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The Benefits of an Advanced Fast Reactor Fuel Cycle for Plutonium Management

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Abstract

The United State has no program to investigate advanced nuclear fuel cycles for the large-scale consumption of plutonium from military and civilian sources. The official U.S. position has been to focus on means to bury spent nuclear fuel from civilian reactors and to achieve the spent fuel standard for excess separated plutonium, which is considered by policy makers to be an urgent international priority. Recently, the National Research Council published a long-awaited report on its study of potential separation and transmutation technologies (STATS), which concluded that in the nuclear energy phase-out scenario that they evaluated, transmutation of plutonium and long-lived radioisotopes would not be worth the cost. However, at the American Nuclear Society Annual Meeting in June, 1996, the STATS panelists endorsed further study of partitioning to achieve superior waste forms for burial, and suggested that any further consideration of transmutation should be in the context of energy production, not of waste management.

The U.S. Department of Energy (DOE) has an active program for the short-term disposition of excess fissile material and a "focus area" for safe, secure stabilization, storage and disposition of plutonium, but has no current programs for fast reactor development.

Nevertheless, sufficient data exist to identify the potential advantages of an advanced fast reactor metallic fuel cycle for the long-term management of plutonium. Some of the key advantages are:

1. Tens of tonnes of plutonium could be quickly secured in a single reactor system.
2. Use of a metal alloy fuel would allow economic fuel recycling at any scale to match the energy production requirements.
3. All actinides would remain in the fuel cycle, out of the waste stream.
4. Throughout the fuel cycle, the plutonium would remain in a highly radioactive environment equivalent to the spent fuel standard.
5. The net rate of plutonium consumption could be controlled to meet future energy requirements.
6. Because all actinides fission in the fast spectrum, the more radiotoxic transuranic isotopes would not build up as they do in a thermal spectrum.
7. Specific fission products would be partitioned into the waste forms in which they would be most stable for disposal.

Introduction and Background

It is now widely accepted that rigorous active management of plutonium is a matter of highest priority [Ref.1]. Stores of separated plutonium require severe physical protection and accountancy to protect against diversion, and to provide timely warning should there be any attempted diversion. Plutonium which is intimately intermixed with highly radioactive materials ("self-protecting") requires a lesser but still a significant degree of physical protection and accountancy, in that a variety of technologies are available and known by which plutonium can be chemically separated.

Internationally agreed priorities are to assure physical protection and accountancy for separated plutonium on an urgent basis, and to provide a web of protection to detect and deter any attempt at an unauthorized program for the chemical separation of plutonium which is now in a self-protecting condition. These measures are generally considered to be capable of providing protection against diversion for the next few years or perhaps decades. Ultimately, a more permanent means of dealing with world accumulations of plutonium must be developed and deployed [Ref. 2].

Given the difficulty in defining an acceptable means of storing plutonium for the millennia necessary for radioactive decay, destruction by fissioning must be considered as an environmentally attractive means for dealing with plutonium. The energy release generated by the fission process creates the prospect for this to be not only environmentally attractive but economically sound. It is this possibility that this paper addresses.

No technology, regardless of its benefits, is without its risks and liabilities, and we must address risks openly and frankly; not just the benefits of various strategies and technologies. For this, we would like to begin by describing the magnitude of the problem as we understand it, and the principal risks and concerns.

Current world holdings of plutonium amount to over 1000 tonnes and are growing at 60 to 80 tonnes per year [Ref. 3]. According to some estimates, several hundred tonnes exist as separated plutonium. We will take it as given that plutonium can be stored and used in peaceful applications without endangering either humans or the environment. The precautions are demanding, but are well within the capabilities of existing technologies. It is outside the scope of this paper to discuss the state of technology for environmentally safe and responsible geological disposal of plutonium. The risks under discussion here therefore are those associated with misuse of the material.

Two misuse scenarios can be postulated: dispersal of plutonium by chemical or other means, and use as a nuclear explosive. For the first, even reasonably small quantities are of concern, and purity is not an issue; the dirtier the better. The direct physical consequences of such an event would be modest [Ref. 4], but could result in massive property and psychological damage. Given the world inventories of radiological wastes and spent fuel, this is a concern which must be addressed regardless of the process that is ultimately adopted for plutonium disposition or consumption.

The opinions expressed in this paper are the technical opinions of the authors, and do not represent an established position of Argonne National Laboratory, the U. S. Department of Energy, or of the U. S. Government.

The second scenario is more complex, and is the subject of much mis-information. Plutonium can only be used to make a nuclear explosive with an implosion device [Ref. 5]. We consider the technology for implosion type weapons to be beyond the capability of terrorist and sub-national groups. If there were to be a terrorist-developed nuclear explosive device, it would almost certainly be based on highly enriched uranium, not plutonium. Diversion by a sub-national group is of concern only because of the potential for it being used in a dispersion type device.

For a technologically advanced country, it is evident that development or expansion of a nuclear weapons capability can be greatly facilitated by improved access to plutonium. For such countries, there are easier ways to accumulate significant stores of weapons-usable plutonium than to separate it from spent commercial reactor fuel; recent incidents suggest that the route of separation is subject to detection in time to permit diplomatic intervention. Diversion of significant stocks of separated plutonium is most likely to be detected at the source, but until complete and secure protection is provided for all separated plutonium, diversion remains as a plausible route for obtaining or augmenting national stocks of separated plutonium.

Based on this perspective, there are two overriding conditions to be addressed when discussing final and permanent disposal of plutonium: minimizing the exposure of separated plutonium to diversion, and assuring a degree of active management and accountancy for large stocks of non-separated plutonium.

The most effective way to minimize the exposure of separated plutonium to division is to minimize the world inventory of separated plutonium [Ref. 6]. Ideally, plutonium would not be separated until there is an immediate use for it. The only effective long term way to assure active management of non-separated plutonium is to consume the plutonium by way of a fission process; there is then no non-separated plutonium to manage and account for.

External Factors

There are clearly external factors which will ultimately influence choices, and which are in fact likely to be decisive. Dominant among these are the need for energy and the ability of nuclear energy to compete economically with alternatives [Ref. 7]. This in turn will depend at least in part on the availability of nuclear and other energy supply resources. Political prejudices with regard to nuclear power may also be a significant factor in some situations. These considerations are outside the scope of this paper.

Schedule Realities

There is no existing industrial infrastructure available to consume or otherwise permanently dispose of the world's inventory of plutonium. On an energy basis, fissioning of one tonne of any material yields enough energy to produce approximately one GW-year of electricity, so the several hundred

tonnes of separated plutonium will involve a significant industrial commitment. While various wartime emergency programs of this general scale have been completed in a few years, it is generally accepted that the development of an appropriate technology, followed by the preparation of the required industrial infrastructure will require several decades.

The U.S. Policy Position

The U.S. policy is addressed at reaching a stable plateau of world inventories of separated plutonium as quickly as possible. To this end, the U.S. has active programs underway to assist in assuring adequate physical protection for existing stocks of separated plutonium, and is actively working to discourage separation (reprocessing) of spent nuclear fuel where there is no established end-use. This priority is based on the recommendations of an august panel of experts [Ref. 2], with detailed programs outlined in a published Draft Environmental Impact Statement [Ref. 8].

The Physics of Plutonium Consumption

The basic physics of plutonium consumption is well understood by specialists, but is frequently not stated clearly when discussing overall strategic alternatives. The basic principles which we consider relevant and significant for this discussion are the following:

- The only way to destroy plutonium is to cause it to fission all other disposition options amount to storage;

- Transmutation of Pu-239 to a mix of higher plutonium isotopes greatly diminishes attractiveness of the material for weapons use, but does not totally eliminate the potential for misuse[Ref. 9]. Nuclear explosives involve fission by fast neutrons, and all plutonium isotopes are fissionable by fast neutrons. However, material containing mixed isotopes of plutonium are far less attractive because of handling complications associated with the radioactivity of the higher isotopes, and because of their heat generation[Ref. 10]. It may become possible in the future, with advanced techniques, to do an effective isotopic separation, in which case material containing mixed isotopes of plutonium would be, from a safeguards point of view, no better than other means of providing for "self-protection";

- No fission process is complete; there will always be some neutron capture and transmutation to higher mass transuranic elements. As with higher plutonium isotopes, these higher transuranics are fissionable with fast neutrons. In general, the heat and radiation from these materials provides a high degree of self-protection;

- The fission process in a fast reactor provides sufficient excess neutrons that, with multiple recycle, total consumption of all isotopes and any higher actinides produced can readily be accomplished. Some concepts for plutonium consumption in a thermal spectrum rely on a feed stream of

additional thermally fissionable material (i.e. U-235, Pu-239 or Pu-241). Providing excess neutron to subcritical systems, such as spallation sources from impacting an accelerated particle beam onto a heavy material target, is also feasible. The physics of each of these processes is well known and well demonstrated;

- To achieve total destruction, it is not possible to rely on the physical stability of the material being destroyed. In practice, this means the plutonium must either be reformulated (recycled) or be in a form where structural integrity is not a requirement; e.g. a fluid or slurry.

- Any system which consumes plutonium based on neutrons generated by the plutonium fission itself can only asymptotically achieve total consumption;

- In a reactor situation (i.e., no external source of neutrons), any system which burns plutonium without producing new fissile material will require a wide band of reactivity control.

How the Fast Reactor Approach Addresses the Fundamental Disposition Requirements

The goal of elimination of plutonium implies that essentially all transuranic materials be fissioned - none left as waste for disposal. Total consumption can in principle be accomplished only in a fast neutron spectrum, or with an external source of neutrons.

The fission of an actinide atom (i.e., atomic number greater than or equal to 89) gives rise to two fission-product atoms, the release of about 200 MeV of energy (approximately 1 MW-day of heat is released per gram fissioned), and the release of two or three neutrons (average about 2.5). To consume the plutonium without an external supply of neutrons, each transuranic atom fissioned uses one neutron to sustain the chain reaction into the next fission generation. In addition, there is unavoidable neutron capture that causes parasitic transmutation of Pu-239 and higher-mass transuranic isotopes, which build to steady state during long exposure to the neutron flux. Illustrative steady-state transuranic inventories which would result from very long exposure to fast and thermal neutron flux are shown in Table 1. In practical designs, still further neutron losses occur from capture in structural materials and leakage from the system. The greater the burnup per cycle, the more fission products there are which compete for excess neutrons.

Table 1. Equilibrium Distribution of Transuranic Isotopic Masses for Thermal and Fast Neutron Spectra.

Isotope	Thermal Neutron Spectrum	Fast Neutron Spectrum
Np-237	5.51	0.75
Pu-238	4.17	0.89
Pu-239	23.03	66.75
Pu-240	10.49	24.48
Pu-241	9.48	2.98
Pu-242	3.89	1.86
Am-241	0.54	0.97
Am-242m	0.02	0.07
Am-243	8.11	0.44
Cm-242	0.18	0.40
Cm-243	0.02	0.03
Cm-244	17.85	0.28
Cm-245	1.27	0.07
Cm-246	11.71	0.03
Cm-247	0.75	2.E-3
Cm-248	2.77	6.E-4
Bk-249	0.05	1.E-5
Cf-249	0.03	4.E-5
Cf-250	0.03	7.E-6
Cf-251	0.02	9.E-7
Cf-252	0.08	4.E-8

Note: All values are atom % of transuranic inventory built up as a result of extended exposure to a neutron flux. (Calculated as the steady-state solution of the depletion-chain equations–independent of criticality considerations.)

The number of neutrons per fission lost to parasitic capture in the transuranics under steady-state conditions can be determined from their capture and fission probabilities; typically, with no fission products present, this is about 0.25 in a fast neutron spectrum and 1.25 in a thermal spectrum. As shown in Fig. 1, for transuranic isotopes the probability of fission relative to parasitic capture is much lower for the thermal neutron spectrum characteristic of a light-water-cooled reactor (LWR) than for the fast neutron spectrum characteristic of a liquid metal cooled reactor (LMR). Indeed, the even-mass-number transuranic isotopes generally do not fission in a thermal neutron spectrum. Thus, in the fast-neutron system a *minimum* release of 1.25 neutrons per fission is required to sustain the steady state, while in a thermal-neutron system at least 2.25 are required. Each actinide fission

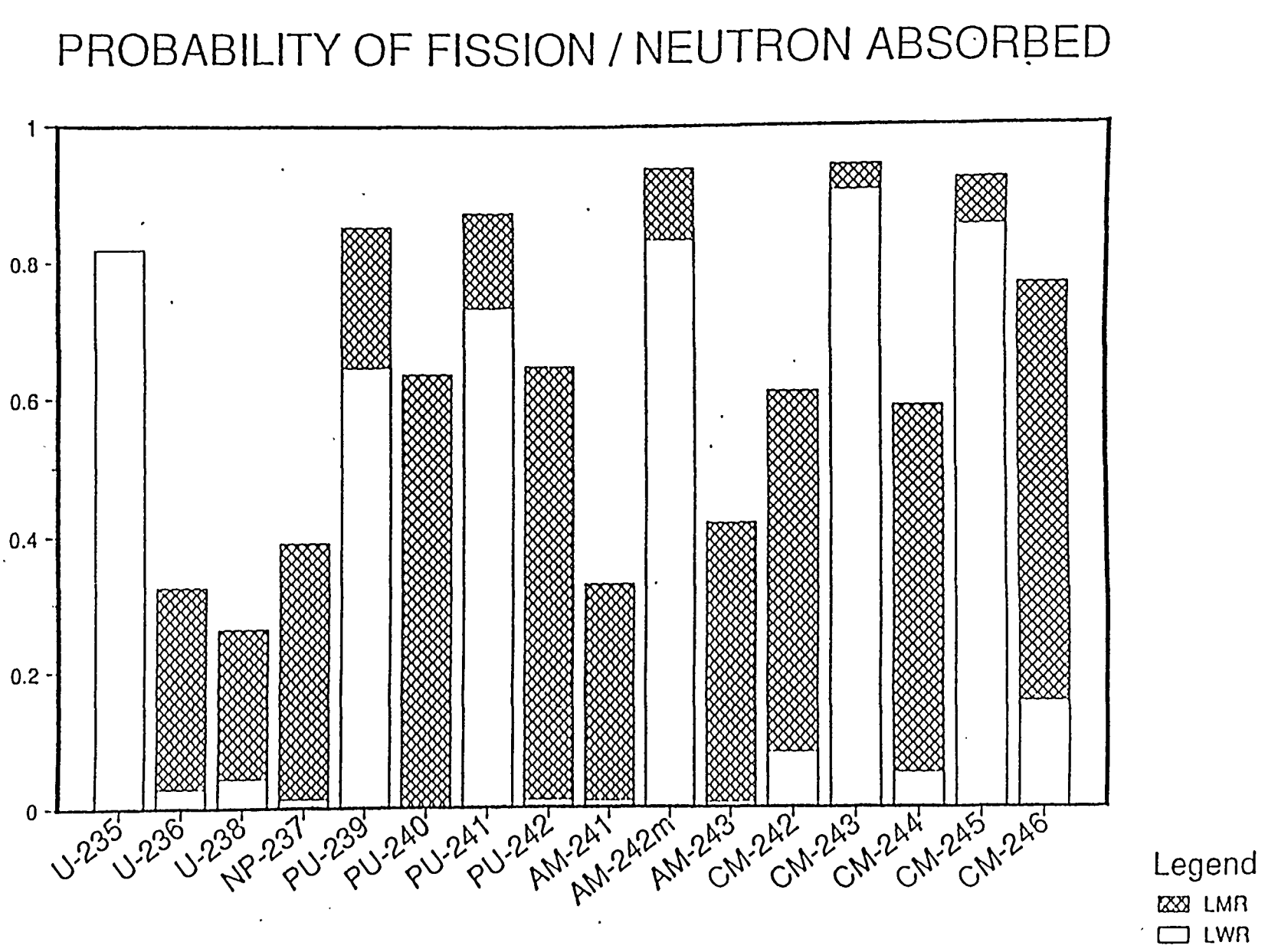

Figure 1: Probability of Fission/Neutron Absorbed

releases only about 2.5 neutrons, so a modest margin exists for a thermal reactor prior to building of a large inventory of fission products, while in a fast reactor there are sufficient neutrons to generate excess plutonium to accommodate vary high burn up, or to give the designers considerable flexibility.

With a fast reactor, the recycle frequency is determined solely by structural considerations, not by the physics of the situation. With a demonstrated 20% burn-up capability for metallic fast reactor fuel elements, this clearly reduces the number of cycles necessary to achieve an effectively total consumption. For a thermal reactor, the simple neutron balance limits the exposure of multiple recycle plutonium based on criticality requirements. Given the feasibility of each of these approaches, We would maintain that from a strictly physics point of view, the fast reactor has a significant advantage in flexibility over thermal reactors.

Recycle Considerations

Practical engineering considerations have led reactor designers world-wide to use solid fuel elements. With solid fuel elements, multiple recycle of fuel is required because of irradiation damage to structural materials. To avoid unacceptable losses to wastes, recycle must be essentially complete. Certain accelerator driven concepts have proposed using a molten salt carrier for the plutonium, but the technology for such a system is not yet proven, and various on-line chemical processes which amount to recycle are also generally required.

Recycle technologies enter the discussion in two quite unrelated ways. From a proliferation point of view, the critical questions are: does the recycle process involve separated plutonium that is attractive for weapons use. And how difficult is it to provide an adequate base of safeguards for both intermediate and final products of the recycle stream? These are precisely the two overriding conditions which we identified in the introduction as needing to be addressed when discussing final and permanent disposal of plutonium.

Because of the limited neutronic margins, thermal recycle requires a clean Pu recycle product, which is generally assumed to come from a PUREX type process [Ref. 11]. This clean product plutonium is suitable for use in a broad range of thermal reactors, but falls directly into the class of materials classified as "weapons-usable." The content of higher isotopes, and therefore the degree of attractiveness, depends on the feedstock, and not on the process. Stringent, real-time safeguards are employed to prevent diversion and to detect attempted diversions.

The AIROX process [Ref. 12], involving cleanup of LWR fuel for further use in a CANDU type reactor, avoids this concern but involves only a modest further consumption, and does not approach elimination unless followed by a more traditional recycle process.

The real advantage of the fast reactor system is its tolerance for direct use of self-protecting fuel; that is, a recycle technology can be used which does not remove all fission products. By utilizing a process which emphasizes the total recovery of all transuranics at the expense of having only a

moderate capability for fission produce removal, it is possible to reduce waste burdens dramatically, and simultaneously to avoid the added burden of providing rigorous safeguards for direct-use material[Ref. 13].

Managed Inventories

At first blush, the concept of using a fast reactor to consume excess plutonium may sound like an oxymoron; after all, the traditional purpose of the fast reactor was to produce excess plutonium to fuel new reactors in an ever-expanding economy [Ref. 14]. But, in fact, a fast reactor produces less net plutonium than does a light water or gas cooled reactor, since it gets essentially all its power from fission of plutonium, not uranium. A light water reactor typically produces 200 to 250 kg of plutonium per GWe reactor year. The nature of a fast reactor closed fuel cycle can be to produce plutonium at the rate at which it is needed for use, but only as there is a *near-term* need for it. In fact, practical designs (see for example Ref. 15) are best suited to operating on a break-even or near-break-even basis, wherein the plutonium acts simply as a catalyst, allowing power production from the backlog of depleted uranium left over from the enrichment process. Given appropriate safeguards, this means that the plutonium inventory can be tailored to the power demand and not, as with the LWR, continually increasing the waste burden.

A fast reactor can be configured to have a conversion ratio anywhere from 0.5 to as high as about 1.3. This large range of performance is precisely what is needed for managing the world's burden of transuranics. Region by geographic region, it allows the amount of plutonium and other transuranics to be held constant (conversion ratio = 1), or to increase (conversion ratio >1) in response to energy requirements. Similarly, existing transuranic inventories could be reduced in an ecologically responsible manner by using core loadings that consume (conversion ration <1) the working inventories of decommissioned sibling units. In this way, the fast reactor fuel cycle allows the transuranic working inventory to be matched to power demand, so that essentially no transuranics are consigned to long-term storage or waste [Ref. 16, 17], and the transuranics are always tied up in the power-producing working inventory.

Figure 2 shows the expected growth in world inventory of plutonium, based on official projections of future nuclear capacity through 2030 [Ref. 18], extended with an assumed linear growth in nuclear capacity from 2030 to 2045 equal to that between 2020 and 2030, and zero growth beyond 2045. The upper two curves show that there is some benefit (reduction in plutonium surplus) from thermal reactor recycle as is being practiced in France [Ref. 19] and as is proposed for Russia [Ref. 20]. The third curve in Fig. 2 is for strategy in which fast reactors are introduced at the following rate:

2010 to 2015:	1 GWe/y
2015 to 2020:	2 GWe/y
2020 and beyond:	all new nuclear power plant construction

The nuclear power capacity is the same as the LWR case. By 2045 all plutonium is in use. The figure demonstrates the fundamental advantages of the fast reactor fuel cycle relative to a throw-away or thermal recycle strategy:

- The world inventory of plutonium can all be put in use in working inventory within a credible planning horizon;
- the inventory can be realistically adjusted to match demand on a near-real-time basis;
- the inventory in all cases is less than that of a throw-away or thermal recycle strategy;
- inventory reduction is a feasible alternative if preferable energy sources become practicable.

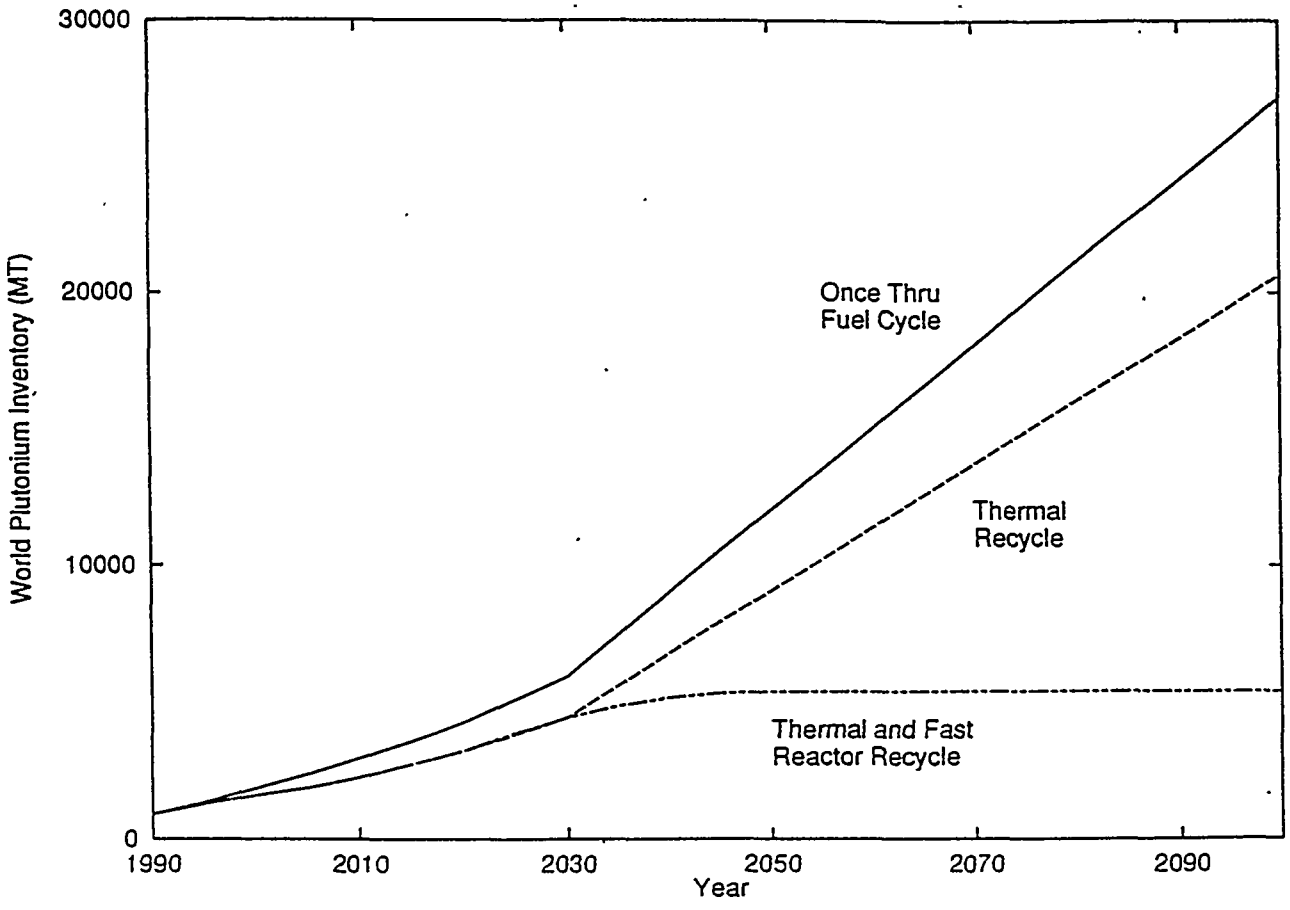

Figure 2: The Effect of Recycle on World Inventories of Plutonium

In short, for all fast reactor scenarios and at all times, transuranic inventory consigned to waste is maintained at essentially zero, and the worldwide transuranic inventory is contained entirely in the working inventories of power-producing fast reactor plants, which ebb and flow with time according to local needs. The revenue stream provides an income to support rigorous safeguards. Thus, rather than steadily growing with no further energy benefit, as is happening today with the once-through LWR throw-away cycle, the world's inventory of transuranics would grow or shrink along with the need for power, and future generations will not have to safeguard a burden of transuranics in spent-fuel storage pools or repositories as a legacy of their predecessors' energy policies.

From a proliferation point of view, the objective should be to leave a residue in the waste stream of no more weapons attractiveness than natural uranium; that is, some small fraction of a percent plutonium. It appears that electrorefining will do far better than this, not only preventing the waste stream from being a long term proliferation concern, but also greatly simplifying the waste disposal concerns. The electrometallurgical recycle technology is designed to discharge less than on part per thousand of the recycled transuranic fuel into the waste -- thereby eliminating any significant actinide contribution to long-term waste radiotoxicity hazard.

Unlike conventional reprocessing using PUREX technology, which emphasizes multi-step melt separation of plutonium to a purity of about one part-per million, electrorefining recycling technology simply concentrates plutonium in a metal alloy of uranium, transuranics, and rare earth fission products. An alloy containing no more than 70% plutonium is the practical limit of product purity. Subsequent process steps partition the fission products into the waste stream while recycling the residual actinides in the electrorefining process fluids. Because there is no need for a pure product for fast reactor fuel, emphasis can be economically placed on producing a relatively pure (actinide-free) waste stream. Because the process fluids are chloride salts and molten metal instead of organic solvents, there is no radiation damage limit to their recycling.

At some level, most of the metal fuel cycle has been demonstrated. Excellent performance of uranium alloy fuel has been demonstrated, although additional testing of U/Pu/Zr alloy would be required before it could be licensed. Uranium electrorefining of spent metallic fuel is currently being demonstrated, although transuranic partitioning has been dropped. An integrated program to qualify the electrorefining waste forms for geologic disposal is currently under way. It would take approximately five additional years to complete development of the metal fuel cycle for large-scale destruction of plutonium.

Radiotoxicity Legacy

The radiotoxicity hazard of the short-lived fission products decays to below that of uranium ore within 500 years -- a time span comparable to demonstrated longevity of human engineered structures and societal institutions. Sequestering the radiotoxicity hazard of the short-lived fission products in a storage repository for 500 years is well within the realm of demonstrated human achievement.

The several cycle MOX recycle option in thermal reactors in no way would preclude subsequent further recycle to total fission consumption in fast burner reactors. The choice between starting with thermal MOX recycle with subsequent fast burner reactor deployment versus starting immediately with fast burner reactors can be made country-by-country on the basis of existing infrastructure, timelines, and cost effectiveness. Whichever choice is made, in the end the long-term radiotoxicity hazard from actinides -- in contrast to being consigned to the stewardship of future generations -- is instead held in the working inventory of the fast burner reactor and its associated recycle equipment.

The case considered presumes a continued deployment of nuclear power. The situation is different if we assume an early, universal phase-out of the use of nuclear power. In this instance, the case for the fast reactor is less clear. The U.S. National Academy of Sciences has recently concluded a study on the potential benefits of separation and transmutation technologies for dealing not only with excess plutonium, but also the transuranics and long-lived radioisotopes in spent nuclear fuel under the assumption of a prompt phase-out of nuclear power [Ref. 21]. The study discussed fast reactor systems, thermal reactor systems, and accelerator transmutation devices. The conclusion was that transmutation could not be justified on the basis of improvement in performance of the first repository, primarily because the risk of any fuel cycle, including the once-through, is so minuscule that substantial investment to introduce new technology simply for waste management could not be justified. However, the report emphasized the potential benefit of advanced separations technologies for the purpose of making better waste forms for the long-lived radioisotopes, and accordingly encouraged a focused research and development program with emphasis on improved separations processes.

Description of a Fast Reactor System for Plutonium Management

Any fission reactor "burns" plutonium at the same rate, roughly 1 gram of plutonium fissioned per MWt-day of energy produced. However, all conventional reactor systems utilize fuel which is primarily uranium; thus, the destruction of plutonium is at least partially compensated by in-situ production of Pu-239. The available range of destruction/production characteristics in fast reactor cores provides for flexibility in plutonium inventory management strategy. Conventional fast reactors maintain or can even increase the plutonium inventory (conversion ratio of 1.0-1.3). Alternately, by removing fertile material and/or altering the neutron balance, the transuranic inventory can readily be reduced.

Plutonium management characteristics have been evaluated for a wide variety of fast reactor core configurations and fuel cycle strategies. Traditionally, the focus was on the plutonium breeding potential of the system based on a perceived need for a quickly expanded energy economy. However, in recent years there have been numerous studies addressing the design and implementation of fast reactor burner systems. These studies include evaluations of the basic physics of higher actinide transmutation [Ref. 22, 23], the design for core flexibility within the same reactor system[Ref. 15], the development of burner designs which optimize a specific performance parameter (e.g., low sodium

void worth) [Ref. 24, 25], the impact of weapons-plutonium introduction[Ref. 26], and radiotoxicity evaluations of closed cycle fast reactor systems [Ref. 27].

To illustrate the capabilities of an advanced fast reactor fuel cycle to operate in a plutonium destruction mode, the performance characteristics of a typical fast reactor burner design will be reviewed. By using a core design with a conversion ratio less than one, the inventory is gradually consumed through repeated recycle; and an external feed of makeup fissile material is required. For this paper, the moderate burner design developed in Ref. 25 will be utilized. These moderate burner core designs are also referred to as "conventional burner" designs because they utilize conventional fuel enrichments. The minimal conversion ratio of conventional burners is roughly 0.5; further reductions in the conversion ratio would require higher enrichment levels. Pure burner designs (where all uranium is removed) were also investigated in Ref. 26; however, unfavorable changes in the safety behavior were observed for such systems.

The moderate burner core design has a power rating of 840 MWt as used in the Advanced Liquid Metal Reactor (ALMR) U. S. design project [Ref. 15]. Radial and axial blanket zones are eliminated to avoid Pu-239 production. The resulting homogeneous core layout is shown in Fig. 3; this core consists of 354 driver assemblies (two enrichment zones), 28 control assemblies, 12 special control elements and 3 alternate shutdown assemblies. A geometry with a short core height (46 cm) compared to a large core diameter (4.44 m) enhances the axial leakage of neutrons which reduces the conversion ratio. An operating cycle length of 12 months (at an assumed capacity factor of 85%) is applied, with a seven batch refueling strategy.

In Ref. 25, the nuclear and safety performance characteristics of this moderate burner design were evaluated in detail for three alternative feed streams (weapons-plutonium, recycled fast reactor transuranics, and recycled thermal reactor transuranics) and two different fuel cycle scenarios (startup and repeated recycle). For the illustrative purposes of this paper, the case with closed recycle within the fast reactor system and an external makeup feed of recycle LWR transuranics is chosen. The performance characteristics are summarized in Table 2.

The 840 MWt fast reactor burner design produces 260,000 MWt-days of energy each year. The core operates at a conversion ratio of 0.5 making it a net consumer of 124 kg/y of transuranics. Thus, an external feed of 124 kg/y of recycled LWR or weapons transuranics is required in addition to the 543 kg/y of transuranics recycled within the closed fuel cycle. The in-core inventory is 4.3 MT of transuranics. The fuel enrichment is at the upper limit of current fast reactor experience, namely 30-35% transuranics/heavy metal. Most of the neutronic performance parameters (power density, discharge burnup, etc.) are similar to current fast power reactor operating conditions; however, the burnup reactivity loss is significantly higher than conventional designs since the internal blankets have been removed.

The burner designs has a large burnup reactivity loss (>$7) and correspondingly large control rod worth. However, the moderate burners has been designed to significantly decrease the sodium void worth and enhance the radial expansion feedback as compared to conventional systems. The net result

is that transient response will be similar to conventional systems where the passive feedback is quite favorable. Thus, the detailed evaluation in Ref. 25 concludes that moderate burner fast reactor core designs have performance characteristics which are comparable to conventional fast reactor cores. In addition, it was shown that alternative feed materials (e.g., weapons plutonium) can be utilized in conventional burners without adversely impacting their performance.

In summary, moderate burner designs (with a conversion ratio near 0.5) will exhibit performance characteristics similar to conventional fast reactor core designs. A 840 MWt moderate burner produces 261 GWt-days of energy each year and consumes 125 kg of transuranics. The in-core inventory of transuranics is 4.3 MT with a similar amount retained in the closed fuel cycle processing facilities.

Table 2: Illustrative Reactor Characteristics

Conversion Ratio[a]	0.490
Net TRU Consumption Rate, kg/y	124
Enrichment, wt.%TRU/Heavy Metal	29/36
Heavy Metal Inventory, MT	
Transuranics	4.28
Pu-239	1.71
Total Heavy Metal	13.90
Equilibrium Loading, kg/y	
Make-up TRU	124
Recycled TRU	543
Total Heavy Metal	2,110
Burnup Reactivity Loss, %Δk	2.37
Peak Linear Power, W/cm	270
Ave. Discharge Burnup, Mwd/kg	118

[a]Ratio of time-integrated transuranic production rate to transuranic destruction rate

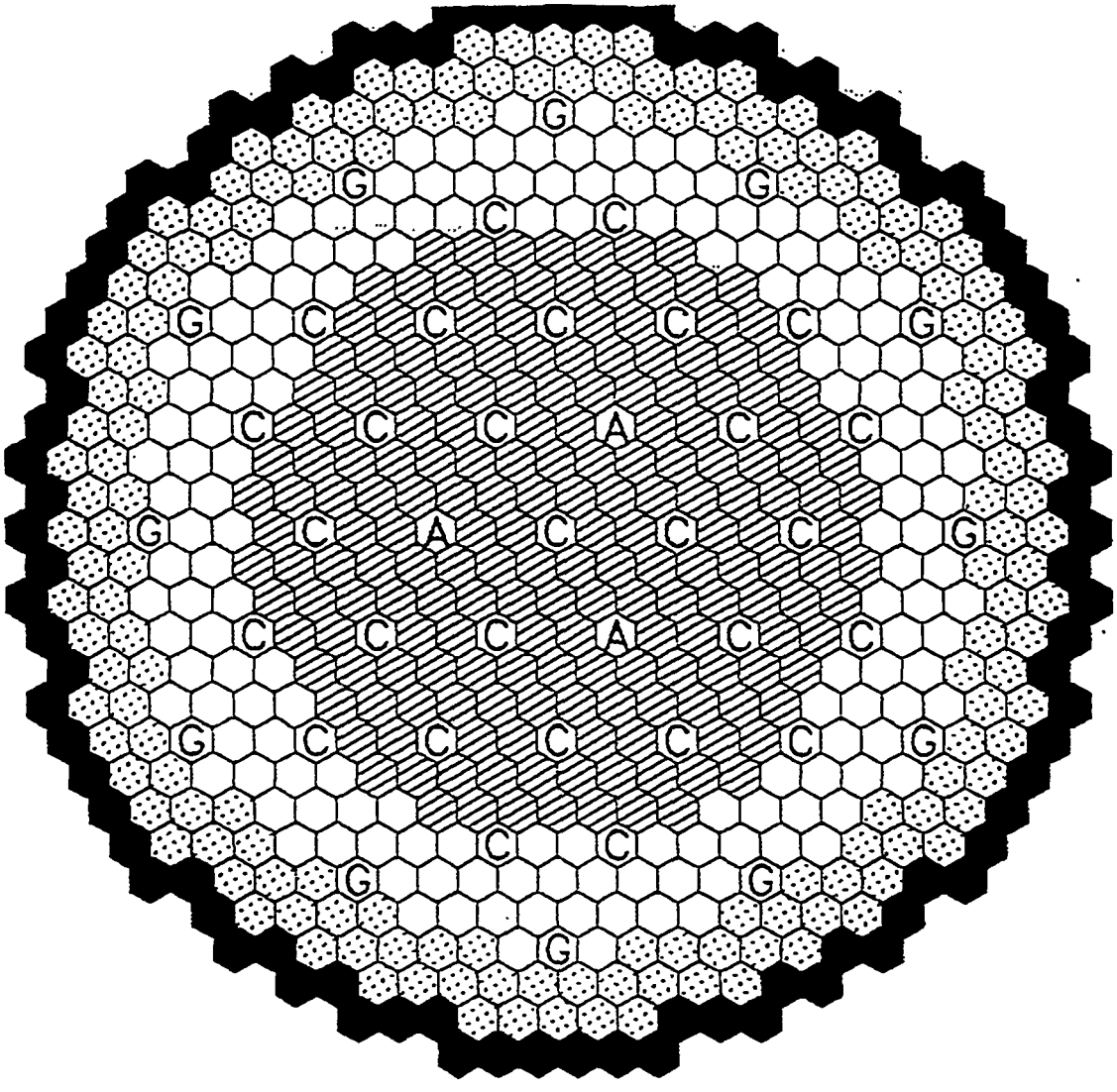
High Enr. Driver (162)
Low Enr. Driver (192)
Reflector (162)
Shield (90)
Control (28)
Alternate Shutdown (3)
GEM (12)

Figure:3

Safeguarding Materials in an Electrorefining Fuel Cycle

Safeguarding is always composed of a combination of institutional barriers and technical barriers. *Institutional barriers* include international and intranational agreements, primarily the NPT, and the response of the community of nations to evidence of diversion. *Safeguards measures* include physical protection, careful accounting, and on-site inspections by the IAEA. There is no basis for treating these requirements differently for a fast reactor fuel cycle than for any other nuclear fuel cycle. *Technical barriers* are intrinsic susceptibility to detection of diversion, and materials of intrinsically low attractiveness.

The effectiveness of a technical barrier depends both on the difficulty of accessing and transporting the material and on the probable time delay before the diversion is detected and announced to the community of nations. Attractiveness depends both on the difficulty of the process steps required to convert the material, once diverted, into weapons usable form, and on the isotopic purity of the output material (degree of contamination by isotopes that undergo spontaneous fission or emit significant heat, or do not fission readily on absorbing a neutron).

Safeguards discussions generally distinguish between active inventories and waste and scrap inventories. For the electrorefining-based fast reactor fuel cycle, this is somewhat meaningless, in that the fast reactor is designed to work on a continual recycle with no significant release of plutonium (or other transuranics) to wastes, and inventories are matched to power requirements. For the foreseeable future, currently envisioned fast reactor fuel cycles would be deployed to reduce the present excess of plutonium; a premature end to the use of this option, with remaining inventories declared to be waste, would not be worse than if the fast reactor deployment had never been used.

In the following discussion, the safeguards implications of the electrorefining-based fast reactor fuel cycle is compared with two major fuel cycle alternatives that are already deployed: once-through thermal fuel cycle, and recycle using PUREX reprocessing.

The electrorefining process was developed specifically to yield a plutonium product that is inherently commingled with minor actinides (americium, curium, neptunium), uranium, and fission products [Ref. 28]. The minor actinides provide substantial decay heat and contamination with alpha, beta, gamma, and neutron emitters.

The electrorefining chemistry inherently limits fission-product decontamination to a factor no greater than about 1000. A typical product composition is compared with a typical PUREX product from the reprocessing of LWR fuel in Table 3. Table 3 also shows the intrinsic heat deposition rates in the transuranics-bearing materials, which is due mostly to alpha decay of the minor actinides. The heating rate per gram of heavy metal (including uranium) is five times that of the unprocessed LWR fuel and about 2.6 times higher as a processed product. Even with radioactive decay, the heating rate per gram never falls substantially below the rate for the heavy metal in LWR spent fuel. Table 3 also shows that the spontaneous neutron emission rates (neutron/s) per gram of heavy metal in the fast reactor spent fuel is three times more for heavy metal from LWR spent fuel.

From the heavy metal alone, the decay heat and spontaneous neutron emission rates are much higher in the electrorefining case. In addition to this, the presence of the residual fission products causes the transuranic-containing materials, at every step of the cycle, to be radioactive enough to be self-protecting due to the gamma radiation from the lanthanides. The radiation level of the material at each step of the pyroprocess easily meets the self-protection criterion of one Si/h at 1 m for the batch quantities of recycle fuels. The PUREX product for LWR recycle is necessarily very low activity.

After examining these factors, U.S. weapon designers have concluded that IFR fuel and recycle materials could not be used to make a nuclear weapon without significant further processing [Ref. 9].

Table 3 further shows that, even if electrorefined material were diverted (from any stage of the cycle) and processed in an unsafeguarded PUREX plant, the pure plutonium from PUREX processing of the diverted material would have spontaneous neutron emission rates and heating rates essentially as large (withing 30%) as those in the pure plutonium that comes from PUREX processing of spent LWR fuel. For weapons purposes, there is no particular significance to the somewhat higher fissile content of the electrorefined plutonium, since the yield, yield uncertainty, and manufacturing difficulty are comparable for the two materials. In both cases, further *isotopic* separation would be needed in order to make highly reliable, efficient nuclear weapons [Ref. 29].

Summary

Plutonium is a fact. World inventories currently exceed 1000 tonnes, and are increasing at 60 to 80 tonnes per year. This can be considered a valuable energy resource or a political and environmental burden. The best approach is that which will maximize the benefits and minimize the burden. A closed fast reactor fuel cycle using an advanced recycle technology provides such an option by using plutonium as a catalyst to extract the full energy content from the world's uranium reserves, while eliminating excess inventories of plutonium and of other long lived transuranic byproducts. Such a system is fully compatible with rigorous safeguards, and in fact presents few safeguard challenges beyond those which are associated with the once-thorough fuel cycle.

The most important long-term contribution of the fast reactor approach to safeguards and prevention of proliferation is that it provides a positive means of managing the overall size of the world's plutonium and transuranic inventory [Ref. 30]. With a fuel cycle management strategy driven by economics, the fast reactor can readily absorb excess plutonium stocks, leaving the world inventory sequestered in plants producing useful energy.

Table 3: LWR and IFR Spent Fuel: Composition, Decay Heat and Spontaneous Neutron Source Levels

	Relative Isotopic Mass (g/kg HM)		Decay Heat (W/kg HM)		Spontaneous Neutrons (neutrons/s/kg HM)	
	LWR	**Fast Reactor**	**LWR**	**Fast Reactor**	**LWR**	**Fast Reactor**
Spent Fuel at Discharge (Normalized to 1 kg HM basis)						
Total Pu	11.23	219.9	0.10	1.43	3.38e+03	4.75e+04
Other Ac	1.12	3.74	2.20	10.4	1.18e+06	3.64e+06
Total TRU	12.35	223.7	2.30	11.8	1.19e+06	3.79e+06
Total U	987.7	776.3	1.48e-03	8.73e-05	1.23e+02	4.18e+00
Total HM	1000.0	1000.0	2.30	11.8	1.19e+06	3.79e+06
Normal Process Products PUREX for LWR and Electrorefining for the Fast Reactor						
Total Pu	1000.0	219.9	9.62	4.30	301e+05	1.42e+05
Other AC		3.74		21.01		9.22e+06
Total TRU		223.7		25.31		9.36e+06
Total U		776.3		1.08e-05		5.17e-01
Total HM	1000.0	1000.	9.62	25.31	3.01e+05	9.36e+06
Pure Pu Product After PUREX Processing of Diverted Materials						
	1000.0	1000.0	9.62	6.56	3.01e+05	2.17e+05

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