

Class Introduction

K.G. Field^{1,a},

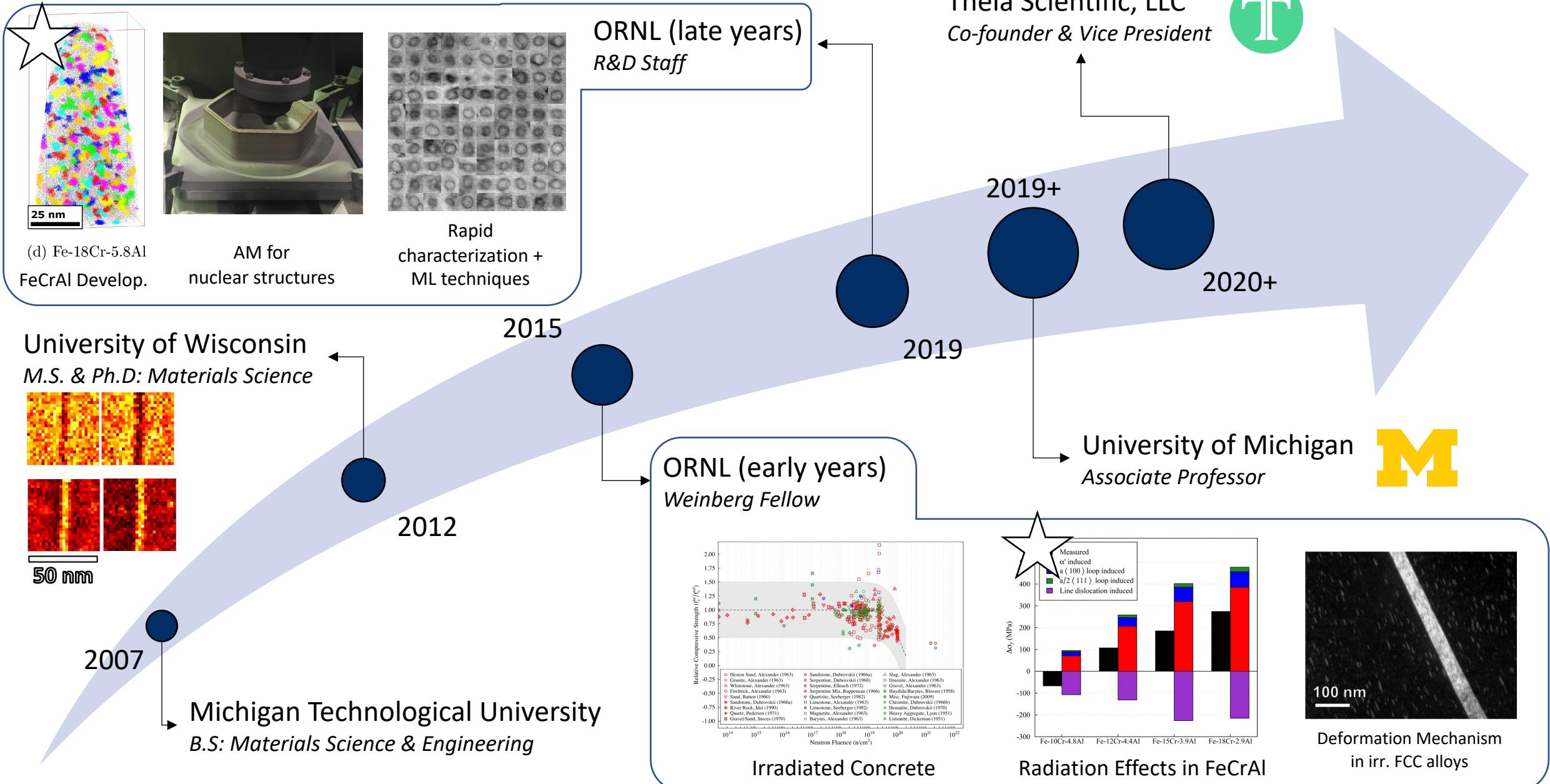
^akgfield@umich.edu

¹University of Michigan



NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

About Prof. Field:





About you - introductions

Minimum amount of information to divulge:

- Name (Given + Family)
- Undergraduate school
- Undergraduate major

Optional:

- Something interesting about your hometown(s)

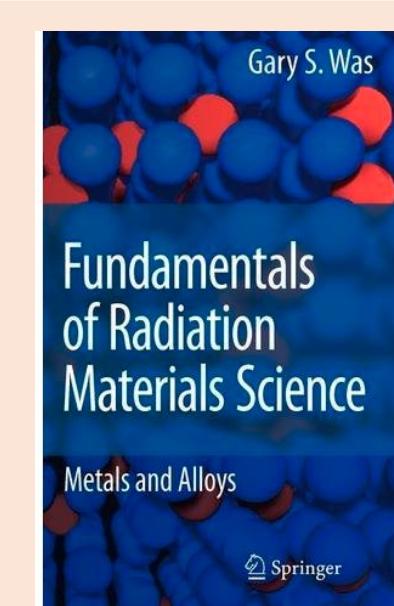
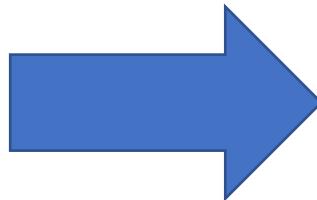
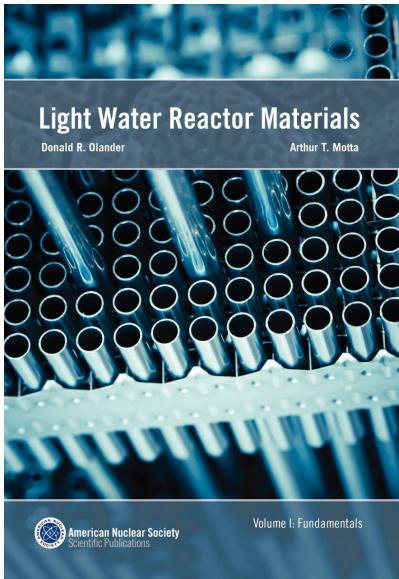


[Go to Canvas Syllabus](#)

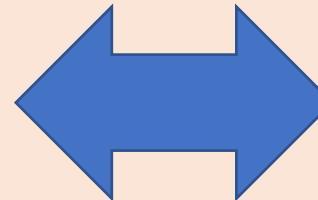
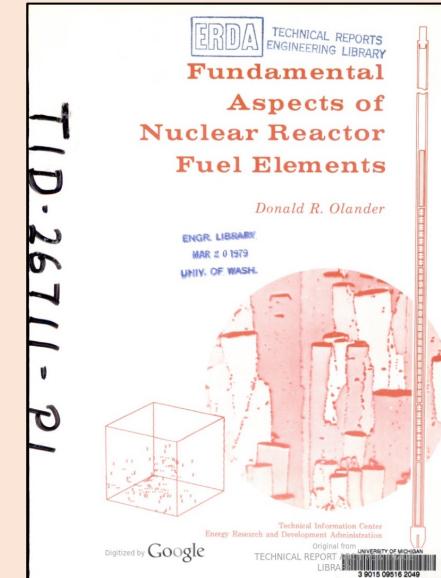


NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Course Materials:

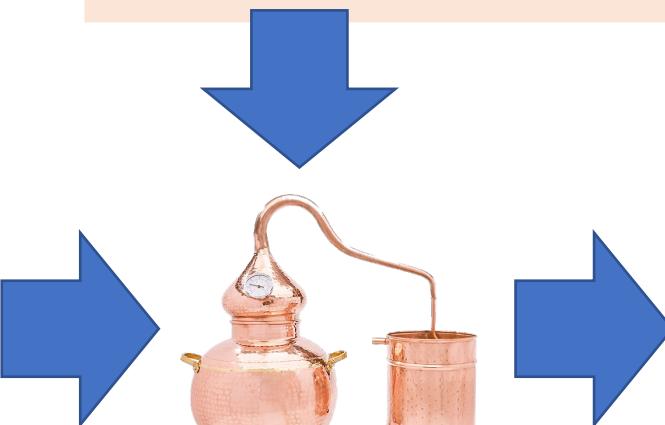


Available Online (see syllabus)



Basics, good resource if you need to familiarize with base concepts

Other books, chapters, papers, lectures, etc.



According to a popular gardening website, name three of the five major varieties of blueberry grown in the United States?

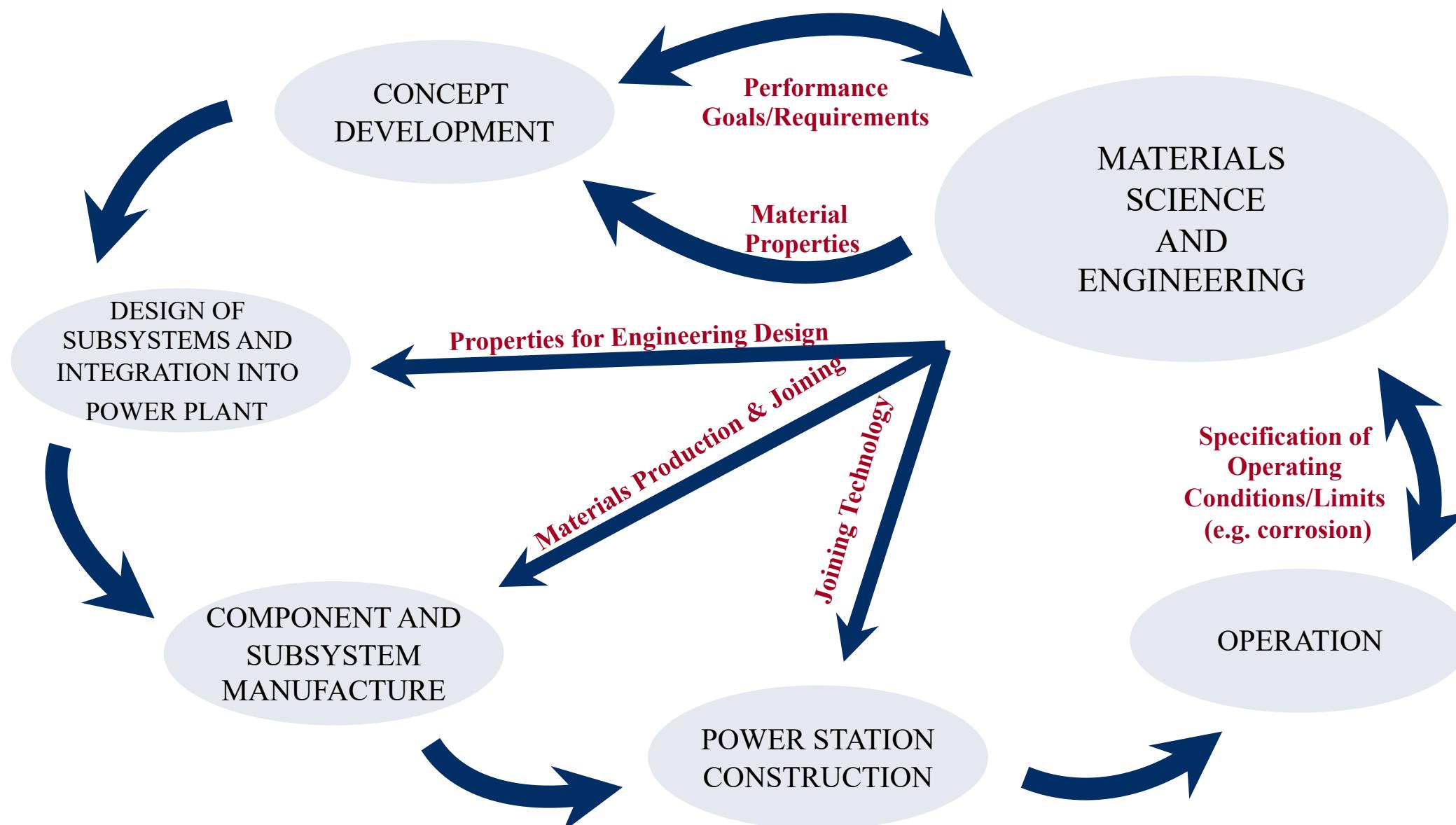


Why Radiation Materials Science?

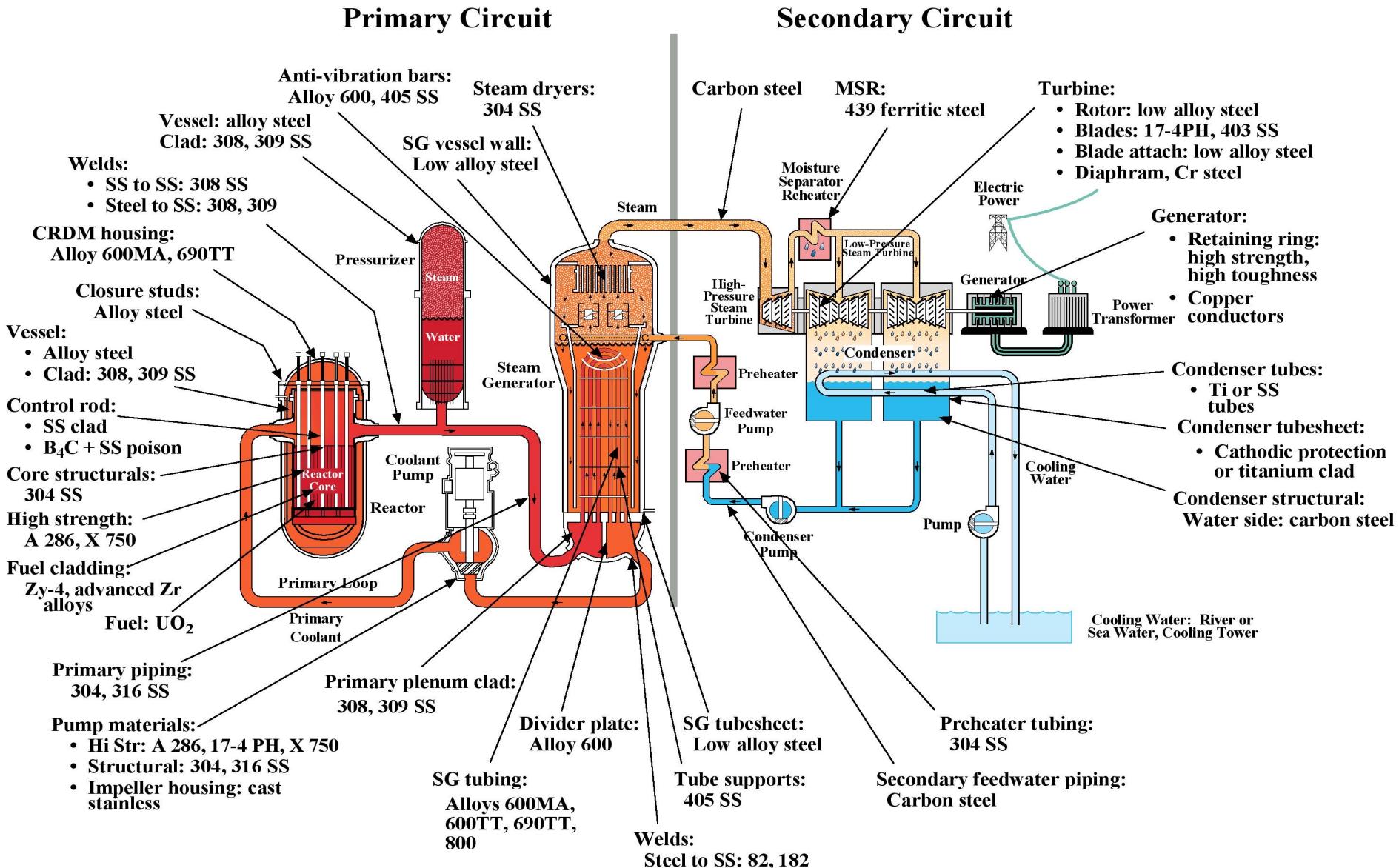


NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Why Radiation Materials Science?

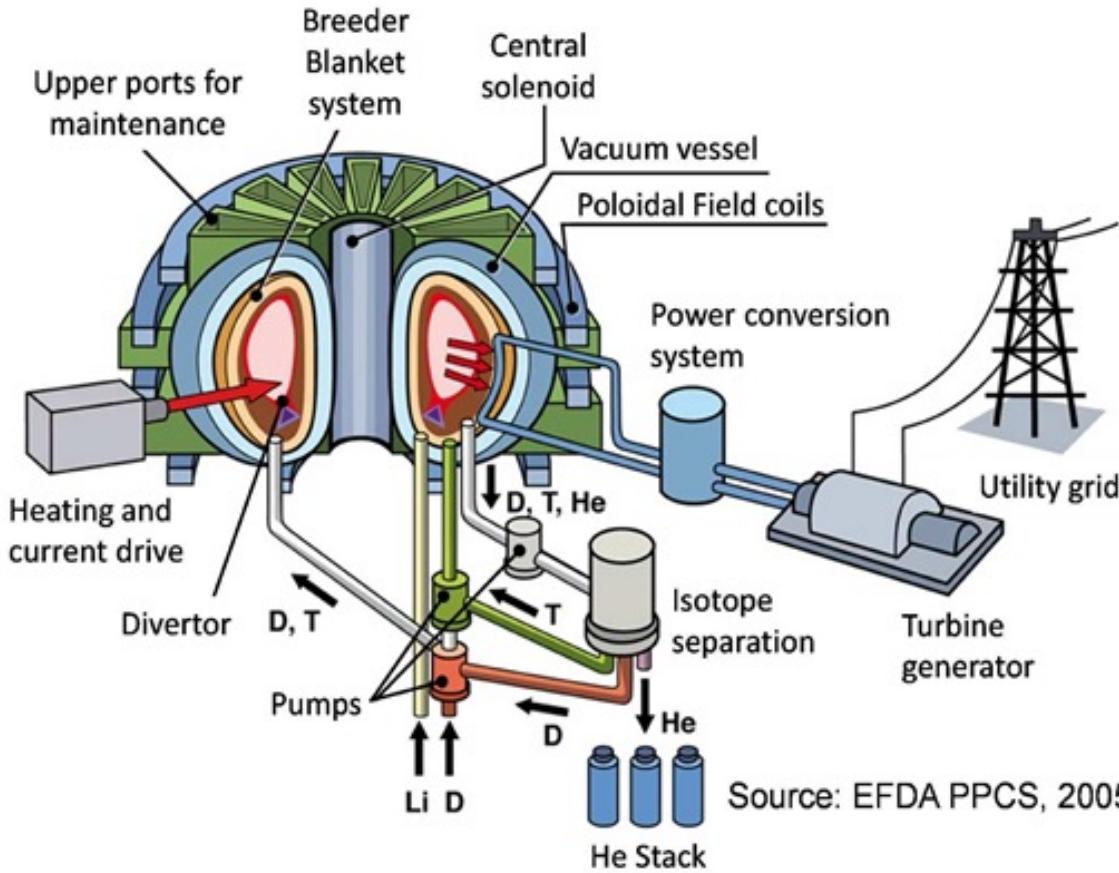


Why Radiation Materials Science?

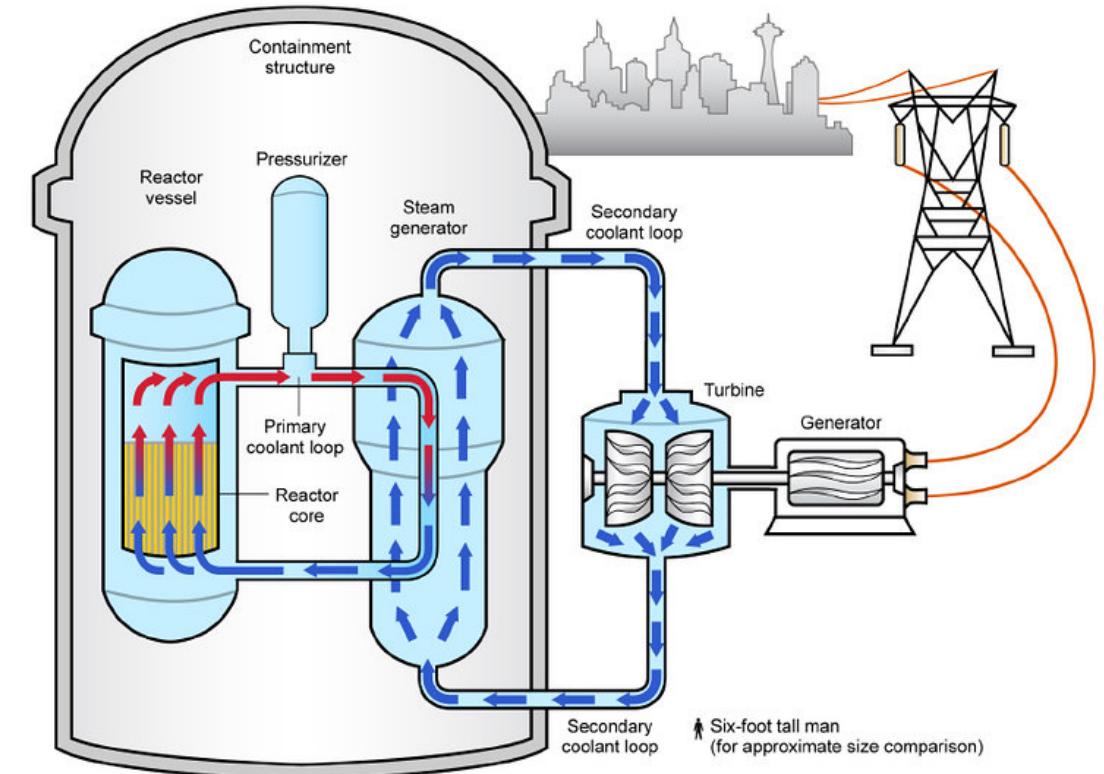


Radiation Materials Science is Applicable to Both Fission and Fusion Power:

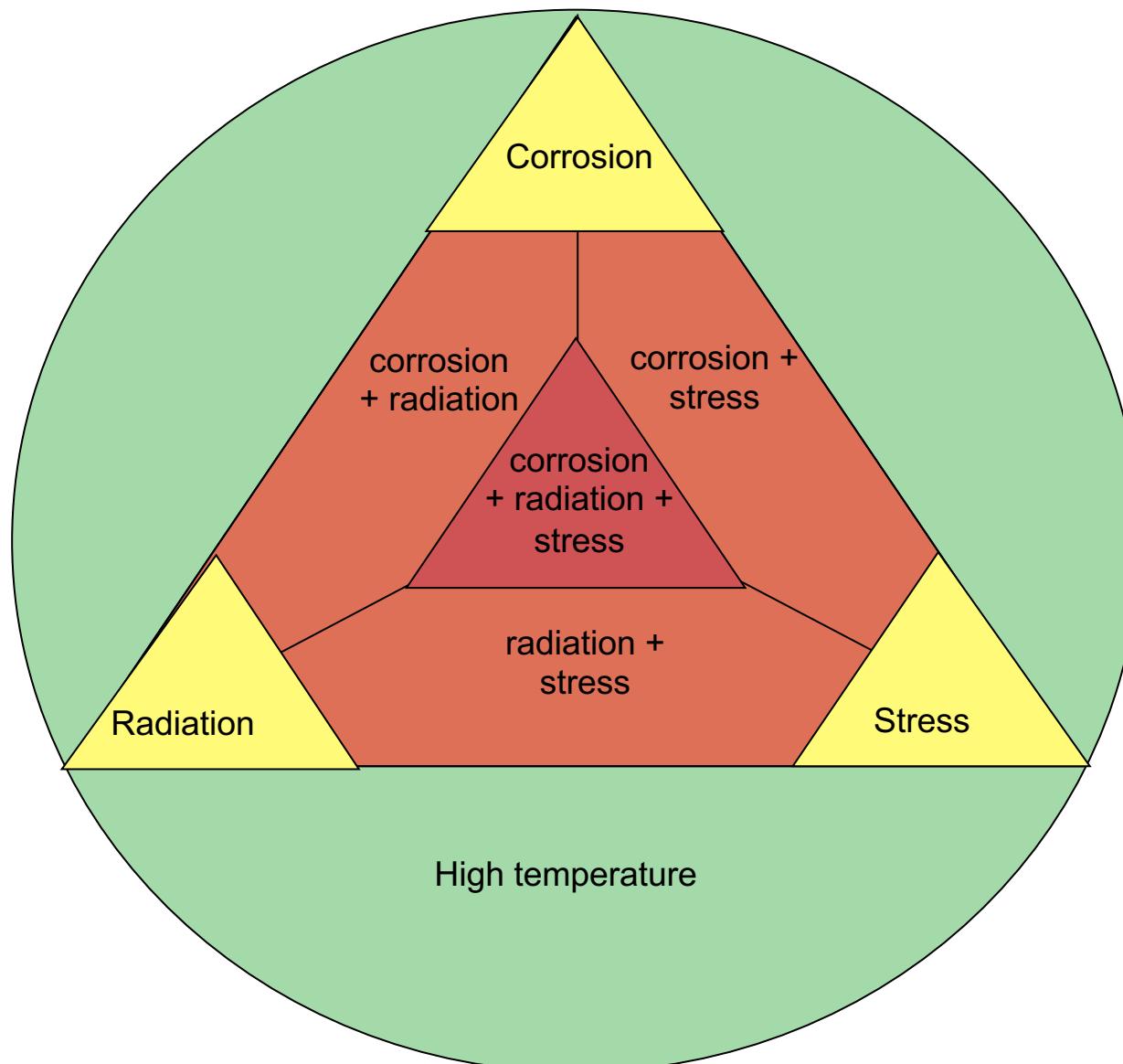
Fusion Power Plant:



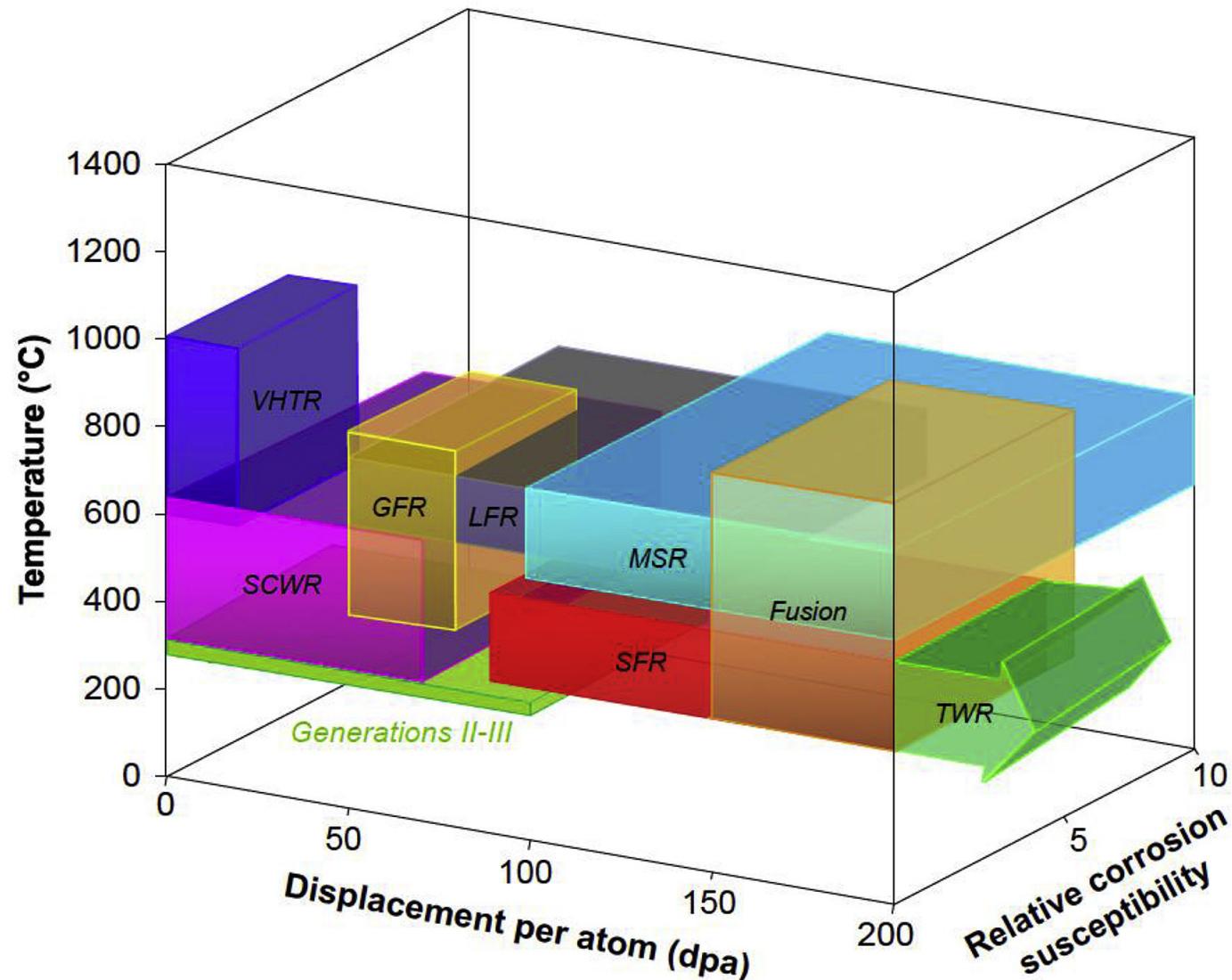
Fission Power Plant:



Materials “stressors” in nuclear reactor systems



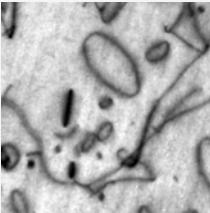
Materials “stressors” on a per reactor basis



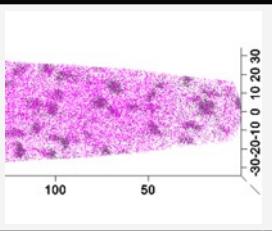
Reactor Type	Inlet Temp (° C)	Outlet Temp (° C)	Maximum Dose (dpa)	Pressure (Mpa)	Coolant
PWR	290	320	100	16	Water
SCWR	290	500	15-67	25	Water
VHTR/F HR	600	1000	1-10	7	Helium, Salt
SFR*	370	550	200	0.1	Sodium
LFR*	600	800	200	0.1	Lead
GFR*	450	850	80	7	Helium/ SC CO ₂
MSR	700	1000	200?	0.1	Molten Salt

Consequences of microstructural changes on mechanical performance

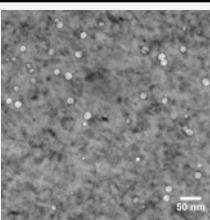
Dislocation loops



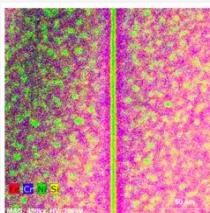
Radiation-Induced Precipitation (RIP)



Cavities, He bubbles, etc.

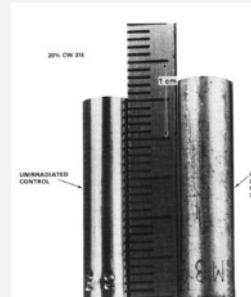


Radiation-Induced Segregation (RIS)



Hardening
Irradiation creep
Deformation localization
Embrittlement

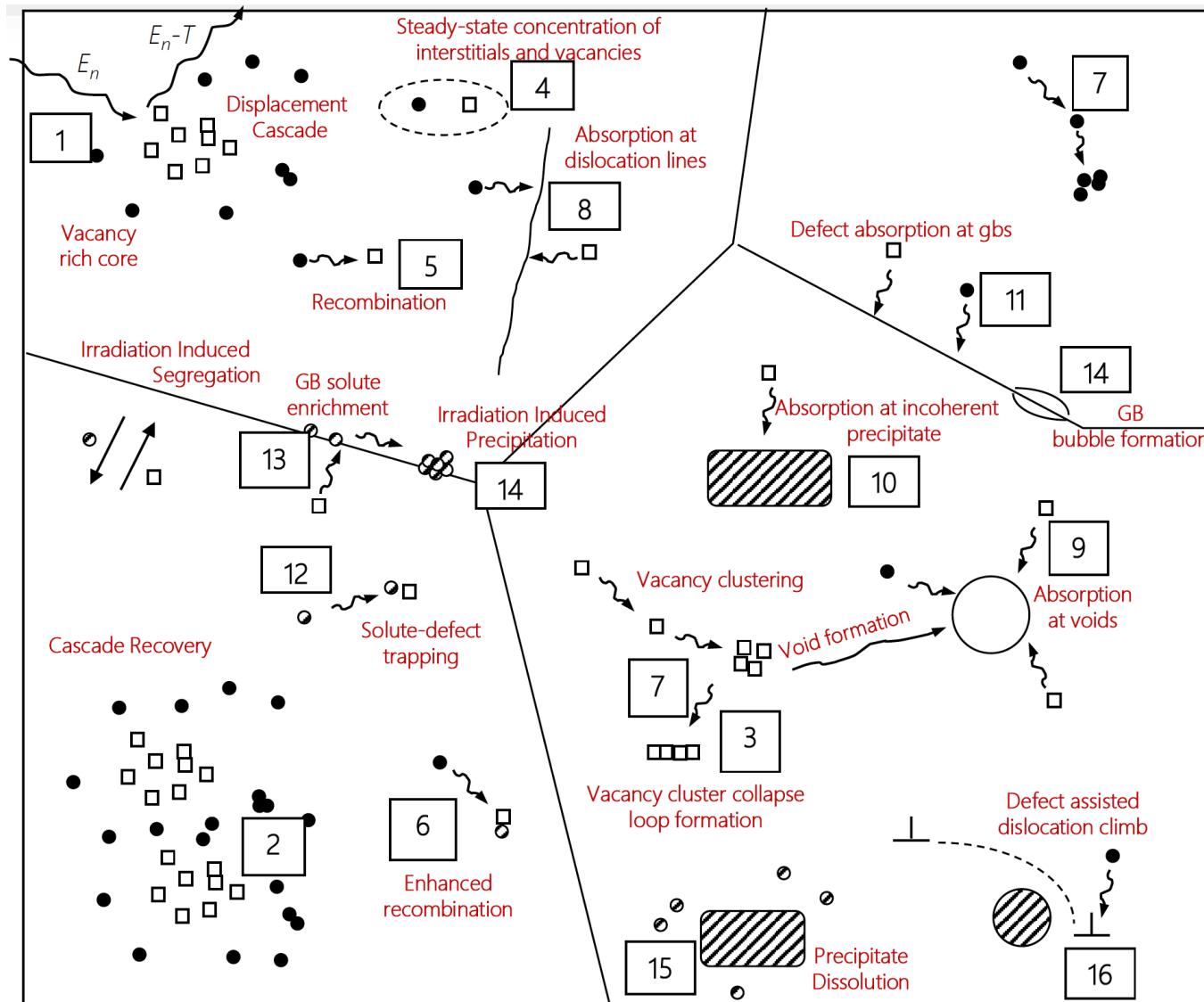
Swelling



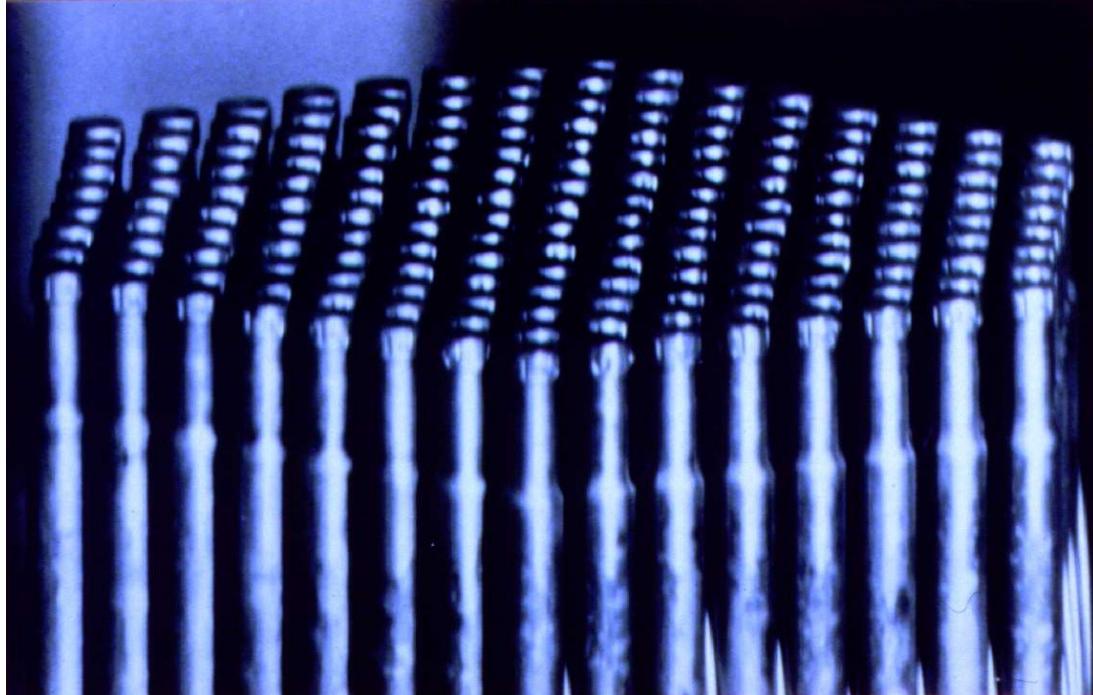
Increased sensitivity to SCC
(IASCC)



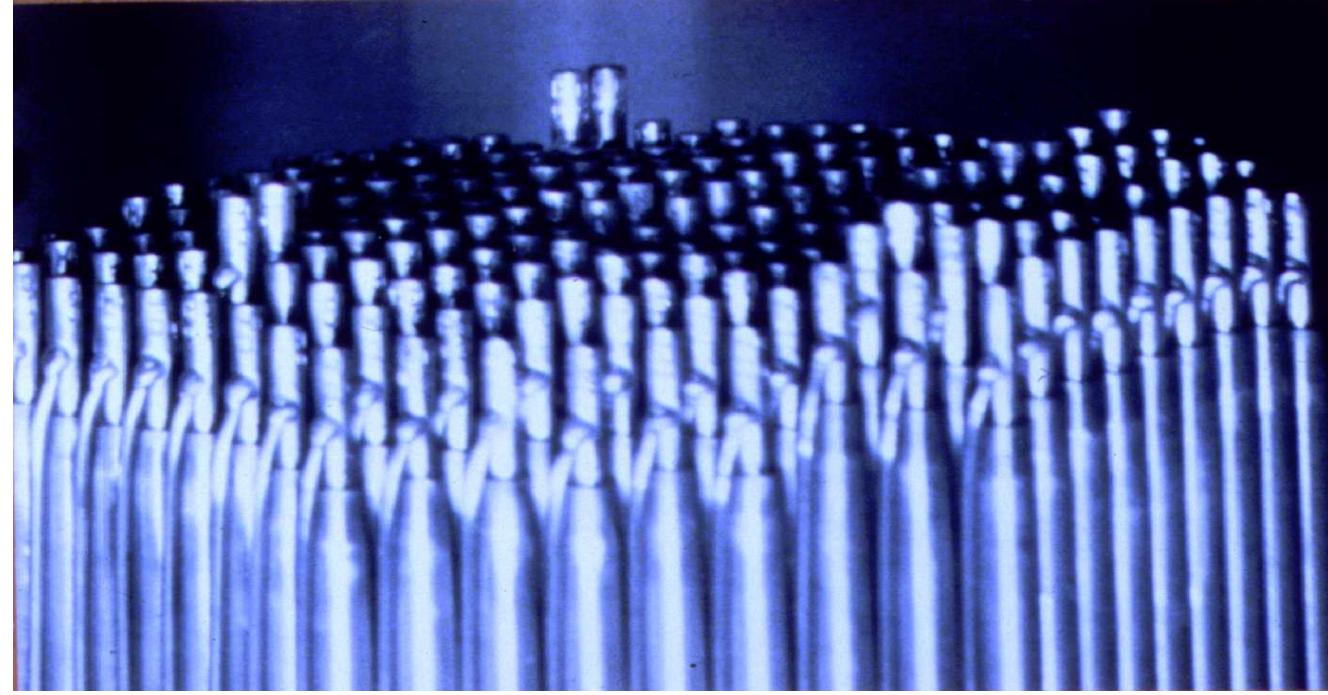
Radiation Effects at the Grain Scale



Radiation damage effects materials differently



HT-9, no swelling



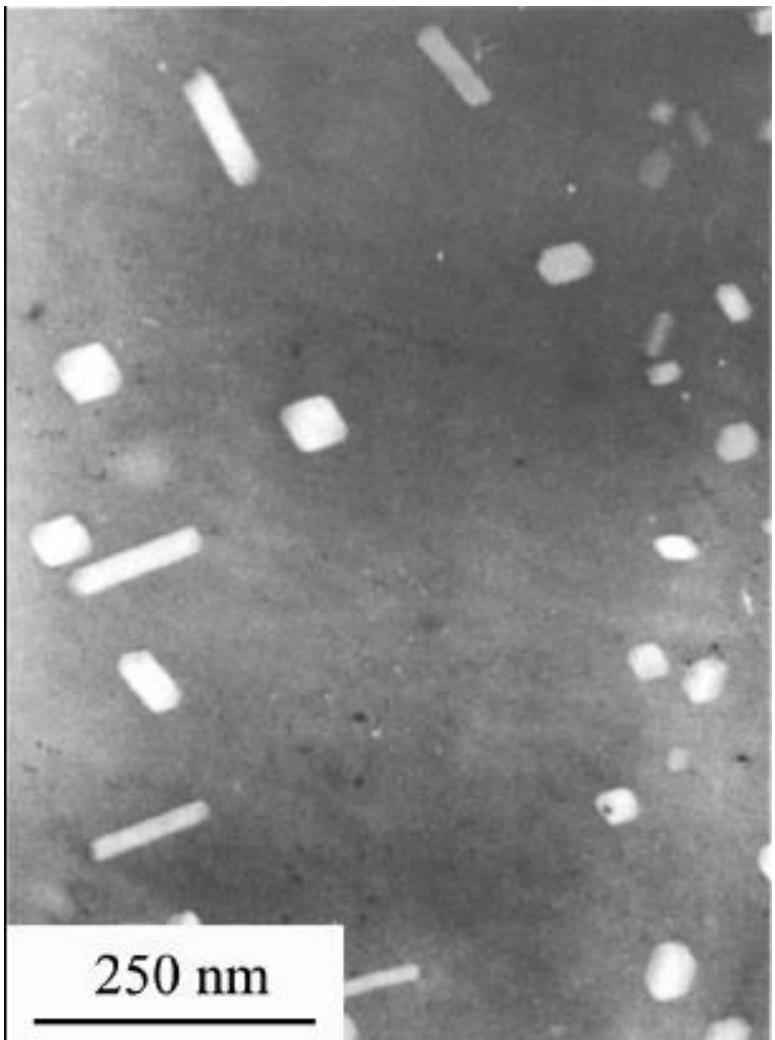
316-Ti stainless, swelling

Source: F. Garner

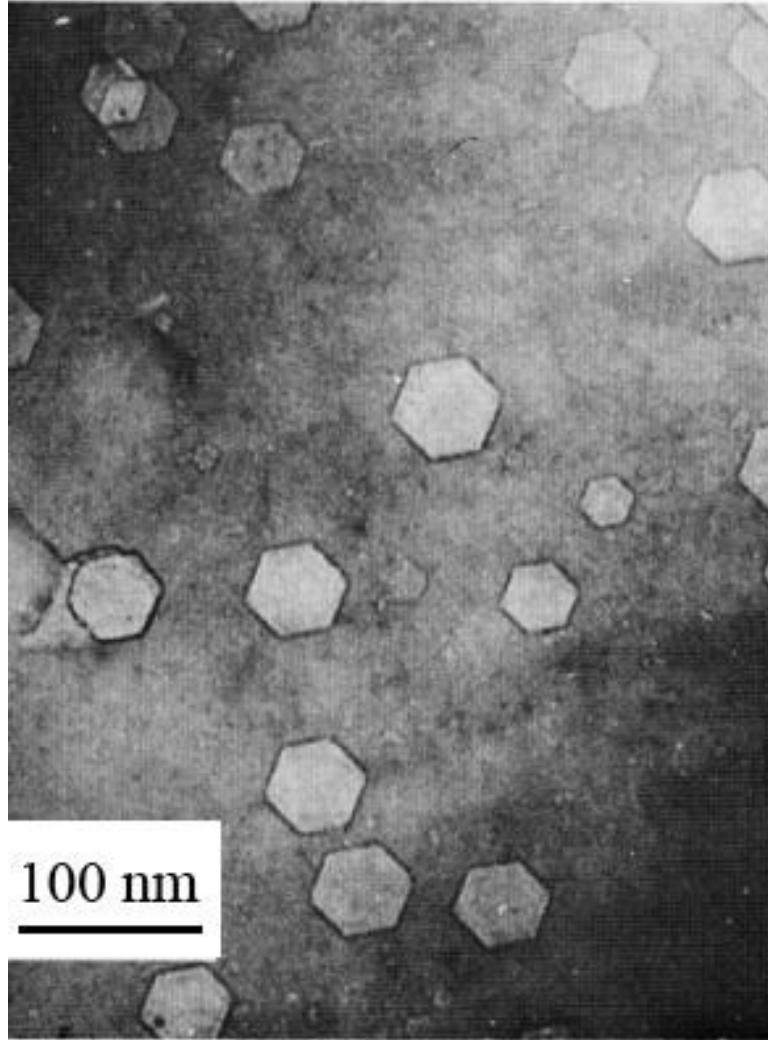


NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

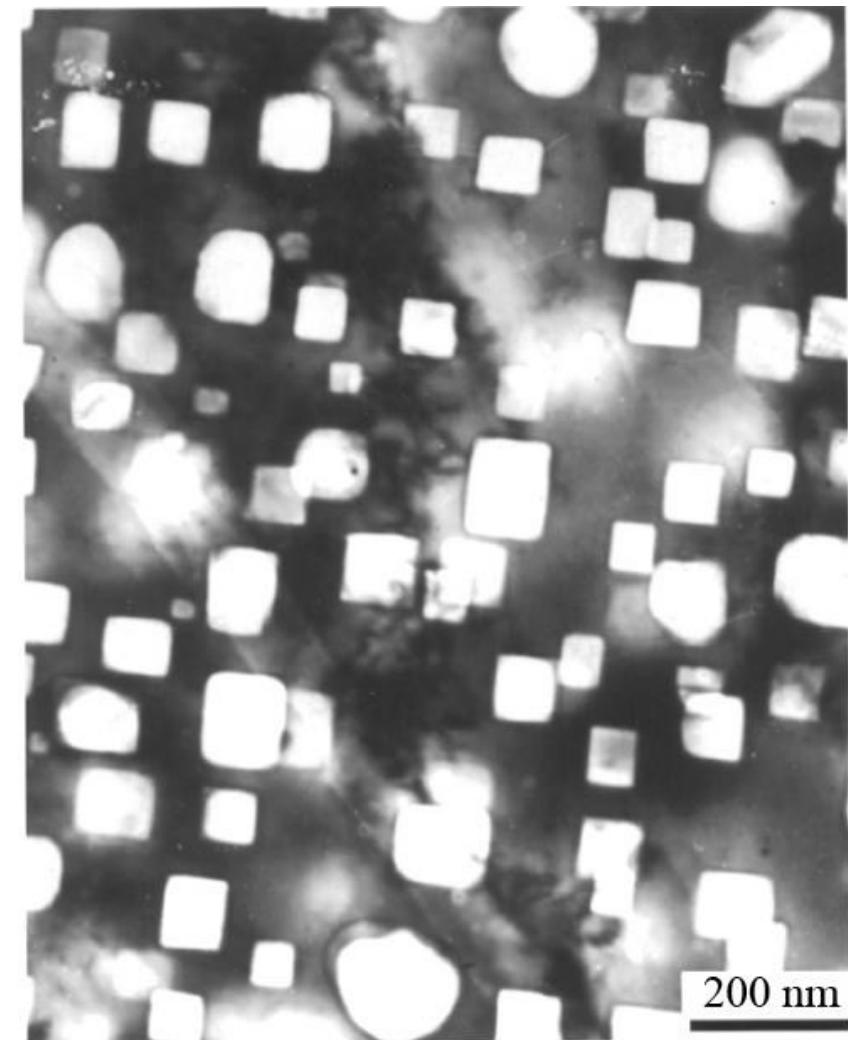
Examples of voids in various materials



Stainless Steel



Aluminum



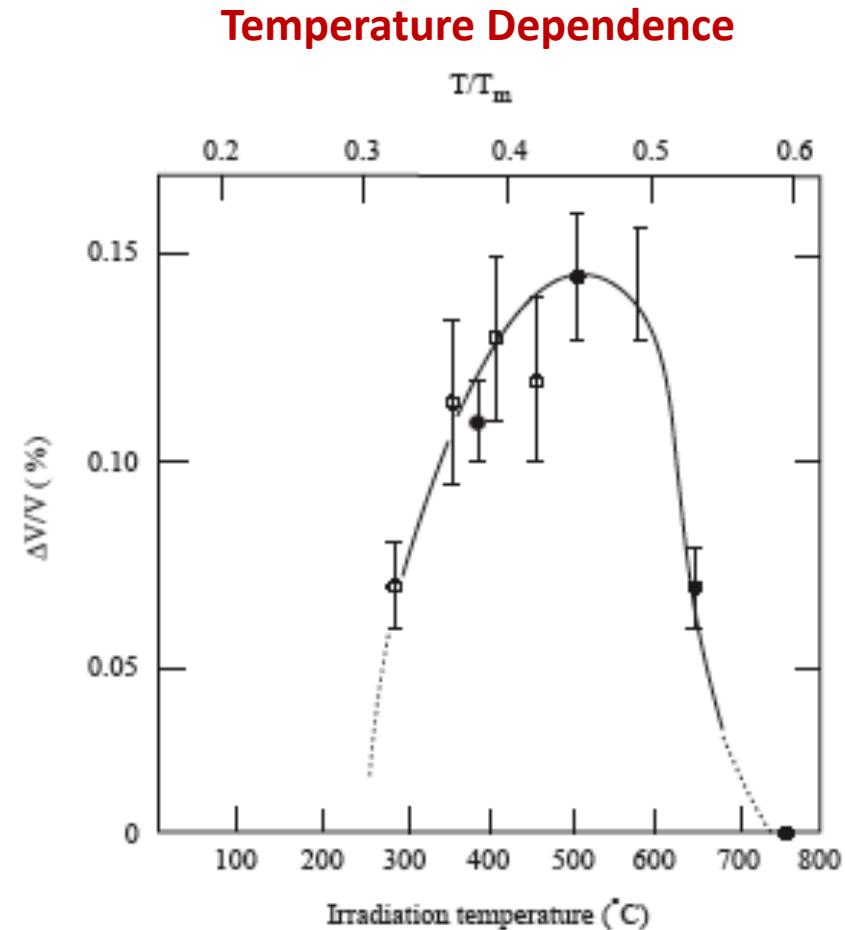
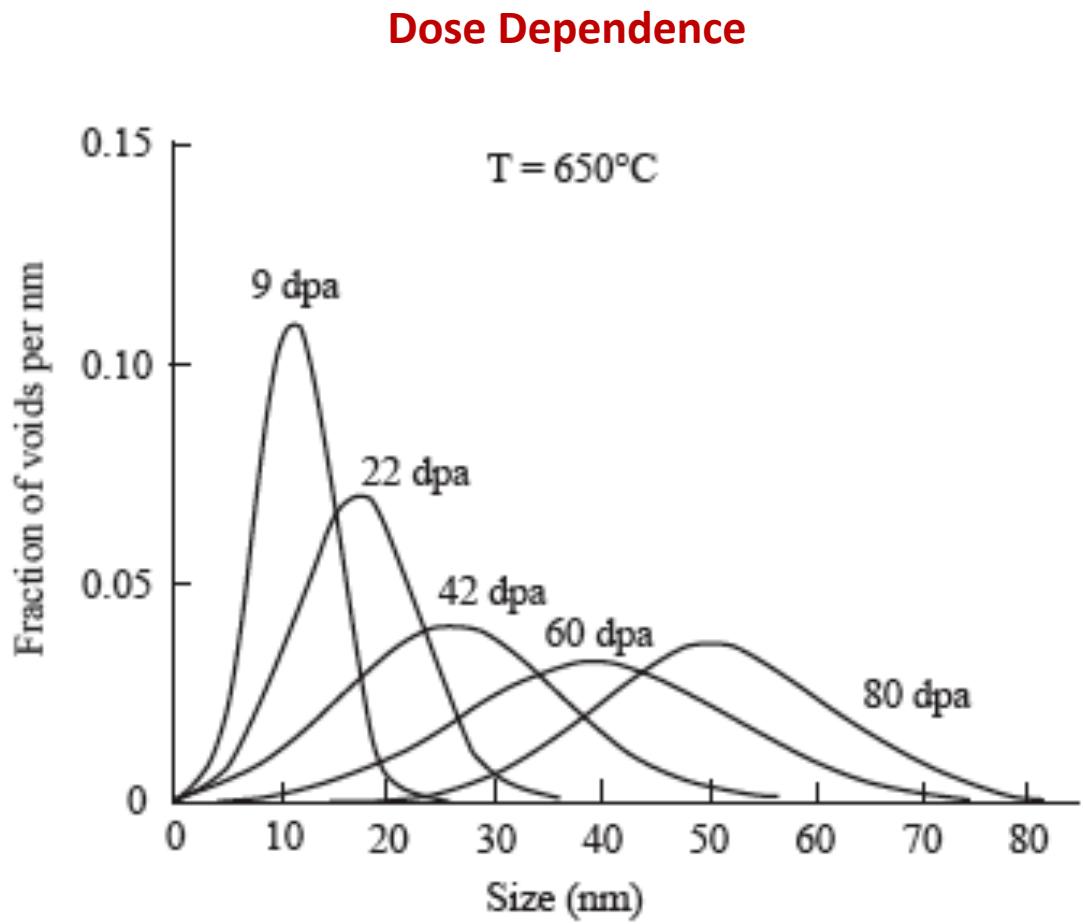
Magnesium

M. L. Jenkins, M. A. Kirk, *Characterization of Radiation Damage by Transmission Electron Microscopy*, Institute of Physics Publishing, Philadelphia, 2001.
U. Adda, Proc. International Conference on Radiation Induced Voids in Metals, CONF-710601, National Technical Information Service, 1972, p. 31.



NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

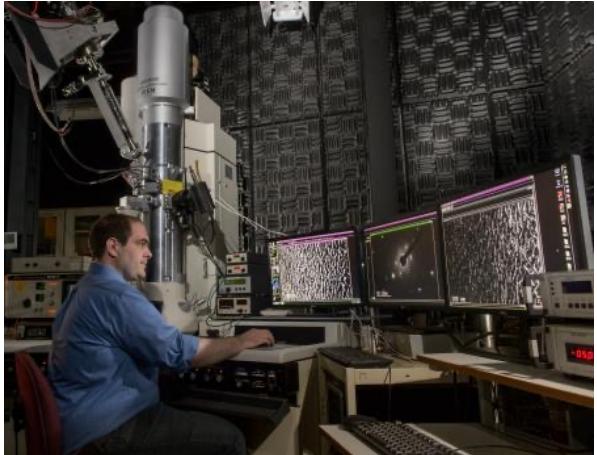
Cavity formation as a function of dose and temperature



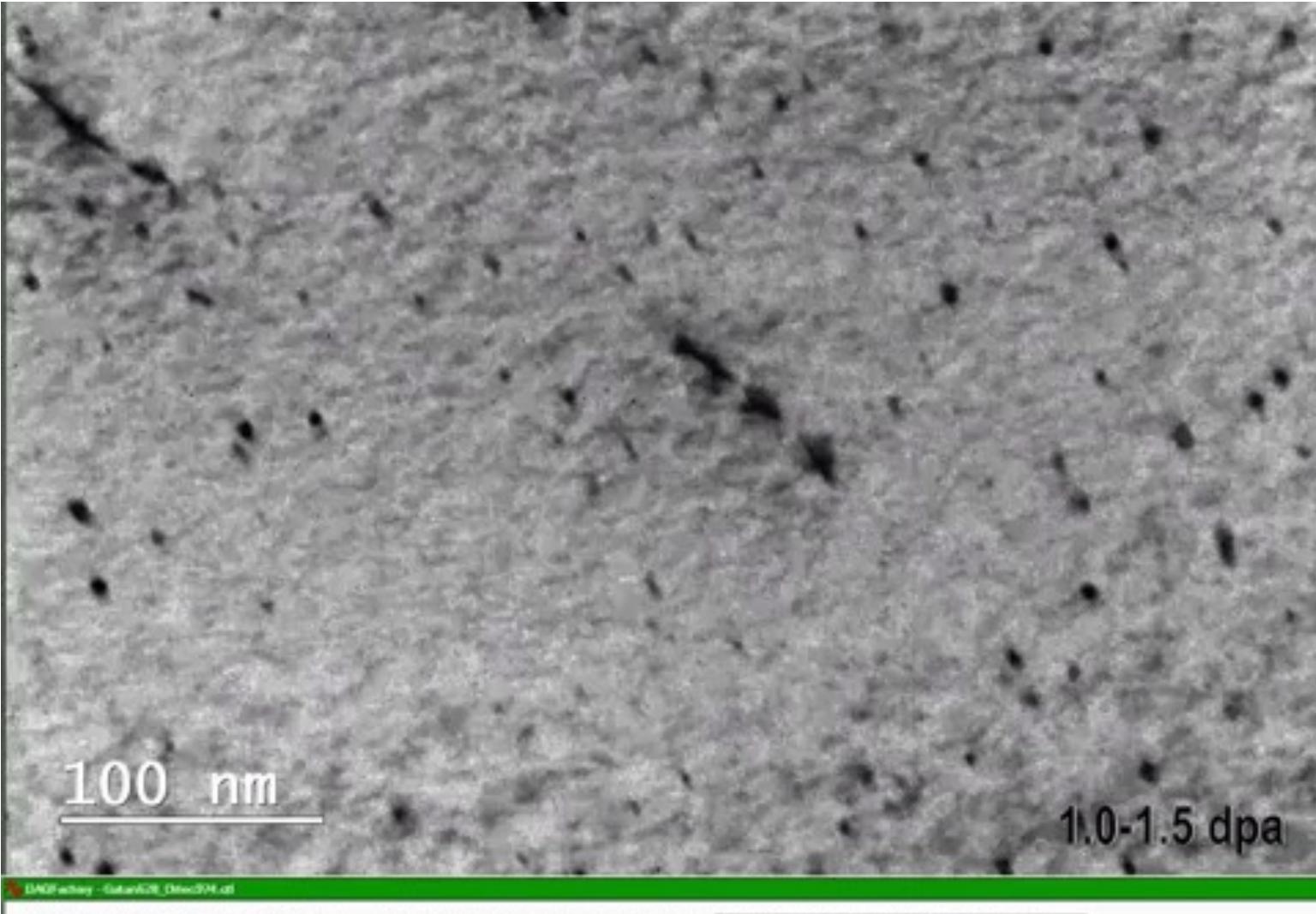
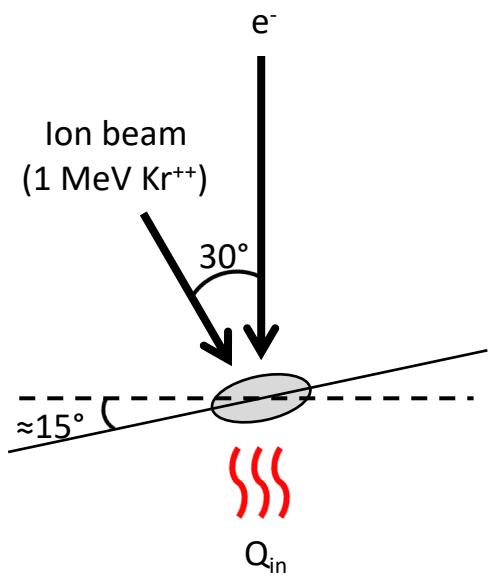
J. L. Brimhall, H. E. Kissinger and G. L. Kulcinski, Proc. International Conference on Radiation Induced Voids in Metals, CONF-710601, National Technical Information Service, 1972, p. 338.

C. Abromeit, J. Nucl. Mater. 216 (1994) 78-96.

Example data on in-situ ion irradiation of a FeCrAl alloy at 320°C



Argonne's IVEM facility

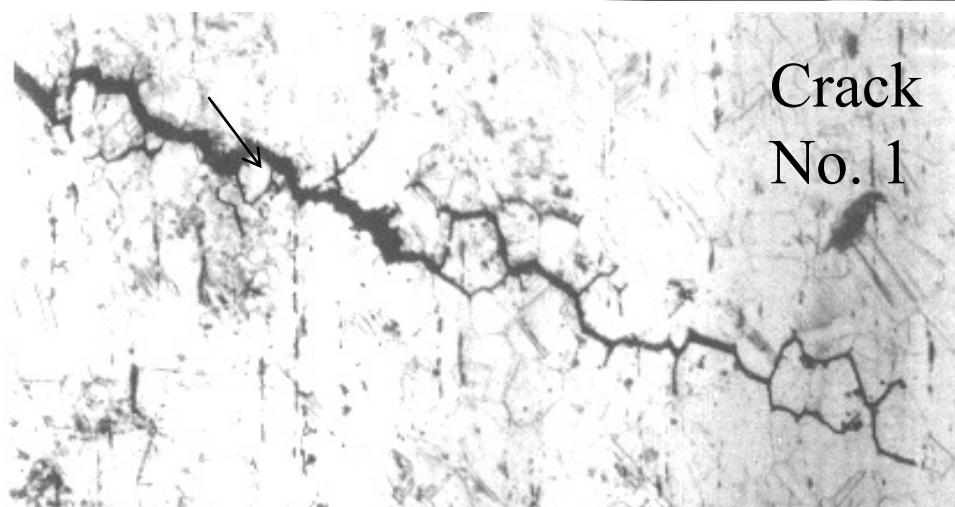
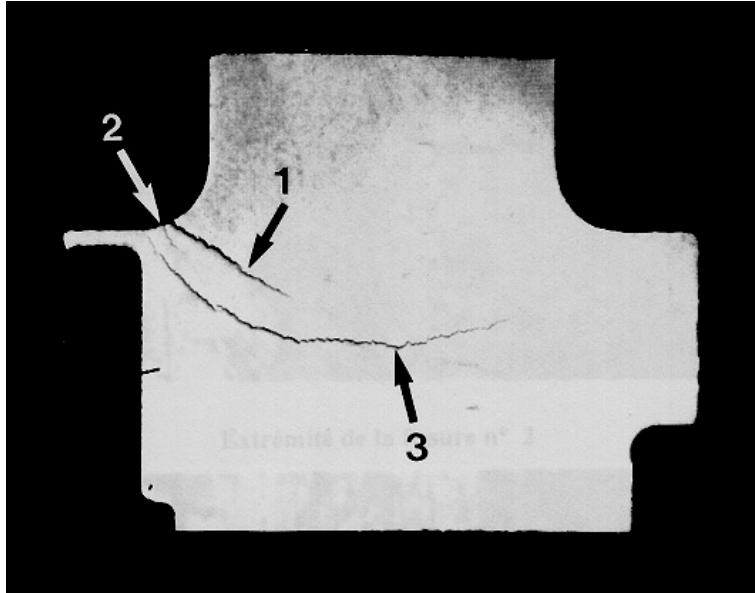
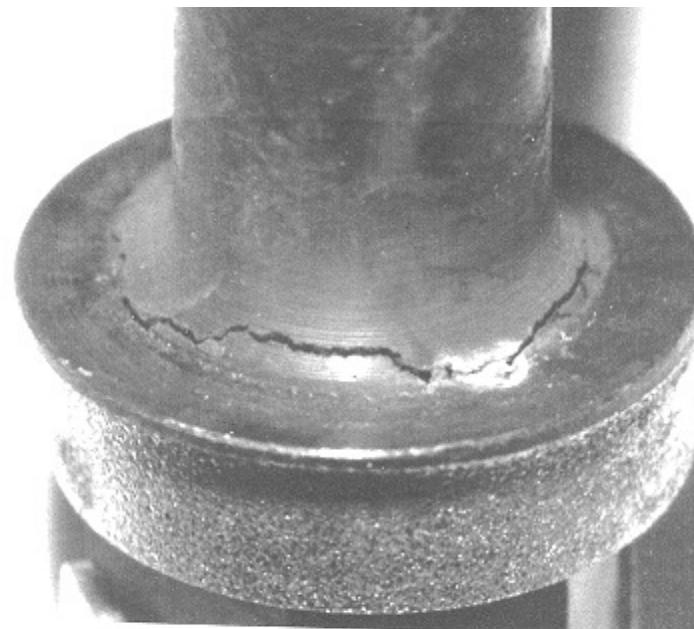


[1] Image courtesy of C. Ulmer (PSU)



NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Radiation damage can enhance degradation

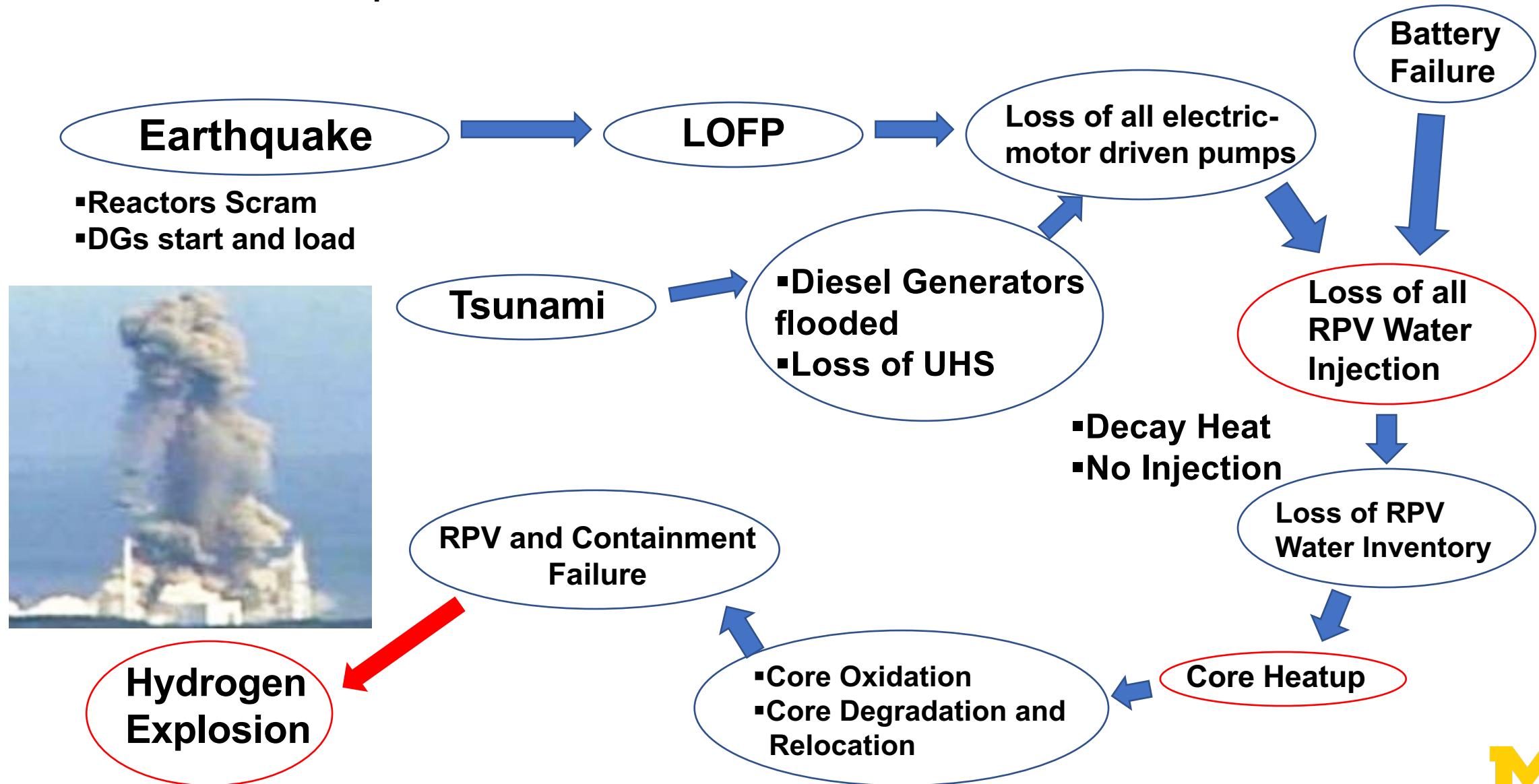


Classical example of
Irradiation Assisted
Stress Corrosion
Cracking in baffle
former bolts for a PWR

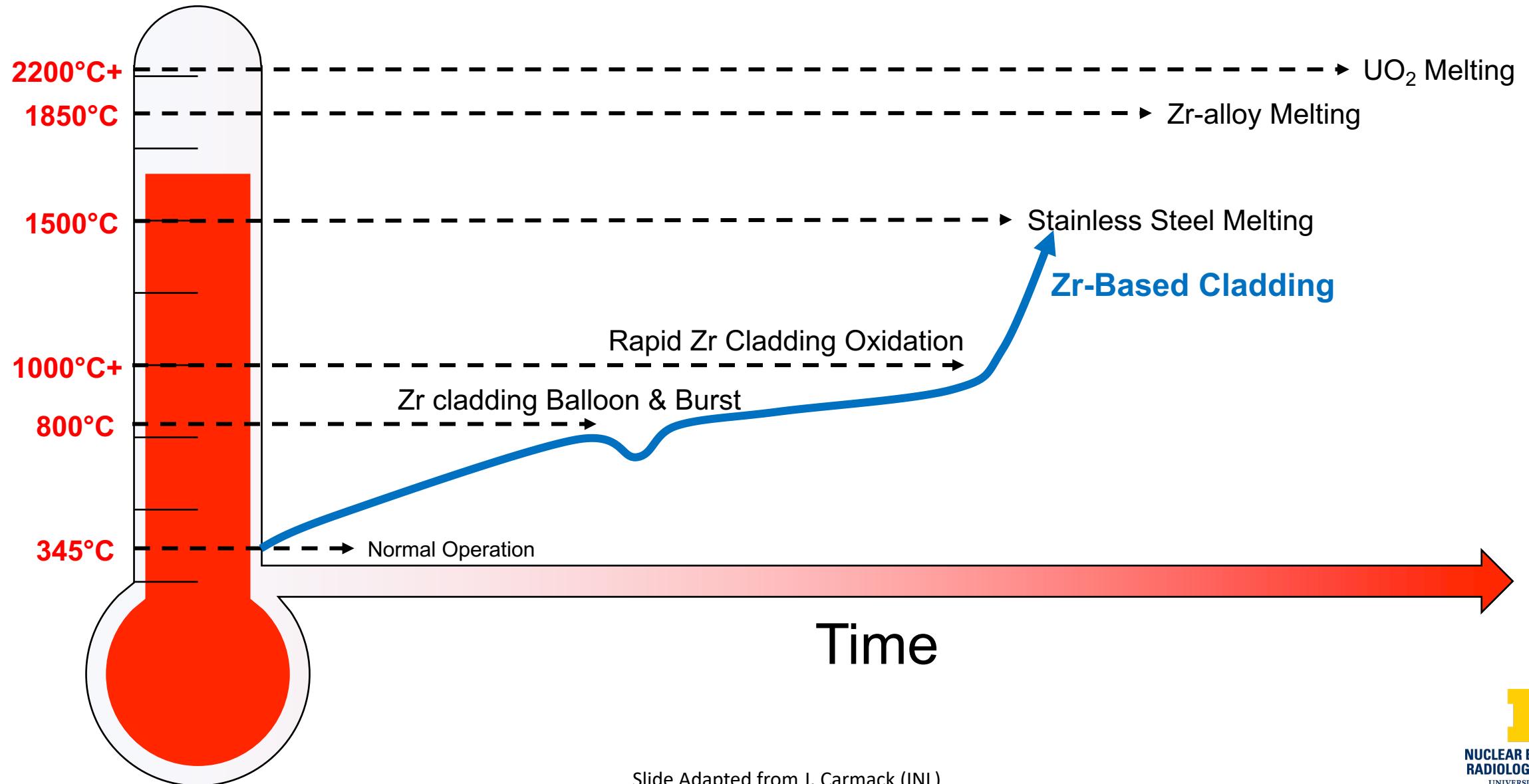
A photograph showing a row of cylindrical metal components, likely automotive transmission fluid filter canisters. They are arranged in a staggered pattern, showing both front-facing and side-facing views. The visible labels on the cylinders read "ATF FeCRA".

A Recent Real-World Example

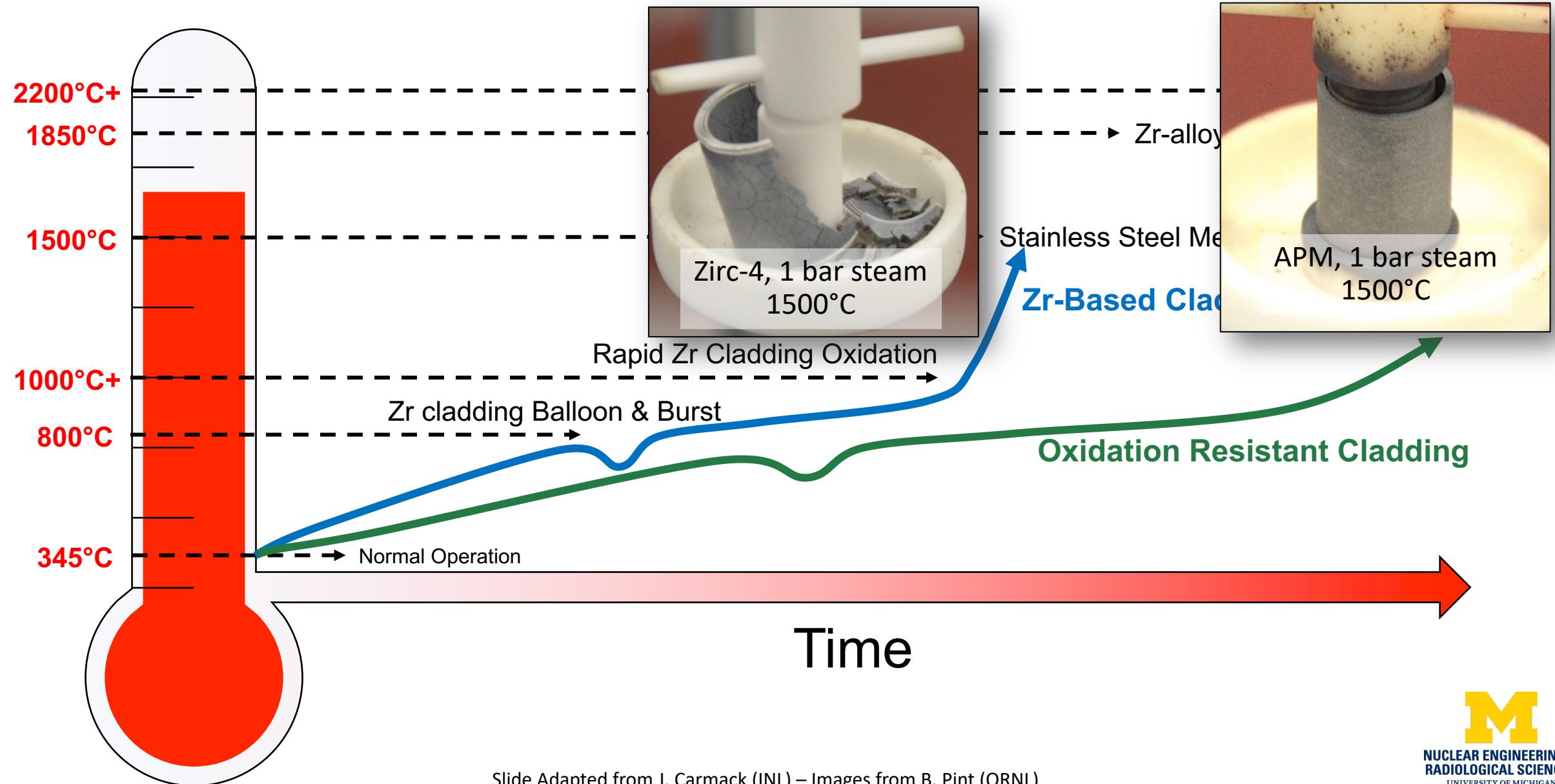
Modern Example: GE's IronClad ATF solution



Oxidation of cladding is key towards core degradation during a coolant-limited accident scenario



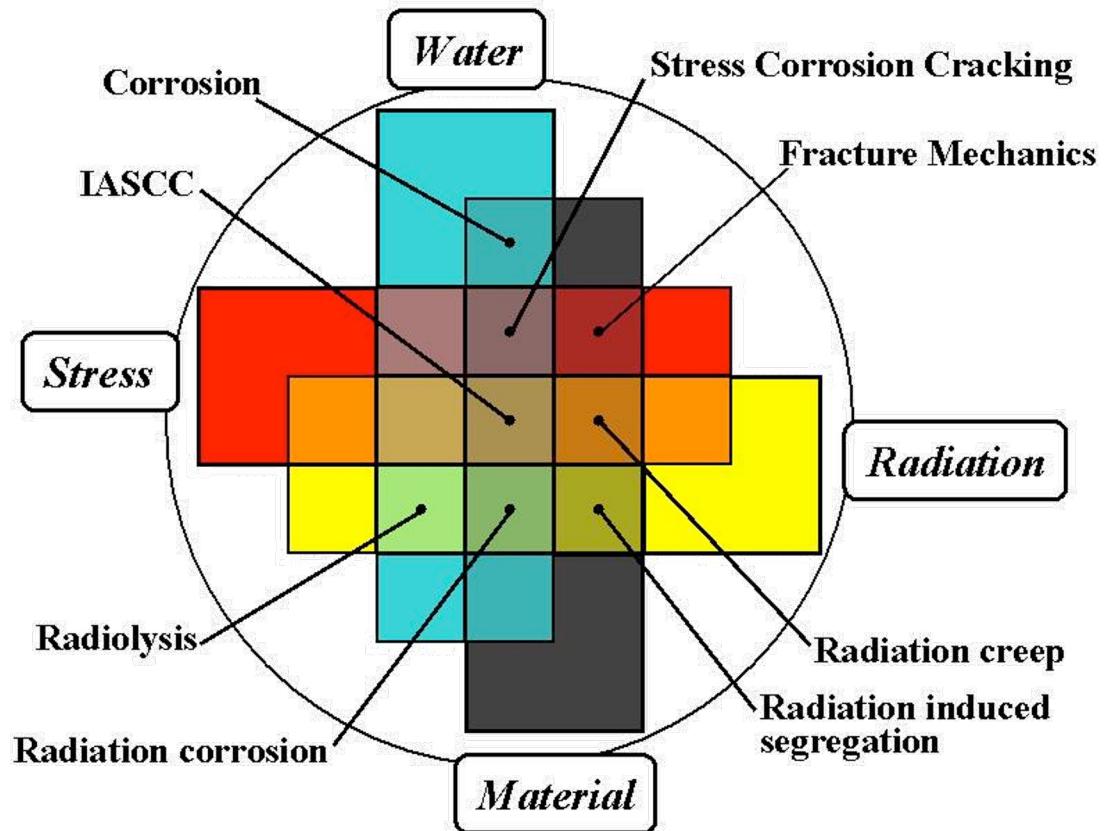
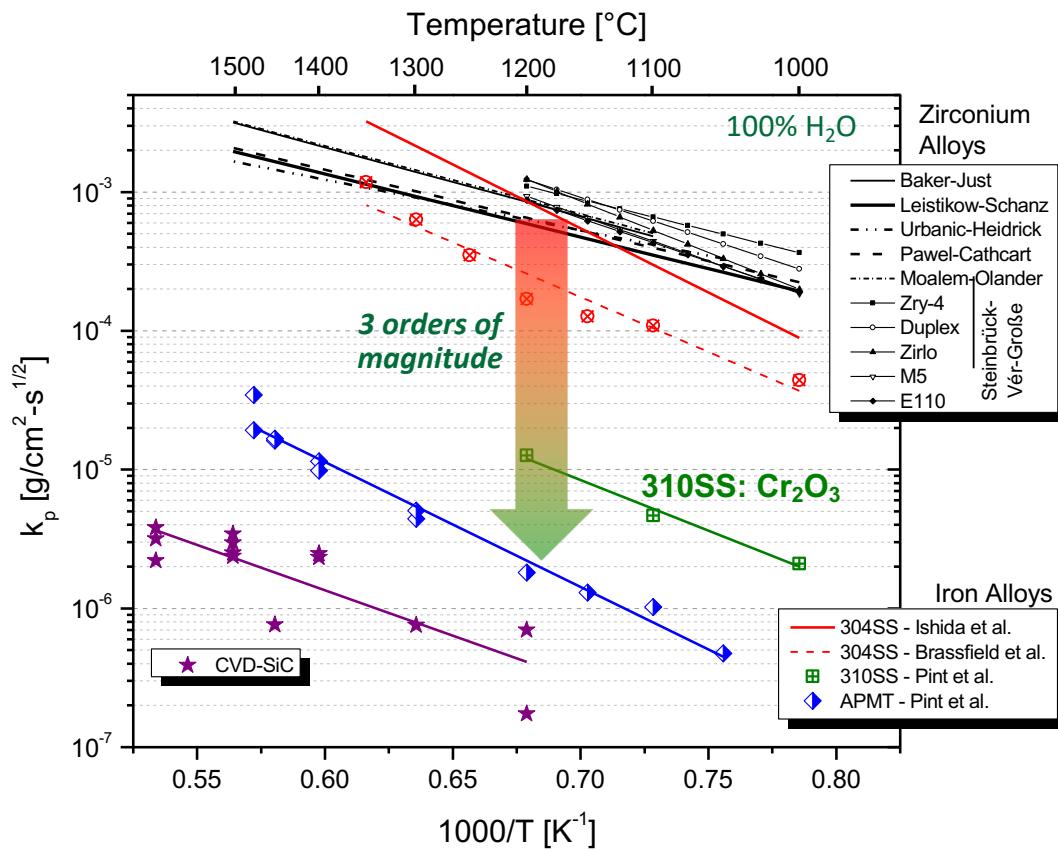
Oxidation of cladding is key towards core degradation during a coolant-limited accident scenario



Slide Adapted from J. Carmack (INL) – Images from B. Pint (ORNL)

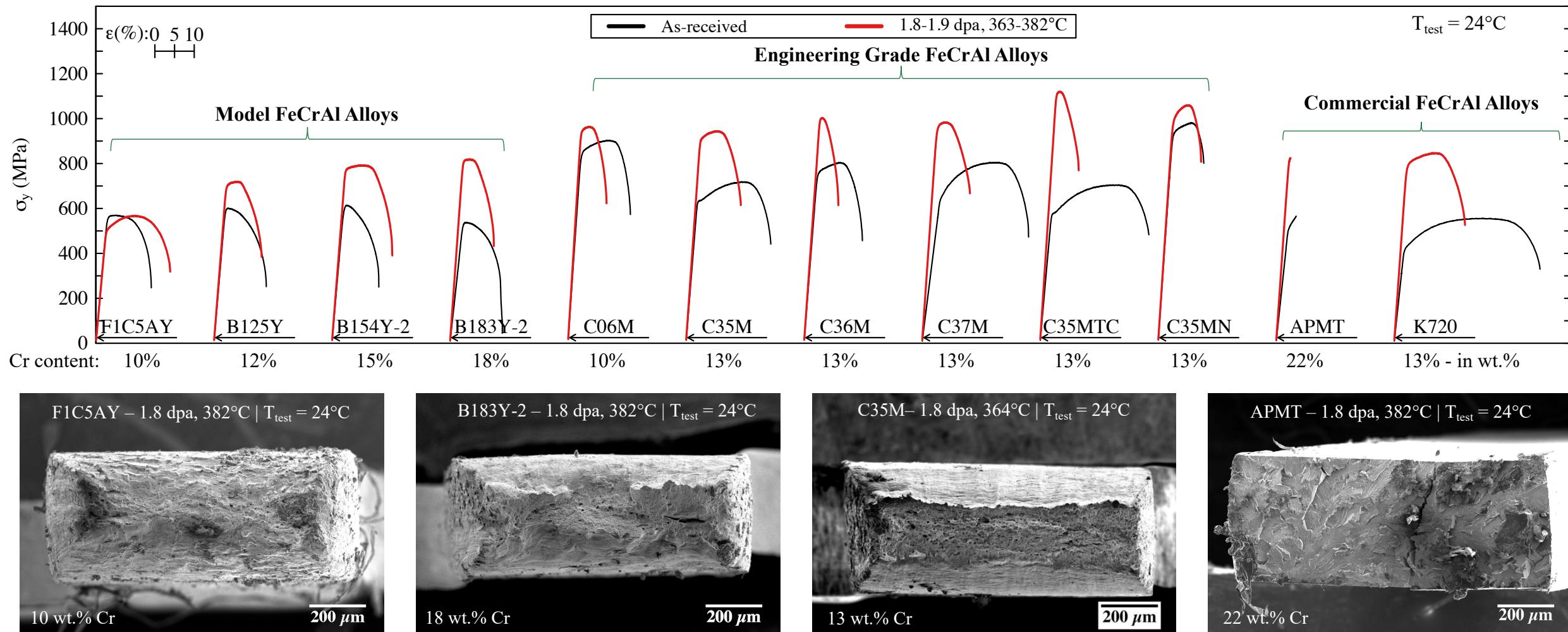


Finding oxidation resistance alloys that increase safety is easy...



...but, understanding how they perform in a LWR is not

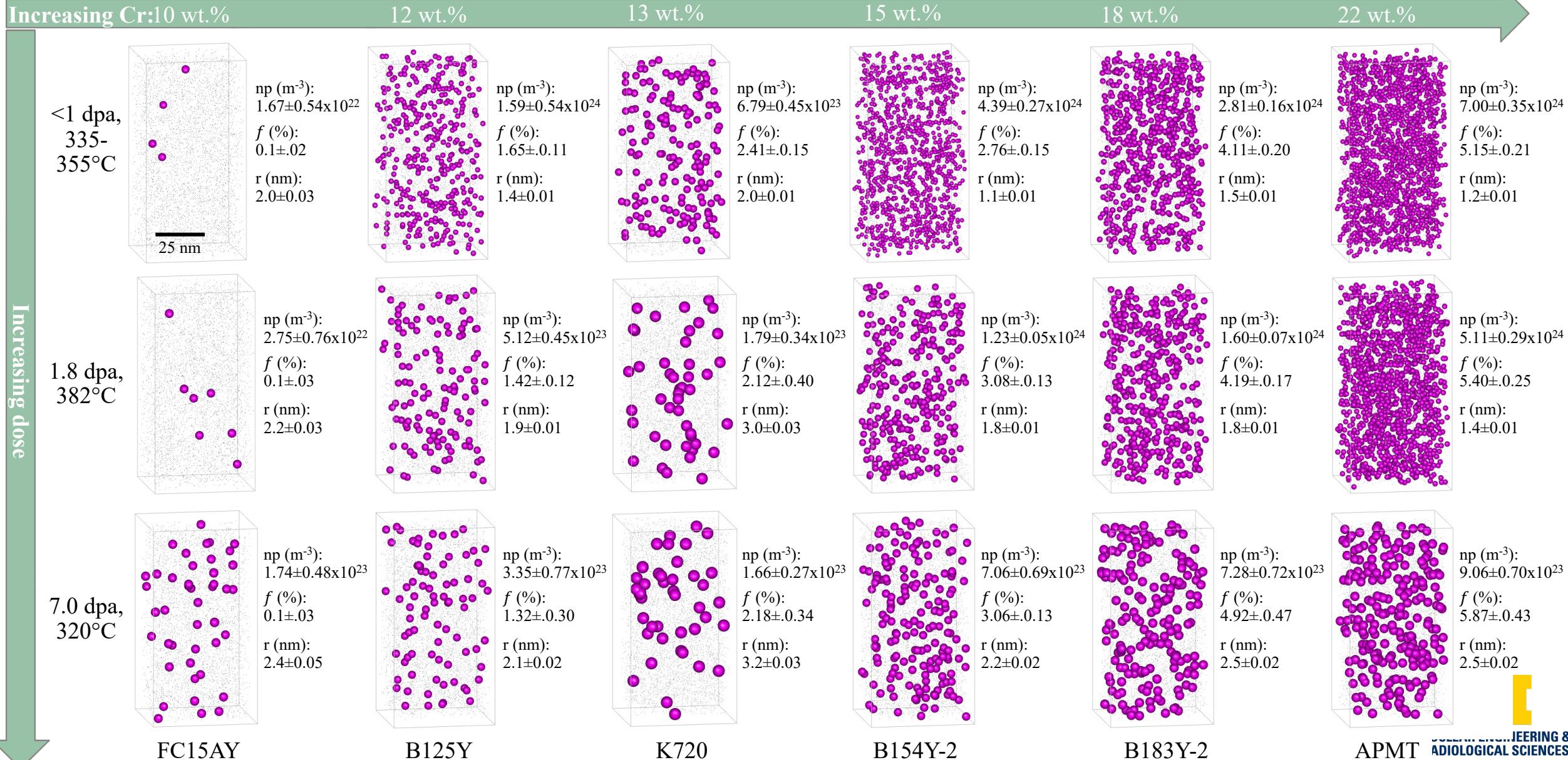
All wrought FeCrAl alloys studied showed typical radiation-induced hardening for high Cr ferritic alloys



- [1] Field, et al. / *Journal of Nuclear Materials* 465 (2015)
[2] Field, et al. / *Journal of Nuclear Materials* 489 (2017)

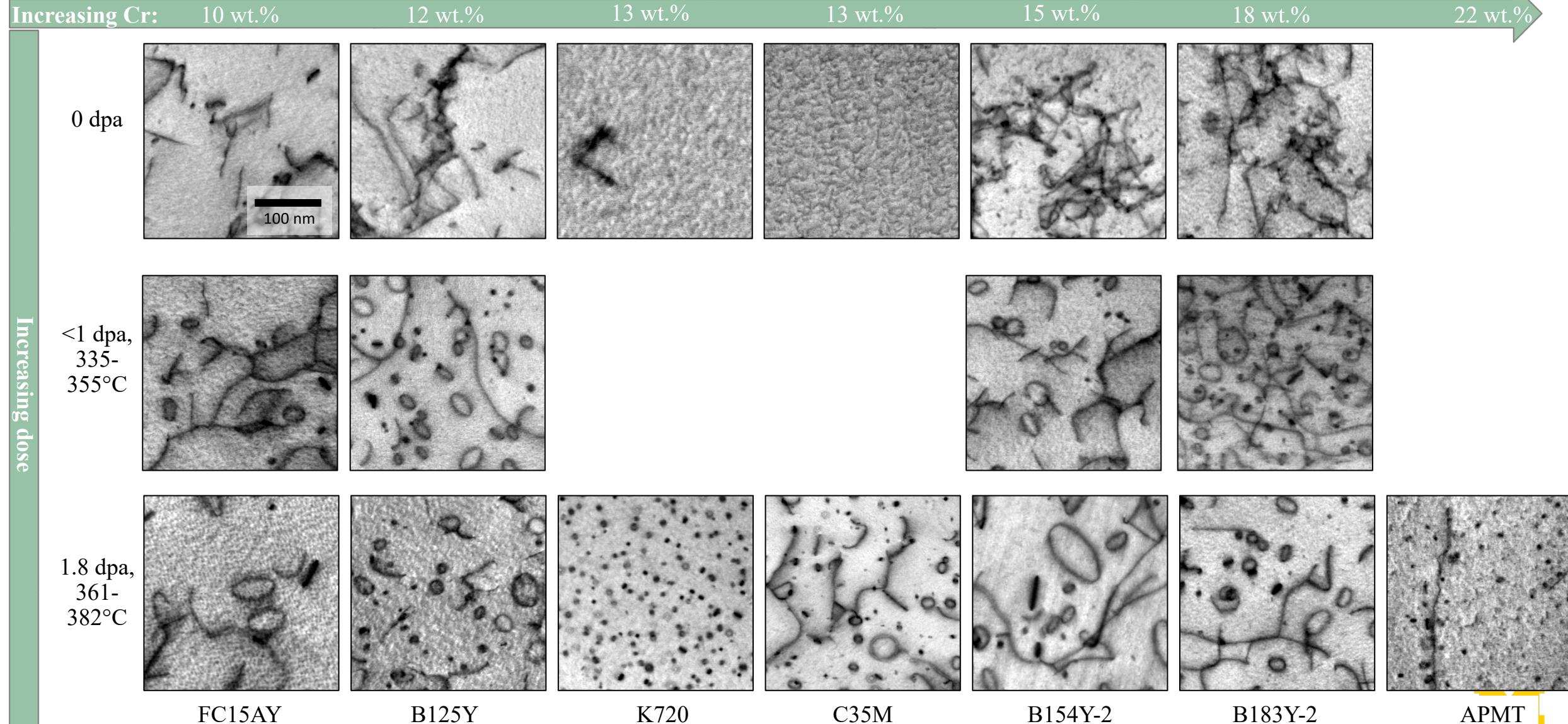


Trends in precipitation of Cr-rich a' in FeCrAl alloys

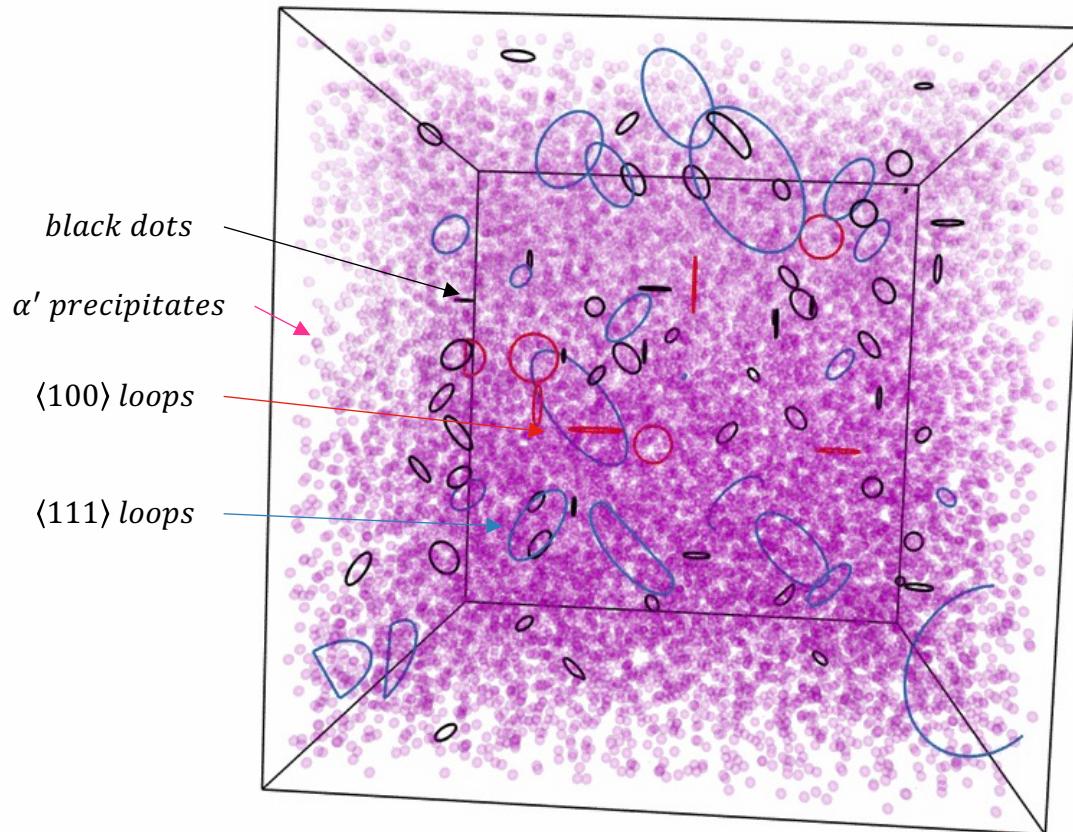


Trends in dislocation loops in FeCrAl alloys

*All images to same scale

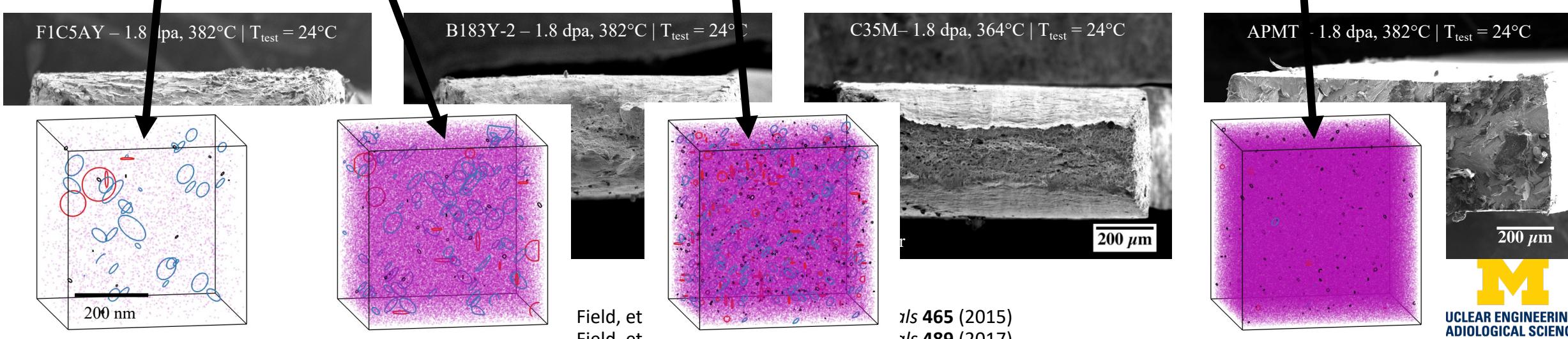
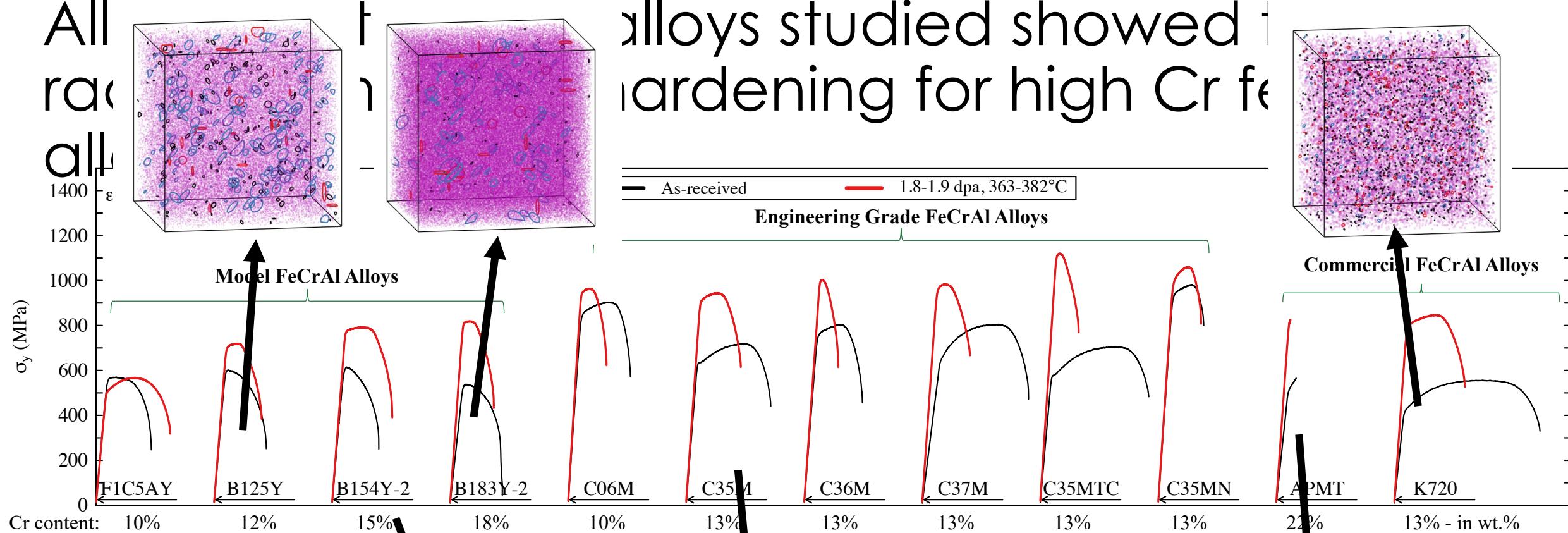


Putting the two together and visualizing:

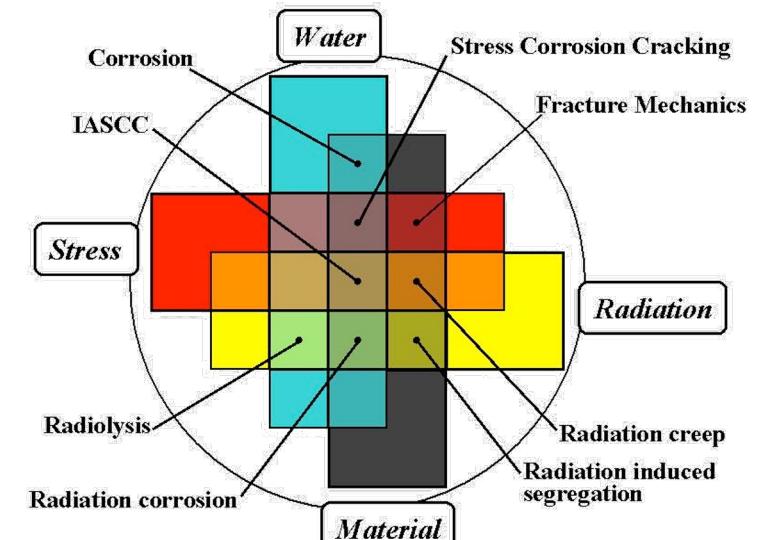
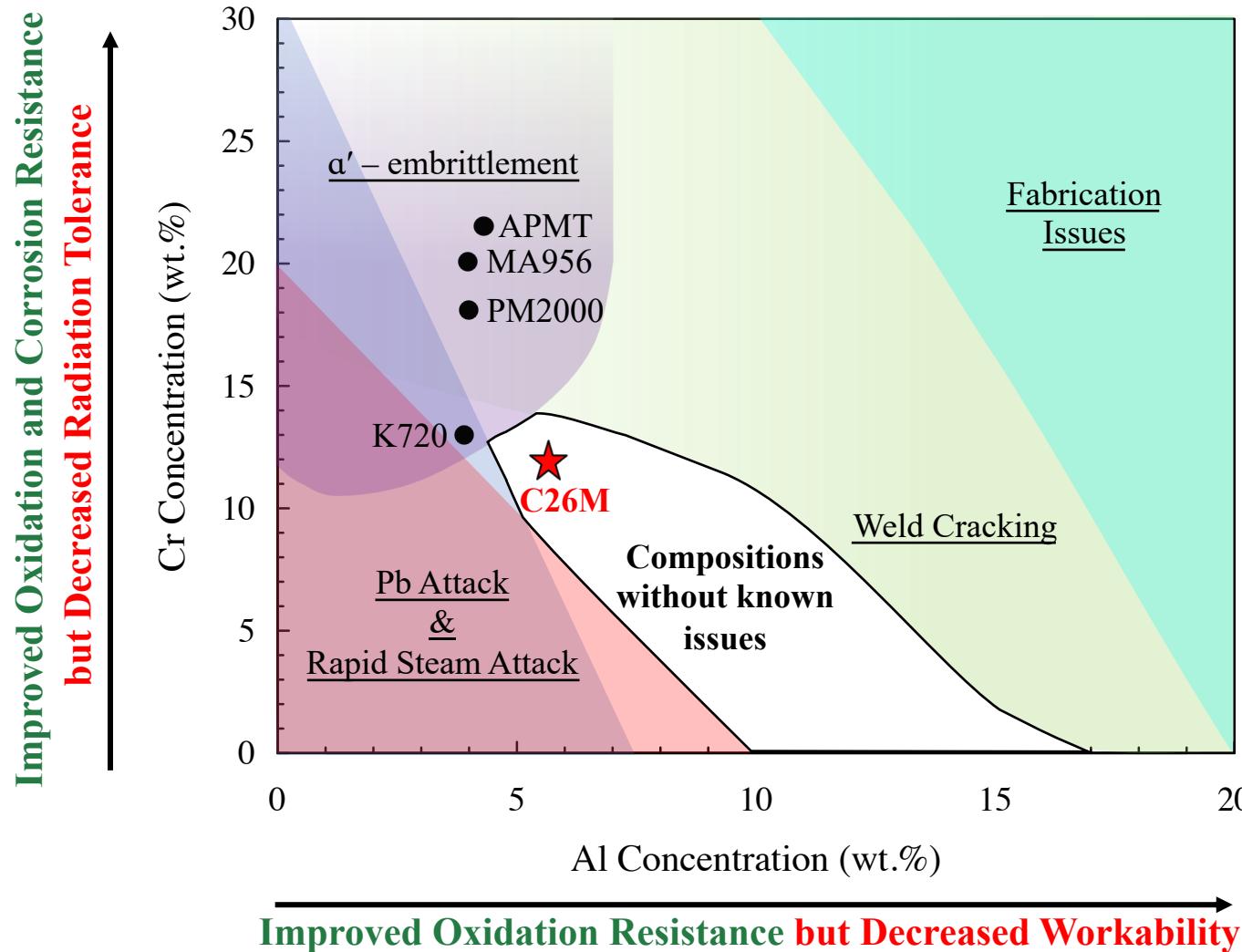


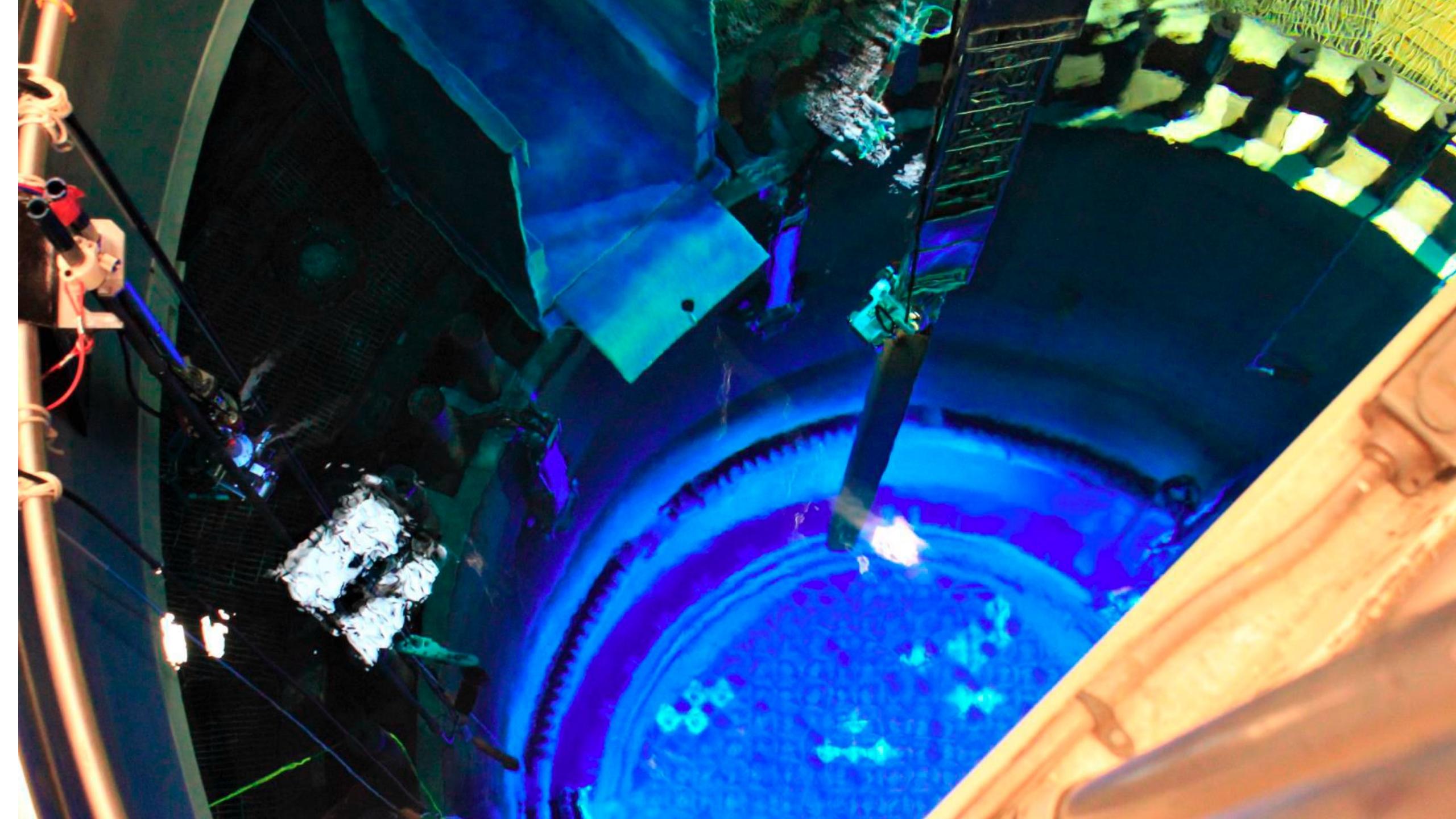
1.8 dpa, 382°C Fe-18Cr-Al synthetically
rendered microstructure (300X300X300 nm)

All
radiation
alloys studied showed hardening for high Cr fe



Weldability and radiation tolerance define the upper bounds on Al and Cr content of FeCrAl alloys¹





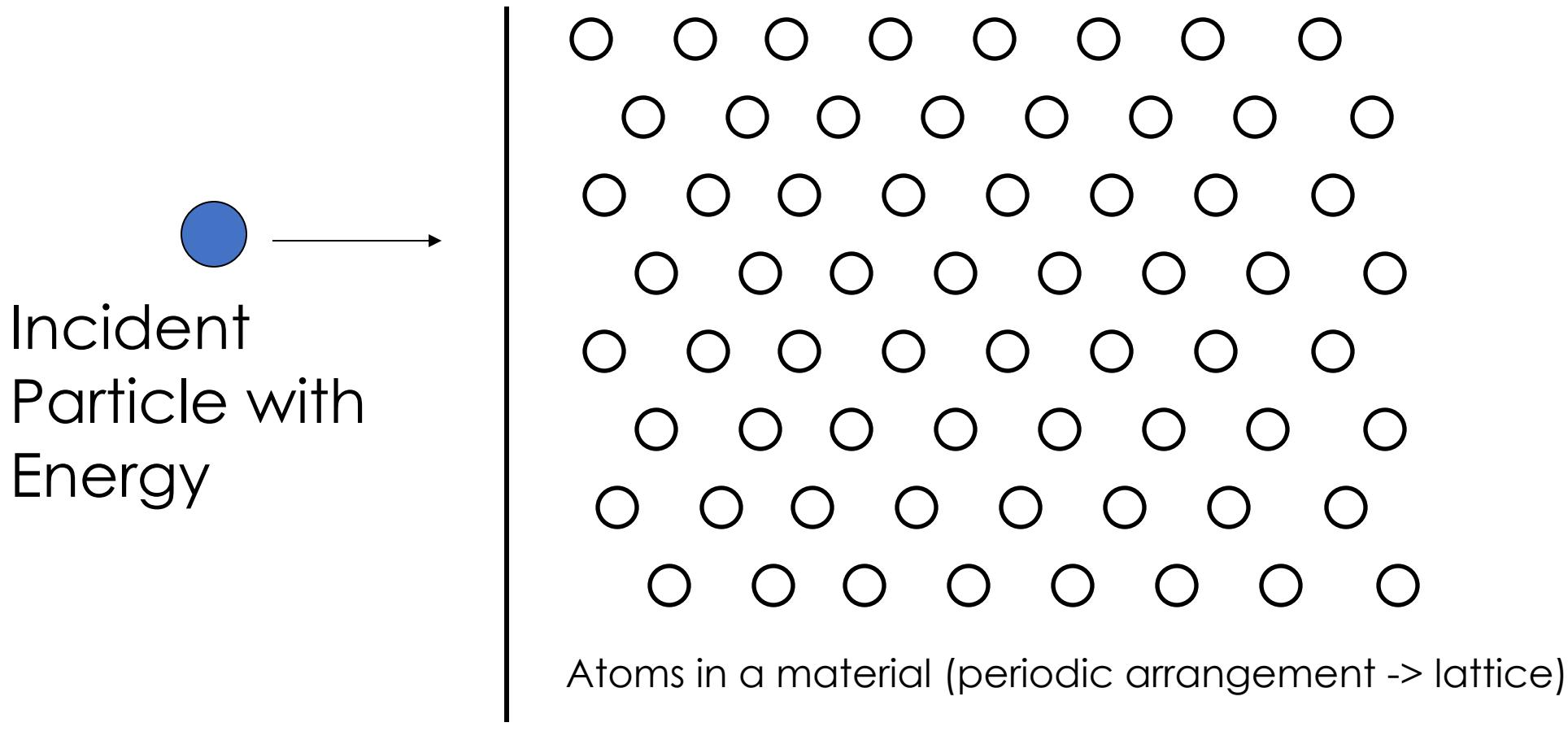
Lecture Break



NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Radiation Damage: the basics

- All of radiation damage boils down to a common step:
collisions between energetic particles and atoms composing a material

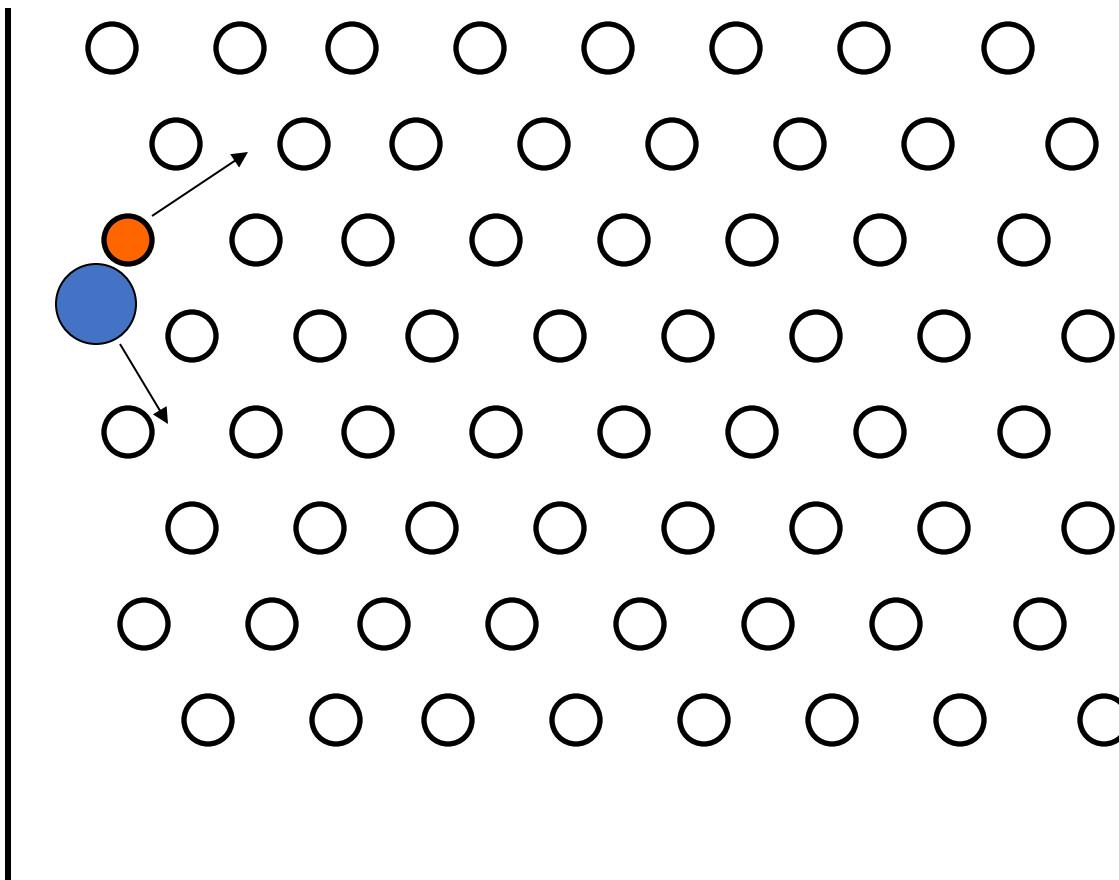


Source: T.R. Allen



Radiation Damage: the basics

- All of radiation damage boils down to a common step:
collisions between energetic particles and atoms composing a material



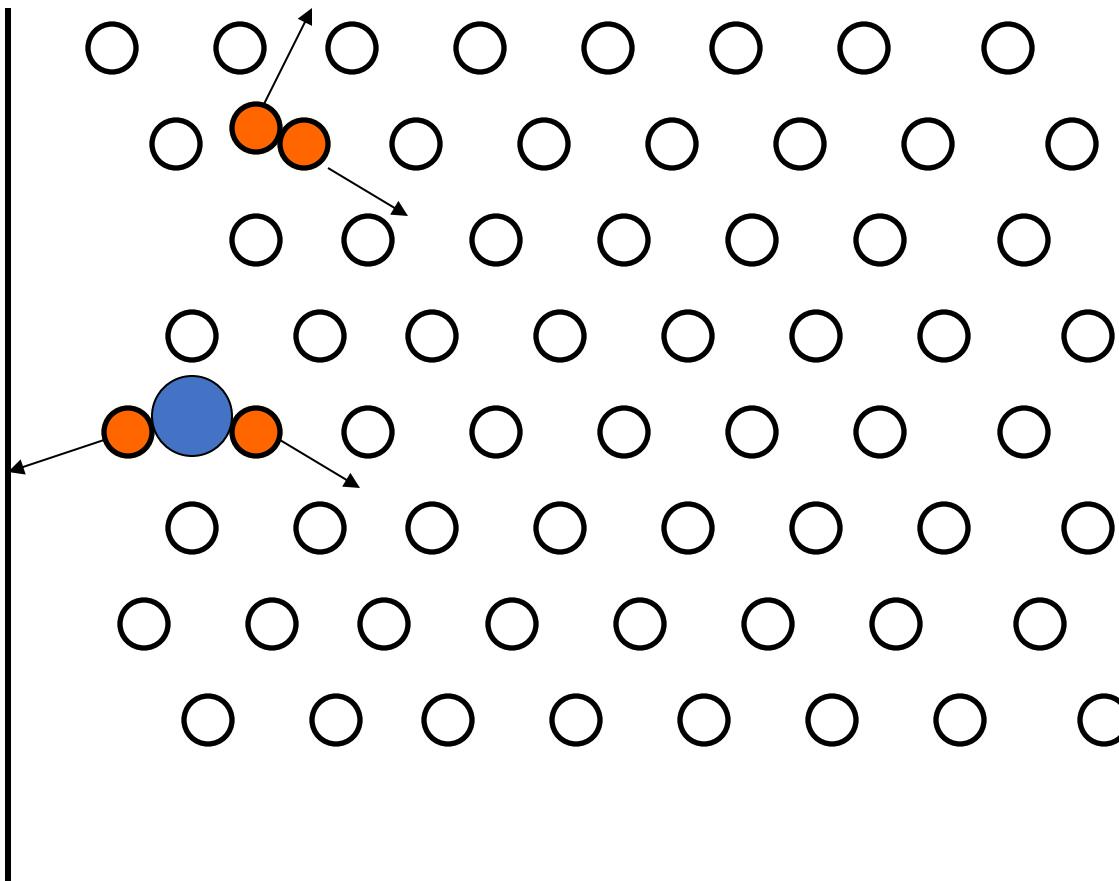
Source: T.R. Allen



NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Radiation Damage: the basics

- All of radiation damage boils down to a common step:
collisions between energetic particles and atoms composing a material

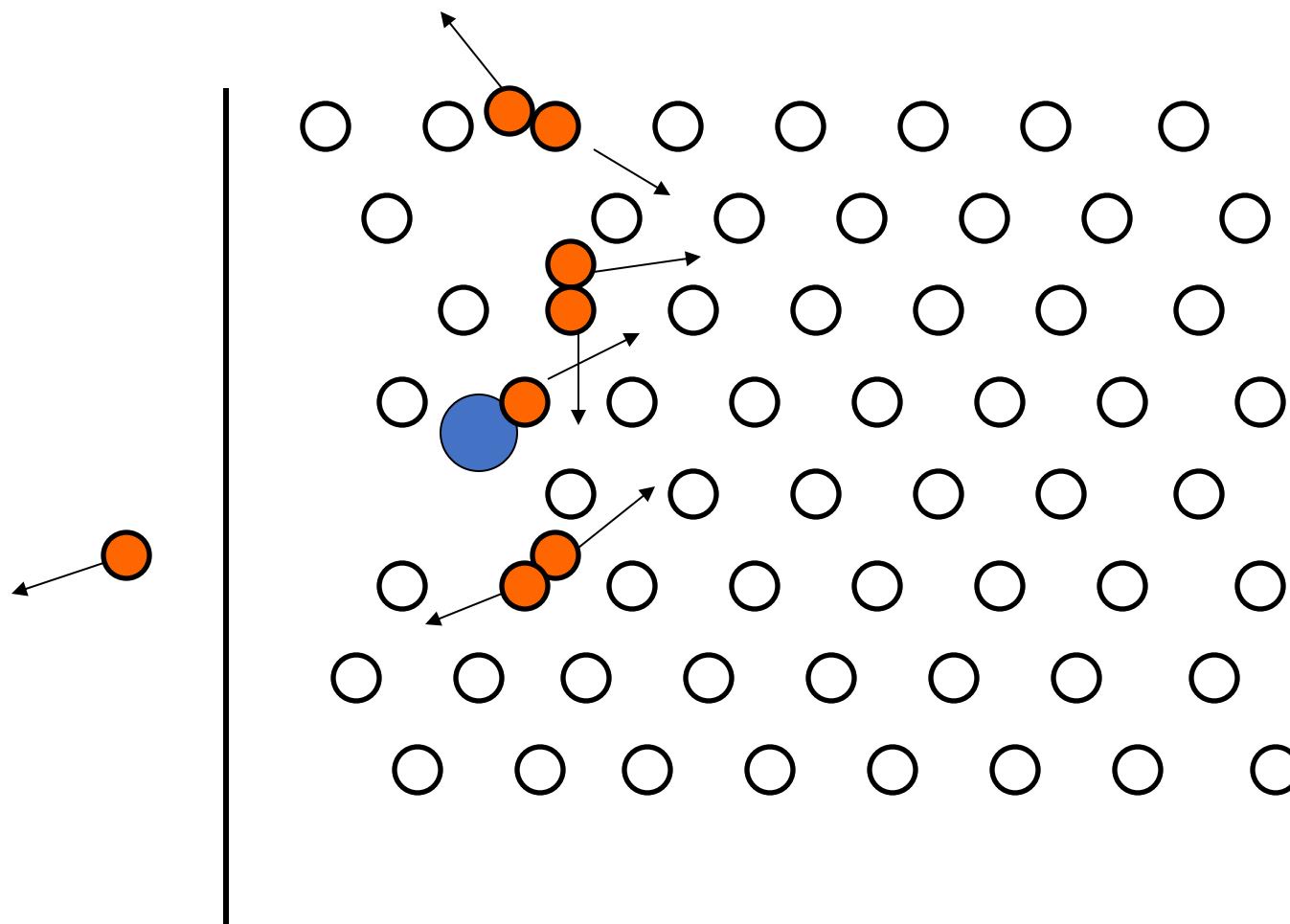


Source: T.R. Allen



Radiation Damage: the basics

- All of radiation damage boils down to a common step:
collisions between energetic particles and atoms composing a material



Source: T.R. Allen

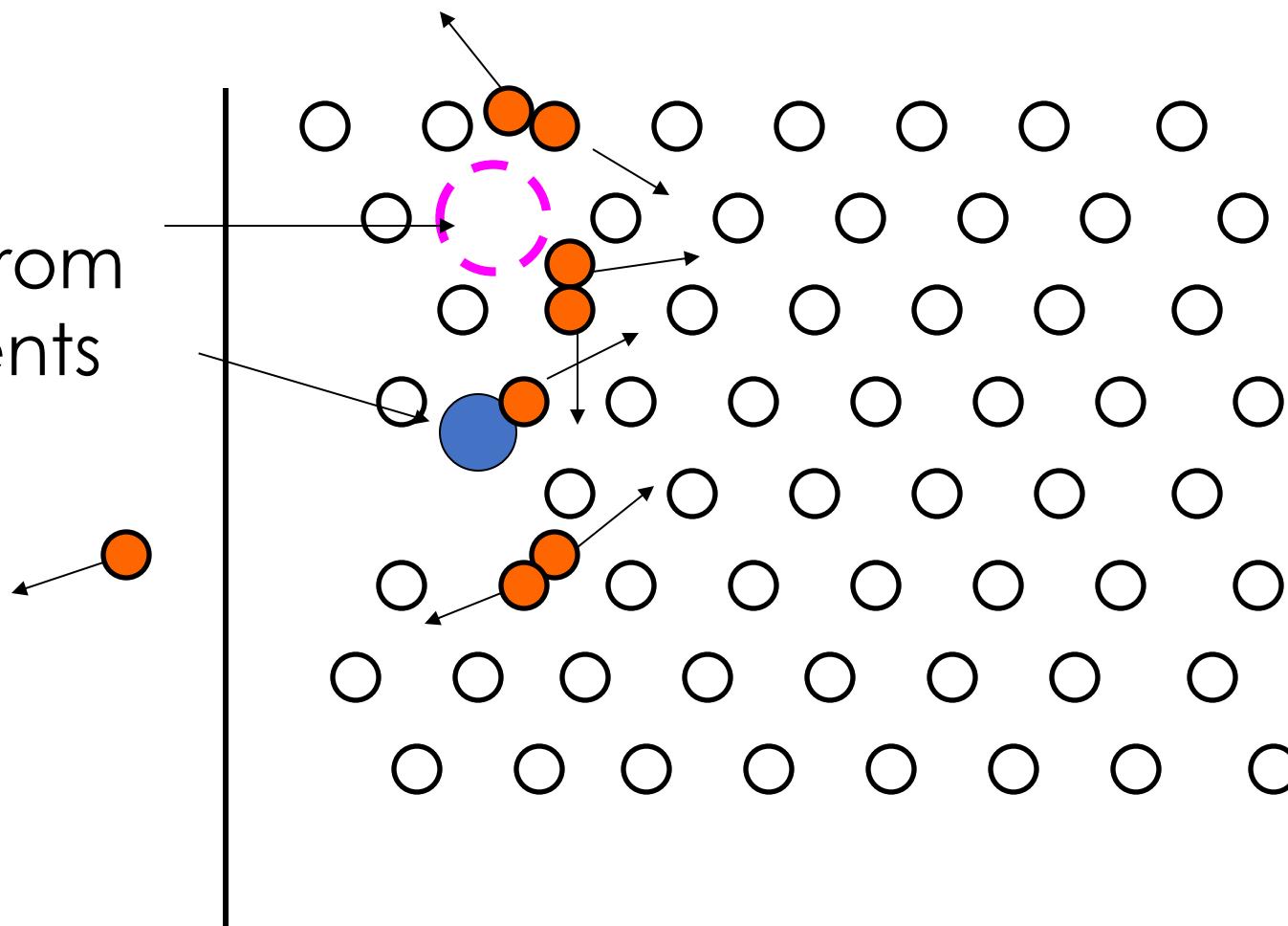


NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Radiation Damage: the basics

- All of radiation damage boils down to a common step:
collisions between energetic particles and atoms composing a material

Defects
produced from
displacements

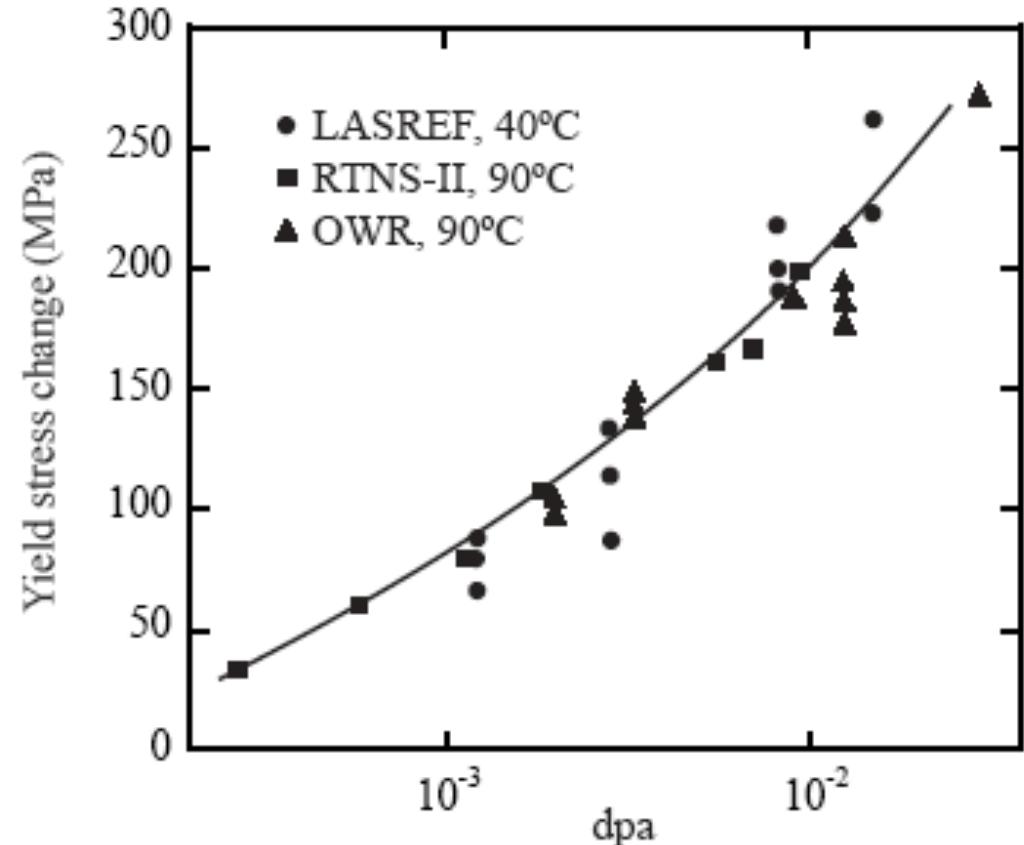
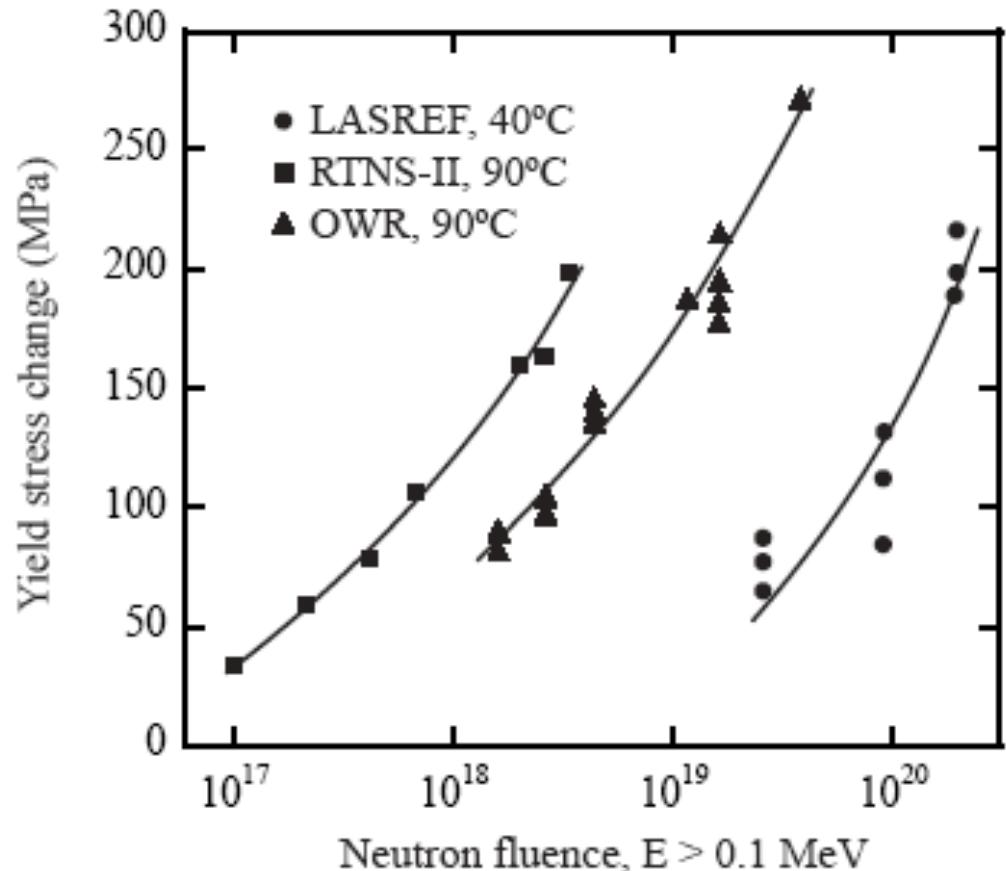


Source: T.R. Allen



NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Importance of displacement versus fluence for this class

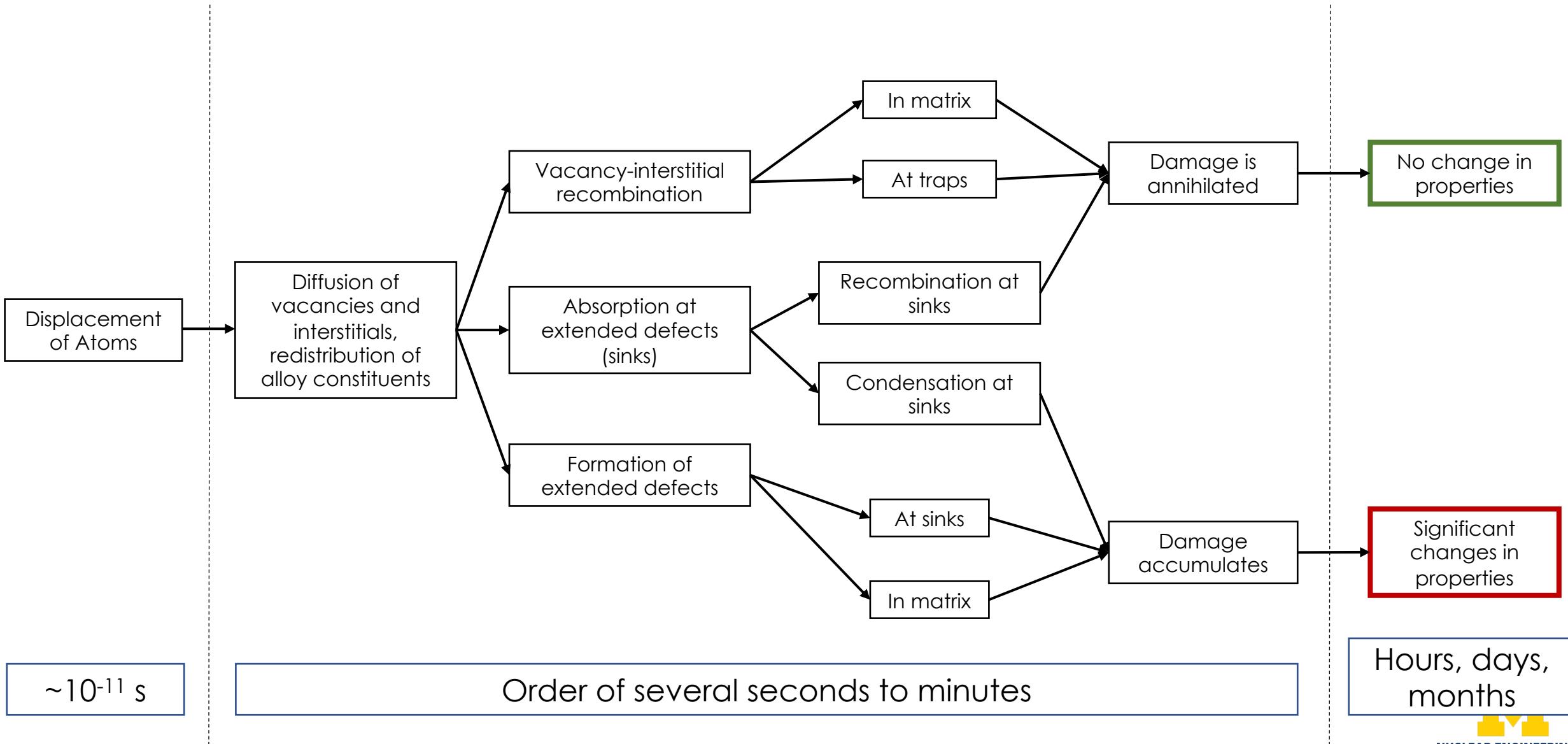


Comparison of yield stress change in 316 stainless steel irradiated in different reactors

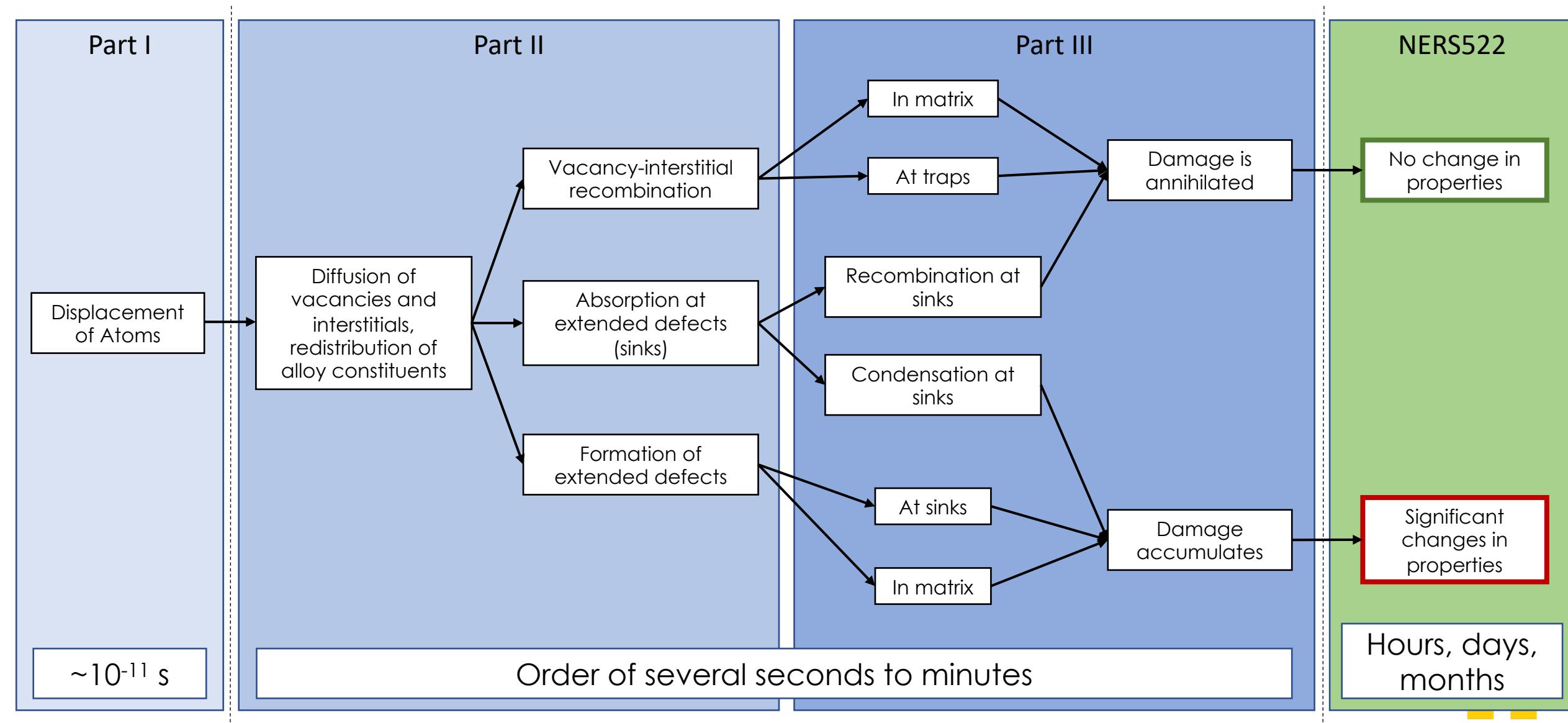


Flow chart for radiation damage

Flow chart for radiation damage



Flow chart for radiation damage



Displacement of Atoms in Detail

Part I

Displacement
of Atoms
(Radiation
Damage
Event)

$\sim 10^{-11}$ s

- Displacement of atoms is primarily evaluated as the **radiation damage event** which is composed of the following sequence of events:
1. The interaction of an energetic particle with a lattice atom
 2. The transfer of kinetic energy to the lattice atom resulting in the primary knock-on atom (PKA)
 3. The displacement of the lattice atom from it's lattice site
 4. The passage of the displaced atom through the structure and the potential accompanying creation of additional knock-on atoms
 5. The production of a displacement cascade
 6. The termination of the PKA as an interstitial in the structure

Displacement of Atoms in Detail

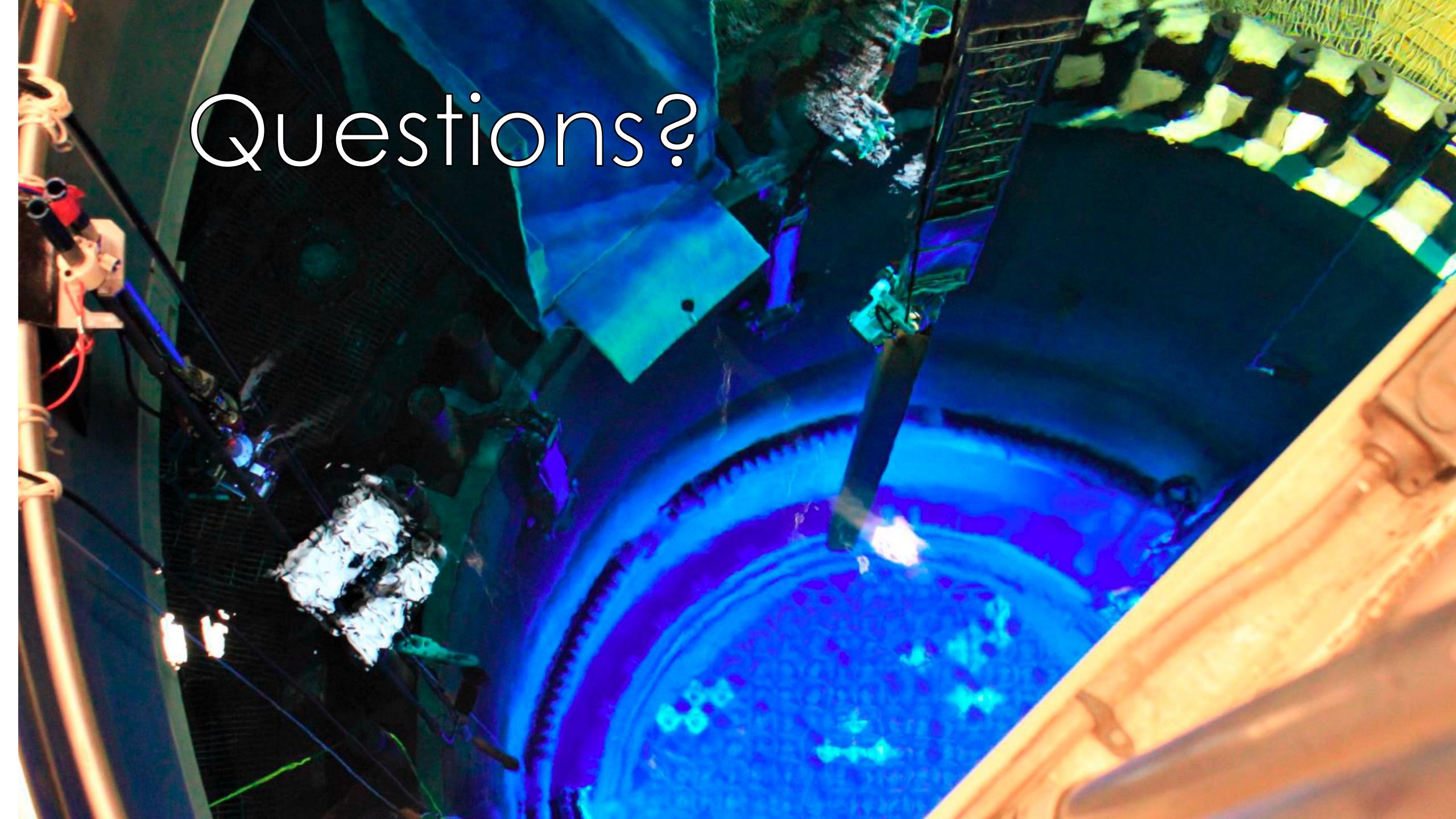
Part I

Displacement
of Atoms
(Radiation
Damage
Event)

$\sim 10^{-11}$ s

- Displacement of atoms is a **radiation damage event** which is composed of the following sequence of events:
1. The interaction of an energetic particle with a lattice atom
 2. The transfer of kinetic energy to the lattice atom resulting in the primary knock-on atom (PKA)
 3. The displacement of the lattice atom from its lattice site
 4. The passage of the displaced atom through the structure and the potential accompanying creation of additional knock-on atoms
 5. The production of a displacement cascade
 6. The termination of the PKA as an interstitial in the structure

Next two
lectures



Questions?