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Waste Transmutation: The Nuclear Alchemy Gamble

BY ANNIE MAKHIJANI AND HISHAM ZERRIFFI

"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] program is expected to serve to revitalize 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.

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. Most countries' preferred option for the

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US DEPARTMENT OF ENERGY

Mobile exhibit of the United States Atomic Energy Commission's "Atoms for Peace" program, 1957. Under the program, which was initiated during the Eisenhower administration, the United States supplied highly enriched uranium for foreign research reactors in 41 countries.

EDITORIAL

Nuclear Power: A Cold War Propaganda Tool

BY ARJUN MAKHIJANI AND MICHELE BOYD

Based on the book The Nuclear Power Deception *by Arjun Makhijani and Scott Saleska*[1]

"It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter..."

— Lewis Strauss, Chairman of the Atomic Energy Commission, 1954

"Heat will be so plentiful that it will even be used to melt snow as it falls....[T]he central atomic power plant will provide all the heat, light, and power required by the community and these utilities will be so cheap that their cost can hardly be reckoned."

— Robert M. Hutchins, president of the University of Chicago, site of the first nuclear chain reaction, 1946

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INSIDE

NUCLEAR POWER

FROM PAGE 1

The idea that nuclear power would be extremely cheap and inexhaustible received a great deal of attention in the immediate aftermath of World War II. As if in purposeful contrast to the new wartime horrors that could be wrought by the atomic bomb, a future in nuclear energy was depicted in glowing terms to evoke a vision of peace, prosperity, and plenty.

Lewis Strauss, chairman of the Atomic Energy Commission (AEC) in 1953, had "faith in the atomic future" and believed that the progress of nuclear power would be guided by "Divine Providence." The US Congress also caught the fever. Its vision was embodied in the Atomic Energy Act of 1954, the major legislation to define the terms for commercialization of atomic energy in ways that were compatible with the manufacture of nuclear weapons. The Act declares that:

> the development, use and control of atomic energy shall be directed so as to promote world peace, improve the general welfare, increase the standard of living, and strengthen free competition in private enterprise.

Applications of nuclear energy to promote the "general welfare" were to be "subject at all times to the paramount objective of making the maximum contribution to the common defense and security."

The US wanted to present a benign image of the atom to the world, even as it built a huge arsenal of ever more powerful weap-

Inaccurate and misleading statements and technological bravado about nuclear power soon became part of the Cold War hysteria that prevailed in the US.

ons. Inaccurate and misleading statements and technological bravado about nuclear power soon became part of the Cold War hysteria that prevailed in the US. By the early 1980s it was clear not only on Main Street but also on Wall Street that far from being "too cheap to meter" nuclear energy was too costly to afford. But other dubious claims have gained currency, such as that the industry can build "inherently safe" reactors or that nuclear power can be used as a practical solution to the problem of greenhouse gas emissions.[2]

Atoms for Peace

After the first Soviet nuclear test in 1949, the United States decided to press ahead with the development of the hydrogen bomb. It began the design, manufacture, and testing of nuclear weapons and opened the Nevada Test Site. The Soviets followed a similar course. The US tested a thermonuclear device on October 31, 1952, and the Soviets did so on August 12, 1953.

Thomas Murray, an AEC commissioner, saw clear "propaganda" benefits in diverting attention from bombs to civilian power, since both the US and the Soviet Union were rushing headlong into the era of the thermonuclear weapons. Such propaganda would show the

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Editor: Lisa Ledwidge

WASTE TRANSMUTATION

FROM PAGE 1

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 admitted 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). Table 1 on page 4 shows the main long-lived radionuclides of concern.

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 contentious 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 target date for opening a repository that could be as early as 2010, there are still no final environmental standards for the protection of the health of future generations and the environment from the proposed repository at Yucca Mountain.[1]

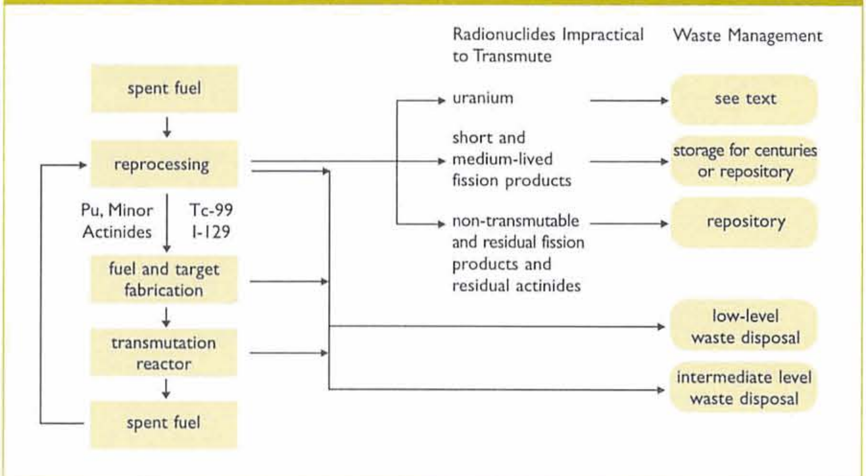
The difficulties and questions associated with repository siting, notably the extremely long periods of isolation required, have caused some to view the transmutation of long-lived radionuclides into short-lived ones as a potential solution to the problem of radioactive waste management. Transmutation 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 problem of long-term isolation into a far less difficult one of storage for several decades or a few hundred years.

The theoretical promise has led proponents of transmutation to claim that it would greatly decrease the problems associated with long-term management. 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. IEER has evaluated the merits and problems associated with transmutation as a waste management concept. This article summarizes our findings and recommendations.[2]

Transmutation basics

Transmutation is the transformation of a radionuclide into another radionuclide, or into two or more radionuclides. Transmutation involves nuclear reactions that would occur in some form of nuclear reactor. 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.

STAGES OF THE TRANSMUTATION PROCESS



The figure on this page 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 short-lived radionuclides into long-lived ones. The fabrication facility manufactures the long-lived radionuclides into fuel and/or targets that are then sent to the transmutation facility, which may consist of a reactor, or a combina-

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TABLE 1: MAIN LONG-LIVED RADIONUCLIDES OF CONCERN

Radionuclide (half-life in years, to two significant digits)	Type	Impact	Transmutation Potential	Transmutation Problems
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.
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 mass). 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 Pu-239, 24,000)	Actinide	Pu-239 Fissile. Radiotoxicity. Goes to bones	Fast reactor required for non-fissile isotopes.	Neutron capture forms higher isotopes and higher actinides (e.g. Am and Cm).

Table is adapted and expanded from Organisation for Economic Co-Operation and Development/Nuclear Energy Agency, *Actinide and Fission Product Partitioning and Transmutation: Proceedings of the Fifth International Information Exchange Meeting.* Mol, Belgium. 25-27 November 1998. Paris: OECD/NEA 1999, p. 470, and 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.

tion of an accelerator, heavy metal target, and subcritical reactor. 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 can also absorb neutrons, resulting in the creation of higher-mass actinides (see below). 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.

But even elaborate schemes cannot practically convert all long-lived radionuclides into short-lived ones. 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 since the main transmutation route for almost all the uranium would be to convert uranium-238 into plutonium-239. 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 still would 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

For nuclear waste management there are two transmutation reactions which are important: neutron capture and fission.[3] The goal is that long-lived radionuclides be transformed into short-lived radionuclides.

The absorption of a neutron by iodine-129 and by cesium-135 are two such reactions (with half-lives shown in parentheses)[4]:

I-129 (1.6×10^7 years) + n → I-130m
(9 minutes) → I-130 (12 hours) + e →
Xe-130 (stable)

Cs-135 (2.3×10^6 years) + n → Cs-136m
(19 seconds) → Cs-136 (13 days) + e →
Ba-136m (0.3 seconds) → Ba-136 (stable)

However, neutron capture can also result in the creation of long-lived radionuclides, defeating the purpose of transmutation, as would be the case with Cs-133:

Cs-133 (stable) + n → Cs-134 (2.1 years) + n →
Cs-135 (2.3×10^6 years)

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.

The following example (with half-lives shown in parentheses, rounded to two significant digits) shows how plutonium-239 would be transmuted by two successive reactions:

Pu-239 (24,000 years) + n → Pu-240 (6,500 years) + n → Pu-241 (14 years)

However, further neutron capture would give Pu-242, which has a long half-life:

Pu-241 (14 years) + n → Pu-242 (380,000 years)

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-live of 430 years. Amercium-241 in turn decays into neptunium-237, which has a half life of over 2 million years. Hence, significant reduction 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, but some of these short-lived fission products can also decay into long-lived ones. 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)	Tc-102 (5.3 seconds)
↓	↓
Xe-135 (9.1 hours)	Ru-102 (stable) + e
↓	
Cs-135m (53 minutes) + e	
↓	
Cs-135 (2.3×10^6 years)	

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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 2, below, 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 low-enriched uranium spent fuel. The MOX spent fuel then would be reprocessed and the transuranic actinides would be extracted to fuel a fast neutron reactor (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.

None of these schemes can, for either fundamental physical reasons or practical reasons, transmute uranium, cesium-135, carbon-14, or some other radionuclides. Table 1 on page 4 shows the various radionuclides of concern from the point of view of long-term management and their status with respect to various transmutation schemes.

Transmutation does not eliminate the need for a repository for high-level waste and spent fuel.

Residual Waste

Transmutation does not eliminate the need for a repository for high-level waste and spent fuel. The theoretical schemes shown above cannot be translated into a practical reality that would eliminate almost all long-lived radionuclides. 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 Cs-133 and Cs-135, above). Second, transmutation of Tc-99 and I-129 is not 100% effective, even with multiple passes through the reactor, and new long-lived fission products are created from the fission of the actinides. Third, fissioning of the actinides is not 100% effective. For instance, in the best estimate of any proposed scheme, transmuting 906 metric tons of transuranics (anticipated to be produced by US nuclear reactors during their licensed lifetimes) would leave a residual of 2.4 metric tons. The composition of the residual transuranic waste would be shifted towards higher isotope actinides and the waste would thus be more radioactive. This would pose greater radiological risks and complicate disposal. Finally, since cesium-137 will be disposed of in the repository with cesium-135, the large amount of heat generated by it would mean that

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TABLE 2: TRANSMUTATION SCHEMES

Reactors and neutron sources	Reprocessing and radionuclides	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 may be possible but only in moderated targets outside the reactor core.	• Sub-critical reactors are only at the R&D stage • Cost is projected to be high. • Reactor safety still an issue • Fission products are not efficiently transmuted

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the space requirements for disposal could be considerable.[5] Only storage of long-lived wastes for hundreds of years, with its attendant uncertainties, risks, and costs, would alleviate this repository capacity problem.

Besides failing to deal with the uranium, which accounts for about 94 percent of the weight of radioactive material in spent fuel, and with significant amounts of long-lived transuranic radionuclides and fission products, transmutation would create significant quantities of additional waste, particularly if aqueous reprocessing is used. (See data on waste generation from once-through LEU and MOX fuel cycles, pages 9-11). It would also shift some material from geologic disposal to low-level waste disposal, particularly if, as has been inappropriately proposed, the uranium is managed as "low-level" waste. This could result in an even greater overall radiological risk to the public, compared to disposal of all spent fuel in an appropriately selected and engineered repository. Transmutation, even in the context of a phase-out of nuclear power, would also require decades to implement and possibly centuries to complete.[6] 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 of transuranic radionuclides. While these schemes may not yield materials attractive to weapons designers in nuclear weapons states, they can be used to make nuclear weapons and would pose significant proliferation risks in that non-state groups or non-weapons states might seek to acquire and use them. Even the reprocessing methods that are labeled as proliferation resistant, such as pyroprocessing, can be easily modified to allow for the extraction of plutonium pure enough to make weapons. These types of facilities may in fact increase proliferation risks due to their compact size and potential problems in developing adequate safeguards. Furthermore, promotion of transmutation as a waste management tool may result in the widespread transfer of this technology. The separation of isotopes like neptunium-237 and americium-241 would also increase proliferation risks, since both of these radionuclides can also be used to make nuclear weapons. Creating and implementing schemes that greatly increase separation of weapons-usable material will considerably increase the risks of proliferation.

Creating and implementing schemes that greatly increase separation of weapons-usable material will considerably increase the risks of proliferation.

Environment and Health. Reprocessing, which is required by all transmutation schemes, is one the most damaging components of the fuel cycle. It results in large volumes of waste and radioactive emissions to air and water. Its health impacts on workers, off-site residents, and even far away populations are well documented. For instance, health and environmental concerns are the basis of the demands of Ireland, Norway, Iceland and other countries that Britain and France eliminate their so-called "low-level" radioactive waste discharges into the seas. Because fuel fabrication does not involve the production of liquid waste, its effects are mainly restricted to workers and are on the same order as for workers in the reprocessing sector. 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 with its attendant effects.

Reactor Safety. Transmutation would require the development and implementation of new reactor technologies and/or the expanded use of existing reactors. Some of these new reactors have been described as "inherently safe." However, increases in certain safety features, in comparison with existing reactors, is countered by decreases in other safety features and the creation of new safety problems unique to the new reactor designs. For example, some feedback effects that help prevent a runaway reaction in existing reactors do not exist in some transmutation reactors. For accelerator based systems, the ability to shut off the neutron source and the fact that the reactor is ordinarily sub-critical provide certain safety advantages. On the other hand, these systems rely strongly on the ability to shut off the neutron source in an emergency. Also, it may be necessary to ensure that the external neutron source is not operating at full power when fresh fuel is in the reactor or else the reactor could become supercritical.

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. 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 even during operations, when electric power

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sales are expected to generate some revenue.

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, transmutation is seen by some as essential to ensuring the continued growth of nuclear power.

Conclusions and Recommendations

Our main finding is that transmutation schemes will not solve long-term waste management problems. Almost all the weight of the waste proposed for transmutation consists of uranium, which would, according to current official proposals, be treated as low-level radioactive waste and be disposed of in ways that will pose far greater risks than disposal in a carefully selected and engineered 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." The evaluations that have promoted transmutation as a waste management technology are seriously deficient in their analysis and have been made mainly by those who would like to see a continuation of nuclear power.

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.

1. See *Science for Democratic Action* vol. 7 no.4 (May 1999) for more information about issues related to the long-term management of nuclear waste.
2. IEER's detailed report evaluating transmutation technologies will be available shortly after the publication of this newsletter.
3. Transmutation is also possible using photonuclear reactions, which use energetic photons to induce transmutation. Photonuclear transmutation schemes pose essentially the same major issues as the schemes discussed in this article and are even less developed than them.
4. n = neutron; e = beta particle; m = metastable (an excited state of the nucleus that does not decay immediately to the ground state).
5. 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.
6. National Research Council. *Nuclear Wastes: Technologies for Separations and Transmutation.* Washington: National Academy Press, 1996. p. 5 and OECD/NEA *Status and Assessment Report* 1999, 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, *Fast Neutron Incineration in the Energy Amplifier as an Alternative to Geologic Storage: The Case of Spain*, CERN/LHC/97-01 (EET), Geneva: European Organization for Nuclear Research, February 17, 1997).

GLOSSARY

Actinide: A group of elements high on the periodic table which includes uranium, plutonium, neptunium, and americium among others. Transuranic actinide refers to those actinides above uranium on the periodic table, primarily plutonium. Minor actinides refers to those actinides other than uranium and plutonium (primarily neptunium, americium, and curium). Elements belonging to the actinide group have broadly similar chemical properties.

Aqueous separation: The use of an aqueous medium — for example, nitric acid in water — to enable the separation of radionuclides.

Beta decay: The emission of electrons or positrons (particles identical to electrons, but with a positive electrical charge) from the nucleus of an element in the process of radioactive decay of the element.

Decay chain: A series of radioactive decays leading to a stable nucleus.

Dry separation: The use of electrochemical techniques to separate radionuclides

Fission product: Any atom created by the fission of a heavy element. Fission products are radioactive (generally by beta decay).

Neutron: An elementary particle slightly heavier than a proton, with no electric charge. The nucleus of an atom consists of protons and neutrons (the number of protons determines the element while the total number of nucleons determines the isotope). Neutron capture refers to the absorption of a neutron by a nucleus to form a new isotope.

Pyroprocessing: A form of dry electrochemical separation proposed for use with metal-based transmutation reactor fuels (e.g. those for accelerator based transmutation or for fast reactors).

Reprocessing: A generic term for the separation of elements in irradiated nuclear fuel.

Sub-critical reactor: A nuclear reactor that is configured to operate with an external source of neutrons to supplement internally generated neutrons to maintain the chain reaction

Supercritical: When each fission in a reactor results in more than one subsequent fission resulting in a runaway chain reaction, except in carefully controlled cases when reactor power is being increased in a controlled way by making it slightly supercritical for brief periods.

Target: In the context of proton-accelerator transmutation schemes, a material which, when struck with protons from the accelerator, emits neutrons through a process called spallation. The term is also used for separated radionuclides that are formed into targets for irradiation.

Radioactive Waste from Nuclear Power

Nuclear power is sometimes presented as an energy source that generates little pollution. However, taking into account all the stages of nuclear power generation, from mining uranium to dealing with spent nuclear fuel and everything in between, nuclear energy produces substantial amounts and varieties of waste and environmental pollution. The failure of government and industry to properly manage, contain, isolate, and regulate toxic and radioactive substances generated throughout the nuclear fuel cycle has often had tragic consequences for human health and the environment.[1]

The health and environmental damage done by uranium mining, milling, processing, and enrichment has been severe and continues. Mill tailings in many parts of the world are still leaking into the soil and contaminating groundwater. Commercial reprocessing operations continue to discharge large volumes of radioactive wastes into bodies of water from which people draw their food, as is the case with the discharges into the Irish Sea and the English Channel by the British reprocessing plants at Sellafield and by the French reprocessing plants at La Hague, respectively.

The table on the two following pages shows estimates of the volumes of radioactive wastes generated by nuclear power.[2] In addition to radioactivity, many of these wastes also contain toxic, non-radioactive materials. For instance, mill tailings contain toxic elements like arsenic and molybdenum. The table shows volumes of waste generated in the once-through low-enriched-uranium fuel cycle and the once-through mixed-oxide fuel cycle. Definitions of the various types of radioactive waste are provided below.

There are considerable uncertainties and variations in waste production and the pollution caused by nuclear power and associated operations, depending on factors such as quality of uranium ore, types of processing facilities and reactors, fuel burn-up, and prevailing regulations and efficacy of enforcement (see Special Atomic Puzzler p.19). The estimates in the table are by Brian Chow and Gregory Jones (RAND 1999). They provide one plausible cradle-to-grave analysis of radioactive waste generation from the two types of nuclear fuel used in light water reactors.

The **once-through low-enriched-uranium (LEU-OT) fuel cycle** is the most common approach. All commercial nuclear reactors in the United States, and most worldwide, use a LEU-OT fuel cycle. "Low-enriched-uranium" describes the type of fuel used; "once-through" refers to fact that the spent fuel is not processed for recovery of plutonium and uranium for fabrication into new reactor fuel.

The **once-through mixed-oxide (MOX-OT) fuel cycle** uses mixed oxide fuel made with plutonium extracted from LEU spent fuel. The reactor core in this cycle is comprised of 30% MOX fuel; the rest is LEU fuel. After irradiation, the MOX spent fuel is slated for disposal and the LEU spent fuel is reprocessed. Presently, approximately 30 commercial nuclear power reactors in Germany, France, and Belgium are using MOX fuel.

Other technologies to manipulate spent nuclear fuel are being proposed, such as transmutation and fast reactors, which require multiple passes through reprocessing. See the main article on page 1 for an analysis of these proposals.

1 For a detailed analysis, see *Nuclear Wastelands*, Makhijani, Hu, and Yih, eds. (Cambridge, Mass.: MIT Press), 1995.

2 Emissions to the air and water are not included other than liquid waste discharges from reprocessing.

IN THE FOLLOWING TABLE, RADIOACTIVE WASTE IS CLASSIFIED INTO FIVE CATEGORIES*:

Spent fuel: Discharged, irradiated fuel. Spent fuel and HLW contain more radioactivity than any other waste in the nuclear fuel cycle.

HLW (High-level waste): Waste generated from the reprocessing of spent fuel. HLW and spent fuel contain more radioactivity than any other waste in the nuclear fuel cycle.

ILW (Intermediate-level waste): Waste contaminated with alpha-emitting transuranic radionuclides with half-lives greater than 20 years and a total concentration of such radionuclides in excess of 0.1 Curie per metric ton of waste at the time of assay. (It is the same as the US Department of Energy's definition of transuranic waste, but ILW is a more commonly used term internationally.)

Tailings: Ore residues from milling after uranium is extracted.

LLW (Low-level waste): None of the above.

* These categories are based on existing regulations in the United States and some other countries. While we use them here in order to more simply communicate the estimates of the RAND study, the US waste classification is fundamentally flawed because the waste categories are based on the origin of the waste rather than the physical or chemical properties that determine the hazards of the waste and hence that determine its proper management. For a discussion, see *Science for Democratic Action*, vol. 6 no. 1, May 1997.

ANNUAL RADIOACTIVE WASTE GENERATION PER REACTOR

Low Enriched Uranium Once Through (LEU-OT) and Mixed-Oxide Once Through (MOX-OT) Cycles[a]

In cubic meters per Gigawatt electricity-year (m^3/GWe-yr)

	LEU Once-Through Cycle				MOX Once-Through Cycle				
Steps	**SF[b]**	**ILW**	**LLW**	**Tailings**	**SF[b]**	**HLW[b]**	**ILW**	**LLW**	**Tailings**
mining and milling	-	-	-	65,000	-	-	-	-	50,060
conversion	-	-	32-112	-	-	-	-	25-86	-
enrichment	-	-	3-40	-	-	-	-	3-35	-
fuel fabrication	-	-	3-9	-	-	-	13	7.4-12.5	-
reprocessing and vitrification	not applicable	not applicable	not applicable	not applicable	-	2-4[c]	17-39	8016-8037[d]	-
reactor operations	-	22-33	86-130	-	-	-	22-33	86-130	-
spent fuel storage and encapsulation[e]	-	2	0.2	-	-	-	0.3	0.03	-
spent fuel final disposal[f]	26	-	-	-	26	-	-	-	-
decommissioning[g]	-	9	333	-	-	-	10.1	315	-
TOTALS	**26**	**33-44**	**457-624**	**65,000**	**26**	**2-4**	**62-95**	**8452-8615**	**50,060**

NOTES:

a. Waste volumes do not include radioactive emissions to the air and water, except for reprocessing-related liquid LLW discharges to bodies of water. Typical characteristics of modern light water reactors are used: All fuel is assumed to have a burnup of 42.5 Gigawatt days (thermal) per metric ton of heavy metal (i.e. uranium and plutonium); reactors are assumed to have a 33% thermal efficiency; it is assumed that 26 metric tons of uranium are required to generate 1 Gwe-yr of electricity.

b. The actual volume of spent fuel and HLW is not an adequate proxy for their disposal burden. It is the heat generated by the spent fuel and HLW, not the volume, that determines, for example, the amount of space they would require in a geological repository. The need to space out the spent fuel and HLW (so they do not, for example, build up heat that could corrode waste packaging or cause unwanted changes in the geology) means that their effective volume in the repository will be much greater than their actual volume.

Sources: All waste volumes are from Brian G. Chow and Gregory S. Jones, *Managing Wastes With and Without Plutonium Separation* (Santa Monica, Calif.: RAND, 1999). The reprocessing LLW figure also uses data from Groupe Radioecologie Nord Cotentin, *Inventaire des rejets radioactifs des installations nucléaires,* vol. 1, July 1999, p. 19, and Cogema, Environmental Report, 1996, p. 54. Comments are from Makhijani, Hu, and Yih, eds., *Nuclear Wastelands: A Global Guide to Nuclear Weapons Production and Its Health and Environmental Effects* (Cambridge, Mass.: MIT Press, 1995).

ANNUAL RADIOACTIVE WASTE GENERATION PER REACTOR
Low Enriched Uranium Once Through (LEU-OT) and Mixed-Oxide Once Through (MOX-OT) Cycles[a]

(continued)

Comments
In terms of radiation doses and numbers of people affected, uranium mining has been one of the most hazardous steps in the nuclear fuel chain, disproportionately impacting indigenous peoples. Mining produces large amounts of waste in the form of low-grade uneconomical uranium-bearing materials, that is not managed as radioactive waste. Mill tailings account for over 95% of the total volume of radioactive waste, not including mine wastes. Many tailings sites all over the world remain unremediated and/or neglected and pollute ground and surface water with radioactive and non-radioactive toxic substances.
A number of chemical forms of uranium are created in the process of making uranium hexafluoride, which goes to the enrichment plant. Besides airborne and waterborne uranium, hazards include chemicals such as hydrofluoric acid, nitric acid, and fluorine gas.
Low-level waste from conversion and enrichment is typically buried in dumps. Many of these "low-level" waste dumps have leached radionuclides into the groundwater. Waste from enrichment also includes non-radioactive toxic chemical waste such as polychlorinated biphenyls (PCBs), chlorine, ammonia, nitrates, zinc and arsenic.
Because fuel fabrication does not involve the production of liquid waste, its effects are mainly restricted to workers and are on the same order as for workers in the reprocessing sector. The increased radiological risk of handling fuel that has been repeatedly irradiated is cause for serious concern.
Reprocessing creates some of the most difficult environmental problems of any part of the nuclear fuel cycle. Wastes from reprocessing, together with spent fuel, contain more radioactivity than any other waste in the fuel cycle. In 1957, a Soviet high-level liquid waste tank exploded. The risk of explosion exists today for other tanks which contain waste from reprocessing in Russia, the US, and elsewhere. Leaks from some of these tanks have contaminated soil and groundwater. By volume, most radioactive waste from reprocessing is discharged directly into bodies of water. Because it involves the separation of weapons-usable material (uranium and plutonium) from spent fuel, reprocessing poses significant proliferation problems. There are also radioactive emissions of krypton-85 and carbon-14 to the air, which are not included here.
Nuclear reactors are vulnerable to catastrophic accidents (e.g., Chernobyl, Three Mile Island). Boiling water reactors have considerable emissions of radioactive noble gases.
Considerable quantities of "low-level" waste are created due to fission products leaking into the spent fuel pools from cracks in the fuel cladding. These fisson products are trapped in resins in filters, which then become "low-level" waste in the United States and intermediate level waste in Europe.
The inability to isolate contamination from spent nuclear fuel from reaching the human environment for the duration of its hazardous lifetime makes the disposal of spent fuel one of the most difficult problems associated with nuclear power.
Most of the radioactivity from reactor decommissioning waste is in a relatively small volume of intensely radioactive material. Most reactors and related commercial nuclear facilities have yet to be decommissioned.

c. This figure does not represent the total original volume of liquid HLW from reprocessing, but rather that which results from the evaporation, concentration, and vitrification of the original volume into a volume approximately 98 percent less (Nuclear Energy Agency, Organisation for Economic Co-operation and Development, *The Economics of the Nuclear Fuel Cycle* [Paris: OECD, 1994], page 33).

d. This figure includes 7956 m^3/GWe-yr of liquid discharges into the environment (Groupe Radioecologie Nord Cotentin, 1999).

e. It is not assumed that the spent fuel storage and encapsulation step involves first transferring the spent fuel to an interim site for storage before final disposal. If, in addition to storing the spent fuel in a water pool, dry casks were used for interim storage, there would be an additional 6 cubic meters LLW/GWe-yr waste generated during interim storage.

f. While the resulting spent fuel volumes of the MOX and LEU fuel cycles are equal, MOX spent fuel is more difficult to manage because it is physically hotter than LEU spent fuel.

g. This includes decommissioning of reactor and conversion, enrichment, fabrication and reprocessing plants.

NUCLEAR POWER

FROM PAGE 2

United States as the promoter of the peaceful uses of nuclear energy in contrast to the horror of the Soviet thermonuclear program. In addition to the propaganda advantage gained by casting the Soviets as the militaristic side (despite the parallel development of Soviet nuclear power plants), another aspect of US urgency to embark on commercial civilian nuclear energy generation on a significant scale was the fear that, if the US delayed, the Soviets would be the first to achieve it. As it turned out, both the Soviets (1954) and the British (1956) succeeded in producing commercial nuclear electricity before the United States (1957).

A speech by President Eisenhower to the United Nations in December 1953 was prepared against this backdrop of US and Soviet nuclear arms development and testing. Initial drafts of the speech focused on the terribly destructive nature of atomic and thermonuclear weapons. In the revised speech, one part contained graphic descriptions of the power and terror of nuclear weapons; another part spoke in glowing terms about the promise of the peaceful atom.

Eisenhower focused a large part of his UN speech on promoting civilian nuclear power development, which became known as the "Atoms for Peace" program. In his speech, Eisenhower said:

> The US would seek more than the mere reduction or elimination of atomic materials for military purposes.
>
> A special purpose would be to provide abundant electrical energy in the power-starved areas of the world. Thus the contributing powers would be dedicating some of their strength to serve the needs rather than the fears of mankind.

In the Atoms for Peace program, countries would contribute fissionable materials to a new international atomic energy agency to be created under the auspices of the United Nations. This agency would prevent proliferation of nuclear weapons and, at the same time, assist in the development of nuclear power. Eisenhower also outlined the functions of the new agency in allocating fissionable material and in providing experts around the world.

Eisenhower's statement that nuclear power could "rapidly be transformed" from a developmental technology into a "universal, efficient and economic usage" was not based on sound analysis. Rather, it converted the early messianic statements about nuclear power into a calculated tool in the Cold War. On nuclear energy, there was no difference of opinion across the Cold War ideological divide. True believers in the Soviet Union were at least as enthusiastic about nuclear energy, which joined the famous dictum of Lenin, that soviets plus electricity equaled communism with Stalin's penchant for massive industrial projects.

A decade-and-a-half later, the US Atoms for Peace policy was given more formal and fervent expression in Article IV of the Nuclear Non-Proliferation Treaty (NPT), which guaranteed its signatories an "inalienable right" to the benefits of nuclear technology, including nuclear energy (full text of Article IV on page 14). In just over two decades, nuclear energy was elevated to a status akin to the right to "life, liberty and the pursuit of happiness," which inspired not only the founders of the United States, but people all over the world ever since.

To many leaders of countries emerging from colonialism hoping for quick alleviation of economic misery, nuclear energy seemed to be a material counterpart of the flags and national anthems that became the symbols of newly acquired freedom. Nuclear energy was "modern" and, like steel plants and national airlines companies, it was assumed that such modernization would propel the "backward" former colonies full steam ahead and put them on a par with the industrialized nations. Even India, where Gandhi had vigorously advocated a course of development different from that pursued in the West, did not undertake an independent evaluation of western claims, despite the fact that it had the scientific and technical capacity in the late 1940s to do so.[3]

The idea of energy "too cheap to meter" was a combination of self-delusion and propaganda without technical foundation.

Atomic Skeptics

Unfortunately for the true believers, the idea of energy "too cheap to meter" that was required for transforming the gossamer stuff of extravagant dreams into hard economic reality was a combination of self-delusion and propaganda without technical foundation. Indeed, all technical evaluations, from those undertaken in the secrecy of the Manhattan Project to studies by government, industry, and academics during the late 1940s and early 1950s, came to the same conclusions. Nuclear energy would be difficult to master and it would not be competitive with coal-generated electricity for quite some time, though it might be competitive with coal, especially if coal prices rose. None came to the conclusion that it would be cheap, much less "too cheap to meter."

According to C.G. Suits, Vice-President and Director of Research of General Electric, in a December 1950 speech,

> At present, atomic power presents an exception-

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> ally costly and inconvenient means of obtaining energy which can be extracted more economically from conventional fuels.... The economics of atomic power are not attractive at present, nor are they likely to be for a long time in the future. This is expensive power, not cheap power as the public as been led to believe.

As another example, in 1948, the AEC presented a report to Congress in which it cited "unwarranted optimism as to the character of the technical difficulties [facing nuclear power] and the time required to surmount these difficulties." This committee, which included Enrico Fermi, Glenn Seaborg, and J.R. Oppenheimer, was not even uniformly optimistic about fuel costs, even though low fuel costs were the minimum necessary requirement for nuclear power to be competitive with fossil fuel-generated electricity.

During the 1940s and 1950s, the United States was undergoing a considerable transformation in its energy situation. Prior to and during World War II, the US was virtually self-sufficient in petroleum. But the enormous growth in the number of automobiles in the decade, as well as the explosive growth of other uses of petroleum, resulted in the United States becoming a consistent net importer by the end of the 1940s. By 1960, the US was importing almost one-fifth of its petroleum consumption.

One of the official reviews of the resource situation in the early 1950s was conducted by a commission appointed by President Truman, called The President's Materials Policy Commission. It came to be known as the Paley Commission, after its chairman.

In the energy sector, the prime area of concern that the Paley Commission addressed was petroleum. The 1952 report predicted oil shortages by the 1970s. Furthermore, the Paley Commission made a strong negative assessment of nuclear energy and called for "aggressive research in the whole field of solar energy – an effort in which the United States could make an immense contribution to the welfare of the world." The Commission also encouraged work on wind energy and biomass. However, despite the Commission's conclusions, a significant renewable energy effort was not made until the oil crisis was upon the US in the 1970s.

Given the assessment that nuclear energy could meet only a modest fraction of energy requirements at best, it seems illogical that nuclear energy was pursued vigorously rather than solar and other renewable energy sources. Evidently, it was assumed that renewable energy sources would not provide the same propaganda capital in the Cold War as nuclear energy. Interestingly, a lack of government money for renewables was accompanied by a lack of corporate research effort and an absence of interest on the part of large numbers of scientists and engineers.

A Persistent Illusion

The history of nuclear power has not sustained the hopes of its proponents. Almost half a century after a nuclear reactor first lighted an electric bulb, [4] orders for nuclear reactors in the industrialized countries are near zero. Sales to the developing world, repair jobs on existing reactors, and decommissioning fill much of the order book of the nuclear power manufacturers and other nuclear vendors. In the United States, no new reactor has been ordered since 1978, and every reactor ordered between 1974 and 1978 has been canceled. Even in France, the bastion of nuclear power where reactors generate about fourth-fifths of the country's electricity, it is now acknowledged that natural gas fired combined cycle plants are more economical than nuclear reactors.

> Despite the dismal performance of nuclear energy relative to the hopes of its progenitors, most of the world's governments seem unwilling to give it up.

In 1986, Chernobyl showed the terrible, widespread, long-lasting, and, to a large extent, irremediable consequences of a severe nuclear reactor accident. Every commercial nuclear reactor design carries with it vulnerabilities of such catastrophic accidents, though the probabilities and specific accident mechanisms may differ from one design to the next and from one country to another.

Despite the dismal performance of nuclear energy relative to the hopes of its progenitors, most of the world's governments seem unwilling to give it up. That reluctance is a complex phenomenon, beyond the scope of this editorial. It seems partly the result of a feeling on the part of many non-nuclear developing countries that the main possessors of this technology in the West are unfairly depriving them of access to a technology guaranteed to them by Article IV of the NPT as part of the bargain for forgoing nuclear weapons. The idea that nuclear power is emblematic of modern "high" technology also continues to have a powerful hold.

Yet, the problems with implementation of Article IV of the NPT are beside the point, for nuclear energy is generally uneconomical and undesirable from a number of different points of view. Even its status as "high" or "advanced" technology is much overrated. For instance, the design and building of photovoltaic cells and the construction of reliable, computer controlled distributed electricity grids that draw their energy from a

SEE **NUCLEAR POWER** ON PAGE 14
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variety of sources and power plants is, in many ways, a more complex and advanced technological enterprise than the design and construction of nuclear reactors.

After the demise of the idea of nuclear energy as "too cheap to meter" by an exigent reality, the nuclear industry has been putting forward environmental and non-proliferation rationales as part of its promotion of nuclear power. Its spokespersons state that nuclear power could be a principal factor in reducing emissions of pollutants, notably carbon dioxide, which contributes to global warming. However, this claim ignores the environmental impacts of uranium mining and radioactive waste, which are inherent parts of the technology (see Science for the Critical Masses, pp. 9-11). Moreover, IEER's analysis has shown that high-efficiency natural gas power plants can reduce greenhouse gas emissions more per unit of investment than nuclear energy.[5] Further, the problems associated with fossil fuels and nuclear energy are incommensurable. Should one trade off the potential for catastrophic accidents like Chernobyl with climate change? (See Dear Arjun, p.17)

In the early years of the Cold War, many nuclear energy proponents proposed that military plutonium production be used to subsidize commercial nuclear power plants. After the end of the Cold War, there are proposals to use surplus military plutonium as fuel in reactors to subsidize existing power plants. The industry is claiming that it can help turn "swords into Plowshares" because surplus plutonium from dismantled nuclear weapons would be used to make fuel for commercial nuclear power reactors. However, such a program would create the financial and physical infrastructure for making plutonium a "commercial" commodity, with attendant proliferation, environmental, and cost concerns.[6]

To address safety concerns, the nuclear industry has been promoting a second generation of commercial nuclear power reactors (see main article, p.1), some of which have been labeled "inherently safe" by their proponents. The safety question is a central one, since public skepticism of industry claims grew markedly after the Three Mile Island and Chernobyl accidents. However, regardless of the validity of claims about immunity to meltdown accidents, this terminology of "inherently safe" has more rhetorical merit than technical content. Although it may be possible to design reactors that are safer *relative* to existing reactors, the technology cannot be considered to have safety as an inherent characteristic. All reactors that have been proposed have some potential for severe accidents.

There are far better and safer energy options available now.[7] It is time to leave nuclear energy behind as a failed dream of the last century. We can and must replace the false propaganda of "atoms for peace" with an "energy for peace" program that can make the well-being of the present generation compatible with the protection of the security and environment of future generations.

ARTICLE IV OF THE NUCLEAR NON-PROLIFERATION TREATY

1. *Nothing in this Treaty shall be interpreted as affecting the inalienable right of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination and in conformity with articles I and II of this Treaty.*
2. *All the Parties to the Treaty undertake to facilitate, and have the right to participate in, the fullest possible exchange of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy. Parties to the Treaty in a position to do so shall also cooperate in contributing alone or together with other States or international organizations to the further development of the applications of nuclear energy for peaceful purposes, especially in the territories of non-nuclear-weapon States Party to the Treaty, with due consideration for the needs of the developing areas of the world.*

Source: Congressional Research Service, *Nuclear Proliferation Factbook* (Washington, DC: US Government Printing Office), September 1980.

1 *The Nuclear Power Deception: US Nuclear Mythology from Electricity "Too Cheap to Meter" to "Inherently Safe" Reactors* (Apex Press 1999). All references can be found in this book, unless otherwise mentioned.

2 For a comparison of reduction of greenhouse gas emissions using nuclear power to replace coal-fired power plants versus using modern combined cycle natural gas fired power plants, see *Science for Democratic Action*, vol. 6, no. 3, March 1998.

3 George Perkovich, *India's Nuclear Bomb: The Impact on Global Proliferation*. Berkeley: University of California Press, 1999, pp. 15-21.

4 In 1951, the Experimental Breeder Reactor I produced the first nuclear electricity that was used to power a light bulb. Both the reactor and the bulb are in a museum in Idaho.

5 See *Science for Democratic Action*, vol. 6 no. 3, March 1998.

6 See *Science for Democratic Action*, vol. 5 no. 4, February 1997.

7 See for example IEER's report, *Wind vs. Plutonium: An Examination of Wind Energy Potential and a Comparison of Offshore Wind Energy to Plutonium Use in Japan* (1999), Chapter 9 of *The Nuclear Power Deception*, and Thomas Johansson et al., *Renewable Energy: Sources for Fuels and Electricity*. Washington, DC: Island Press, 1993.

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DEAR ARJUN

Dear Arjun:

I hear all kinds of claims about nuclear power. How can I compare it to fossil fuels or to renewable energy sources like wind and solar power?

— Wondering in Wyoming

Dear Wondering:

Once upon a time, people made claims when they wrote to insurance companies for damages. Now that the government has provided free insurance for nuclear power plants, much of the claims business has moved to Madison Avenue.

Madison Ave. claims for nuclear power plants are as follows:

1. Severe accidents happen only in the former Soviet Union and can't happen here.

SEE **DEAR ARJUN** ON PAGE 18

COMPARISON OF FOSSIL FUELS AND NUCLEAR POWER

	Nuclear with breeders	Nuclear, once-though uranium use	Fossil Fuels, present approach	Limited fossil fuels and renewables
Resource base, present economics*	indefinite future	50 to 100 years, possibly more	a few hundred years	indefinite future
Resource base, including very low-grade resources	not required	indefinite future	thousands of years	not required
incremental climate change risk	none**	none	potentially catastrophic	none if fossil fuels are largely phased out
potential consequences of catastrophic accidents	severe: long-lasting effects over large regions	severe: long-lasting effects over large regions	no consequences for large regions but may be locally severe; effects generally short-term	no consequences for large regions but may be locally severe; effects generally short-term
air pollution, routine operations	relatively low	relatively low	severe to moderate, depending on control technology	moderate to low depending on control technology
water pollution, routine operations	potentially serious at mines and mills, but limited due to low uranium requirements; potentially serious at waste disposal sites	often serious at mines, mills, and uranium processing sites (includes radioactive and non-radioactive pollutants); potentially serious at waste disposal sites	often serious at coal mines; serious at some oil fields (includes non-radioactive and radioactive pollutants, notably radium-226 near many oil-wells)	potentially very low
Risk of nuclear weapons problems	yes	yes, but less than with a breeder reactor system	none	none

* The judgments in this table are based on present practices and on presently available technologies that are commercial or nearly so. Statements about consequences and pollution refer to consequences of further use and not on accumulated damage so far.

** Questions have been raised about the effect of krypton-85 from extensive reprocessing necessary for a breeder reactor system on cloud formation and hence potential climate change. However, krypton-85 can be removed from exhaust gases by cryogenic cooling.

This table has been reprinted from IEER's *Energy & Security* no. 1, 1996.

DEAR ARJUN

FROM PAGE 17

2. Nuclear power plants produce no emissions.
3. Nuclear power plants produce electricity too cheap to meter. (oops, obsolete ad)
4. Nuclear power plants can be made inherently safe.
5. An energy economy based on nuclear power plants can be made proliferation proof.
6. Nuclear power is a good way to eliminate greenhouse gas emissions.

There is no particularly polite way to accurately describe the first five of these claims. In plain English, one could call them balderdash. For more scientific descriptions, see the editorial on page 1, Science for the Critical Masses on page 9-11, the table on the previous page, and the book *Nuclear Power Deception*, wherein there are also large numbers of references.

The one claim that merits more detailed discussion is whether nuclear power plants might be a good way to eliminate the build-up of greenhouse gases. In theory, nuclear power plants emit relatively small amounts of carbon dioxide compared to coal-fired power plants. However, the matter of reducing greenhouse gas emissions is only partly a technical matter of choosing technologies that can do the job. Even apart from increases in energy efficiency, many energy supply technologies can reduce carbon dioxide emissions: wind and solar energy are supply technology examples. Sequestration of carbon dioxide, that is, storage of carbon dioxide in various ways so that it does not vent to the atmosphere, is also technically possible.

One of the primary constraints is economic: which set of technologies can reduce greenhouse gas emissions for a given amount of money? Seen in this light, nuclear power is most assuredly not the answer to reducing greenhouse gas emissions. The other essential question is: what are the other liabilities that the reduction to greenhouse gas emissions will produce for future generations? Central to this is the vulnerability of nuclear power to catastrophic accidents, the problem of long-lived nuclear wastes, and the proliferation potential associated with all nuclear power systems (in varying degrees). While there are some impacts associated with every energy source, such severe long-term and irreversible liabilities can be avoided with renewable energy technologies implemented with the proper attention to ecological issues from the start.

For information on nuclear power and global climate change, refer to *Science for Democratic Action*, vol. 6 no. 3, March 1998.

SELECTED PUBLICATIONS

- *The Nuclear Power Deception: U.S. Nuclear Mythology from Electricity "Too Cheap to Meter' to "Inherently Safe" Reactors* by Arjun Makhijani and Scott Saleska (Apex Press, 1999), 266 pages. $15.00, check payable to IEER.

This book provides critical analysis and historical evidence to refute claims that nuclear power can alleviate the build-up of greenhouse gases and reduce US dependence on foreign oil. It also reveals the proliferation hazards from the growing quantities of plutonium generated by nuclear power plants worldwide.

- *India's Nuclear Bomb: The Impact on Global Proliferation* by George Perkovich (University of California Press, 1999), 610 pages. To order, call 1-800-UC-BOOKS or visit http://www-ucpress.berkeley.edu/books/pages/8386.html.

A definitive political history of India's nuclear weapons program. Also provides crucial insights into Pakistan's program and US non-proliferation policy. Perkovich's analysis has been described as "timely, sobering, and vital."

ERRATA

In the book by IEER and the International Physicians for the Prevention of Nuclear War, *Plutonium: Deadly Gold of the Nuclear Age* (Cambridge, Mass.: International Physicians Press, 1992), the following corrections apply to Table 3.2 on page 55:

The volume of low-level liquids should be 2.2×10^9 gallons. The volume of low-level solids should be 213 cubic meters. The radioactivity figures for low-level liquids should read:

Tritium	4.0×10^4
Strontium-90	2.9
Cesium-137	5.1

The box on page 17 of *Science for Democratic Action* vol. 8 no. 2 (February 2000) should have indicated that Italy has signed and ratified the Comprehensive Test Ban Treaty.

Sharpen your technical skills with Dr. Egghead's
Special Atomic Puzzler

Win $108! Solve this.

Dr. Egghead's trusty dog, Gamma, is puzzled. In doing research for the centerfold of this issue (pp. 9-11), he found that different sources contain considerably different estimates for radioactive waste generated throughout the nuclear fuel cycle. He wanted to alert SDA readers to this problem, and also to ask for help in determining why these discrepancies exist.

So, we are putting this challenge to you, our readers, as a *special* Atomic Puzzler.

We will award a prize of $108.00 to the person who submits the most accurate explanation as to why estimates of radioactive waste generation vary among two given sources. The sources, reports by DOE and RAND, are cited below. The relevant waste volumes are provided in the table below. If you're interested in delving a bit deeper, the DOE document, now out of print, can be found on the internet at http://osti.gov/resource.html (from there, go to DOE Information Bridge, then search for the title "integrated data base" and choose Rev. 8 [1992]). The RAND study can be ordered ($8.00 including shipping) by contacting RAND at order@rand.org, 310-451-7002 (phone) or 310-451-6915 (fax).

This is not a get-rich-quick scheme! Solving this Puzzler is likely to be difficult and time-consuming. (In fact, we don't even have the answers yet.) Thus IEER is offering a larger than usual prize and giving participants several months to submit their answers.

Submissions will be judged by Dr. Egghead and Gamma. Entries must be sent to IEER by September 7, 2000. We will publish our findings in SDA shortly thereafter.

Good luck!

Annual lifetime radioactive waste generation per reactor[a], in m^3/GWe-yr
(LLW=low-level waste, ILW=intermediate level waste; GTCC=Greater-than-Class-C LLW[b])

	DOE 1992[c]	***RAND***
Mining & milling	tailings 119,000	tailings 65,000
Conversion	LLW 10.5	LLW 32-112
Enrichment	LLW 3.7	LLW 3-40
Fuel fabrication	LLW 82.7	LLW 3-9
Reactor operations	LLW 165.7	LLW 86-130 ILW 22-33
Decommissioning	LLW 290 GTCC 0.15	LLW 333 ILW 9
TOTALS	*tailings 119,000* *LLW 552.6* *GTCC 0.15*	*tailings 65,000* *LLW 457-624* *ILW 33-44*

a Pressurized water reactor is the reference.

b GTCC waste is a category used in the United States and includes the most radioactive irradiated reactor parts and some instruments. ILW is defined on page 9.

c These figures are updated from those printed on pp. 24 and 32 in IEER's report, *High Level Dollars, Low Level Sense* (Apex Press, 1992), which used 1990 DOE data.

DATA SOURCES:

- ***DOE 1992:*** US Department of Energy, *Integrated Data Base for 1992: US Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics*, DOE/RW-0006, Rev. 8, October 1992, page 279.
- ***RAND:*** Brian G. Chow and Gregory S. Jones, *Managing Wastes With and Without Plutonium Separation*, P-8035, Santa Monica, Calif.:RAND, 1999, page 37.

Send us your answer via fax (1-301-270-3029), e-mail (ieer@ieer.org), or regular mail (IEER, 6935 Laurel Ave., Takoma Park, MD 20912 USA), postmarked by September 7, 2000. IEER will award one prize of $108.00 to the person who most accurately explains why the estimates of radioactive waste generation, provided in the table above, vary. In the event that the winning answer is submitted from outside the United States, the winner will receive one copy of each of the books *Nuclear Wastelands: A Global Guide to Nuclear Weapons Production and Its Health and Environmental Effects* (MIT Press, 1995) and *The Nuclear Power Deception: US Nuclear Mythology from Electricity "Too Cheap To Meter" to "Inherently Safe" Reactors* (Apex Press, 1999) in lieu of the cash prize, due to exchange rates. In the event of more than one most accurate answer, the prize will be awarded to the first one received.

Answers to Atomic Puzzler, *SDA* vol. 8 no. 2, February 2000, "In Pursuit of Nuclear Trivia"

1. Ronald Reagan
2. Brazil, Egypt, Ireland, Mexico, New Zealand, South Africa, and Sweden
3. International Atomic Energy Agency
4. None
5. About 5,000
6. Twenty; none on high alert
7. $3.6 billion
8. 16 megatons, or 16,000 kilotons
9. On-site inspections, satellite imagery, seismic monitoring, radionuclide detection, underwater listening devices, infrasound instruments, etc.
10. Approximately 100
11. 321

It pays to increase your jargon power with Dr. Egghead

fast reactor

a. Another term for a fire truck.
b. Medical term for a patient who scores well on his or her knee reflex exam.
c. One who thinks quickly on their feet.
d. A reactor that is designed to use fast neutrons for sustaining the nuclear chain reaction. Fast reactors can be used to produce more fissile material than they consume.

sub-critical reactor

a. Describes a nuclear power reactor that, contrary to being above criticism, is below it.
b. Name given by students to a teacher who gives easy grades.
c. A power plant that does not produce enough electricity.
d. A nuclear reactor that is configured to operate with an external source of neutrons to supplement internally generated neutrons to maintain the chain reaction.

light water reactor

a. A reactor that runs on sparkling water.
b. A depressed person who responds well to the consumption of water to which a euphoric substance has been added.
c. Diet supplement that decreases the density of the body's water, thereby aiding weight loss.
d. The most common type of nuclear reactor in the world. Uses light water (ordinary water) as a moderator (to slow down neutrons in the reactor) and a coolant. Light water reactors are built in two variants: pressurized water reactors and boiling water reactors.

fissile material

a. Industry term for the carbonation in soda pop.
b. A very delicate fabric.
c. Misspelling of the term "facile material," books designed to help students study for tests.
d. A material consisting of atoms whose nuclei can be split when irradiated with low energy (ideally, zero energy) neutrons. Well-known examples are plutonium-239 and uranium-235.

fission products

a. Children of a nuclear family that has split apart.
b. Items sold in a bait-and-tackle shop.
c. Used equipment (file cabinets, machinery, scrap metal, etc.) taken from nuclear weapons facilities and sold on the open market.
d. Any isotope created by the fission of a heavy element. Fission products are usually radioactive.

Answers: d, d, d, d, d

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Address correction requested.

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