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University of Nevada, Las Vegas Transmutation Research Program Annual Report 2002

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University of Nevada, Las Vegas

Transmutation Research Program

Annual Report 2002

Harry Reid Center for Environmental Studies

University of Nevada, Las Vegas Transmutation Research Program Annual Report 2002

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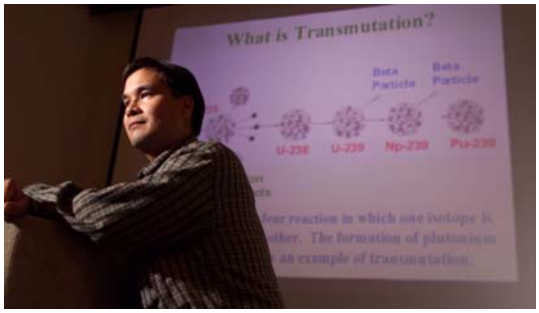
Letter from the Director



Anthony E. Hechanova, Ph.D.
Director, UNLV Transmutation Research Program

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

It is my pleasure to present the UNLV Transmutation Research Program's second annual report that highlights the academic year (AY) 2002. Supporting this document are the many technical reports and scientific papers that have been generated over the past two years, which can be found on our program's website at http://aaa.nevada.edu.

In the second year of our program, we experienced an increase in our funding that allowed us to increase the number of students, faculty, laboratories, and projects we support. In AY 2001, we initiated 12 independent student research tasks, supporting 25 graduate students and 17 undergraduates. This year these 12 tasks were continued and expanded, and four new research tasks were initiated, bringing the total number of students in the program to 37 graduate students and 18 undergraduate students in 6 academic departments across the UNLV scientific and engineering communities.

Our research tasks span the range of technology areas for transmutation, including chemical separation of uranium from spent nuclear fuel, methods of fuel fabrication, optimization of super-conducting components for proton accelerators, and corrosion of materials exposed to lead-bismuth eutectic.

In order to continue the growth and vitality of the research effort at UNLV, we also invested in our research infrastructure. We emphasized actinide chemistry and basic analytical techniques in our enhancements to UNLV this year to build a foundation in areas that are in line with UNLV's strategic growth and our ability to address student-appropriate research in the transmutation program.

Finally, I believe that through the Transmutation Research Program, UNLV has established itself as the core university participant in transmutation research with active collaboration with Los Alamos, Argonne, Lawrence Berkeley and Oak Ridge National Laboratories, Idaho State University, Georgia Tech, Texas A&M, and the University of Florida. We've also included international collaboration with the Khlopin Radium Institute in St. Petersburg, Russia, the Institute for Physics and Power Engineering in Obninsk, Russia, and Tbilisi State University in the Republic of Georgia.

I congratulate our students and faculty on a job well done and I look forward to the opportunities and challenges of this exciting research endeavor.

Sincerely,

Anthony E. Hechanova

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UNLV Transmutation Research

The UNLV Transmutation Research Program was established in March 2001 as part of the national transmutation program (currently called the Advanced Fuel Cycle Initiative of the U.S. Department of Energy, Office of Nuclear Energy, Science and Technology) to develop the technologies necessary for the ecological and economical treatment of spent nuclear fuel.

The goal of the UNLV program is to develop a sustainable and robust research community at UNLV that is able to contribute to and support the national effort through faculty-supervised, student-conducted research. In establishing the UNLV program, four basic principles were followed: peer review, program focus, integration with the national program, and commitment to the long-term goals of transmutation.

The primary role of the UNLV program in the national effort is the training of graduate and undergraduate students in nuclear engineering and other related fields to support the augmentation of the human infrastructure for transmutation technologies. However, the research conducted by UNLV faculty and students is also an integral part of the national research effort. This is accomplished through the direct involvement of students in collaborative research supporting the national transmutation research and development program.

27 UNLV students attended the ANS Student Conference at the University of California, Berkeley, April 2-5, 2003.

TRP Director Anthony Hechanova gave an invited lecture on transmutation to the Boulder City, NV, Rotary Club, May 28, 2003

Twelve independent student research tasks, supporting 25 graduate students and another 17 undergraduates, were initiated in the first year of the UNLV program. In this year, the second year of the program, these 12 tasks were continued and expanded, and four new research tasks were initiated, bringing the total number of graduate students in the program to 37 and the total number of undergraduate students to 18. The program includes the involvement of 33 faculty in 6 academic departments in three colleges (College of Engineering, College of Health Sciences, and College of Sciences).

UNLV research tasks span the range of technology areas for transmutation: separations of used fuel materials, fuel fabrication, accelerator design, and materials corrosion and other transmutation sciences.

UNLV students presented 8 posters at the ANS Annual Meeting, San Diego, CA, June 1-5, 2003.

Program Overview

The UNLV Transmutation Research Program consists of four components: Program Support, Research Infrastructure Augmentation, International Collaboration, and Student Research.

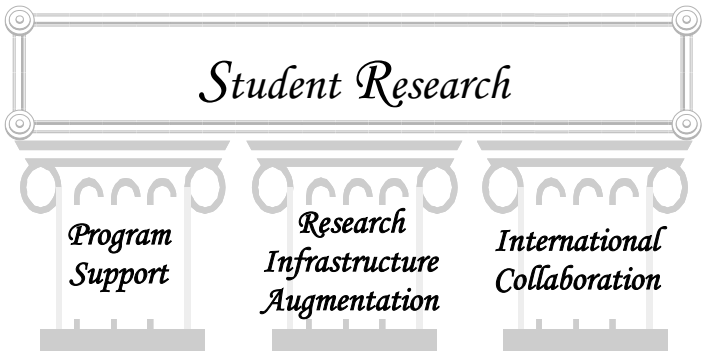
In the first year of the program, the student research component was supported by the infrastructure augmentation and the program support components. In the second year of the program, the fourth leg of the support system, international collaborations, was added to the research support system.

These components are responsible for all aspects of the program that are not directly related to the student research projects, such as hiring new faculty, bringing new research equipment to campus, assisting the development of new student research projects, coordinating with the national program, coordinating with the international research programs, as well as the typical administrative details of a program of this size.

The primary goals of these components are to support the current UNLV research efforts in transmutation technologies, to augment faculty and staff, and to increase research infrastructure necessary for the strategic growth of the UNLV research mission.

Through the infrastructure augmentation component, this year, the UNLV program enabled the development of a new Inductively Coupled Plasma – Atomic Emission Spectroscopy User Facility, the development of a temporary home for the Target Complex 1 (TC-1) system (a molten lead-bismuth target loop), and the deployment of a new computer-controlled milling machine. These new facilities are in addition to the program's continued support for the operation of the Electron Microanalysis and Imaging Laboratory (EMIL), Materials Performance Laboratory (MPL), and Transmission Electron Microscopy User Facility.

The infrastructure augmentation component also supported the addition of an additional Ph.D. researcher to the university faculty, and helped enable the Chemistry department to open a second position for new faculty, in addition to the continued support of the three Ph.D. researchers added to the UNLV faculty in the first year of the program.



UNLV Transmutation Research Program Components

Through the new international collaborations component, the program was able to host the International Science and Technology (ISTC) team responsible for developing the ISTC TC-1 loop, allowing UNLV scientists to work directly with the international experts to develop a research plan for lead-bismuth research at UNLV.

The international collaboration component also supported the development of two joint research proposals between UNLV and the Khlopin Radium Institute in St. Petersburg, Russia. These projects, UNLV Tasks 15 and 16, address significant issues relating to the chemical processing of nuclear fuel.

The program support component sponsored a number of workshops and meetings this year between UNLV researchers and scientists from our national laboratory partners and the international community for the development of transmutation technologies, as well as sponsoring the participation of 27 UNLV students in the American Nuclear Society Student Conference at the University of California, Berkeley.

UNLV Graduate students explain their research to visiting scientists from the International Molten Metal Advisory Committee.

Transmutation at a Glance

Introduction

Over 20% of the electricity generated in the U.S. is provided by nuclear power reactors. It is estimated that the amount of used nuclear fuel in the U.S. will reach 140,000 tons by the end of the operational period of current reactors.

Many countries take different approaches to the management and recycling of used nuclear reactor fuel. The U.S. is pursuing a strategy of waste management that would place used nuclear fuel in deep geologic repositories for a long time, separating it from the biosphere and allowing the radioactive isotopes of the waste to decay to more stable progeny.

Transmutation is an alternative waste management strategy undergoing research and development in the U.S. The new national program was authorized by Congress to begin in fiscal year 2001, as the Advanced Accelerator Applications program. In fiscal year 2002, the national program was continued and expanded by Congress, and renamed the Advanced Fuel Cycle Initiative (AFCI) program. The goals of the national program are to develop fuel cycle technologies that:

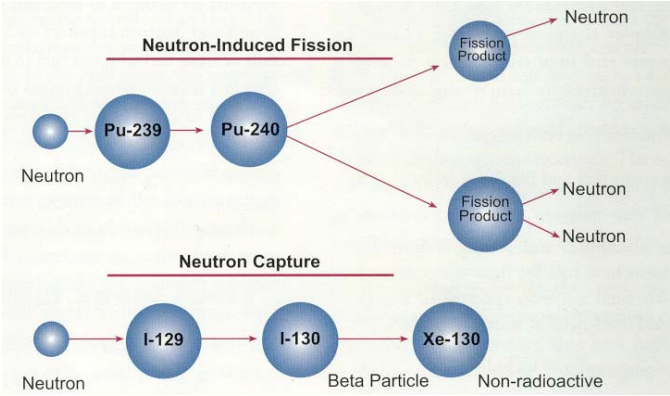
- Enable recovery of the energy value from commercial used nuclear fuel,
- Reduce the toxicity of high-level radioactive waste bound for geologic disposal,
- Reduce the inventories of civilian plutonium in the U.S.,
- Enable more effective use of the currently proposed geologic repository and reduce the cost of geologic disposal.

The transmutation concept could provide a dramatic shift in the U.S. waste management strategy by lessening the inventory of residual radioactivity, allowing recycling of fuel, providing optimization of final waste forms, and potentially removing much of the material from Nevada.

What is *Nuclear Transmutation*?

For centuries, alchemists have been trying to transform elements into other elements, primarily lead into gold. With modern nuclear science, we can finally accomplish this. Scientists are using nuclear transmutation to change one isotope into another more favorable isotope by changing its nuclear structure. This process is aimed at plutonium, other actinides, and long-lived fission products, with the ultimate goal of converting them into short-lived isotopes that can be managed over a reasonable timeframe.

Transmutation can be done with two different processes: neutron-induced fission or neutron capture. Both processes start with the target nucleus absorbing an incident neutron. After the neutron is absorbed by the target nucleus, the nucleus can either fission (splitting of the nucleus) or go through another nuclear transmutation process such as radioactive decay. Both processes lead to the same final result: transmutation of waste. These processes are illustrated in the figure below.

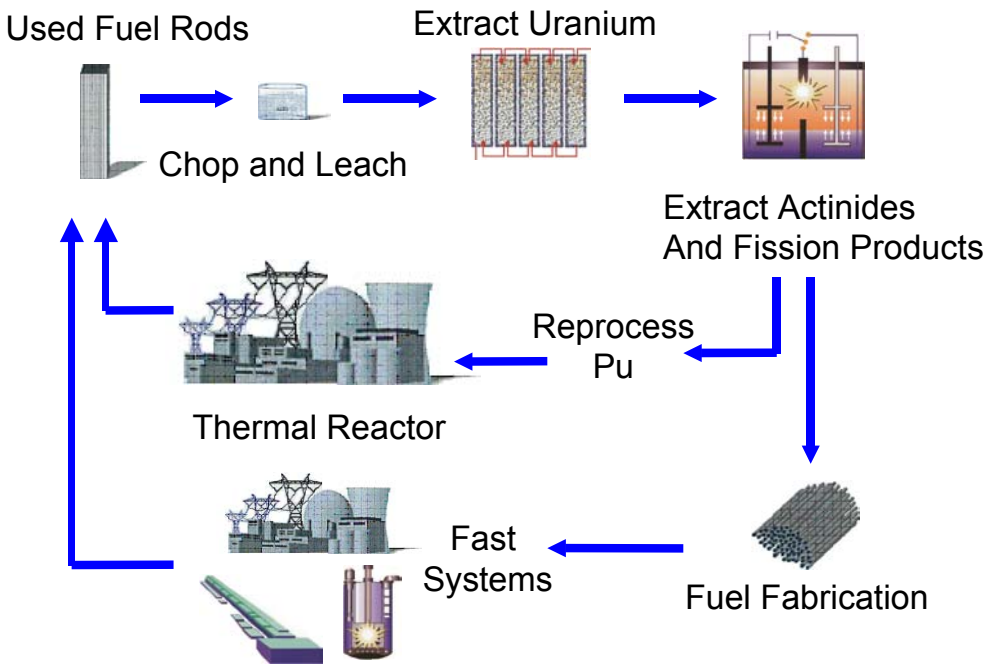


This picture illustrates how neutrons are used to transmute actinides and fission products.

Neutron-Induced Fission (Top): a neutron is captured by a fissile actinide (e.g. Plutonium-239) and is induced to split (or fission).

Neutron Capture (Bottom): a neutron is captured by a nucleus (e.g. Iodine-129). A new nucleus is produced, Iodine-130, which decays into Xenon-130 which is a stable isotope (i.e., not radioactive). This decay process is complete within a few days.

Multi-tier Transmutation Concept



The above figure shows how used nuclear fuel could be managed under a multi-tiered transmutation strategy. In the first tier, plutonium would be recycled from used fuel and transmuted in a new advanced thermal reactor. In the second tier, remaining long-lived radioactive isotopes would be transmuted using a fast spectrum reactor and/or accelerator-driven system.

REDUCE, REUSE, RECYCLE, RESEARCH

Benefits from Transmuting Nuclear Waste

Many benefits are obtained from transmutation of nuclear waste. Some of them are:

(1) The initial amount of high-level radioactive waste will be reduced by virtue of separation (only two percent of used nuclear fuel is highly radioactive, the rest, if separated, can be classified as low-level or non-radioactive).

(2) The radiotoxicity of the residual waste will be reduced such that it could be less radiotoxic after 300 years than direct disposal of used nuclear fuel after 100,000 years.

(3) Usable energy is produced by destroying hazardous components of used nuclear fuel. Plutonium and other isotopes can be continuously recycled.

(4) Someday other used nuclear fuel materials, such as uranium, may be reused. It is possible that other isotopes separated from nuclear waste could have a useful purpose in medicine and industry.

(5) The accelerator process will provide a powerful proton source that could be used in medical therapy and to produce isotopes for a variety of applications such as: medical isotopes, industrial isotopes and research isotopes.

Task 1

Design and Analysis of a Process for Melt Casting Metallic Fuel Pins Incorporating Volatile Actinides

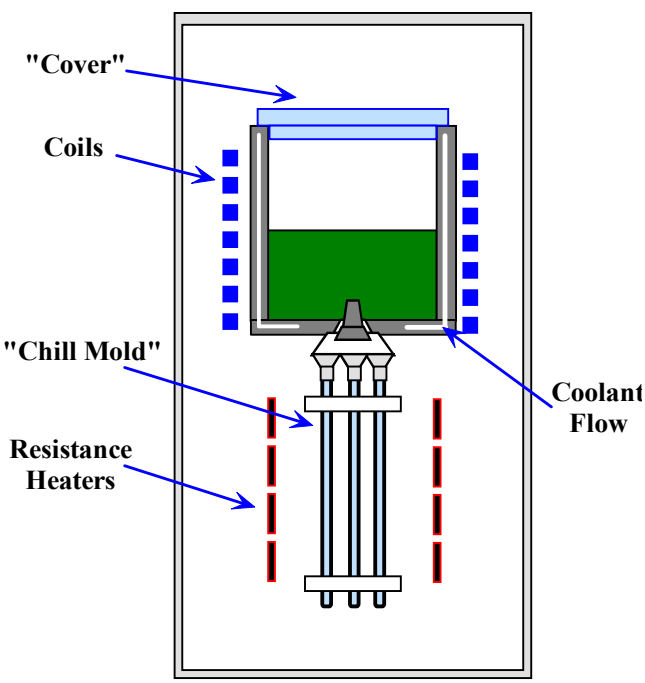
Y. Chen, D.W. Pepper, and R. Clarksean

BACKGROUND

The Transmutation Research Program requires the incorporation of non-fertile actinides into the fuel matrix for the transmuter blanket. One of three currently proposed candidate matrices for the transmuter is a metallic alloy fuel matrix. Metallic fuels are an outstanding candidate for a transmutation fuel due to excellent irradiation performance and ease of fabrication. However, incorporating a volatile constituent during fabrication of these fuel pins presents a challenge.

Volatile actinides, particularly americium, are susceptible to rapid vaporization during the traditional metal fuel casting processes. The actinide vapors boil off, and flow out of the system into the off-gas recovery system, resulting in only a fraction of the volatile actinide charge being incorporated into the fuel pins. The loss of these actinides from the fuel greatly complicates the task of preparing them for transmutation, requiring additional recovery and fuel fabrication steps to try to incorporate the volatile actinides into the transmuter fuel.

The goal of this project is to investigate the casting processes for metallic fuels to help design a process that minimizes the loss of the volatile actinide elements from the fuel.



Schematic of proposed induction skull melting furnace for the casting of high americium content fuels.

The research effort centers on the development of advanced numerical models to assess conditions that significantly impact the transport of volatile actinides during the melt casting process and represents a joint effort between researchers at the University of Nevada, Las Vegas (UNLV) and Argonne National Laboratory (ANL).

RESEARCH OBJECTIVES AND METHODS

The objective of this research is to assist in implementing technology that will eventually be applicable to transmutation fuel fabrication on a production scale. Assessing critical equipment and process variables required to build a successful system will do this. Additionally, a cooperative effort between UNLV and ANL establishes a working relationship that assists with developing an approach to generate the next casting furnace for the Advanced Fuel Cycle Initiative (AFCI) program.

RESEARCH ACCOMPLISHMENTS

Development of the induction-heating model: Modeling efforts centered on the development of the governing equations, incorporating these equations into computer codes, setting up a test problem, and making preliminary calculations for the geometry of interest.

Modeling of casting process: Efforts continued to improve a model for the casting of fuel pins. Work considered the flow of the melt into the mold and heat transfer into the mold during solidification (after flow has stopped). Results from an energy balance model indicate that the thermal mass would typically be greater than needed to solidify the melt within the mold. The results of this simple model have aided in designing a mold to hold and solidify the fuel pins.

Parametric Analysis of Casting Process: In order to test the impact of process parameters (temperature, pressure, alloying elements, etc.) on the casting process, a parametric study of the casting model was performed on different processing parameters. These studies centered around model development and analysis of the impact of mold preheating on heat transfer into the model. Results will assist with determining which process parameters are critical in manufacturing a suitable metallic fuel pin.

Americium Transport Models: A model that analyzes the transport of americium from the melt to the vapor phases above the crucible has also been developed. The model considers mass transport in the melt, vaporization at the surface, and transport through the vapor phase. Parametric studies are underway to evaluate the impact of different properties or situations on the transport of americium from the melt.

Casting Furnace Performance Model: Researchers in the group developed more detailed heat and mass transfer models that could be used successfully in the analysis of an advanced casting furnace design.

Develop Prototype Furnace Design: A preliminary furnace design that can be built and tested with surrogate materials is critical in order to assess the viability of metal fuels. A preliminary analysis of potential surrogate materials has been completed. Manganese appears to be an acceptable surrogate material. Discussions will be held with Argonne National Laboratory staff members to insure that no health and safety issues prevent manganese from being used in future tests.

FUTURE WORK

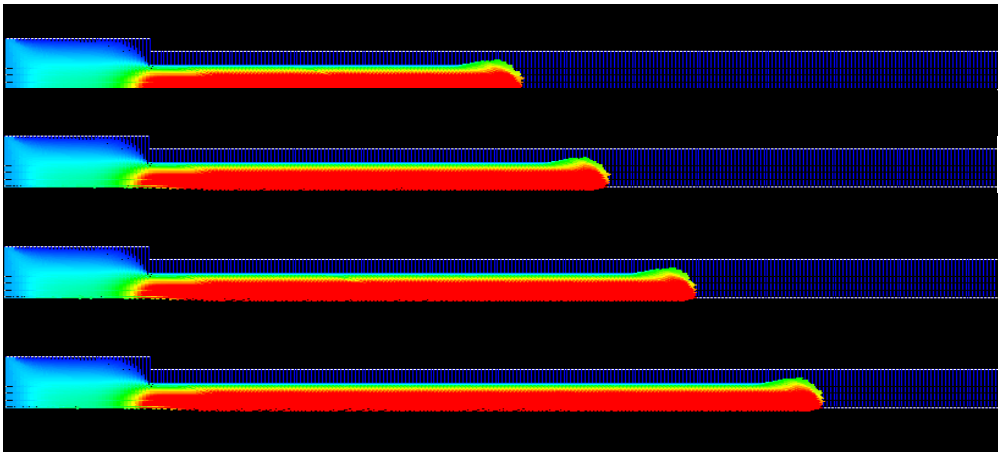
The following are the research objectives for the next year of this project:

- Continue analysis of americium transport and loss from the melt process using the combined heat and mass transfer models developed at UNLV.
- Continue to revise and refine the combined heat and mass transfer model of representative furnace geometry.
- Benchmark and validate the model through comparisons to experimental tests.
- Perform a series of engineering analyses with the models to aid in the design of the next generation casting furnace.

HIGHLIGHTS

- "An Analysis of the Melt Casting of Metallic Fuel Pins" presented at the ASME International Mechanical Engineering Congress, New Orleans, LA, November 17-22, 2002.
- "An Analysis of the Melt Casting of Metallic Fuel Pins" presented at the AFCI Semi-Annual Review Meeting, Albuquerque, NM, January 22-24, 2003.
- "Numerically Simulating the Solidification Process of a Melt Casing Metallic Fuel Pin Mold Using FIDAP" presented at the ANS Student Conference, Berkeley, CA, April 2-6, 2003.
- Abstract "Simulation and Analysis for Melt Casting a Metallic Fuel Pin Incorporating Volatile Actinides" submitted to the ASME International Mechanical Engineering Congress and R&D Expo, Washington, DC, November 16-21, 2003.

Engineering Analyses for the preliminary design of the furnace will be carried out in conjunction with ANL-West staff. System throughput, processing rates, material handling, and other pertinent issues will be taken into consideration as the next generation casting furnace is developed. A detailed model will be used for the preliminary design of an inductively heated skull-crucible casting furnace, designed to be remotely operated in a hot cell environment, which is one of the primary concerns of the AFCI program.



Velocity vectors of melt flowing into chill mold (transient conditions). Red represents high velocities; blue represents lower velocities.

Research Staff

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Mitchell K. Meyer, Leader of Fabrication Development Group, Nuclear Technology Division, Argonne National Laboratory
Steven L. Hayes, Manager of Fuels & Reactor Materials Section, Nuclear Technology Division, Argonne National Laboratory

Task 2

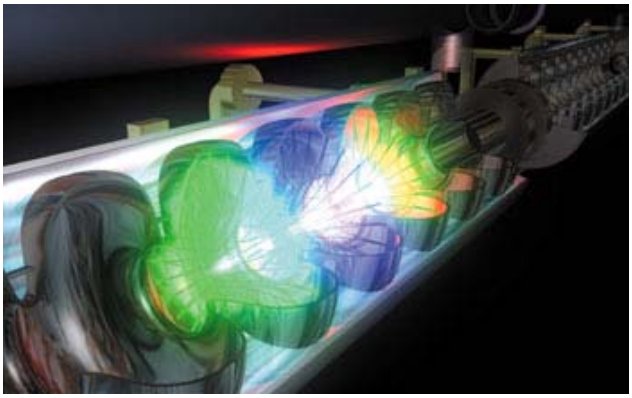
Modeling, Fabrication, and Optimization of Niobium Cavities

R.A. Schill, Jr., M.B. Trabia, and W. Culbreth

BACKGROUND

One of the key technologies for the deployment of accelerator-driven transmutation systems is the accelerator itself. To increase the efficiency of the high-power accelerators needed to support the transmutation mission, the national and international accelerator teams have proposed using elliptical superconducting niobium cavities. This project is tasked with examining the impacts of the design and fabrication technologies for these elliptical niobium cavities on their performance. Niobium was selected primarily due to its behavior at low temperatures.

One of the major sources of energy loss from a superconducting accelerator cavity is a process known as multiple impacting (or "multipacting") of electrons. This phenomenon limits the maximum amount of energy and power that the niobium cavity can store. As a result, the maximum power available for accelerating the desired charge, as well as the overall performance of the accelerator is reduced. Furthermore, the energy absorbed as a result of multipacting eventually turns into heat. This negatively impacts the performance of both the super conducting cavity and the accelerator.



Schematic of the elliptical cavity portion of an accelerator system.

Multipacting is effected by the surface properties of the niobium wall. This is usually described in terms of the secondary electron emission coefficient. The presence of chemical products or foreign particles on the surface of the cavity undesirably impacts this coefficient. To help reduce this potential source of multipacting, the cavity walls are polished after manufacturing using chemical etching and high pressure rinsing. However, these chemical etching processes can result in non-uniform cavity surfaces with some unclean areas with contaminants and micron size particles. These imperfections significantly affect multipacting. Further, a non-uniform etch leaves areas with damaged grain structure.

These defects further reduce the superconducting properties of the niobium. Researchers at Los Alamos National Laboratory (LANL) employ a baffle to improve uniformity in the etching process. The baffle's ability to improve the uniform etching was not known *a priori*.

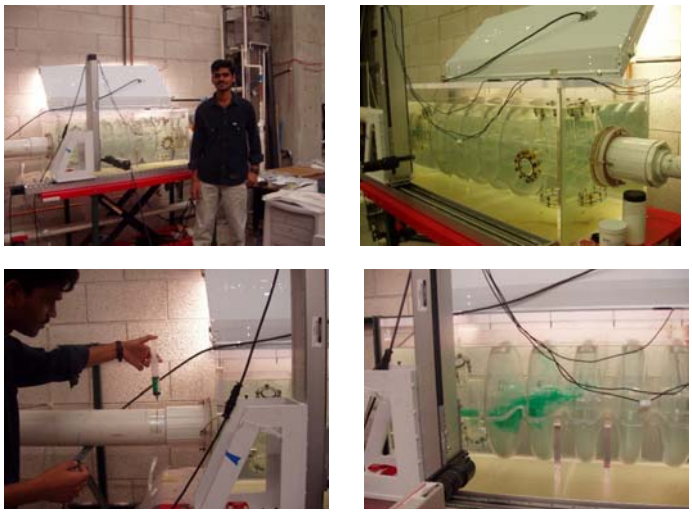
Mitigating multipacting processes is the major concern dictating the elliptical shape of the superconducting cavity. This complicates the etching process and, in particular, the uniform etch. Modeling codes, optimization techniques, and experimentation will provide UNLV researchers with a well-rounded study to examine existing and novel niobium cavity designs for the superconducting radio frequency high-current accelerator.

RESEARCH ACCOMPLISHMENTS

Development of Optimization Model: A framework for interacting two dimensional field codes and an optimization program was created. The code has been used to optimize the end cell of a five-cell niobium cavity based on resonant frequency and mode. Multipacting studies are well underway for this new geometry. Some of our results have been disseminated at the 2003 American Nuclear Society Conference on Accelerator Applications in a Nuclear Renaissance in San Diego, California.

SEE (Secondary Electron Emission) Studies: The vacuum chamber and various elements have been purchased for secondary electron emission studies on niobium in a superconducting mode. Computer simulations are underway to aid us in the study of the secondary electron trajectories in the presence of the cryostat, electron gun, and electron positioning diagnostic. These simulations will aid us in choosing the diagnostic tool to measure SEE.

Revised Etching Process: The current etching method, which uses a baffle to direct the etching fluid toward the surface of the cavity, partially succeeded in achieving this task. However, flow was restricted to the right half of the cavity with very limited circulation in the left half. An alternative design is proposed and modeled. The proposed baffle design is also modified so that it can be extended inside the cells of the cavity. The exit flow is now parallel to flow inlet. Results show that flow circulation is eliminated. The flow is now closer to the surface of the cavity. We used optimization techniques to improve this design.



Satishkumar Subramanian demonstrates a flow visualization experiment.

Developed Flow Visualization System: To confirm the predictions from the fluid flow models used to analyze the etching process, the UNLV team developed and deployed a flow visualization system. LANL lent UNLV a transparent model of an elliptical cavity section to assist with flow visualization while simulating different etching conditions. A transparent plexiglass box was manufactured to enclose the cavity. The external pump and piping system were also modeled. A complete experimental setup, including a computer-controlled x-y traverse and digital camera, was assembled. Flow visualization experiments using a plastic prototype of the niobium cavity provided by LANL are currently going on. Dye is injected to verify that the numerical codes accurately predict the flow behavior seen in the experimental model system. Dye injection provides quantitative verification that laminar flow exists within the niobium cavities during etching. Additionally, it verifies the absence of re-circulation pockets within the cavities.

FUTURE WORK

This task examines the flow characteristics in chemical etching of a niobium cavity with the aid of a baffle. It also examines the multipacting properties of a five-cell niobium cavity employing modeling codes with optimization techniques included.

HIGHLIGHTS

- "Modeling and Optimization of the Chemical Etching Process in Niobium Cavities" presented at the International Congress on Advanced Nuclear Power Plants (ICAPP), Hollywood, Florida, June 2002.
- "Modeling Optimization and Flow Visualization of Chemical Etching Process in Niobium Cavities" presented at the ANS Student Conference, Berkeley, CA, April 2-5, 2003.
- "Optimization of a Five-cell Niobium Cavity" presented at the ANS Annual Meeting, San Diego, CA, June 1-5, 2003.

Myong Holl explains her work at the ANS Annual Meeting, San Diego, CA, June 2003.

Future work will conclude experimental studies of flow characteristics and compare these to simulation. Alternative baffle studies may be improved upon based on fluid flow models. Designing an expanding baffle presents a challenge due to space limitations and the chemically aggressive environment.

Optimization techniques have been imbedded in a MATLAB controlling code based on the desired resonant frequency and mode of operation. The optimized geometries are to be examined using multipacting codes and compared to the existing LANL five-cell cavity. The controlling code will also be modified to allow mid-cell parameters to be optimized.

Secondary electron emission experiments are to be conducted on niobium at superconducting temperatures in the last year of this research. The data obtained from this study will be made available for multipacting codes.

Research Staff
Robert A. Schill, Jr., Co-Principal Investigator, Associate Professor, Department of Electrical and Computer Engineering
Mohamed B. Trabia, Co-Principal Investigator, Chair, Mechanical Engineering Department
William Culbreth, Associate Dean for Research, College of Engineering

Students
Satishkumar Subramanian and Anoop George, Graduate Students
Myong Holl, Undergraduate Student

Collaborator
Tsuyoshi Tajima, Team Leader, Accelerator Physics & Eng., LANSCE-1, Los Alamos National Laboratory

Task 3

Corrosion of Steel by Lead Bismuth Eutectic

J.W. Farley, A. Johnson, and D.L. Perry

BACKGROUND

Materials for transmuter systems must be able to tolerate high neutron fluxes, great temperatures, and chemical corrosion. For lead bismuth eutectic (LBE) systems, there is an additional challenge in that the corrosive behaviors of materials in LBE are not well understood. Most of the available information on LBE systems has come from the Russians, who have over 80 reactor-years experience with LBE coolant in their Alpha-class submarine reactors. The Russians found that the presence of small amounts of oxygen (on the order of parts per million) in the LBE significantly reduced corrosion. However, a fundamental understanding and verification of its role in the corrosion of steels is incomplete.

RESEARCH OBJECTIVES AND METHODS

This research program will analyze various steel samples that have been exposed to LBE as part of the national program to develop LBE and transmutation technologies. The goal of this research is to understand the basic science of corrosion in the steel/LBE system. This information will be paramount in developing engineering efforts to control, avoid, and/or minimize the effect of corrosion of steels by LBE in transmuter and LBE systems. Additionally, this program provides UNLV researchers with hands-on experience that will be crucial in developing the UNLV LBE program, supporting the University's mission with the ISTC target complex, and the future development of additional facilities to examine LBE systems.

Investigators performed post-experiment testing and analysis on steel samples that have been in intimate contact with LBE. They employed surface analysis techniques that included Scanning Electron Microscopy (SEM), Energy Dispersive X-ray (EDAX) spectroscopy, X-ray Photoelectron Spectrometry (XPS), and laser Raman spectrometry.

Allen Johnson and John Farley next to an X-ray Photoelectron Spectrometer (XPS).

These techniques, applied to the steel surface, have probed the surface morphology, elemental composition, and oxidation states as a function of position. Chemical alterations and resulting chemical species were studied at the steel surface. Additionally, the X-ray fluorescence microprobe at the Advanced Light Source at Lawrence Berkeley National Laboratory was used. This allowed spectroscopic characterization of the stainless steel before and after interaction with LBE to determine its composition.

RESEARCH ACCOMPLISHMENTS

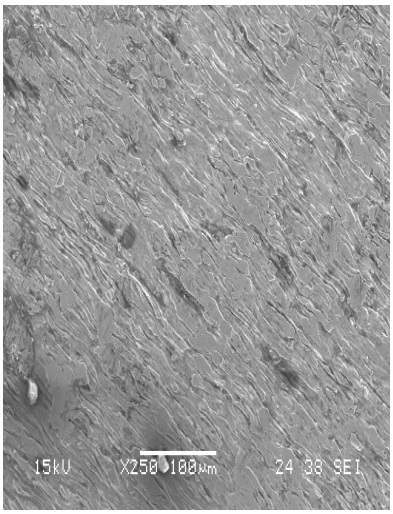
Using the technique of XPS/sputter depth profiling, researchers observed that the lead and bismuth were confined to the surface of the oxide – there was little or no penetration of the coolant into the protective oxide layer. Two forms of oxide layer were found on the 316 steel; on other alloys, a complicated structure composed primarily of iron oxide with an underlying oxide containing both chromium and iron was found. A chromium oxide layer on the metal substrate was also found on the 316L steel. This is similar to findings on the non-corroded starting materials. Ultimately, these analyses provide insights into the migration of materials, the composition of the protective oxide layer, and the basic science of the corrosion process. Overall, dramatic differences between the exposed and unexposed samples were found.

Images of the oxide layers of the 316 and 316L samples revealed a fairly uniform 10-micron thick oxide layer in the 316 samples and a 1-micron thick oxide in the 316L samples. The bottoms of the etch pit were optically examined and the 316L was seen to have a "patchy" bottom compared to the smooth bottom of the etch pits on 316 stainless. These results contrast findings from the material exposed at IPPE but are not unexpected from the literature.

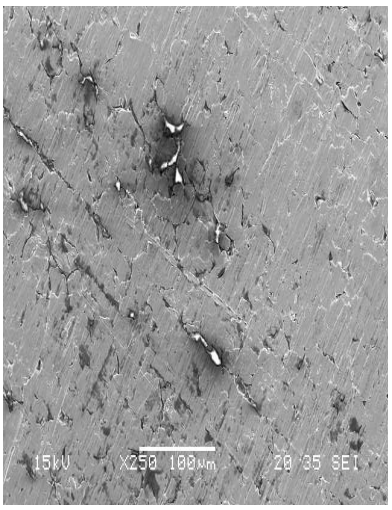
Further utilization of the XPS machine permitted experimentation on steel samples using Argon ions. The argon beam was used to mill the surface layers of the sample away, allowing researchers to examine the oxide and alteration layers as a function of depth.

Investigators took depth-profiling data on D9 steel that had been exposed to LBE. This is the first time that this type of steel was examined. This analysis enables researchers to separate out two effects and determine their effect on corrosion (composition of the steel vs. surface preparation).

Finally, an optical microscope was purchased and installed February 2003. This enhances researchers' abilities to make accurate distance measurements on steel samples.



Scanning Electron Microscope (SEM) image of the surface of 316 stainless steel before exposure to lead-bismuth eutectic (LBE).



SEM image of 316 stainless steel that is corroded from being exposed to LBE.

FUTURE WORK

Depth profiling of steel samples using the XPS technique will continue. Other steels such as D9, HT9, and T410 will be examined. Raman measurements will also be made; these are essential with regards to measuring chemical speciation.

HIGHLIGHTS

- "Surface Studies of Corrosion of Steel by Lead-Bismuth Eutectic" presented at the Federation of Analytical Chemistry and Spectroscopy Societies Annual Meeting , Oct 13-17, 2002, Providence, RI.
- "Surface Studies of Corrosion of Stainless Steel by LBE" presented at the meeting of the American Vacuum Society 49th international symposium, Denver, CO, Nov 3-8, 2002.
- Dan Koury completed a Physics Master of Science thesis "Investigation of the Corrosion of Steel by Lead-Bismuth Eutectic using Scanning Electron Microscopy and X-Ray photoelectron microscopy" December 2002.
- "Surface Studies of Corrosion of Stainless Steel by Lead-Bismuth Eutectic" presented at the ANS Student Conference, Berkeley, CA, April 2-5, 2003.
- Manuscript "Spectroscopic and Microscopic Investigation of the Interaction of Lead-Bismuth Eutectic (LBE) with 316 and 316L Stainless Steel at Elevated Temperatures" was submitted to refereed *Journal of Nuclear Materials*.

Samples will be characterized using a number of experimental techniques. Each technique has its own strength. Spectroscopic data can be combined with microscopic data, along with x-ray diffraction data, to fingerprint structural forms of the elemental species formed in the reactions. Plans to perform tests using synchrotron radiation (SR) based x-ray fluorescence (XRFF), a sensitive analytical technique capable of providing direct quantitative information on chemical compositions, are underway. X-ray fluorescence will provide a detailed map of the heavy metal ions being studied. Ultimately, data will then be analyzed and compared with the predictions from corrosion models.

Researchers also plan to expose samples to LBE in the new Molten Metal Small Experiments Facility (proposed 2004). By examining the samples before and after exposure to the LBE, researchers should be able to gain insights into the corrosion processes and kinetics. This should also allow the team to test the hypotheses postulated through the experiments with the already exposed materials.

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Task 4

Environment-Induced Degradation and Crack-Growth Studies of Candidate Target Materials

A. Roy, B.J. O'Toole, Z. Wang, and D.W. Hatchett

BACKGROUND

The primary objective of this task is to evaluate the potential for the environmentally-assisted cracking of candidate target materials for applications in spallation-neutron-target systems, such as accelerator-driven system for the transmutation of waste. The materials selected for evaluation and characterization are martensitic stainless steels (SS) including Alloys HT-9, EP 823 and Type 422 stainless steel.

More recently, this experimental program has been expanded to evaluate the effect of molten lead-bismuth eutectic (LBE) on the corrosion behavior of target materials in the presence of oxygen. Since the materials performance laboratory (MPL) at UNLV currently cannot accommodate this type of testing, the Delta loop, a molten LBE loop at the Los Alamos National Laboratory (LANL), is used to contain the stressed test specimens to evaluate the stress corrosion cracking (SCC), and localized corrosion behavior in the molten LBE environment. Since the magnitude of the applied load during these tests cannot be monitored or controlled (as in conventional SCC experiments) in the LBE environment, the test specimens will be self-loaded. Two types of specimen configurations, namely C-ring and U-bend, are used to perform these experiments. SCC tests using these types of self-loaded specimens are also being performed at the MPL in aqueous environments having neutral and acidic pH values at ambient and elevated temperatures.

RESEARCH OBJECTIVES AND METHODS

The susceptibility to stress corrosion cracking has been evaluated by using both smooth and notched uniaxial tensile specimens, which were pulled in two aqueous environments of different pH values at ambient and elevated temperatures using either a constant load or a slow-strain-rate (SSR) technique. The SSR testing was performed at a strain rate of 3.310^{-6} sec^{-1} to optimize the effects of mechanical constraints and environmental parameters. The notched specimens were used to increase the severity of cracking. The cracking susceptibility under a constant loading condition can be characterized either by the time-to-failure (TTF) or a threshold stress for SCC, below which no cracking occurs. For SSR testing, the cracking behavior was evaluated in terms of the ductility parameters such as percent elongation, percent reduction in area, and true fracture stress obtained from the stress-strain diagram.

Since electrochemistry can influence the localized corrosion (pitting and crevice) behavior, the susceptibility to localized attack was determined by cyclic potentiodynamic polarization (CPP) technique in similar environments. The SCC tests have so far been performed without applied potential. However, the most recent tests are being performed under controlled cathodic potential to study the effect of hydrogen on cracking susceptibility. The magnitude of controlled potential is based on the measured corrosion potential obtained in specific test environments.

Constant load test setup.

Crack-growth behavior of target materials during the transmutation process is of significant importance, particularly under irradiated conditions. In view of this rationale, sub-size compact tension specimens, irradiated and unirradiated, will be tested using fracture mechanics-based techniques. This type of testing will enable the evaluation of the radiation effect on the metallurgical properties including the hardness, yield strength and microstructures.

RESEARCH ACCOMPLISHMENTS

Ambient temperature mechanical properties of Alloys EP-823, HT-9 and Type 422 stainless steel were evaluated using smooth and notched tensile specimens.

A significant number of SCC tests using proof rings and smooth tensile specimens of martensitic Type 422 SS, and Alloys EP-823 and HT-9 have been completed in both neutral and acidic aqueous environments under constant load conditions at ambient temperature and 90°C. Additional tests are ongoing at reduced applied stresses to determine the threshold stress for SCC. Simultaneously, tests are being conducted using the notched tensile specimens.

SCC testing using SSR technique has been completed in aqueous environments at ambient temperature, 60°C, and 90°C involving smooth and notched tensile specimens of all three martensitic alloys.

SEM micrograph of a cracked specimen of Alloy HT-9.

Optical micrograph of etched sample of Alloy EP-823 (20 times magnification).

Extensive efforts were made to analyze the fracture modes in all broken specimens. Secondary cracks along the gage section of the broken specimen were evaluated by optical microscopy.

The susceptibility of all three alloys to pitting and crevice corrosion in both neutral and acidic aqueous solutions has been determined by using the CPP technique, based on a three-electrode polarization concept.

SCC testing using C-ring and U-bend specimens of Alloys HT-9 and EP-823 is in progress in acidic solution both in the presence and absence of air at ambient and elevated temperatures. Similar types of specimens will also be tested soon at LANL in the molten LBE environment.

HIGHLIGHTS

- "Stress Corrosion Cracking of Type 422 Stainless Steel for Applications in Spallation-Neutron-Target Systems," presented at SNS-JINS-NICEST, March 12, 2003, Oak Ridge, TN.
- "Stress Corrosion Cracking of Martensitic Stainless Steel for Transmutation Applications," presented at the 10th IHLRWM Conference, March 30-April 3, 2003 Las Vegas, NV.
- "Stress Corrosion Cracking of Type 422 Stainless Steel," presented at ANS Student Conference, April 2-5, 2003, Berkeley, CA.
- "Stress Corrosion Cracking of Target Materials," presented at ANS Student Conference, April 2-5, Berkeley, CA. Mohammad Hossain received Outstanding Paper Award.
- "Effects of Environmental Variables and Stress Concentration on Target Materials," presented at ANS Student Conference, April 2-5, Berkeley, CA.
- "Effects of Environmental Variables and Stress Concentration on Cracking of Spallation Target Materials," presented at 203rd Meeting of the ECS, April 27-May 2, 2003, Paris, France.
- "Environment-Induced Degradation of Spallation Target Materials," presented at ANS Annual Meeting, June 1-5, 2003, San Diego, CA.

FUTURE WORK

The third and final year of this task includes the following scope of work:

- Perform stress corrosion cracking and hydrogen embrittlement testing of all three types of martensitic stainless steels under controlled cathodic potentials.
- Perform localized corrosion testing using cyclic potentiodynamic polarization technique at elevated temperatures.
- Continue microstructural characterizations by optical microscopy and failure analyses by SEM.
- Analyze hydrogen content by secondary ion mass spectrometry (SIMS).

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Task 5

Modeling Corrosion in Oxygen Controlled LBE Systems with Coupling of Chemical Kinetics and Hydrodynamics

S. Moujaes and Y. Chen

BACKGROUND

The corrosion of structural materials is a major concern for the use of lead-bismuth eutectic (LBE) systems for nuclear applications such as in transmuter targets or fast reactors. Corrosion in liquid metal systems can occur through various processes, including, for example, dissolution, formation of inter-metallic compounds at the interface, and penetration of liquid metal along grain boundaries. Predicting the rate of these processes depends on numerous system operational factors: temperature, system geometry, thermal gradients, solid and liquid compositions, and velocity of the liquid metal, to name a few. Corrosion, along with mechanical and/or hydraulic factors, often contributes to component failure.

The goal of this project is to develop a corrosion model that combines the chemical kinetics and hydrodynamics in the system to predict corrosion rates. In this effort, these models will be developed for the Delta test loop at Los Alamos National Laboratory (LANL) and a theoretical LBE accelerator target system. The resulting models will be predictive tools that can be validated with corrosion test data and used to systematically design tests, interpret the results, and provide guidance for optimization in LBE system designs.

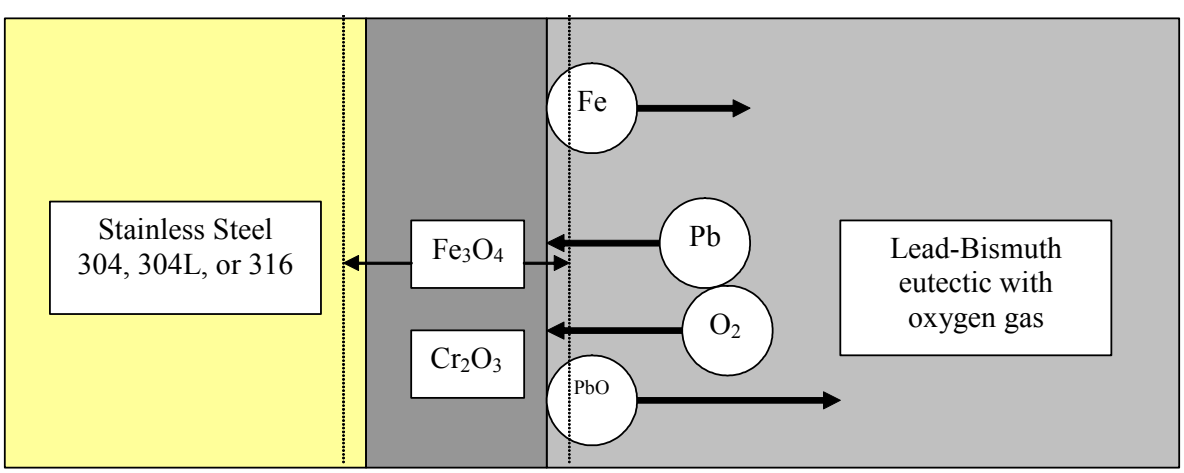
RESEARCH OBJECTIVES AND METHODS

There are two subtasks to this research. The first subtask develops the necessary tools to predict the levels of oxygen and corrosion products close to the boundary layer using Computational Fluid Dynamics (CFD) modeling. The second subtask predicts the corrosion process kinetics between the LBE and structural materials by incorporating pertinent information from the first subtask.

STAR-CD software was used to model the corrosion and precipitation rates in the LBE loop. This allowed researchers to compare the theoretical analysis with available experimental results. The surface corrosion analysis was obtained using a subroutine attached to the STAR-CD code, called CHEMKIN. The information obtained from this analysis theoretically predicts likely locations for corrosion and precipitation along the axial lengths of the test loop.

The first subtask involved performing a series of parametric runs. Models prepared from the previous year were used as guides for the parametric studies. Variables investigated included the average eutectic flow velocity, average mean bulk eutectic flow, inlet temperatures, and average inlet oxygen concentrations in the three geometries: a straight flow section, an elbow bend and a tee section. The thermal-hydraulics study involved using a 2-D CFD code simulation to obtain averaged values of stream-wise velocity, temperatures, and oxygen and corrosion product concentrations at various axial locations close to the walls of several partial loop sections within the LBE loop. The oxygen and corrosion products inside the test loop were simulated to participate in chemical reactions with the eutectic fluid as it diffused towards the walls. Details of the geometry of these loops will be obtained from scientists at LANL. These values acted as a set of starting boundary conditions for the second task.

The second subtask focused on the kinetics of the dissolution/deposition process as a function of temperature, flow velocities, dissolved metal concentrations, oxygen potentials of the system, the kinetics of film formations in the presence of oxygen, and the kinetics of metal transport through the oxidized surface film.



Schematic of corrosion processes between the metal surface and the liquid metal.

RESEARCH ACCOMPLISHMENTS

Geometries and flow conditions similar to experimental results in the literature were set up and used to benchmark the models assembled using the STAR-CD software. Test case studies indicated that the outcome from STAR-CD was correct and that numerical modeling is applicable to the research in this problem.

Using these models, concentration flux profiles were obtained for both laminar and turbulent profiles in a straight pipe. This information was then used for the chemical kinetics analysis for corrosion on the inside walls of the LBE loop.

A 2-D model problem was simulated under the premise that the expected corrosion rate along the pipe's length may vary as a result of local flow condition differences and concentration profiles normal to the wall. The corrosion rate was found to vary inversely with distance in the pipe length raised to the one-third power. The results show a good agreement with the analytical solutions. Concentration of corrosion decreases exponentially with distance.

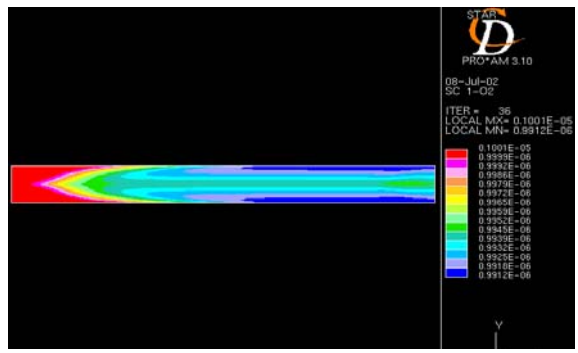
Another 2-D test case, set up with sudden expansion geometry, indicated a fluctuation of flow in the bulk area. This fluctuation gave rise to the production, propagation and disappearance of vortexes in the near-wall region. These findings demonstrate consistency with experimental results.

A 3-D gradual expanding pipe model was built in the shape of a cone. Results indicate that gradual expansion demonstrates simple and straightforward corrosion phenomena. Findings emphasized the relationship between corrosion rate and flow conditions, such as vortexes and separation.

An additional set of simulations was executed on a closed loop using a straight pipe. These runs compared previously obtained results representing a diffusion-controlled reaction with conditions similar to the Delta loop at LANL. A "momentum source" within STAR-CD simulated the effect of a pump. This provided constant flow without the need for a detailed description of the pump flow. Analytical and numerical simulations show several similarities. However, the numerical results showed some peculiarities and differences from the straight loop concentration flux distribution. These happen to coincide with the location of the elbows around the loop. This may suggest that a secondary phenomenon occurs that does not take place in the straight loop.

HIGHLIGHTS

- "Modeling of Corrosion in Oxygen Controlled Lead Bismuth Eutectic Systems with the Coupling of Chemical Kinetics and Hydrodynamics" presented at the AFCI Semi-Annual Review Meeting, Albuquerque, NM, January 22-24, 2003.
- "Modeling of Corrosion and Precipitation in the LBE flow Loop and Study of Geometric Effects in Local Corrosion Rates" presented at the ANS Student Conference, Berkeley, CA, April 2-6, 2003.
- "Study of the Geometry Effects on Local Corrosion Rates for LBE Loop" presented at the ANS Annual Meeting, San Diego, CA, June 1-5, 2003.



Profile of Oxygen Concentration along the Pipe Axis

FUTURE WORK

Research to simulate the results of diffusion-controlled reactions and reaction-controlled kinetics on the three predefined geometries will continue. Comparisons will be made with previously obtained experimental values and other analytical studies to compare and validate the code. Attempts will be made to compare some of the simulation results with any experimental data available in the literature.

The STAR-CD models will be used to simulate the 3-D hydrodynamics of the LBE loop. The concentrations and mass fluxes of species that diffuse into the surface will be calculated. Programming scripts for the species transport equations will be written using the STAR-CD subroutine. Fluxes of iron and lead oxide from the surface will be calculated based on the product concentrations from the reactions. Corrosion and precipitation for the entire loop will also be calculated. Finally, 2-D and 3-D corrosion kinetic finite difference models will be developed to study the corrosion rates for sudden expansion and contraction geometries, as well as for multi-branch outlets at junctions.

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Task 6

Neutron Multiplicity Measurements of Target/Blanket Materials

C.D. Hull and D. Beller

BACKGROUND

To optimize the performance of accelerator driven transmutation systems (ADS), engineers will need to design the system to operate with a neutron multiplication factor just below that of a critical, or self-sustaining, system. This design criteria requires particle transport codes that instill the highest level of confidence with minimal uncertainty, because the larger the uncertainties in the codes, the larger the safety margin required in the design and the lower the efficiency of the ADS transmuter. For current design efforts, the MCNPX code is used to determine neutron production and transport for spallation neutron systems.

While providing a very useful research and modeling tool, the uncertainties in MCNPX, particularly at higher energies, require engineers to increase the safety margin in the designs of the ADS transmuter. Much of the uncertainty associated with MCNPX is thought to be due to the escape of multiple high-energy particles from the target (multiple scattering), along with uncertainties in the predictions of source term volume measurements. Determining a reliable method that measures, validates, and benchmarks the code calculations of such a volume source term is necessary.

The primary goal of this research is to develop and deploy the detector systems necessary for the measurement of neutron leakage from targets in calibrated beam lines, and to produce precise, position sensitive measurements of the source term volume for neutron production.

RESEARCH OBJECTIVES AND METHODS

Two prototype neutron detector systems utilizing different detection technologies, a ^{3}He gas tube system and a ^{6}Li glass optical fiber ("neutron glass fiber") system, will be developed to measure the neutron multiplicity of scaled lead accelerator targets (~4 cm diameter by 8 to 10 cm long). Performing measurements using both detector systems produces a consistent set of relative measurements. This should enable the quantification of systematic errors in the LAHET Code System (LCS) as incorporated in the latest MCNPX beta test version and library codes. Neutron leakage measurements should provide a systematic set of precision data that will enable direct comparison with code calculations. Comparison of results from the two detector systems may decrease uncertainties and allow the derivation of relative measurements in the few percent range at the 95 percent confidence level. A consistent set of relative measurements enables quantification of systematic errors within the MCNPX beta test versions and neutron cross-section data files. Improved models of beam line experiments, accelerator targets, and detector designs will result from these code improvements.

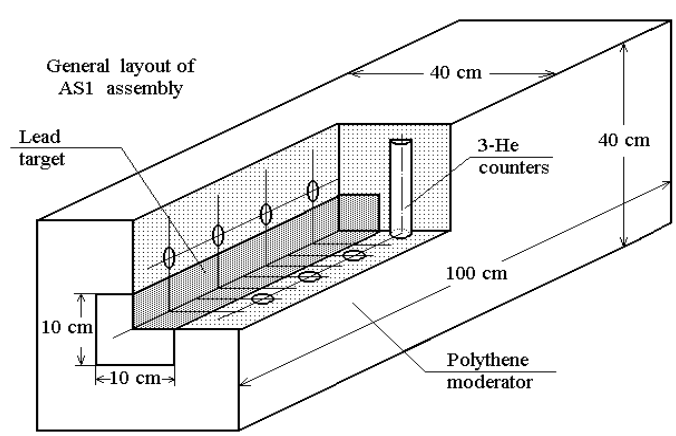
Producing precise, position sensitive measurements of the source term volume for neutron production allows systematic determination of major uncertainties in the code. This enables the performance of very low uncertainty measurements in the few percent range at 95% confidence level. High-resolution source volume measurements using the position sensitive detector permits a direct comparison of the code results with the neutron source term volume produced by the proton interaction in the target.

Additionally, these systems will be used to perform neutron-multiplicity measurements on a variety of targets over a range of energies (800-3,000 MeV), which should provide the data necessary to validate and benchmark the MNCPX code.

RESEARCH ACCOMPLISHMENTS

MCNPX models of neutron leakage from target systems were performed. Modeling efforts were refined prior to each set of neutron multiplicity measurements of ADS target and blanket materials. These dynamic models require review, revision, and refinement based on the results with the observed data of neutron leakage. Additional MCNP/MCNPX models were developed to optimize detector designs for performing multiplicity measurements for both the neutron glass fiber and ^{3}He detector systems.

Nuclear transport code models and calculations of neutron detection efficiency at various points in the target-detector assemblies were completed and interpreted prior to developing designs of the neutron detection systems needed to perform multiplicity measurements.



General layout of test assembly "AS1," a 36-element ^{3}He detector system that was constructed at the Khlopin Radium Institute to verify the operation of the sysem.

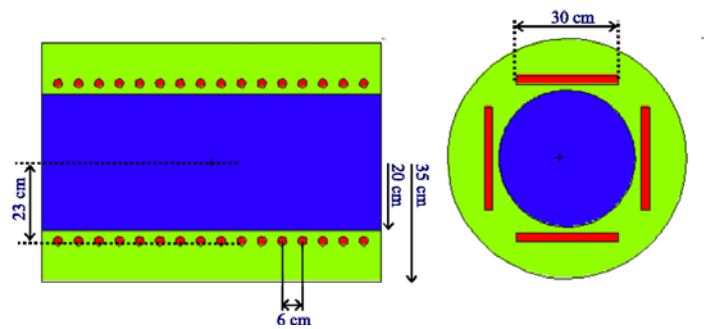
The 60-element ^{3}He-based system, developed in conjunction with collaborators at the Khlopin Radium Institute (KRI) in St. Petersburg, Russia, and fabricated by KRI, has been completed and is presently in transit. A series of MCNPX models were developed at UNLV for a cylindrical target. A generic model (termed AS1) was created to examine response times, collection efficiencies, and escape probabilities. Colleagues at the Khlopin Radium Institute (KRI) completed preliminary nuclear transport modeling using the CONTROL code developed by KRI researchers. A ^{252}Cf source was used to calibrate the KRI detector. Detection efficiencies in ^{3}He as well as fractional capture in Pb and polyethylene were calculated along with the percentage of neutrons lost. As expected, higher capture efficiencies for ^{3}He occurred with the source being placed in the center (because of reduced leakage). As the point source was moved from the center, the fraction of neutrons that escaped increased. These efficiency values are comparable to calculations and measurements done at KRI.

Lead target configuration for the ^{3}He system was computationally changed to that of a rectangular block target and additional MCNPX models were constructed for this target/detector geometry. This difference between the UNLV prediction with MCNPX and the KRI measurement is most likely due to different detector configurations (geometry, numbers of counting tubes, source description and spectrum, and materials). These models will be repeated.

The glass fiber detector prototype is nearing completion in Oak Ridge, TN and will be ready to test in upcoming target experiments at the Crocker Nuclear Laboratory at the University of California, Davis. A series of MCNPX models was used to optimize the design for a Neutron Glass Fiber Detector for use in the calibrated proton beam line at the cyclotron facilities at UC Davis. Models also were developed to evaluate the optimal size and length of the detector and the position of the lead target within the detector element. The neutron glass fiber detector was re-designed after it became apparent from MCNPX modeling that internally moderated systems are not useful for determining the source term volume for neutron generation in the target; one of the long-term objectives of this project. The models needed to finalize the Li glass fiber neutron multiplicity detector prototype design were verified by UNLV and the Pacific Northwest National Laboratory.

HIGHLIGHTS

- "Modeling Neutron Multiplicities in a 60-element ^{3}He detector system" presented at the ANS Annual Meeting, San Diego, June 1-5, 2003. Dean Curtis won overall best student poster award.
- Fabrication of the ^{3}He-based neutron detector system has been completed by KRI. The system is in-transit to UNLV, with delivery and installation expected by the end of the summer.



2-D Cross Sections of the geometry used in this MCNPX model of the KRI 60-element ^{3}He detector system.

FUTURE WORK

The experimental measurement of neutron production in scaled Pb targets using the two prototype neutron detector systems will be performed over the next year. Initial measurements would best be performed at UC Davis, which may result in the ability to deploy a more robust system for target measurements to be performed at Los Alamos during the next academic year (early FY04). Other testing may be possible on beam lines at the Idaho National Laboratory.

These measurements of real time neutron leakage collected with these systems will be compared with the MCNPX models of the experiments. The ongoing MCNPX modeling of high-energy neutron leakage from Pb-Bi targets will be coordinated with Lujan Center at LANL and KRI. Modeling efforts will most likely be further refined subsequent to performing each set of neutron multiplicity measurements of target / blanket material materials. Additional MCNP/MCNPX models will be developed to optimize detector designs for performing multiplicity measurements for both the neutron glass fiber and ^{3}He detector systems.

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Task 7

Development of Dose Coefficients for Radionuclides Produced in Spallation Targets

P.W. Patton and M.J. Rudin

BACKGROUND

Ensuring the safety of workers at accelerator-driven nuclear facilities is paramount before these systems can be deployed for nuclear transmutation or any other mission. Spallation neutron sources produce as many as 660 rare radionuclides in either the target or blanket during the spallation process. No data exists for many of these radionuclides in the current radiation protection guidelines and standards. This research program seeks to address this problem through generating internal and external dose coefficients (DCs) for these "new" isotopes.

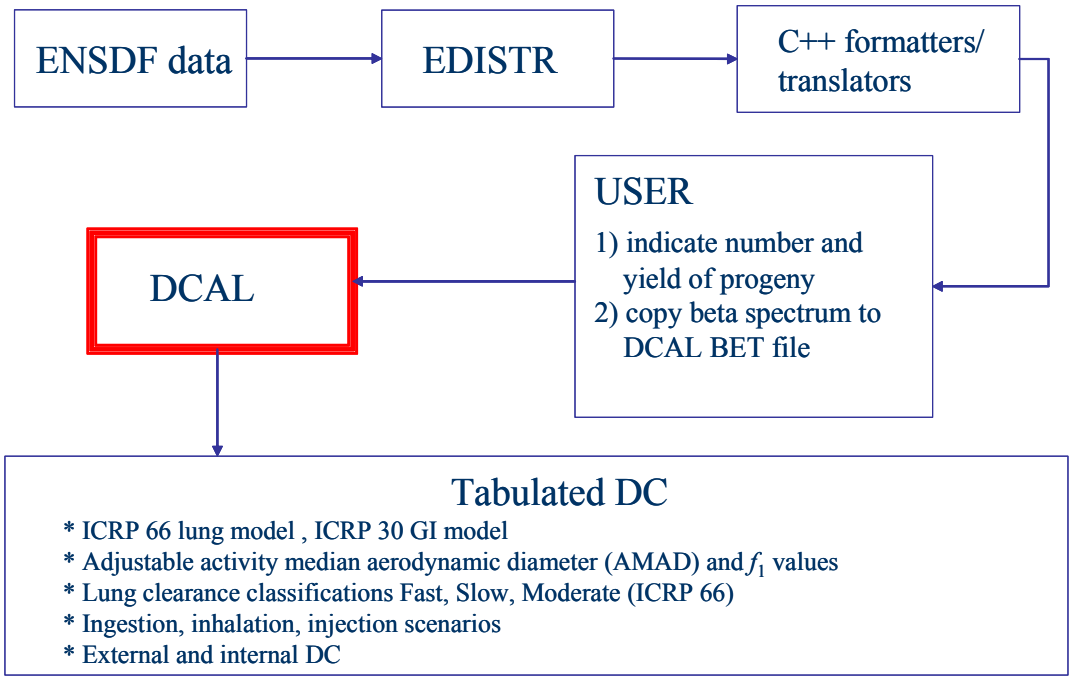
Dose coefficients permit simple determination of radiation dose associated with various exposure scenarios, and ultimately permit radiation safety personnel to assess the health risks to workers in a nuclear facility. Specifically, radiation safety personnel use dose coefficients to determine the radiation dose incurred to a tissue or organ system from a given exposure. These parameters are often expressed in terms of Annual Limits on Intake (ALIs) and Derived Air Concentrations (DACs).

Results from this study will be used to produce ALIs and DACs for these rare radionuclides created by spallation target systems that are not included in Federal Guidance Report (FGR) No. 11. Additionally, DCs developed will augment the radiological data in Publications 68 and 72 of the International Commission on Radiological Protection (ICRP), contributing to the safe operation of accelerator-driven nuclear systems in the United States and abroad.

RESEARCH ACCOMPLISHMENTS

A Dose Coefficient Working Group was established in 2001 (the first year of the project) to direct and oversee consortium activities. Representatives from the Dose Coefficient Working Group developed and verified a methodology to determine internal and external dose for select radionuclides. The first step involved obtaining radiological data from the ENSDF nuclear physics database developed at Brookhaven National Laboratory. Data collected included decay modes, decay energy levels, and radiation energies and intensities.

The DC working group prioritized a list of radionuclides projected to be released via air emissions or in the inventory of a mercury target following a lengthy irradiation period. Only radionuclides with a half-life greater than one minute were considered. These 81 radionuclides were then categorized into three distinct categories, based on half-life, available information, and other technical factors.



Dose Coefficient Working Group Methodology Flow Sheet. The ENSDF code is used to obtain nuclear physics data. The EDISTR code prepares the data for input into the dose calculation code DCAL.

Dose coefficients were then generated for the Category one radionuclides, along with six radionuclides already present in the nuclear database (for methodology validation and quality control). Metabolic models and data from ICRP publications (30 and 66) were applied in order to use the best technology available and to maintain consistency with current standards. In accordance with FGR No. 11, dose coefficients were evaluated for an adult male with the target tissues of gonads, breast, lung, red marrow, bone surface (endosteum), thyroid, remainder, and total committed effective dose equivalent (this considers total dose incurred to specific organs or tissues with respect to radiation type over a period of 50 years). Following determination of these variables, values of ALIs and DACs were then calculated for each radionuclide.

Efforts to add representatives from other countries to serve as members on the Transmutation Research Program (TRP) DC consortium were also initiated. Currently, faculty and students from the following academic institutions participate in the consortium: Georgia Institute of Technology, University of Nevada Las Vegas, Idaho State University, Texas A&M University, and Tbilisi State University (in Tbilisi, Republic of Georgia). Los Alamos National Laboratory and Oak Ridge National Laboratory are also represented in the consortium.

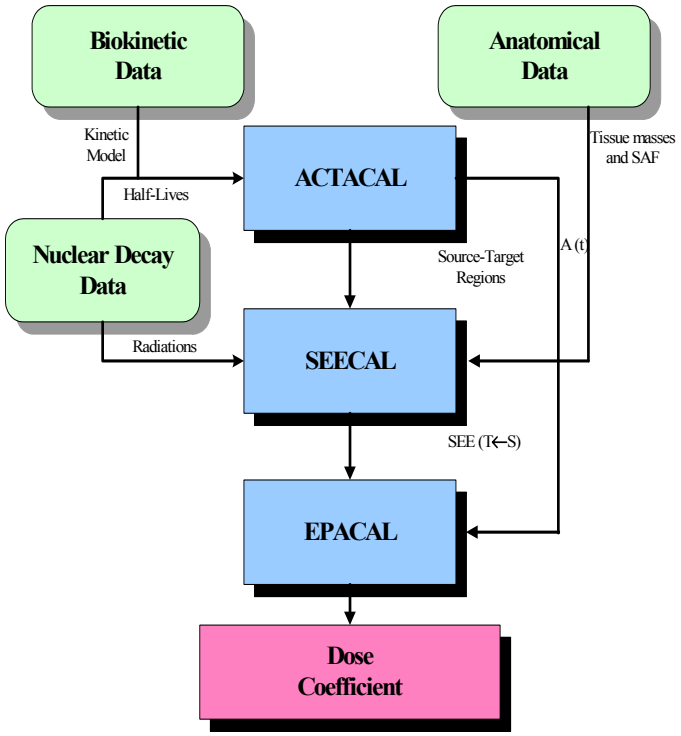
FUTURE WORK

Results from this work will be invaluable to individuals and organizations responsible for ensuring the safety of their workers in accelerator facilities, and the national and international radiation safety profession in general.

During the third year of this project, the consortium will devote its time to obtaining nuclear data that permits calculation of dose coefficients for radionuclides in the second and third categories. These calculations prove challenging. Radiological data exists for radionuclides in category two, but conflict amongst various databases. Incomplete radiological data characterizes those radionuclides in category three. After investigating sources to determine the availability of needed nuclear data, dose coefficients can then be calculated. Efforts to refine a reproducible methodology to determine internal and external DCs will be implemented in order to simplify this task.

HIGHLIGHTS

- Completion of Dose Coefficient Calculations for Category One radionuclides resulting from the Spallation process.
- J. Shanahan, M. Rudin, and P. Patton published "Dose Coefficient Methodology Report," UNLV, Aug. 2002.
- "An Interdatabase Comparison of Nuclear Decay Data Utilized in the Calculation of Dose Coefficients for Radionuclides Produced in a Spallation Neutron Source" presented at the ANS Student Conference, Berkeley, CA, April 2-6, 2003.



Schematic of DCAL System—adopted from ORNL/TM-2001/190 (Eckerman et al. 2001)

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Task 8

Development of a Systems Engineering Model of the Chemical Separations Process

Y. Chen, D.W. Pepper, R. Clarksean, and S. Hsieh

BACKGROUND

The chemical processing of used nuclear fuel is an integral component of any strategy for the transmutation of nuclear waste. Due to the large volume of material that must be handled in this first step of the transmutation process, the efficiency of the separations process is a key factor in the potential economic viability of the transmutation strategies. The ability to optimize the chemical separation systems is vital to ensure the feasibility of the transmutation program.

Systems analysis, or total systems modeling, is one of the strongest tools available to researchers for understanding and optimizing complex systems such as chemical separations processes. Systems analyses permit researchers to present decision-makers concise evaluations of system options and their characteristic features. The primary goal of this project is to develop a systems model that can be used to parameterize and optimize chemical separations processes.

RESEARCH OBJECTIVES AND METHODS

The initial step of this project is designing a systems engineering model that involves defining project goals and needs, defining all unit operations (processes and waste streams), selecting modeling software packages, and developing a basic system model.

Argonne National Laboratory (ANL) has developed the Argonne Model for Universal Solvent Extraction (AMUSE) code for the analysis of the Uranium Extraction (UREX) and other related solvent extraction processes. While the AMUSE code defines many of the process streams that are integral to the systems engineering model, it requires better interaction to modularized and well-developed systems optimization packages.

Yitung Chen and Haritha Royyuru by their poster at the ANS Annual Meeting, San Diego, CA, June 2003.

This work includes reviewing and analyzing the AMUSE code structure, examining other possible implementations, defining software activities, developing a verification plan, and modifying and improving the software. This work also involves redefining the graphical user interface (GUI) to increase the utility of the AMUSE code suite as a stand-alone analytical package.

Developing a systems engineering model requires ongoing discussions with Argonne National Laboratory personnel to identify pertinent components of the chemical separations process. Each step requires model development to establish its significance with regards to the overall process. Comprehensive model development involves defining the inputs and outputs from individual models and establishing how each connects to the other within in the chemical separations process.

RESEARCH ACCOMPLISHMENTS

The framework and environment for a systems engineering model of the chemical separations system was developed during the first year. This model was established as the baseline model, which will be used as a reference for examining the impacts of any modifications or improvements. The model was implemented using a combination of MATLAB OPTIMIZATION toolbox and SIMULINK module from Mathworks.

A “drag and drop” type of graphical user interface was designed and developed by the UNLV team. The interface allows the user to quickly and easily define the UREX process and process inputs.

Object-oriented design is used to identify four major objects. First, the data input interface takes the user input from these blocks and creates an export file. Secondly, an export file serves as the input to the AMUSE code that performs all the chemical extraction calculations. The third component handles result file open and save. The fourth component acts as an optimization tool that continuously interacts with MATLAB commercial components until the optimization objectives are achieved. The AMUSE macros used were not modified by the UNLV’s researchers. Instead, the Microsoft Visual Basic (VB) interface was designed to call the AMUSE macros directly as part of the analysis of the system, thus preserving the original code developed and validated by the ANL team.

Further system enhancement allows the user to select various process types. An object-oriented programming concept is carefully implemented for higher flexibility on further process modification and module addition. An interface for conducting multiple runs has been created. The GUI includes a list of variables, a range for those variables, all of which provide an envelop of end results.

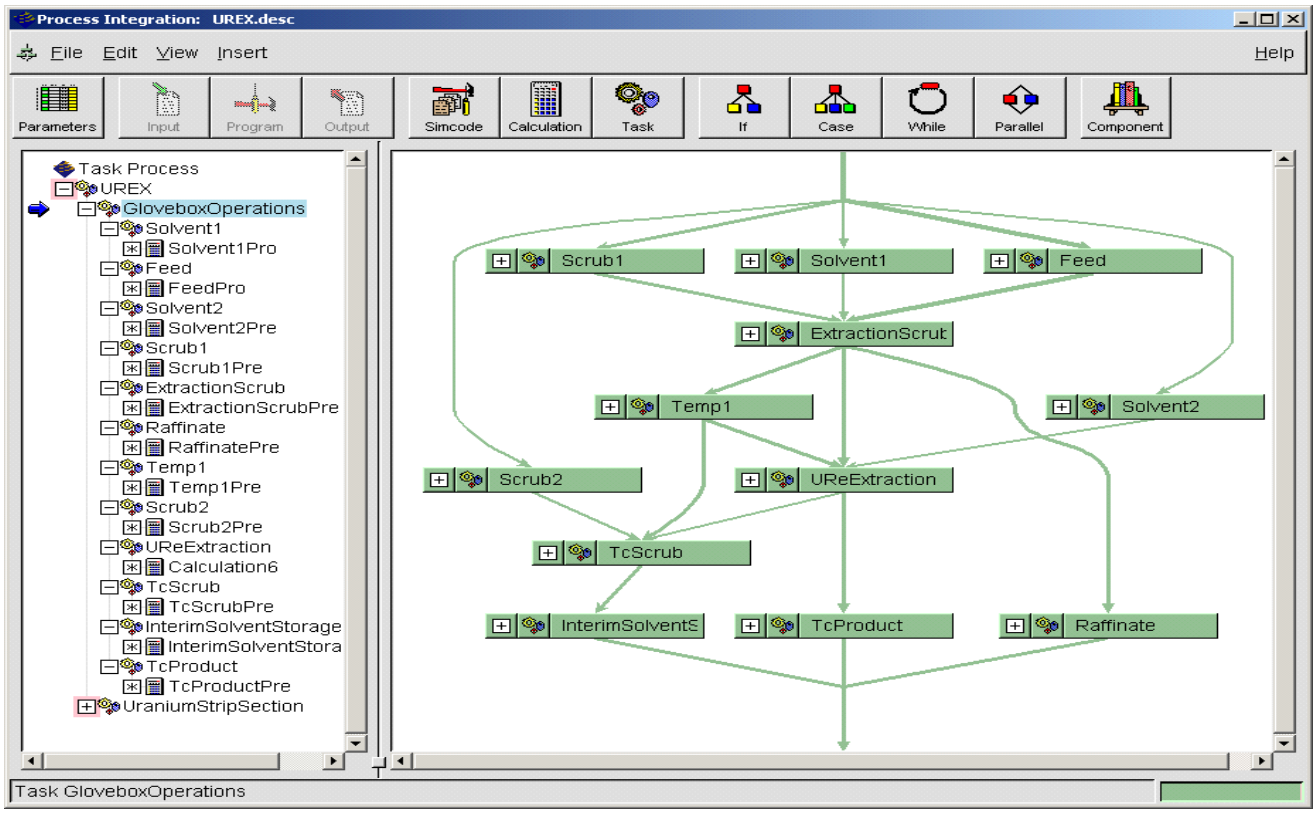
The researchers also accomplished the design and development of a mass balance interface code, as well as design and implementation of the UREX Visual Basic interface.

FUTURE WORK

The future work scope for the project includes increasing the sophistication of the systems engineering model. As optimization constraints are provided, relative comparisons of process options with regard to waste generation, proliferation resistance, throughput capabilities, facility requirements, and cost are possible. The final results from this project will provide engineers and scientists a user-friendly Window-based graphical user interface package. Increased confidence in the models and further refinements render greater objectivity and technical credibility to the decision-making process.

HIGHLIGHTS

- "Development of a Systems Engineering Model of the Engineering Chemical Separations Process" presented at the International Congress on Advanced Nuclear Power Plants, Hollywood, FL, June 9-13, 2002.
- "Development of a Systems Engineering Model of the Chemical Separations Process" presented at the AFCI Semi-Annual Review Meeting, Albuquerque, NM, January 22-24, 2003.
- "Development of an Optimization Systems Engineering Model for Spent Fuel Extraction Process" presented at the ANS Student Conference, Berkeley, CA, April 2-6, 2003.
- "Development of Systems Engineering Model for Spent Fuel Extraction Process" presented at the ANS Annual Meeting, San Diego, CA, June 1-5, 2003.



Example of a graphical user interface for one of the separations processes.

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Task 9

Design and Evaluation of Processes for Fuel Fabrication

G. Mauer

BACKGROUND

The safe and effective manufacturing of actinide-bearing fuels for any transmutation strategy requires that the entire manufacturing process be contained within a shielded hot cell environment. To ensure that the fabrication process is feasible, the entire process must be designed for remote operation. The equipment must be reliable enough to perform over several decades, and also easy to maintain or repair remotely. The facility must also be designed to facilitate its own decontamination and decommissioning. In addition to these design factors, the potential viability of any fuel fabrication process will also be impacted by a number of variables, such as the current state of technology, potential problem areas, deployment scaling, facility safety, and cost.

The goal of this research project is to provide technical support to process designers working on the development of the fuel cycles for transmutation applications. Detailed process models are developed to better define the impact of fuel choice on the transmuter fuel cycle, including relative process losses, waste generation, and plant capital cost. These process models provide insight regarding required plant size and number of plants needed to mesh with the fuel recycling line. They also determine requirements for automation.

Manufacturing models for large-scale production in a hot cell environment are also developed. Combined, these two models allow the assessment of plant layout, and provide the framework for estimation of plant capital and operating cost estimates, and for feasibility in general. The need for development in the areas of robotic and sensor technology is assessed. The manufacturing technology developed for hot cell applications is also applicable to other, more general uses, where occupational hazards prevent human presence near processes.

RESEARCH OBJECTIVES AND METHODS

Research work during the second year of the task was devoted to developing data and the knowledge base on the cost and feasibility of automated fuel manufacture in a hot cell. The manufacturing processes were simulated as robotic operations supervised by remote operators. Normal operations and failure scenarios were investigated, analyzed, and simulated. Development of the conceptual designs for the fabrication plants and their accompanying supervision and control systems was initiated. Impacts on transmutation system capital cost, economics of operation, estimates of process loss, and environmental and safety issues were considered in further detail.

The research work was divided into several tasks and subtasks:

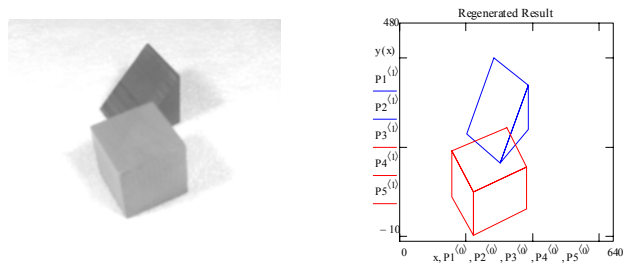
Methods and Processes – A literature survey and detailed analysis of the research and development pertaining to candidate processes for transmuter fuel manufacture continued. Industry standards were used to refine equipment, instrumentation, and control specifications, and assessed the reliability and safety of operations.

Simulations – This task modeled manufacturing processes to generate a realistic assessment of plant layout, size, feasibility, and technology development required for large-scale remote fabrication of fuel. Modeling of the candidate fuel manufacturing processes was initiated using the MSC Visual Nastran and ProEngineer simulation software tools.

Process and Equipment for Autonomous Manufacturing – This task attempts to develop an understanding of the cost and capability of current generation remotely operated equipment suitable for use in radiation environments. Monitoring of the market for equipment and components with regard to suitability for automated manufacturing under hot cell conditions continued.

Sensors, Controls, and Operational Safety – This task determines the adequacy of current technology and the need for suitable sensor technology development for deployment in hard radiation environments. A means to identify the precise location and spatial orientation of all parts in the robot's work envelope were implemented. The ability to position and handle materials along with trouble shooting techniques were evaluated. Radiation hardened vision systems appear to be promising technologies.

Cost, Feasibility, and Large Scale Deployment – This task develops the database necessary to provide cost estimates and differential cost for various fuel manufacturing options. Efforts began to tabulate and quantify estimates regarding projected cost, reliability, and plant life.



3-D recognition of grey tone images of physical objects.

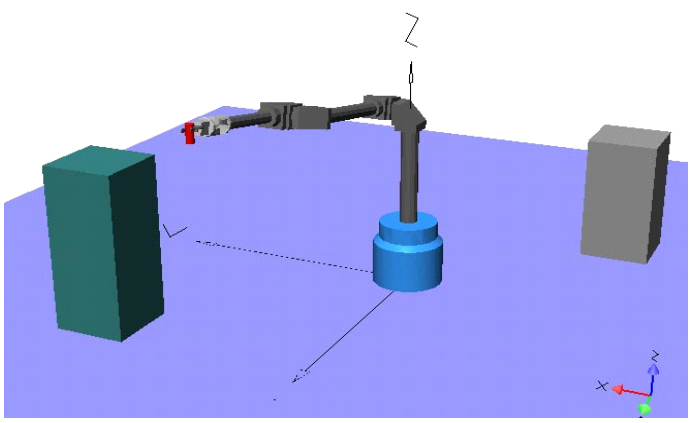
RESEARCH ACCOMPLISHMENTS

A simulation model with a Waelischmiller hot cell robot was developed and coupled with MatLab control software. Matlab provides the interface with the robot and is used to control the system. This renders a realistic simulation of the forces and torques present during robot motion. Efforts began to develop the 3-D manufacturing process simulation using CAD models. Results exist in the form of movies, data sets, and images. Simulations for several robot types were developed and their proper kinematic configuration was verified.

While the simulation process generally worked flawlessly, the simulation time rose considerably as more details were added to the simulation. Options were investigated to increase the speed, especially since researchers anticipate adding significantly more complexity to the simulation as the project progresses.

Efforts began to develop a vision-based methodology for locating and identifying objects within the robot's workspace and included the development of an Artificial Intelligence (AI) algorithm for object identification.

Another accomplishment involved the development of algorithms for knowledge based pattern recognition using IF (a set of conditions is satisfied) THEN (a set of consequences can be executed) routines. Other simulation variables established included pattern matching using clustered indexing vectors containing information about an object and feature vector indexing, where a 3-D object is segmented into a set of simple geometric features. Each feature is stored with its vector segmentation and geometry information (magnitude, inner angle, etc.).



Interactive graphical user interface process simulation of moving a part from one place to another.

HIGHLIGHTS

- "Design and Evaluation of processes for Transmuter Fuel Fabrication" presented at the ANS Winter meeting, Washington DC, November 2002.
- "Object Recognition Over an Expanded Range of Viewing Angles Using Indexing Methods" presented at ISCA 2002, San Diego, CA.
- PhD. Student Jae-Kyu Lee presented his dissertation proposal to the doctoral advisory committee and passed the preliminary examination.
- Dr. Mauer visited CEA Cadarache and CEA Marcoule in France, the institute for transuranics in Karlsruhe, and the Framatome Manufacturing Plant in Lingen, Germany.
- "Design and Evaluation of Processes for Transmuter Fuel Fabrication" presented at the AFCI Semi-Annual Review Meeting, Albuquerque, NM, January 2003.
- "3-D Simulation of Manufacturing Processes for Transmuter Fuel Fabrication" presented at the ANS Student Conference, Berkeley, CA, April 2-5, 2003.

FUTURE WORK

Further efforts will be devoted to increasing data and knowledge regarding the cost and feasibility of automated fuel manufacture in a hot cell. Artificial intelligence concepts will be further developed with respect to object identification and hot cell dynamics simulations. Following completion and testing of the operation of a single robot, multiple robots will be placed into a hot cell and controlled simultaneously by a supervisory program.

The simulation environment will enable designers to create a virtual mock-up environment in which possible scenarios can be executed and analyzed at any desired level of detail. Normal operations and failure scenarios will be investigated, analyzed, and simulated. The results of the simulations will be used by AFCI program personnel to perform sensitivity studies on the impact of different fuel types on transmutation system operation. Conceptual designs of the fuel fabrication processes will allow evaluations of issues related to maintainability, robust design, and throughput rate, and lead to identification of areas where improvements in technology are required to meet the goals of the transmutation system.

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Task 10

Development of a Mechanistic Understanding of High-Temperature Deformation of Alloy EP-823

A. K. Roy and B.J. O'Toole

BACKGROUND

Materials used in the target for accelerator-driven waste transmutation systems (ADS) will be subject to extreme temperatures and corrosive environments. The mechanical properties, such as the yield strength and ductility parameters, for most candidate materials have yet to be evaluated under these conditions. Martensitic alloy EP-823, a leading candidate material for use in ADS applications, has demonstrated excellent corrosion resistance in lead bismuth eutectic (LBE) nuclear coolant applications, such as those needed for fast neutron spectrum operations.

The focus of this work is to determine the effect of elevated temperatures on the tensile properties of Alloy EP-823. The information obtained through this work describing the mechanism of elevated-temperature deformation will assist in developing suitable target materials possessing enhanced LBE corrosion resistance at process temperatures, allowing the continued development and eventual deployment of these technologies.

RESEARCH OBJECTIVES AND METHODS

The purpose of this task is to evaluate the mechanical properties of Alloy EP-823 at temperatures relevant to the transmutation processes. Testing has been initiated to evaluate the tensile properties of martensitic Alloy EP-823 stainless steel at temperatures ranging from ambient (25 °C) to 600°C. The test materials were thermally treated prior to the evaluation of their tensile properties. The deformation characteristics of these tensile specimens, upon completion of testing, will be evaluated by surface analytical techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

The ASTM Standard E8 ("Standard Test Methods for Tension Testing of Metallic Materials") served as the guide for evaluating the tensile properties in the presence of an inert atmosphere. Cylindrical tensile specimens were machined in the longitudinal rolling direction. An elevated temperature chamber with an inert gas (nitrogen) atmosphere, in conjunction with the Materials Testing System (MTS), enabled researchers to perform the desired testing. The resultant data include the uniform elongation, reduction in area, yield strength, and ultimate tensile strength as functions of the test temperature and thermal treatments. Investigators initiated testing of three specimens under each of the three metallurgical conditions at these temperatures.

RESEARCH ACCOMPLISHMENTS

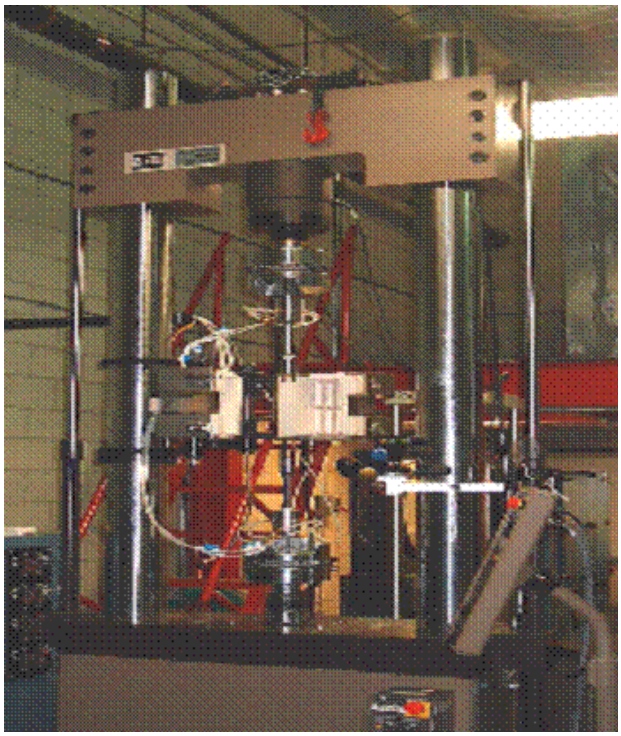
The MTS machine was modified to accommodate ambient and high-temperature testing in the presence of nitrogen. A high temperature chamber capable of testing tensile specimens in the temperature range of 200 to 1000 °C was added to this machine. A pair of custom-built water-cooled specimen grips, made of maraging steel (M250), was attached to the MTS machine. This water-cooled assembly was designed to prevent the grips from being heated from the temperature inside the chamber by conduction.

A laser extensometer, added to the MTS unit, measures the displacement of the test specimens in their gage sections. This displacement occurs during plastic deformation under tensile loading at the desired strain rate.

Testing has so far been performed at ambient temperature and 100 °C using tensile specimens fabricated from vacuum-melted and heat-treated (at the Timken Company) bars of martensitic Alloy EP-823. Preliminary data indicate that both the yield strength and the ultimate tensile strength of the tested material were slightly reduced at the elevated temperature. However, no significant reduction in ductility was observed in these tests.

Temperature profiles have been developed to determine the times needed to achieve the desired test temperature, as part of the furnace calibration process. Tests are in progress.

Testing specimens.



High Temperature Mechanical Testing in Inert Atmosphere (up to 1000°C)

FUTURE WORK

Testing of Alloy EP-823 will continue. The current test matrix includes testing at 300, 400, 500, and 600 °C. The tensile properties at all testing temperatures will be evaluated as a function of thermal treatments that include austenitizing followed by quenching and tempering. These tests are expected to enable the measurement of the following tensile properties:

- Uniform elongation vs. temperature;
- Reduction in area vs. temperature;
- Yield strength vs. temperature;
- Ultimate tensile strength vs. temperature;
- Metallurgical microstructure vs. thermal treatment;
- Failure modes (ductile vs. brittle) vs. thermal treatment (SEM) and,
- Deformation modes (TEM).

HIGHLIGHTS

- "High-Temperature Deformation of Alloy EP-823 for Transmutation Applications" presented at the ANS Student Conference, Berkeley, CA, April 2-6, 2003. Martin Lewis received a Best Paper Award.
- "High-Temperature Deformation of Alloy EP-823 for Transmutation Applications" presented at the ANS Annual Meeting, San Diego, CA, June 1-5, 2003.

Tensile testing machine with elevated temperature jacket.

The metallurgical microstructures of the failed tensile specimens will be evaluated using the standard metallographic methods of polishing and etching. SEM will be used to determine the morphology (ductile versus brittle) and extent of failure in each specimen tested at different temperatures. TEM will be used to develop high-temperature deformation characteristics including the distribution and nature of dislocations and other imperfections. This information will aid in the development of deformation mechanisms for Alloy EP-823 as functions of thermal treatments and testing temperatures.

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Task 11

Nuclear Criticality, Shielding, and Thermal Analyses of Separations Processes for the Transmutation Fuel Cycle

W. Culbreth and D. Beller

BACKGROUND

The first step in any transmutation strategy is the separation of radionuclides in used nuclear fuel. The current separation strategy supporting the Advanced Fuel Cycle Initiative (AFCI) program is based on the use of a solvent extraction separation process to separate the actinides, fission products, and uranium from used commercial nuclear fuel, and on the use of pyrochemical separation technologies to process used transmuter fuels. To separate the fission products and transuranic elements from the uranium in used fuel, the national program is developing a new solvent extraction process, the Uranium Extraction Plus, or UREX+, process, based on the traditional solvent extraction reprocessing technologies.

Preparing fuel for possible burn up in light water reactors, fast reactors, or accelerator-driven systems involves various chemical processes to partition the transuranics (neptunium, americium, plutonium, and curium) from the fission products. This results in waste streams that are highly radioactive and require radiation shielding for safety. These transuranic elements pose varied criticality, thermal, and radiation risks during storage and handling. Additionally, the radioactive decay of strontium and cesium waste products of the UREX+ technique produce roughly half of the thermal products and gamma radiation emissions in spent fuel. These radioisotopes require storage for approximately 300 years before heat and radiation hazards decrease to a safe level.

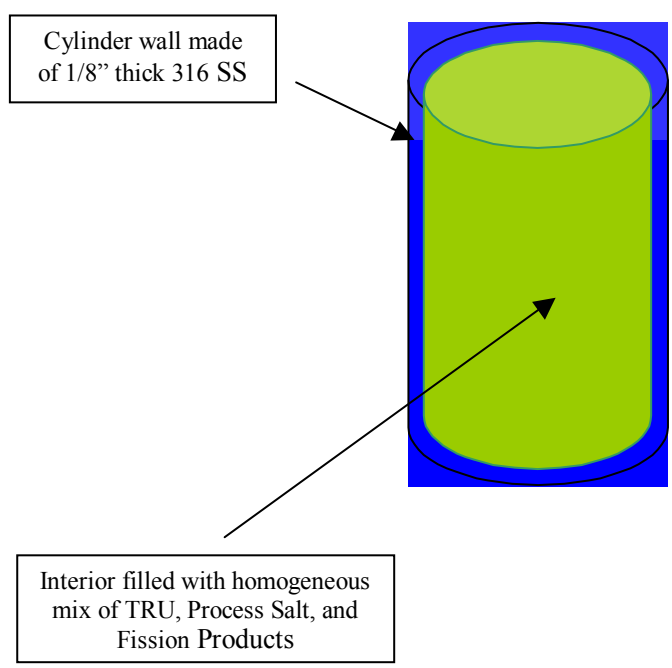
As the volume of waste requiring treatment increases, a higher probability exists that fissionable isotopes of plutonium, neptunium, and curium can accumulate and form a critical mass. Criticality concerns warrant an assessment of the effective neutron multiplication factor, or k_{eff}, to prevent a possible sustained fission reaction. Maintaining k_{eff} below a safe level (<0.95) prevents criticality events. This parameter can be computed for any combination of fuel and geometry using Monte Carlo neutron transport codes. Monte Carlo simulations establish the best means of examining the criticality safety of the proposed separation processes, and allow engineers to develop proper safety measures for the reprocessing and fabrication of actinide fuels.

Candidate storage containers also require analysis to assess the need for radiation shielding. Since minor actinides generate significant amounts of heat through radioactive decay, proposed containment measures must be designed to avoid excessive temperatures. Radioactive decay also generates heat that can lead to melting of the fuel during storage and handling.

RESEARCH OBJECTIVES AND METHODS

The primary goal of this research program is to provide the nuclear and thermal modeling support for the development of this new separation process. The assessments of nuclear criticality, radiation for shielding, and thermal analyses of wastes in the Cs/Sr, Pu/Np, and Cm/Am waste streams will assist in designing the UREX+ process. This project has been identified as a critical R&D need of the Chemical Technology Division (CTD) at the Argonne National Laboratory (ANL) as safety concerns associated with criticality, shielding, and heat buildup must be addressed prior to further development of the UREX+ process.

UNLV students used nuclear analysis codes to perform assessments of k_{eff} at different points in the separation processes that have been identified by the project collaborators at ANL-CTD. They also worked on problems to assess the need for radiation shielding and to develop software to assess the possibility of excessive temperatures due to radioactive decay in separated wastes. ANL-CTD has provided sample fuel process geometries and compositions for calculation of k_{eff} as a function of the relative concentrations of process salt, transuranics, and fission products.



Cylindrical problem with TRU, process salt, and fission products.

RESEARCH ACCOMPLISHMENTS

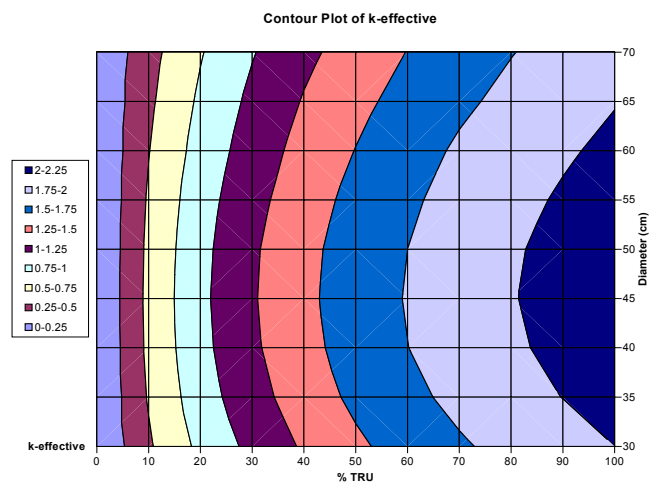
An investigation and analysis of criticality and thermal effects for the safe storage of curium was completed. The assessment involved determining k_{eff} as a function of fuel burnup, initial enrichment, and time since irradiation. Additionally, since curium generates a substantial quantity of decay heat, an analysis was completed to determine the mass of curium that will lead to temperatures high enough to melt the metal. A spherical geometry was used in the analysis. Heat removal from the sphere was assumed to be a combination of natural convection and radiation heat transfer. This heat transfer analysis was also modified and resulted in an analysis that utilized a more sophisticated and suitable cylindrical container. A report developed for Dr. Laidler at ANL described the in-depth investigation regarding the criticality and thermal properties of curium. The heat transfer spreadsheet will be used for other combinations of minor actinides as indicated by ANL.

Investigators initiated preparatory efforts to investigate and analyze the properties of the other minor actinides, including plutonium and americium. A study was begun on the values of k_{eff} and ultimate temperature for varying combinations of plutonium, americium, and the remaining minor actinides.

Elizabeth Bakker presenting her research at the ANS Student Conference, Berkeley, CA, April 2-6, 2003.

HIGHLIGHTS

- "Critical and Thermal Investigation of Curium and Other Minor Actinides for Safe Storage and Disposal" presented at the ANS Student Conference, Berkeley, CA, April 2-6, 2003.



Contour Plot of the Effective Neutron Multiplication Factor as a function of cylinder diameter and % TRU in the mixture.

FUTURE WORK

UNLV students will use nuclear analysis codes SCALE 4.4 and/or MCNPX to perform assessments of k_{eff} at different points in separation processes that have been identified by ANL-CTD. They will also work on problems to assess the needs for radiation shielding and develop software to assess the possibility of excessive temperatures due to radioactive decay in separated wastes. ANL-CTD has provided sample fuel process geometry and composition for calculation of k_{eff} as a function of the relative concentrations of process salt, TRU actinides, and fission products. The research team will analyze the cesium/strontium waste stream, the plutonium/neptunium waste stream, and the americium/curium waste stream.

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Task 12

Radiation Transport Modeling using Parallel Computational Techniques

W. Culbreth, and D. Beller

BACKGROUND

One of the most significant tools available for the design and analysis of accelerator-driven systems, such as the systems proposed for transmutation, is the high-energy particle transport code MCNPX. The MCNPX code suite, developed by the national laboratories, allows researchers and engineers to model the complex interactions of high-energy particles with the target and related systems, including the spallation reaction and subsequent neutron multiplication expected in the accelerator targets.

The next stage in the development of the MCNPX code suite is to validate the code by comparing the theoretical predictions from the models with experimental observations. Additionally, the nuclear database, particularly the cross sections (i.e., reaction probabilities) for high-energy particle interactions, needs to be revisited to reduce the uncertainties associated with key nuclear properties.

The Department of Energy, through its national laboratories, has initiated several experiments geared towards removing uncertainties in the MCNPX libraries, with more in the planning stages. These experiments utilize the proton and neutron beam lines at the LANSCE proton accelerator at the Los Alamos National Laboratory to irradiate a target, producing a pulse of neutrons which are observed by the experimenters. The results of these experiments are then compared against the predictions from the MCNPX models of the system. By comparing the predicted system behavior to the data acquired from the experiments, the experimenters will be able to validate the MCNPX code and its nuclear data libraries.

Through this project, UNLV researchers are involved in support of these experiments by developing the system models in MCNPX and benchmarking/validating the models against the experimental results. UNLV students have also been involved in conducting experiments at LANL and in assisting researchers in designing new experiments.

RESEARCH OBJECTIVES AND METHODS

The second year of this project involved modeling several aspects of the LANCSE beam experiments:

- Modeling targets of varying diameter in air, in a vacuum, and in the presence of humid air;
- Modeling various proton beam profiles;
- Modeling the effects of off-axis proton beam impingement on the target;
- Modeling the asymmetry introduced by the steel table below the target;
- Modeling the effect of varying ratios of Pb to Bi and the effect of impurities; and
- Modeling the system, including other structures within the test room.

With the experience gained through modeling these systems, the UNLV researchers plan, with the assistance of their national laboratory collaborators, to develop a benchmark program for the neutron leakage tests and other tests related to transmuter development. A comprehensive three-dimensional computer-aided design (CAD) image of the LANSCE experiments was prepared using ProEngineer to help benchmark the experiments and provide accurate geometric data for MCNPX modeling.

RESEARCH ACCOMPLISHMENTS

Undergraduate student Daniel Lowe worked on neutron spallation tests at the LANSCE facility (Summer 2002). He performed MCNPX runs and worked on calculations for initial benchmarking data. His early MCNPX calculations helped the experimenters determine where foil packets should go and what types of neutron flux to expect from these foils. He also prepared foils to determine neutron flux from the experiment and assisted in radiation counting of the foils. Mr. Lowe completed Solid Works CAD models of the Blue Room at LANSCE and conducted MCNPX simulations of the summer experiments when he returned back to UNLV. His MCNPX runs included estimations of the effect of the proton beam striking the target at positions slightly off of the centerline. He also estimated the neutron energy spectra expected from the time-of-flight neutron detectors.

Through MCNPX simulations of the neutron leakage from lead-bismuth targets, the UNLV team was able to assist in the design of the experimental configurations for the LANCSE experiments. These models were also used to predict the results for the experiments, and assist in positioning detectors for measuring the leaking. Similar computational support was also provided for proton activation experiments in sodium coolant.

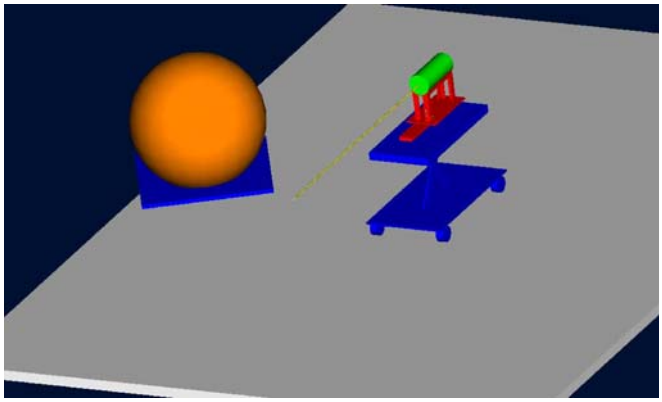
Graduate student Suresh Sadenini assisted with experiments on the lead neutron-production target at the Idaho Accelerator Center. He ran MCNPX simulations to predict the performance of the target when exposed to 25 MeV electrons produced by an accelerator and assisted with the experiments.

Graduate student Ashraf Kaboud worked on associated calculations to determine the neutron and photon flux resulting from a target field with deuterium. He performed radiation shielding calculations for radiation coming from Dense Plasma Focus Device.

Parallelization of MCNPX for a Parallel Virtual Machine was completed. Efforts began to resolve Message Passing Interface (MPI) bugs and compiling problems.

Analysis of linearization characteristics on a Beowulf cluster was completed. They are now working on characteristics of the Supercomputing Center and the linearization of criticality studies.

Experimental facility at LANSCE, Los Alamos, NM.



Schematic of the experimental facility at LANSCE used for modeling.

HIGHLIGHTS

- Suresh Sadenini completed his Master of Science degree in Mechanical Engineering (Dec. 2002), thesis entitled "Benchmarking Photoneutron Production of MCNPX Simulations with Experimental Results."
- Ashraf Kaboud successfully completed his Master of Science degree in Mechanical Engineering during the spring term 2003.
- A 16-processor LINUX cluster, coupled to a 4-processor system, was developed. This system will be used to run the parallelized version of MCNPX.
- "Monte Carlo Verification and Modeling of Lead-bismuth Spallation Target" presented at the AFCI Semi-Annual Review Meeting, Albuquerque, NM, January, 2003.
- "Monte Carlo Verification and Modeling of Lead-Bismuth Spallation Targets" presented at the ANS Student Conference, U.C. Berkeley, April 2-6, 2003. Daniel Lowe received an Outstanding Paper Award.
- "Measurements from Activation Foils of a Proton Irradiated Lead-Bismuth Target" presented at the ANS Annual Meeting, San Diego, CA, June 1-5, 2003

FUTURE WORK

The primary focus of the ongoing work in this project consists of the continued benchmarking and optimization of MCNPX to run on multiple platforms. This insures that the user will not be limited to a specific system type when running simulations. In addition, the MCNPX simulations of planned and future experiments will continue. Along with the work to implement MCNPX on multiple platforms, user guides will be developed for future users.

They will describe how to implement an optimized version of MCNPX on a heterogeneous cluster using a Message Passing Interface. Efforts to increase the speed of MCNPX on parallel clusters of computers will be initiated. Researchers will also begin the preliminary development of a graphical user interface (GUI) for MCNPX, using open source code and tools. Codes developed for this program will be made available to Advanced Fuel Cycle Initiative (AFCI) researchers.

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Task 13

Developing a Sensing System for the Measurement of Oxygen Concentration in Liquid Pb-Bi Eutectic

Y. Jiang, B. Fu, and W. Yim

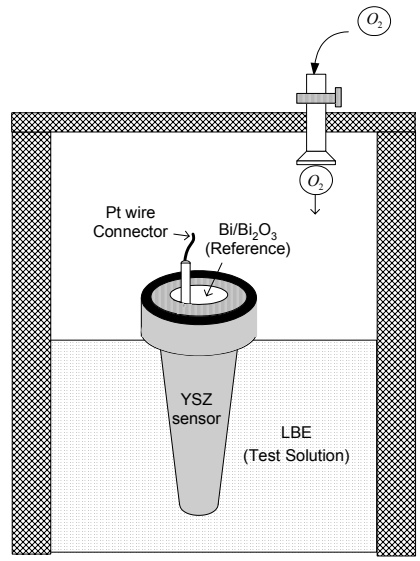
BACKGROUND

Lead-bismuth eutectic (LBE) is a candidate as a spallation target in sub-critical transmutation systems and as a coolant in nuclear programs. One of the primary concerns with LBE systems is the corrosion of stainless steel, the primary structural material used in nuclear systems. To mitigate this problem, trace levels of oxygen can be introduced into the system, causing the formation of a protective oxide layer at the interface between the LBE and steel. To protect the steel components, this oxide layer must be properly maintained. However, too much oxygen will produce unwanted oxide precipitation within the coolant and elsewhere in the system. With the current generation LBE systems, the stability of the oxide layer on the internal components is maintained through controlling the temperature of the system and the dissolved oxygen concentration in the coolant. Controlling these two operating parameters is the key to operating LBE systems and minimizing corrosion. While the temperature of the system is easy to measure, the concentration of dissolved oxygen in the LBE is more complicated.

Yttria-stabilized zirconia (YSZ) solid-electrolyte oxygen sensing systems are currently employed by Los Alamos National Laboratory (LANL) scientists to measure oxygen levels in the Delta Loop, an engineering-scale LBE experimental system. By measuring the voltage difference across the YSZ sensor, the oxygen concentration in test solutions can be determined relative to that in the reference solutions (the potentiometric method). The theoretical model for calculating oxygen concentration based on voltage measurements from YSZ sensors in static conditions is well understood. The real world performance of these systems, however, is less predictable.

One of the more significant challenges to measuring the dissolved oxygen concentration in LBE using the YSZ sensor is that the YSZ sensors are temperature-dependent. At high temperatures, the potential exists for electrons from bonding orbitals to become mobile and contribute to the electrical signal from the sensor. This component must be accounted for in electrical measurements, since it can be confused with the signal from the ionic conductivity.

Furthermore, device and material imperfections, such as irregular porous membrane and ohmic contributions, also contribute to deviations observed in the measured voltage response of the oxygen sensor system with respect to theoretical conditions. Therefore, there is a need to develop a complete set of calibration curves for YSZ sensor systems under various temperature and flow conditions in an LBE environment.



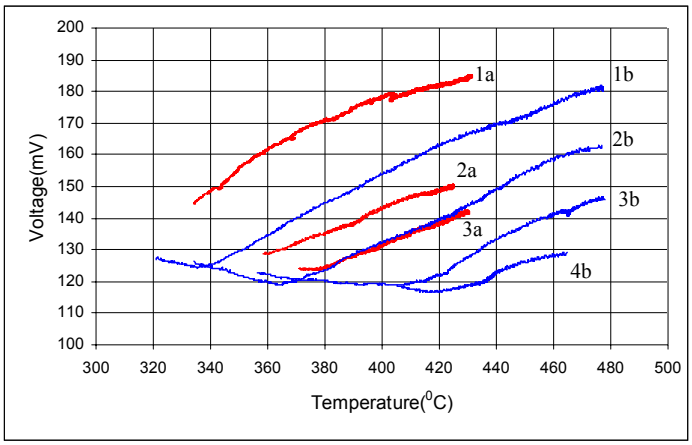
Schematic of YSZ Bi/Bi_2O_3 oxygen sensor in a heating chamber. The reference solution of Bi/Bi_2O_3 is filled and sealed inside the sensor core.

The primary goal of this research project is to examine the major factors impacting the performance of YSZ oxygen sensing systems. The research effort will serve to fill the gaps in the current sensor calibration/validation work and further the development of new sensors for oxygen concentration measurement in a nuclear environment. Ultimately, acquired data will lead to the full implementation of the instrumentation in the system. Through this work, the research group will also generate the calibration curves for the YSZ sensors over various temperature ranges.

RESEARCH OBJECTIVES AND METHODS

The research objectives of this project are as follows:

- To generate calibration curves of voltage versus oxygen concentration for the YSZ oxygen sensor system under various temperatures in liquid LBE.
- To determine the sensor characteristics of the YSZ sensor system.
- To determine oxygen dissolving rates in LBE under different temperatures in vitro.
- To study the effects of unwanted electrical conductivity, contributed by the mobility of the electrons at high temperatures, for more accurate oxygen measurement.
- To study alternative and promising oxygen measuring methods.



Sensor voltages at different oxygen concentrations (experimental results). Red lines are for sensor A and blue lines are for sensor B.

RESEARCH ACCOMPLISHMENTS

A set of calibration curves for output voltage versus temperature ranging from 300° C to 500° C under various oxygen concentrations in liquid LBE for the YSZ oxygen sensor have been produced. The current calibration strategy uses the direct injection of hydrogen and oxygen gases. Based on the experiments done so far, producing the correct level of oxygen in the system using the direct injection method does not appear to be adequate for producing the extremely low levels of oxygen concentration needed. To address this, the research team, along with their collaborators from LANL, switched to an alternative approach for controlling the oxygen level in the system. By varying the hydrogen to steam ratio in the system, it was possible to produce the low levels of dissolved oxygen needed. Experiments aimed at choosing a possible oxygen sensor to measure very low oxygen concentration in LBE using this technique are underway.

A new experimental apparatus for testing the oxygen sensors, based on an older version at LANL, is currently being developed at UNLV. The preliminary design of the system, referred to as the O_2 sensor pot, has been completed. The components for the system have been ordered, and the fabrication/assembly of the O_2 sensor pot is underway.

In parallel to this effort, the researchers have developed models of the proposed system. These models, designed to predict the dissolved oxygen concentration distributions in the experimental set-up, were used to assist in the design process and should serve as a vital tool to assist the research and sensor development. Using these models, the researchers hope to be able to examine the oxygen dissolving rates under various conditions including changing temperatures and inlet oxygen supply and to determine the diffusion coefficient of oxygen in liquid LBE under different temperatures through theoretical modeling and experimental measurement. The results obtained from the simulations also provide a means to cross-check and cross-validate with the experimental data.

A model of the oxygen-sensor and LBE experimental set-up was completed using FEMLAB. After several simulations, the investigators recognized that this program is not suitable for the simulation of the oxygen concentration and dissolving rate in LBE. A Lab View module for the acquisition and control of the apparatus has been designed and is undergoing testing and improvement.

FUTURE WORK

Calibrations that vary hydrogen to water steam ratio in the system will continue in order to control the dissolved oxygen concentrations at the required low levels, . Once completed, these calibration curves will allow researchers to easily adjust the dissolved oxygen concentrations by simply varying the partial pressures of hydrogen and water steam. Additionally, calibrations for oxide dissociation limits will be conducted. Cross-calibration of different electrode sensors will also be undertaken.

YSZ sensor signals can also be processed using amperometric methods. In this method both anode and cathode are contained within the sensor assembly, and no electrical contact is made with the outside sample. The investigators hope to be able to design a new oxygen sensor system based on an amperometric method. This will allow investigators to compare the potentiometric and ameprometric methods and determine which one is most conducive for the LBE system.

Techniques facilitating fully operational sensor systems will be obtained. In addition, these research efforts build a solid foundation for future development of new oxygen sensing systems.

Research Staff

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Peng Guo, Post Doctoral Research Associate, Department of Mechanical Engineering

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Collaborators

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Task 14

Use of Positron Annihilation Spectroscopy for Stress-Strain Measurements

A. K. Roy

BACKGROUND

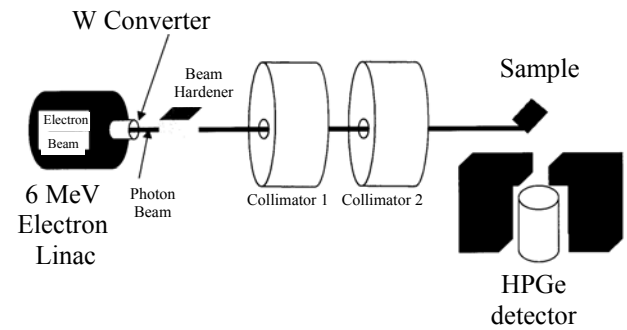
One of the greatest challenges in evaluating the performance of materials in the real world is the determination of residual stresses, or the stresses induced in a material. Plastic deformation of metals and alloys produces an increase in the number of lattice imperfections known as dislocations, which by virtue of their interaction results in higher state of internal stress and reduces ductility. These stresses, if not properly annealed (released) can significantly degrade the long-term performance of the materials.

Due to the high temperatures and radiation fields typically encountered in most nuclear systems, such as accelerator-driven transmutation systems (ADS) and nuclear power reactors, the residual stress in materials can be even more significant. To minimize the impact of residual stress, most designs limit the residual stresses allowed in the structural materials in the systems. As a result, the ability to measure these residual stresses, while potentially challenging, is essential to the design and operation of nuclear systems.

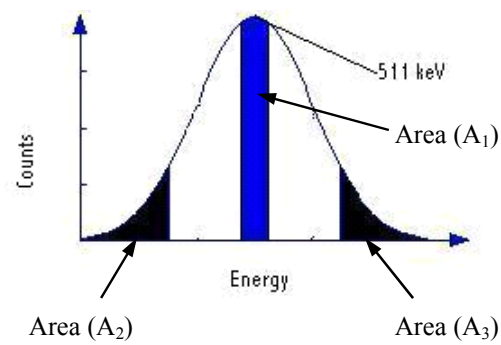
RESEARCH OBJECTIVES AND METHODS

Residual stresses can be measured using destructive and non-destructive techniques. The primary focus of this research is to evaluate the feasibility of determining residual stresses in engineering materials for transmutation applications using a new nondestructive technique based on positron annihilation spectroscopy (PAS). In this project, the modified PAS method is compared to residual stress measurements performed by three other techniques: the ring-core method (destructive), X-ray diffraction (XRD, Non-destructive), and neutron diffraction (non-destructive).

These four techniques are being used to measure residual stresses in cold-worked and welded samples of austenitic Type 304L stainless steel (SS), and martensitic Alloys EP-823 and HT-9. Alloy EP-823 is a leading structural material to contain molten lead-bismuth-eutectic (LBE) nuclear coolant needed for fast spectrum operations of the ADS system. Type 304L SS is a universally known corrosion resistant low carbon iron-nickel-chrome alloy having optimum formability and weldability.

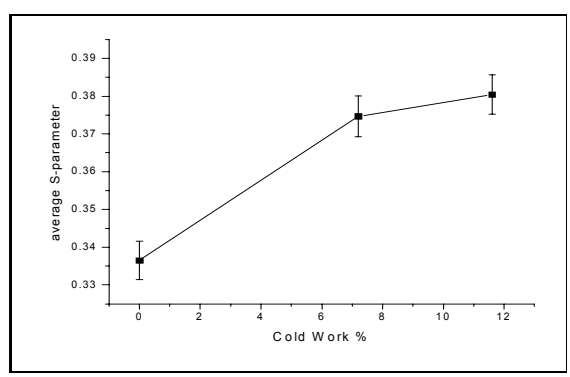


Positron Annihilation Spectroscopy Experimental Setup



S- Parameter = Area A_1/ Total Area (A)
W-Parameter = (Area A_2+Area A_3) / Total Area (A)
T-Parameter = W/S

Positron Annihilation Spectroscopy Data Interpretation



Positron Annihilation Spectroscopy Data on Cold-Worked Specimens

RESEARCH ACCOMPLISHMENTS

Experimental heats of Type 304L SS, and Alloys EP-823 and HT-9 were melted at the Timken Research Laboratory using a vacuum induction melting process. They were subsequently forged and rolled into plates of desired dimensions. Plates of both martensitic alloys were subsequently austenitized, oil quenched, and tempered to achieve a fully tempered martensitic microstructure. Type 304L SS plates were solution-annealed (austenitized and air-cooled).

Three types of specimens, namely cold-worked (7 and 11%), bent (three-point-bending), and welded specimens were prepared by using these heat treated materials. The bent specimens were fabricated at the Lambda Research Laboratory (LRL). The welded specimens were prepared by Los Alamos National Laboratory (LANL) by welding plates of similar and dissimilar materials, using gas-tungsten-arc-welding method.

All three types of specimens are currently being tested at the Idaho Accelerator Center (IAC) and LRL to determine the residual stresses using positron annihilation spectroscopy, X-ray diffraction and ring core techniques.

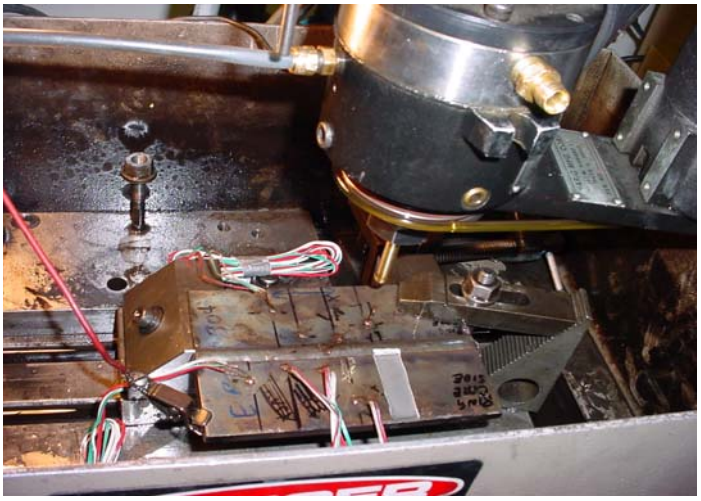
FUTURE WORK

The second year of this task includes the following scope of work:

- Perform positron annihilation spectroscopy measurements on cold-worked and welded specimens at IAC.
- Establish calibration curves by PAS measurements on unstressed/stressed tensile specimens.
- Perform residual stress measurements by neutron diffraction method at Atomic Energy Canada Ltd (AECL)/ LANL.
- Use transmission electron microscopy to analyze imperfections/defects resulting from plastic deformation/ welding.
- Perform metallographic evaluation of welded specimens by optical microscopy to reveal microstructural differences between the base metal and the heat affected zone.
- Determine residual stresses in all materials including Alloy 718, irradiated and unirradiated.

HIGHLIGHTS

- "Residual Stress Measurement in EP-823 Using Non-Destructive Evaluation Techniques", presented at the ANS Student Conference, Berkeley, CA, April 2-5, 2003.
- "Residual Stress Measurement in Type 304 Stainless Steel Using Non-Destructive Techniques", presented at the (ANS) Student Conference, Berkeley, CA, April 2-5, 2003.
- "Residual Stress Measurements by Non-Destructive and Destructive Methods" presented at the ANS annual Meeting, San Diego, CA, June 1-5, 2003.
- "Applications of Electron Linacs in Defect and Stress Measurements" presented at the ANS annual Meeting, San Diego, CA, June 1-5, 2003.
- "Residual Stress Measurements for Spallation Target Materials" to be presented at the ASM International Surface Engineering Congress, Indianapolis, IN, September 15-17, 2003.
- "Residual Stress Measurements by Positron Annihilation Spectroscopy" to be presented at the 46th Annual Non-Destructive Testing Forum, Montreal, Quebec, Canada, September 22-25, 2003.
- "Residual Stress Measurements in Target Materials" to be presented at the SAMPE Technical Conference, Dayton, OH, September 28-October 2, 2003.



Ring-Core Method

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Task 15

Immobilization of Fission Iodine by Reaction with a Fullerene Containing Carbon Compound and Insoluble Natural Matrix

S.M. Steinberg, G.S. Cerefice, and D.W. Emerson

BACKGROUND

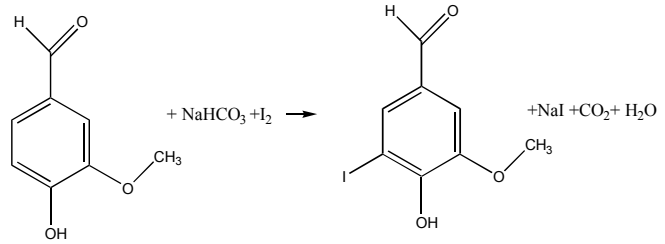
The recovery of iodine released during the processing of used nuclear fuel poses a significant challenge to the transmutation of nuclear waste. Iodine-129, a long-lived fission product formed by both commercial nuclear power generation and nuclear weapons production, is released when reprocessing nuclear fuel. Since iodine can be concentrated in the human thyroid, any uncontrolled release of iodine may result in an increased rate of thyroid cancer in the exposed population. For this reason, recovery of iodine is important for implementing any nuclear transmutation strategy.

The first step in any transmutation strategy is the processing of the used nuclear fuel. This step involves separating the used fuel into its constituent elemental components, allowing the recovery of the uranium, actinides, long-lived fission products, and other components, depending on the strategy and processes involved. This involves declading the used fuel rods and dissolving the fuel pellets with concentrated nitric acid. The elements of interest are then extracted from the acid solution and the spent acid solution is further processed to immobilize or recover other byproducts.

When used fuel rods are dissolved in concentrated nitric acid in preparation for actinide recovery, iodine is released from the fuel. A significant fraction of the iodine is lost to the vapor phase during this process, where it may potentially become a fugitive emission and be released from the plant. To avoid this, specialized filtration systems are used to try to trap and sequester the released iodine (and other fission product gases).

The primary goal of this research is to capture and immobilize the iodine released from these processes in a form that can easily be converted to a suitable target for neutron-induced transmutation. The investigators believe that iodine released during fuel reprocessing can be immobilized in a Fullerene Containing Carbon (FCC) compound or a Natural Organic Matter (NOM) matrix.

Natural organic matter (such as spaghnum moss, peat or brown coal) is an inexpensive and a renewable resource. NOM contains a myriad of reactive functional groups such as phenols and a-methyl carbonyl groups that react with iodine or hypoiodite. Further processing of the trapped iodine using simple desorption or combustion processes should be able to produce iodine in a form suitable for transmutation. Furthermore, the researchers at KRI, now collaborators in this project, have proposed that the iodine-loaded FCC material, when combined with ceramics, is stable enough for use as a long-term storage form, and may be usable as a transmuter target matrix.



Ring addition of iodine to a phenolic compound.

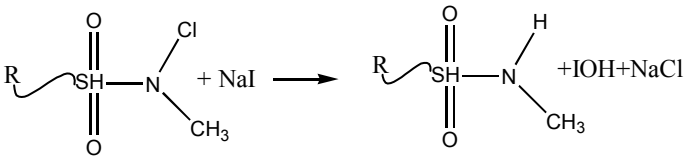
RESEARCH OBJECTIVES AND METHODS

The stability of the association of iodine with FCC and NOM products will be studied. Product distributions for the various matrices under various reaction conditions will be examined in order to maximize the binding of iodine. The recovery of the iodine from the sequestration matrices will also be examined, along with the conversion of the iodine to matrices more suitable for geological storage and/or use as transmutation targets.

The following are the specific research objectives and goals that have been identified:

- Develop bench-scale experimental set-up and procedures for simulating PUREX head-end vapor phase.
- Develop experimental procedures for evaluating iodine sequestering methods using bench-scale procedures.
- Develop FCC bearing material as potential iodine sequestration matrix.
- Determine binding of iodine to FCC and NOM.
- Examine alternate iodine sequestration matrices using techniques developed for FCC and NOM studies.
- Examine the effect of reaction conditions on binding.
- Elucidate the nature of the reaction products (volatile, hydrophobic, soluble, insoluble)
- Develop methodology and host matrix for converting sequestered iodine to solid matrix for evaluation as transmutation target and/or disposal matrix.
- Examine recovery of iodine from sequestration matrices.

The FCC compounds are developed and prepared by the Khlopin Radium Institute's Research Industrial Enterprise (KRI-KIRSI). The KRI-KIRSI team will research the impacts of process parameters on sorption of iodine, and will examine the material properties, such as how iodine attaches to the FCC compounds. The KRI-KIRSI team will also examine the conversion of the iodine loaded FCC compound to a stabilized matrix (similar to ceramic) for potential use as a disposal form, acceptable transportation material, or potential target material.



Transformation of iodide to iodine by N- chlorosulfonamide resin.

UNLV will examine the FCC material, along with NOM and other potential sequestering agents, under simulated process conditions. Both teams will examine the recovery of the iodine from the sequestering matrices.

Initial experiments for FCC characterization will be performed following construction of an iodine (I_2) vapor generator. Additionally, a device will be constructed to simulate nuclear fuel dissolution using iodine sequestration under more realistic conditions. The reversibility of the sorption of iodine on FCC will be explored through a variety of experiments. The stability of the FCC to leaching with simulated groundwater and with solutions containing various reagents that can change the oxidation state of the iodine will be assessed.

Thermal stability of the iodine-FCC association will be measured using pyrolysis mass spectrometry on the FCC material exposed to iodine vapor in simulated fuel rod processing experiments. Information from this will be useful for assessing geological stability of FCC-iodine associations and for devising a method for recovery of iodine from FCC for transmutation. Additional studies using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) may provide information to associate iodine loss with thermally induced physical and chemical transformations of the FCC sorbent.

Initial studies of iodine binding using NOM involve condensing the off-gas from nuclear fuel dissolution using a cooled trap. The role of pH in the conversion process will be examined. Iodine bound in insoluble organic matter will be measured after alkaline oxidation.

The potential production of volatile iodine species thermally released from charcoal and adsorbable organic iodide species will be measured and analyzed.

RESEARCH ACCOMPLISHMENTS

Highlights of accomplishments to date include the following:

- Several different NOM materials have been characterized.
- Iodine uptake experiments on NOM have been conducted and indicate favorable sequestration.
- The iodine vapor generator assembly was completed. Experimental results indicate that 97% of the iodine was trapped.
- Several tests of iodine sequestration/adsorption were conducted with a commercial peat moss. The results indicated extremely low breakthrough at iodine vapor concentrations close to saturation
- Ion chromatography methods to separate various iodine species were tested.
- A number of experiments have been conducted with alkali lignin and sphagnum moss to study iodide binding. The iodinated materials have been examined by pyrolysis. Researchers have discovered that pyrolysis releases the bound iodide as methyl iodide.
- The alkali stability of several model organic iodides was studied to see if base promoted hydrolysis will be useful in concentrating iodine from NOM
- Materials for a device to simulate rod acid dissolution have been received and assembly has begun on the apparatus that simulates nuclear fuel dissolution.
- The transfer of iodide to organic matter as facilitated by the chlorine sulfonamide resins was examined. Using NOM analogs, iodine was shown to become associated with organic matter in the presence of the active chlorine sulfonamide resins.

FUTURE WORK

Trials with NOM will be continued in the second year of the project. Additional sequestration experiments with the iodine generator will be performed. The effects of nitric acid vapor on the binding of iodine will be explored. Investigation into the speciation of iodine in the NOM in an exposed trap will be implemented. The role of active chlorine in iodine binding will be examined. Additionally, rate constants for the formation of iodate and for the formation of iodophenols will be estimated.

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Task 16

Evaluation of Fluorapatite as a Waste-Form Material

D.W. Lindle and D.L. Perry

BACKGROUND

High Temperature Gas-Cooled Reactor (HTGR) designs are currently being designed and evaluated as part of the Advanced Fuel Cycle Initiative, both as a future nuclear reactor design (in the Generation IV reactor program) and as a potential system for burning plutonium in a dual-tier transmutation strategy. HTGR designs use a TRISO-coated fuel (a silicon-carbide and pyrocarbon composite coating) to provide much of the passive containment for radionuclides.

Although this fuel form is quite stable and comprises one of the key components in the safety performance of these reactor systems, TRISO-coated fuel is comparatively difficult to recycle. If HGTR systems are to be used as part of either the first tier of a transmutation strategy or as primary power reactors, the plutonium and other actinides in the used TRISO fuel must be processed to recycle plutonium and permit recovery of minor actinides and other fission products produced.

Argonne National Laboratory has proposed a new extraction procedure to handle TRISO-coated fuels, the Fluoride Extraction Process, or FLEX. The FLEX process is designed to separate the uranium in the fuel from the actinides and most fission products by taking advantage of the unique properties of uranium hexafluoride (UF_6). In the FLEX process, the used TRISO fuel is reacted with zirconium fluoride salt, forming UF_6 and the fluoride salts of the actinides and fission products. At process temperatures, the UF_6 volatizes into a gas, and is released from the molten salt mixture. This leaves behind the actinides and most fission products in a fluoride salt, which is subsequently processed using pyrochemical techniques to recover the actinides and other long-lived fission products for transmutation. The UF_6 is then cooled, causing it to sublime into solid form, which is processed for disposal or reuse.

The primary waste stream from the FLEX process is the fission products from the fuel, which are in a zirconium fluoride salt at the end of the process. Due to the fluorine in this waste stream, the fluoride salts are unsuitable for conversion into the traditional borosilicate waste glass. Without a suitable disposal form, this process can not be deployed.

This research attempts to develop a waste form for disposing of the zirconium fluoride fission product waste stream. Fluorapatite, a naturally-occurring fluorinated calcium phosphate, has been identified as a potential matrix for the entombment of this waste stream. If the efficacy of fluorapatite-based waste-storage can be demonstrated, then new and potentially more efficient options for handling and separating high-level wastes, based on fluoride-salt extraction, will become feasible.

Green colored crystal (fluorapatite)

RESEARCH OBJECTIVES AND METHODS

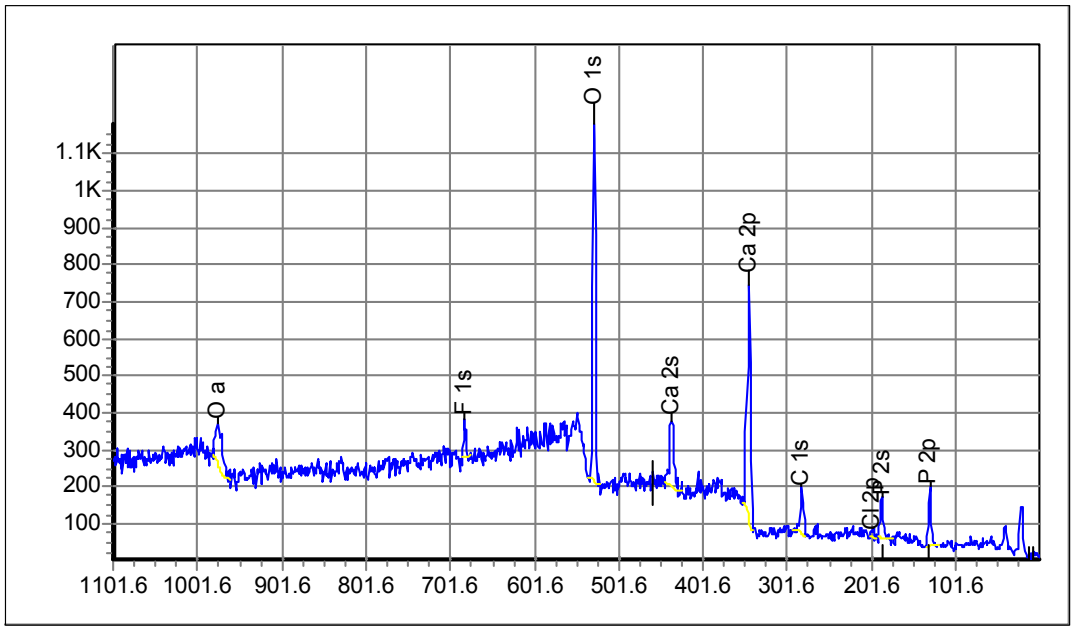
The following are the specific research objectives:

- To develop a waste matrix for the disposal of the fission product waste stream from the FLEX process;
- To develop a process to make synthetic fluorapatite that incorporates the FP-bearing ZrF_4 salt;
- To develop a fundamental understanding of the chemistry of this new waste form in order to better predict its long term behavior in a repository environment;
- To develop a fundamental understanding of natural, fluoride-bearing mineral phases to use as natural analogs to bound the predicted behavior of the FLEX fission product waste stream.

The research effort has been divided along two parallel paths: the Fabrication path, led by collaborators at the Khoplin Radium Institute (KRI) in St. Petersburg, Russia; and the Characterization path, led by researchers from UNLV.

The Fabrication path is focused on examining and evaluating various techniques for fabricating synthetic fluorapatite; synthesizing synthetic fluorapatite; and examining the impacts of waste loading and other fabrication process factors on the performance of the synthetic fluorapatite as a potential waste form.

The Characterization path is focused on adapting and refining the X-ray spectroscopy techniques currently used to characterize borosilicate glass for use in examining the fluorapatite system. This path will also encompass the examination of the ceramic and synthetic mineral waste forms created at KRI, with subsequent examination of these techniques to develop a molecular-level understanding of natural fluorapatite and other fluorine-bearing natural phases as natural analogs for the waste form. These techniques will also be used to examine the changes in surface chemistry caused by environmental degradation of these materials.



X-ray Photoelectron Spectroscopy (XPS) data for Hydroxyapatite.

Composition Table

XPS Line	Atom %
C 1s	16.494
F 1s	2.914
O 1s	46.569
Ca 2p	19.344
Cl 2p	1.000
P 2p	13.679

Waste form development at KRI involves the formulation, synthesis, and examination of ceramic samples to investigate the impact of processing parameters and composition on material properties (e.g. homogeneity) and performance (via leach testing). The most promising fabrication process developed will be used to synthesize the ceramic in varying compositions to examine the impact of process parameters, ceramic formulation, and waste loading on the final ceramic phase. Based on these experiments, a baseline composition and fabrication process will be established. Finally, alternate fabrication processes, compositions, and potential alternate waste matrices will be examined and compared against the baseline composition.

Waste form characterization carried out at UNLV employs state of the art techniques that characterize the molecular structure of both natural fluorapatite and fluoride-bearing minerals and the fluorapatite-based ceramic waste form. Changes in the surface/interfacial chemistry of these materials as they undergo reactions with species in the environment will also be examined to help develop a basis for understanding the corrosion chemistry that the waste form and its natural analogs may experience under repository conditions.

RESEARCH ACCOMPLISHMENTS

Research highlights for the first year can be summarized as follows:

- Baseline XPS, FT-IR, and Raman spectra have been obtained for hydroxyapatite and fluorapatite.
- Natural fluorapatite crystals have been obtained commercially, and will be examined spectroscopically to determine what contaminants naturally occur.
- Plans were developed for chemically preparing samples in which some of the calcium in apatite materials is substituted by non-radiaoctive actinide surrogates or elements produced by decay of actinides.
- SEM images of natural fluorapatite crystals have been obtained, indicating the presence of natural inclusion containing transition metals (e.g. Ni), possibly providing useful information for comparison of man-made wastes with the same or similar species.

FUTURE WORK

Continued research efforts will focus on developing a fluorapatite-based waste form and a fabrication process/flow sheet for the FLEX process fission product waste stream. The research will include characterizing the molecular structure and corrosion behavior of natural fluorapatites and fluorapatite-based waste forms.

Research Staff
Dennis W. Lindle, Principal Investigator, Professor, Chemistry Department
Dale L. Perry, Lawrence Berkeley National Laboratory, Adjunct Professor, UNLV Department of Physics

Students
Chirantha Rodrigo and Chinthalka Silva, Graduate Students, Chemistry Department

Collaborators
James J. Laidler, Senior Scientist, Chemical Technology Division, Argonne National Laboratory
Alexander A. Rimsky-Korsakov, Director General, V. G. Khlopin Radium Institute, St. Petersburg, Russia
Evgeniy B. Anderson and Boris E. Burakov, V. G. Khlopin Radium Institute, St. Petersburg, Russia

Materials Performance Laboratory

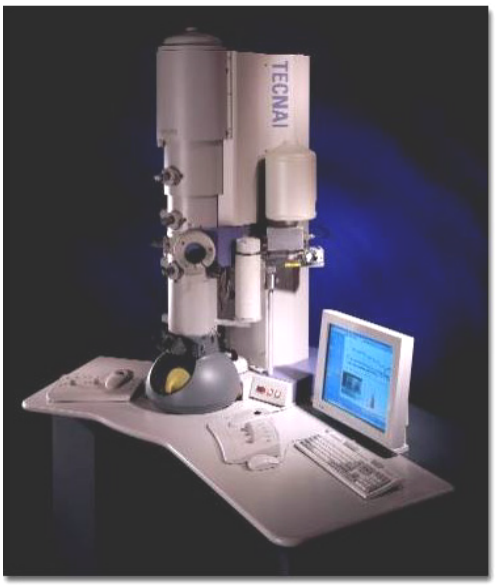
To support research into the materials properties of candidate structural materials for transmutation applications, the UNLV Transmutation Research Program established the Materials Performance Laboratory (MPL) during the first year of the program. By leveraging ongoing research efforts at UNLV, the MPL was equipped with state-of-the-art systems for conducting materials properties experiments (yield strength, ductility, constant load testing, slow strain rate testing, crack propagation, etc.) while exposing materials to a variety of conditions. These systems allow the researchers to study the susceptibility of many metallic materials to environmentally-induced degradation phenomena, such as localized corrosion, stress corrosion cracking and hydrogen embrittlement, using both conventional and electrochemical test methods. Pictures of equipment in the MPL can be found on pages 12 and 25.

Major Equipment, Instruments, and Capabilities

- Constant Load Systems (Cortest Constant Load Testing Fixtures, 7500 lb Load Capacity)
- High-Temperature (up to 500°C) Corrosion-Resistant Autoclave
- Electrochemistry systems (EG&G Model 273A Potentiostats)
- High Temperature (up to 1000°C) Inert Gas Furnace Chamber and Materials Test System (MTS) unit
- Optical Microscopy (Leica Optical 1000X resolution system)
- Sample Preparation Equipment (Heat treatment furnace, precision saw, sample polisher)

Transmission Electron Microscope (TEM)

The ability to understand and examine the world at the atomic level has become one of the most powerful tools available to researchers studying materials science, biology, biochemistry, nanotechnology, computer design, and many other cutting edge fields. To expand the capabilities of researchers at UNLV to study systems at the atomic scale (sub-nanometer to Angstrom), the Transmutation Research Program has acquired a new, state-of-the-art Transmission Electron Microscope (TEM). The new system, the Technai F-30 S/TEM, utilizes a 300 keV electron accelerator to view images with a resolution of less than 2 Angstroms (0.2 nm), providing researchers with the equivalent of 1,350,000 times magnification of the image. The system is also equipped with both Energy Dispersive Spectrometry (EDS) and Electron Energy Loss Spectrometry (EELS) systems, which will allow researchers to not only "see" systems at the atomic level, but to also determine elemental and even chemical composition. This system will be one of the best available in the university community, and should serve as a bridge for expanding collaborative research with other universities around the country. The system is expected to be deployed and available for researchers by the end of 2003.



Electron Microanalysis and Imaging Laboratory (EMIL)

Students at work on the JEOL-5600 Scanning Electron Microscope.

To maintain the research infrastructure necessary for the ongoing materials research work under the Transmutation Research Program (Tasks 3, 4, 10, and 14), the TRP has continued its support of the Electron Microanalysis and Imaging Laboratory (EMIL). The EMIL facility was developed under a cooperative agreement between the Department of Energy – Office of Civilian Radioactive Waste Management to study fluid inclusions in rock from the Yucca Mountain site, and has since been used by a variety of UNLV researchers in support of faculty research, Ph.D. dissertation and Master's thesis research in a diverse set of scientific disciplines, including geology, biology, physics, and engineering. The primary workhorses of the EMIL facility are the Scanning Electron Microscope (SEM) and the Electron Microprobe.

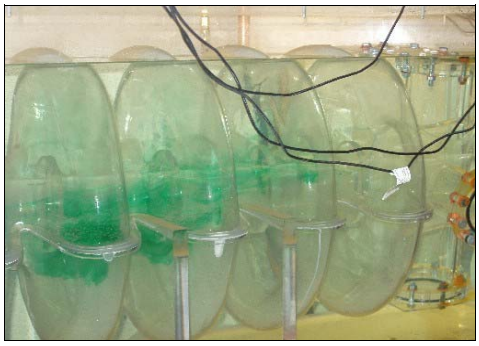
The JEOL-5600 Scanning Electron Microscope is optimized for imaging micron to millimeter scale topography. The system is also equipped with a backscattered electron detector and an energy dispersive spectrometer, capable of qualitative compositional (elemental) analysis. Topographic and compositional images can be processed on the screen to show pseudo-color and critical point measurements of features.

JEOL-8900 Electron Probe Microanalyzer.

The JEOL-8900 Electron Probe Microanalyzer allows researchers to perform quantitative, non-destructive, chemical analyses of solid materials at the micron scale. The system uses four automated wavelength dispersive spectrometers and an energy dispersive spectrometer to collect a full spectrum of X-rays simultaneously. These spectrometers can examine up to eight elements at a time while obtaining high-precision X-ray maps and line scans of spatial variation in chemical composition. With these detectors, researchers can either observe "real time" images or collect automated images in tandem with X-ray mapping to further characterize the area of interest.

Flow Visualization System

One of the most basic tools available for understanding any system is the ability to directly observe the phenomena and processes occurring in the system. This is particularly true for analyzing fluid flow, or fluid dynamics, problems. In support of the research already underway at UNLV as part of Task 2 on optimizing accelerator cavity fabrication, the TRP acquired a flow visualization system, which consists of a computer-controlled traverse mechanism and high-speed digital camera, along with the supporting electronics and analytical software.

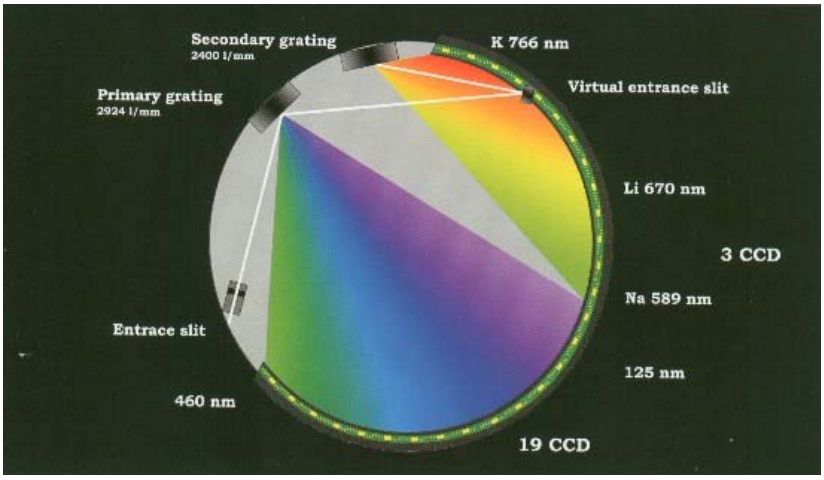


This system will allow researchers to directly observe the flow paths in the system, providing an increased understanding of the processes occurring within the system, as well as allowing researchers to quantitatively measure the velocities and flow vectors through the use of the digital camera systems and computer software. For the experiments shown in the accompanying pictures, and on page 9, the system was used to analyze an optically transparent full-scale mock-up of the spoke resonator cavity, developed at LANL and provided to UNLV by the Task 2 collaborators.

Inductively Coupled Plasma – Atomic Emission Spectrometer

The ability to rapidly determine elemental concentrations is a fundamental tool for the study of most chemical systems, including the study of chemical process streams, corrosion products, etc. Emission spectroscopy, in which sample elements are induced to emit light at characteristic wavelengths, is a common tool for determining elemental concentrations, providing researchers with a tool to easily measure concentrations below the parts per million (ppm) level for most elements without significant sample preparation.

To augment the analytical research capabilities at UNLV, the TRP has acquired a new Inductively Coupled Plasma – Atomic Emission Spectroscopy system, the CirOS ICP-AES. This solid-state, computer controlled system is expected to be installed and available to researchers by the end of the summer. In support of the research into the sequestration of Iodine by carbon-containing materials (Task 15), the ICP-AES will be coupled with a new pyrolysis system (CDS AS2500), allowing researchers to directly analyze solid carbon samples without the need for additional sample preparation or extraction processes.



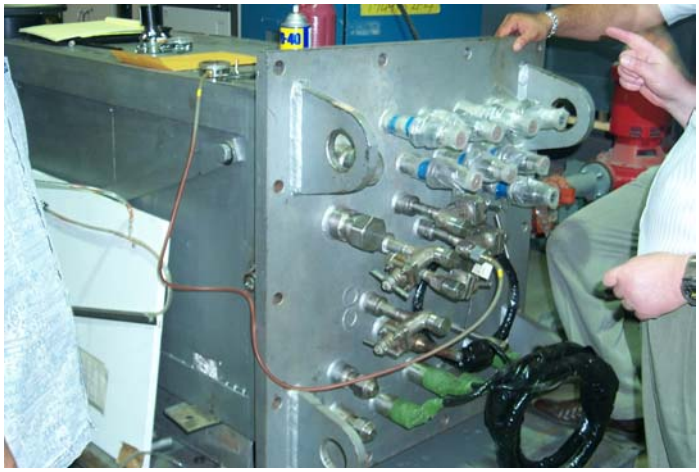
Vertical Machining System

During the first year of the TRP, experimental researchers (Tasks 2, 3, 4, and 10, in particular) encountered a persistent problem: the campus lacked the necessary infrastructure to fabricate samples and components needed to support their research efforts. Researchers were forced to send samples and components off campus for fabrication, significantly adding to the experimental costs, or had to fabricate the components in the existing, out-dated machine shops, greatly increasing the time and effort required and delaying the experiments. To address this problem, the TRP, along with other major research programs at UNLV, acquired a new vertical machining system, the Haas VF5 Vertical Machining Center, to upgrade the fabrication facilities at UNLV. The VF5 system is a 3-axis, computer-controlled, automated fabrication system capable of machining metallic components and samples directly from the CAD (Computer-Aided Design) drawings. By changing the tools, the system can be adapted for machining most metals, and even some ceramics, greatly expanding the fabrication capabilities for the campus.

Target Complex 1 – "the Lead-Bismuth Loop"

In 1998, the International Science and Technology Center began the design and construction of a prototype lead-bismuth eutectic accelerator target, the Target Complex 1 (TC-1), under ISTC Project #559 ("Pilot Flow Lead-Bismuth Target of 1 MW Power for Accelerator Driven Systems"), in support of the international efforts to develop accelerator-driven spallation systems for nuclear transmutation and other applications. The TC-1 design, fabrication, and initial testing were completed at the Institute of Physics and Power Engineering (IPPE) in Obninsk, Russia, in mid-2001. The system was then prepared for transport and shipped to UNLV, arriving in May 2002, where the performance testing and out-of-beam experiments will be performed.

Scientists from Russia, Los Alamos, and UNLV evaluate the condition of Target Complex 1 after delivery.



Leak testing is performed on Target Complex 1.

To support the loop, significant modifications were required to the facilities in the Thomas Beam Engineering complex, including the design of a seismically-stable stand, as well as the addition of new transformers to provide the power (and voltages) required for the system. The design efforts have been completed, and the modifications to the facility are underway. It is expected that the TC-1 loop will be mounted into the stand by the end of the summer, and that the final installation of the TC-1 will be completed by year's end.

Delivery of Target Complex 1 to UNLV on May 29, 2002.

Target Complex 1 awaiting installation in UNLV's Howard R. Hughes College of Engineering.

UNLV TRP WORKSHOPS AND EVENTS
Academic Year 2002-2003

May 28, 2002
ISTC Target Complex 1 arrives from LANL for new LBE loop facility

June 1, 2002
Dr. Robert Fairhurst joins the College of Science

June 5, 2002
UNLV Materials Performance Laboratory holds Open House. The MPL is officially completed.

June 20, 2002
TEM (valued at over $2 million) purchased from FEI for $1.3 million.

June 27, 2002
UNLV TRP Director gives invited presentation on transmutation to the Clark County Yucca Mountain Nuclear Waste Advisory Committee.

July 13, 2002
Two UNLV graduate students begin their summer internships at Los Alamos National Laboratory.

July 29 - August 2, 2002
Russian scientists visit UNLV to evaluate TC-1 lead-bismuth eutectic loop.

August 1-2, 2002
UNLV hosts the International Molten Metal Advisory Committee meeting.

August 21-30, 2002
UNLV TRP Director participates in the Frederic Joliot and Otto Hahn Reactor Physics Summer School on transmutation technologies.

August 26, 2002
Fall academic term begins: 2 new student research tasks start, 8 continuing student research tasks begin their second year.

September 30, 2002
UNLV TRP Director gives invited presentation to the NERAC Subcommittee on Advanced Nuclear Transformation Technology in Washington, DC.

October 4-6, 2002
Transmutation poster displayed at the Pahrump Harvest Festival.

January 10, 2003
AFCI Performance Evaluation Review Meeting, Las Vegas, NV. UNLV TRP receives an "excellent" score of 94.

January 22-24, 2003
AFCI Semi-Annual Review Meeting, Albuquerque, NM. UNLV TRP presents 7 posters.

January 30, 2003
UNLV applies to the International Science and Technology Center for Partner Organization status.

April 2-5, 2003
ANS Student Conference, Berkeley, CA. UNLV TRP sends 27 students who presented 17 papers at the University of California, Berkeley. UNLV TRP students awarded one best session award and two outstanding presentation awards.

April 14, 2003
UNLV TRP Director gives invited presentation to the MIT Nuclear Engineering Department.

April 17, 2003
UNLV hosts a workshop on High Temperature Heat Exchangers.

April 28, 2003
UNLV approves a new Ph.D. program in Radiochemistry. Program proposal submitted to the Board of Regents of the University and Community College of System of Nevada.

April 29, 2003
UNLV hosts an international workshop on Accelerator-Driven Transmutation System Technologies.

May 15, 2003
Two UNLV professors visit Los Alamos National Laboratory to participate in the installation and demonstration of the German-made Oxygen Control System.

May 19, 2003
Summer academic term begins: 2 continuing student research tasks begin their second year, 4 continuing student research tasks begin their third and final year.

June 1-5, 2003
ANS Annual Meeting, San Diego, CA. 13 UNLV students and 10 faculty attend from the UNLV TRP. 14 papers and posters are presented. UNLV TRP undergraduate student Dean Curtis awarded best overall poster at the Accelerator Applications Division poster session.

June 9-10, 2003
AFCI Materials Modeling and Simulations for Nuclear Fuels Workshop, Santa Fe, NM. Two faculty and one student from UNLV TRP participate.

Transmutation Research Program
Financial Statement

Program Administration	FY01	FY02	TOTAL
Program Support			
Labor	$187,305	$316,395	$503,700
Travel (e.g. conferences, meetings)	$95,082	$82,087	$177,169
Other Costs (e.g. services, supplies)	$51,502	$31,871	$83,373
LANL Subcontract	$150,000	$162,500	$312,500
Infrastructure Augmentation: New Hires	$121,887	$290,648	$412,535
Infrastructure Augmentation: Facilities	$1,490,919	$768,862	$2,259,781
International Collaboration	$112,500	$348,457	$460,957
Totals	**$2,209,195**	**$2,000,820**	**$4,210,015**
Student Research Tasks			
Labor	$524,323	$1,718,660	$2,242,983
Other Costs	$266,482	$780,520	$1,047,002
Totals	**$790,805**	**$2,499,180**	**$3,289,985**
Totals	**$3,000,000**	**$4,500,000**	**$7,500,000**

Student Research Task by Task

	FY01	FY02	Total
Task 1	$97,379	$185,495	$282,874
Task 2	$127,146	$195,148	$322,294
Task 3	$98,896	$285,346	$384,242
Task 4	$108,615	$179,270	$287,885
Task 5	$40,655	$142,081	$182,736
Task 6	$58,952	$219,403	$278,355
Task 7	$55,565	$201,791	$257,356
Task 8	$57,700	$206,215	$263,915
Task 9	$21,609	$109,376	$130,985
Task 10	$57,175	$112,610	$169,785
Task 11	$41,308	$68,815	$110,123
Task 12	$25,805	$146,974	$172,779
Task 13		$146,048	$146,048
Task 14		$120,438	$120,438
Task 15		$74,050	$74,050
Task 16		$106,120	$106,120
Totals	**$790,805**	**$2,499,180**	**$3,289,985**

Infrastructure Facilities Augmentation

	FY01	FY02	Total
Electron Microanalysis and Imaging Laboratory	$42,313	$63,000	$105,313
Materials Performance Laboratory	$148,606	$78,887	$227,493
Transmission Electron Microscope	$1,300,000	$159,369	$1,459,369
ICP – Atomic Emission Spectrometer		$106,675	$106,675
Lead-Bismuth Eutectic Facilities		$241,862	$241,862
Vertical Machining System		$73,200	$73,200
Flow Visualization System (Task 2)		$22,207	$22,207
Pyrolizer, Baths, and Controller (Task 15)		$23,662	$23,662
Totals	**$1,490,919**	**$768,862**	**$2,259,781**

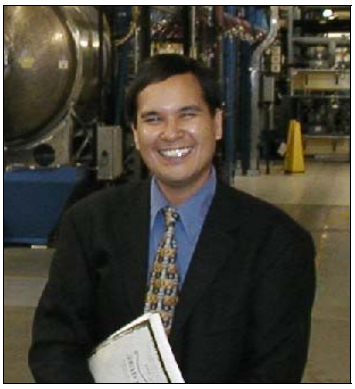
International Collaboration

Khlopin Radium Institute Contracts	$112,500	$229,500	$342,000
International Science and Technology Center Contracts		$87,500	$87,500
International Collaboration Program Coordinators		$31,457	$31,457
Totals	**$112,500**	**$348,457**	**$460,957**

Photo Gallery

Transmutation Research Program Organizational Chart

Program Administration



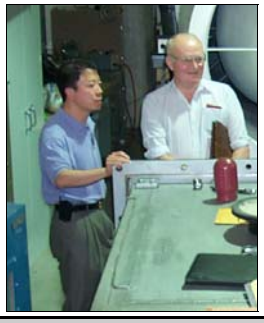
Director,
Anthony E. Hechanova (HRC)

Finance Director,
Patricia Baldwin (HRC)

Deputy Director, Harry Reid Center
Gary S. Cerefice

Deputy Director, College of Engineering
William G. Culbreth

Deputy Director, College of Sciences
Malcolm F. Nicol



International Programs Coordinator
Ning Li (LANL)

Intercollegiate Programs Coordinator
Denis Beller (LANL)

Conference Coordinator
Kathleen D. Lauckner (HRC)

Ning Li and IPPE Laboratory Head Evgeny Yefimov with Russian-built loop at UNLV.

Thomas Ward and Khlopin Radium Institute General Director Alexander Rimski-Korsakov in St. Petersburg, Russia.

International Programs Adviser
Thomas Ward

Transmutation Research Program Support Staff and Students

Materials Performance Laboratory College of Engineering

Research Associate,
Konstantin G. Zabotkin, MPL
College of Engineering

Mechanical Engineering Associate Research Professor Ajit Roy (left) explains some MPL experiments to Harry Reid Center Executive Director Donald Baepler.

Electron Microanalysis and Imaging Laboratory, College of Sciences

EMIL Research Scientist
Robert Fairhurst
College of Sciences

Dr. Fairhurst recieved his B.S. in Applied Chemistry from Nottingham University in 1995, and his Ph.D. in Chemistry from the University of Houston in 2002. He currently provides research support in his role as Research Technician and currently he manages the Electron Microanalysis & Imaging Laboratory .

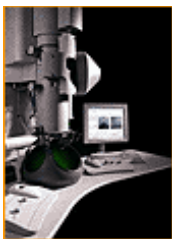
The JEOL-5600 Scanning Electron Microscope (SEM) is optimized for imaging micron to millimeter scale topography. Resolution of up to 50 nm at 100,000 times magnification is possible.

The JEOL-8900 Electron Probe Microanalyzer (EPMA) is optimized for quantitative, non-destructive chemical analysis of solid materials on a micron scale.

Transmission Electron Microscope Harry Reid Center

TEM Research Scientist
Longzhou Ma
Harry Reid Center

Dr. Ma's experience in superalloy environmental-assisted crack propagation studies, fracture mechanics analysis, microstructure characterization using SEM, TEM and optical microscopy, as well as materials failure analysis augment his role in the Transmutation Research Program.



This highly versatile tool is used to explore in-depth structure within the microscopic world in disciplines spanning life sciences and materials sciences. This acquisition institutes tremendous scientific advancement for research at UNLV and within the research community.

Photo Gallery

Transmutation Research Program Student and Faculty Researchers

Harry Reid Center
Student and Staff Support

Laboratory Manager
Jeanette Daniels
Harry Reid Center

Elizabeth Johnson
Technical Writing

Christina Crossan (U)

David Edwards (U)

Demian Gitnacht (U)

Ingrid James (U)

John Knoten (U)
Webmaster

Joe Lloren (U)

Mosese Ohia (U)

Erica Summers
Administrative Assistant

Diana Switaj (U)

Photo Gallery

Transmutation Research Program Student and Faculty Researchers

Task 1
College of Engineering

Principal Investigator
Yitung Chen
Interim Director, NCACM

Darrell W. Pepper
Interim Dean
College of Engineering

Randy Clarksean
Adjunct Professor
Mechanical Engineering Department

Xiaolong Wu (G)

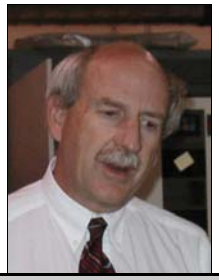
Taide Tan (G)

Not Pictured: *Byarlaga Yarlagadda (G)*
Yulien Chen (U)

Task 2
College of Engineering

Co-Principal Investigator
Robert A. Schill, Jr.
Associate Professor, ECE Department

Co-Principal Investigator
Mohamed B. Trabia
Chair, ME Department



William Culbreth
Associate Dean for Research
College of Engineering

Satishkumar Subramanian (G)

Anoop George (G)

Myong Holl (U)

Photo Gallery

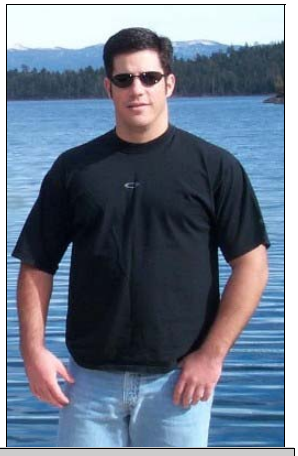
Transmutation Research Program Student and Faculty Researchers

Task 3
College of Sciences

Principal Investigator
John Farley
Professor, Department of Physics

Allen Johnson
Assistant Professor, Chemistry

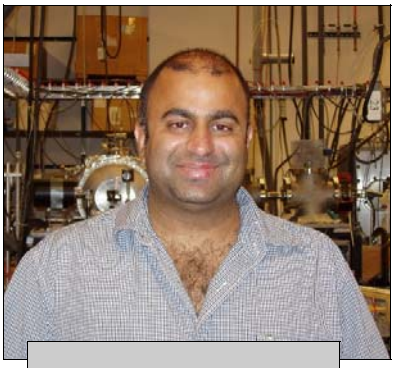
Dale Perry (LBNL)
Adjunct Professor, Physics



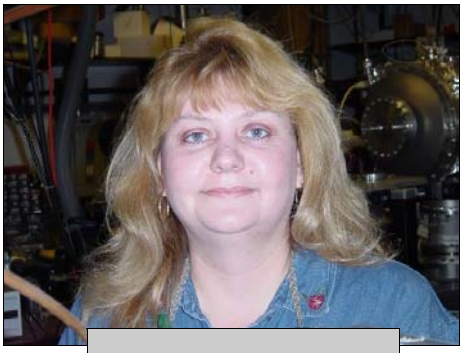
Dan Koury (G)

Brian Hosterman (G)

Julia Manzerova (G)



Umar Younas (G)



Denise Parsons (U)

Transmutation Research Program Student and Faculty Researchers

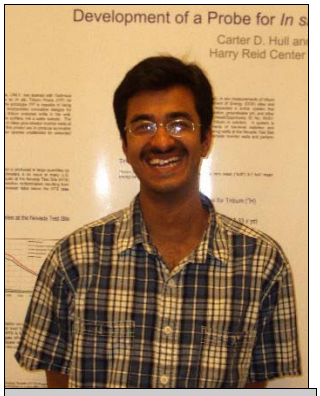
Task 4
College of Engineering

Co-Principal Investigator
Ajit K. Roy
Associate Res Prof, ME Dept

Co-Principal Investigator
Brendan J. O'Toole
Associate Professor, ME Dept

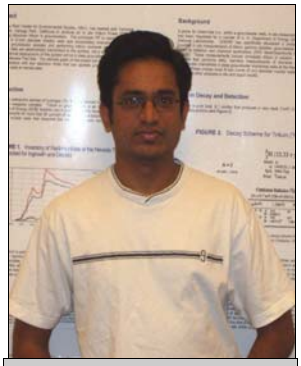
Zhiyong Wang
Assistant Professor, ME Dept

David Hatchett
Assistant Professor
Chemistry Department



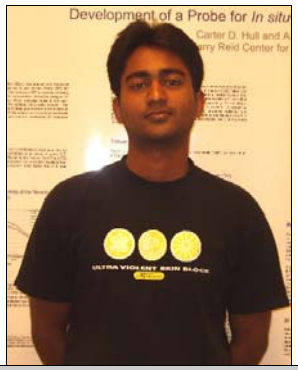
Phani Gudipati (G)

Mohammad Hossain (G)



Sudheer Sama (G)

Ramprashad Prabhakaran (G)



Venkataramakrishnan Selvaraj (G)

Photo Gallery

Transmutation Research Program Student and Faculty Researchers

Task 5
College of Engineering

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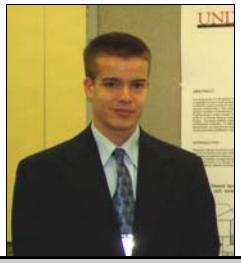

Dean Curtis (U)

Transmutation Research Program Student and Faculty Researchers

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Photo Gallery

Transmutation Research Program Student and Faculty Researchers

Task 9
College of Engineering

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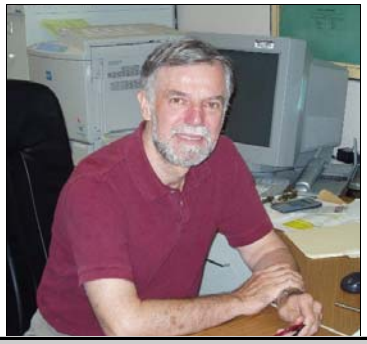

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Transmutation Research Program Student and Faculty Researchers

Task 11
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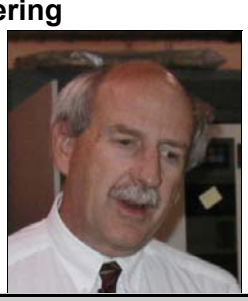

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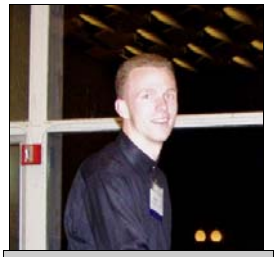
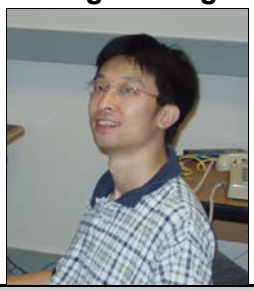


Daniel Lowe (U)

Photo Gallery

Transmutation Research Program Student and Faculty Researchers

Task 13
College of Engineering



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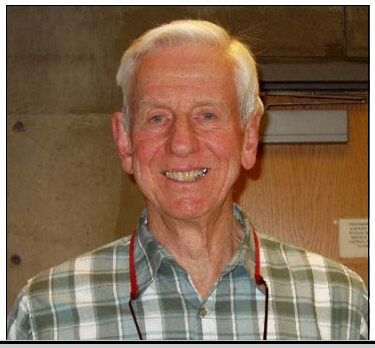

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Acronyms

AAA	Advanced Accelerator Applications
ADS	Accelerator driven transmutation systems
AECL	Atomic Energy Canada, Ltd.
AFCI	Advanced Fuel Cycle Initiative
ALI	Annual Limit on Intake
AMUSE	Argonne Model for Universal Solvent Extraction
ANL	Argonne National Laboratory
ANL-CTD	Argonne National Laboratory, Chemical Technical Division
ANS	American Nuclear Society
ASME	American Society of Mechanical Engineers
BNL	Brookhaven National Laboratory
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CPP	Cyclic potentiodynamic polarization
DAC	Derived Air Concentration
DC	Dose Coefficient
DSC	Differential Scanning Calorimetry
EDAX	Energy dispersive x-ray spectroscopy
EDISTR	Nuclear database generator for internal radiation dosimetry calculation
EDS	Energy Dispersive Spectrometry
EELS	Electron Energy Loss Spectrometry
EMIL	Electron Microanalysis and Imaging Laboratory
ENSDF	Evaluated nuclear structure data file
FCC	Fullerene containing carbon
FEMLAB	A software system to model and simulate scientific and engineering problems based on partial differential equations
FGR	Federal Guidance Report
FLEX	Fluoride extraction process
GUI	Graphical User Interface
HTGR	High Temperature Gas-Cooled Reactor
HRC	UNLV Harry Reid Center for Environmental Studies
IAC	Idaho Accelerator Center
ICAPP	International Congress on Advanced Nuclear Power Plants
ICP-AES	Inductively Coupled Plasma—Atomic Emission Spectrometer
ICRP	International Commission on Radiological Protection
IHLRWM	International High Level Radioactive Waste Management
IPPE	Institute for Physics and Power Engineering, Obninsk, Russia
ISCA	International Society for Computers and Their Applications
ISTC	International Science and Technology Centre
JINS	Joint Institute for Neutron Sciences
KRI	Khlopin Radium Institute, St. Petersburg, Russia
KRI-KRISI	Khlopin Radium Institute Research Industrial Enterprise, St. Petersburg, Russia
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LBE	Lead-Bismuth-Eutectic
LBNL	Lawrence Berkeley National Laboratory
LCS	LAHET code system
Linac	linear accelerator
LRL	Lambda Research Laboratory
MATLAB	A software system integrating mathematical computing and visualization to provide a flexible environment for technical computing

Acronyms

MCNP	Monte Carlo n-particles
MCNPX	Monte Carlo n-particles code, extremely high-energy version
MPI	Message Passing Interface
MPL	UNLV Materials Performance Laboratory
MTS	Materials Testing System
NERAC	DOE Nuclear Energy Research Advisory Committee
NICEST	Neutrons in Solid State Chemistry and the Earth Sciences Today and Tomorrow
NOM	Natural Organic Matter
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PAS	Positron annihilation spectroscopy
SAMPE	Society for the Advancement of Material and Process Engineering
SCC	stress corrosion cracking
SEE	Secondary electron emission
SEM	Scanning Electron Microscope
SIMS	Secondary Ion Mass Spectrometer
SNS	Spallation-Neutron-Source
SR	synchrotron radiation
SS	Stainless Steel
SSR	Slow Strain Rate
TC-1	Target Complex 1
TEM	Transmission Electron Microscope
TGA	Thermogravimetric Analysis
TRISO	A silicon carbide and pyrocarbon composite coating
TRP	Transmutation Research Program
TTF	time-to-failure
UNLV	University of Nevada, Las Vegas
UREX	Uranium Extraction process
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction
XRFF	X-ray fluorescence
YSZ	Yttria-stabilized zirconia

The Last Page

References

UNLV Transmutation Research Program references, current activities and other miscellaneous information can be found on the TRP website at http://aaa.nevada.edu

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This report was produced by Anthony Hechanova, Elizabeth Johnson, Erica Summers and Gary Cerefice.

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