The NRC-MIT Collaborative Agreement For Advanced Reactor Technology

Progress Report for the Period

June 2007 through August 2008

Principal Investigator:

Mujid S Kazimi

Participants:

Task 1: Metallic Fuel Modeling for Liquid-Metal Cooled Fast Reactors

Aydin Karahan, Prof. Jacopo Buongiorno, and Prof. Mujid Kazimi

Task 2: Uncertainties in Passive Safety System Performance

Dustin Langewisch, Prof. George Apostolakis, and Prof. Michael Golay

Task 3: Studies for Improved Safety Analysis of High Temperature Reactors

Caroline Cochran and Prof. Andrew Kadak

September 22, 2008

The NRC-MIT Collaborative Agreement
For Advanced Reactors Technology
Progress Letter Report
September 2008

This agreement was officially started in July of 2007, and is meant to continue for three years, with possibility of additional years after renewal. Its second year started in July 2008 and will end by 31st of June, 2009.

A summary of progress by the end of January 2008 was provided with the statment describing the intended scope for Year 2 of the agreement. Progress through April 15, 2008 was provided in presentations to NRC at a review meeting held in the Flint Building on April 17, 2008.

Progress since that time and through August 31, 2008 is described in the highlights summerized in this letter. As this is the first progress letter, a more detailed coverage of previous work is provided in separate attachements.

Highlights:

TASK 1: Modeling of Metallic Fuel for Liquid-Metal Fast Reactors

Investigators
Aydin Karahan (PhD student), Prof. Jacopo Buongiorno and Prof. Mujid Kazimi

Objectives and Relevance to NRC
To develop a robust and reliable code to model the irradiation behavior of metal fuels (both at steady conditions as well as during transients) in sodium-cooled fast reactors. This code can ultimately be useful to the NRC in the licensing process of metal-fuelled fast reactors, such as the Toshiba 4S reactor proposed for Alaska, and demonstration plants invovled in GNEP and Generation-IV programs.

Progress in the Previous Period
The work in Year 1 focused on development of the code structure and its capabilities to analyze the steady-state irradiation behavior of metal fuels. All details of the work have been documented in a report submitted in August 2008; that information is provided as Attachment A to this report. A short summary is provided here.

Computational models to analyze in-reactor behavior of U-Zr and U-Pu-Zr metallic alloy fuel pins have been developed and implemented in a new code, the Fuel Engineering And Structural analysis Tool (FEAST). FEAST consists of several modules working in coupled form with an explicit numerical algorithm. These modules are (1) Fission Gas Release and Swelling, (2) Fuel Constituent Redistribution, (3) Temperature Distribution, (4) Fuel-Clad Chemical Interaction and (5) Fuel-Clad Mechanical Analysis. The main purpose of FEAST is to model metal fuel performance by adopting non-empirical approaches to increase the ability to extrapolate the existing database with a reasonable accuracy. As a consequence, mechanistic models for the fission gas release and swelling module, the fuel constituent redistribution and the Fuel Clad Chemical Interaction, were adopted. The mechanical analysis and temperature distribution modules adopt 1-D approaches. The code predictions were compared to the available EBR-II experimental database. The results show that FEAST is able to predict the important phenomena such as axial fuel growth, cladding strain and fission gas release satisfactorily. Moreover, a code-to-code benchmark has been performed against the Japanese code ALFUS, using recent PHENIX reactor irradiation data. Again, the agreement is reasonably good for fuel swelling, while some discrepancies are observed in the cladding strain predictions.

Progress this Period:
The code capabilities have been expanded to include the analysis of fast transients. Specifically, the fuel and coolant thermal capacity terms have been added to the energy equations, a mechanistic creep failure model based on a critical crack length concept is used to predict clad rupture, and a fast diffusion model is used to predict fuel-clad chemical interaction at the high temperatures typical of undercooling transients. A comparison of the code predictions to the (very) limited EBR-II-related metal-fuel transient performance database suggests that the code captures the important transient phenomena reasonably well. The transient analysis module has been fully integrated into the main code, such that a steady-state irradiation and a rapid transient at any given time during the irradiation can be run from a single input file. A code-user interface similar to FRAPCON was implemented, which should increase appeal of FEAST to the relatively large community of experienced users of FRAPCON.

TASK2. Reliability of Passive Safety Systems

Invstigators
Dustin Langewisch (PhD student), Prof. George Apostolakis and Prof. Michael Golay

Objectives and Relevance to NRC
Advanced reactor designs have increased the use of passive safety systems and have often considered their performance more reliable than that of active systems. The IAEA defines four categories of passive systems. Of interest here is Category B, i.e., systems with moving fluids with no moving parts (valves). These systems rely on gravity and density changes of fluids with temperature to perform their function. These phenomena are weak, and therefore the performance of coolant driven passive systems is much more sensitive to changes in their surroundings. Draft Regulatory Guide 1145 acknowledges this sensitivity and states: "Because of limited data and experience with the passive systems, thermal-hydraulic uncertainties could impact the PRA results. Specifically, thermal-hydraulic uncertainties can directly impact the determination of success criteria for accident sequences in the PRA." This task is focused on the development of methods for quantification of uncertainties in passive safety performance. The expected work products are methods for quantifying the uncertainties in the performance of passive safety systems that will be useful to the NRC staff in their risk-informed regulatory activities.

Progress in the Previous Period
Research efforts focused on defining the characteristics of passive safety systems and reviewing the reliability assessment methodologies for passive safety systems. The details of the findings are given in Appendix B. Here only a brief summary is given. Three such methodologies have been identified as representing, collectively, the state of the art in reliability assessment for passive safety systems: the Reliability Methods for Passive Safety Functions (RMPS) developed at CEA, France; the Assessment of Passive System Reliability (APSRA) developed at BARC, India; and the methodologies developed at MIT for risk-informed design studies on the Gas Cooled Fast Reactor GFR. One of the key differences among the different methodologies was found to be the treatment of uncertainties. For instance, with the RMPS methodology, uncertainties, estimated through expert judgment, are assigned to input parameters and are propagated through a best-estimate code model to estimate the uncertainty of the system performance. This approach presents a large computational burden. On the other hand, the APSRA methodology proposes to eliminate this issue by estimating uncertainties based upon comparisons between code-predicted results and experimental data obtained from in-house test facilities located at BARC. This is expected to reduce the number of computational simulations that must be performed, but is limited by the availability of experimental facilities. While each of these approaches has been applied to simplified passive systems, the feasibility of each approach for estimating the reliability of real, innovate reactor systems has yet to be determined.

Progress this Period
To develop a robust and economic methodology to estimate the uncertainties in passive systems, a review of the phenomena involved in such sytems was undertaken. The focus has been on IAEA Catergory-B thermal-hydraulic systems (e.g., natural circulation heat removal systems). A large number of phenomena were found to be important in the functioning of such systems, particularly the potential for instabilities that might affect natural convection flows and small amounts of non-conendsable gases that might affect the rate of condensation in isolation condensors. The focus in the current effort is on coupling a ranking for the phenomena with the class of passive safety systesm and deciding on the range of safety analysis parametric calculations that would be required to characterize the impact of the uncertain phenomena. More details are given in Appendix B.

TASK 3: Studies for Improved Safety Analysis of High Temperature Reactors

Invisgtigators:
Caroline Cochran (MS student) and Prof. Andrew Kadak

Objective and Relevance to NRC
The objective is to build a full transient FLUENT model that has been benchmarked against suitable experiments for use in high temperature reactor safety analysis. This

includes: air ingress analysis and natural convection behavior for decay heat removal. The work will involve taking data from this and previous models, performing data mining and ultimately creating an effective 1-D model and producing correlations suitable for heat transfer applications in system codes such as MELCOR and RELAP. This capability will be very useful for the NRC to performing the accident analysis for either the pebble bed or prismatic reactor since running FLUENT, or similar 3-D CFD tools, is much more demanding in terms of execution time and modeling sophistication.

Progress in the Previous Period
Physical experiments and already published data were used to provide benchmarking of FLUENT, a sophisticated but complicated software for fluid and energy transport. The FLUENT code was used to blind predict the results of air ingress experiments conducted in Germany at the NACOK facility. Two series of tests were conducted – (1) an open chimney test and (2) a hot and cold leg test using a pebble bed reactor type heated core. Much of the work on this test can also be used for both pebble bed and prismatic designs since the lower reflector, where much of the corrosion takes place, is similar in structure and design.

Progress this Period
The results of these blind analytical benchmarks are being used to improve the previous FLUENT models. The improved models are being used to understand the details and the importance of phenomenon which can then be used to develop the simplified algorithms and equations for use in faster running systems codes such as MELCOR. Improved FLUENT results for open chimney and hot leg/cold leg NACOK tests were obtained. A meticulously meshed, 2-D model was developed, which has already allowed for ten times faster runs than runs by the previous student with *double* precision, and has shown interesting results. For example, the arrival to a true steady state is not as quick as was shown previously using porous media assumptions. Several factors are involved, as detailed in Appendix C to this report. Diffusion alone, as assumed in previous analyses, is not sufficient to determine steady state points and conditions.

Also, we have been learning MELCOR and applying data mining software for application to analysis of FLUENT results.

Publications that derived full or partial support from NRC collaborative agreement since June 2007:

Metallic Fuel Modeling

1) *A. Karahan, J. Buongiorno, M. S. Kazimi, "Development of a New Irradiation Performance Code for Metal Fuels", Nuclear Fuels and Structural Materials for the Next Generation Nuclear Reactors (NFSM), embedded topical meeting at the Annual Meeting of the American Nuclear Society, June 8 - 12, 2008, Anaheim, CA.*

2) A. Karahan, J. Buongiorno, M. S. Kazimi, *Modeling of Metallic Fuel for Liquid-Metal Fast Reactors*, FY-2008 Annual Progress Report (draft), NRC, August 2008.

Risk-Informed Decision Making

1) Phillip E. Dawson, "Evaluation of Human Error Probabilities for Post-Initiating Events," MS Thesis, 2007.

Nanofluids For Severe Accident Cooling of LWRs

1) J. Buongiorno, L.W. Hu, G. Apostolakis, R. Hannink, T. Lucas, A. Chupin, ìA Feasibility Assessment of the Use of Nanofluids to Enhance the In-Vessel Retention Capability in Light-Water Reactorsî, Nuclear Engineering and Design, 2008.
2) R. Hannink, J. Buongiorno, L.W. Hu, G. Apostolakis, "A Conceptual Nanofluid Injection System Design for In-Vessel Retention Enhancemen", Trans. Am. Nuc. Soc., vol.96, pp.304-305, 2007.
3) R. Hannink, J. Buongiorno, L.W. Hu, and G. Apostolakis, Using Nanofluids to Enhance the Capability of In-Vessel Retention of Fuel Following Severe Reactor Accidents, MIT-ANP-TR-116, June 2007.
4) R. Hannink, J. Buongiorno, L.W. Hu, G. Apostolakis,"ìEnhancement of the In-Vessel Retention Capabilities of Advanced Light Water Reactors through the Use of Nanofluids", Paper 7106, Proceedings of ICAPP 2007, Nice, France, May 13-18, 2007.
5) R. Hannink, J. Buongiorno, L.W. Hu," In-Vessel Retention Enhancement through the Use of Nanofluid"î, Trans. Am. Nuc. Soc., vol.95, pp.691-692, 2006.

Modeling High Burnup Fuel Behavior

1) Wenfeng Liu and Mujid S. Kazimi,"A Model for Assessment of Failure of LWR Fuel During an RIA", Int. Conf. on LWR Fuel Performance, San Francisco, September, 2007.
2) Wenfeng Liu and Mujid S. Kazimi, Modeling of High-Burnup LWR Fuel Response to Reactivity-Initiated Accidents, MIT-NFC-TR-096 (October 2007).

Stability of Boiling Water Reactors

1) Rui Hu and Mujid.S. Kazimi, Stability Analysis of Natural Circulation in BWRs at High Pressure Conditions, MIT-ANP-PR-118 (October 2007).