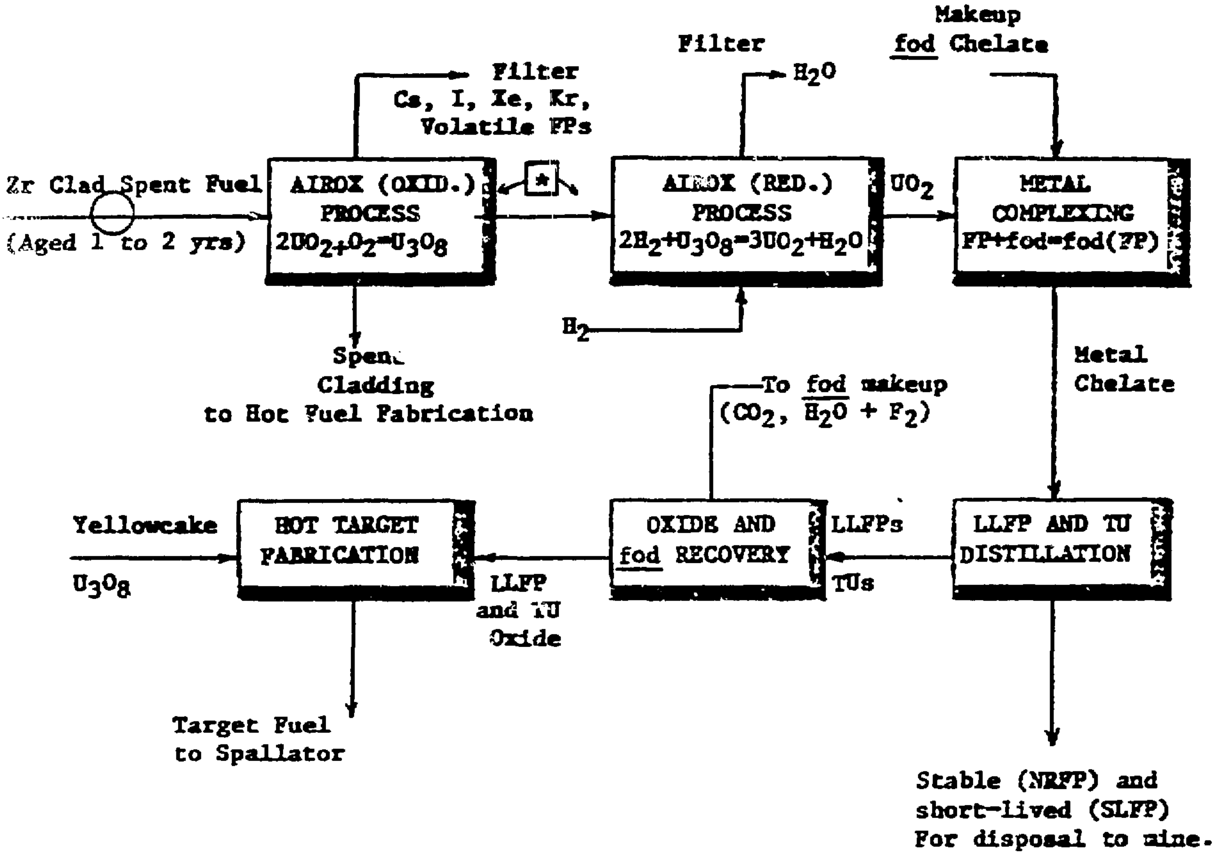
Legend

⊖- Storage
FM - Fertile Material (U-238)
FF - Fissile Fuel (Pu-239, U-235, TUs)
NRFP - Non-radioactive fission product
SLFP - Short-lived fission products (<2 yrs)
LLFP - Long-lived fission products (Cs, Sr, Kr, I, etc.) 2 yr.
TU - Transuranics (Pu, Am, Cm, etc.)
FE - LWR Fuel Element

APEX NUCLEAR FUEL CYCLE
for U/Pu fuel cycle

Includes 1) Spallator for generating Pu fissile fuel, 2) Chelox reprocessing for recycling radioactive waste, 3) LWRs for generating power and eliminates enrichment and need for long-term geological-age storage of long-lived radwaste. System can be modified for application to the Th/U-233 fuel cycle.

FIGURE 3



Legend

[*] - alternate process - decladding by chopping and leaching with β-diketonate reagent

fod - fluorinated β-diketonate

FM - ferile material (U-238 or Th-232)

FF - fissile fuel (Pu-239, U-235, U-233 and TUs)

NRFP - non-radioactive fission products

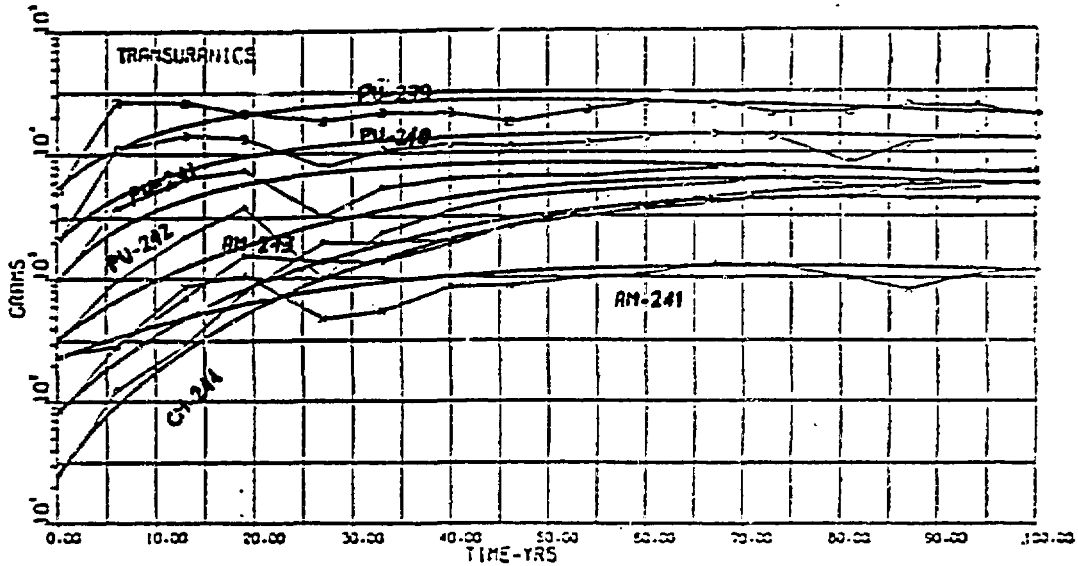
SLFP - short-lived fission products (<2 yrs)

LLFP - long-lived fission products (>2 yrs)

TU - transuranics

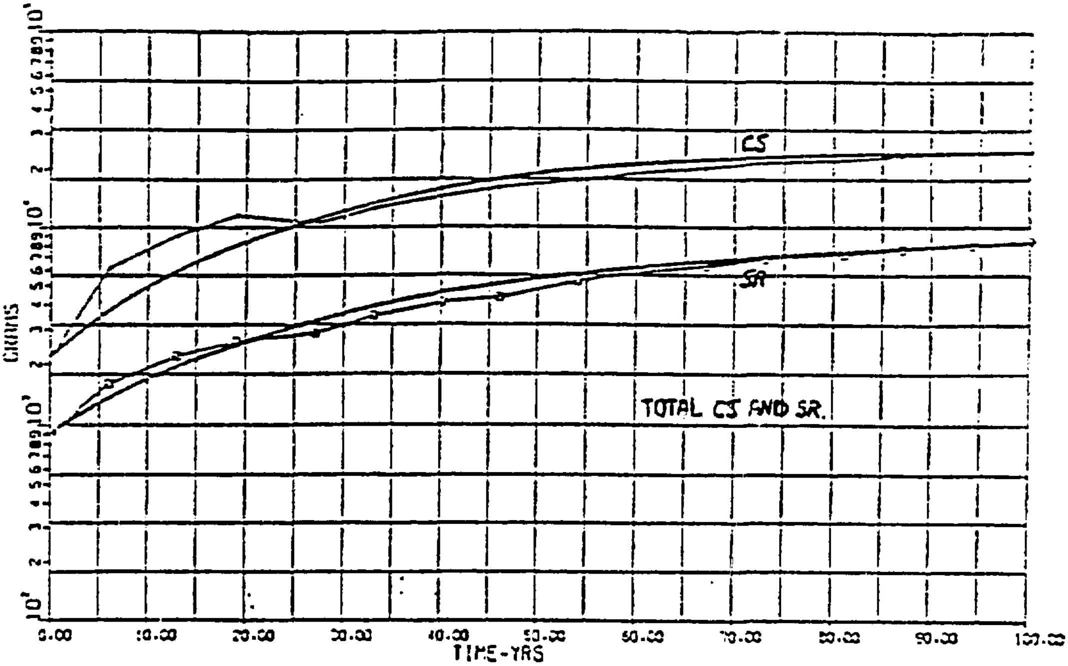
CHELOX FUEL REPROCESSING SYSTEM

FIGURE 4



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

FIGURE 5



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

FIGURE 6