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Roald Wigeland
Temitope Taiwo
Michael Todosow
William Halsey
Jess Gehin

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Roald Wigeland,[a] Temitope Taiwo,[b] Michael Todosow,[c] William Halsey,[d] Jess Gehin,[e]
[a]*Idaho National Laboratory, 2525 N. Fremont Avenue, P. O. Box 1625, Idaho Falls, ID 83415,USA.*
[b]*Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, U.S.A.*
[c]*Brookhaven National Laboratory, P. O. Box 5000, Upton, NY 11973-5000, U.S.A.*
[d]*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550, U.S.A.*
[e]*Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831, U.S.A.*
Tel:+1 516 732 4234 , Fax:+1 208 526 2930 , Email:Roald.Wigeland@inl.gov

Abstract – *A systematic evaluation has been conducted of the potential for advanced nuclear fuel cycle strategies and options to address the issues ascribed to the use of nuclear power. Issues included nuclear waste management, proliferation risk, safety, security, economics and affordability, and sustainability. The two basic strategies, once-through and recycle, and the range of possibilities within each strategy, are considered for all aspects of the fuel cycle including options for nuclear material irradiation, separations if needed, and disposal. Options range from incremental changes to today's implementation to revolutionary concepts that would require the development of advanced nuclear technologies.*

I. INTRODUCTION

According to political statements and public opinion surveys, there are a number of issues with use of nuclear power in the United States that may influence decisions on continued use, potential expansion, and the approaches and technologies considered. Issues such as nuclear waste management (given the current uncertainty about spent, or used, fuel disposal), the risk of nuclear weapons proliferation, and the cost and safety of nuclear power plants have contributed to the reluctance to expand the use of nuclear power, even though it is recognized that nuclear power is a proven, reliable, and cost-effective method of producing large amounts of electricity with very low emissions of "greenhouse" gases and other pollutants.

Current, evolutionary, and revolutionary nuclear fuel cycle options are assessed in this study for their abilities to address the issues. Similar studies have been conducted in the past that compared advanced nuclear technology capabilities with possible missions for the purpose of providing direction for research and development, especially within the last decade, and such studies provided important background for the current effort.[1,2] However, in all of the previous examples, one or more constraints were imposed that limited the scope of the assessments, such as (1) siting a geologic repository at Yucca Mountain for used fuel and high-level waste (HLW) disposal; (2) limited choice of nuclear irradiation and power production technologies such as light-water reactors (LWRs), fast reactors, gas-cooled reactors, and/or accelerator-driven sub-critical systems, (3) considering only a few separation technology options such as UREX+ and electrochemical; or (4) by the desire to move forward quickly with implementation of an advanced nuclear fuel cycle.

In this paper, the issues with nuclear power, their root causes, and the evaluation measures for judging the effectiveness of an advanced nuclear fuel cycle are described. This is followed by a discussion of possible nuclear fuel cycle strategies and options, with identification of option characteristics and specific options that would have the potential for significant beneficial impact in addressing the issues.

II. NUCLEAR POWER ISSUES

There have always been a number of issues associated with the use of nuclear power, and the perceived importance of specific issues at any given time has been instrumental in past decisions on the directions of nuclear energy research and development (R&D) in the United States. From the 1950s through the 1970s, the perception that uranium resources would be limited and that energy demand would grow substantially prompted R&D into breeder reactors for providing much larger supplies of nuclear fuel. In the 1980s and into the 1990s, safety, proliferation risk, and economics concerns focused R&D on safer, more secure and affordable nuclear energy systems. Later in the 1990s and into the 21st century, the growing issue of nuclear waste and used fuel disposition resulted in R&D being focused on approaches for treating used nuclear fuel to reduce its radiotoxicity and the volume and mass of materials requiring long-term geologic disposal. Looking forward, it is likely that all of these past issues will continue to be relevant, at least to some degree, and all have been retained in this study.

II.A. Specific Issues and Root Causes

This study has focused on six general issues as the basis for examining alternatives to the current commercial strategy in the United States of using light water reactors (LWRs) with a once-through fuel cycle followed by direct disposal of the used fuel. For comparison purposes, the performance of a repository at Yucca Mountain in the United States has been used as a reference in this study.

- Nuclear Waste Management – Current commercial nuclear power operations produce radioactive wastes such as used nuclear fuel (UNF) and high-level waste (HLW) that contain fission products and transuranic elements (TRU). These UNF and/or HLW represent a significant long-term risk due to the presence of long-lived radioactive isotopes, prompting decisions that the only acceptable disposal path is geologic isolation for hundreds of thousands of years or longer. Uncertainty about the ability of a repository to provide sufficient isolation has proven to complicate implementation of geologic disposal. Risk from most low-level waste (LLW) disposal has been judged to be minimal, resulting in licensed, yet controversial, disposal using near-surface burial, and there is the potential for some greater than Class C (GTCC) LLW that may require geologic disposal. Even with advanced fuel cycles, some disposal will be required, although the type and amount may be altered, and successfully addressing this issue will depend on the disposal site availability and acceptability.
- Proliferation Risk – Today, global proliferation risk concerns arise from the continued and expanding use of commercial nuclear power in non-weapons states and the association with nuclear materials and technologies that could be used for military purposes, including production of weapons-usable materials by irradiation of uranium or thorium in nuclear reactors or other irradiation facilities and obtaining these materials by processing used fuel, or production of weapons-usable uranium using uranium enrichment technology. Since the use of nuclear power requires irradiation of uranium and/or thorium, production of fissile material that is potentially weapons-usable is unavoidable. Successfully addressing this issue requires minimizing or preventing acquisition of weapons-usable materials.
- Safety – All facilities and activities, including reactor operation, processing, transportation and storage may have safety-related risks due to the potential for events or accidents that can disperse radioactive materials. The root cause of safety concerns is that nuclear power creates and uses significant amounts of highly radioactive materials. Successfully addressing this issue has always required the use of facilities and activities with sufficient safety features and operational procedures to minimize or eliminate the likelihood of such events.
- Security – The security risk concern arises from the perception that a terrorist attack or sabotage could result in radioactive material release from a nuclear power related facility or activity. (Security of any items containing nuclear weapons-usable materials is considered as part of the Proliferation Risk issue in this study.) Addressing this issue requires either significant reduction in hazardous material amounts or eliminating the potential for terrorist attack or sabotage.
- Economics – Cost of nuclear power has been an issue for several decades, primarily due to the large capital investment required for building nuclear reactors, and affected by uncertainties about licensing, the time required for plant construction prior to operation, permission to operate the plant once constructed, and cost recovery once the plants have been approved for operation. The large capital investments arise from the complex nature of nuclear reactor systems, which have to be operated safety and continuously to provide reliable bas-load to the power grid. Addressing this issue may require improvements in all areas.
- Sustainability – The sustainability of nuclear power depends on resolving existing issues and on the availability of resources in the future. The root cause of sustainability concerns is the uncertainty about the availability of natural resources required to support nuclear power, including adequate disposal space, fuel supply, and materials. Addressing this issue could require developing systems that need less disposal space, less natural resources for fuel, and less material for construction and operation, or alternatively, more attractive disposal options, additional fuel supplies, and other material choices.

II.B. Evaluation Criteria – Performance Measures

For the purpose of assessing the ability of alternate nuclear fuel cycle strategies to find solutions to the perceived issues with nuclear power utilization, a set of measures or criteria was created. The evaluation measures were based on, or similar to, measures used in previous studies.

For evaluating waste management characteristics of proposed options, measures included: estimated peak dose rate; radiotoxicity of disposed materials; UNF, HLW, and LLW mass; interim (decay) storage impact and capacity; and the material heat load.

The measures for proliferation risk were developed in recognition of more detailed proliferation risk assessment analysis methodologies and measures, such as those developed for the Gen IV Proliferation Resistance – Physical Protection initiative.[3] Inventory of special nuclear materials (SNM), material attractiveness of the material, need for uranium enrichment, and safeguardability of materials were identified for this purpose.

Safety requirements have been defined by the United States Nuclear Regulatory Commission (USNRC) to ensure that nuclear activities (facilities and operations) can be conducted safely without posing a significant risk to public health and safety. The measure utilized in this study focuses on the level of difficulty in licensing the facilities and performing nuclear operations, including the potential for introducing new safety issues with alternative fuel cycle strategies and technologies. It is important to note that safety is greatly affected by design and operational details as well as supporting activities, including transportation.

Addressing security concerns requires reduction in the amounts of hazardous radioactive materials or minimizing the potential for terrorist and sabotage acts to occur. Measures considered were the inventory of radioactive material and the ability to provide physical security.

The economic impact of an alternative fuel cycle was evaluated using measures including: similarity to existing infrastructure; capital at risk; technical maturity and risk; technology development time; and life-cycle costs.

Sustainability measures include some of those previously listed for the other areas and those associated with fuel resources and disposal needs. No determination was made regarding the potential ultimate availability of uranium or thorium resources. Only information on the relative natural resource requirements between fuel cycle and technology options is considered.

III. NUCLEAR FUEL CYCLE STRATEGIES

There are two basic nuclear fuel cycle strategies, depending on what is done with used fuel, the once-through fuel cycle where used fuel is disposed, and recycle strategies where used fuel is processed to recover and recycle one or more chemical elements. In this section, the impact of the fuel cycle strategy on the issues of nuclear waste management, proliferation risk, and sustainability is discussed as this choice has a profound impact on these issues. The other issues of safety, security, and system economics are better discernable as specific technology options and are discussed in Section IV.

III.A. Once-through Nuclear Fuel Cycle Strategy

The once-through fuel cycle strategy is defined in this evaluation as consisting of fabricating nuclear fuel from naturally-occurring material, using it once in a nuclear reactor, followed by disposal of the UNF, typically in a deep geologic repository. Interim storage prior to disposal may be considered for reduction in near-term radiotoxicity and decay heat or for managing UNF handling and placement. The high level of radiation associated with UNF requires isolation from the biosphere for hundreds of thousands of years to allow time for radioactive decay.

The fuel could be utilized in critical and subcritical nuclear systems using neutron irradiation in the once-through fuel cycle. Other irradiation approaches include the use of non-neutron elementary particles (like protons, electrons, ions, and photons) to induce nuclear fission and other reactions, but these are considered impractical for power production or material transmutation, as they have low efficiencies and low intensities.

Only uranium or thorium-uranium resources are usable in the once-through fuel cycle strategy utilizing nuclear reactors since thorium by itself is not capable of sustaining a fission chain reaction. In the case where external neutrons are used for sustaining the fission process, as with accelerator-driven systems, it is possible to use thorium-only or un-enriched uranium fuel, but a significant amount of neutrons will be required until sufficient fissile material (U-233 or Pu-239) has been created in the fuel.

It is possible to use natural uranium for new fuel, as in heavy-water or graphite-moderated reactors, although fuel usage may be inefficient, requiring frequent refueling of the reactor and generating large amounts of UNF per unit of energy produced. Typically the uranium needs to be enriched in U-235 content in order to sustain the nuclear chain reaction, but this results in low utilization of natural uranium resources (typically about 0.6% for LWRs), since for many once-through fuel cycles, depleted uranium from the enrichment process is not usable as fuel and becomes waste, lowering resource utilization. Fast reactors have been proposed for use in a once-through mode where the depleted uranium is used for breeding and used as fuel without reprocessing, which can increase uranium resource utilization once equilibrium has been achieved, possibly in the range of 10-15%, perhaps higher.

Uranium enrichment is limited to less than 20% U-235 due to proliferation concerns, placing an upper limit on burnup in reactors. Consideration of higher enrichment would allow higher burnup, but not necessarily result in greater utilization of natural uranium resources although less UNF would result on a per unit of energy generated basis. The use of highly enriched uranium (HEU) is not considered for commercial power production in this study.

On the other hand, externally-driven subcritical systems, such as the fusion-fission hybrid system, do not require uranium enrichment to achieve high burnup, and are being suggested for near-complete burnup of the fuel. The system would build in and consume fissile material, but it is not likely that such systems will be able to achieve complete burnup of the fuel in practice due to the long irradiation time that would be required at typical neutron flux levels and the consequences on fuel and cladding materials.

In evaluating the importance of fuel resources in a nuclear energy strategy, it should be recognized that the largest environmental impacts and public health effects from nuclear energy arise in the front end of the fuel cycle, in particular from the mining and milling of uranium ore to obtain the uranium needed for fuel.[4]

III.B. Recycle Nuclear Fuel Cycle Strategies

In recycle strategies, the UNF is processed to recover certain elements for further transmutation into less hazardous or shorter-lived materials, substantially altering the characteristics of materials destined for disposal. Recycle strategies that include the disposal of UNF and HLW are termed *limited recycle* in this study. Those with only disposal of HLW and processing of all UNF for recycle are termed *continuous recycle*.

In contrast to the once-through strategy, there are other major components and operations with recycle strategies. In addition to the fuel, the power plants, and disposal, the new components are UNF processing, fabrication of recycle fuel, and the irradiation facilities for transmutation of the recycle fuel. The irradiation facilities may not be the same ones that created the UNF initially, and may not be power production facilities, depending on the strategy. Disposal of LLW needs to be considered as part of recycle strategies since it is likely that the additional operations will create more LLW than once-through options. Transportation requirements may be increased since material would need to be transferred between fuel cycle facilities. Interim storage can be used in the same manner as in once-through strategies with the same potential benefits to planning and logistics for waste management. In addition, since there may be more scientific and technological issues with recycle strategies, there is the benefit of providing the time needed for identifying, developing, and demonstrating the desired technologies.

Although recycle strategies are more complex than once-through strategies, the additional components in a recycle strategy could provide opportunities to address the issues with nuclear power, by significantly changing the contents of UNF and HLW prior to disposal, improving resource utilization, and other similar benefits.

The disposal environment options for the recycle strategy are the same as those available to the once-through strategy. The difference for a recycle strategy is the content of the materials to be disposed and the amounts and forms of the waste materials. The economics of the recycle strategies is determined by the costs for each of the components in the strategy. Some of the major costs may be similar to those for the once-through strategy (costs for fuel resources, costs for construction of irradiation facilities if similar technologies are used, and costs for developing and operating disposal sites). However, recycle strategies will add major cost elements for the construction of UNF processing facilities and fuel fabrication facilities and any new irradiation facilities for recycle fuel. On the other hand, recycle strategies may avoid major costs depending on the need for fuel resources, uranium enrichment, and the utilization of the disposal sites.

III.C. Nuclear Fuel Cycle Strategy Impact

Using the criteria discussed in Section II.B., the abilities of nuclear fuel cycle strategies to address the issues of waste management, proliferation risk, and sustainability have been evaluated. The focus was on identifying where significant improvements, i.e., an order of magnitude or more, are possible instead of those where impacts only result in an incremental change. Evaluation results are given in Table 1 on a per unit energy generated basis.

The evaluation indicates that there is likely to be no significant changes from the reference fuel cycle with an alternative once-through cycle or with limited recycle on radiotoxicity and other nuclear waste management measures due to the disposal of all UNF. Continuous recycle options that keep the bulk of the hazardous radioactive materials out of the waste stream may have significant effects, depending on the importance of the recovered materials to waste management metrics, e.g., is actinide recycle effective in reducing the estimated peak dose rate for the proposed geologic disposal environment? If the near-complete consumption of natural uranium is possible using externally-driven subcritical systems, such as the fusion-fission hybrids, it could have waste management characteristics similar to those of the continuous recycle systems where the TRU is recycled. However, achieving such a once-through system without processing of any kind depends on the availability of fuel-cladding material that can maintain integrity for the very long residence time required in such systems.

There is SNM in all UNF due to the presence of fissile plutonium or uranium generated/remaining in nuclear fuel during irradiation. With continuous recycle, there can be a substantial reduction in the amount of SNM in materials sent for disposal, but processing potentially makes the material available in the fuel cycle. Achieving complete burnup with once-through, externally-driven subcritical systems could be an attractive option, since the UNF would contain essentially no SNM and natural uranium could be used without enrichment. As a consequence, the main concern for most fuel cycles may be whether or not the SNM can be adequately safeguarded.

For sustainability, the once-through strategy with near-complete utilization of the fuel could also be attractive, in the same manner as continuous recycle, since fuel resources are used to the maximum extent. However, such externally-driven, near-complete burnup systems are considered impractical due to irradiation time required and the resulting technological challenges.

Overall, certain recycle strategies may favorably impact the issues of waste management and sustainability, but there are costs and other issues as well, especially with respect to the proliferation risks.

TABLE I

Relative Impact of Alternative Fuel Cycle Strategies on a Per Unit Energy Generated Basis

Fuel Cycle Strategy	**Alternate Once-Through**	**Limited Recycle**	**Continuous Recycle**
Nuclear Waste Management			
Estimated Peak Dose Rate	No significant change due to UNF disposal	No significant change due to UNF disposal	*Possibly significantly* lower with actinide (TRU) recycle and HLW disposal
Radiotoxicity of Disposed Materials	No significant change due to UNF disposal	No significant change due to UNF disposal	Significantly lower with actinide (TRU) recycle and HLW disposal
UNF & HLW Mass for Disposal	Similar UNF and HLW content; less UNF with higher burnup	Less combined UNF & HLW content due to recycle	No UNF; TRU content in waste is significantly lower due to TRU recycle
LLW Mass for Disposal	No significant change in LLW	*Possibly significantly* more LLW due to processing	*Possibly significantly* more LLW due to processing
Effect of Interim Storage	Lower near-term radiotoxicity and heat load for UNF and HLW	Lower near-term radiotoxicity and heat load for UNF and HLW	Lower near-term radiotoxicity and heat load for UNF and HLW
Heat Load	No significant change due to UNF disposal	No significant change due to UNF disposal	Significantly lower with TRU recycle, Cs/Sr management, and HLW disposal
Proliferation Risk			
SNM Inventory	No significant change	Higher fuel cycle inventory, lower waste disposal inventory	Higher fuel cycle inventory, significantly lower waste disposal inventory
Material Attractiveness	No significant change	Technology dependent; may be lower or higher	Technology dependent; may be lower or higher
Uranium Enrichment	Technology dependent; may be lower or higher	Technology dependent; may be lower or higher	Technology dependent; may be lower or higher
Safeguardability	No significant change	No significant change	No significant change
Sustainability			
Fuel Resources	*Possibly significantly* lower with fast breeder reactor	*Possibly significantly* lower with fast breeder reactor	Significantly lower with actinide recycle
Disposal Needs	No significant change	No significant change	Significantly lower with actinide recycle

Green: Significant favorable impact from the strategy
Green/white: Potential for significant favorable impact may exist but is technology dependent

White: No significant change
Red/white: Potential for significant unfavorable impact may exist but is technology dependent
Red: Significant unfavorable impact from the strategy

IV. TECHNOLOGY OPTIONS

Technology options associated with nuclear fuels, irradiation and separations facilities, and disposal sites, and their impacts on the nuclear utilization issues have been evaluated and are summarized in the following sections.

IV.A. Fuel Options

Nuclear reactors require fissionable materials, whether using a critical system or an externally-driven sub-critical system. The fuel forms include solid and mobile fuels and the choice depends on the reactor design. The physical form of the fuel has significant implications on the entire fuel cycle system in terms of the means of manufacture of the fuel, the achievable burnup during irradiation, the processes used to recycle the fuel, and the ultimate disposal. In all cases, the fuel or reactor system must be designed to maintain its integrity for long term retention of the radioactive hazardous materials under high temperature and radiation.

For recycle, the fuel must be compatible with approaches for processing allowing separation and fabrication of new recycle fuels. The use of liquid fuels in recycle allows processing to be performed in an integrated manner with the irradiation system by having the liquid fuel flow through the processing system.

Uranium and thorium based fuels have been considered for the fuel cycles. The uranium-based, thorium-based, and TRU fuel options have various impacts on the fuel cycle. On the subject of proliferation risk, there doesn't appear to be a significant difference between uranium-based fuels or thorium-based fuels, either for once-through (due to plutonium) or recycle (due to Pu and U-233) strategies. Similarly, regarding safety and security, there does not appear to be any significant difference between any of the options in that licensable systems meeting USNRC requirements could be designed using any of the fuel options. However, this is not to say that all options are equally attractive or at a comparable stage of development.

IV.B. Irradiation Options

Neutron irradiation in nuclear reactors is currently the most developed and cost-effective approach for using fission to produce energy or to transmute elements. Neutron irradiation can be implemented using nuclear reactor systems, externally-driven sub-critical systems, or other non-neutron elementary particles to induce nuclear fission. A variety of such systems has been proposed in the United States and internationally.

Application of LWRs for the purpose of transmutation (addressing waste management and proliferation concerns) could entail existing infrastructure and familiar technology, although additional infrastructure for reprocessing and recycling, transportation, minor actinide-containing fuels and targets, and appropriate safeguards would be required. An example of the approach is MOX fuel utilization in LWRs. Typically, MOX fuel utilization is only viewed as one component of a continuous recycle strategy, where advanced fast reactor systems are planned for more effective management of TRU. Fast reactors and fast spectrum systems are better suited for the destruction of most transuranics, having surplus neutrons that could be used for this purpose. Fast reactors can increase sustainability of nuclear power by extending resources through breeding of fissionable materials, whether from uranium or thorium, although breeding using thorium in a thermal spectrum is also a possibility.

Generally, fast reactors are considered to be more expensive than LWRs, although this cost differential is apparently the subject of continuing debate. Countries such as Japan, Russia and India have indicated that estimated costs for advanced fast reactors systems are potentially lower than for comparable operating water-cooled systems.

All reactors could theoretically be configured to support near-complete burnup using a continuous recycle strategy. Achieving critical reactor states for near-complete burnup could be problematic, although it appears that fast reactors would be better suited for this role in the overall system. The molten fuel reactor systems attempt to resolve some of the practical issues by combining features that allow continuous online reprocessing of the fuel and no cladding material that could limit fuel performance. However, while these systems have some attractive features, operations and maintenance issues must also be considered.

Externally-driven sub-critical systems are certainly more costly than reactor options due to the additional complexity and size of the systems. However, such systems may offer additional options for UNF and waste management, since it might be more advantageous to use the systems for the transmutation of minor actinides, fission products, and other hazardous radionuclides. It is noted in this regard that from a transmutation viewpoint none of the externally-driven sub-critical systems currently being proposed appear to have any advantage over the reactor systems that could also be configured for similar missions. Additionally, externally-driven sub-critical systems introduce new safety concerns due to the independence of the neutron generation in the external source and the response of the fission component of the system, which in a reactor provides reactivity feedback to maintain control of the system.

Proliferations risk concerns apply to all nuclear systems, with no significant difference due to the reactor type or irradiation environment since all will produce SNM. Safeguards have been established to counter this potential, allowing nuclear technology to contribute to energy security.

Non-neutron systems for nuclear power production are ineffective due to fundamental physics limitations, low intensity of particles, and cost of the system, resulting in more power being required to operate them than is produced, and such systems would be impractical to be considered as part of a power production system, having been relegated to use as scientific instruments where efficiency is not relevant.

IV.C. Processing Options

In this evaluation, processing technologies have only been considered to be relevant for recycle strategies although one could propose processing prior to disposal in a once-through strategy for waste management purposes. Processing can range from a simple reconstitution into new fuel for further irradiation to a complete separation of the chemical elements for waste management and fabrication into recycle fuel. In the broader context, processing is designed to separate UNF into chemical elements or groups of elements, with some destined for transmutation and others to be discarded as waste.

Depending on the desired characteristics and products of the separations systems, many approaches have been developed, and can be grouped into two categories: aqueous-based systems and non-aqueous-based systems. The aqueous-based systems use single or multi-phase processes where at least one phase is water-based in order to separate and recover the desired elements in product streams from UNF. The aqueous-organic two-phase technologies (PUREX, UREX, co-extraction, etc.) include many options for separating uranium, plutonium, minor actinides, fission products, and other elements, individually or in groups, using a solvent extraction approach with specially-designed chemical extractants. Non-aqueous-based technologies are single or multi-phase approaches without using water in the process. Examples of non-aqueous technologies include ionic liquids/ electrochemical (LiCl/KCl, etc); gaseous (fluoride volatility, etc); supercritical fluids (CO_2, etc); plasma (Archimedes process, etc); laser (AVLIS, MLIS, etc); and thermomechanical processes.

In principle, many of the processing technologies can be structured to separate and recover any desired set of elements, either singly or in groups, for waste management purposes, while others may have a strictly limited application, especially those used in limited recycle strategies. All of the separations processes may result in some level of proliferation concern, although it is difficult to distinguish differences between technologies. In principle, proliferation risk may be judged to be lower for technologies where the fission products are intended to remain with any weapons usable materials, making the materials less attractive, although it also appears that these intentions can be easily circumvented.

The additional cost of any processing facility in a recycle fuel strategy must be factored into the overall fuel cycle cost, and not be treated as a consideration in itself since recycle may have the potential for substantial avoided disposal costs. Analyses have shown that these costs would not typically be a large fraction of the overall cost of electricity. The potential drawbacks from generating and handling increased number of waste streams that result from processing must be considered, in recognition that there may be opportunities to tailor the contents of each waste stream for improved compatibility with the disposal environments. In general, processing could potentially reduce HLW waste volume, hazard, and decay heat, depending on the HLW composition. However, processing would also increase the amount of LLW from the nuclear power system.

IV.D. Disposal Options

In general, one or more disposal environments will always be needed for UNF, HLW, and LLW to provide the required disposal of hazardous radioactive materials regardless of the fuel cycle strategy. Additionally, interim storage may be used in combination with a waste disposal option to affect overall waste management performance.

Potential disposal options are usually deep underground, typically either in *mined geologic* repositories at depths up to about 1 km or in more remote, *non-retrievable* conditions with depths up to 4-5 km. The risk from disposal of UNF and HLW in mined geologic repositories can be considered in two parts, one for the undisturbed or normal evolution of the conditions in the repository and the other for situations where the repository environment is disturbed by either natural or man-made causes. Overall, for disposal environments studied to date, it appears that fission products are the major contributor to the risk for mined geologic repositories for normal evolution, while the actinide elements and a few of the fission products may dominate the risk for disturbed conditions.

More remote disposal such as placement 4-5 km down in deep boreholes may lessen the likelihood that any of the disposed materials will be released to the inhabited environment due to the extreme depths of waste placement. Such approaches can reduce the importance of uncertainties about details of the disposal environment and may greatly reduce the probability of human intrusion events. However, the constraints on loading of disposal sites such as deep boreholes may be more severe due to anticipated system temperatures, as well as higher risks from the placement operations.

The disposal options are intended to address waste management issues sufficient to eliminate concern about long-lived hazardous radioactive wastes. Whether this succeeds in practice is not known at this time since no repository for the disposal of UNF or HLW from processing commercial UNF has been licensed. In the United States, the USNRC review will determine if this approach is ultimately judged to be technically acceptable.

Proliferation risk from mined geologic repositories may arise due to the availability of SNM in UNF with little radiation protection, offering an attractive source of materials for military purposes. There appears to be no distinction between the options in their ability to address this concern, although for continuous recycle options, the HLW does not contain significant amounts of SNM, eliminating this concern. Non-retrievable disposal and extremely remote disposal may essentially prevent access to the SNM materials, lowering the proliferation risk associated with disposal. In general, there is insufficient SNM in LLW to pose a proliferation risk.

Safety and security of the geologic disposal options will depend on the operations at the disposal sites and the long-term performance of the repository. Licensing review will address these concerns, although it appears that in principle all of the geologic disposal options would be able to satisfy regulatory requirements for operations and closure and this is not a discriminator between options.

Sustainability in this case is a matter of having adequate disposal space for the UNF and HLW, something that becomes easier with lower UNF and HLW amounts. There may be a significant, i.e., order of magnitude, change in this requirement only for continuous recycle options, or for nearly-complete consumption with a once-through strategy, depending on the importance of actinide content in determining disposal requirements. In all cases, fission product content, on a per unit energy generated basis, is unaffected, and if that is determining disposal space requirements, no alternative strategy or technology option can affect the required disposal space.

The major issue for LLW disposal is the availability of suitable disposal sites and the LLW volume. Nuclear fuel cycles involving recycle will increase the amount of LLW, with the increase dependent on the technologies used, the amount of material recycled, and the ability to limit LLW generation in reprocessing facilities, fuel fabrication facilities, and the irradiation facilities. Evaluations have indicated that the LLW from an advanced nuclear fuel cycle, even with recycle, might not necessarily be the major contributor to total LLW disposal when all other sources of LLW are considered, including medical and industrial uses.

V. CONCLUSIONS

This options study has examined the issues ascribed to the current use of nuclear power and the impacts of advanced fuel cycle strategies and technology options in addressing them. It was indicated that only the continuous recycle strategy can make significant impacts in resolving the issues associated with TRU management, while choice of fuel cycle strategy appears to have no effect on issues related to fission products. The near-complete burnup of nuclear fuel in a single pass might also be useful, but technology considerations suggest that this is impractical, maybe even impossible, with known technology.

For reactor or irradiation options, continuous recycle of TRU in fast spectrum systems may be preferable due to the more favorable transmutation environment, i.e., more surplus neutrons, less disturbance to the system due to the introduction of additional TRU, etc. Either fast neutron reactors or externally-driven sub-critical systems could be used, but due to the increased size, complexity and cost of the latter, any deployment would likely be limited to specialized applications such as minor actinide transmutation.

Processing is usually only associated with recycle strategies, although it could also be considered for once-through use if the benefit of having HLW instead of UNF was high enough to offset all of the added costs. Applicable processing options in any given fuel cycle strategy will be determined by the separations and recovery goals, and the types and characteristics of the fuel being processed, with economics being a consideration.

The study recognized that waste disposal remains a common element for all nuclear fuel cycle strategies, being required in all cases for the disposal of highly radioactive materials, whether from fission products alone or including long-lived TRU. All UNF and HLW disposal options face the same issue of demonstrating the required isolation for these materials. There are also non-technical issues such as political and public acceptance that can dominate the decision-making process for siting and licensing such facilities. Continuous recycle appears to be the only practical fuel cycle strategy that can significantly affect waste management issues for UNF and HLW, but only if all of the TRU is recycled, leaving only fission products and residual amounts of TRU in the HLW.

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NOMENCLATURE

Am	Americium
Cm	Curium
Cs	Cesium
USDOE	United States Department of Energy
Gen IV	Generation IV
GTCC	Greater than Class C
HEU	Highly-enriched uranium
HLW	High-level waste
LEU	Low enriched uranium
LLW	Low-level waste
LWR	Light water reactor
USNRC	United States Nuclear Regulatory Commission
Pu	Plutonium
PUREX	Plutonium-Uranium Extraction
R&D	Research and development
SNM	Special nuclear material
Sr	Strontium
TRU	Transuranic
U	Uranium
UNF	Used nuclear fuel
UOX	Uranium dioxide fuel
UREX+	Uranium extraction

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