LA-UR- 96-2996

CONF-9605143--3

TITLE: ACCELERATOR-DRIVEN TRANSMUTATION TECHNOLOGIES FOR RESOLUTION OF LONG-TERM NUCLEAR WASTE CONCERNS

AUTHOR(S): Charles D. Bowman

SUBMITTED TO:

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DISCLAIMER

Accelerator-Driven Transmutation Technologies for Resolution of Long-term Nuclear Waste Concerns

Charles D. Bowman

Abstract

The paper provides a rationale for resolution of the long term waste disposition issue based on complete destruction of fissile material and all higher actinides. It begins with a brief history of geologic storage leading to the present impasse in the U. S. The proliferation aspects of commercial plutonium are presented in a new light as a further driver for complete destruction. The special problems in Russia and the U. S. of the disposition of the highly enriched spent naval reactor fuel and spent research reactor fuel are also presented. The scale of the system required for complete destruction is also examined and it is shown that a practical system for complete destruction of commercial and defense fissile material must be widely dispersed rather than concentrated at a single site. Central tenants of the U. S. National Academy of Sciences recomendations on waste disposition are examined critically and several technologies considered for waste destruction are described briefly and compared. Recommendations for waste disposition based on Accelerator-Driven Transmutation Technology suitable for both the U. S. and Russia are presented.

Introduction

From the beginning of the development of commercial nuclear power, it was recognized that means for safe disposition of the remnant waste would have to be developed. The waste was to consist of fission products alone because it was expected that the actinide component of the waste would be destroyed by fission with enhancement of the total energy output of the fuel. Since the decay half-lives of the longest lived fission products are measured in the hundreds of thousands and millions of years, it was not possible to build storage canisters for which the integrity could be guaranteed for such a long period. Therefore geologic storage of the waste fission product was proposed for the purpose of confining the movement of the waste away from the storage site after the emplacement canister had decayed away.

Nuclear proliferation concerns in the 1970s led to an additional challenge for geologic storage. The reprocessing of spent fuel from commercial power reactors to recover and burn the plutonium it contained was viewed as being a key element in an international market for plutonium. Some of this might be stolen for use in developing nuclear weapons for terrorists or rogue states. Therefore in the late seventies President Carter issued a Presidential Order stopping the development of reprocessing and establishing the "once through" policy which required that commercial spent fuel assemblies be placed directly in geologic storage. The plutonium they contained and other higher actinide was therefore added to the burden of long lived radioactive species which must be contained by geologic storage. The U. S. policy since that time has been to discourage foreign countries from the development of reprocessing and to encourage the adoption of the once through approach. Over the past twenty years few nations have adopted this policy partly owing to lesser concerns about proliferation, partly to enhance the yield of electric energy from a given mass of fresh fuel by burning plutonium, and partly for proliferation concerns about the large amount of plutonium which would be stored in many repositories around the world. (The world's inventory of plutonium in spent fuel would approach 6000 tons by the middle of the next century if nuclear energy continued to be deployed at the present capacity. Recent U. S. National Academy studies assert that only about 5000 grams are required for making a several kiloton nuclear weapon.)

This author believes that the U. S. was right about the problems of proliferation associated with reprocessing as long as the existing aqueous technology (PUREX and its extensions) resulted in the production of a pure stream of plutonium. The development of other separations and fuel fabrication technology which would allow the plutonium and higher actinide to be fissioned completely without separating a pure plutonium stream would eliminate the primary justification for the U. S. ban against reprocessing. The intent of other nations to burn the plutonium helps reduce the large plutonium inventory, but it does little good to burn half or even two-thirds of the plutonium since the inventory would still be measured in thousands of tons. If plutonium is to be destroyed by fission to eliminate proliferation concerns, it must be destroyed completely so that the remnant is small, the isotopic content of the remnant is unfavorable for weapons material, and so that natural decay does not eventually convert the remnant into weapons material. Therefore, all nations' concerns about plutonium would be met if plutonium and other higher actinide could be destroyed completely by a system which is efficient in generating electric power from the fission heat and which did not produce pure weapons material along the way. Accelerator-driven transmutation for spent commercial fuel promises to achieve these objectives.

More recently with the end of the cold war the clean-up of the nuclear defense complex in the U. S. and Russia has also required these nations to address the disposition of excess weapons plutonium and an apparently large inventory of spent fuel from naval reactors. Attention to these materials also has drawn highly enriched spent research reactor fuel into the spotlight. A prominent option for the U. S. for these three highly enriched fissile materials was emplacement in geologic storage and a strong movement in this direction was initiated. Since these fissile materials and some of their fissile daughters have half lives of millions of years, dissolution of their emplacement canisters is assured allowing these fissile materials to reconfigure. This prospect provided the rationale behind Los Alamos work which showed that these materials could reconfigure into critical masses, that the reconfiguration could have positive feedback , and that the confinement provided by the surrounding rock taken together with positive feedback might give rise to large nuclear explosions in a repository[1]. Although it is difficult to quantify the likelihood of such events or to show that the likelihood is too low as to be ignored, the possibility of the occurrence of such events has been confirmed[2]. Mitigation means to reduce the possibility of such events have been proposed and further study to evaluate such strategies has been proposed[2]. It also has been reported that commercial spent fuel also will exhibit criticality with positive feedback in emplacement configurations currently planned by the U. S. Department of Energy[3,4].

The viability of repository storage of fissile material also was dealt another blow by studies comparing the cost and speed of obtaining fissile material by removal from geologic storage with isotopic separation of ^{235}U or reactor production of ^{239}Pu. The results of the study were that it was more than ten times faster and ten times cheaper to remove the fissile material from a repository than to make it by either of the alternatives[5]. The proliferation concern about fissile material in repository storage was seconded by the IAEA which has concluded that the repositories must be guarded into perpetuity[6].

Finally the very nature of the scientific process for finding a best single site for storing the spent fuel assures difficulties in political acceptance. The purely technical challenge is to find the single best site in the nation for storage of nuclear high level waste and to scientifically characterize it to the highest possible degree in order to understand the best emplacement procedure. The fact that there probably is in principle such a single best place imposes on the host community the obligation to accept this waste, which many believe to be the worst of the nation's wastes. Other types of society's waste can be stored locally, but the worst waste must be treated with the greatest care, stored in the single best place as verified by thorough scientific investigation, and must be monitored indefinitely since its toxicity never decreases on time scales relevant to human experience. The citizens of Nevada are unhappy with this and the rest of the nation understands that it's fundamentally unfair to force this waste on a single community which doesn't want it.

Current uncertainty in the U. S.

The U. S. DOE and the Congress seem to be giving up for the time being on Yucca Mountain or any other site for permanent waste storage. The Congress has therefore just voted instead for interim storage of commercial spent fuel near Yucca Mountain. Of course this is not acceptable either to the Nevada residents because without means for ultimate disposition the interim site becomes a defacto permanent site. Furthermore once the waste is placed at a single site, there is less motivation to search out means other than storage for dealing with the waste and there is little possibility that the waste ever will be moved to another site. Apparently interim storage will not be implemented because President Clinton intends to veto the bill and it was not passed with sufficient majority to override the veto. The commercial spent fuel therefore will stay for the foreseeable future on the reactor sites in dry storage. The situation will be viewed as unsatisfactory and other disposition strategies which do not have the single-best-site feature may finally get considered. It is useful to note here that if the long lived species of the waste is destroyed sufficiently well such that storage canisters can be made which outlast the waste, then a single best geologic storage site is not required. The waste can be stored almost anywhere that it can be physically guarded well until it decays to low level Class C waste which can be stored following established Nuclear Regulatory Commission and Environmental Protection Agency guidelines. No alternative to complete burnup of all long-lived species of the waste appears to be in prospect . Without Yucca Mountain neither the storage option or the partial burn-up option for weapons plutonium is viable. The same may be said for the spent naval fuel and research reactor fuel. Burn-up of the long-lived species is the only option if geologic storage is impractical.

The energy released in total burn-up of actinide exclude the possibility that all of the commercial plutonium could be destroyed on a single site. The power generated in burning the plutonium and other higher actinide by fission using accelerator-driven systems (ADS) or by other means from a single commercial power reactor operating at 3000 MWt is smaller by about one quarter or about 750 MWt . This 4 to 1 ratio implies that it would take about 25 ATW systems operating at 3000 MWt for about 40 years to burn the waste from our roughly 100 reactors of 3000-MWt power. The cost to build and operate these twenty five 3000-MWt systems for 40 years is impossibly large unless the heat generated from destruction of the waste by fission is converted efficiently to electric power and sold to pay these costs. All of these systems would have to be located in the Yucca Mountain vicinity and all of this power from the equivalent of 25 reactors would have to be sold from this one site into the grid. This is far too much power to be absorbed from one site.

It becomes more practical to burn the plutonium and minor actinides if the waste is hauled to several regional sites. In the U. S. for example, if the commercial waste were equally distributed to Savannah River, Oak Ridge, Idaho Falls, the Nevada Test site, and Hanford, then only five ATW systems would be required on each site. The grid might well manage to accept this power of about 5 GWe from each of 5 sites and pay a competitive price for it. The remnant waste could then be transported to Yucca Mountain for final permanent disposition in this denatured form or stored locally in canisters which would reach Class C levels after 300 years. Canisters certainly can be made which can maintain their integrity until the waste remaining after transmutation has decayed to Class C levels.

It seems increasingly likely that when the DOE takes title to the waste that it will remain at the reactor site. This would appear to insure certain death for new nuclear reactor construction unless the DOE/Congress can come up with a plan to denature the waste. This problem might be resolved by building on each reactor power plant site an ADS to burn the waste on site. A single ADS operating at 750 MWt (300 MWe) would destroy the actinide in 40 years from a 3000 MWt reactor with an operating life of 40 years. Or alternatively an ADS system four times larger (3000 MWt) could burn the waste in ten years and then be converted to electric power generation (Accelerator-Driven Energy Production (ADEP)) using the Th-U cycle which doesn't produce the plutonium and higher actinides in the first place. It is important to note that a market at a satisfactory price for the electric power probably already exists at the site because the ADS system would replace an older nuclear reactor which was supplying an established market.

Weapons Usefulness of Commercial Plutonium

To express the need for total burn-up of commercial plutonium in the clearest terms, the following conversation might be of interest. This past February I found myself wearing a heavy ski jacket in the back of a cold conference hall in St. Petersburg, Russia beside a slightly bored Russian former nuclear weapons designer. We were there to discuss technology affecting the future of the two kinds of plutonium...weapons plutonium taken from nuclear weapons in stockpile reductions and the commercial plutonium being produced worldwide in commercial nuclear reactors. My Russian colleague was restless and presently he leaned over and whispered, "I don't understand the U. S. policy at all with regard to weapons plutonium? Why turn weapons plutonium into commercial plutonium when it's much easier to build nuclear weapons with commercial plutonium?" This was more interesting than the speaker's paper so I nodded to him to proceed. His words are paraphrased below.

He said, "Three technologies must be mastered to make a nuclear weapon out of weapons plutonium. First, you have to master the compression technology...driving the plutonium into a highly compressed ball with conventional high explosive. Second you must produce a burst of neutrons to start a rapidly growing chain reaction and that's not so easy. And third, you have to time the burst of neutrons just right or the neutrons will come too late or to early. If you fail at any of these three requirements the bomb will be a dud." Everything he said was true. It had been first stated publicly in unclassified and published work[7] by Dr. Carson Mark, a leader in nuclear weapons design at Los Alamos in the 1960's. Mark's work also was referenced in the highly publicized study conducted by the U. S. National Academy of Sciences entitled, "Management and Disposition of Excess Plutonium[8]" and similar information has been communicated by Russian scientists[9]. So where was he headed?

He continued, "For nuclear weapons from commercial plutonium you need only the compression technology. Lots of neutrons are already present because the commercial plutonium contains isotopes which undergo spontaneous fission and produce neutrons all of the time. Because they are there already, one cannot control the timing of the injection of neutrons so the explosive power is quite uncertain. It might be anywhere in the range from 2000 tons of TNT to 18,000 tons." Well", I thought, "2000 tons is about 1000 times larger than the Oklahoma City bomb which produced no radioactive fallout."

He went on, "Who cares whether the explosion is 2,000 or 18,000 tons when the damage is proportional to the cube root of the yield and is therefore only about a factor of two different? Terrorists wouldn't and even a rogue nation's war planners wouldn't care much. So why does Washington keep pushing us to convert difficult-to-use weapons plutonium into easy-to-use commercial plutonium? Your policy is influenced too much by your weapons designers at Los Alamos and Livermore. With the advanced technology developed in the U. S. and Russia, sure, weapons plutonium is the best because the explosive power is highly dependable and therefore always the maximum and you also can make all kinds of fancy bombs such as nuclear artillery shells and so forth. But suppose you don't have nuclear weapons and you want to get them quickly and easily and you have the choice of commercial or weapons plutonium. Your U. S. weapons designers believe a terrorist organization or rogue state will choose the weapons plutonium. But the clever fellow who has to build a reliable bomb for the boss fast and cheaply will choose the commercial plutonium every time."

The Russians wish partly for this reason to burn the excess weapons and commercial plutonium as does most of the rest of the world. The Russians have developed new reactor technology to do this and the French, Japanese, and others also are working on other approaches. My group at Los Alamos, working with modest internal funding is studying new means for destroying this material using accelerators, which promises to make complete destruction ultra-safe and affordable. From this array of technologies could emerge practical means for total destruction of plutonium before the first plutonium anywhere in the world finds its way into geologic storage.

Input from the National Academy of Sciences

Work on the development of this new accelerator-driven technology has not been supported by the National Academy of Sciences recommendations[10,11] and the U. S. policy has been rather neutral instead of supportive of such studies in other countries[11]. The U. S. Department of Energy is proposing the adoption of the U. S. National Academy of Sciences recommendations[12] which urge placement of plutonium of all types underground either with or without partial burn-up. It is now in the final stages of information gathering prior to a decision to embark on the implementation of these options[13]. It would be useful to examine the arguments which have steered thus far the selection of underground storage. Five statements underlying the National Academy of Sciences position are discussed below.

1. Reprocessing promotes an international market in plutonium.

Perhaps the weakest technical element in total plutonium destruction using existing technology is the PUREX process for separating plutonium from spent nuclear fuel. This technology was developed in the post war years and it or its derivatives are now widely deployed except in the U. S. It is presently not capable of dealing with the build-up of highly radioactive constituents of the waste produced in the course of complete plutonium destruction. One might develop the technique further to deal with its shortcomings, but it also has the problematic feature that it produces a pure stream of plutonium. The Swedes call this "naked" plutonium. The separation of this naked plutonium does not necessarily or perhaps ever match perfectly the feed into the plutonium destroying systems. Therefore the excess must be stored, and perhaps to get a better balance between those who store and those who burn plutonium, it could be sold thereby creating a plutonium market. As with any commodity market it's not easy to prevent some of the commodity from being lost or stolen. The U. S. is correct on the point of avoiding a market and should push on to prevent the development of a market in plutonium.

The solution to destruction of plutonium without producing a market in plutonium is not to ban reprocessing of any kind but to develop separations processes which do not produce pure plutonium. From the beginning of our work on plutonium destruction at Los Alamos the focus has been on separations which allow the destruction of plutonium without the production of naked plutonium[14]. Only the weakly radioactive zirconium fuel cladding and the uranium are removed so that the plutonium remains mixed with the most radioactive ingredients of the nuclear waste. The concentration of radioactivity of this product is about 100 times higher than in commercial spent fuel and this product can be fed directly into an accelerator-driven transmuter. The Los Alamos process also only makes accessible as much plutonium as the system burning it can use, so no excess is accumulated. With highly contaminated plutonium and no excess and with separation and burning integrated together on the same site, it is almost certainly feasible to develop means for destroying plutonium without promoting a market in plutonium.

2. Plutonium is safe in geologic storage.
This statement already has been addresses in the introduction of the paper.

3. Accidental or purposeful repository intrusion is inconsequential.
Of course natural processes are not the only ones that could lead to critical configurations. The repository studies supported by the U. S. Department of Energy acknowledge the possibility of accidental intrusion into the repository as for example in drilling for water or minerals, although these studies had not recognized the possibility of criticality with positive feedback. The IAEA study and the Peterson study make the case that there are strong reasons to reenter and recover the plutonium from the repository for those wishing to obtain nuclear weapons capability. The repositories may be the richest or only source for other non-fissile materials of possible future interest. For example, all of the elements in the waste have isotopic concentrations different from those that occur naturally and have potential value for that reason. Mining a repository purposefully is therefore almost a certainty and if the mining is not done with great care, critical configurations could be created accidentally. Finally it is not out of the question that repository explosions might be deliberately induced for malevolent reasons. If the possibility for spontaneous criticality could be reduced to an acceptably low value (and how would that be decided?), the possibility of purposeful, accidental, or spontaneous reconfiguration to criticality remains.

4. Conversion to the "spent fuel standard" is worthwhile.
For the many years while plutonium was stored in large inventories of nuclear weapons, the safety of weapons plutonium was not questioned. Since relative peace has brought major stockpile reductions, the disposition of the excess weapons plutonium particularly Russian plutonium has become an issue of major focus. There is good reason to want to get Russian weapons plutonium under control as quickly as possible. In response to this concern, the U. S. Academy of Sciences conducted a study entitled Management and Disposition of Excess Weapons Plutonium[8] to evaluate possible options. The recommendations included (1) declarations of weapons plutonium in the U. S. and Russia, (2) Safeguarded storage of this material, and (3) final disposition including storage underground or partial burn-up in reactors before storage underground. After settling on underground storage, the issue of burning before storage underground was addressed by the NAS in a separate study with a report entitled, Management and Disposition of Excess Weapons Plutonium....Reactor-Related Options[11].

Both reports were strongly influenced by the concept of the "spent fuel standard." The plutonium in the commercial spent fuel as we have already seen is a mixture of isotopes which has some disadvantages for making sophisticated nuclear weapons. In addition the commercial spent fuel is in the form of spent fuel assemblies. The presence of the fission product radioactivity in the assemblies with the plutonium is felt to be another considerable deterrent to attempts to remove the plutonium for possible weapons use. Since there is so much more commercial plutonium than weapons plutonium, the transformation of weapons plutonium to commercial plutonium by burning in a reactor gets rid of the weapons plutonium but increases the amount of commercial plutonium by only about 10 %.

Therefore conversion of weapons plutonium to commercial plutonium by partial burning is seen to be worthwhile.

The conversion of weapons plutonium to the spent fuel standard of commercial plutonium by partial burning would be an exercise of rather little value. As we have already seen, the commercial plutonium is more useful to those we wish not to have plutonium than weapons plutonium. The value of the radioactivity as a deterrent decreases with time such that in about one to two hundred years the chemical separation of plutonium from the waste could be accomplished without the radioactivity being a significant barrier. Whatever advantage from the presently proposed policy of conversion to the spent fuel standard would be temporary and mainly passes the resolution of the problem to future generations. They would have the responsibility for destruction following the probably dangerous task of recovery.

5. Weapons plutonium has only negative value.
Of course the main objective of this U. S. policy might not be U. S. weapons plutonium but Russian weapons plutonium. The Russians understand that weapons plutonium has significant positive value and expect to receive come considerable societal benefit from the destruction of this material. The U. S. argues that weapons plutonium has negative value citing the energy value of the plutonium which is no different than for any fissile material. In the U. S. this case is valid because we currently have no technology available to extract the energy efficiently. However Russia has developed an advanced lead-cooled naval reactor[15] which its advocates would like to move into the commercial sector. It can burn the plutonium with significant advantage. In addition the Russians understand that the primary value of the weapons plutonium is not in the fission energy produced from burning but in the neutrons it produces. Much of the reason weapons plutonium is valued for sophisticated weapons is that it is an exceedingly rich source of neutrons. Since the key to nuclear energy is sustaining a chain reaction, the burning of weapons plutonium could enhance the reactor neutron economy allowing the chain to continue to operate while performing other useful functions such as destroying nuclear waste by transmutation using these neutrons. Studies at Los Alamos show that the economics of transmutation of commercial nuclear waste is very significantly enhanced by the burning of weapons plutonium and highly enriched uranium concurrently[16].

Technologies for complete destruction of plutonium
Although there are several promising technologies which have been proposed for complete destruction of plutonium, none have been demonstrated yet because the plutonium problem was not prominent until U. S. and Russian stockpile reductions created an excess of plutonium and the problems of repository storage of commercial plutonium became apparent. Several appoaches are briefly described below.

Sodium-cooled fast-spectrum reactors
This technology has received billions of dollars of support worldwide because of its capability to breed plutonium. By operating these reactors differently it is possible also to burn plutonium and this technology is perhaps the most prominent candidate technology now. However these systems are criticised for reactivity problems in case of loss of coolant and for their use of sodium coolant which burns actively in oxygen, nitrogen, and even with concrete. Perhaps the main U. S. criticism of them is that deployment of them for plutonium destruction opens the door to future use as breeders of plutonium and therefore for proliferation of nuclear weapons. For this reason development of this technology was halted last year in the U. S. and the U. S. government is putting pressure on other nations to halt this technology development as well. Since only 15 % or so of the plutonium in a single fuel load can be destroyed, these systems require removal of

plutonium and recycling of this plutonum back into the reactor. The separations necessary for recycling this plutonium repeatedly to complete burnup has not been demonstrated and the National Academy of Sciences believes that the relationship of burn-up to inventory is such that a practical burn-up plan might take over 200 years to complete[11]. There is much to be debated about this technology, but the fact that it has not yet reached acceptance after more than 25 years of development speaks to a considerable degree for itself.

Lead-cooled fast-spectrum reactors

The Russians have developed a different version[15] of the fast reactors which employ the much safer lead-bismuth as the coolant. The reactor was developed for use in Russian submarines where high power from a compact power plant is desireable and submarines powered with it hold the world submarine speed record. The reactor is reported to have eighty reactor-years of successful operation which substantially exceeds that of the sodium-cooled reactors. It was developed primarily to resolve the flammability problem of the sodium coolant but it avoided the fast reactor positive void coefficient issue as well. Furthermore the passive solidification of the lead-bismuth if it leaks from the reactor is an additional significant safety advantage for confining the system radioactivity in normal or accident conditions. This reactor was developed in military secrecy, but a Russian private company has been organized to commercialize it. Its design allows the complete burn-up of plutonium and the minor actinides provided proposed new non-aqueous separations techniques are proven to be practical. The most effective start-up fuel is weapons plutonium or the highly enriched uranium recovered from weapons reductions. Russia therefore has a technology unavailable in the U. S. or elsewhere which can use their excess weapons material to great advantage. Russia therefore has a practical option for destruction of excess fissile materials which is unavailable in the U. S. The impact of the relative inactivity in the development of advanced nuclear technoogy over the past two decades in the U. S. is beginning to show.

Mixed-oxide burning in commercial light water reactors

Existing commercial light water reactors can be employed to burn weapons plutonium as an alternative fuel consisting of plutonium mixed with uranium called mixed oxide fuel (MOX). After one cycle the plutonium can be recycled once more for a further reduction. However, after that cycle exisiting fuel reprocessing systems cannot cope with the high radioactivity of the remaining plutonium and its higher actinide products. Complete burn-up therefore is not possible although burn-up to the "spent fuel standard" is possible. Therefore the only reactor capability that the U. S. has can only do a job partially which should be done to completeness or not at all. The fact that *something* can be done perhaps accounts partly for the current support in the U. S. for this MOX approach. Since the U. S. has no MOX fuel fabrication plants, it is considering transporting the 50 tons of weapons plutonium to Europe for fabrication into fresh MOX fuel. Since the MOX partial burning of plutonium cannot pay its way, the U. S. government would be paying for converting the weapons plutonium to a form more readily useful by terrorists and rogue states than the original weapons plutonium! The MOX option might be used to destroy some of the commercial plutonium, but plutonium is not eliminated by this means.

High-temperature gas-cooled reactors with accelerator assistance

The General Atomics Corporation has pursued the development of high-temperature gas cooled reactors (HTGRs) for commercial production of nuclear power. The corporation has proposed to burn weapons plutonium to completeness without fuel reprocessing by burning the fuel first in their existing reactor design until the reactor can no longer maintain criticality and then to move the fuel to an accelerator-driven system which continues the burn down to a much higher degree in a subcritical assembly[17]. Both systems sell electric power to pay the costs of this operation. The resulting 5 % remnant of plutonium and higher actinide mixture is not useful for nuclear weapons owing to its pure isotopic content and its high specific decay heat. The same system also could be used to destroy commercial plutonium. The Corporation believes that the weapons plutonium has a positive value in this mode; the economic situation is less clear for commercial plutonium owing to the complications of the additional reprocessing required. The design of this system is relatively mature following many years of research and development. Although this type of reactor has not been adopted for production of commercial nuclear power, it might be competitive for the waste burn-up mission with the accelerator addition.

Accelerator-driven transmutation technology

All reactors operate as critical systems with criticality being a considerable constraint on system function and fuel usage. The use of accelerators as intense neutron sources to allow reactor-like systems to operate as subcritical systems has been considered for many years. The advantages are safer operation as subcritical systems, operation over a wider dynamic range of fuel burn-up, a superior neutron economy owing to the supplemental neutrons supplied by the accelerator, and the absence of neutron losses in control rods[18]. The safe subcritical operation also makes possible operation with a liquid fuel which allows continuous refueling and removal of fission products. The liquid fuel improves the neutron economy further and avoids the cost and infrastructure for fuel fabrication and refabrication. The reactor-like system with its on-line separations capability allows one to feed fissile material into the system continually and to remove fission product alone continuously. Therefore total fissile material burn-up is possible. If these systems were deployed as thermal rather than fast spectrum systems, the burn-up per year would be a large fraction of the fuel inventory. An examination of the logistics of plutonium destruction shows that such a system could destroy both commercial and weapons plutonium in a period of about sixty years[11] instead of the 200 required for a fast spectrum system.

The study of these systems was always limited in the past by the absence of a satisfactory accelerator technology. However advances over the years made it clear by 1990 that the required accelerators could be built and accelerator-driven transmtuation technology (ADTT) has been under study at Los Alamos since that time. Interest has grown in this technology the world over with a large international meeting[19], "The Second Internaltiona Conference on Accelerator-Driven Transmutation Technology" planned for June 1996 in Kalmar, Sweden. Studies also are underway in France, Europe, Japan and Russia. The viability of a large accelerator in an industrial context was given a large boost by the U. S Department of Energy's endorsement of the construction of a 1.3 billion volt 100 milliamp proton accelerator producing 130 megawatts of steady state beam power to produce tritium for the U. S. nuclear weapons stockpile. The accelerator beam will produce neutrons which will be absorbed into the helium 3 isotope to convert it to tritium (hydrogen 3). This tritium-producing accelerator is larger than the largest accelerators contemplated for transmutation technology

At Los Alamos three versions of this accelerator-driven technology have been studied. The first called accelerator-based conversion (ABC) is aimed at the total burn-up of weapons plutonium. It is expected to have capability for burn-up not only of the high-quality plutonium which is returned from weapons stockpile reductions, but it should also readily destroy the plutonium remnant which was left as the 1-10 % contamination of the waste from the plutonium production process. This system would have its primary application in Russia and the U. S. where the excess and waste weapons plutonium exists.

The second system called accelerator-transmutation of waste (ATW) is aimed at the destruction of commercial plutonium, the minor actinides, and the long-lived fission products. The system therefore would provide the means for destruction of the world's commercial plutonium and also perhaps all of the long-lived high-level waste produced from commercial nuclear power plants. One ATW facility operating at the same fission power level as a typical commercial power reactor would destroy the waste from four commercial power reactors. Since there are about 400 commercial power reactors in the world today, the destruction of just the waste from them would require 100 ATW systems. Obviously this would be impossibly expensive unless the fission heat from the destruction of the waste could be converted to electric power and sold to pay the construction and operating costs for the destruction of the waste. If all of these costs could be paid by electric power sales, the destruction of the waste would cost nothing. Society probably is willing to pay a modest surcharge for the disposition of these wastes, but will not accept a waste solution requiring a major increase in the nuclear electric power cost.

Destruction by fission of the plutonium and the minor actinides is less costly than the fission products because the neutrons provided by the accelerator are supplemented significantly by the neutrons produced in the fission process. It appears that the destruction of the plutonium and minor actinides can be made economically practical by this means. However for the fission products, one neutron is required to transmute each atom of fission product. Therefore transmutation of the fission products is considerably more expensive in terms of requirements on the accelerator unless some other supplemental source of neutrons can be identified. Weapons plutonium and highly enriched uranium are good materials for weapons mainly because they are good sources of the neutrons necessary to drive the exponentially growing chain reaction in a nuclear explosive. If these weapons materials were used to supplement the neutron economy in fission product burning, the destruction of the long-lived fission products would be much more nearly economically practical. The destruction of all long-lived constituents of the waste is therefore made more viable by the feeding of some of the weapons plutonium or highly enriched uranium into the ATW system.

The third component of the ADTT project is the production of nuclear energy from thorium using the accelerator to make possible the production of nuclear energy from thorium without the production of weapons material and with concurrent destruction of the long-lived high-level fission product waste. The energy available from thorium is virtually unlimited, there would be no output stream of long-lived high-level waste, and operation as a subcritical system prevents nuclear runaway. These three features are the primary advantages of fusion programs. We believe that this technology could be made available in 12-15 years and that the present technical maturity and likelyhood of technical success far exceeds that of fusion.

Up to the present this ADTT project has been supported only with internal discretionary funds of the Los Alamos National Laboratory. With this limited funding, it is impossible to conduct demonstration experiments at a scale justified by the present design maturity.

Solving the plutonium problem using transmutation

If the recommendations of the U. S. National Academy of Science are not to be accepted, what course of action should be followed instead? The following are recommended:

1. Implement to the degree possible the Academy's call for declarations, accounting, and safe storage of excess weapons plutonium.

2. Continue the U. S. policy discouraging a plutonium economy, the implementation of MOX burning of plutonium, and the use of PUREX-based processing which produces a naked plutonium stream.

3. Recognize that transforming weapons plutonium to the spent fuel standard makes the plutonium more dangerous and only puts the ultimate solution off on future generations.

4. Announce as the U. S. national goal the destruction of both commercial and weapons plutonium and of all other weapons material not contained in existing nuclear weapons stockpiles.

5. Support development and demonstrations in the U. S. of means for destroying weapons plutonium, commercial plutonium, and other higher actinide if the technology improves on the safety and proliferation vulnerability of present deployed nuclear technology.

6. If repository storage is necessary, reserve it for fission products and the more innocuous remnants of the nuclear waste stream, and devise means for interim weapons plutonium storage for the 30-50 year period required to destroy it using newly developed technology.

7. Encourage the development of new means for generating nuclear energy which do not concurrently produce weapons.

Conclusion

The present author believes that the U. S. and the rest of the world is beginning to understand that permanent storage of plutonium and minor actinides is not practical and that accelerator-driven transmutation technology with liquid fuel and on-line separations and refueling offers the most attractive approach for elimination. It may be satisfactory to proceed with the use of existing technology for *beginning* the destruction of these wastes so long as one recognizes that these systems will not destroy all of the waste on an acceptably short time scale and that strong financial support of accelerator-driven systems is required immediately in order to take over and complete the destruction on a time scale less than a human life span. The resolution of our waste problems should not be passed on to future generations.

References

1. C. D. Bowman and F. Venneri, "Underground Supercriticality from Plutonium and Other Fissile Material," Science and Global Security 5, pp. 279-303 (1996)

2. W. E. Kastenberg, P. F. Peterson, J. Ahn, J. Burch, G. Casher, P. Chambre, E. Greenspan, D. R. Olander, J. Vujic, B. Bessinger, N. G. W. Cook, F. M. Doyle, and B. Hilbert, Submitted to Nuclear Technology, "Mechanisms for Autocatalytic Criticality of Fissile Materials in Geologic Repositories," University of California, Berkeley, California, Report UCB-NE-4214 (June 1996). A shortened version has been submitted to the journal, Nuclear Energy.

3. J. S. Choi and T. H. Pigford, "Nuclear Criticality in Geologic Disposal of Radioactive Waste" submitted to Nuclear Technology (1996)

4. J. S. Choi and T. H. Pigford, "Underground Criticality in Repository Storage," International Conference on Emerging Nuclear Energy Systems, Obninsk, Russia, June 1996

5. P. F. Peterson, "Long-Term Safeguards and Security Parameters for Plutonium in Geologic Repositories," Science and Global Security 6, pp. 1-29 (1996)

6. G. Linsley, and A. Fattah, IAEA Bulletin 36, 22-26 (1994)

7. J. Carson Mark, "Reactor Grade Plutonium's Explosive Properties, Nuclear Control Institute, (August 1990). The National Academy of Sciences in its recent reviews refers also to another report by Mark which is neither endorsed nor criticized by the U. S Department of Energy entitled. "Explosive Properties of Reactor-Grasde Plutonium, "Science and Global Security, Vol.4, no. 1 pp. 111-128 (1993)

8. Management and Disposition of Excess Plutonium, Committee on International Secrutity and Arms Control, National Academy of Sciences, National Academy Press, Washington, DC (1994)

9. N. V. Ptitsyna, V. I. Chitaikin, and L. I. Shibarshov, "Plutonium and Its Chemical Compounds: The Problem of Nuclear Weapon Non-Proliferation," Managing the Plutonium Surplus: Applications and Technical Options edited by R. L. Garwin et. al. pp. 157-170, Kliewer Academic Publishers, Netherlands (1994)

10. "Nuclear Wastes, Technologies for Separations and Transmutation," Committee on Separations Technology and Transmutation Systems; Board on Radioactive Waste Management; Commission on Geosciences, Environment, and Resources; National Research Council; National Academy Press; Washington, DC (1996)

11. "Management and Disposition of Excess Weapons PLutonium, Reactor-Related Options", Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium, Committee on International Security and Arms Control, National Academy of Sciences, National Academy Press, Washington, DC (1995)

12. The exception is the U.S. funding of Project 17 of the International Science and Technology Center entitled, "Feasibility Studies of Technologies for Accelerator-Based Conversion of Military Plutonium and Long-Lived Radioactive Waste." This project supports Russian scientists from many institutes including the Institute for Experimental and Theoretical Physics and the The Kurchatov Institute in Moscow and institutes in Obninsk, Arzamas, Chelyabinsk and other sites. Altogether about 350 former Russian nuclear weapons scientists are being supported by this project.

13. The receipt of public input on the report, "Storage and Disposition of Weapons-Usable Fissile Materials Draft Programmatic Environmental Impact Statement" was completed on May 7, 1996. The document may be obtained from U. S Department of Energy, Office of Fissile Materials Disposition, P. O. Box 23786, Washington, DC 20026-3786

14. The latest work is described in the report by F. Venneri , C. D. Bowman, M. A. Williamson, L. Ning, T. S. Bhatia, R. J. Jensen, B. E. Newnam, and S. A. Wender, "Accelerator-Driven Transmutation of Nuclear Waste Status, New Concepts and Future Development," Los Alamos National Laboratory Report LA-Ur 96-500 (1996)

15. "White Land. New Russian Closed Cycle Nucelar Technology for Global Deployment," report prepared by C. D. Bowman after attending a conference in Russia entitled, "First International "White Land" Chapter Conference, Scientific and Technological Basis for Global Energy System," St. Petersburg, Feb 4-7, 1996

16. C. D. Bowman and F. Venneri, "High Value Use of Weapons-Plutonium by Burning in Molten Salt Systems or Reactors," in Global Security through Disarmament, A Special Workshop Sponsored by the NATO Division of Scientific and Environmental Affairs, Ettore Majorana Center for Scientific Culture, Erice, Italy, Autust 19-24, 1993

17. A unsuccessful proposal was made to the U. S. Department of Energy's Office of Fissile Material Disposition for study of this prospect in 1995. More details are available from the General Atomic Corporation in San Diego, California.

18. C. D. Bowman, E. D. Arthur, P. W. Lisowski, G. P. Lawrence, R. J. Jensen, J. L. Anderson, B. Blind, M. Cappiello, J. W. Davidson, T. R. England, L. N. Engle, R. C. Haight, H. G. Hughes III, J. R. Ireland, R. A. Krakowski, R. J. LaBauve, B. C. Letellier, R. T. Perry, G. J. Russell, K.P. Stauthammer, G. Versamis, and W. B. Wilson, "Nuclear Energy Generation and Waste Transmutation Using an Accelerator-Driven Intense Thermal Neutron Source," Nuclear Instruments and Methods in Physics Research A320, 336-367 (1992)

19. The first meeting in this series was entitled, "International Conference on Accelerator-Driven Transmutation Technologies and Applications," Las Vegas, NV, AIP Conference Proceedings 346 (1994)