Report to Congress

Advanced Fuel Cycle Initiative: Status Report for FY 2005

Prepared by

U.S. Department of Energy
Office of Nuclear Energy,
Science, and Technology

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Executive Summary

The Department of Energy, Office of Nuclear Energy, Science and Technology has prepared this report in response to the requirements of the Energy Policy Act of 2005 (EPACT) which directs the Secretary of Energy to submit an annual summary report on the activities of the Advanced Fuel Cycle Initiative (AFCI).

The mission of the AFCI program is to develop advanced fuel cycle technologies, which include spent fuel treatment, advanced fuels development, and transmutation technologies, for application to current operating commercial reactors and next-generation reactors and to inform a recommendation by the Secretary of Energy in the 2007-2010 timeframe on the need for a second geologic repository. Current legislation requires the Secretary to make a recommendation on the need for a second repository after January 1, 2007, but before January 1, 2010.

The strategic goals of the AFCI program focus on the development of separation and fuels technologies needed for commercial deployment of advanced fuel cycle facilities within the United States. The AFCI program is organized into five program elements focused on Separations Technology Development, Advanced Fuels Development, Transmutation Engineering, Systems Analysis, and Transmutation Education. This report summarizes the progress made by the AFCI program in FY 2005 toward achieving its strategic goals.

There were many accomplishments in FY 2005, and these are highlighted in this report. The two most significant accomplishments were in the Separations Technology Development and Advanced Fuels Development areas. In FY 2005, the Separations Technology Development element demonstrated the various separation steps of the UREX+ process at Argonne National Laboratory using irradiated fuel from the Cooper Nuclear Station in Nebraska. The demonstration achieved high extraction efficiencies for uranium and other elements and the purity of the recovered uranium was more than sufficient to have it classified as a Class C low-level waste. Successful completion of this demonstration represents the first sequential processing of spent nuclear fuel from an operating light water reactor using a group transuranic extraction process. Cumulative laboratory-scale successes in spent fuel separations indicate that engineering scale demonstrations should be pursued in the near-term.

Also in FY 2005, the Advanced Fuels Development activity successfully demonstrated the performance of light water reactor mixed-oxide fuel containing plutonium and neptunium. These test fuels had been developed in the program in FY 2003, and irradiation of these fuels commenced during FY 2004 in the Idaho National Laboratory's Advanced Test Reactor (ATR). Irradiation of these samples was completed in FY 2005 and, after removal from the ATR, preliminary post irradiation examinations were performed. Initial results indicate that all three mixed-oxide fuels forms, each containing at least 5 percent plutonium, performed well and maintained integrity during the irradiation. Preliminary post irradiation examinations showed no significant differences in behavior among the three mixed-oxide compositions included in the ATR irradiations.

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1. Introduction

The Department of Energy (DOE), Office of Nuclear Energy, Science and Technology (NE), has prepared this report in response to the requirements of the Energy Policy Act of 2005 (EPACT). Section 953 of the EPACT (see Appendix A) directs the Secretary of Energy, acting through the director of DOE-NE to:

> … conduct an advanced fuel recycling technology research, development, and demonstration program to evaluate proliferation-resistant fuel recycling and transmutation technologies that minimize environmental and public health safety impacts as an alternative to aqueous reprocessing technologies deployed as of the date of enactment of [the EPACT] …

Furthermore, the EPACT requires the Secretary to:

> … submit, as part of the annual budget submission of the Department, a report on the activities of the program.

This report summarizes the activities and accomplishments of the Advanced Fuel Cycle Initiative (AFCI) program for FY 2005. A listing of the major AFCI research areas and the FY 2005 funding for each are provided in the table below:

Technical Area	**FY 2005 Funding ($000)**
Separations	24,491
- UREX+ Development	- 4,374
- Pyroprocessing Development	- 17,465
- Advanced Process Development	- 1,694
- Advanced Fuel Cycle Facility Preconceptual Design	- 958
Fuels	10,760
- LWR Oxide Fuel Development	- 3,550
- Generation IV Fuels Development	- 7,210
Transmutation Engineering	4,560
Materials Test Station Design	6,994
Systems Analysis	5,775
Transmutation Education	10,498
Program Management/SBIR/STTR	4,972
AFCI TOTAL:	**68,000**

2. AFCI Program Overview

The mission of the AFCI program is to develop advanced fuel cycle technologies, which include spent fuel treatment, advanced fuels development, and transmutation technologies, for application to current operating commercial reactors and next-generation reactors and to inform a recommendation by the Secretary of Energy in the 2007-2010 timeframe on the need for a second geologic repository. Current legislation requires the Secretary to make a recommendation on the need for a second repository after January 1, 2007, but before January 1, 2010.

Of the challenges that must be addressed to enable a future expansion in the use of nuclear energy in the United States and worldwide, one of the most challenging is dealing effectively with spent nuclear fuel. Compared to other industrial waste, the spent nuclear fuel generated during the production of electricity is relatively small in quantity. However, it remains toxic for many thousands of years, and its disposal requires that many political, societal, technical, and regulatory issues be addressed. For many years, several countries around the world have pursued advanced technologies that could treat and transmute spent nuclear fuel from nuclear power plants. These technologies have the potential to dramatically reduce the quantity and toxicity of waste requiring geologic disposal. Over the last four years, the United States has joined this international effort and found considerable merit in this area of advanced research.

While these technologies are clearly not an alternative to a geologic repository, they could provide a means to optimize the use of the first U.S. repository and reduce the technical need for additional repositories. To achieve these benefits, the strategic goals of the AFCI program are to develop:

- Separations technology needed by industry to deploy a proliferation-resistant commercial-scale spent fuel treatment facility, and
- Fuels needed by industry to deploy advanced reactors capable of destroying the dominant radiotoxic components of spent fuel through transmutation.

The AFCI program consists of five main program elements spanning all activities necessary to support advanced fuel cycles including:

- Separations Technology Development
- Advanced Fuels Development
- Transmutation Engineering
- Systems Analysis
- Transmutation Education

The AFCI program also maintains robust research collaborations with international partners including Japan, France, Canada, the European Union, and The Republic of Korea.

The following sections provide a status report on the accomplishments of each of the AFCI program elements. A more detailed description of the AFCI program accomplishments in FY 2005 is provided in Appendix B.

3. Separations Technology Development

The AFCI program is investigating technologies in two primary separations areas – advanced aqueous-based processing and pyroprocessing. Many aqueous-based approaches to treat spent nuclear fuel exist. The Uranium Extraction Plus (UREX+) method is an advanced aqueous process with significant potential for meeting proliferation-resistant separations objectives while minimizing the waste generation historically associated with aqueous separations technologies. While UREX+ has great potential to address the spent fuel challenge associated with today's light water reactors, pyroprocessing is potentially best suited to address the needs of next generation fast neutron spectrum reactor fuels.

3.1 Advanced Aqueous Processing - UREX+ Experiment

Experiments completed in FY 2003 as well as continued testing in FY 2004 have proven the advanced, aqueous-based UREX+ technology to be capable of removing uranium from spent fuel at such a high level of purity that the uranium is expected to be sufficiently free of high-level radioactive contaminants to allow it to be disposed of as low-level waste or reused as reactor fuel. These laboratory-scale tests have proven uranium separation at purity levels of 99.999 percent. If spent fuel were processed in this manner, the potential exists to reduce significantly the volume of high-level waste requiring disposal in a geologic repository.

In FY 2005 a demonstration of the various separation steps of the UREX+1a process was performed at Argonne National Laboratory using irradiated fuel from the Cooper Nuclear Station in Nebraska. The demonstration achieved high extraction efficiencies for uranium, technetium, and the transuranic elements, and the purity of the recovered uranium, better than 99.999 percent, is more than sufficient to be classified as a Class C low-level waste. Successful completion of this demonstration represents the first sequential processing of spent nuclear fuel from an operating light water reactor (LWR) using a group transuranic extraction process.

3.2 Pyroprocessing Development

Pyroprocessing technology development activities since FY 2003 have focused on treating highly-enriched, sodium-bonded driver fuel while investigating alternatives to more cost-effective technologies for processing sodium-bonded blanket fuel. This focus is reflected in the *Report on the Preferred Treatment Plan for EBR-II Sodium-Bonded Spent Nuclear Fuel* (June 2003).

As part of the pyroprocessing development activity in FY 2005, electro-refiner development efforts were focused on addressing two significant inefficiencies in the current planar electrode electro-refiner (PEER) design. Analysis of work performed on Experimental Breeder Reactor (EBR)-II blanket fuel suggests that a significant increase in throughput can be achieved with the new PEER design as compared to the existing design.

4. Advanced Fuels Development

In FY 2005 the AFCI Advanced Fuels Development activity was focused on developing proliferation-resistant fuels for thermal neutron spectrum LWR and gas-cooled reactor systems. These fuels will enable the consumption of significant quantities of plutonium from accumulated spent fuel while simultaneously extracting more useful energy from the spent fuel materials. Development of advanced fuels containing higher actinides for transmutation in next generation fast neutron spectrum systems is also being conducted under the advanced fuels development program element. Transmutation of the actinides in these advanced reactor fuels would significantly reduce the actinide inventory in the spent fuel, thereby reducing the radiotoxicity and long-term heat load in a geologic repository.

4.1 LWR Oxide Fuel Development and Testing

In FY 2003, the AFCI program developed the first series of LWR mixed-oxide fuel pellets containing plutonium and neptunium for insertion into a test article for irradiation in the Advanced Test Reactor (ATR) at Idaho National Laboratory. Irradiation of these samples commenced in FY 2004 and was completed in FY 2005. After removing the test samples from the ATR, preliminary post irradiation examinations were conducted; this completed a major milestone for FY 2005. Initial results indicate that all three mixed-oxide fuels forms, each containing at least five percent plutonium, performed well and maintained integrity during the irradiation. Preliminary post irradiation examinations showed no significant differences in behavior among the three mixed-oxide compositions included in the ATR irradiation.

4.2 Generation IV Reactor Fuel Development and Testing

ATR irradiation of 11 metal and five nitride fuel samples was also initiated in FY 2003 to support qualification of these fuels for irradiation in the French Phénix fast reactor scheduled for FY 2007. Irradiation of these fuel samples was completed and post irradiation examination was initiated in FY 2005. The non-destructive tests performed showed no fuel failure during irradiation for the test articles.

AFCI also supports fuel development activities for the Advanced Gas-cooled Reactor fuels program. In FY 2005, low-enriched uranium oxycarbide fuel kernels were fabricated and trial tests for coating process optimization were conducted. All required characterization techniques for coated particles and compacts were completed in FY 2005 to prepare for the first ATR irradiation test scheduled for FY 2007.

5. Transmutation Engineering

AFCI Transmutation Engineering activities are developing the engineering basis for the transmutation of minor actinides and long-lived fission products from spent fuel. This includes computer programs, experimental measurements, benchmark calculations, maintenance and updating of nuclear cross-section data, nuclear physics data and codes, coolants and corrosion, structural materials, and pursuit of international collaborations to support technology decisions on reactor- and accelerator-assisted transmutation systems.

In FY 2003 and FY 2004, key transmutation-related neptunium and americium cross section measurements were performed to reduce uncertainties in transmutation reactor computations. The Transmutation Engineering element also engaged in international collaborations to leverage transmutation program funds in the areas of transmutation science and materials research.

In FY 2005 transmutation physics activities continued to focus on the development of nuclear data to allow accurate prediction of transmutation rates. The neptunium-237 fission and capture cross section measurements, which marked the production of the first AFCI-funded actinide fission and capture cross sections in FY 2004, were completed in FY 2005. Results indicated reduced systematic errors and uncertainty in measurements and provided useful insights into guiding new theoretical evaluations for this isotope. The data measurements are unique in that the cross sections for fission and capture reactions span ten decades of incident neutron energy. This was accomplished using two separate instruments at the Los Alamos Neutron Science Center, LANSCE.

6. Systems Analysis

The primary function of the AFCI Systems Analysis element is to develop and apply evaluation tools to formulate, assess, and guide program activities to meet programmatic goals and objectives. The focus of this activity is on operations research and computer modeling of various separations and transmutation options.

In FY 2003, the AFCI program:

- Established a baseline deployment scenario, as well as upper- and lower-bound deployment scenarios;
- Undertook activities that develop and benchmark an integrated fuel cycle model;
- Conducted a preliminary scoping study to estimate cost and schedule requirements for a spent fuel treatment facility; and
- Initiated studies on the performance expectations of individual transmutation systems.

In FY 2004, the AFCI program identified the nuclear fuel cycle technologies that offer the greatest promise for future use, developed the information necessary to conduct cost-benefit analyses for each of these technologies, and prioritized program technology development by determining the optimum mix of facilities and systems. This effort included the conduct of broad system studies, integrated nuclear fuel cycle system studies, transmutation system studies, and technology and facility assessments.

In FY 2005, the AFCI Cost Basis Development Team established a credible cost basis and created a reference source and associated database for fuel cycle unit costs. The database, along with the 2005 AFCI Cost Basis report, provides a comprehensive collection and analysis of reference fuel cycle costs that support an ongoing, credible, technical cost analysis basis for the AFCI program. Additionally, the database contains citations from over 200 reports used in the preparation of the AFCI Cost Basis report.

7. Transmutation Education

Transmutation Education activities include the successful university fellowship program established to support the development of new U.S. scientists and engineers studying science and technology issues related to transmutation and advanced nuclear energy systems; the Transmutation Research Programs at the University of Nevada, Las Vegas and the Idaho Accelerator Center at Idaho State University; the university-based Nuclear Energy Research Initiative (NERI) program; and national laboratory supported research. The FY 2005 AFCI budget supported these activities, which included the research of more than 70 graduate students at U.S. universities.

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Appendix A – Energy Policy Act of 2005 Excerpts

Advanced Fuel Cycle Initiative Language

119 STAT. 886 PUBLIC LAW 109–58—AUG. 8, 2005

(C) use fuels that are proliferation resistant and have substantially reduced production of high-level waste per unit of output; and

(D) use improved instrumentation.

(e) REACTOR PRODUCTION OF HYDROGEN.—The Secretary shall carry out research to examine designs for high-temperature reactors capable of producing large-scale quantities of hydrogen.

42 USC 16273.

SEC. 953. ADVANCED FUEL CYCLE INITIATIVE.

(a) IN GENERAL.—The Secretary, acting through the Director of the Office of Nuclear Energy, Science and Technology, shall conduct an advanced fuel recycling technology research, development, and demonstration program (referred to in this section as the "program") to evaluate proliferation-resistant fuel recycling and transmutation technologies that minimize environmental and public health and safety impacts as an alternative to aqueous reprocessing technologies deployed as of the date of enactment of this Act in support of evaluation of alternative national strategies for spent nuclear fuel and the Generation IV advanced reactor concepts.

(b) ANNUAL REVIEW.—The program shall be subject to annual review by the Nuclear Energy Research Advisory Committee of the Department or other independent entity, as appropriate.

(c) INTERNATIONAL COOPERATION.—In carrying out the program, the Secretary is encouraged to seek opportunities to enhance the progress of the program through international cooperation.

(d) REPORTS.—The Secretary shall submit, as part of the annual budget submission of the Department, a report on the activities of the program.

42 USC 16274.

SEC. 954. UNIVERSITY NUCLEAR SCIENCE AND ENGINEERING SUPPORT.

(a) IN GENERAL.—The Secretary shall conduct a program to invest in human resources and infrastructure in the nuclear sciences and related fields, including health physics, nuclear engineering, and radiochemistry, consistent with missions of the Department related to civilian nuclear research, development, demonstration, and commercial application.

(b) REQUIREMENTS.—In carrying out the program under this section, the Secretary shall—

(1) conduct a graduate and undergraduate fellowship program to attract new and talented students, which may include fellowships for students to spend time at National Laboratories in the areas of nuclear science, engineering, and health physics with a member of the National Laboratory staff acting as a mentor;

(2) conduct a junior faculty research initiation grant program to assist universities in recruiting and retaining new faculty in the nuclear sciences and engineering by awarding grants to junior faculty for research on issues related to nuclear energy engineering and science;

(3) support fundamental nuclear sciences, engineering, and health physics research through a nuclear engineering education and research program;

(4) encourage collaborative nuclear research among industry, National Laboratories, and universities; and

(5) support communication and outreach related to nuclear science, engineering, and health physics.

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Appendix B – AFCI Program Highlights

B.1 Separations Technology Development

AFCI Separations Technology Development focuses on partitioning and waste management technologies which, by extracting and transmuting the long-lived actinides, can reduce the volume of high-level waste, the heat load imposed on a geologic repository, and the time required for waste to decay to low levels. Partitioning spent fuel into selected groups of constituents allows more effective energy recycling and waste management approaches.

A primary objective of the light water reactor spent fuel separations activity is to support the 2007-2010 Secretarial recommendation on the need for a second repository. Support from a broad program of process technology development will be directed towards establishing the basis for the technologies necessary for plants which can treat the large quantities of spent fuel being generated in the United States. Included in this work are process chemistry and technology, as well as consideration of deployment strategies and separations criteria. Treatment and disposition of EBR-II spent fuel is also included in the Separations Technology Development element.

Both advanced aqueous and pyrochemical processing methods are being developed under the scope of AFCI. One aqueous process, known as UREX+, is at an advanced stage of technological maturity with possible commercial deployment in the 2020–2025 time period. The process represents a minor but significantly proliferation-resistant departure from the processes presently utilized in commercial reprocessing plants in other countries. Pyrochemical processing methods are directed principally toward the treatment of spent fuels arising from the operation of fourth generation reactor plants and the development benefits greatly from the experience gained in processing spent fuel from the EBR-II fast reactor.

During FY 2005 important advancements were made in both aqueous and pyrochemical processing technology. Completion of laboratory-scale testing of the UREX+1 process was a milestone for the Separations Technology Development activity, and a major accomplishment was the completion of a preconceptual design for the Advanced Fuel Cycle Facility.

Aqueous UREX+ Process Hot Demonstration

In FY 2005, a demonstration of the various separation steps of the UREX+1a process was performed at the Argonne National Laboratory (ANL) using irradiated fuel from the Cooper Nuclear Station in Nebraska. The demonstration achieved high extraction efficiencies for uranium (U), technetium (Tc), and the transuranic elements, and the purity of the recovered U, better than 99.999 percent, is more than sufficient to be classified as a Class C low-level waste. Successful completion of this demonstration represents the first sequential processing of spent nuclear fuel from an operating light water reactor using a group transuranic extraction process, rather than discrete batch mode experiments using simulant materials.

The test revealed the need for process improvements in that the separation of rare earth fission products from the transuranic product was less than complete (11.8 percent of the rare earths, principally neodymium, appeared in the product, although most were removed with approximately 95 percent efficiency). The most likely cause was a slow rate of rare earth complexing and its reverse, necessitating greater contact time per extraction and stripping stage. That rate is currently being measured, and contactor modifications are planned before the next flowsheet test in FY 2006.

24-Stage Contactor Array used to perform the UREX+ demonstration at ANL.

Advanced Fuel Cycle Facility (AFCF) Preconceptual Design

A draft mission need statement was prepared for a proposed AFCF. The purpose of the AFCF is to develop and demonstrate advanced fuel processing and fuel fabrication techniques at various throughputs including engineering scale, over a 50+ year period. The AFCF will include (1) large hot cell(s) to validate/demonstrate spent fuel treatment (aqueous and pyrochemical processes) and remote fuel fabrication processes on an integrated engineering scale, and (2) small hot cells and gloveboxes to carry out and validate bench-scale unit operations and conduct other related development activities. The technology development conducted in this laboratory will (1) provide critical path information for design confirmation of the future full-scale production facilities and (2) support future operations and process development as improvements to the nuclear fuel cycle and related proliferation risk reducers continue to evolve. The latter includes the development and testing of advanced instrumentation for improved process control and accountability.

Following completion of the draft mission need statement, work was directed toward preparation of the AFCF high-level Functional and Operational Requirements (F&OR) report that will support conceptual design activities in early FY 2006. The F&OR report describes the AFCF's principal functional features, defines basic system requirements, and develops preliminary facility layout concepts to guide design and construction of this proposed world-class research and development facility. The development of the F&OR report draws on the best technical resources throughout the DOE complex and its international partners to ensure that all features necessary for conducting technology development for future nuclear fuel cycles are included in the design.

Pyrochemical Partitioning of Americium/Curium

In addition to aqueous processing techniques, the AFCI program is also developing pyrochemical methods for the treatment of both legacy light water reactor and future advanced reactor fuels. One promising concept under current development is a hybrid process which initially uses aqueous techniques to dissolve the irradiated light water reactor fuel, but incorporates pyrochemical methods for the separations.

In FY 2005, a significant pyrochemical processing accomplishment occurred with the down-selection and subsequent implementation of an experimental demonstration to separate americium (Am) and curium (Cm). A transpiration process based on the relative volatility of americium and curium hydroxides and oxy-hydroxides was tested. The process employs a stream of gas containing oxygen, water, and argon which is passed over the oxide material at the desired temperature, and the volatile species are vapor transported to the condenser of the system. The simplicity of the experimental system design was of primary concern due to the difficulties of working with these materials in a remote facility.

Planar Electrode Electro-Refiner Development

Development efforts for the planar electrode electro-refiner (PEER) in FY 2005 were focused on addressing two significant inefficiencies in the current electro-refiner design:

- Removal of the electrodeposited U from the cathode surface, and
- Removal of the electro-refined U from the process vessel.

Analysis of work performed at the Idaho National Laboratory (INL) on EBR-II blanket fuel suggests that a significant increase in throughput can be achieved with the new PEER design as compared to the existing electro-refiner design.

B.2 Advanced Fuels Development

The Advanced Fuels Development element includes activities directed toward both existing and next generation reactor systems. Fabrication capabilities for mixed-oxide, metallic, and nitride fuels have been reconstituted over the past three years within the U.S. national laboratories and the first mixed actinide fuels, representative of those required by an advanced fuel cycle, have been successfully fabricated. Test fuel assemblies have been manufactured with sufficient quality assurance to permit placement in test reactors, and in-reactor testing is in progress in the Phénix fast reactor in France.

AFCI Advanced Fuels Development includes Generation IV fuels, advanced and proliferation-resistant light water reactor fuels, and prototypic transmutation fuels for Generation IV reactors. Activities include research, development, testing, safety analyses required for NRC licensing, and technology demonstrations that enable the design and construction of proliferation-resistant fuel fabrication facilities. FY 2005 was a productive year in which considerable progress was made in AGR TRISO, metal, nitride, inert matrix, sphere-pac and dispersion fuel development and testing, and in post-irradiation examinations (PIE).

LWR Oxide Fuel Development and Testing

In FY 2003, the AFCI program developed the first series of LWR mixed-oxide fuel pellets containing plutonium and neptunium for insertion into a test article for irradiation in the Advanced Test Reactor (ATR) at the Idaho National Laboratory. Irradiation of these samples commenced in FY 2004 and was completed in FY 2005. After removing the test samples from the ATR, preliminary post irradiation examinations were conducted; this completed a major milestone for FY 2005.

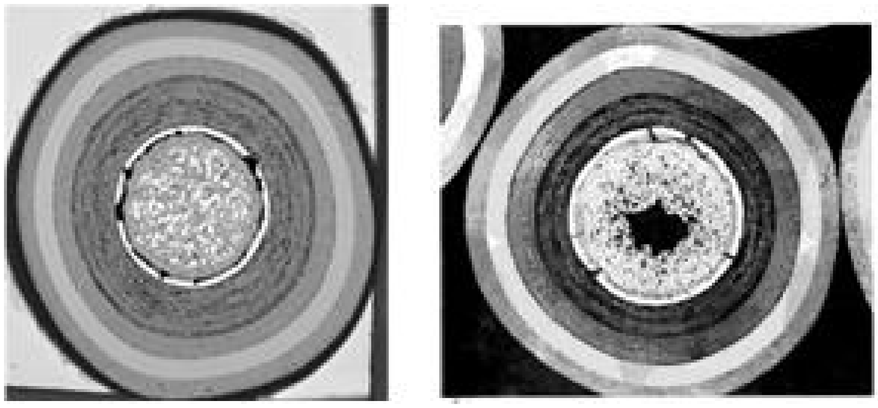
Post-Irradiation Examination Findings

In 2003-2004, transmutation fuels for both fast and thermal neutron systems were irradiated in the LWR-1 and AFC-1 series tests conducted at the ATR. In FY 2005, the AFCI program conducted preliminary PIE on these transmutation fuels. Non-destructive examinations, including dimensional and visual scans, gamma scans, and neutron radiography were performed. Initial results indicate that all three LWR-1 mixed oxide fuel forms, each containing at least 5 percent plutonium, performed well and maintained integrity during irradiation. Inspections on 18 AFC-1 metal and nitride fuel rodlets showed no failures during irradiation.

Neutron radiography of the nitride fuel rodlets revealed that there was axial fuel relocation in two rodlets due to inversion during rodlet disassembly and storage after irradiation; however, this was not exhibited by all nitride fuels.

AGR TRISO Fuel Development

The AFCI program supports fuel development activities for the Advanced Gas-cooled Reactor (AGR) fuels program, which seeks to develop, test, and qualify particle fuels for the Generation IV Very-High Temperature Reactor. In FY 2005, low-enriched uranium-oxycarbide fuel kernels were fabricated at BWXT Technologies, Inc. (formerly the R&D Division of Babcock & Wilcox), and coating trial tests were conducted and optimization of the coating process was initiated at the Oak Ridge National Laboratory (ORNL). All required characterization techniques for coated particles and compacts were completed, as well as the final design review and selection of the variants for the AGR-1 test.



TRISO fuel particles.

Nitride Fuel Development

Low-fertile AFC-1G nitride fuel pellet fabricated at LANL.

During FY 2005, the fuel pellet fabrication for the AFC-1G experiment was completed, including 14 pellets each of the low-fertile and non-fertile compositions. Residual carbon and oxygen levels in the non-fertile composition were reduced by 50 percent from measurements on previous AFC-1Æ nitride pellets, and these pellets were shipped to INL for rodlet fabrication, sodium bonding, and insertion into ATR as part of the AFC-1G test. However, many of the AFC-1G fuel pellets displayed structural defects and, as a result, only one rodlet was prepared for ATR irradiation in the AFC-1G test.

Additional nitride fuel development activities include:

- Submission of the FUTURIX research report on the fabrication of nitride compositions for irradiation in December 2004. This report provided information to bound the safety case for irradiation of the material in the Phénix reactor.
- Experiments using ZrN as a surrogate to determine the effect of sintering temperature and atmosphere on the mechanical properties, stoichiometry, Am loss, and phase stability of the pellets. This study will provide a systematic assessment of the sintering behavior in ZrN and will be used to determine optimum fuel processing parameters.

Metal Fuel Development

Excellent progress was made at INL in FY 2005 in the development of advanced metal fuels for fast reactor transmutation. Key accomplishments include the fabrication and characterization of AFC-1H irradiation experiment rodlets, initial fabrication and characterization of metallic fuels for the FUTURIX-FTA irradiation experiment, and irradiation testing of metallic fuel in the AFC-1-1H experiments in ATR.

Un-sectioned pieces of the U-29Pu-2Np-4Am-30Zr metal alloy FUTURIX-FTA fuels fabricated by arc-casting.

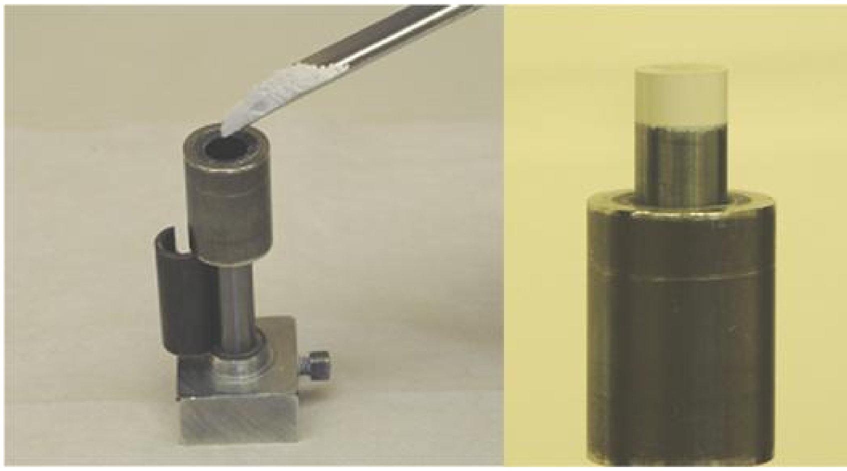
Additionally, the report, "FUTURIX-FTA Metal Alloy Fuel Fabrication and Characterization Research and Development Report," was completed and transmitted to the *Commissariat à l'Énergie Atomique* (CEA) in December 2004 as required by the Implementing Arrangement between the United States and France for this fuel test.

Inert Matrix Fuel Development

Inert matrix fuel (IMF) consists of an inert matrix with either a macrodispersion of discrete, dispersed fuel particles, approximately 0.1-0.5 mm in diameter, or an inert matrix with plutonium (Pu) powders intimately mixed. The advantage of IMF is that it can be used in standard light water reactors as part of a transition fuel cycle where separated plutonium and selected minor actinides can be burned in current reactors.

ZrO_2 is the primary fuel matrix candidate internationally for IMF; however, it has low thermal conductivity and is difficult to reprocess using conventional processes. MgO is a very attractive alternative, but it is not stable in water—a severe drawback for use in light water reactors. AFCI IMF activities have focused on a ceramic solid solution of MgO-ZrO_2. In this solution, the MgO provides good thermal conductivity and is easily dissolved in conventional acids while the ZrO_2 provides resistance to water attack. In FY 2005, MgO-ZrO_2 pellets were fabricated and characterized at INL, and were found to last 700 hours in 300°C deionized water at saturation pressure without cracking. Although the pellets exhibited hydration reaction at the surface, the bulk of the MgO is protected by ZrO_2.

Following the success of the feasibility studies with the MgO-ZrO_2 inert matrix, MgO-ZrO_2-PuO_2 microdispersion pellets were fabricated and characterized. Results indicate improved product quality compared to earlier results, reinforcing findings that neither PuO_2 nor ZrO_2 dissolved in the highly thermally conductive MgO phase and establishing that Er_2O_3 preferentially dissolves in the ZrO_2 phase. By remaining free from dissolved species, the MgO phase is expected to maintain high thermal conductivity acting as efficient means of increasing the thermal conductivity of the entire ceramic composite.

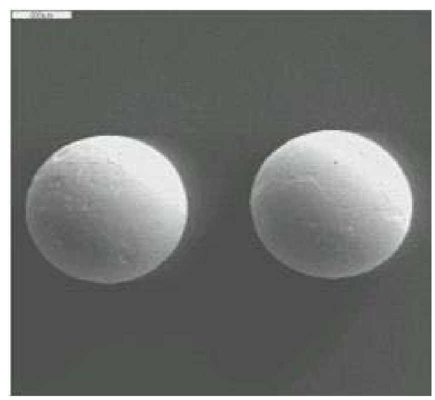


Inert matrix pellet fabrication.

Experiments to assess the feasibility of reprocessing $MgO-ZrO_2$-based IMF in nitric acid were carried out. The attempt to dissolve MgO-ZrO2 resulted in a selective leaching of the crystalline MgO phase; the second phase, $MgO-ZrO_2$ solid solution, failed to completely dissolve, leaving behind a ZrO_2 skeleton. This will allow acid to penetrate inside the pellet and dissolve fission products making reprocessing feasible. Insolubility of the ZrO_2 phase provides an opportunity for its easy separation.

Dispersion Fuel Development

Dispersion fuels are being considered for the Gas-cooled Fast Reactor (GFR). In this concept, uranium and plutonium carbide fuel particles with a silicon carbide (SiC) coating are dispersed in a SiC matrix with an outer cladding. Accomplishments in preparation for the GFR-F2 irradiation experiments include:



Uranium carbide particles produced by atomization at INL.

- Development and demonstration of the fuel fabrication process for GFR-F2 fuels using surrogates,
- Development and refinement of the UC fuel particle fabrication process,
- Fabrication of U-bearing specimens; microstructural characterization of the SiC-matrix GFR fuel, and
- Development of a SiC-clad pin-type fuel.

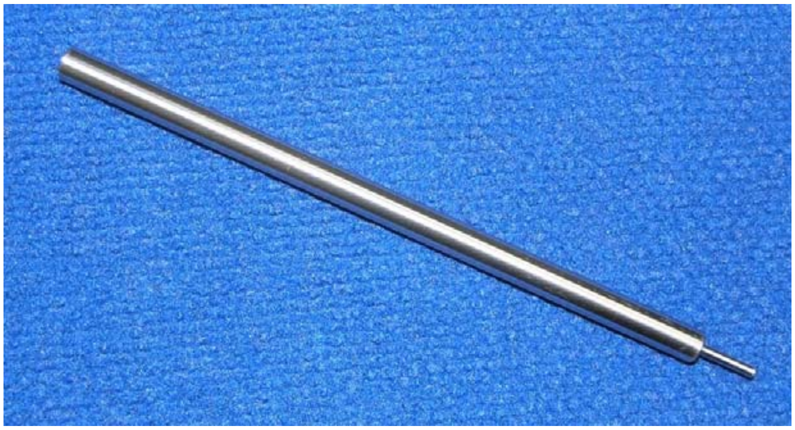
A technique to successfully fabricate carbon preforms with minimal shrinkage (~2 volume %) was demonstrated. Silicon infiltration and reaction experiments were conducted using the density-stable preforms, and resulted in some success. Additionally, two silicon infiltrated samples were compared to investigate the effects of adding a SiC filler powder to the preform, which tended to result in a finer as-fabricated microstructure.

During FY 2005, a variety of test samples of candidate matrix materials were fabricated and shipped to the CEA for irradiation in the Phénix reactor as part of the FUTURIX-MI experiments.

Sphere-Pac Fuel Development

AFCI sphere-pac fuel development is focused on creating transmutation targets containing Am or Am/Cm mixtures as a means of burning the Am and Cm in spent fuel. One advantage of sphere-pac fuels is the dustless fabrication of "pellet-like" fuel. The handling of radioactive powders can be minimized and remote operations are simplified and minimized by fabricating spheres with an internal gelation process and mixing together spheres of two sizes.

During FY 2005, ORNL evaluated sphere-pac fuel for transmutation in thermal and fast spectrum reactors and prepared a report entitled "Sphere-Pac Evaluation for Transmutation." Additionally, ORNL established the capability for loading sphere-pac pins, and a surrogate pin was loaded and shipped to INL.



Surrogate sphere-pac pin fabricated at ORNL

B.3 Transmutation Engineering

Transmutation Engineering activities focus on developments in physics and materials that support the implementation of fast neutron spectrum transmutation systems. Transmutation physics provides the nuclear data needed for accurate predictions of the overall performance of transmutation systems. The transmutation materials activities include development, testing, and modeling of structural materials, as well as research and testing of coolant materials and systems for advanced fast reactors.

Cross Section Measurements

To reduce the uncertainties in transmuter design, transmutation physics activities continued to focus on development of nuclear data to allow accurate prediction of transmutation rates. The neptunium-237 (^{237}Np) fission and capture cross section measurements, which marked the production of the first AFCI-funded actinide fission and capture cross sections in FY 2004, were completed in FY 2005. Results indicated reduced systematic errors and uncertainty in measurements and provided useful insights into guiding new theoretical evaluations for this isotope. The data measurements are unique in that the cross sections for fission and capture reactions span ten decades of incident neutron energy. This is accomplished using two separate instruments at the Los Alamos Neutron Science Center (LANSCE). Data is currently being taken for the isotopes ^{240}Pu and ^{242}Pu. With special measurement foils being produced by INL, isotopically pure samples will be developed for the other actinides of interest.

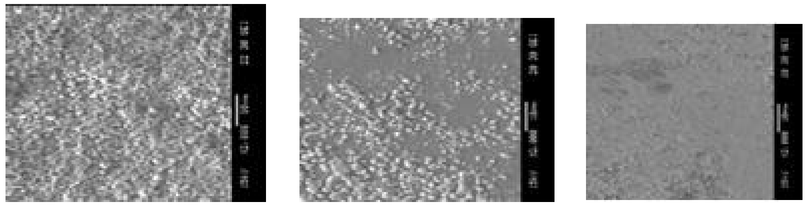
In addition, gas production cross section measurements on tantalum (Ta) and chromium (Cr) were measured to determine the amount of (hydrogen (H) and helium (He)) gases produced via neutron interactions. These gases can lead to significant detrimental changes in materials properties such as embrittlement and swelling. The results will be used to accurately predict gas production in the fast spectrum transmuter structural materials while in service; thereby, allowing accurate prediction of material lifetimes.

Structural Materials Research

To provide for efficient transmutation in fast spectrum burner reactors, it is necessary that the fuel and cladding survive very high burnup and attendant neutron dose. New cladding alloys are necessary to safely reach the desired dose and avoid irradiation induced material degradation. Structural materials testing is being performed to evaluate material properties (e.g., strength, fatigue, ductility) under varying temperature and dose conditions. The effects of fast neutron irradiation on the tensile properties of potential AFCI structural materials such as JFMS (Japanese Ferritic-Martensitic Steel) and HT-9 were recently investigated showing that these alloys hold promise for future transmuter use.

Liquid Heavy Metal Coolant

Coolant options for the fast spectrum transmutation reactors include sodium and lead. Attributes of heavy liquid metals (lead or lead-bismuth) offer the potential for improvements in safety and thermal efficiency over sodium with the downside of increased corrosion of stainless steels at temperatures above 400ºC. Thus as part of the materials research efforts, Transmutation Engineering is developing techniques for mitigating corrosion in these systems. The primary testing facility is the DELTA (Development of Liquid Metal Technologies and Applications) loop at Los Alamos National Laboratory (LANL). Recent long-term (1000-hour) corrosion tests included 30 different materials and surface treatments. The DELTA loop produces a unique oxygen-controlled flowing lead-bismuth eutectic (LBE) environment for materials testing with temperatures up to 550ºC possible. The research team has developed a thorough understanding of the corrosion process and has determined that certain alloying elements in stainless steel can be added that develop a stable oxide surface that passivates the bulk material and eliminates corrosion. Other surface treatment and coating techniques have produced similar results. The next phase in the development is to test materials in flowing lead at temperatures up to 700ºC in collaboration with researchers from the University of Nevada Las Vegas (UNLV) and the development of a large-scale engineering test at INL.

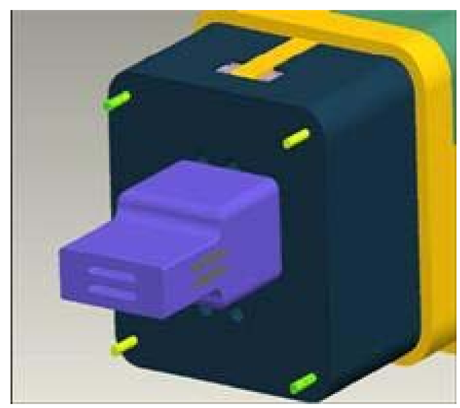


a) 200 hr **b) 400 hr** **c) 600 hr**

First ever observation of accelerated magnetite removal completion from DELTA test as predicted by corrosion modeling.

Material Test Station Design

The irradiation testing of fuels and materials in a prototypic environment is essential to the implementation of fast spectrum transmutation reactors. With the shutdown of the Fast Flux Test Facility and EBR-II reactors in the early 1990s, the United States has no fast spectrum irradiation capability. Some irradiations are possible in foreign reactors, but scheduling such tests are difficult, time consuming, and expensive. To alleviate this problem, considerable effort has been put into the preconceptual design of a Materials Test Station (MTS) at LANSCE. Using the existing proton accelerator and a very large unused experimental area, the MTS will produce an intense neutron irradiation environment very similar to a fast spectrum reactor. The MTS would use the existing LANSCE 800 MeV high power proton beam in conjunction with a spallation target to generate the neutrons. Because each proton creates about 15 neutrons, a total neutron flux of 1.2e15 n/cm^2/s can be generated. Design reviews and initial estimates for the MTS cost and construction schedule have been completed. If funding continues and needed upgrades to the LANSCE accelerator are implemented, the MTS could be completed and operational by 2009. The potential for upgrading the accelerator to higher power in the future would enable the MTS to double the neutron intensity; therefore, shortening irradiation times by a factor of two.



MTS monolithic target design concept

B.4 Systems Analysis

Systems Analysis crosscuts the other AFCI program elements and provides the models, tools, and analyses to assess design feasibility of design and deployment options and inform key decision makers. This activity is conducted jointly with the Generation IV Nuclear Energy Systems Initiative, coordinated through the technical integration function of each program, and successively builds upon previous results to define potential nuclear waste management approaches for the United States. Early studies indicate various fuel cycles and implementation strategies have the potential to meet program objectives. More detailed studies will address the practicality and attractiveness of the most promising approaches.

Recently, work has begun on developing cost estimates for these options to provide an objective basis for comparison.

High-level objectives of the Systems Analysis function are to:

1. Develop deployment strategies for the best fuel cycles in the intermediate and long term based on environmental, nonproliferation, energy, and economic benefits of advanced fuel cycles balanced with an understanding of development costs and technology risks;
2. Assess transmutation approaches and optimize a preferred nuclear fuel cycle for the United States, including major alternatives and options;
3. Assess and optimize individual Generation IV systems for the purpose of comparison and technology selection;
4. Assess performance for specific technology options and facility alternatives that support the program; and
5. Perform the analysis needed to support the Secretarial recommendation on the need for a second repository.

FY 2005 saw the development of a number of important reports and databases supporting these long-term objectives.

The Systems Analysis integration activity will enable key DOE decisions in FY 2007 on fuel cycles and technologies that best support AFCI and Generation IV goals. Analyses and validations data will be completed by the end of calendar year 2007 to inform a Secretarial recommendation on the technical need for a second repository. FY 2005 activities focused on preliminary studies of intermediate-term fuel cycle technology options and facility needs and alternatives.

Congressional Reports

Two reports were submitted to Congress in FY 2005:

- The "Advanced Fuel Cycle Initiative: Objectives, Approach and Technology Summary" report identified capacities and timescales for implementation of advanced recycle technologies and was submitted in March 2005. The report is available for review on the DOE-NE website (http://www.nuclear.gov/reports/AFCI_RptCong_ObjApp[TechSummMay2005.pdf).

- The "Advanced Fuel Cycle Initiative (AFCI) Comparison" report identifies and assesses options to improve upon the current once-through fuel cycle that are attractive, adaptable, robust, and compelling and provides a portfolio of viable options that best address energy independence, climate change, and other global challenges. The focus is on four major category comparisons: advanced fuel cycle strategies, separation technologies, reactor technologies, and transmutation fuel technologies. The report was submitted in May 2005 is available for review on the DOE-NE website (http://www.nuclear.gov/reports/May2005_AFCI_COMPARISON_REPORT.pdf).

Fuel Cycle Scenario Definition, Evaluation, and Trade-offs

FY 2005 work led to completion of a report clarifying many issues being discussed within the AFCI program including:

- IMF vs. MOX fuel,
- Single-pass vs. multi-pass recycling,
- Thermal reactors, fast reactors and combinations thereof,
- Potential need for transmutation of Tc and iodine (I), and
- The value of separating Cs and Sr.

The report represents the first attempt to calculate a full range of metrics covering all four AFCI program objectives—waste management, proliferation resistance, energy recovery, and systematic management/economics/safety—using a combination of "static" calculations and a system dynamic model, DYMOND (DYnamic Model of Nuclear Development).

Cost Basis Database

In FY 2005, the AFCI Cost Basis Development Team established a credible cost basis and created a reference source for fuel cycle unit costs. The AFCI Cost Database was completed and is now available to program participants via the Sandia National Laboratory Web FileShare system. The database, along with the 2005 AFCI Cost Basis report, provides a comprehensive collection and analysis of reference fuel cycle costs that support an ongoing, credible, technical cost analysis basis for the AFCI program. Additionally, the database contains citations from over 200 reports used in the preparation of the AFCI Cost Basis report. A Users' Manual for the AFCI Cost Database was also developed to assist cost analysts and data users in downloading future updates.

Transmutation Systems Studies

Transmutation systems studies provide systematic analysis of the waste management potential of existing and future reactor systems and fuel cycle options. Specific research tasks address priority strategic and programmatic issues, distributed among three areas: transmutation criteria, transmutation options and analysis, and nonproliferation and safeguards.

The AFCI program is investigating the feasibility of IMF as a technology to reduce the overall inventory of Pu and minor actinides in the fuel cycle. Plutonium in spent light water reactor fuel may be recycled in IMF and further irradiated in light water reactor systems. It is also an efficient fuel form for Pu destruction, as no fertile U is present for the further production of Pu. Unfortunately, IMF containing only Pu has a sharp reactivity swing over the life of the fuel and also has positive temperature and void coefficients of reactivity. In FY 2005, the AFCI program analyzed the possibility of using ^{241}Am and ^{237}Np as "convertible poisons" in plutonium IMF as burnable poisons added to counteract these effects in light water reactor systems. As typical for IMF, the fuel resulted in the destruction of high levels of fissionable Pu as well as much of the Am and Np poisons.

Repository Impact Evaluation

The objective of the Systems Repository Benefits activity is to assess how AFCI and repository technologies can optimize the future evolution of the fuel cycle. Evaluation of repository technical issues provides feedback on criteria and metrics for AFCI; whereas, evaluation of AFCI waste streams creates technical alternatives for future repository optimization. The task area also promotes integration of the AFCI and DOE Office of Civilian Radioactive Waste Management (OCRWM) programs, and cooperative evaluations are underway which combine AFCI fuel cycle knowledge with OCRWM repository expertise.

The first draft of the AFCI input to OCRWM for the Secretarial recommendation required by the Nuclear Waste Policy Act was completed describing waste management challenges, disposal and recycle options for separated materials, and specific options for transuranic management evolving from once-through to continuous recycle. The draft report integrates information generated by the AFCI program relevant to the Secretarial recommendation, and is intended to be a summary of major findings and reference documents. The purpose of the draft is to provide a framework for the report, with significant portions awaiting completion of technical efforts having only general descriptions of the current status. Specific information, including numerous references, will be added in the following years.

B.5 Transmutation Education

The AFCI Transmutation Education element supports university research and development in nuclear science and engineering through a number of funded research activities and graduate fellowships. These AFCI university programs support DOE-NE's investment in human resources and infrastructure in nuclear science and engineering and related fields.

B.5.1 University Research Alliance (URA)

University Research Alliance, located in Canyon, Texas and sponsored by Texas A&M University, manages the AFCI University Fellowship Program and communications related to all AFCI university programs. The University Fellowship Program supports top students across the nation in disciplines that will support transmutation research and technology development in the coming decades. Major accomplishments of the URA program in 2005 included:

- Enrollment of eight new Masters Degree fellows in the program, raising the total enrollment to 33 since program inception in 2002
- Extension of the program to include Oregon State University, University of Missouri-Rolla, and UNLV, bringing the total number of universities participating in the program to 18
- Graduation of four fellows enrolled in the AFCI Fellowship program in 2002 and 2004.

B.5.2 The University of Nevada, Las Vegas (UNLV) Transmutation Research Program

Students and faculty in the UNLV transmutation research program have been directly involved in collaborative research supporting the broader AFCI transmutation research effort for the past five years. During the 2004-2005 academic year, 23 faculty-supervised graduate student projects performed research in collaboration with the AFCI transmutation program utilizing 42 graduate students in five academic departments at UNLV. In addition, the UNLV Ph.D. program in Radiochemistry surpassed expectation with 11 graduate students (ten U.S. citizens) enrolling in its second year of existence. The following sections describe other significant achievements of the UNLV program during the 2004-2005 academic year.

Target Complex 1 (TC-1) Lead-Bismuth Test Loop

The Russian-built TC-1 lead-bismuth loop was installed and operated at the UNLV Howard Hughes College of Engineering. Along with the UNLV Lead Calibration Stand, the TC-1 loop is used to extend research in experimental thermal hydraulics, oxygen control against corrosion, high-temperature heat exchange, and oxygen sensor development. Development of the TC-1 research plan involves close collaboration between the UNLV and the LANL lead-bismuth coolant loop research teams.

Transmission Electron Microscopy (TEM) User Facility

The UNLV TEM User Facility was officially recognized by the UNLV administration allowing it to charge for services to recover costs. The TEM was used to directly support AFCI research activities in ZrN IMF development at LANL during 2005.

Actinide Chemistry Laboratory Completed

The Actinide Chemistry Lab, also called the High Activity or "Hot" lab, is designed to allow researchers to work with up to 10 grams of ^{239}Pu, or its equivalent, in almost any experimental system. The laboratory, coupled with the low activity laboratory and the adjoining instrumentation laboratory provide researchers with a state-of-the-art facility for performing experiments with radioactive elements addressing a number of AFCI-related challenges.

Inductively Coupled Plasma – Atomic Emission Spectroscopy (ICP-AES) User Facility Completed

The ICP-AES system allows researchers to rapidly determine the elemental concentration of most elements in solution down to the sub-parts-per-million level. The ICP-AES technique provides researchers with a fundamental solution chemistry tool for the study of most chemical systems, including the study of chemical process streams such as those seen in aqueous reprocessing of spent nuclear fuel.

B.5.3 Idaho Accelerator Center (IAC)

The IAC at Idaho State University provides facilities for research and education in charged particle accelerator applications in nuclear and radiation science. IAC students and researchers have been supportive of the AFCI program for the past five years. The following sections describe other significant achievements of the IAC program during the 2004-2005 academic year.

Eurotrans-ECATS Collaboration

The groundwork for a memorandum of understanding between the U.S. Reactor-Accelerator Coupling Experiments (RACE) and European (Eurotrans-ECATS) reactor accelerator coupling experiments was established. Coordination meetings were held in Brussels and at ISU that included representatives from the UNLV program as well as related programs in Belorussia and Russia. Research in accelerator-driven systems (ADS) within the AFCI transmutation engineering program element relies heavily on activities being performed at UNLV, IAC, and within the Eurotrans program.

Positron Annihilation Spectroscopy (PAS)

The PAS imaging technique developed by the IAC was used to provide the first two-dimensional PAS defect image of stress damage in a metal plate. The PAS technique is known to have capabilities of characterizing defects in thick specimens that could not be accomplished by conventional positron techniques or other nondestructive methods. In addition to standard structural applications this new technique holds great promise in assessing radiation damage and measurement of dynamic effects in materials used for nuclear systems.

Reactor-Accelerator Coupling Experiments (RACE)

A zero-power 20 MeV accelerator system built at ISU was installed at the Nuclear Energy Teaching Laboratory at the University of Texas, Austin (UT-Austin) to support the RACE program. The UT-Austin work is a continuation of the RACE program initiated at IAC in 2003 and will be expanded in 2006 to include Texas A&M University. The RACE program provides important data for ADS development within the AFCI transmutation engineering program element.

B.5.4 Nuclear Energy Research Initiative (NERI)

The NERI program was established by DOE-NE in 1999 to fund nuclear science and engineering research through university, laboratory, and industry partnerships. In 2004 the program was modified to promote university participation in the major DOE-NE research and development programs (AFCI, Generation IV, and NHI). Each of these research programs dedicate a portion of their annual funding to the NERI projects. In 2005, the AFCI program funded 19 new NERI projects at 14 U.S. universities. Notable contributions have been made by NERI research projects to a number of AFCI program elements, including:

- Development of lead-cooled fast reactor coolant technology
- Investigation of irradiation damage in iron
- Development of advanced inert matrix materials
- Fuel irradiation research
- Reprocessing engineered waste product research

B.6 International Collaborations

International collaborations are an important component of the AFCI program and include collaborations between individual researchers, agreements between institutions, and bilateral and multilateral agreements between governments. International collaborations allow the U.S. to leverage its research and development investment with other countries interested in the same research areas. The following sections highlight some of the international collaborations in the AFCI program.

International Nuclear Energy Research Initiative (I-NERI)

The I-NERI program was established by the DOE in 2002 as an international component of the NERI program to promote bilateral and multilateral research in advanced nuclear energy systems. The I-NERI program has funded a number of research efforts relevant to the AFCI program. In FY 2005, the I-NERI program was modified such that the collaborations are now funded by the nuclear energy research and development programs, including AFCI. Currently there are active I-NERI projects with the Republic of Korea, the European Union, France, and Canada.

Switzerland

The Swiss Spallation Neutron Source (SINQ) at the Paul Sherrer Institute (PSI) continued to provide an important neutron irradiation source supporting AFCI research in 2005. The SINQ Target Irradiation Program (STIP) has provided neutron irradiated samples of candidate core structural materials for ADSs. Mechanical testing of these samples continued in 2005 at LANL with some results presented at the 7^{th} International Workshop on Spallation Materials Technology in Thun, Switzerland. In addition, the AFCI program is providing support to the PSI MEGAPIE test program through the transmutation engineering program element. The MEGAPIE effort seeks to demonstrate the feasibility of a liquid lead-bismuth target for spallation neutron facilities and will provide valuable data for ADS development.

Japan

Negotiations, initiated with Japanese officials in 2004, continued in 2005 regarding the use of the JOYO and MONJU fast reactors as material and fuel irradiation facilities. The objective of these negotiations is to develop agreements for JOYO and MONJU irradiations in 2006. The JOYO and MONJU facilities will provide a valuable international resource for fast neutron irradiation environments after the Phénix reactor in France is decommissioned in 2009.

France

A broad bilateral agreement was established in 2000 between the AFCI program and the CEA covering a range of research areas. The most active of these research areas are separations technology and advanced fuels development. In the separations technology area, collaboration on the development of advanced aqueous processing technologies is ongoing. In the advanced fuels development area, the Phénix sodium-cooled fast reactor joint irradiation agreements, FUTURIX-FTA and FUTURIX-MI, will respectively provide irradiated advanced transmutation fuel samples and irradiated matrix material samples for candidate gas fast reactor fuels. In 2005, fabrication of both fertile and non-fertile metal fuel samples was completed in accordance with the FUTURIX-FTA implementing arrangement. Nitride fuel pellets will be completed in the early part of FY 2006.

CEA is also engaged with DOE and Japan Atomic Energy Agency in developing the collaboration arrangements for the JOYO and MONJU irradiation tests.