8. FY 2000 NERI RESEARCH AWARDS

The following abstracts summarize the NERI research awards for FY2000.

Optimization of Heterogeneous Schemes for the Utilization of Thorium in PWRs to Enhance Proliferation Resistance and Reduce Waste

PI: Michael Todosow, Brookhaven National Laboratory

Project Number: 00-0014

The thorium-U-233 fuel cycle promises a number of benefits relative to the conventional U-Pu cycle for commercial reactors, including reduced plutonium generation/enhanced proliferation resistance, reduced waste generation per unit energy production and reduced toxicity characteristics of the spent fuel. Heterogeneous assembly and/or core design options allow the flexibility needed to maximally realize the potential benefits of this cycle; this work is therefore complementary to a study of homogeneous approaches currently underway by a team headed by Idaho National Engineering Laboratory (INEEL). The assessments concentrate on key measures of performance, including: proliferation characteristics of the spent fuel focusing on quantity and quality of weapons usable material produced, fraction of power generated in U-233, safety, cost, and the characteristics of the waste stream. Key to this evaluation is the identification of any feasibility "go-no-go" issues, as well as areas requiring further study. The focus of the investigations will be on current and advanced pressurized-water reactor (PWR) designs (e.g., AP600 with its 19x19 fuel assembly), with the ability to retrofit into the envelope of a standard 17x17 fuel assembly, and utilize available control and burnable designs viewed as a positive attribute; some limited examination of “clean-slate” concepts will be performed as time and resources permit.

Study of Cost Effective Large Advanced Pressurized Water Reactor that Employs Passive Safety Features

PI: J. W. Winters, Westinghouse Electric Company LLC

Project Number: 00-0023

Market analysis of the U.S. market indicates that a new electric generating facility must have an overnight capital cost of approximately $1000/kw. More importantly, the generating cost must be less than $0.03/kw-hr, when such factors as an attractive return on investment and payback period are considered. Industry executives indicate that any new nuclear plant must be able to compete in the deregulated generation wholesale marketplace and provide a return to the shareholders.

Against this standard, the costs of Generation III nuclear power plants (ABWR, AP600, System 80+) are too high. For example, Westinghouse Electric Company has designed an advanced 600 MWe Generation III nuclear power plant called the AP600. The AP600 has recently received Design Certification by the Nuclear Regulatory Commission when it formally approved the final rule amending 10 CFR Part 52 to certify the AP600 standard plant design. The overnight capital cost for the first AP600 plant is estimated to be between $1300-1500/kw depending on the site selection. This places the AP600 as the most cost effective nuclear power option (Generation III or other) available for deployment in the world today. It is, however, too expensive to compete in the U.S.

Implementation of aggressive cost reductions combined with conventional, state-of-the-art power upratings could potentially realize a 10% decrease in the $/kw for a Generation III plant. This still will not place its cost within the competitive range. Therefore if nuclear power is to be commercially attractive in the U.S. in the next 5-7 years, a dramatic decrease in the capital cost of a Generation III plant is necessary. This program is to complete a feasibility study and perform design activities to increase the power output of an AP600 to at least 1000 MWe while preserving the design and licensing basis of the plant. This will require innovative engineering solutions to design issues associated with increasing the power output of the AP600. By increasing the generating capacity of the AP600 to this level while incurring not more than an additional $50 million in capital cost, the overnight capital cost of this Generation III+ plant will be dramatically reduced and be competitive to approximately $1000/kw.

The DOE and the nuclear industry have invested heavily in the design and licensing of the so-called Generation III reactors including the AP600, ABWR and System 80+. These plants are ready for the U.S. market today. However, even though the AP600 is the most cost competitive nuclear option available today and is cost-competitive with coal plants, it is still not competitive with combined-cycle natural gas plants in the United

States. Successful implementation of this program would provide the impetus for the industry to realize the rewards of the investment in the Generation III reactors. It will permit competitive, near term deployment of a Generation III+ nuclear power plant. It will be based upon the safest, simplest, most advanced and most cost competitive nuclear plant available today with a Design Certification. It will also be cost competitive in the U.S. market with any available electric energy choice today including combined-cycle natural gas plants.

Design and Layout Concepts for Compact, Factory-Produced, Transportable, Generation IV Reactor Systems

PI: Fred R. Mynatt, The University of Tennessee

Project Number: 00-0047

Development and deployment of a new generation of nuclear electric power plants is urgently needed both within the United States and worldwide. The need for new electric power plants is very evident both to replace old power plants and to expand the power supply. While global warming is widely debated, there is a growing consensus that it is a potential worldwide problem and that generation of greenhouse gases should be avoided in new and replacement electric power plants. It is also clear that new nuclear power plants will not be readily accepted by the public until sufficient changes are evident to resolve economic, safety, waste and proliferation concerns. The public generally accepts nuclear power plants already deployed, but this same public will demand resolution of long-standing problems prior to deployment of new nuclear power plants.

Generation IV nuclear power plant concepts developed in the U.S. Department of Energy (DOE) Nuclear Energy Research Initiative offer the potential for resolving the problems that prevent the deployment of new nuclear power plants. Concepts for compact, modular, power plants have been developed with inherent design features to mitigate proliferation and safety concerns (1,2,3,4,5,6). The biggest concern for these compact plant concepts is economics. Can they be produced at an acceptable cost, and will they facilitate innovative financing and ownership arrangements to make deployment economically feasible?

The purpose of this research project is to develop compact Generation IV nuclear power plant design and layout concepts that maximize the benefits of factory-based fabrication and optimal packaging, transportation and siting. The potentially small footprint of Generation IV systems offers the opportunity for maximum factory fabrication and optimal packaging for transportation and siting. Barge mounting is an option to be considered and will offer flexibility for siting including floating installation, on-shore fixed siting, and transportation to nearby inland sites. Railroad and truck transportation of system modules will also be considered in this work.

Integrated Nuclear and Hydrogen-Based Energy Supply/Carrier System

PI: David C. Wade, Argonne National Laboratory

Project Number: 00-0060

This proposed three year program of R&D aims to develop an economical, proliferation resistant, sustainable nuclear-based energy supply system suitable for deployment in both industrialized and developing economics in the decades following 2020.

It is based on a modular-sized fast reactor, passively safe, and cooled with heavy liquid metal which supplies high temperature heat to an integrated gas turbine power/process heat chemical plant to generate dual energy carriers - electricity and hydrogen (with optional capability for potable water production from brackish or salt water desalinization).

Innovations and benefits include:

- Flexible mix of energy products - The integrated system is to be compatible with state of the art energy conversion systems (gas turbines, fuel cells, etc.) producing a flexible mix of "billable" product including electricity, high level and low level process heat, hydrogen, oxygen, and fresh water supply (via desalinization). The energy carrier can be stored to meet energy peaking needs, and may be used to power fuel cells for emission-free vehicle propulsion.
- Flexible system capacity - The use of standardized modules for the heat source, hydrogen production, and energy conversion functions enables the system capacity to be sized for small service areas using a single set of modules (300 MWt) or for larger and growing service areas using multiple, coupled sets of modules.
- Economic competitiveness - The nuclear and hydrogen-based energy system is aimed at low capital and operating cost through:
  - Compactness and radical simplification.
  - Modularization and standardization for factory "mass production" and fast site assembly.
  - Long-life core with cartridge refueling (15-30 year interval) and near 100% capacity factor.
  - High fuel energy utilization.
  - High-energy conversion efficiency (~50 percent for hydrogen production, >50 percent for fuel cells).
  - Base load operation and storable energy products (synthetic fuel and potable water).
  - Semi-autonomous operation.

- Sustainability - The system is designed for sustainability:
  - The nuclear fuel source utilization in a fast reactor is sustainable and lessens competition in the electric power, process heat, and vehicle propulsion sectors for other scarce, irreplaceable energy sources.
  - The integrated, nuclear and hydrogen-based energy supply/carrier system essentially eliminates greenhouse emissions in the electric power, process heat, and fuel cell based transportation sectors which it serves.
  - The integrated system reduces waste streams to low level heat and used nuclear fuel, and enables use of "waste" from one process to be a beneficial input to another process.
  - Integration of desalinization into the process system for recovery of "waste" heat and for sustainable production of fresh water for public works, industrial, and agricultural purposes.
  - The nuclear heat source achieves maximum utilization of the nuclear energy resource whether based on the once-through fuel cycle or, where permitted, fuel recycle.
- Proliferation resistance - The defense-in-depth approaches addressing proliferation concerns include:
  - Long-life core with cartridge refueling (15-30 year interval) and no on-site
  - fuel handling equipment.
  - Fuel ownership and (15-30 year interval) cartridge refueling by internationally monitored regional consortium.
  - Fuel facility and material transportation under international, guarded conditions.
  - Fuel protected by a high-level radiation "shield" at all stages.
- Inherent/Passive reactor safety - The liquid-metal-cooled fast reactor incorporates and extends proven inherent and passive safety features based on decades of development of sodium-cooled systems, which are heightened using Pb or Sn heavy liquid metal coolant. The nuclear heat source features:
  - Low power density core.
  - 100 percent natural circulation heat transport (eliminating the loss of coolant flow class of accident initiators).
  - Reactivity coefficients are such to inherently shut the reactor down in case of power-to-flow mismatch.
  - Passive decay heat rejection together with passive system shutdown eliminates concern from "loss-of-heat sink" accident initiators.
  - High boiling temperature of Pb and Sn together with system passive response eliminates core melt accidents.
  - Large fuel rod diameter and very large lattice spacing (eliminates core blockages).
  - Worth of burnup reactivity control system < $1 (eliminates possibility of prompt excursion).
  - Low atmospheric pressure system and use of guard vessel eliminate loss of coolant accident initiators.

- Core compaction is eliminated by integral core design (without subassemblies) and use of spacer grids and recriticality potential is eliminated by fuel, which floats in coolant.
- Seismic isolation is provided in the basic design.
- The reactor and heat transport modules are compact, enveloped by a close-fitting containment, and are located in a silo which can be "hardened" to the extent necessary to protect against external threats.
- The inexhaustible heat sink is site-specific, including atmospheric air, ground, or ground water.
- The coolant and working fluids are separate systems, eliminating possibility of radiological transport to the hydrogen production or energy conversion parts of the plant even in the event of heat exchanger tube rupture (insofar as the working fluid pressure is higher than the reactor system pressure).

This proposal is responsive to the Generation IV/Alternative Power Conversion Cycles element of the NERI call for proposals.

Development of Design Criteria for Fluid-Induced Structural Vibration to Steam Generators and Heat Exchangers

PI: Ivan Catton, University of California, Los Angeles

Project Number: 00-0062

Present designs of heat exchangers and steam generators in pressurized water reactors (PWR) are based on past designs that worked, over design or difficult to obtain one-of-a-kind expensive empirical data. Although present guidelines provide an ad-hoc solution to the problem of fluid induced vibration, at present a unified approach based on simultaneous modeling of thermal-hydraulics and structural behavior does not exist. As a result designs are overly constrained with a resulting economic penalty. If, on the other hand, less constrained designs are developed, the possibility of occurrence of damaging component vibration exists. The objective of the proposed work is to develop complete models that will delineate stability boundaries for fluid-structural interactions that are supported by laboratory experiments and can be used for steam generator and heat exchanger design avoiding economic penalties resulting from overdesign and conservatisms needed to accommodate safety issues.

A basic study of single and two-phase flow across tube bundles is proposed. The study has both experimental and theoretical components to it. Single-phase studies will involve velocity and pressure measurements in tube arrays. Laser Doppler Anemometry will be used to determine the velocity field. In two-phase flow studies, void profiles in the passages between tubes and pressure distribution around tubes will be measured. Most of the experiments will be conducted on arrays of flexible tubes. The tube arrangement and tube pitch to diameter ratio will be varied parametrically. In the experiments, data for transient fluid force acting on the tube, average void fraction around the tubes, damping factors in two-phase flow, and displacement of the tubes from their initial position will be obtained. Instability maps for the onset of fluid-elastic instability in tube arrays will be developed. To study the effect of stiffness of the flow system, experiments will be conducted with air-water and steam-water mixtures. In the experiments with steam-water mixtures, tubes will be heated to initiate boiling on the tubes.

Theoretical work will include development of constitutive relations and the solution of governing fluid-structure equations with appropriate boundary conditions. Vorticity transport formulation will be used to solve the governing equations numerically. A combination of experimental data and modeling will be used to develop design guidelines that include the functional relationship of stability and the design parameters like tube material, wall thickness, distance between supports and type of support.

An In-Core Power Deposition and Fuel Thermal Environmental Monitor for Long-Lived Reactor Cores

PI: Donald Miller, Ohio State University

Project Number: 00-0069

The three Generation IV reactor designs currently supported by the DOE have the common characteristic that they are expected to operate up to 15 years with a sealed core. These reactors will be built, operated and disposed of without access to the core, minimizing opportunities for proliferation and for servicing. Monitoring the power distribution and coolant conditions of such a reactor poses a challenge. Serviceable ex-core sensors can only monitor neutron flux on the periphery of the core. Existing in-core sensors do not have sufficiently long lifetimes, with the possible exception of low-sensitivity platinum SPNDs. This research effort proposes to develop a new sensor that is particularly well suited for use in a sealed reactor core, and to apply this sensor to produce a robust in-core monitoring system that is suitable to all three reactor designs

The sensor is fabricated from a small kernel of actual reactor fuel sealed in a metal tube that provides a thermal conduction path to the coolant. A small electric heating element surrounds this fuel/tube assembly. The total heat flux from the fuel kernel and electric heater is measured by differential thermocouples placed on the conduction path. The heater is then controlled by feedback from the thermocouples, such that a constant heat flux is maintained regardless of the nuclear energy generation in the fuel kernel. The input electrical power provided to the heater is thus inversely related to the actual nuclear energy generation. Because the temperature of the sensor remains nearly constant, the sensor will have a better time response than that of a similar uncontrolled sensor.

This controlled calorimeter concept, denoted the constant-heat flux power sensor (CHFPS), is well suited for use in a sealed core. It will give a measure of the local nuclear power generation, including decay heat, so it can be used to monitor thermal limits during operation, post-shutdown, and in permanent storage. The sensor will be fixed to, and will deplete with, the local fuel, so no compensation for depletion will be required. The sensor will simply act like the surrounding fuel over the entire core lifetime. Unlike any other sensor, this sensor is in a feedback control loop. This means that the sensor dynamic response can be monitored, allowing measurement of the heat transfer characteristics of the coolant while simultaneously measuring the generated power. In addition, feedback control combined with modern signal processing techniques offer a means of evaluating the sensor calibration and performance *in-situ.* It is expected that the sensors could operate with substantial degradation given this capability, an important feature in a sealed-core reactor. The basic performance characteristics of this type of sensor, very high sensitivity combined with good bandwidth, have already been proven through testing of an earlier design of controlled calorimetric sensor.

The project team thus proposes to design, fabricate, and test CHFPS sensors, along with the supporting digital control and signal processing capabilities, using fuel materials specific to the DOE-supported Generation IV reactor designs. The sensor design will include a high degree of internal redundancy. This sensor will then be incorporated, with other complementary neutron flux or temperature sensors if advantageous, into an integrated in-core monitoring system with a high degree of external redundancy and *in-situ* diagnostic capability. This final monitoring system is expected to provide a high degree of reliability, safety, operating efficiency, and flexibility for each of the three DOE-supported Generation IV reactors.

Design and Construction of a Prototype Advanced On-Line Fuel burn-Up Monitoring System for the Modular Pebble Bed Reactor

PI: Bingjing Su, University of Cincinnati

Project Number: 00-0100

The Modular Pebble Bed high temperature Reactor (MPBR) has been proposed as a candidate to meet future needs of the nuclear industry, due to its safety, high-efficiency, and proliferation resistance. This type of reactor requires a unique on-line fuel burnup monitoring and handling system. This project will conceptually design and experimentally test an advanced on-line fuel burnup monitoring system for the MPBR. Compared with previous designs, this work proposes a novel approach to analyzing pebble bed fuel in real time using combinations of gamma spectroscopy and passive neutron counting of spontaneous fission neutrons in order to provide the speed, accuracy, and burnup range required for the MPBR. The real time results will be used to provide on-line automated go/no-go decision on fuel disposition on a pebble-by-pebble basis. Advanced design concepts included here are not limited to just the counting methods—also included are innovative concepts for handling pebble bed fuel in order to provide the throughput and reliability which this system will require.

Design and Analysis of Turbo-Machinery and Heat Exchangers for the Gas-Cooled Reactor Systems

PI: Ronald G. Ballinger, Massachusetts Institute of Technology

Project Number: 00-0105

The purpose of this project will be to develop systems analysis tools for the evaluation of turbo-machinery and BOP power conversion in high temperature gas cooled reactor systems. These tools will then be used to develop optimized power conversion systems for high temperature gas-cooled reactor systems. Current concepts for high temperature gas cooled reactor systems call for modular designs with electrical output in the 110 MWe range. Key questions which must be addressed in order for such systems to be adequately evaluated include: (1) can a helium power turbine be developed in the 110 MWe range, (2) can advanced compact heat exchanger technology be used in the design of intermediate heat exchangers (for indirect cycle plants) and/or recuperators (direct and indirect cycle plants), (3) can structural and materials issues be adequately characterized to allow for detailed life-cycle analysis, and (4) how do specific component designs impact overall cost?

Forewarning of Failure in Critical Equipment at Next-Generation Nuclear Power Plants

PI: L. M. Hively, Oak Ridge National Laboratory

Project Number: 00-0109

A deviation from normal operating conditions may indicate performance degradation or the onset of imminent failure in critical equipment. Real-time monitoring can detect a deviation in process-indicative data. Prompt response is needed to avoid failures, maintain optimal performance, and improve performance savings. Oak Ridge National Laboratory has patented technology for assessment of condition change in complex nonlinear systems. The method is data-driven and makes no assumptions about the underlying process dynamics. One- or multichannel time-serial data is converted to geometric (phase space) representation, which in turn is transformed to a distribution function (DF). The dissimilarity between a nominal base case DF and a test case DF is quantified by robust nonlinear metrics. A significant trend in the dissimilarity measures over time indicates a change in the system's condition and provides forewarning for appropriate response. Next-generation nuclear power plants will have many imbedded sensors in critical equipment, such as turbines, pumps, and valves. These sensors will acquire data, such as vibration (acceleration), motor current, electrical power, and acoustic data for both continuous and transient operations. If successful, this technology will reliably detect condition change and/or forewarn of failure in critical next-generation machinery, allowing just-in-time maintenance to improve plant efficiency, to avoid plant down time, and to eliminate safety faults. This project will be conducted jointly with Duke Engineering & Services, which, will provide operational data and expertise.

Isomer Research: Energy Release Validation, Production, and Applications

PI: John A. Becker, Lawrence Livermore National Laboratory

Project Number: 00-0123

The goal of this applied nuclear isomer research program is the search for, discovery of, and practical application of a new type of high energy density material (HEDM). Nuclear isomers could yield an energy source with a specific energy as much as a hundred thousand times as great as that of chemical fuels. There would be enormous payoffs to the Department of Energy and the country as a whole if such energy sources could be identified and applied to a range of civilian applications.

Despite the potential payoff, efforts in applied isomer research have been rather limited and sporadic. There has been basic research on nuclear isomers since their discovery in 1935 with an occasional hint to tantalize interest in HEDM. In most cases, these hints were refuted by careful examination by other groups.

The project team believes it is time for the Department of Energy to re-examine its strategy in this area. The potential payoffs are large enough to warrant inclusion of applied nuclear isomer research in the U.S. portfolio of high-risk, high-payoff activities. This research proposal details a strategy for such a program. It is in direct response to a call for the fundamental science studying nuclear isomers that could be beneficial for civilian application by DOE/NE (LAB-NE-2000-1). There are several key elements of this strategy, which we propose for the Department's consideration.

- Every effort should be made to leverage the strengths in nuclear physics that exist at the DOE National Laboratories. Appropriate collaborations with university groups should be encouraged.

- A solid base of knowledge about and experimental capabilities in nuclear isomers must be established and maintained. In the current environment, there is a tendency to spend limited resources to refute spurious experimental results. A coordinated program of basic experiments and theory is needed to establish the knowledge base required for civilian applications.

- While the long-term goal includes amassing significant quantities of any new energy source, the Department should not proceed with such production activities until and unless there is compelling, proven scientific evidence that such a source exists.

- The Department needs an independent, expert isomer evaluation capability so that claims of discovery can be checked quickly with the highest precision warranted and policy decision makers are fully and accurately informed.

The project team believes that the needs of the country can be best met by collaboration among the National Laboratories specializing in nuclear physics research. That collaboration would initially involve Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) to form the equivalent of a Virtual National Laboratory on applied nuclear isomer research. The LLNL and LANL co-Principal Investigators will control the scientific direction of this program while LLNL will serve as the administrative lead laboratory for this effort. The collaboration includes nuclear physicists, radiochemists, and atomic physicists with access to unique resources, and it would hopefully become a major element in the Department's arsenal as it attempts to understand the place of applied nuclear isomer research in its overall R&D portfolio. It is expected also to serve as the advocate for appropriate collaborative research among the university community, other national laboratories, and industry.

The isomer research area is rich with possibilities and several areas have been prioritized that are likely to be the most rewarding and fruitful for initial experimental and theoretical investigation because these areas directly bear on important issues: Can the energy stored in nuclear isomers be released on demand? Is the size of the atomic-nuclear mixing matrix element large enough to be useful? Can we initiate quantal collective release of isomeric energy from a crystal? What is the precise energy of the 3.5 eV level in ^{229m}Th?

The specific target experiments are:

- X-ray induced decay of ^{178m2}Hf with a sensitivity 10^5 times recent work.
- Nuclear Excitation by Electronic Transition (NEET): A measurement of the atomic-nuclear mixing matrix element in ^{189}Os.
- Superradiance in ^{93m}Nb.
- TEEN (defined as the opposite of NEET): Nuclear isomer energy release in ^{178m2}Hf.
- Energy and lifetime of the ^{229m}Th isomeric level at 3.5 eV.