## Project Title

Non-Linear Ultrasonic Testing and Microstructural-based Modeling towards the Development of Prognostic Damage Maps for Reactor Structural Materials

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**Program**: MS-NEET-1: Nuclear Energy Related R&D

**ABSTRACT:**

The nuclear industry and nuclear science would greatly benefit from new non-destructive technologies that could probe the relative healthiness of materials in real time or nearly real time. An operating nuclear reactor has thousands of structural components undergoing severe combinations of thermal-mechanical loads in combination with neutron radiation damage processes and other environmental exposures, such as corrosion and erosion. Reactor safety is predicated on knowing the safety limits and average lifetimes of such structures. Greater safety and more accurate lifetime predictions are possible if the state of damage of a given structure could be determined, even partially, during reactor operation. This requires the science, technology, and knowledge that is the subject of the proposed mission supporting research project. Specifically, the use of ultrasonic sound wave excitations can be used to non-destructively probe the state of health, if you will, of a given component if the details of the ultrasonic wave's interactions with the material can be measured, modeled, and quantified.

The use of non-linear ultrasound (NLU) as a tool for non-intrusive damage diagnostics and prognostics in advanced reactors materials is in its infancy but is able to discriminate between different microstructural defects, defect clusters, dislocation configurations, and other microstructural features that are important in determining the remaining life of a structural material. However, its use as a successful prognostic tool relies on 1) *in situ* non-intrusive signal generation and measurement, 2) improved models of NLU-defect interactions, 3) radiation resistant sensor development, and 4) wireless technologies for signal extraction, transmission and remote processing. This proposal addresses items 1 and 2 in the above list by using a microstructural-based modeling and a new *in situ* pitch-and-catch NLU measurement system integrated with thermal-mechanical environments for testing materials. This new integrated system applies controlled thermal-mechanical loadings to study important aspects of microstructural evolution relevant to advanced reactor materials with simultaneous NLU experiments in support of damage prognostics. These microstructure evolution effects include thermal aging and precipitation, thermal creep, fatigue loading, and creep-fatigue loading at temperatures and mechanical stresses that span water-cooled reactor and advanced reactor environmental conditions. Understanding NLU signal generation under these different loading conditions will help advance the state-of-the-art in non-destructive materials evaluation and prognostic damage prediction.

The specific objectives of this project are to: (i) develop 3D microstructure-based NLU models that simulate the dynamic interaction between ultrasound and microstructural defects, (ii) use laboratory-scale measurements of relevant (to advanced reactors) damage to verify and optimize model parameters, and (iii) apply NLU models to improve signal discrimination between defects and defects configurations of interest to mechanical properties and lifetime predictions. This research will develop unique experiments and simulation capabilities to investigate the relationship between the measured ultrasonic harmonics and the parameters characterizing microstructural defects, such as defect type, spatial and size distributions of defects, and defect morphologies that occur during typical thermal-mechanical exposures in order to address gaps in our knowledge of NLU signal generation in materials undergoing microstructural evolution. The proposed

effort is divided into two integrated tasks with a logical path to accomplishing this scope and addressing the stated objectives. The first task is focused on generating NLU data correlated to known microstructures. The second task develops beyond state-of-the art phase-field models of NLU signal generation in simulated 3D microstructures to provide the science behind the NLU datasets. Modeling, together with experiments, seeks to develop a *prognostic damage map* for reactor structural materials so that, in the future, NLU data can be used to predict microstructural changes accurately.

This integrated research project will demonstrate the framework of experiments and modeling for analyzing the effect of microstructural differences on NLU signals, and significantly increase the capability for signal discrimination for the life prediction of reactor materials. The program workscope contains *"Development of practical techniques that are non-intrusive with respect to irradiation specimens is encouraged, as are concepts that examine the feasibility and practical use of nontraditional methods such as optical fibers and ultrasonic techniques as well as other incorporated wireless transmission techniques."* This project integrates experiment and modeling to **better establish the relationship between NLU signals and defect microstructures, and improve the capability of signal discrimination for life prediction of reactor components in simulated reactor conditions.** The resulting capability will be broadly applicable to existing and advanced reactor concepts. Further, the capability provides a mechanism for nondestructively monitoring and characterizing reactor materials in a laboratory setting, which improves the ability to design and test materials for nuclear power reactors.

This project will lay the groundwork for establishing improved relationships between higher order ultrasonic harmonics and microstructural defects through a combination of advanced modeling and *in situ* measurements in a customized test-bed, and enable: (1) in-situ monitoring of reactor materials to identify the onset of mechanical property degradation, (2) prognostic damage maps for materials that provide a real-time assessment of microstructural changes under irradiation. Scientifically, this project will fill in several of the NLU knowledge gaps that exist, including the microstructural coupling effect.