Report of
ADVANCED NUCLEAR TRANSFORMATION TECHNOLOGY SUBCOMMITTEE
Of the
NUCLEAR ENERGY RESEARCH ADVISORY COMMITTEE

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I. INTRODUCTION

The ANTT Subcommittee met in Washington on 4-5 December 2002 to review progress in the transmutation program, and to learn about major organizational changes that affect the management of the program. The NE's new Advanced Nuclear Research Office (NE-20) now oversees both the transmutation program (ANTT) and the Generation-IV program (GEN-IV).

Our meeting took place at a time of considerable budgetary uncertainty when DOE's operations were funded by a continuing resolution, clouding the future of all of DOE's programs. While Congressional actions and the President's FY-04 Budget Submission will determine what is possible in the ANTT program, we, of necessity, proceeded under the assumption that the program will move into its next phase as it was defined in our 15 April 2002 report to NERAC. In this report we will comment on systems studies, engineering, fuel development, and separation technology issues including some priority recommendations to help guide the program until the present budgetary uncertainties are resolved.

We have a major concern on the Systems side. NE-20 now oversees two program lines: GEN-IV and the Advanced Fuel Cycle Initiative (AFCI). The transmutation program is AFCI's largest component, but AFCI also has responsibility for the development of GEN-IV fuels. There is the potential for several problems here. First, the ANTT and GEN-IV programs have different time scales. While the goals of GEN-IV include dealing with its own spent fuel, the transmutation program has to deal with the waste stream from all the existing light-water reactors (LWRs) and all of the new ones that might be deployed through the year 2050 (the earliest time that GEN-IV reactors might have significant market penetration), and possibly longer.

The present structure of NE-20 has a single systems analysis group overseeing both programs. The transmutation program needs a dedicated subgroup for its own program, and we understand that this will be implemented.

Second, requirements of the ANTT program do not appear to have been taken into account in DOE's GEN-IV decisions. We have said in our previous reports that accomplishing all of the goals of the transmutation program will require a final system whose neutron spectrum has a fast component. Neither of the two leading GEN-IV candidates (VHTR and SCWR) is suitable. If the GEN-IV program sticks with those two possibilities, still another system, perhaps accelerator-driven, would have to be developed and deployed to complete the transmutation job.

Third, the AFCI program includes fuel development for the GEN-IV reactors. This is certainly sensible as long as care is taken to make sure that funding for GEN-IV fuels comes from the GEN-IV budget and not from the transmutation budget. There is a broad gray area that gives the potential for confusion and funding shifts.

The transmutation program itself has been restructured in a sensible fashion. The major focus in the beginning will be on treatment of spent fuel from existing and new LWRs. This program, called Series One by NE, will first carry out R&D on a sufficient scale to demonstrate feasibility and then move on to implementation. Successful implementation would eliminate the need for a second repository, and begin to reduce the inventory of plutonium. The radiotoxicity of the output stream would be reduced but the goal of reducing it to below that of the initial uranium ore in a thousand years could not be reached without the implementation of what is called the Series Two program. As we indicated in our 15 April 2002 report, the full cost of the Series One feasibility demonstration will be about $500 million. If the program were fully funded and successful, a decision on implementation could be made in about six years and the spent fuel treatment program could begin in about 15 years.

Broadly speaking, the Series Two aim is the final treatment of LWR spent fuel to reduce the required isolation time, and also to develop procedures for treating GEN-IV spent fuels. Clearly Series Two has lower priority today than has Series One in the event of serious budget constraints.

There has been considerable progress in systems studies, engineering studies, fuels design, and separation technologies. These are commented upon in later sections of this report. Given present budget uncertainties, we have also made suggestions on what we believe to be appropriate priorities within the program.

II. SYSTEMS ANALYSIS

In an effort to better coordinate its R&D programs for studies of future nuclear reactor technologies, DOE-NE has coupled two broad efforts. The first effort concerns the treatment of radioactive reactor wastes, which previously was conducted under the Advanced Accelerator Applications (AAA) Program and in FY-03 is housed under a new program, called the Advanced Fuel Cycle Initiative (AFCI). The waste treatment goals are stated as follows:

- Reduce high-level nuclear wastes: mass by a factor of twenty and volume by a factor of four.
- Reduce the cost of geologic waste disposal, with a net savings of $35-40 billion during the period 2007-2040.
- Reduce the civilian inventories of plutonium in forms that are conducive to weapons proliferation.
- Reduce the radiotoxicity of high-level nuclear waste to that of natural uranium ore within 1,000 years.

The second R&D effort, GEN-IV, concerns the identification and down-selection of the most appropriate technologies for sustaining ? and even increasing ? nuclear energy production for the rest of the 21st century. Its goals are the following:

- Provide sustainable energy generation that meets clean air objectives.
- Minimize and efficiently manage GEN-IV nuclear waste so as to protect the public health and the environment.
- Prove the economic advantage of GEN-IV nuclear reactors over other energy production technologies.
- Ensure the high level of safety and reliability for GEN-IV systems.
- Maximize the proliferation resistance of weapons-usable material, as well as protect such materials from theft by terrorists.

Clearly, the AFCI and GEN-IV R&D efforts overlap and need to be coordinated. To date, the ANTT Subcommittee has critiqued and advised NE's program activities on transmutation. At the same time, another NERAC Subcommittee, called the GEN-IV NERAC Subcommittee (GRNS), (co-chaired by Professor Neil Todreas of the Massachusetts Institute of Technology and Salomon Levy of Levy & Associates) is working with ten partner countries in an international organization called the GEN-IV International Forum (GIF) to develop a GEN-IV Nuclear Energy Systems Technology Roadmap. While there has not been a close working relationship to date between DOE's transmutation program and the GEN-IV program or their corresponding advisory committees, ANTT and GRNS, there have been many discussions among the relevant DOE program officers, as well as among members of NERAC who sit on the ANTT and GRNS Subcommittees.

To date, GEN-IV programs have not considered the transmutation program in selecting priority technologies. However, now the stakes have risen. The transmutation effort seeks to produce a deployable system within 15 years. At the same time, substantial progress will be demanded on the GEN-IV side to produce a deployable system by the year 2030, with ambitious R&D landmarks along the way.

Recognizing these lofty goals, DOE-NE has reorganized and established the new Advanced Nuclear Research Office, which includes both the AFCI and GEN-IV programs. These are to be coordinated by Dr. Ralph Bennett of INEEL who will serve as the Head of Systems Analysis. His role will be to ensure that the two efforts pursue highly compatible technologies. At DOE, the program officers heading the transmutation effort have been relocated from Central Headquarters in Washington, D.C., to Germantown, Maryland, in order to facilitate daily interactions with corresponding GEN-IV officials. As part of this reorganization, the fuels and separations R&D for GEN-IV will be moved to the new AFCI Program. The ANTT Subcommittee considers this move to be a good one, provided that the previous budget for fuels and separations technologies under GEN-IV will be moved in its entirety over to the AFCI Program. With the AFCI Program already struggling with a stressed budget, it would be disastrous if part of the current budget were directed away from the transmutation effort.

To better assess the systems analysis and coordination of the two efforts, it is important to examine the programs in more detail. As for the transmutation part of the AFCI Program, it will be divided into two overlapping activities, called Series One and Series Two. Series One is envisioned to have more short/intermediate-term goals for fuels, separations, and transmutation technologies. The technologies developed in Series One would be applicable for current and near-term reactor technologies. It would be during this activity that DOE would prove that a second repository would be unnecessary. Currently, there are 44,000 metric tonnes (Mt) of spent fuel waste stored at nuclear reactors around the United States, with about 2,000 Mt added each year. At this rate, the 63,000 Mt statutory limit of Yucca Mountain would be reached by about 2015. Thus, if transmutation is to have a significant effect on the reduction of the mass and volume of reactor waste, and thereby increase the potential of Yucca Mountain, major energies must be devoted immediately to the AFCI Series One R&D Program. Another potential benefit of the transmutation program is that it includes the possibility of extracting unspent energy from the reactor waste. Transmutation of plutonium and the minor actinides could provide a 25% increase in the energy extracted from reactor fuel. This could be an important supplement to mined uranium ore.

A recent study by the Organization for Economic Cooperation and Development estimates that spent fuel treatment and transmutation would add at least 10% to the overall cost of electricity. The hope is that the AFCI Series One Program will find a suitable technology to reduce this expense and achieve its goal of making nuclear energy including transmutation more economic.

The AFCI Series Two activity will address the long-term radiotoxicity issue associated with spent reactor fuel, as well as treatment of GEN-IV fuels. Presently, we feel that the Series Two activity is not clearly defined. Perhaps it cannot be until more progress is made in selecting GEN-IV technologies.

The ANTT Subcommittee notes what may be a breakthrough in the separation of uranium from spent fuel. In our April 15, 2002, report we concluded that the radiological impact of reactor waste could be reduced to below that of natural uranium in a period of a few thousand years, based on R&D up to then. Now it appears that the picture may have improved greatly. During August 2002, the AAA/AFCI team, performing experiments at the Savannah River Technology Center, demonstrated that the uranium extraction technology called UREX could recover nearly all uranium from spent Light Water Reactor (LWR) with a level of contamination below Nuclear Regulatory Commission criteria for disposal as Class C waste. It may be that the radiological impact of reactor waste might be reduced to below that of natural uranium ore in less than a thousand years. This is discussed further in Section V.

In the final analysis, after removal of the uranium and radioactive fission products, one has to transmute the transuranics. Plutonium can be recycled multiple times through a LWR; however, a fast reactor is needed to burn the minor actinides (MA) that build up in the recycled fuel.

The availability of a fast reactor in the GEN-IV portfolio is perhaps the most crucial compatibility issue that DOE must address in integrating the AFCI and GEN-IV efforts. Currently, the GEN-IV International Forum has identified six reactor technologies for further study, and they are the following:

- Very-High Temperature Reactor (VHTR)
- Supercritical Water-Cooled Reactor (SCWR)
- Sodium-Cooled Fast Reactor (SFR)
- Gas-Cooled Fast Reactor (GFR)
- Lead-Bismuth-Cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR).

While the international community will study all six concepts, DOE's GEN-IV program will place highest priority on the first four. We understand that as of now the VHTR is of highest priority because of its hydrogen-generating capability, SCWR is next, and the SFR and GFR seem to be a distant third. The VHTR and SCWR are not capable of adequately burning the minor actinides in the recycled fuel and the GFR is of limited capability. Thus, it is important that DOE continue R&D on the SFR, because it is the most compatible of the four for performing a final burn of the minor actinides.

Finally, for the overall systems analysis, the ANTT Subcommittee makes the following recommendations:

- Continue with the integration of the AFCI and GEN-IV R&D efforts.

- Move swiftly to establish a transmutation subgroup within the AFCI side of the overall Systems Analysis Program. This would ensure that the transmutation program would not lose its identity among the broader AFCI objectives. Apparently, top DOE officials have agreed to the establishment of such a subgroup.

- Ensure that the fuels and separations R&D that is being transferred from the GEN-IV to the AFCI comes with its full budget, so as not to decrease funding to the AFCI transmutation activities. Budget shortfalls will make a negative impact on DOE's ability to down-select AFCI and GEN-IV technologies by the Congressionally-mandated deadline of 2007.

- Clarify the R&D Program for the AFCI Series Two activity. While Series One is clear, Series Two is a bit murky, complicated by its overlap with Series One objectives.

- Seek more international cooperation in the AFCI effort. Through the GEN-IV International Forum, the GEN-IV effort is closely tied to international participation. We recommend that DOE seek to establish an analogous international collaboration for its AFCI Program, especially as regards transmutation. We are pleased that progress already has been achieved along this line, and note that, to its credit, DOE has received over $100 million worth of transmutation data from France and Switzerland.

- Seek governmental approval for recycling plutonium from commercial reactors. This is a crucial part of the transmutation process and technologies should be pursued that improve proliferation resistance.

- The AFCI effort should mark key critical decision points along its R&D path. The OMB has made the valid criticism that there are few "off ramps" built into the program.

- The DOE should increase the involvement of students and university faculty in the AFCI Program. The AAA Program nationally has impacted roughly 120 students. In the Senate 2003 budget proposal, $4.5 million is allocated to continue transmutation research at the University of Nevada-Las Vegas (UNLV), and additional monies are proposed for establishing a university consortium, to be headed by UNLV, for conducting research in this area.

- Develop proliferation resistance criteria for AFCI Series One and Two technologies. This is especially crucial for the more immediately deployable Series One technologies. We applaud DOE's recent appointment of a Blue Ribbon Panel to examine such criteria and encourages the Panel not to move too fast. It will be important to do a thorough job in its efforts to produce a draft of its report by late January and a final report to DOE by March '03. Also, we encourage the Panel to expand its membership to include both a weapons and safeguards expert.

Finally, we again note that the biggest obstacle to progress in transmutation R&D is the uncertain budget future. If DOE could solve this problem by taking the lead in proposing robust AFCI funding, there are indications that Congress would follow DOE's lead toward realizing a transmutation technology that would improve the first repository at Yucca Mountain and obviate the need for a second repository at considerable savings for the taxpaying public.

III. ENGINEERING

A top-level objective of transmutation engineering is to develop the engineering basis for the transmutation of minor actinides and long-lived fission products so that informed decisions can be made on a path forward for implementing transmutation technologies in Series One and Series Two efforts. As defined in the program plan, transmutation-engineering research is focused on three areas:

- Transmutation-engineering physics to provide nuclear data (fission cross sections, capture cross sections, temperature coefficients, etc.) for minor actinides in thermal, epithermal and fast neutron spectra. Data will be used to develop, validate, and benchmark analysis codes that can be used for fuel safety and licensing analyses.
- Transmutation engineering materials data to evaluate the impact of fast neutron spectrum and mixed particle environments on structural materials (gas production, fatigue, ductility, strength, radiation damage, etc.). Currently, this research area also includes tasks to obtain data for lead and lead-alloy coolants (corrosion, oxygen, sensors, etc).
- Accelerator Driven System (ADS) activities to evaluate the physics, startup, and operation of a coupled accelerator and subcritical system. Activities to support development of a target for ADSs.

Transmutation engineering physics and engineering materials data research includes tasks pertinent to Series One and Two; whereas ADS activities only include tasks pertinent to Series Two.

A wide range of tasks is proposed in the program plan for all three areas. Some of the key tasks proposed in each area include:

- Transmutation engineering physics:
  - Fission and capture cross-section measurements and evaluations for several isotopes (Np-237, Am-241, Am-242m, Cm243, Pu-238, Pu-240, Pu-241, and Cm-242). Thermal, epithermal, and fast neutron-spectra data will be obtained.
  - Temperature coefficients and gas production cross section data for higher priority isotopes and fuel mixes in the thermal, epithermal and fast-neutron

spectra using heated samples in low-power critical assemblies at LANL (sensitivity and uncertainty analyses were completed to identify isotopes and energy levels where data are needed most).
  - Maintenance and validation of the MCNPX code (MCNPX is a general-purpose Monte Carlo N-Particle code that extends the capabilities of the Los Alamos MCNP code).
- Transmutation engineering materials data:
  - Gas production cross sections in structural materials (Fe, Ni, Cr).
  - High-temperature fatigue, ductility, and strength testing of irradiated structural materials.
  - Developing and benchmarking radiation damage models for structural materials.
  - Update existing materials handbook.
  - DELTA-loop operation to determine a performance envelope, and natural circulation capability of lead and lead-alloy coolants.
  - Long-term corrosion testing of materials in coolants.
  - Development of oxygen sensors that can withstand radiation environment in lead and lead-alloy coolants.
  - Develop and maintain lead and lead-alloy coolant handbook containing performance envelope, corrosion potential, and sensor information.
- ADS activities, which are primarily international, include:
  - Lead TRIGA Reactor Accelerator Driven Experiment (TRADE). An ANL-W employee is overseeing the experimental program of this facility in which a reactor is coupled to an accelerator.
  - Megawatt Proton Irradiation Experiment (MEGAPIE). Reactor physics support is being provided to this experiment which is being conducted at the Paul Scherrer Institute in Switzerland. Mechanical and thermal-hydraulic support is also being provided for developing the MEGAPIE target design.
  - Import target and initiate testing of lead-bismuth target that was designed and built by the Russian Institute of Physics and Power Engineering (IPPE) to University of Nevada at Las Vegas (UNLV) in a coolant loop.

Several of these activities are already underway. For example, in the transmutation-engineering physics area, cross sections have been obtained for Pu-239 up to high energies (relevant to ADS). These data were used to benchmark the MCNPX code. Lead inelastic-scattering cross-section evaluations that are needed to predict reactivity coefficients have been completed. Samples irradiated in the MEGAPIE facility have been received from PSI. A high-temperature furnace is being installed at the LANL Chemical and Materials Research Building so that high-temperature testing can be conducted.

The ADS activities rely heavily on international cooperation. For example, U.S. engineers are completing long-term assignments in Italy to oversee the TRADE experimental program and in Switzerland to support the MEGAPIE facility. The IPPE target developed in Russia has been transported to UNLV so that it can be tested. Benchmarks for materials irradiation effects obtained by completing high-temperature tests on pre-irradiated cladding materials to quantify helium and hydrogen gas production. The DELTA loop has been set up, and initial operational testing has been completed.

Some of the proposed transmutation research is independent of which concept is used for a transmuter. Reactor physics data is sorely needed for minor actinides, for which there is currently a high degree of uncertainty irrespective of which burner is selected. Sufficient data and review are required for safety and licensing analyses. Hence, the committee believes that this research should be given a higher priority within the transmutation engineering area. Likewise, the committee recommends that research on structural materials be focused on structural materials that may be used in various transmuter concepts, such as steel components or high-temperature cladding materials. The subcommittee would also like to note that high-temperature testing of cladding materials is clearly an area where close collaboration between the GEN-IV and AFCI will be beneficial.

Although the committee concurs that research on ADS related research is a lower priority, the committee encourages the program to continue their participation in international collaborations, such as the TRADE facility, which can provide the U.S. insights about the viability of such systems for a fraction of the cost of doing it all ourselves. The committee believes that research proposed for the lead and lead-alloy coolant and the remaining ADS activities are of lower priority. Currently, the U.S. has ranked lead-cooled reactors as a lower priority GEN-IV concept. Hence, lead and lead-alloy coolant research would only pertain to ADS's, which are less desirable burners.

IV. FUEL DEVELOPMENT

The fuel development program for the Advanced Fuel Cycle Initiative (AFCI) is being modified to support a two-tier nuclear system architecture as developed in earlier systems studies. These systems studies, conducted during the Advanced Accelerator Applications (AAA) program, identified a two-tier architecture as the most effective means for disposing of plutonium in the near term and avoiding a second geologic repository. But the two-tier architecture requires the development of a fuel system for each tier. This requirement leads to a fuel development program with a Series One fuel supporting Tier I, and a Series Two fuel supporting Tier II.

There are two goals for the Series One fuel system. One is to address near-term issues associated with spent nuclear fuel by reducing the volume and heat load in the geologic repository. Doing so will ease the burden on the first repository and possibly eliminate the need for a second repository. Another goal is to develop a proliferation-resistant fuel system capable of destroying significant quantities of plutonium.

The Series One program is a deployment-driven program whose objective is commercial use of this fuel beginning in 2018. This timing is coincident with the design and construction of a new fabrication facility which, if the program is to proceed full speed, would be scheduled for startup in 2016. To meet this schedule, lead test assemblies must be fabricated beginning in 2007. As a precursor to this, feature testing must begin in 2004.

While there are many uncertainties to be resolved, one of the near-term uncertainties is that of proliferation resistance. At present, the program intends to resolve this by incorporating neptunium into the fuel. The fissile material, in this case, is a mixture of neptunium and plutonium. This has the advantage of increasing intrinsic proliferation resistance by adding a somewhat larger radiation barrier during fabrication. Yet the radiation barrier is not so large as to preclude using a fabrication technology based upon remote fabrication and contact maintenance. The neptunium also produces Pu-238 during the first burn, which degrades the plutonium isotopic vector and makes it less attractive for weapons use after the first burn. While the overall attractiveness and feasibility of this approach are still under discussion, the approach is worth exploring. The addition of neptunium may increase the need for a strong international collaboration program. Feature tests on the effects of adding selected actinides to MOX fuel have been conducted in other national programs, such as the French program.

The Series Two fuel development program is a longer program that must support reactors in the GEN-IV time frame. Rather than focusing on a single fuel and reactor type as Series One does, Series Two must deal with several fuel types in order to support a variety of fast-spectrum transmuters. Among these are: the traditional accelerator-driven system, the GEN-IV fast reactors, and the Very High-Temperature Gas Reactor (VHTGR). Inclusion of the VHTGR requires consideration of fuels for both thermal and fast reactors. Inclusion of the GEN-IV fast reactors requires consideration of a variety of coolants such a gas, sodium, and lead-bismuth. To span the breadth of this task, the program will concentrate on investigative efforts during the first five years followed by proof-of-performance tests after 2007.

The lack of a true fast-test environment seriously constrains the Series Two fuel development program. In order to compensate for this, the program will explore the possibility of developing a fast flux booster in ATR. It will insert some tests into Phenix, the French test reactor, before its shutdown. Neither solution is optimal, since the fast flux booster in ATR is likely to have a small volume and a low fast flux, implying that only feature tests can be conducted. Moreover, the short testing time in Phenix will preclude high-burnup tests. Artfully combining the two sub-optimal testing approaches will be a major challenge for the fuel development program.

If a funding shortfall occurs, then the fuel development program has some difficult decisions to make. For Series Two fuel, the path forward is filled with multiple options, and the most straightforward approach with a funding shortfall would be to reduce the number of options. One possibility would be to transfer the TRISO development to other programs, and allow the AFCI to concentrate on fast-transmuter fuel development. An early decision on the reference actinide burner would reduce the number of options that this program must support.

V. SEPARATIONS TECHNOLOGY

Dr. James Laidler (ANL) is the AFCI National Technical Director for Separations Technology Development and coordinates the efforts of six DOE laboratories. This should ensure the development and utilization of the best-known techniques and methods. There are also a number of mutually beneficial interactions with foreign organizations, especially in France and Switzerland.

The transmutation portion of the AFCI program is divided into two overlapping efforts called Series One (short- and intermediate-term goals) and Series Two (long-term issues associated with spent reactor fuel) as defined earlier. Obviously, these are highly interrelated. The separations approaches to meeting these proposed Series One and Series Two goals are as follows.

Series One: Develop efficient, cost-effective separations methods for the treatment of LWR spent oxide fuel. Establish optimum means for interim or long-term storage of separated radionuclides, e.g., Pu/Np, Am/Cm, Cs/Sr. Develop a sound basis for the design of a large spent-fuel treatment plan to be operational in 2015.

Laidler estimated that at the current level of nuclear generating capacity in the U. S. the Yucca Mountain statutory capacity limit would be reached by about 2010-2015, although based on limited geologic exploration more capacity is likely available there but would require building a second repository. A separations/processing plant capable of treating 2000 tons per year could reduce the annual volume of waste generated that would have to go to a repository from 2210 m^3 per year to about 110 m^3 and thus delay the necessity for repository expansion as well as make disposal less expensive.

Series Two: Develop efficient; cost-effective separations methods for the treatment of recycle fuel/targets for transmuter reactors. Establish economical methods for closure of the fuel cycle for GEN-IV reactors.

Series One Program:
The purified U product from UREX is assumed to be >99.9% U (probably actually much better than this) while the Tc product is >95% Tc, and the raffinate is >99.9% TRU. These fractions can then be subjected to further purification, separation, etc.,

as desired using the UREX+ processes. As Series One deliverables, a small-scale demonstration of the full UREX+ flow sheet by December 2003 was proposed to validate that the flow-sheet design would meet the initial separations criteria. If so, the cost of geologic disposal would be reduced by reducing the annual waste volume generation rate from 2210 m^3 per year to about 110 m^3 per year by removing U, TRUS, and heat-generating fission products, reducing high-level waste mass (cladding hulls and assembly hardware) from 2000 tonnes to about 600 tonnes, reducing the number of waste packages, reducing heat load by 97-99% and thus reducing facility ventilation requirements. It was estimated that spent fuel treatment costs could be reduced to ~$400/kg, that the inventories of Pu sent to the repository could be reduced from about 17,000 kg per year to 75 kg per year, and that the toxicity of high-level nuclear waste would be less than that of the original U ore in less than 1000 years. The radiotoxicity is to be <1% of the comparable amount of unprocessed spent fuel, and long-lived fission products, such as ^{99}Tc and ^{129}I, can be separated for transmutation or incorporated in durable waste forms to further reduce their dose risk by a factor of ~100. Other Series One elements to be included assuming adequate funding, are pyrochemical process development for LWR fuel, engineered product storage, and support for design of a spent fuel treatment facility. Detailed UREX+, Cs/Sr, and Pu/Np extraction flow sheets were presented. A flow sheet for extraction of minor actinides (MAs) is also given, but considerable development work is probably still required to efficiently separate the trivalent actinides from their trivalent lanthanide homologues. Details of the various flow sheets and processes are given elsewhere.

Pyrochemical process development for application to LWR oxide fuel is ongoing as resources permit and its optimum use is probably for direct recycle to fast reactors and requires a hybrid process for thermal recycle of Pu (Np). The hybrid process would combine a PYROX process with UREX+ to produce TRUs for recycle in a fast reactor or it could be used to separate TRUs from lanthanide fission products for Series One recycle.

Initial separations criteria for a spent fuel treatment facility were presented and appear to be achievable. For example, recovery efficiencies of 99.0% for U, 99.5% for TRUs, 95% for Tc, I, and 99% for Cs, Sr and a purity of 99.99% for U with no more than100 nCi/g TRU were proposed. Reirradiation or transmutation of some products in an appropriate reactor would also be beneficial. Meeting such criteria could preclude or significantly delay the need for a second geologic repository and significantly reduce costs in the Yucca Mountain repository if operation of such a plant were begun soon enough! Costs of treatment of LWR were estimated at ~$500/kg or less and at $2000/kg HM or less for transmuter spent fuel.

Series One Priorities:

- **Advanced aqueous separations.** Complete UREX hot demonstration and issue a final report by end of FY-03. Concurrently, continue UREX+ process development, including UREX+ small-scale demonstration started in FY-03 to be completed in mid-FY-03, and preparation for the engineering scale demonstration at INEEL in FY-04/05 with the demonstration to start in FY-07 to extend beyond this time frame.

- **PYROX process development.** This was given lower priority than the UREX+ demonstrations. We agree with this although some development work could probably be carried and there may be other funding for this.
- **Engineered product storage.** This was given lower priority as applied to actinide and fission product waste streams and cladding/structural components.

Series Two Priorities:

- **GEN-IV fuel treatment process development.** Currently there is a relatively low level of effort as some fuel systems such as for the gas-cooled reactor are not well defined. The program includes the wrapup of nitride fuel treatment process development. Metal fuel treatment (SFR) is covered under EBR-II spent fuel treatment program. As GEN-IV fuels are better defined, additional process concepts will be developed.
- **Advanced processing concepts.** New concepts that could reduce costs, simplify operations, and minimize wastes are being evaluated, initially in concept. Some examples are actinide crystallization, room-temperature ionic liquids, high-temperature dissolver designs, and improved extraction methods are examples.

Progress in Separations Technology in 2002.

There was impressive progress in the separations development program over the past year. The UREX process was demonstrated successfully with actual LWR spent fuel and the advanced AMUSE code was validated. The EBR-II spent fuel treatment effort was moved to the AFCI program with an emphasis on development of advanced recycle technologies for both Series One and Two applications. An electrochemical method for processing of LWR oxide spent fuel appeared promising on a laboratory scale and an electrolysis technique for pyrochemical recovery of TRUs was demonstrated.