# High Fidelity Ion Beam Simulation of High Dose Neutron Irradiation

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**Program**: IRP-RC: Simulation of Neutron Damage for High Dose Exposure of Advanced Reactor Materials

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**ABSTRACT:**
The objective of this proposal is to ***demonstrate the capability to predict the evolution of microstructure and properties of structural materials in-reactor and at high doses, using ion irradiation as a surrogate for reactor irradiations.***

The promise for developing new, advanced nuclear reactor concepts that significantly improve on the safety, economics, waste generation and non-proliferation security of commercial nuclear power reactors, and the extension of life of existing light water nuclear reactors rests heavily on understanding how radiation degrades materials that serve as the structural components in reactor cores. In high dose fission reactor concepts such as the sodium fast reactor (SFR), lead fast reactor (LFR), molten salt reactor (MSR) and the traveling wave reactor (TWR), structural materials must survive up to 200 dpa of damage at temperatures in excess of 400°C. At such high damage levels, the major degradation modes are likely to be driven by void swelling and phase stability. Void swelling occurs at homologous temperatures of 0.35–0.55TM, which for steels (325–650°C) overlaps the temperature range of the reactor core for these four high-temperature, high-dose concepts. Exacerbating the problem is phase instability at high doses due to radiation-induced or -enhanced solute segregation and ballistic dissolution of precipitates by energetic displacement cascades. Irradiation can nucleate or dissolve phases, changing the solute composition of the matrix and enhancing void growth. Further, dissolution of particles added to increase the strength of the alloy results in softening and compromises high-temperature strength and creep. For example, γ' matrix precipitates that provide strength to nickel-base alloys used in high-temperature applications are unstable under irradiation. Radiation can induce the formation of brittle phases along grain boundaries and other defect sinks, reducing ductility and degrading fracture toughness. Light water reactor core components have been plagued by irradiation assisted stress corrosion cracking, which is one of the most life-threatening degradation modes in LWRs, and will be exacerbated in the supercritical water reactor. Thus, virtually all existing LWRs and advanced reactor concepts require a solution to the radiation damage problem. As materials degradation due to irradiation is both a life-limiting and a concept-validating phenomenon, it is truly the grand challenge for the growth and vitality of nuclear energy world-wide.

Traditionally, research to understand radiation-induced changes in materials is conducted via radiation effects experiments in test reactors (both fast and thermal), followed by a comprehensive post-irradiation characterization plan. This is a very time consuming process because of the low damage rates that even the highest flux reactors exhibit. This fact prevents radiation damage research from "getting ahead" of problems discovered during operation. In addition the dearth of available test reactors worldwide, and the high cost of research on irradiated materials in the face of shrinking budgets put additional constraints on this approach. All of these constraints have compromised our ability to advance the understanding of neutron radiation effect at high doses. A promising solution to the problem is to use ion irradiation to irradiate materials to very high doses. The advantages of ion irradiation are many. Dose rates (typically 10-3 to 10-4 dpa/s) are much higher than under neutron irradiation (10-7 to 10-8 dpa/s), which means that 100s of dpa can be reached in days or weeks instead of years. Because there is little activation the

samples are not radioactive. Control of ion irradiation experiments is much better than experiments in reactor. Measurement of temperature, damage rate and damage level is difficult in reactor, resulting in reliance on calculations to determine the total dose, and estimate irradiation temperature. By contrast, ion irradiations have been developed to the point where temperature is extremely well controlled and monitored, and damage rate and total damage are also measured continuously throughout the irradiation and with great accuracy.

Challenges to the implementation of ion irradiation as a surrogate for neutron irradiation include rate effects, small irradiation volumes, accounting for transmutation and the lack of data to establish the equivalence. Addressing these challenges constitutes the main focus of this program. This program consists of four major elements, or thrusts: 1) establishment of the capability to conduct dual- and triple- ion irradiations that capture the key elements of the BOR-60 reactor neutron spectrum and development of both ion and reactor irradiation programs, 2) a description (both experimental and computational) of the evolution of the irradiated microstructure over a wide dose range relevant to fast and thermal reactors, and 3) establishment of the microstructure – property relationship for irradiated materials, and 4) engaging the worldwide radiation effects community through creation of workshops and working groups to address ion irradiation techniques and the analysis of defects in the irradiated microstructure. Cross-cutting activities will help unify these major thrusts. Ion and neutron irradiation will be performed on the same alloys/heats, both damage and transmutation effects will be incorporated seamlessly into the irradiations, and the meshing of experiment and modeling efforts will occur across all length scales and all aspects of the program. The set of alloys was selected to represent potential candidate alloys for fast reactors and as replacement alloys for LWRs at high dose. Additionally complementary neutron irradiation data exists for several of these alloy heats. Finally they are amenable to inclusion in a fast reactor irradiation campaign designed to produce a substantive data set to allow for a comprehensive comparison of ion and neutron irradiation effects.

This project will demonstrate the capability to evaluate the behavior of reactor materials at high irradiation doses. This effort will include a benchmarking of the microstructures formed under ion irradiation and neutron irradiation and the resulting mechanical properties by a combined experimental and analytical approach. This will be a multiphysics effort from atomistic defect studies and production, to microstructure development to the effect of these microstructure changes on mechanical properties. The final product will provide a path and a methodology for qualifying materials for service at very high doses using ion irradiation.

This project addresses the NE programmatic objectives of materials performance in fast reactor core materials and fuels, and core structural materials in light water reactors. The project will be able to do this by strong leveraging of other efforts and by including the efforts of a wide range of collaborators who will contribute to the project outcome. The program leverages activities in the FCRD, LWRS, AGR and ATF programs, and the new DOE/EPRI ARRM program. It engages national laboratories (ANL, INL, LANL, LLNL, ORNL), industry (TerraPower LLC, EPRI) and major international programs and organizations (University of Manchester, University of Oxford, Areva, CEA, Queen’s University), and leverages multiple, on-going NEUP and I-NERI programs. The Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom will provide funding to the University of Manchester and the University of Oxford specifically to support their collaboration. This project provides for the establishment of a dual- and triple-ion beam national user facility for radiation damage studies in the U.S. It includes dedicated fast reactor irradiations in the BOR-60 reactor, specifically for this program, for which samples have already been inserted in-reactor. It utilizes national user facilities (ShaRE and ATR-NSUF) for sample characterization through grants that have already been awarded for this purpose. It employs a coordinated ion and neutron irradiation program out to 120 dpa on identical alloy heats as well as incorporation of existing neutron data. It engages the worldwide radiation effects community in a truly global effort to develop ion irradiation as a tool to serve as a surrogate for neutron irradiation.

The outcome of this program will be the establishment of the conditions by which ion irradiation can be used as a surrogate for neutron irradiation in reactor. It will provide a path for materials qualification at high doses with a significant reduction in both the time and cost to evaluate core materials response to irradiation, as well as the implementation of materials and processes to improve the safety and economics of the existing light water reactor fleet and advanced reactor designs.