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Nuclear Alchemy Gamble: An Assessment of Transmutation as a Nuclear Waste Management Strategy

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May 2000

Executive Summary

Table of Contents, Full Report | Findings | Recommendations | Acknowledgements | References | Endnotes

> *"Research on partitioning and transmutation is rather seductive to all of us. It requires new reprocessing techniques, new fuel developments, additional nuclear data, new reactors and irradiation facilities, new waste treatment and disposal concepts, and specific safety studies. The global nuclear scientific and engineering community is challenged by this opportunity."*
>
> *Everybody realizes however that this voyage to the promised land will pass a desert with a lot of mountains and that we are not so sure that the horizon will be as bright as one can hope."*
>
> ---Paul Govaerts, SCK-CEN (Belgian Nuclear Research Center). "Welcome Address" to the Fifth International Information and Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Mol, Belgium, 25-27 November 1998.

> *"The [transmutation] programme is expected to serve to revitalise the nuclear R&D in general, and also to attract capable young researchers dedicated to bringing the nuclear option into the 21st century in a healthy state."*
>
> ---"OMEGA Programme: Partitioning and Transmutation R&D Programme of Japan," in Organisation for Economic Co-Operation and Development/Nuclear Energy Agency, *Actinide and Fission Product Partitioning and Transmutation: Status and Assessment Report*, Paris: OECD/NEA, 1999, page 253.

Summary

One of the biggest obstacles facing the nuclear industry is what to do with the nuclear waste generated in the form of spent fuel discharged from commercial reactors or in the form of high-level waste originating from the extraction of plutonium from spent fuel.[1]

Most countries' preferred option for the isolation of nuclear waste from the public and the environment is to bury it underground in a deep geological repository. However, because the spent fuel and the high-level waste contain a number of radionuclides that have very long half-lives (thousands of years to millions of years) it is generally acknowledged that it is impossible to ensure the isolation of the waste for such long periods of time. Besides the likelihood of leakage of some long-lived radionuclides, it is also impossible to guarantee against human intrusion (intentional or inadvertent).

The extremely difficult questions regarding ensuring isolation of waste to a degree sufficient to prevent severe contamination of resources, notably water resources, has made the siting of repositories a controversial scientific and policy issue and has been at the center of much of the public concern and opposition to repositories. Further, the political expediency that has frequently accompanied the selection of sites for study has intensified this opposition. While programs for siting repositories for spent fuel and high level waste are in various stages in different parts of the world, these still face immense scientific hurdles and intense public opposition. In the United States, which has a 2010 target date for opening a repository, there are still no final environmental standards for the protection of the health of future generations and of the environment from the proposed repository at Yucca Mountain. [2]

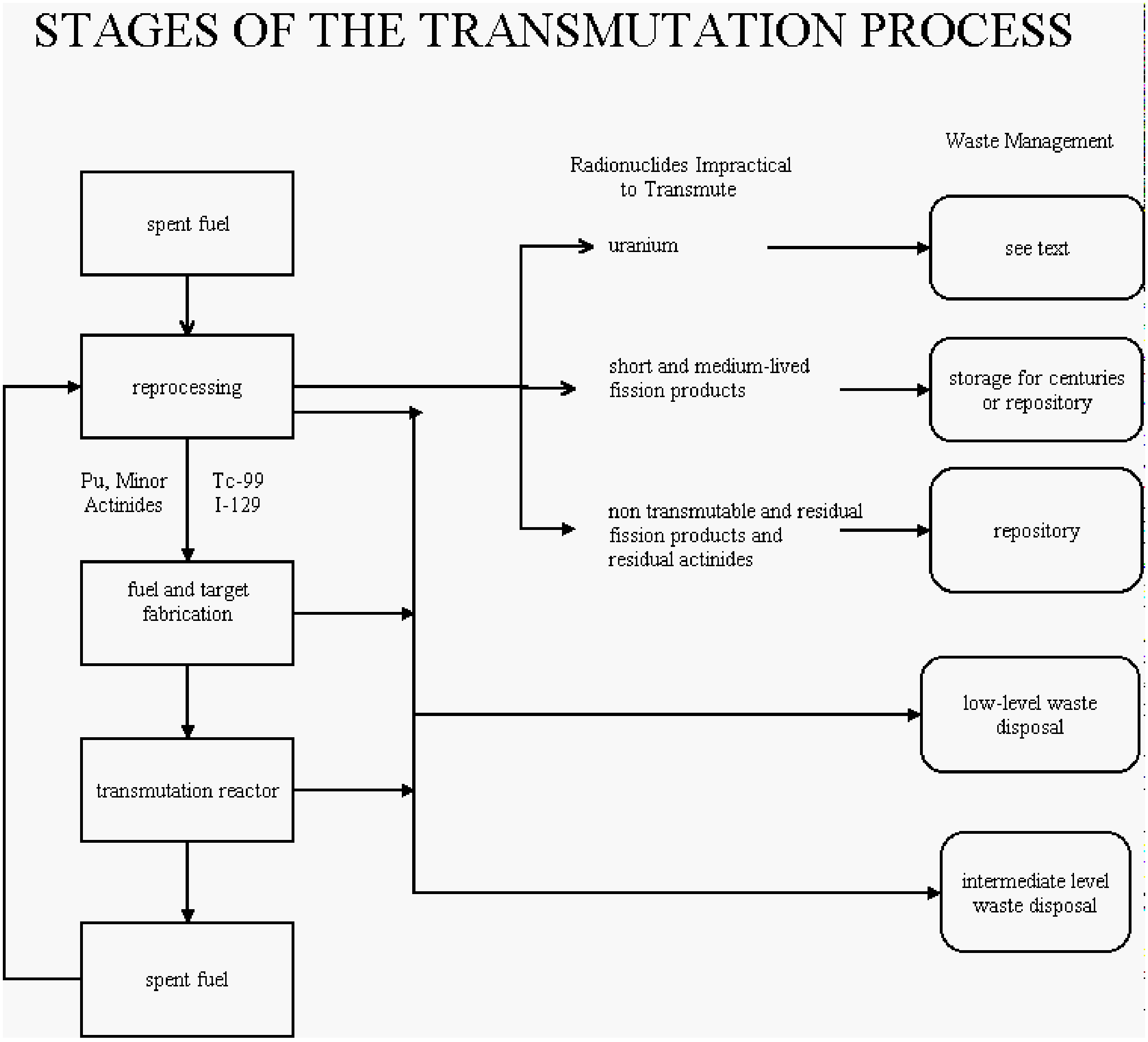
The difficulties and questions associated with repository siting, notably the extremely long periods of isolation required, have caused some to view the transmutation of long-lived radionuclides into short-lived ones as a potential solution to the problem of radioactive waste management. Transmutation is done by inducing nuclear reactions of various types in the nuclei of long-lived radionuclides. The theory is that a transmutation program would transform the vexing problem of long-term isolation into a far less difficult one of storage for several decades or a few hundred years.

This *theoretical* promise has led proponents of transmutation to claim that it would greatly decrease the problems associated with long-term management of nuclear waste. Occasionally, they have even claimed that it might eliminate the need for a repository, though such claims have tended to recede as investigations into the practicalities of transmutation have progressed. At the same time, environmental, waste management, cost, and proliferation concerns have risen. In addition to its promise of a solution to the nuclear waste problem, some transmutation proponents have touted it as the only complete solution to the proliferation problems posed by plutonium. They argue that as long as plutonium remains, either in stockpiles of separated plutonium or in spent fuel that can be reprocessed to obtain separated plutonium, the proliferation risks will remain. Their solution is to use the plutonium as fuel in reactors even if this requires the separation of the plutonium and therefore an increase in proliferation risks over the short term.

Transmutation basics

Transmutation is the transformation of a radionuclide into another radionuclide, or into two or more radionuclides. Nuclear waste transmutation involves nuclear reactions that would occur in some form of nuclear reactor (thus producing electricity at the same time as transmuting the radionuclides).[3] A variety of reactor schemes have been proposed, but they all possess a common characteristic: a substantial amount of energy must be delivered to the nucleus of a long-lived radionuclide in order to induce a nuclear reaction that would convert it into a short-lived radionuclide or a stable element.

Figure 1



The figure above shows the main components of an idealized transmutation system. A reprocessing plant is needed to sort out the candidate radionuclides slated for transmutation by separating certain long-lived radionuclides from the others. (In the context of transmutation, reprocessing is also called "separation" or "partitioning.") This allows the selective conversion of long-lived radionuclides into short-lived ones when they are irradiated in a reactor. Without reprocessing, the opposite kind of nuclear reactions would cause a counterproductive conversion of some short-lived radionuclides into long-lived ones.

The fabrication facility then manufactures the long-lived radionuclides into fuel and/or targets that are then sent to the transmutation facility, where the conversion of the nucleus actually takes place. The central component of a transmutation facility is a nuclear reactor. It may be a critical reactor, which is a self contained transmutation device, or a sub-critical reactor, which needs an outside source of neutrons to sustain a chain reaction.[4]

The neutron induced reactions in the reactor transmute the long-lived fission products into short-lived ones; they also fission the actinides, such as plutonium, creating new fission products. Most of these fission products are short-lived, but new long-lived fission products are also created (see below). The actinides, like uranium and plutonium, can also absorb neutrons, resulting in the creation of higher-mass actinides (see below). So plutonium and other transuranic radionuclides are actually being created in some portions of the fuel in transmutation devices, while in others they are being destroyed. Further, not all actinides can be transmuted before the nuclear reactor becomes very inefficient. Hence, a number of passes through the reprocessing, fuel fabrication, and reactor facilities are needed in order to transmute most long-lived radionuclides.

Transmutation of all long-lived radionuclides into short lived ones to a degree sufficient to obviate the need for a geologic repository is practically impossible. In particular, the transmutation of separated uranium, which constitutes about 94 percent of the weight of light water reactor spent fuel and which is very long-lived and generally contaminated with some fission products, would be counterproductive. The main transmutation route for almost all the uranium would be to convert uranium-238 (the dominant isotope) into plutonium-239. Hence, the complete transmutation of uranium-238 essentially requires the creation of a plutonium economy, which would be unsound whether viewed from an economic, environmental, or non-proliferation standpoint. Almost all the uranium must therefore be disposed of without transmutation as a matter of practical necessity. Other long-lived fission products as well as residual transuranic actinides would also need disposal. Hence, a repository, as well as other waste management and storage facilities would still be an essential part of transmutation schemes.

The merits of transmutation schemes and the difficulties associated with them become clearer if we understand some basics about the physics of transmutation.

The physics of transmutation

Two transmutation reactions are important for nuclear waste management: neutron capture and fission.[5] The goal is that long-lived radionuclides be transformed into short-lived radionuclides that then decay into stable isotopes.

To provide concrete examples, this section will discuss neutron capture by two long-lived fission products: iodine-129 and cesium-135. In addition we illustrate two reactions involving plutonium-239 transmutation.[6]

The absorption of a neutron by iodine-129 results in the production of short-lived I-130 and then in the stable isotope xenon-130.[7] Cesium-135 captures a neutron to become short-lived Cs-136, which decays into stable barium-136.[8] Hence, in these two cases, nuclear theory indicates that transmutation of these troublesome long-lived radionuclides into non-radioactive, stable ones is possible. However, as a practical matter only I-129 can actually be considered a candidate for transmutation. In the case of cesium-135, transmutation would first require the separation of this specific isotope from cesium-133, which is stable. This is because successive capture of neutrons by cesium-133 converts it first into Cs-134 (short-lived) and then into Cs-135, which is long-lived.[9] The cesium in spent fuel is a mixture of both Cs-133 and Cs-135 isotopes which cannot feasibly be separated, in part because the presence of the very radioactive Cs-137 isotope makes the handling and processing of the cesium extremely difficult, expensive, and dangerous. Thus, it is easy to see that the benefit of transmuting Cs-135 would be negated by the production of more Cs-135 from the neutron capture of Cs-133.

Some neutrons interactions with plutonium-239 result in fission while others result in the formation of plutonium-240 with a half-life of 6,500 years, which while shorter than the 24,000-year half-life of Pu-239, is evidently still very long. Successive neutron captures result in higher plutonium isotopes.[10]

This illustrates that transmutation nuclear reactions would need to be closely controlled so that there is an overall change from long-lived to short-lived radionuclides without a build up of new long-lived radionuclides.

Note also that neutron capture by plutonium-239 and -240 would not solve the problem of eliminating long-lived radionuclides even if all the plutonium were converted to short-lived plutonium-241. This is because plutonium-241 has an entire decay chain associated with it. It decays into americium-241, which has a half-life of 430 years. Amercium-241 in turn decays into neptunium-237, which has a half-life of over 2 million years. It is evident that neutron capture and the creation of heavier plutonium isotopes creates new problems in place of old ones. By contrast, when plutonium-239 fissions, most fission products are short-lived, while some are long-lived. Hence, significant reduction of the mass of long-lived actinides, such as plutonium, generally necessitates fission of the nuclei.

Fission transmutation reactions produce mostly short-lived fission products that decay into stable elements. The example below shows the production of two short-lived fission products, tellurium and molybdenum. They both undergo a series of beta decays. The decay chain of molybdenum-102 consists of short-lived radionuclides until it reaches stable (non-radioactive) ruthenium-102. Tellurium decays into long-lived cesium-135.

Pu-239 + n → Pu-240 → Te-135 (19 seconds) + Mo-102 (11 minutes) + 3 n

↓ ↓

I-135 (6.6 hours) + e Tc-102m (4.4 minutes) + e

↓ ↓

Xe-135 m (15 minutes) + e Tc-102 (5.3 seconds)

↓ ↓

Xe-135 (9.1 hours) Ru-102 (stable) + e

↓

Cs-135m (53 minutes) + e

↓

Cs-135 ($2.3x10^{6}$ years)

Proposed transmutation schemes

Various schemes have been proposed for transmutation. Three types of reactors (light water reactors, fast reactors, and sub-critical reactors) and two types of reprocessing have been proposed. Table 1 shows the type or types of reprocessing associated with each type of reactor and the radionuclides that would be candidates for transmutation. Most transmutation schemes would use a combination of reactors and associated reprocessing technologies. For example, in one scheme, light water reactors would be fueled with mixed oxide (MOX) fuel - that is, fuel made with plutonium extracted from conventional reactor spent fuel which is mixed with depleted uranium, with both materials being in an oxide chemical form. The MOX spent fuel then would be reprocessed and the transuranic actinides would be extracted to fuel a fast neutron reactor (also commonly called a breeder reactor). The fast reactor fuel would, in turn, be reprocessed and the remaining actinides would fuel a sub-critical accelerator driven reactor.

Table 1: Transmutation schemes

Reactors and neutron sources	Type of reprocessing and candidate radionuclides for transmutation	Comments
Light water reactors (LWRs) (the most common type of commercial nuclear reactor) The reactor is critical and fueled with either low-enriched uranium or mixed oxide uranium-plutonium fuel.	Reprocessing: aqueous Radionuclides: Primarily plutonium, Tc-99, I-129.	• Creates high proportion of higher mass actinides with associated severe radiation hazards • Reprocessing creates large amounts of liquid radioactive waste • Issues of reactor safety • Cannot fission most actinides • Heavy transuranic build-up, creating waste management problems
Fast reactors: The reactor is critical and can be fueled with plutonium, uranium or, potentially, fuel containing some minor actinides.	Reprocessing: mostly dry in advanced schemes. Radionuclides: Plutonium and possibly minor actinides. Tc-99 and I-129 may be possible but only in moderated targets outside the reactor core.	• The development of fast reactors has been crippled by persistent problems • Fission products are not efficiently transmuted • Heavy transuranic build-up though to a lesser extent than with LWRs • Issues of reactor safety
Sub-critical reactors: an accelerator-target system provides fast neutrons to a sub-critical reactor	Reprocessing: the reprocessing can be all aqueous or all dry or a combination of the two Radionuclides: plutonium and minor actinides. Tc-99 and I-129	• Sub-critical reactors are only at the R&D stage • Cost is projected to be high. • Reactor safety still an issue

	may be possible but only in moderated targets outside the reactor core.	• Fission products are not efficiently transmuted

None of these schemes can transmute uranium, cesium-135, carbon-14, and some other radionuclides. **Table 2** (below) shows the various radionuclides of concern from the point of view of long-term management and their status with respect to various transmutation schemes.

Table 2: Main Long-lived Radionuclides of Concern

Radionuclide (half-life in years, to two significant digits)	Type	Impact	Transmutation Potential	Transmutation Problems
Tin-126 (100,000)	Long-Lived Fission Product	Groundwater release	Difficult	Difficult to separate from spent fuel/HLW. Long time to transmute. Lower isotopes result in new production of radionuclide
Selenium-79 (60,000)	Same	Same	None	Same
Cesium-135 (2.3 million)	Same	Same	None	Formation of more Cs-135 from Cs-133. Isotopic separation difficult due to presence of Cs-137
Zirconium-93 (1.5 million)	Activation Product	Groundwater release	None	Presence of stable Zr isotopes would produce more Zr-93. Would require expensive isotopic separation.
Carbon-14 (5,700)	Activation Product	Groundwater release and/or air release as CO_2; incorporation into living matter	None	Small neutron capture cross-section. Often released as gas from reprocessing operations
Chlorine-36 (300,000)	Activation Product	Groundwater	None	Presence of natural Cl-35 would generate more Cl-36
Technetium-99 (210,000)	Long-Lived Fission Product	Groundwater Release. Affects thyroid	Yes. Requires slow neutrons	Would require several transmutation cycles
Iodine-129 (16 million)	Long-Lived Fission Product	Same	Yes. Requires slow neutrons	Same. Also, difficulty in capturing during separation. Difficulty in fabricating targets. Could pose corrosion problems
Uranium (mainly U-238, 4.5 billion)	Actinide source material	Forms bulk of spent fuel (~94 percent by weight). Has higher radioactivity than TRU waste slated for geologic disposal	None. Would be separated and disposed of as LLW or used like depleted uranium	U-238 transmutation would result in the generation of more Pu-239 defeating the purpose of transmutation as a waste management strategy. Would essentially create a breeder reactor economy.
Americium-241 (430)	Actinide	Gamma-emitter. Human intrusion. Groundwater release (parent of U-233). Radiotoxicity	Preferably in fast reactors	Would require multiple separation and irradiation cycles. Would result in creation of curium which would make subsequent cycles more difficult
Neptunium-237 (2.1 million)	Actinide	Groundwater release	Preferably in fast reactor	Formation of more radioactive shorter-lived Pu-238
Curium-244 (18)	Actinide	Highly radioactive alpha and gamma emitter. Contributes to heat of spent fuel.	Difficult. Requires fast reactor	Difficult to separate from other actinides in HLW due to handling and chemistry problems. Would require multi-recycling along with other actinides. Could require storage of decades or even a century. More Cm-244 and other Cm isotopes created in irradiation of lower actinides (Pu and Am).
Plutonium (mainly	Actinide	Pu-239 Fissile.	Fast reactor	Neutron capture forms higher isotopes and

Pu-239, 24,000)		Radiotoxicity. Goes to bones	required for non-fissile isotopes.	higher actinides (e.g. Am and Cm).
Strontium-90 (29)	Medium-lived Fission Product	Contributes to initial heat of waste. Determines repository capacity. Intrusion scenario dose. Behaves like calcium in the body	None	Cannot be transmuted due to small neutron cross-section. Forms a large part of the heat of spent fuel and high level waste and therefore limits increase in repository capacity from transmutation..
Cesium-137 (30)	Same	Same except behaves like potassium in the body. Also radiation barrier to proliferation.	None	Same. Also, separation from fissile materials eliminates radiation shielding for proliferation prevention.

Residual Waste

Even the most elaborate transmutation schemes will leave behind substantial amounts of long-lived radionuclides requiring disposal, while generating large new volumes of operating and decommissioning wastes. Transmutation does not eliminate the need for a high-level waste repository. First, no transmutation scheme is able to deal with all of the radionuclides of concern since many cannot be transmuted for practical purposes (see example of uranium and Cs-135, above). Second, transmutation of Tc-99 and I-129 is not 100% effective, even with multiple passes through the reactor. Third, new long-lived fission products are created from the fission of the actinides. Fourth, fissioning of the actinides is not 100% effective in eliminating them. For instance, even the most optimistic, best-case estimate concedes that at least 2.4 metric tons of transuranic radionuclides would be left over after the transmutation of 906 metric tons of transuranics anticipated to be produced by US nuclear reactors during their licensed lifetimes.[11] Moreover, the composition of the residual transuranic waste would be shifted towards higher isotope actinides, making the residual fraction more radioactive per unit weight. This would result in greater radiological risks, complicate disposal, and limit any gains in repository capacity due to a smaller actinide inventory. Fifth, the disposal in a repository of cesium-137, which is mixed with cesium-135 in spent fuel, would necessitate a large repository. This is because the intense radioactivity of cesium-137 results in the generation of a large amount of heat, which necessitates an increase in spacing of the disposal canister. The large space requirements would negate one of the most important benefits of transmutation - that of reducing repository size for a given nuclear energy generation.[12] Only storage of long-lived wastes for a hundred years or more, with its attendant high uncertainties, risks, and costs, would significantly alleviate this repository capacity problem.[13] Finally, waste from prior reprocessing operations, whether for commercial or military purposes, is highly unlikely to be transmuted since almost all of it will have been vitrified for safety reasons before a transmutation program can be put into place. This large amount of waste would have to be sent directly to the repository. In other words, there are fundamental and substantial limitations to the reduction in long-lived radioactivity that can be achieved even with an elaborate and very expensive transmutation program.

Table 2 shows the main long-lived radionuclides of concern and the feasibility of their transmutation. As can be seen from this table there are a large number of radionuclides, which cannot be transmuted due to complicating factors or because of the nature of the radionuclide. These include the medium-lived fission products, uranium (which forms about 95 percent of spent fuel), and many long-lived radionuclides that arise either from fission or from neutron activation.[14] Of the long-lived fission products, only technetium-99 and iodine-129 have the potential to be fabricated into targets and transmuted in a reactor. The plutonium, and in some cases, the other minor actinides, would be made into fuel to run the transmutation reactor. The actinides could either undergo fission or capture a neutron, though for the purposes of transmutation, which is trying to reduce the amount of actinides, fission is preferred.

Transmutation would also create significant quantities of additional transuranic and low-level waste, particularly if aqueous reprocessing is used. Furthermore, it has been proposed in the United States to dispose of uranium separated from spent fuel in a transmutation program as "low-level" waste in shallow land burial sites. This, along with the possible shallow-land disposal of other long-lived radionuclides, could result in an even greater overall radiological risk to the public from transmutation, compared to disposal of all spent fuel in an appropriately selected and engineered repository. The same observation is also likely to be true of worker and public health hazards arising from repeated reprocessing of spent fuel, fabrication of increasingly radioactive fuels and operation of new reactor types with which there is little commercial experience. Transmutation, even in the context of a phase-out of nuclear power, would also require decades to implement and possibly centuries to complete.[15] This may require institutional control over the waste for time periods much longer than is feasible or desirable.

Implications of Transmutation

The implementation of any of the transmutation schemes discussed above would also have a number of implications for nuclear proliferation, the environment and human health, safety, cost, and the future of nuclear power.

Proliferation. All transmutation schemes require reprocessing and separation of transuranic radionuclides. The current use of commercial reprocessing and MOX fuel, the simplest of schemes to transmute a small fraction of existing plutonium, results in the separation of significant quantities of plutonium, which is undesirable from a proliferation standpoint. The current mismatch between reprocessing capacity and reactor capacity for MOX use has meant that a significant stockpile of commercial separated plutonium has accumulated worldwide (including 30 metric tons in Russia). While some new transmutation schemes would materials that would be unattractive to weapons designers in nuclear weapons states, they are nonetheless weapons-usable and would pose significant proliferation risks. Non-state groups or non-weapons states that do not have weapons-usable materials today might seek to acquire and use them because they may be more available in less secure facilities. Even the reprocessing methods that are labeled as proliferation resistant, such as pyroprocessing, can be modified to allow for the extraction of plutonium pure enough to make weapons.

Some reprocessing technologies proposed for transmutation may increase proliferation risks due to their compact size and attendant difficulty of detection. These would lead to new and more difficult problems in developing adequate safeguards in an already complex field. Furthermore, promotion of transmutation as a waste management tool may result in the widespread transfer of reprocessing technology. The separation of isotopes like neptunium-237 and americium-241 (which are two of the radionuclides produced during irradiation of fuel in a reactor) would also increase proliferation risks, since both of these radionuclides can also be used to make nuclear weapons. In sum, transmutation is a scheme that would greatly increase separation of weapons-usable material and/or the diffusion of technologies that would facilitate such separation. It will thereby considerably increase the risks of nuclear proliferation.

Environment and Health. Reprocessing, which is required in all transmutation schemes, is one the most damaging components of the fuel cycle. It results in the discharge of large volumes of waste and radioactive emissions to air and water. Health and environmental concerns regarding reprocessing are the basis of the demands of Ireland, Norway, Iceland, and Denmark that Britain and France eliminate their so-called "low-level" radioactive waste discharges from their reprocessing plants into the seas. The increased radiological risk of handling fuel that has been repeatedly irradiated is cause for serious concern. Finally, the increased transportation of high level waste required under a number of transmutation schemes would increase the probability of a transportation accident.

Reactor Safety. All transmutation schemes that would transmute significant amounts of plutonium and other transuranic materials require the use of reactors that are currently not commercial. Some schemes would use breeder reactors, which face serious technical issues even after five decades of development, and have not yet been commercialized. Other schemes would use accelerator-driven sub-critical reactors, which have not yet been built. Yet other schemes would use combinations of these two reactor types.

Some new reactors, notably accelerator-driven sub-critical reactors, have been described as "inherently safe." However, increases in certain safety features, in comparison with commercial light water reactors, is countered by decreases in other safety features and the creation of new safety problems particular to the new reactor designs. According to Dr. Lawrence Lidsky of MIT's Nuclear Engineering Department, "sub-critical systems can actually be more dangerous than conventional reactors if, as is often the case, there are more subsystems that can fail or initiate failures, and fewer backups. Probabilistic risk analysis is a complex art, requiring a deep understanding of possible accident initiators and accident progression, and the ATW design is far too rudimentary at this time to apply this powerful tool. However, it is clear that the currently envisaged ATW systems are more complex than fission reactors, have more accident initiators, and many fewer backup safety systems." It is thus premature, at best, to label these reactors as inherently safe. And according to one eminent authority, they could be a lot more dangerous. There is therefore ample reason for caution.

Cost. The cost of transmutation, particularly for the advanced schemes that would be required in order to have significant reduction of actinides, is prohibitively expensive (even in comparison to the billions to be spent on repository programs). Furthermore, while electricity would be produced to offset these costs, it is highly unlikely that these revenues will be sufficient. Transmutation would likely require tens of billions of dollars to develop, and additional large subsidies during operations, even after accounting for electric power sales. Even current uses of plutonium in reactors, both in light water reactors and in fast reactors, are not economical. The overall cost can be expected to be many tens of billions of dollars of net costs and overall investments up to hundreds of billions of dollars.

Continuation of Nuclear Power. Transmutation is not only considered in the context of managing the waste from the current generation of nuclear reactors (i.e. as part of a phase-out of nuclear power). Most transmutation schemes, particularly in Europe and Japan, assume an indefinite continuation of nuclear power, with transmutation as one part of a new nuclear fuel cycle. By supposedly solving some of the current problems with nuclear power (particularly waste management, but also reactor safety in some cases), transmutation is seen by some as essential to ensuring the continued growth of nuclear power. Seen in this light, transmutation of waste is actually a Trojan horse for perpetuating nuclear power and hence the generation of more and more radioactive wastes for the indefinite future. This is surely not the way to solve the problem of managing radioactive waste from the current generation of commercial reactors.

Conclusions and Recommendations

Our main finding is that transmutation schemes will not solve long-term waste management problems. Well over 90 percent of the weight of spent fuel consists of uranium. According to according to current US proposals, the uranium would be treated as low-level radioactive waste and be disposed of in ways that will likely pose far greater risks than disposal in a carefully selected and engineered deep geologic repository. In addition, considerable quantities of transuranic materials would remain after transmutation, along with long-lived fission products. Large quantities of new waste would be created, along with new proliferation risks and high costs. Despite these severe limitations, transmutation continues to be seen by some as a "seductive" area of research and essential for revitalizing the "nuclear option."

In light of these conclusions, IEER's main recommendation is that, because there is no sound technical basis for proceeding, transmutation should be abandoned as a waste management technology. Detailed findings and recommendations are given below.

Findings

1. Transmutation will not solve either the problem of long-term radioactive waste disposal nor the proliferation risks posed by current stockpiles of plutonium. While solutions are required for both of these problems, the use of reprocessing and nuclear reactors is not the best option.
2. The transmutation literature does not evaluate overall risk and is unclear about environmental or proliferation consequences relative to the once-through fuel cycle. The lack of comprehensive and consistent criteria by which to judge transmutation has led to a number of erroneous conclusions concerning its benefits.
3. Reprocessing is required for all transmutation schemes. Reprocessing is one of the most environmentally damaging parts of the nuclear fuel cycle, resulting in emissions to the air and water and in large volumes of radioactive waste. The increased separation requirements of transmutation means that even more processing is required as additional process steps are added to remove specific radionuclides.
4. The separation of radionuclides necessary for transmutation will increase proliferation risks by providing easier access to fissile materials. All separation processes, including those labeled "proliferation resistant," result in an increased proliferation risk over the once through fuel cycle. The implementation of transmutation as a waste management technology will result in more widespread application of reprocessing.
5. Transmutation can only be used to reduce the inventory of some of the radionuclides of concern for waste management. Even for those radionuclides, the process is not 100% efficient and significant amounts of long-lived waste will remain. Transmutation will not eliminate the need for a high-level waste repository or other form of isolation from the biosphere. The remaining long-lived radionuclides, including the uranium which accounts for about 94% of the spent fuel mass, as well as the radionuclides produced during the transmutation process will require disposal. Furthermore, transmutation can only be applied to spent nuclear fuel and some high level waste and not to the full range of radioactive wastes (e.g. transuranic wastes or mining wastes) which exist.
6. While the radiological risk from disposing of radioactive waste in a geologic repository may decrease as a result of transmutation, the overall risk to workers and the public may increase from a combination of disposal of separated uranium and other materials, emissions from new reprocessing and irradiation facilities, and processing of fuel that is more radioactive. These risks have not been adequately assessed in proposals for transmutation.
7. Transmutation will increase the mass and volume of radioactive material requiring disposal. In addition to the high level waste and uranium that would still require repository disposal (see Finding 5, above) reprocessing and transmutation operations will result in more transuranic and low level waste requiring disposal. These newly generated wastes will be in addition to the original mass of the spent fuel, resulting in an overall increase in mass of waste to be disposed of.[16] Decommissioning wastes will also increase and can be expected to be substantial.
8. Transmutation will be expensive to implement. Life-cycle cost estimates are rarely presented, but current cost estimates which have been done are unrealistically low, particularly for reprocessing and decommissioning. Even with these low cost estimates and sales of electricity to offset those costs, full-scale transmutation will require some form of government funding and subsidy or substantial increase in utility waste disposal fees. In the United States alone, the net costs over the course of 118 years, after electricity sales, could be over $150 billion (as opposed to $36 billion for direct disposal at Yucca Mountain).[17]
9. Transmutation will rely on nuclear reactors that would pose serious hazards in case of accident. Both sub-critical and critical reactors contain large inventories of radioactive materials, which can be released during an accident. Transmutation, if it is to achieve any significant reduction in the inventory of actinides, will require the construction and operation of a significant number of fast reactors, whether critical or sub-critical, posing significant safety issues.
10. The increased radiological risks of working with reprocessed materials, particularly fuel that is repeatedly reprocessed, will increase risks to nuclear fuel cycle workers and increase the cost of protecting those workers.
11. Transmutation would require a sustained effort over very long periods of time. Assuming an immediate start to research and development activities, transmutation of the expected spent fuel from existing U.S. reactors would take 118 years to transmute (including development time). The Nuclear Energy Agency of the Organization for Economic Co-operation and Development estimates that transmutation could take decades, and even centuries, depending on various factors.

12. The reliance of some transmutation proposals on above-ground monitored storage for highly radioactive fission products for hundreds of years (e.g. in Carlo Rubbia's proposal for Spanish waste management) is unrealistic and risky.
13. Transmutation will increase the number of shipments of nuclear high level waste and therefore the probability of a transportation accident. Spent fuel or high level waste would have to be shipped from current storage locations to transmutation sites and then to final disposal. In cases where reprocessing facilities would not be co-located with reactors, the waste would have to be repeatedly shipped between reactors and reprocessing facilities. If transmutation does not begin until after a repository is opened and has started to accept waste (as would be the case in the United States), then spent fuel would be shipped from current storage locations to the repository, removed from the repository for shipment to the transmutation site, and then the residual spent fuel and high level waste would be shipped back to the repository.
14. Transmutation of nuclear waste appears to be one component of a nuclear industry effort to increase the use of nuclear power. Significant development of nuclear power reactors would be required to implement transmutation and, at the same time, transmutation would be seen as a "solution" to the nuclear waste problem. The result could be a continuation of nuclear power, even beyond what would be necessary to transmute current reactor fuel, and thus a continual production of new nuclear waste. Hence, instead of reducing nuclear waste, it could result in increasing and continual generation of waste into the far future.

Recommendations

1. **Regulations governing the disposal of uranium should be strengthened.**
   The uranium extracted during transmutation has a higher enrichment than natural uranium and will be contaminated with fission products and actinides. The uranium will exceed the radioactivity concentration limit placed on plutonium waste in the United States many times over.[18] Despite this fact, transmutation proposals call for the uranium to either be used for commercial re-use in conventional nuclear power plants or disposed of as low-level waste. Neither of these options would be protective of public health. Therefore, uranium should be regulated using the same criteria that are used for transuranic waste.
2. **The current use of plutonium fuel in nuclear reactors should be halted.**
   Transmutation schemes build upon the current use of plutonium in light water reactors as MOX fuel and on breeder reactor demonstration programs, which were supposed to produce more plutonium than they consumed. MOX fuel is uneconomical in comparison to other energy sources, such as wind power, and the use of MOX was only initiated when breeder reactor programs did not live up to expectations. Commercial MOX fuel use also increases proliferation risks due to the need for reprocessing in order to separate plutonium and complicates safety and environmental problems connected to reactor operation and waste disposal. Breeder reactor programs, which form the basis of a number of transmutation technologies, have been plagued by problems throughout their history, including safety deficiencies, technical operating problems, and uneconomical operation. They would pose even greater proliferation problems than the use of MOX in light water reactors, particularly as full-scale breeder reactor programs would result in even greater quantities of separated plutonium. Breeder reactors can also be relatively easily reconfigured from a waste transmutation role to one of making weapon-grade plutonium.
3. **Current reprocessing operations in all countries should be halted and commercial stockpiles of separated plutonium should be considered a waste to be immobilized.**
   Plutonium reprocessing operations pose unacceptable environmental, proliferation and financial risks and should cease. Existing stocks of separated plutonium should be immobilized (encasing it in a solid material like glass). This would reduce the proliferation risks of separated plutonium while not encouraging the further separation of plutonium from spent fuel. Feasibility studies should be conducted in the United Kingdom, France, and Japan (with the aid of the United States and Russia) on the conversion of MOX fuel fabrication facilities to ceramic immobilization facilities.[19]
4. **The definition of reprocessing should be clarified**
   Any technology which processes spent fuel, and results in a product that includes separated fissile materials, or from which it is easier to separate fissile materials, should be considered a reprocessing technology. This is because virtually any combination of plutonium isotopes, as well as actinides such as americium and neptunium, can be used to make nuclear bombs. Thus, proliferation impacts should be evaluated according to the separation of weapons-usable materials and the potential of the technologies that are used for being modified for producing such materials even if that is not their normal function as part of a waste transmutation system.
5. **Waste management research efforts should be redirected towards scientifically sound long-term management of nuclear waste.**
   High-level waste management has been plagued by short-sighted political expediency. For instance, in the United States only one site, Yucca Mountain, is being actively developed, which has resulted in severe pressures to open it despite extensive evidence of its unsuitability. Reforms should be implemented to stop politically expedient repository projects, and those, like transmutation, which seem to have keeping nuclear power alive as a subterranean goal. We need a broad-based scientific search for appropriate disposal options in contrast to efforts on transmutation.
6. **Evaluations of transmutation should be based on the overall risks of such a program.**
   Much of the current technical literature on transmutation focuses on the possibility of transmutation to reduce the amount of actinides in high-level waste. This is a questionable approach, given the potential for significant increases in worker and public doses due to increased fuel cycle activities, inappropriate disposal of some

reprocessing waste such as uranium, generation of more waste especially in reprocessing operations, and the open questions about the effect that transmutation will have on doses from a repository. All of these various risks need to be included in any overall analysis. At the very least transmutation programs should be suspended until such an analysis, conducted by an appropriate *independent* body, has been openly and thoroughly done with public input.

7. **Government funding of transmutation research should be stopped.**
   In Europe and Japan, where transmutation research budgets are substantial, funds should be redirected to repository programs or other nuclear waste management programs that do not rely on reprocessing and nuclear reactors. Transmutation programs are diverting valuable resources from other, more appropriate, waste management options. Similarly, in the United States, further work on Accelerator Transmutation of Waste (ATW) or other transmutation schemes should be halted. Furthermore, the United States Department of Energy should halt all research on separation processes, including those based on electrometallurgical techniques. This research should be considered a violation of the federal policy against reprocessing of commercial fuel.

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Full Report, Table of Contents
Press Release
Statement of Hisham Zerriffi
Statement of Annie Makhijani
Ordering information

Also see article on transmutation in *Science for Democratic Action* vol. 8 no. 3 (May 2000)

Return to IEER Home Page

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Endnotes

1. There are over 400 nuclear power reactors currently operating worldwide. About 220,000 metric tons of spent fuel have been discharged from these reactors to date (the year 2000), and the number is increasing at a rate of about 10,000 metric tons per year. Almost 20 percent of the plutonium in this fuel has been extracted by reprocessing, while the rest is stored as spent fuel. See IAEA 1997b, p. 119, and Energy Information Administration, U.S. Department of Energy. *World Spent Fuel Discharges, Reference Case, 1999-2020*. http://www.eia.doe.gov/cneaf/nuclear/n_pwr_fc/data98/table10.html. For reprocessing data and estimates, see Albright, Berkhout, and Walker 1997, Chapter 6.

2. See *Science for Democratic Action* vol. 7, no. 3 (May 1999) for more information about issues related to the long-term management of nuclear waste, particularly in the United States, and for just some of the evidence concerning Yucca Mountain's unsuitability as a repository location.

3. Reactors do not necessarily have to produce electricity. For instance, with one exception, none of the reactors used to produce plutonium for nuclear weapons in the United States produced electricity. However, the sale of electricity is the only way to recoup some of the high costs associated with transmutation. This requirement can create its own problems, however, by raising the reliability requirements of some transmutation systems so as to not disrupt electricity supply once it is operational (see section on accelerator reliability in Chapter IV).

4. Accelerated protons hitting a target made of heavy metal, which produces neutrons through a nuclear reaction called spallation, would produce the supplemental neutrons.

5. Transmutation is also possible using photonuclear reactions, which use energetic photons to induce transmutation. Photonuclear transmutation schemes share many technical details with schemes discussed in this report and pose essentially the same major problems. However, phototransmutation is even less developed and would pose even greater research and development hurdles.

6. Reactions are shown in the footnotes with half-lives shown in parentheses. n = neutron; e = beta particle; m = metastable (an excited state of the nucleus that does not decay immediately to the ground state). Half-lives are rounded to two significant figures

7. I-129 (1.6x10^{7} years) + n → I-130m (9 minutes) → I-130 (12 hours) → Xe-130 (stable) + e

8. Cs-135 (2.3x10^{6} years) + n → Cs-136m (19 seconds) → Cs-136 (13 days) → Ba-136m (0.3 seconds) + e → Ba-136 (stable)

9. Cs-133 (stable) + n → Cs-134 (2.1 years) + n → Cs-135 (2.3x10^{6} years)

10. The reactions are: Pu-240 + n → Pu-241 (14 years); Pu-241 (14 years) + n → Pu-242 (380,000 years)

11. ATW Roadmap 1999d. p. 38

12. In this case strontium-90 would also likely be disposed of in the repository, since its half-life is about the same as cesium-137.

13. For the first one hundred years the fission products dominate the radioactivity of spent fuel (with Cs-137 and Sr-90 being the predominant radionuclides). After 300 years it is the actinides which dominate the radioactivity. Both fission products and actinides contribute to the radioactivity in the period between 100 and 300 years (see NAS-NRC 1983, p. 30).

14. Neutron activation refers to a process by which materials that are not originally radioactive become radioactive after being irradiated with neutrons (e.g. structural materials in the core of a reactor or the material that surrounds the reactor fuel).

15. NAS-NRC 1996, p. 5 and OECD-NEA 1999b, p. 204. Some transmutation schemes would store medium-lived fission products for up to 600 years in order to allow them to decay (see Rubbia et al. 1997).

16. Though not addressed extensively in this report, it must be noted that each of the new facilities operated for the purposes of transmutation will eventually have to undergo decontamination and decommissioning procedures. This will result in even greater amounts of radioactive waste for disposal, including major components of the facilities such as the reactor cores. It is not clear how the increased radioactivity of fuel which has been repeatedly irradiated will affect the D&D process and the disposal requirements.

17. ATW Roadmap cost estimate (ATW Roadmap 1999g) adjusted to reflect more realistic reprocessing costs as established by the National Research Council (NAS-NRC 1996). Figures are in undiscounted 1999 dollars.

18. See Chapter V

19. The issue of separated commercial plutonium will be further explored in a forthcoming report by IEER.