ABSTRACT

A roadmap has been established for development of ATW Technology. The roadmap defines a reference system along with preferred technologies, which require further development to reduce technical risk, associated deployment scenarios, and a detailed plan of necessary R&D to support implementation of this technology. The potential for international collaboration is discussed which has the potential to reduce the cost of the program. A reference ATW plant was established to ensure consistent discussion of technical and life cycle cost issues. Over 60 years of operation, a reference ATW plant would process about 10,000 tn of spent nuclear reactor fuel. This is in comparison to the current inventory of about 40,000 tn of spent fuel and the projected inventory of about 86,000 tn of spent fuel if all currently licensed nuclear power plants run until their license expire. The reference ATW plant was used together with an assumed scenario of no new nuclear plant orders in the U.S. to generate the deployment scenario for ATW. In the R&D roadmap, key technical issues are identified and timescales proposed for the resolution of these issues. A key recommendation is that, in the first year of any ATW program, trade studies intended to lead to confirmation of technology choices and optimization of design be conducted. These studies will then be used to define future R&D. International collaboration will be important in this endeavor.

INTRODUCTION

Congress appropriated $4 million in fiscal year 1999 for the Department of Energy (DOE) to conduct a study of accelerator transmutation of waste (ATW) technology. DOE, in coordination with its laboratories, was requested “...to establish a roadmap for the development of ATW technology that identifies: technical issues that must be resolved; a proposed time schedule and program to resolve those issues; and the estimated cost of such a program. The roadmap should consider and propose collaborative efforts with other countries developing ATW technology and other programs developing accelerator technology. Institutional challenges of the proposed program should be assessed as well as areas of ATW technology development that could have benefits to other ongoing programs. In addition, the roadmap and report to Congress...
should assess the potential impact of this technology on the civilian spent nuclear fuel program and the estimated capital and operational life cycle costs to treat civilian spent nuclear fuel.”

The Systems Scenarios and Integration Technical Working Group, was responsible for both evaluating the role of ATW in energy and waste reduction scenarios and the work of the other three technical working groups to ensure consistency of technical assumptions, schedules, and key system parameters. In response to the congressional mandate, the report [1] contains a technology development roadmap, identifies the technical issues to be resolved and a plan and schedule to carry out the program. The report also addresses possible international collaborations and the identification of key institutional issues as part of the system study.

The Congressional mandate identifies the need for an ATW technology road map and the development of specific R&D plans to support this road map. Section 3 describes possible future scenarios for nuclear energy in the USA, and the consequences on spent fuel production. Key assumptions are highlighted and a no new orders scenario is selected as the basis for this study. The choice of scenario was made for expediency in preparing the roadmap. No statement is made as to the likelihood or desirability of this scenario. This ATW technology is based on the use of liquid metal coolants, fast neutrons and pyrochemistry for the separations as discussed in Section 4. This choice is based upon some comparability among international groups but is not the only technical option.

This report should not be considered as a comprehensive evaluation of the merits of ATW technology or as recommending a particular choice of technology. What this report does seek to do, in conjunction with the reports of the other working groups, is to answer the following questions:

- What technology options exist for the ATW?
- What are the necessary steps required to develop and implement ATW technology?
- What is the R&D required to confirm these choices and provide a basis for development of the ATW concept?
- How could the U.S. utilize international cooperation to meet its goals?

RATIONALITY FOR TRANSMUTATION

The final disposition of spent fuel has been and continues to be an issue of national and international importance. In the U.S., an aggressive program is ongoing to characterize a candidate site at Yucca Mountain, Nevada for a geological repository for spent fuel and high-level waste. The Yucca Mountain repository is being sized to safely dispose of 63,000 t of spent fuel from nuclear power reactors and 7,000 t of spent fuel and high-level waste from DOE operations. Current reactor operations in the U.S. discharge about 2000 t of spent fuel annually.

At the time of its removal from the reactor, most of the radioactivity in spent fuel is from the fission products Cs-137, Sr-90, and other products that have relatively short half-lives. Short-lived fission products can be readily retained in repositories for reasonable periods to minimize their threat to the human environment. The major constituent, uranium, can be separated and reused in fresh reactor fuel, or disposed of as low-level radioactive waste.
Table 1. Typical Composition of Spent Fuel

<table>
<thead>
<tr>
<th>Component</th>
<th>Fresh Fuel</th>
<th>Spent Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238+</td>
<td>967.9</td>
<td>943.7</td>
</tr>
<tr>
<td>U-235</td>
<td>32.1</td>
<td>6.7</td>
</tr>
<tr>
<td>Plutonium</td>
<td></td>
<td>9.3</td>
</tr>
<tr>
<td>Minor actinides</td>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td>Sr-90</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Cs-137</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Te-99</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>I-129+</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Other Fission Products</td>
<td></td>
<td>36.3</td>
</tr>
<tr>
<td>Total</td>
<td>1000.0</td>
<td>1000.0</td>
</tr>
</tbody>
</table>

+ Includes other isotopes

This composition is for 37.2 MWt-d/kg burnup, 20 years after discharge (grams per kg of initial U). This composition is not the same as the average spent fuel composition from a wide distribution of burnups with the same average burnup.

In addition to the uranium and short-lived fission products, spent fuel contains small quantities of plutonium, other transuranic elements, and long-lived fission products. Long-lived constituents present challenges to repository performance because it is difficult to predict performance hundreds of thousands of years in the future. The treatment of spent fuel to deal with these constituents could simplify some of the technical difficulties of geologic repository disposal. Such treatment can be considered as a technology option to enhance repository development. By removing and transmuting the plutonium, other transuranic constituents, and the long-lived fission products from spent fuel, several objectives can be met:

- Public acceptance could be improved by reducing the inventory of long-lived radionuclides in the repository thereby decreasing the period of time that the repository has to maintain integrity.
- The potential for future removal of plutonium from the repository for use in nuclear weapons is avoided.
- The energy content of the transuranics could instead be used in power reactors. The transuranics alone have an energy content equivalent to 25--30% of the energy released during the formation of the spent fuel.

The primary benefit from ATW, and the impetus for its development, is improved management and disposal of spent fuel from commercial nuclear power production. Benefits for the management of spent fuel include improved isolation, safety or “repository performance”, improved confidence in repository performance, design flexibility, simplicity or optimization and increased capacity or reduced cost via the reduction in radionuclide inventory, reduction in thermal load, elimination of the criticality risk and customized wasteforms. A further direct benefit from ATW comes in the form of the reduction of risk of material diversion for weapons use. The present ATW concept does not separate weapons usable fissile materials at any time.
during the processing. Thus, the conditioning of spent fuel to remove and transmute the plutonium, other transuranics, and long-lived fission products has the potential to provide significant benefits to the overall repository disposal program, and enhance flexibility in future efforts to optimize radioactive material management.

These benefits may only be realized if a number of significant institutional issues are able to be overcome, in addition to the technical problems described below. The institutional issues include regulatory/NEPA issues, funding and resource management, and public acceptance.

ATW DEPLOYMENT SCENARIOS

In order to understand whether an ATW system can realize these benefits it is necessary to construct deployment scenarios. These scenarios allow us to size a typical ATW plant. The reference scenario chosen for this study, that of no new orders for nuclear power plants in the U.S. Major variants to this scenario, which include life extension of existing plants or construction of new capacity to maintain a 100 GWe nuclear in the U.S., are also described. Scenarios that describe alternate U.S. nuclear futures are also discussed. It is concluded that the predominant factor in choosing the size of the ATW plant is the need to dispose of the energy released (as electricity). Different scenarios might lead to differences in fuel form but the fundamental technology choices are unchanged.

The Reference Scenario

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., [2] with corrections for recent activities including changes in performance and early retirements of nuclear plants. This is 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.[3]

The current spent fuel inventory in the U.S. is about 40,000 tn. For the Reference Scenario, this inventory is 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 depends 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.[2] 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 contain about 93 tn of the problematic long-lived fission products technetium (73 tn) and iodine (20 tn).

The energy in the TRU waste, if it could be efficiently utilized, would be sufficient to provide more than twice the current total annual electricity sales in the U.S. (or about 28% of the
electricity expected to be produced by U.S. nuclear power through 2036). As a result, reference ATW plants (see Section 4) are chosen to be fairly large, producing a net 2100 MWe of electric power per eight-burner plant (1475 MWe-yr/yr with a projected 70% capacity factor). Even so, an estimated 8.5 plants will be needed to complete the mission (this is a support ratio of about 6.6 LWRs per ATW plant). The scale of this process is not driven by ATW technologies or capabilities, but rather by the amount of energy released during transmutation. Under this deployment scenario, 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 projections are based on energy production and spent fuel generation with existing U.S. nuclear plants, a capacity factor that increases from 78.6% in 1998 to 85% in 2008, and an average burnup at discharge that initially increases then declines at end of reactor lifetimes, with a cumulative U.S. average of 37 MWt-d/kg.

Limited Nuclear Future

The most 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. To examine a range of potential nuclear power futures, other ATW deployment scenarios were modeled. These included the ATW Reference Scenario (Ref.), also with 20-year license extensions for some plants and a greater average burnup, and a scenario with a continuation of the current 100 GWe of nuclear generating capacity from LWRs. Whereas the cumulative spent fuel from the Reference Scenario is 86,300 tn; this production increases in 2050 to 100,000 tn with license extensions and 150,000 tn for the 100-GWe-capacity scenario. Existing U.S. nuclear power plants generate approximately 2,000 tn of spent fuel per year, and an ATW plant can be expected to process about 10,000 tn of spent fuel during its lifetime. Therefore, a new ATW plant would be built about once every five years to continue to support the existing nuclear generation.

Alternate U.S. Nuclear Futures

A future U.S. nuclear industry may be significantly different from that currently envisaged. The MOX fuel cycle is currently constrained by policy in the U.S., but it is feasible and policy can change with new discoveries or new national priorities. Fast reactors have been explored for decades, and prototypes have been built, tested, and operated; it is conceivable that farther in the future, these fuel cycles with their production of fissile materials may become desirable. In addition, global attention is returning to thorium-uranium fuel cycles, because of the possibility of using increased resources and a potential for reduced proliferation risk.

A Future with MOX Fuel

The U.S. may choose to burn MOX in light water reactors, as is done in Europe and Japan, and similar to one of the “dual paths” of the U.S. Pu disposition program. Fissioning of plutonium in MOX form would reduce the plutonium loading for ATW systems, but the degree depends on how many passes are made through MOX-fueled reactors and what portion of the total fuel
loading includes Pu. Use of MOX fuel leads to a larger discharge of minor actinides per unit power or burnup. However, that through-put of minor actinides would more than triple the through-put from the once-through fuel cycle, which will result in an overall increase in support ratio of ATWs of about a factor of 3. Thus, ATW would provide a support ratio of about 20 MOX-fueled LWR reactors per ATW plant. Even if few Pu recycles are used followed by transfer of the nth-cycle TRU to ATW systems, the support ratio can increase substantially.

A Future with Fast Reactors

Fast spectrum reactors have inherent advantages regarding consumption of much of their own waste stream and a range of options exists for their implementation. As power producers, fast reactors provide the best performance in terms of utilization of natural resources, with plutonium making up roughly one-quarter of the fuel and uranium making up the balance. In such a mode, fast reactors are capable of providing a nearly endless supply of energy through a process of producing plutonium at least as quickly as it is consumed. In this context, ATW systems could transmute the minor actinides and fission products with a support ratio that is five to ten times greater than the support ratio for light water reactor systems. The support ratio could possibly be between 40 and 80 fast reactors per ATW plant.

Transition to a Thorium-Based Fuel Cycle

Although the U.S. interest in thorium cycles is currently very localized, there are some interesting advantages to such a fuel cycle. It would reduce the production of plutonium and minor actinides, which would eliminate some troublesome components of the nuclear waste stream. In addition, the cycle can enhance proliferation resistance by spiking the thorium with uranium so that $^{233}\text{U}$ 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. [4]

ATW System Implementation

An ATW system implementation to addresses the 86,300 tn of spent fuel using the reference plant described in Section 4.3, is illustrated in Fig. 1. The first ten to twelve years includes R&D at small scale and at pilot scale. Concurrent with much of the early R&D and pilot scale work, planning and work to gain approvals for the ATW demonstration facility (Demo) would progress. 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. The Demo facilities could be easily upgraded 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 allows two years of start-up testing on the accelerator, focusing on improving the reliability over conventional accelerators.

Start-up of a small fuel load would begin in 2015. Periodic upgrading of the fuel loading, the $k_{\text{eff}}$ and the fission heat production would lead to a full ATW transmuter loading by the early-
mid-2020’s. Successful operation of that transmuter would lead to an accelerator upgrade to 45 MW capacity (needs about two years) and construction of three additional target/blankets. At this point (around 2030), the ATW Demo is effectively converted to an ATW power plant and a significant revenue stream is established. Demo will eventually process about 5000 tn of spent fuel. The full deployment of an eight-unit ATW system could then proceed. Although not shown, it is also likely that pairs of transmuters would come on line in staggered fashion, possibly one per year after the accelerators are up and running.

The time for elimination of the spent fuel inventory, about 75 years, is chosen 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. Not long after 2100, when the spent fuel has been transmuted, nearly 800 gigawatt years of electric power have been generated from the waste. With respect to total waste volume, the spent fuel reaches a maximum of about 33,000 cubic meters of waste, and the ATW waste residue in the currently assumed customized waste forms occupies about 20,000 cubic meters of “high level waste (HLW)” of a waste repository.

**TECHNICAL REFERENCE**

The ATW technical reference reflects the current national and international thinking as to the best technology options and size of the facility. However, there are various technology options still under discussion worldwide, and several potential backup or advanced technology options...
have been identified. Optimization of the size and configuration will be a lengthy iterative process as the design teams explore and evaluate options. Therefore, the reference design described here should be viewed as a preliminary implementation that will undergo evaluation.

**Basic Technology Choices**

The ATW system requires three major technologies, the accelerator technology to provide a high power beam of charged particles (protons), target/blanket technology needed to transmute the long-lived hazards into stable or short-lived materials and the chemistry processes that allows the materials to be separated. The reference ATW design is based on known technologies in each of these major areas, although some mission-specific requirements necessitate some modifications/extensions to current technology.

**Accelerator**

A linear accelerator is chosen for the reference design because of high beam power requirements. Linear accelerators are believed to be capable of accelerating over 100 mA of protons to several thousand MeV, this implies that continuous beams in the few hundred megawatt range are practical. The other main option for high power beams, cyclotrons, are cheaper but are limited to a few megawatts of beam power. by both energy (relativistic effects) and current. Although such beam powers may suffice to drive energy amplifier thorium-based systems, they do not appear sufficient for the currently envisioned U.S. application.

**Target/Blanket**

A few choices are required in the design of the target/blanket. A fast spectrum is chosen for two reasons. First, nearly all actinides will fission in a fast spectrum, giving maximum flexibility for the blend of fuel. In contrast, in a thermal spectrum some isotopes are fissile and some are fertile. Therefore the system reactivity changes significantly during the burnup process, almost forcing the designer to use liquid fuel forms with continuous refueling, which in turn raises significant safety issues. Second, the fast spectrum produces many excess neutrons that can be used to transmute iodine and technetium.

In order to achieve a fast spectrum, a liquid metal is chosen as a coolant. Because there exists an extensive international experience base with sodium coolant, it is designated as the reference coolant. However, liquid lead-bismuth may offer significant advantages over sodium as both a spallation target and as a coolant, and is designated the preferred technology (and is to be developed aggressively). The choice of sodium as the reference coolant allows for recent detailed cost studies of the ALMR (PRISM) design to be used as a reference in the life cycle cost part of the study. 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 (75% Zr by weight as opposed to <10% by weight in PRISM), 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.

Separations

In selecting a reference separation technology there are two primary options, the comparatively well-known aqueous separations and pyrometallurgical separations that provide some specific advantages useful for ATW. Because of its capacity for high through-put and its ability to provide a uranium stream that meets Class C Low-level waste requirements, an aqueous process named “UREX” is the reference technology for processing “cold” spent fuel. After the initial separation of uranium, all further ATW separations and processing steps are based on pyrometallurgical processing. This choice is made for two reasons: the bulk separations provide greater proliferation resistance and the pyroprocess is more tolerant of the high heat and radiation 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 pyrometallurgical, will be modularized and constructed at the plant sites. This has the primary advantage of limiting all materials transport to either spent fuel from current nuclear power reactors or waste forms from ATW plants. Although these assumptions are useful in defining a reference ATW system, there are clearly alternatives available. Should there be problems with the chosen processes, materials, or technologies, these alternate technology choices could be employed, often with minimal consequences. There are also instances where advanced technology options might be utilized in order to gain one advantage or another.

Sizing the System

The size of an ATW target/blanket facility for this study has been selected to be 840 MWt, for two reasons. First, it matches a version of the advanced liquid-metal cooled reactor (ALMR) known as PRISM for which extensive cost-analyses were performed. Because ATW transmuters are likely to physically resemble the ALMR units, the costs are likely to be similar. This choice then helps provide a firm basis for the estimate of the cost of ATW. 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 transmuters would have similar results. Starting from this size of transmuter the proton beam power is derived using the subcritical multiplier M, which scales with the inverse of 1-keff. The parameter keff can only be finally determined after extensive physics and safety analyses, but is expected to lie in the range between 0.96 and 0.98. For this study we have assumed keff=0.97, which implies a proton beam power of about 11.25 MW is required to drive a 840 MWt transmuter.

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

The separations processes are performed at two different scales. The front-end processing of spent fuel is a large-scale process and particularly suitable for aqueous treatment. Regardless of whether and 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. Back-end process for removing fission products from ATW spent fuel and reforming that fuel for subsequent irradiation can be much smaller and based on pyrometallurgical processing. Because pyrometallurgical processing is typically performed at a relatively small scale, it is easily scaled to support ATW unit throughput.

Lastly, it is necessary to estimate the ATW plant lifetime. Accelerators are inherently modular and don’t accumulate significant materials damage from radiation. As a result accelerators have an indefinite lifetime. Most separations processes are also inherently modular, and one can replace the equipment as necessary. In contrast, the transmuters 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.

Reference ATW Plant

A reference ATW plant is illustrated in Fig. 2. Over sixty years of operation, the ATW reference plant would process 10,155 tn of spent fuel. This is in comparison to the current inventory of about 40,000 tn of spent fuel and the projected inventory of 86,317 tn of spent fuel if all currently licensed nuclear power plants run until their licenses expire. The configuration shown in Fig. 2 has two large linear accelerators to provide proton beam to eight transmuters. This configuration allows transmuters to receive beam whenever at least one accelerator is operating, improving systems availability. The capital cost of this configuration may be higher than the cost of one large linac driving eight 840 MWt transmuters, but it is thought the improved availability will bring a larger revenue stream from electric power sales.

The separations process illustrated includes three steps. If we assume the reference of an aqueous front-end, the first step removes the uranium via the UREX process. The second step is an oxide-reduction process, converting the wastes from oxide to metallic form. The third step then removes the transuranic components and converts them into ATW fuel form. For an entirely pyrometallurgical process, the first step is oxide-reduction, which convert the spent fuel from oxide form to metal form. It is at this stage that the iodine is isolated. The second step separates the uranium, reducing the spent fuel waste stream by roughly a factor of twenty. Technetium can be isolated at this stage. In the final step, the transuranics are separated from the remaining fission products. Of the 10,155 tn of spent fuel, approximately 9684 tn of uranium can be first
separated. Although some of this uranium could be recycled in power plants (it has higher fissile content than natural uranium), the assumption is that it would probably be discarded as Class C Low Level waste.

Of the remaining 470 tn, about 355 tn are mostly stable, short-lived, or longer-lived but comparatively harmless isotopes. Also included are somewhat 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 long-lived waste forms that would resist dispersion by natural phenomena, including ground water penetration, leaching, and transport. The cesium and strontium products 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.

The transuranics would be blended with zirconium (about 80 to 90 atom per cent) to form ATW fuel rods. The high zirconium content provides some advantageous fuel characteristics including high melting temperatures and good tolerance for fission gas build-up. The assumption for the reference case is that about 30% of the TRU content will be fissioned per pass through ATW, but it is hoped that much higher burnups (perhaps 50%) should be reached through an aggressive fuels development program. The technetium and iodine will be formed separately into fission product targets. Because technetium transmutes to another solid (ruthenium), and because technetium has a large resonance capture cross section (prefers to capture neutrons as they are slowing down), there are no apparent problems in transmuting technetium except the fact there is a great deal of it to be converted. For
this reason, the technetium rods are likely to remain in the ATW transmuter for many years and perhaps decades before any processing is needed. 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 venting features.

The throughput of transuranics is derived directly from the fission heat rate of the transmuters. Therefore, the 1.76 tn per year of transuranics corresponds directly to the amount of fission required for the eight transmuters to generate 6720 MWt (including around 90 MWt of beam power). The technetium and iodine throughput is based on consuming those materials in proportion to transuranic consumption. About 0.33 of the excess fission neutrons must undergo capture for fission product transmutation. Each fission event should produce well over one excess neutron, so this requirement should be easily achievable, and a significantly higher burn rate may be feasible. Although the fuel rods will be regularly unloaded for fission product extraction, technetium and iodine would likely remain for many years.

The power production goal assumes 37% thermal efficiency. Liquid lead bismuth could support higher conversion efficiencies due to its high boiling temperature; however, temperature limits associated with corrosion may limit the operating temperature. This conversion assumption results in 2490 MW electric. 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 significant fraction of the plant capital and operating costs. After sixty 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 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. It might also be burned in a dedicated thermal spectrum device.

Target/Blanket Design Issues

The reference ATW blanket 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 U.S. DOE, led by General Electric with support from ANL, and was formally reviewed by the NRC. If the ATW target/blankets are based on sodium-coolant technology, it is likely that a system that resembles PRISM would be nearly optimized regarding systems engineering, safety, and costs. Such a unit is illustrated in Fig. 3, which shows the proton beam entering from a bermed accelerator and then being bent downward into the target/blanket vessel. The spallation target module is assumed to be separated from the blanket region so as to keep spallation products from entering the entire blanket cooling system. This feature would also allow different coolants to be used in the spallation target and the blanket regions.
SYSTEM INTEGRATION

Objective

This section describes the integration of these R&D plans into an overall coherent plan, including a definition of the schedule and major milestones, the description of the integration tasks which allow for the project to meet its objectives, a definition of the critical R&D and implementation paths, and the development of an R&D roadmap.

The reference technology and design parameters defined in the report were chosen without the benefit of detailed engineering, design, and optimization studies. Thus it is deemed essential to launch these types of studies at the initiation of the R&D program. Furthermore, certain concept parameters might be drastically modified by these studies, and this in turn could significantly affect the choice of reference options and the required follow on R&D tasks. A typical example is the choice of fuel composition where the reference design is heavily loaded in zirconium; this might make the pyroprocessing tasks quite difficult, and thus requires an integrated trade study taking into account neutronics, safety, fuels, and processing issues.

The reference technology was chosen on the basis of an extrapolation of the technical knowledge available in the U.S. Despite many conferences and workshops held during the past several years, a clear and finalized technical international consensus has not yet been developed and no clear international leadership has emerged. To a large extent, the concept of accelerator driven systems is still in a pre-development stage, with no country or organization having committed budgets beyond an initial R&D phase. The international focus on a diverse set of technologies is actually beneficial to the U.S. program, as it keeps open several avenues of research into alternate solutions, and allows
the U.S. to concentrate its efforts on driving the chosen reference options towards successful demonstration.

**RD&D rationale and criteria**

The development plan for the ATW will be articulated around three types of the technologies:

- Reference technologies have been chosen on the basis of the existing U.S. experience: these are the technologies with the minimum amount of development risk associated to them. Use of these technologies reduces the licensing difficulties, the development and implementation times, and the R&D costs. In certain cases (fuel coolant, spallation target) the chosen reference technologies might provide inferior performance to certain emerging but still unproven technologies: an aggressive R&D program should be undertaken to demonstrate the new technologies; international collaboration in certain non-sensitive areas must be stressed to leverage the U.S. program; collaborations on basic technical and scientific issues will be easy to establish at the inception of the U.S. program and might led to later shared demonstration activities. These reference technologies will provide a technical backup for the case when more advanced technologies cannot be implemented.

- Preferred technologies have been identified, which may provide superior performance provided a large scale R&D plan is completed successfully. These technologies have been chosen from either foreign technologies or ongoing U.S. R&D programs. It should be noted that for certain technologies no backup or alternate option has been identified: these are the cases when the preferred technologies have already reached a good level of maturity with superior performance and their adaptations to the ATW program are expected to be feasible. Failure of their development plans, while unlikely, would force the ATW to rely on foreign technologies currently under development. Preferred technologies are in certain cases similar to the technologies pursued by foreign programs.

- Alternate technologies have been identified which would be implemented in case reference/backup or preferred technologies do not meet project requirements (due to technical or institutional issues). In general, the ATW project should not invest significant amounts of efforts in these technologies, and will rely on exchange of information with foreign organizations. The framework for these exchanges still needs to be established. It might rely on existing international forums such as the regular OECD activities.

Table 2 identifies the reference and preferred technologies.

The implementation of this dual approach calls for building successive facilities with the reference technologies, until successful completion of the preferred R&D paths. At these times, decisions will be taken by the project to either continue reliance on the baseline technologies, or switch to the preferred technology.

The development plan for the ATW comprises the following four phases:
- A preliminary investigative phase, where the available technologies are assessed and simplified system concepts are assembled from the most promising technologies. This task has been initiated and partially completed by LANL with internal funds.

- A system integration phase, which defines the system performance requirements, runs trade studies, followed by detailed design studies, and defines optimized reference parameters and R&D needs in view of performance and licensing requirements. This task has not yet been started.

- A R&D phase which is aimed at first evaluating the feasibility of the reference and preferred technical options, and then continues during the demonstration stage of the program to provide data for improving the system performance. This R&D program also initially collects the existing information on the chosen technologies and sets the operating conditions of the first phase of the demonstration task. The R&D program concentrates on the technological elements which are novel in the ATW project: lead-bismuth technology investigated in parallel with a minimal sodium technology program, coupling of a spallation source to a subcritical system, core and system control, fuel fabrication and performance, aqueous treatment and pyrochemical separation for the LWR SNF, pyrometallurgical treatment of a new fuel form, extrapolation of accelerator size and performance, system safety, and development of technologies for eliminating long lived fission products.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Preferred Technology</th>
<th>Experience for Preferred Technology</th>
<th>Reference/Backup Technology</th>
<th>Experience for Reference/Backup Technology</th>
<th>Alternate Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel coolant</td>
<td>LBE</td>
<td>No U.S. experience. 30 years of proprietary Russian experience. Several reactors built and operated. R&amp;D programs are being initiated in Europe and Asia.</td>
<td>Sodium</td>
<td>40 years of U.S. and open international programs. Several reactors built and operated.</td>
<td>Helium</td>
</tr>
<tr>
<td>Spallation target</td>
<td>LBE</td>
<td>None</td>
<td>Tungsten</td>
<td>APT program</td>
<td>None</td>
</tr>
<tr>
<td>Spent LWR nuclear fuel treatment</td>
<td>Aqueous process</td>
<td>30 years of U.S. and international program. Several plants built and operated.</td>
<td>Aqueous process</td>
<td>30 years of U.S. and international program. Several plants built and operated.</td>
<td>Pyrochemistry</td>
</tr>
<tr>
<td>Fuel form</td>
<td>Metallic</td>
<td>IFR Program</td>
<td>Metallic</td>
<td>IFR Program</td>
<td>Nitride</td>
</tr>
<tr>
<td>ATW fuel treatment</td>
<td>Pyrochemistry</td>
<td>IFR Program</td>
<td>Pyrochemistry</td>
<td>IFR Program</td>
<td>None</td>
</tr>
<tr>
<td>Accelerator</td>
<td>Linac</td>
<td>IFR Program</td>
<td>Linac</td>
<td>IFR Program</td>
<td>None</td>
</tr>
</tbody>
</table>

- A spallation test facility will be built at the site of the LANSCE accelerator to test the spallation characteristics of the lead bismuth eutectic and of the tungsten target. There is a strong potential for international collaboration in this area.

- A small LBE loop will be built to validate the Russian database and technologies. There is a strong potential for international collaboration in this area.

- Benchtop experiments will be run to demonstrate the feasibility and performance of the fuel processing technologies.

- Fuel fabrication and sample irradiation experiments will be run in existing facilities.

- Neutronics experiments will be conducted in collaboration with foreign organizations in existing facilities.
A demonstration phase where successive sets of facilities are built or upgraded with increasing levels of system optimization and increasing sizes. The first small-scale demonstration phase consists of constructing (possibly within existing complexes) pilot facilities for the front and back end fuel treatment. These facilities are used to demonstrate the concept feasibility, confirm the reference options, gain operating experience, and collect data for supporting the licensing of the following phases. The front-end fuel treatment pilot facility will also be used to provide the fuel for the startup of the accelerator driven subcritical system. The second large scale demonstration phase consists of constructing a set of demonstration facilities comprising an upgradeable accelerator, full scale front end and back end processing facilities, and an upgradeable subcritical target with operating conditions close to expected final nominal conditions. These facilities will be built on a government site and will be used to demonstrate the performance of the concept including the waste burning rate and waste form performance. The prototype phase will consist of building facilities centered on a full size subcritical target, full size accelerator and full size fuel processing facilities. These facilities will be used to demonstrate the feasibility of a full-scale system and will provide data for further system optimization and deployment.

Major Technical Issues and Associated R&D Program

This section provides an overview of the major technical issues that have been identified during the ATW roadmapping exercise, and briefly summarizes the R&D plans that will address these issues. The issues are classified by broad categories: system-wide issues, and issues relevant to each technical area (accelerator development, separation process development, and target-blanket development).

System-wide Technical Issues

Three major issues have been identified which are relevant to the global system design:

- System sizing: in the reference path used for this roadmap, it was assumed that the burners would have the power and size of a PRISM module, that one accelerator would serve four burners, and that one Fuel Target Facility would serve eight burners. Trade studies will need to be run to optimize these parameters.

- System control: the control of the basic system (one accelerator, four burners) can rely on adjusting several elementary parameters: accelerator power, beam sharing between burners, control rods, burnable poisons. The control problems are significantly more complex than for a standard fast reactor, due to the presence of the accelerator and also due to the large burnup swing expected in the system. Furthermore, safety criteria and a global safety strategy have not yet been fully developed. System control has been identified as an R&D task in the blanket/target program, and also as a subject of the necessary trade studies.

- System safety: The safety approach for the ATW has not yet been fully defined. It is likely that safety scenarios not related to criticality will be similar for ATW and standard reactor
designs. A new approach must be devised for criticality and accelerator related scenarios and adequate licensing requirements need to be developed.

**Accelerator Development**

One major technical issue has been identified relevant to accelerator development: it concerns accelerator reliability. In the past development of accelerators, reliability had systematically received a lower priority than system protection. Nevertheless, when the accelerator is coupled to a sub-critical system, its reliability becomes of prime importance to the system performance: even a very short accelerator trip can trigger thermal shocks in the reactor component and might also imply a lengthy reactor restart. Two tasks have been identified:

- System studies will be run to quantify the reliability requirements for the accelerator, taking into account consequences on the reactor integrity and global system performance.

- An extensive R&D program is planned to identify the root causes of accelerator trips, and correct them in time for the design of the first ATW accelerator.

**Blanket/Spallation Target Development**

Six major technical issues have been identified relevant to blanket spallation/target development:

- Subcriticality control has already been mentioned in regards to global system control. The control problem is made difficult by the expected large burnup swing, and the lack of finalized safety criteria. An R&D plan has been devised to consider several options: use of control rods and burnable poisons, use of movable fuel and reflector assemblies, design of a low burnup swing core reload and shuffling strategy.

- Safety strategy: the subcriticality of accelerator driven systems is believed to offer an important safety advantage over critical systems in that the former are able to accommodate unprotected reactivity insertion accidents when fertile-free fuels (with low Doppler feedback and small delayed neutron fraction) are employed. On the other hand, accidental increases of the source are possible in accelerator driven systems, and thus the ability of ATW system to safely accommodate various source transients must be demonstrated. In addition, the weaker sensitivity of accelerator driven systems to reactivity feedback effects, makes these mechanisms ineffective in reducing power, making the shutdown of the neutron source essential to preventing system damage under such accident conditions. The potential for fuel melting due to under-cooling and for subsequent accumulation of fuel into a critical mass is particularly serious in view of the low Doppler co-efficient, small delayed neutron fraction and (for LBE coolant) the high inertial resistance of the heavy liquid metal to fuel dispersal. A similar safety concern arises from the potential of attaining supercriticality through seismically induced compaction of the core. Thus, a new safety strategy needs to be developed; a series of trade studies will be required to refine this strategy and optimize the system design accordingly; existing analysis tools might need to be updated.
- Fuels performance: while the ATW fuel has some similarity with the IFR fuel form, new challenges appear due to its high Zirconium content, high minor actinide content, and high target burnup. Trade studies that involve fuels, separation, and core physics aspects are planned to define the optimal fuel composition and target burnup. The fuels development plan addresses the issues of fabricability, compatibility, and irradiation performance.

- Transmutation target design and performance: specific targets will need to be used for the transmutation of the Long Lived Fission Products. The international R&D programs in this area are still in their infancy. A vigorous R&D program is planned to assess the design, fabricability, and irradiation performance of these targets.

- The target window material is subjected to high intensity exposure to charged and neutral particles, and to large thermal stresses. Design and materials R&D programs are planned to understand the irradiation behavior of the window and optimize its design.

- The LBE technology has been essentially developed in Russia and remains proprietary. Licensing criteria will be developed for the U.S. program, and the technology will be transferred and verified.

**Separations Technologies**

Three major technical issues have been identified relevant to the separation technologies:

- The feasibility of pyroprocessing as a treatment option for the spent commercial fuel needs to be evaluated. Difficulties are related to the scale up in size required from present benchtop processes and to the purity requirements used for this roadmapping. Trade studies will be run to assess the possibility of relaxing the purity requirements. An extensive R&D plan will aim at developing and demonstrating the process.

- The performance of the pyroprocessing of ATW fuel needs to be established. Difficulties arise from the large fraction of Zirconium in the fuel, and from the significant amount of Americium. Specific process development and demonstration tasks are planned.

- The performance of the final waste forms with respect to radionuclide retention over long periods of time in geological repositories will be established.

**R&D Roadmap**

A roadmap has been developed for the initial investigative and R&D phases of ATW. This roadmap does account for later activities, stemming from feedback from operating facilities, by allowing for improving the performance of the options developed during the R&D phase. Fig. 4 summarizes the R&D roadmap for the ATW.
Fig. 4. R&D Roadmap

<table>
<thead>
<tr>
<th>Year</th>
<th>System Integration</th>
<th>Accelerator</th>
<th>Fuel Form</th>
<th>Target Material</th>
<th>Coolant Material</th>
<th>Front End Separations Process</th>
<th>ATW Fuel Processing</th>
<th>Subcritical Target Design and Control</th>
<th>LLFP disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Trace Studies, System Optimization</td>
<td>Set Goals</td>
<td>Metal</td>
<td>Tungsten in Sodium Loop</td>
<td>LBE coolant</td>
<td>Aqueous</td>
<td>Pyro processing</td>
<td>Accelerator</td>
<td>To separation, burn in targets</td>
</tr>
<tr>
<td>2001</td>
<td></td>
<td>Accelerator</td>
<td>Alternates</td>
<td>Sodium coolant</td>
<td></td>
<td>Pyro</td>
<td></td>
<td>Burnable Ppen Pins</td>
<td>To burn in fuel</td>
</tr>
<tr>
<td>2002</td>
<td>International Cooperation</td>
<td>Accelerator</td>
<td>LBE Loop</td>
<td>Design Decision</td>
<td></td>
<td></td>
<td></td>
<td>Movable Control Rods</td>
<td>To burn in fuel</td>
</tr>
<tr>
<td>2003</td>
<td></td>
<td>Compactness</td>
<td>Target Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fuel Management</td>
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<tr>
<td>2004</td>
<td></td>
<td>Reliability</td>
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<td>Safety Assessment</td>
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<td>2005</td>
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<td>2006</td>
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<td>2008</td>
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</tbody>
</table>

Legend:
- Reference Technology
- Preferred Technology
- Alternative Technology
- Continuous Improvement
- Decision
- Decision to design demo
- Beyond 2000 extended studies will continue

Fuel form performance
Coolant performance
Design Decision
Filot Scaling Testing
Extension & Validation
Element 1: System integration

The system integration task coordinates the project management and the R&D programs. It organizes the trade studies and defines system criteria and R&D requirements. The task also provides the framework for international collaboration and monitors development of alternate concepts and technical options in international programs.

Element 2: Accelerator development

The accelerator development R&D program has two components. The objective regarding compactness is to design a more compact accelerator. It will rely on superconducting technologies. Design studies and experimental demonstrations are planned. Regarding reliability improvement, the causes for accelerator trips will be identified and studied. Technological improvements will be designed and assessed experimentally. While the design of the demonstration accelerator will be frozen in 2005, the task will continue, and provide input for upgrades or modifications.

Element 3: Fuel form development

The R&D task will be concentrated on the base technology (metal fuel); its objective is to demonstrate fabricability, compatibility, and irradiation performance by 2008. Foreign programs will be monitored. A decision point occurs in 2008: if the baseline R&D program is successful, that technology will be adopted for system design, and R&D task will continue for improving the fuel performance; failure of the R&D task would imply a major setback for the ATW program: alternate foreign fuels would need to be adopted.

Element 4: Target material

Tasks will include: spallation characteristics, technology transfer and QA of Russian data, confirmatory test of material corrosion characteristics and chemistry monitoring technology, window material development, and engineering design.

Element 5: Fuel coolant material

For the sodium coolant, a small R&D program will be needed to confirm existing data until the demonstration burner design is frozen in 2008. For the LBE coolant the R&D program will be aimed at transferring the Russian LBE technology and confirming it. Irradiations of the reference fuel form in a LBE environment will be required. Data will be collected to provide the basis for design and licensing in 2008.

Element 6: Front end separations process

Two parallel R&D paths will be pursued until reaching a decision point in 2008. An R&D path for the aqueous process will be concentrating on flowsheet development and analysis, and on the
recovery rate of LLFP’s. An R&D path for the pyroprocess will concentrate on improving the Uranium stream purity, and on scaling up the process.

Element 7: ATW fuel processing

A unique technology is considered for processing the ATW fuel. The first three years of R&D will be aimed at establishing the reference processes. The R&D program will be aimed at demonstrating and optimizing the process.

Element 8: Core design and system control

An R&D path to design an optimal core configuration and fuel management strategy (along with the fuel composition and maximum burnup). This task will result in a preliminary conceptual core design in 2002. Activities would be continued thereafter to obtain an optimized final core design by 2008. A second path to study and demonstrate technologies for system control: the baseline technologies will be burnable poisons and control rods. The use of accelerator intensity control will also be studied. A decision point is scheduled for 2005.

Element 9: System safety

An R&D path to identify ATW safety issues and establish an approach for resolving them, should produce a preliminary definition after 2 years. A second path develops the required tools, performs analyses to resolve safety issues and ensures a high level of safety, and designs the system accordingly. This activity will establish an ATW safety basis after 5 years.

Element 10: LLFP disposal

Two baseline approaches will be studied and implemented for Tc disposal: homogeneous (Tc in fuel) and heterogeneous (Tc targets) technologies. The R&D task will study the performance of these two approaches, and implement the tests needed for demonstrating the Tc separation capability, the target and fuel fabrication, and the expected burning rates. The baseline technology for iodine separation is the heterogeneous approach. The R&D task will evaluate concepts, study their performance, and implement the tests needed for demonstrating the Iodine separation capability, the target fabrication, and the expected burning rates and recycle requirements. An alternate approach for Iodine disposal will be considered: namely its disposal in an improved waste form.

SUMMARY

The main technical issues in the ATW system turns on the need to dispose of the energy created in the transmutation process. The amount of energy is too large and potentially valuable to be simply discarded. As a result each ATW system becomes a large energy park with a net output of 2100MWe, together with associated fuel treatment facilities.
The reference for ATW is a fast spectrum liquid metal cooled system. Sodium coolant is chosen simply because it represents the lowest technical risk and an excellent basis for estimating the life cycle cost of the systems exists in the work carried out under DOE’s ALMR (PRISM) program. For ease of technology transfer from the IFR program metal fuel and associated pyrochemical treatment is assumed. Similarly a linear accelerator has been adopted as the baseline.

For the accelerator the main issue is the achievement of the necessary reliability in operation. To avoid frequent thermal transients and maintain grid stability the accelerator must reach levels of performance never previously required. For the target material the main technical choice is between solid or liquid targets. This issue is interlocked with the choice of coolant. Lead-Bismuth eutectic may be a superior choice for both missions but represents a path with greater technical risk. Metal fuel is the obvious choice due to the positive experience gained in the U.S., and also due to the possibility of associating it with a set of proliferation resistant partitioning techniques. The reference method of processing of spent fuel from LWRs to provide the input material for ATW is chosen to be aqueous because of the large quantity of Uranium that needs to be brought to a state that it can be treated as less than Class C waste. Again this is the path of least technical risk although the pyrometallurgical option will be pursued as an alternative. Processing of the TW fuel after irradiation in ATW will be undertaken using pyrometallurgical methods. The transmutation of Tc and I represent special issues and various options will be pursued.

FOOTNOTES

1 Throughout this document we use the SI notation where tn represents 1 metric tonne.
2 Burnup is described in terms of MWt-d/kg (identical to GWt-d/tn) where MWt is the thermal power in megawatts, d is days and kg is kilograms.

REFERENCES


