

Class Introduction

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

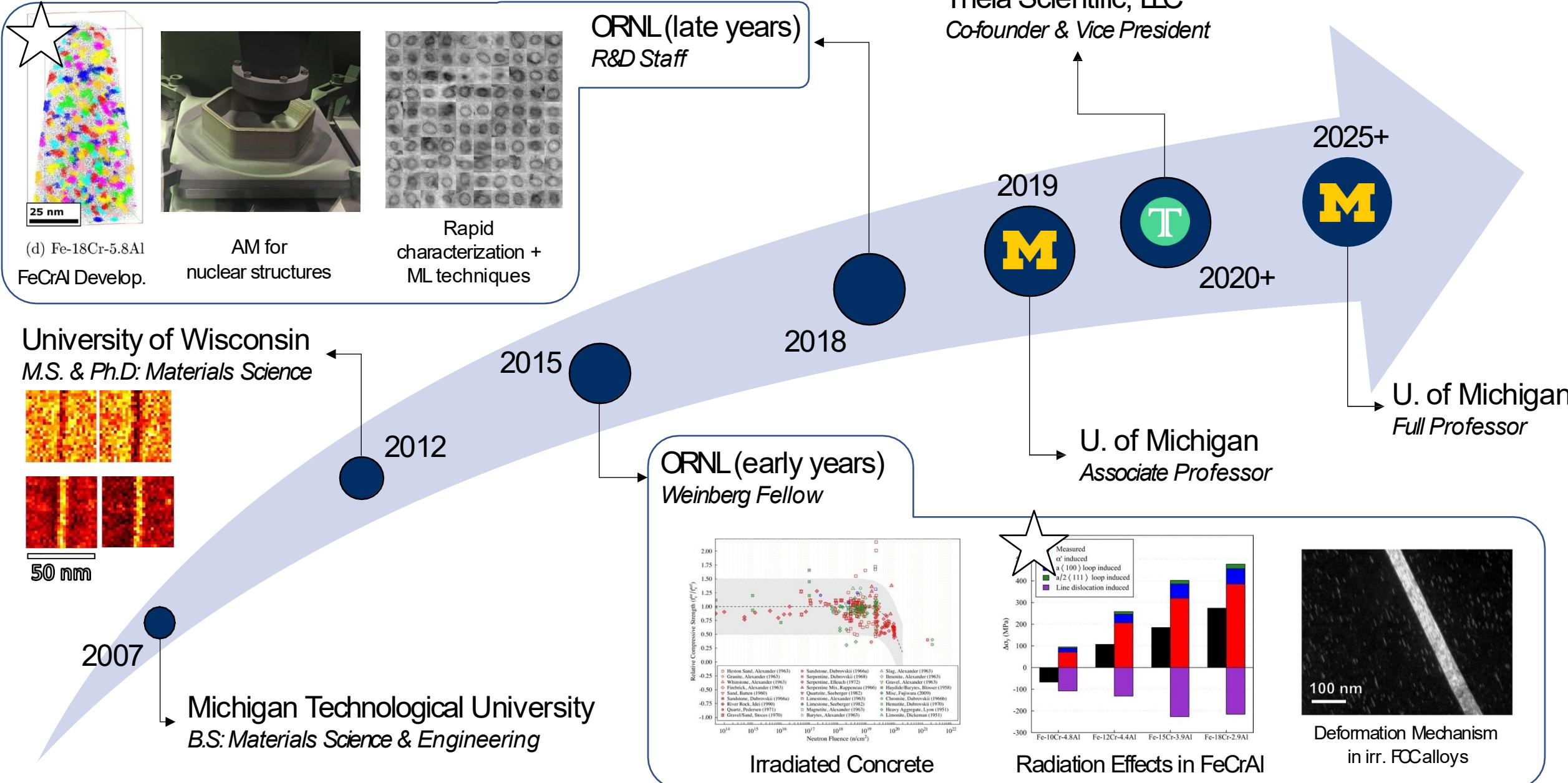
^a kgfield@umich.edu

¹University of Michigan



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About me:





About you - introductions

Minimum amount of information to divulge:

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

Optional:

- Something interesting about your hometown(s)

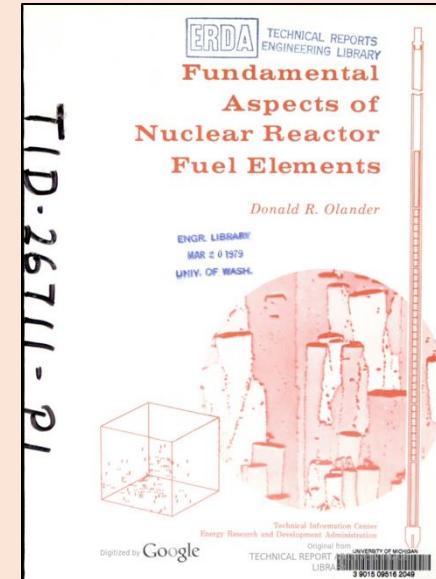
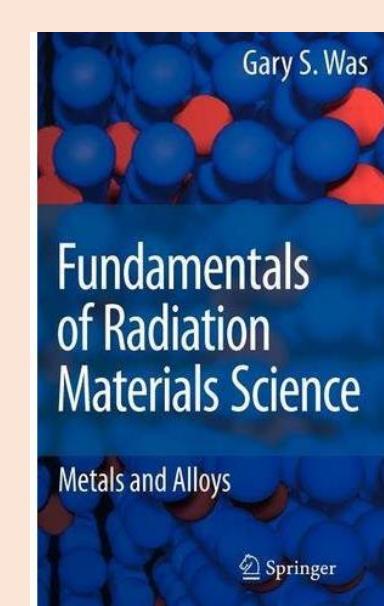
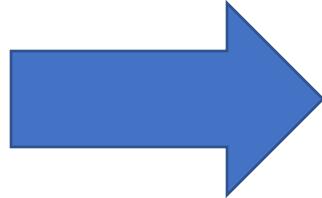
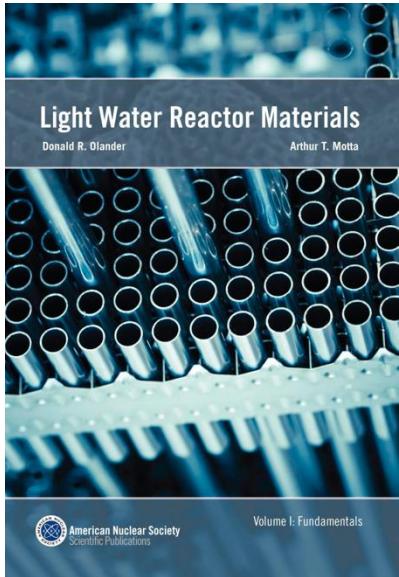


Go to Canvas Syllabus



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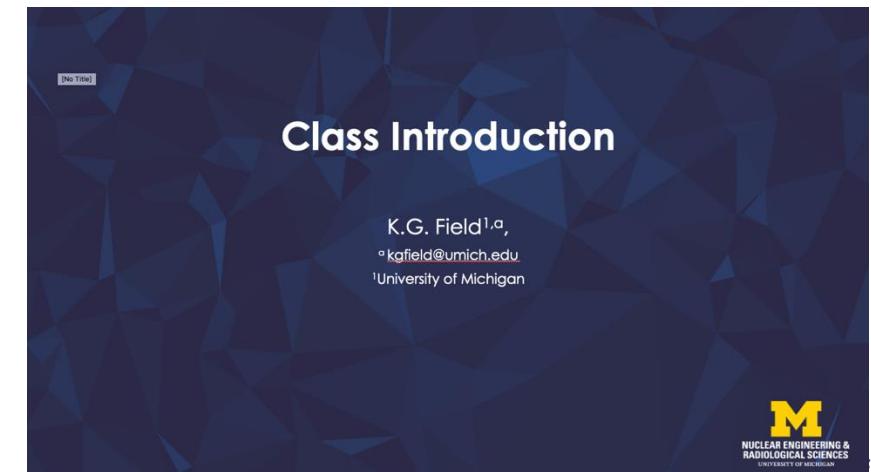
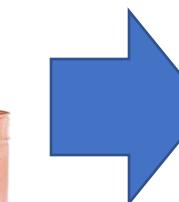
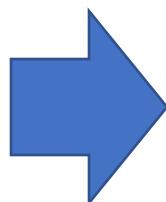
Course Materials:



Available Online (see syllabus)

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

Other books, chapters, papers, lectures, etc.



Half-time!

In Ernest Hemingway's celebrated short story, "Big Two-Hearted River," the author describes a restorative fishing trip in Michigan's Upper Peninsula. However, the story is based on his experiences on a different river, not the one in the title.

What actual Michigan river was Hemingway writing about?

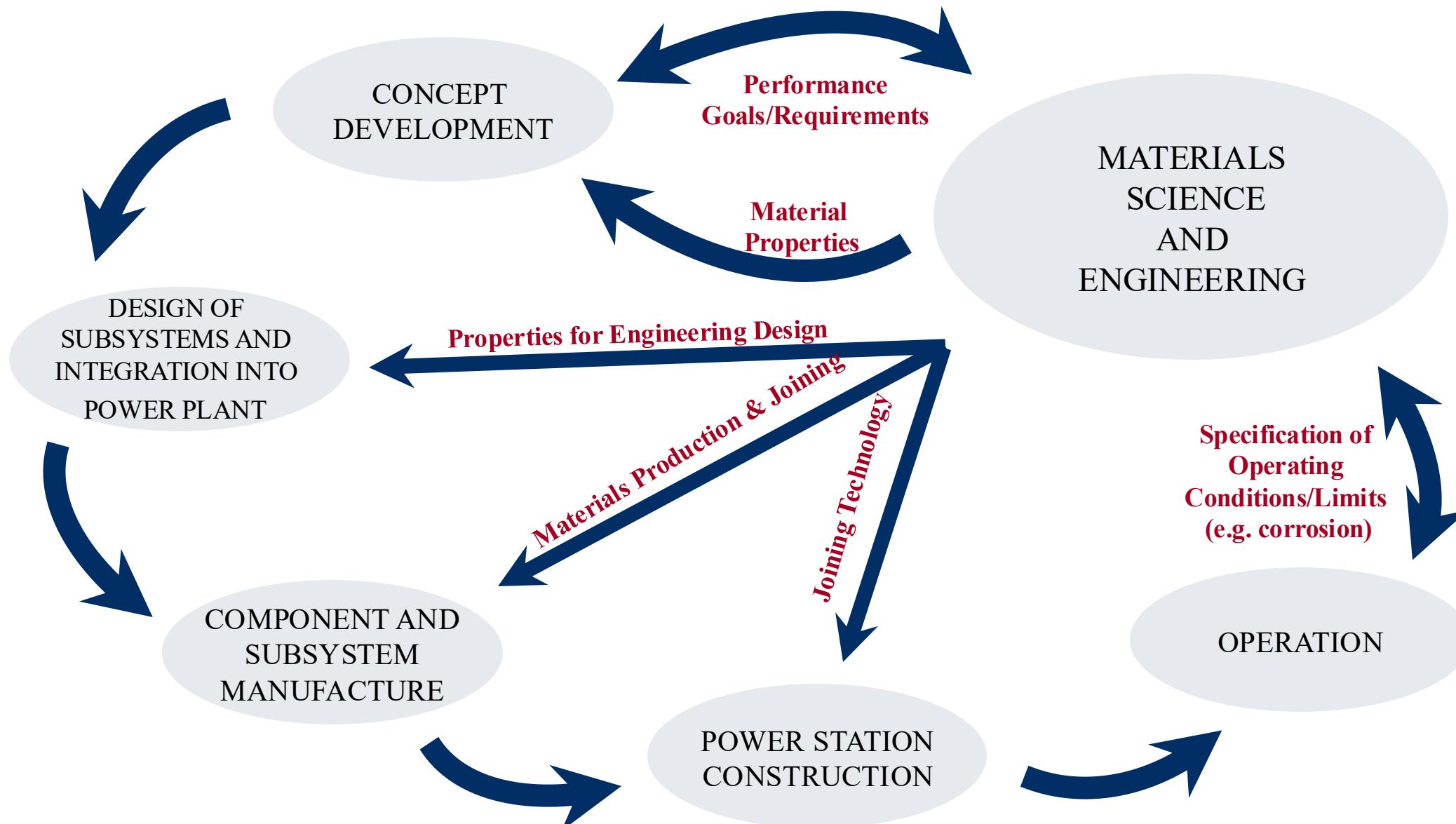


Why Radiation Materials Science?

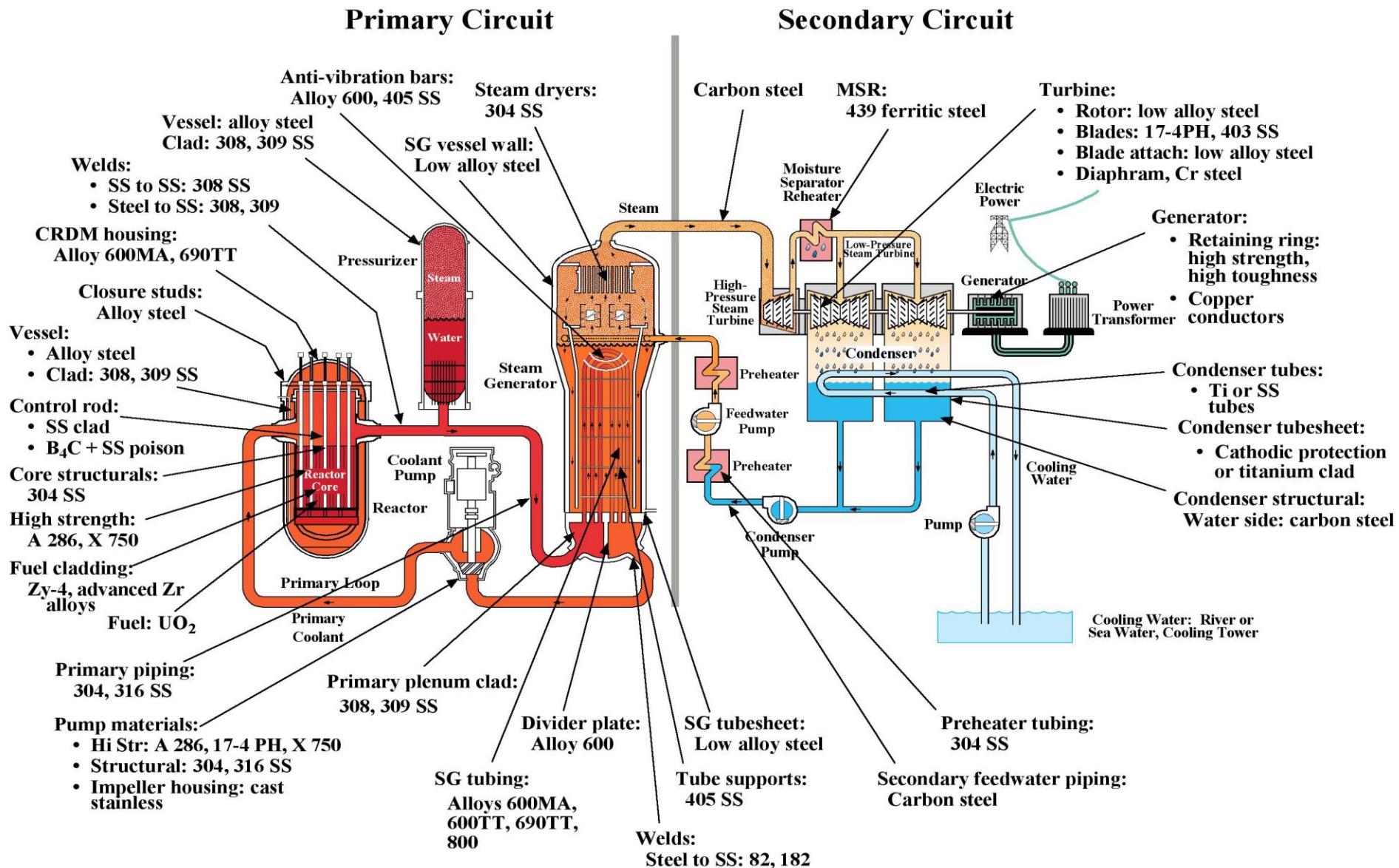


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Why Radiation Materials Science?

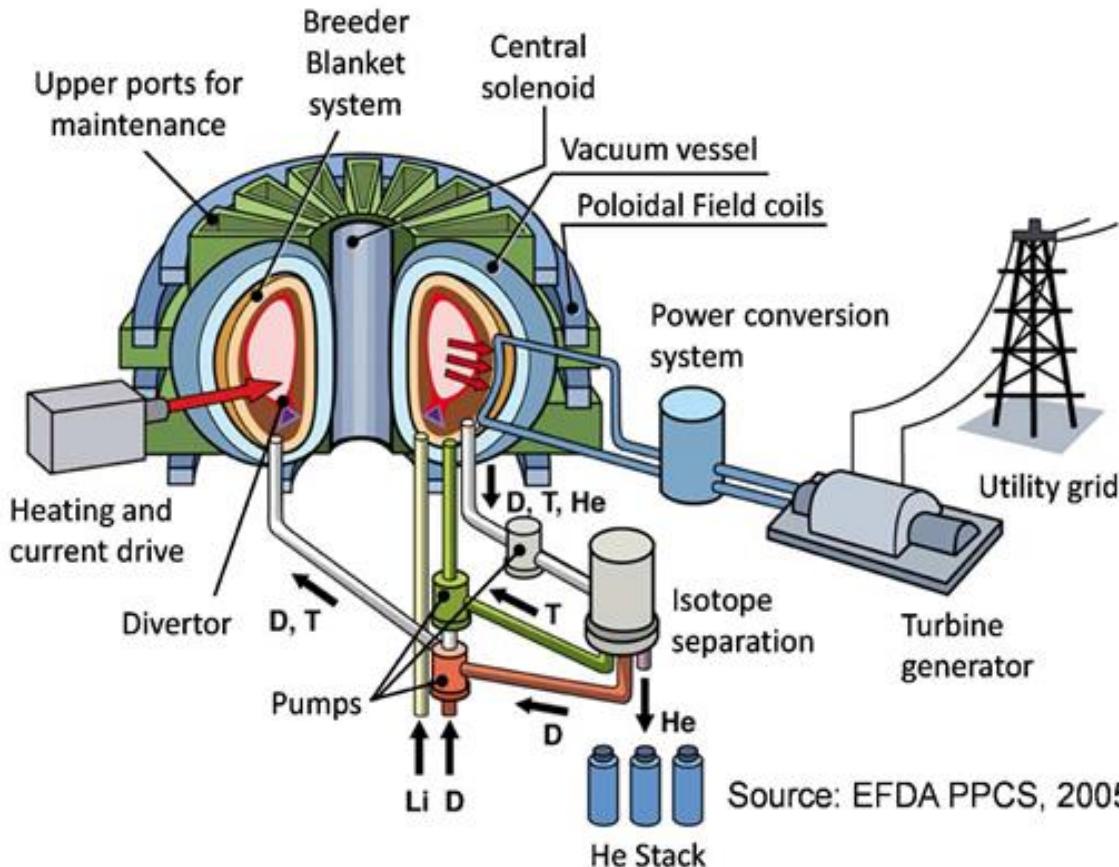


Why Radiation Materials Science?

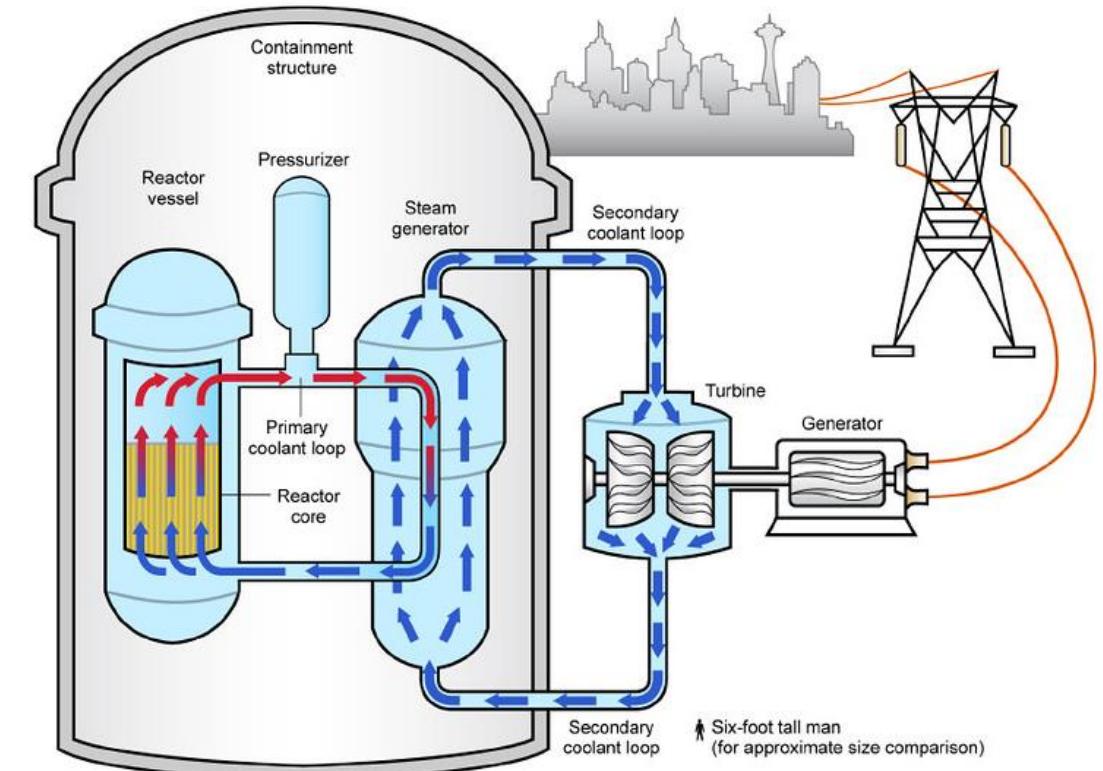


Radiation Materials Science is Applicable to Both Fission and Fusion Power:

Fusion Power Plant:

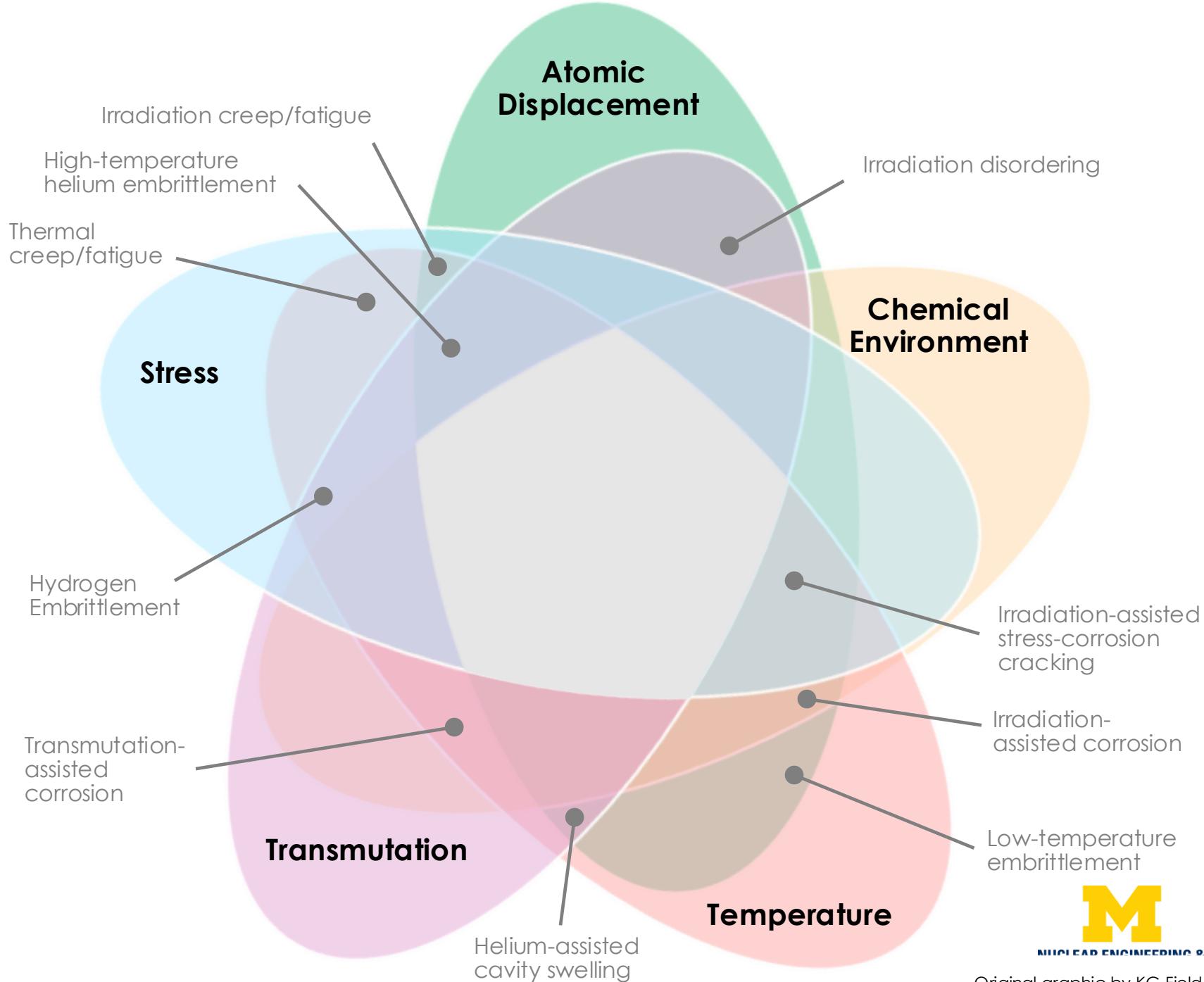


Fission Power Plant:



Materials degradation in a fusion and fission energy system can occur due to single- and **combined-effects**

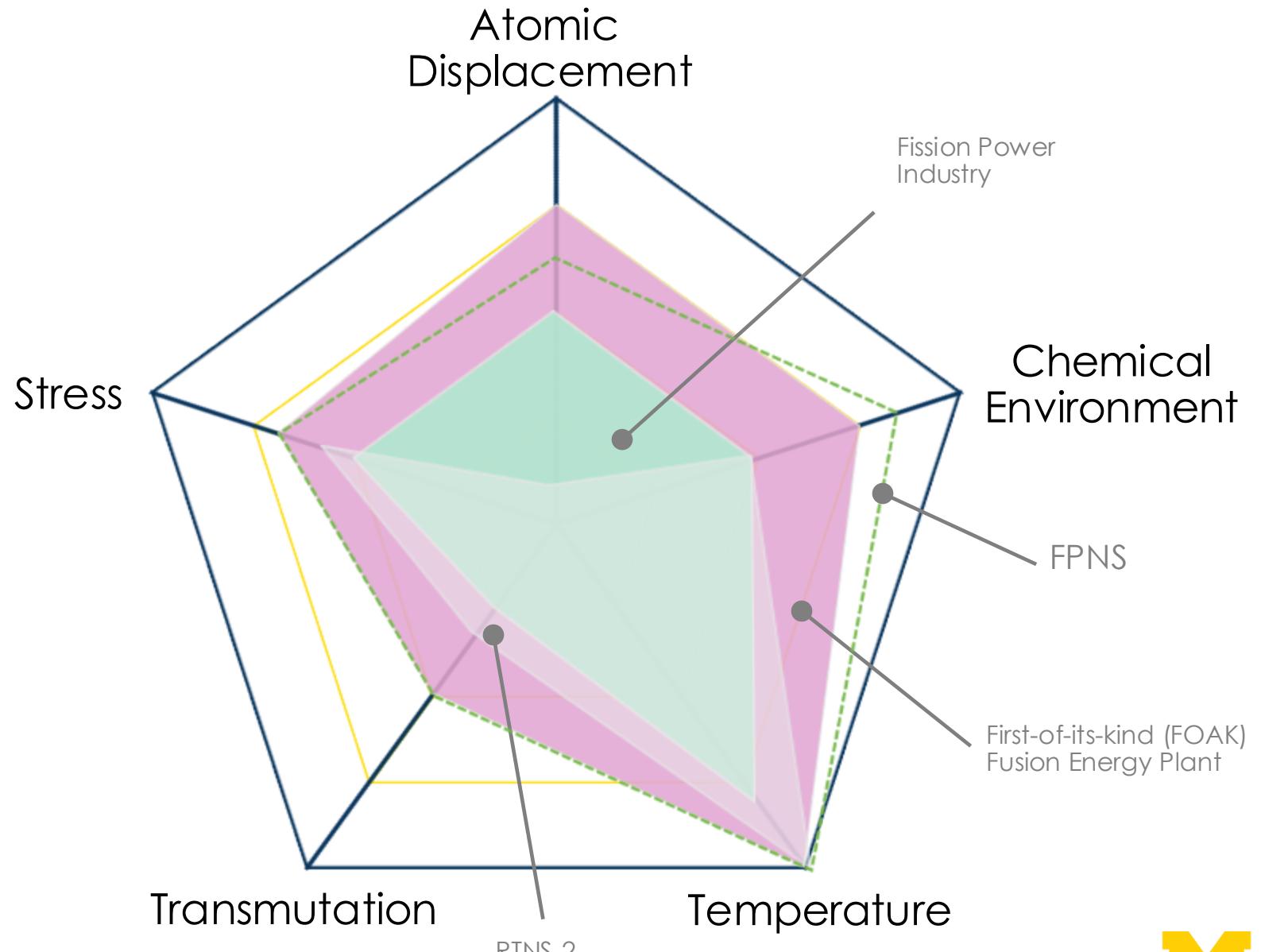
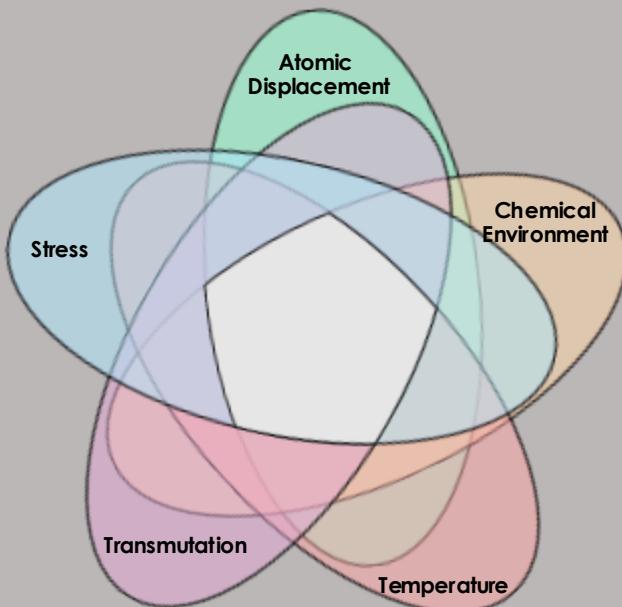
Listed degradation modes for structural materials



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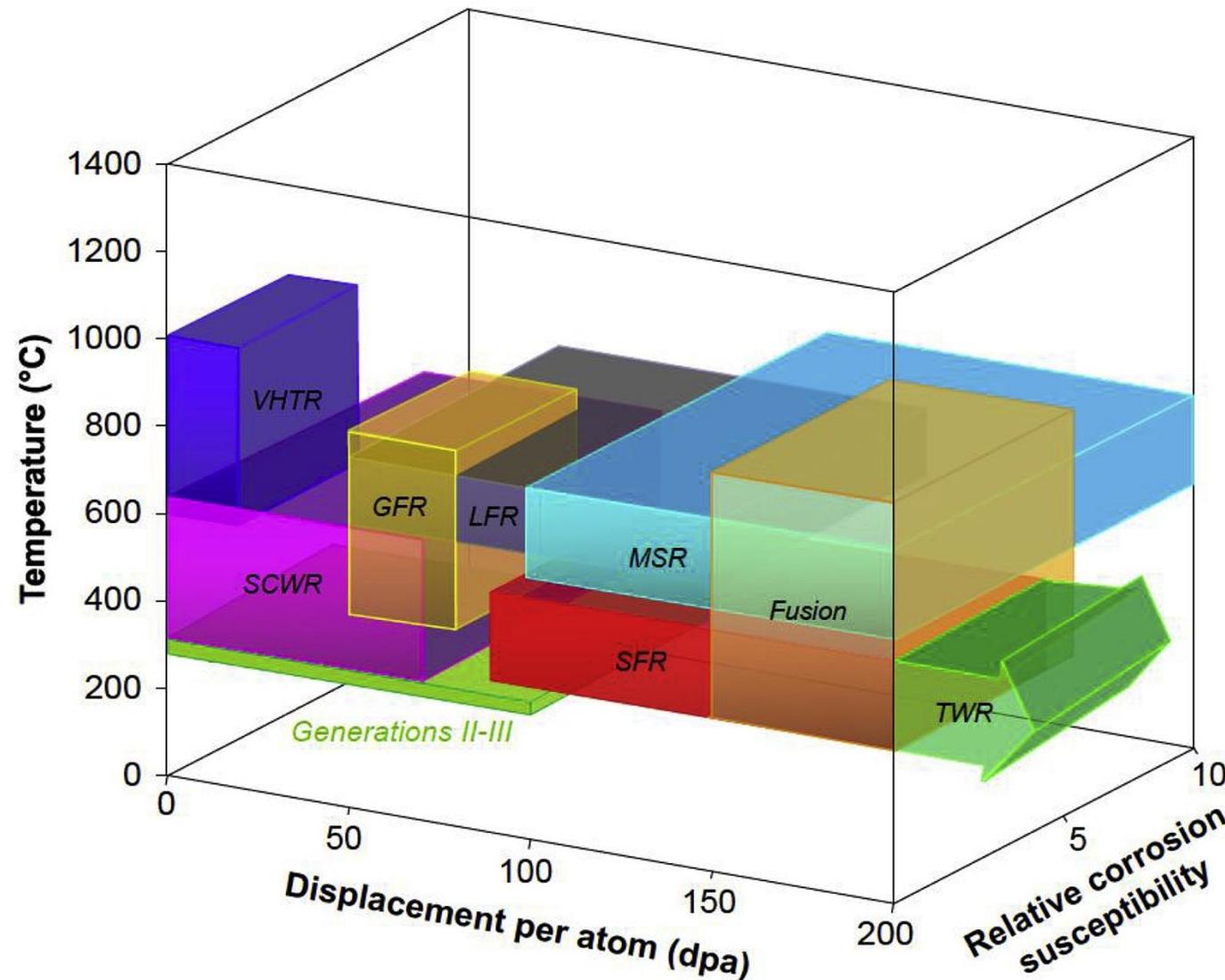
Original graphic by KG Field

Fusion and Fission Energy Systems will each have a **unique environment** for materials



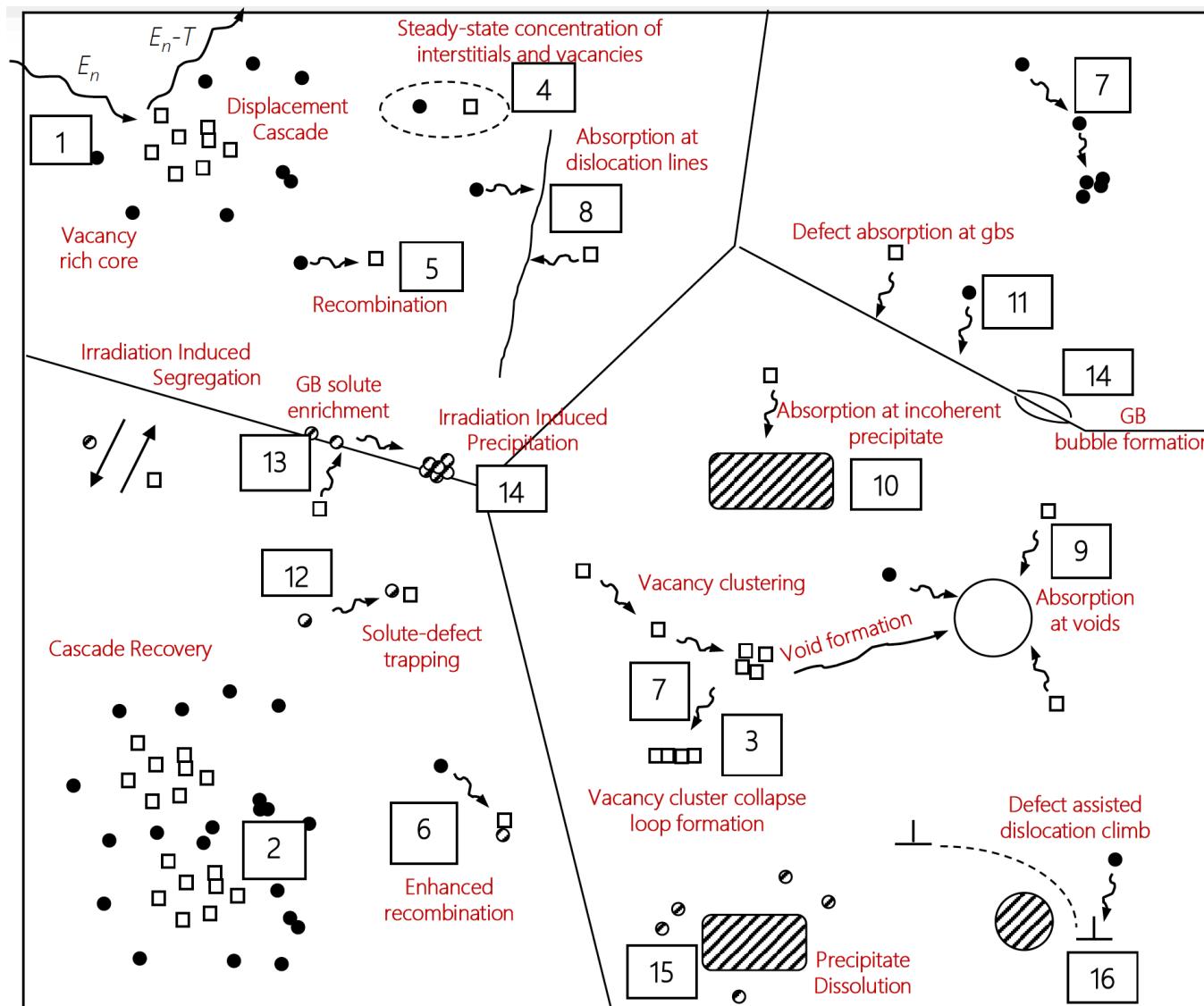
Original graphic by KG Field

Materials “stressors” on a per reactor basis

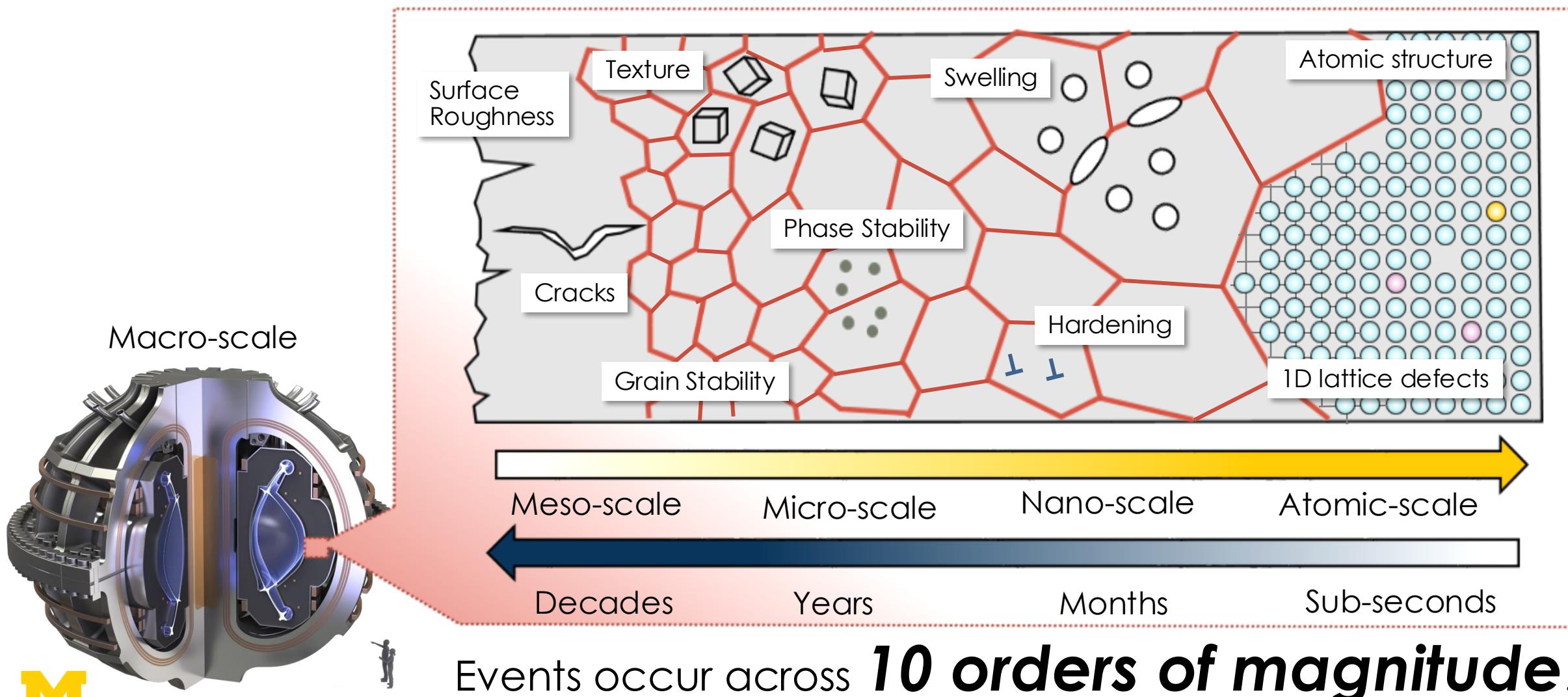


Reactor Type	Inlet Temp (° C)	Outlet Temp (° C)	Maximum Dose (dpa)	Pressure (Mpa)	Coolant
PWR	290	320	100	16	Water
SCWR	290	500	15-67	25	Water
VHTR/F HR	600	1000	1-10	7	Helium, Salt
SFR*	370	550	200	0.1	Sodium
LFR*	600	800	200	0.1	Lead
GFR*	450	850	80	7	Helium/ SC CO ₂
MSR	700	1000	200?	0.1	Molten Salt

Radiation Effects at the Grain Scale

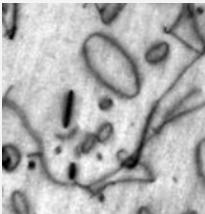


Science and technology for nuclear materials is fundamentally **Temporally and Spatially Multi-scale**

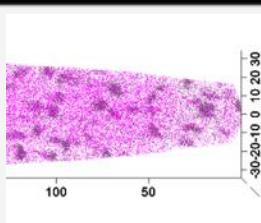


Consequences of microstructural changes on mechanical performance

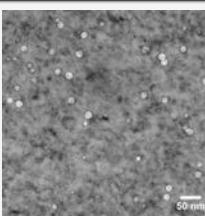
Dislocation loops



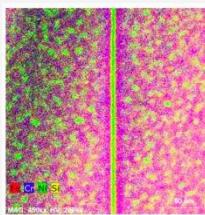
Radiation-Induced Precipitation (RIP)



Cavities, He bubbles, etc.

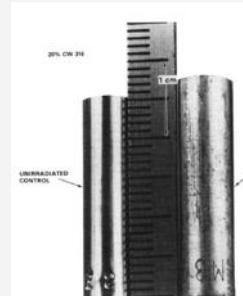


Radiation-Induced Segregation (RIS)



Hardening
Irradiation creep
Deformation localization
Embrittlement

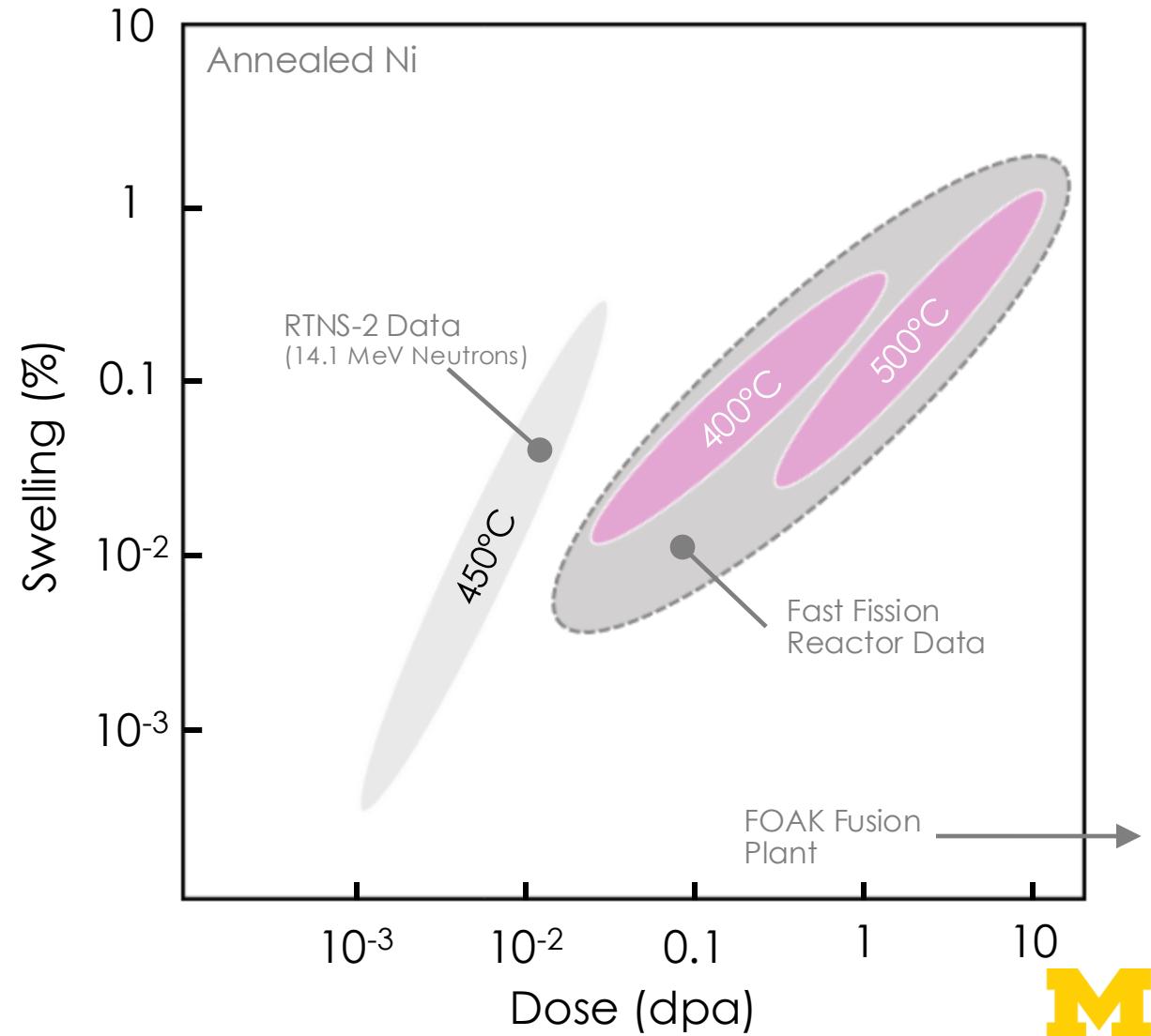
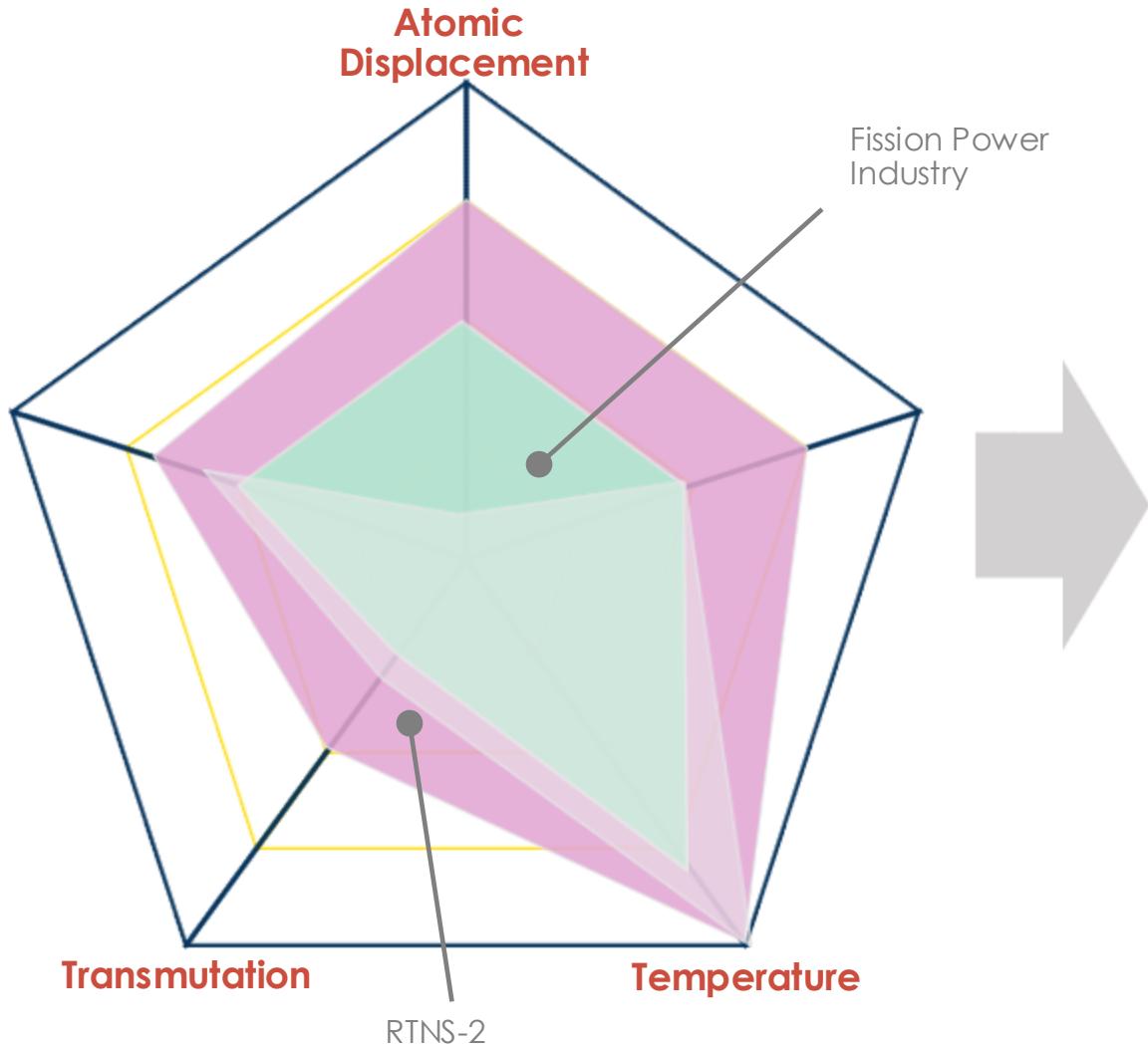
Swelling



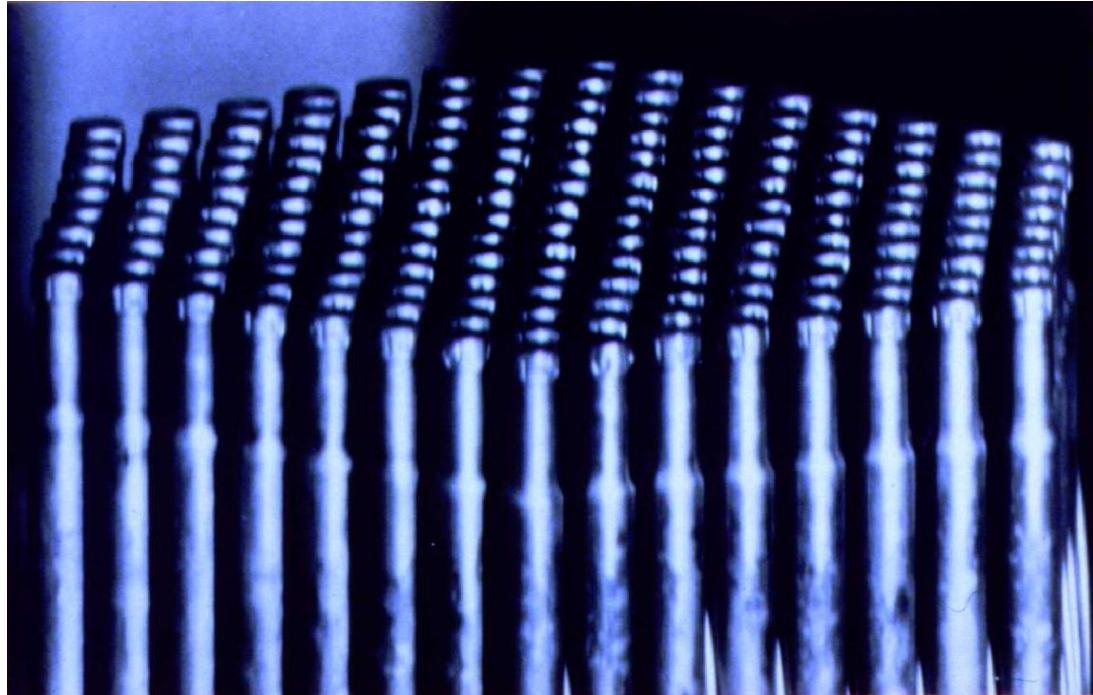
Increased sensitivity to SCC (IASCC)



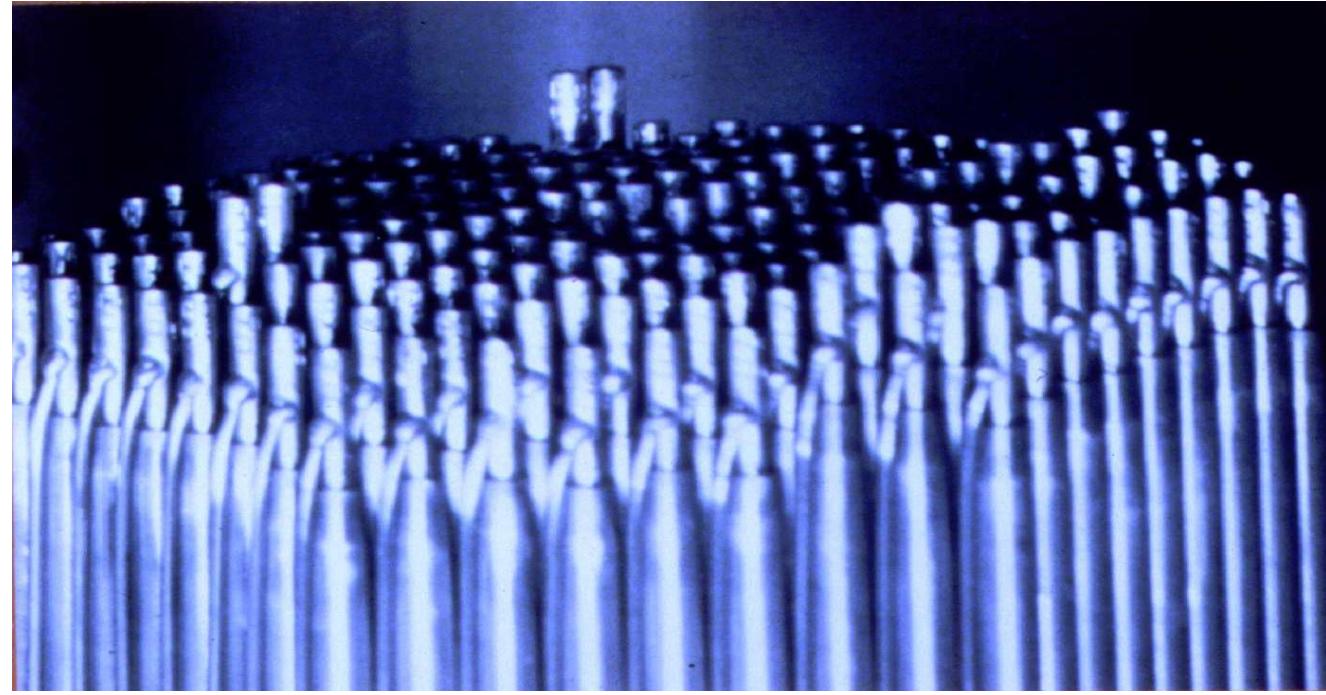
Different environmental exposures can drive significant deviations in materials response



Radiation damage effects materials differently



HT-9, no swelling



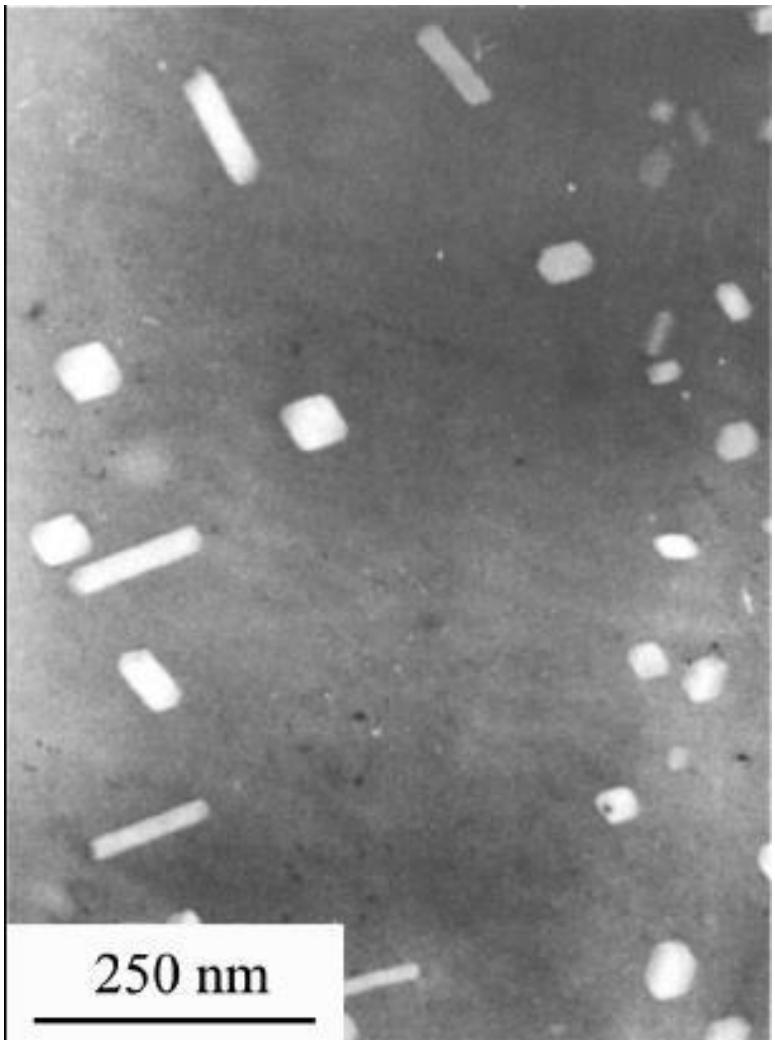
316-Ti stainless, swelling

Source: F. Garner

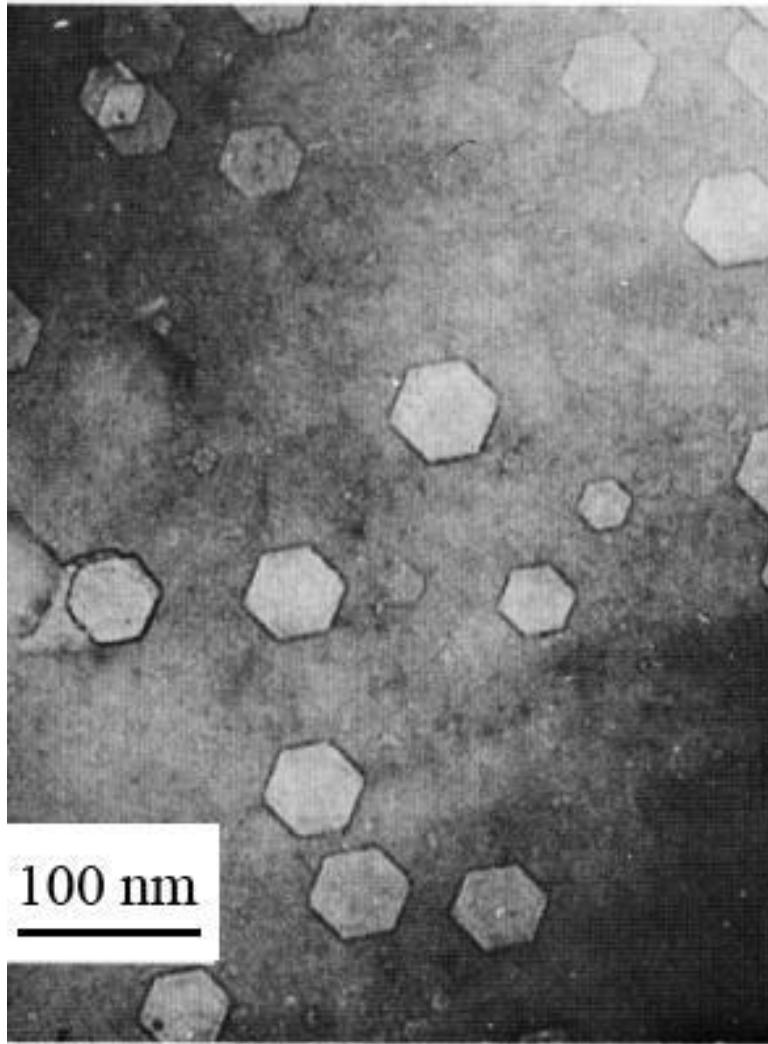


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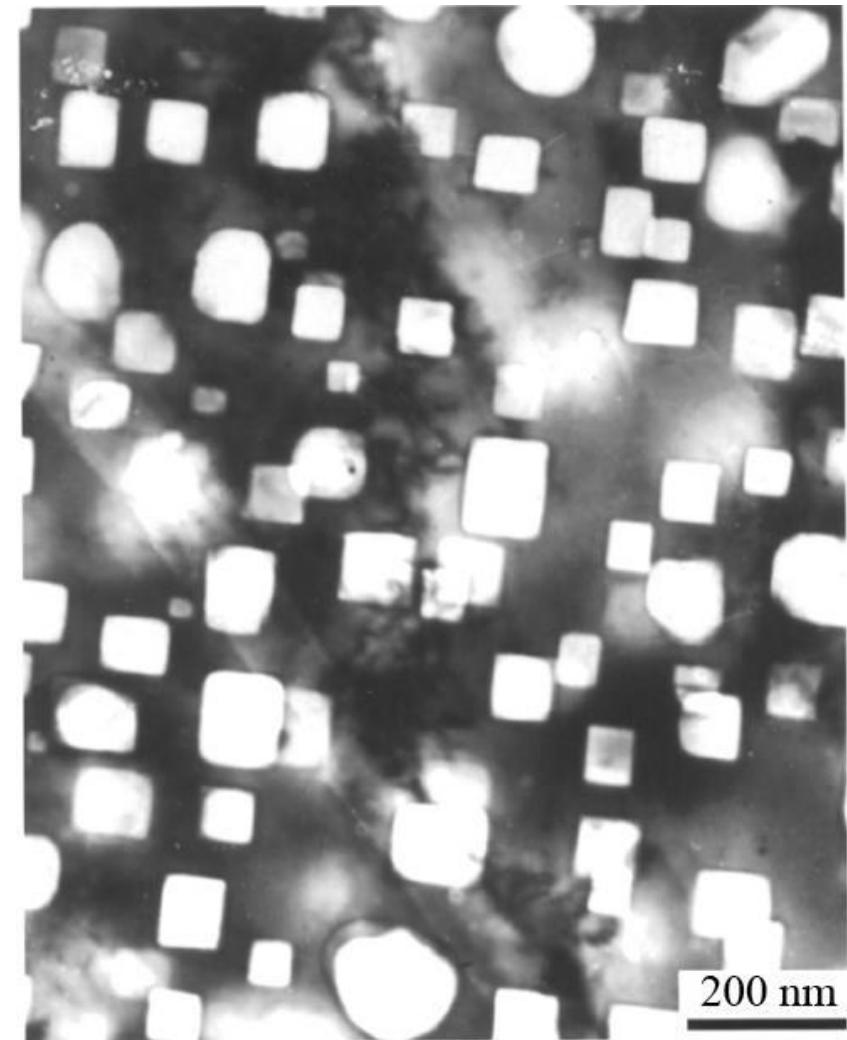
Examples of voids in various materials



Stainless Steel



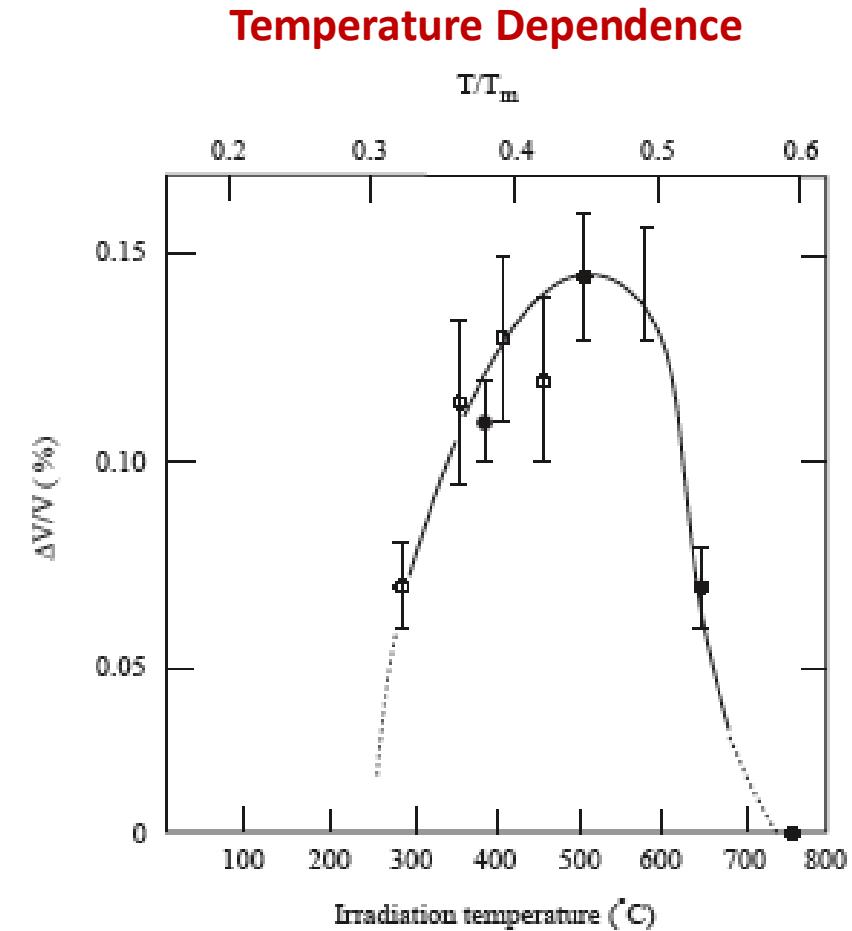
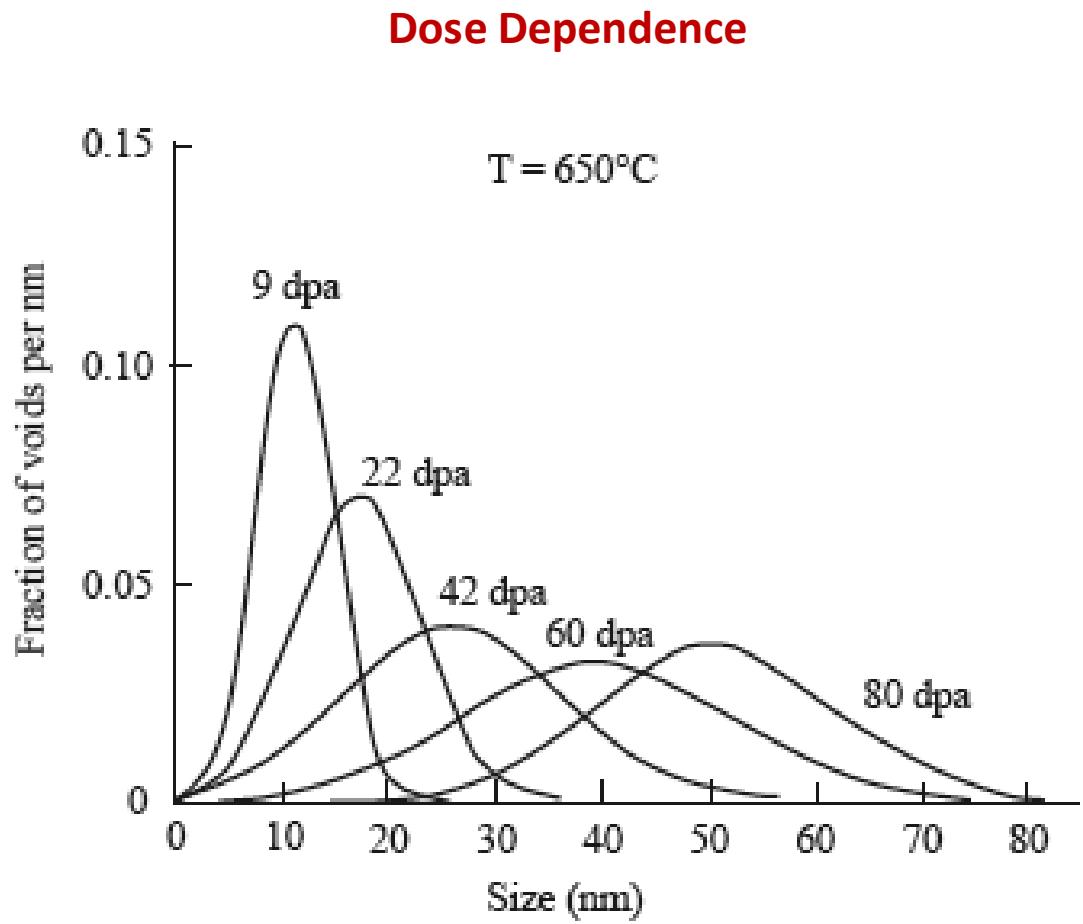
Aluminum



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.

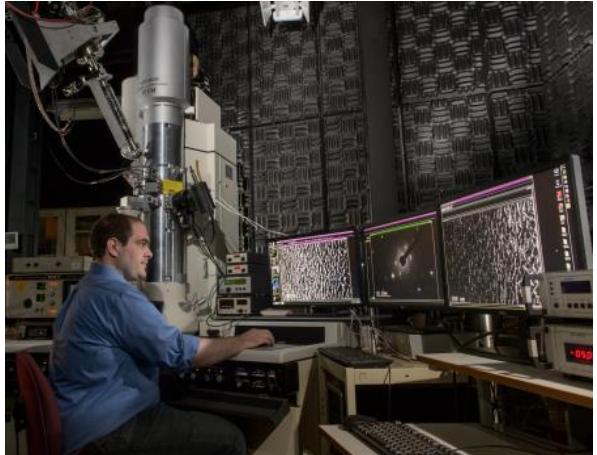
Cavity formation as a function of dose and temperature



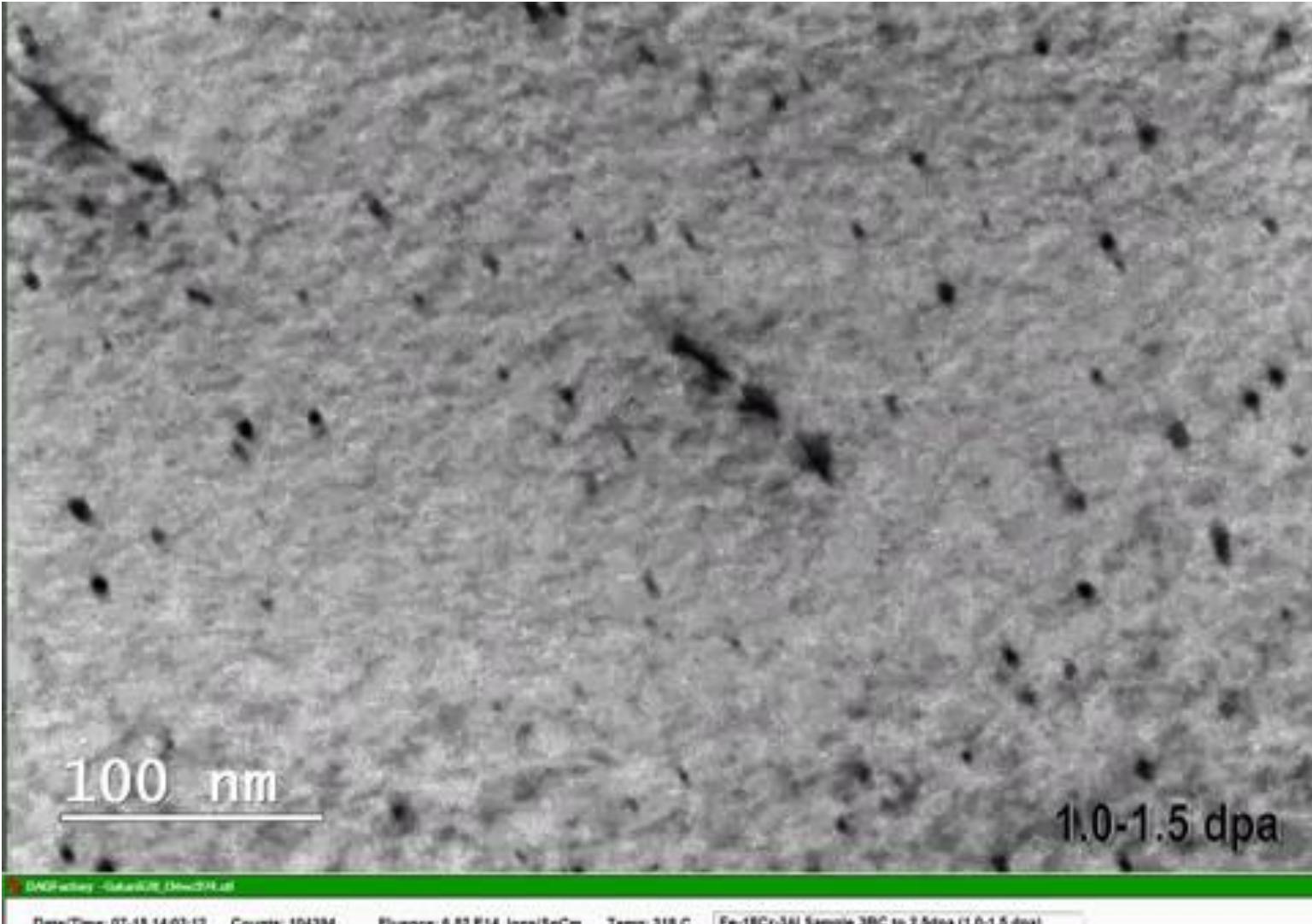
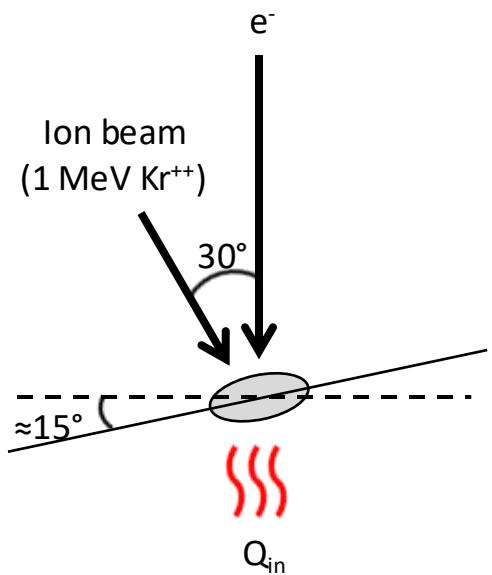
J. L. Brimhall, H. E. Kissinger and G. L. Kulcinski, Proc. International Conference on Radiation Induced Voids in Metals, CONF-710601, National Technical Information Service, 1972, p. 338.

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 IVEF facility

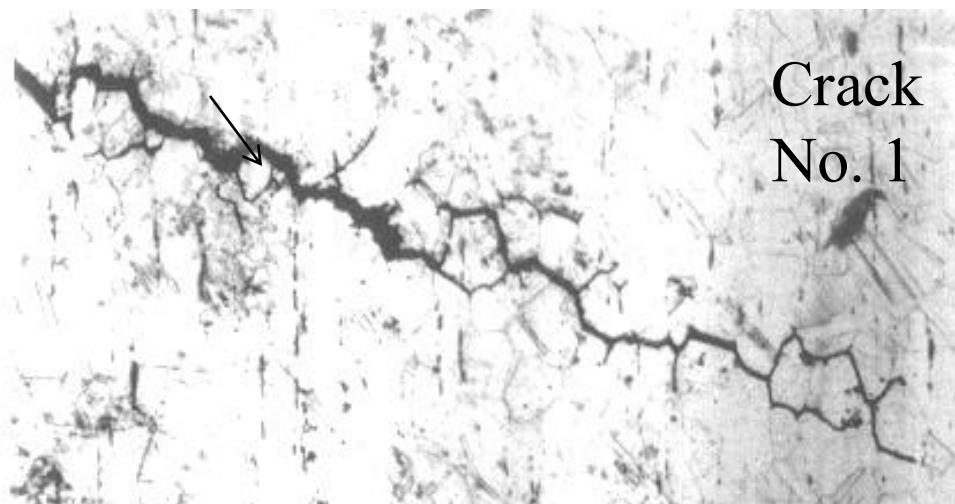
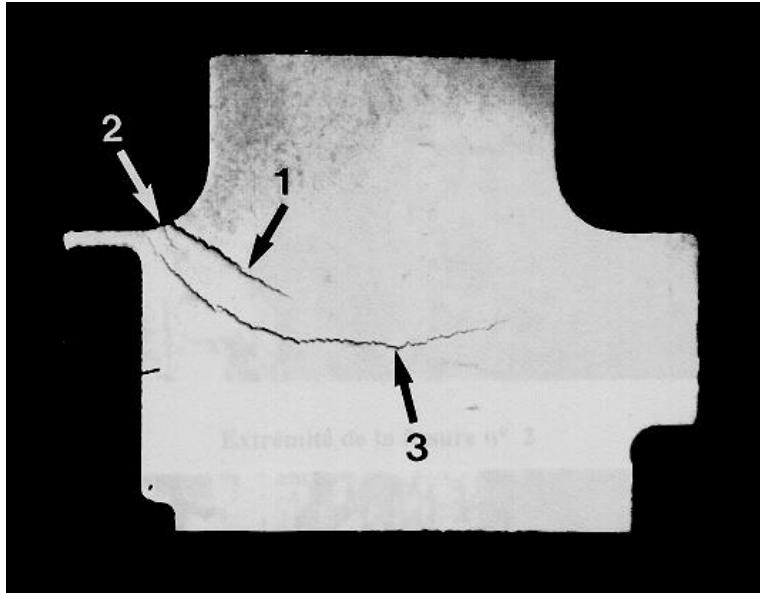
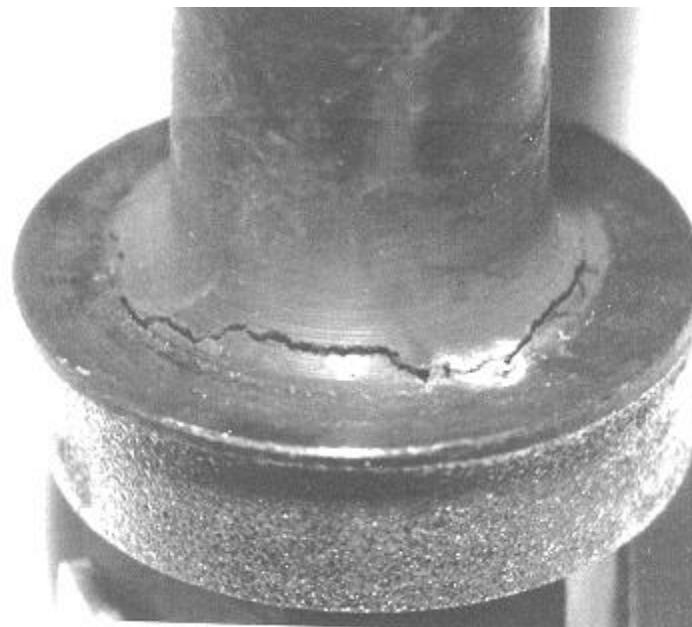


[1] Image courtesy of C. Ulmer (PSU)



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Radiation damage can enhance degradation

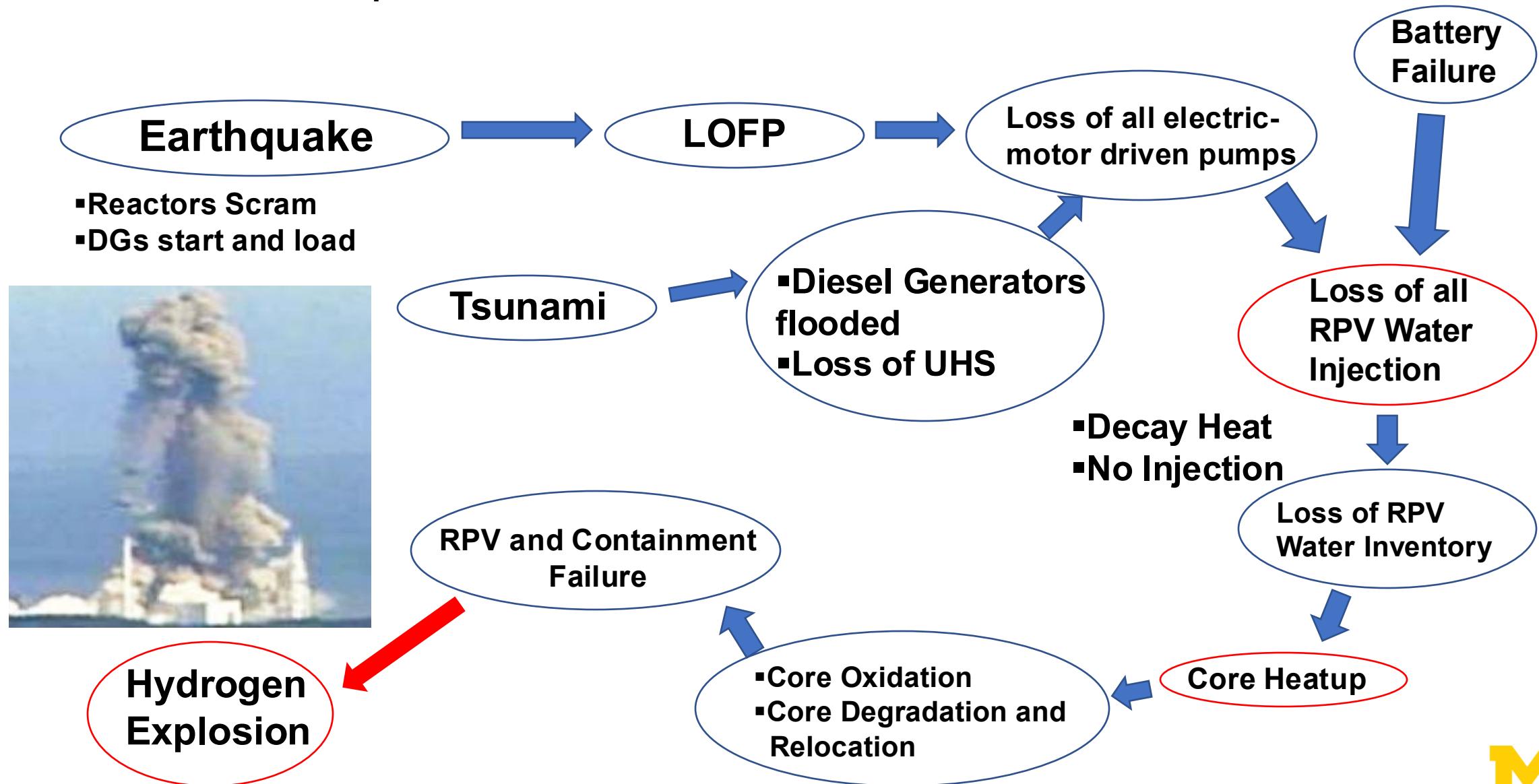


Classical example of
Irradiation Assisted
Stress Corrosion
Cracking in baffle
former bolts for a PWR

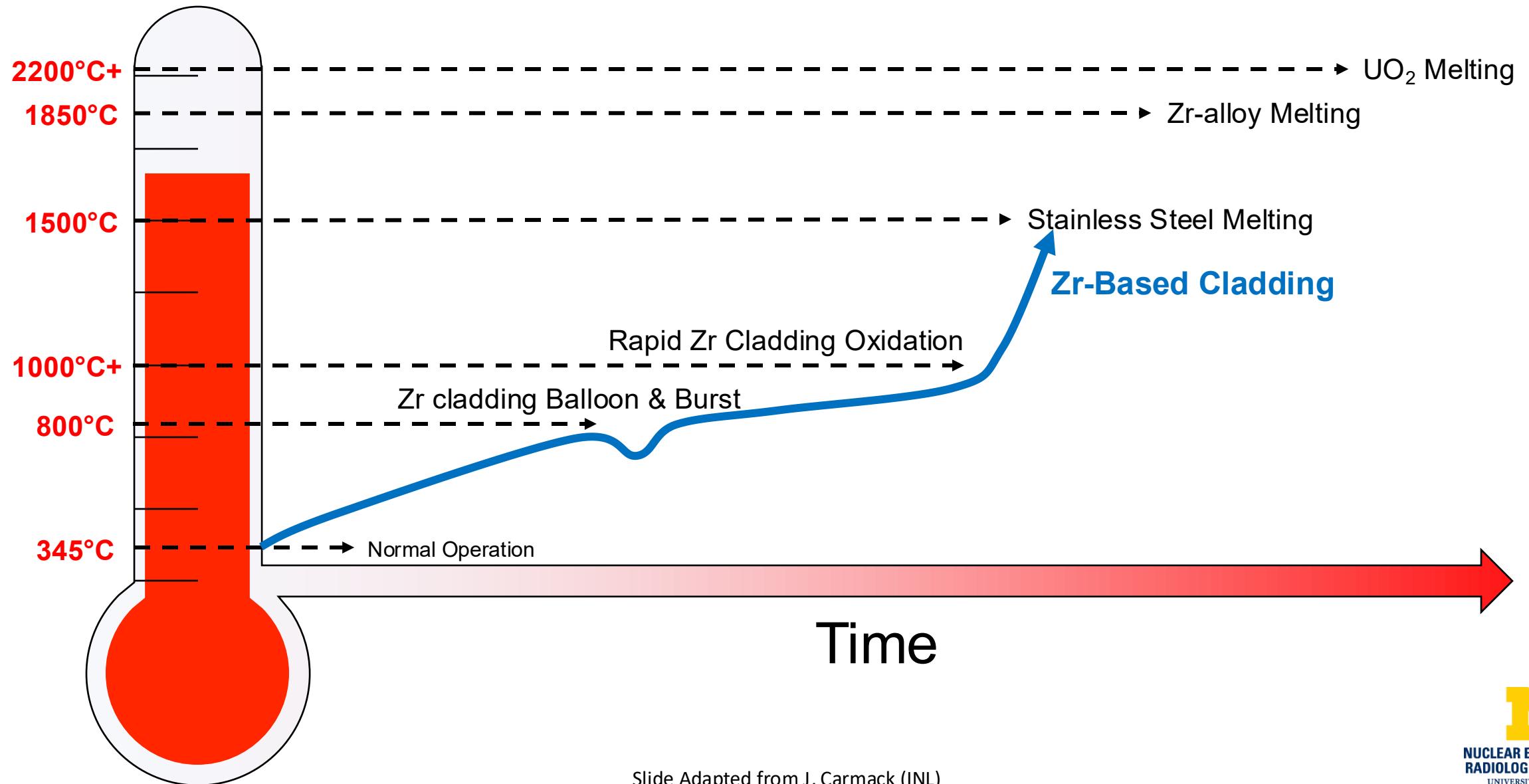


A Recent Real-World Example

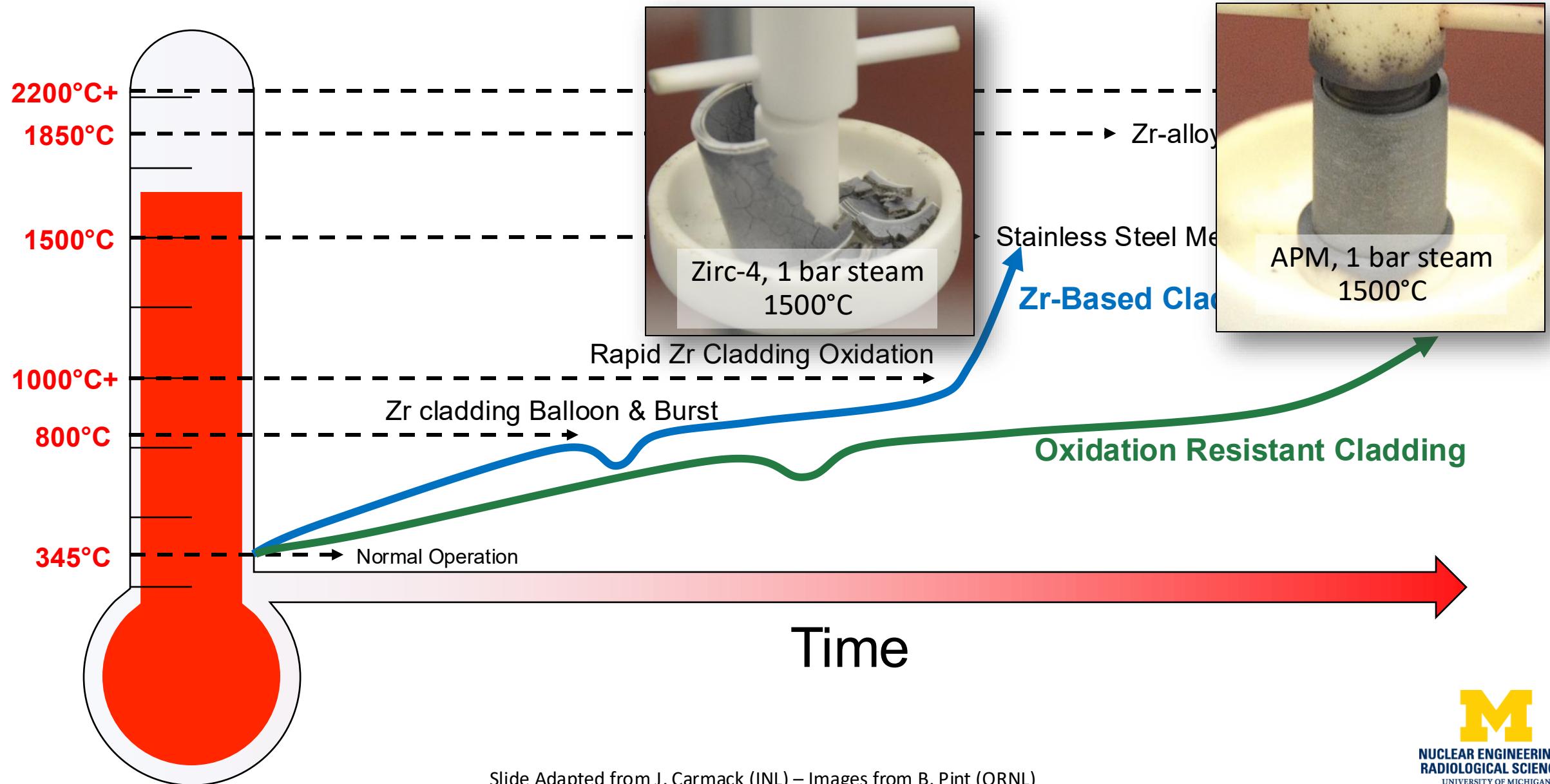
Modern Example: GE's IronClad ATF solution



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



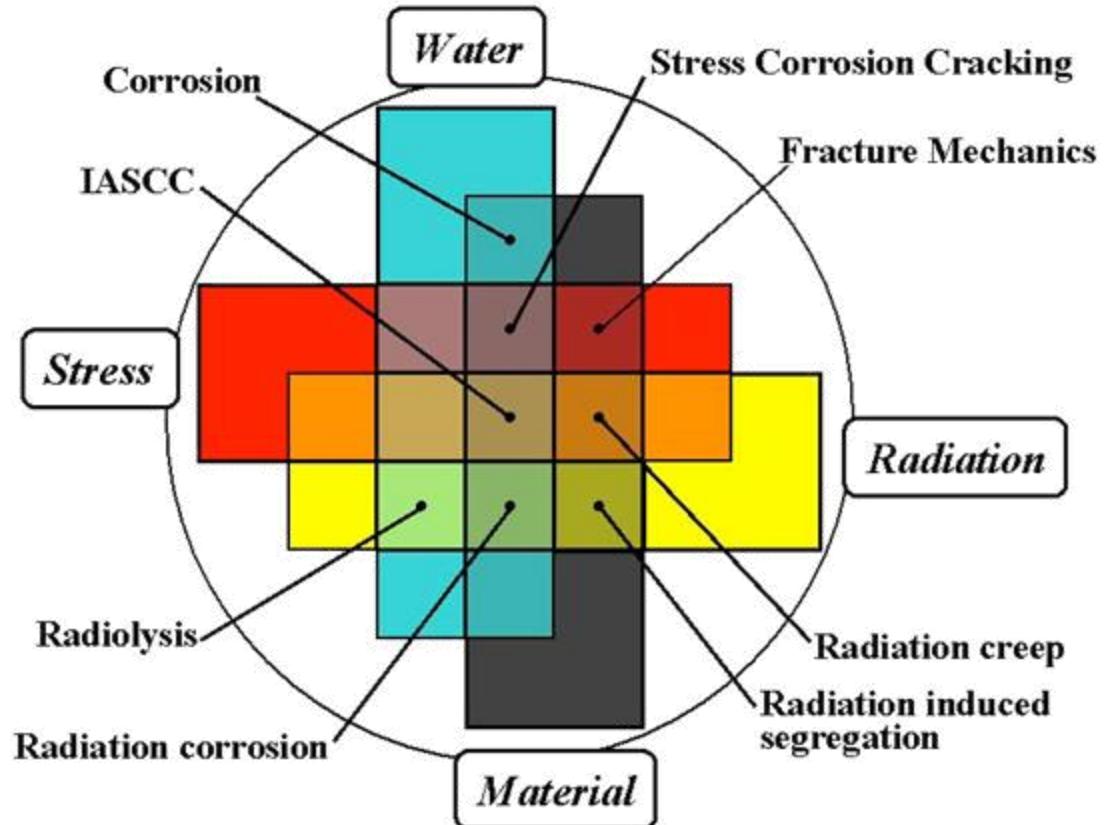
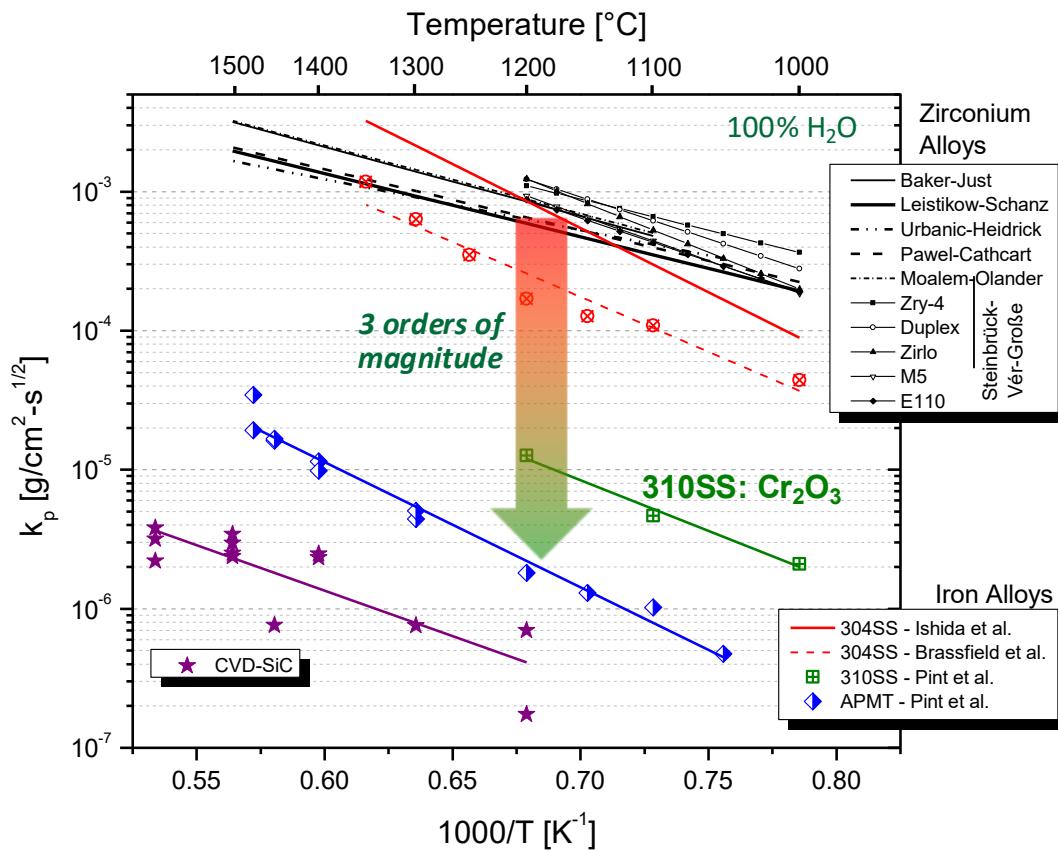
Oxidation of cladding is key towards core degradation during a coolant-limited accident scenario



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

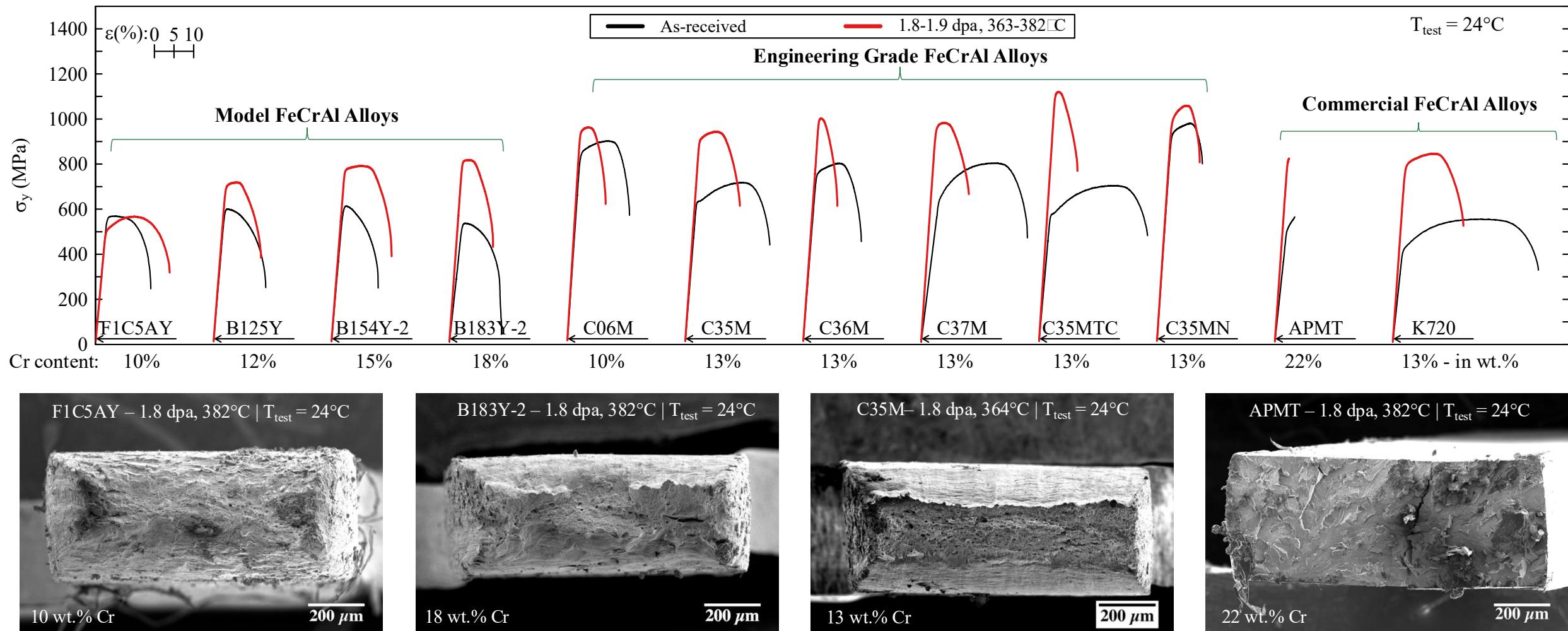


Finding oxidation resistance alloys that increase safety is easy...



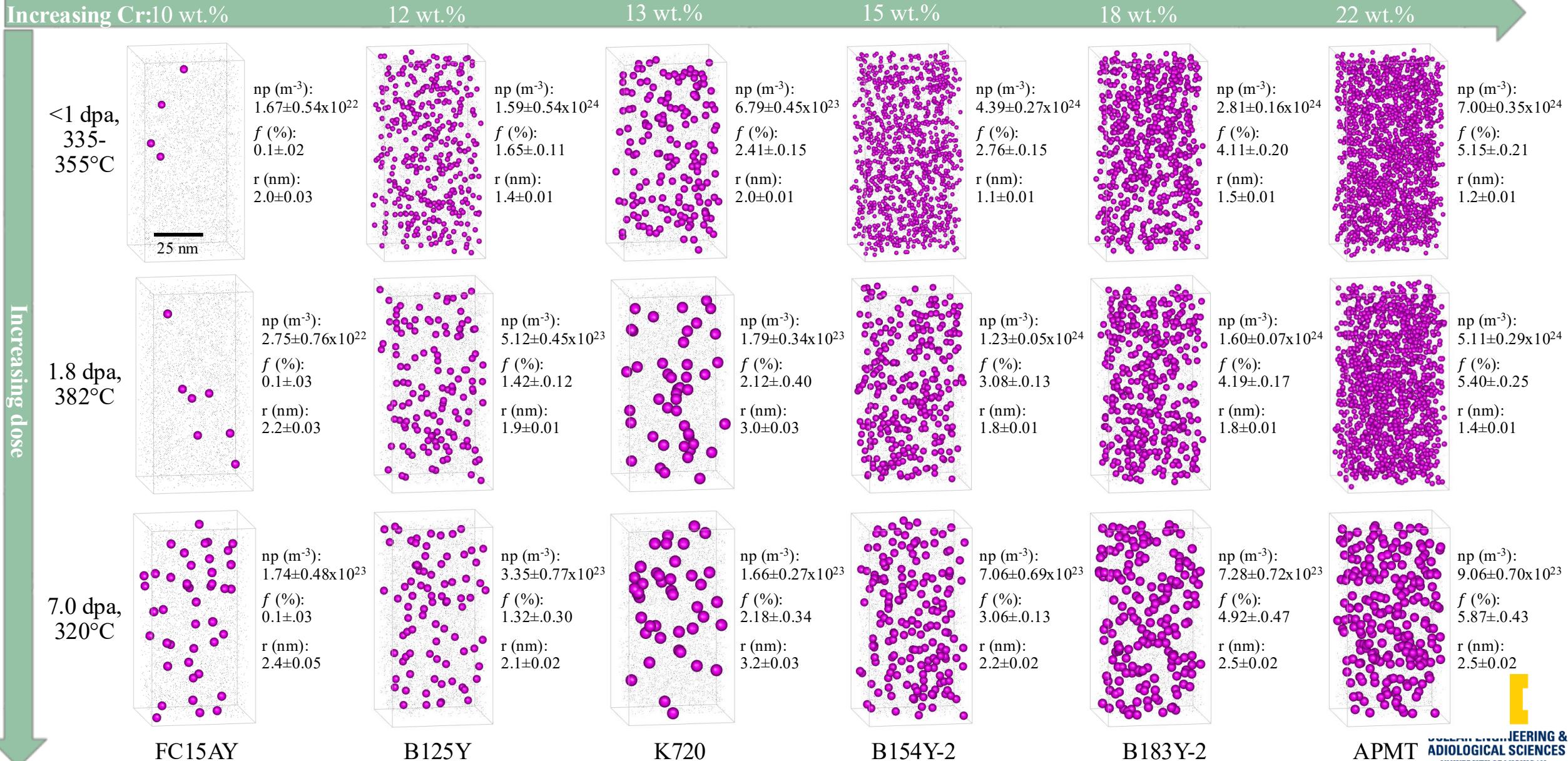
...but, understanding how they perform in a LWR is not

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



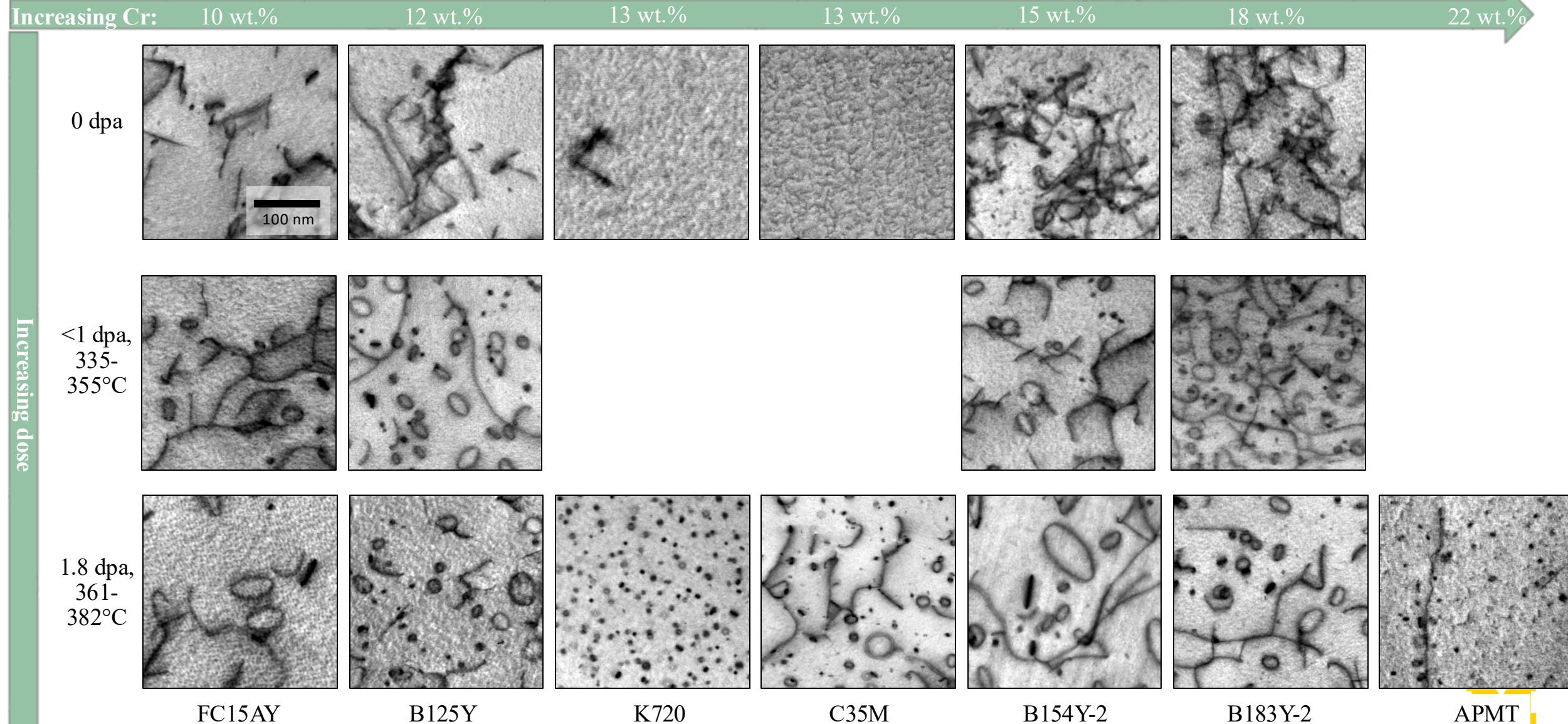
- [1] Field, et al. / *Journal of Nuclear Materials* 465 (2015)
[2] Field, et al. / *Journal of Nuclear Materials* 489 (2017)

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

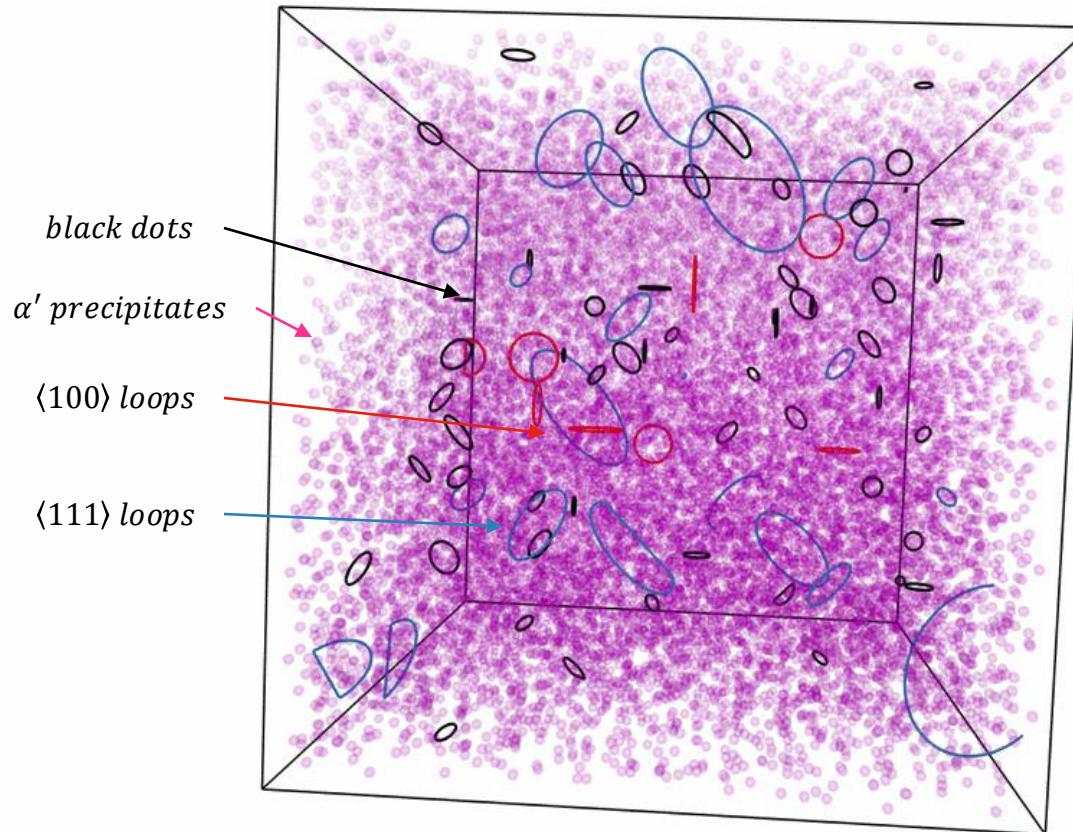


Trends in dislocation loops in FeCrAl alloys

*All images to same scale

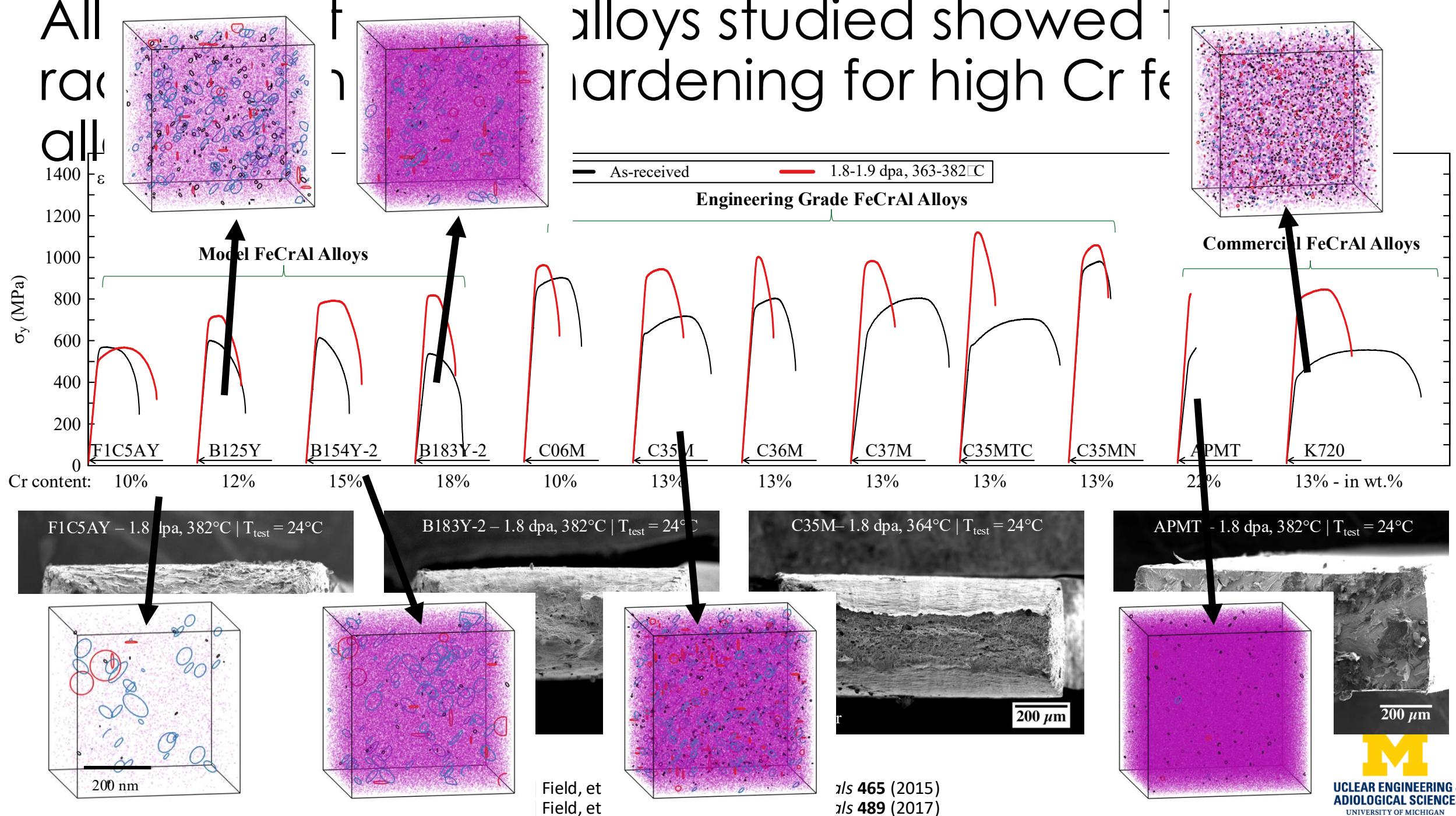


Putting the two together and visualizing:

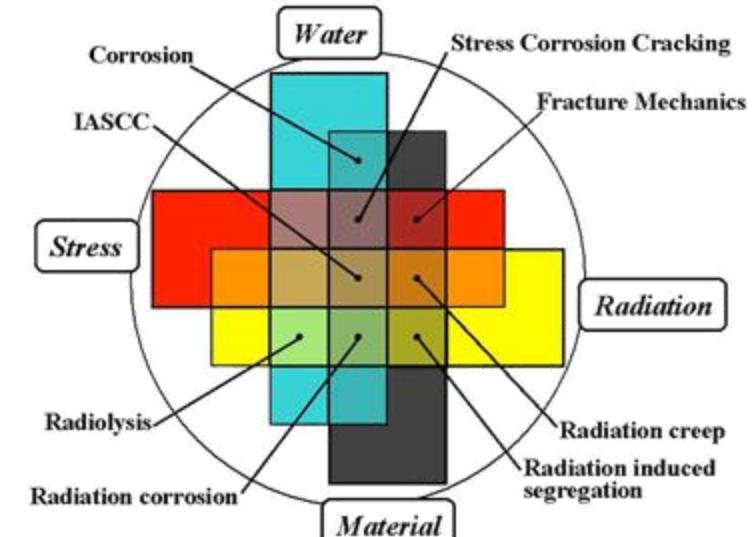
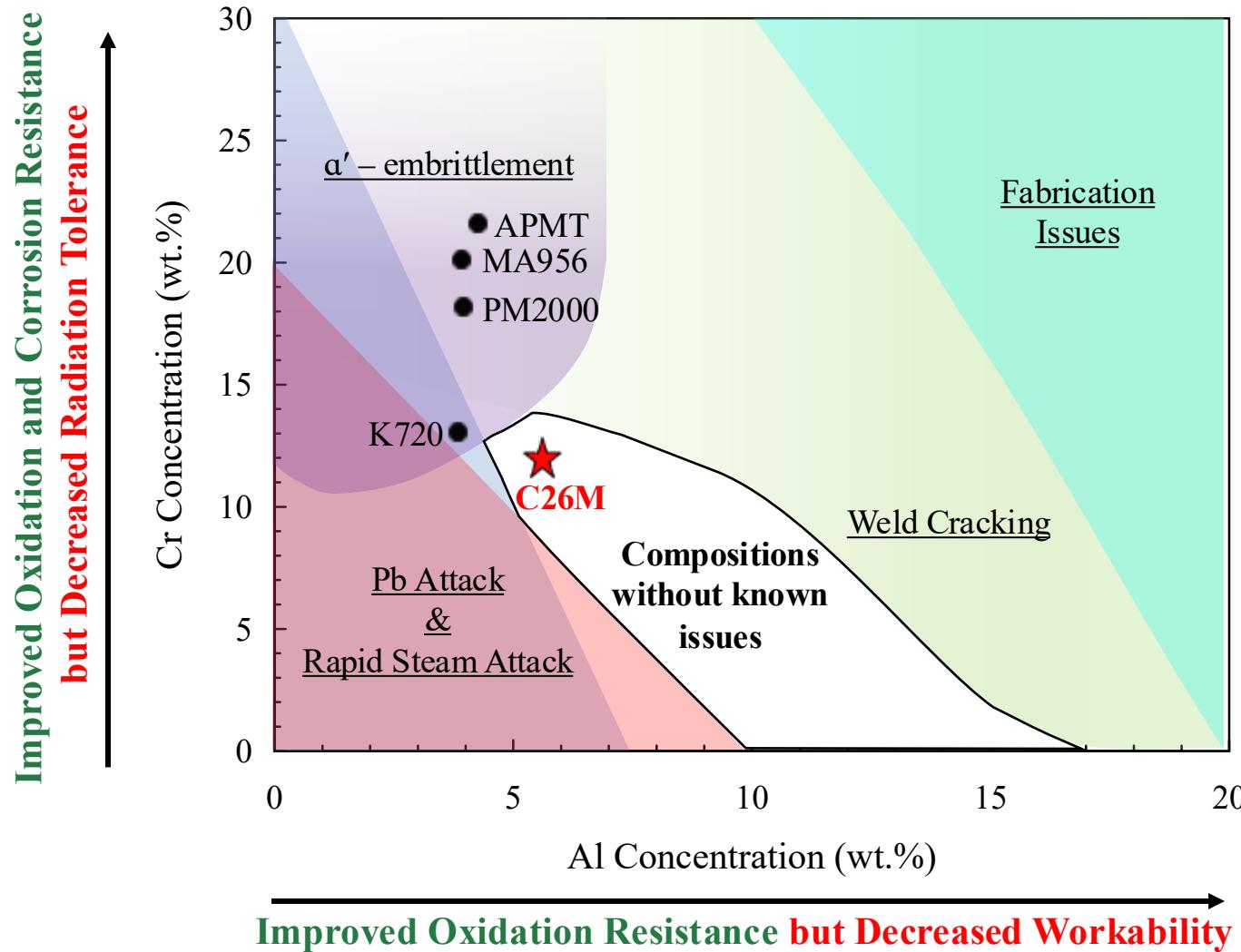


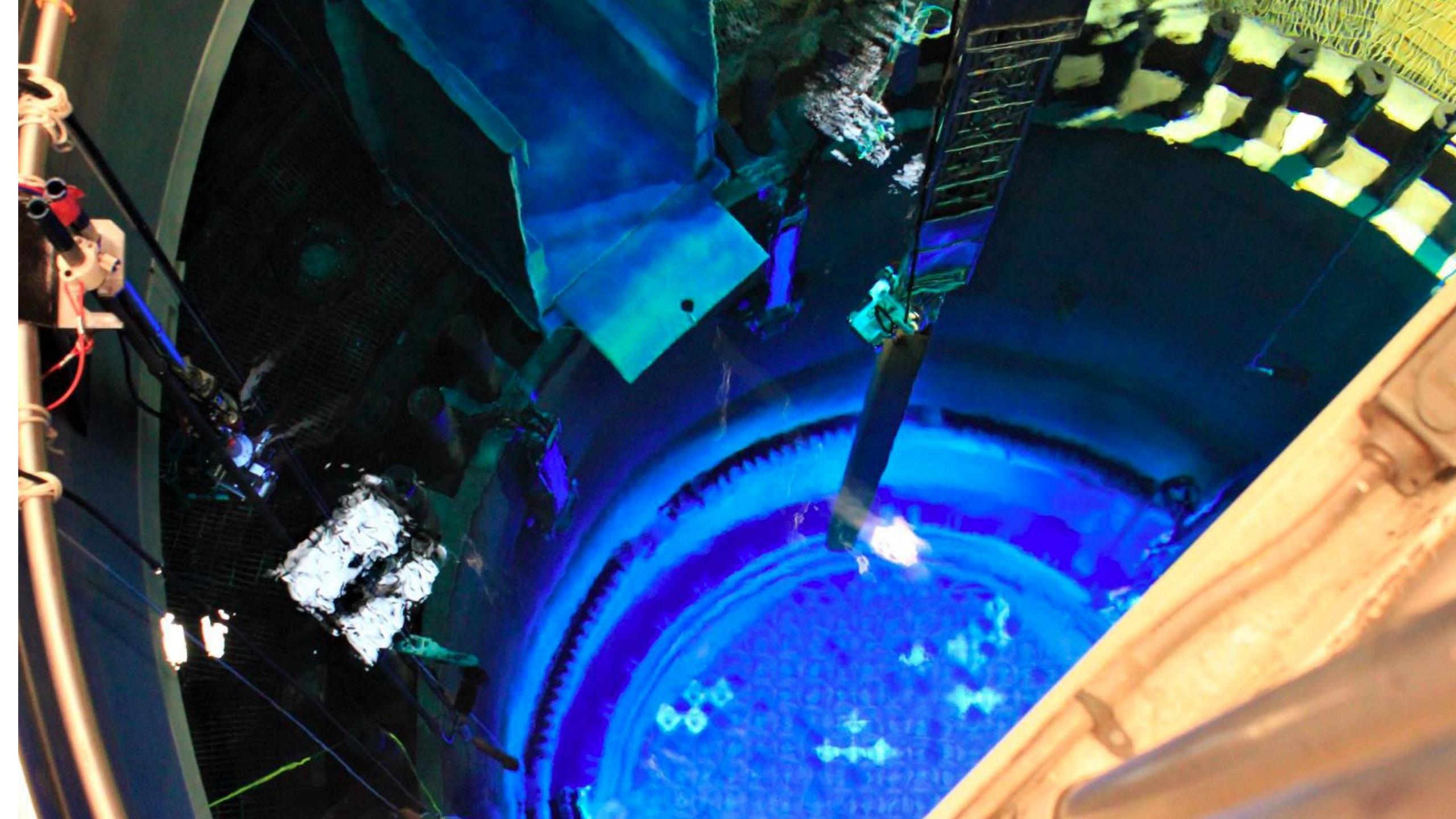
1.8 dpa, 382°C Fe-18Cr-Al synthetically
rendered microstructure (300X300X300 nm)

All
radiation
alloys studied showed hardening for high Cr fe



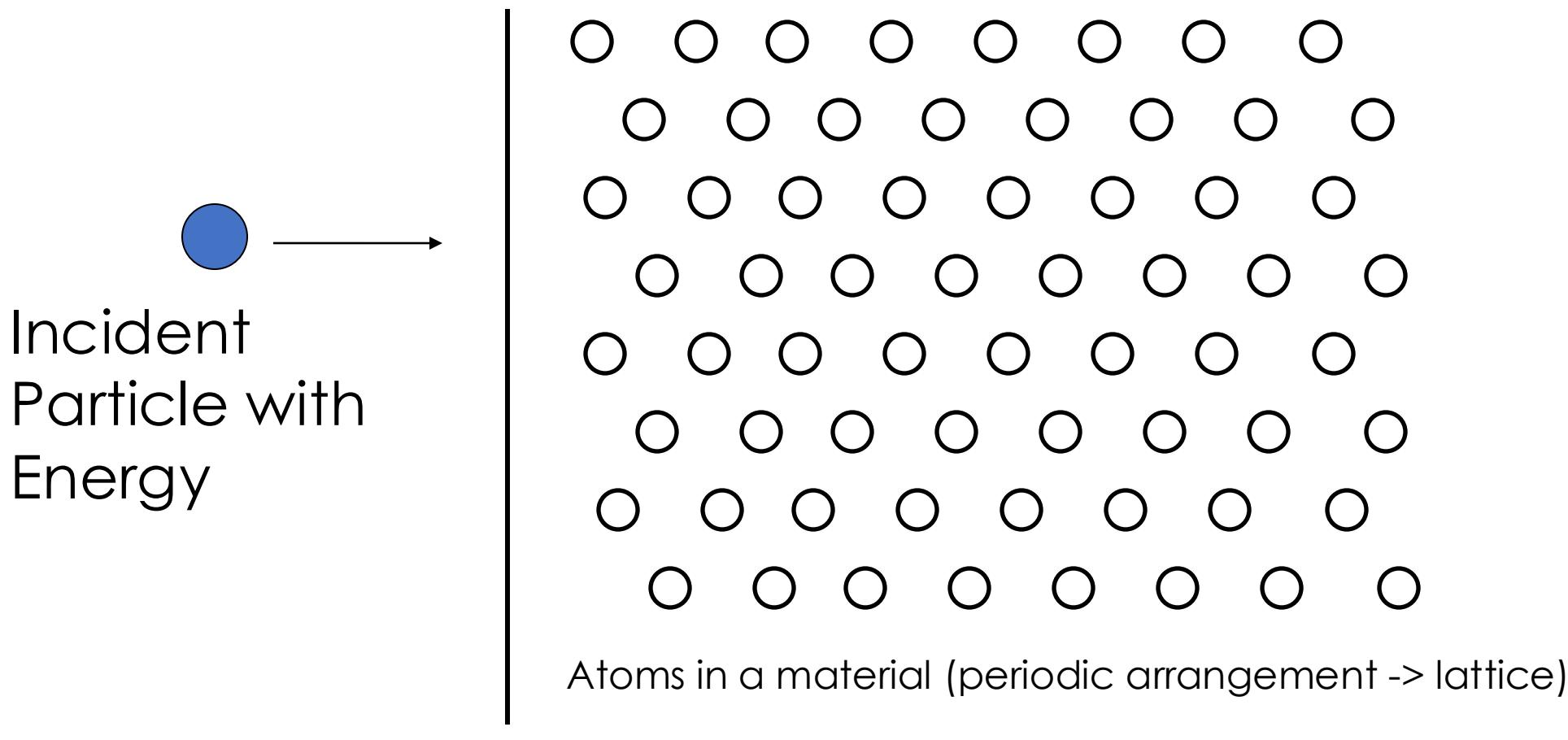
Weldability and radiation tolerance define the upper bounds on Al and Cr content of FeCrAl alloys¹





Radiation Damage: the basics

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

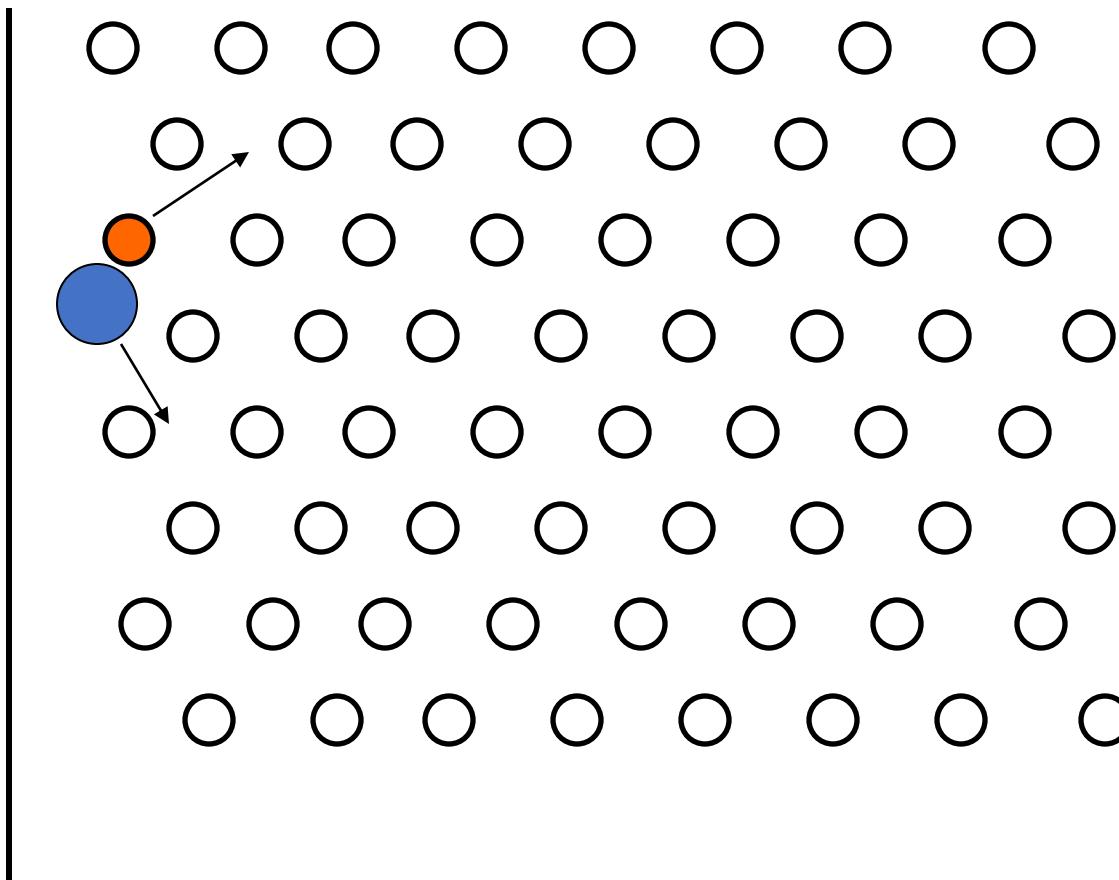


Source: T.R. Allen



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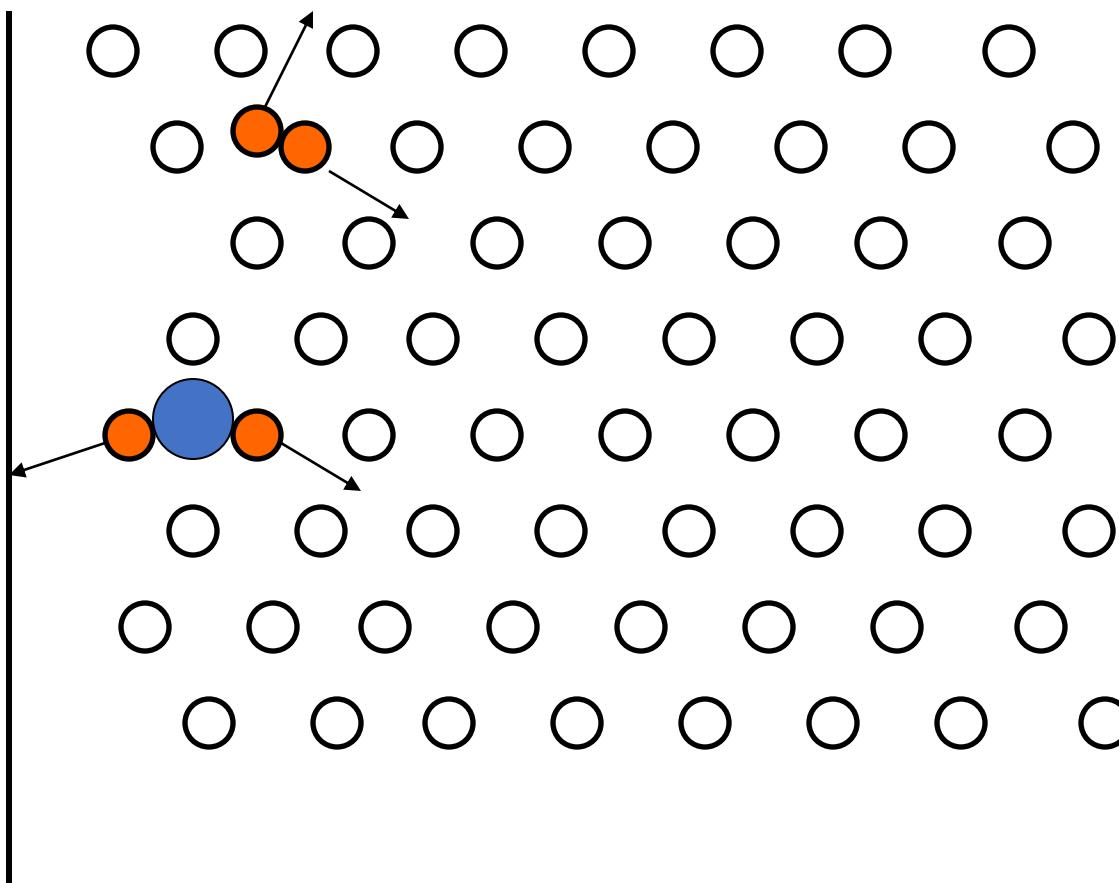
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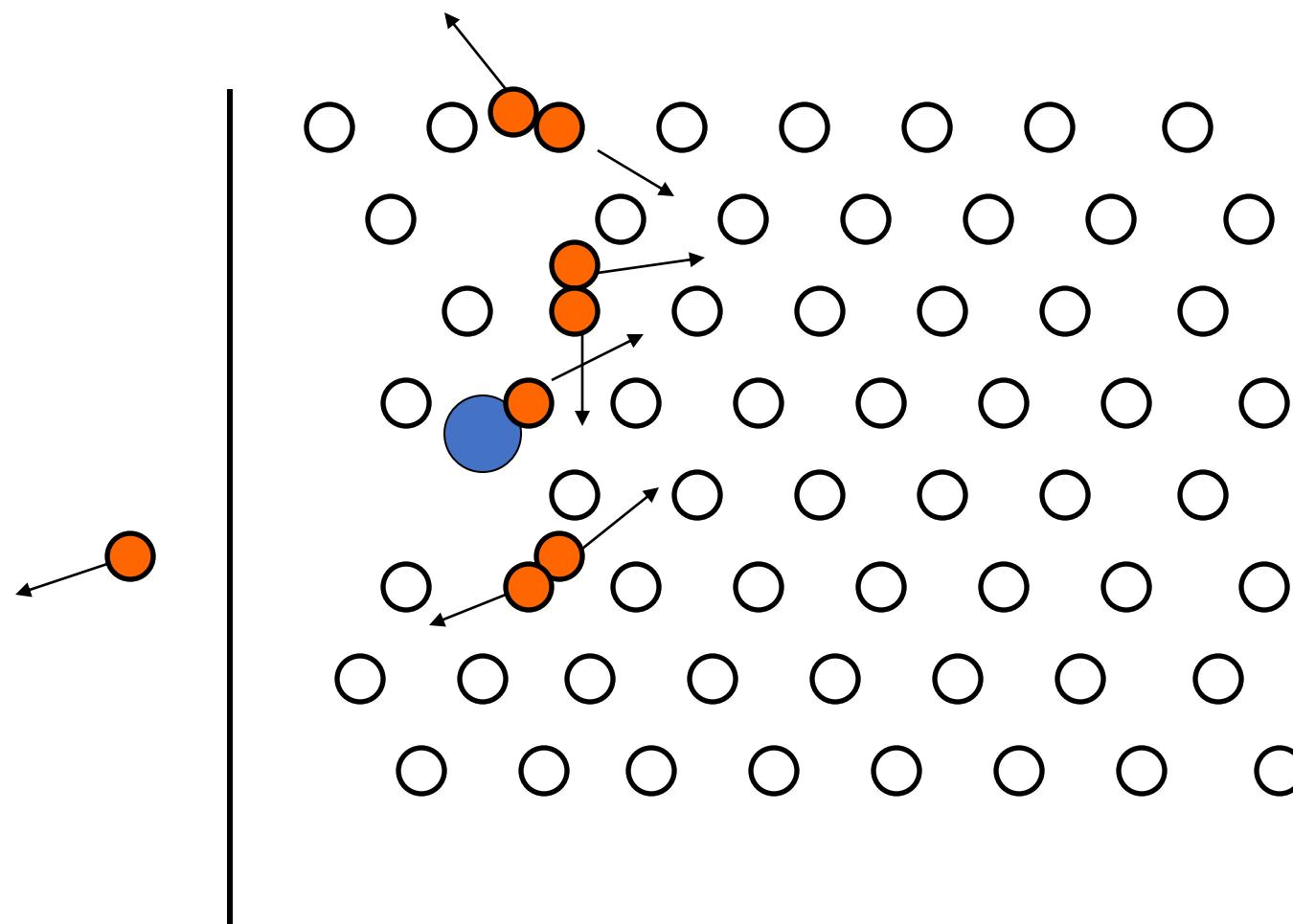


Source: T.R. Allen



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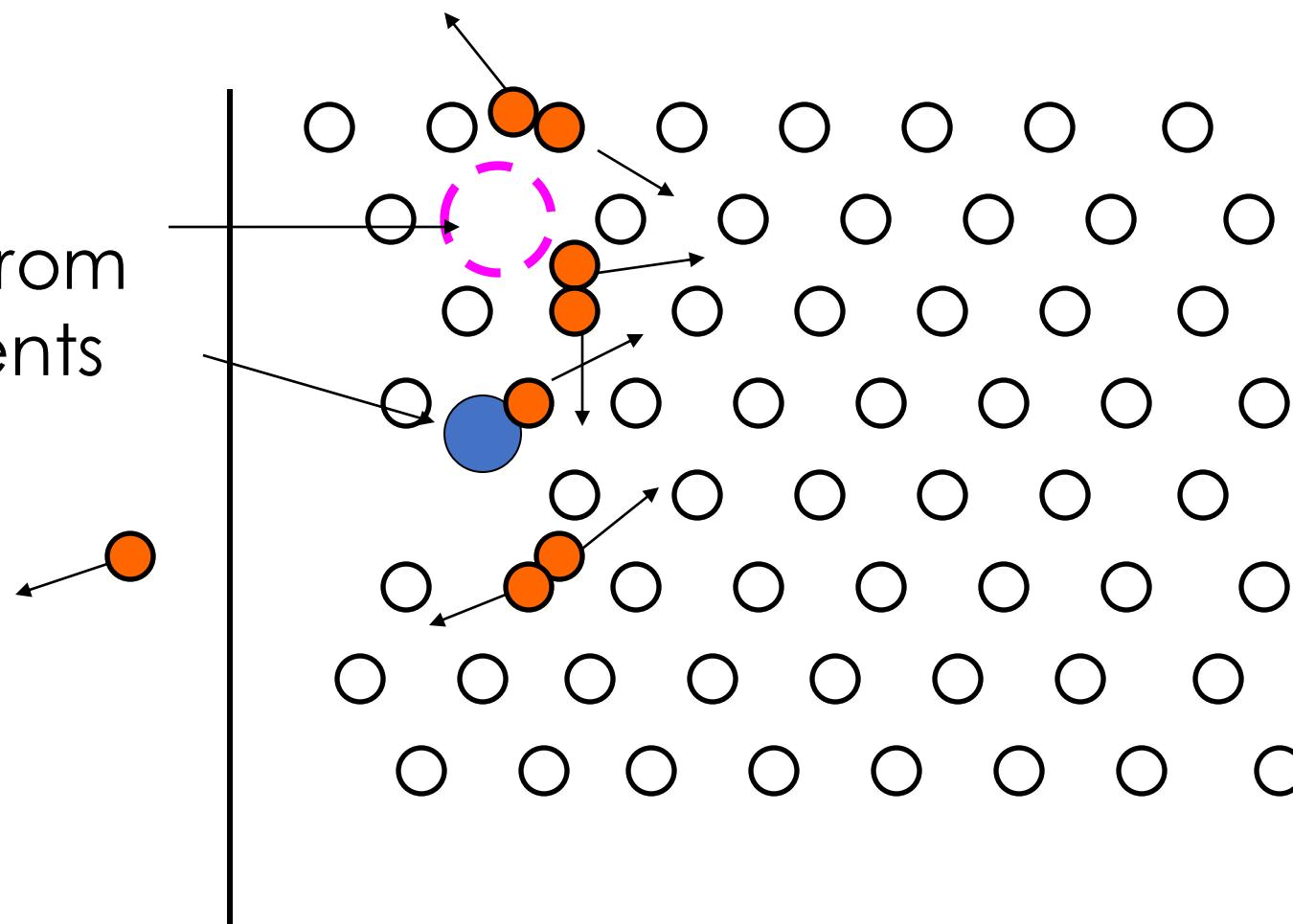


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Radiation Damage: the basics

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collisions between energetic particles and atoms composing a material

Defects
produced from
displacements

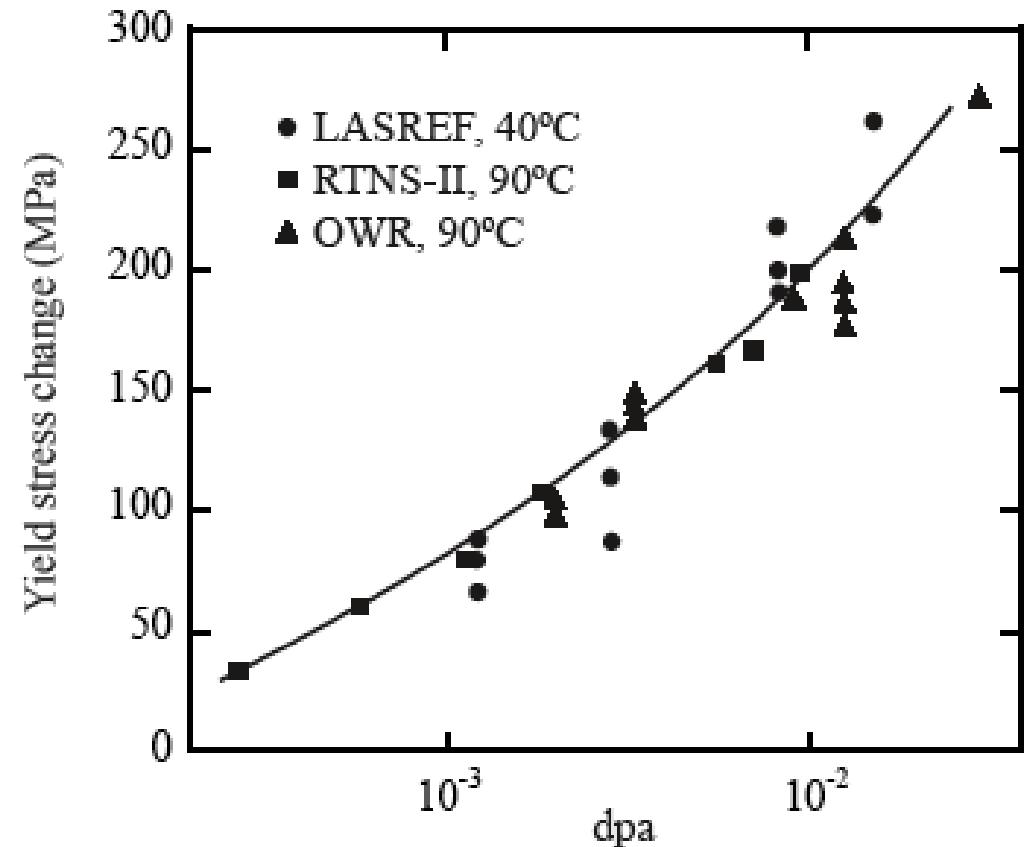
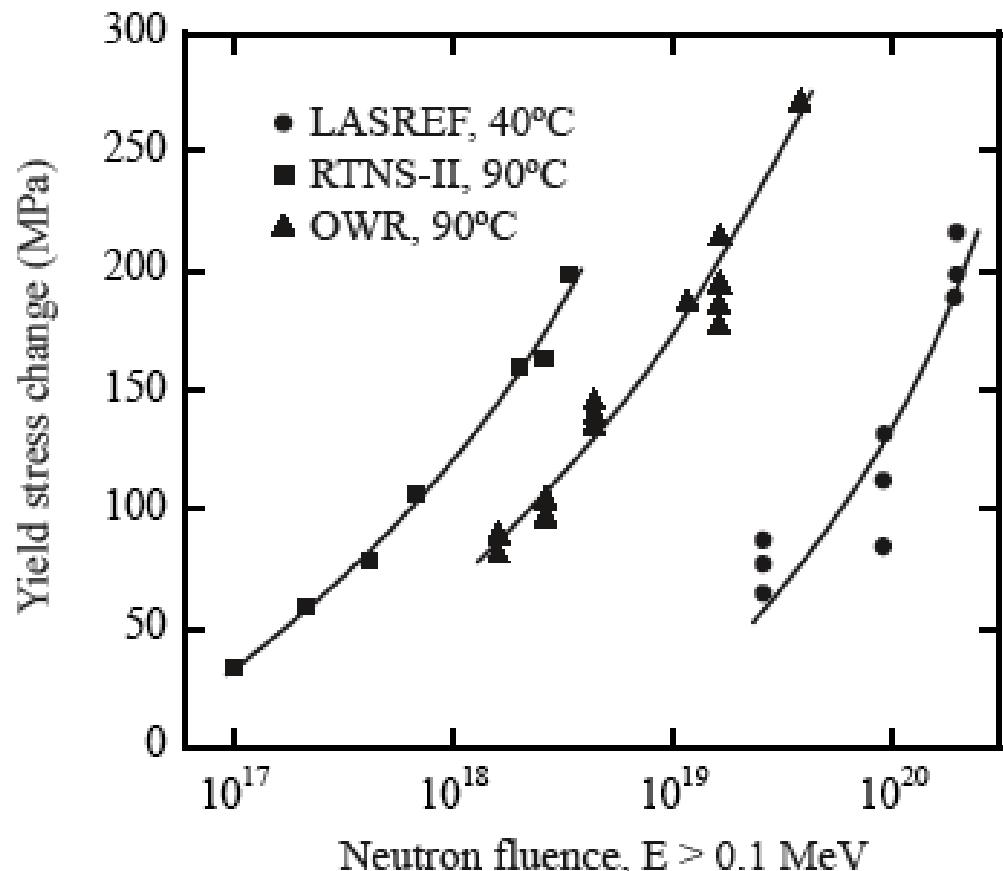


Source: T.R. Allen



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Importance of displacement versus fluence for this class



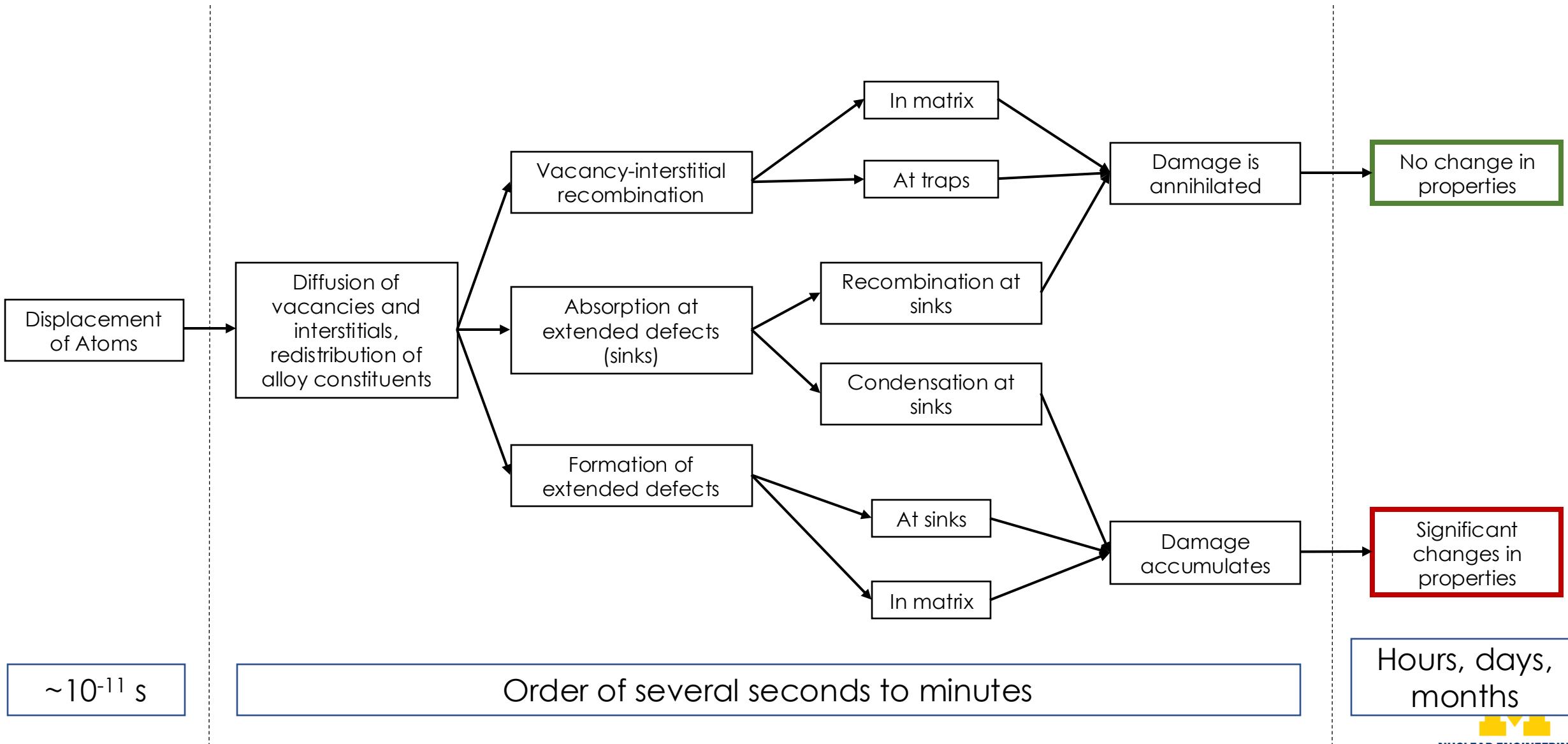
Comparison of yield stress change in 316 stainless steel irradiated in different reactors



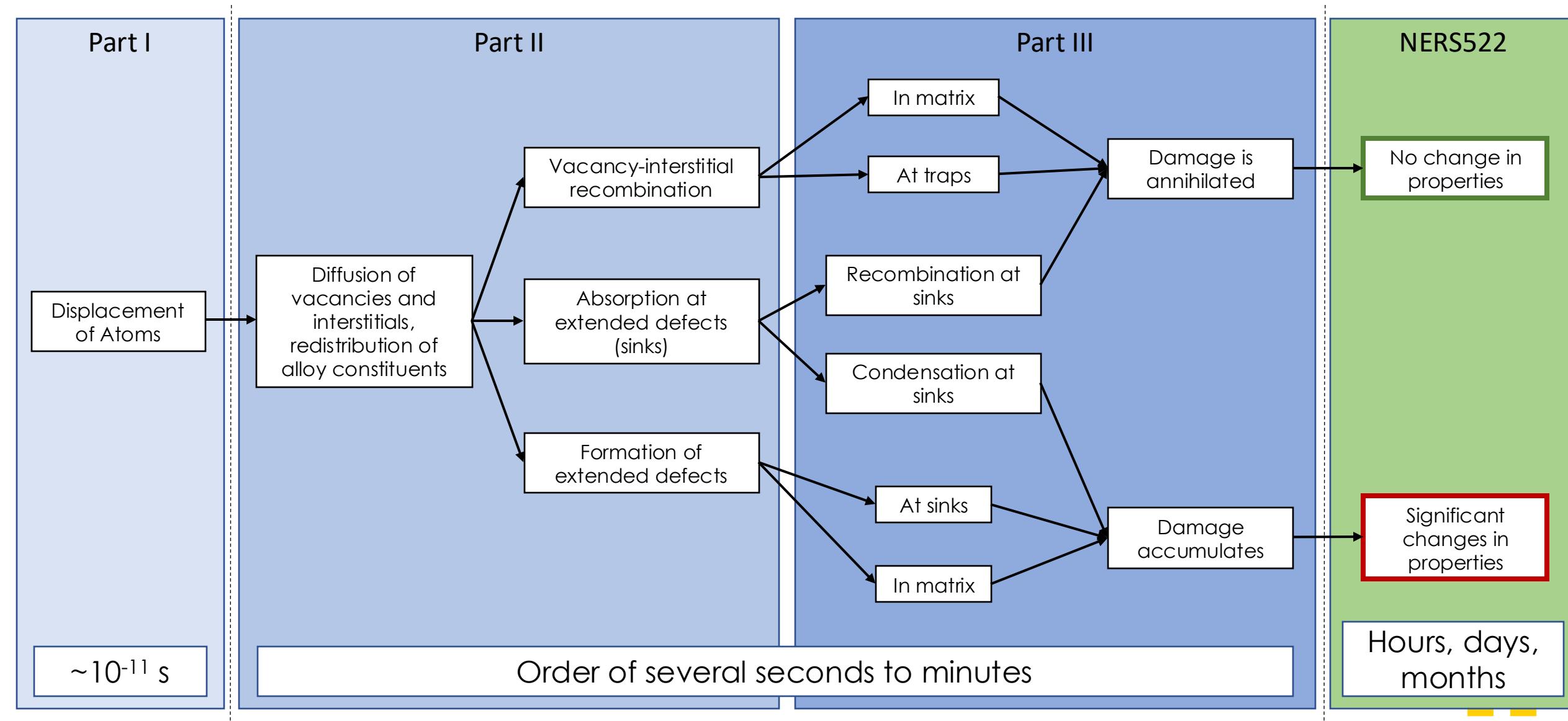
Flow chart for radiation damage



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)

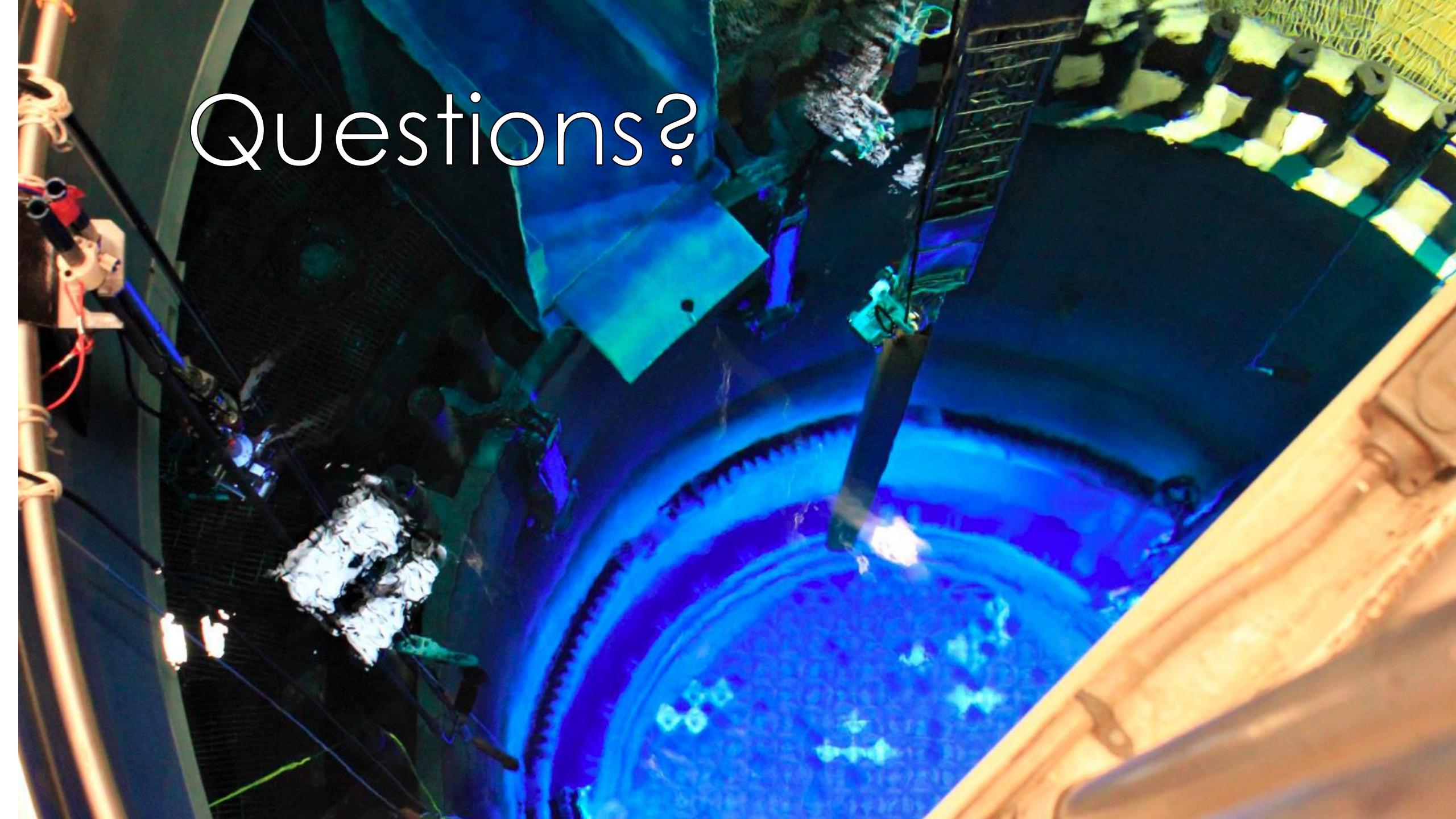
$\sim 10^{-11}$ s

Displacement of atoms is a **radiation damage event** which is composed of events:

Next two
lectures

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
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Questions?