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

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April 12, 2001

Dr. Yitung Chen
Assistant Director
Nevada Center for Advanced Computational Methods (NCACM)
Department of Mechanical Engineering
University of Nevada-Las Vegas
4505 Maryland Parkway, Box 454027
Las Vegas, NV 89154-4027

Dear Dr. Chen:

Having reviewed your research proposal entitled "Design and Analysis of a Process for Melt Casting Metallic Fuel Pins Incorporating Volatile Actinides," I am writing to offer my enthusiastic support for the proposed project. As a leader in the AAA/ATW fuel development program currently underway at Argonne National Laboratory, and in cooperation with other DOE laboratories, I am in a position to say that the success of your proposed work would be immensely beneficial to the ATW fuel development effort.

We currently consider a metallic alloy to be an outstanding candidate for an ATW transmutation fuel because of both the excellent irradiation performance and ease of fabrication that has been demonstrated over the years with other metallic alloy fast reactor fuels. However, the need to include volatile actinide elements (i.e., americium) in the fuel alloy presents a serious roadblock to the use of conventional injection casting processes in the fabrication of this candidate fuel form. Success in your proposed research, by identifying the primary mechanisms of actinide volatilization and transport and incorporating engineering solutions into the design of a new type of casting furnace, would be a critical component in demonstrating the overall feasibility of metallic alloys for use as transmutation fuels.

I support your proposal and wish you success in this important research endeavor.

Sincerely,

Steven L. Hayes
Manager, Fuels & Reactor Materials Section
Nuclear Technology Division

SLH:smr
pc: RF

Project Title:
Phase I: Design and Analysis for Melt Casting Metallic Fuel Pins Incorporating Volatile Actinides

April 30, 2001

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AAA Research Area: Fuels

First Year (Summer 2001–Spring 2002) Funding Request: $141,437

Abstract

UNLV investigators will evaluate and select a process for the melt casting of metallic fuel pins that contain volatile actinides. This work will be performed with the guidance of Argonne National Laboratory (ANL) engineers to insure that their knowledge and experience benefits the project. The research to be conducted during year one will center on selecting, evaluating, and modeling potential alternatives to the traditional injection casting process used at ANL. Processing conditions will be analyzed, basic models utilized, and detailed heat and mass transfer models will be developed to analyze the most promising processes. The goal of the first year of phase I is to select a casting technology, which will be further developed and tested in subsequent funding years.

Proposed Work

Candidate design concepts will be evaluated for their potential to successfully cast alloys containing volatile actinides. The selection of design concepts will be conducted in close cooperation with ANL staff. The research will center on the development of advanced numerical models to assess conditions that significantly impact the transport of volatile actinides during the melt casting process. The work will include the collection and documentation of volatile actinide properties, development of several conceptual designs for melt casting furnaces, modeling and analysis of these concepts, development of sophisticated numerical models to assess furnace operations, and analysis of these operations to determine which furnace concept has the greatest potential of success. UNLV is uniquely qualified to perform this work because of resident expertise in the analysis of engineering systems. Research efforts will focus on the development of complex heat transfer, mass transfer, and inductive heating models.

1. Background and Rationale

An important aspect of the Advanced Accelerator Applications (AAA) program is the development of a casting process by which volatile actinide element (i.e., americium) can be incorporated into metallic alloy fuel pins. The traditional metal fuel casting process uses an inductively heated crucible. The process involves evacuation of the furnace. The evacuation of the furnace also evacuates quartz rods used as fuel pin molds. Once evacuated the open ends of the molds are lowered into the melt; the casting furnace is then rapidly pressurized, forcing the molten metal up into the evacuated molds where solidification occurs.

This process works well for the fabrication of metal fuel pins traditionally composed of alloys of uranium and plutonium, but does not work well when highly volatile actinides are included in the melt. The problem occurs both during the extended time period required to superheat the alloy melt as well as when the chamber must be evacuated. The low vapor-pressure actinides, particularly americium, are susceptible to rapid vaporization and transport throughout the casting furnace, resulting in only a fraction of the charge being incorporated into the fuel pins as desired. This is undesirable both from a materials accountability standpoint as well as from the failure to achieve the objective of including these actinides in the fuel for transmutation.

The proposed research would be conducted in 3 phases. Each of the phases would be carried out over a one-year period. Phase I (discussed in this proposal) would include the study, analysis, and selection of a new casting furnace design. Phase II of the program would lead to the fabrication of a laboratory scale furnace at UNLV to demonstrate the proposed furnace concept using nonradioactive surrogate materials. Additional analysis work would be conducted during this time to validate the modeling efforts and to support the testing program. Detailed modeling work would continue from year 1 to refine the existing models and to make detailed comparisons to the experimental test results. These detailed modeling results would also be used to assist in the system design. One or two master's degree student(s) will work on the design and analysis of the proposed casting furnace system. Students would develop the drawings, work with ANL and LANL engineers and scientists to refine the proposed design, procure components, fabricate components as needed, select surrogate non-radioactive materials with the assistance of ANL and LANL scientists, develop a test plan, and perform tests. Phase III would be a joint effort between UNLV and Argonne National Laboratory (ANL) to demonstrate the acceptable use of the new furnace in a simulated remote environment, possibly at ANL-W using actinide elements. The Phase III work would include the design and modification/fabrication of a small test furnace for remote operation. Students would work directly with ANL and LANL scientists to modify the existing furnace, or to fabricate a new furnace for use in a simulated remote environment.

Students will be assigned to ANL-W to work in conjunction with scientists there to design and fabricate the furnace. Testing would be conducted using actinide elements. Model refinement would continue to overcome any limitations or shortcomings exhibited during Year 2 of the project. Some materials property testing could possibly be included to better define some of the transport properties needed to accurately model the proposed furnace.

Some of the casting furnace techniques that will be evaluated include the skull crucible approach, continuous casting, and the modification of the present process to operate at higher pressures.
Three major positive outcomes of the project are: (1) Develops the infrastructure to assist in dealing with spent nuclear waste and trains engineers in the issues involved with spent fuel processing and ultimately transmutation. (2) Students will gain practical experience in the analysis and design of casting equipment, which directly applies to the materials processing industry across Nevada and the U.S. (3) It expands on the expertise that already exists in computational analysis of engineering systems at UNLV and applies that knowledge to materials processing. The types of casting processes to be examined are used throughout the industry. Gaining expertise and knowledge in these areas enhances the ability of UNLV to expand its research program and to aid in the process of dealing with spent nuclear fuel. In addition, the experience will also assist the materials processing industry across the state of Nevada as needed.

2. Research Objectives

There are three research objectives for year one of this project. These objectives are to

1. Document volatile actinides transport properties and issues,
2. Parametrically model/evaluate volatile actinide transport, and
3. Select a melt casting process that has the most potential for casting metallic fuel pins, which contain volatile actinide elements.

The key to the success of this project is to clearly define and understand the transport of the volatile actinide elements of interest (i.e. americium). Successfully completing each of the research objectives will insure a clear understanding of the physics controlling the volatilization and transport of the actinide elements. By understanding these transport issues, one can more effectively evaluate potential casting processes. This evaluation process will allow the determination of which process has the most potential to successfully cast metallic fuel pins that contain volatile actinides.

The documentation of the transport issues is important to clearly define the scope of the problem. Work in support of this activity will include literature research and possibly the numerical estimation of physical properties. Experiments may also be recommended for future testing if key information is not available or cannot accurately be estimated.

Parametric models will be used to assess the impact of process parameters on the transport of the volatile actinides. Varying process parameters (temperatures, pressures, alloying elements, etc.) in general process models will determine which process parameters are critical in retaining the volatile actinides in the metallic fuel pins. If data is not available for specific properties, we can parametrically vary these properties over the expected range these properties might exhibit and determine how critical these properties are to the processing of the fuel. If it is found that the selection of a melt casting process is dependent on these properties, this could be a follow on project for those in the chemistry field. Actinide chemists at LANL will be consulted as well as the ANL scientists and engineers with regards to those transport parameters.

Completion of the first two objectives will tie directly to the third and most important objective, the selection of a melt casting process. The work completed in support of the first two objectives will be used in more detailed process models. These detailed process models will incorporate heat transfer, mass transfer, and induction heating to assess casting furnace designs and operating conditions. The thorough analysis of these modeling results will assist in the final selection of a melt casting process.

All of this work will be conducted in close cooperation with the research staff at ANL. Their experience and expertise is crucial in the selection of the next generation melt casting furnace suitable for fabricating metallic alloy actinide transmutation fuels.

3. Technical Impact

The AAA/ATW program requires a non-fertile actinide form to serve as the “fuel” for the transmuter blanket. Currently proposed candidates for this fuel form include metallic alloy fuel, cermet fuel, and nitride fuel. Each of these candidates has been proposed based on known performance of the fertile fuel (i.e., uranium) analogue. Of primary concern to the ATW program is the requirement for fabrication of the selected fuel form in a remote, hot cell environment. Of the three candidate fuel forms identified, only the metallic alloy fuel has actually been demonstrated to be amenable to hot cell fabrication operations. This presents a strong motivation to select the metallic alloy fuel form if its irradiation performance proves acceptable.

The primary technical hurdle to overcome in the fabrication of metallic alloy transmutation fuel is that of efficiently including the highly volatile actinide elements (i.e., americium) into the alloy when using a melt casting process. Previous attempts at incorporating americium into metallic alloy fuels using standard injection casting processes have resulted in the volatilization and loss of up to one-half of the initial americium charge introduced into the melt. This magnitude of loss due to volatilization is unacceptable, and would almost certainly exclude metallic alloy transmutation fuels from consideration if an engineering solution cannot be developed in the near term. An attempt to arrive at such a solution is the objective of the proposed work.

4. Research Approach

The proposed research has been broken down into seven specific tasks. These tasks for the first year of phase I are outlined below. One graduate student will be supervised to work on these tasks.

1. *Conceptual Design Concepts for Melt Casting Process*: Potential processes will be selected and discussed to document what technologies exist that could potentially be modified for the AAA program. Operating ranges and conditions will also be defined and documented. This work will be conducted in cooperation with ANL staff.
2. *Development of Preliminary Process Models*: General process models will be developed to assist in the evaluation of the designs proposed in Task 1. These process models will be used to select two candidate melt casting processes, with the guidance and input of ANL staff. The models will only assess the major operating features.
3. *Documentation of Volatile Actinide Transport Properties*: Conduct a thorough literature search on the transport properties of the volatile actinides of interest. If critical transport properties have not previously been measured or reported in the literature, attempts will be made to numerically estimate them, or experiments will be proposed.
4. *Development of Induction Heating Model*: An important and complex aspect of melt casting furnaces is induction heating. This mode of heating is complex and not well understood throughout the industry. "Rules-of-thumb" and one-dimensional relationships are traditionally relied upon to design new casting furnaces. A finite element technique will be developed to allow for the detailed analysis of induction heating in casting furnaces.
5. *Parametric Modeling of Volatile Actinide Transport*: A general model and geometry will be selected to assess processing conditions on volatile actinide transport. Process conditions, physical properties, and geometric issues will be varied to gain an understanding of those conditions that have the greatest impact on volatile actinide transport.
6. *Detailed Models of Candidate Melt Cast Processes*: A detailed heat and mass transfer model will be developed to provide an in-depth assessment of process conditions for a realistic range of design conditions for the furnaces. The model will be developed to allow for issues such as frequency, mixing, coil height, etc. to be assessed.
7. *Reporting Requirements*: Quarterly progress reports will be completed and filed with the program office in addition to being sent to ANL collaborators. Researchers will publish the results of this project at the appropriate technical conferences and journals. A final report will be compiled and submitted for review as well.

5. Capabilities at UNLV and DOE Labs

Dr. Yitung Chen is Research Associate Professor of the Department of Mechanical Engineering and Assistant Director of the NCACM at the University of Nevada Las Vegas, and would serve as Principal Investigator. He received his B.S. degree in Chemical Engineering in 1983, and his M.S. and Ph.D. degrees in Mechanical Engineering in 1988 and 1991, respectively, from the University of Utah. He also has a minor degree in Nuclear Engineering. He was a consultant for several engineering companies from 1991 to 1993. Dr. Chen is an expert in experimental and computational aspects of momentum, heat, and mass transfer. His research interests include chemical kinetics modeling, high level radioactive waste repository design, atmospheric sciences, magnetohydrodynamics modeling, ground water transport, energy conservation, and biomedical engineering. He also has a strong background in organic chemistry, biochemistry, polymer chemistry, and physical chemistry. His research experience includes being PI and co-PI on projects involving the study of flow and heat transfer and species transport in unsaturated porous media funded by DOE, the burning of rocket motors under the Joint Demilitarization Technology (JDT) program funded by DOD, and atmospheric modeling funded by the NOAA Cooperative Institute for Atmospheric Sciences and Terrestrial Applications. He is also co-PI on an EPA project dealing with environmental monitoring for public access and a groundwater modeling project funded by DOE.

Dr. Pepper is Professor and Chairman of the Department of Mechanical Engineering, Director of the Nevada Center for Advanced Computational Methods (NCACM), and Director of Engineering of the HiPSEC at the University of Nevada Las Vegas. Dr. Pepper would serve as Co-Principal Investigator. He has been actively involved in the generation, development, and use of hybrid, multi-dimensional algorithms for heat transfer, fluid flow, and species transport applications for many years, and has developed models for the NRC, NOAA, INEL, LLNL, and DOE (OHER; NVOO). His previous work experiences at the Savannah River Site (E. I. Du Pont de Nemours) which included the heat transfer and hydraulics laboratory, the Marquardt Company, and Advanced Projects Research, Inc., have resulted in numerous publications and presentations.. He served on a NRC project to assess consequences of natural phenomena on various reactor sites and fuel fabrication facilities located within the U.S., and has developed 3-D dispersion models for the NRC and DOD. Dr. Pepper is the co-author of three textbooks on the finite element method, co-editor of two books on environmental modeling, and directs the AIAA Home Study Courses and ASME short courses on finite elements. He is a Fellow of ASME and Associate Fellow of AIAA.

Dr. Randy Clarksean's experience in process modeling and the casting furnace process currently employed at ANL will provide a solid base from which to devise and evaluate new casting furnace concepts under the unique conditions that exist with volatile actinides. He is familiar with current casting furnace operations at ANL and has developed first order models of the system previously. Dr. Clarksean completed his Ph.D. at the University of Utah in 1990, with an emphasis on computational methods in the thermal and fluid sciences. In 1990, he started work for Argonne National Laboratory at their Idaho facilities. He worked on a number of different process and safety projects while with Argonne National Laboratory. Since 1995, Dr. Clarksean has worked on a number of projects independently. These projects have involved materials processing, spent nuclear fuel storage, electronics cooling, phase change, and other general heat and mass transfer processing. Funding for these projects have come from the DOE, DOD, private industry, international research organizations, and the State of California. He is an expert in the analysis of engineering systems and has numerous publications in heat transfer and fluid mechanics.

ANL-W has extensive experience in injection casting of uranium and plutonium alloys, having fabricated literally hundreds of thousands of metallic alloy fuel pins for irradiation in EBR-II using this process. Currently, two injection casting furnaces are in operation at ANL-W, and previous experimentation attempting to incorporate americium into U-Pu alloys has been conducted. This past experience has led investigators at ANL-W to hypothesize over the period of almost 10 years as to what process modifications or furnace design changes might improve the chances for successful melt casting of actinide alloys. The cooperation between the laboratories will provide a good working relationship to develop a solid approach to developing the next generation casting furnace for the AAA Program.

Extensive computing facilities exist for the modeling efforts at UNLV, ranging from workstations to a multiprocessor Origin 2000. These facilities will be available for the analysis and design of the proposed concepts. A wide range of computational tools exists on these systems.

6. Project Timeline with Milestones and Deliverables

The proposed schedule for all tasks and significant meetings is shown on the following page. Two meetings are planned for the year. The first meeting is to narrow the potential list of processes to be further analyzed in Task 6. ANL staff will be an integral part of this process. The second meeting is to present and discuss all of the research completed during year 1. Any comments, suggestions, or criticisms can then be taken into account when writing the final report.

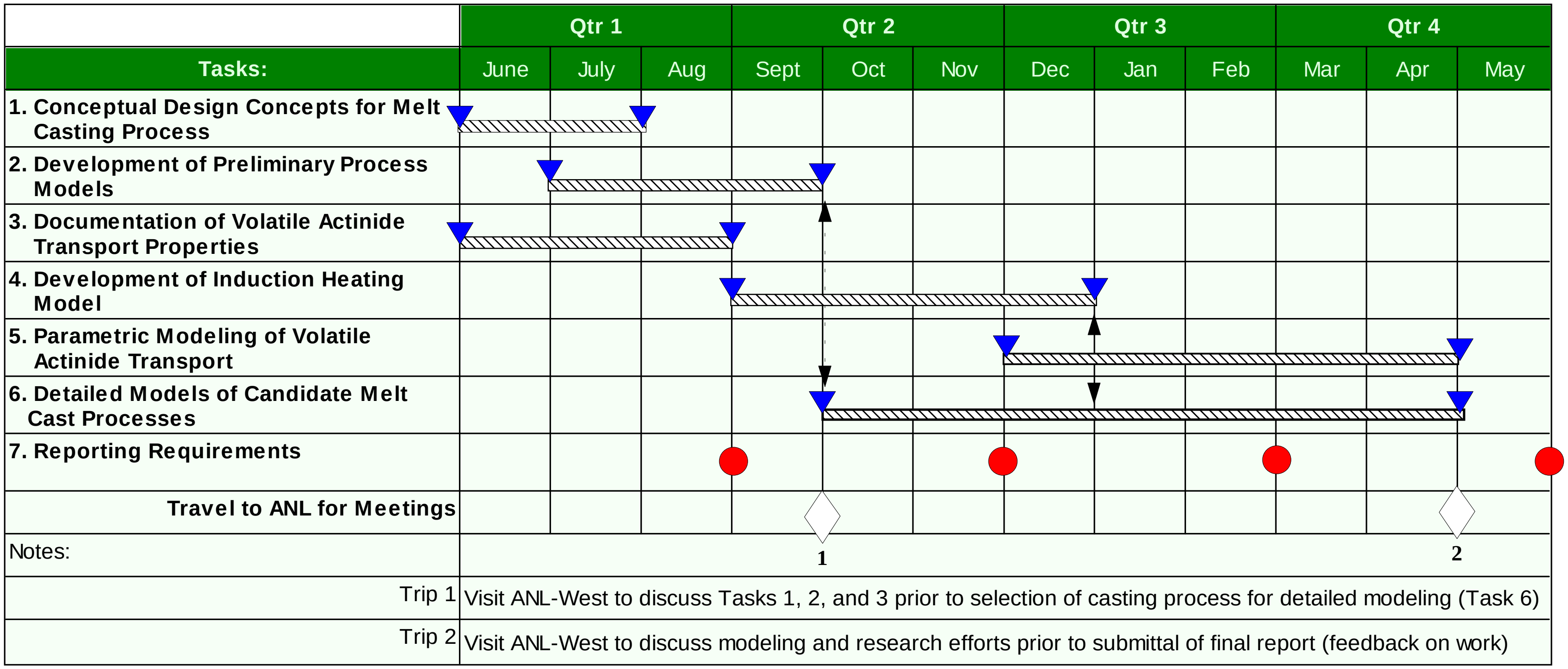

Figure 1 - Proposed Timeline for Research Tasks.

Work is assumed to commence on June 1, 2001. Additional travel may be necessary for interactions relating to other specific tasks.