INL/CON-22-66181-Revision-0

Environmentally Assisted Cracking Research for Current and Advanced Nuclear Structural Materials

March 2022

Changing the World's Energy Future

Rongjie Song, Michael D McMurtrey, Boopathy Kombaiah, Drew Coulson Johnson, Michael P Heighes, Peng Xu, Colin D Judge

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About the Presenter

- Rongjie Song, Idaho National Laboratory
  - Metallurgical Engineer, Ph.D.
- Physical Metallurgy and Materials Science and Engineering. Focus on materials design, processing, testing, characterization, evaluation, and application, developing a mechanistic understanding of microstructure evolution during processing and how it can impact the macroscopic properties and performance.
- Co-authors: Michael McMurtrey, Boopathy Kombaiah, Drew Johnson, Michael Heighes, Peng Xu, Colin Judge
- Contact: Rongjie.Song@inl.gov

Content

- Environmentally Assisted Cracking (EAC) fundamental theories
- Examples of irradiation assisted EAC
- EAC modeling
- Development of corrosion-fatigue testing capability at INL
- Continuous development of in-pile testing capability at INL
- Future capability for EAC study at INL (a new construction of sample preparation lab)
- Summary

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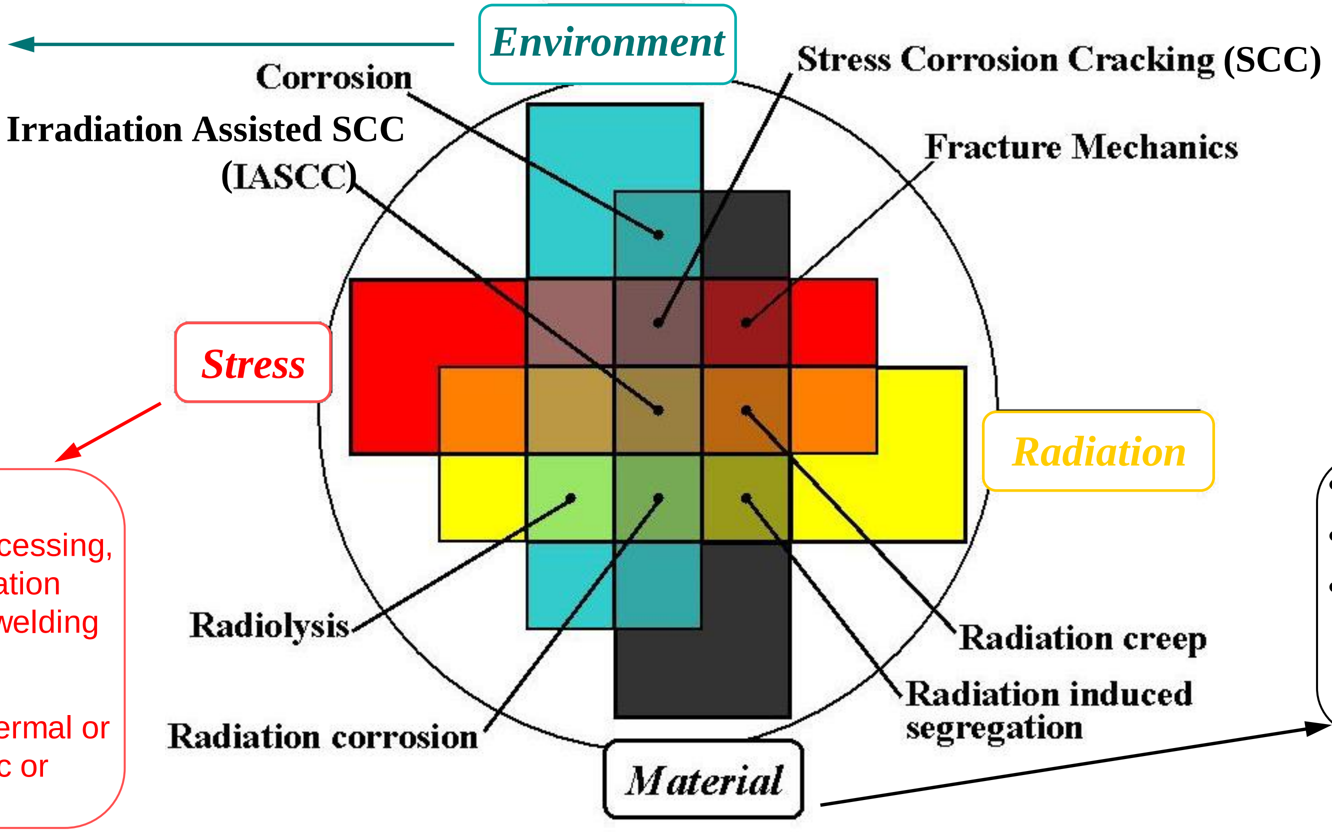
EAC in Nuclear Industry: Basic Principles

- **EAC is a synergetic action of environment and stresses on a given material. Additional irradiation effects especially for the components close to the reactor core.**

- Corrosion potential
- Flow conditions
- Temperature
- pH-value
- Dew point
- Impurities



- Residual stress
  - thermo-mechanical processing, specific surface preparation
  - assembly procedures: welding
- Applied stress
  - in-service operation: thermal or mechanical: either static or dynamic.

- Chemical composition
- Microstructure
- Impurities
  - Metallic materials exposed to EAC in the nuclear industry: Ni-based alloys, Stainless steels

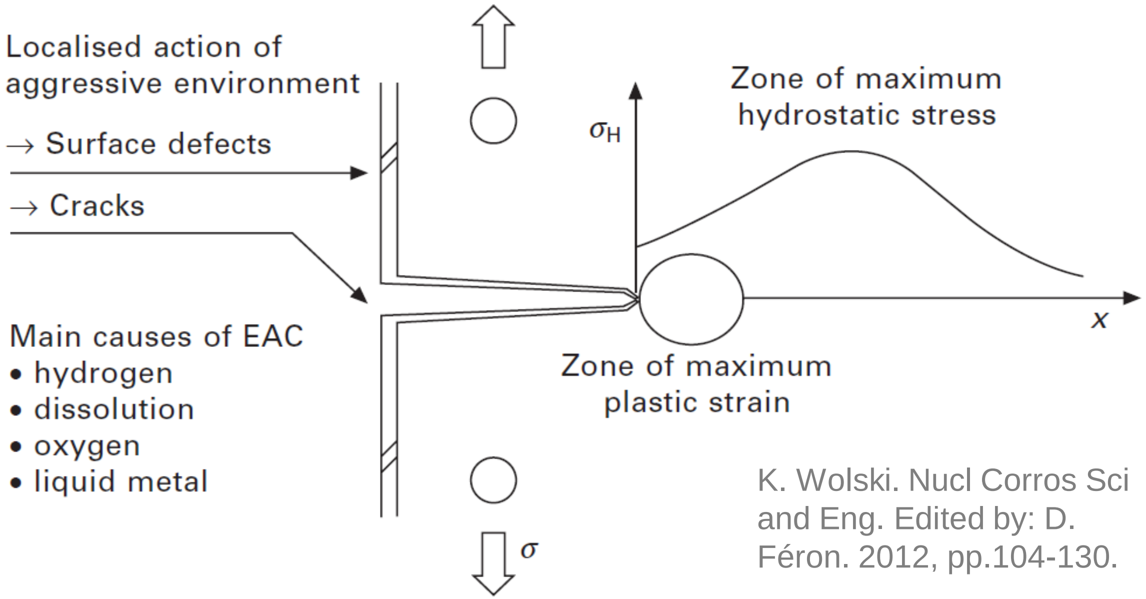
S.A. Shipilov. Allied Nations Technical Corros Conf. Paper No. 2019-0099.

EAC Types, Fracture Appearance

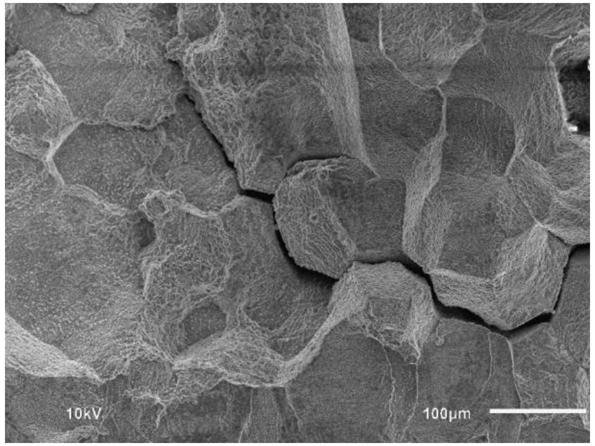
- **Types:**
  - Stress corrosion cracking (SCC)
  - Hydrogen embrittlement (HE)
  - Corrosion fatigue
  - Oxygen embrittlement
  - Liquid metal embrittlement (LME)
  - Irradiation assisted stress corrosion cracking (IASCC)

- **Phenomenon is associated with strong localization:**
  - Metallurgical inhomogeneities in the vicinity of the material's surface
  - From the breakdown of the protective surface film

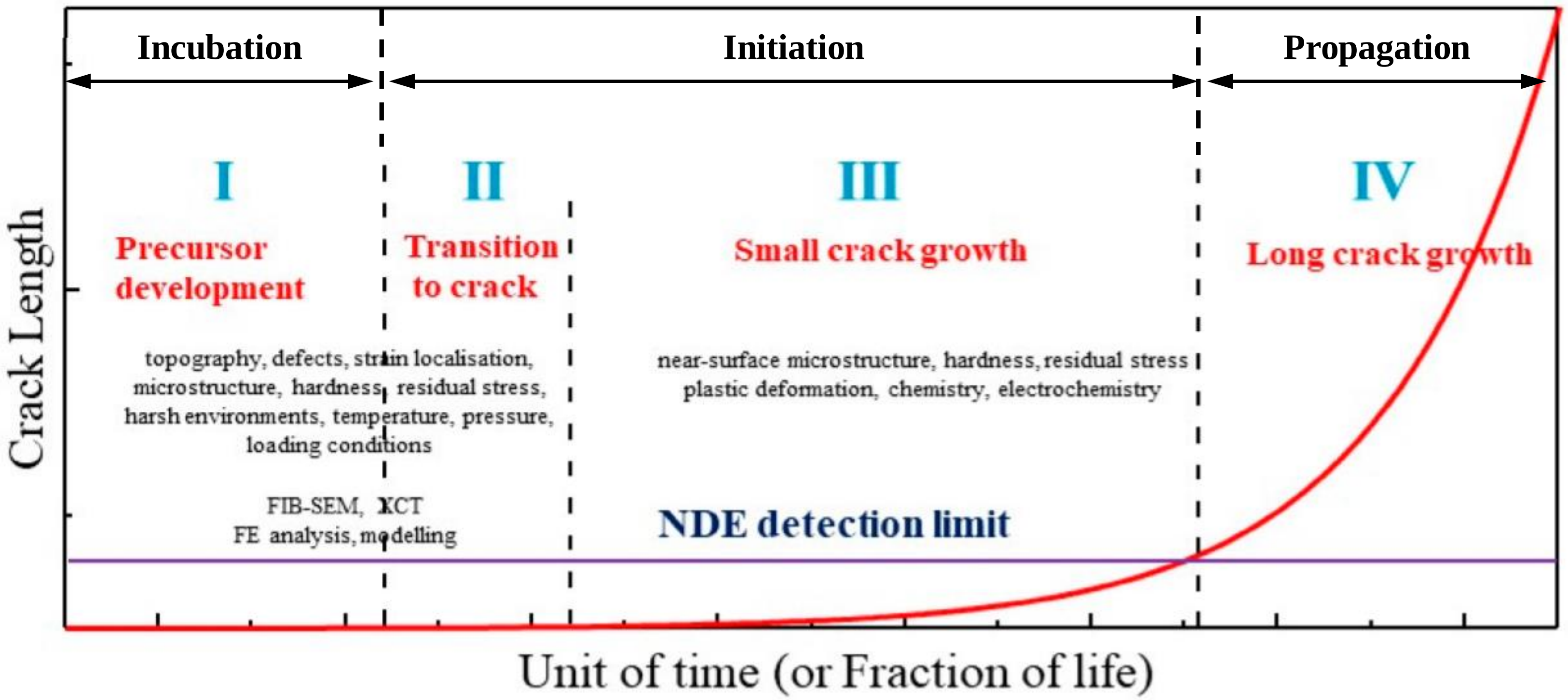
- **Fracture appearance:**
  - Mainly intergranular, less often intragranular



K. Wolski. Nucl Corros Sci and Eng. Edited by: D. Féron. 2012, pp.104-130.

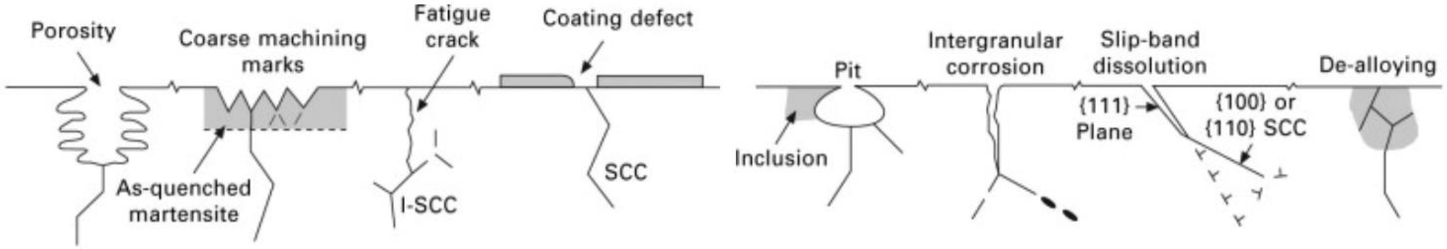


EAC Crack Development



A. Turnbull. Corros. Mater. Degrad. 2(2021)568.

S.P. Lynch. Stress Corrosion Cracking Theory and Practice. Edited by: V.S. Raja. 2011, pp.772-792.



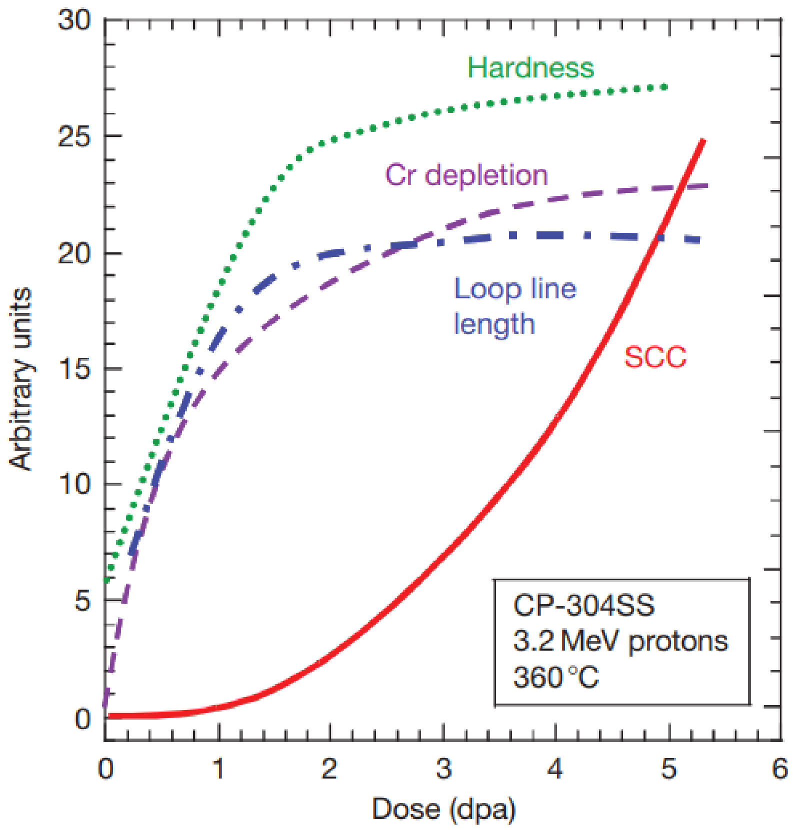
The most common crack-initiation sites

EAC Mechanisms (in General)

- **Adsorption-based mechanisms**
  - involving weakening of substrate interatomic bonds so that dislocation emission or decohesion is facilitated. Embrittling adsorbed species include some metal atoms, hydrogen, and complex ions produced by de-alloying
- **Decohesion at grain boundaries (Oriani and Josephic, 1977)**
  - segregated hydrogen and impurities
- **Hydrogen-enhanced localized-plasticity mechanism (Birnbaum et al., 1997)**
  - based on solute hydrogen facilitating dislocation activity in the plastic zone ahead of cracks, makes a contribution in some cases, but is relatively unimportant compared with these other mechanisms for most fracture modes
- **Film-induced cleavage mechanism (Newman, 2002)**
  - proposed especially for stress-corrosion cracking in systems involving de-alloying at crack tips

Important Mechanisms in IASCC

- Radiation Induced Segregation (RIS)
- Radiation induced dislocation loop
- Radiation hardening
- Formation of defect clusters
- Radiation-induced precipitation
- Stress owing to swelling
- Transmutation-production of helium and hydrogen



Composite diagram showing the increase in parameters (RIS, loops, hardness) with dose.

G.S. Was, et. al.. Corros Rev 29(2011)7.

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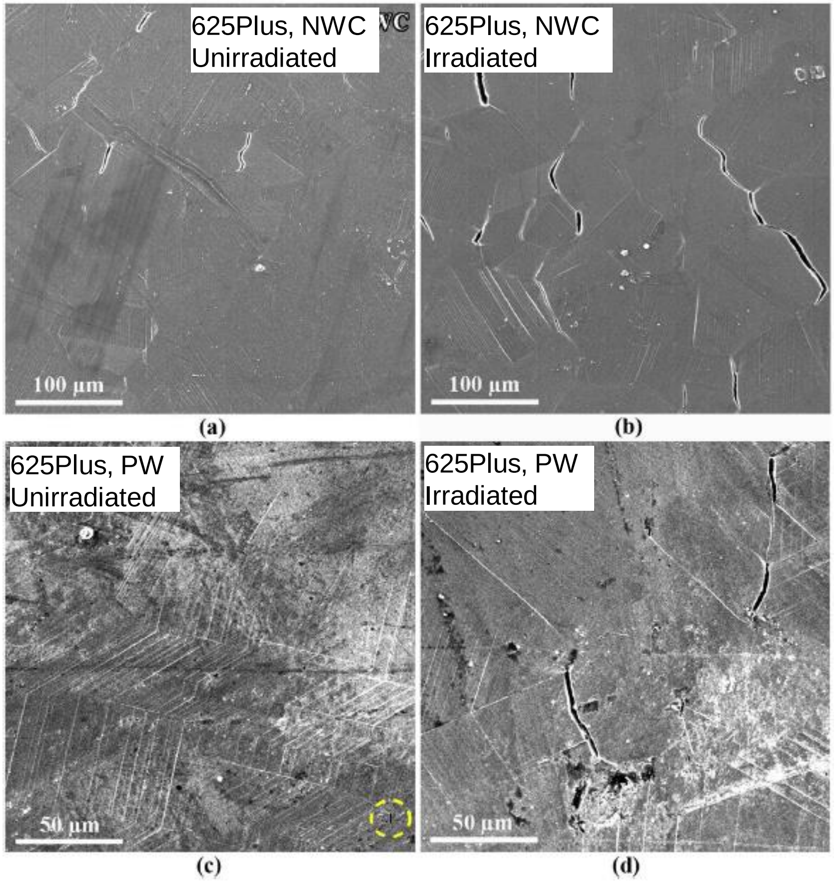
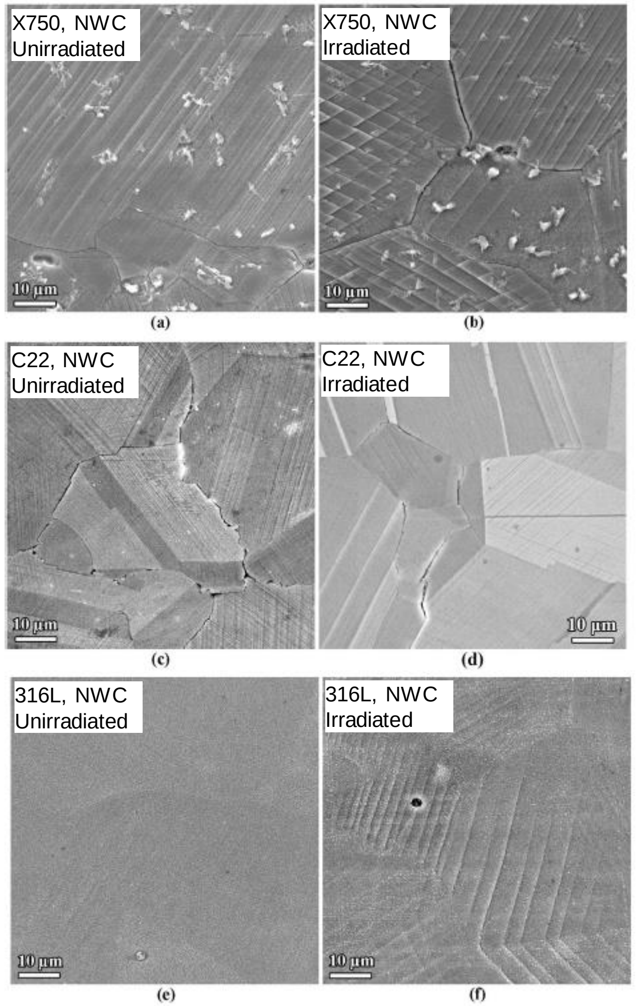
Examples of Irradiation Effects on Microstructure of Commercial Alloys for LWR Core Internals



Cracking behavior: normal water chemistry (NWC), primary water (PW). Irradiation increases in both crack length and density, which was more noticeable in NWC than in PW.



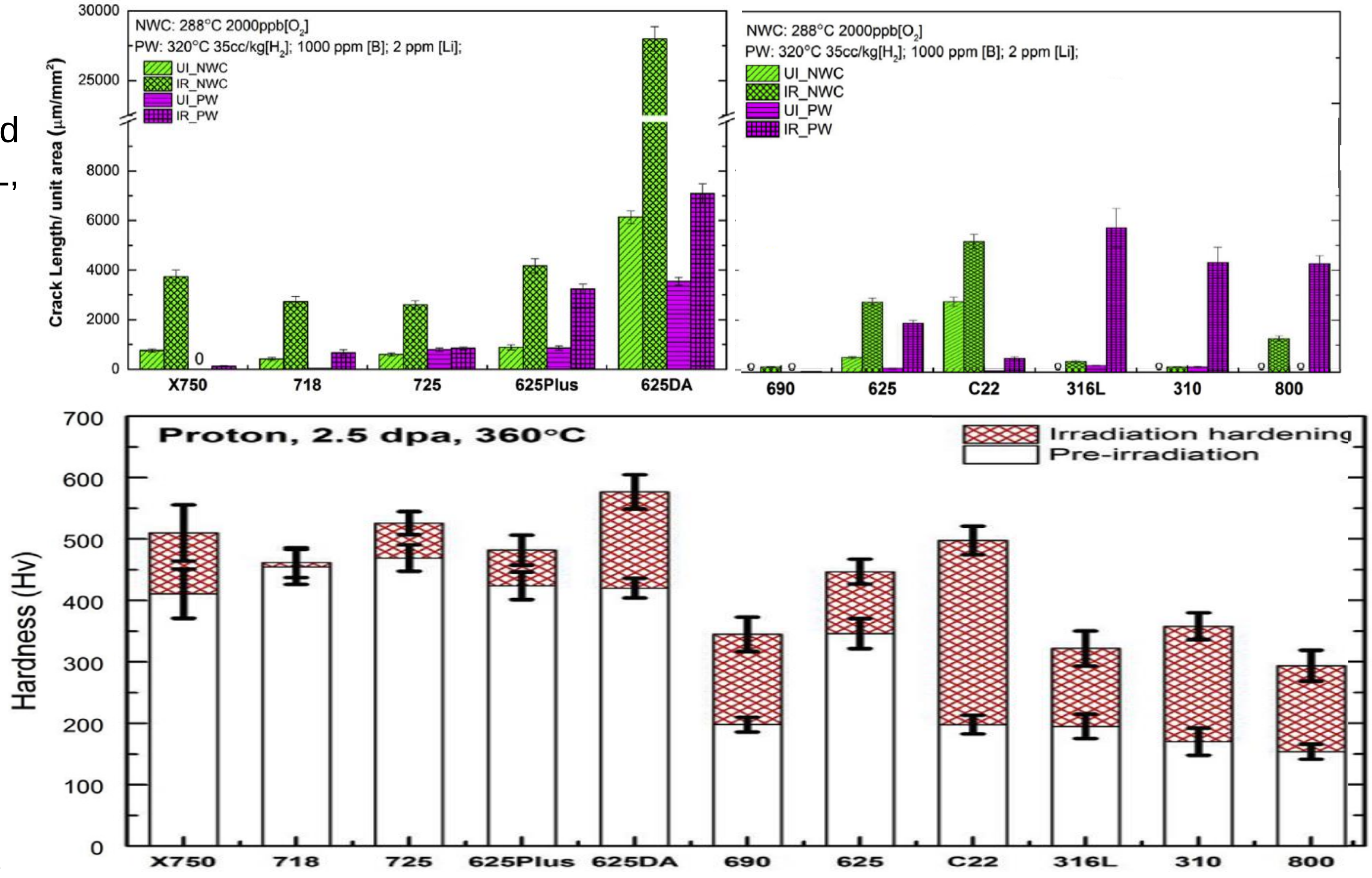
Surface deformation morphology

Irradiation increased the intensity between the dislocation channels and generating higher local stresses at grain Boundaries, increasing IASCC susceptibility.

M. Wang, et.al. J. of Nucl Mater 515 (2019) 52.

IASCC of Commercial Alloys for LWR Core Internals

- **Material:**
  – High strength nickel-base alloys (alloys X750, 718, 725, 625Plus, 625DA), low strength nickel-base alloys (625, 690, and C22), low strength iron-base alloys (316L, 310, and 800)
- **Testing:**
  – Proton irradiation doses: 2.5 dpa at 360 °C; SCC testing (Constant Extension Rate Tensile Test): NWC, PW environment
- **Results:**
  – High strength nickel-base alloys had greater IASCC in NWC than in PW. IASCC occurred in all the samples and more pronounce with irradiation.
  – Low strength nickel-base alloys was less susceptible to IASCC.
  – Low strength iron-base alloys were more susceptible to IASCC in PW than in NWC.

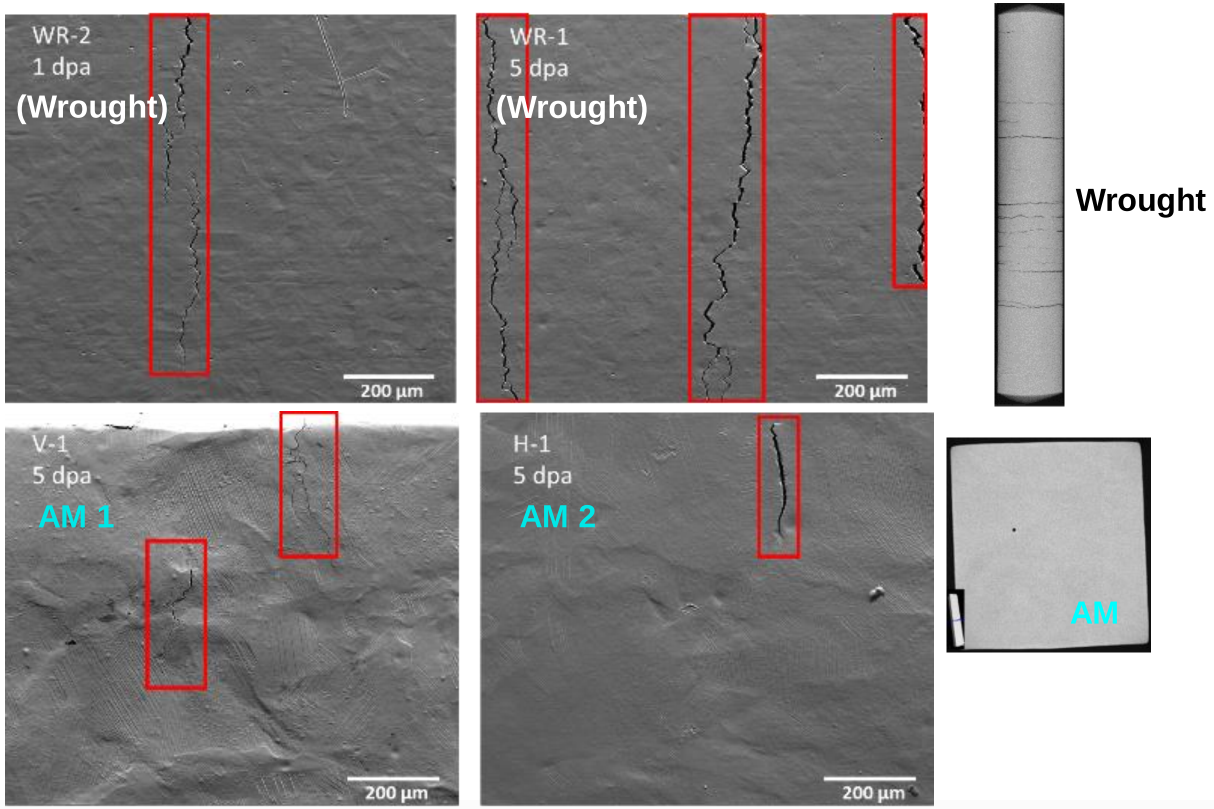


M. Wang, et.al. J. of Nucl Mater 515 (2019) 52.

IASCC in the Materials Processed by Convectional and Additive Manufacturing (AM) Methods

- **Material:**
  - SS316L Wrought, and AM processed
- **Testing:**
  - Proton irradiation doses: 1 dpa, and 5 dpa
  - SCC testing (Constant Extension Rate Tensile Test): 288°C water, ~2 ppm oxygen, conductivity 0.2 µS/cm and ~3x10-7s^{-1} strain rate up to 4% plastic strain
- **Characterization:** SEM and X-ray
- **Results:**
  - No cracking in AM specimens at 1 dpa
  - Very little in the 5 dpa AM specimens

		Crack density	
Sample ID	dpa	Number (#/mm^2)	Length (µm/mm^2)
Wrought	1	0.15	85
AM 1, 2, 3	1	0, 0, 0	0, 0, 0
Wrought	5	0.55	1050
AM 1, 2, 3	5	0.35, 0.05, 0	135, 13, 0



M. McMurtrey, et.al. J. of Nucl Mater 545 (2021) 152739.

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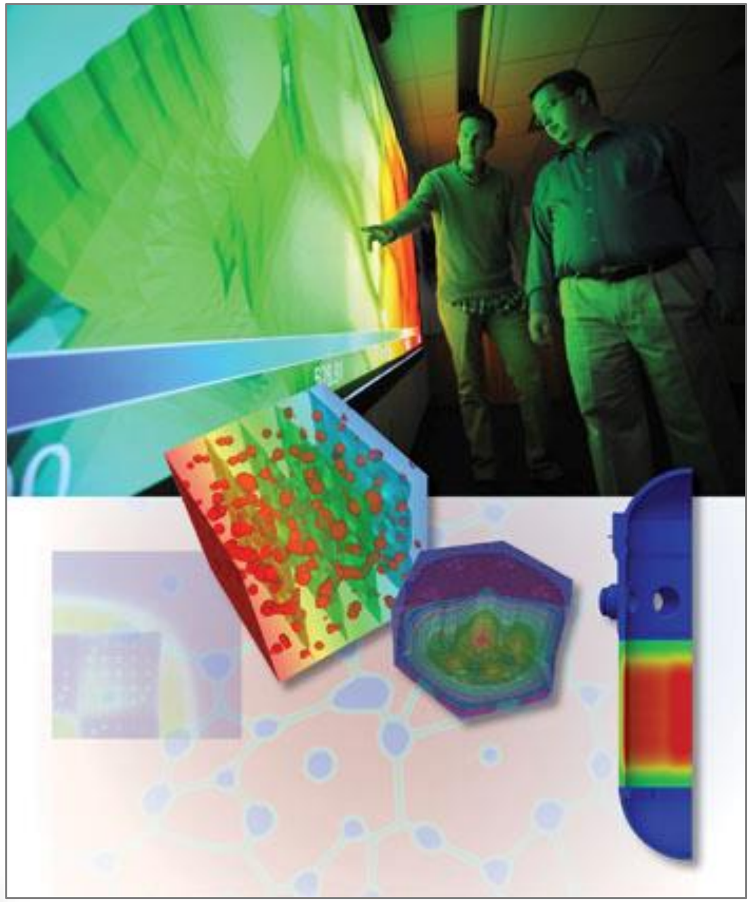
Multiphysics Object Oriented Simulation Environment (MOOSE)

- **MOOSE is a finite element, multiphysics framework that simplifies the development of advanced numerical application.**

- **It provides a high-level interface to sophisticated nonlinear solvers and massively parallel computational capability.**

- **MOOSE has been used to model solid mechanics, heat transfer, neutronics, geomechanics, reactive transport, microstructure modeling, computational fluid dynamics and perform statistical analysis.**

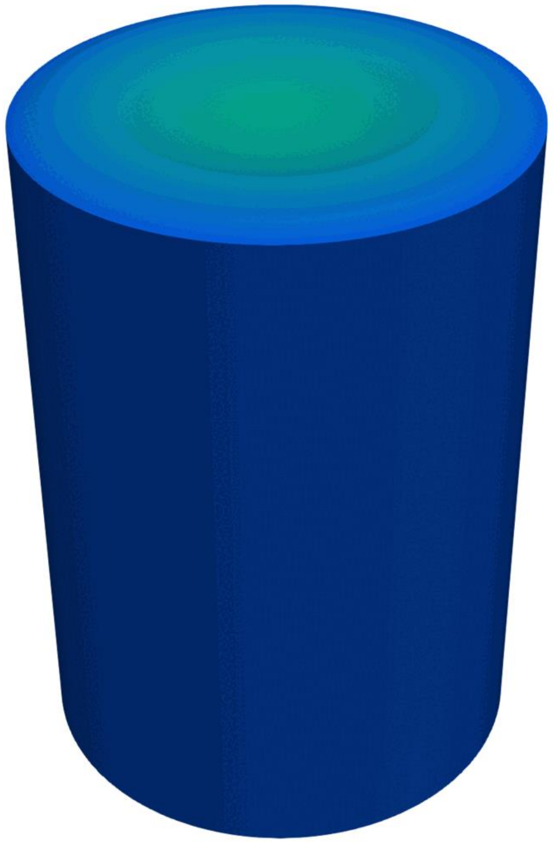


MOOSE

R&D 100 2014 Winner

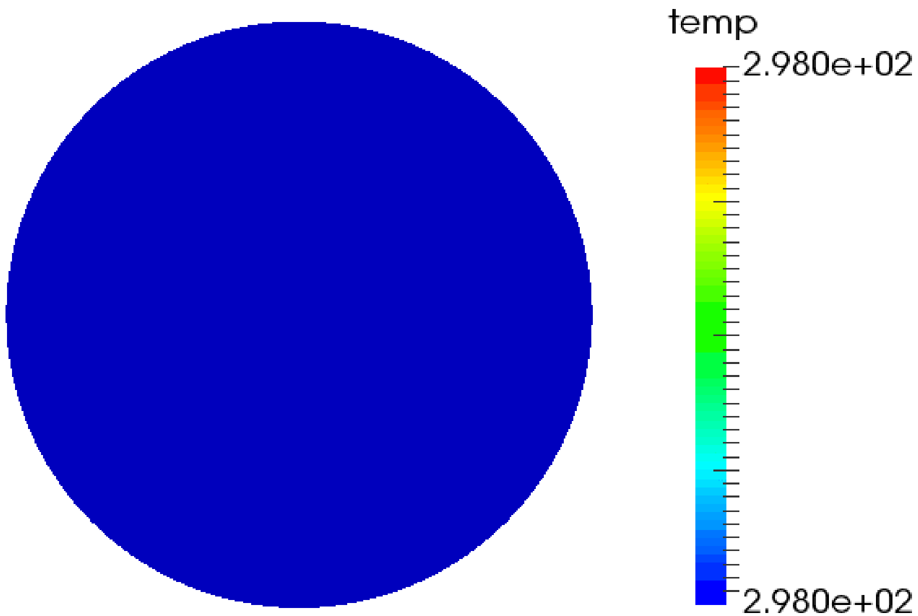
MOOSE Fracture Modeling Capabilities

- MOOSE has a variety of fracture modeling capabilities:
  - Extended finite element method (X-FEM)
  - Phase field fracture
  - Cohesive zone method
  - Peridynamics
- MOOSE fracture models have been successfully used at both meso and macro-scales to simulate cracking for nuclear fuel and structural materials.
- Many of them are suitable for modeling fractures in multiphysics environment, such as environmentally assisted cracking.

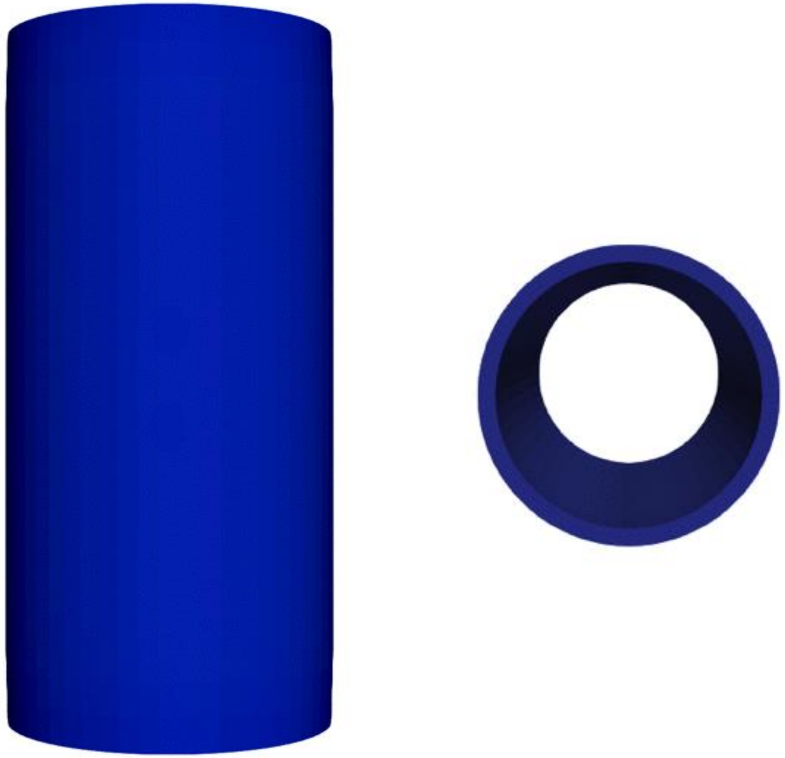


Extended Finite Element Method

- **X-FEM represents crack faces with enrichment functions, which can eliminate the need to remesh.**
- **Because of the flexibility of its underlying multiphysics solution framework, X-FEM in MOOSE readily permits the inclusion of multi physics.**



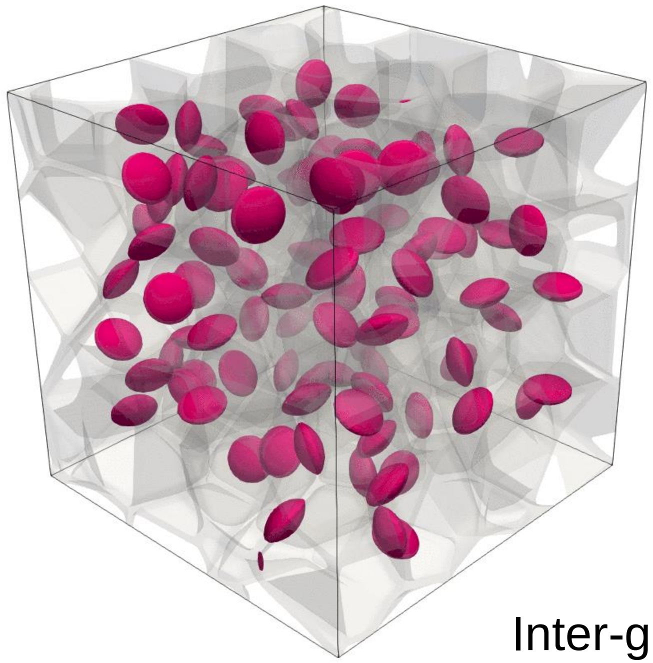
UO_2 Fuel fragmentation



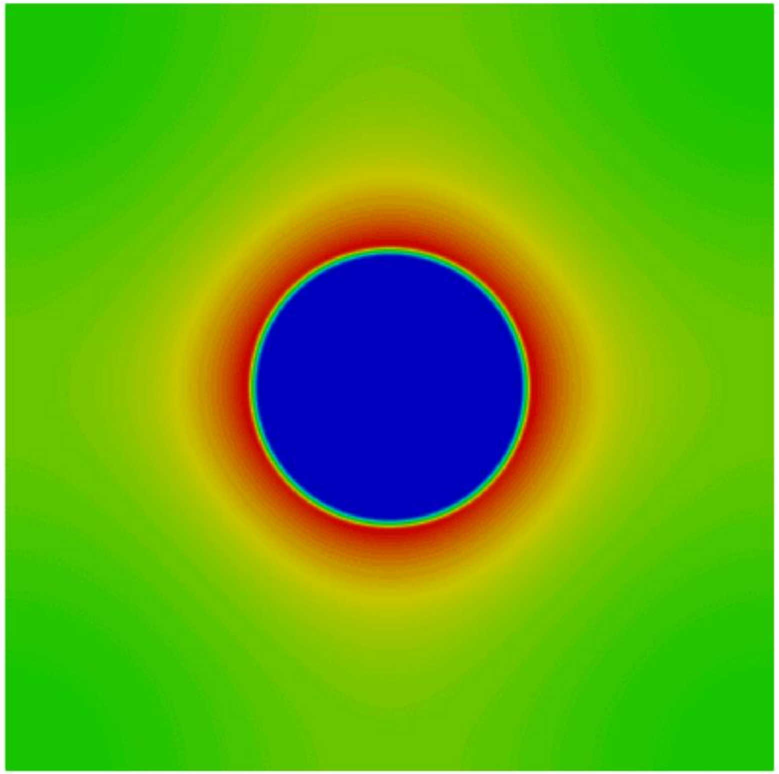
Cladding rapture

Phase Field Fracture

- Phase field fracture represents crack in a diffusive manner.
- Advantages of phase field model
  - Avoid re-meshing
  - Determine crack nucleation and propagation automatically
  - Handle joining and branching of multiple cracks
  - Easy to incorporate multiple physics.



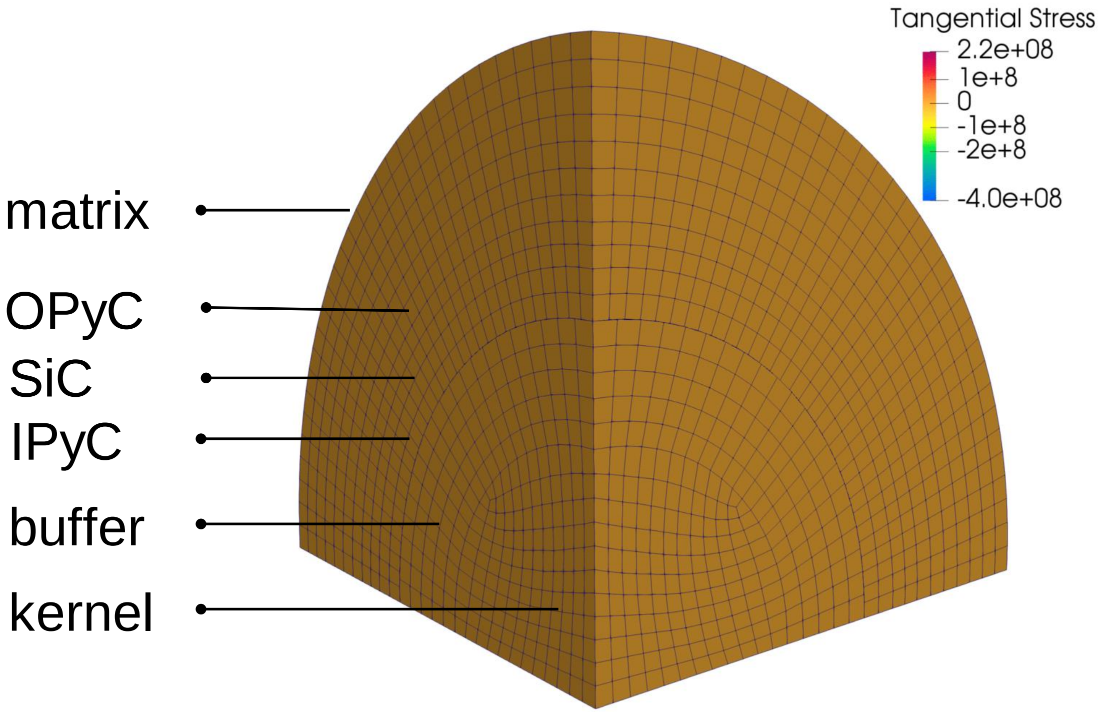
Inter-granular fracture with porosity



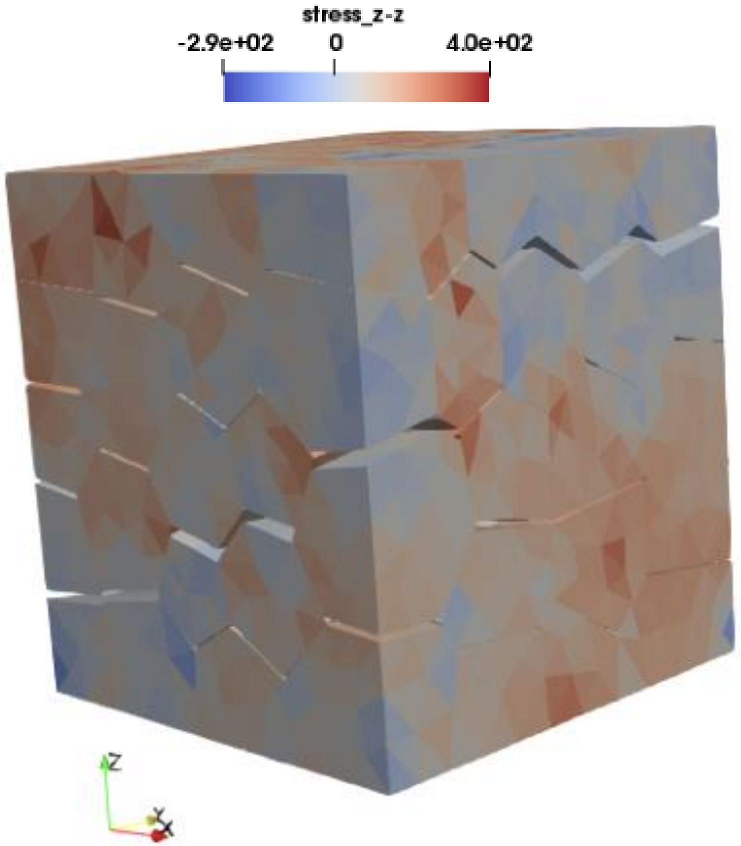
High-burnup fuel fragmentation

Cohesive Zone Method

- **CZM is a powerful tool for predicting delamination in adhesively bonded structures and inter-granular fracture in polycrystalline structures.**
- **CZM relies upon this traction-separation law to represent accurately the fracture of the material or interface being modeled**



TRISO particle-matrix debonding



Inter-granular cracking of grains

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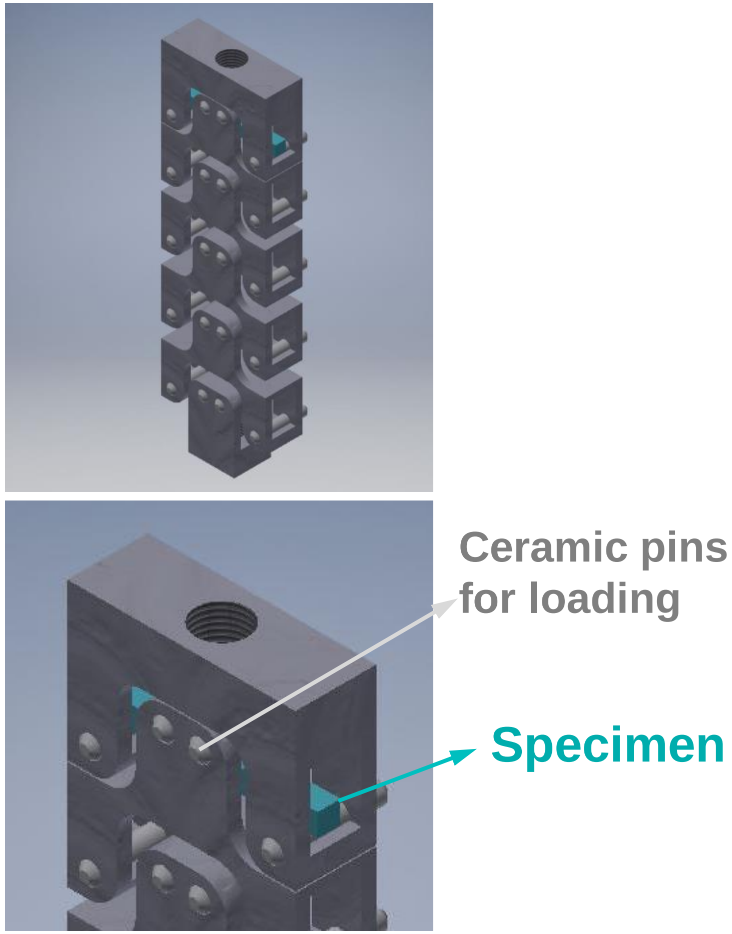
Development of An Innovative Testing Framework to Assess Crack Initiation Assisted by Corrosion-Fatigue

- **Background**
  - Crack initiation and growth under cyclic loading (fatigue) are aggravated by the presence of a corrosive environment
  - Limited facilities are currently capable of assessing irradiation assisted corrosion fatigue in a simulated corrosive environment like BWR or PWR within the US

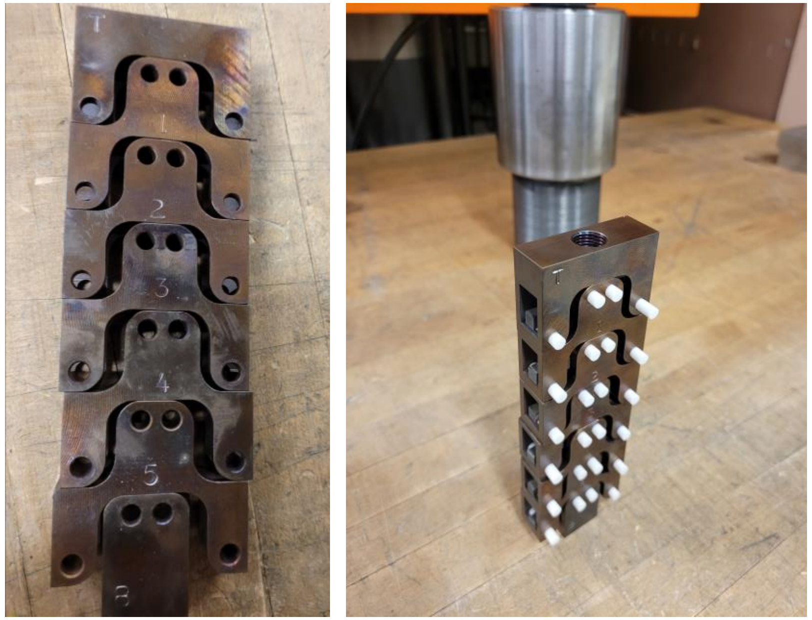
- **Technical Challenges**
  - Testing multiple specimens at a time for accelerated corrosion fatigue testing
  - Detection of crack initiation in multiple specimens during corrosion fatigue tests



Multi-specimen corrosion fatigue testing fixture design

Development of An Innovative Testing Framework to Assess Crack Initiation Assisted by Corrosion-Fatigue

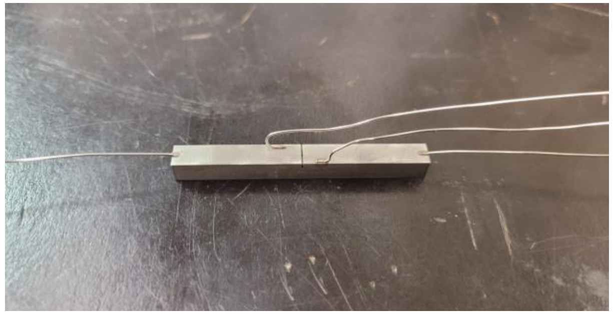
- **Objective**
  - To design and develop a corrosion-fatigue testing fixture with a direct current potential drop (DCPD) method capable of testing multiple specimens at once that can be placed within the autoclave of the present SCC testing systems
- **Approach**
  - Four-point bending daisy chain configuration
  - Fixture machined from 17-4 PH for high temperature testing
  - Ceramic pins apply bending loading
  - Uniform load applied on all the specimens
  - Crack detection on the specimens using DCPD measurements from individual samples



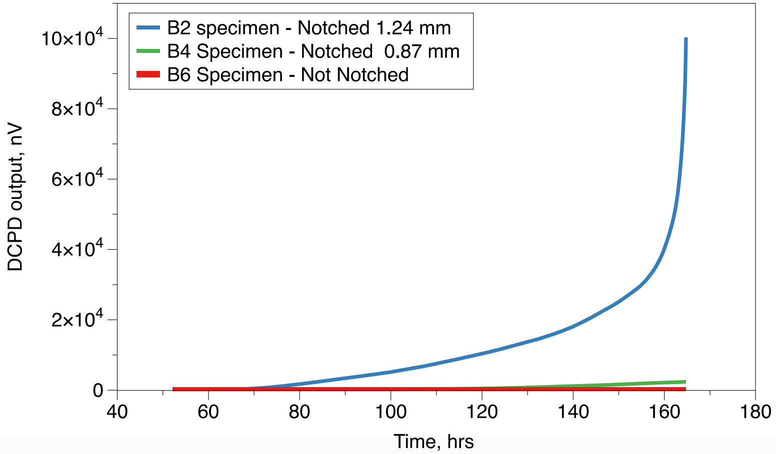
Machined corrosion fatigue testing fixture

Development of An Innovative Testing Framework to Assess Crack Initiation Assisted by Corrosion-Fatigue

- **Cyclic loading crack initiation-Example**
  - Testing conducted using an Instron servo-electric load frame
  - Applied load is 31% of the yield strength of X-750 Stress ratio = 0.3; Load cycle = 1 Hz
  - Testing performed in air at room temperature
- **Significance**
  - Material selection for reactor applications must consider environmental degradation and susceptibility to crack initiation
- **Impact**
  - Accelerate advanced nuclear structural materials qualification at INL



Notched X-750 alloy specimen (5x5x50.8 mm) with connections for DCPD



Funded by INL Laboratory Directed Research & Development (LDRD) program, project 20A1052-025FP

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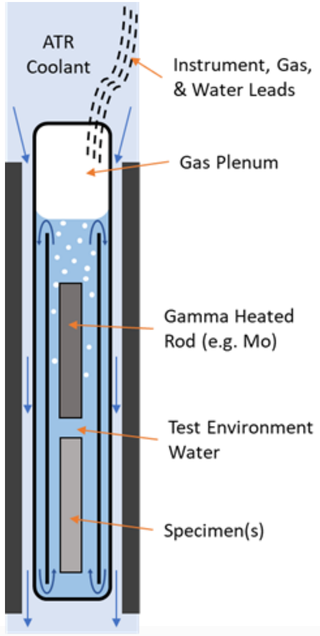
In-Pile Testing and Experimentation

- **Necessity of in-pile testing and experimentation**
  - Sustain the existing nuclear fleet of reactors
  - Provide new technology options and innovations for development of advanced nuclear energy systems
  - Enable a better understanding of aging and degradation phenomena for materials exposed to the harsh environments of irradiation, high temperature, and corrosive environments
  - The shut down and decommissioning of Halden Boiling Water Reactor (HBWR) in Norway led to a significant loss of in-pile testing for the global R&D community.

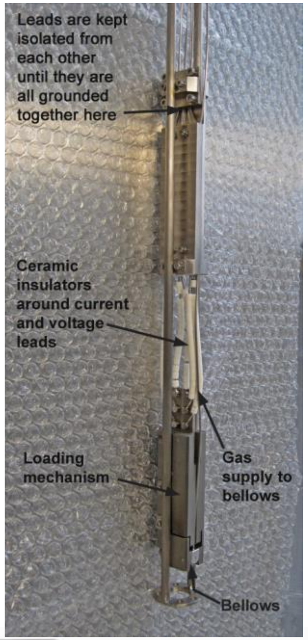
- **Status of in-pile testing at INL**
  - On-going program: the DOE-NE Advanced Sensors and Instrumentation (ASI) program
  - Partnered with the Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) in two Joint Experimental Programs (JEEPs) in the Multinational Nuclear Energy Agency (NEA) Framework for in-pile fuel and materials testing:
    - Development, deployment and demonstration of an in-pile crack growth rate capability in a high flux. (NRC)
    - Development, deployment and demonstration of an in-pile stress relaxation and creep rig for structural materials in a high flux. (EPRI)

In-Pile Crack Growth Experiment

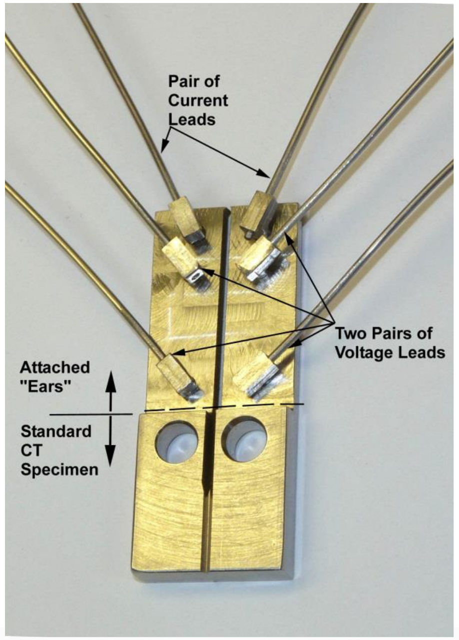
- The Advanced Test Reactor (ATR) water chemistry loops at INL are in high demand, the objective is to develop an experiment that can be placed in a non-loop position.
- The testing frame includes:
  - An in-pile crack growth system which INL developed and is in use at the material test reactors (MTR) at the Massachusetts Institute of Technology (MIT)
  - A water-capsule/thermosyphon with a water refresh to maintain chemistry
- INL-MIT collaboration: develop a system that can be demonstrated at low flux in the MTR to help build the safety case for deployment in a high flux position in ATR.



Water capsule



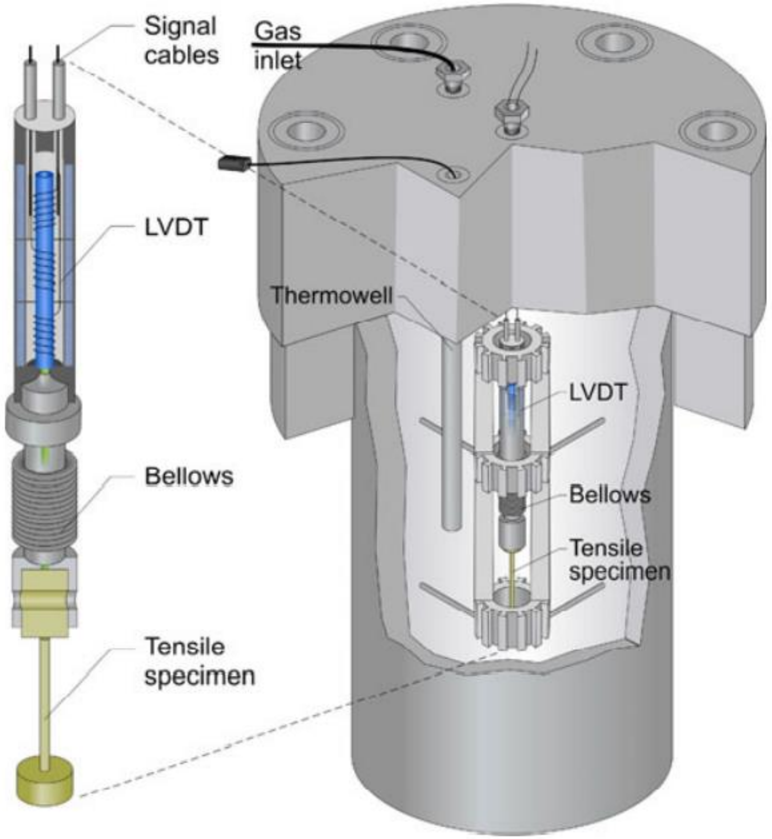
In-pile portion of test rig



Electrical connections to specimen

In-Pile Stress Relaxation and Creep Experiment

- **In a mature design phase, the introduction of in-pile linear variable differential transformers (LVDT's) is a technology which INL is already collaborating with the Halden research group as part of the DOE ASI program. This has been tested in an autoclave and is ready for in-reactor demonstration.**
- **A gas refresh capsule/ a water capsule allows greater control of temperature over the duration of the in-pile experiment**
- **INL-MIT collaboration: deploy the technology in the MTR to help build the safety case for ATR, and in this way, data is collected for in-reactor creep at low (MTR) and high (ATR) flux.**



Schematic of test rig positioned in autoclave for testing at INL

B.G. Kim, et al. Nucl Technol. Vol 179 (2012) 417.

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Sample Preparation Lab (SPL) at INL – Post Irradiation Examination

- Construction Start – June 2020
- Construction Completion – 3Q FY 2023 (forecast)
- Start of Operations – 2Q FY 2025 (forecast)

BASIC CAPABILITIES

- Hazard category 3 nuclear facility
- Fatigue and fracture toughness testing
- Tensile testing at ambient and elevated temperature
- Charpy impact testing
- X-ray photoelectron spectroscopy (XPS)
- Electron microscopy
- Hardness testing
- Shielded x-ray diffraction
- High throughput sample preparation
- Receipt of medium-sized casks (BRR, NRBK, GE-100, etc.)
- Automated sample transfers to instruments
- Heat treatment of irradiated materials
- Remote operation of instruments
- Long-term storage of critical material samples
- Research space for user defined instruments

SPL entryway taking shape with exterior framing and insulation

Setting roof top air handling units

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- Environmentally Assisted Cracking is a complex phenomenon that limits the life of reactor components
- Using modeling, INL is trying to assist with investigations and get a better understanding
- INL is developing a novel corrosion-fatigue test capability to experimentally assess that aspect of EAC with high efficiency
- INL continues to develop in-pile testing capabilities to allow investigation of irradiation assisted cracking
- The development and deployment of in-pile instrumentation to acquire the dimensional changes during irradiation will drastically decrease the time from experimentation to data analysis and reporting, will provide immediate, long-term access to trends and data from the experiment
- INL is building to a new sample preparation lab to help with this and other irradiation studies

Thank you !