Hearing on Nuclear Fuel Reprocessing

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Summary

Management of spent nuclear fuel from commercial nuclear reactors can be addressed in a comprehensive, integrated manner to enable safe, emissions-free, nuclear electricity to make a sustained and growing contribution to the nation's energy needs. Legislation limits the capacity of the Yucca Mountain repository to 70,000 metric tons from commercial spent fuel and DOE defense-related waste. It is estimated that this amount will be accumulated by approximately 2010 at current generation rates for spent nuclear fuel. To preserve nuclear energy as a significant part of our future energy generating capability, new technologies can be implemented that allow greater use of the repository space at Yucca Mountain. By processing spent nuclear fuel and recycling the hazardous radioactive materials, we can reduce the waste disposal requirements enough to delay the need for a second repository until the next century, even in a nuclear energy growth scenario. Recent studies indicate that such a closed fuel cycle may require only minimal increases in nuclear electricity costs, and are not a major factor in the economic competitiveness of nuclear power (The University of Chicago study, "The Economic Future of Nuclear Power," August 2004). However, the benefits of a closed fuel cycle can not be measured by economics alone; resource optimization and waste minimization are also important benefits. Moving forward in 2007 with an engineering-scale demonstration of an integrated system of proliferation-resistant, advanced separations and transmutation technologies would be an excellent first step in demonstrating all of the necessary technologies for a sustainable future for nuclear energy.

Nuclear Waste and Sustainability

World energy demand is increasing at a rapid pace. In order to satisfy the demand and protect the environment for future generations, energy sources must evolve from the current dominance of fossil fuels to a more balanced, sustainable approach. This new approach must be based on abundant, clean, and economical energy sources. Furthermore, because of the growing worldwide demand and competition for energy, the United States vitally needs to establish energy sources that allow for energy independence.

Nuclear energy is a carbon-free, secure, and reliable energy source for today and for the future. In addition to electricity production, nuclear energy has the promise to become a critical resource for process heat in the production of transportation fuels, such as hydrogen and synthetic fuels, and desalinated water. New nuclear plants are imperative to meet these vital needs.

To ensure a sustainable future for nuclear energy, several requirements must be met. These include safety and efficiency, proliferation resistance, sound nuclear materials management, and minimal environmental impacts. While some of these requirements are already being satisfied, the United States needs to adopt a more comprehensive approach to nuclear waste management. The environmental benefits of resource optimization and waste minimization for nuclear power must be pursued with targeted research and development to develop a successful integrated system with minimal economic impact. Alternative nuclear fuel cycle options that employ separations, transmutation, and refined disposal (e.g., conservation of geologic repository space) must be contrasted with the current planned approach of direct disposal, taking into account the complete set of potential benefits and penalties. In many ways, this is not unlike the premium homeowners pay to recycle municipal waste.

The spent nuclear fuel situation in the United States can be put in perspective with a few numbers. Currently, the country's 103 commercial nuclear reactors produce more than 2000 metric tons of spent nuclear fuel per year (masses are measured in heavy metal content of the fuel, including uranium and heavier elements). The Yucca Mountain repository has a legislative capacity of 70,000 metric tons, including spent nuclear fuel and DOE defense-related wastes. By approximately 2010 the accumulated spent nuclear fuel generated by these reactors and the defense-related waste will meet this capacity, even before the repository starts accepting any spent nuclear fuel. The ultimate technical capacity of Yucca Mountain is expected to be around 120,000 metric tons, using the current understanding of the Yucca Mountain site geologic and hydrologic characteristics. This limit will be reached by including the spent fuel from current reactors operating over their lifetime. Assuming nuclear growth at a rate of 1.8% per year after 2010, the 120,000 metric ton capacity will be reached around 2030. At that projected nuclear growth rate, the U.S. will need up to nine Yucca Mountain-type repositories by the end of this century. Until Yucca Mountain starts accepting waste, spent nuclear fuel must be stored in temporary facilities, either storage pools or above ground storage casks.

Today, many consider repository space a scarce resource that should be managed as such. While disposal costs in a geologic repository are currently quite affordable for U.S. electric utilities, accounting for only a few percent of the total cost of electricity, the availability of U.S. repository space will likely remain limited.

Only three options are available for the disposal of accumulating spent nuclear fuel:

- Build more ultimate disposal sites like Yucca Mountain.
- Use interim storage technologies as a temporary solution.
- Develop and implement advanced fuel cycles, consisting of separations technologies that separate the constituents of spent nuclear fuel into elemental

streams, and transmutation technologies that destroy selected elements and greatly reduce repository needs.

A responsible approach to using nuclear power must always consider its whole life cycle, including final disposal. We consider that temporary solutions, while useful as a stockpile management tool, can never be considered as ultimate solutions. It seems prudent that the U.S. always have at least one set of technologies available to avoid expanding geologic disposal sites.

Spent Nuclear Fuel

The composition of spent nuclear fuel poses specific problems that make its ultimate disposal challenging. Fresh nuclear fuel is composed of uranium dioxide (about 96% U238, and 4% U235). During irradiation, most of the U235 is fissioned, and a small fraction of the U238 is transmuted into heavier elements (known as “transuranics”). The spent nuclear fuel contains about 93% uranium (mostly U238), about 1% plutonium, less than 1% minor actinides (neptunium, americium, and curium), and 5% fission products. Uranium, if separated from the other elements, is relatively benign, and could be disposed of as low-level waste or stored for later use. Some of the other elements raise significant concerns:

- The fissile isotopes of plutonium, americium, and neptunium are potentially usable in weapons and, therefore, raise proliferation concerns. Because spent nuclear fuel is protected from theft for about one hundred years by its intense radioactivity, it is difficult to separate these isotopes without remote handling facilities.
- Three isotopes, which are linked through a decay process (Pu241, Am241, and Np237), are the major contributors to the estimated dose for releases from the repository, typically occurring between 100,000 and 1 million years, and also to the long-term heat generation that limits the amount of waste that can be placed in the repository.
- Certain fission products (cesium, strontium) are major contributors to the repository's short-term heat load, but their effects can be mitigated by providing better ventilation to the repository or by providing a cooling-off period before placing them in the repository.
- Other fission products (Tc99 and I129) also contribute to the estimated dose.

The time scales required to mitigate these concerns are daunting: several of the isotopes of concern will not decay to safe levels for hundreds of thousands of years. Thus, the solutions to long-term disposal of spent nuclear fuel are limited to three options: the search for a geologic environment that will remain stable for that period; the search for waste forms that can contain these elements for that period; or the destruction of these isotopes. These three options underlie the major fuel cycle strategies that are currently being developed and deployed in the U.S. and other countries.

Options for Disposing of Spent Nuclear Fuel

Three options are being considered for disposing of spent nuclear fuel: the once-through cycle is the U.S. reference; limited recycle has been implemented in France and elsewhere and is being deployed in Japan ; and full recycle (also known as the closed fuel cycle) is being researched in the U.S., France, Japan, and elsewhere.

1. Once-through Fuel Cycle

This is the U.S. reference option where spent nuclear fuel is sent to the geologic repository that must contain the constituents of the spent nuclear fuel for hundreds of thousands of years. Several countries have programs to develop these repositories, with the U.S. having the most advanced program. This approach is considered safe, provided suitable repository locations and space can be found. It should be noted that other ultimate disposal options have been researched (e.g., deep sea disposal; boreholes and disposal in the sun) and abandoned. The challenges of long-term geologic disposal of spent nuclear fuel are well recognized, and are related to the uncertainty about both the long-term behavior of spent nuclear fuel and the geologic media in which it is placed.

2. Limited Recycle

Limited recycle options are commercially available in France, Japan, and the United Kingdom. They use the PUREX process, which separates uranium and plutonium, and directs the remaining transuranics to vitrified waste, along with all the fission products. The uranium is stored for eventual reuse. The plutonium is used to fabricate mixed-oxide fuel that can be used in conventional reactors. Spent mixed-oxide fuel is currently not reprocessed, though the feasibility of mixed-oxide reprocessing has been demonstrated. It is typically stored or eventually sent to a geologic repository for disposal. Note that a reactor partially loaded with mixed-oxide fuel can destroy as much plutonium as it creates. Nevertheless, this approach always results in increased production of americium, a key contributor to the heat generation in a repository. This approach has two significant advantages:

- It can help manage the accumulation of plutonium.
- It can help significantly reduce the volume of spent nuclear fuel (the French examples indicate that volume decreases by a factor of 4).

Several disadvantages have been noted:

- It results in a small economic penalty by increasing the net cost of electricity a few percent.
- The separation of pure plutonium in the PUREX process is considered by some to be a proliferation risk; when mixed-oxide use is insufficient, this material is stored for future use as fuel.

- This process does not significantly improve the use of the repository space (the improvement is around 10%, as compared to a factor of 100 for closed fuel cycles).
- This process does not significantly improve the use of natural uranium (the improvement is around 15%, as compared to a factor of 100 for closed fuel cycles).

3. Full Recycle (the Closed Fuel Cycle)

Full recycle approaches are being researched in France, Japan, and the United States. This approach typically comprises three successive steps: an advanced separations step based on the UREX+ technology that mitigates the perceived disadvantages of PUREX, partial recycle in conventional reactors, and closure of the fuel cycle in fast reactors.

The first step, UREX+ technology, allows for the separations and subsequent management of highly pure product streams. These streams are:

- Uranium, which can be stored for future use or disposed of as low-level waste.
- A mixture of plutonium and neptunium, which is intended for partial recycle in conventional reactors followed by recycle in fast reactors.
- Separated fission products intended for short-term storage, possibly for transmutation, and for long-term storage in specialized waste forms.
- The minor actinides (americium and curium) for transmutation in fast reactor
- The UREX+ approach has several advantages:
- It produces minimal liquid waste forms, and eliminates the issue of the "waste tank farms."
- Through advanced monitoring, simulation and modeling, it provides significant opportunities to detect misuse and diversion of weapons-usable materials.
- It provides the opportunity for significant cost reduction.
- Finally and most importantly, it provides the critical first step in managing all hazardous elements present in the spent nuclear fuel.

The second step – partial recycle in conventional reactors – can expand the opportunities offered by the conventional mixed-oxide approach. In particular, it is expected that with significant R&D effort, new fuel forms can be developed that burn up to 50% of the plutonium and neptunium present in spent nuclear fuel. (Note that some studies also suggest that it might be possible to recycle fuel in these reactors many times – i.e., reprocess and recycle the irradiated advanced fuel – and further destroy plutonium and neptunium; other studies also suggest possibilities for transmuting americium in these reactors. Nevertheless, the practicality of these schemes is not yet established and requires additional scientific and engineering research.) The advantage of the second step is that it reduces the overall cost of the closed fuel cycle by burning plutonium in conventional reactors, thereby reducing the number of fast reactors needed to complete the transmutation mission of minimizing hazardous waste. This step can be entirely bypassed, and all transmutation performed in advanced fast reactors, if recycle in conventional reactors is judged to be undesirable.

The third step, closure of the fuel cycle using fast reactors to transmute the fuel constituents into much less hazardous elements, and pyroprocessing technologies to recycle the fast reactor fuel, constitutes the ultimate step in reaching sustainable nuclear energy. This process will effectively destroy the transuranic elements, resulting in waste forms that contain only a very small fraction of the transuranics (less than 1%) and all fission products. These technologies are being developed at Argonne National Laboratory and Idaho National Laboratory, with parallel development in Japan, France, and Russia.

The full recycle approach has significant benefits:

- It can effectively increase use of repository space by a factor of more than 100.
- It can effectively increase the use of natural uranium by a factor of 100.
- It eliminates the uncontrolled buildup of all isotopes that are a proliferation risk.
- The fast reactors and the processing plant can be deployed in small co-located facilities that minimize the risk of material diversion during transportation.
- The fast reactor does not require the use of very pure weapons usable materials, thus increasing their proliferation resistance.
- It finally can usher the way towards full sustainability to prepare for a time when uranium supplies will become increasingly difficult to ensure.
- These processes would have limited economic impact; the increase in the cost of electricity would be less than 10% (ref: OECD).
- Assuming that demonstrations of these processes are started by 2007, commercial operations are possible starting in 2025; this will require adequate funding for demonstrating the separations, recycle, and reactor technologies.
- The systems can be designed and implemented to ensure that the mass of accumulated spent nuclear fuel in the U.S. would always remain below 100,000 metric tons – less than the technical capacity of Yucca Mountain – thus delaying, or even avoiding, the need for a second repository in the U.S.

Conclusion

A well engineered recycling program for spent nuclear fuel will provide the United States with a long-term, affordable, carbon-free energy source with low environmental impact. This new paradigm for nuclear power will allow us to manage nuclear waste and reduce proliferation risks while creating a sustainable energy supply. It is possible that the cost of recycling will be slightly higher than direct disposal of spent nuclear fuel, but the nation will only need one geologic repository for the ultimate disposal of the residual waste.

APPENDIX 1: Reprocessing Technologies

There are currently three mature options to reprocess spent nuclear fuel.

PUREX – Is the most common liquid-liquid extraction process for treatment of light water reactor spent fuel. The irradiated fuel is dissolved in nitric acid, and uranium and plutonium are extracted in the organic phase by an organic solvent consisting of tributyl phosphate in kerosene, while the fission products remain in the aqueous nitric phase. Further process steps enable the subsequent separation of uranium from plutonium.

Advantages – fully commercialized process, with over 50 years of experience.

Disadvantage – it is not efficient enough to achieve the present requirements for separations of technetium, cesium, strontium, neptunium, americium and curium.

UREX+ – Is an advanced liquid-liquid extraction process for treatment of light water reactor spent fuel. Similar to PUREX, the irradiated fuel is dissolved in nitric acid. The UREX+ process consists of a series of solvent-extraction steps for the recovery of Pu/Np, Tc, U, Cs/Sr, Am and Cm.

Advantages – meets current separations requirements for continuous recycle. Builds on engineering experience derived from current aqueous reprocessing facilities such as La Hague.

Disadvantage – can not directly process short-cooled and some specialty fuels being designed for advanced reactors.

Pyroprocessing - These technologies rely on electrochemical processes rather than chemical extraction processes to achieve the desired degree of conversion or purification of the spent fuel. If oxide fuel is processed, it is converted to metal after the irradiated fuel is disassembled. The metallic fuel is then treated to separate uranium and the transuranic elements from the fission product elements.

Advantages - ability to process short-cooled and specialty fuels being designed for advanced reactors.

Disadvantages – does not meet current separations requirements for continuous recycle in thermal reactors, but ideal for fast spectrum reactors.

APPENDIX 2: Answers to Specific Questions

1. What are the advantages and disadvantages of using reprocessing to address efficiency of fuel use, waste management and non-proliferation? How would you assess the advantages and disadvantages, and how might the disadvantages be mitigated?

Reprocessing of spent fuel is a necessary step in an advanced fuel cycle, but is insufficient to yield any significant benefits by itself: benefits are only incurred once the reprocessed materials are recycled and partially or totally eliminated. Two types of recycle schemes are typically considered: limited recycle in conventional reactors, and full recycle in advanced reactors.

Limited Recycle

Limited recycle options are commercially available in France, Japan, and the United Kingdom. They utilize the PUREX process, which separates uranium and plutonium, and directs the remaining transuranics to vitrified waste, along with all the fission products. The uranium is stored for eventual reuse. The plutonium is used to fabricate mixed oxide (MOX) fuel that can be used in conventional reactors. Spent MOX fuel is currently not reprocessed (though feasibility of MOX reprocessing has been demonstrated) and is typically stored or eventually sent to a geologic repository for disposal. Note that a reactor partially loaded with MOX fuel can destroy as much plutonium as it creates. Nevertheless, this approach always results in an increase in the production of americium (a key contributor to the heat generation in a repository). This approach has several advantages:

- It can help manage the accumulation of plutonium,
- It can help significantly reduce the volume of spent nuclear fuel (SNF) (the French examples indicates a volume decrease by a factor of 4).

Several disadvantages have been noted:

- It results in a small economic penalty, as the increase in the net cost of electricity is a few percent.
- The separation of pure plutonium in the PUREX process is considered by some to be a proliferation risk; when MOX utilization is insufficient, this material is stored for future use as fuel.
- This process does not significantly improve the utilization of the repository space (the improvement is around 10%, as compared to a factor of 100 for closed fuel cycles).
- This process does not significantly improve the utilization of natural uranium (the improvement is around 15%, as compared to a factor of 100 for closed fuel cycles).

Full Recycle (the Closed Fuel Cycle)

Full recycle approaches are being researched in France, Japan, and the United States. This approach is typically comprised of three successive steps: an advanced separations step based on the UREX+ technology that mitigates the perceived disadvantages of PUREX, partial recycle in conventional reactors, and closure of the fuel cycle in fast reactors.

The first step, UREX+ technology, allows for the separations and subsequent management of very pure streams of products. It produces the following streams of products: uranium, that can be stored for future use or can be disposed of as low-level waste; a mixture of plutonium and neptunium that are intended for partial recycle in conventional reactors followed by recycle in fast reactors; separated fission products intended for short term storage, possibly for transmutation, and for long term storage in specialized waste forms; and the minor actinides (americium and curium) for transmutation in fast reactors. The UREX+ approach has several advantages: it produces minimal liquid waste forms (and eliminates the issue of the “waste tank farms”); through advanced monitoring, simulation and modeling it provides significant opportunities for detecting misuse and diversion of weapons usable materials; it provides the opportunity for significant cost reduction; and, finally and most importantly, it provides the critical first step in managing all hazardous elements present in the SNF.

The second step, partial recycle in conventional reactors can expand the opportunities offered by the conventional MOX approach. In particular, it is expected that with significant R&D effort, new fuel forms can be developed that can burn up to 50% of the plutonium and neptunium present in the SNF. (Note that some studies also suggest that it might be possible to recycle fuel in these reactors multiple times (i.e., reprocess and recycle the irradiated advanced fuel) and further destroy plutonium and neptunium; other studies also suggest possibilities for transmuting americium in these reactors. Nevertheless, the practicality of these schemes is not yet established and requires additional scientific and engineering research.). The advantage of the second step is that it reduces the overall cost of the closed fuel cycle by burning plutonium in conventional reactors, and reducing the number of fast reactors needed to complete the transmutation mission of minimizing hazardous waste. This step can be entirely bypassed, and all transmutation performed in advanced fast reactors, if recycle in conventional reactors is judged to be undesirable.

The third step, closure of the fuel cycle, using fast reactors to transmute the fuel constituents into much less hazardous elements, and pyroprocessing technologies to recycle the fast reactor fuel, constitutes the ultimate step in reaching sustainability for nuclear energy. This process will effectively destroy the transuranic elements, resulting in waste forms that contain only a very small fraction of the transuranics (less than 1%) and all fission products. These technologies are being developed at Argonne National Laboratory and Idaho National Laboratory, with parallel development in Japan, France, and Russia.

The full recycle approach has significant benefits:

- It can effectively increase the utilization of the repository space by a factor in excess of 100.
- It can effectively increase the utilization of natural uranium by a factor of 100.
- It eliminates the uncontrolled buildup of all isotopes that are a proliferation risk.
- The fast reactors and the processing plant can be deployed in small co-located facilities that minimize the risk of material diversion during transportation.
- The fast reactor does not require the use of very pure weapons usable materials, thus increasing their proliferation resistance.
- It finally can usher the way towards full sustainability to prepare for a time when uranium supplies will become increasingly difficult to ensure.
- These processes would have limited economic impact: the increase in the cost of electricity would be less than 10% (ref: OECD).

- Assuming that demonstration of these processes is started by 2007, commercial operations are possible starting in 2025; this will require adequate funding for demonstrating the separations, recycle, and reactor technologies.
- The systems can be designed and implemented to ensure that the mass of accumulated SNF in the U.S. would always remain below 100,000MT, (Note: less than the technical capacity of Yucca Mountain) thus delaying, or even avoiding, the need for a second repository in the U.S.

Several disadvantages have been noted:

- These processes would have limited economic impact: the increase in the cost of electricity would be less than 10% (ref: OECD).
- Management of potentially weapons-usable materials may be viewed as a proliferation risk.

These disadvantages can be addressed by specific actions:

- Fuel cycle and reactor R&D is currently going on in the DOE Advanced Fuel Cycle Initiative (AFCI) and Gen-IV programs to reduce the costs of processing, fuel fabrication, and advanced reactors.
- Advanced simulation, modeling, and detection techniques can be used in fuel cycle facilities to improve material accountability and decrease the risk of misuse or diversion.
- An aggressive development and demonstration program of the advanced reactors and recycling options is needed to allow commercialization in a reasonable timeframe.

2. What are the greatest technological hurdles in developing and commercializing advanced reprocessing technologies? Is it possible for the government to select a technology by 2007?

To answer the first part of the question, the first major hurdle is the current inability to test the chemical processing steps at a pilot-scale using spent nuclear fuel (both as individual process steps and in an integrated manner simulating plant operations) to verify that both the process itself and the larger scale equipment will function as intended, and to minimize the technical risks in designing the commercial-scale plant. The processing methods currently being refined under the scope of the DOE AFCI program are being designed to very high standards for purity of products and efficiency of recovery, in order to reduce costs and minimize the hazardous content of high-level wastes. The processes have been successfully tested at laboratory scale (about one-millionth of industrial scale). Normal expectations for scale-up of industrial chemical processes are that the processes proven in the laboratory will perform well at full scale, provided that the process and equipment function as intended. In order to test process operations and equipment designs, it is necessary to conduct pilot plant operations at one/ one-hundredth to one/ one-thousandth of industrial scale with the complete process.

The second major hurdle is related to the first, in that there is an insufficient supply of some of the various chemical elements needed for the development and testing of product storage forms and waste disposal forms. However, it is anticipated that these would become available as a result of pilot-scale testing, but the lack of materials will hinder progress prior to that time.

For the second part of the question, yes, it is completely reasonable to select a processing technology by 2007, given the present state of development for the processing technologies. The level of success achieved in the DOE AFCI program to date indicates that the development of at least one processing technology satisfying program goals, UREX+, will be advanced to the stage where pilot-scale testing is warranted. At that time, it should also be possible to evaluate whether any of the other promising technologies currently being studied have proven capable of meeting program goals, and are also near to pilot-scale testing.

However, it must be emphasized that the reprocessing technology by itself will not provide any significant benefits unless the development of such capability is matched by similar advances in recycling technologies. In the case of full recycle, the development of both suitable reactors for recycling transuranics and appropriate nuclear fuel forms containing transuranics must proceed in parallel to testing and implementation of spent fuel processing. Only with all of the pieces in place will substantial benefits be achievable.

3. What reprocessing technologies currently are being developed at Argonne or at other national labs? What technical questions must be answered?

AFCI processing (chemical separations) technology is being developed at Argonne National Laboratory, Idaho National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratory, and Savannah River National Laboratory. All are involved with the development of aqueous solvent extraction technologies (the suite of UREX+ processes), while ANL and INL are also developing the pyrochemical processing technology that will be required for the nuclear fuel cycle associated with Gen-IV reactors. The aqueous technology is needed for near-term application, and the emphasis is on process optimization, equipment development, and plant design. The pyrochemical technology is needed for deployment of the Gen-IV reactors, and requires large scale demonstration. Emphasis on pyroprocessing is in testing of process features, with some work in progress on process equipment and facility design.

The UREX+ solvent extraction demonstrations have shown that it can meet separations criteria; however, integrated, engineering-scale testing is required to complete development. Continuing work is required to optimize flowsheets and increase process robustness and operations efficiency. An adequate facility is required for engineering-scale demonstrations to test equipment, advanced instrumentation for process control and PR&PP (Proliferation Resistance and Physical Protection), conversion of product and waste forms.

Pyroprocessing requires continued process development followed by engineering-scale demonstration of flowsheets developed for reprocessing the many alternative advanced reactor fuels. Improvements in the areas of transuranic element recovery and process equipment design needs to be completed. Similar to the UREX+ process an adequate facility is required for engineering-scale demonstration.

4. What reprocessing technologies are still in the basic research stage, what advantages might they offer, and what is the estimated timeline for development of laboratory scale models?

There are currently two mature technologies for reprocessing, UREX+ and pyroprocessing. For industrial scale implementation optimization of these technologies is still necessary:

- Off-gas treatment from fuel decladding and dissolution for retention of tritium, carbon-14, ruthenium, and technetium to prevent their migration to downstream operations where they are harder to sequester. Development of high efficiency scrubbers is currently an effort in other countries.
- Advanced instrumentation and process-sampling techniques for near real time accounting for process control and material accountability.
- Process diagnostics for early on-line detection using signals from process instrumentation to differentiate legitimate process operation versus clandestine product diversion.
- Waste forms optimization for preventing migration of radionuclides and reduce potential heath hazard to the public.

Nevertheless, there are a number of novel technologies where basic research could provide an alternative to the current technologies, with the potential of minimizing dose to the public and workers and environmental impacts. These research areas are:

- Development of ligands, chelating agents, and advanced extractant molecules based on fundamental principles to guide their preparation. Advantages - molecules could be tailored to perform a specific function such as separations of a given transuranic element. Estimated timeline 20 years.

- Development of environmentally benign separations processes such as based on magnetic and electronic differences. Advantages - produce minimum secondary wastes and significantly decrease the consumption of chemicals. Estimated timeline 30 years.

- Development of bio-based separations. Advantages – identify methods and replicate biological compound functions leading to new separation schemes, for example, separations of actinides over lanthanides. Estimated timeline 50 years.

5. How would you contrast what is being done internationally with U.S. plans for reprocessing, recycling and associated waste management? What countries recycle now? What components of the waste fuel are or can be used to make new reactor fuel?

Commercial reprocessing plants in France, the United Kingdom and Japan utilize the PUREX process, which separates uranium and plutonium and directs the remaining transuranics (americium, neptunium, and curium) to vitrified waste along with all of the fission products. Reprocessing operations in the U.K. may be terminated within the next 10 years, primarily because the shutdown of gas-cooled power reactors is limiting the need for the Sellafield B-205 plant. BNFL's THORP plant at Sellafield is principally used for light water reactor (LWR) spent fuel processing; the U.K. has only one LWR in operation and the market for foreign LWR fuel processing is decreasing. A shutdown of THORP has been announced for 2010. In contrast, a vigorous reprocessing activity is in progress in France at the La Hague plant of COGEMA. This plant is processing spent fuel from foreign sources as well as from the 57 power reactors of Electricité de France. Plutonium is recovered for recycle to the EdF reactors as mixed oxide (MOX) fuel. Research on means for improving waste management through reprocessing have been stimulated by the 1991 law, and research is in progress now at the laboratories of the Commissariat à l'Énergie Atomique (CEA) that is following much the same lines as that pioneered in the AFCI program of DOE. Commercial reprocessing will begin soon in Japan at the Rokkasho-mura plant of Japan Nuclear Fuel Ltd. The Rokkasho Reprocessing Plant is designed for the production of a mixed uranium-plutonium product that can be used to produce mixed oxide fuel for recycle in Japanese light water reactors. Japanese laboratories are also experimenting with advanced spent fuel processing methods.

The U.S. program represents a transition to an advanced nuclear fuel cycle. In the U.S., emphasis is being placed on technologies that can be successfully deployed in the next 20 years or so and be economically competitive as well as secure against all threats. The wastes arising from future U.S. process plants will be virtually free of radiotoxic elements, and there will be no generation of liquid wastes requiring underground tank storage. We expect our efforts to help us regain international leadership in the field of nuclear energy.

Both Japan and France are currently developing advanced fuel cycles, similar to the ones described in this paper, where there first would be partial recycle in conventional reactors, followed by closure of the fuel cycle in fast reactors. The U.S. program has had significant international collaborations with these two countries, and there have been excellent exchanges of research results. The approaches in the three countries are relatively well aligned, with a stronger emphasis on the short term development of separations technologies in the U.S., and a stronger emphasis on the long term development of fast reactors in France and Japan.