Welcome Remarks

Kathryn Huff
DOE

Abstract: Comments on the importance and relevance of VTR from the perspective of DOE-NE, with recognition of the broad range of applications that could be enabled by a domestic fast spectrum test reactor, including radiation of materials for accelerator applications.

Radiation Damage of HEP High-Power Targets at Fermilab

Kavin Ammigan
Fermilab

Beam-intercepting devices such as beam windows and secondary particle-production targets are critical devices in accelerator target facilities of High Energy Physics (HEP) experiments. The reliable operation of these devices is essential in delivering the particles of interest and maximizing uptime of the physics experiments. However, continuous bombardment by high-energy high-intensity pulsed particle beams poses serious challenges to the operation and maintenance of these devices. Over time, beam-induced radiation damage effects change the bulk properties of the beam-intercepting materials and degrade the devices' lifetimes. Several major accelerator facilities have already had to limit their beam powers because of the survivability of their targets and windows, rather than as a limitation of the accelerators themselves. As beam power in next-generation multi-megawatt accelerator target facilities continue to increase, it is critical to understand and assess radiation effects in beam-intercepting materials. This presentation describes the radiation damage challenges in HEP high-power target facilities and the necessary materials irradiation and characterization R&D studies needed to enable reliable operation of future facilities.

Beam testing and post-irradiation examination activities at CERN in support of collider programs and targetry technologies

Nicola Solieri
CERN - European Laboratory for Particle Physics

Beam-intercepting devices such as collimators, absorbers, and particle producing targets are essential accelerator systems components for the execution of the high energy and nuclear physics program at CERN. In the constant pursuit of ever more energetic, intense and focused particle beams, these devices have to withstand increasingly challenging operational conditions. The development of these devices require ad-hoc and detailed FEA as well as CFD techniques, coupled with an in-depth knowledge on the material properties at the operational regimes. However, these studies are not complete if the modification of the properties induced by particle beams is not taken into account. The presentation will detail the beam testing and post-irradiation examination efforts that have taken place in recent years at CERN to study these phenomena and their direct impact on current and future operational devices. These include in-beam testing of target materials, thermal shock experiments of prototypes, as well as autopsies of formerly operational devices.

In-situ TEM of the Radiation Effects on Material Microstructures in IVEM-Tandem Facility: Overview and Recent Development

Wei-Ying Chen, Meimei Li, Dzmitry Harbaruk, Josh Hlavenka
Argonne National Laboratory

Abstract

The IVEM-Tandem Facility at Argonne National Laboratory (ANL) is a user facility for *in-situ* TEM study of the radiation effects on material microstructures. It interfaces a 500 kV ion accelerator and a 20 kV helium ion source to a 300 kV Hitachi H-9000NAR TEM, allowing real-time microscopy under dual-beam ion irradiation damage/implantation with well-controlled conditions (specimen orientation, temperature, ion type, ion energy, dose, dose rate, applied strain). The superior electron brightness of LaB_6 filament of the H9000 microscope makes it suitable for diffraction contrast imaging, permitting effective real time observation of the irradiation-induced defects in nanoscale.

The IVEM-Tandem Facility was commissioned in 1995 and is now supported by DOE Office of Nuclear Engineering. It provides no-cost access to its in-situ irradiation capability for researchers worldwide through Nuclear Science User Facility (NSUF) Program. The first part of the presentation today will give an overview of the capability of IVEM-Tandem Facility and the research conducted here, including fundamental studies of defect formation and evolution, tomography of defect distribution, phase stability and computer modeling and simulation in basic materials, advanced alloys, accident tolerant fuels and storage of spent nuclear fuels.

The second part of the presentation is about our recent efforts to implement computer vision (CV) in *in-situ* TEM studies. TEM videos of *in-situ* ion irradiation experiments provide dynamic information of microstructural evolution that cannot be obtained from post-irradiation examinations. However, a dauntingly huge amount of video data has practically inhibited manual analysis, often leaving valuable dynamic information under-utilized in the past. To overcome the challenge, we took advantage of the recent advance in CV to fully exploit TEM video data. We will talk about two projects under development using semantic segmentation and multi-object tracking, respectively, to automatically analyze the evolution of irradiation-induced voids and

cascade-induced vacancy clusters in nickel irradiated with 1 MeV krypton ions at between 550ºC to 700ºC. The nucleation, growth, coarsening and shrinkage of individual defect clusters were analyzed frame by frame. The application generates a unique data set that is rarely available before, and it enables a new way to measure the dynamic properties of materials under irradiation environments.

"Breaking the rules" – Advanced post irradiation examination and characterization capabilities at Oak Ridge National Laboratory

David McClintock
Oak Ridge National Laboratory

Structural materials operated in high-radiation environments are altered during service through atomic level interactions with high-energy radiation. The radiation-induced microstructure changes affect the mechanical properties of materials, typically manifested as an increase in strength and decrease in ductility for metallic engineering alloys. It is essential that engineers and designers understanding how the mechanical properties change during service to ensure safe and uninterrupted operation. The Spallation Neutron Source (SNS) maintains dose limits on several high-dose components to limit the risk associated with radiation-induced changes to mechanical properties, including the target vessel, proton beam window, and beam dumps. A post irradiation examination (PIE) program is maintained at the SNS to characterize the changes in mechanical properties for these critical components. Recently, significant "breaking the rules" discoveries were made during mechanical testing and microstructure examinations of 316L stainless steel from SNS targets and Inconel 718 from a proton beam window. These discoveries were possible due to cooperation with an industrial collaborator and the advanced characterization capabilities available at Oak Ridge National Laboratory. This presentation will include a discussion on the recent observations during PIE testing at the SNS and briefly describe the advanced capabilities available at ORNL for irradiated materials characterization.

Capabilities for Irradiation and Post-Irradiation Materials Properties Assessment

Zhijie Jiao, Fabian Naab, Prashanta Niraula, Catherine Nicoloff, Kevin Field, Gary Was
University of Michigan Ion Beam Laboratory

Abstract: The Michigan Ion Beam Laboratory (MIBL) is part of the Department of Nuclear Engineering and Radiological Sciences at the University of Michigan. The laboratory was created to advance our understanding of ion-solid interactions by providing unique and extensive facilities to support both research and development in the field. Understanding the radiation damages in materials using ion irradiations is one of the major focuses of researches conducted at the laboratory. Accelerator-based ion irradiation has been considered as a surrogate for neutron irradiation with many advantages and great potentials. This presentation will discuss the

capabilities of the laboratory to conduct multiple ion beam irradiations, irradiation accelerated corrosion and in-situ ion irradiations with direct TEM observation.

Irradiation damage research of CSNS target

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The target is the most severely damaged component of spallation neutron source, and the radiation damage of the target had been paid close attention to. The first target of CSNS had been in normal operation for nearly three years. It was changed in August, 2020 with the maximum radiation damage 2.3dpa. In order to understand the irradiation effect of the target material, CSNS plans to carry out the irradiation damage study of retired targets in the hot chamber to obtain the performance data of the target material after irradiation. At present, equipment for target disassembly, sample preparation and performance analysis are being developed.

In addition, the behavior of helium is also an important point of radiation damage. In order to understand the diffusion behavior of helium produced in tantalum coated tungsten target after irradiation, helium ion implantation combined with neutron reflection were used to study the migration behavior of helium at the interface of Ta/W and Ni/W. In the Ta/W experiment, the results showed that after helium injection, helium bubbles were accumulated near the Ta layer at the interface, there were few helium bubbles in the W layer near the interface, meanwhile at the interface, helium migrates from W to Ta. In Ni/W experiment, after helium injection, helium bubbles were observed in Ni and W layer, and the density of bubbles in Ni layer was much higher than that in W layer, helium enriched layer were observed at implanted W/Ni interface.

Nuclear Material Characterization at Bristol

Dr. Dong (Lilly) Liu

University of Bristol, UK

A large range of nuclear materials were studied at the University of Bristol including nuclear graphite, TRISO particle fuels, SiC-based accident tolerant fuel cladding and Cr coated Zircaloy cladding in terms of their thermal and mechanical properties in unirradiated and irradiated conditions. As these materials all have complex microstructures, a multiple length-scale approach has been adopted.

Using nuclear graphite as an example, in situ micro-/meso-scale mechanical testing with SEM imaging and macro-scale characterisation using X-ray micro-tomography at temperatures up to 1100°C have revealed the underlying mechanisms contributing to the increased strength and fracture toughness of the material at elevated temperatures. In particular, the high-temperature X-ray tomography techniques developed have been extended to coated cladding and ceramic-matrix composites (both in nuclear and aerospace) to investigate their deformation and fracture in harsh environments.

Most recently, under the UK Advanced Fuel Cycle Programme (AFCP), capabilities of Time-domain ThermoReflectance (TDTR) and micro-scale focussed ion beam digital image correlation (FIB-DIC) ring-core method was developed to characterise the local thermal conductivity and residual stresses in TRISO coatings. These were applied to neutron irradiated TRISO particles to assist the understanding of irradiation induced dimensional changes and irradiation creep.

Last but not the least, due to the large amount of focussed ion beam (FIB)-tomography and X-ray microtomography data generated, an artificial intelligence-based image segmentation method has been established to assist the interpretation of the testing results.

Post-Irradiation Examination Capabilities with EBSD and PED

Assel Aitkaliyeva
University of Florida

Electron backscatter diffraction (EBSD) and precession electron diffraction (PED) are routinely utilized to provide information on grain orientation and size distribution, texture, dislocation density, phase analysis, and residual strain. In this contribution, we will discuss the advantages and disadvantages of these two techniques as applied to irradiated fuels and materials. We will compare different sample preparation options and best practices on how to prepare specimens for high resolution EBSD and PED analyses. The provided examples will cover both structural materials (neutron irradiated 304 and HT-9) and fuels (oxide and metal).

Post-Irradiation Examination Capabiities at PNNL

Stuart Maloy, Dave Senor and Andy Casella
Pacific Northwest National Laboratory

A multitude of testing capabilities are available for testing irradiated materials including actinide fuels and structural materials at PNNL. Testing and characterization is available in the hot cells for highly radioactive materials as well as in low radiation areas for less radioactive materials. A summary will be provided of the mechanical testing and characterization facilities including TEMs, APTs, SEMs, FIBs and more.

Designing Pulsed Reactor Heating Experiments for Plutonium Thermomechanical Property Testing

Ari Foley, Ed Lum, and Dan Olive
Los Alamos National Laboratory

A multi-laboratory team including Los Alamos National Laboratory (LANL) and Sandia National Laboratory (SNL) is reestablishing the capability to perform thermophysical material analysis of HEU and plutonium targets with transient tests at SNL's Annular Core Research Reactor (ACRR). The objective of the inaugural test series is to accurately measure the thermal response of fissionable materials induced in a neutron environment. The mixed radiation environment and temporal effects of the different constituents in these experiments will expand the understanding of dose, dose rate, and temperature rise in fissioning samples and its correlation to radiation damage. This presentation overviews the design and execution process used for special nuclear material (SNM) testing in pulsed reactors, with respect to this test series and beyond. MCNP6 simulations complemented the experiment design by assessing the neutronic qualities of the package, shielding effects, and expected energy deposition in the samples from the mixed radiation environment. Planned post-irradiation examination (PIE) of the samples at LANL's unique combination of facilities will permit characterization of the radiation damage in the samples, as it relates to changes in mechanical properties and corrosion, effects which may have implications for materials in the accelerator community.

Observations of Damage in Material Proposed for the Advanced Photon Source Upgrade Collimators*

Jeffrey Dooling†
Argonne National Laboratory

Ultra-low emittance particle beams yield high-energy-density (HED) conditions when striking beam-facing surfaces. In the case of present and planned fourth generation storage ring (SR) light sources, valuable machine components such as superconducting undulators as well as the vacuum envelope itself must be pro- tected from high-intensity electron beams. The Advanced Photon Source (APS) is in the process of replacing its double-bend achromat SR lattice with a multibend achromat system. The upgraded system known as APS-U will yield a two-order-of-magnitude increase in beam intensity. Initial MARS simulations suggested that most materials would be melted or vaporized during APS-U unplanned whole- beam dumps. Two experiments were conducted in the APS SR attempting to replicate APS-U beam dump conditions on proposed collimator material. These experiments confirmed predictions that both titanium and aluminum alloys can be damaged by beam strikes. Aluminum alloy T6061 is one of several workhorse materials used in accelerator-based x-ray sources. Other important materials are copper and stainless steel which are even more susceptible HED beam dump conditions. Recent simulations performed with the hydrodynamics code FLASH show the melt zone extending well beyond the region of visible damage. This talk will present measurements taken of the test pieces before, during, and after the irradiation experiments. Post irradiation measurements carried out

on the collimator test pieces included photography, 3-D microscopy, and metallurgy. Some of the challenges to evaluation posed when the materials become activated will also be discussed.

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Understanding Irradiation Effect on Mechanical Deformation with High-energy X-ray Diffraction

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Synchrotron x-ray diffraction-based techniques are ideal tools for probing the evolution of deformation microstructures at multiple length scales and for revealing the underlying deformation mechanisms in bulk irradiated materials in situ and/or in 3D. Such tools are also advantageous in the study of additively manufactured materials. This talk will feature a few recent studies conducted at the Advanced Photon Source (APS) in Argonne National Laboratory, in particular, an in situ diffraction study of the effect of neutron irradiation on the martensitic phase transformation in a Type 316 stainless steel, and an in situ 3D characterizations of grain-level response to tensile deformation in neutron-irradiated Fe-9Cr ferritic alloy. The current development of the Activated Materials Laboratory, a new radiological facility to facilitate the study of nuclear materials at the APS that is built in conjunction with the APS-Upgrade project supported by the Nuclear Science User Facilities, will also be presented.

Rapid sample irradiations and material characterization facilities at the University of Missouri Research Reactor

John Brockman
University of Missouri, Columbia

The University of Missouri operates a 10 MW light water cooled research reactor with a peak thermal neutron flux of 4.5 x 10^{14} n/cm^2/s. The graphite reflector region of the MURR core can be accessed from the laboratory building using two pneumatic tube irradiation systems. The peak neutron flux in the pneumatic tube irradiation system is 9.0 x 10^{13} n/cm^2/s. The transit time from the laboratory to the irradiation position is 5 seconds. The facility is routinely used for neutron activation analysis and for the production of radiotracers. Irradiations have also been conducted to study the effects of radiation on polymeric materials. The physical characteristics and neutronics of the irradiation position will be described. Additional resources at MURR for material science include an SEM and FIB in a radiation laboratory.