2021 Research and Development Grant Awards

Institution	Amount	Title
Kansas State University	$499,768	Statistical Learning Based Multiscale Safety Analysis Framework for Advanced Reactors
Worcester Polytechnic Institute	$499,509	Developing the Research Facilities, Shielding, and Licensing Strategy for a Next-Generation Hybrid Research and Power University Nuclear Reactor
Purdue University	$500,000	Degradation Assessment of Advanced Welds for Pressure Vessels
Virginia Polytechnic Institute	$499,930	Development of a Novel Multi-Modal In-Situ Detection System Supporting Human-Machine Collaboration in Core Monitoring and Control of Advanced Reactors
Clemson University	$499,859	Coupling Life-Cycle Impact Assessment and Risk Assessment for Sustainability-Informed Decision Making
Auburn University	$499,999	Development of a Soil-Structure-Interaction Framework in Support to Enhance Regulatory Oversight for Small Modular Reactors
Virginia Commonwealth University	$500,000	Advanced Characterization Of ATF Cladding for Understanding their Degradation Under Short-Time Temperature Excursions And Implications in Dry Storage
University of Cincinnati	$455,991	In Vivo Measurement of Low Energy Photon Associated with an Internal Deposition of Mixed Oxide Nuclear Fuel
University of Texas at Arlington	$500,000	High-Fidelity Experiments and Simulations of Heat Pipe Performance under Steady-State, Transient, and Accident Conditions
University of Texas at Austin	$500,000	Advanced Condition Monitoring of Dry Storage Canisters by Helical Guided Ultrasonic Waves
Auburn University	$500,000	A High-Throughput Approach to Establish the Regulatory Basis for Qualifying Laser Additive Manufactured Stainless Steel for Nuclear Applications

Statistical Learning Based Multiscale Safety Analysis Framework for Advanced Reactors

Executive Summary:

The main objective of this proposed work is to provide an experimentally validated multiscale approach for safety analysis of advanced reactors, that will be valuable in licensing and regulation. Current techniques for system analysis lack capabilitiesin resolving detailed 3D thermal hydraulic behavior that are critical for the design and performanceevaluation of advanced reactor candidates. The risk evaluation and uncertainty envelop of safetyfeatures in advanced reactors are highly dependent on complex physics in contrast to probabilisticfailure rates of engineered safety features in existing reactors. Therefore, accurate physical depiction in system analysis tools is essential for risk quantification. This project will result in a statistical learning-based coupling mechanism between multiscale models – one-dimensional (1D) system level models and detailed 3D Computational Fluid Dynamics (CFD) simulations of advanced reactor systems for safety analysis. This coupled framework will be implemented with System Analysis Module (SAM) and Nek5000, which are part of NRC's Comprehensive ReactorAnalysis Bundle (BlueCRAB). It will be demonstrated on two test cases relevant to advanced reactors such as liquid metal (sodium fast reactors - SFRs) and high temperature gas-cooled reactors (HTGRs). The existing experimental capabilities at KSU will be used for validating 1D/3Dcoupled models. KSU will develop closure relations for multiscale coupling and obtain validation grade experimental data, while VCU team will lead the CFD simulations and SAM development scope.

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Developing the Research Facilities, Shielding, and Licensing Strategy for a Next-Generation Hybrid Research and Power University Nuclear Reactor

Executive Summary:

<u>Objectives and Benefits</u>: the goals of this proposal to use the MCNP6 Monte Carlo program todevelop the research facilities for a next-generation hybrid university reactor (one that provides both research and power), to optimize these research facilities for neutron flux, to determine the shielding needed for their safe operation, to ensure that the facility design does not affect reactorbaseline reactivity, and to develop a plan for licensing this hybrid reactor with the NRC. This facilitywill be developed for a Gen-IV eVinci™ MicroReactor with reactor design support provided by Westinghouse. Achieving these goals will expand the demand and utility of next-gen microreactors, expand the number of available high flux neutron research facilities, enhance research programs in a broad range of fields, dramatically decrease a university's carbon footprint, and educate nuclear students in next-generation technologies and techniques.

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Degradation Assessment of Advanced Welds for Pressure Vessels

Executive Summary:

The objective of this project is to provide data to form the scientific and engineering basis for evaluatingrisk of irradiation embrittlement in advanced welds on the reactor pressure vessel (RPV). In the 1960s,the Nuclear Regulatory Commission (NRC) mandated that RPVs be forged in one piece due to extreme irradiation embrittlement in submerged-arc welds caused by nanoscale precipitates and dislocation loops. But modern advanced welding technologies exhibit superior quality and performance than conventional arc welds. Hence, there is a need to assess embrittlement risks of modern RPV welding technologies, and to do so at the length scales at which embrittlementmechanisms occur. Our scientific approach utilizes phenomena identification and ranking tables (PIRT) with systematic experiments to rank key nano/microscale embrittlement mechanisms relative to their importance in predicting the figure of merit for the intended RPV application. Work will focus on advanced autogenous electron beam (EB) welds on A508, Class 1, Grade 3 RPV steel; submerged-arc welds will also be studied as a control. We will conduct a series of proton irradiationsand leverage prior neutron irradiated specimens of the same alloy feedstock; we will characterize theirradiated microstructure and assess embrittlement through state-of-the-art small-scale mechanical testing. The engineering outcomes are microstructure-yield stress-DBTT correlations for welds acrossa wide irradiation temperature-dose space; we will generate an updated NUREG/CR-6551 and lay thefoundation for NRC to re-regulate RPV welds through follow-on probabilistic risk assessment (PRA) studies. This work is innovative because it challenges long-standing norms on the viability of welds inRPVs and will represent a transformational modernization of the NRC toward a mechanistic-based regulatory approach for RPV integrity. Educationally, four students will work on this project and will become prepared to enter the nuclear workforce.

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Development of a Novel Multi-Modal In-Situ Detection System Supporting Human-Machine Collaboration in Core Monitoring and Control of Advanced Reactors

Executive Summary:

We propose to develop an in-situ detection and monitoring system with a physics-based MachineLearning (ML) algorithm to infer nuclear reactor core physics data with high fidelity and facilitate human-machine interaction for next generation nuclear reactors. This in-situ monitoring system, with its ML algorithm, will significantly contribute to improved safety and efficacy by making systemadjustments in response to the data generated by the proposed in-situ detection system. For thisproject we will develop a software interface to couple the CHANDLER multi-modal detection system and the VRS-RAPID (Virtual Reality System for Real-time Analysis for Particle transport and In-situ Detection) neutronics code system, and expand on the exiting ML algorithm and virtualreality visualization framework to provide an effective means for the human-machine collaboration. The proposed software will be validated using the Jozef Stefan Institute's researchreactor in Slovenia and the Dominion Energy's North Anna Power Station in Virginia. This proposal addresses several areas of interest, identified by the NRC, including: 'advanced sensorsand controls'; 'human reliability analysis for advanced nuclear applications'; 'Analyses, data and evaluations'; and, 'advanced technology approaches that enhance regulatory decision making'.

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Coupling Life-Cycle Impact Assessment and Risk Assessment for Sustainability-Informed Decision Making

Executive Summary:

To support the role of nuclear energy in the fight against escalating climate change, the nuclear enterprise must reframe critical assessments that drive decision-making. Integration of life cycle assessment with radiological risk assessment will cross disciplinary boundaries, forcing clarity in communication of approximations and outcomes that will drive public confidence in the decision-making outcomes. We propose to integrate life cycle impact assessment and risk assessment to provide regulatory guidance with respect to key fuel cycle issues, specifically a shifting fuel supply chain and an aging generation of nuclear power reactors. For the former, a shift from U.S. dependency on nuclear fuel from Russia requires a clear assessment of the risksand impacts associated with expanded U.S. uranium mining. For the later, life cycle impacts for decommissioning aging U.S. reactors will provide extended guidance for decision-making that can help avoid premature closure. Further, the potential for decontamination and reuse of construction materials after decommissioning may reduce the overall life cycle impacts of nuclear technologies. Overall, complex interdependencies of climate change, energy security, and aging nuclear infrastructure require interdisciplinary solutions.

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Development of a Soil-Structure-Interaction Framework in Support to Enhance Regulatory Oversight for Small Modular Reactors

Executive Summary:

Most small modular reactor (SMR) designs place the critical compartments (e.g., reactor containment) or the entire structure below ground level. This structural layout is advantageous in protecting compartments with critical equipment from natural and man-made external hazards. However, partially or fully burying these structures cause uncertainties related to the performance against earthquakes, where soil-structure-interaction (SSI) and interface behavior are expected to have a significant impact on the structural response; including changes in the energy dissipation, calculated seismic demands, and in-structure response spectra. In order to address some of these uncertainties associated with the performance of new generation SMR designs under seismic loading, this research will aim to develop a framework for conducting nonlinear soil-structure interaction (NLSSI) studies on idealized SMR structures using time-domain finite element models validated against both experimental and field data. The developed NLSSI analysis framework will be applicable for a wide range of structural layout and surface material types by reflecting generic structural attributes of SMRs that are under development. The projectwill also bridge the gap in large-scale SSI experiments for other researchers to validate their numerical models in the future. The overall goal of this project will be to highlight the importanceof SSI on the seismic response of SMR designs while accounting for their distinct features in a generic manner and providing technical basis for improved regulatory oversight for enhanced safety. The experimental data and the modeling framework will be seminal in guiding vendors and researchers to conduct investigations for specific combinations of structure-soil conditions.

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Advanced Characterization Of ATF Cladding for Understanding their Degradation Under Short-Time Temperature Excursions And Implications in Dry Storage

Executive Summary:

The proposed project will investigate the oxidation, degradation, and mechanical behavior of Cr-coated Zircaloy and FeCrAl alloys accident-tolerant fuel (ATF) claddings under short-time temperature excursions and dry storage conditions. The implementation of ATF claddings for lightwater reactors (LWRs) or advanced reactor designs requires fuel reliability and safety during design-basis and beyond-design-basis accident scenarios. Given the high-temperatures during accident scenarios, understanding of the materials' surface chemistry and the evolution of pre- existing oxides as a result of in-reactor operation when accident scenarios occur is critical. The materials' fast response toward accident scenarios will be studied by simulating rapid and controlled high-temperature excursions followed by quenching using an induction furnace experimental setup. These tests will be followed by investigations of the materials' behavior underdry storage conditions. This project will lead to knowledge of oxidation mechanisms and kinetics,ultimately explaining materials' performance and safety limits. Advance destructive and non- destructive characterization techniques will be implemented for the valuation of the ATF claddingmaterials. The advanced surface and mechanical characterization performed by the destructive testing will allow us to develop a rapid non-destructive examination (NDE) tool based on X-ray fluorescence (XRF) and high-fidelity radiation transport modeling for quality control of cladding materials before and after the proposed testing conditions. The combined experimental and computational analysis will provide a robust platform that U.S. regulatory entities and fuel vendorscan use during licensing and commercial use of ATFs in advanced nuclear reactors.

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In Vivo Measurement of Low Energy Photon Associated with an Internal Deposition of Mixed Oxide Nuclear Fuel

Executive Summary:

The goal of this proposed research is development of a practical, robust method to evaluate direct, *in vivo* measurement results of internally deposited, isotopic mixtures of uranium,plutonium, and americium relevant to the composition of new and mixed oxide nuclear fuels andwaste streams commensurate with small modular and advance reactor designs. The lack of a predictable isotopic composition for these fuels and potential waste streams plus the predominance of low energy photon and x-ray emissions from these isotopes makes it challengingto accurately measure and rapidly evaluate an internal deposition using *in vivo* measurements, especially when decisions about remedial actions must be made in a timely manner to be effectivefollowing accidental exposure. Existing gamma spectroscopy programs are not sufficient to resolve the low energy x-rays and photons produced by mixtures of these isotopes.

This project will develop a new method to analyze low x-ray and photon energy spectra generated by *in vivo* measurement of isotopic mixtures of internally deposited uranium, plutonium,and other transuranic isotopes. The method will utilize a matrix of response functions for an arrayof high-resolution germanium detectors using a combination of Monte Carlo simulations to predictphoton interactions in the detectors plus empirical measurements using anthropometric phantomshaving known distributions of ^{241}Am, ^{235}U, ^{238}U, and ^{239}Pu arranged in lungs, skeleton, liver and axillary lymph nodes. The phantoms will be designed and constructed as part of this project andmeasured at the University of Cincinnati In Vivo Radiation Measurement Laboratory. The isotopicmixtures used in the phantoms will be guided by the outcome of mathematical simulations that predict photon interactions and the x-ray and photon energy spectrum generated by the detectorarray.

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High-Fidelity Experiments and Simulations of Heat Pipe Performance under Steady-State, Transient, and Accident Conditions

Executive Summary:

The objective of this proposal is conduct high-fidelity experiments, modeling and simulations ofLiquid Metal Heat Pipes for micro-reactor applications under steady-state, transient, and accident conditions. The data produced will support the validation of the specialized tools included in the Comprehensive Reactor Analysis Bundle (CRAB). We will produce unique sets ofmeasurements of internal thermal-hydraulic parameters using advanced techniques, and measurements' uncertainty will be quantified. The datasets produced will fill the known technology gaps, can be 'directly' used for the development of code closure models, and ultimately advance the predictive capabilities of Computational Fluid Dynamics (CFD) codes andsystem codes adopted for heat pipe reactors technologies.

- We will produce a unique high-fidelity experimental and computational database for liquid-metal heat pipes with uncertainty.
- The database will support the validation and increase SAM's predictive capability maturitylevel, and other MOOSE-based tools.
- The database will become available for validation of other specialized codes.

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Advanced Condition Monitoring of Dry Storage Canisters by Helical Guided Ultrasonic Waves

Executive Summary:

The objective of this research program is to develop a technology to enable the next generation of “intelligent spent nuclear fuel dry storage canisters (DSCs),” that is, canisters with integrated sensing and processing capabilities to enable real-time state awareness. It is proposed to use a novel low-cost sensing system based on helical guided ultrasonic waves (HGUW) and advanceddata processing techniques for interrogating the outer surface of the canister. The crux of this proposal is to generate helical waves into the external surface of the canister, and detect its multiple echoes, generated from its cylindrical geometry, at a receiving transducer. Therefore, instead of monitoring only the direct path connecting two transducers (i.e., first echo arrival), multiple paths taken by each helical wave (i.e., late echo arrivals) can be monitored. We hypothesize that these echoes carry valuable information about the containment function of the canister, and the ability to monitor and analyze these signals can yield a completely new inspection modality that can be used to identify and track the onset of conditions conducive to component degradation (e.g., stress corrosion cracking, internal temperature and pressure). Thesolution represents a change in paradigm – multiple wave reflections, considered undesirable incurrent inspection techniques, will be used to enable real-time state awareness from only a few monitoring points. This reduces the number of sensors needed to perform an inspection. The key advantages of the proposed HGUW-based monitoring technology include: (*1*) the ability to interrogate the internal conditions of the canister from only a few monitoring points, thusincreasing the inspection cost effectiveness, (*2*) the ability to monitor simultaneously the entire circumferential area of the canister, (*3*) the increased sensitivity to many parameters (e.g.: internal pressure and temperature, helium leakage, stress corrosion cracking) owing to the wavestructure choice, (*4*) the capability to detect onset of damage (e.g., leaks, or cracks) and to estimate internal parameters (e.g., temperature and pressure) by toggling between the modes of“passive” acoustic emission testing and “active” ultrasonic testing. Furthermore, the sensing system based on HGUW can be integrated with existing robotic vehicle(s) to remotely apply the HGUW technology on in-service DSCs.

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A High-Throughput Approach to Establish the Regulatory Basis for Qualifying Laser Additive Manufactured Stainless Steel for Nuclear Applications

Executive Summary:

This project takes a high-throughput and integrated approach by using microstructurally-graded specimen design, small-scale mechanical testing, proton irradiation, and high-throughput testing,and material characterization to accelerate the data development and understandings of (1) irradiation-assisted stress corrosion cracking (IASCC), (2) deformation behavior, (3) microstructural evolution of irradiated additive-manufactured (AM) 316L stainless steel (SS) in light water reactor environments. The study aims to fulfill the data need to identify the safety concerns of laser AM for nuclear and support NRC to develop guidelines for reviewing industry proposals and licensing of laser AM. The research contributes to NRC's regulatory activities through rapidly developing a large dataset of radiation properties of proton-irradiated AM 316L SS, revealing the fundamental mechanisms of IASCC and irradiation behavior, surveying differentpost-process treatments to AM SS to support industry's interests, demonstrating the validity of the proposed high-throughput approach for other radiation experiments including neutron irradiation.

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