MaRIE – FFMF FISSION FUSION MATERIALS FACILITY

What is MaRIE FFMF, Why & Why now	Mark Bourke [1]
Reactor materials challenges & FFMF relevance	Stuart Maloy [2]
Unique model validation needs and opportunities	Carlos Tome [3]
Advocating FFMF & defining requirements	Jack Shlachter [4]
First experiments & open questions	Mark Bourke [1]

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[3] Modeling team leader
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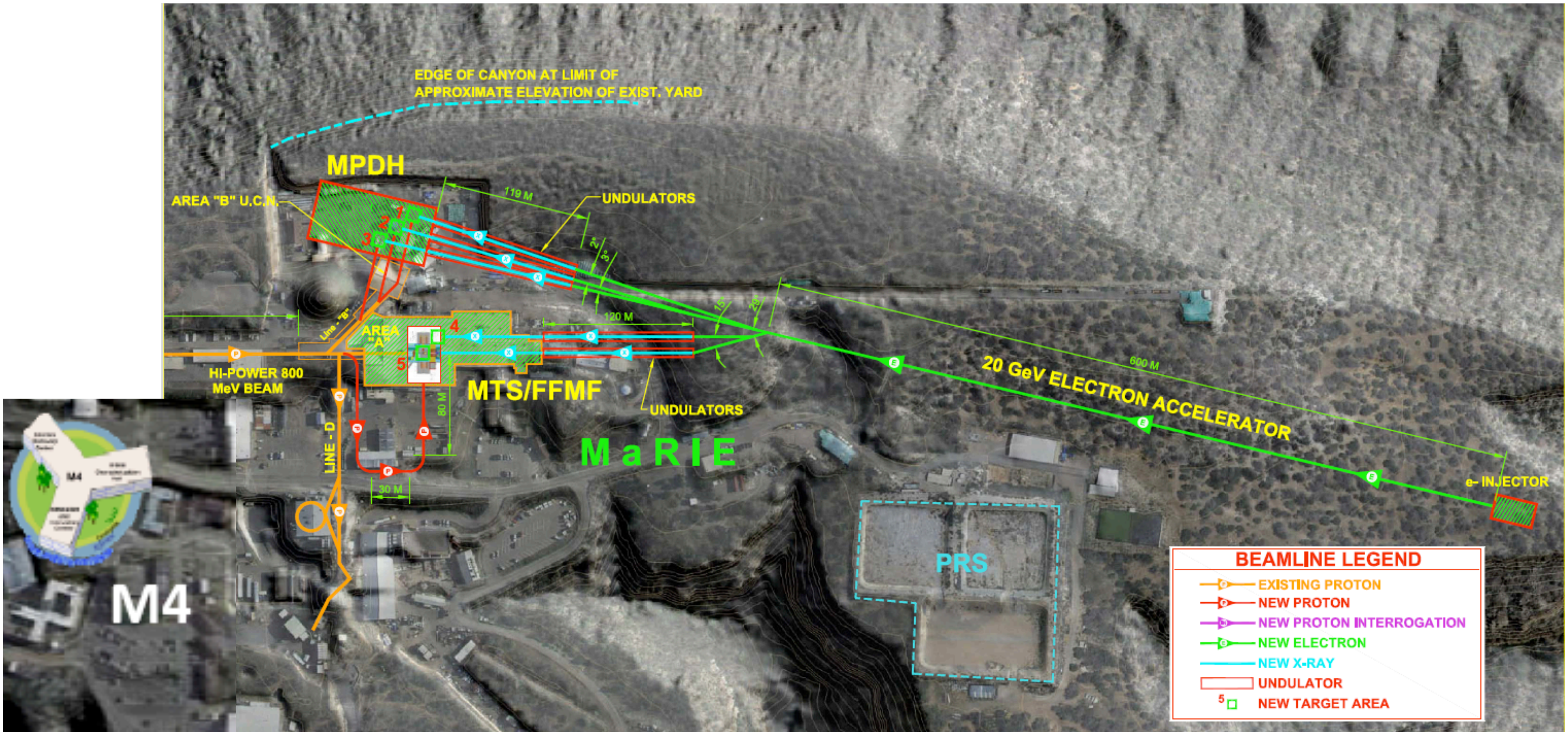
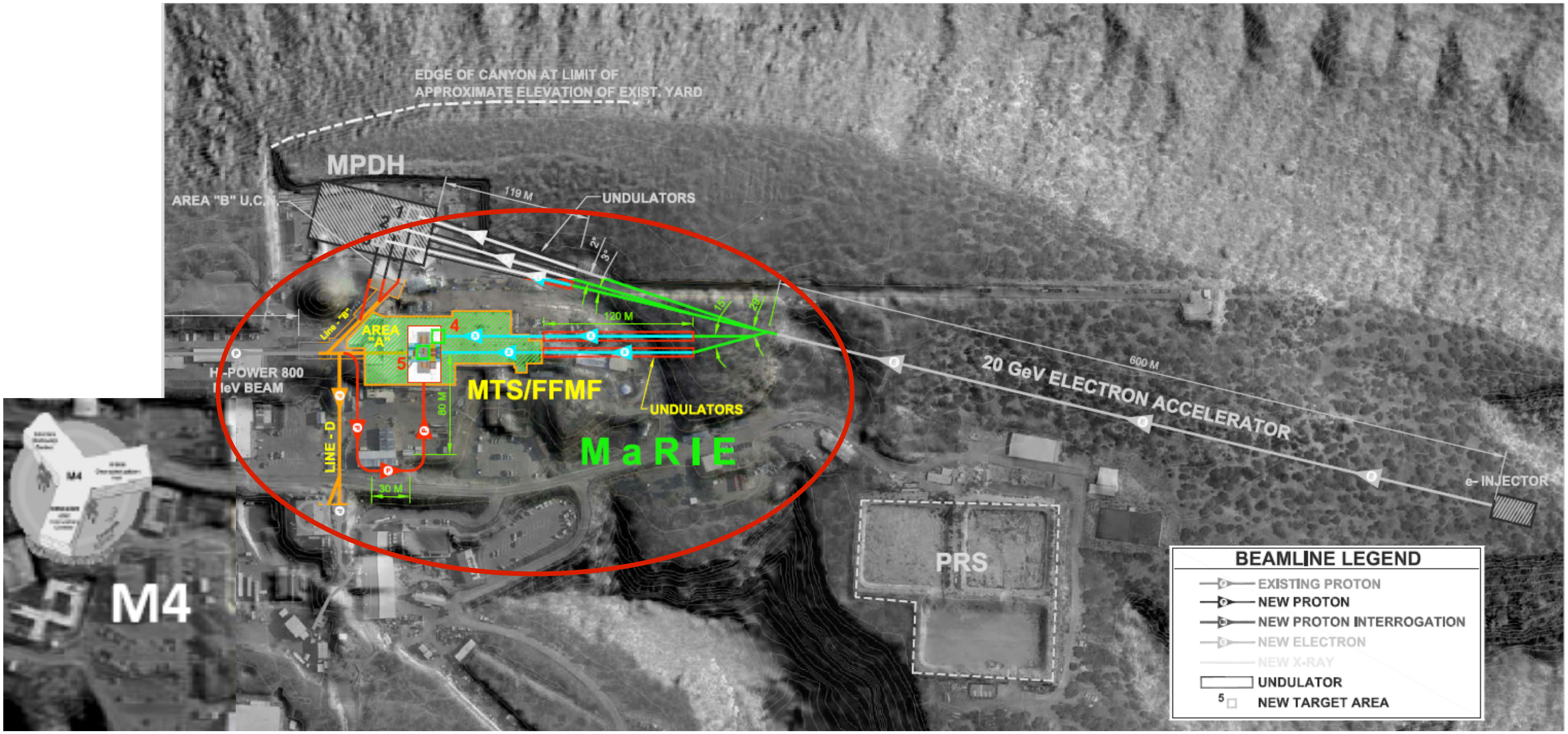
MaRIE – MATTER RADIATION INTERACTIONS (in) EXTREMES



Conceptual layout

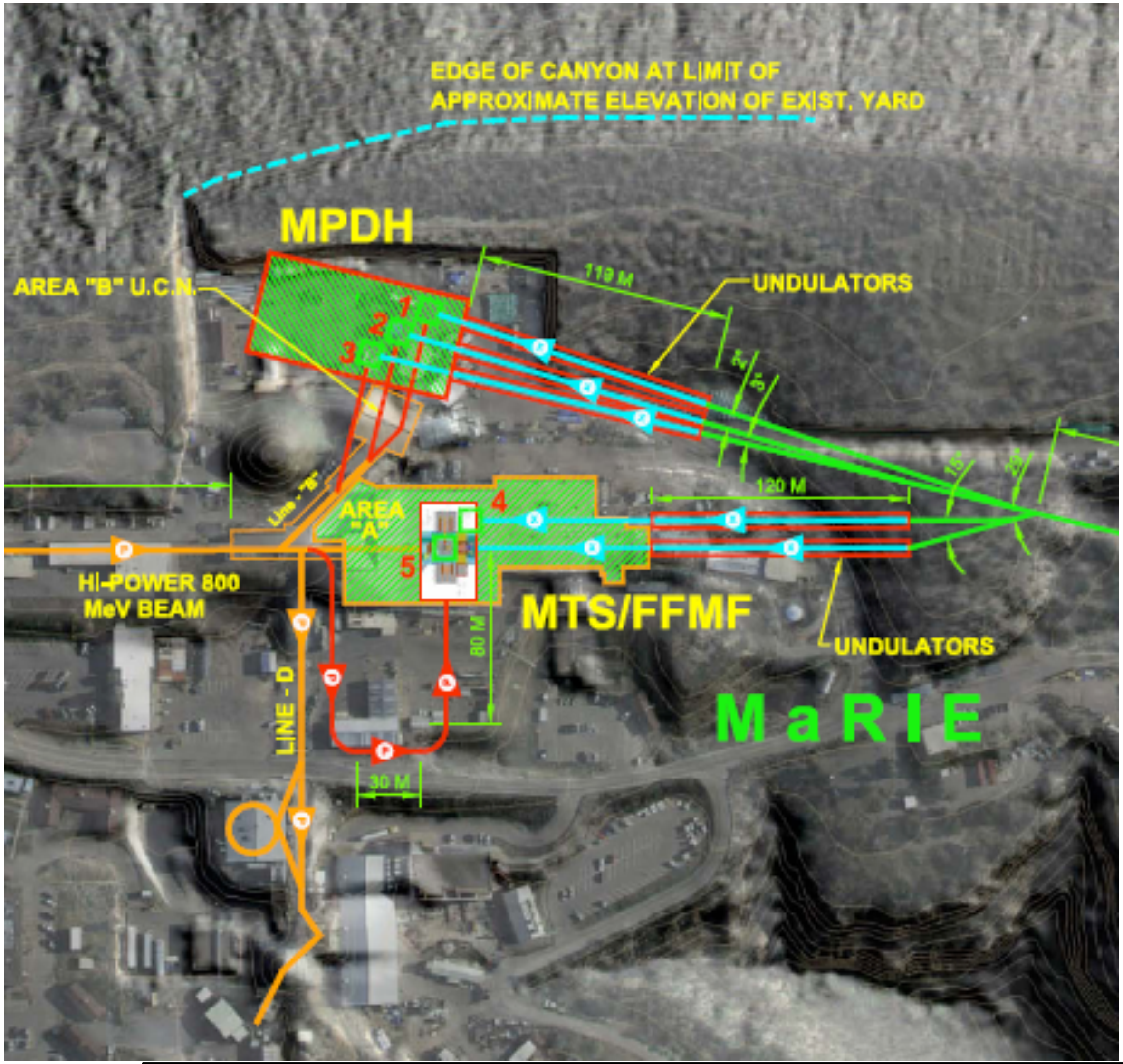
MPDH, FFMF, M4

MaRIE – FFMF FISSION FUSION MATERIALS FACILITY



SYNERGY

MaRIE – FFMF FISSION FUSION MATERIALS FACILITY



Current FFMF Concept:-

- **Materials Test station**
- **Fast neutron spectrum**
- **Long term irradiations**

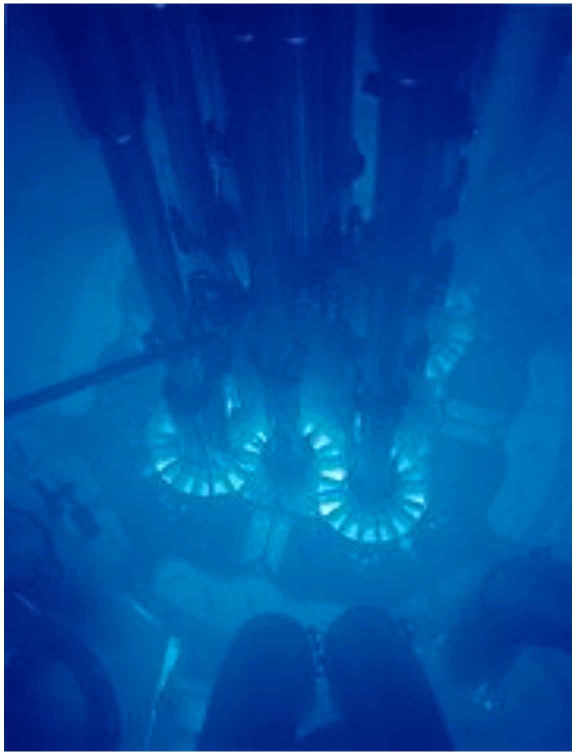
- **2 MW LANSCE (to provide 50 dpa (Fe) / FPY)**
- **In situ X-ray &? probes**
- **Ex situ X-ray & proton probes**
- **Hot cells**

FACILITY UPGRADE AND INVESTMENT GLOSSARY

FACILITY	FUNCTION	CUSTOMER	COST	COMPLETION	STATUS
LANSCE	Multipurpose neutron science center	Multiple	Operational	On – Line	Aging ☺
LANSCE-R	Adds reliability & 20 year lifetime to existing facility	NNSA	$150M	2014 ?	LANL presume s this will happen
Materials Test Station (MTS)	Fast neutron irradiation facility	Office of Nuclear energy	$100M	LANSCE-R completion +1 year?	Depends on national politics
LANSCE Power upgrade	Increases damage rate to , at least, IFMIF levels	Office of fusion energy, ? Office of nuclear energy ?	$150 M	?	MaRIE-FFMF
MTS in situ & ex situ X-ray & proton probes in hot cells	Unique probes of reactor level neutron fluence + state of the art tools for radiological materials	Multiple ?	$100M + Fraction of light source cost	?	MaRIE - FFMF

*** All costs +- $50M , All information subject to politics**

Why now? Prevailing materials discovery paradigm “cook & look”



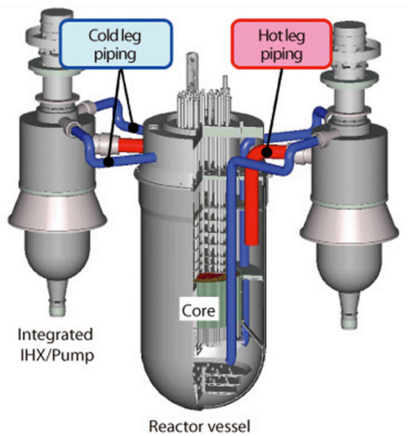
Advanced test reactor

Hot Cells

Why now :- Need for new materials for extreme radiation applications

LWR life extensions

Dose ↑



New fast reactors

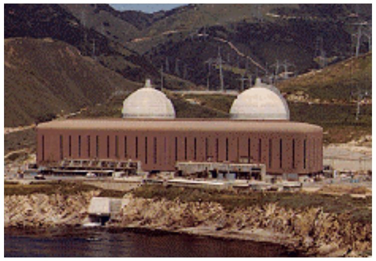
Dose ↑ He ↑ Temp ↑ Burn-up ↑

Fusion reactor

Dose ↑↑ H, He ↑↑ Temp. ↑↑

Why now? Time is right

600 US coal plants



104 US nuclear plants

DOE Energy Innovation Hubs

- **Energy Efficient Building Systems Design** (EERE)
- **Solar Electricity** (EERE)
- **Grid Materials, Devices and Systems** (OE)
- **Carbon Capture and Sequestration** (FE)
- **Extreme Materials** (NE)
- **Modeling and Simulation** (NE)
- **Fuels from Sunlight** (SC)
- **Batteries and Energy Storage** (SC)

Reactor materials challenges & FFMF relevance

STUART A MALOY

Reactor materials challenges & FFMF relevance

Stuart A. Maloy

- **PWR/BWR**
- **Gen IV Reactors**
    - SFR
    - LFR
    - VHTR
    - SCWR
    - MSR
    - FGR
- **Fusion**
- **Experiments with FFMF/MaRiE to address challenges**

Reactor Materials Challenges

- **PWR/BWR**
- **Gen IV Reactors**
  - SFR
  - LFR
  - VHTR
  - SCWR
  - MSR
  - FGR
- **Fusion**
- **Experiments with FFMF/MaRiE to address challenges**

Pressurized water (PWR) & Boiling Water Reactors (BWR)

Reactor Conditions

- Water coolant (~215-330C)
- Thermal spectrum

Materials Issues

Cladding-

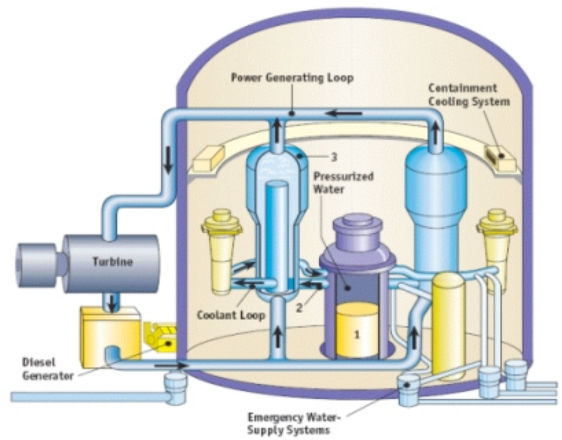
- Pellet clad mechanical interaction
- Fuel clad chemical interaction
- Hydride formation
- Zircaloy corrosion

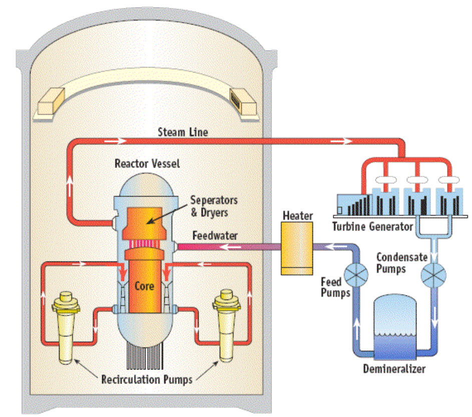
Coolant piping

- Stress Corrosion Cracking
- IASCC

Pressure Vessel

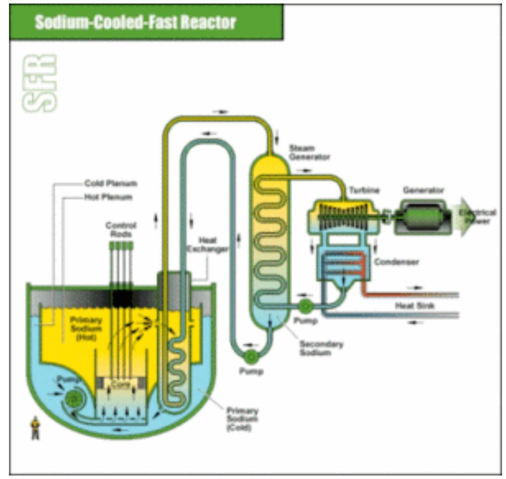
- Aging

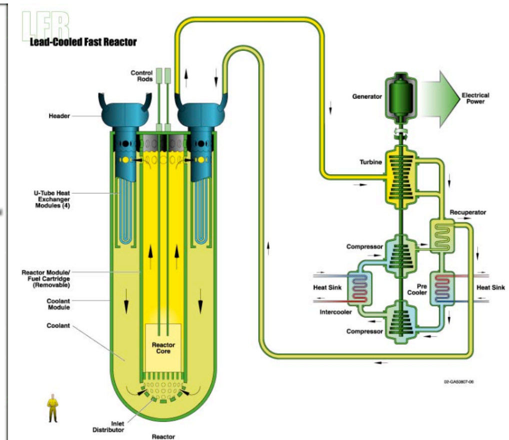




Corrosion in nuclear plant reactor lid

Sodium cooled fast reactor/ Lead Fast Reactor





Reactor Conditions

- Na, Pb or Pb/Bi coolant
- 550C to 800C outlet temperature

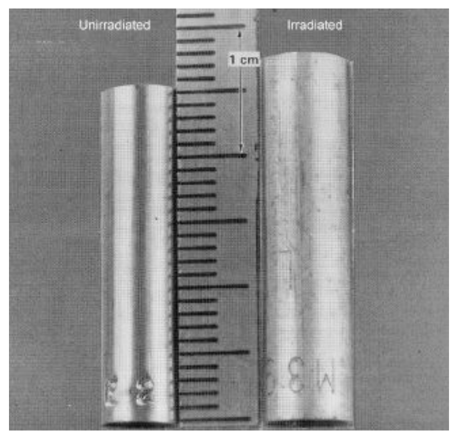
Materials Issues

In Core-

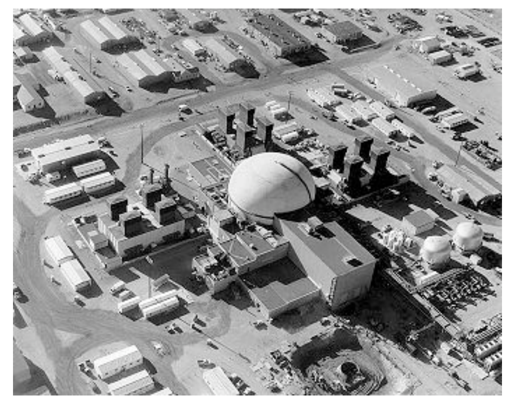
- High dose irradiation effects
- FCCI

Liquid metal corrosion

- Lead corrosion of materials
- Liquid metal embrittlement

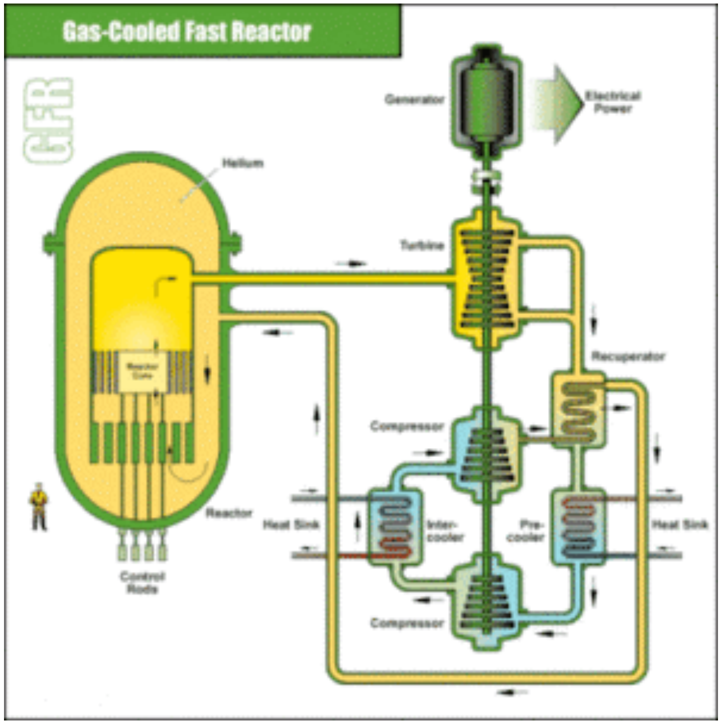


Swelling in 316L SS



FFTF research reactor Hanford (1980-1993)

Gas cooled fast reactor



Reactor Conditions

He or Supercritical CO2 coolant

850C outlet temperature

Several fuel options and core configurations

Materials Issues –

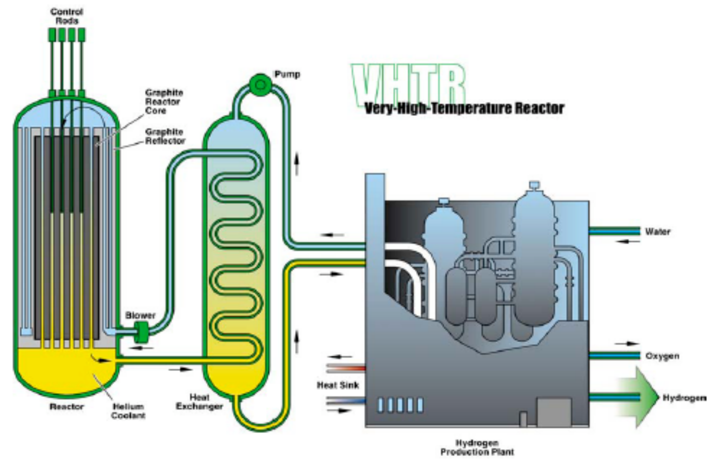
Fuel development (must achieve high-power density and retain fission gases at high burnup and temperature)

- Proposed fuel is a composite ceramic (CERCER) with closely packed and coated actinide carbide kernels or fibers.
- Alternative fuel concepts
  - fuel particles with large kernels and thin coatings and ceramic-clad solid solutions.
  - Nitride compounds, enriched 99.9% in N-15

Very High Temperature Reactor VHTR- NGNP

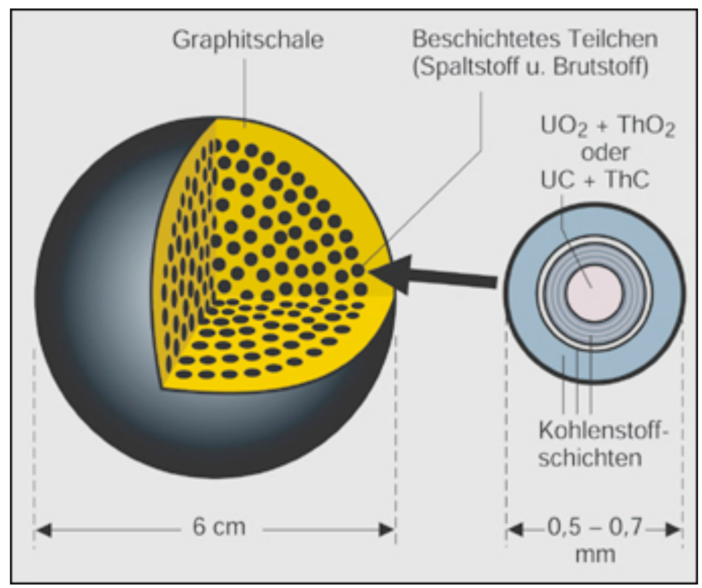
Reactor Conditions

- He coolant
- 1000C outlet temperature
- 600 MWe
- Solid graphite block core



Materials Issues

- Improved metallic materials for VHTR pressure vessels (operating temperature ~450C).
- Improvements in graphite properties (oxidation resistance and structural strength)
- High Temperature Mechanical proerties of coolant piping (e.g. Inconel 617)
- Development of materials for the intermediate heat exchanger



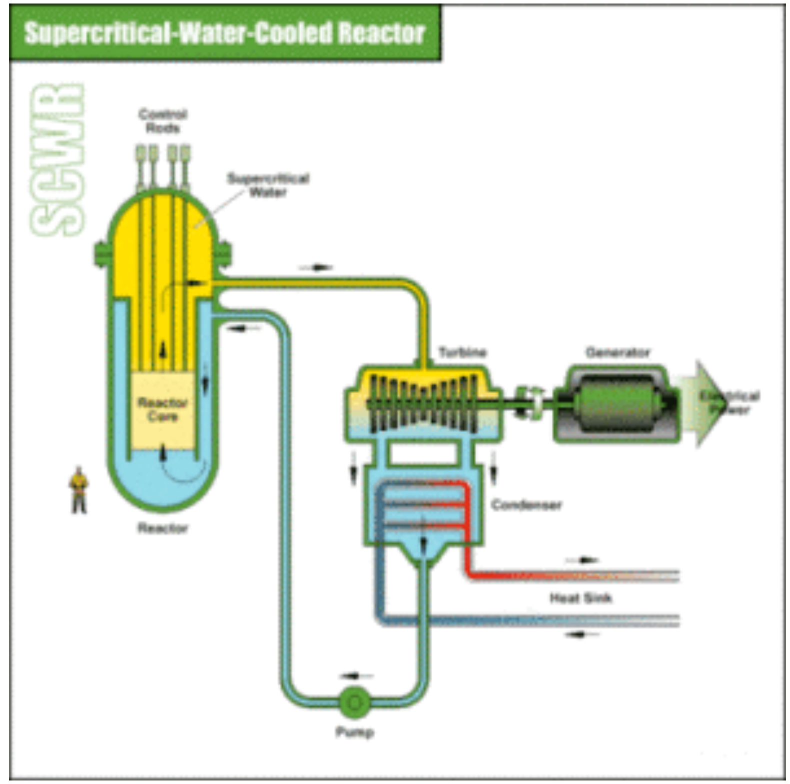
Supercritical Water Reactor

Reactor Conditions

- Supercritical water coolant
- 550C outlet temperature
- 1700 MWe
- >20 Mpa

Materials Issues

- corrosion and stress corrosion cracking,
- radiolysis and water chemistry
- dimensional and microstructural stability and strength,
- embrittlement and creep resistance of fuel cladding and structural materials.
- temperature range of 280–620°C and irradiation damage dose ranges of 10–30 displacements per atom (dpa) (thermal spectrum) and 100–150 dpa (fast spectrum)



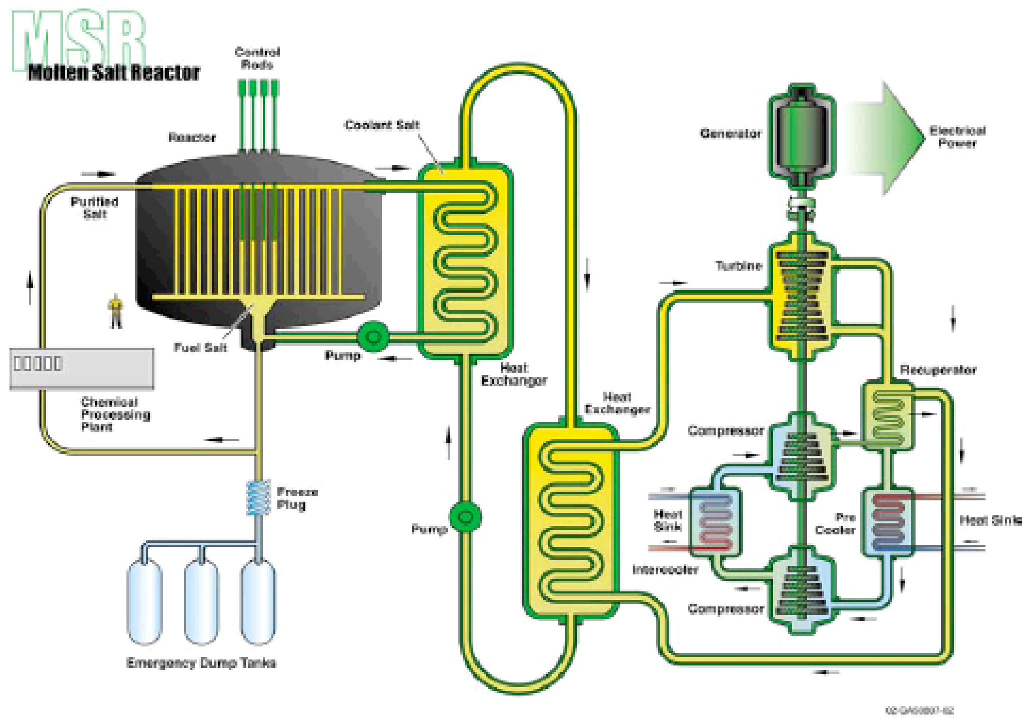
Molten Salt Reactor

Reactor Conditions

- Fuel: liquid Na, Zr, U and Pu fluorides
- 700-800C outlet temperature
- 1000 MWe
- Low pressure (<0.5 MPa)

Materials Issues

- Materials compatibility testing in a controlled chemistry test loop
- Materials compatibility testing in a controlled chemistry test loop under irradiation.



Fusion Reactor

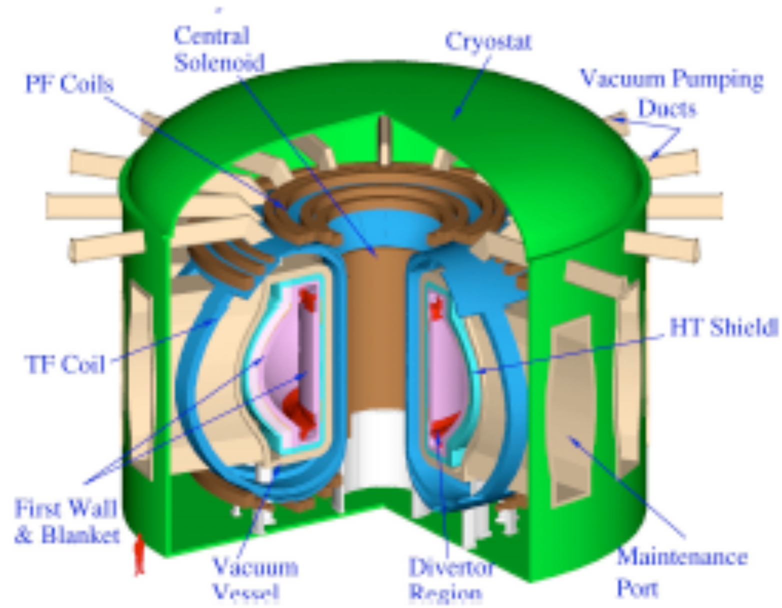
Reactor Conditions

- 14 MeV neutrons
- Total dose 200 dpa
- 10 appm He/dpa
- Steady-state and Transient Heat flux

Materials Issues

- Plasma/Materials Interactions
- Sputtering/erosion
- Tritium deposition
- Energetic ion implantation

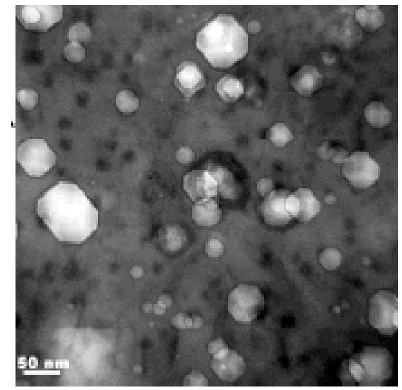
Tokamak fusion reactor:



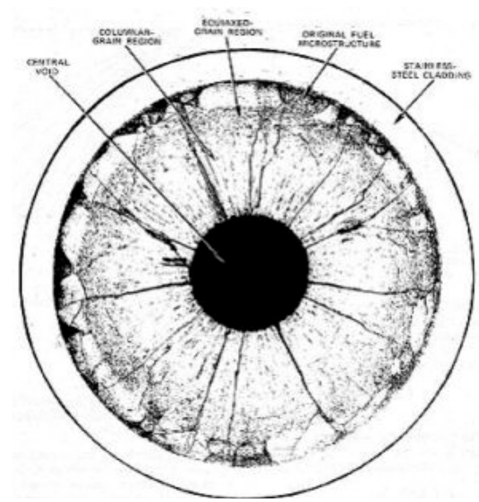
(Kurtz & ARIES)

Experiments with FFMF/MaRiE to address challenges

- **Microstructural Evolution**
  - Void measurements under irradiation
  - Interstitial/vacancy cluster formation under irradiation (in situ resistivity/positron annihilation measurements)
  - Second phase formation under irradiation (e.g. aging of a pressure vessel steel)
  - Monitor intergranular stresses under irradiation
- **Mechanical Properties**
  - Irradiation Creep
  - Irradiation-assisted Crack Growth Measurements
- **Corrosion**
  - In situ corrosion measurements in water
  - In situ corrosion measurements in Pb, LBE or Na
- **Fuels microstructural changes**
  - Formation central void
  - Fuel clad chemical/mechanical interaction
  - Thermal conducitivity measurements under irradiation



Void development in HT-9, 155 dpa



Microstructural Development in an Oxide fuel under fast reactor irradiation

Unique model validation opportunities

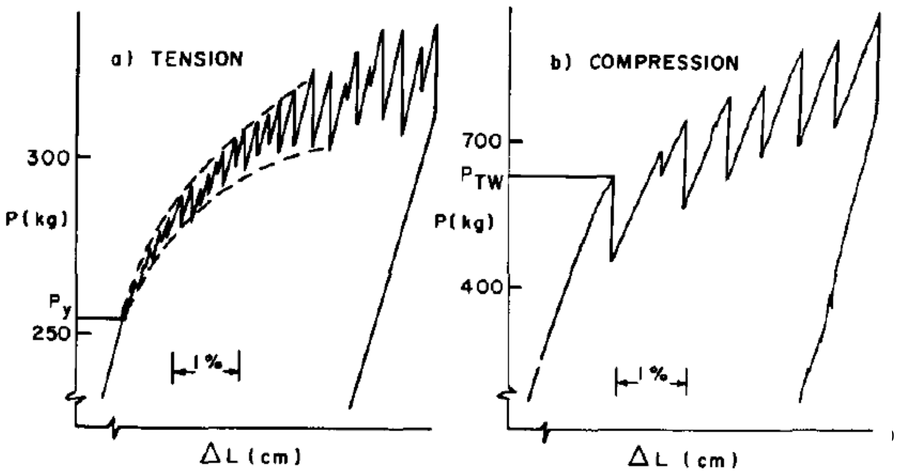
CARLOS TOME

Modeling: future and experimental requirements

Approach
Relate microstructure evolution with macroscopic response

Issue
Characterize microstructure

Measurement Issues
- In-situ
- Reduce measuring times (~ 1 sec)
- Characterize small domains (<1 micron)
- Characterize 3D structures
- Temperature capabilities



Modeling: future and experimental requirements

Areas where modeling can benefit from advanced experimental in-situ characterization

Plastic forming: internal stresses, hardening evolution, phase transformations **(*)**

Creep: primary (transients) and secondary creep **(*)**

Welds: in-situ phase transformations, grain size evolution (recrystallization)

Twinning: nucleation, propagation and growth of twins; associated stress relaxation **(*)**

Cracks: stress concentrations and relaxation mechanisms

Damage evolution: cavity growth vs strain or vs irradiation **(*)**

(*) → polycrystal models currently exist

Fuel channels in nuclear reactors

Reactor components are subjected to neutron flux and temperature conditions.

Under normal or abnormal stress conditions, thermal creep and irradiation creep take place and produce dimensional changes.

Creep is usually detrimental. However, creep can be desirable if it helps to relax stress at stress concentration points, such as crack tips or material flaws.

Mapping local stresses and their evolution with time under irradiation and temperature conditions would help in reactor material design and in safety assessment.

Because primary creep relaxation takes place in short times (minutes), fast diffraction techniques are required for characterization.

Clad Deformation

Importance:

• Deterioration of clad materials is one of the main reasons for replacing the fuel element.

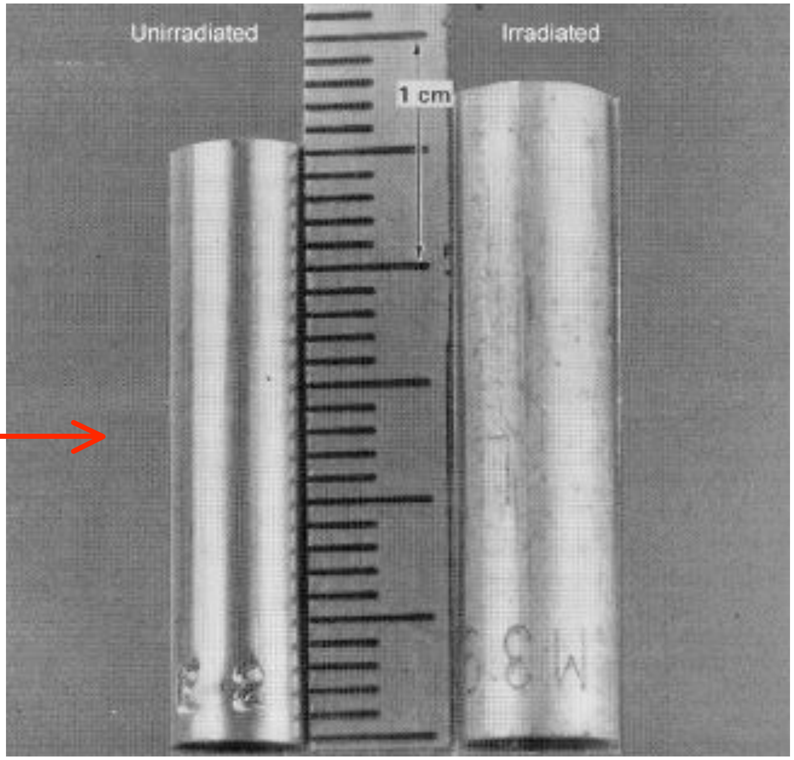
Irradiation effects:

• Clad materials swell under irradiation, occasionally leading to severe deformation and even rupture.

• Chemical constituents (elements, compounds) segregate and/or precipitate, leading to hardening of the cladding.

• Changes in microstructure modify the effective thermal conductivity of the clad, reducing heat transfer.

• Anisotropy of mechanical properties, such as elastic constants, favors stress concentrations.

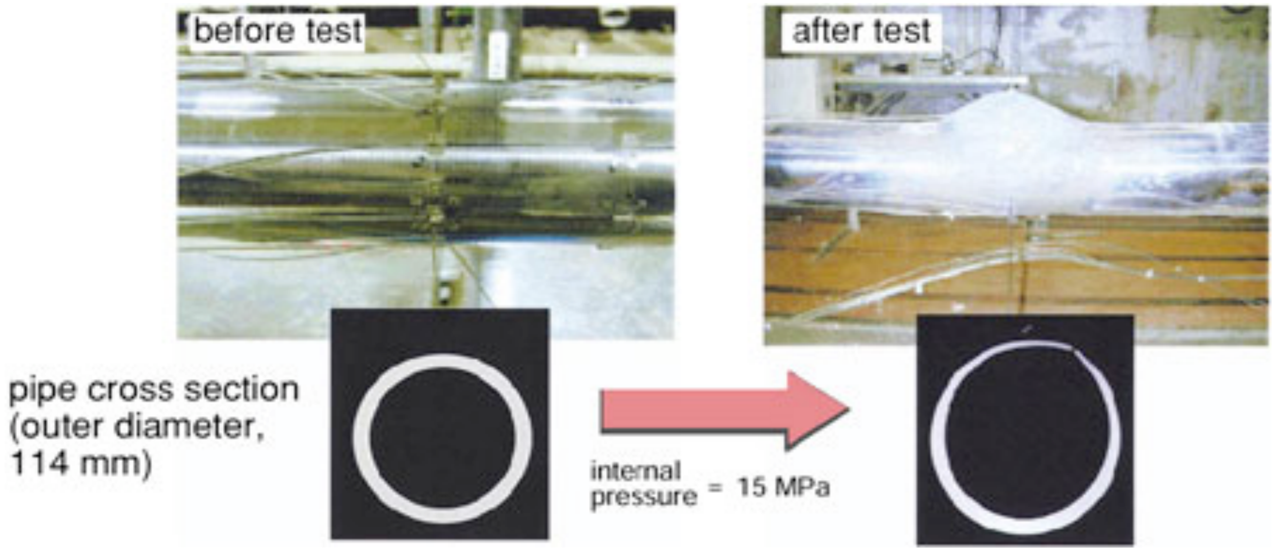


Photograph of 20% cold-worked 316 stainless steel rods before (left) and after (right) irradiation at 533°C to a fluence of 1.5×1023 neutrons m-2 in the EBR-11 reactor.[1]

[1]L. K. Mansur, J. Nucl. Mater., 216 (1994) 97-123.

Creep

Importance:
Creep is the slow deformation of a material under the long term influence of stresses (mechanical or thermal) that are below the yield strength of the material.
Creep can lead to severe deformation and reactor accidents.



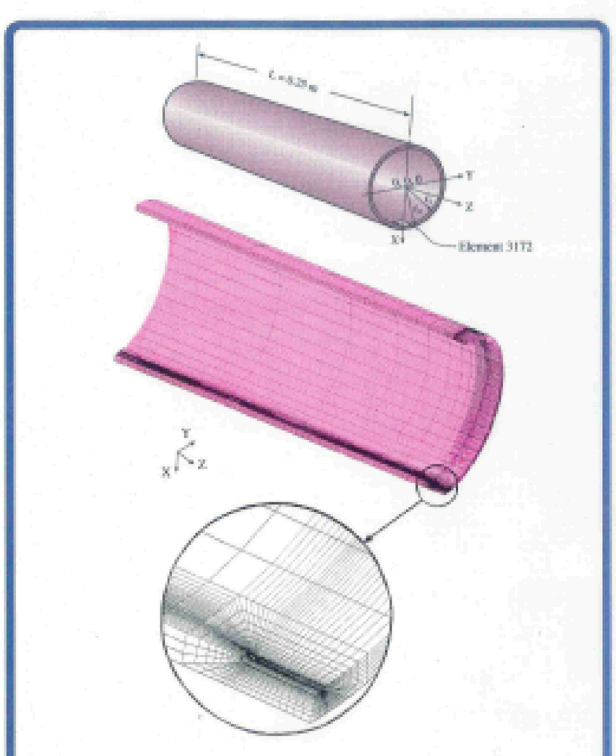
internal pressure, at 1000 ºC[1]

Irradiation Effects:
- In the reactor, thermal creep and irradiation creep produce dimensional changes of the fuel element.
- Anisotropy of mechanical properties, promotes stress concentrations.
- Because primary creep relaxation takes place in short times (minutes), fast diffraction techniques are required for characterization.
- Mapping local stresses and their evolution with time under irradiation and temperature conditions would help in reactor material design and in safety assessment.

[1]E. Chino et al., Creep Failure of Reactor Cooling System Piping of Nuclear Power Plant under Severe Accident Conditions, Proc. of the 7th International Conference on Creep and Fatigue at Elevated Temperatures (CREEP7), Jun. 3-8, 2001, Tsukuba, Japan, 107 (2001).

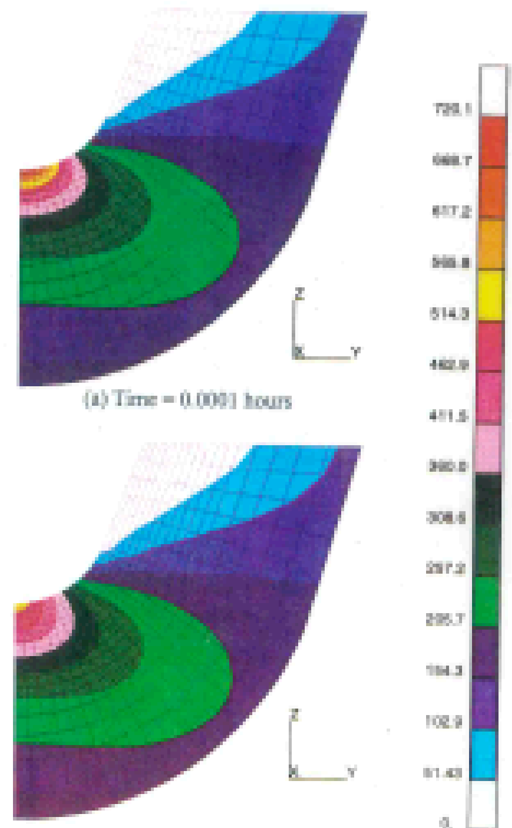
Stress relaxation by creep at flaw in Zr-Nb (HCP) pressure tube

FE model: each element is an aggregate represented by 109 orientations.



Pressure Tube Fret Flaw Finite Element Model

Ontario Hydro



(a) Time = 0.0001 hours

(b) Time = 5000 hours

Case G - Hoop Stress Distribution, σ_{22}
Axial Notch Under Circumferential Bending Stress
$\sigma_{yield} = 750\ MPa,\ \sigma_{app} = 700\ MPa$

Stress relaxation by creep at the tip of a notch

Issue: can stresses at a crack tip be relaxed by combined irradiation and thermal creep?

In this particular application for Zr-Nb the stresses where measured by neutron diffraction and modeled for a Compact Tough Specimen

Problem: fast data acquisition required for capturing the stress evolution at the tip of the notch

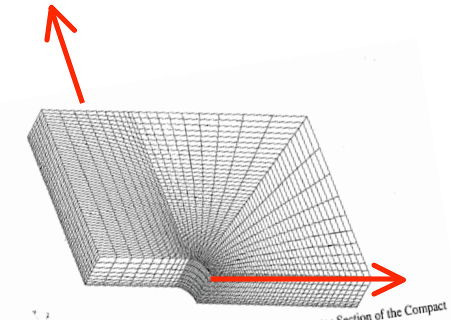


Figure 1. Three Dimensional Finite Element Model of a Quarter-Section of the Compact Toughness Specimen.

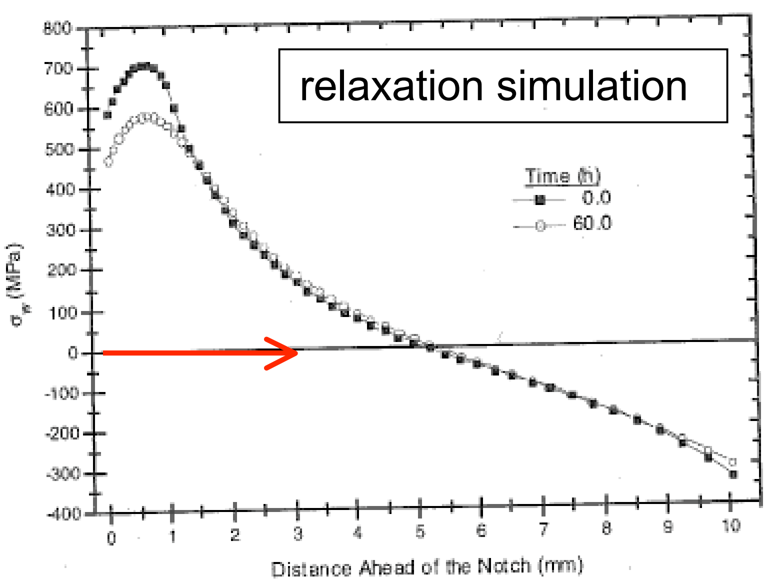


Figure 2. Stress Normal to the XZ Symmetry Plane at 0.0 and 60.0 hours.

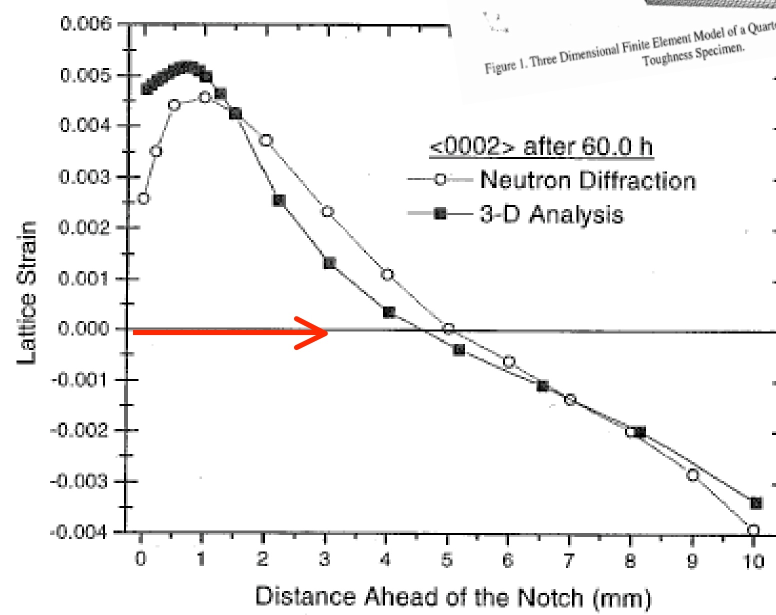
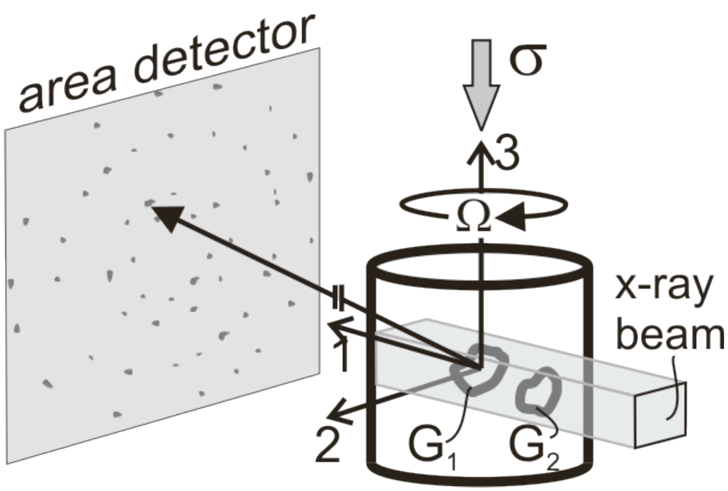


Figure 3. Lattice Strain in the <0002> Direction Measured by Neutron Diffraction Compared to the 3-D EPSC Calculations after 60h.

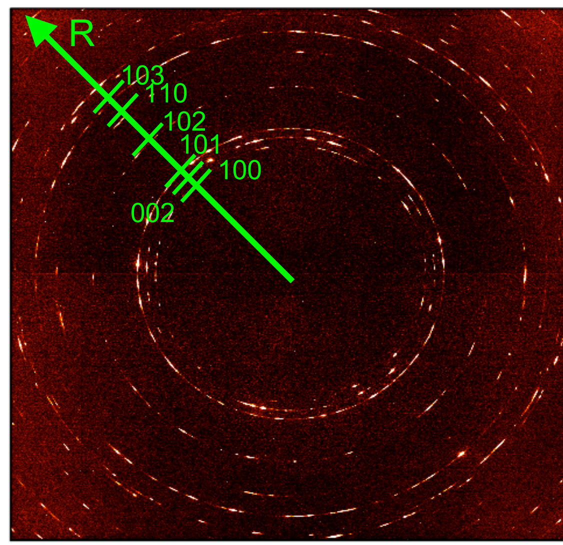
Study of twin-parent-neighborhood interaction by photon diffraction

Goal: Measure stress state in individual grain and twin as a function of strain

Approach: in-situ X-ray diffraction (APS at Argonne) on a Mg polycrystal under compression



Center grain (G_1) in the beam and obtain 100 spot patterns for 100 angular positions of Ω.



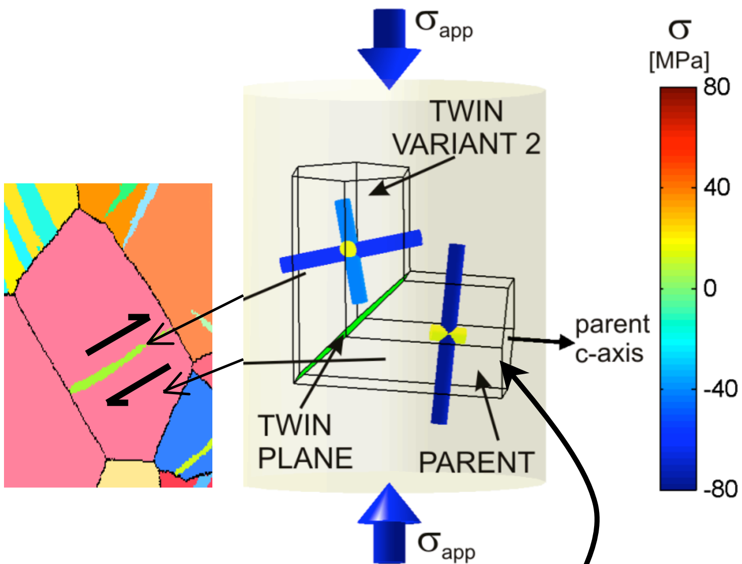
DIFFRACTION PATTERN

Spot pattern: ~50 grains in the beam

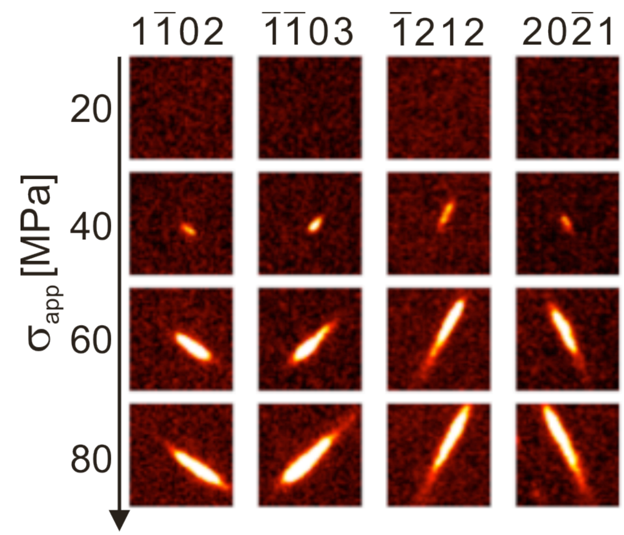
Identify grain: hkl spots give grain orientation and lattice strain

Study of twin-parent-neighborhood interaction by photon diffraction

- Choose parent orientation → calculate spot position of all twin variant orientations.
- If twin spots appear → twin variant starts forming
- Spot intensity increasing → twin volume fraction increases → **quantify !**
- **Combine info of ~25 (hkl) patterns to derive elastic strain tensor in twin and parent !**



Parent is oriented
for twin activation

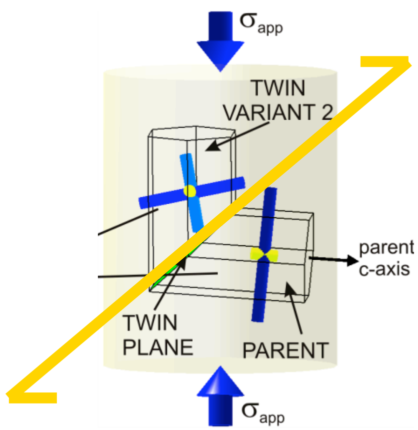


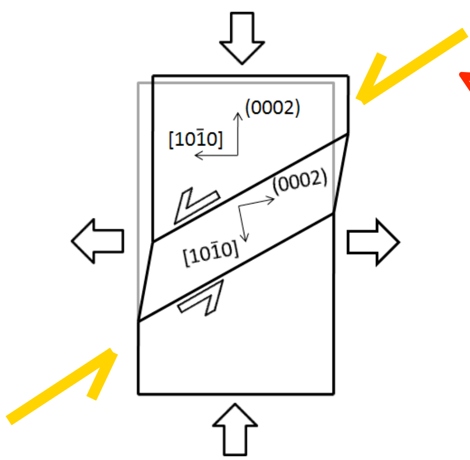
Twin is formed in the 20 to 40 MPa interval.

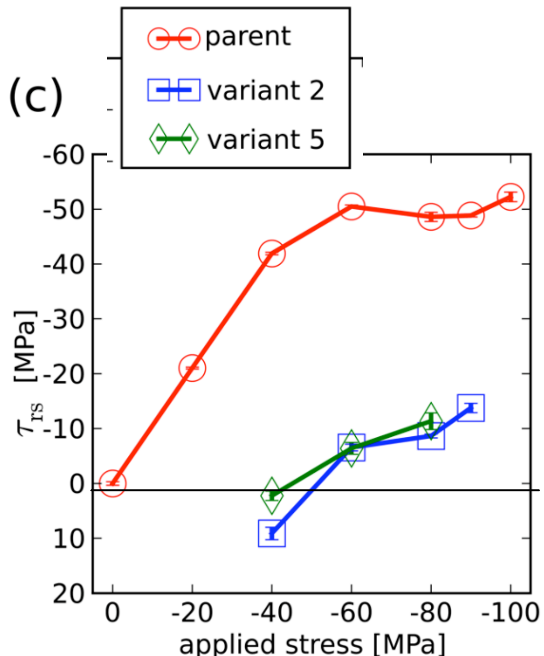
Peak position gives strain in twin.

Study of twin-parent-neighborhood interaction by photon diffraction

Evolution of shear components on twin plane common to parent and twin







Shear stress on twin plane of parent increases with loading until twin appears.

At such point twin activity relaxes parent stress and keeps it steady.

Initial shear in twin has opposite sign, and remains much smaller than the parent shear !

What we see here is the reaction to the twin shear from the surrounding medium !!

Advocating FFMF & defining requirements

JACK SHLACHTER

What is the current status of the Fission Fusion Facility?

Define frontier experiments that are killer apps

Help quantify the requirements for future science

Analyze the technical alternatives

Propose preferred alternatives

Initial ideas exist for each step, but this process is iterative and evolving

Establishing the Mission Need for MaRIE requires a proposal

1.0 Messaging

2.0 Marketing and Sponsorship

3.0 Building the Science Case

4.0 Determining the Proposed Facility

5.0 Integration

Science Frontier Experiments for Fission Fusion Facility (3.0)

To enable frontier experiments in …

Corrosion	Swelling	Structural integrity	Phase Stability	Thermal Transport

May require *in-situ* measurement of ….

Corrosion *Growth rate* *Oxidation rate*	Void / Bubble *Total volume* *Nucleation* *Growth rate & size* *Spatial distribution*	Mech. properties *Creep strength* *Tensile strength* *Residual stress*	Phase *Composition* *Microstructure* Grain *Growth rate & size*	Thermo. properties *Heat capacity* *Conductivity* *Diffusivity*
Layer *Thickness* *Composition* Fuel/cladding *Interaction thickness*	Defects *Number* *Type* *Volume*	Cracks *Size* *Volume* *Shape*	Fission Product *Distribution* *Segregation* *Accumulation*	Temperature *Distributions*

Building the Science Case for measurement in extreme radiation environment

• Corrosion	Gordon Jarvinen
• Swelling	Turab Lookman
• Strength and Structural Integrity	Stu Maloy
• Phase Stability	Mike Nastasi
• Thermal transport	Marius Stan

Deliverables for each:- **Problem Statement**

Theory, Modeling, & Simulation Requirements Statement

Solution Impact Statement

Identify User Community

Outreach

Inreach

Scientific Functional Requirements

User Team Creation

First Experiments Document

Functional requirements for diagnostic measurements (3.0)

	Spatial resolution	Temporal resolution
Temperature	**0.1mm** Internal profiles	**10^{-3} seconds**
Macroscopic dimensions	**0.1 mm** Macroscopic swelling	**1 second**
Force (stress)	**10 μm** loading / spatially resolved	**10^{-3} seconds to days** strength/fatigue/creep / relaxation
Displacement (strain)	**1 μm** loading / spatially resolved	**10^{-3} seconds to days** strength / fatigue /creep / relaxation
Cracks	**0.1 to 1000 μm** nucleation– growth- existence	**10^{-3} seconds to days** nucleation – growth - existence
Phase composition	**0.1 to 1000 μm** grains– corrosion- composition	**10^{-9} seconds to seconds** segregation – solid solid - corrosion
Bubbles / Voids	**0.5 nm to 1000 nm** nucleation– coalescence	**10^{-12} seconds to days** nucleation –coalescence
Defects	**0.1 nm to 10 nm** atomistic volume average	**10^{-12} seconds to days**

Establishing the Mission Need for MaRIE requires a proposal

1.0 Messaging

2.0 Marketing and Sponsorship

3.0 Building the Science Case

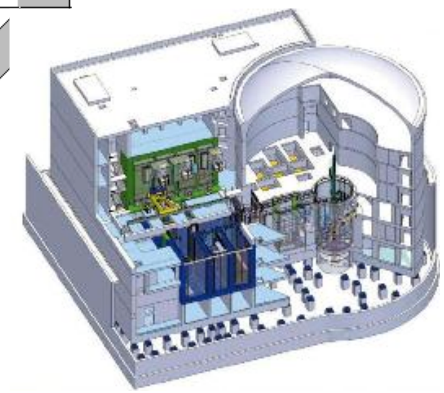
4.0 Determining the Proposed Facility

5.0 Integration

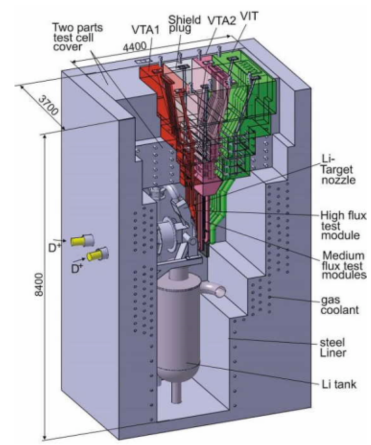
Analysis of future facilities to identify performance gaps (4.0)

REQUIREMENTS MET Green=Yes, Orange=Maybe, Red=No

NEUTRON SOURCE	COUNTRY	POWER	In-Situ Measurement: Temperature	Macroscopic dimensions	Force (stress)	Displacement (strain)	Cracks	Bubbles / Voids	Phase	Defects	Dose Rate & Spectrum: Irradiation Volume	Flux gradient over irradiation volume	Primary recoil spectra	Damage Rate	Fast / thermal neutron flux ratio	Helium to dpa ratio	Facility availability / lifetime
SNS	USA	1.4 MW Spallation source	No Known plans														2008
JPARC	JAPAN	0.6 MW Spallation source	No Known plans														2008
ESS	?	?	?	?	?	?	?	?	?		?	?	?	?	?	?	?
MYRRHA	Belgium	600 MeV - 2.5 mA proton beam to a liquid	No Known plans														2017
IFMIF	TBD	40-MeV, 10-MW d beam on-Li target					No Known plans										?
FDF [1]	TBD	150-250MW Tokamak	?	?	?	?	?	?	?		?	?	?	?	?	?	?
Concepts [2]	TBD	TBD	?	?	?	?	?	?	?		?	?	?	?	?	?	?
J. Horowicz	FRANCE	100MW Thermal research reactor															
Fast reactor	France / Japan ?	?	?	?	?	?					?	?	?	?	?	?	?
MaRIE-FFMF	USA	1.8 MW Spallation source (0.8 GeV)								?							



Jules Horowitz Reactor (100 MWt LWR) at Cadarache



IFMIF

[1] Fusion development facility , after R.D Stambaugh ; ReNeW Mtg UCLA 2009

[2] e.g. Gas dynamic trap D-T neutron source , after Simenon ; ReNeW Mtg UCLA 2009

Determining the Proposed Facility (4.0)

• Diagnostic probe beams and techniques	[Don Brown]
• Irradiation environment	Eric Pitcher
• Detectors	[TBD]

Deliverables for each:

- Facility Functional Requirements
- Current Facility Options
- Performance Gaps
- Technical Specifications
- Technical Options
- Technological Community Outreach
- Technological Community Inreach
- Cost-Risk-Benefit Analysis

What are intermediate steps to MaRIE?

BEYOND ESS, DEMO, CTF, New Fast reactor

DECADE [IFMIF]

3-5 YEARS MTS, SNS ?

Lab-scal

LS , EuroXFEL,

ADSPEC ?

1-2 YEARS JOYO

US Tri

eam f

PRESENT HFIR, ATR, BOR-60

JaN

Lab-scale

PS, ESRF,

LAB SPRING 8

PAST PHENIX

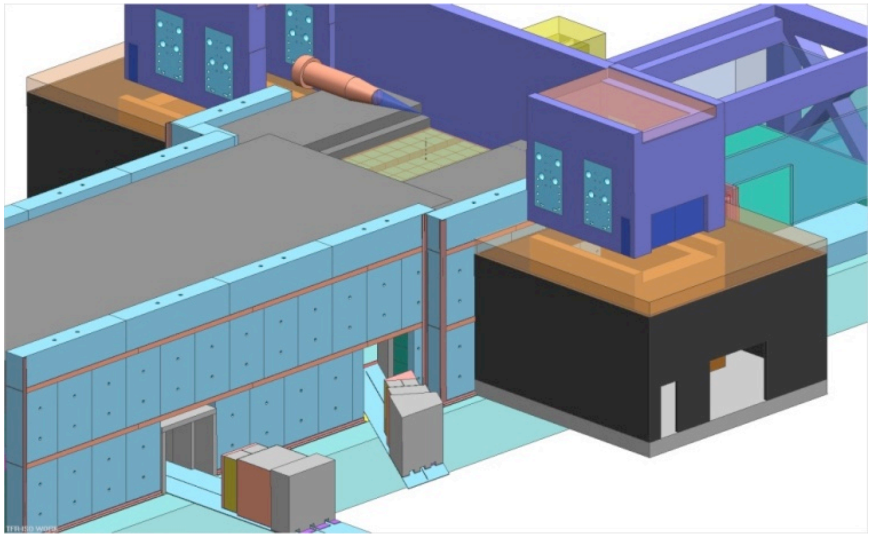
e.g. Ion beam facility at a synchrotron X-ray source?

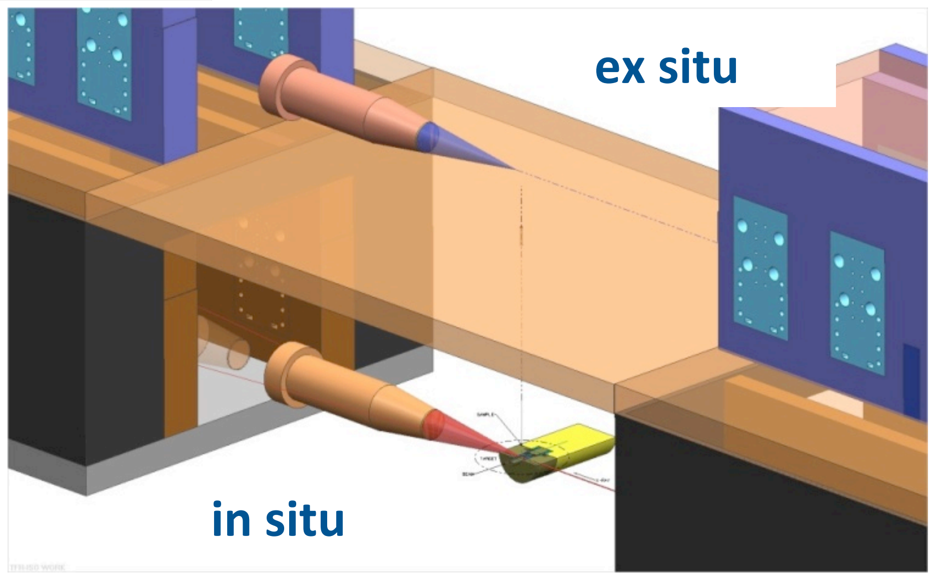
e.g. Measure highly radioactive samples at a neutron or X-ray source?

First Experiments and Open questions

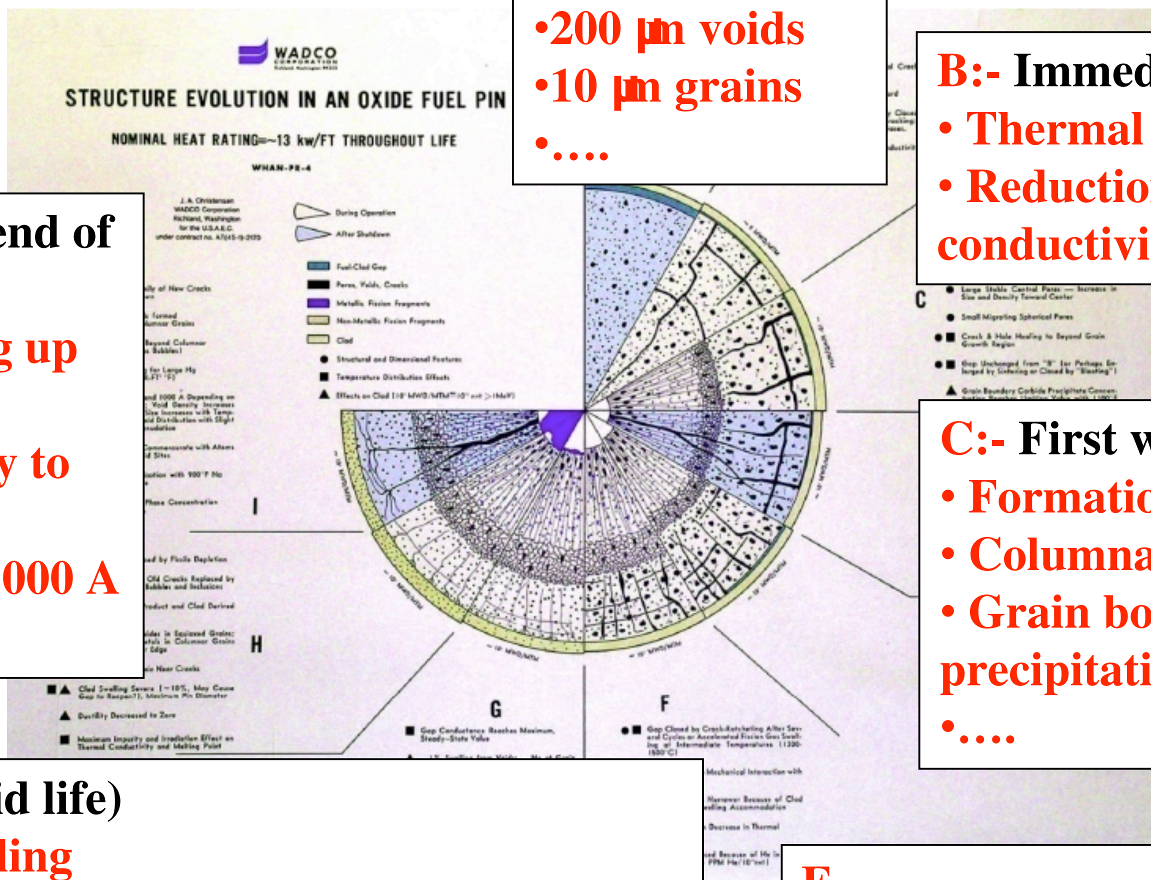
MARK BOURKE

MaRIE FFMF – conceptual layout





First Experiments – Monitor the Structure evolution of an oxide fuel pin



A:- Pre-start-up

- 200 µm voids
- 10 µm grains
- ….

B:- Immediately on start-up

- Thermal shock cracks
- Reduction in thermal conductivity

C:- First weeks

- Formation of central void
- Columnar grain growth
- Grain boundary carbide precipitation
- ….

F

- Ductility decrease due to grain boundary He ($T>T_m$)
- ….

G:- 5 years (mid life)

- 1% Void swelling
- Recrystallization
- Clad derived inclusions
- Ductility decrease (He at grain boundaries)
- ….

H:- 10 Years (end of life

- Clad swelling up to 10%
- Clad ductility to zero
- Voids 75 to 1000 A
- ….

First experiments – e.g. monitor intergranular stress during a load test

e.g. Hasylab; X-Ray diffraction ; 1mm thick TiAl ; 100KeV ; 7m sample to detector

SEVIER Nuclear Instruments and Methods in Physics Research B 200 (2003) 315–322

www.elsevier.com/locate/nin

Internal stress measurements by high-energy synchrotron X-ray diffraction at increased specimen-detector distance

J. Böhm [a], A. Wanner [a,*], R. Kampmann [b], H. Franz [c], K.-D. Liss [b], A. Schreyer [b], H. Clemens [b]

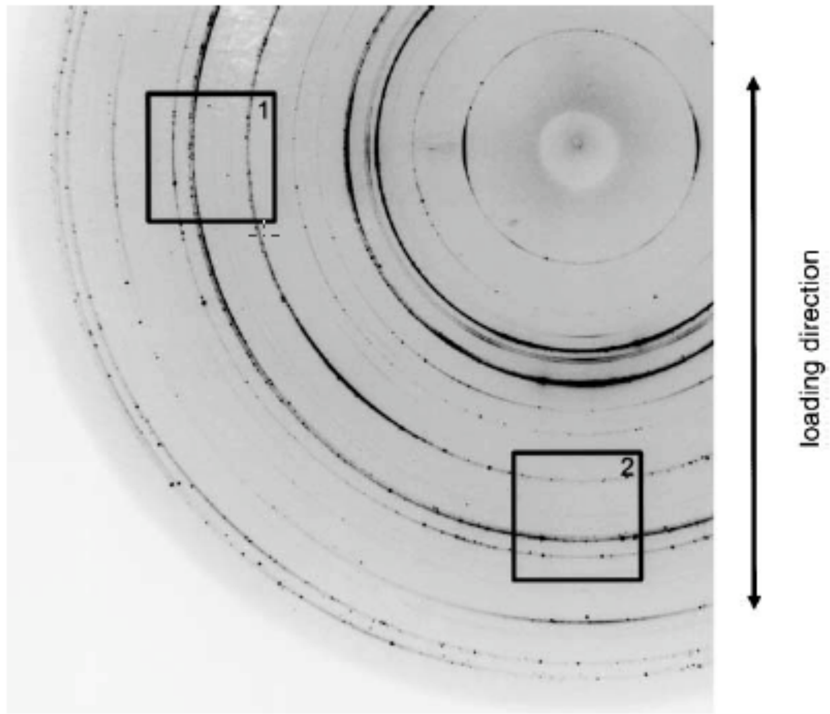


Fig. 3. Part of a typical diffraction pattern of the γ-TiAl-based alloy, recorded by the image plate detector at beamline BW5. A closeup of area "2" is shown in Fig. 4(a).

First experiments – e.g. monitor cavitation development

e.g. ESRF; X-Ray tomography ; Cu 40Zn 2Pb; 2mm^3 ; 80KeV; Voxel 2*2*2 µm

In situ 3D quantification of the evolution of creep cavity size, shape, and spatial orientation using synchrotron X-ray tomography

A. Isaac[a,*], F. Sket[a], W. Reimers[b], B. Camin[b], G. Sauthoff[a], A.R. Pyzalla[a]

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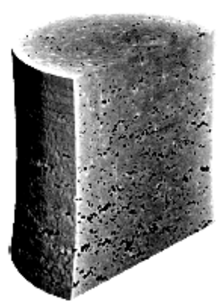
[b] Technische Universität Berlin, Ernst-Reuter-Platz 1, 10587 Berlin, Germany

Received 28 February 2007; received in revised form 21 May 2007; accepted 22 May 2007



(e)

Fig. 5. Tomography revealing the cavities in the initial condition and at diff
361 min. (e) 389 min and (f) 440 min.

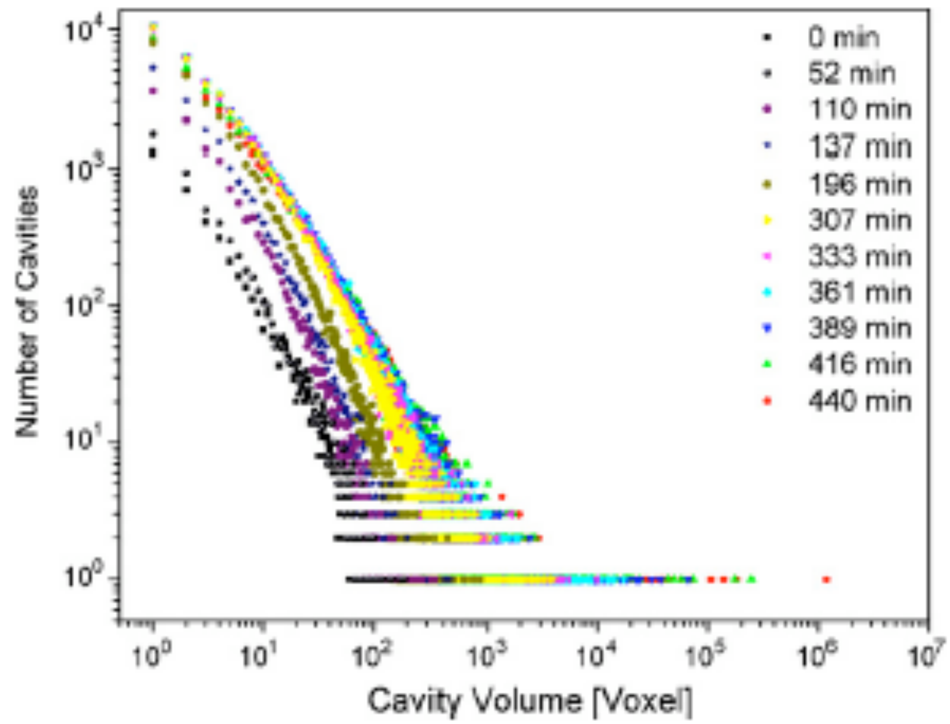


Fig. 10. Cavity size histograms at different creep times.

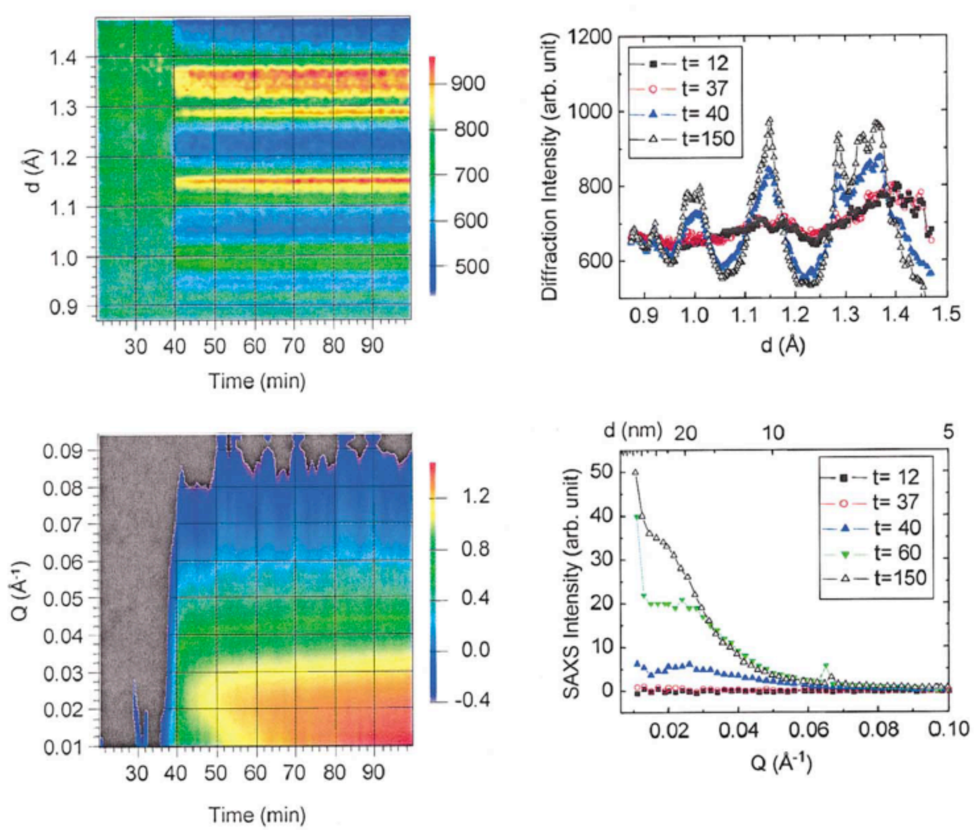
First experiments – e.g. simultaneous diffraction and small angle scattering

e.g. APS; Simultaneous diffraction & SAX; BMG; 77KeV; 1 mm thick; 30 sec resolution

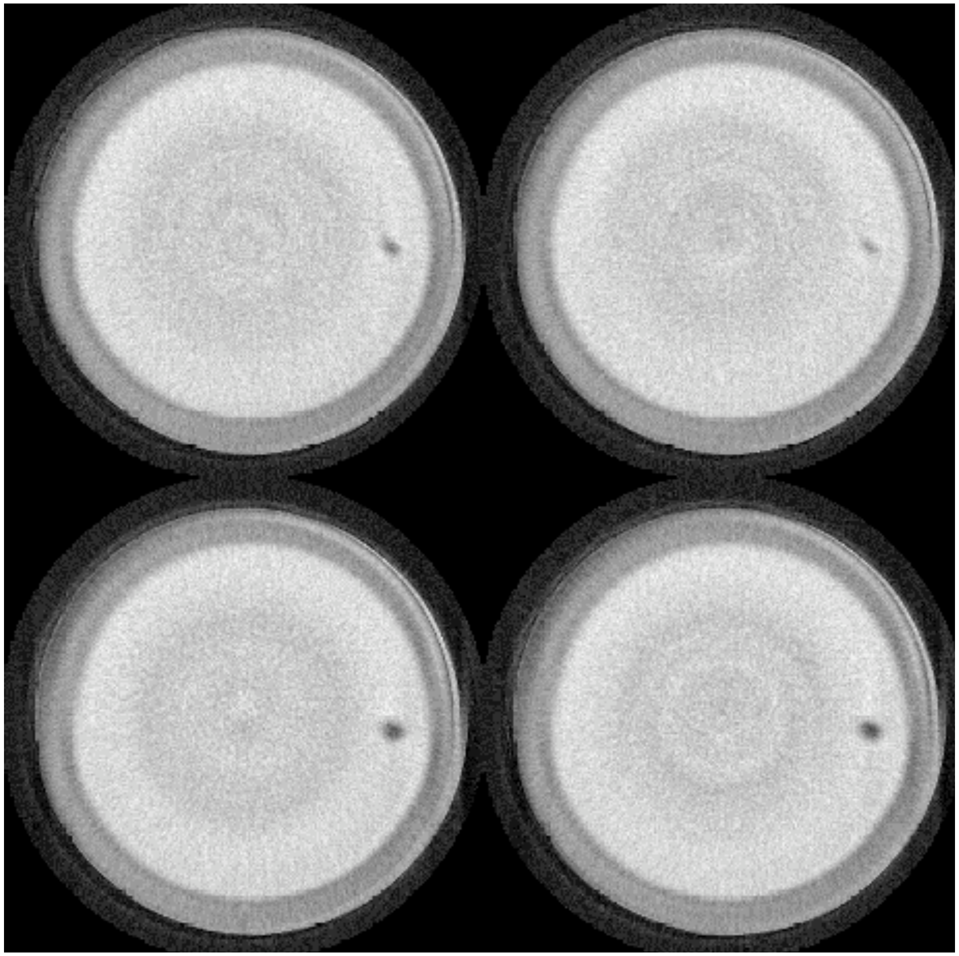
VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

In situ Synchrotron Study of Phase Transformation Behaviors in Bulk Metallic Glass by Simultaneous Diffraction and Small Angle Scattering

X.-L. Wang,[1,2] J. Almer,[3] C. T. Liu,[2] Y. D. Wang,[1] J. K. Zhao,[1] A. D. Stoica,[1] D. R. Haeffner,[3] and W. H. Wang[4]
[1]*Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA*
[2]*Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tenness…*
[3]*Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 604…*
[4]*Institute of Physics, Chinese Academy of Sciences, Beijing 100080, People's Repub…*
(Received 30 June 2003; published 23 December 2003)

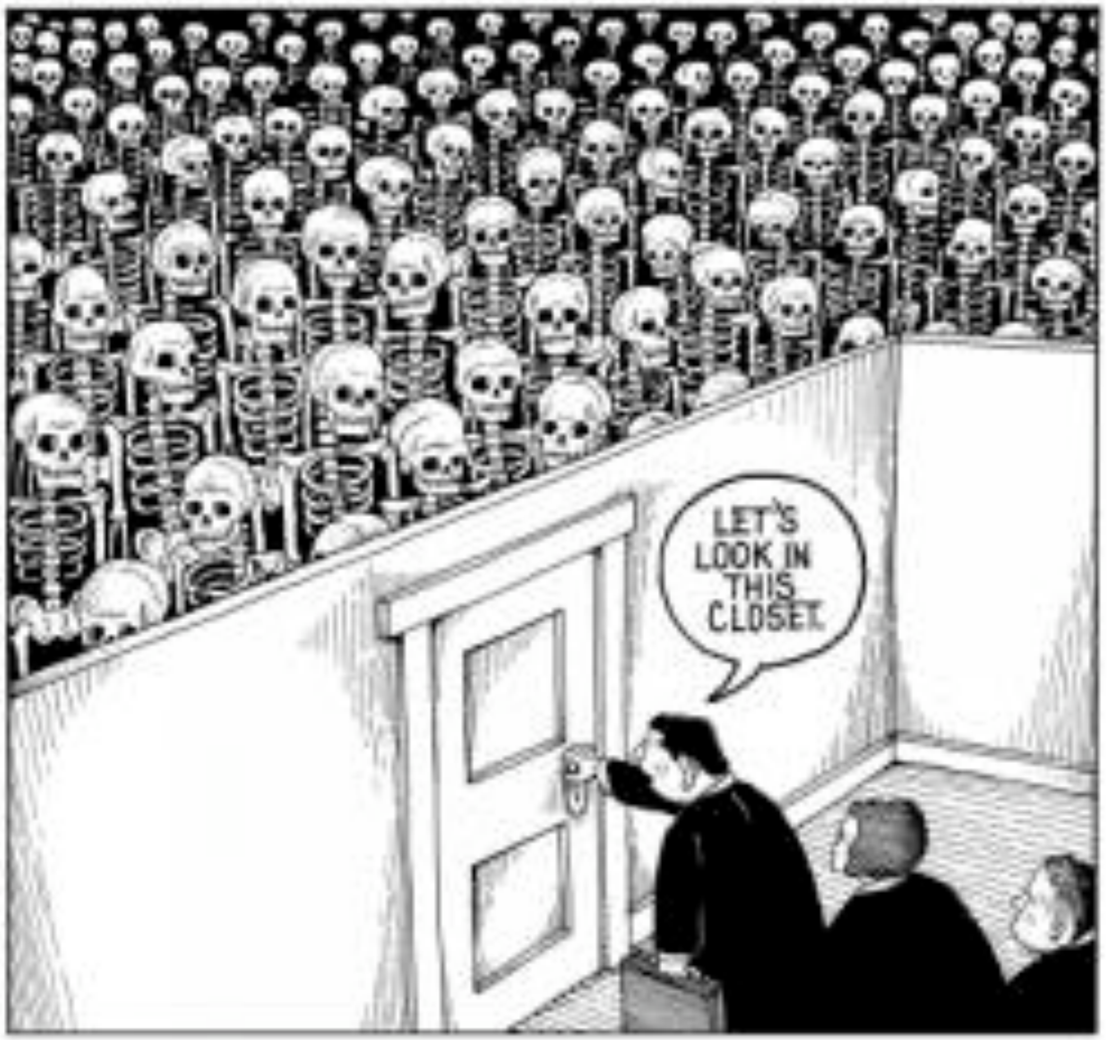


MaRIE FFMF …. Open question – how far can we take proton radiography ?



e.g. Proton radiography of haffnia surrogate fuel pellets

More Open questions



Detector operation

Spectral effects

Pulsed effects

PIE vs In situ

Ion beam irradiation

Can we use the time structure

Character of FFMF light source

LANSCE power upgrade

Workshops on the Road to 12/09

- Jan 20-22, 2009 "Research Frontiers and Capability Gaps for Controlling and Designing Functional Materials
- **July 29-31, 2009 "Structural Stability of Materials Under Extreme Conditions"**
- **Sept 21-22, 2009 "Opportunities for studies of activated samples at national user facilities"**
- **Sept 23-25, 2009 "21st Century Needs in Compression Science"**

• Culminating in12/09 workshop on "Decadal Challenges for Predicting and Controlling Materials Performance in Extremes"
• Outcomes to be documented in a publically available workshop report

Making the MaRIE FFMF case - YOUR HELP NEEDED!!!

Identify the “Killer Apps

Feasibility
- Demonstrate which scattering techniques feasible
- Demonstrate detector viability
- Assess relative merits of proton , X-ray (electron) radiography
- Merits of “phasing” to improve signal to noise

Portfolio
- Establish energies and beam characteristics for proposed suite of tools
- Identify complementary ion, photon, and proton irradiation opportunities

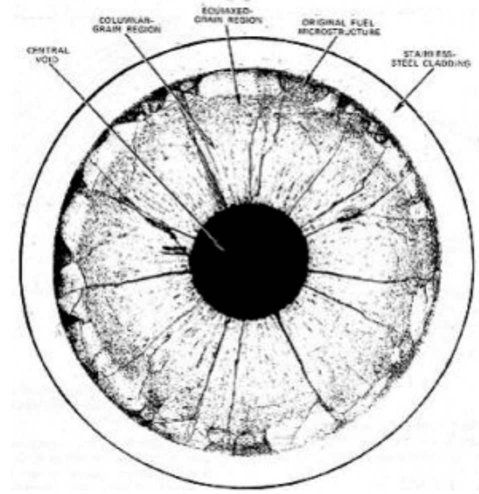
Unique opportunities
- Assess value of pico second interrogation used in conjunction with neutron pulses as a potential tool to examine defects

National context & alternatives
- Assess merits of accelerator upgrade paths to 50 dpa/fpy

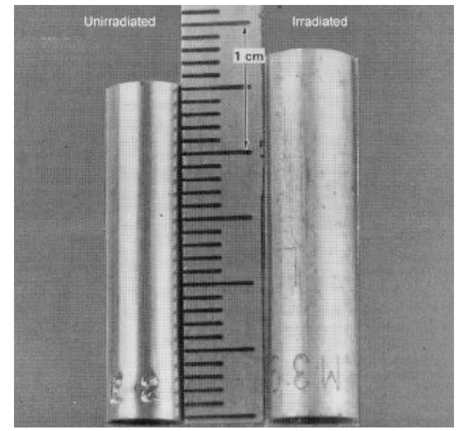
BACKUPS

Radiation damage effects

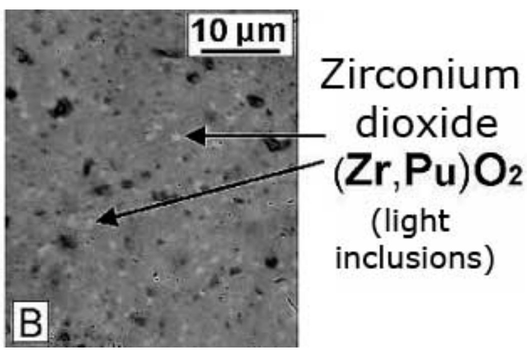
Corrosion in nuclear plant reactor lid



Cracks in nuclear fuel



Steel pre & post irradiation[3]

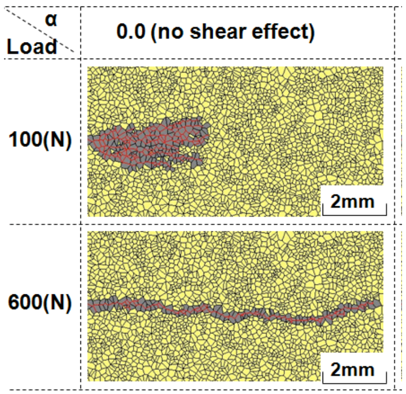


Phase evolution in nuclear waste

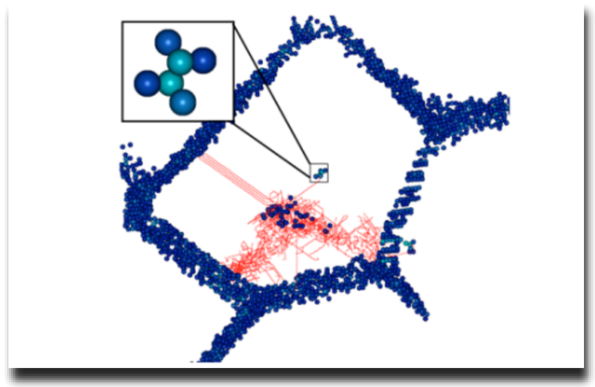
FOREVER-vessel at melt ejection

Science based licensing ….

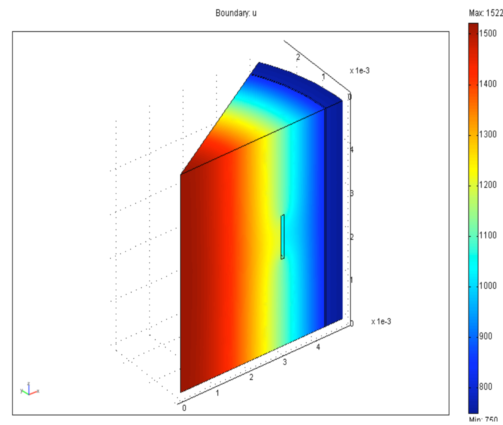
To enable trustworthy modeling and simulation insight…



SCC sim.



M.D. sim. (20 KeV cascade)



FE Temperature sim.

Requires *in-situ* measurement of e.g. …

Corrosion *Growth rate* *Oxidation rate*	Void / Bubble *Total volume* *Nucleation* *Growth rate & size* *Spatial distribution*	Mech. properties *Creep strength* *Tensile strength* *Residual stress*	Phase *Composition* *Microstructure* Grain *Growth rate & size*	Thermo. properties *Heat capacity* *Conductivity* *Diffusivity*
layer *Thickness* *Composition*Fuel cladding *Interaction thickness*	Defects *Number* *Type* *Volume*	Cracks *Size* *Volume* *Shape*	Fission Product *Distribution* *Segregation* *Accumulation*	Temperature *Distributions*

The MaRIE FFMF opportunity ……

Materials test station at LANSCE can produce neutron fluence and spectral characteristics fast reactor

A free electron laser class light source could probe MTS environment

Complementary proton radiography could characterize samples

… enabling in situ characterization opportunities …

XAFS, XANES Electrochemical impedance spectroscopy	Small angle X-ray scattering Ultrafast X-ray techniques	Radiography & Tomography X, p, e, n Custom load designs	100KeV X-ray diffraction Diffuse scattering	Thermocouples

D) Alternatives analysis Part 1 - **In situ measurements e.g. (4 of 4)**

Technique	Beam Characteristics	Detector	Comment
Tomography	White (Pink) Beam DE/E~10%	Fast CCD camera	• Sample rotation necessary • Positioning accuracy required • 1 cm aperture for beam raster • Sample to detector distance?
Phase and texture evolution	White (Pink) Beam ~50-100Kev	Energy sensitive Ge point detector	• Energy dispersive diffraction • Second detectors
Residual Stress and Temperature.	Monochromatic Beam ~80 KeV	Large Area CCD or Pixel Array Detector	• Angular dispersive diffraction • Second detector • Temperature stability and uniformity important
etc	etc	etc	etc

D) Alternatives analysis Part 1 - **Dose rate & spectrum**

Ion beam

- \+ dpa / time rate
- \- Shallow damage depth
- \- Not neutrons
- \- No fission product production, No gas bubble production (w/single beam)

………

Thermal reactor (spectrum modified)

- \+ ATR & HFIR available now
- • He to dpa ratio limited(well suited for fission)

Spallation source

- \+ Opportunity for innovation
- • He to dpa ratio wide (well suited for fusion)
- \- Accelerator trips and resulting sample temperature excursions

Fast reactor

- \- None currently available in US
- \- He to dpa ratio small (optimal for fission)

Fusion concepts [IFMIF, DTNS, FDF, ….]

- \- Cost / Risk

Spectral effects - Different reactor types (1 of 4)

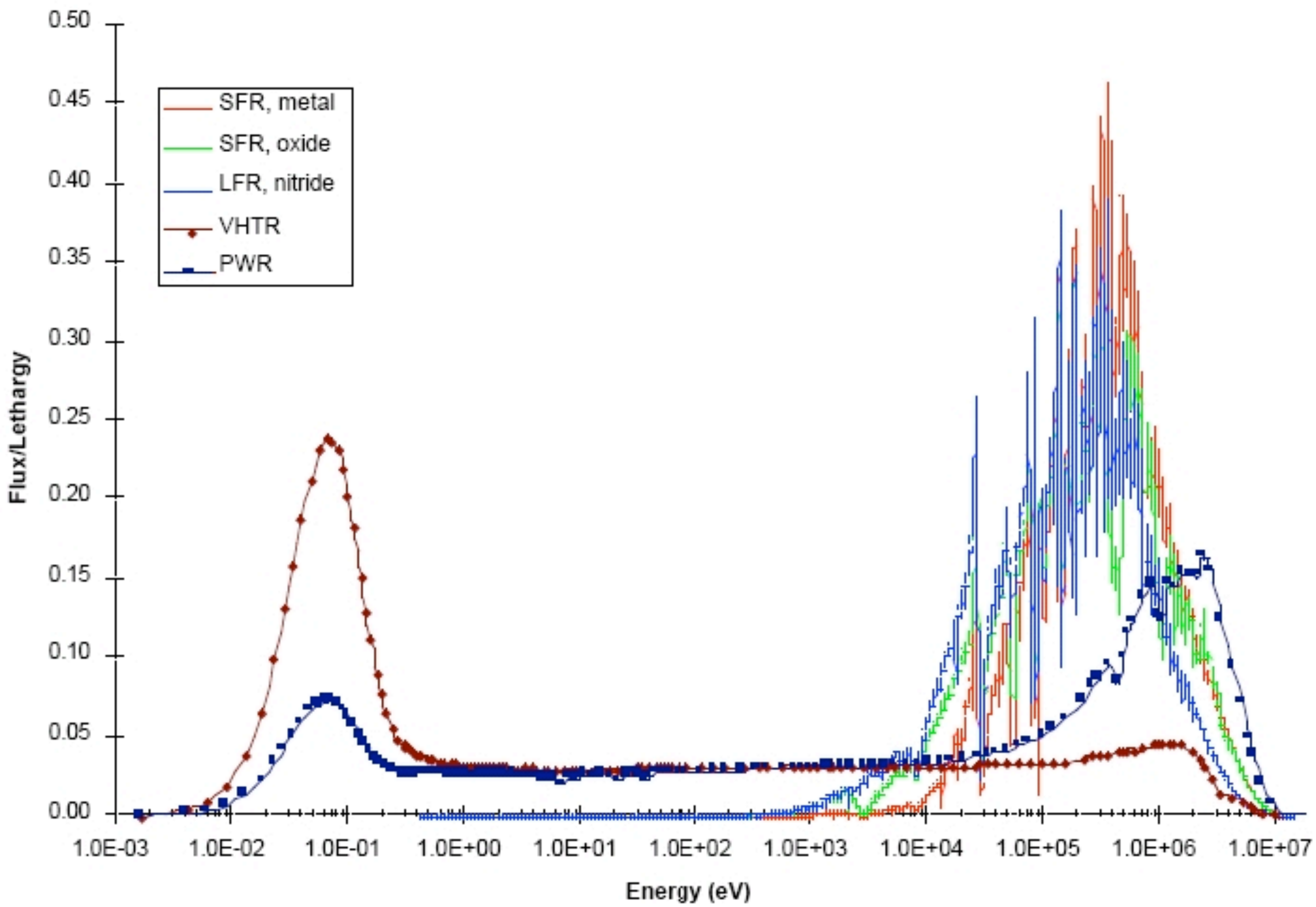


Fig. 1, Neutron Energy Spectrum for Various Reactor Types

Spectral effects - **MTS, IFMIF, ITER spectra – log (3 of 4)**

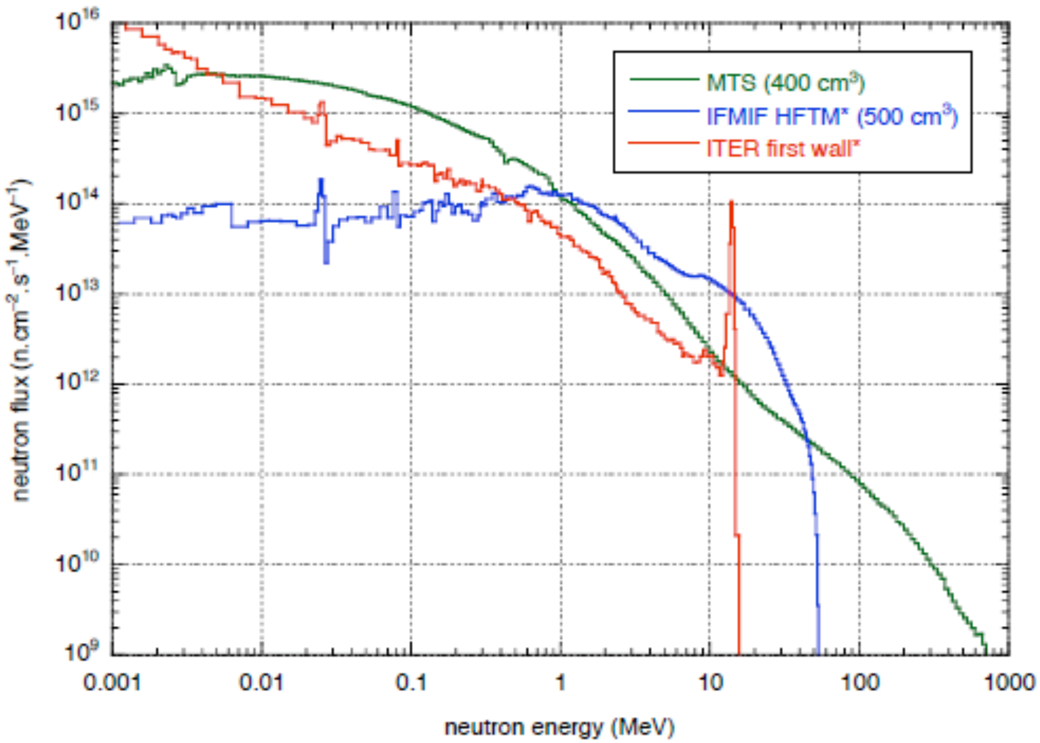
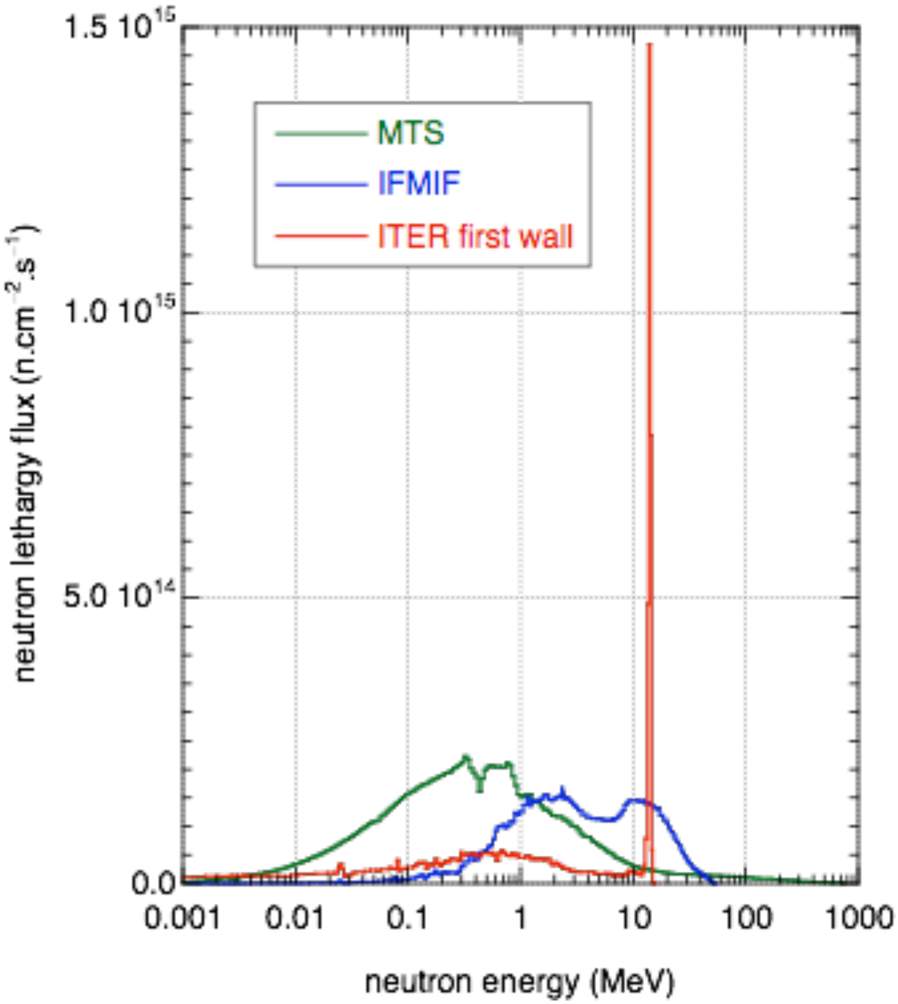


*Figure 1. Neutron spectra for MTS, IFMIF, and ITER [*data courtesy of Dr. U. Fischer et al., Fusion Engineering and Design 63-64 (2002) 493-500]. The 400-cc MTS volume is in the fuel irradiation region.*

Spectral effects - MTS, IFMIF, ITER spectra – linear (4 of 4)



	MTS	IFMI	Fusion Reactor
dpa/fpy	3-35	20-55	20-30
appm He/dpa	4-25	10-12	10-15
appm H/dpa	20-200	35-54	40-50
transmutations in Fe appm Mn/dpa	10	37	20-24

- **Spallation sources have higher recoil energies, but these ultimately yield sub-cascades similar to fusion first wall and IFMIF.**

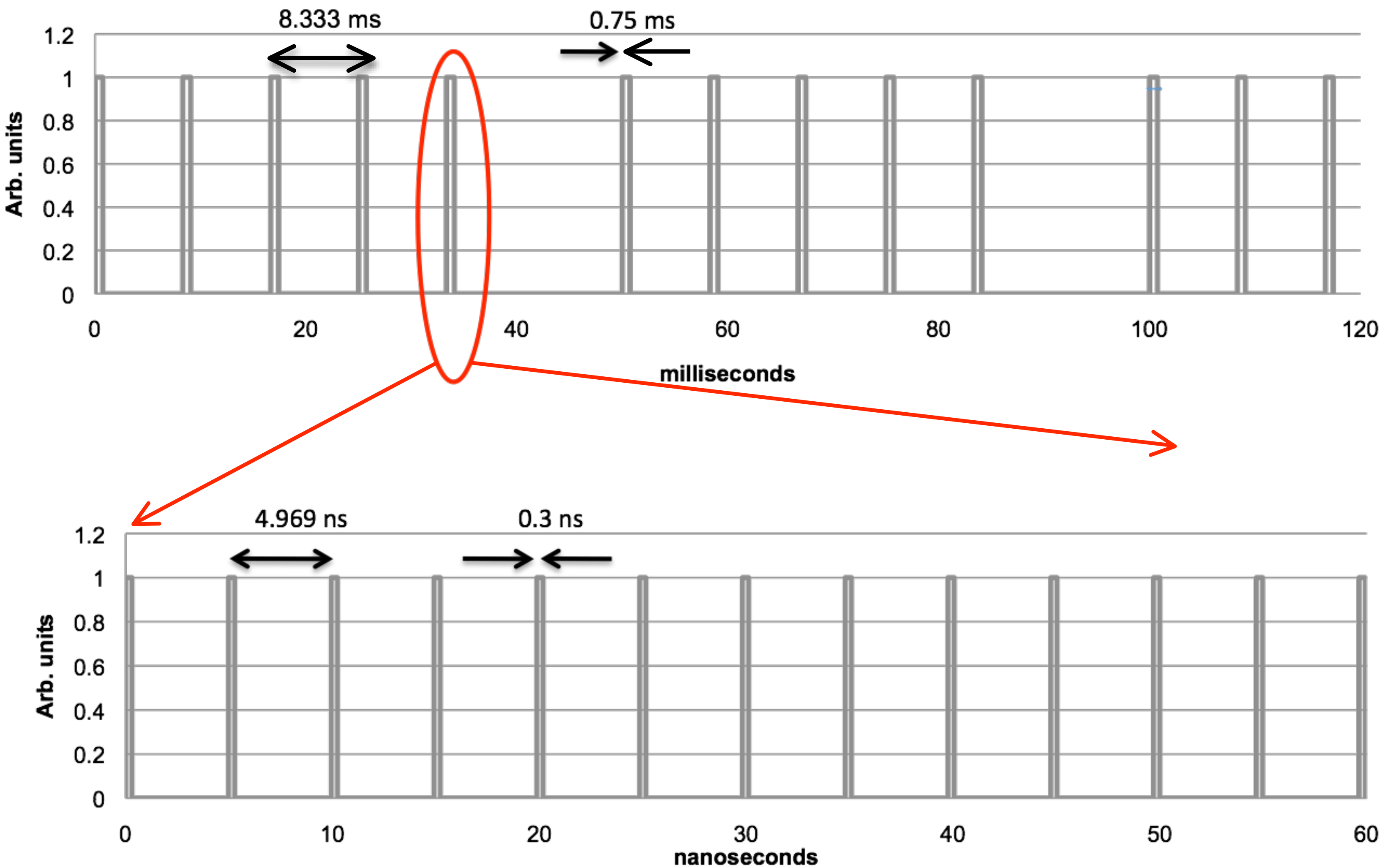
Time structure - Proton timing (1 of 2)

Proton macropulses

[120 Hz , every 6^{th} pulse diverted]

Proton micropulses

[at 201.25 MHz approx. 150 000 micropulses / macropulse]



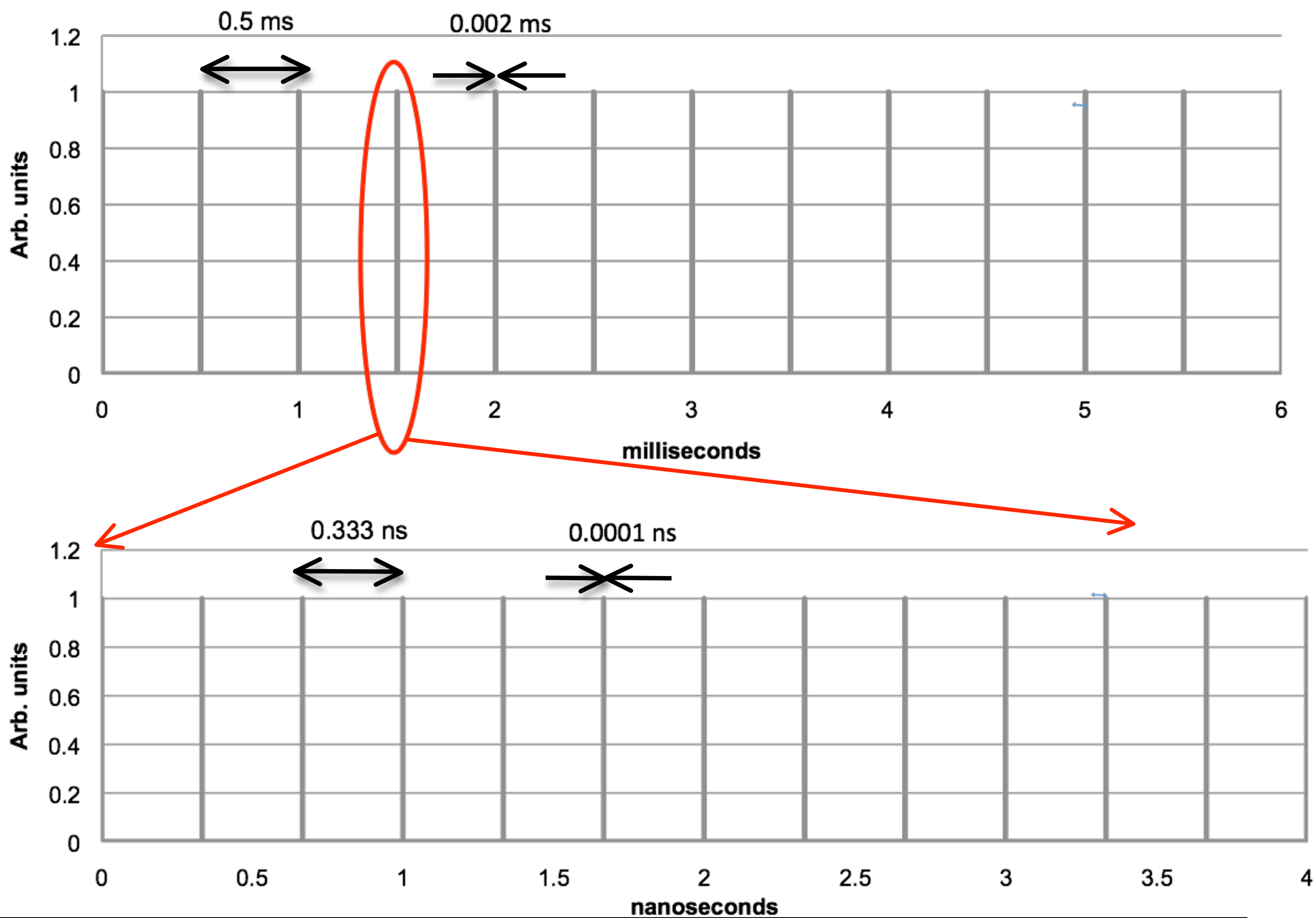
Time structure - Electron timing (2 of 2)

Electron macropulses

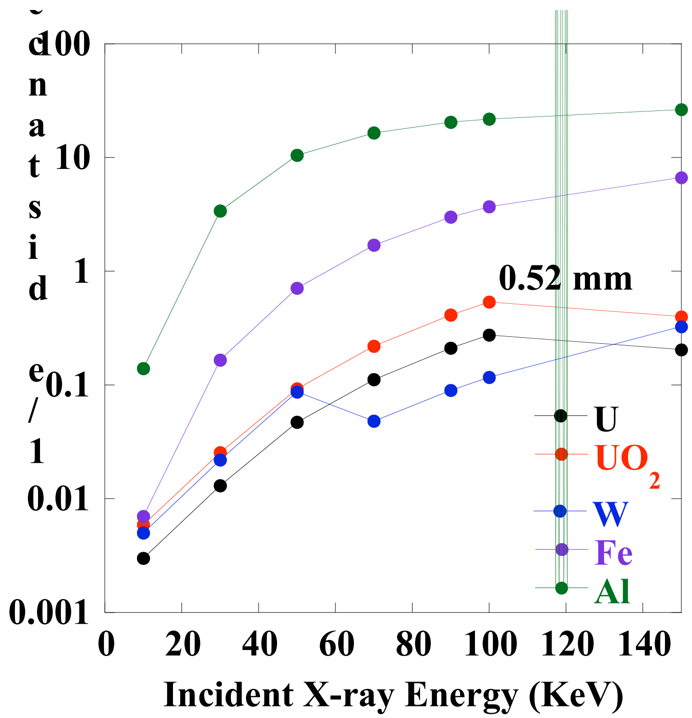
[2 Khz]

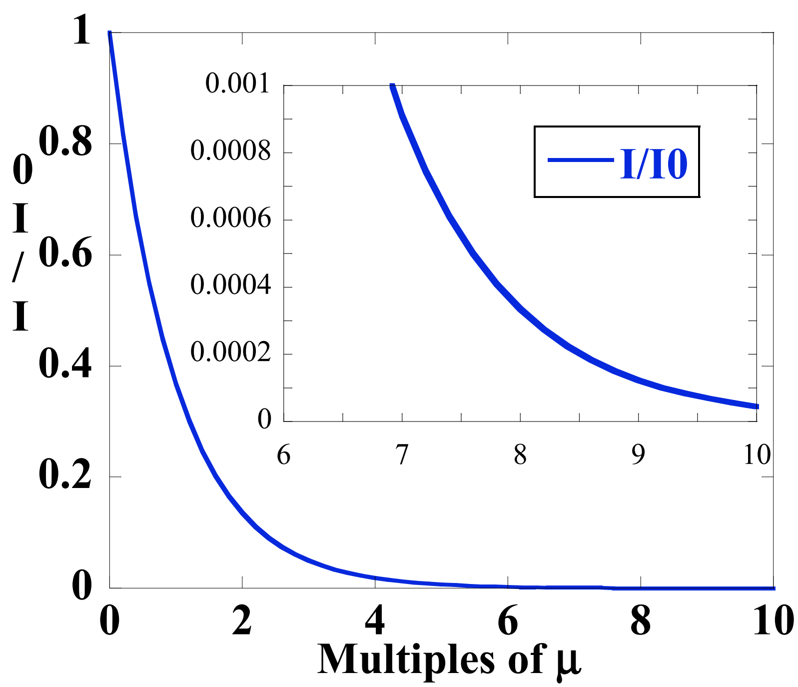
Electron micropulses

[< 1000 micropulses/ macropulse]

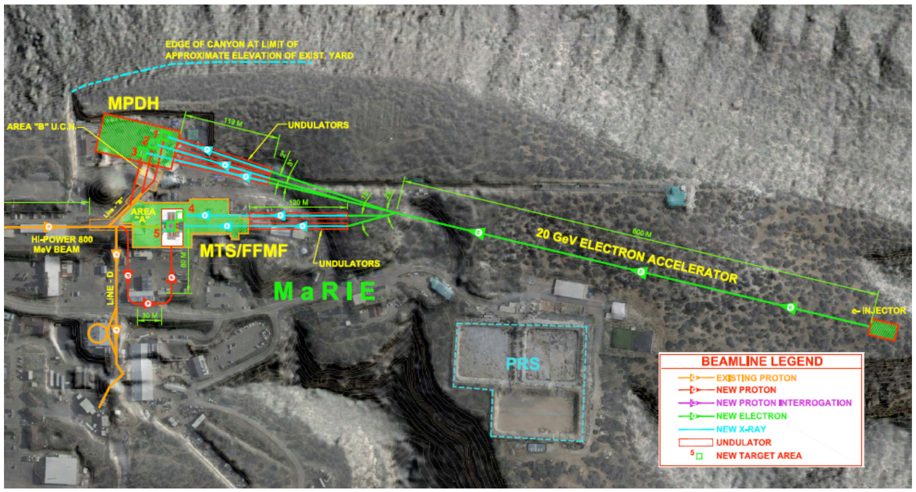


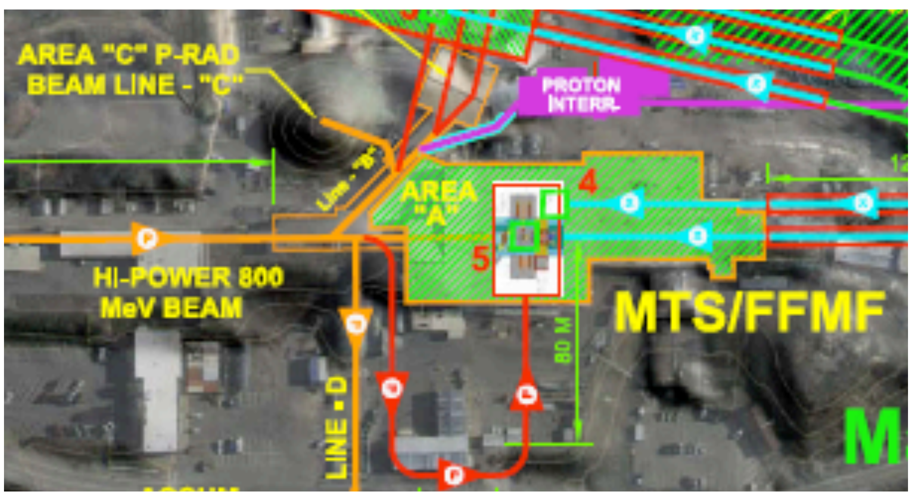
X-ray penetration, energy dependence





Concept to fill performance gaps – MaRIE Fission Fusion Facility





1a) In situ probe beam(s) characterization of transient effects in MTS target

1b) Ex situ probe beam(s) characterization of persistent effects in a hot cell adjacent to MTS

2) LANSCE power upgrade

Functional requirements on irradiation environment to address user needs

Irradiation facility that provides neutron fluence & spectral conditions relevant to fast fission & fusion applications for both in situ & multiple sample irradiations

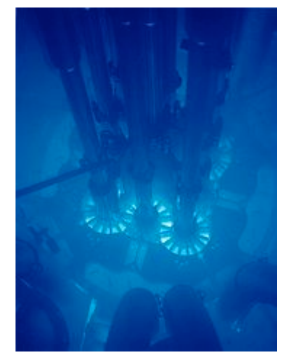
Irradiation Volume	> 1	liter
Neutron flux gradient over irradiation volume	< 1	% / mm
Primary recoil spectra	Comparable to fast fission or fusion applications	-
Damage rate	Up to 50	dpa / full power year (Fe Equiv.)
Fast / thermal*	➢10^4	Neutron flux ratio
Fast* neutron flux	> 2 10^{15}	n cm^{-2} / second
Average fast* neutron flux	> 3 10^{22}	n cm^{-2} / year
Helium to dpa ratio	0.2 to 20	appm/dpa (Fe equiv.)
Facility availability	> 70%	
Facility lifetime	20	years

*Fast (>0.1 MeV)
Thermal (<0.625 eV)

Analysis of "existing" neutron irradiation environments

REQUIREMENTS MET Green=Yes, Orange=Maybe, Red=No

			In-Situ Measurement								Dose Rate & Spectrum						
NEUTRON SOURCE	COUNTRY	POWER	Temperature	Macroscopic dimensions	Force	Displacement	Cracks	Voids	Phase	Defects	Irradiation Volume	Flux gradient over irradiation volume	Primary recoil spectra	Damage Rate	Fast / thermal neutron flux ratio	Helium to dpa ratio	Facility availability / lifetime
ATR	USA	250MW Thermal Research	Green	Orange	Orange	Orange	Red	Red	Red	Red	Green	Green	Green	Red	Red	Orange	1967 [2]
HFIR	USA	85-MW Thermal Research Reactor	Green	Orange	Orange	Orange	Red	Red	Red	Red	Green	Green	Green	Red	Red	Orange	1966
HALDEN	Norway	25MW thermal research reactor	Green	Green	Green	Green	Red	Red	Red	Red	Green	Green	Green	Red	Red	Orange	1959
etc	etc																
BOR-60	Russia	60MW Fast research reactor	Green	Orange	Orange	Red	Red	Red	Red	Red	Green	Green	Green	Green	Green	Orange	1980
JOYO	Japan	140-MW Fast Breeder Research	Green	Green	Green	Green	Red	Red	Red	Red	Green	Green	Green	Green	Green	Orange	1977
MTS[1]	USA	0.8-GeV, 1MW spallation source	Green	Orange	Orange	Orange	Red	Red	Red	Red	Green	Green	Green	Red	Green	Orange	2007 CD-0



Advanced test reactor USA

JOYO Fast reactor , Japan

[1] Materials Test Station Compliance With Fast Neutron Irradiation Capability Requirements LA-UR-07-5429

[2] Year of first criticality, core replaced every 7 years