Class Introduction

K.G. Field[1,a],

[a] kgfield@umich.edu

[1]University of Michigan

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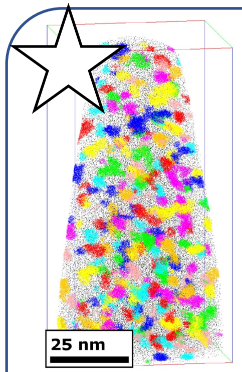
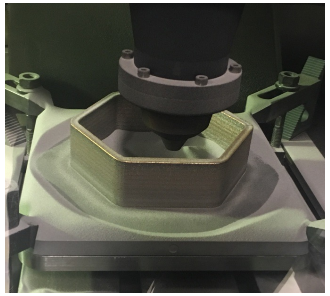
UNIVERSITY OF MICHIGAN

About Prof. Field:

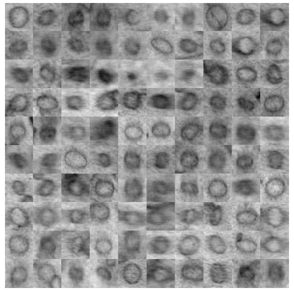


(d) Fe-18Cr-5.8Al

FeCrAl Develop.



AM for nuclear structures



Rapid characterization + ML techniques

ORNL (late years)

R&D Staff

Theia Scientific, LLC

Co-founder & Vice President

2019+

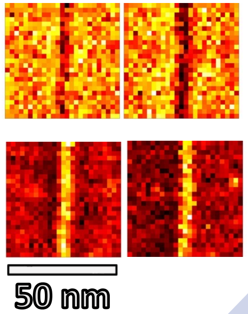
2020+

2015

2019

University of Wisconsin

M.S. & Ph.D: Materials Science



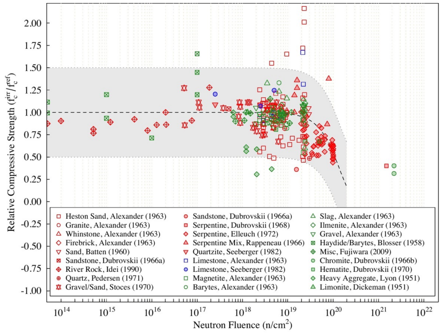
2012

University of Michigan

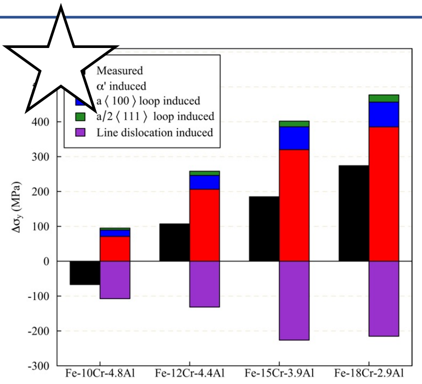
Associate Professor

ORNL (early years)

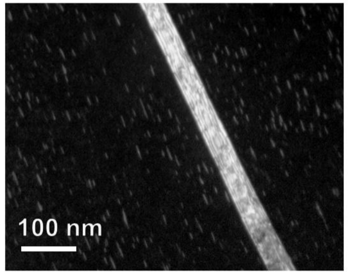
Weinberg Fellow



Irradiated Concrete



Radiation Effects in FeCrAl



Deformation Mechanism in irr. FCC alloys

2007

Michigan Technological University

B.S: Materials Science & Engineering


OWNED

About you - introductions

Minimum amount of information to divulge:

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

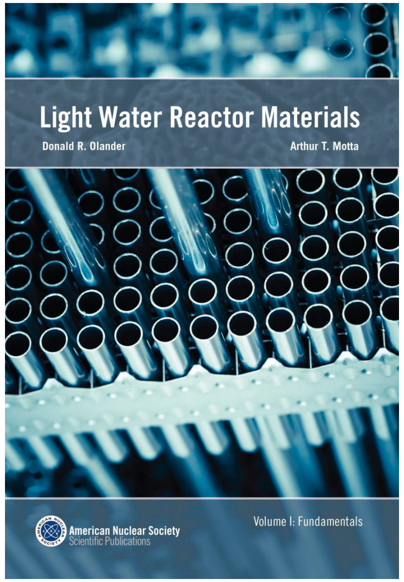
Optional:

- Something interesting about your hometown(s)

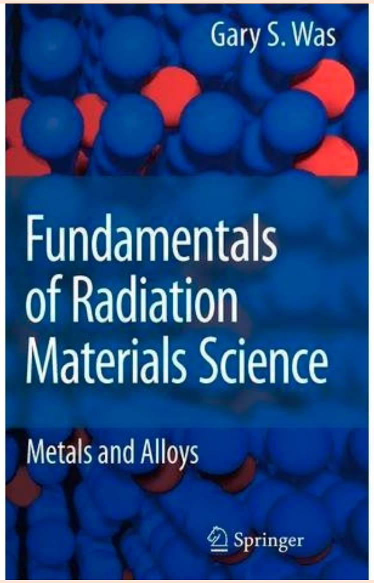
Go to Canvas Syllabus

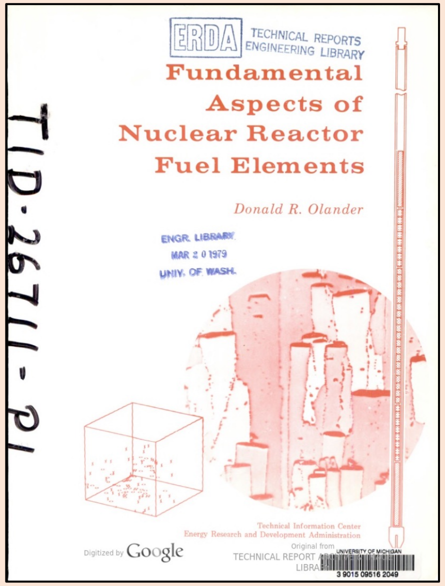
Course Materials:

Available Online (see syllabus)



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



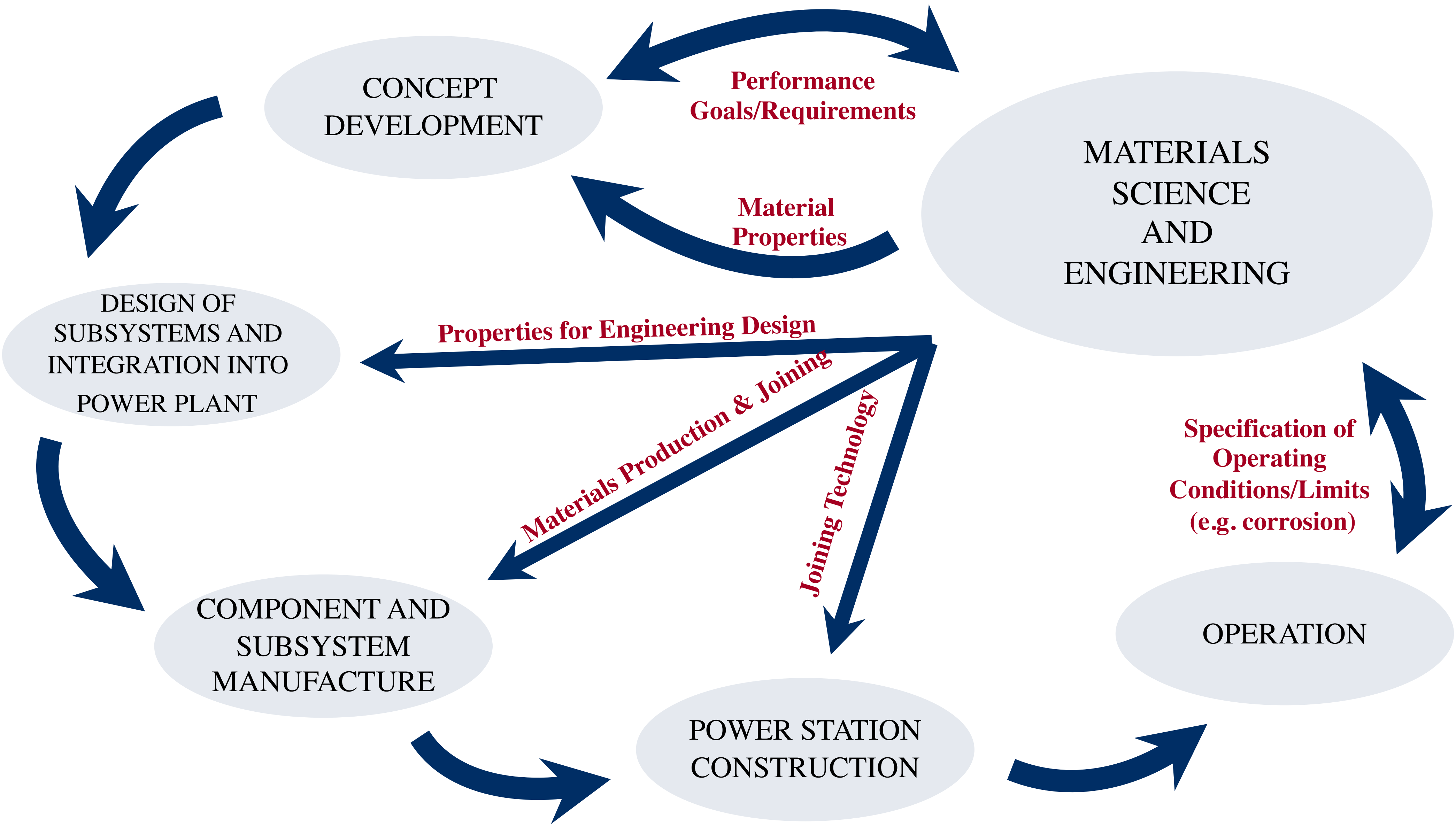


Other books, chapters, papers, lectures, etc.

Lecture Break: On Sunday Max Verstappen won consecutive races from 10th or lower in F1. The last person to do this was Bruce McLaren in what year?

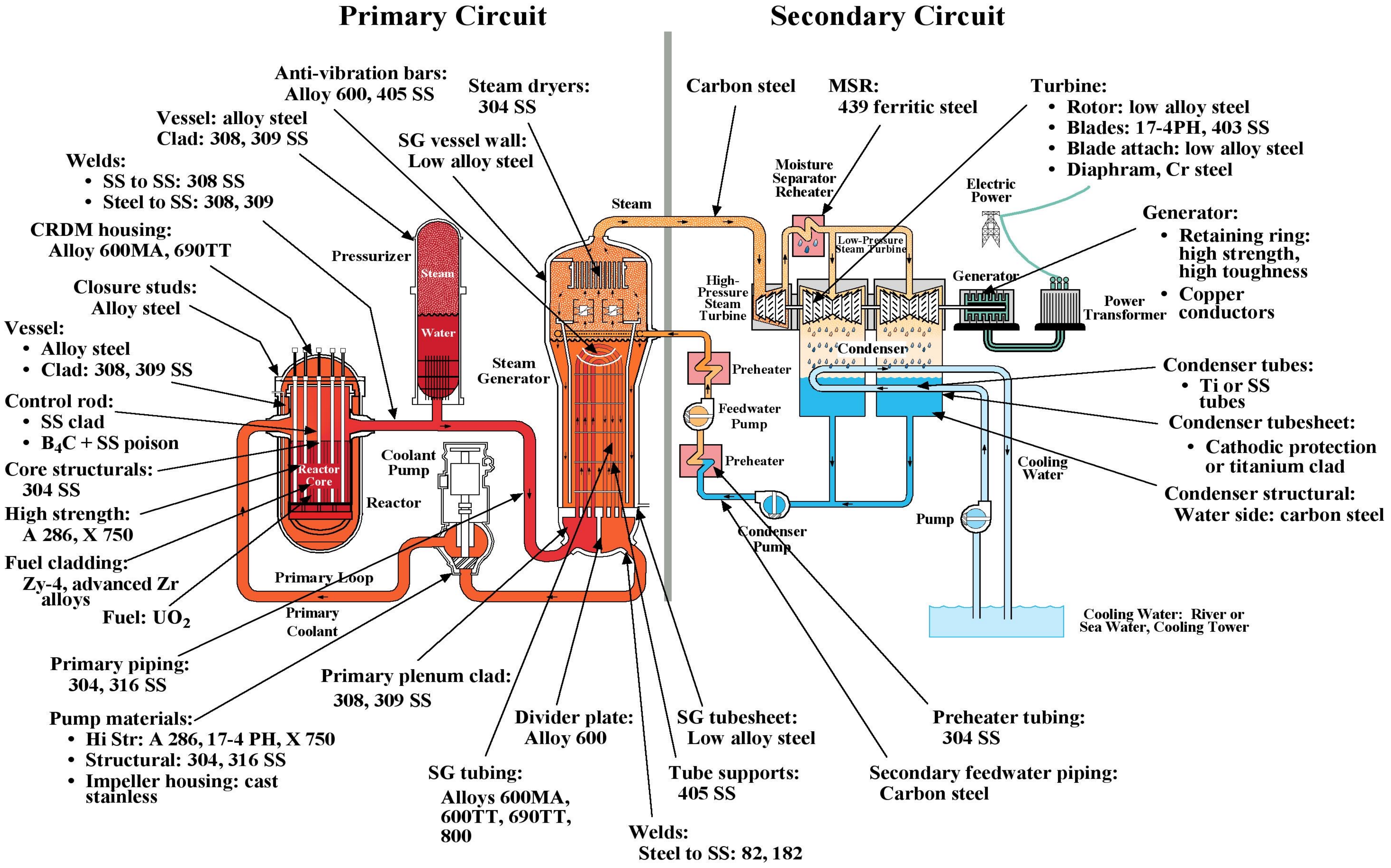
Why Radiation Materials Science?

Why Radiation Materials Science?



Slide courtesy of J. Busby (ORNL)

Why Radiation Materials Science?



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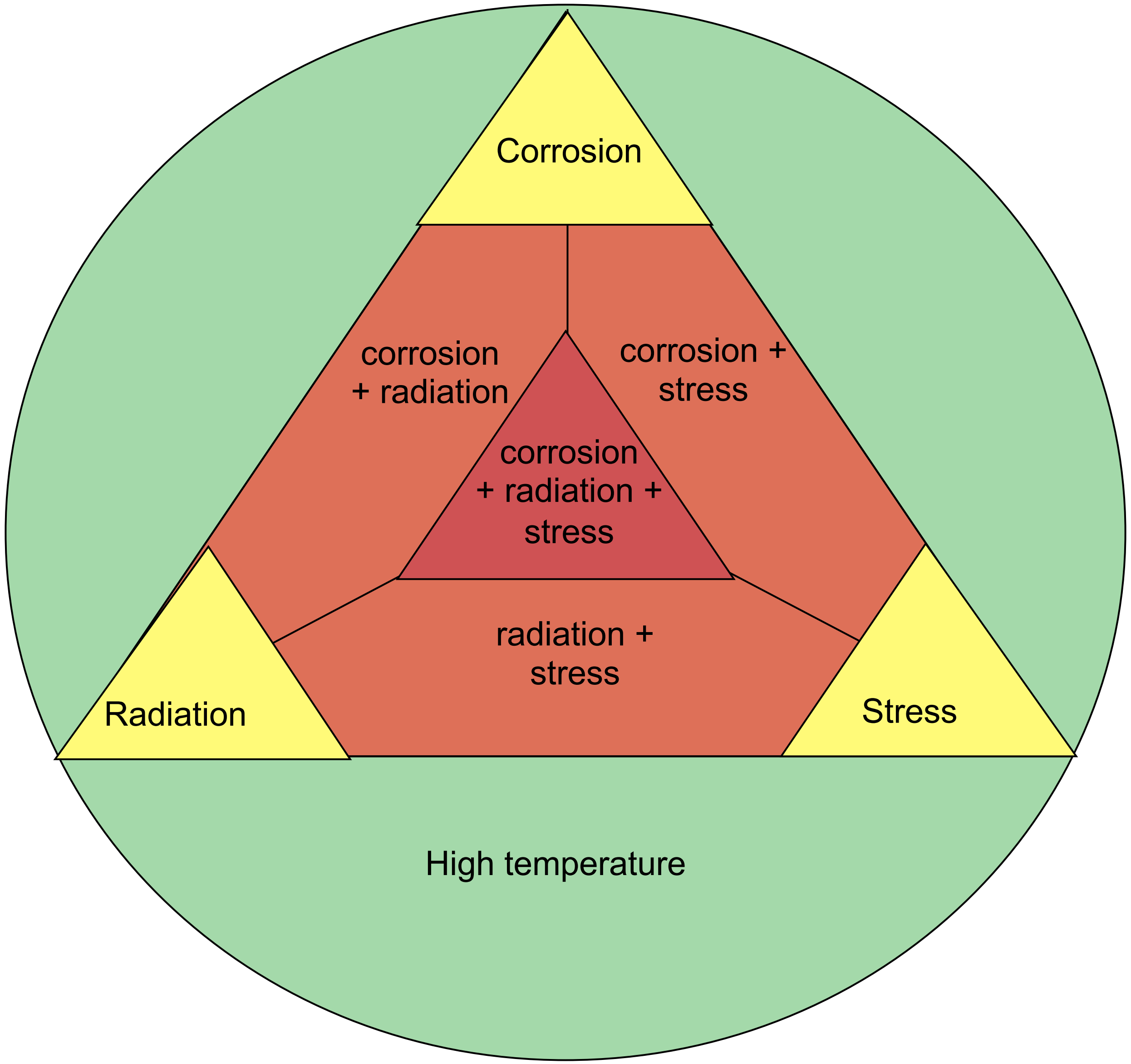
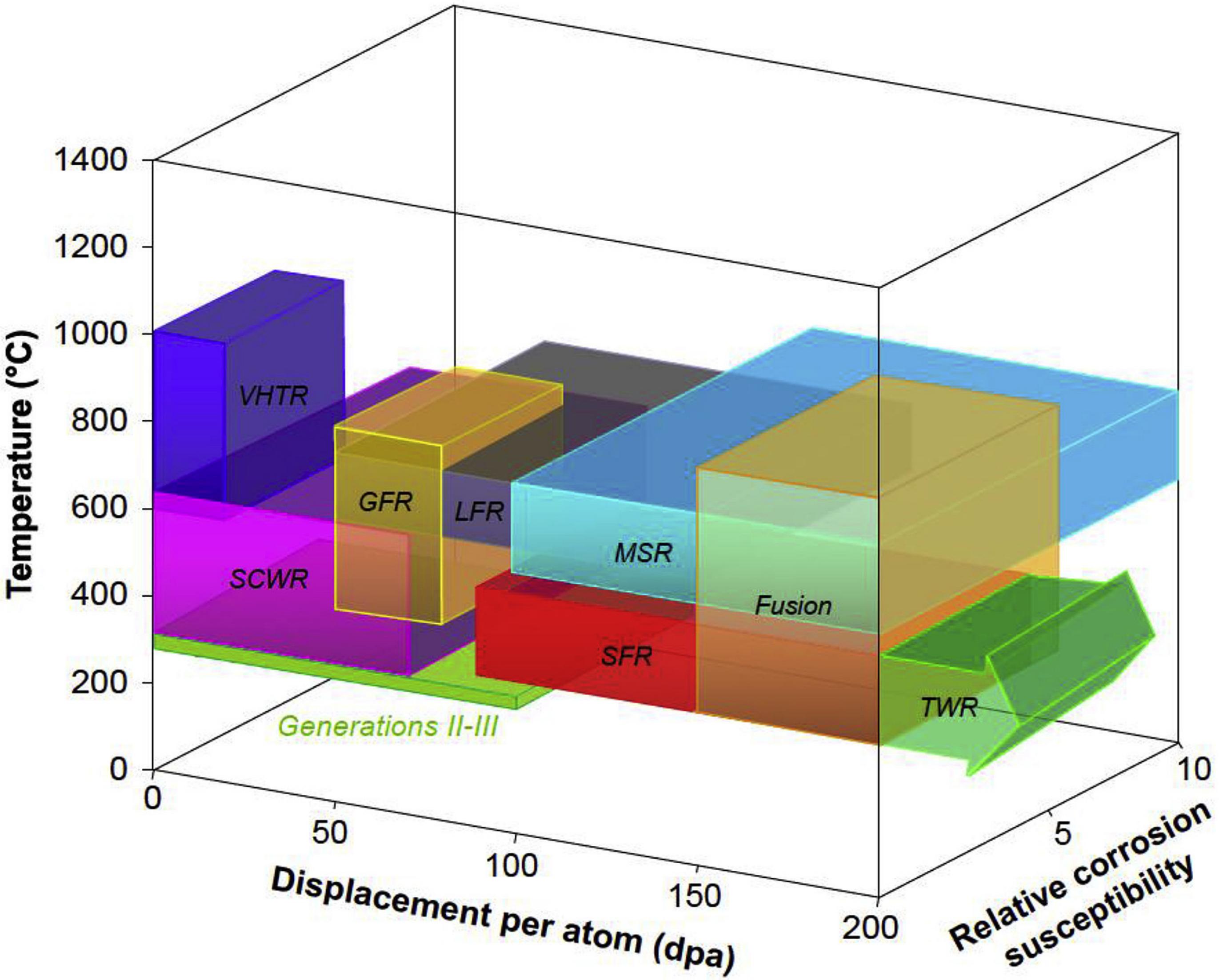
Materials "stressors" in nuclear reactor systems



Slide courtesy of G. Was (UM)

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/FHR	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

https://doi.org/10.1016/j.jnucmat.2019.151837

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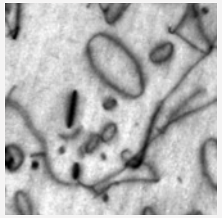
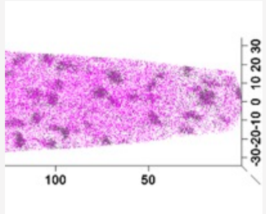
Consequences of microstructural changes on mechanical performance

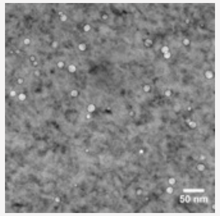
Dislocation loops



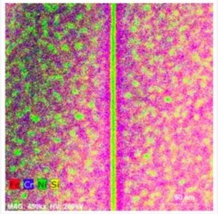
Radiation-Induced Precipitation (RIP)



Cavities, He bubbles, etc.

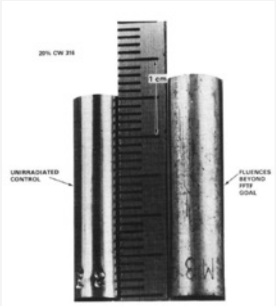


Radiation-Induced Segregation (RIS)



Hardening
Irradiation creep
Deformation localization
Embrittlement

Swelling



Increased sensitivity to SCC (IASCC)

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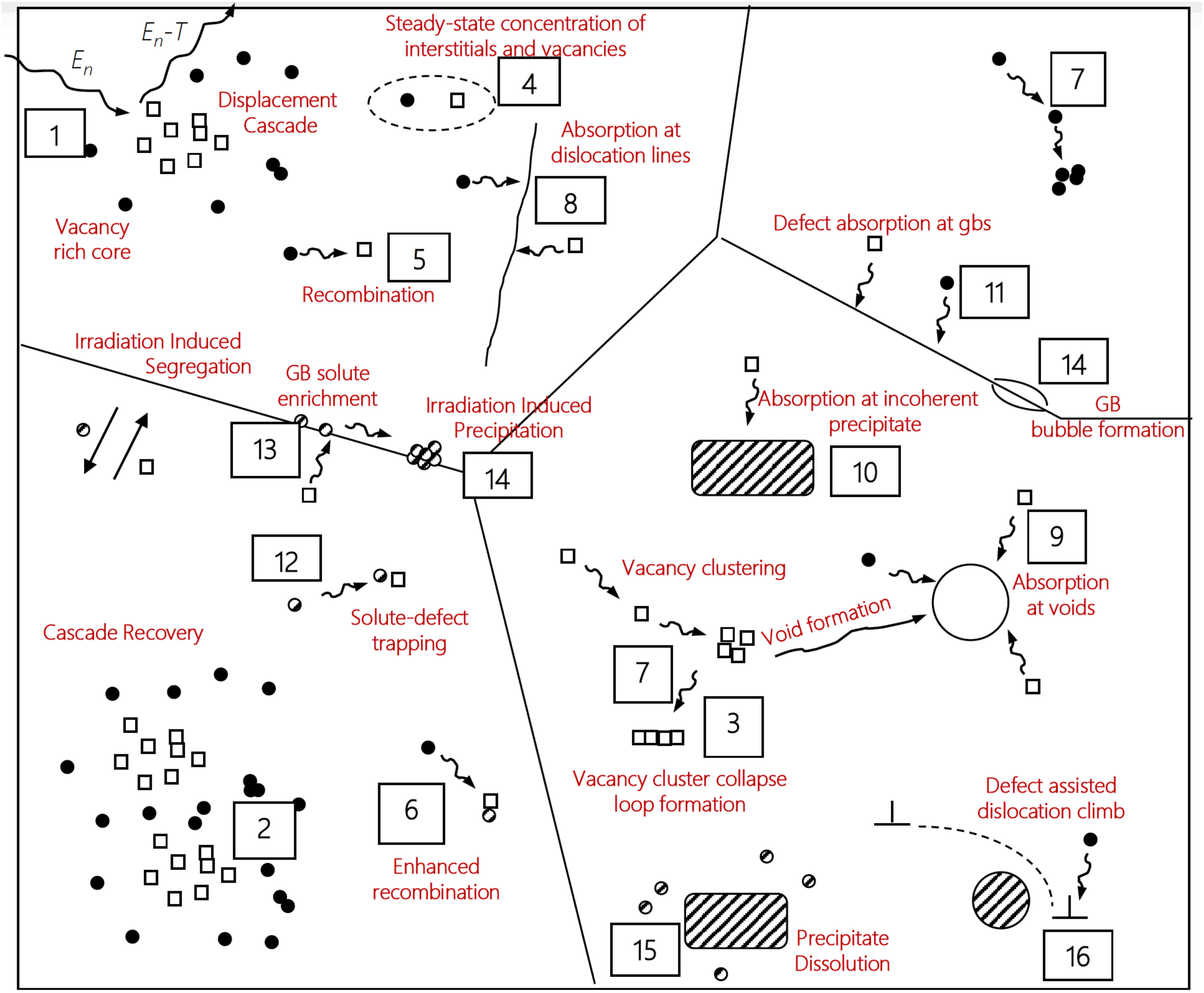
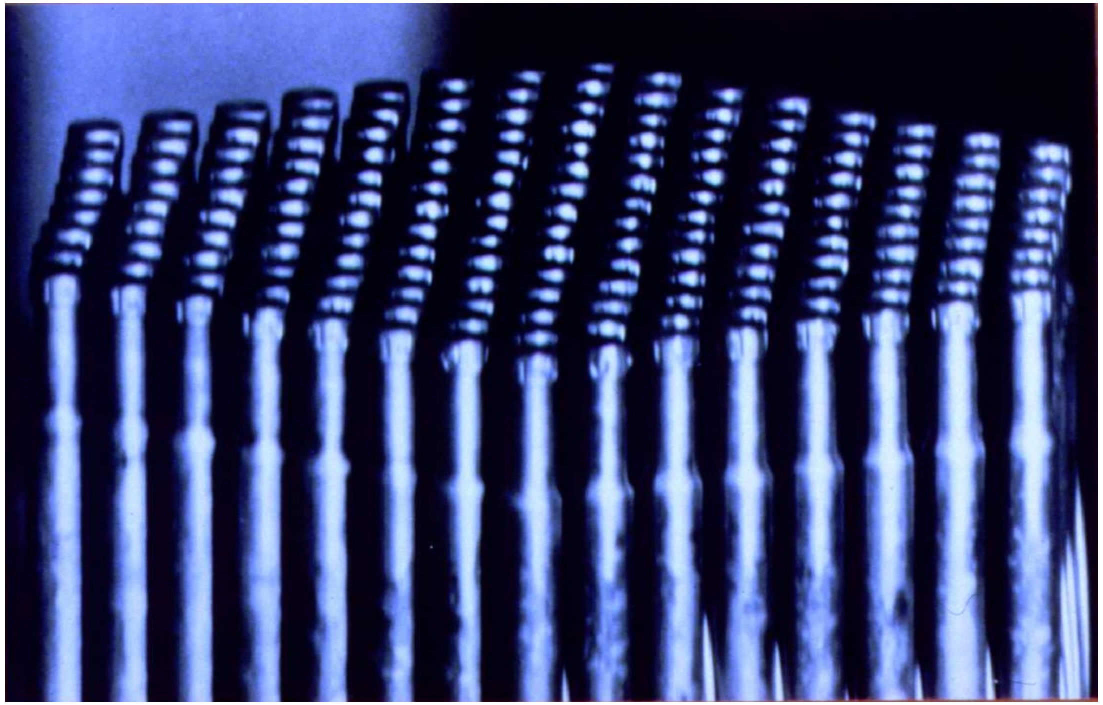
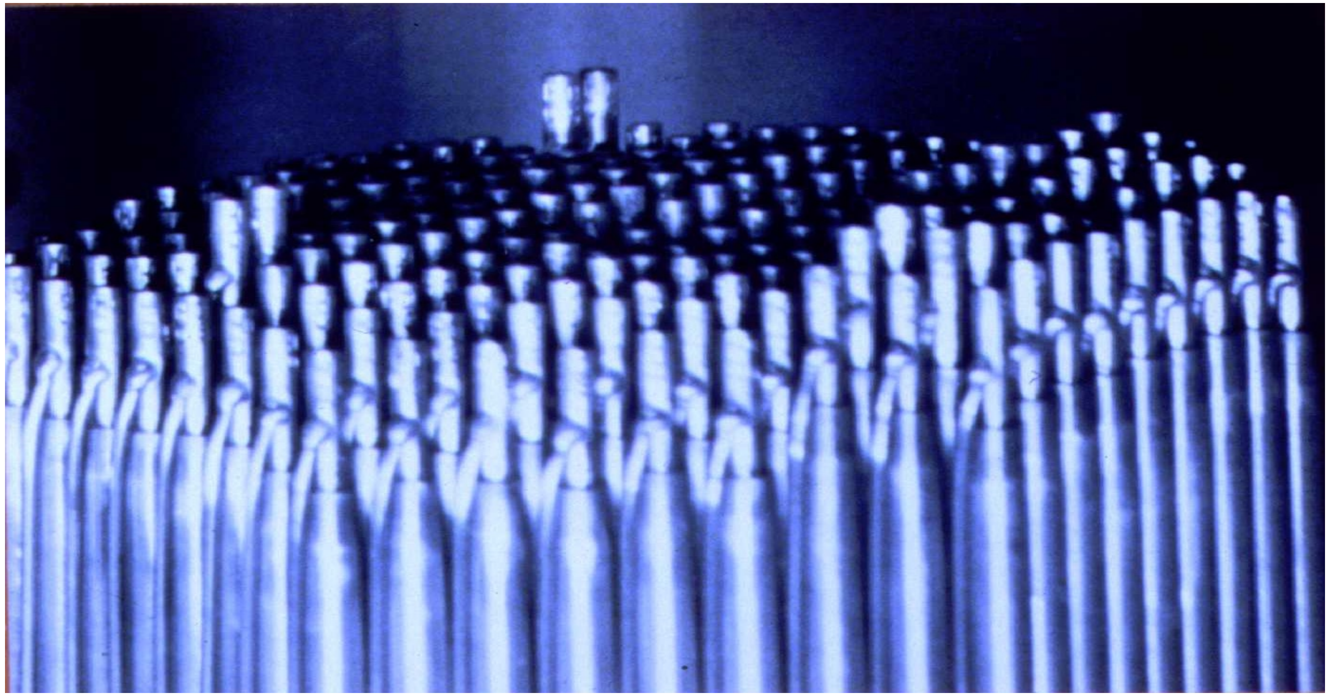
Radiation Effects at the Grain Scale



Radiation damage effects materials differently



HT-9, no swelling



316-Ti stainless, swelling

Source: F. Garner

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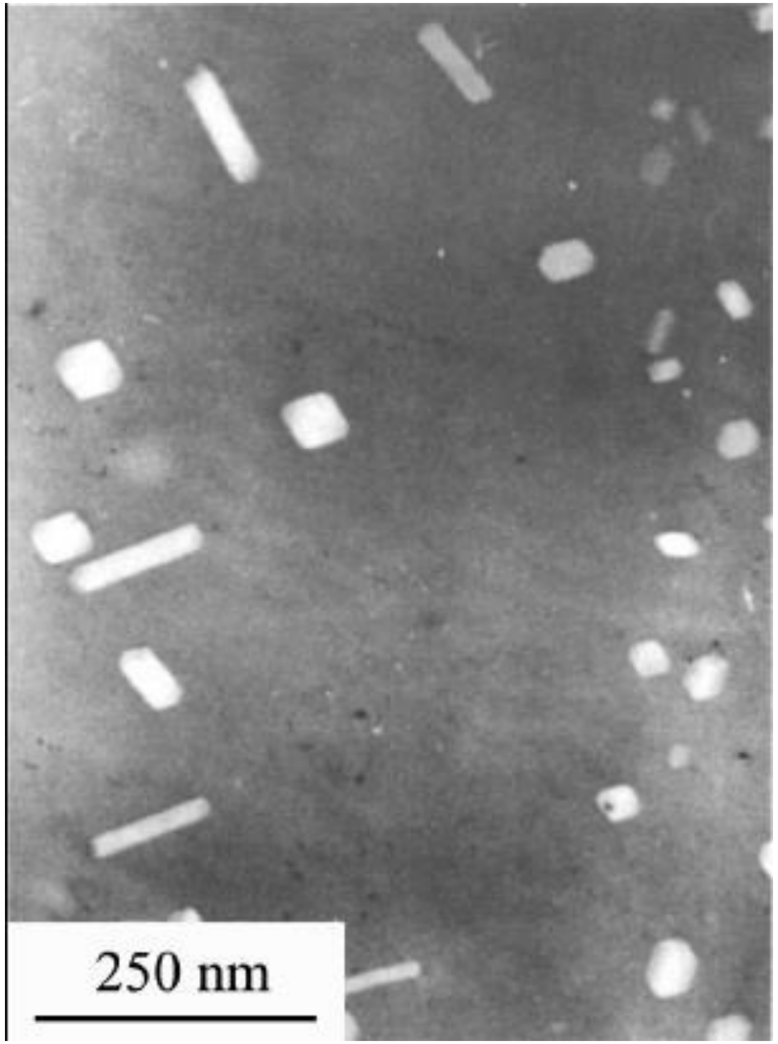
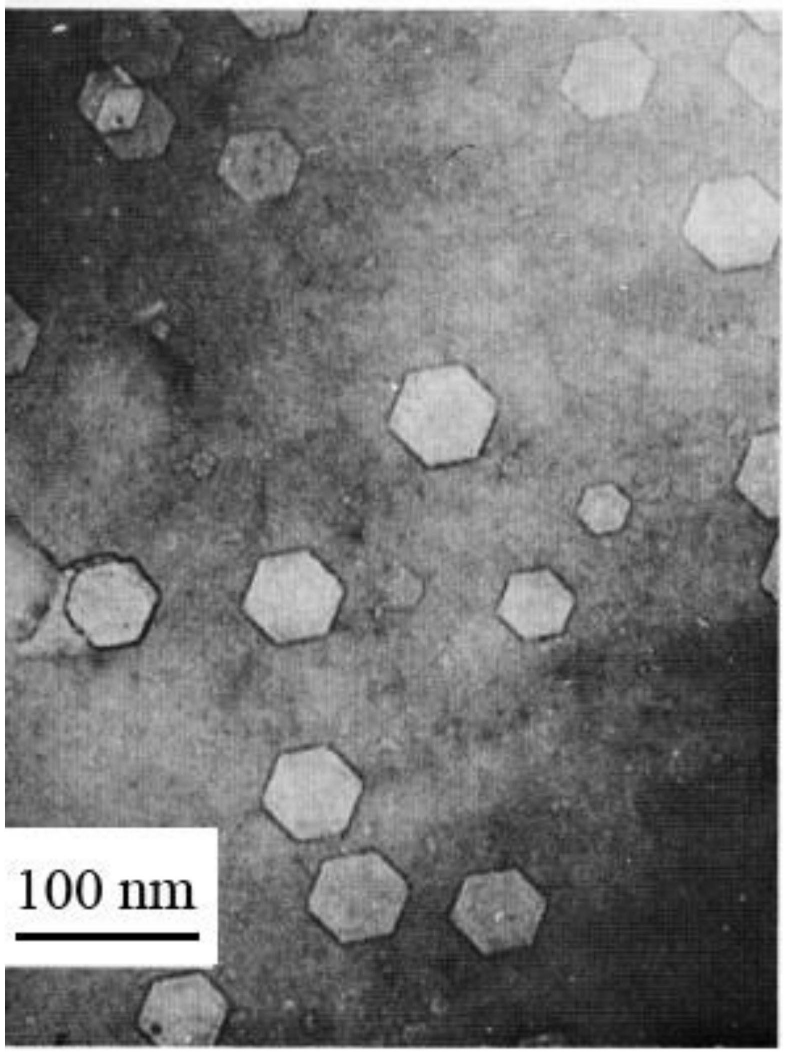
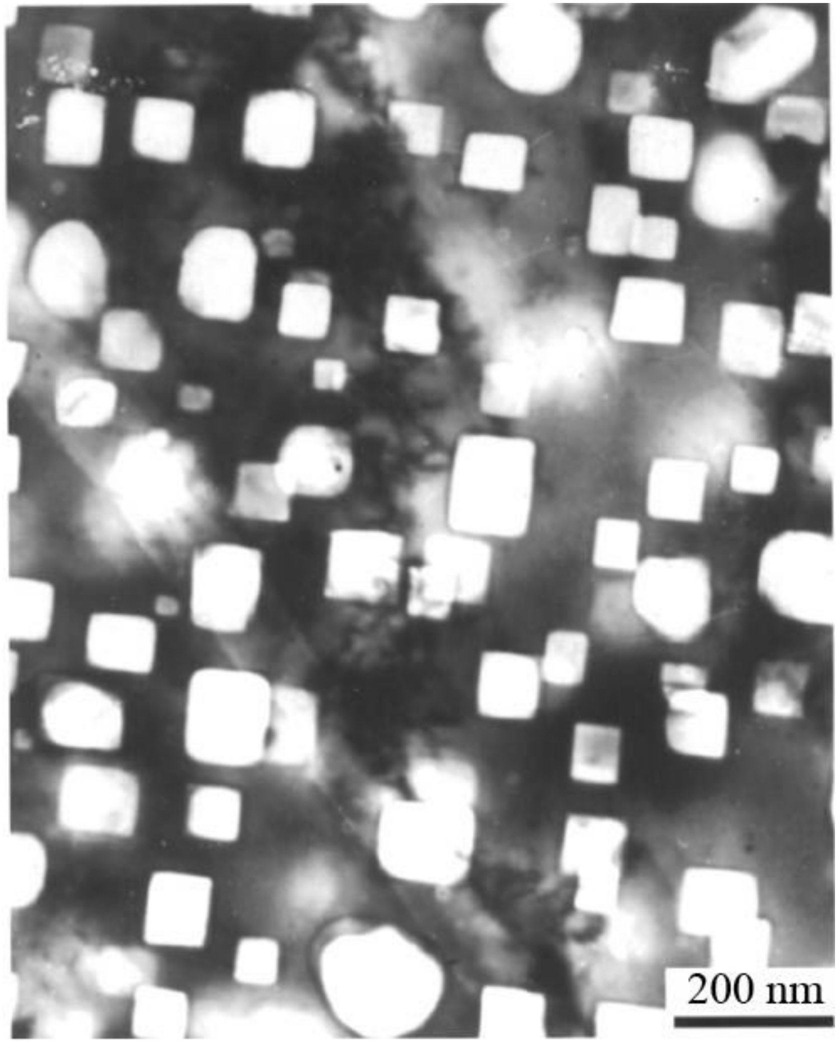
Examples of voids in various materials



Stainless Steel



Aluminum

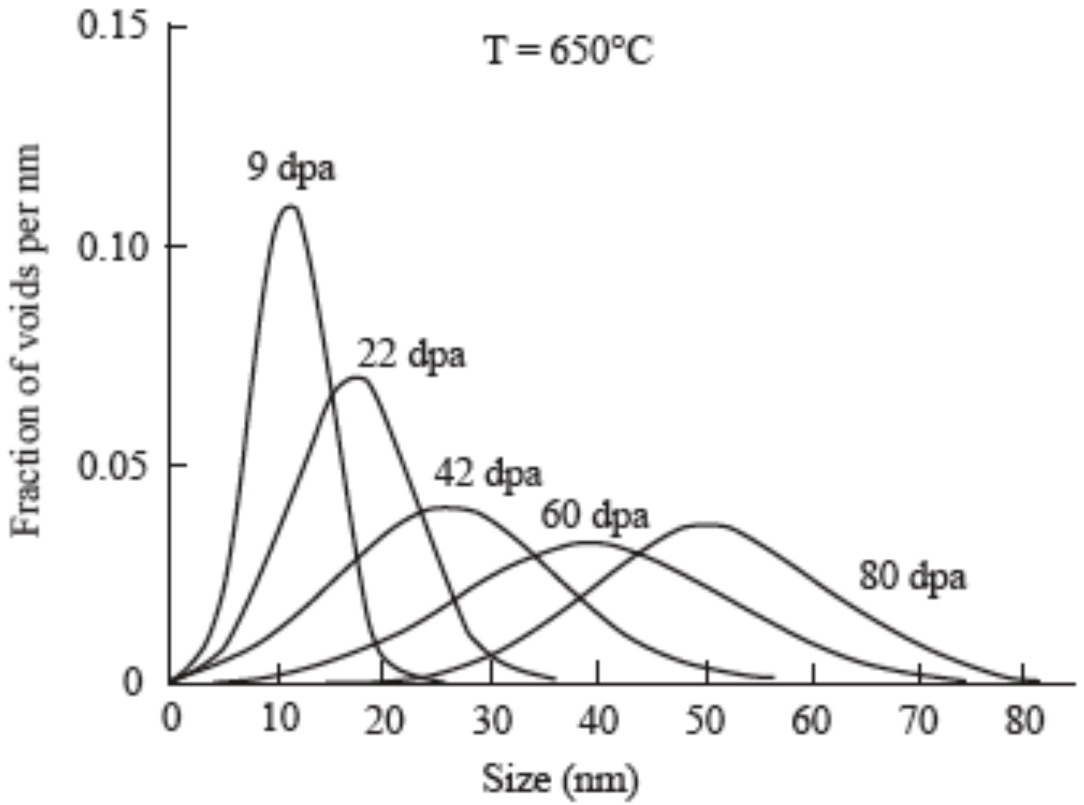


Magnesium

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.

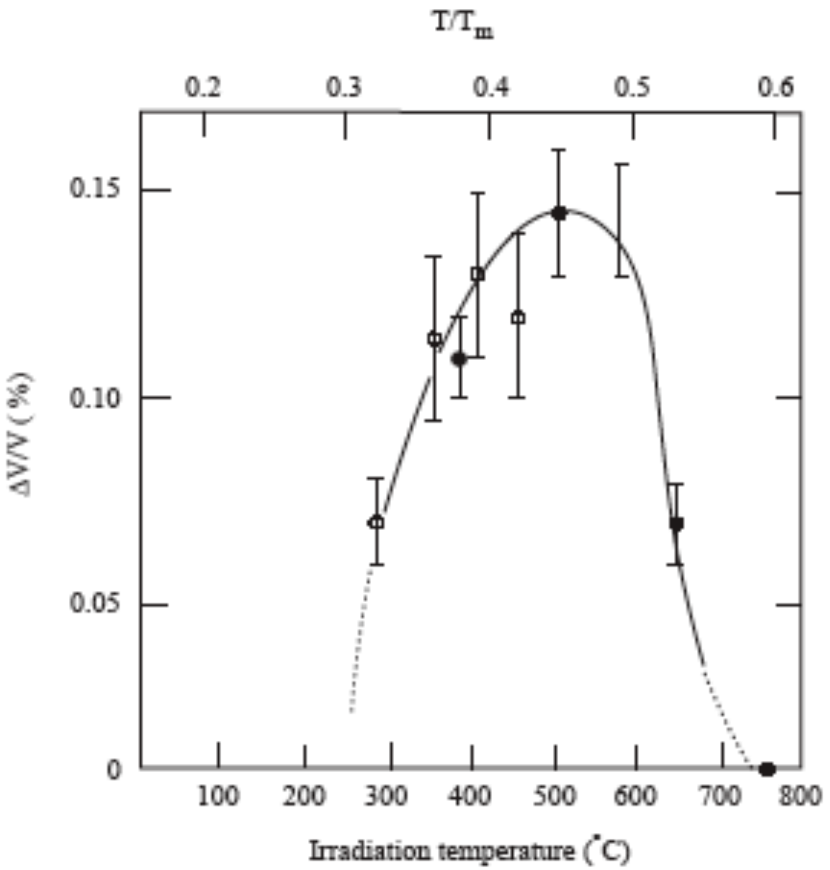
Cavity formation as a function of dose and temperature

Dose Dependence



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.

Temperature Dependence



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

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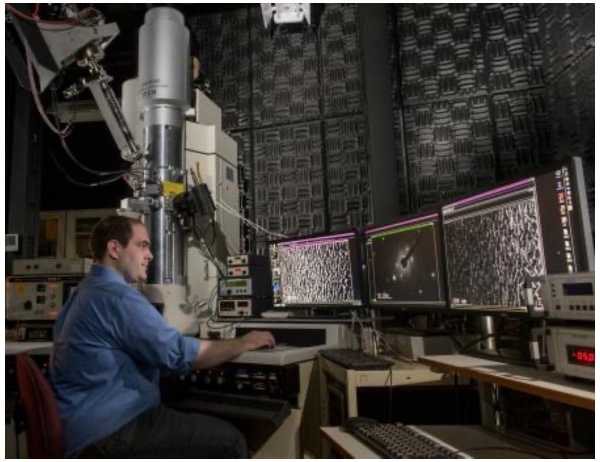
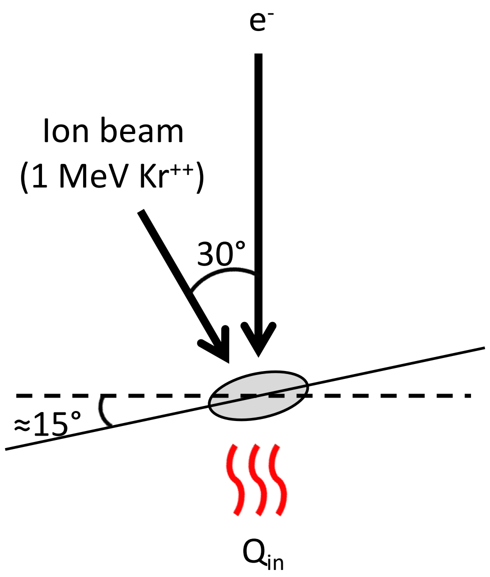
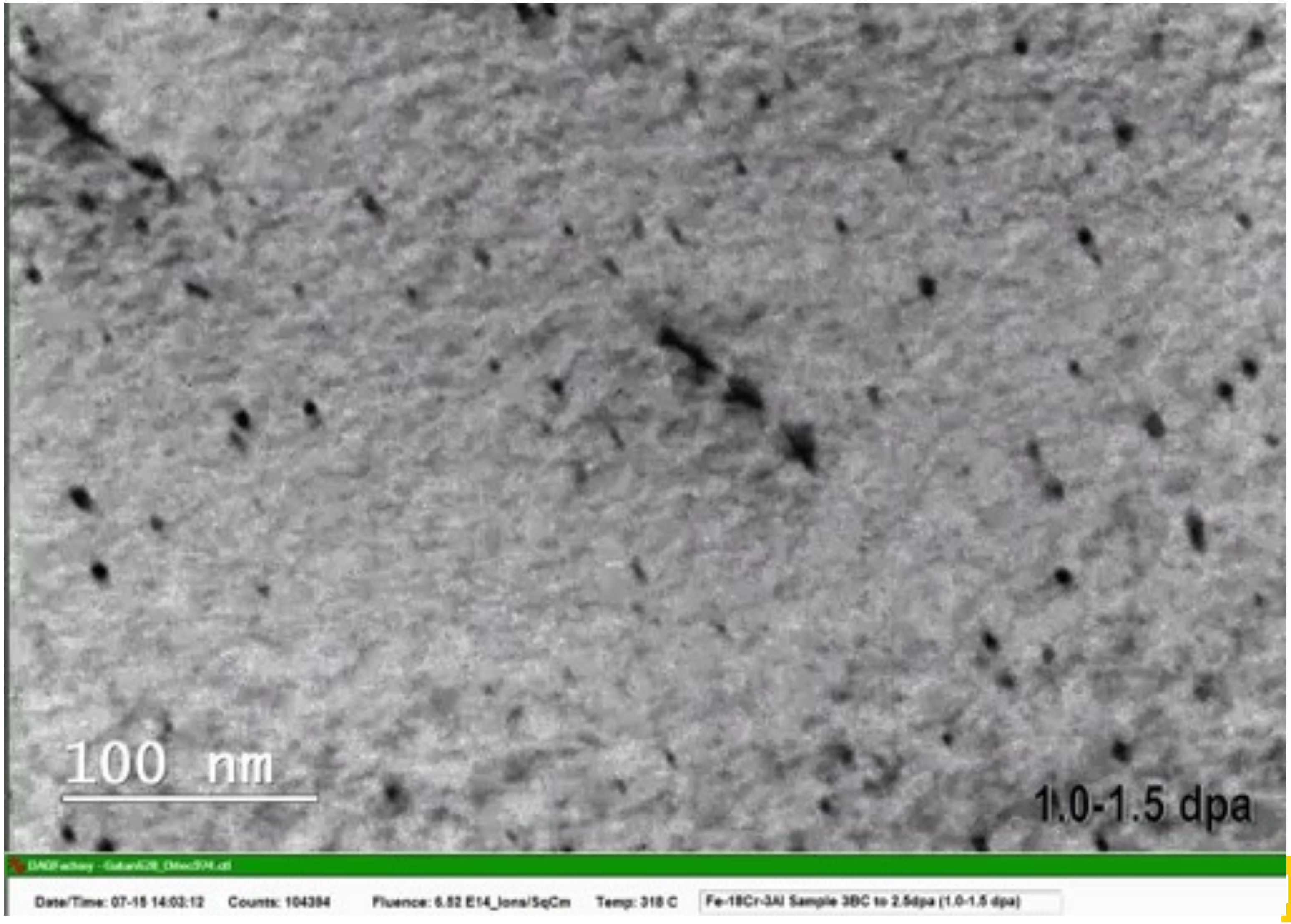
Example data on in-situ ion irradiation of a FeCrAl alloy at 320°C



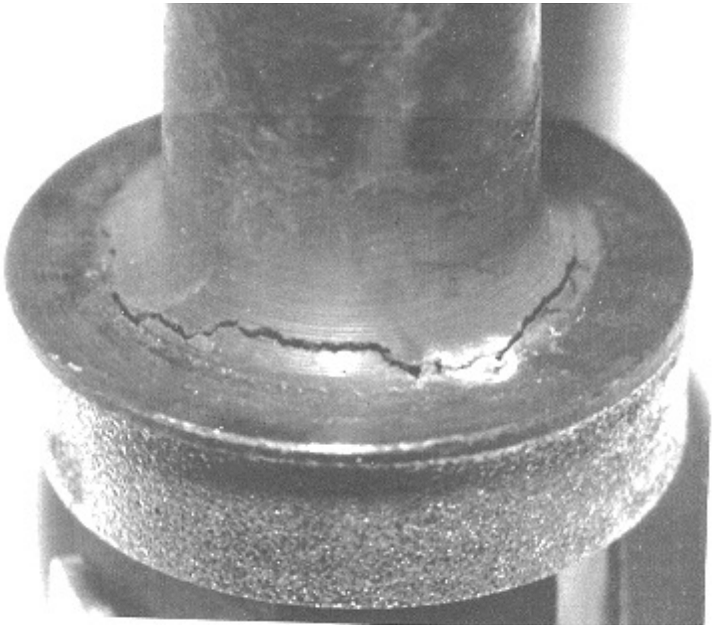
Argonne's IVEM facility



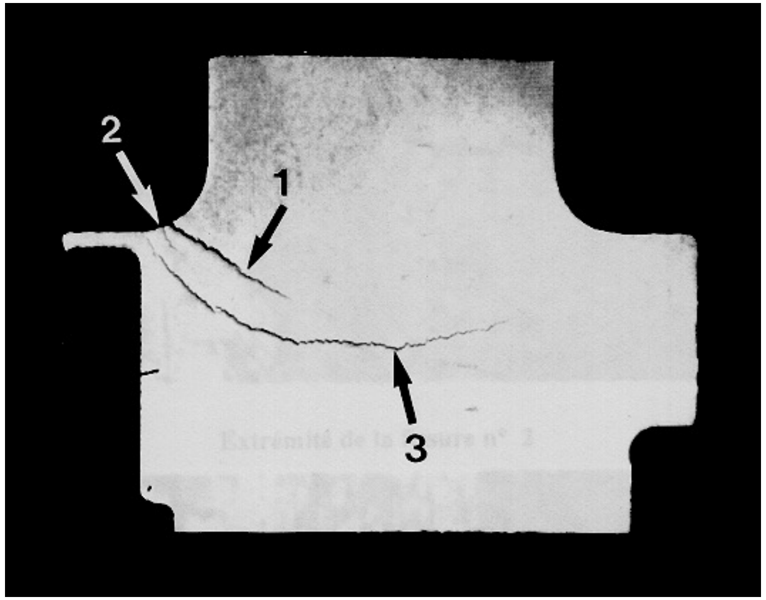


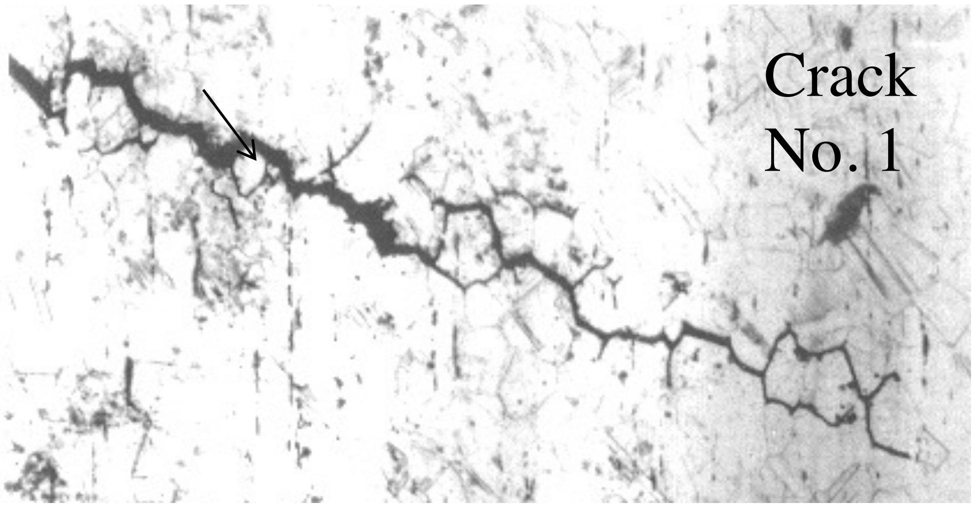
[1] Image courtesy of C. Ulmer (PSU)

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

Earthquake → LOFP → Loss of all electric-motor driven pumps

- Reactors Scram
- DGs start and load

Tsunami →

- Diesel Generators flooded
- Loss of UHS

Battery Failure

Loss of all RPV Water Injection

- Decay Heat
- No Injection

Loss of RPV Water Inventory

Core Heatup

- Core Oxidation
- Core Degradation and Relocation

RPV and Containment Failure

Hydrogen Explosion

Slide Adapted from L. Ott (ORNL)

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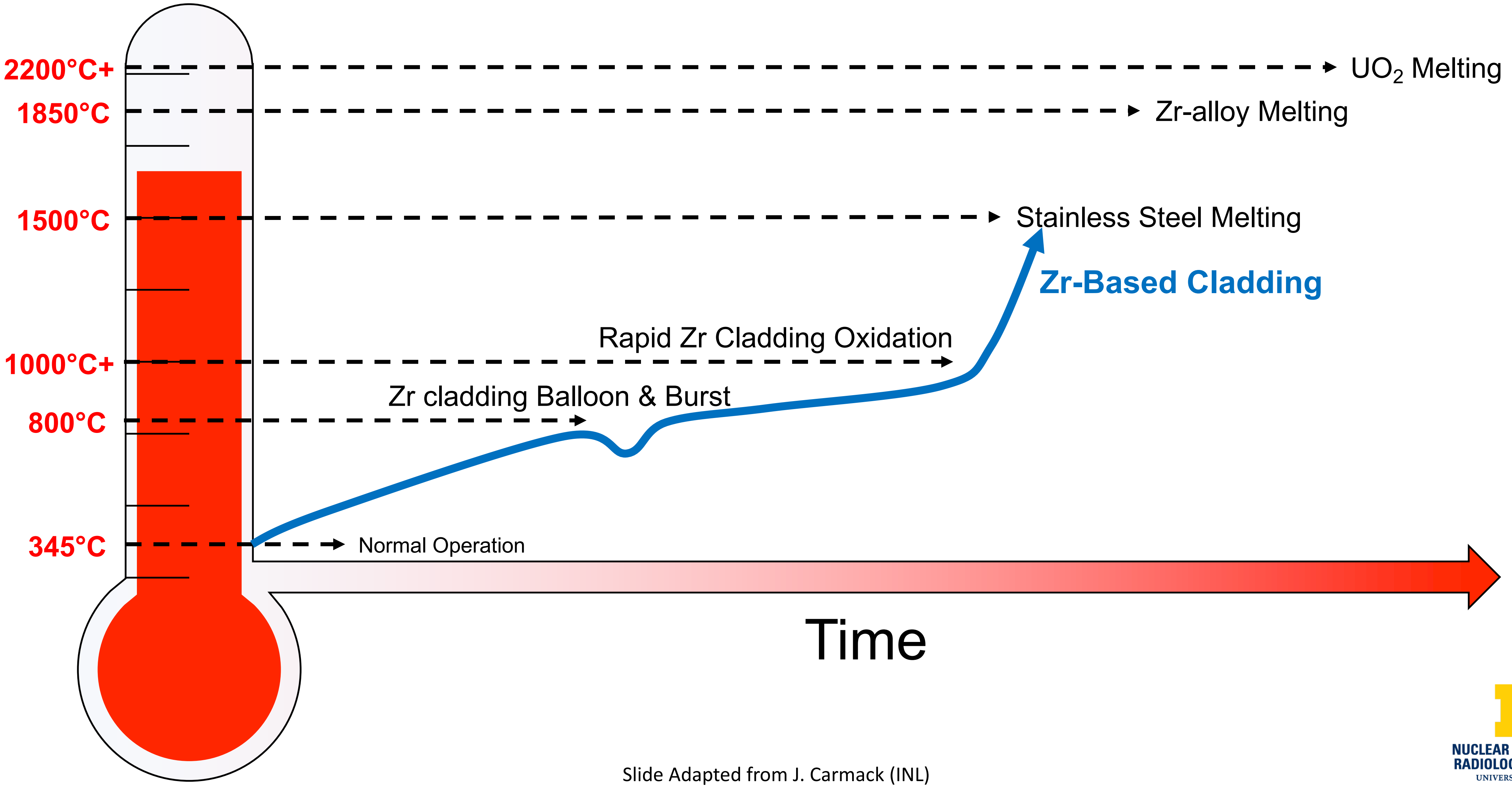
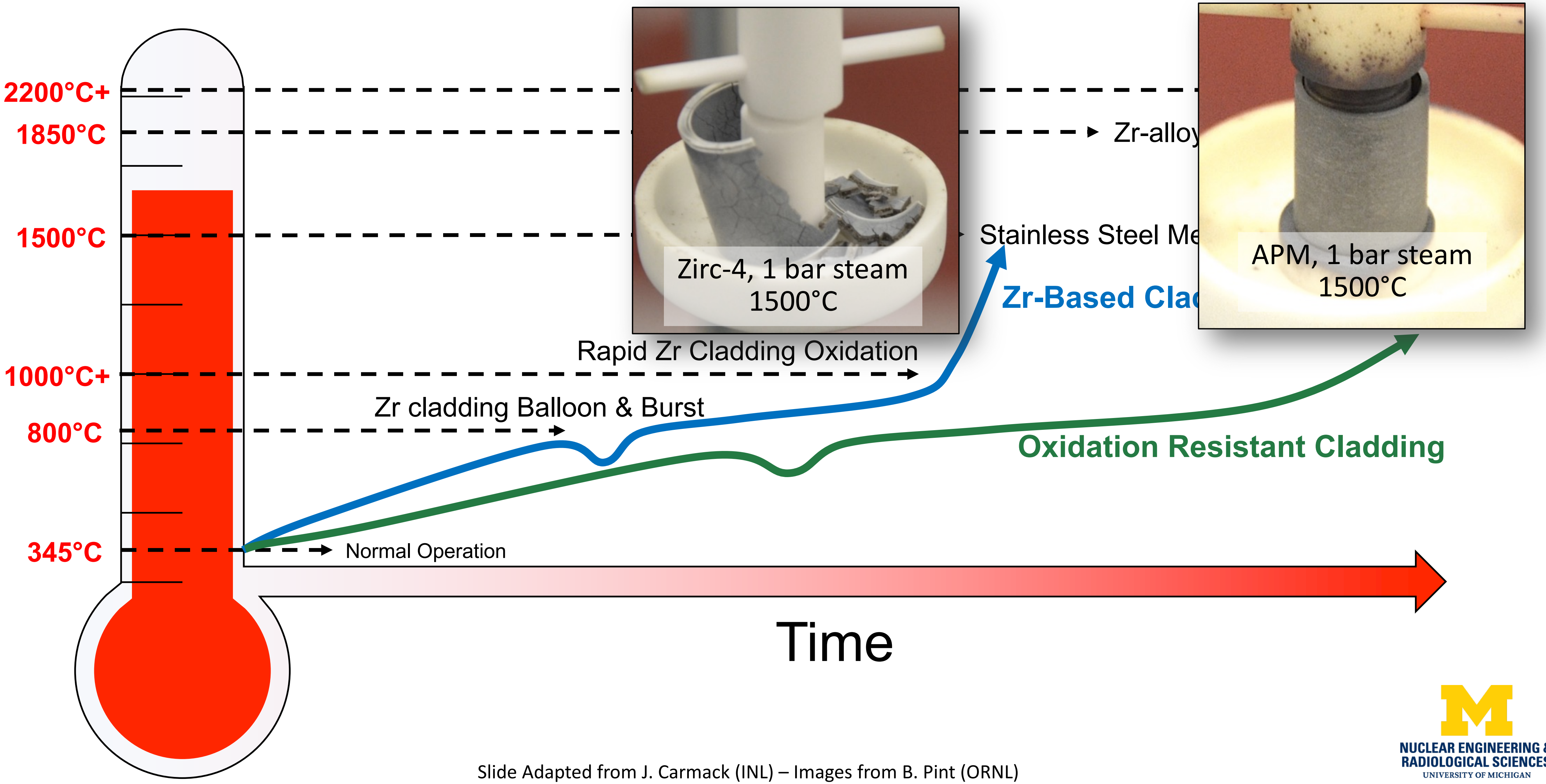
Oxidation of cladding is key towards core degradation during a coolant-limited accident scenario



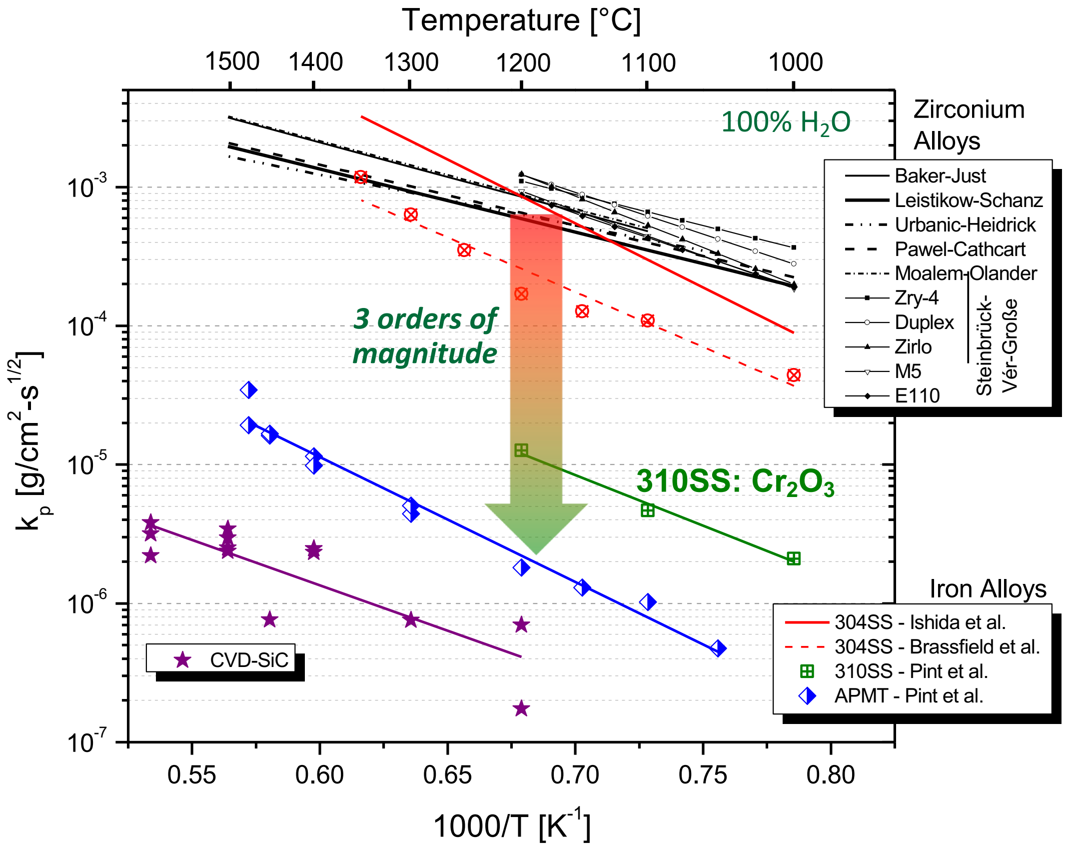
Slide Adapted from J. Carmack (INL)

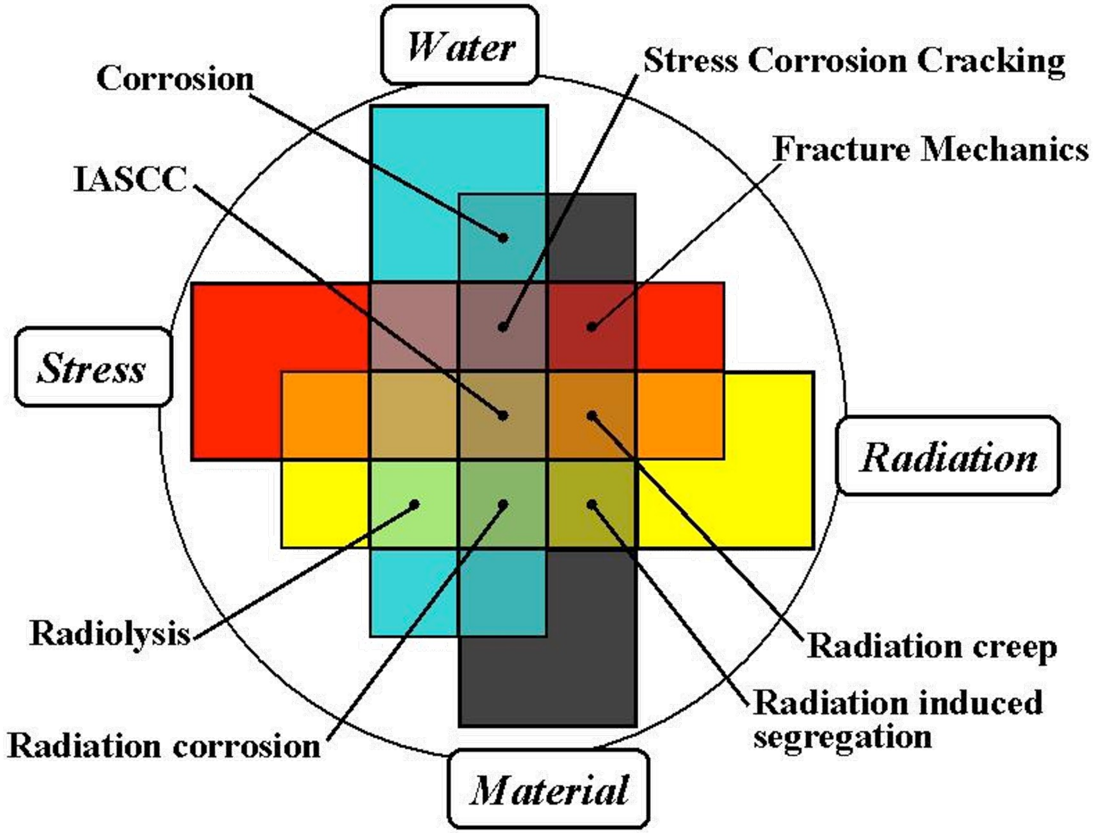
Oxidation of cladding is key towards core degradation during a coolant-limited accident scenario



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

[1] Terrani, et al. / *Journal of Nuclear Materials* **448** (2013) – Image from J. Busby (ORNL)

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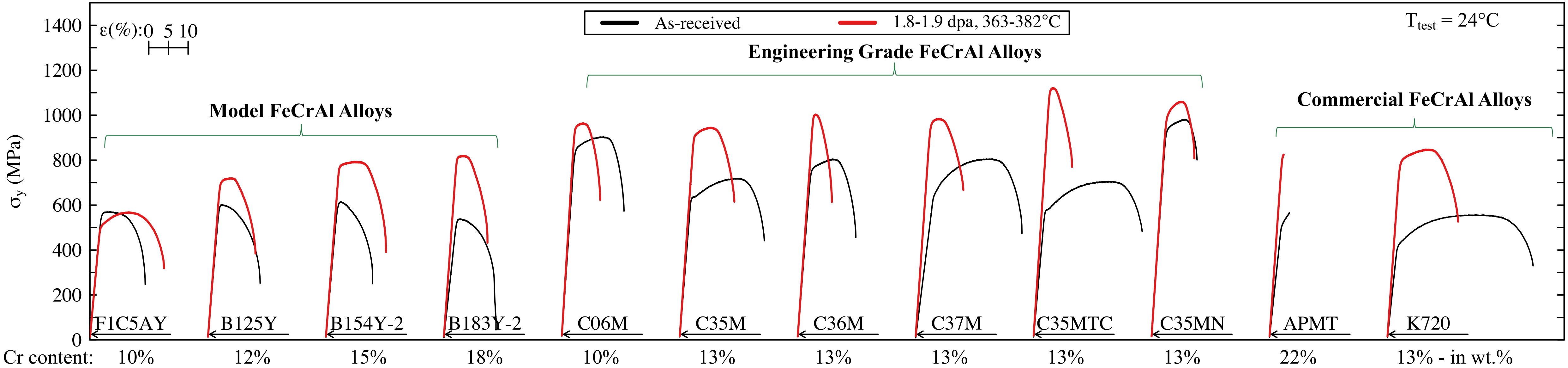
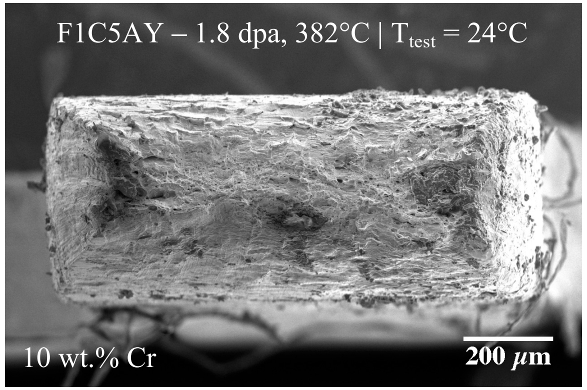
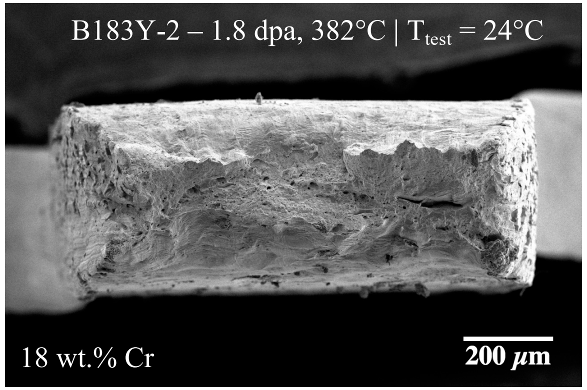
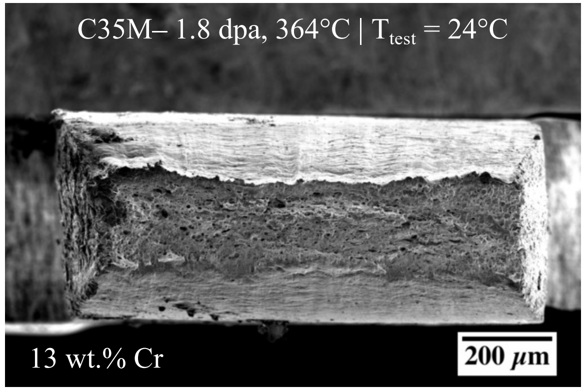
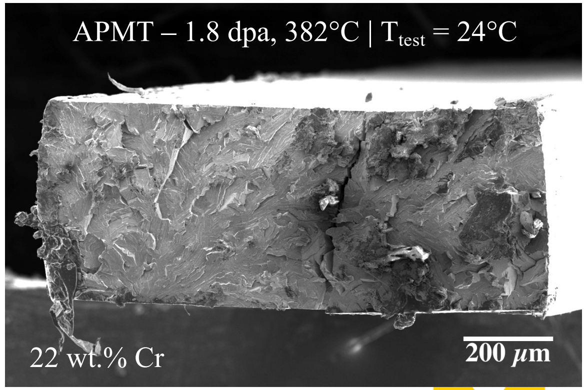
All wrought FeCrAl alloys studied showed typical radiation-induced hardening for high Cr ferritic alloys











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

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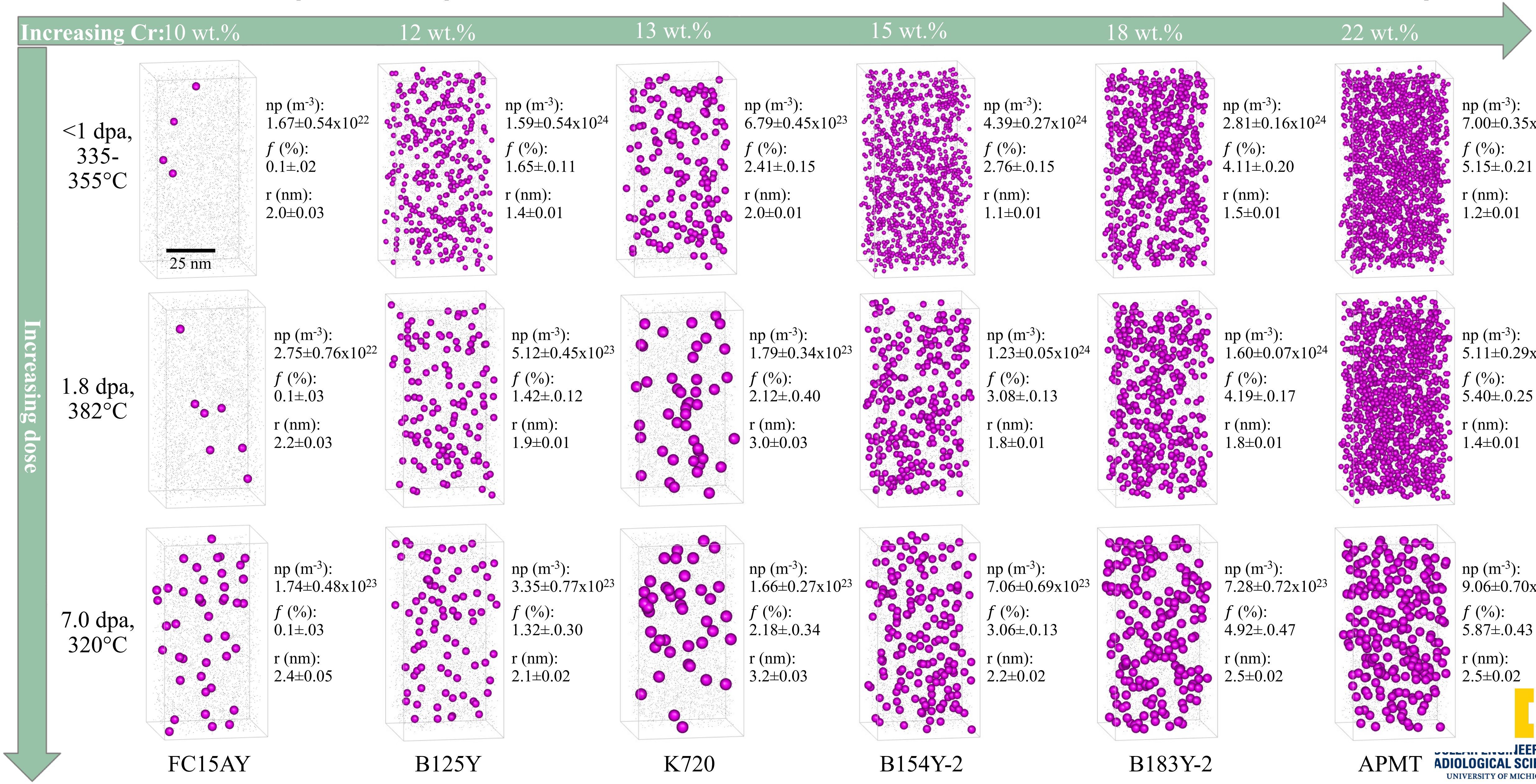
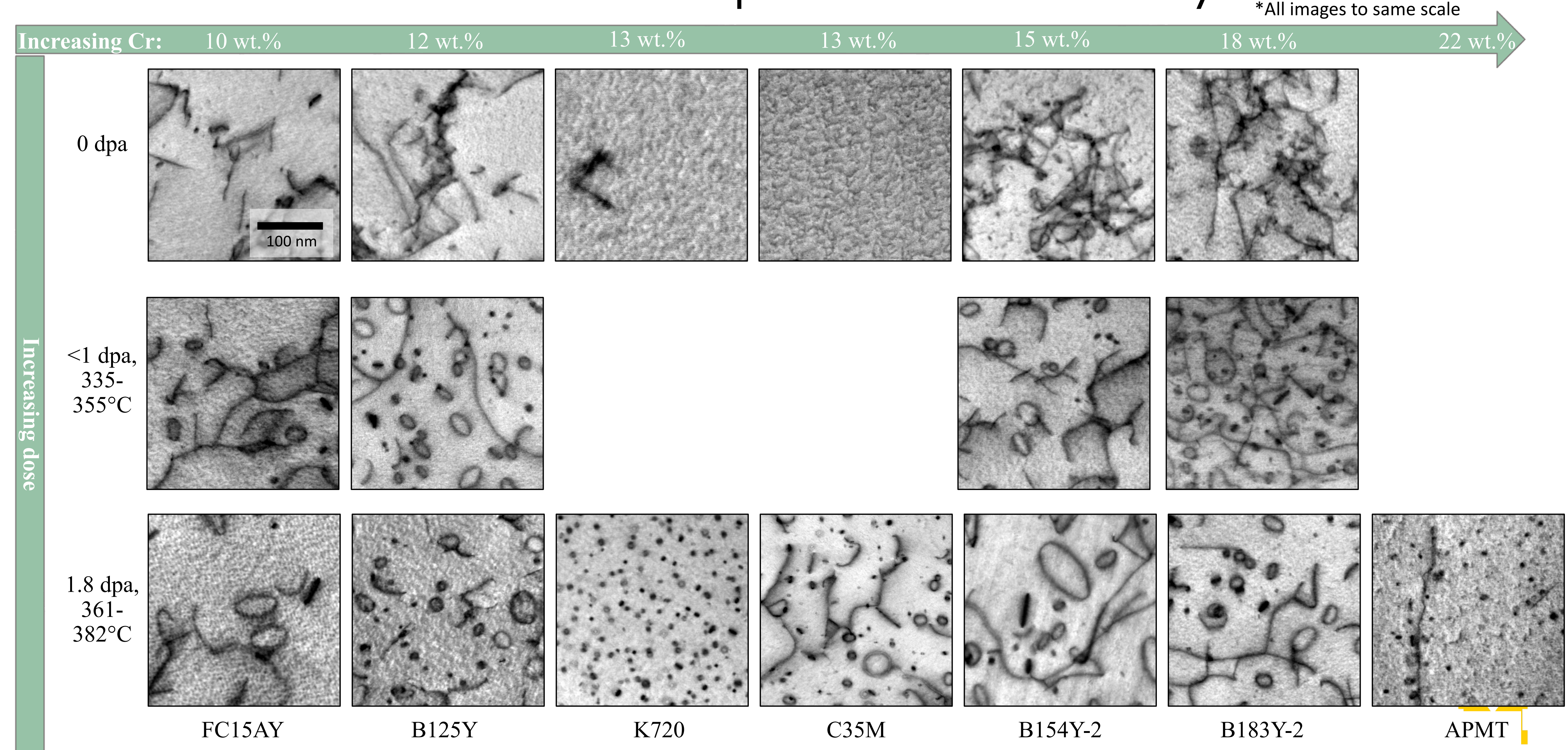
Trends in precipitation of Cr-rich a' in FeCrAl alloys



	FC15AY (10 wt.%)	B125Y (12 wt.%)	K720 (13 wt.%)	B154Y-2 (15 wt.%)	B183Y-2 (18 wt.%)	APMT (22 wt.%)
<1 dpa, 335-355°C: np (m^{-3})	1.67±0.54x10^{22}	1.59±0.54x10^{24}	6.79±0.45x10^{23}	4.39±0.27x10^{24}	2.81±0.16x10^{24}	7.00±0.35x10^{24}
f (%)	0.1±.02	1.65±.0.11	2.41±0.15	2.76±0.15	4.11±.0.20	5.15±0.21
r (nm)	2.0±0.03	1.4±0.01	2.0±0.01	1.1±0.01	1.5±0.01	1.2±0.01
1.8 dpa, 382°C: np (m^{-3})	2.75±0.76x10^{22}	5.12±0.45x10^{23}	1.79±0.34x10^{23}	1.23±0.05x10^{24}	1.60±0.07x10^{24}	5.11±0.29x10^{24}
f (%)	0.1±.03	1.42±.0.12	2.12±0.40	3.08±0.13	4.19±0.17	5.40±0.25
r (nm)	2.2±0.03	1.9±0.01	3.0±0.03	1.8±0.01	1.8±0.01	1.4±0.01
7.0 dpa, 320°C: np (m^{-3})	1.74±0.48x10^{23}	3.35±0.77x10^{23}	1.66±0.27x10^{23}	7.06±0.69x10^{23}	7.28±0.72x10^{23}	9.06±0.70x10^{23}
f (%)	0.1±.03	1.32±0.30	2.18±0.34	3.06±0.13	4.92±0.47	5.87±0.43
r (nm)	2.4±0.05	2.1±0.02	3.2±0.03	2.2±0.02	2.5±0.02	2.5±0.02

Trends in dislocation loops in FeCrAl alloys



[1] Field, et al. / *Journal of Nuclear Materials* **465** (2015) [2] Field, et al. / *Journal of Nuclear Materials* **483** (2017)

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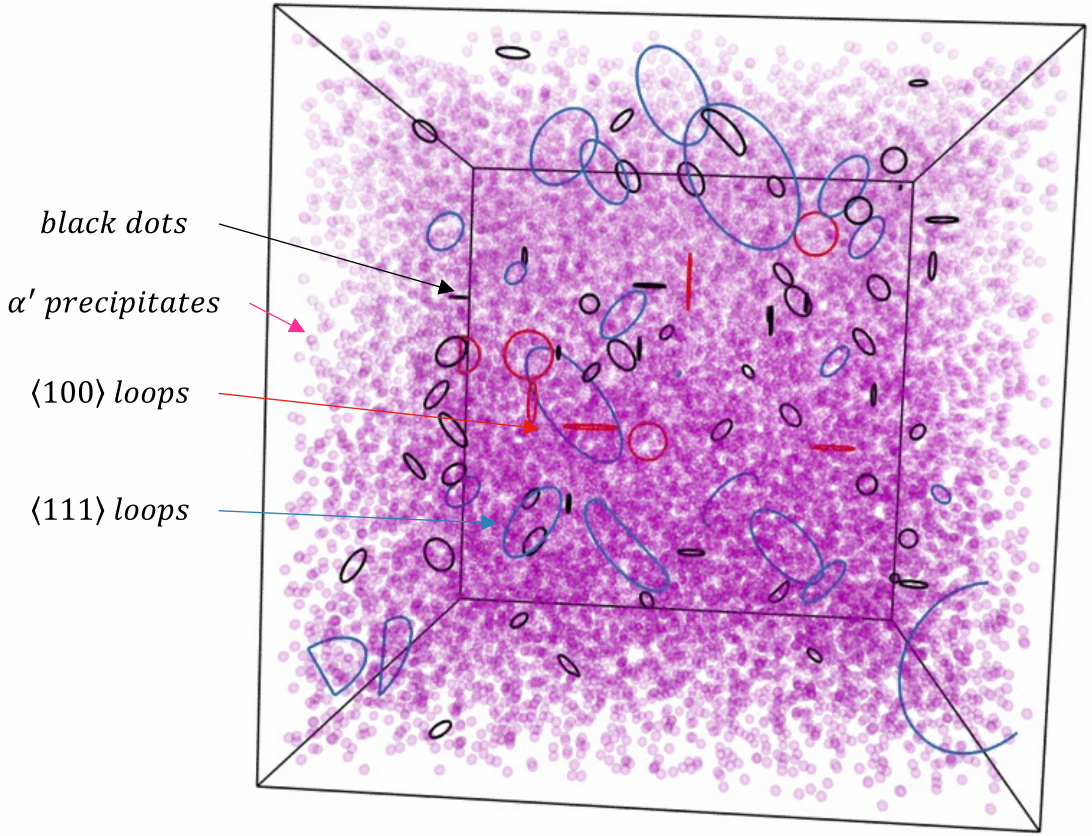
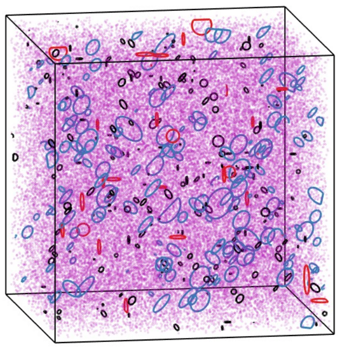
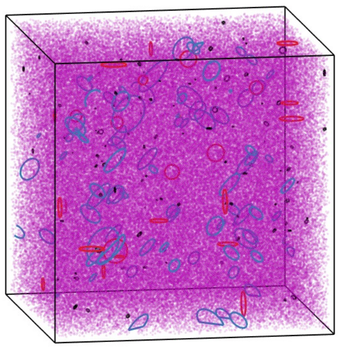
Putting the two together and visualizing:

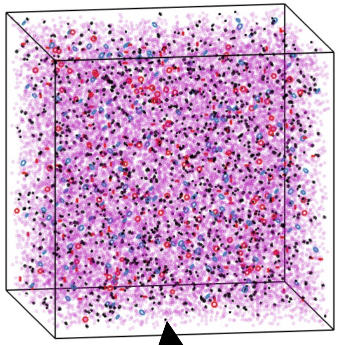


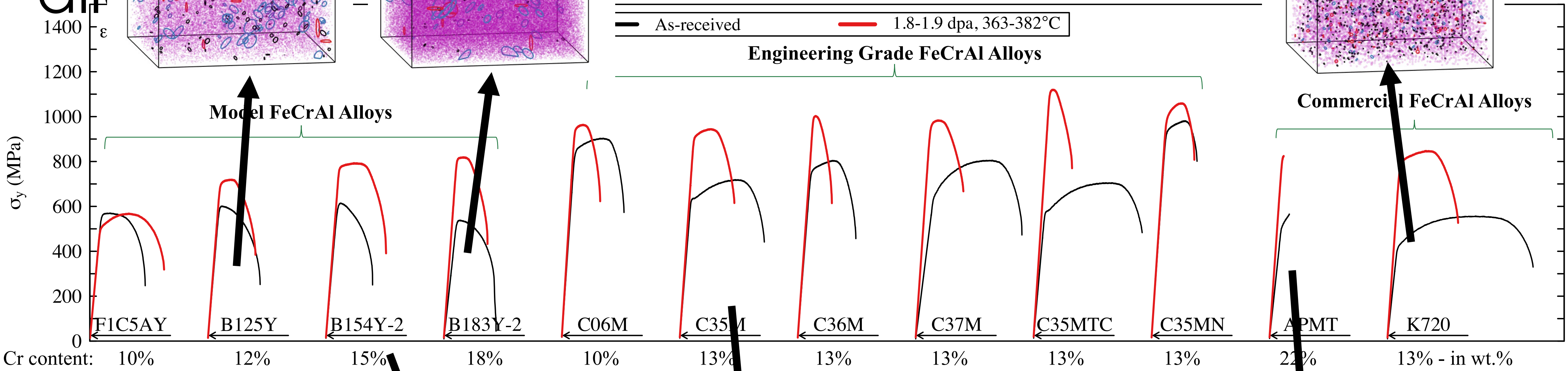
1.8 dpa, 382°C Fe-18Cr-Al synthetically rendered microstructure (300X300X300 nm)

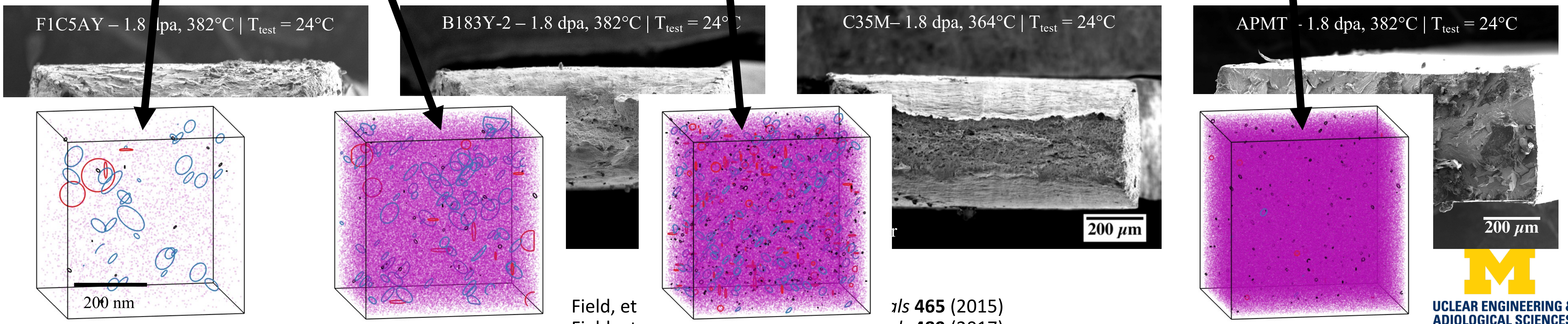
All … t… alloys studied showed t… rad… h… hardening for high Cr fe… all…











Field, et … als **465** (2015)
Field, et … als **489** (2017)

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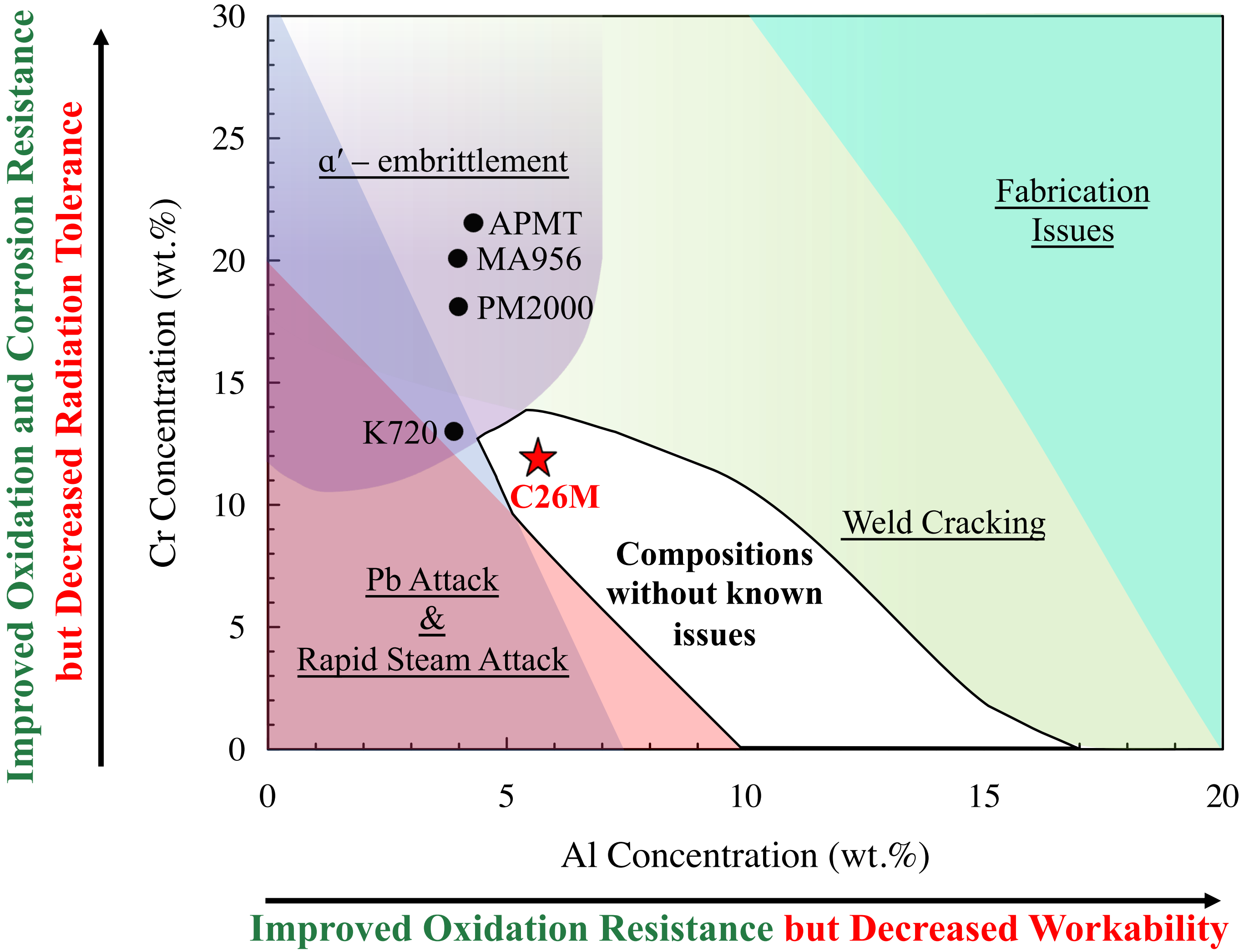
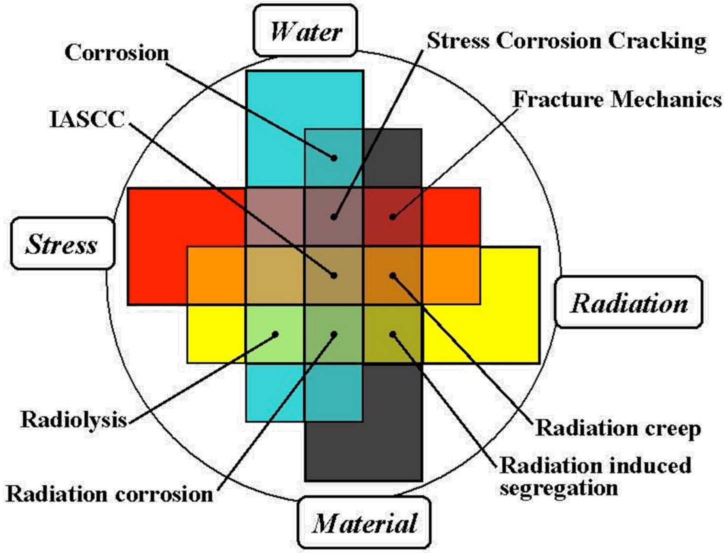
Weldability and radiation tolerance define the upper bounds on Al and Cr content of FeCrAl alloys[1]



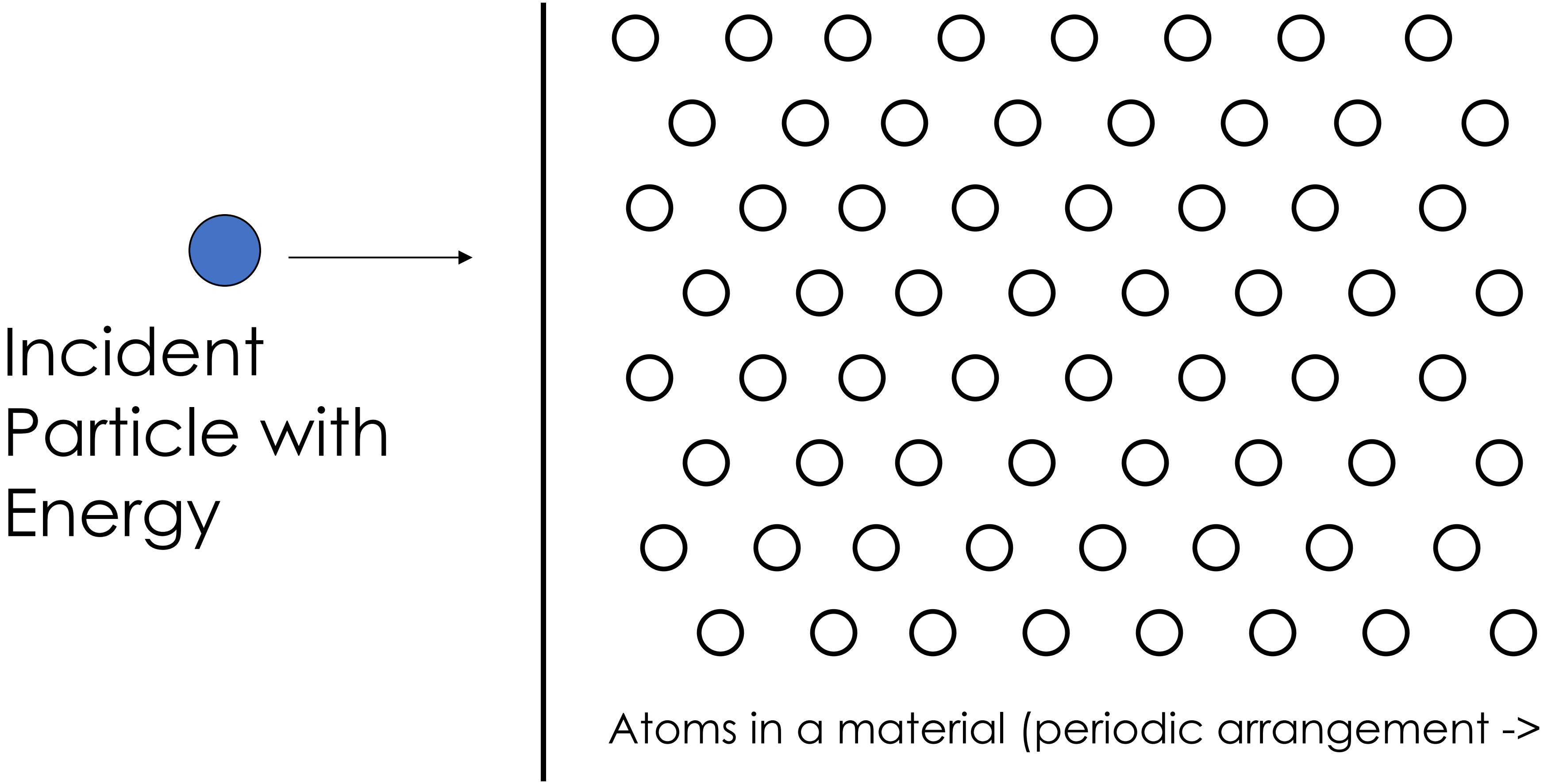


[1] M.N. Gussev, et al., *Materials & Design* **129** (2017)

Lecture Break

Radiation Damage: the basics

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

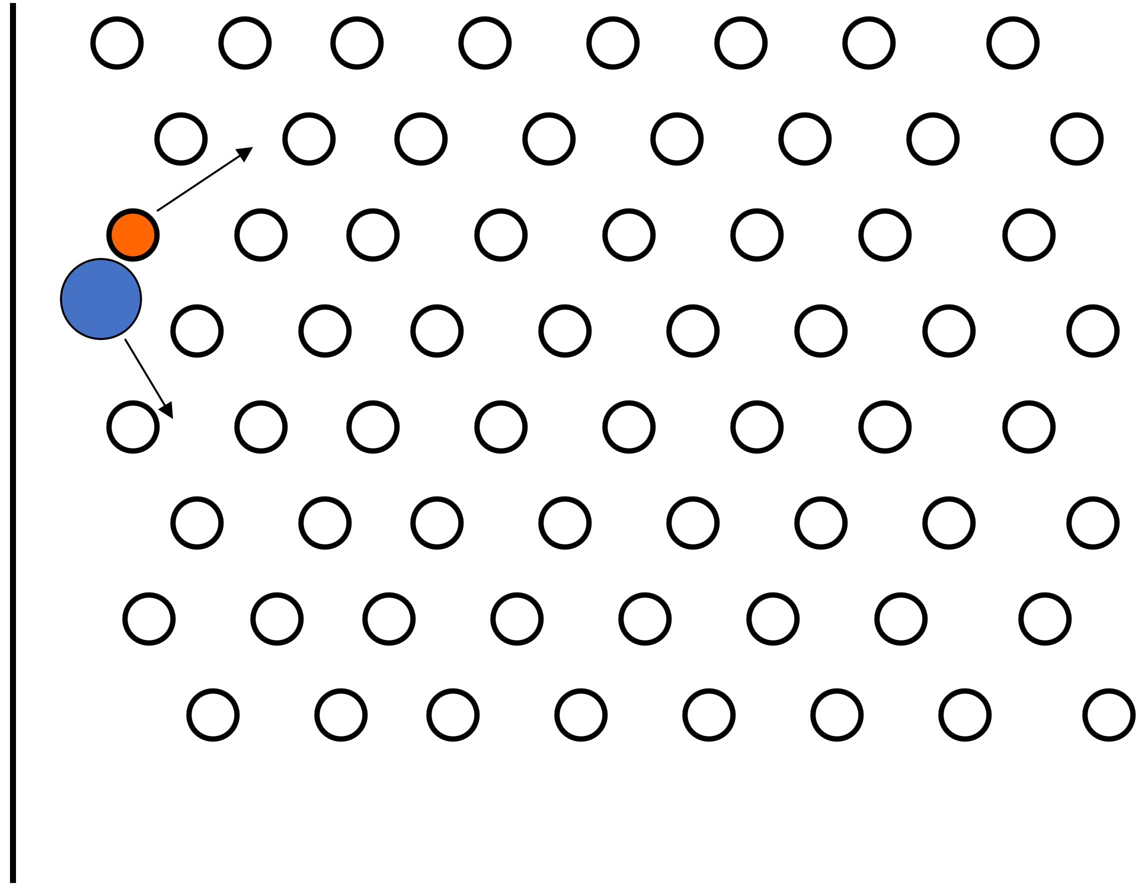


Atoms in a material (periodic arrangement -> lattice)

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*

Radiation Damage: the basics

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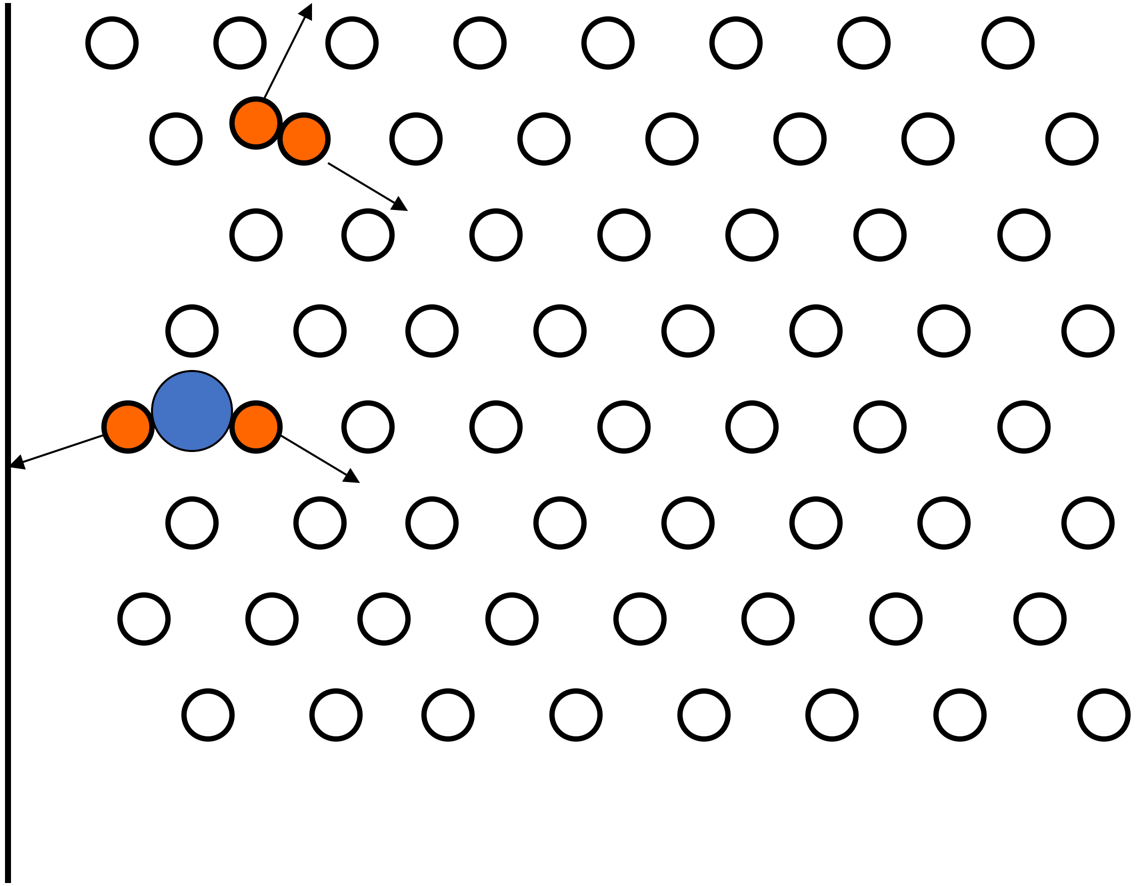

Source: *T.R. Allen*

Radiation Damage: the basics

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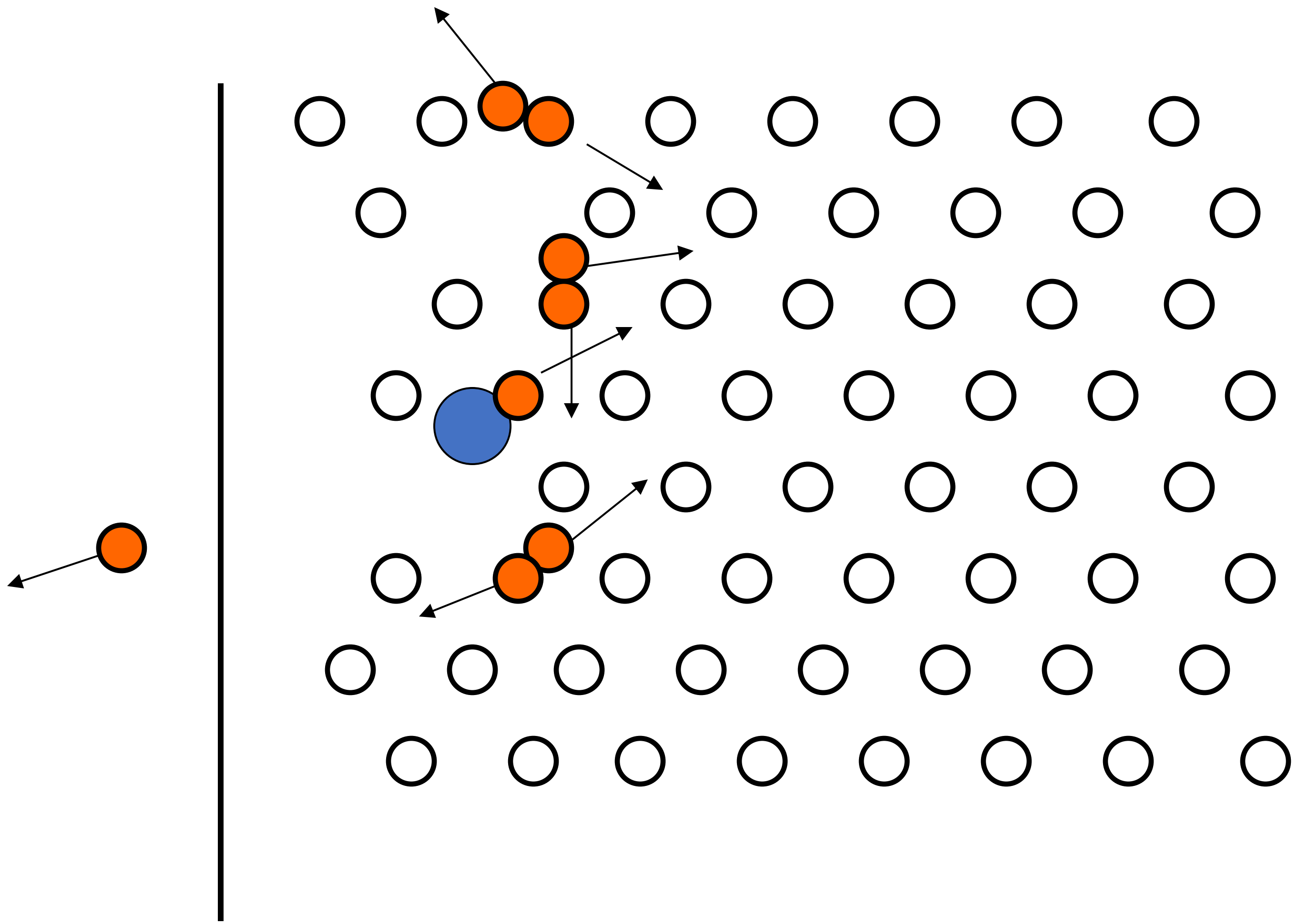

Source: *T.R. Allen*

Radiation Damage: the basics

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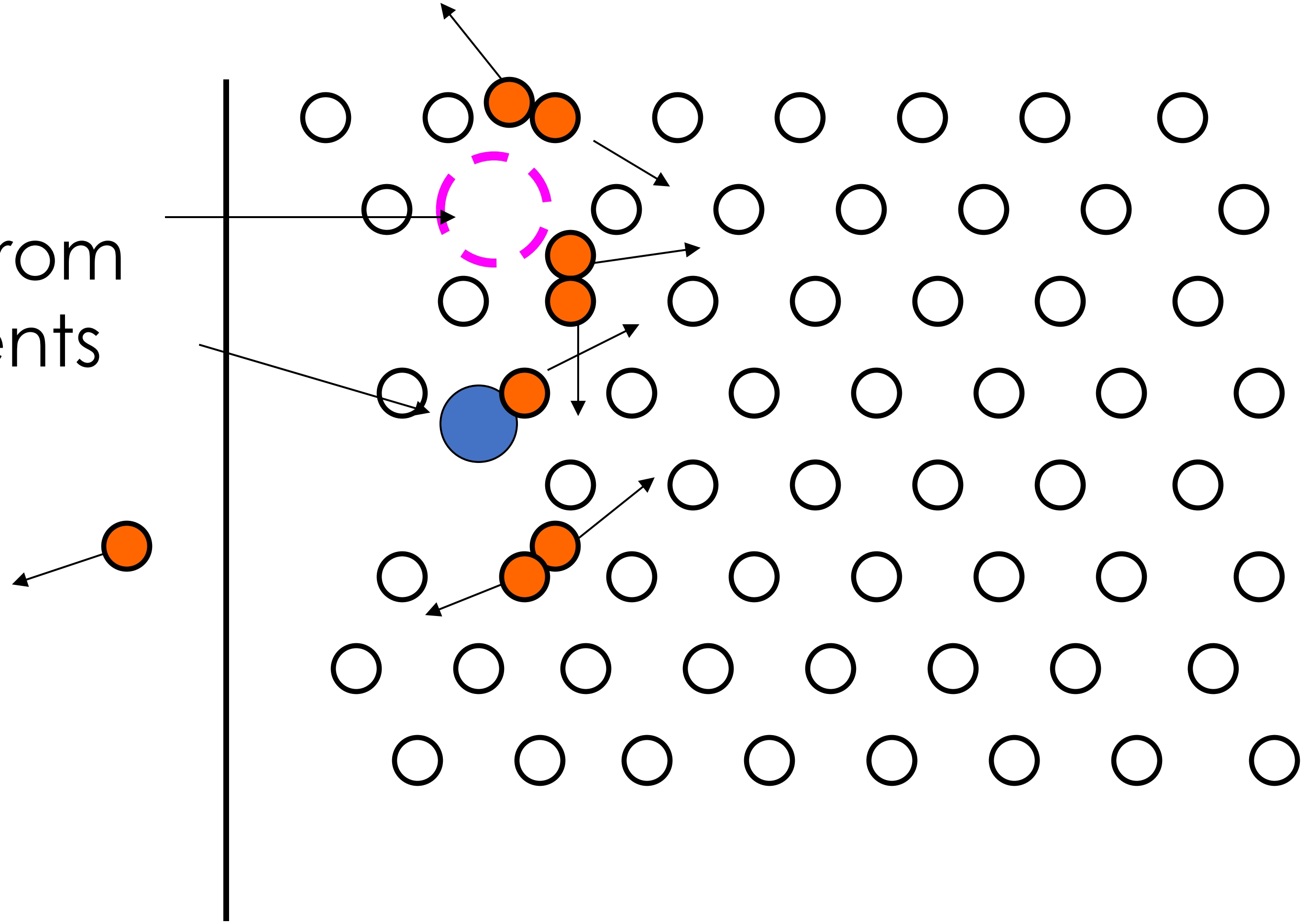
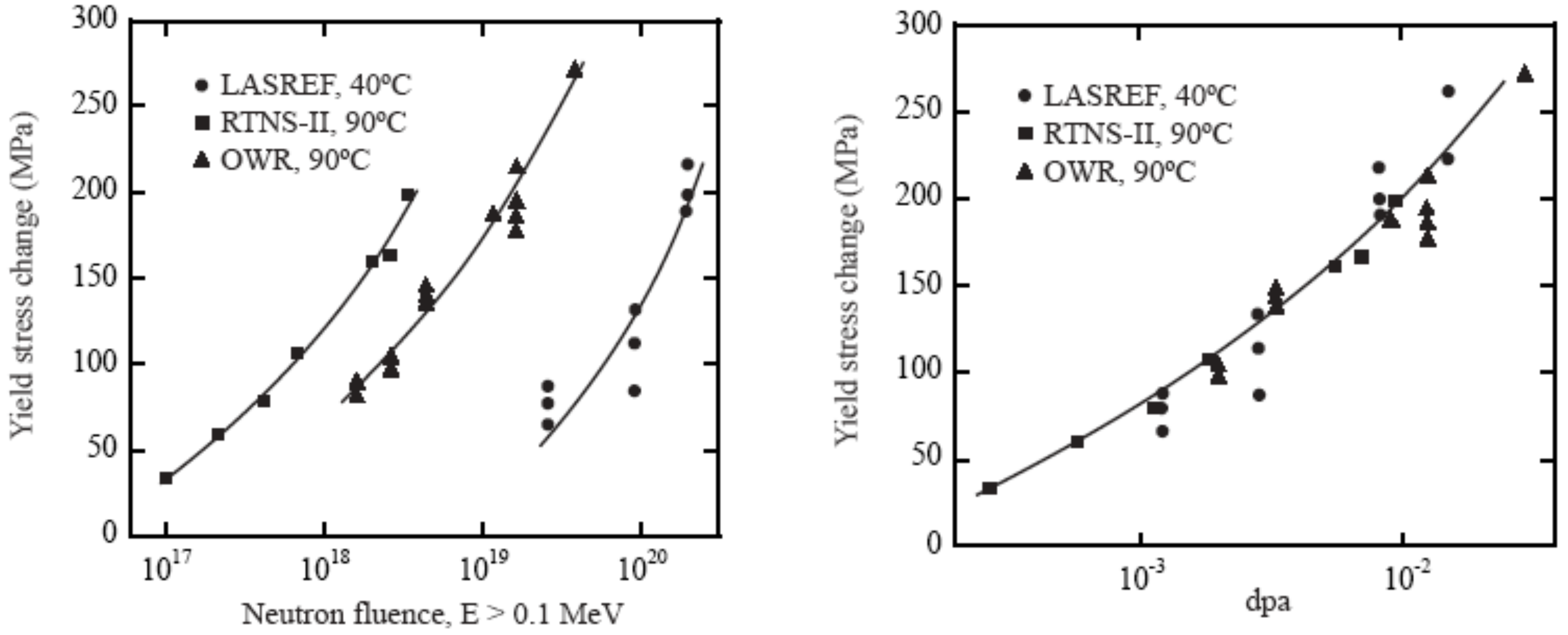
Defects produced from displacements



Source: T.R. Allen

Importance of displacement versus fluence for this class



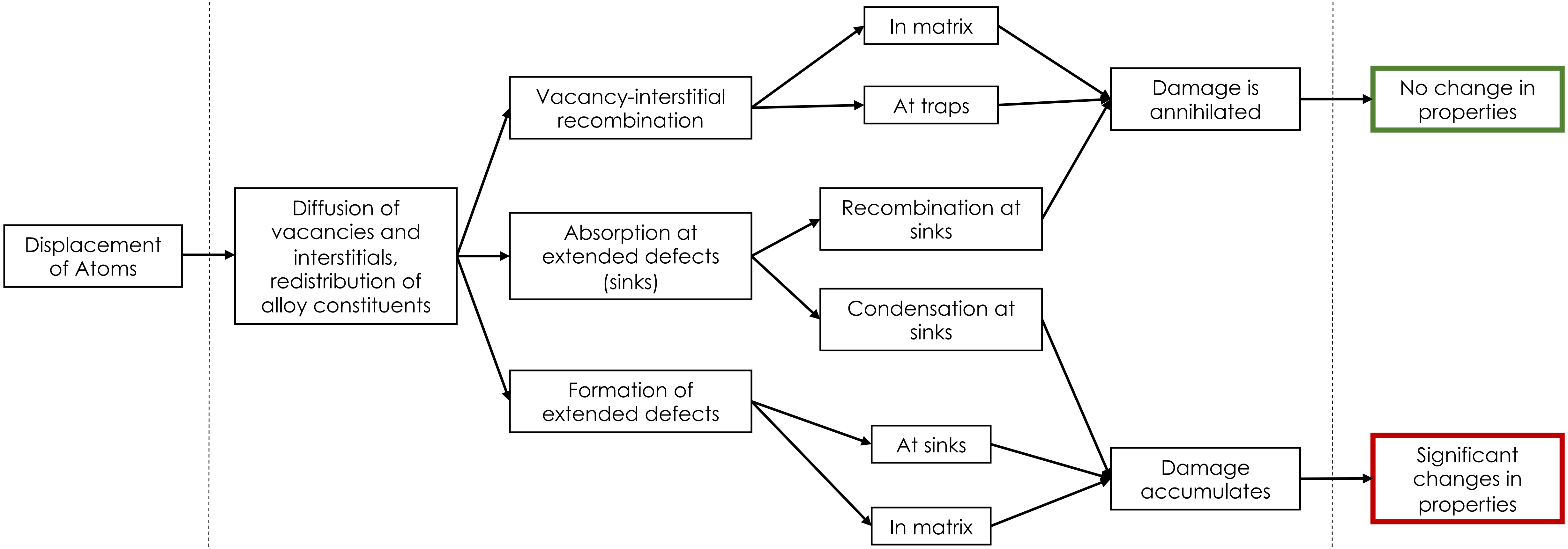
Comparison of yield stress change in 316 stainless steel irradiated in different reactors

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Flow chart for radiation damage

Louis Mansur, “Mechanisms & Kinetics of Radiation Effects in Metals and Alloys”, in: Kinetics of Nonhomogeneous Processes, 1987

Flow chart for radiation damage



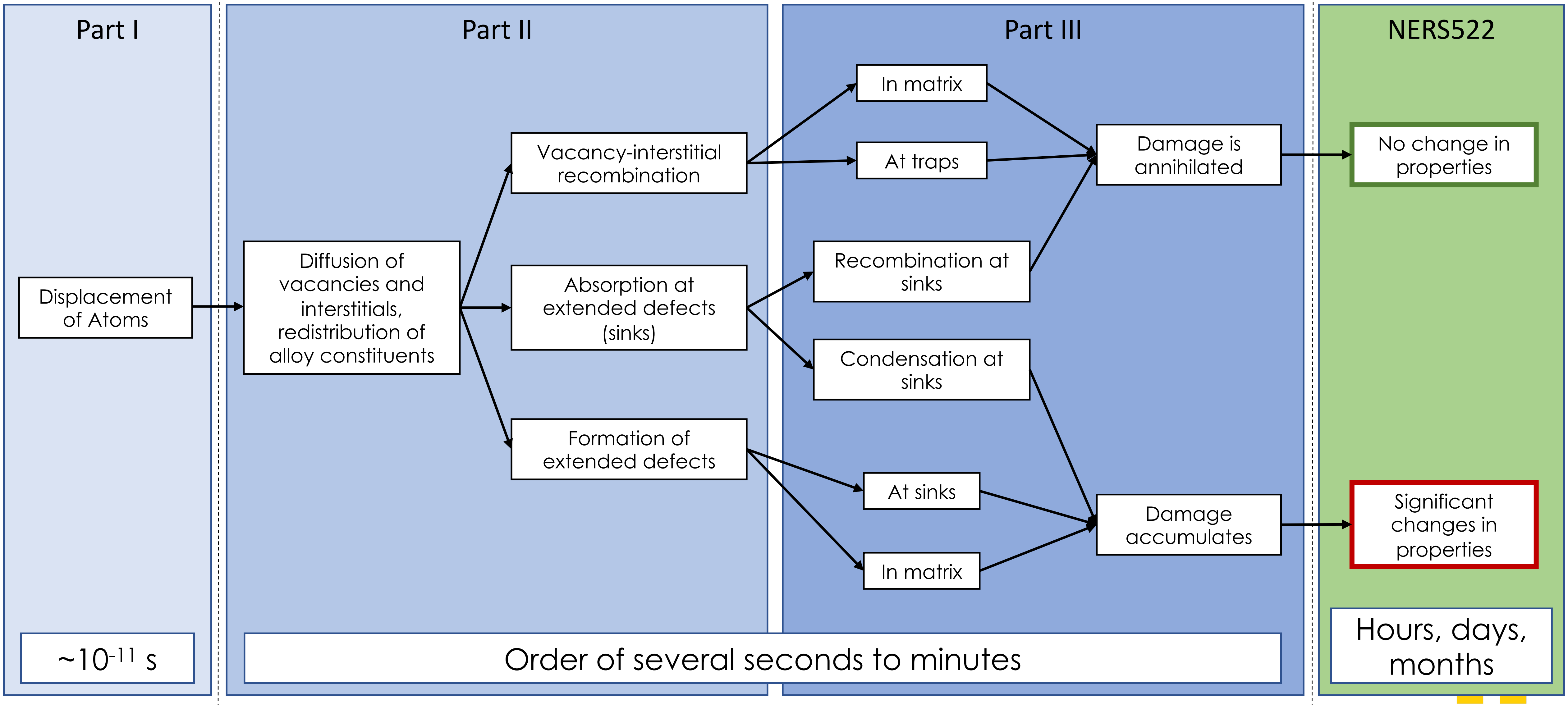
~10^{-11} s

Order of several seconds to minutes

Hours, days, months

Louis Mansur, "Mechanisms & Kinetics of Radiation Effects in Metals and Alloys", in: Kinetics of Nonhomogeneous Processes, 1987

Flow chart for radiation damage



Louis Mansur, “Mechanisms & Kinetics of Radiation Effects in Metals and Alloys”, in: Kinetics of Nonhomogeneous Processes, 1987

Displacement of Atoms in Detail

Part I

Displacement of Atoms

(Radiation Damage Event)

~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)

~10^{-11} s

Next two lectures

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Questions?