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Title:	ACCELERATOR TRANSMUTATION OF WASTE TECHNOLOGY AND IMPLEMENTATION SCENARIOS
	August 2000
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Submitted to:	*12th Pacific Basin Nuclear Conference (PBNC-2000), Seoul, Republic of Korea, Oct 29-Nov 2, 2000, co-sponsored by the Korea Atomic Industrial Forum, Inc. (KAIF) and Korean Nuclear Society (KNS, an affiliate of the American Nuclear Society)*

This paper was prepared for publication in the Proceedings of the 12th Pacific Basin Nuclear Conference (PBNC-2000), Seoul, Republic of Korea, Oct 29-Nov 2, 2000. Because changes may be made before publication, this pre-print is made available with the understanding that it will not be cited or reproduced without the permission of the author.

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ACCELERATOR TRANSMUTATION OF WASTE TECHNOLOGY AND IMPLEMENTATION SCENARIOS

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Abstract

During 1999, the U.S. Department of Energy, in conjunction with its nuclear laboratories, a national steering committee, and a panel of world experts, developed a roadmap for research, development, demonstration, and deployment of Accelerator-driven Transmutation of Waste (ATW). The ATW concept that was examined in this roadmap study was based on that developed at the Los Alamos National Laboratory (LANL) during the 1990s. The reference deployment scenario in the Roadmap was developed to treat 86,300 tn (metric tonnes initial heavy metal) of spent nuclear fuel that will accumulate through 2035 from existing U.S. nuclear power plants (without license extensions). The disposition of this spent nuclear reactor fuel is an issue of national importance, as is disposition of spent fuel in other nations. The U.S. program for the disposition of this once-through fuel is focused to characterize a candidate site at Yucca Mountain, Nevada for a geological repository for spent fuel and high-level waste.

The ATW concept is being examined in the U.S. because removal of plutonium, minor actinides, and two very long-lived isotopes from the spent fuel can achieve some important objectives. These objectives include near-elimination of plutonium, reduction of the inventory and mobility of long-lived radionuclides in the repository, and use of the remaining energy content of the spent fuel to produce power. The long-lived radionuclides iodine and technetium have roughly one million year half-lives, and they are candidates for transport into the environment via movement of ground water.

The scientists and engineers who contributed to the Roadmap Study determined that the ATW is affordable, doable, and its deployment would support all the objectives. We report the status of the U.S. ATW program, describe baseline and alternate technologies, and discuss deployment scenarios to support the existing U.S. nuclear capability and/or future growth with a variety of new fuel cycles.

Introduction

The disposition of spent nuclear reactor fuel continues to be an issue of national and international importance. The U.S. disposition program is focused to characterize a candidate site at Yucca Mountain, Nevada for a geological repository for spent fuel and high-level waste.[1] Its capacity is defined to safely dispose of 63,000 metric tonnes (tn) of spent fuel from nuclear power reactors and 7,000 metric tonnes of spent fuel and high-level waste from DOE operations (often called "defense wastes"). In comparison, the current fleet of about 100 nuclear power plants generates about 2000 tn of spent fuel per year.

Following a U.S. policy that has been in effect since the mid-1970s, nuclear power reactors in the U.S. operate on a once-through fuel cycle. During reactor operation much of the ^{235}U inventory and some of the transuranic isotopes that are produced by neutron capture are fissioned, thus producing fission products. After providing fission heat for several years in a reactor, the "spent fuel" is removed from the core for three reasons: 1) consumption of ^{235}U reduces reactivity; 2) buildup of fission and activation products increases parasitic absorption of neutrons; and 3) the mechanical integrity of the fuel is degraded. The heavy-metal content (i.e., other than oxygen or zirconium) of fresh fuel is composed of 95-98% ^{238}U and 3-5% ^{235}U (natural uranium is about 0.7% ^{235}U). The blend of materials in spent fuel tracing to heavy metals (includes fission products) about twenty years after removal from the reactor is 94.4% U-238, 0.7% U-235 (similar to natural uranium), 0.9% plutonium, 0.16% minor actinides (Np, Am, Cm), and 3.6% fission products that are not considered to be significant problems (these values are for "average" U.S. spent fuel: 37.2 MW thermal-days/kg initial heavy metal (MWt-d/kg IHM) burnup). The balance of the spent fuel, about 0.27%, is made up of four fission products that pose disposal problems. Two of these, 0.04% ^{90}Sr and 0.09% ^{137}Cs, are heat generating isotopes with about 30-year half-lives. The other two, 0.09% Tc-99 and 0.03% I-129, are very long-lived isotopes (roughly one million year half-lives) that are candidates for transport into the environment via ground water movement. However, much useful potential energy remains in "spent" nuclear fuel.

Important objectives can be achieved with the removal of the plutonium, the minor actinides, and the long-lived iodine and technetium from the spent fuel:

- The potential for future removal of plutonium from the repository for use in nuclear weapons is avoided.
- The inventory of long-lived radionuclides in the repository would be reduced, thereby decreasing the period of time that the repository has to maintain integrity.
- The energy content of the uranium and transuranics could instead be exploited in producing power. The energy potential in the transuranics (plutonium and minor actinides) is roughly 30% of the energy already produced by the "spent" fuel, and can be readily harvested. The energy remaining in the uranium is potentially much larger (one to two orders of magnitude beyond the energy already produced), although breeder reactor technology would be needed to extract most of that energy potential.

One concept for reducing the amount and toxicity of this spent fuel is Accelerator-driven Transmutation Technology (ADTT). Transmutation is a nuclear transformation that effectively converts one isotope into another. In terms of dealing with the problem components in spent nuclear fuel (roughly 1%), this involves fissioning the transuranic isotopes and converting the long-lived fission products into short-lived or stable isotopes. One of the most effective methods to achieve nuclear transmutation is through exposure of material to neutrons, either in a critical nuclear reactor or in an accelerator-driven subcritical nuclear system.[2] In the latter, additional neutrons result from a beam of high-energy particles, e.g. protons, that collide with a dense, high-atomic-number target. These neutrons are then multiplied through interactions with fuel materials in a surrounding blanket. In either case, the exposure of materials to neutrons results in their transformation and destruction through a variety of nuclear processes.

The lead ADTT concept in the U.S. is the Accelerator-driven Transmutation of Waste (ATW) project being managed at LANL. In the FY1999 Federal budget, $4 million was provided for a technology roadmap to ".... identify the technical issues that must be resolved, a proposed time schedule and program to resolve those issues, and the estimated cost of such a program."[3] The Federal budget for FY2000 included about $9 M to initiate the ATW R&D Program and to begin systems studies, which are now under way at LANL and other U.S. institutions.

Accelerator Transmutation of Waste (ATW)

The ATW system requires three major technologies:

- the chemistry processes that allow the spent fuel components to be separated,
- the accelerator technology needed to provide a high power beam of charged particles (protons), and
- the target/blanket technology needed to transmute the long-lived hazards into stable or short-lived materials.

The reference design in the ATW Roadmap is based on known technologies in each of these major areas, although some mission-specific requirements necessitate modifications and/or extensions to current technology. In addition, the performance of the ATW system may be improved through future development of advanced technologies, such as lead-bismuth coolant or advanced fuel separation and manufacturing technologies.

For the reference separation technology, two primary options provide some specific advantages: comparatively well-known aqueous separations and pyrometallurgical separations. Because of its capacity for high through-put and its ability to provide a uranium stream that may meet Class C Low-level Waste requirements, an aqueous process named "UREX" is the reference technology for processing the "cold" spent fuel. An alternate path for processing the spent fuel based on pyrometallurgical separations may offer advantages including greater proliferation resistance, but this technology requires some development. After the initial separation of uranium, all further ATW separations and processing steps are based on pyrometallurgical processing for two reasons. First, the bulk separations provide greater proliferation resistance, and second, the pyroprocess is more tolerant of the high heat and radiation environments anticipated during the processing of fuel that has been irradiated in the ATW target/blankets. At the scale of the reference ATW plants, all separations, either aqueous or pyro-based, will be modularized and constructed at the plant sites. This has the primary advantage that all materials to be transported off site will be either spent fuel from current nuclear power reactors or waste forms from ATW plants.

A linear accelerator (linac) was chosen for the accelerator technical baseline because of high beam power requirements. Linear accelerators are believed to be capable of accelerating over 100 mA of protons to several thousand MeV, meaning continuous beams in the few hundred megawatt range are practical. The other main option for high power beams, cyclotrons, are cheaper to build but are limited in both energy

(because of relativistic effects) and current. As a result, cyclotrons appear to be fundamentally limited to a few megawatts of beam power. Although such beam powers may suffice to drive energy amplifier thorium-based systems,[4] they do not appear sufficient for the currently envisioned U.S. application.

In the design of the subcritical converter, options include a fast, epi-thermal, or thermal spectrum and a variety of coolant and fuel concepts. A fast spectrum was chosen for two reasons. First, nearly all actinides will fission in a fast spectrum, giving maximum flexibility for the blend of fuel. In contrast, a thermal spectrum renders some isotopes fissile and some fertile. Therefore the system reactivity changes significantly during the burnup process, almost forcing the designer to use liquid fuel forms, which in turn raises significant safety issues. Second, the fast spectrum produces many excess neutrons that can be used to transmute iodine and technetium. To achieve a fast spectrum, a liquid metal is chosen as a coolant. Sodium was designated as the reference coolant because of an extensive international experience base. However, liquid lead-bismuth may offer significant advantages compared to sodium as both a spallation target and as a coolant, and is designated the preferred technology (and to be developed aggressively). The choice of pyrometallurgical separation technology drives the design towards metal fuel. Although this metal fuel would have a different composition than traditional Integral Fast Reactor program metal fuel, the high zirconium content suggests this fuel should have some very desirable characteristics, including the ability to tolerate high burnup levels. Structural materials and cladding must be compatible with the chosen coolants. With sodium coolant, inconel and HT-9 (a ferritic steel developed and tested as part of the ALMR program) are nearly ideal materials, with an excellent experience base that covers most conditions of interest. With liquid lead-bismuth, the Russians have had excellent success with a few steels including one that is similar to HT-9. However, inconel is not compatible with lead-bismuth, so alternate materials would need to be demonstrated for the beam entrance window, where adequate performance in a high proton-irradiation environment must be demonstrated.

Although these designated systems are useful in defining a reference ATW system, alternatives are clearly available. Should there be problems with the chosen processes, materials, or technologies, alternate choices could be employed, often with minimal consequences. Advanced technology options might be utilized in order to gain one advantage or another; to provide for evaluating these options, a national ATW workshop to develop a five-year plan for technology R&D was held in August.

ATW Roadmap Technical Reference

The ATW technical reference for the purpose of planning the technology development ("Road Mapping") reflects the current national and international thinking as to the best technology options and size of the facility. Optimization of the size and configuration of ATW plants will be a lengthy iterative process as the design teams explore and evaluate options. Therefore, this reference design should be evaluated as a proposed implementation that could change several times before being built. ATW technology is driven by the problematic materials--what they are and in what quantities. The capacity of the ATW system was required to consume the spent fuel legacy of the current generation of nuclear power reactors, which continue to operate until their operating licenses expire, but no new plants are licensed and there are no license extensions for existing plants. Without advanced reactors that might consume some of the plutonium, the entire plutonium inventory would be consumed in ATW. In addition, the mission should be completed in a manner that is both cost-effective and expeditious, preferably within about a century.

Although only about 1% of the spent fuel mass needs to be transmuted in ATW systems, the energy in those materials is enormous--equivalent to approximately two years of total electric power consumption in the U.S. at the 1999 rate of consumption. This large amount of energy determines the size of an ATW system. Although the ATW mission is to transmute the long-lived wastes, revenue from harvesting/marketing that energy is essential to paying for the full ATW system deployment. Effectively, one is constructing large nuclear energy systems that are accelerator-driven to safely operate on the waste-stream-based fuel.

Sizing the System

The ATW target/blanket facility, a.k.a., subcritical converter/transmuter, has been sized at 840 MWt, which accomplishes two objectives. First, it matches a version of the advanced liquid-metal cooled reactor (ALMR, specifically known as "PRISM") for which extensive cost analyses were performed.[5] Because ATW subcritical converters are likely to physically resemble the ALMR units, the costs are likely to be quite similar, simplifying the ongoing efforts to project the cost ATW systems. Second, the

ALMR system was the product of an extensive cost and safety optimization effort, and it is not unreasonable to expect that a similar effort for ATW converters would have similar results. A key parameter that links the fission power to the proton beam power is the subcritical multiplier M, which scales with the inverse of $1 - k_{eff}$. This parameter can only be finally determined after extensive physics and safety analyses, but will probably end up somewhere between 0.96 and 0.98. We have assumed k_{eff} will be 0.97 (M will be about 40), which implies a proton beam power of about 11.25 MW is required to drive an 840 MWt subcritical converter.

Linear accelerators are more efficient and more cost effective if they are driving high currents, as is the case for the Accelerator Production of Tritium (APT) linac.[6] Further, accelerator beams are nearly always shared between multiple target facilities. A high power beam that is shared ("split") between several subcritical converters would be economical. It is relatively straightforward to divide a beam equally, using radio frequency (rf) splitters, which makes sharing between 2, 4, 8, or 16 targets straightforward (the beam splitters cycle among the targets perhaps a hundred times per second, minimizing any potential transients in the targets). For the reference case, two 45 MW accelerators drive eight 840 MWt subcritical converters, with cross-linking provided so one accelerator can support any four converters. This provides high likelihood that at least half of the total generating capacity with be available most of the time.

Separations processes are performed at two scales. Because of the large inventory of spent fuel, the first separations step is a large-scale process. However, regardless of whether an aqueous or a pyro-based front end is used to separate the uranium, the facility can be modularized and therefore scaled for the site requirements. In contrast, the step of removing fission products from ATW spent fuel and reforming that fuel for subsequent cycles would be much smaller and based on pyrometallurgical processing. Because pyro processing is typically performed at a relatively small scale (many batches through small processing cells), it is easily scaled to support ATW unit throughput.

The final issue determining the size of the ATW system is plant lifetime. Because accelerators are inherently modular and don't accumulate significant materials damage from radiation, accelerators have an indefinite lifetime. Most separations processes are also modular, and the cells can be replaced as necessary. In contrast, the subcritical converters are the most likely source of lifetime limitations. Over several decades, structural materials accumulate significant radiation doses, and some portions of the device could be difficult to replace. A sixty-year lifetime has been assumed, consistent with the objectives of most advanced reactor design efforts and recent license extensions in the U.S. The issue of replaceable components will be evaluated as part of the design process.

Reference ATW Plant

A reference ATW plant based on the previous discussion is illustrated in Fig. 1. This layout includes two large linear accelerators to provide proton beams to eight subcritical converters. This configuration allows converters to receive beam whenever at least one accelerator is operating, which will improve systems availability (reliability). Although the capital cost of this configuration may be modestly higher than the cost of one large linac driving eight 840 MWt (megawatt-thermal) converters, for example, it is thought that the improved availability will bring a larger revenue stream from electric power sales to cover any additional investment. During 60 years of operation, the reference ATW plant would process 10,155 tn of spent nuclear reactor fuel by separating TRU, Tc, and I from the uranium and other fission products, then transmuting 99.9% of the TRU and 95% of the Tc and I. This compares to about 2,000 tn/year currently being produced by operating U.S. nuclear plants. Details about the assumptions and computed performance of this system are provided in Tables I through IV.

The separations process illustrated in Fig. 1. includes three steps. The uranium is first removed via the UREX process, then an oxide-reduction process converts transuranics and fission products from oxide to metallic form; finally the transuranic components are separated and converted into ATW fuel.

About 9,684 tn of uranium can first be separated from the spent fuel. Of the remaining 470 tn, about 355 tn are mostly stable, short-lived, or longer-lived but comparatively harmless isotopes, plus less than a tonne of technetium, iodine, and transuranic content that the separations process fails to fully separate. The 355 tn can be cast into highly durable waste forms that would resist dispersion by natural phenomena, including ground water penetration, leaching, and transport because they would be more stable than as-discharged spent fuel. The cesium and strontium products in this waste have roughly 30-year half-lives, so this part of the waste stream generates significant decay heat for the first several decades. This portion

of the waste stream does require long term disposal in some form of waste repository, although the requirements for isolation may be reduced to assurance of containment for only a few hundred years from the ten thousand years needed for the current repository approach.
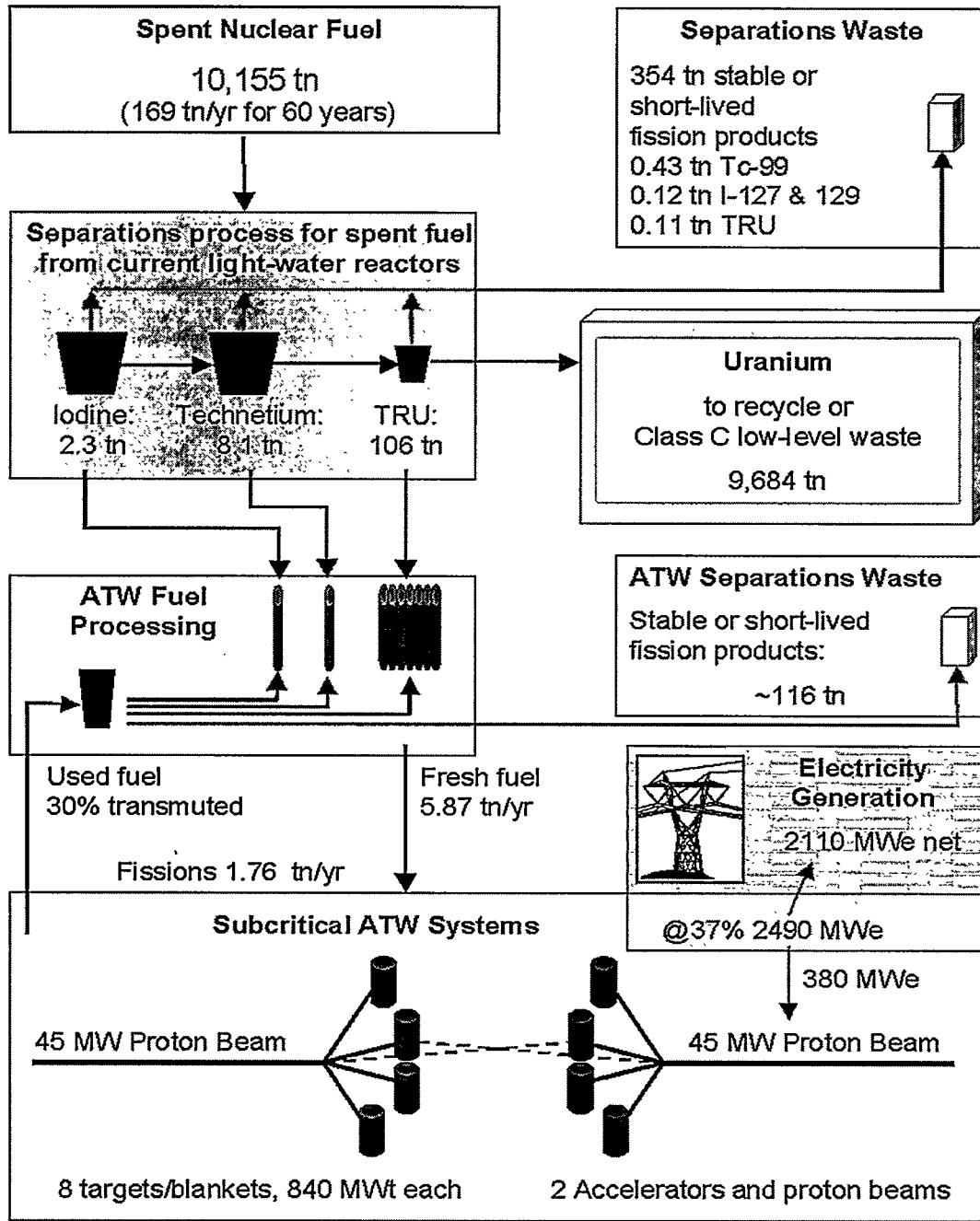
Figure 1. Reference ATW plant sized to process 10,155 tn of spent fuel.

The transuranics would be blended with zirconium to form ATW fuel rods. The high zirconium content (about 80 to 90 atom percent) provides some advantageous fuel characteristics including high melting temperatures and good tolerance for fission gas build-up. About 30% of the TRU content will be fissioned per pass through ATW (much higher fission utilization is desirable, perhaps 50%). The technetium and iodine will be formed separately into fission product targets. Because technetium transmutes to another solid (ruthenium), and because it has a large resonance capture cross section (i.e., it

prefers to capture neutrons as they are slowing down), the major problem is that there is a great deal of it to be converted. For this reason, the technetium rods will remain in the ATW converter for many years before any processing is needed. Although most (over 80%) of the technetium will reside in separate rods, the technetium produced during the transmutation process will likely be retained with the remaining transuranics and thus be recycled into the converters as part of the fuel rods. During transmutation, the iodine must be converted to xenon gas, and some of the xenon isotopes may compete with the iodine in capturing neutrons. Therefore, there may be incentive to design these targets with gas plena or other features to vent the xenon. It is even conceivable that the iodine may not be in solid target form, and may instead be piped in liquid or gaseous form through the shielding region (iodine is transmuted by very slow neutrons). Fortunately, there is far less iodine than technetium to be converted.

TABLE I. Reference ATW Plant Parameters for the Separations Facility

TRU loss fraction per pass	0.0010	^{99}Tc Throughput	135.6 kg/yr
Total processing loss	0.0033	I Throughput	37.9 kg/yr
Tc & I processing loss	0.05	Spent Fuel Throughput (IHM)	169.2 tn/yr
TRU Throughput	1765.8 kg/yr		

TABLE II. Reference ATW Plant Parameters for the Accelerator System

Proton Energy	1 GeV	Power Required-Accelerator	304.0 MWe
Proton Current	90 mA	Accelerator net efficiency	29.6 %
Number of beam lines	2	Power Required-Plant	378.6 MWe
Beam Power	90.0 MW		

TABLE III. Reference ATW Plant Parameters for the Facility

Lifetime	60.0 years	Annual energy production	1475 MWe-yr
Total TRU fissioned	105.6 tn	Annual energy production	12.9 TWe-hr

TABLE IV. Reference ATW Plant Parameters for the Transmuter (Reactor) Systems

$k_{effective}$	0.97	Fissions/year/target	5.52e26
ν (neutrons/fission)	2.95	Neutron/fission for Tc	0.534
Spallation threshold	0.2 GeV	Neutron/fission for Iodine	0.115
n/p multiplier-lead	33.8	Neutrons/fission for Tc and I	0.649
Energy per fission	208 MeV	kg TRU fissioned/year/target	220.0 kg TRU/yr
Beam Energy Deposit fraction	0.7	kg TRU fissioned/year total	1760.0
Thermodynamic efficiency	37.0 %	Fission heat	832.1 MWt
Plant capacity factor	70.0 %	Target/blanket total heat	840.00 MWt
Atoms per kg of TRU	2.51e24	Electricity per target/blanket	310.8 MWe
Atoms per kg of Tc-99	6.08e24	Facility total electricity	2486.4 MWe
Atoms per kg of Iodine	4.71e24	Auxiliary power	74.6 MWe
Tc conversion efficiency	0.7	Net facility electricity capacity	2107.8 MWe
Iodine conversion efficiency	0.7	Net annual electric production	1475 MWe-yr
Neutrons per proton	27.0	Net plant efficiency	31.4 %
Neutron multiplier	33.3	Electric prod. re-circulated	52.2 MWe yr/yr
Neutrons per second/target	7.60e19	Elect. prod. Re-circ. to accel.	212.7 MWe yr/yr
Fissions/second/target	2.50e19	Total elect. Prod. re-circulated	264.9 MWe yr/yr

The throughput of transuranics is derived directly from the fission heat rate of the subcritical converters. Therefore, the 1.76 tn per year of transuranics corresponds directly to the amount of fissionable material required for the eight subcritical converters to generate 6,720 MWt (includes around 70 MWt of beam power). The technetium and iodine throughput is based on consuming those materials in proportion to transuranic consumption. Each fission event will produce at least one excess neutron, so the requirement

of 0.33 of the excess fission neutrons for fission product transmutation is easily met, and a significantly higher conversion rate may be feasible.

The power production in the figure and tables is based on 37% thermal efficiency, which results in 2490 MW electric (MWe). Liquid lead-bismuth could support much higher conversion efficiencies due to its high boiling temperature. However, temperature limits associated with the corrosion issue may limit the operating temperature. The power allocation of 380 MWe covers the accelerator power requirements and an allocation to support the separations processing and balance of plant systems. The net power production of 2110 MWe would be sold via the electric grid, providing a large revenue stream that can be used to cover a large fraction of the plant capital and operating costs.

After 60 years of operation, nearly all of the transuranics will have been fissioned, most of the technetium will have been converted to stable isotopes of ruthenium, and most of the iodine will have been transmuted to stable isotopes of xenon. Any residual quantities of transuranics, technetium, and iodine would be fed into any ATW plants that remain in operating mode. Eventually, the residual inventories of transuranics, technetium, and iodine from the last ATW unit would be placed into long-lived waste forms and placed into a waste repository. That residual inventory is likely to be on the order of a few hundred kilograms.

As mentioned previously, the reference ATW converter is based on an Advanced Liquid Metal Reactor (ALMR) developed during the late 1980s and early 1990s . Also known as PRISM, the design work was sponsored by the USDOE, led by General Electric with support from ANL, and was formally reviewed by the Nuclear Regulatory Commission. If the ATW target/blankets are based on sodium-coolant technology, as is currently the assumption a system that resembles PRISM may be nearly optimized regarding systems engineering, safety, and costs. In this concept, the proton beam enters from a bermed accelerator (above grade but with earth piled above the accelerator to provide added shielding) and is then bent downward into the target/blanket vessel. The spallation target module is assumed to be separated from the blanket region to keep spallation products from traversing the entire blanket cooling system. This feature would also allow different coolants to be used in the spallation target and the blanket regions. See Reference 7 for a detailed description of this concept as well as spallation targets.

Deployment-driven ATW System Implementation

An ATW system implementation to address the 86,300 tn of spent fuel using the reference plant is illustrated in Fig. 2. The first ten to twelve years includes R&D at small scale and at pilot scale. A Spallation Target Facility (STF) will be developed at LANSCE; it will fit within the existing buildings and is covered under the site-wide EIS. This facility would test the proposed spallation target module(s) and provide a useful source of spallation neutrons for testing ATW candidate fuels and materials.

The reference scenario is based upon the current deployment and generation capacity of PWRs and BWRs in the U.S., no construction of additional nuclear power stations, and no license extensions. The implications of this scenario are based on the 1996 evaluation of the nuclear industry in the U.S.,[8] with corrections for recent activities including changes in performance and early retirements of nuclear plants. This was an appropriate starting point for this study as it is the scenario referred to by the Energy Information Administration of the Department of Energy in many of their energy projections;[9] however, recent performance improvements and license extensions will necessitate a re-evaluation of future projections of spent fuel. The calculation of spent fuel production and the transuranics and fission products contained in the spent fuel is summarized below.

The current spent fuel inventory in the U.S. is about 40,000 tn. For the Reference Scenario, this inventory was predicted to increase to about 71,000 tn by 2015 and 86,317 tn by 2036, when the license of the last operating plant will expire. The statutory limit for the proposed Yucca Mountain geologic repository is 70,000 tn, although that limit might some day be increased. The inventory of transuranics (TRU) in the 86,317 tn of spent fuel is projected to be about 900 tn with about 90% of that being plutonium. The actual quantity of TRU in 2036 will depend on burnup levels and power history of the discharged fuel; for this scenario we used the results of an analysis of historical and projected burnup.[10] The average burnup of spent fuel that was discharged during 1998 was about 41 MWt-d/kg, and the cumulative average projection is 37.2 MWt-d/kg by 2036. The spent fuel would also contain about 93 tn of the problematic long-lived fission products technetium (73 tn) and iodine (20 tn).

Because of the energy content in TRU waste, reference ATW plants are fairly large, producing a net 2100 MWe of electric power per eight-converter plant (1475 GWe-yr/yr with a projected 70% capacity factor).

Even so, an estimated 8.5 plants will be needed to complete the mission. The scale of this process is not driven by ATW technologies or capabilities, but rather by the amount of energy released during transmutation. ATW systems will convert that energy potential to electricity, leaving behind an inventory of about 1000 tn of additional stable or short-lived fission products and less than one tn of the long-lived problem materials. The production of electricity and spent fuel by LWRs and the elimination of spent fuel by ATWs for this basis scenario is illustrated in Fig. 2.

Planning and licensing for the ATW demo facility would be concurrent with much of the early R&D and pilot scale work. Because the cost of constructing demonstration scale and full scale accelerators and target/blanket are quite similar, the economics favor building full-scale facilities with partial power capabilities. Therefore, the demo facilities could be upgraded easily as the technology demonstration effort proceeds. Construction of an 11 MW accelerator would take place from 2009 through 2013, with the target/blanket construction lagging about two years behind. This is to allow two years of start-up testing on the accelerator, focusing on improving the reliability over conventional accelerators. Start-up of a small fuel load (low k_{eff}) would begin in 2015. Periodic upgrading of the fuel loading, the k_{eff}, and the fission heat production would lead to a full ATW transmuter loading by the early- to mid-2020's. Successful operation of that transmuter would lead to an accelerator upgrade to 45 MW capacity in about two years and construction of three additional target/blankets. At this point (around 2030), the ATW Demo would be effectively converted to an ATW power plant with a significant revenue stream. ATW Demo will process about 5000 tn of spent fuel during its lifetime.
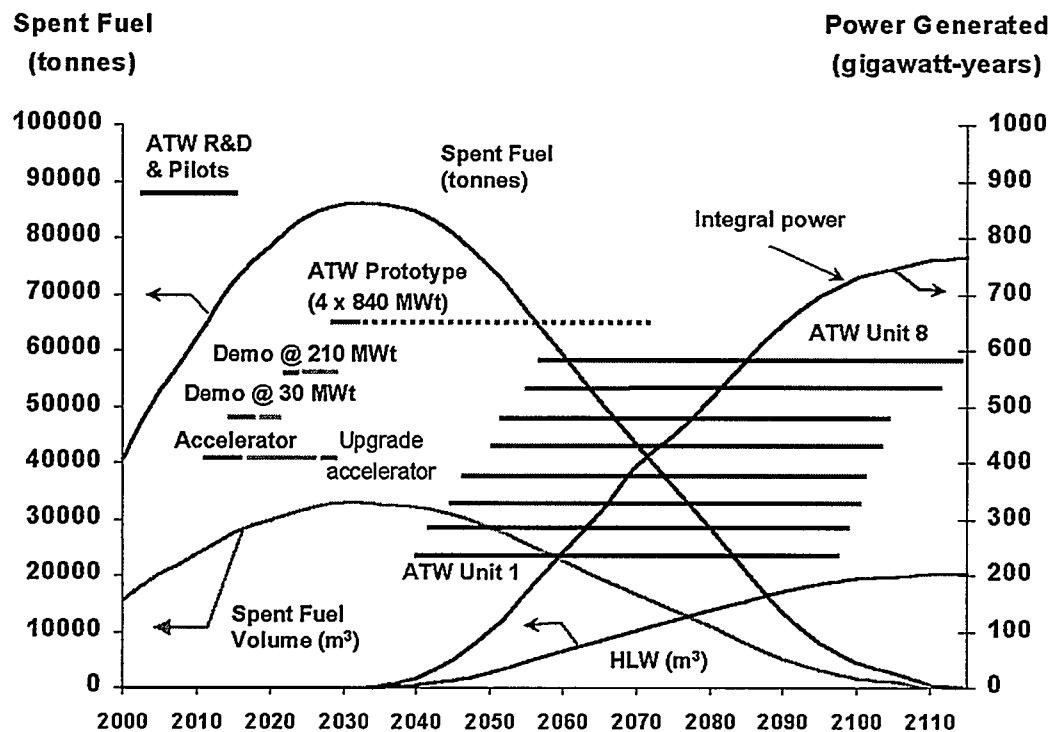

Figure 2. Reference ATW plant implementation to address the 86,300 tn of spent fuel that are expected to accumulate by 2036. This case is based on the assumption that 900 tn of TRU will be transmuted by 8.5 ATW Units and that a Demo plant is converted to an ATW Prototype plant with 50% capacity (four 840 MWt transmuters). This case also assumes the current generation of power reactors are retired as licenses expire and that no new reactors will be constructed. The integral power from this ATW scenario is about double current total U.S. annual consumption.

The full deployment of an eight-unit ATW system could then proceed, probably after completion of an involved decision-making process including a PEIS. Although not shown, it is also likely that pairs of

subcritical converters would come on line in staggered fashion, possibly one per year after the accelerators are up and running.

The use of ATW technology capitalizes on the residual energy in the spent fuel, and no new transuranics are produced during the process. The scope of the spent fuel transmutation mission is reflected in the ATW power production. Not long after 2100, when the spent fuel has been transmuted, nearly 800 gigawatt years of electric power will have been generated from the waste. This amounts to roughly two years of *total* electricity consumption in the U.S. during 1999, or 28% more power from the once-through fuel cycle. The time frame required to transmute the inventory, about 75 years, is to make efficient use of the capital investment required to convert the fission energy into electricity. During the period from 2060 until 2095, ATW power plants would be generating nearly 20 GWe, or about 5% of the current rate of total power consumption in the U.S. With respect to total waste volume, the un-separated spent fuel without ATW would reach a maximum of about 33,000 cubic meters of waste, whereas the ATW waste residue based on the Reference design and the currently assumed waste forms would occupy about 20,000 cubic meters of "high level waste (HLW)" of a waste repository.

Alternate ATW Deployment Scenarios

In the previous section we described the reference scenario for the U.S., i.e., that of no new orders for nuclear power plants and no license extensions, and the effect on deployment of ATW. The future of the U.S. nuclear industry is changing rapidly, and may be significantly different from that used in the Roadmap study. Major variants to this scenario include life extension of existing plants, construction of new capacity to maintain a 100 GWe nuclear in the U.S., and alternate fuel cycles like the MOX fuel cycle, fast-spectrum breeder reactors, and thorium-uranium fuel cycles.

The Reference ATW that was developed for the ATW Roadmap would process 1197 kg of TRU per year per ATW GWe produced. The support ratio for different scenarios or fuel cycles is then determined by the quantity of TRU that they discharge per unit power output. This output depends on fuel type, reactor operation, spectrum (thermal, epithermal, fast), recycle (number of cycles, fraction recycled), and fuel utilization. The denatured thorium-uranium (DTU-LWR) fuel cycle was modeled with a utilization of 50,000 GWt-d/MTIHM, a conversion efficiency of 33%, and a production rate of 127 kg TRU/yr/GWe (compared to 315 kg TRU/yr/GWe for a OT-LWR at 40,000 GWt-d/MTIHM). The discharge from a MOX-LWR depends likewise on fuel management, and we assume here a 4-cycle system (TRU is recycled only 3 times) and 50,000 GWt-d/MTIHM which produces 174 kg TRU/yr/GWe. The discharge from a LMFBR depends on whether it is a once-through concept or whether it breeds and recycles. With extremely high utilization and some recycle, we can assume the LMFBR produces 90 kg TRU/yr/GWe for feed to ATWs. Finally, the HTGR is assumed to operate on a once-through fuel cycle, with high utilization (100,000 GWt-d/MTIHM) and a higher thermal-electric efficiency of 40%, and discharges just 76 kg TRU/yr/GWe. These five reactor types, TRU production, and support ratios are summarized in Table V.

Alternate LWR Futures

One plausible alternative scenario of the energy future in the U.S. includes more light-water cooled reactors with a continuation of the existing once-through fuel cycle. ATW deployment scenarios include the ATW Reference Scenario (Reference), a similar scenario with 20-year license extensions for some plants (Ref.+LE) and a greater average burnup, and a scenario with a continuation of the current 100 GWe of nuclear generating capacity from LWRs. Spent fuel production from these two additional scenarios can be compared with the Reference Scenario by examining Fig. 3. Whereas the cumulative spent fuel from the Reference Scenario is projected to be 86,300 tn, the cumulative production by 2050 increases to 100,000 tn with license extensions and 150,000 tn for the 100-GWe-capacity scenario.

A Future with MOX Fuel

The U.S. may choose to utilize MOX in light water reactors, as is done in Europe and Japan. This is also similar to one of the "dual paths" of the U.S. weapons disposition program. Fissioning of plutonium in MOX form would reduce the plutonium loading for ATW systems, but the degree of reduction depends on how many passes are made through MOX-fueled reactors and what portion of the total fuel loading includes Pu. Ultimately, the use of MOX fuel leads to a larger discharge of minor actinides per unit power or burnup, as well. If enriched uranium is blended in with MOX, it is possible to transition to an equilibrium in which only minor actinides reach the ATW plants. However, that through-put of minor actinides would more than triple the through-put from the once-through fuel cycle. Thus, ATW would

provide a support ratio of about 20 MOX-fueled LWR reactors per ATW plant (nominal 1000-GWe capacity LWRs per ATW). Even if few Pu recycles are used, followed by transfer of the nth-cycle TRU (Pu and M.A.) to ATW systems, the support ratio can increase substantially. For a 4-cycle MOX scenario (3 Pu recycles), the support ratio increases to 12.5 MOX-fueled LWR reactors per ATW plant.

Table V. Comparison of transuranic production and support ratios for five reactor types

Reactor Type	TRU production (tn/GWe-yr)	Support Ratio (reactors per ATW plant)	Power Support Ratio (GWe per ATW GWe)	Number of ATW Plants required for this scenario
Once-through LWR (OT-LWR)	0.315	6.6	3.7	9
Denatured-Th-U LWR (DTU-LWR)	0.128	16	9	12
MOX-fueled LWRs (MOX-LWR)	0.174	12	7	10
Liquid metal fast breeder reactors (LMFBR)	0.090*	23	13	7
Modular high-temperature gas-cooled reactors (MHTGR)	0.076	27	16	6

*in this design, much of the excess Pu is destined for new reactors. However, for this analysis, 20% of the discharged Pu is sent to ATWs along with the minor actinides.
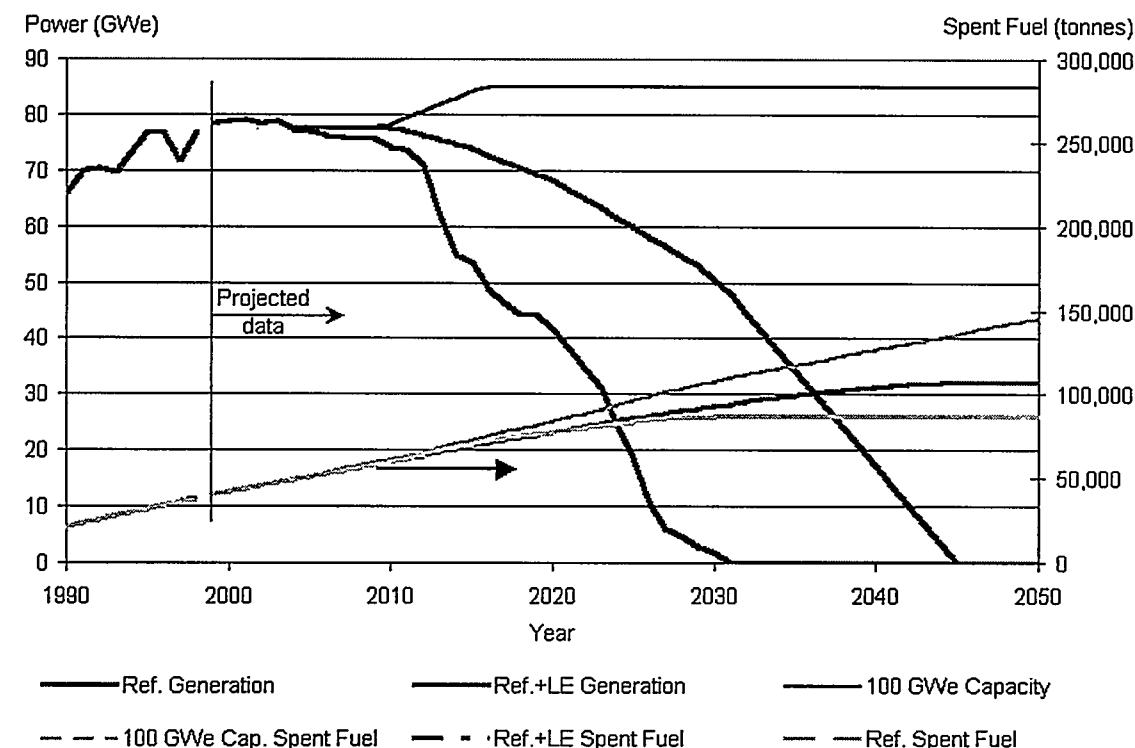

Figure 3. Comparisons of Power and Spent Fuel Production for Three Nuclear Power Scenarios. Ref. = Reference Scenario, Ref. + LE = Reference with 20-year license extensions, and 100 GWe = 100 GWe LWR capacity with an 85% capacity factor by 2008.

A Future with Fast Spectrum Reactors

Although fast spectrum reactors (FSR, e.g. liquid-metal fast breeder reactor, LMFBR, and Advanced Liquid-Metal Reactor, ALMR) have inherent advantages regarding consumption of much of their own waste stream, a range of options exists for their implementation. As power producers, FSRs provide the best performance in terms of utilization of natural resources, and are capable of providing a nearly endless supply of energy through a process of breeding plutonium. In such an operating mode, ATW systems

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could transmute the minor actinides and fission products with a very high support ratio that is five to ten times greater than the support ratio for light water reactor systems. The support ratio could be between 40 and 80 FSRs per ATW plant (again, nominal 1000-GWe-capacity FSRs), so that one or two ATWs could close the back end of this fuel cycle for the current U.S. nuclear generating capacity.

Transition to a Thorium-Based Fuel Cycle

Although the U.S. interest in thorium cycles is currently very localized, interesting advantages include reducing the production of plutonium and minor actinides, enhancing proliferation resistance by spiking the thorium with uranium so that ^{233}U is diluted as it is produced (this is called the DTU, or denatured-thorium-uranium, fuel cycle). In one recent study the support ratio for a DTU-LWR fuel cycle, with recycle of thorium and uranium, was determined to be 14 DTU-fueled LWR reactors per ATW plant.[10] In addition to the technical rationale, the strong advocacy of the Energy Amplifier by the CERN group is sure to draw attention in the U.S. eventually.

For the reference or alternate nuclear futures, the final ATW support ratio will depend on the kinds of fuel cycles that are deployed, and will vary from a low of 3-4 for once-through LWRs, to about 7-9 for DTU-fueled LWRs, to as high as 20 for high-converting, high utilization, breeding or recycling concepts.

Summary

Although the current assumption in the U.S. regarding ATW implementation is that it would address only a limited nuclear waste legacy, including all of the plutonium in reactor spent fuel, this assumption may not prove to be true in the long term. A resolution of the waste issue may help clear the way for future uses of nuclear energy, and those uses could either increase or decrease the mission for ATW. In all cases ATW plants will need to dispose of energy as electricity and this will determine the size of the particular system chosen for implementation. The ATW concept could be focused on spent fuel, a different blend of plutonium and minor actinides, solely on minor actinides, or possibly on a transition to a thorium-based fuel cycle. All these possibilities are already being considered in the U.S. and other countries. Therefore it is essential that ATW technology be developed in a way that maximizes its flexibility in dealing with different compositions of spent fuel waste and ATW fuel. The mix of new reactors and ATWs required to meet growing demand for clean, safe nuclear energy will be determined by support requirements based on the diversity of new reactor types.

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