INL/MIS-18-51676-Revision-0

NSUF Fuels and Materials Understanding Scale & Industry Inpact Highlights

October 2018

Changing the World's Energy Future

Simon M Pimblott, John Rory Kennedy, John Howard Jackson

Idaho National Laboratory

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

NSUF Fuels and Materials Understanding Scale & Industry Impact Highlights

Simon M. Pimblott, J. Rory Kennedy & John H. Jackson

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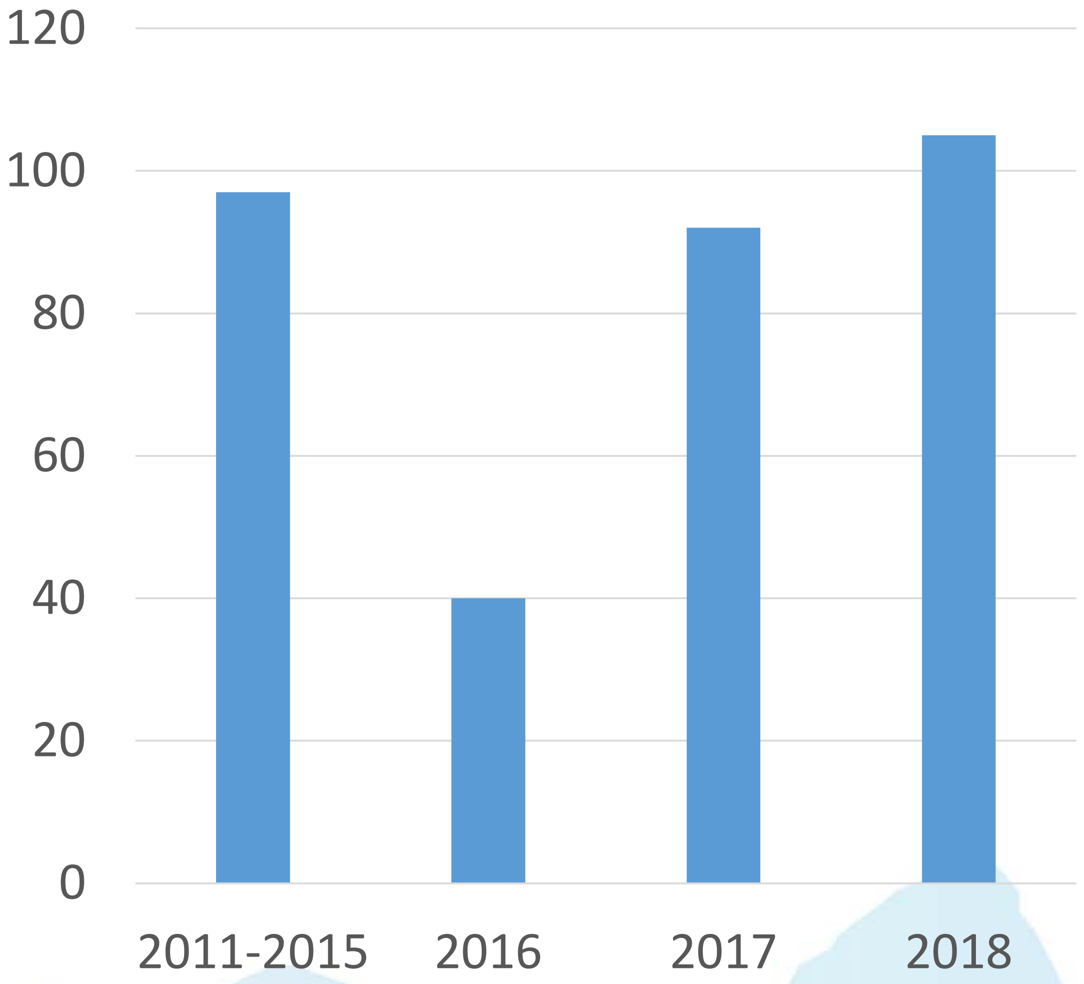
Nuclear Science User Facilities

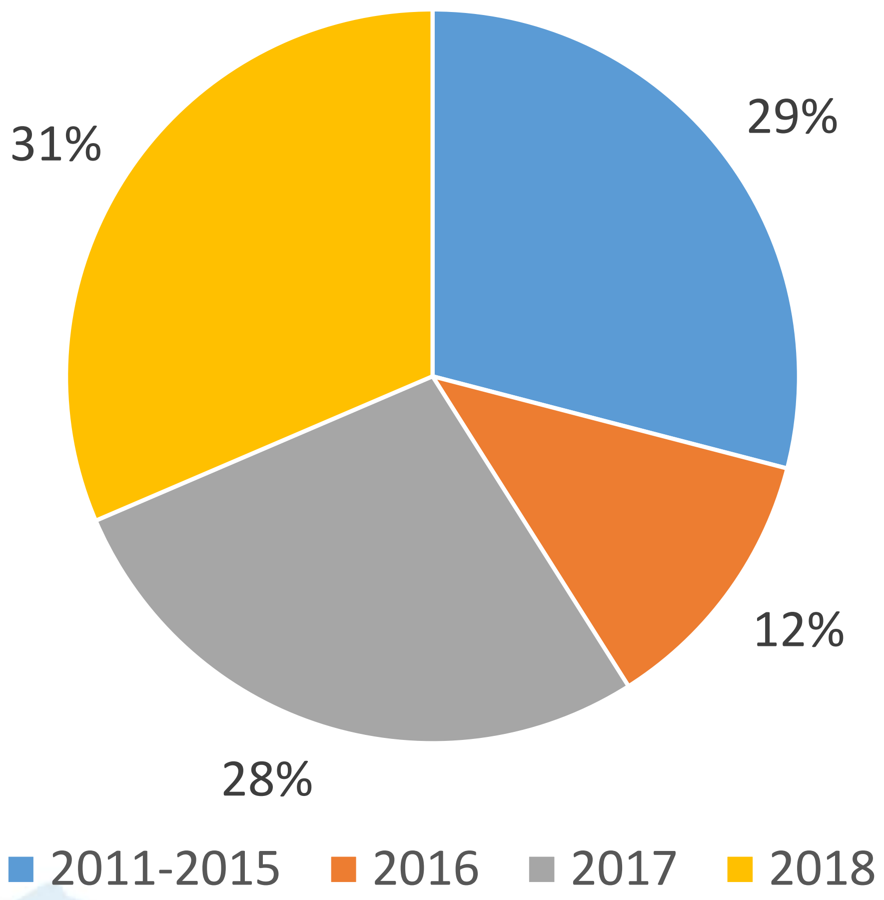
NSUF Ten Year Impact Assessment

Review of NSUF research portfolio

- Purpose of research project
- Relevance to DOE-NE mission
- Topics of DOE-NE interest
- NSUF capability utilization
- Science and Technology gaps
- Accomplishments and success stories

RTE Experiments





Purpose of Research
& Relevance to DOE-NE Mission

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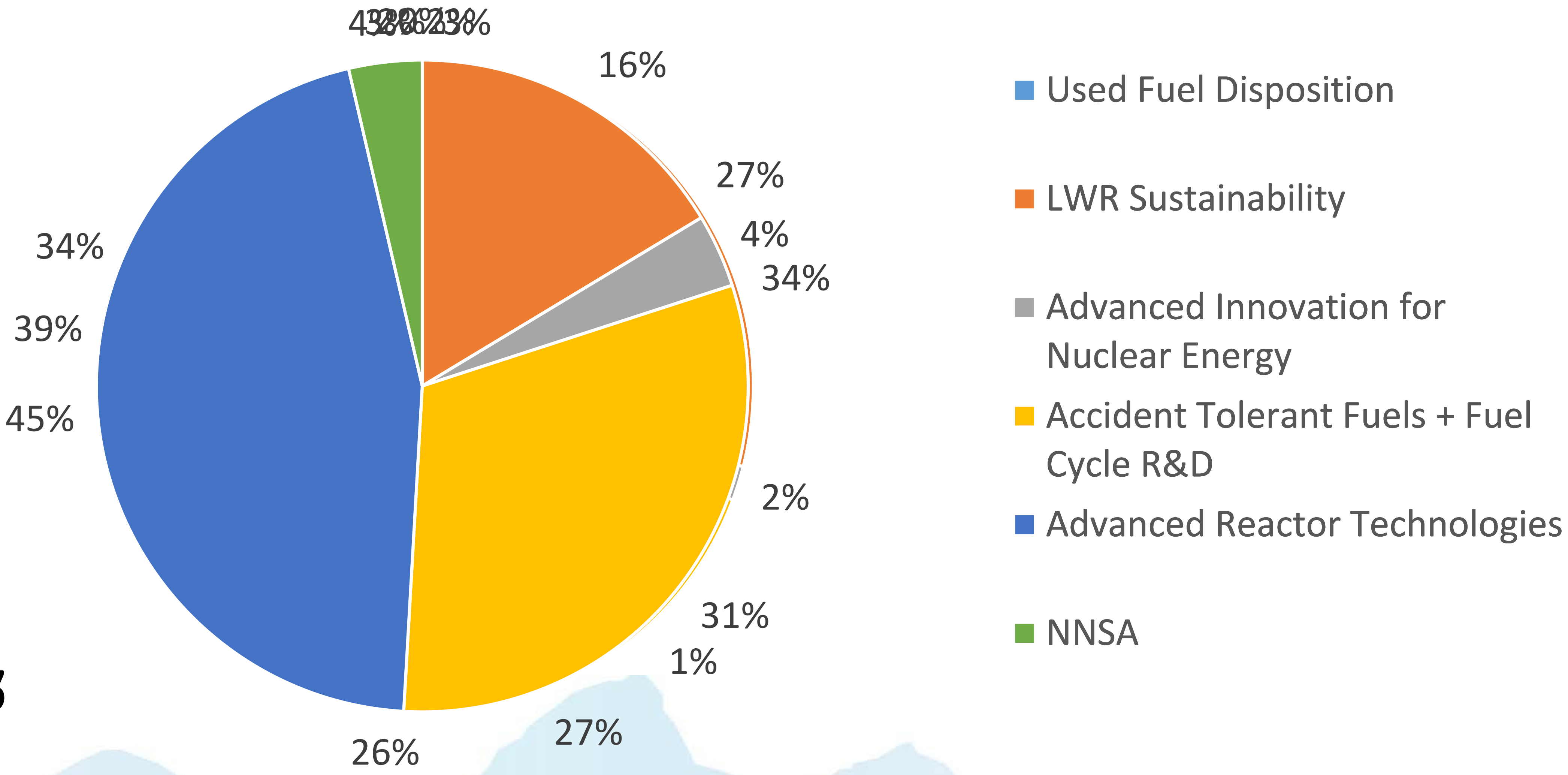
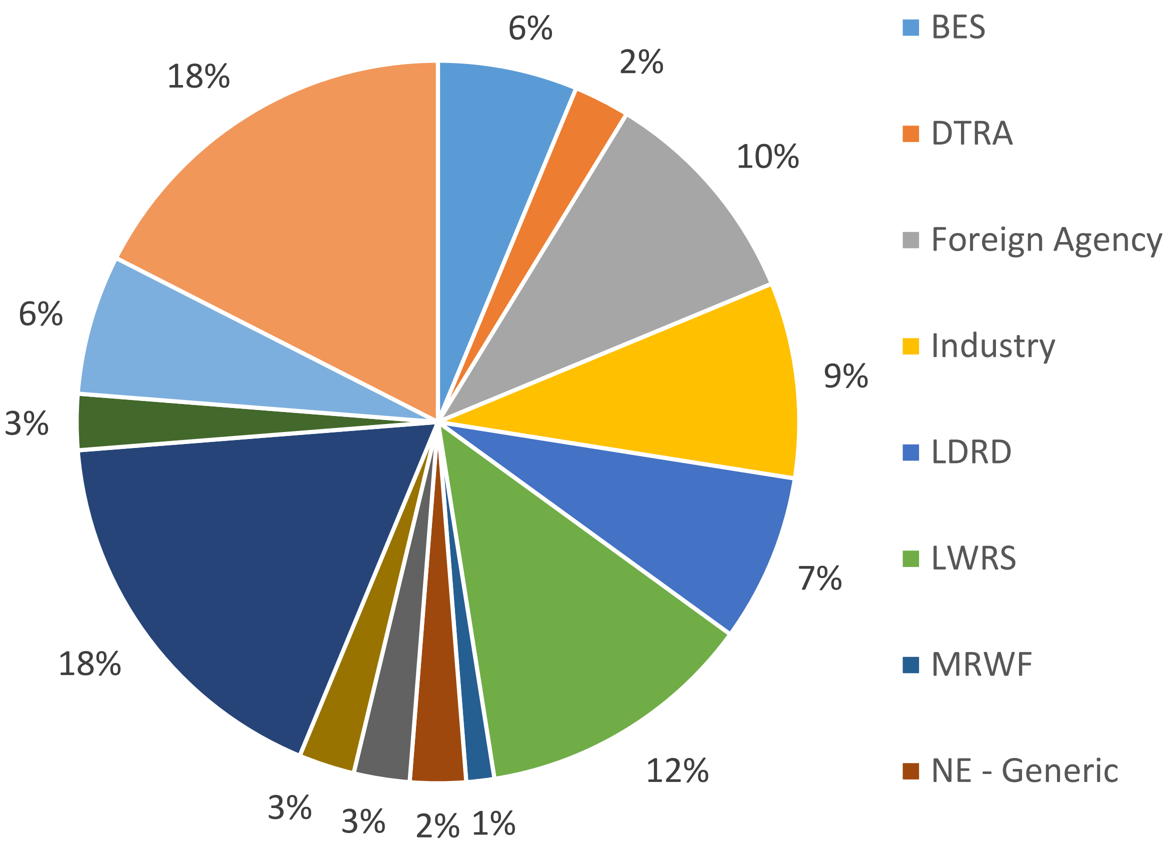
Nuclear Science
User Facilities

DOE-NE Research Area



Research Funding



2017

Topics of DOE-NE Interest

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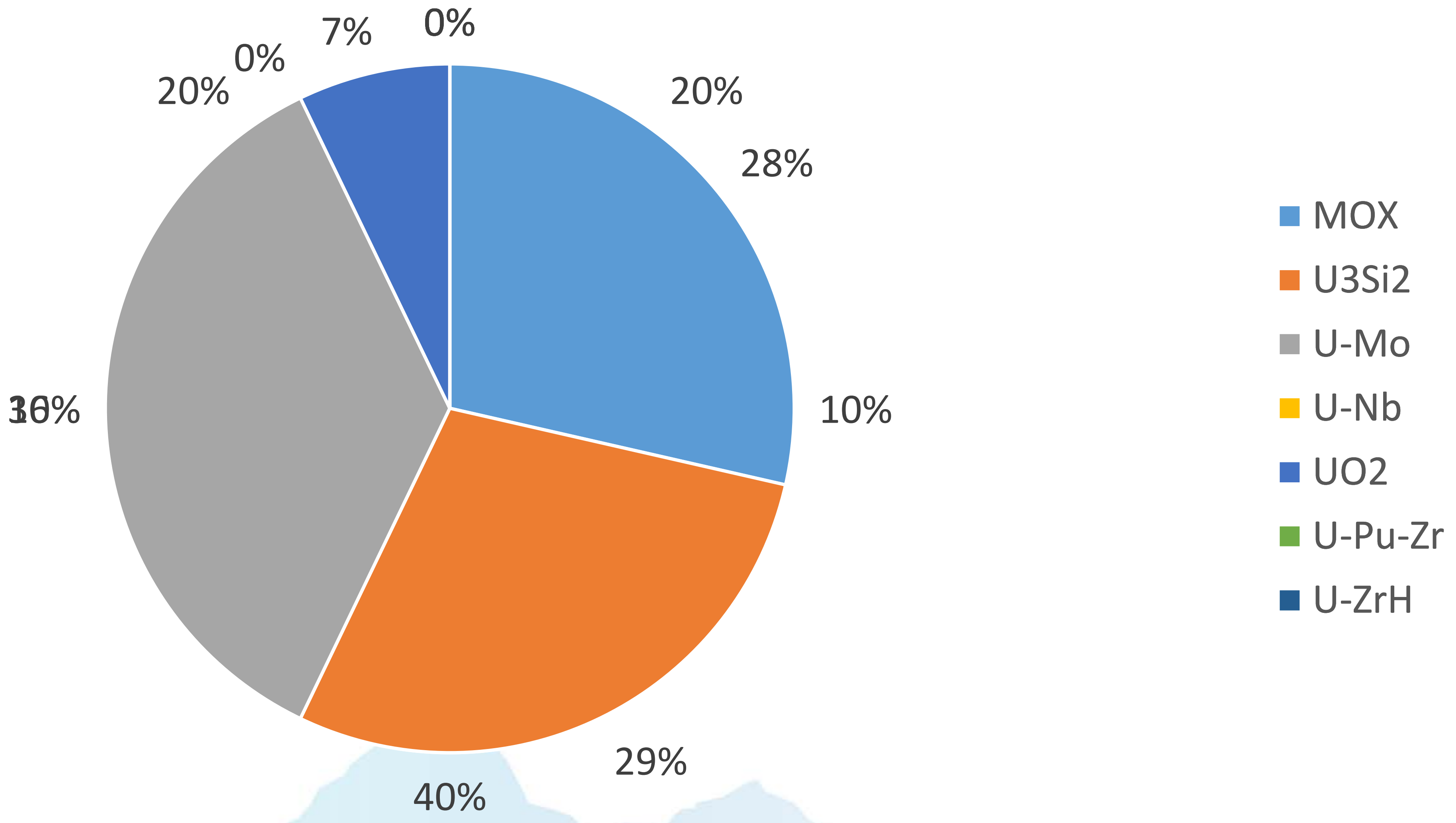
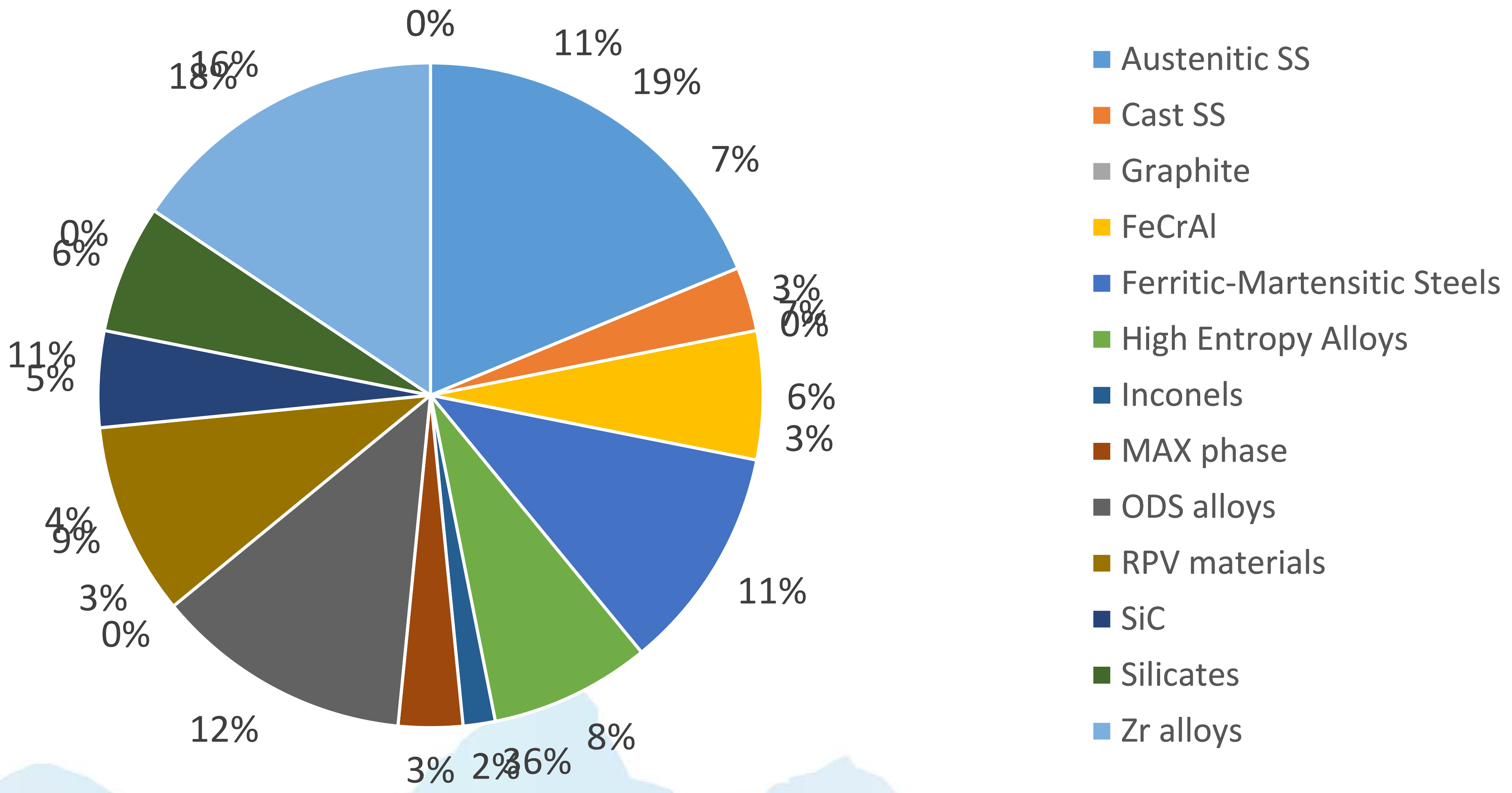
Nuclear Science User Facilities

Fuel Samples



2016 / 2017

Structural and Clad Material Samples



2016
2017

NSUF Capability Utilization

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Nuclear Science User Facilities

Neutron Irradiations	Ion Irradiations	Gamma Irradiations	Hot Cells & Shielded Cells	Low Activity Laboratories	Beamlines	High Performance Computing
Idaho National Laboratory	Wisconsin University of Wisconsin-Madison	Idaho National Laboratory	Idaho National Laboratory	Idaho National Laboratory	Illinois Tech Since 1890	Idaho National Laboratory
Oak Ridge National Laboratory	University of Michigan	Oak Ridge National Laboratory	Oak Ridge National Laboratory	CAES Center for Advanced Energy Studies	Brookhaven National Laboratory	
Massachusetts Institute of Technology	Argonne National Laboratory	Sandia National Laboratories	PNNL	Oak Ridge National Laboratory	NC State University	
NC State University	Sandia National Laboratories		Los Alamos National Laboratory	Cal	Los Alamos National Laboratory	
Ohio State	Texas A&M University		Westinghouse	PNNL		
Sandia National Laboratories	Lawrence Livermore National Laboratory		University of Michigan	Los Alamos National Laboratory		
SCK•CEN			SCK•CEN	NC State University		
				University of Michigan		
				Purdue University		
				University of Florida		
				UNLV		
				SCK•CEN		
				Wisconsin University of Wisconsin-Madison		

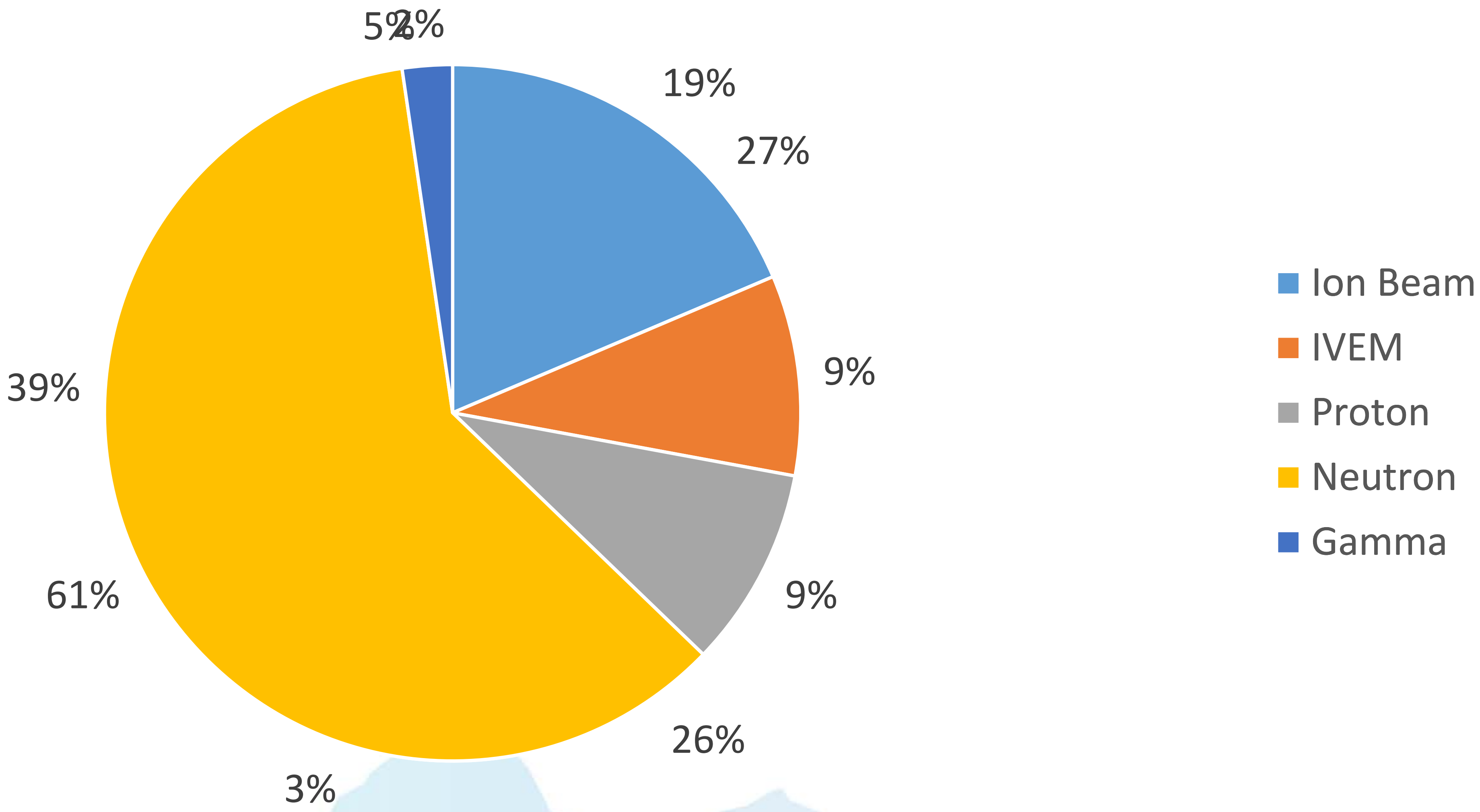
11 Universities

CAES (4 Unis)

7 National Labs

1 Industry

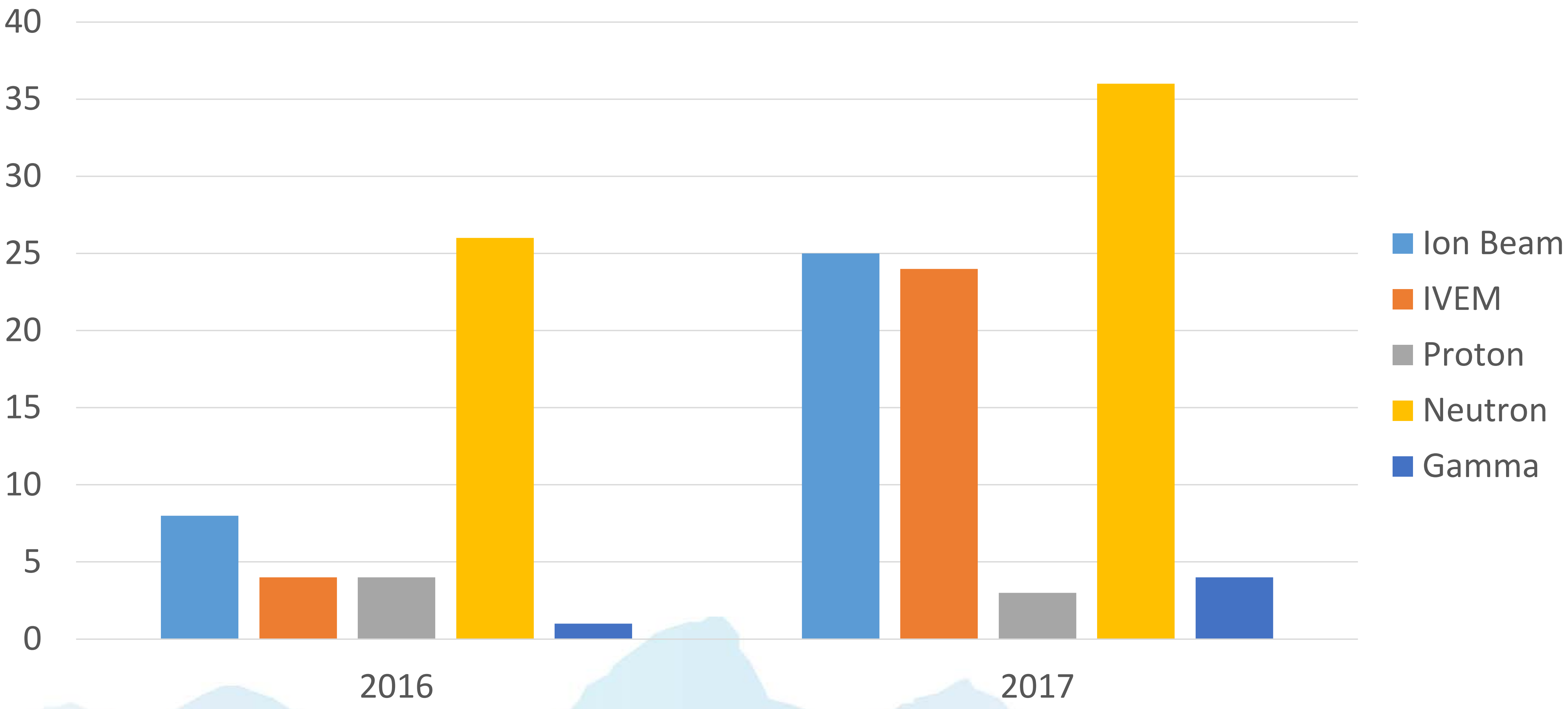
Sample Irradiation Mode



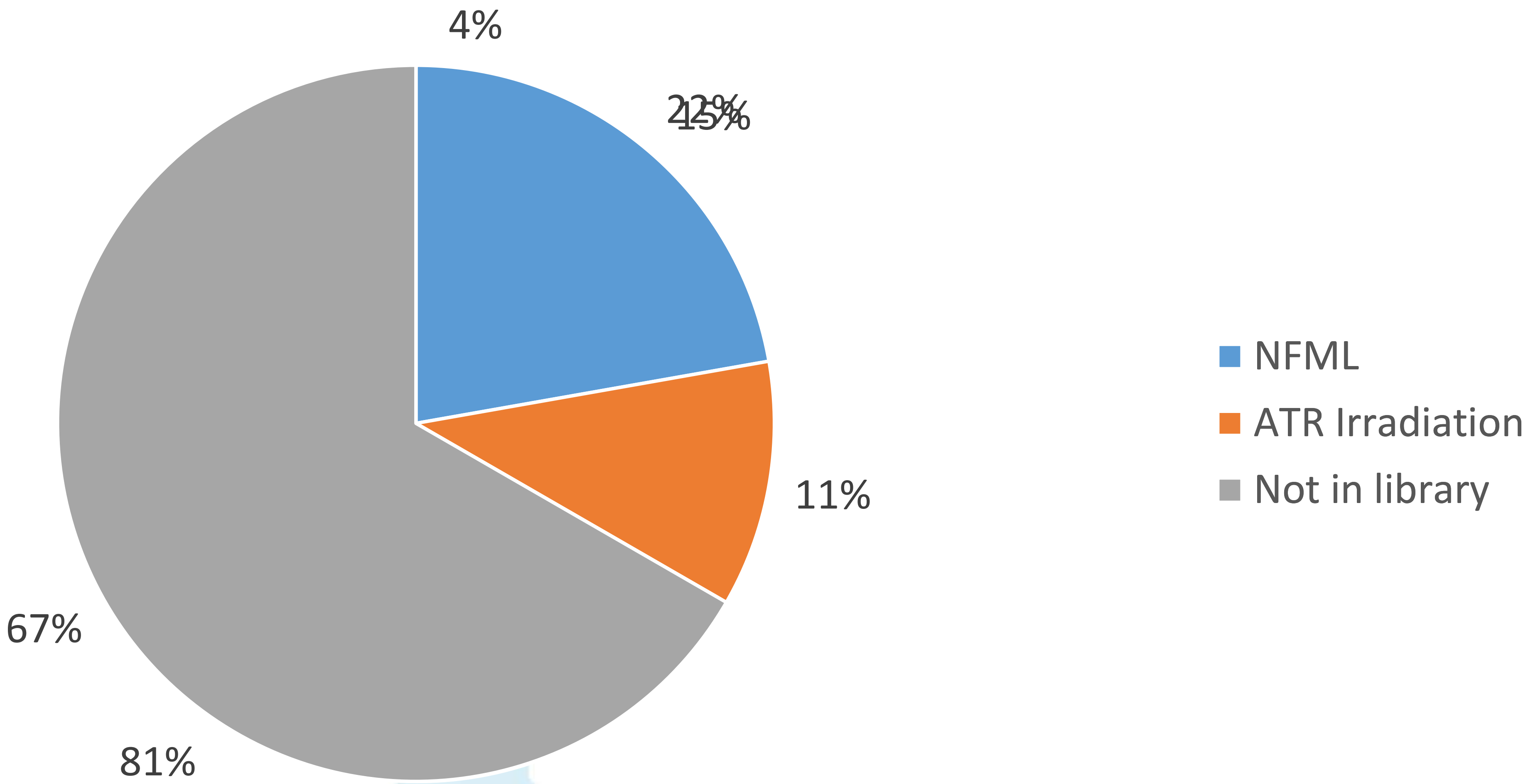
2016

2017

Ion Beams as a Surrogate for Neutrons



NFML Utilization



2016
2017

Science and Technology Gaps

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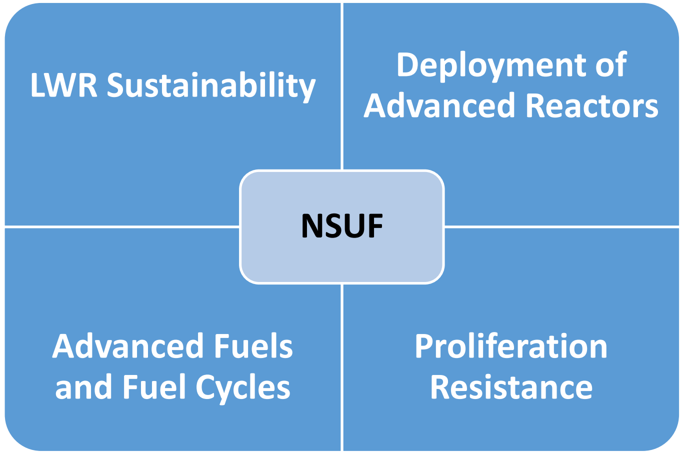
Nuclear Science
User Facilities

Portfolio Gap Analysis

- Strengths, Weaknesses, Opportunities & Threats
- Utilization of Facilities – INL, CAES, & Partners
- Utilization of Nuclear Fuels and Materials Library (NFML)
- Additions to the NFML – SAM experiments
- Value for money

Capability Management

- Balancing Capability
  - To reflect DOE-NE and NSUF Strategic Plan
- Goal
  - To align portfolio to areas of strength and national importance and to maintain international standing
- Research Areas
  - Emphasize & Enhance – strategic intervention
  - Maintain – active monitoring
  - Encourage Excellence – reduce without affecting impact vision and goals
- Balancing
  - Based on evidence such as:
    - Publications
    - Potential future needs
    - Community engagement
    - Portfolio
- Themes determined by DOE-NE mission



Measuring Technology Maturity

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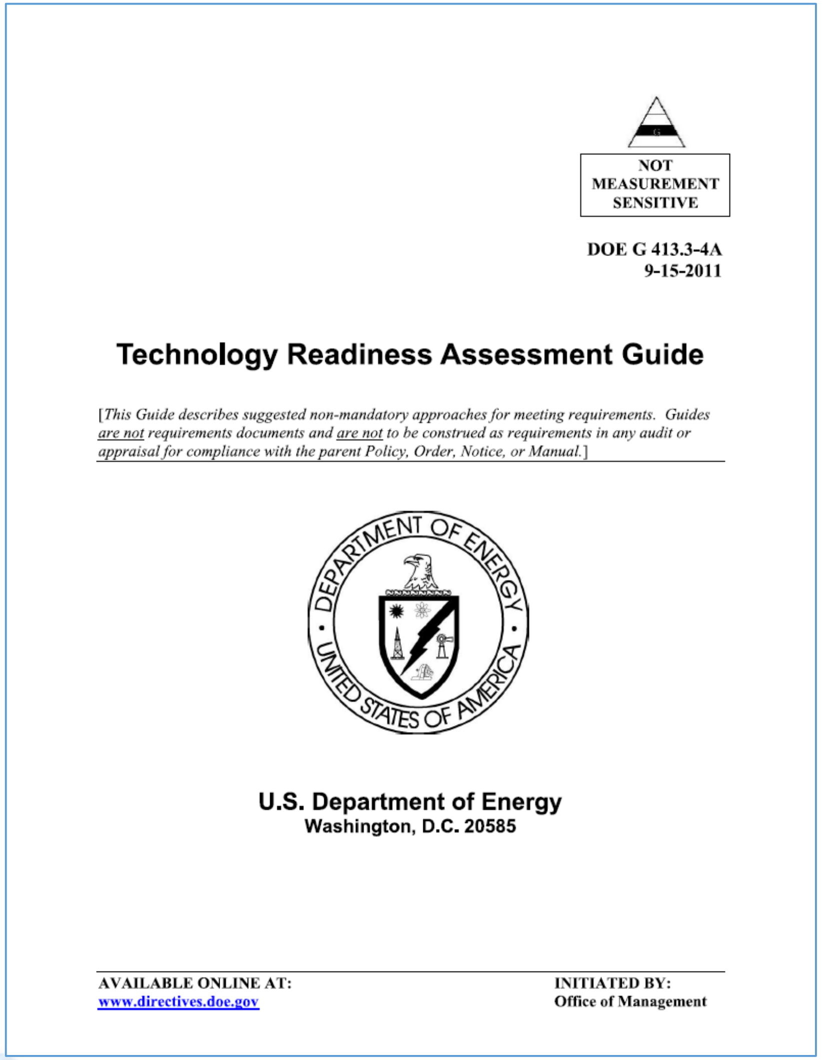
NSUF Nuclear Science User Facilities

Technology Readiness Levels for Advanced Materials

- DOE G 413.3-4A "Technology Readiness Assessment Guide"
- Process pioneered by NASA and DOD
- TRA provides
  - snapshot of the maturity of a technology and allows judgement of potential,
  - guide to steps needed for development and deployment

but is not a pass/fail test.


NOT MEASUREMENT SENSITIVE

DOE G 413.3-4A
9-15-2011

Technology Readiness Assessment Guide

[This Guide describes suggested non-mandatory approaches for meeting requirements. Guides are not requirements documents and are not to be construed as requirements in any audit or appraisal for compliance with the parent Policy, Order, Notice, or Manual.]

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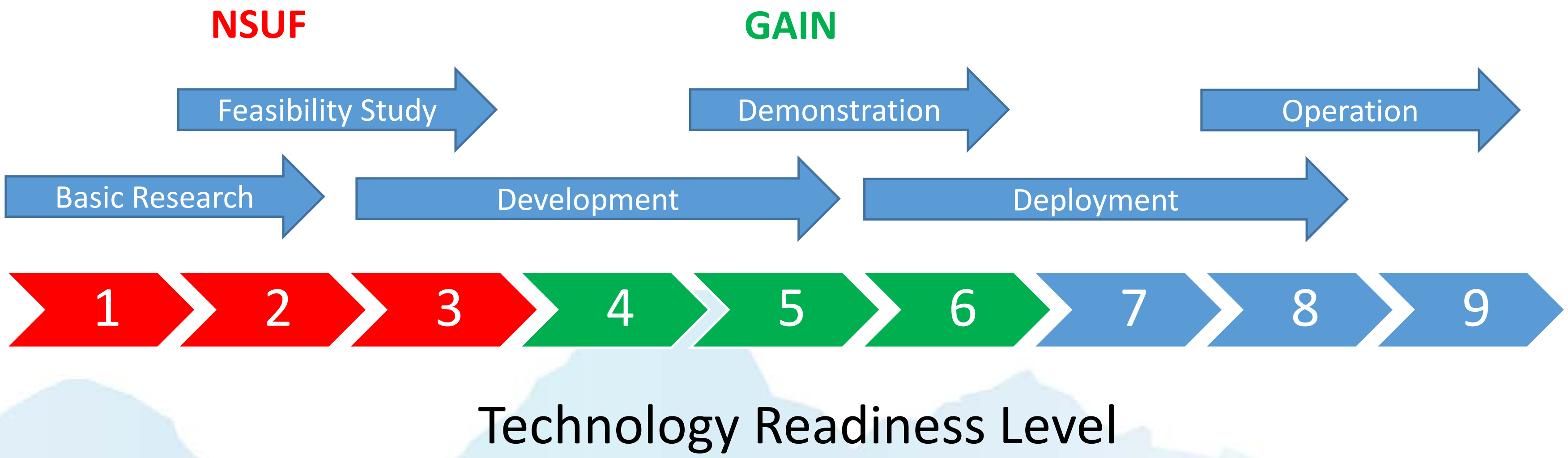
Technology Readiness Levels

- Way of assessing the maturity of a technology
- Based on analysis of
  - concepts,
  - requirements, and
  - demonstrated capabilities
- Range from 1 to 9 representing scientific concept to technical maturity



Critical TRL Evaluation

- Detailed questions tailored to the particular challenge, specific for each TRL.

- The TRL is the level at which all questions are answered positively.

- Objective:
  - Identify gaps in testing, demonstration and knowledge
  - Increase attention and direct resources
  - Increase transparency

TRL Calculator

TRL 9	Has the material been successfully deployed in an operational environment?
TRL 8	Has the material been successfully deployed in a limited operational environment?
TRL 7	Has the material been successfully deployed in a relevant operational environment?
TRL 6	Has engineering scale testing been demonstrated in a relevant environment?
TRL 5	Has lab scale testing been demonstrated in relevant environment?
TRL 4	Has lab scale testing been completed in a simulated environment?
TRL 3	Has proof of concept demonstration been performed in a simulated environment?
TRL 2	Has a fabrication technology been formulated?
TRL 1	Have the basic properties of the material been observed and reported?

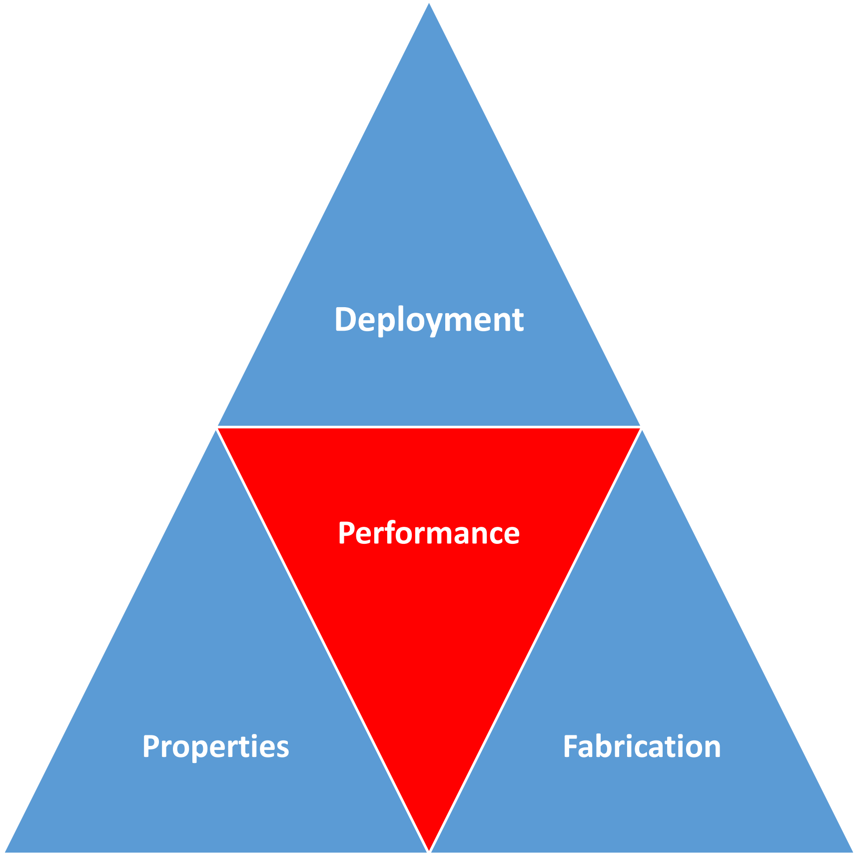
Technology Readiness Levels

- Advantages
  - common understanding
  - common judgement for funding
  - common judgement for transition of technology

- GAO has recommended DOE adopt TRA using TRL

“premature application of technologies by DOE
was the reason for cost growth”

- System needs to be broken down into a number of sub-systems



TRL Development Workshop

- Scheduled for w/c 14th January 2018
- Panel comprising:

Peter Andresen – GE retired	Stu Malloy - LANL
Mike Burke – EPRI	Simon Pimblott
Jim Cole	Lance Snead – Stony Brook
Rory Kennedy	Steve Zinkle - Tennessee

- Objectives:
  - TRL definitions, descriptions and supporting information needs
  - Top level questions to determine anticipated TRL (work down from TRL 9).
  - TRL Assessment tools – TRL calculator criteria, TRL checklists, TRL testing definitions (scale, system, and environment)
  - Template for TRA Report

Materials Understanding and Development

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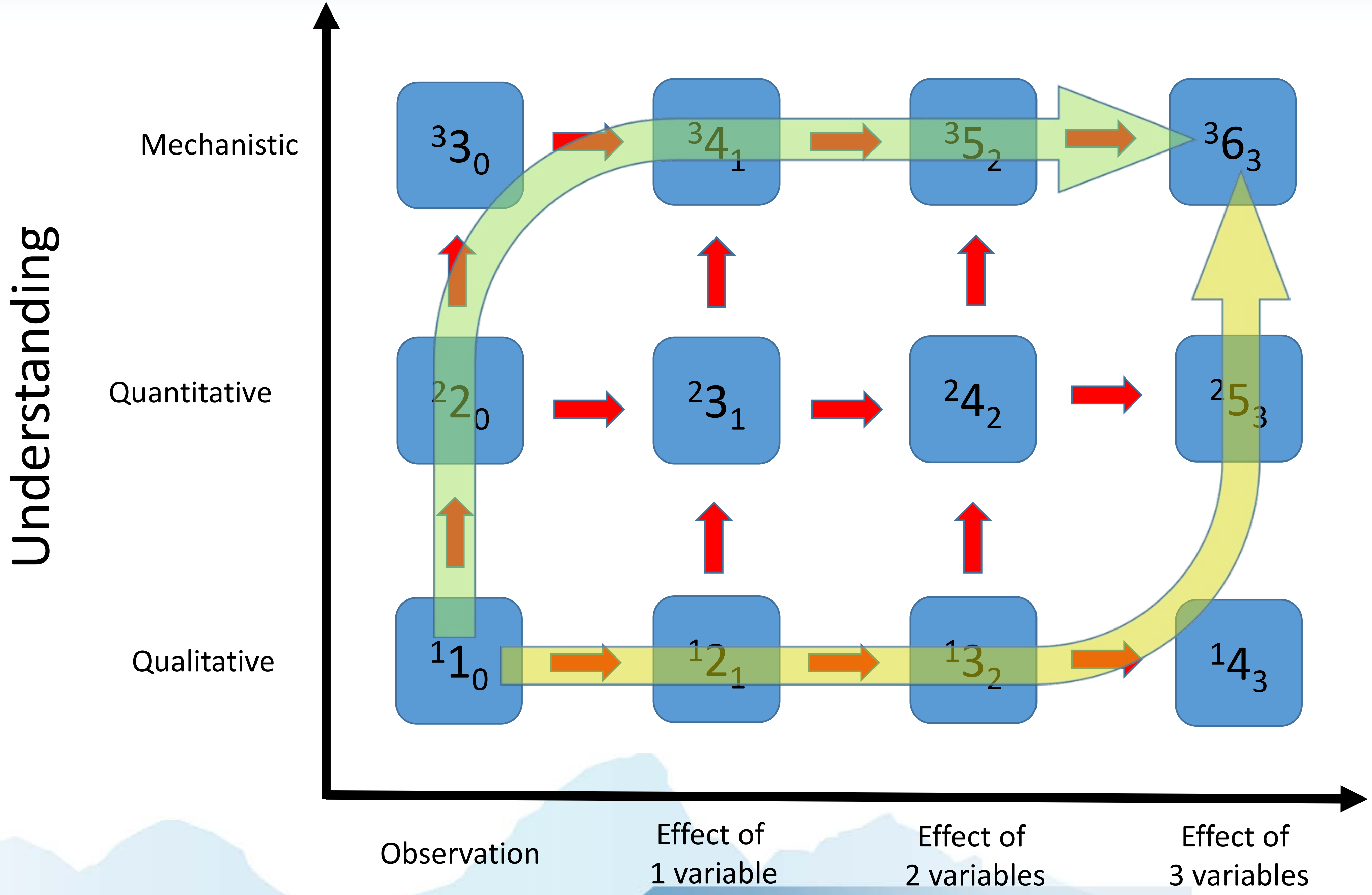
NSUF Nuclear Science User Facilities



Understanding
Mechanistic
Quantitative
Qualitative
³3₀
³4₁
³5₂
³6₃
²2₀
²3₁
²4₂
²5₃
¹1₀
¹2₁
¹3₂
¹4₃
Observation
Effect of 1 variable
Effect of 2 variables
Effect of 3 variables

Material Assessment Exercise

Goal:

- To allow judgement of where the NSUF has added value to nuclear fuel or material development and deployment.

Approach:

- To look at the change in the term symbols for a particular fuel or material.

Example:

- The increased understanding of a radiation induced effect due to a series of RTEs and subsequent analysis might be described by the path:

$$^{2}3_{1} \rightarrow {}^{2}4_{2} \rightarrow {}^{2}5_{3} \rightarrow {}^{3}6_{3}$$

  - The starting point, $^{2}3_{1}$, is a phenomenon that has been experimentally observed as a function of one variable, displacement dose, and has been measured quantitatively allowing empirical prediction/extrapolation.
  - The first step, $^{2}3_{1} \rightarrow {}^{2}4_{2}$, reflects an experimental study quantifying the effect of a second variable such as dose rate.
  - The second step, $^{2}4_{2} \rightarrow {}^{2}5_{3}$, represents a further experimental study quantifying the effect of a third experimental variable such as temperature.
  - The third step, $^{2}5_{3} \rightarrow {}^{3}6_{3}$, the development of a mechanistic understanding of the effect of the three experimental parameters on the observed phenomenon.

Industry Impact

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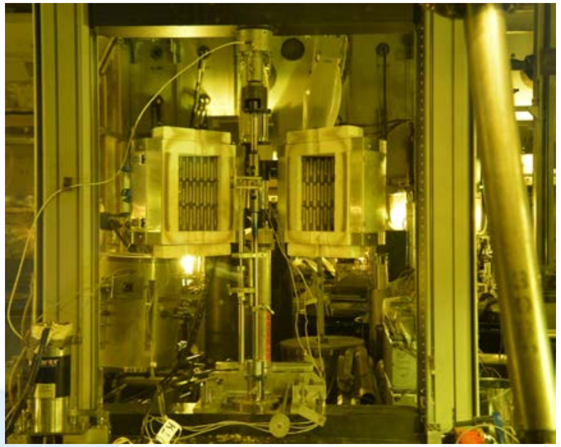
Nuclear Science User Facilities

Industry Engagement 2016 to 2018

- Consolidated Innovative Nuclear Research FOA
  - 1 award in 2016
    - GE-Hitachi
  - 5 awards in 2017, 1 includes R&D funds
    - General Atomics
    - Areva (Framatome)
    - EPRI (2)
    - Westinghouse Electric Company
  - 1 award in 2018
    - Aeroprobe
- Rapid Turnaround Experiments
  - 4 awards in FY2018

Industry Program Base Activities

- Replacement of HFEF Instron furnace
  - Previous furnace was single zone and lacked proper insulation
  - New, 3 zone furnace with custom insulation inserts at top and bottom
  - Completed installation and testing in 2018
- Addition of extensometer to HFEF Instron
  - Previously relied on crosshead displacement and compliance measurement
  - Require measurement across specimen gage length
  - Completed installation and testing in 2018
- In-situ calibration for extensometer
  - Procured and modified calibration stand
  - Completed in 2018



NFML Ex-Plant Materials

- 347 Stainless Steel Baffle Bolts
  - 34 bolts
  - Extracted from U.S. PWR plants
  - ~1 – 40 dpa
  - Provenance provided
- 304 Stainless Steel Control Rod Blade Handle
  - Extracted from U.S. BWR plant
  - Pending EPRI decision
  - ~2 – 3 dpa (needs to be calculated)
- Both sets of material at Westinghouse hot cell
  - Currently negotiating transfer of title for 347 SS bolts
  - Materials to remain at Westinghouse hot cell
    - Machining capability readily available
    - Mature shipping capability

The Future of Nuclear

Nuclear Science
User Facilities

QUESTIONS?

Supplementary Slides

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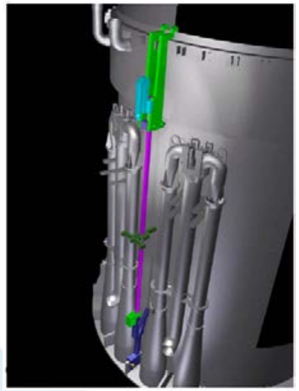
Nuclear Science User Facilities

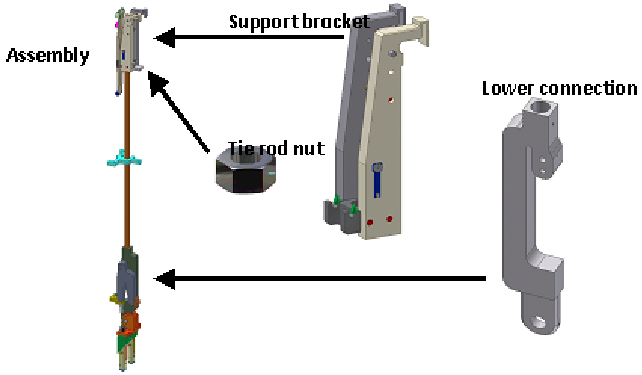
NSUF Pilot Projects and others of interest

- EPRI Pilot Project I: Irradiation and PIE of alloys X-750 and XM-19 (three phases)
  - Irradiate to three fluences (5×10^{19}, 2×10^{20}, 1×10^{21} n/cm^2) at ATR
  - Perform tensile, CGR, FT tests, and TEM microstructural analyses
- EPRI Pilot Project II: Zirconium alloy irradiation growth
  - Measure hydrogen assisted irradiation induced growth under BWR relevant conditions.
  - Characterize irradiation induced defects and correlate to growth
- GE-Hitachi: Irradiation Testing of LWR Additively Manufactured Materials (new in 2017)
  - Direct Metal Laser Melted (DMLM) 316 SS and 718
  - Irradiation at ATR to 0.5-1.0 dpa plus IASCC, FT, and TEM

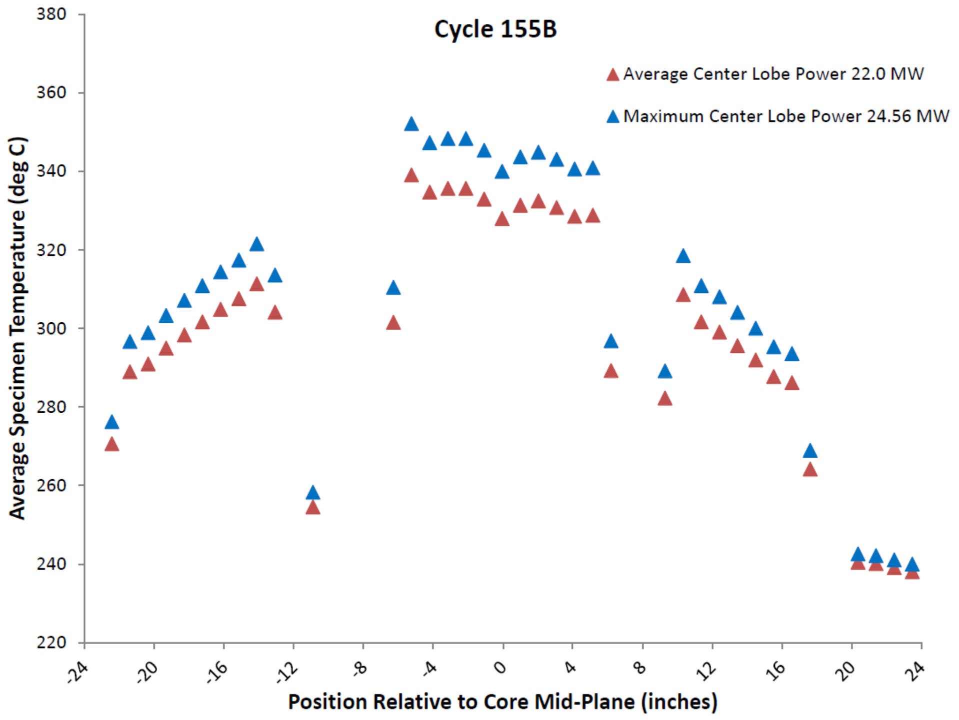
EPRI Pilot Project 1: Irradiation and PIE of alloys X-750 and XM-19

- Alloys X-750 and XM-19 are used in many structural applications in BWRs ranging from original equipment to modifications and repair hardware
  - SCC and fracture toughness data in BWR water chemistry conditions are rather limited, particularly when exposed to neutron irradiation
- A multi-year program is in place to examine the SCC and fracture toughness behavior of these materials under a variety of BWR conditions, both un-irradiated and irradiated





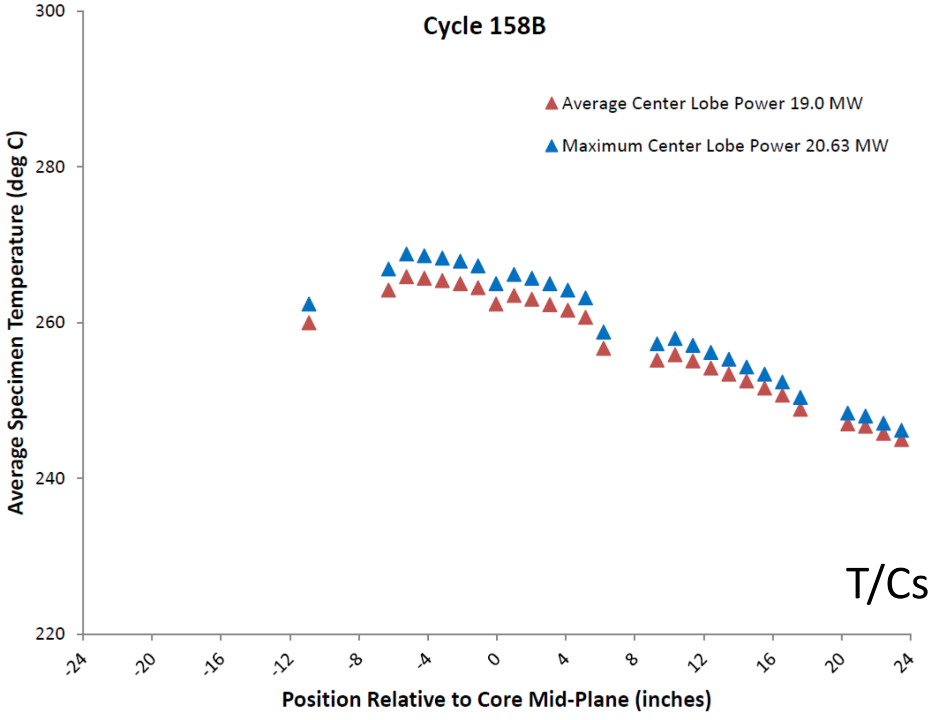
Cycle 155B temperatures (estimated) -irradiation temperature issues



		Average Center Power 22.0 MW	Maximum Center Power 24.56 MW
Specimen Identifier	Position Relative to Mid-Plane	Average Temperature of Specimen (°C)	Average Temperature of Specimen (°C)
spacer	-23.48		
EPRI-3A-1	-22.44	270.7	276.3
EPRI-3A-2	-21.40	289	296.7
EPRI-3A-3	-20.36	291	298.9
EPRI-3A-4	-19.32	295	303.3
EPRI-3A-5	-18.28	298.4	307.2
EPRI-3A-6	-17.24	301.7	310.9
EPRI-3A-7	-16.20	304.9	314.4
EPRI-3A-8	-15.16	307.6	317.4
EPRI-3A-9	-14.12	311.4	321.6
EPRI-3A-11	-13.08	304.2	313.6
EPRI-3A-12	-10.91	254.6	258.3
spacer	-7.33		
EPRI-3B-1	-6.29	301.6	310.5
EPRI-3B-2	-5.25	339.1	352.2
EPRI-3B-3	-4.21	334.7	347.3
EPRI-3B-4	-3.17	335.7	348.4
EPRI-3B-5	-2.13	335.7	348.4
EPRI-3B-6	-1.09	333	345.4
EPRI-3B-7	-0.05	328	340
EPRI-3B-8	0.99	331.4	343.7
EPRI-3B-9	2.03	332.5	344.9
EPRI-3B-10	3.07	330.8	343.1
EPRI-3B-11	4.11	328.6	340.6
EPRI-3B-12	5.15	328.9	340.9
EPRI-3B-14	6.19	289.3	296.9
spacer	8.26		
EPRI-3B -13	9.30	282.3	289.2
NRC-3C-1	10.34	308.6	318.6
NRC-3C-2	11.38	301.7	310.9
NRC-3C-3	12.42	299.1	308.1
NRC-3C-4	13.46	295.6	304.1
EPRI-3C-5	14.50	292	300.1
EPRI-3C-6	15.54	287.8	295.4
EPRI-3C-7	16.58	286.2	293.6
EPRI-3C-8	17.62	264.2	269
spacer	19.58		
EPRI-3D-TC	20.36	240.5	242.6
	21.40	240.1	242.2
	22.44	239.1	241.1
	23.48	238.1	240

- 339 C – 352 C over middle section
- Two packages close to target irradiation temperature
  - EPRI-3B-13: 282 C – 289 C
  - EPRI-3B-1: 302 C – 311 C

Cycle 158B temperatures (estimated)



- 255 C – 269 C

		Average Center Power 19.0 MW	Maximum Center Power 20.63 MW
Specimen Identifier	Position Relative to Mid-Plane	Average Temperature of Specimen (°C)	Average Temperature of Specimen (°C)
spacer	-23.48		
spacer	-22.44		
spacer	-21.40		
spacer	-20.36		
spacer	-19.32		
spacer	-18.28		
spacer	-17.24		
spacer	-16.20		
spacer	-15.16		
spacer	-14.12		
spacer	-13.08		
EPRI-3A-12	-10.91	260	262.4
spacer	-7.33		
EPRI-3B-1	-6.29	264.2	266.9
EPRI-3B-2	-5.25	265.9	268.8
EPRI-3B-3	-4.21	265.7	268.6
EPRI-3B-4	-3.17	265.4	268.3
EPRI-3B-5	-2.13	265	267.9
EPRI-3B-6	-1.09	264.5	267.3
EPRI-3B-7	-0.05	262.4	265
EPRI-3B-8	0.99	263.5	266.2
EPRI-3B-9	2.03	263	265.7
EPRI-3B-10	3.07	262.3	265
EPRI-3B-11	4.11	261.6	264.2
EPRI-3B-12	5.15	260.7	263.2
EPRI-3B-14	6.19	256.7	258.8
spacer	8.26		
EPRI-3B -13	9.30	255.2	257.3
NRC-3C-1	10.34	255.9	258
NRC-3C-2	11.38	255.1	257.1
NRC-3C-3	12.42	254.2	256.2
NRC-3C-4	13.46	253.4	255.3
EPRI-3C-5	14.50	252.5	254.3
EPRI-3C-6	15.54	251.6	253.4
EPRI-3C-7	16.58	250.7	252.4
EPRI-3C-8	17.62	248.9	250.4
spacer	19.58		
EPRI-3D-TC	20.36	247	248.4
	21.40	246.7	248
	22.44	245.8	247.1
	23.48	245	246.2

IASCC crack growth rate testing summary

Specimen ID	Alloy	Fluence (DPA)	Irradiation Temp (C)	HWC CGR (mm/s)	NWC CGR (mm/s)	Applied K (Mpa√m)
	X-750	0	N/A	1.3 – 5.0 X 10^{-8}	1.2 – 8.0 X 10^{-7}	27.5
**	XM-19	0	N/A	2.0 – 3.0 X 10^{-9}	3.0 – 13 X 10^{-8}	33.0
10A0002A08	X-750	0.31	329-338	3.1 – 6.2 X 10^{-8}	1.1 – 22 X 10^{-7}	27.5
10A0002A10	X-750	0.31	349-359	3.0 – 6.0 x 10^{-8}	6.8 – 16 X 10^{-7}	27.5
10A0001B03	XM-19	0.29	349-359	Crack arrested	4.1 – 20 x 10^{-8}	27.5
10A0001B02	XM-19	0.29	350-360	6.5 x 10^{-9}	2.9 X 10^{-7}	27.5
10A0002B09	X-750	1.54	333-345/266*	5.0 - 11 x 10^{-8}	1.2 – 4.0 X 10^{-7}	27.5
10A0002B03	X-750	1.44	282-289/256*	ongoing	ongoing	
10A0001B07	XM-19	1.32	282-289/256*	ongoing	ongoing	

*Two cycles

** Source: *Andresen, P.; Morra, M.; and Carter, B. "SCC and Fracture Toughness of XM-19", Proceedings of the 18th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Volume 2, (TMS, 2017), pp. 391-406.*

EPRI Pilot project I progress and current conclusions

- Irradiations complete
  - EPRI-1 – Target: 5.0 X 10^{19} n/cm^2; Actual: 5.35 X 10^{19} n/cm^2
  - EPRI-2 – Target: 2.0 X 10^{20} n/cm^2; Actual: 1.93 X 10^{20} n/cm^2
  - EPRI-3 – Target: 1.0 X 10^{21} n/cm^2; Actual: 0.96 X 10^{21} n/cm^2
- IASCC testing
  - No clear effect of fluence at medium (2.0 X 10^{20} n/cm^2) or high (1 X 10^{20} n/cm^2) level compared to unirradiated
  - Low fluence tests will not be conducted
- Fracture toughness
  - Effect of irradiation is apparent for X-750 (comparison of J-R curves)
  - Only single fluence tested to date for XM-19, effect is evident (compared to GE-GRC measured value) but not to the same degree as X-750
- TEM analysis
  - Baseline examination for comparison to irradiated microstructure
  - All electropolishing and sample prep completed
  - Dislocation analysis completed
  - Study of high angle grain boundaries to be performed

EPRI Pilot Project II – Irradiation and PIE to Investigate Hydrogen Assisted Anomalous Growth in Zr Alloys

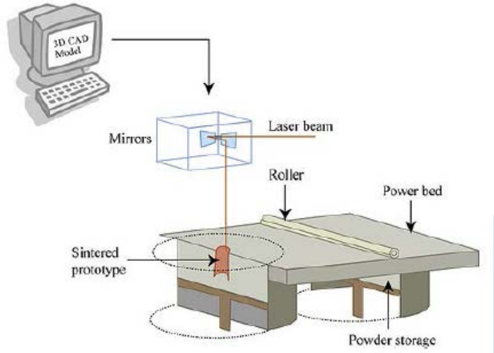
- Experiment objectives: (fuel channel bowing issue)
  - Measure hydrogen assisted, irradiation induced growth under BWR relevant conditions
  - Determine effects of hydrogen content (soluble vs. insoluble) and neutron fluence on growth strain
  - Characterize irradiation induced defects and correlate to macroscopic growth strain
- Experiment strategy:
  - Prepared 200 specimens; 35 mm long X 6.5 mm wide X 0.8 mm thick
  - 4 different Zr alloys (as received ~= 10 ppm H)
  - Pre-charged to H concentrations (~= 40 and 125 ppm)
  - Irradiate to 4 fluences and maintain temperature ~=285 C
  - Helium filled capsule for temperature control
  - Measure before and after irradiation using INL designed and built equipment

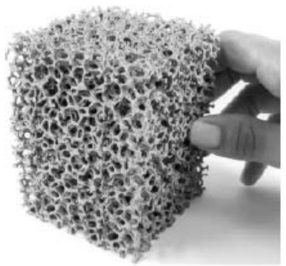
EPRI Pilot Project II status

- First two irradiation capsules (EPRI-ZG-A, EPRI-ZG-B)
  - ZG-A – 6.7 DPA
  - ZG-B – 12.3 DPA
  - Analyses (strain measurement and TEM) completed in 2017
- TEM report finalized and delivered to EPRI in 2018
  - Fairly inconclusive results from TEM analyses so far
- Project idling while irradiations complete
  - ZG-C – 20 DPA, projected 19.9 DPA in December, 2019
  - ZG-D – 30 DPA, projected 24 DPA by Core Internals Changeout (mid-2021)

CINR award in 2016 – GE-Hitachi (NSUF access only)

- Irradiation Testing of LWR Additively Manufactured Materials
  - Direct Metal Laser Melting (DMLM) processed
- Objectives
  - Irradiate and characterize additively manufactured 316L and IN 718
  - Compare data to similar data obtained in wrought material
  - Extend knowledge base from un-irradiated characterization
- NSUF Facilities
  - ATR, EIL SCC, IASCC, EML
- Address fundamental knowledge gap
  - No data on AM materials in prototypical LWR conditions



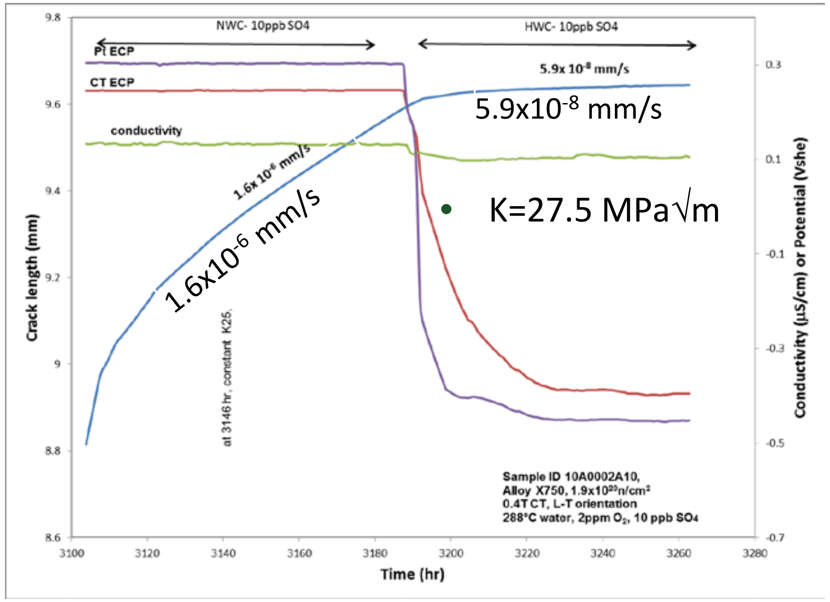


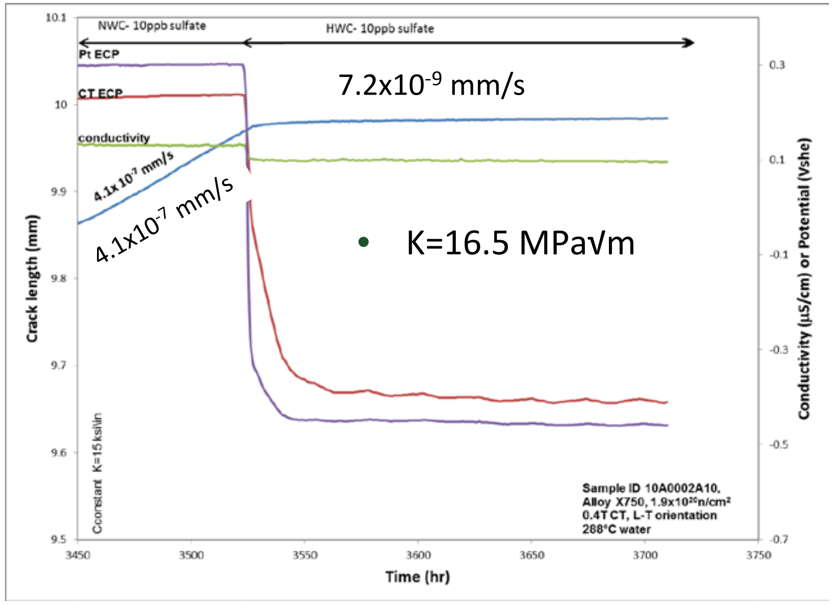
Ref: UTEP

Ref. Within Labs, UK

Irradiated X-750 (HTH), 1.93 X 10^{20} n/cm^2 IASCC CGR Testing

Confirmatory test and effect of K applied

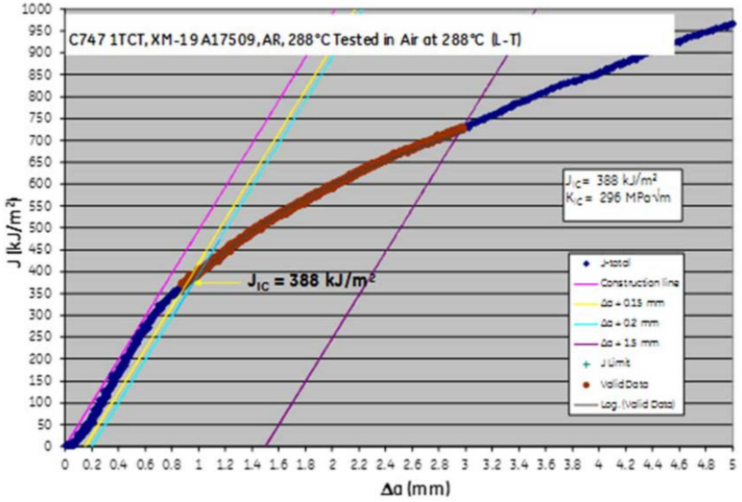




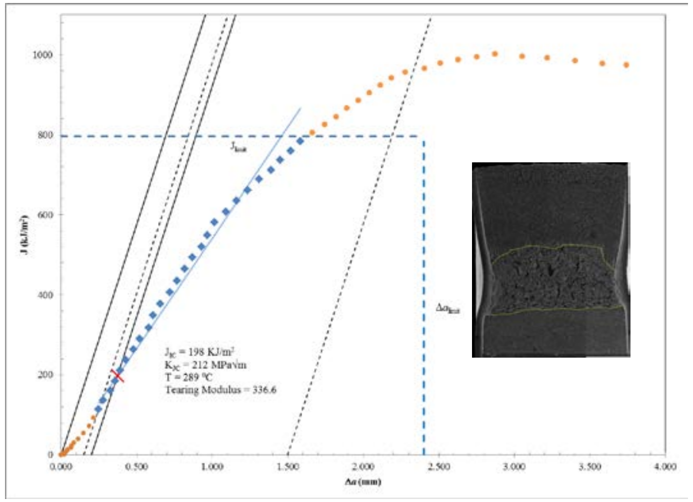
Irradiated (1.9 X 10^{20} n/cm^2) Crack Growth Rate	
HWC	3.0 – 6.0 x 10^{-8} mm/s
NWC	6.8 – 16 x 10^{-7} mm/s

Irradiated (1.9 X 10^{20} n/cm^2) Crack Growth Rate	
HWC	7.2 x 10^{-9} mm/s
NWC	4.1 x 10^{-7} mm/s

EPRI-2 fracture toughness

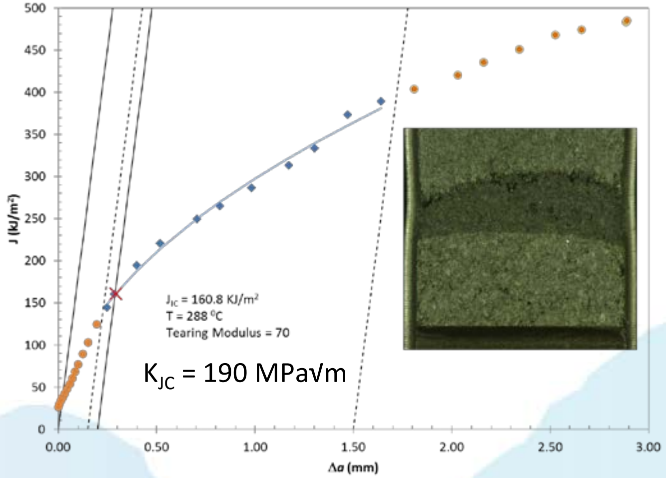


Unirradiated

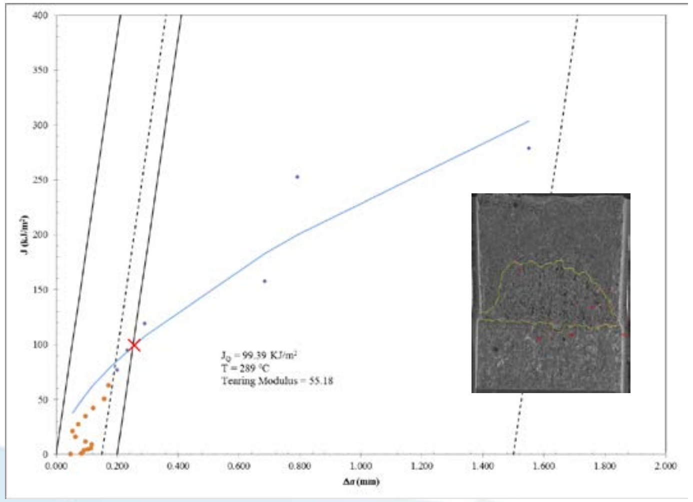


1.93 X 10^{20} n/cm^2

XM-19

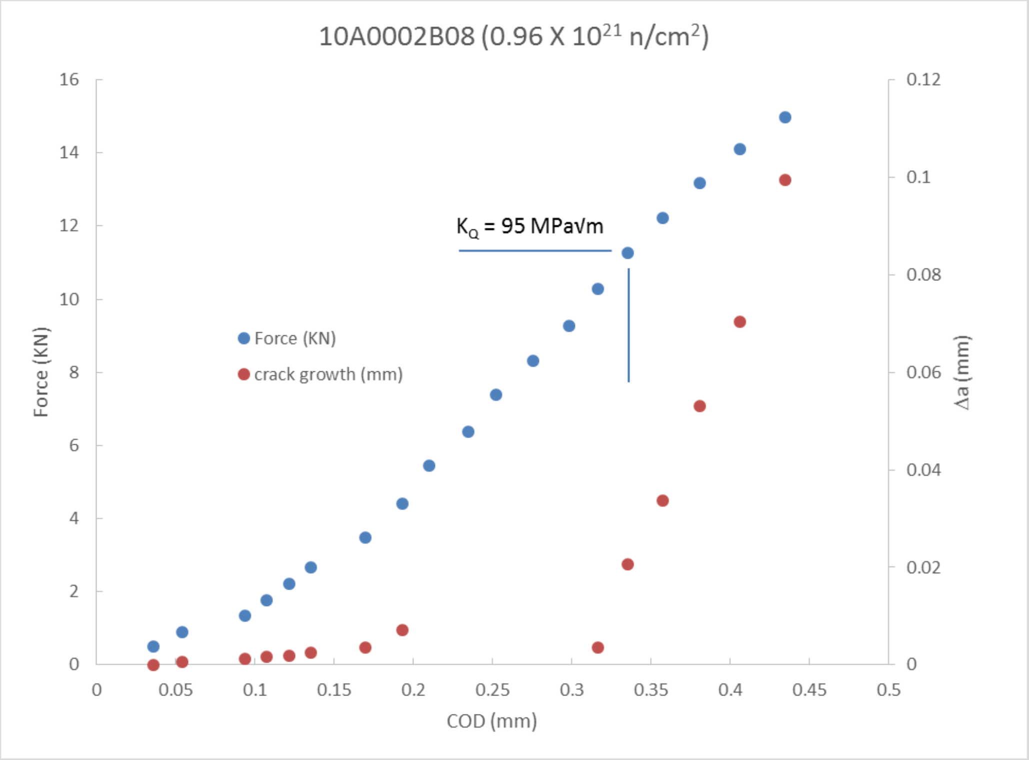


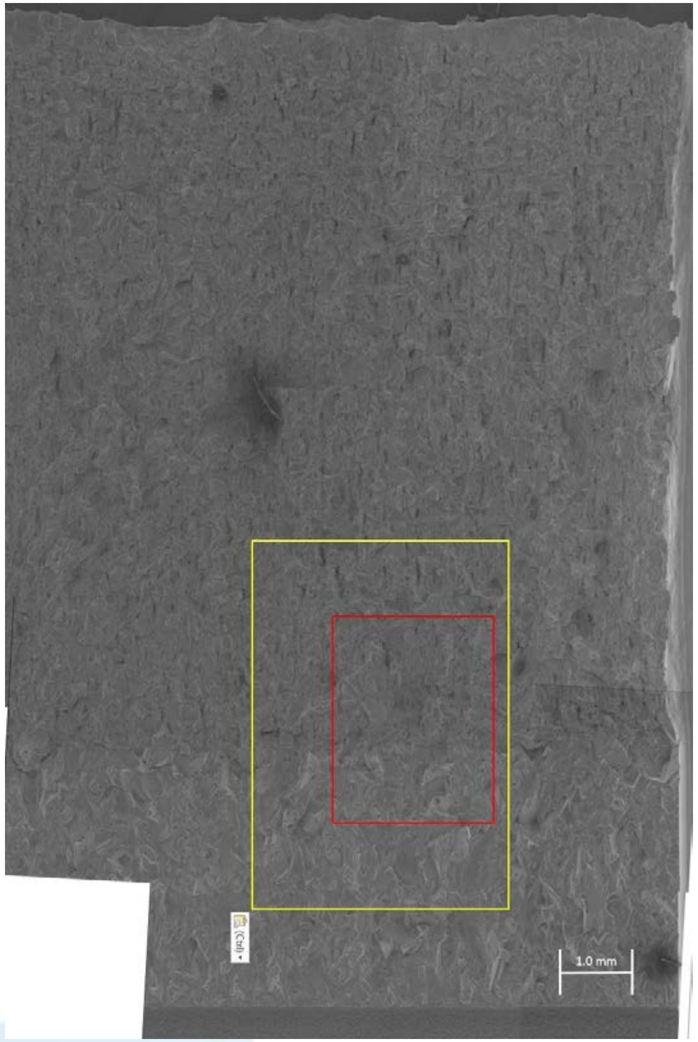
K_{JC} = 190 MPa√m



X-750

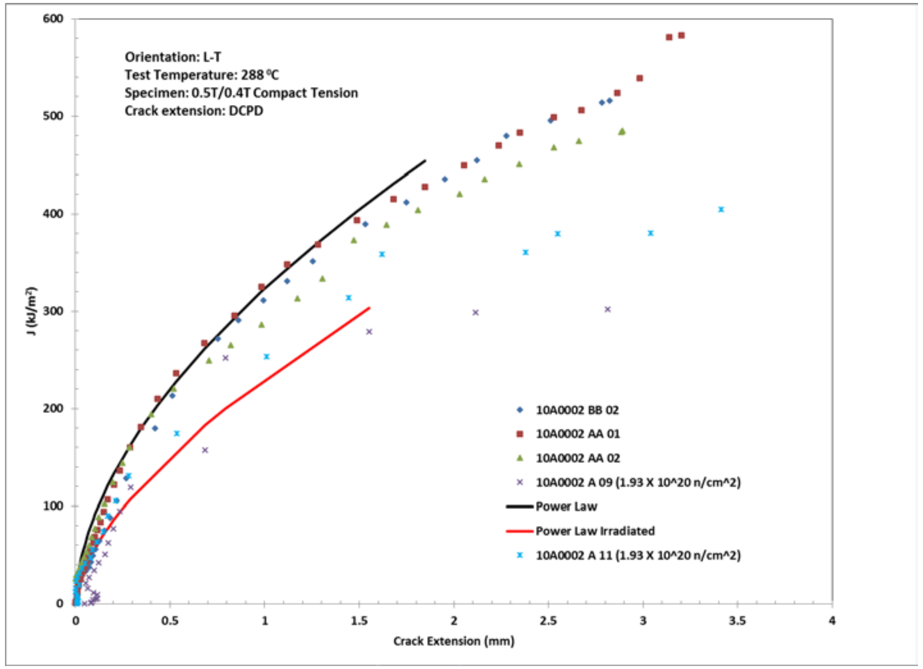
EPRI-3 Fracture Toughness (X-750 @ 0.96 X 10^{21} n/cm^2)



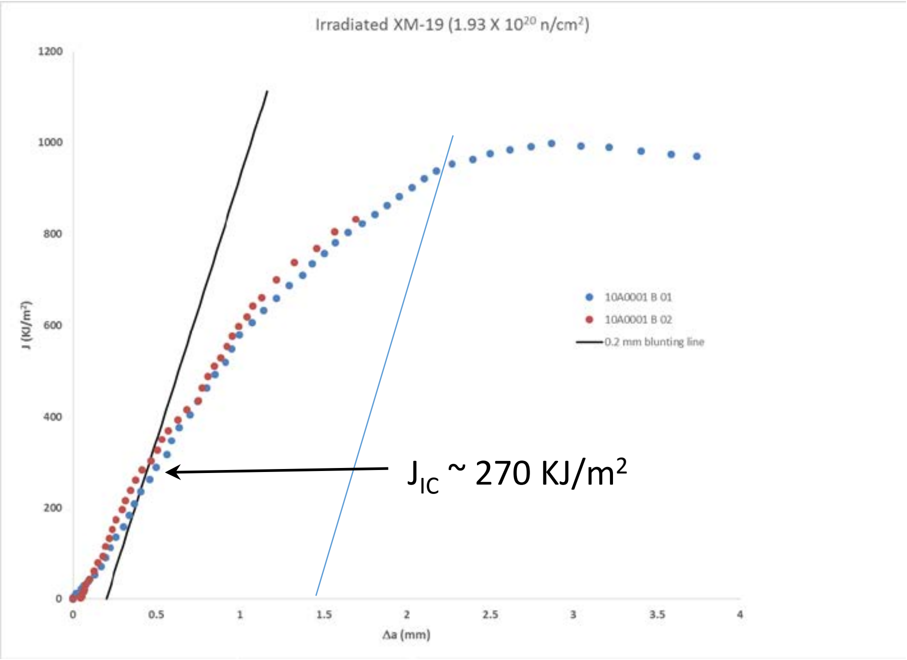


EPRI-2 Fracture toughness (comparisons)

X-750



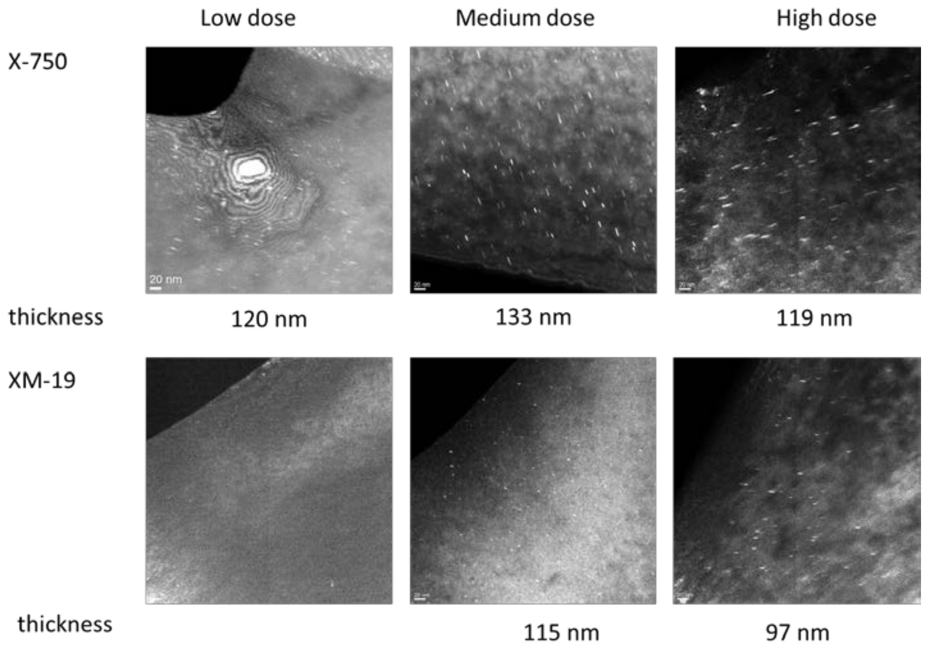
XM-19



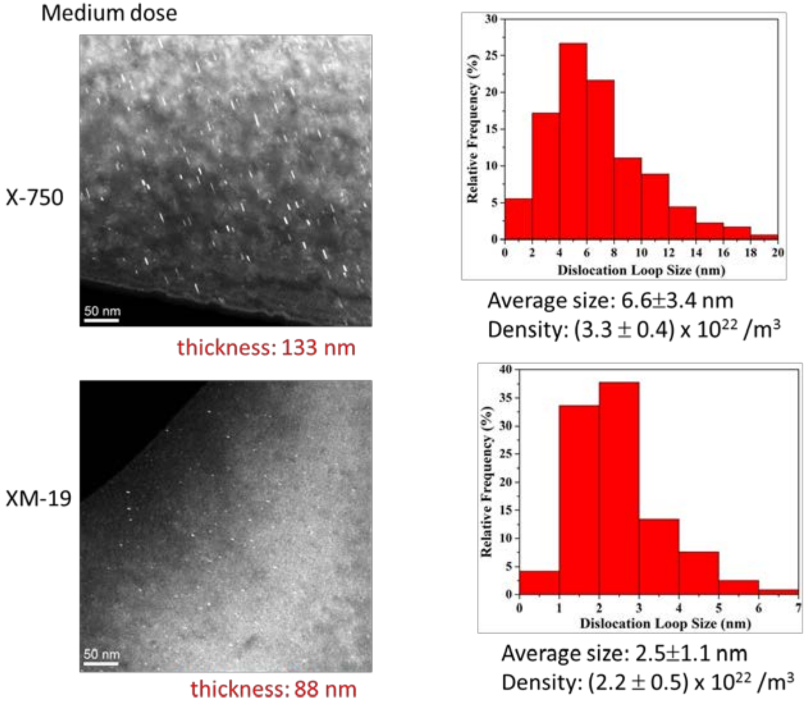
- Highest fluence no J-R curve
- Lowest fluence yet to be tested

TEM analyses

- Irradiated microstructure



Rel-rod dark-field images showing faulted dislocation loops vs. dose



TEM analyses

➢ Summary of dislocation loop analyses

Sample	Low dose (EPRI 1) (5.30×10^{19} n/cm^2)	Medium dose (EPRI 2) (1.93×10^{20} n/cm^2)	High dose (EPRI 3) (9.73×10^{20} n/cm^2)
X-750			
Loop size (nm)	5.7±3.0	6.6±3.4	12.0±4.9
Loop density (m^{-3})	$(2.1 \pm 0.2) \times 10^{22}$	$(3.3\pm0.4) \times10^{22}$	$(2.2 \pm 0.4) \times 10^{22}$
XM-19			
Loop size (nm)	0*	2.5±1.1	5.9±2.1
Loop density (m^{-3})	0	$(2.2\pm0.5) \times10^{22}$	$(2.8\pm0.7) \times10^{22}$

*Loop size for XM-19 at low dose is too small to be detected using TEM