INL/MIS-24-77467-Revision-0

# Promoting the regulatory acceptance of combined ion and neutron irradiation for material degradation in nuclear reactors

May 2024

Changing the World's Energy Future

Andrea M Jokisaari, Yiren Chen, Rongjie Song, Stephen Taller, Wei-Ying Chen

Idaho National Laboratory

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**Idaho Falls, Idaho 83415**

**http://www.inl.gov**

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AMMT ADVANCED MATERIALS AND MANUFACTURING TECHNOLOGIES

# Promoting the regulatory acceptance of combined ion and neutron irradiation for material degradation in nuclear reactors


Andrea Jokisaari[1], Wei-Ying Chen[2], Yiren Chen[2], Rongjie Song[1], Stephen Taller[3]

[1]Idaho National Laboratory, [2]Argonne National Laboratory, [3]Oak Ridge National Laboratory


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# AMMT Vision, Mission, and Goals

## Vision

Expansion of reliable and economical nuclear energy enabled by advanced materials and manufacturing technologies.

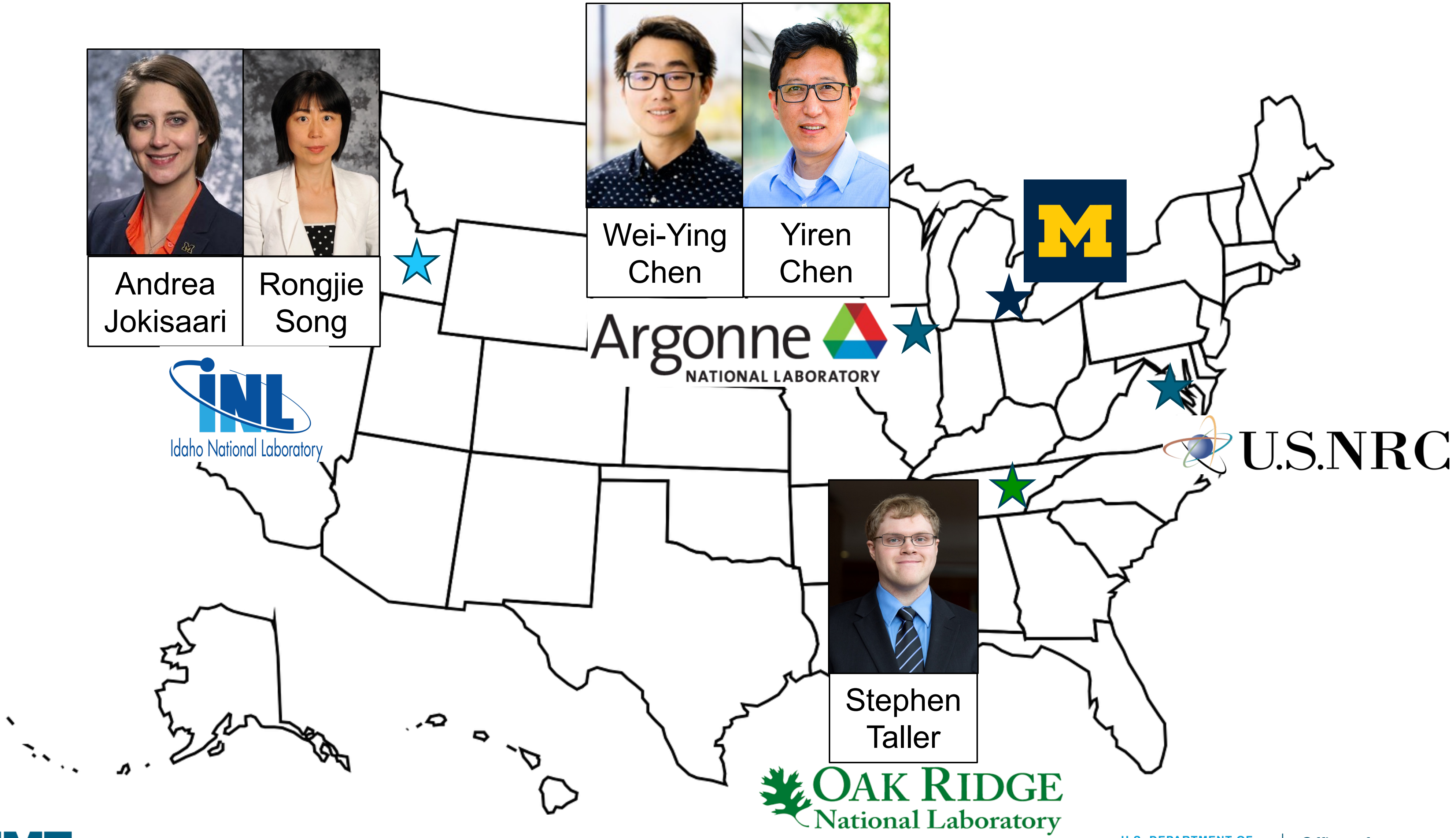
## Mission

Accelerate the development, qualification, and deployment of advanced materials and manufacturing in support of U.S. leadership in a broad range of nuclear energy applications.

## Goals

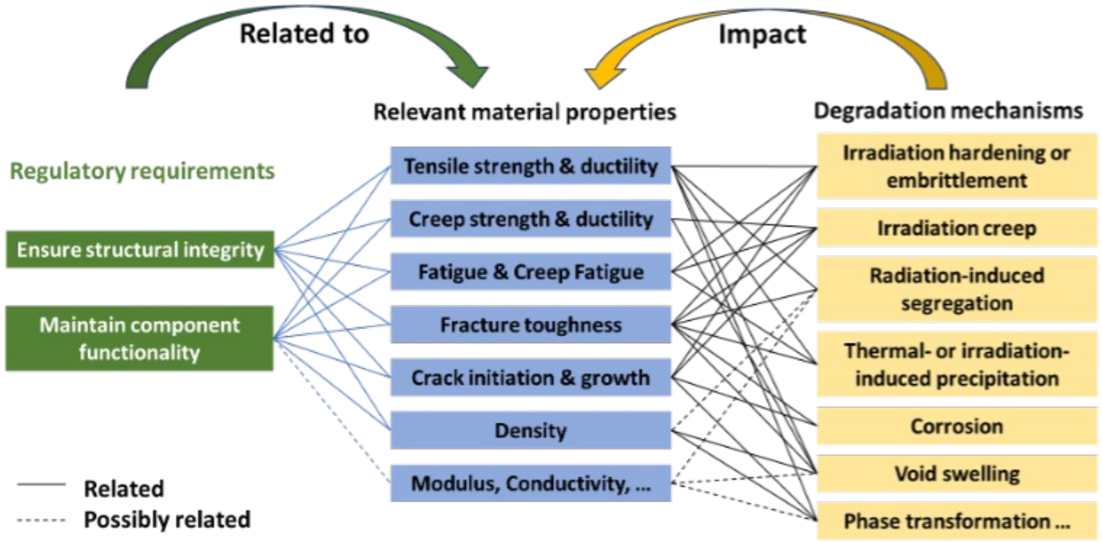
- Develop advanced materials & manufacturing technologies.
- Evaluate materials performance in nuclear environments.
- Establish and demonstrate a rapid qualification framework.
- Accelerate commercialization through technology demonstration.

# Team members

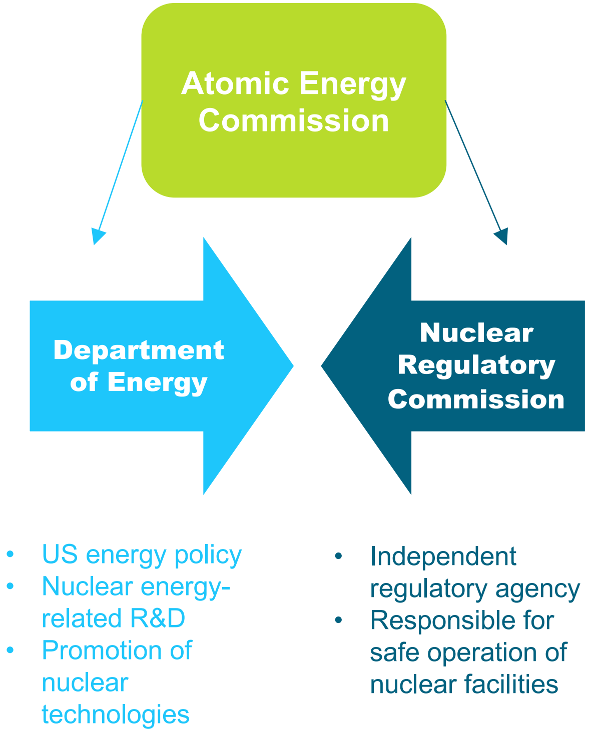


# Regulatory bodies governing materials for nuclear reactors

- **The NRC's mission is to license and regulate the use of radioactive materials for public health and safety, security, and environmental protection, and materials used in facilities is an important part of that consideration**
  - Licensing: process through which the NRC grants permission to engage in regulated nuclear activities
  - Regulatory acceptance: acceptance of a set of specific methodologies or approaches used to support safety assessments or design evaluations within the regulatory framework
- **Technical basis of regulatory issues for materials – a review of federal codes (10 CFR Part 50, 52, 54)**
- **NRC has standards and relies on external Standards Development Organizations, especially ASME, ANS, and ASTM**
  - ASME regulates and standardizes materials used in reactors
  - Section III, Division 5 covers high-temperature reactors
  - ASTM testing methods frequently referred to by ASME standards
  - No ASME standard deals with irradiation effects

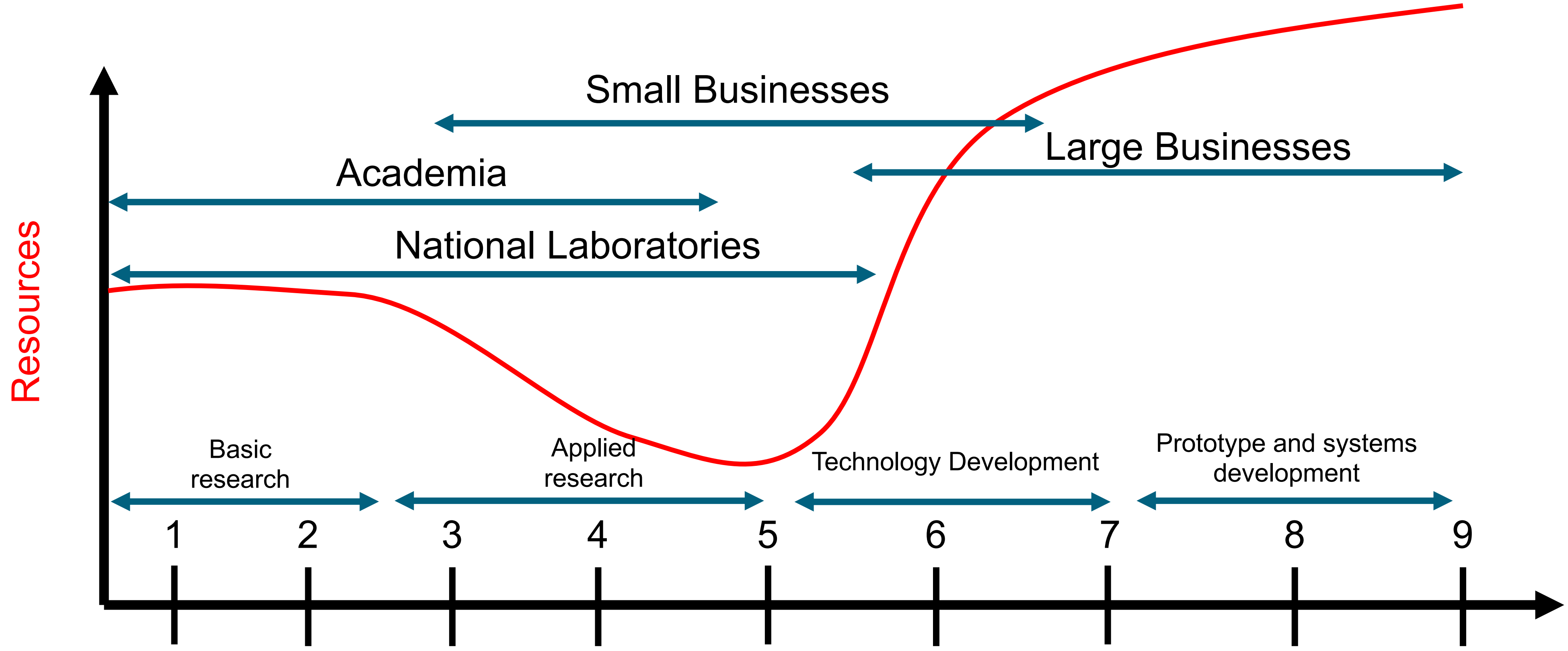



Material properties, degradation mechanisms, and regulatory interaction




Interaction between US Department of Energy and US Nuclear Regulatory Commission and historical relationship

# Ion Irradiation May Enable Materials Qualification Efforts to Traverse over "The Valley of Death"




- **Materials qualification efforts typically require a large investment in neutron irradiations to overcome the hurdle from applied research to developed technology**
- **Ion irradiations as a quick, relatively cheap tool may reduce the overall cost if applied correctly**

# Why now?

CONF-760673

proceedings of the workshop on
CORRELATION OF NEUTRON AND
CHARGED PARTICLE DAMAGE

OAK RIDGE NATIONAL LABORATORY • JUNE 8-10 1976

**1976**

**1978**

**CORRELATION OF NEUTRON AND HEAVY-ION DAMAGE ***

**I. The influence of dose rate and injected helium on swelling in pure nickel**

N.H. PACKAN, K. FARRELL and J.O. STIEGLER
*Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA*

**CORRELATION OF NEUTRON AND HEAVY-ION DAMAGE ***

**II. The predicted temperature shift if swelling with changes in radiation dose rate**

L.K. MANSUR
*Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA*

**1982**

**THE CORRELATION OF ELECTRON, HEAVY-ION AND FAST-NEUTRON IRRADIATION DAMAGE IN M316 STEEL**

R. BULLOUGH
*Theoretical Physics Division, AERE Harwell, Oxon, 0X11 ORA, UK*

T.M. QUIGLEY
*Department of Theoretical Physics, Oxford University, Oxford, UK*

**1993**

Theory of transitions in dose dependence of radiation effects in structural alloys*

L.K. Mansur
*Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6376, USA*

**2002**

Emulation of neutron irradiation effects with protons: validation of principle

G.S. Was [a,*], J.T. Busby [a], T. Allen [b], E.A. Kenik [c], A. Jenssen [d], S.M. Bruemmer [e], J. Gan [e], A.D. Edwards [e], P.M. Scott [f], P.L. Andresen [g]

**2003**

Proton irradiation emulation of PWR neutron damage microstructures in solution annealed 304 and cold-worked 316 stainless steels

Bulent H. Sencer [a,*], Gary S. Was [b,1], Mitsuyuki Sagisaka [c,2], Yoshihiro Isobe [c,2], Gillian M. Bond [d,3], Frank A. Garner [e,4]

**2017**

Roadmap for the Application of Ion Beam Technologies to Challenges for the Advancement and Implementation of Nuclear Energy Technologies

2017

NSUF Nuclear Science User Facilities

**2019**

Emulation of fast reactor irradiated T91 using dual ion beam irradiation☆

Stephen Taller [a,*], Zhijie Jiao [a], Kevin Field [b], Gary S. Was [a]

**2021**

**Predicting structural material degradation in advanced nuclear reactors with ion irradiation**

Stephen Taller[1,2], Gerrit VanCoevering[1], Brian D. Wirth[3] & Gary S. Was[1]

The technique has reached a threshold maturity!

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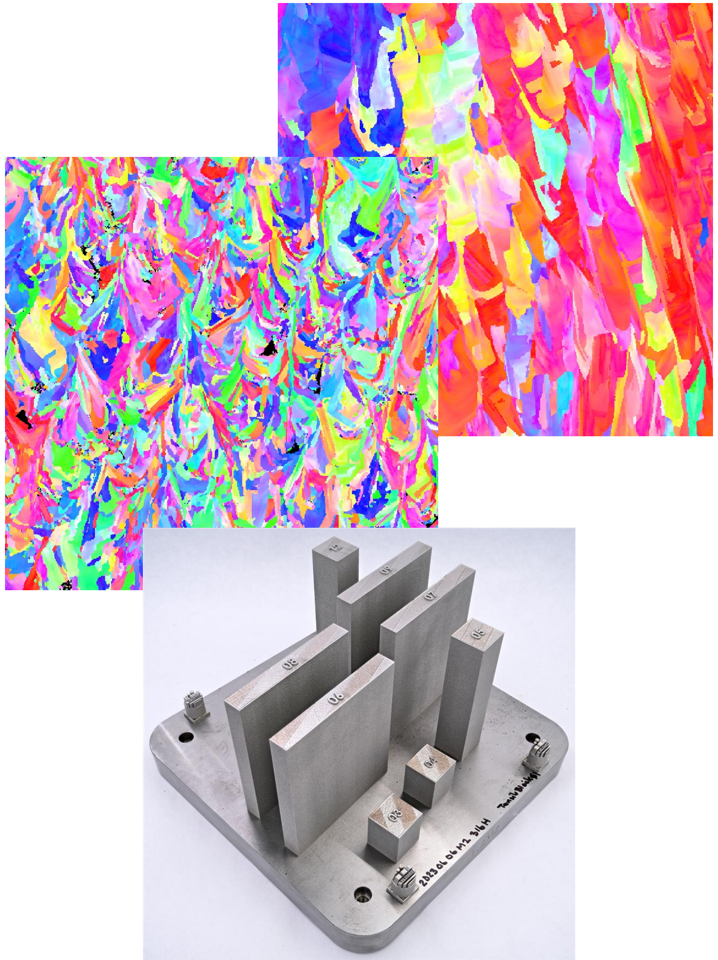
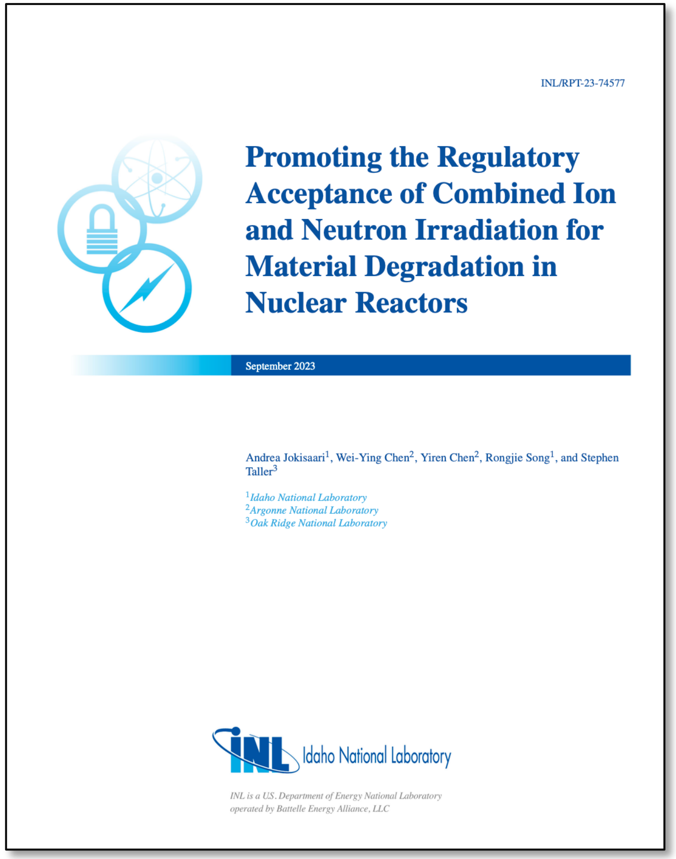
# Additional challenges for AM materials for advanced reactors

- **Metal AM techniques have inherent process variability**
- **Challenges for qualifying as-deployed AM components**
  - Witness specimens for high-temperature, time dependent performance will result in a prohibitively large and time-consuming test matrix
- **The case for ion irradiation testing of AM materials**
  - Increased process variability (microstructure and microchemical variability) makes it prohibitive to use neutron irradiation as the only source of qualification data



# Objective of the white paper

- **Establish the framework to recommend the path forward for the accelerated qualification of structural materials in nuclear environments using combined ion irradiation, neutron irradiation and modeling**
- **Develop a collaborative path forward for academia, industry, and national laboratories developed with input from the Office of Regulatory Research within the U.S. Nuclear Regulatory Commission**
- **The white paper is intended for a broad audience and to provide a technical, generalist-level overview on complex interplay of topics**
  - Domain expertise is necessary to apply the approach correctly, because the detailed strategy must be specified for each property of interest


INL/RPT-23-74577

**Promoting the Regulatory Acceptance of Combined Ion and Neutron Irradiation for Material Degradation in Nuclear Reactors**

September 2023

Andrea Jokisaari[1], Wei-Ying Chen[2], Yiren Chen[2], Rongjie Song[1], and Stephen Taller[3]

[1]*Idaho National Laboratory*
[2]*Argonne National Laboratory*
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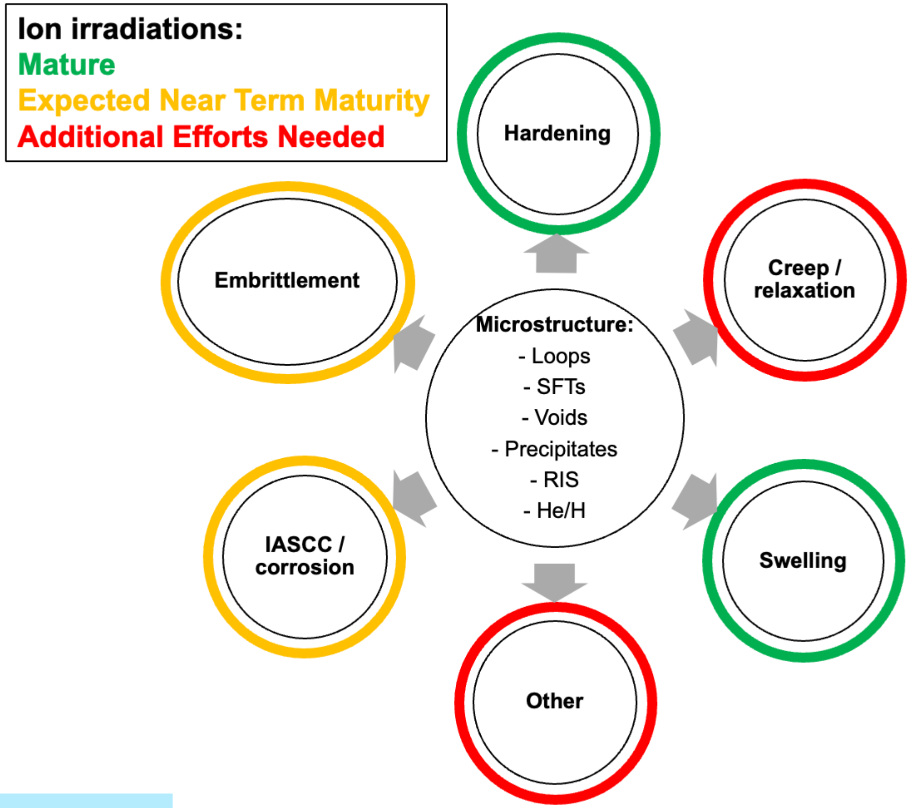
# Where can ion irradiation help accelerate qualification?

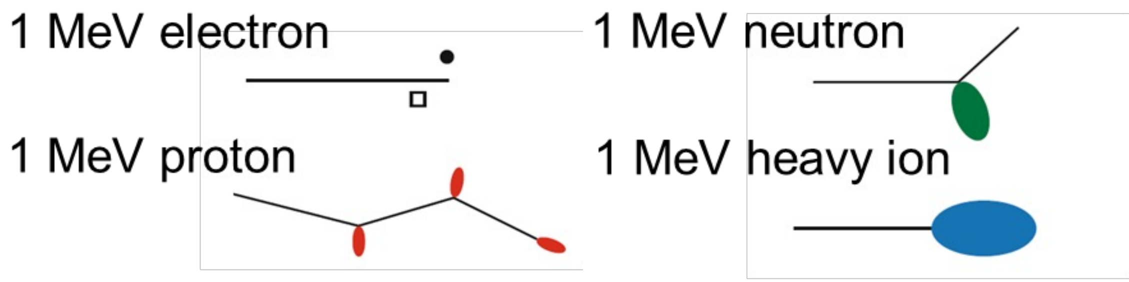
- **Decades of effort have led to sufficient understanding on the differences between ion and neutron irradiations, making it is possible to generate relevant irradiation microstructures with ions**
  - Note: not all structures can be generated at the same time
  - The material property of interest must be linked to the microstructure of interest
- **Ion irradiations, in general, have smaller uncertainty in experimental parameters, making modeling more precise**
- **The gap between microstructure and properties can be addressed with careful measurements, modeling and simulation**
- **Approaches with "surveillance" materials/samples can provide sufficient coverage and is and historically acceptable by regulators**

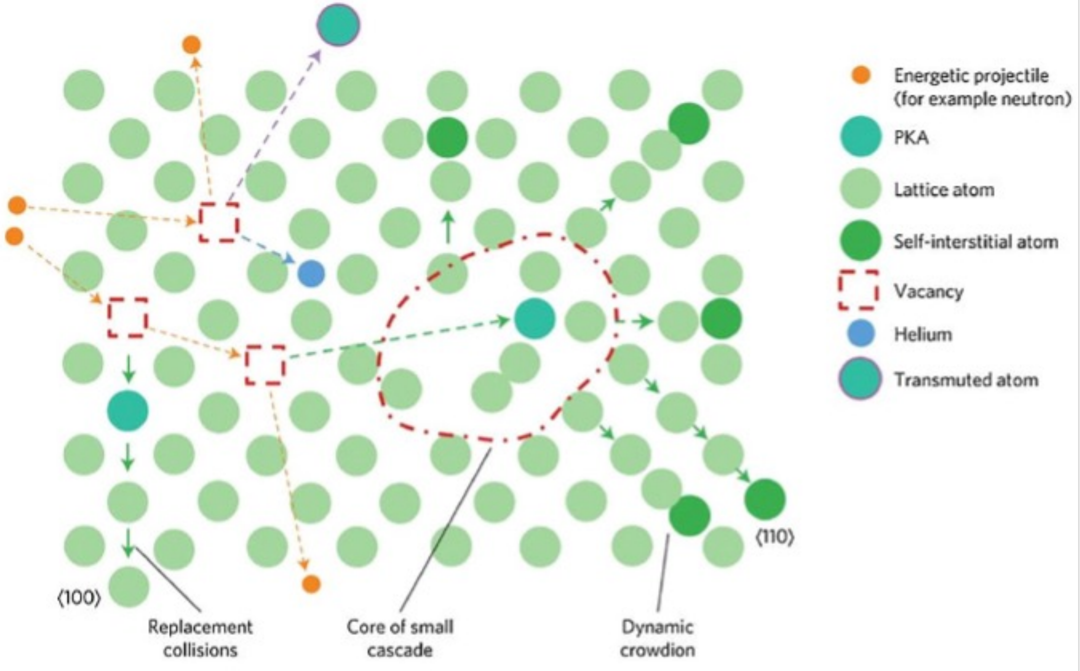



**How can a "surveillance" approach with ions capture the relevant processes?**

# Fundamental basis for comparison of ion- and neutron-induced microstructures

- **Fundamentals of radiation damage**
  - Primary radiation damage, damage rate, damage profile, surface and size effect of specimens, and transmutation
- **Radiation particle types**
- **Microstructure changes from irradiation**
  - Dislocation structure and stacking fault tetrahedra
  - Radiation-induced chemistry and phase changes
  - Corrosion and IASCC
  - Cavities and voids
- **Mechanical property changes from irradiation**
  - Radiation hardening
  - Localized deformation
  - Irradiation creep and stress relaxation

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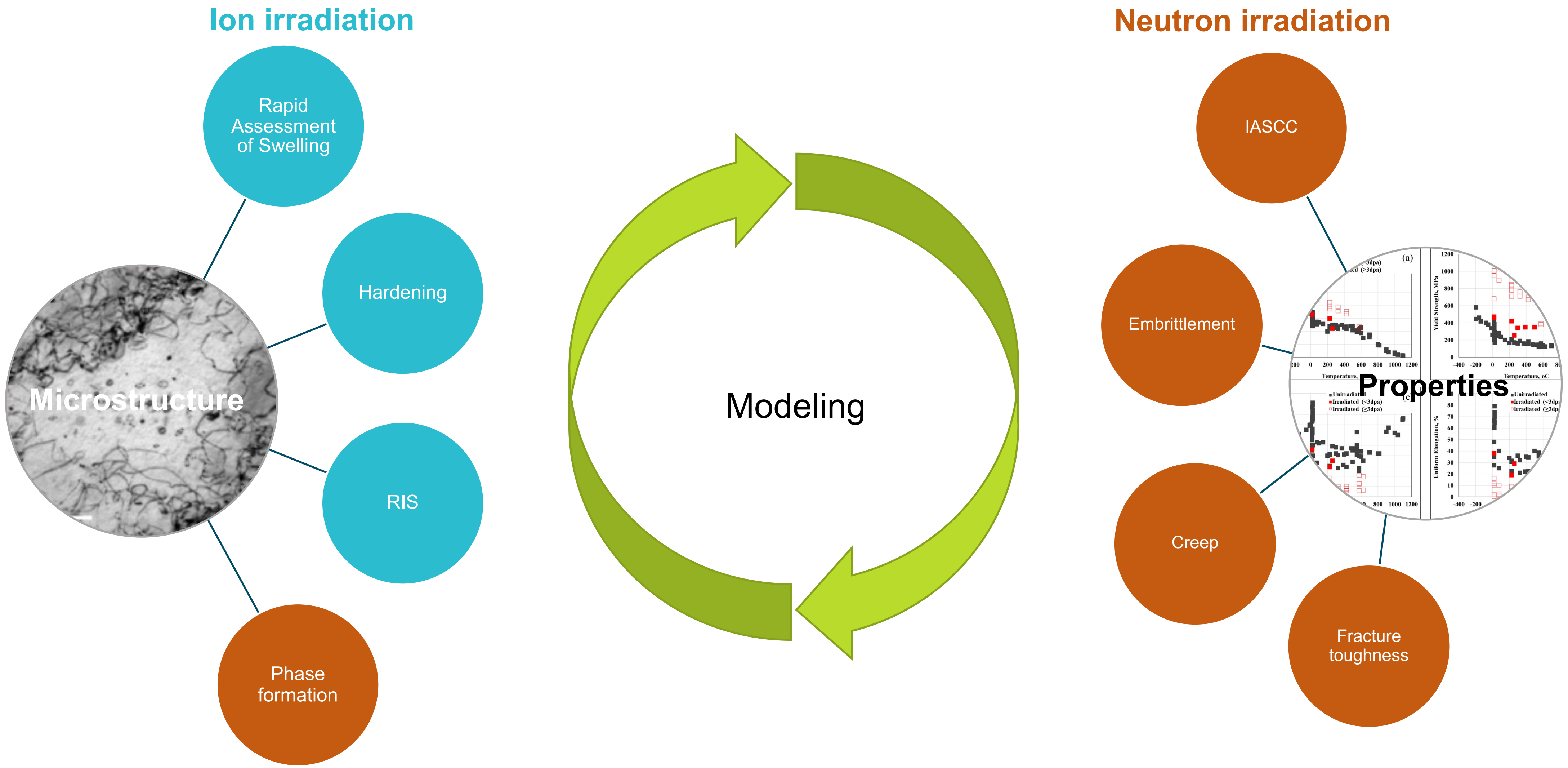
# Select the right tool for the job




- High level conceptualization of radiation testing for design achievement
- Timelines to obtain data (accelerated vs prototypical)
- Ion irradiations can reduce, but do not eliminate, the need for neutron irradiation tests.

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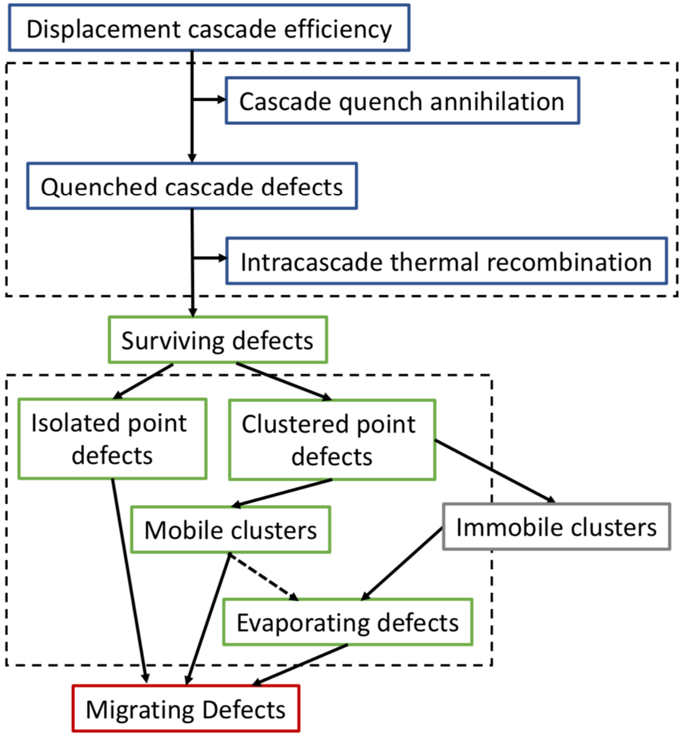
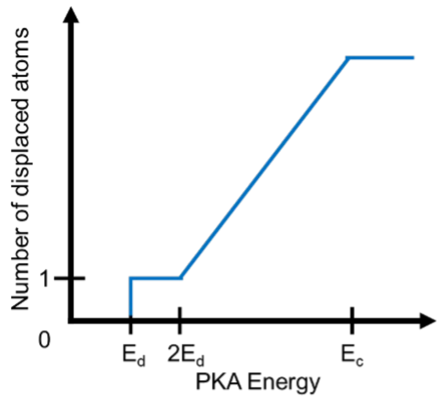
# Interpreting radiation damage with theory, modeling, and software

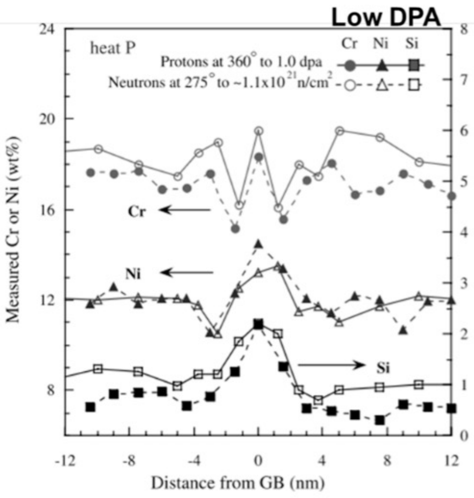
- **Physical basis of radiation-driven microstructure evolution**
  - Production of defects vs thermodynamic recovery processes
  - Details of radiation damage: transmutation, damage cascade extent and type of defects produced
  - Nucleation and growth of extended features
- **Damage calculations**
  - Collision kinematics: PKA energy spectrum
  - NRT-dpa or related damage calculations
- **Atomistic modeling**
  - BCA (SRIM), DFT, MD
- **Modeling diffusive length and time scales**
  - Mansur invariance relationships
  - Mean field rate theory, cluster dynamics
  - Phase field, kinetic Monte Carlo
- **Codes, standards, quality assurance, and recommendations**
  - ASTM standards (especially E521) discusses the math of dpa calculations
  - NO testing standard exists for software, benchmarking or quality assurance for dpa or damage profile (BCA) calculations
  - Critical point of failure within the field exists with reliance on SRIM

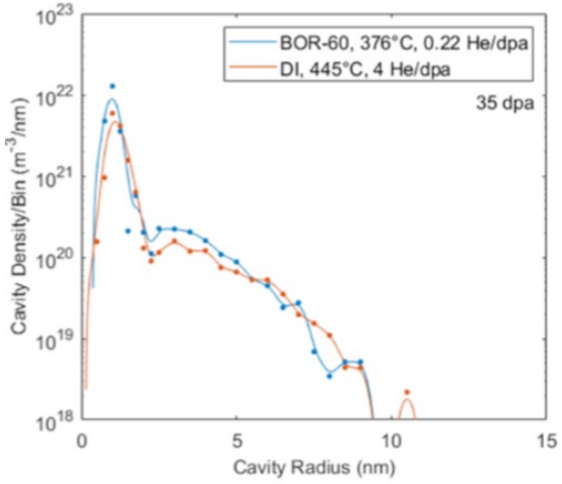


# State of the art for correlating ion and neutron irradiation results

- **Correlation factors based on testing parameterization for equivalent irradiation damage**
  - NRT-dpa, neutron energy threshold and transmutation damage
  - NRT-dpa limitations include variations in stable radiation-induced defect production
  - arc-dpa, rpa, crc-dpa proposed as improvements to NRT-dpa
- **Correlation factors based on physical results of irradiatio tests**
  - Microstructure equivalence: dislocation loops, RIS, cavities, cluster formation
  - Hardness (nanohardness, Vickers hardness)
  - Creep
- **Sources of uncertainty in irradiation experiments**
  - Materials impurities
  - Temperature, total fluence

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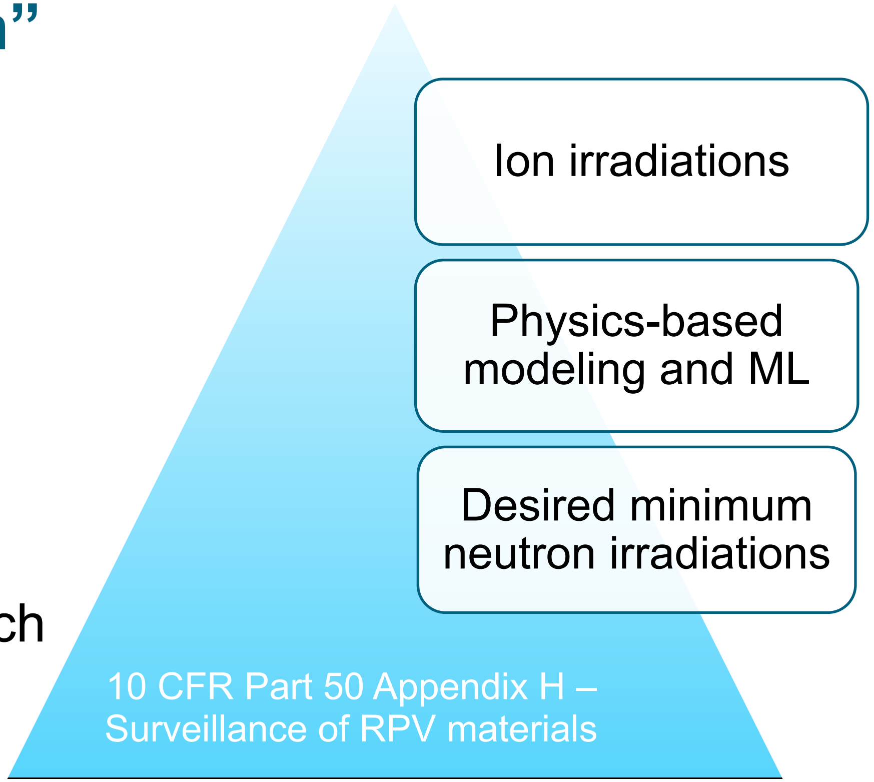
# Recommended path forward for regulatory acceptance of combined ion and neutron results to accelerate materials qualification

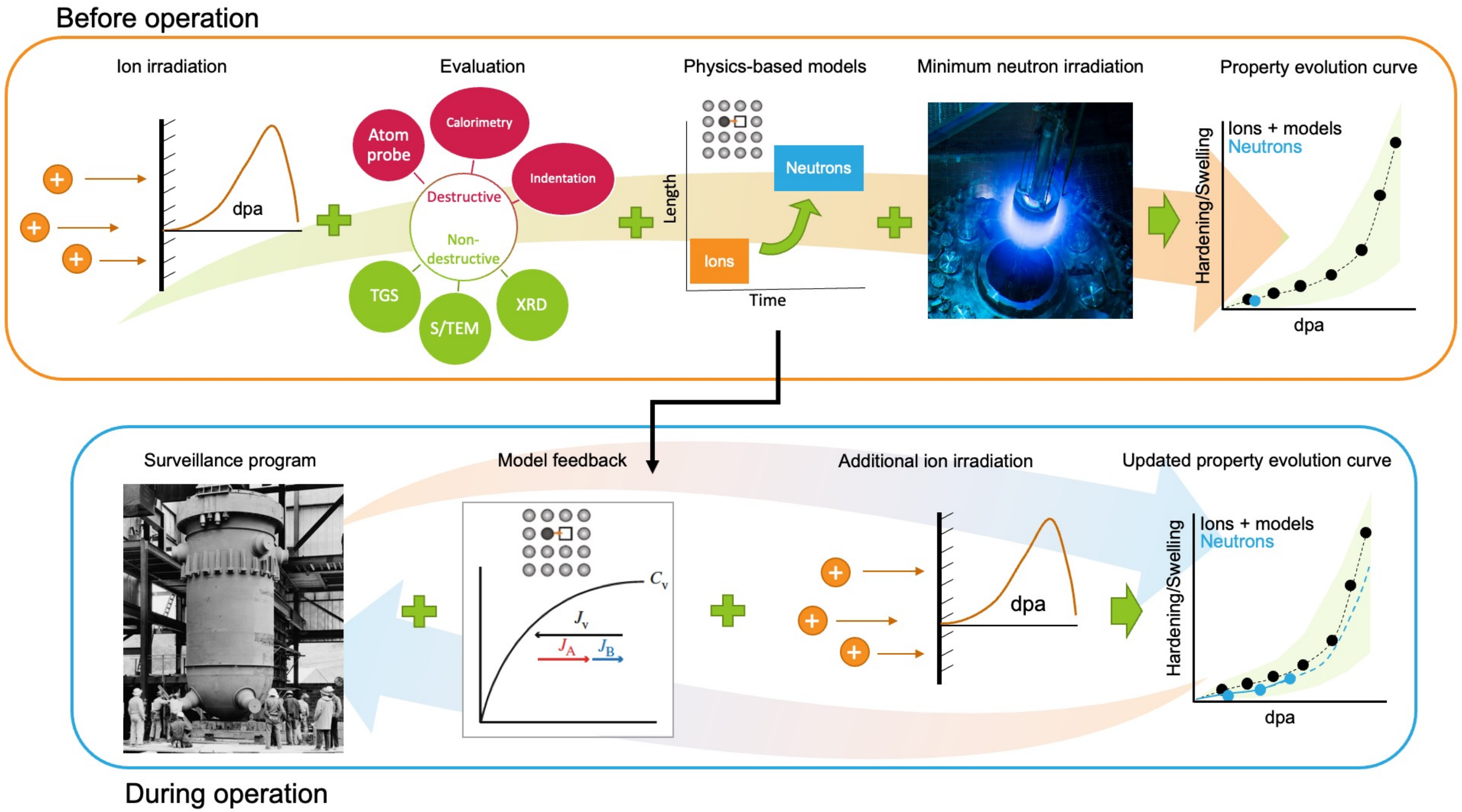
- **Framework is based on the "materials tetrahedron" and can be used to develop new materials and provide information for NRC safety cases**
- **Roles of academia, industry, national laboratories**
  - Academia supports complex research challenges and fundamental questions on radiation damage
  - Industry provides input for concerns to generate useful test matrices and support a license application using this approach
  - National labs perform large translational research and engineering campaigns to qualify materials and provide a springboard for industry; support update of standards, and serve as stewards for software



Bootstrapping approach

# Licensing Approach with Ions and Neutrons (LAIN)

- **Demonstrate with LPBF 316H stainless steel**
  - Temperature boundary up to 650 C
  - Dose boundary up to 10 dpa
  - Desired minimum neutron irradiation tests
  - Demonstrate irradiation-induced hardening relating microstructure and nanohardness / Vickers hardness
- **Continue to engage with NRC Office of Regulatory Research with regular discussion and progress updates**
- **Partnering needed to initiate surveillance program and use of approach in NRC licensing application**




Similar to 10 CFR 50 App. H
ASTM E531, E853, E2215

The ability to re-evaluate the state of knowledge and incrementally improve the prediction using ion irradiations + modeling is the essence of the proposed approach.

# Detailed decision pathway for developing a combined ion and neutron test strategy to accelerate material qualification

**Select property of interest**
- Swelling, embrittlement, stress relaxation...

**Construct application envelope**
- Reactor design, service temperature, neutronics...

**Complete pre-qualification steps**
- Codes and standards, heat treatment...

**Describe project and testing goals**
- QA, organization, methods...

**Construct and start neutron irradiations**
- Initial target dpa

**Construct and execute ion irradiation**
- Assess microstructure and local properties

**Physics-based modeling and ML**
- Interpret ion results and relate to neutron irradiation

**Perform PIE and compare to ion/modeling results**
- Use results to refine modeling approach, possibly do 2nd round of ion irradiations

**Use complete data set for initial safety basis**
- Confidence intervals used for risk-informed decisions

**Initiate surveillance program in licensed reactor for more prototypical results and higher dpa**
- Periodically test witness specimens

**Update physics-based prediction and ion irradiations**
- Update confidence intervals for license modifications

# What is still needed

- Bulk sub-sized specimen and micro-/nano- mechanical testing that can be related to engineering properties via physics-based models
- *In situ* ion irradiation and neutron irradiation mechanical testing capabilities (creep, creep-fatigue)
- Updated ASTM standard E521, “Standard Practice for Investigating the Effects of Neutron Radiation Damage Using Charged-Particle Irradiation”
- Robust computer vision algorithms for automated microstructure feature identification
- Mechanistic models that enable microstructure and property evolution predictions at different temperatures, damage particle types and damage rates
- Community consensus-driven acceptance of ion-irradiation techniques
- Integration of efforts from academia, national laboratories, and industry, with continued engagement with US NRC Office of Regulatory Research

# Conclusions

- The language for regulating materials within the NRC framework is very broad and there are only a handful of high-level regulations
- There is no one-size-fits-all approach to demonstrate every possible radiation-induced behavior with ion irradiation, necessitating at least a limited set of neutron irradiation
- Surveillance programs with intermittent evaluation and modification of operation based on physical models are a strong strategy for adoption
- If this is first applied in an area with significant redundancy and less safety significance, then its more likely to be implemented and used to gather operational experience

- AMMT is combining neutron irradiation, ion irradiation and modeling to progress a comprehensive framework for rapid qualification.

Questions or comments? Interested in collaborating? Please contact *andrea.jokisaari@inl.gov*

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