FY2024 Research and Development Grant Executive Summaries

Institution Name	Award Amount	Title of Grant Award
University of Pittsburgh	$ 500,000.00	Drastically Reducing Variation of Melt Pool and Microstructure in Laser Powder Bed Fusion Additive Manufacturing via Scan-Resolved-Simulation-Based Feedback-Feedforward Control
North Carolina State University	$ 500,000.00	Microstructure-Based Strength Prediction of Additively Manufactured 316H Stainless Steel After Post-Build Processing
University of Illinois Urbana-Champaign	$ 499,988.00	Adaptive Zero Trust Cybersecurity Architecture with AI-Driven Real-Time Threat Monitoring for Advanced Reactors
University of Nevada - Reno	$ 500,000.00	Large-scale soil-structure-fluid interaction testing and analysis to enhance seismic risk assessment models of advanced reactor designs
University of Florida	$ 499,581.00	Enhancing Nuclear Reactor Safety and Longevity: Data-Driven Prediction Lifespan of Stainless-Steel Welds in Extended-Life Nuclear Reactors
University of Nebraska-Lincoln	$ 500,000.00	Control of hybrid additive manufacturing to enhance mechanical performance for nuclear power applications
University of Connecticut	$ 499,995.00	Enabling Reasoning, Secure, and Resilient Autonomy for Heterogeneous Mult-Robert Fleet in Nuclear Domain
University of Nevada - Las Vegas	$ 500,000.00	Cable-Driven Parallel Robots for Radiological Decommissioning Surveys
University of Illinois Urbana-Champaign	$ 500,000.00	Radiation-hardened Digital Boron-coated Straw Neutron Detectors
Georgia Tech Research Corp.	$ 500,000.00	Evaluating Scalability of Dose-based Siting Boundaries for Multi-Unit Advanced Reactor Plants Using a Consequence-Driven Physical Security-Informed Framework
University of Maryland - College Park	$ 500,000.00	Improved analysis and visualization of DPRA simulation data
University of Missouri - Columbia	$ 499,628.00	Reactive Laser Powder Bed Fusion of Borated Aluminum Alloy 6061 for Nuclear Applications
Virginia Commonwealth University	$ 500,000.00	Prediction and Uncertainty Assessment of Irradiated Fueled Fluoride Molten Salt Thermophysical Properties and Thermal Hydraulic Response for MSR Licensing
The Ohio State University	$ 499,981.00	Enhancement of NRC's CRAB Neutronics Modeling Capabilities for Advanced Reactor Transient Analysis
Carnegie Mellon University	$ 500,000.00	Establishing Fracture Toughness Criteria for Qualification of Laser Powder Bed Fusion Additive Manufacturing in Nuclear Applications
Regents of the University of California - Riverside	$ 500,000.00	Predictive Quantum Calculations and Experiments to Design Scintillator Materials for Enhanced Monitoring of Nuclear Materials

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Massachusetts Institute of Technology	$ 500,000.00	Advancing Evaluation of Multiphase Flow in Large Geometric Configurations
University of Nevada - Reno	$ 500,000.00	Regulatory Framework for Microreactor Transport Fire Risk Assessment
University Of New Mexico	$ 500,000.00	Confirmatory Testing and Analysis of Vessel Cooling Systems in Support of Design Certifications for Advanced Reactors

FY2024 Research and Development Grant Executive Summaries

University of Pittsburgh

Drastically Reducing Variation of Melt Pool and Microstructure in Laser Powder Bed Fusion Additive Manufacturing via Scan-Resolved-Simulation-Based Feedback-Feedforward Control

Executive Summary:

Managing the impact of local geometry on laser powder bed fusion (L-PBF) additive manufactured product performance is considered one of the highest priorities by the nuclear community. Accordingly, the goal of this program is to develop a simulation-based feedback feed forward control method for maintaining the consistency of melt pool and microstructure throughout an L-PBF part. Specific research objectives include: (1) Develop an experimentally validated computational fluid dynamics (CFD) model based on measured melt pool dimensions produced by different process parameters; (2) Develop an efficient hybrid CFD and FEM (finite element method) model to simulate multi-track, multi-layer scenarios; (3) Develop an iterative simulation-based feedback-feedforward control model. The material of focus in this project is a nickel-based alloy Inconel 718, which is widely used in high-temperature nuclear applications such as nuclear reactor cores and heat exchangers.

The proposed research addresses a critical barrier toward qualification and broader adoption of the L-PBF process in the nuclear community. Nuclear applications such as nuclear cores and heat exchangers often contain geometric features of different sizes, which cause the melt pool and microstructure to vary significantly throughout a part. By optimally controlling the melt pool dimensions via adjusting process parameters (both laser power and scan speed) on the fly using accurate scan-resolved process simulation, the melt pool and microstructure are expected to be much more consistent throughout a complex part. The great improvement in melt pool and microstructure consistency will enable qualification to be performed more efficiently at a lower cost by reducing the number of expensive experiments in new L-PBF product development.

The critical innovation in the proposed research is the development of a hybrid CFD-FEM simulation model for which the feedback-feedforward control method is based. Most L-PBF thermal process simulation models employ either CFD or FEM; however, the former is accurate but computationally very expensive, while the latter is efficient but not accurate enough to capture the melt pool dimensions and temperatures as local geometry varies. In the proposed CIFEM (CFD imposed FEM) process simulation model, the transient thermal fields are computed from a high-fidelity CFD simulation and inferred by deep learning. These temperature values are imposed in the local FEM region encompassing the melt pool according to the local thermal environment, while heat conduction elsewhere is solved by FEM. The developed CIFEM-based process simulation is expected to be 30-50 times more efficient than CFD-based simulation while maintaining the prediction accuracy of the melt pool and temperature field. Using the CIFEM model to optimally control the local process parameters, the variation of melt pool dimensions is expected to be reduced by 50-70%, resulting in much more consistent microstructure. Thus, this project would address one of the essential priorities in the community and help promote broader adoption of the L-PBF process in safety-critical nuclear applications.

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North Carolina State University

Microstructure-Based Strength Prediction of Additively Manufactured 316H Stainless Steel After Post-Build Processing

Executive Summary:

316H stainless steel (SS) has garnered significant attention from the nuclear industry as a promising structural material for deployment in advanced non-light water reactors (ANLWRs). The Advanced Materials and Manufacturing Technologies (AMMT) program within the US Department of Energy (DOE), Office of Nuclear Energy (NE), is dedicated to expediting the advancement, qualification, demonstration, and deployment of cutting-edge materials and manufacturing technologies. The AMMT program has selected 316H SS fabricated via laser powder bed fusion (LPBF) as its primary material for design enhancements, optimization, and expedited qualification processes. The mechanical properties of additively manufactured (AM) materials significantly depend on AM processing and post-build treatments due to microstructural changes. The collaborative research project between North Carolina State University and North Carolina A&T State University aims to develop a microstructure-based physics model to predict the mechanical strength of LPBF manufactured 316H SS following post-build processing. This model will be informed by advanced characterization and simulation of the phase structure and composition, precipitates and defects size and number density, and mechanical property data. The models will be implemented in the LPBF 316H SS performance code to investigate the effects of post-build treatment on the mechanical properties of LPBF 316H SS. The project is aligned with nuclear industry needs and will benefit the Nuclear Regulatory Commission (NRC) by closing one of the critical knowledge gaps associated with the qualification of LPBF 316H SS for ANLWRs.

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Adaptive Zero Trust Cybersecurity Architecture with AI-Driven Real-Time Threat Monitoring for Advanced Reactors

Executive Summary:

In alignment with the U.S. Presidential Executive Order (2022) to support “Federal Zero Trust Strategy,” the U.S. Nuclear Regulatory Commission (NRC) disseminated a Zero Trust Architecture (ZTA) strategy that warrants federal agencies to implement specific cybersecurity standards by the end of fiscal year 2024. U.S. NRC initiated an emergency study to assess its progress in implementing zero trust standards. Moreover, the U.S. DOE also addresses ZTA as a viable future cybersecurity solution for advanced reactors (ARs). Considering the importance and significance of this timely study, we propose to develop a robust ZTA, integrating a Defense-in-Depth (DID) strategy, to enhance nuclear cybersecurity practices through Cyber-Informed Engineering (CIE), effectively safe-guarding the Critical Digital Assets (CDAs) and other digital and non-digital I&C assets from intelligent malware within the AR’s high-security zone. The objectives of this project are to:

Objective 1:

Develop adaptable ZTA to counter the unchecked lateral movement of AI-Malware and ensure secure access management and data integrity, tailored to Operational Technology (OT).

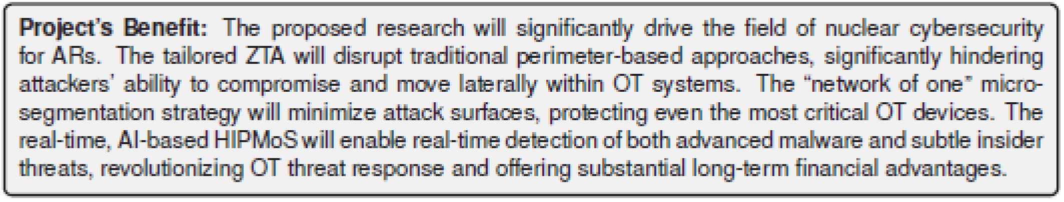
Scope of Objective 1: (1) Develop a Secured Zero Trust (ZT) Data Plane by implementing (a) ‘network of one’ micro-segmentation for critical OT devices. (b) Quantum-Safe Cryptography to minimize the attack surface and offer resistance for quantum-safe wireless communications and remote monitoring of ARs. (2) Develop a ZT Control Plane by implementing (a) continuous verification with multi-factor authentication, and (b) granular access controls to ensure the integrity and confidentiality of data.

Objective 2: Develop a “real-time” and “autonomous” Host Intrusion Prevention and Monitoring System (HIPMoS) to combat evolving AI-Malware and insider threats.

Scope of Objective 2: Develop deep operator network (DeepONet)-powered HIPMoS that will feature (a) “Intrusion Prevention Module” for real-time autonomous anomaly detection and (b) “User Behavior Module” for adaptive baseline analysis. This risk-informed cyber defense will ensure high system availability and proactive defense against both external malware and subtle insider threats.

Objective 3: Develop a virtual testbed by modeling intranet architecture for OT/ZTA for ARs.

Scope of Objective 3: Conduct synthetic simulation and real case studies to test/validate the proposed methods by evaluating the ZTA framework’s adaptability to new threats and its scalability within different nuclear facility configurations.



Project’s Benefit: The proposed research will significantly drive the field of nuclear cybersecurity for ARs. The tailored ZTA will disrupt traditional perimeter-based approaches, significantly hindering attackers’ ability to compromise and move laterally within OT systems. The “network of one” micro-segmentation strategy will minimize attack surfaces, protecting even the most critical OT devices. The real-time, AI-based HIPMoS will enable real-time detection of both advanced malware and subtle insider threats, revolutionizing OT threat response and offering substantial long-term financial advantages.

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University of Nevada - Reno

Large-scale soil-structure-fluid interaction testing and analysis to enhance seismic risk assessment models of advanced reactor designs

Executive Summary:

Designing nuclear power plants under long return period earthquakes results in significant ground accelerations at the sites of many plants in seismically active regions. Recent incidences have also brought more attention to beyond-design-basis earthquakes. Increasing the design-basis seismic hazard at nuclear power plant sites may trigger significant nonlinear behavior in soil and at soil-structure interfaces, for which direct nonlinear analysis is needed to model the system's response reliably. Additionally, the partially or fully embedded designs of advanced reactors with coolant pools have brought more complexities and uncertainties to modeling the underlying soil-structure-fluid interaction (SSFI) mechanisms and the system's seismic resilience.

Substructure and frequency domain-based modeling approaches have been the basis of the most widely used analysis tools in seismic analysis of nuclear facilities. These programs likely result in accurate predictions for low intensity shaking where linear behavior is expected in all components. However, their rigor in modeling the system's response is questionable under increasing shaking intensity, where material and geometric nonlinearities render superposition assumptions to be invalid. Although nonlinear time-domain analysis tools are well-suited to model such nonlinear mechanisms, the previously well-designed experiments have not been at the scale and configuration to validate their performance under loading and boundary conditions expected in the field.

This project aims to complement and address the shortcomings of previous experimental programs by conducting large-scale experiments at a recently completed Laminar Soil Box Testing Facility at the University of Nevada Reno. The main objectives are: (i) to design and conduct large-scale free-field, soil-structure interaction (SSI) and SSFI experiments to systematically generate data under more realistic boundary conditions and over broad ranges of frequencies and soil strains and (ii) to analyze the collected data and model the conducted experiments numerically, using best-practice analysis tools. This modeling exercise will determine the accuracy of coupled physics linear and nonlinear time domain analysis methods in capturing the key response quantities. Developing rigorous analysis tools to accurately predict the nonlinear seismic demands in advanced reactor structures will create pathways to developing reliable risk-informed performance-based design and isolation approaches to facilitate their siting at seismically active regions.

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University of Florida

Enhancing Nuclear Reactor Safety and Longevity: Data-Driven Prediction Lifespan of Stainless-Steel Welds in Extended-Life Nuclear Reactors

Executive Summary:

Recognizing the urgent need to address the aging of reactors, many of which are running on their 60-year licenses, the project focuses on the crucial aspect of assessing the integrity and longevity of stainless-steel welds in reactor components. This effort is vital for ensuring continuous, safe, and clean energy generation. The research utilizes an advanced machine learning model, specifically Bayesian Neural Networks (BNNs), to enhance the precision of predicting fracture toughness in stainless-steel welds, especially under high neutron irradiation conditions found in extended reactor operation. This innovative approach overcomes the limitations of current methods, enabling more accurate and reliable assessments for extended-life reactors. The project's methodology integrates experimental testing, finite element modeling, and AI-driven analysis. It involves comprehensive data collection from varied sources, extensive experimental characterization, and mechanical testing of materials such as cast stainless steels and stainless-steel welds. The Finite Element Modeling (FEM) uses the Gurson-Tvergaard-Needleman (GTN) damage model to simulate fracture behavior, which informs the development of the BNN machine learning model. The BNN model's robustness will be ensured through rigorous validation against experimental data.

Additionally, the project extends its impact beyond research, fostering educational and research capabilities in nuclear engineering at Florida International University, a Minority Serving Institution (MSI). This partnership aims to enrich the nuclear engineering curriculum, provide research opportunities, and prepare a diverse group of skilled professionals for the nuclear energy sector. This project not only promises to enhance the safety and longevity of nuclear reactors but also sets a precedent for the integration of AI in nuclear material research.

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University of Nebraska-Lincoln

Control of hybrid additive manufacturing to enhance mechanical performance for nuclear power applications

Executive Summary:
The research goal of this proposal is to control and to verify the residual stress profile throughout samples created by hybrid metal additive manufacturing (AM). Such control of the manufacturing outcome is significant because it will allow the production of parts which are much safer and more durable. Manufacturing in many industry sectors, including nuclear power, is undergoing a transformation because metal AM promises functional flexibility in the production of engineering components. Great progress has been made recently with respect to part geometry and overall part density for AM parts. However, challenges remain with respect to performance properties, such as strength, fracture, and fatigue, that are dependent on the material state including the anisotropy (i.e., texture), microstructure, and residual stress. Hybrid AM is an emerging approach to achieve organized microstructures without introducing additional materials or varying the chemical composition. A hybrid AM process is the synergistic combination and full coupling of one or more processes and/or energy sources during printing and ultrasonic peening is the primary process to be studied here. In addition, nondestructive evaluation (NDE) approaches must be leveraged to ensure that AM builds meet design requirements with respect to material texture and residual stress. The project team led by the University of Nebraska-Lincoln (UNL) with partners from Iowa State University (ISU) and Navajo Technical University (NTU), includes researchers with experience in metal AM, NDE, materials science, and microscopy. Our preliminary results provide the foundation for the proposed study which will provide new insight into component designs of 304L and 316L stainless steels with enhanced performance through hybrid metal AM. The project includes the following objectives:

Objective 1: Establish Relation between Mechanical Performance and Hybrid Treatment
Objective 2: Quantify the Degree of Material Texture and Residual Stress Nondestructively
Objective 3: Demonstrate Control of Mechanical Performance

The results of this project will have clear benefits to the nuclear power industry because we will establish the value of hybrid AM using quantitative testing and NDE methods to validate the sample builds.

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University of Connecticut

Enabling Reasoning, Secure, and Resilient Autonomy for Heterogeneous Mult-Robert Fleet in Nuclear Domain

Executive Summary:
Producing sustainable, clean energy is paramount in our time, and while nu-clear energy poses its own set of challenges, it remains a significant contributor to carbon-free electric-ity worldwide. Throughout the history of nuclear power plants (NPPs), robotics have played a pivotal role in ensuring their management, safety, and operational efficiency. Heterogeneous multi-robot fleet (HMuRF) has emerged as indispensable assets in this domain, supporting various tasks such as re-mote inspection, dosage reduction, decommissioning, cleanup, and more. Existing decision-making methodologies for HMuRF are primarily rule-based and reactive in nature, which may fail in unfore-seen circumstances due to their rigid protocols. Thus, the question arises: Can we equip HMuRF with human-like reasoning and cognitive capabilities? Additionally, given that HMuRF operate as a Cyber-Physical System (CPS) deployed in mission-critical and safety-critical NPPs, they are highly vulnerable to malicious attacks from both cyber and physical spaces under dynamic and adversarial environments. These attacks can have potentially dangerous consequences as they can lead to the compromise, disruption, or manipulation of HMuRF, leading to tremendous losses in equipment. The ongoing Russia-Ukraine war has shown the importance of energy independence, and the significance of including energy security in national defense strategies. Can we endow HMuRF with secure and resilient capabilities to fully adapt to adversarial environments? To address these challenges, this project aims to enable reasoning, secure, and resilient autonomy for HMuRF in dynamic and adversar-ial nuclear environments. There are three core research objectives: i) Utilizing Large Language Models (LLM) as high-level decision-making components for complex operational scenarios that require human commonsense understanding and reasoning. We will devise a multi-agent interactive reasoning frame-work to enable comprehensive reasoning with LLM in solving complex operational tasks, for example, the Combinatorial Optimization problem. This high-level decision will then be translated into actionable commands and seamlessly integrated with low-level controllers; (ii) A cyber-attack detection and local-ization layer will be developed leveraging Artificial Intelligence (AI) methodologies, notably deep neural networks (DNN). This layer aims to fortify the risk assessment and anomaly detection capabilities within networked HMuRF, thereby enhancing situational awareness of the adversarial cyber landscape, and (iii) Modeling and analyzing the dynamics and vulnerabilities of HMuRF in adversarial environments, considering two types of cyber-physical attacks: exponentially unbounded false-data injection (EU-FDI) attacks on sensors, actuators, and communication channels and general denial-of-service (DoS) attacks on measurement, control, and communication channels. Subsequently, developing a unified cyber-physical attack-resilient control layer to enhance the self-resilience of HMuRF against these at-tacks by using adaptive control and event-triggered (ACET) techniques. We will evaluate the proposed research results in both simulated environments and cyber-physical testbeds to demonstrate their po-tential in revolutionizing robotic operations in dynamic and adversarial environment. The outcomes of this endeavor will provide crucial theoretical support in facilitating the reasoning, security, and resilience of HMuRF operations in the nuclear domain.

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University of Nevada - Las Vegas

Cable-Driven Parallel Robots for Radiological Decommissioning Surveys

Executive Summary:

This proposal is in response to the "Areas of Interest" given in Section I.1.A of the NOFO: "drones and robotics for the purpose of remote monitoring and autonomous/remote control in operations and maintenance activities". Drones and robot dogs (quadrupeds) have found utility in many enterprises including the nuclear sector. Currently, there are no regulations specifically on drones or automated data collection aside from broadly generic performance-based ones in CFR 10 Subpart F (§ 20.1501). There have been data discussions but mostly at the site-specific level. Recently, there have been solicitations for public comment in the Federal Register. *The critical gap that prevents NUREGs from incorporating robots is the lack of testing-and-evaluation (T&E) and verification-and-validation (V&V) of robots in decommissioning radioactive surveys*. Data must be gathered precisely, accurately, repeatedly and robustly in a broad range of surveys in a wide variety of sites. Filling this gap will enhance risk management.

A cable-driven parallel robot (CDPR) provides a suitable platform to gather radiological data and fill this gap. The Skycam is perhaps the most-recognized CDPR. It suspends and translates a broadcast camera over football fields and indoor arenas. It serves as an "existence proof" of a platform with the technology readiness level (TRL) suitable to gather radiological data meticulously. Unlike drones, CDPRs are quieter, operate 24/7, are rugged against adverse weather, carry heavier and bulkier payloads, and do not need FAA licensing or skilled pilots. Unlike quadrupeds, CDPR motions are steady, independent of ground terrain, and can scan vertical surfaces like walls. Proposed is to *fill this gap with a CDPR to conduct a broad range of radiological survey studies in a wide variety of sites* with these research objectives:

1. Conduct T&E and V&V radiological studies with CDPR
2. Demonstrate a reconfigurable CDPR for small, large, indoor and outdoor sites
3. Disseminate results towards authoring NUREGs

UNLV is partnered with the College of Southern Nevada (CSN) to meet *Workforce Training* objectives. CSN is a public 2-year community college and the largest minority-serving institution (MSI) in the state. Both UNLV and CSN are federally designated Hispanic-Serving Institutions (HSI) and Asian American Pacific Islander-Serving Institutions (AANAPISI). The tandem creates a pipeline for nuclear-based careers and graduate research in nuclear engineering.

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Radiation-hardened Digital Boron-coated Straw Neutron Detectors

Executive Summary:

This project aims to enable the accurate measurement of neutron flux for nuclear reactor power monitoring at modular reactors. By developing an innovative position-sensitive boron-coated-straw (PS-BCS) neutron detector coupled with a radiation-hardened digital front-end, our project aims to advance reactor monitoring capabilities. The PS-BCS detector will provide enhanced spatial resolution and flexible operation to different reactor operating regimes, facilitating autonomous monitoring. Considering the unique constraints and the novel challenges presented by modular reactors, such as the compact configuration and the sealed vessel, we propose three key advancements to achieve a new sensor paradigm: (1) development and characterization of detector and signal readout technologies capable of withstanding these harsh conditions (2) development of automated detector working mode selection, and (3) vertical core flux monitoring without detector motion. The proposed solution offers potential cost savings by enabling more efficient operational monitoring and maintenance. Furthermore, the project aims to inform regulatory practices, ensuring the safe and effective integration of advanced monitoring systems into modular reactor designs.

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Georgia Tech Research Corp.

Evaluating Scalability of Dose-based Siting Boundaries for Multi-Unit Advanced Reactor Plants Using a Consequence-Driven Physical Security-Informed Framework

Executive Summary:

The heightened interest in Small Modular Reactors (SMRs) and micro-reactors as reliable, portable power sources for remote locations and critical infrastructure necessitates the evaluation of safety and security implications for new advanced reactor (AR) concepts. Unlike traditional Light Water Reactors (LWRs) constructed onsite, many AR concepts are factory-built modules pre-loaded with fuel, eliminating the need for onsite refueling but introducing complexities in spent fuel storage and onsite fuel movement activities. The overarching goal of this project is to address postulated security vulnerabilities and potential health consequences associated with multi-unit operation and with expanded operational activities from spent fuel storage and onsite fuel movement at fixed-site modular and micro-reactor sites. The proposed study will expand a prior established framework by coupling radiological health consequence modeling with sabotage-based security design in an integrated safety-security and technology-inclusive framework for AR operations to determine the scalability of dose-based regulatory siting boundaries for sites with multiple units, inclusive of onsite spent fuel handling and onsite fuel movement activities.

To achieve the project goals, the technical objectives are as follows:
Objective 1: Assess fundamental systems-level correlations between sabotage-based security events and radiological health consequence assessment from spent fuel handling and onsite fuel movement activities at fixed-site modular and micro-reactors driven by 10 CFR 73.55.

Objective 2: Demonstrate the risk-informed approach for a high-temperature gas-cooled reactor concept using enhancements to state-of-the-art severe accident and consequence analysis computer codes (MELCOR, Maccs), with expanded uncertainty analyses to satisfy licensing requirements under the proposed language of 10 CFR 53.

Objective 3: Evaluate the scalability of dose-based siting boundaries from radiological health consequence assessment in the purview of current policy-driven risk-informed approaches under 10 CFR 53, 50.34, and 52.79 using sabotage-based source terms, and comparative analysis of national (EPA/NRC) and international (ICRP) dose coefficients with atmospheric modeling.

Objective 4: Conduct a comparative benchmark using the risk-informed, consequence-driven framework for spent fuel storage and onsite fuel movement against traditional PPS (e.g., DEPO), historical NRC LWR SOARCA safety studies, and current NRC RAMP codes.

If successful, the proposed study will create a technology-inclusive framework to determine the appropriate sizing of the necessary onsite physical security, optimize the security of reactors from identified vulnerabilities during spent fuel handling and movement activities, and promote the NRC's efforts to credit safety features of ARs through proposed amendments to physical security licensing under 10 CFR 73 and 53.

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University of Maryland - College Park

Improved analysis and visualization of DPRA simulation data

Executive Summary:

Context: Dynamic probabilistic risk assessment (DPRA) represents an advanced method for nuclear power plant (NPP) risk analysis. DPRA has gained interest in academia for over 40 years and found applications in a variety of areas, including assessing the benefit of accident tolerant fuels, physical security risk analysis, cybersecurity risk analysis in recent academic and national laboratory studies. These applications showed DPRA's promise in improving NPP operating efficiency, safety, and security. A DPRA analysis typically involves simulations of thousands or millions of accident scenarios in an NPP. Besides the large size, the simulation data is high-dimensional because of the large number of physical process variables and time steps in the simulations. Despite existing efforts, how to efficiently and effectively analyze this large-size and high-dimensional time series simulation data to extract useful risk insights and visualize and present the accident progression simulation results and any risk insights to stakeholders remains a major barrier to the wider adoption of DPRA.

Objective: In this project, we propose to take advantage of recent advances in machine learning and develop new methods and tools to improve the analysis and visualization of large-size and high-dimensional time series simulation data from DPRA. These methods and tools will supplement existing efforts in DPRA and further simplify the use of DPRA in a variety of NPP application areas, for example, design, regulation, and operation.

Benefits: The products from this project present both original intellectual contributions and practical application values. For the nuclear industry, this project will help overcome a major barrier to the use of DPRA by improving DPRA simulation data analysis and visualization and ultimately make the usability of DPRA to be comparable to existing static PRA tools. This will unleash the potential of DPRA in NPP design and operation to achieve low-cost, safe, and secure nuclear energy. For the U.S. NRC, the results of this project will enable the regulator to more easily interpret a DPRA analysis and support its regulatory process involving DPRA. This is particularly important for the regulation of advanced reactors with highly passive systems, to which it is expected to see more DPRA applications. In the long term, this project will enable DPRA to be a great supplement to existing PRA tools and facilitate the integration of DPRA into the risk-informed, performance-based regulatory framework. In addition, this project will support the training of graduate students and future workforce in the field of risk analysis, which is essential to the U.S. NRC's regulatory activities.

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University of Missouri - Columbia

Reactive Laser Powder Bed Fusion of Borated Aluminum Alloy 6061 for Nuclear Applications

Executive Summary:
This proposed project between the University of Missouri (MU), Auburn University (AU), and Tuskegee University (TU) investigates the effects of finely dispersed boron in additively manufactured aluminum alloy 6061 (AA-6061) for structural and shielding applications in nuclear environments. Leveraging Reactive Additive Manufacturing (RAM) with laser powder bed fusion (L-PBF), the team will create AA-6061-RAM using 2%, 5%, and 10% (by volume) ceramic additions. Miniature tensile specimens (harvested vertically and diagonally via EDM) will undergo up to 6 months of irradiation at MU's high-flux research reactor (MURR). Comprehensive characterization includes hardness testing, room/high temperature tensile testing, and advanced microscopy (SEM, EBSD, TEM) to analyze both irradiated and non-irradiated materials. Additionally, neutron attenuation will be measured, and the impact of build orientation will be assessed. Wrought AA-6061-T6 will provide a baseline for comparison.

This project offers significant potential benefits that directly support the certification of advanced nuclear reactor components through the development and characterization of 3D printed borated AA-6061 tailored for harsh environments. Key benefits include: (i) Generating crucial data to understand the radiation response of AM borated aluminum; (ii) Utilizing MURR's high-flux irradiation and in-house characterization for a comprehensive understanding of material degradation; (iii) Developing a new class of borated aluminum which can function as a neutron absorbing material while also providing unprecedented strength and high-temperature performance; (iv) Determining the effects of L-PBF and L-PBF build orientation on radiation damage response, potentially enabling component designs with optimized neutron shielding capabilities; and (v) Integrating DEI activities designed for traditionally-underrepresented engineering (TUE) students to receive mentorship and unique collaborative research opportunities to aid their pursual of an advanced degree in STEM.

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Prediction and Uncertainty Assessment of Irradiated Fueled Fluoride Molten Salt Thermophysical Properties and Thermal Hydraulic Response for MSR Licensing

Executive Summary:

With multiple liquid fueled molten salt reactors (MSR) involved in pre-licensing activities, a key technical issue that needs to be addressed for future licensing activities is the prediction of the evolving fuel and coolant molten salt properties with changes in chemical composition. The molten salt composition changes due to nuclear fuel depletion/addition (irradiation), build-up of fission products, and salt purification during operation. Consequently, the molten salts' fluid thermophysical properties (density, viscosity, thermal conductivity, and heat capacity) will change and influence the thermal hydraulic behavior and as a result, the accident progression of the reactor. The molten salt thermophysical properties of density, viscosity, thermal conductivity, and heat capacity are also necessary for safety analysis tools such as the BlueCRAB system codes (TRACE and SAM) used for predictive modeling. Currently, the available molten salt properties data in literature are insufficient for the majority of licensing activities due to the large gaps across the desired operating temperature ranges and poorly understood changes in chemical compositions. This project, led by two minority serving institutions (VCU and UML), has significance in its broader impact of developing and deploying an artificial intelligence driven predictive modeling effort for molten salt thermophysical properties and uncertainty estimations of select fluoride and chloride molten salts for MSRs. The project will include thermal hydraulic system response modeling with uncertainty quantification for performance envelope creation. This will result in a methodology to support licensing of liquid fueled MSRs experiencing changes in thermal hydraulic responses due to molten salt chemical composition changes.

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The Ohio State University

Enhancement of NRC's CRAB Neutronics Modeling Capabilities for Advanced Reactor Transient Analysis

Executive Summary:

The NRC will rely on the CRAB code system to perform confirmatory safety analysis for advanced non-LWR reactor designs. Codes for non-LWRs must be capable of simulating the physical phenomena associated with the specific design and important accident scenarios. The novel neutronics modeling capabilities and coupling techniques proposed in this project will not only provide the NRC with much needed high-fidelity reference solutions for deterministic neutronics analysis tools (e.g., Griffin and PARCS), but they can be directly employed to simulate reactivity induced dynamics for advanced reactors, while it would be challenging for deterministic codes because of complex core geometries and novel moderator materials. The project will address the areas of particular interest in "Activities in the areas of neutronics, thermal hydraulics, and severe accident analysis will help validate the NRC's scientific computer codes" outlined in the NRC's FY2024 NOFO.

The objectives of the project are 1) to implement a multilevel quasi-static (QS) kinetics module in the Monte Carlo code Shift to enable the code for efficient high-fidelity multiphysics simulation; and 2) to improve coupling techniques in the CRAB code system, particularly for neutronic/thermal-hydraulic calculations by leveraging our latest developments in the Picard iteration algorithm. We will apply adaptive convergence criteria and relaxation schemes to improve computational efficiency and stability of the coupled nonlinear systems.

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Establishing Fracture Toughness Criteria for Qualification of Laser Powder Bed Fusion Additive Manufacturing in Nuclear Applications

Executive Summary:
The objective of this project is to develop a fundamental, mechanistic understanding of the process-structure-property relationships for fracture toughness of laser powder bed fusion (LPBF) additively manufactured (AM) 316L SS for nuclear reactor components. The resulting knowledge will address the high priority need for fracture toughness data for 316L SS LPBF in existing codes and standards to support LPBF use in nuclear applications. LPBF AM is a layerby-layer fabrication process that is identified as a top candidate for near term use for nuclear components.

The fracture toughness – a key performance metric for nuclear materials qualification and regulation – depends on the microstructural features such as the porosity, grain, oxide and dislocation structures. Specifically, increased porosity will decrease toughness especially in the case of interconnected porosity which provides a less resistant path to crack propagation. On the other hand, finer oxides and grains formed at higher cooling rates improve toughness. These material outcomes are governed by processing parameters (e.g., power, velocity, scanning strategy) and post processing conditions such as hot isostatic pressing (HIP) to tailor the pore, grain and oxide microstructure. Further, there could be variation in the material outcomes depending on the part geometry that may introduce heterogeneity under constant processing conditions. Thus, to responsibly establish regulatory guidelines for LPBF 316L SS, there is a critical need established by the NRC to understand the interrelationship of porosity, microstructure, part geometry, and fracture toughness.

The scientific outcome is a fundamental, mechanistic understanding of the effects of porosity and microstructure (oxide and grain distributions) on the fracture toughness of LPBF 316L SS. The engineering outcome is a map to guide acceptable fracture toughness values based on porosity and microstructure characteristics, providing a regulatory basis for risk assessment of LPBF 316L SS. LPBF process parameters will be varied to create a range of pore and microstructure variations. Further, specimen geometry effects would also be considered by fabricating bulk samples for test coupon extraction as well as near net shape test coupons. Following LPBF, HIP will be utilized to minimize porosity and probe the effects of grain size and oxide characteristics on toughness. Advanced and conventional characterization techniques, as well as advanced data processing and computer vision techniques, will enable the determination of fracture toughness. This work is relevant to NRC as it expressly fills three of the most significant research gaps identified in the NRC's recent LPBF Technical Assessment, including initial fracture toughness, post-processing, and local geometry impacts on product properties and performance.

The team possesses collective expertise in areas crucial to the project, including LPBF AM, HIP, multi-scale defect and microstructure characterization, and mechanical testing and advanced characterization relevant to nuclear components. The project builds upon an existing collaboration between Carnegie Mellon University and The University of Texas at El Paso, a leading Hispanic Serving Institution and adds a new collaboration with University of Illinois Urbana-Champaign. The team is uniquely positioned to train students at various levels, from technicians to scientists, which aligns with the goals of the NRC to develop a diverse and multi-faceted nuclear workforce.

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Predictive Quantum Calculations and Experiments to Design Scintillator Materials for Enhanced Monitoring of Nuclear Materials

Executive Summary:

This project will use synergistic computational and experimental approaches to down-select materials with good scintillation properties (specifically energy resolution and stopping power) for detecting radiation emitted by nuclear materials. Current scintillation materials are limited in their applicability to detect nuclear radiation due to a lack of an optimal combination of energy resolution, stopping power, light output, decay time, and cost. The goal is to go beyond existing materials, and the primary objective of this project is to use high-throughput computation (Wong, UC Riverside) and experiment (Hawrami, Fisk University) to find compositions that produce the best combination of scintillation and material properties. Both universities participating in this NRC project are minority/black-serving institutions, and the training of students in computation and experiment will have a strong and broad impact on NRC research and the professional development of underrepresented minorities. The benefits of using predictive quantum-based simulations to rationalize/guide experiments will result in the efficient synthesis of promising scintillator materials as advanced sensors for nuclear materials. In addition, securing the US from radiological and nuclear threats continues to be a serious concern for both NRC and US national security. The conventional approach for detecting and analyzing data in search of these illicit sources is time-consuming and requires significant operational involvement to achieve accurate results. Constructing better scintillator materials can significantly improve the speed and accuracy of these time-consuming analyses. As such, using computational techniques and experimental synthesis approaches will enable a deep understanding of dopant elements, energies, and configurations for the rational synthesis of promising scintillator materials, resulting in an exciting opportunity for NRC leadership to harness these new materials.

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Advancing Evaluation of Multiphase Flow in Large Geometric Configurations

Executive Summary:

The evaluation of advanced light water reactors (ALWRs) demands an enhanced ability to simulate multiphase flow, particularly in scenarios featuring novel design elements like large unpartitioned in-vessel chimneys. These complex configurations introduce challenges beyond the capabilities of current lumped parameter-based system codes, aggravated by the absence of relevant experimental data. Notable ALWR designs such as the small modular BWR and PWR variants (e.g., GE BWRX300 and NUSCALE) and large passive cooling systems, like those envisioned for the AP300 reactor, are emblematic examples of these challenges. To address this pressing need, the application of multiphase computational fluid dynamics (CFD) is imperative. This allows for the scaling of simulations to conditions not practically attainable in experiments. However, the current maturity of multiphase CFD is insufficient to tackle the intricacies of such complex flow regimes. Furthermore, a comprehensive understanding of the associated uncertainties is essential to support safety evaluations. This project builds upon the extensive groundwork laid at MIT in advancing multiphase flow modeling capabilities, notably under the sponsorship of the DOE CASL program. The proposed effort aims to extend these capabilities towards simulating high void fraction regimes in large geometric configurations representative of prototypical reactor conditions. Central to this approach is the utilization of the Eulerian multiphase flow framework, augmented by a synergistic integration of interface capturing simulations and available experimental data. By leveraging these methodologies, this project will advance the maturity of multiphase CFD for ALWR evaluation, with a specific focus on addressing complex flow phenomena in novel reactor designs. The outcomes of this research will not only enhance the predictive capabilities crucial for ALWR safety assessments but also contribute to the broader advancement of multiphase flow simulation methodologies in nuclear engineering.

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Regulatory Framework for Microreactor Transport Fire Risk Assessment

Executive Summary:

This project focuses on enhancing the safety and efficiency of transporting factory-constructed nuclear microreactors, which can generate up to ~20 MW of thermal energy and are designed for rapid deployment to various sites for electric power, process heat, hydrogen production, and desalinization. These microreactors, potentially containing irradiated fuel, require compliance with U.S. Nuclear Regulatory Commission (NRC) regulations for safe transport under conditions that could arise from accidents. Traditional spent nuclear fuel (SNF) is transported in robust, shielded packages designed to withstand severe accident conditions. However, the unique characteristics of microreactors pose additional challenges, as they might not inherently meet the safety levels required by federal regulations after experiencing hypothetical accident conditions (HAC).

To address these challenges, the project aims to develop computational models to assess the impact of fire accidents, coupled with earlier assumed structural damage and water immersion, on the performance of microreactor safety components. This analysis will evaluate the degradation of containment, shielding, neutron poison, and heat conduction components under such conditions. Furthermore, the project seeks to establish a risk-informed framework by comparing the safety of microreactor transport to SNF transport, using historical accident data to assess the likelihood of accident scenarios per mile of transport. This framework will assist the Nuclear Regulatory Commission in developing microreactor-specific transport regulations, ensuring that even under special one-time authorizations, the transport of microreactors can achieve a comparable level of safety to that of SNF.

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Confirmatory Testing and Analysis of Vessel Cooling Systems in Support of Design Certifications for Advanced Reactors

Executive Summary:

This research proposal aims to conduct confirmatory testing and analysis of vessel cooling systems to support the design certifications of advanced reactors. Licensing constitutes a critical component in the operation and deployment of advanced reactors, ensuring their safe and secure functionality. This project aims to enhance the understanding of safety and licensing requisites for Fluoride-salt-cooled High-temperature Reactors (FHRs) based on computational and experimental investigations. In particular, this project proposes a thorough investigation of passive post-shutdown decay heat removal under molten salt loss of coolant accident (LOCA) conditions. Multiple mechanisms through which molten salt coolant loss can affect decay heat removal in FHRs, such as disruption of in-core circulation, reduction of core's heat capacity following a large breach, elimination of buoyancy force acting on pebbles, and changes to the heat conduction medium and pathways in the core. The effectiveness of an ex-core passive vessel cooling system e.g., RCCS, will be comprehensively evaluated under salt-loss conditions. In addition, a PRACS with the reactor immersed in a different salt pool to deliver reactor vessel cooling will be examined for FHRs. Computational investigations will involve numerical multi-physics modeling and system-level analyses using MELCOR and in-house codes. Scaled-down experiments under prototypical temperature conditions will be conducted to enable validation of the computational models.

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