Material & Irradiation Design

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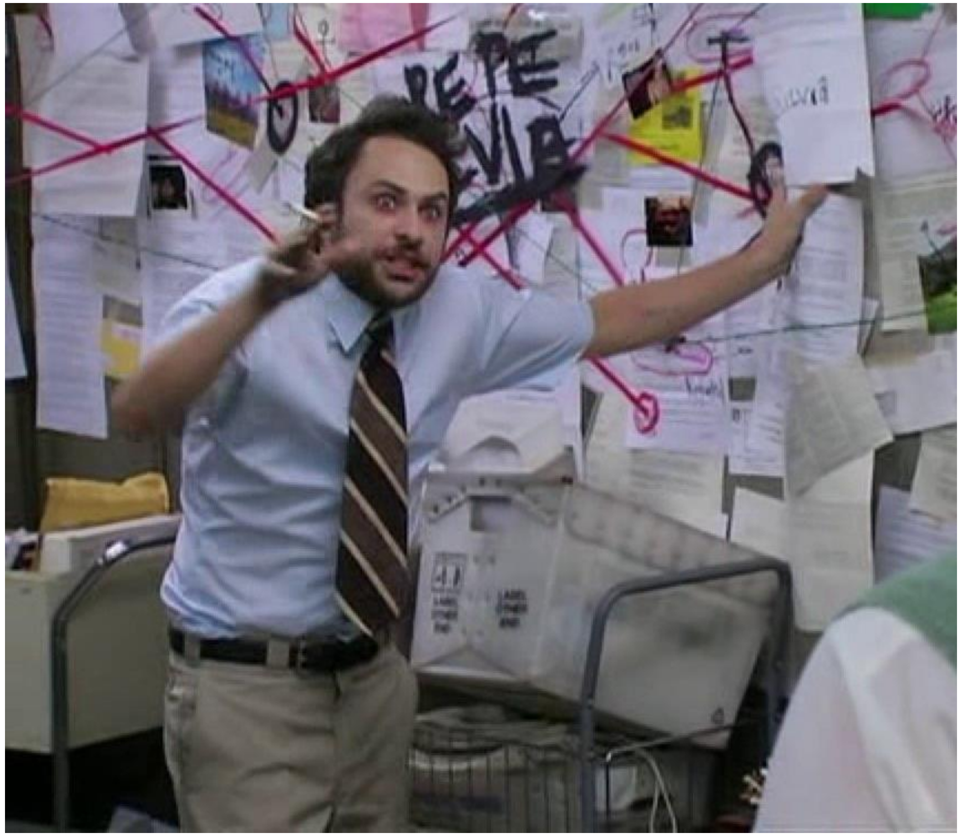
Don’t forget to submit HW5!

Final Exam Structure

- We will follow a similar format to the mid-term:
  - Non-cumulative: covers topics on previous slide



Poll 1

Take it during the normally scheduled final exam time of 12/16/2024 from 4-6 pm in the normal classroom environment (e.g., conventional, in person examination similar to midterm)	3 respondents	27 %	✓
Take it during the last scheduled class time of Dec. 5th from 10:30 am – 12:00 pm in the normal classroom environment (e.g., conventional, in person examination like midterm). This would eliminate the flex lecture on Dec. 3 to do a final wrap up and review and mean some general/interesting topics will not be covered. It is also likely that grading of HW5 would come on Dec. 4.	6 respondents	55 %	✓
Take it during the week of Dec. 9th during a time that works with most of the class participants schedules via normal classroom environment (e.g., conventional, in person examination similar to midterm)	5 respondents	45 %	✓
Take it during the week of Dec. 9th online via Canvas where the final is “take-home”. Each student would be given a 2 hr block to complete the final once they click “start” on the Canvas page. This would then be an online, take-home final exam. The topics covered would be similar but the questions would be modified to suit auto grading via Canvas.	3 respondents	27 %	✓
Do a final project instead of a final exam. This would likely involve picking a material and a reactor and calculating general factors such as dpa and evaluate the radiation effects possible based on factors such as temperature, dose rate, sink strength, etc. The final project would be due the day of the final, 12/16.	1 respondent	9 %	
I do not have a preference.	1 respondent	9 %	

Poll 2

Take it during the last scheduled class time of Dec. 5th from 10:30 am – 12:00 pm in the normal classroom environment (e.g., conventional, in person examination like midterm). This would eliminate the flex lecture on Dec. 3 to do a final wrap up and review and mean some general/interesting topics will not be covered. It is also likely that grading of HW5 would come on Dec. 4.	4 respondents	31 %	✓
Take it during the week of Dec. 9th during a time that works with most of the class participants schedules via normal classroom environment (e.g., conventional, in person examination similar to midterm)	8 respondents	62 %	✓
I do not have a preference.	1 respondent	8 %	✓

Radiation Disordering

- The steady state solution then becomes:

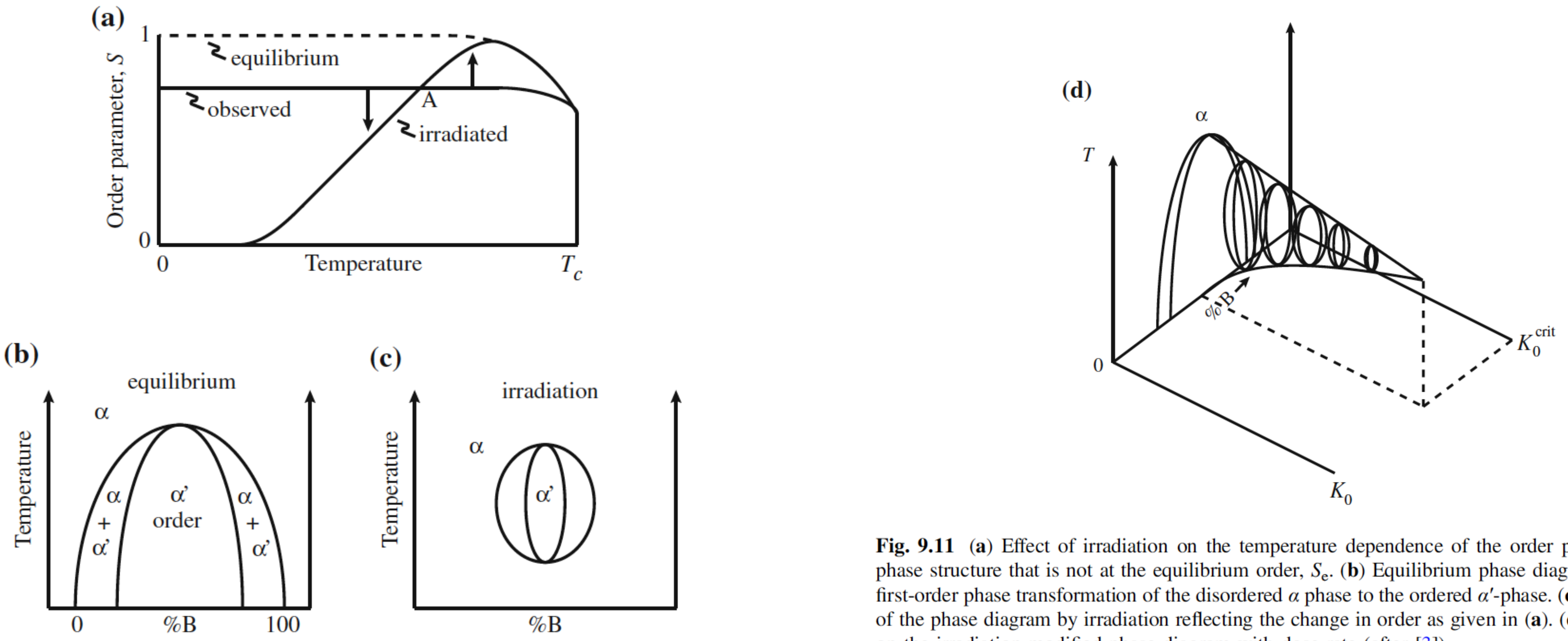
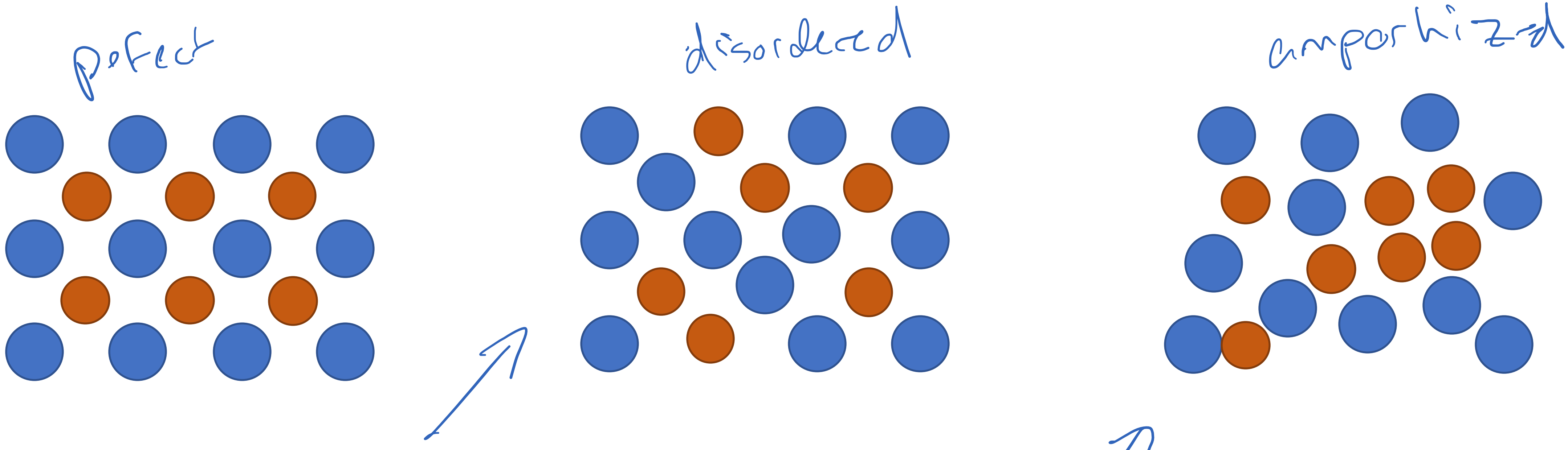


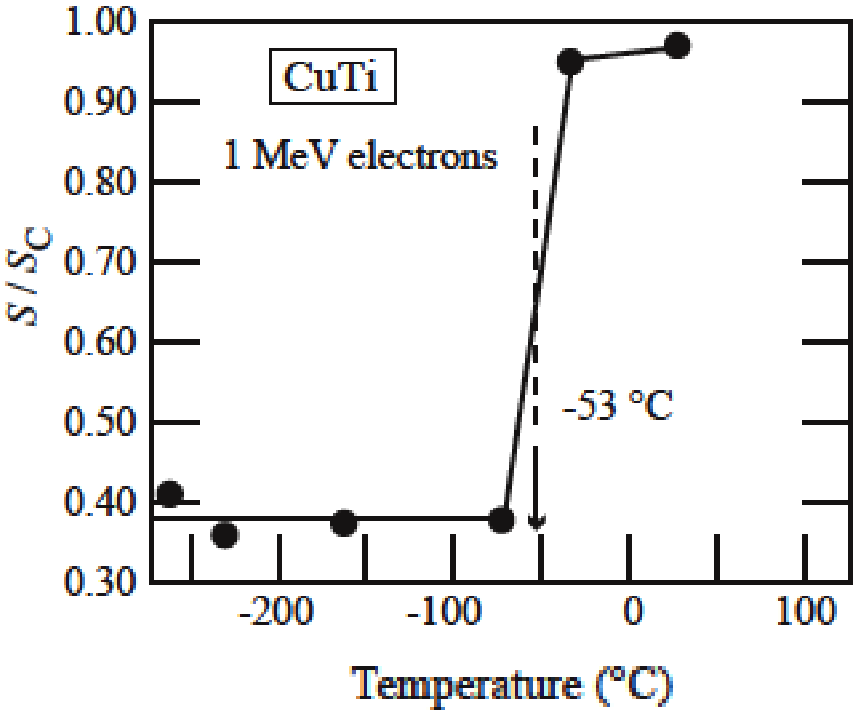
Fig. 9.11 (**a**) Effect of irradiation on the temperature dependence of the order parameter for a phase structure that is not at the equilibrium order, S_e. (**b**) Equilibrium phase diagram showing a first-order phase transformation of the disordered α phase to the ordered α'-phase. (**c**) Modification of the phase diagram by irradiation reflecting the change in order as given in (**a**). (**d**) Dependence on the irradiation-modified phase diagram with dose rate (after [3])

Temperature dependence of amorphization

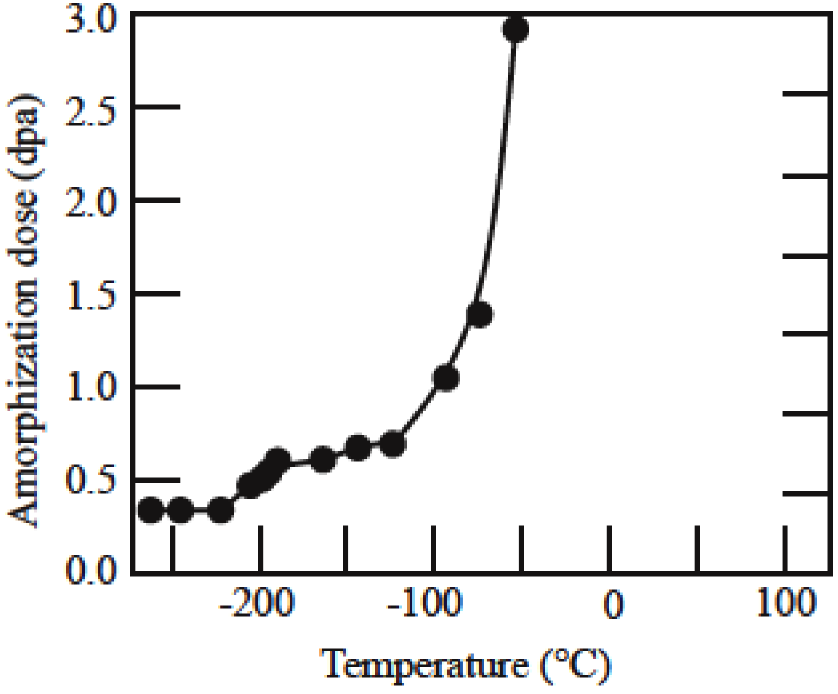


- Disordering means the destruction of the sub-lattice patterns in ordered alloys (e.g., creation of anti-site defects)
- Amorphization by particle irradiation refers to the complete loss of long-range crystalline structure

Temperature dependence of amorphization



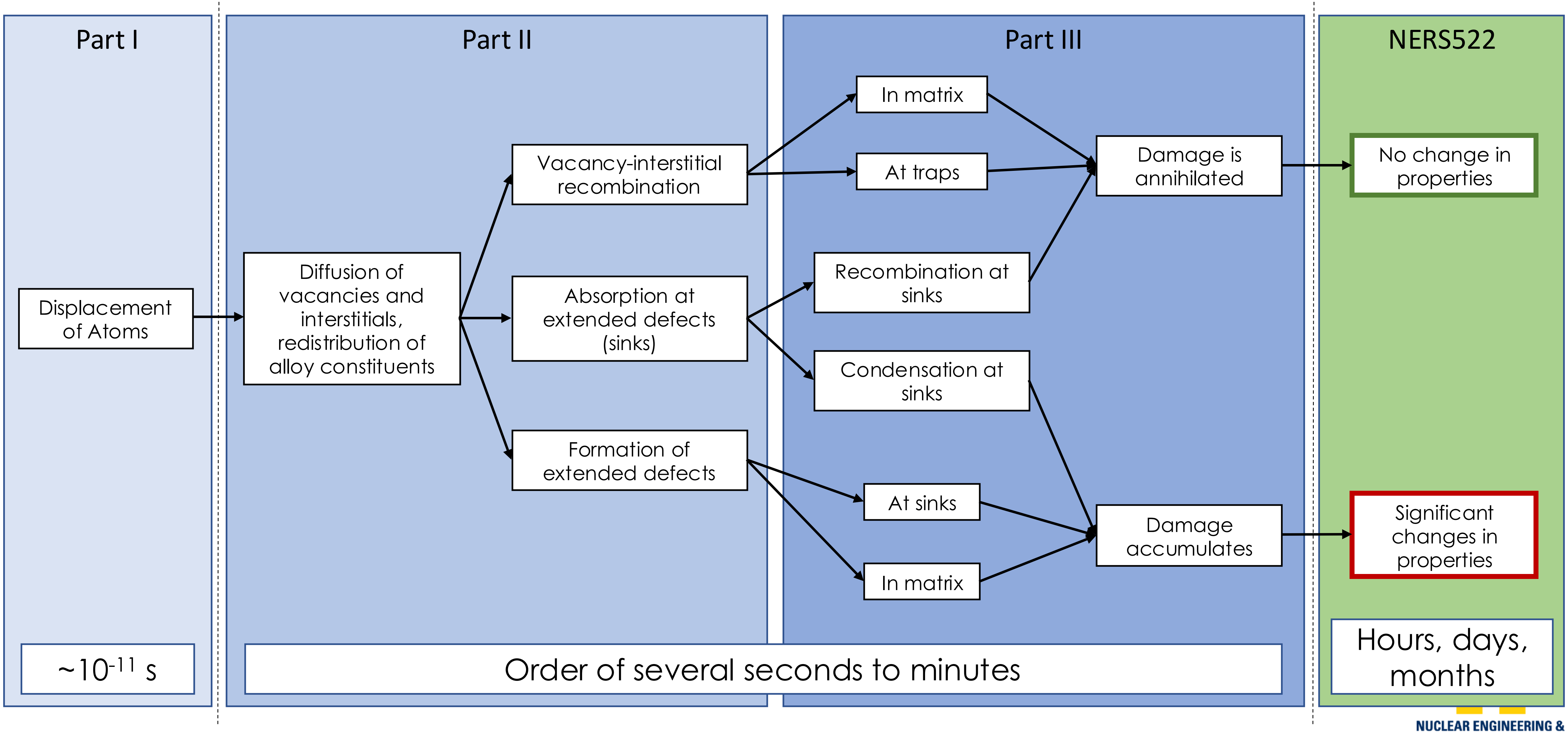
a



b

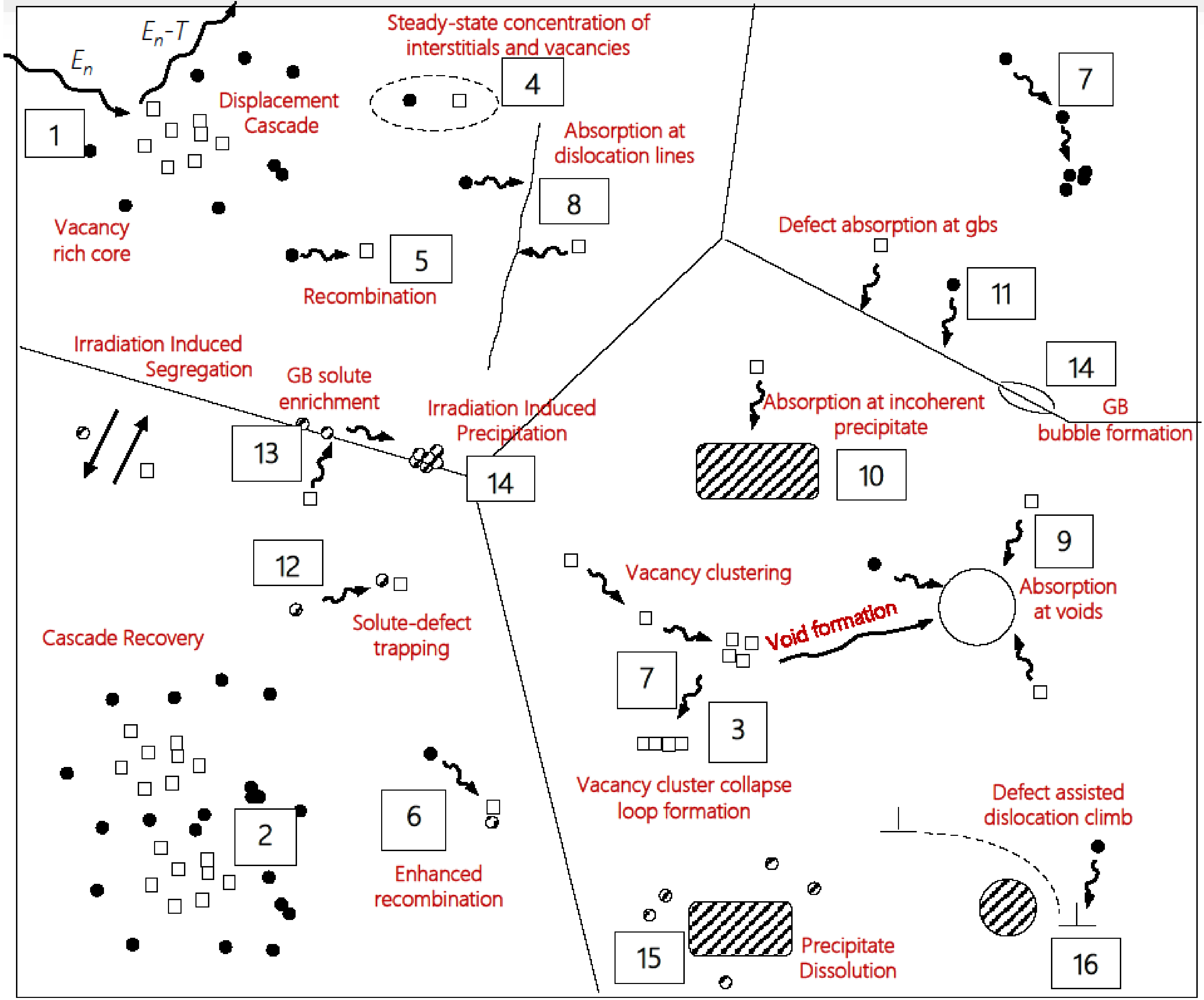
Temperature dependence of a) the long-range order parameter S/S_C, and b) the critical amorphization dose for CuTi, irradiated with 1 MeV electrons

Flow chart for radiation damage



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

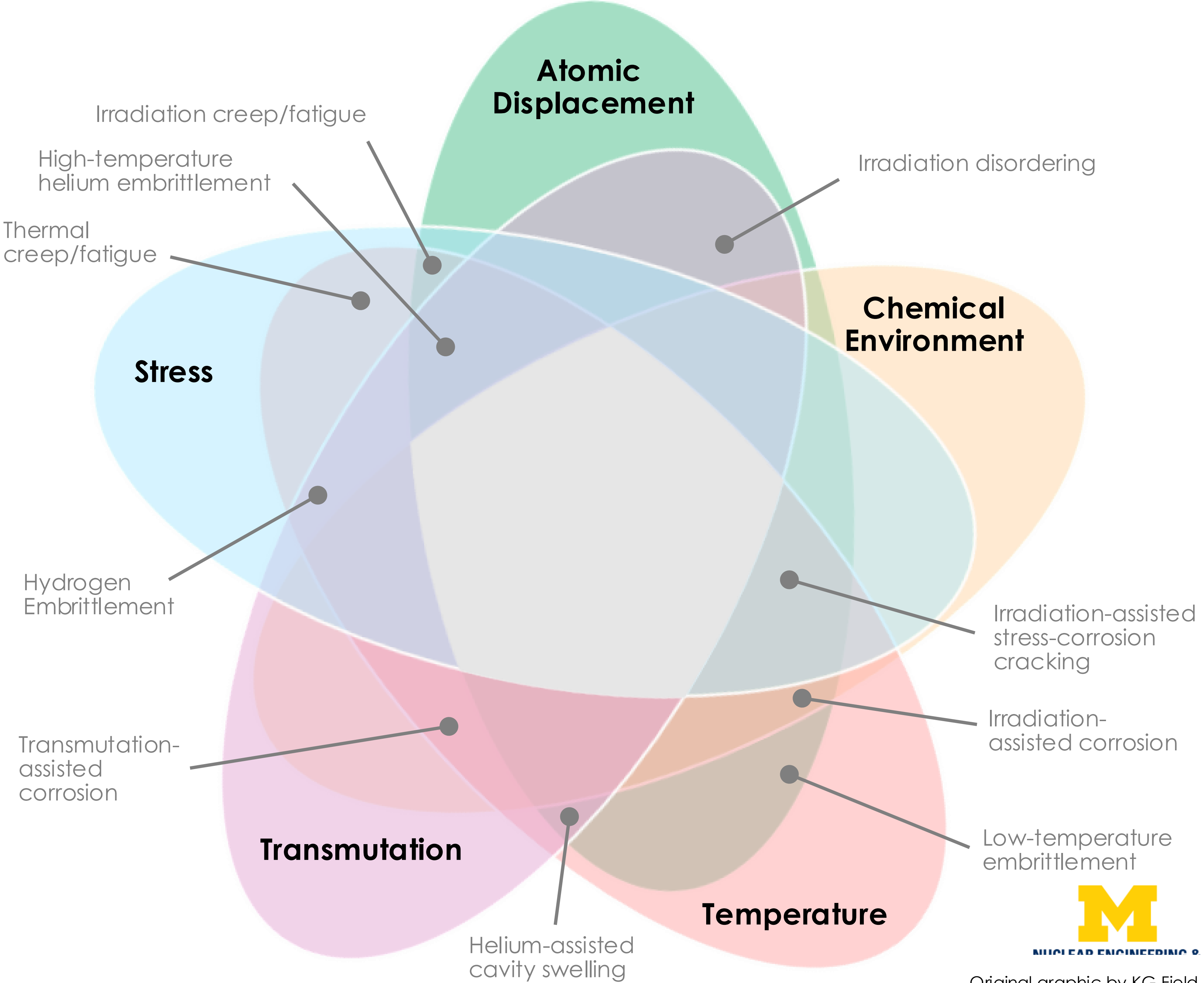
Putting it into a visual



Applying the concepts of NERS521 to material design

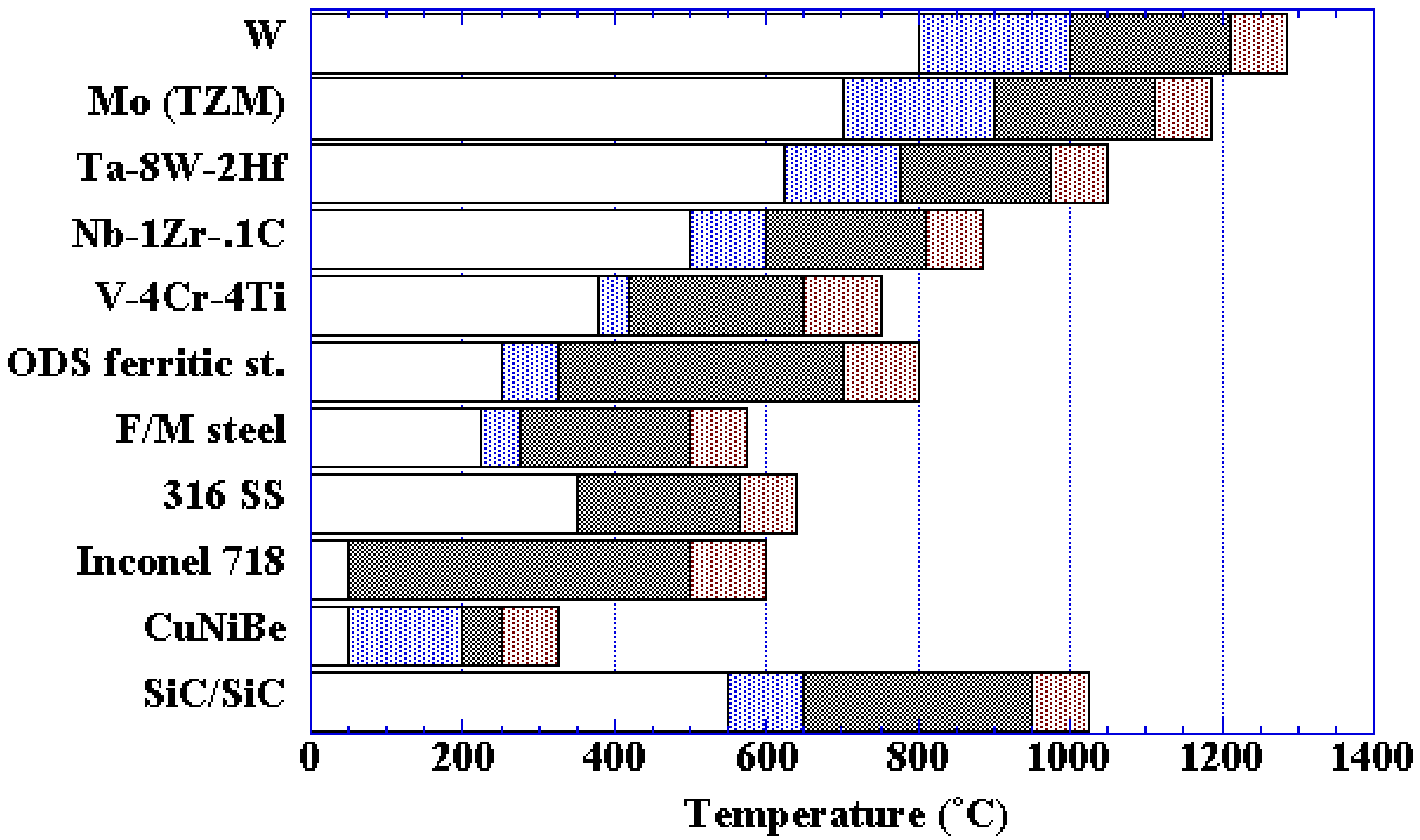
Materials degradation in a fusion and fission energy system can occur due to single- and ***combined-effects***

Listed degradation modes for structural materials



Original graphic by KG Field

Bringing it together: Radiation Materials Design



Zinkle and Ghoniem, Fusion Engr. Des. 49-50(2000) 709; S.J. Zinkle & J.T. Busby, Mater. Today 12(2009) 12

Three options exist for designing radiation resistance materials

1. Use materials with negligible point defect mobility at desired operating temperatures
    - Slow down diffusion, but ideally want one defect type (e.g. vacancy/interstitial) mobile but the other not (to avoid amorphization/disordering)
2. Use materials with intrinsic resistance to radiation damage accumulation
    - Increased defect formation energies (e.g. stacking fault energies)
    - Examples: BCC alloys, high entropy/multicomponent alloys, nanocrystalline materials
3. Make materials with a high density of benign nanoscale recombination sites
    - Add microstructural features such as precipitates or nanolayered structures

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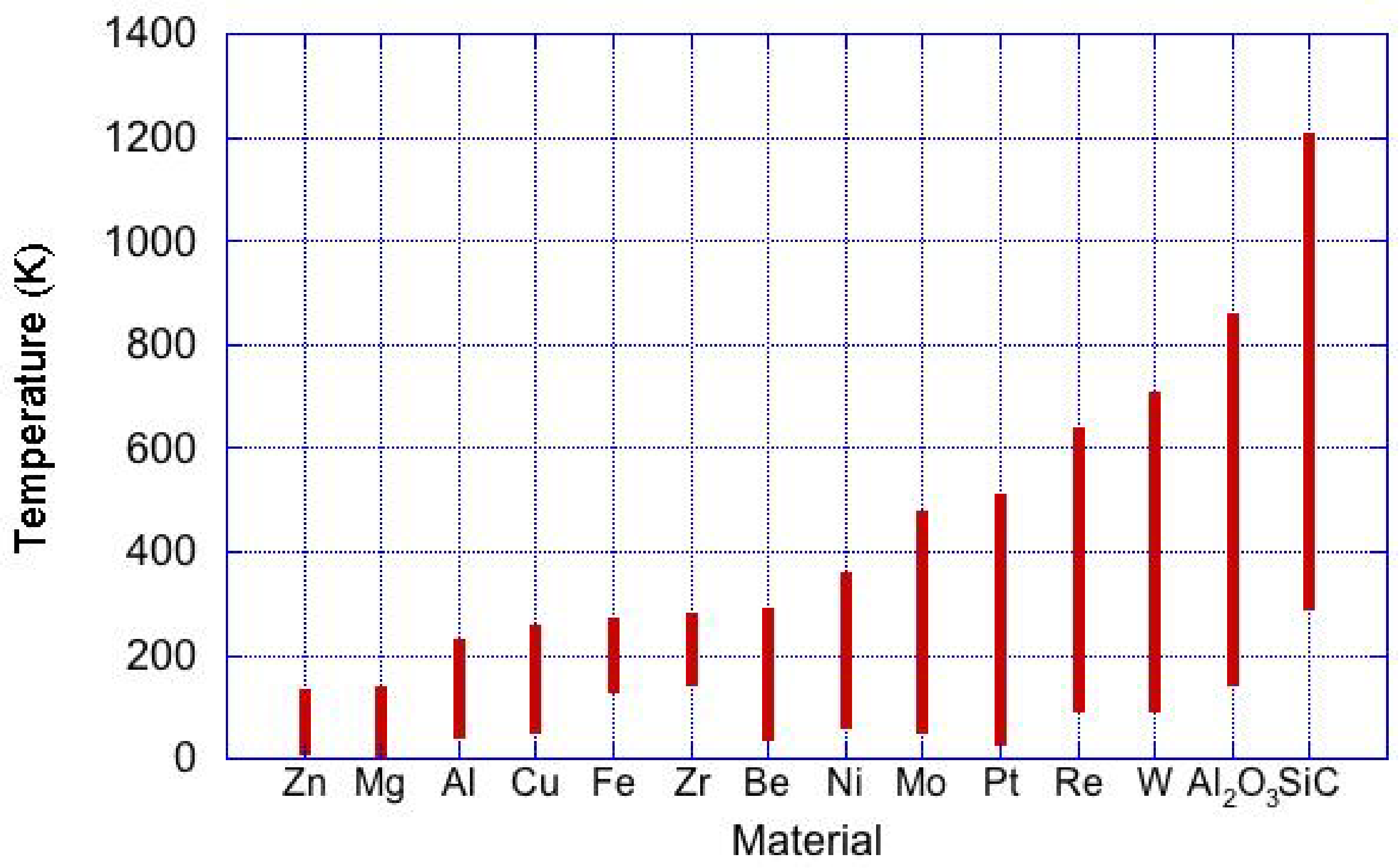
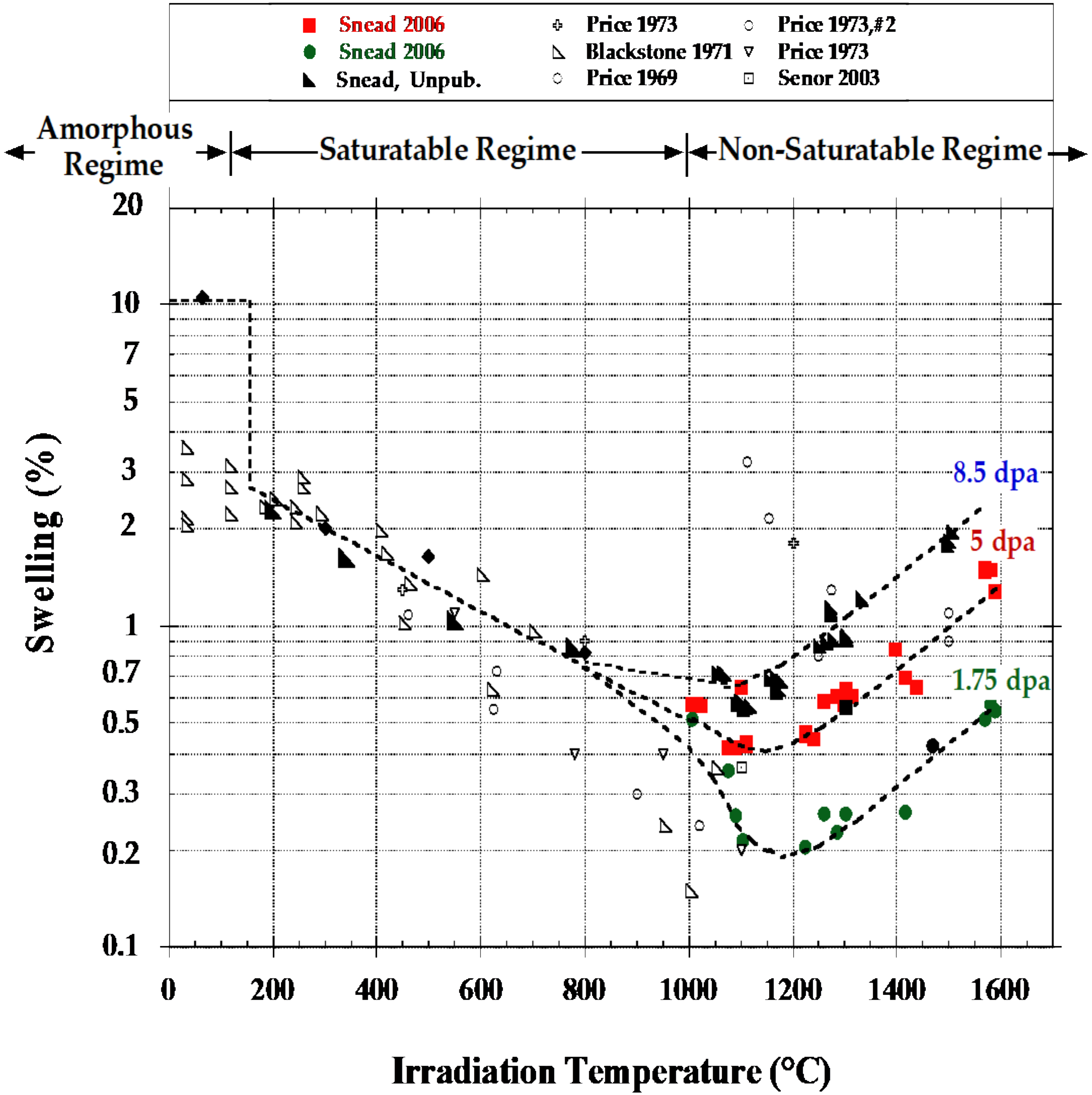
Design for Radiation Resistance I: Immobile point defects



Temperature regime where intrinsically high point defect recombination typically occurs



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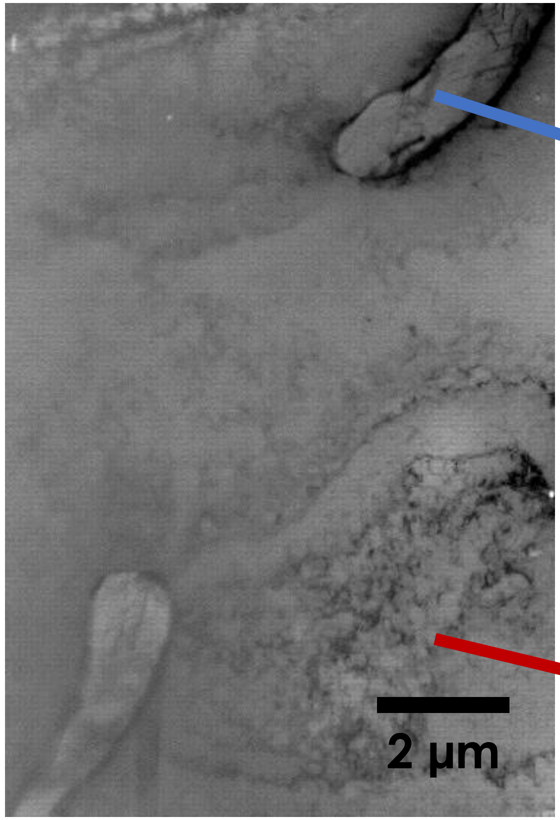
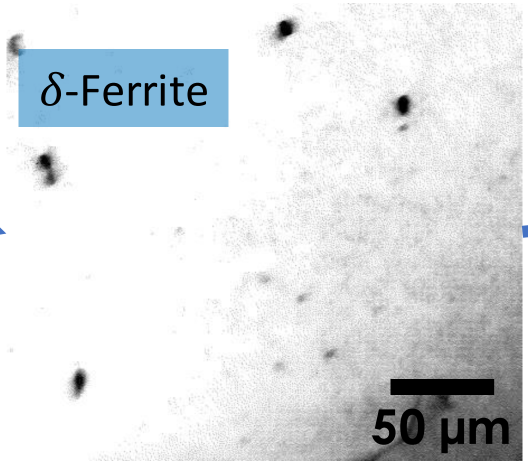
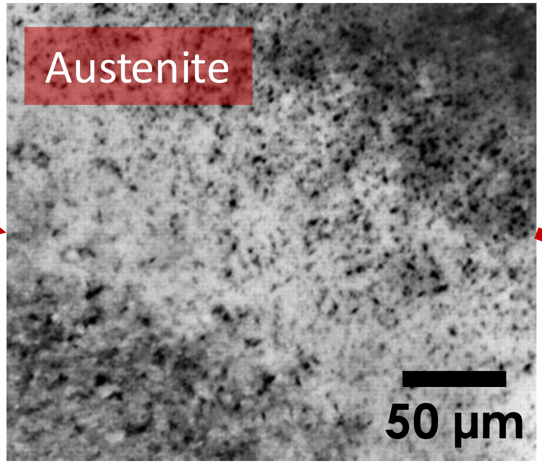
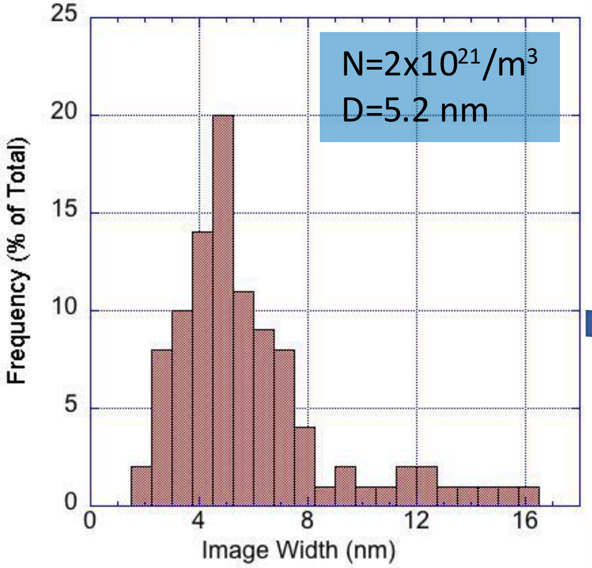
Design for Radiation Resistance II: Use radiation resistant phases

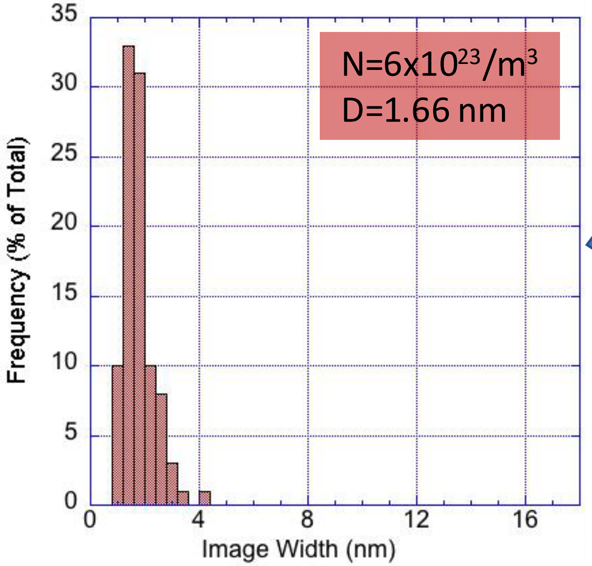


Type 308SS
0.065 dpa, 120°C









30x lower visible defect accumulation for BCC phase

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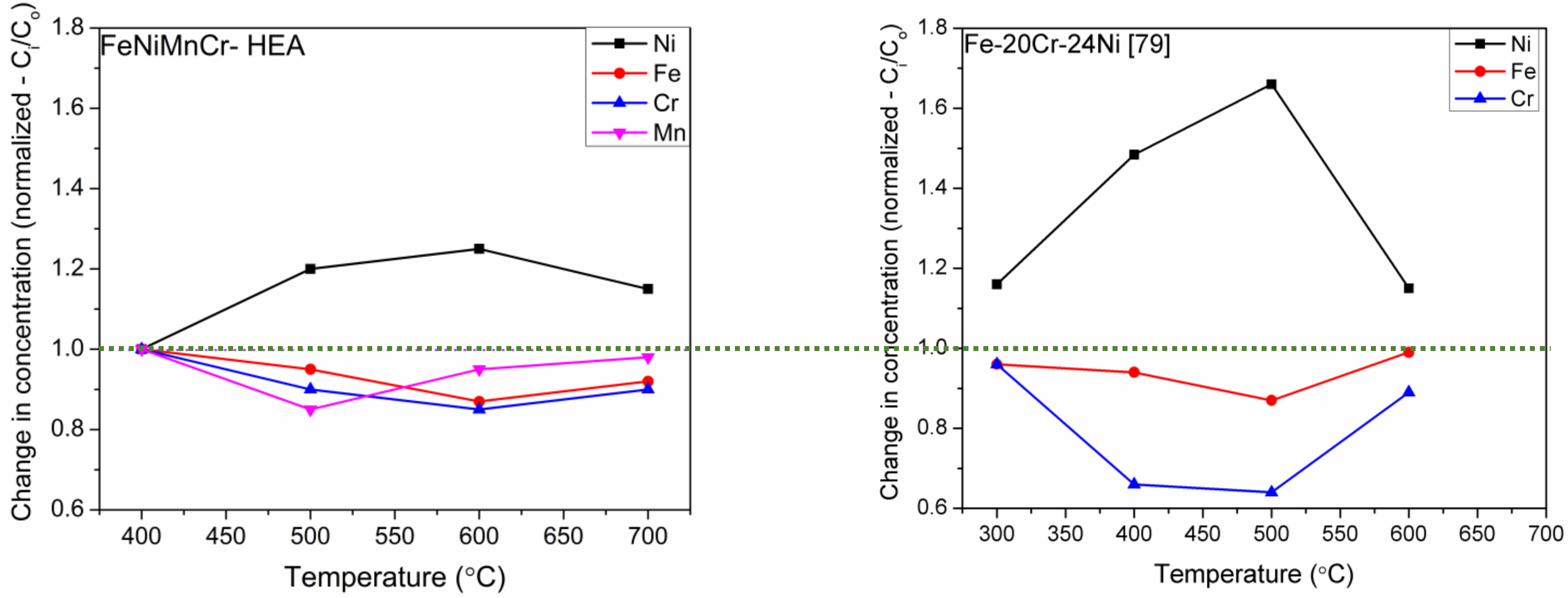
Design for Radiation Resistance II: Use radiation resistant phases

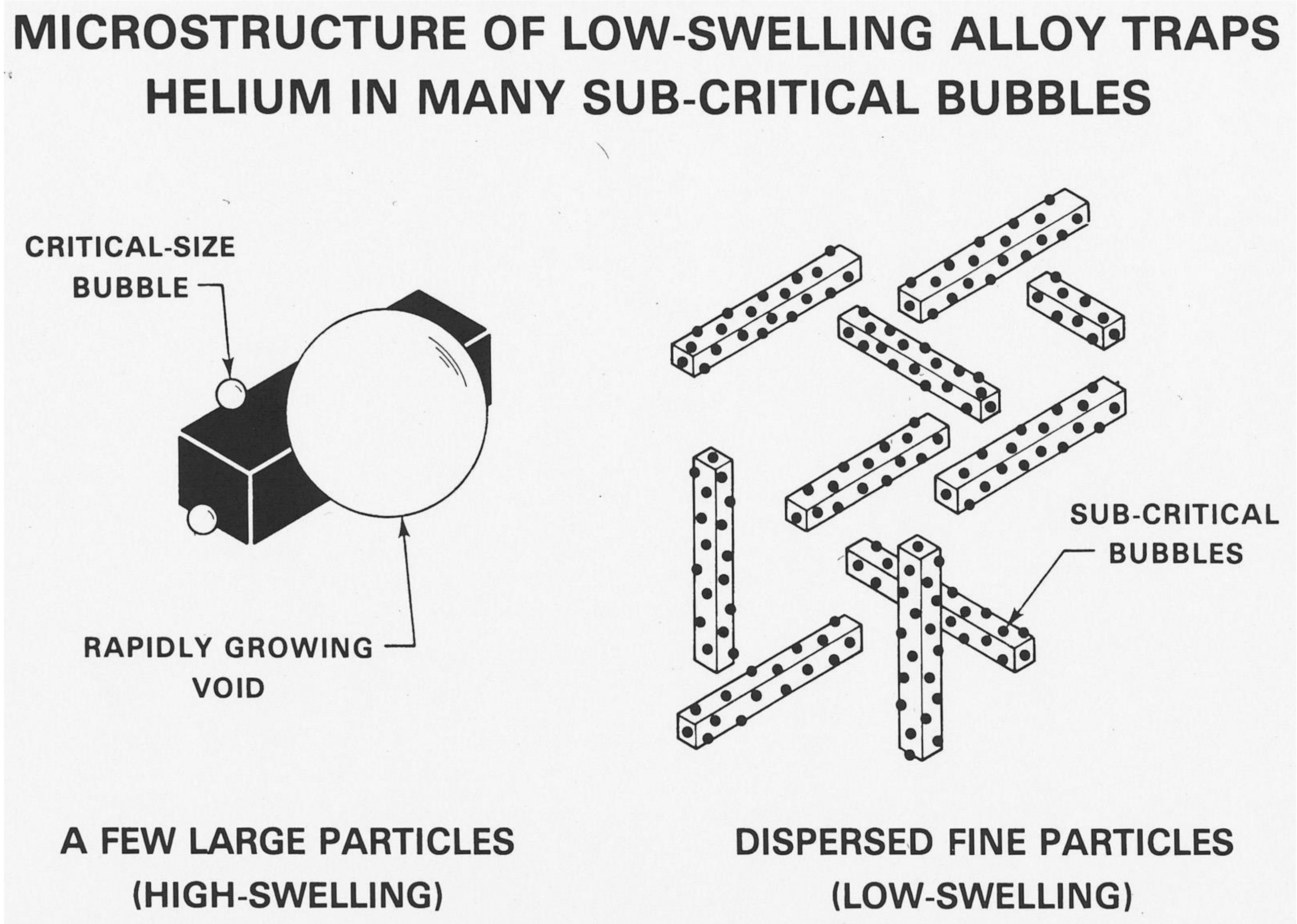


- RIS behavior for High Entropy Alloys is less pronounced than in traditional FCC FeCrNi(Mn) Alloys

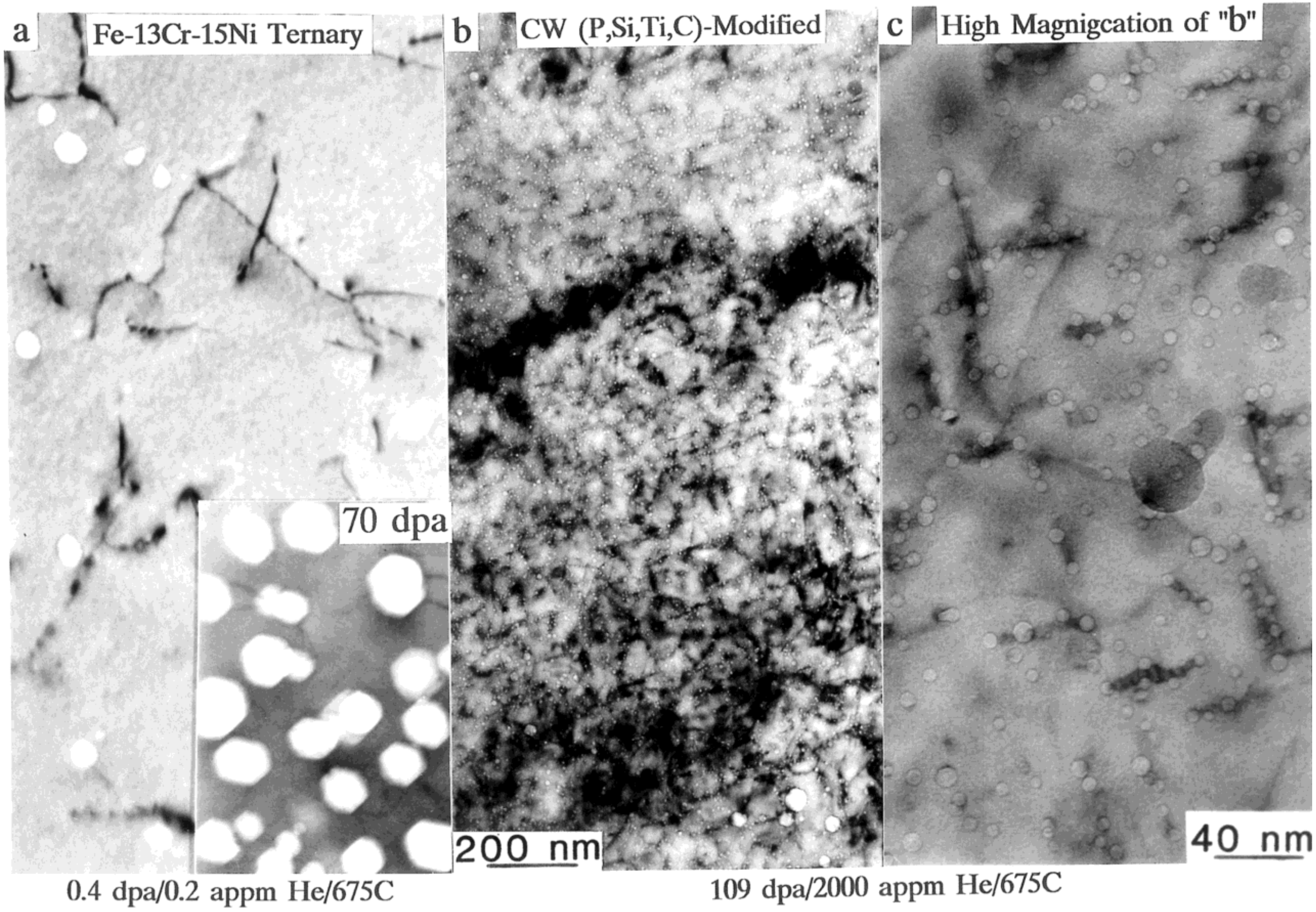
=> HEA effect on solute diffusivities

N.A.P. KiranKumar et al., ActaMat. 113(2016) 230

Design for Radiation Resistance III: High Sink Strength



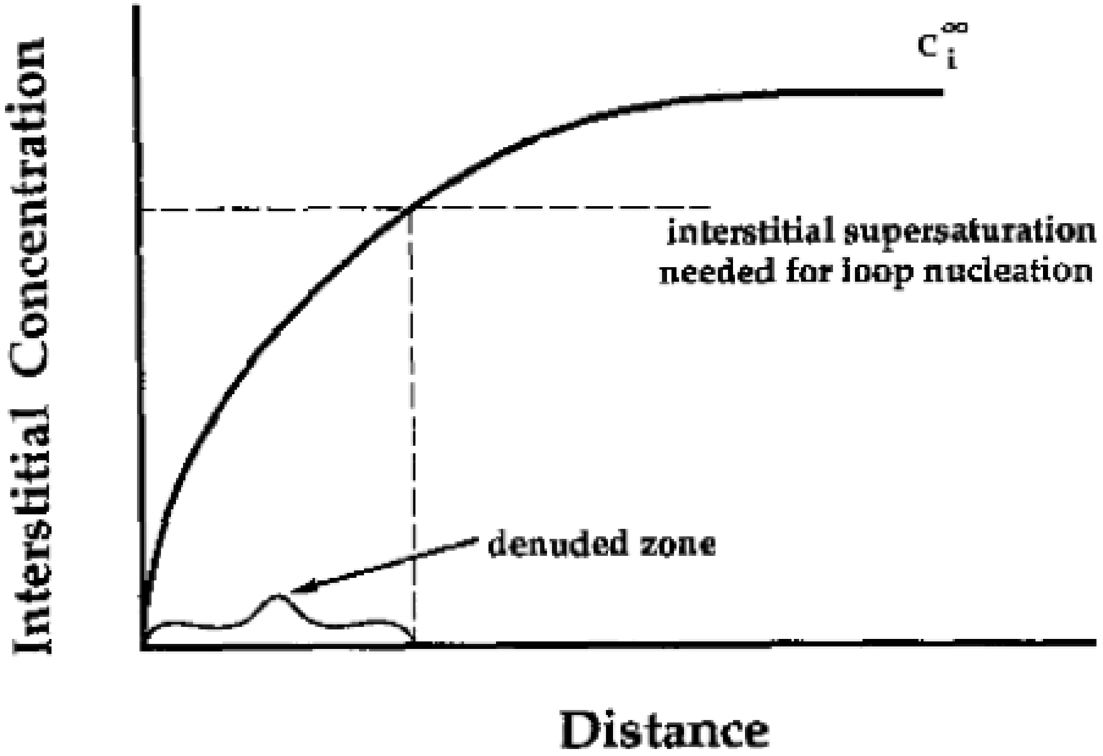
Design for Radiation Resistance III: High Sink Strength



L.K. Mansur & E.H. Lee, J. Nucl. Mater. 179-181(1991) 105

Design for Radiation Resistance III: High Sink Strength

- Early research also investigated fine grained architectures for radiation resistance, but sufficiently stable nanoscale grain boundaries were not discovered
  - Fine-grained materials are susceptible to radiation-enhanced grain growth



S.J. Zinkle, Nucl. Instr. Meth. B 91(1994)234

R. Yamada, S.J. Zinkle and G.P. Pells, J. Nucl. Mater. 209(1994) 191

L.K. Mansur & E.H. Lee, J. Nucl. Mater. 179-181(1991) 105

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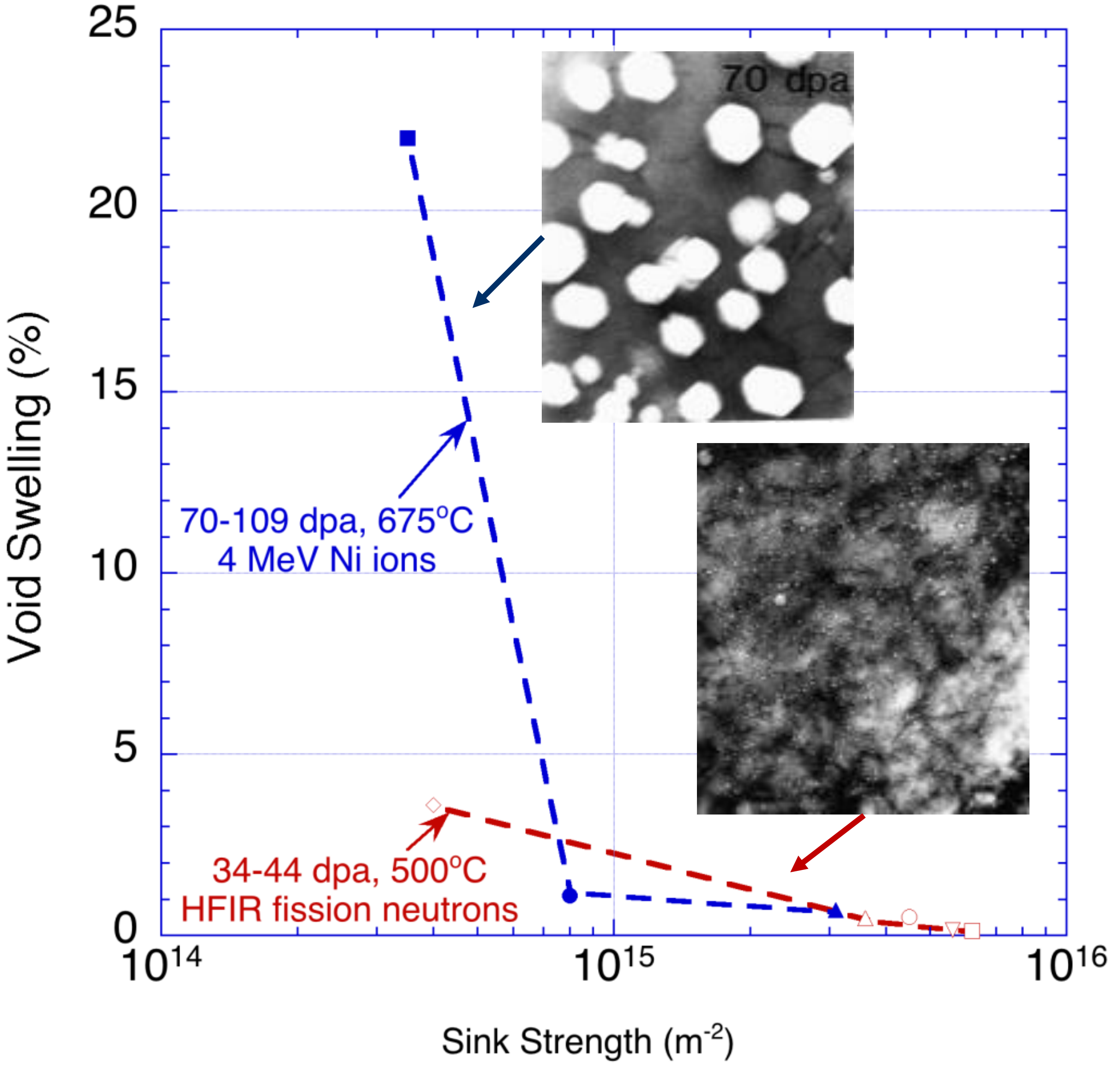
Design for Radiation Resistance III: High Sink Strength



Dramatic reduction in void swelling occurs when average spacing between voids is >10x average spacing between defect sinks

$$N_v^{-1/3} \gg S_{tot}^{-1/2}$$

For void swelling resistance, sink strengths $>10^{15}/m^2$ are generally sufficient for fission reactors; fusion reactor irradiation may require even higher sink strengths ($>10^{16}/m^2$?) due to transmutant He production

S.J. Zinkle and L.L. Snead, Ann Rev. Mat. Res., 44(2014) 241; S.J. Zinkle et al., Nucl. Fusion (2017) 092005

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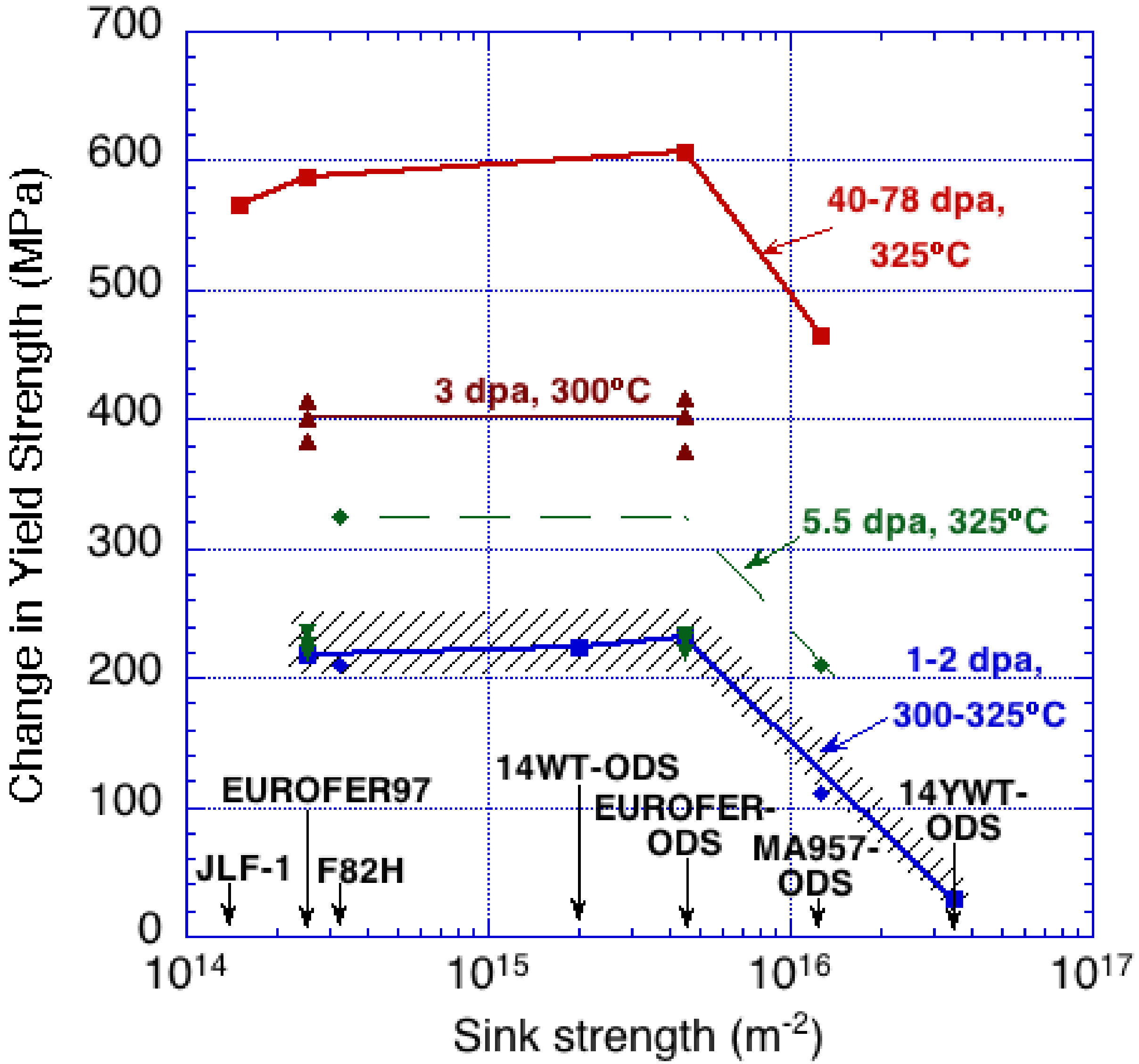
Design for Radiation Resistance III: High Sink Strength



Dramatic reduction in radiation hardening occurs when average spacing between defect cluster nuclei (dislocation loops, etc.) is much greater than average spacing between defect sinks

$N_{loop}^{-1/3} >> S_{tot}^{-1/2}$

-or-

$S_{tot} >> S_{rad\ defects}$

S.J. Zinkle and L.L. Snead, Ann Rev. Mat. Res., 44(2014) 241; S.J. Zinkle et al., Nucl. Fusion (2017) 092005

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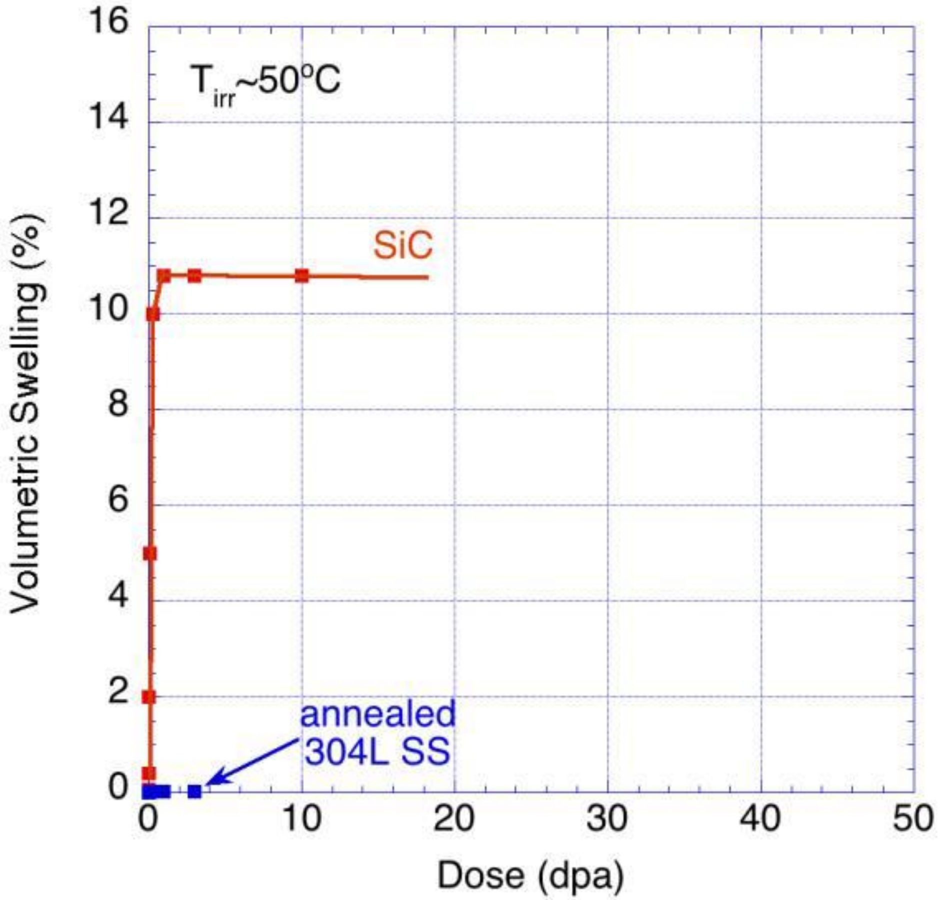
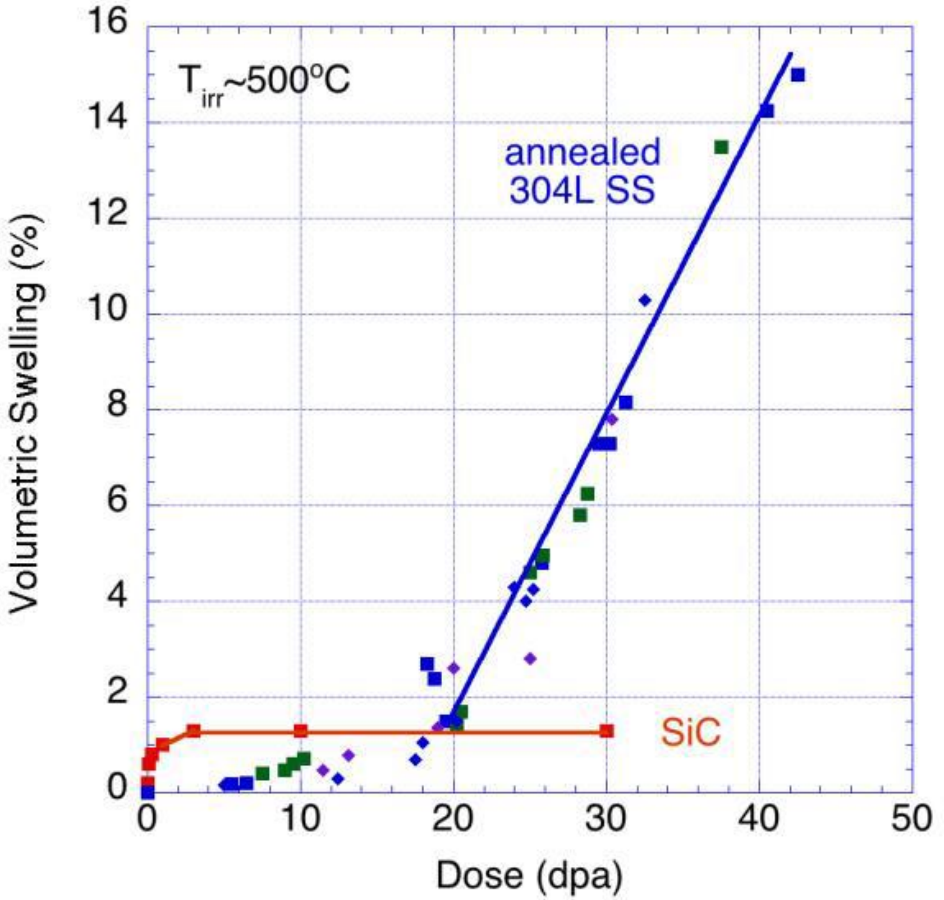
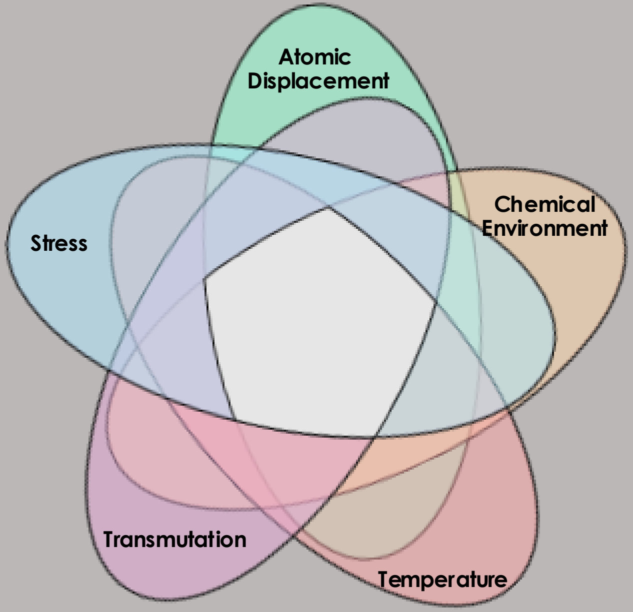
BUT, don't forget about irradiation regimes!

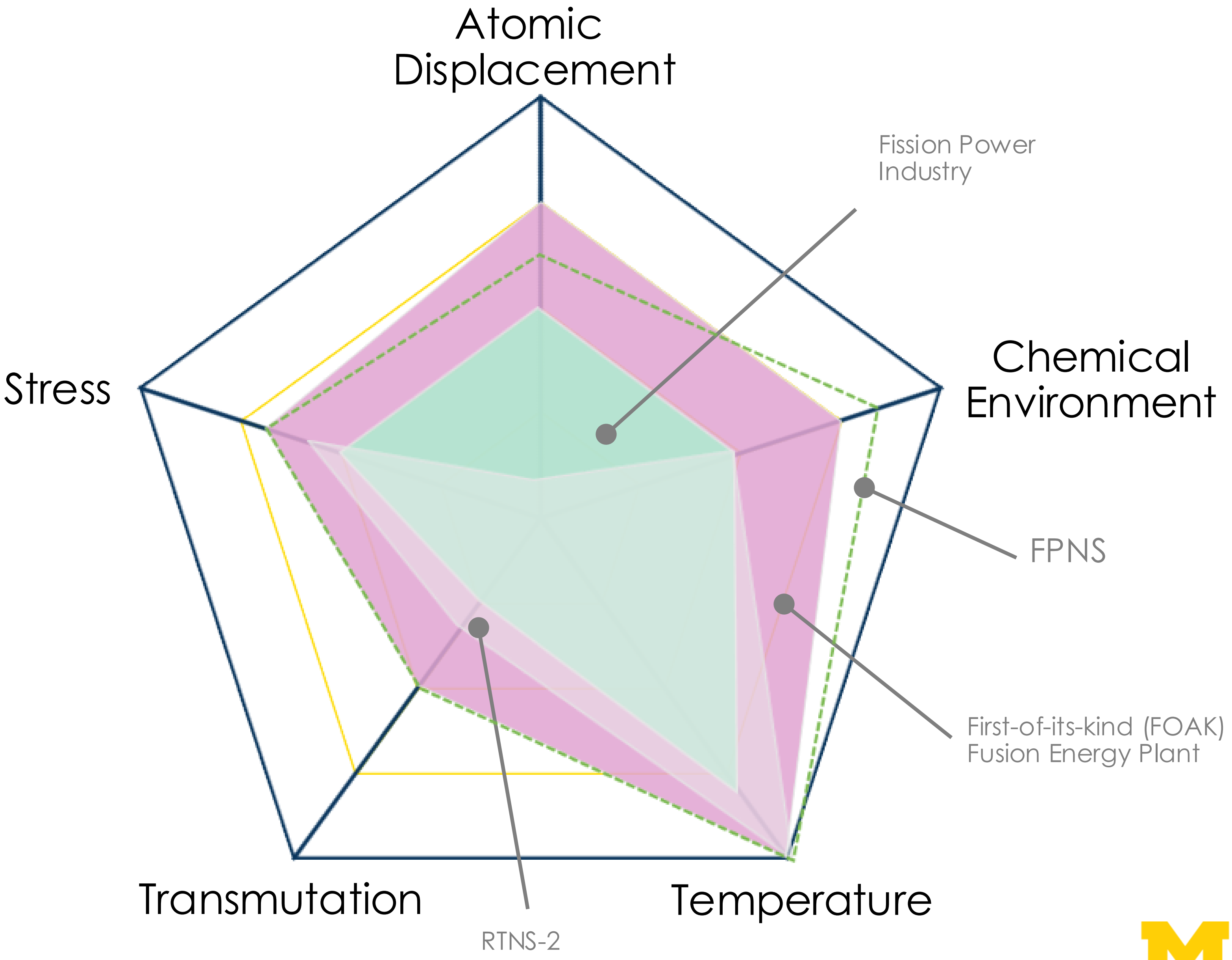




Swelling differences largely due to difference in melting temperatures (point defect mobility)

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



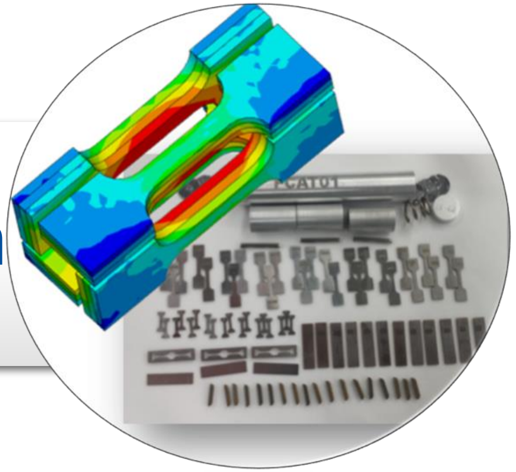


Original graphic by KG Field

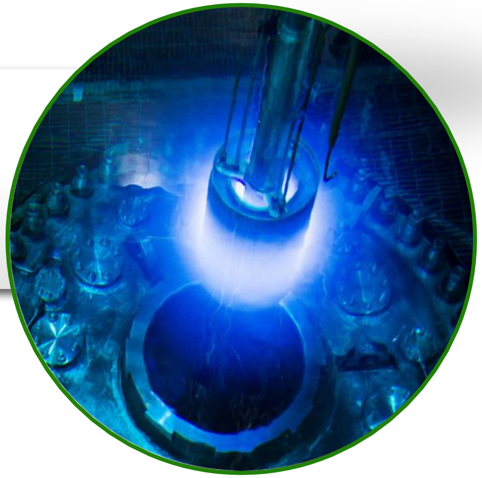
Irradiation experiment workflow overview

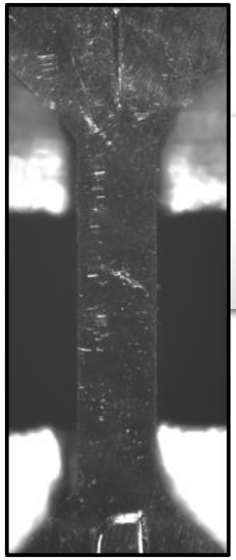
Preparation of experiment campaign

Experiment design



Irradiation





Post-irradiation examination

Analysis and publication

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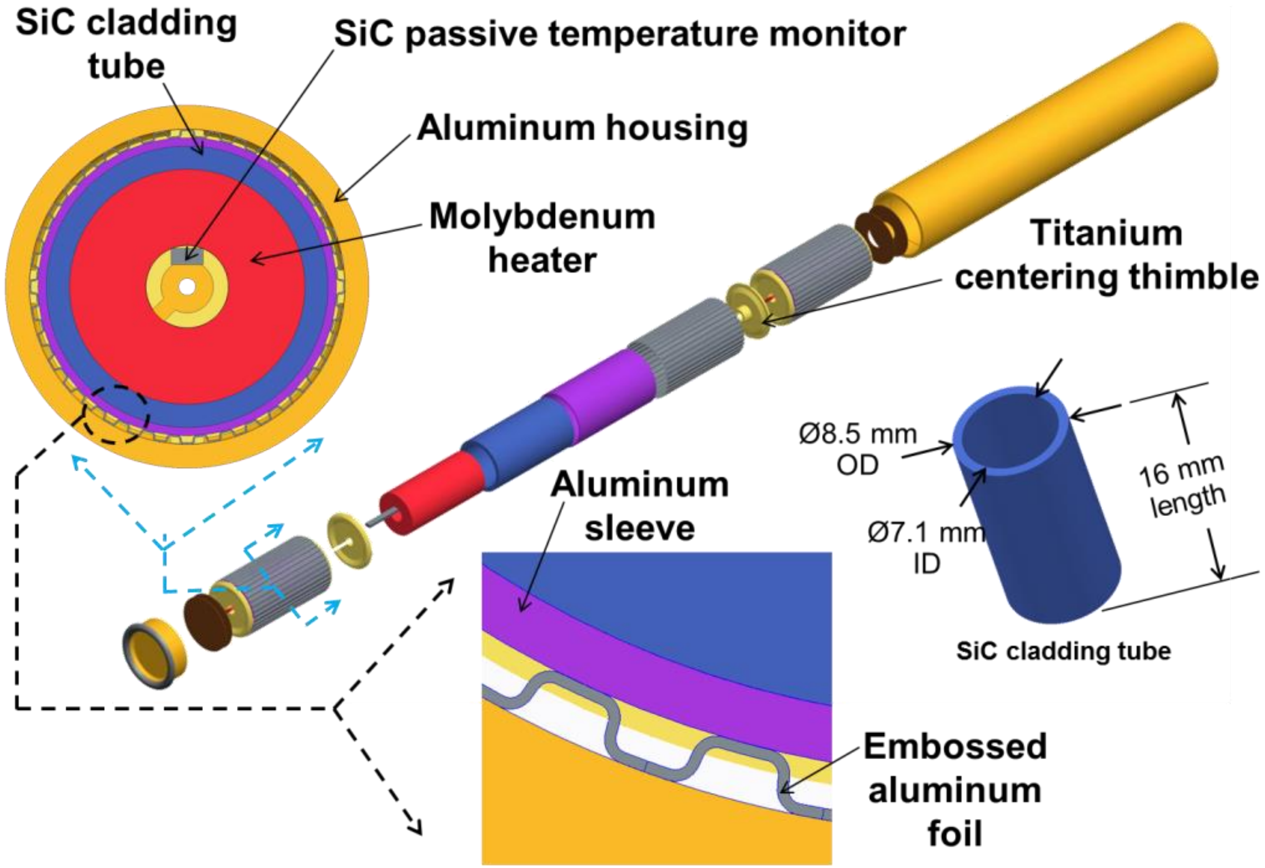
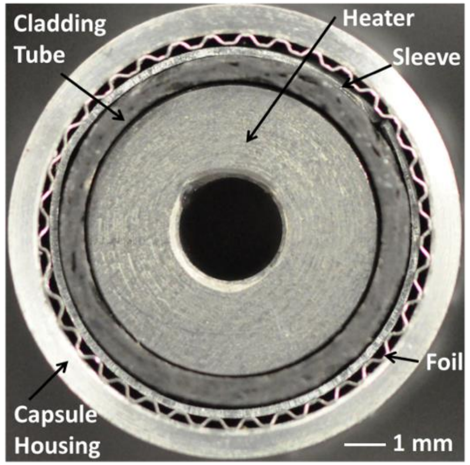
In-reactor Design

- Cycle length/duty cycle (e.g. what's my dose/year)
- Power/flux stability per cycle (e.g. how stable?)
- Experimental space (e.g. what's the biggest thing I can put in it?)
- In-situ monitoring/test capabilities
- Spectrum, He/dpa, and/or transmutation effects
- Uniformity of irradiation (e.g. axial peaking)
- Acceptability of data to regulator (e.g. can ion beam data be used to build a neutron source?)
- Accessibility (will changing political/economic environments impact my science?)
- Operating temperature capabilities
- Cost





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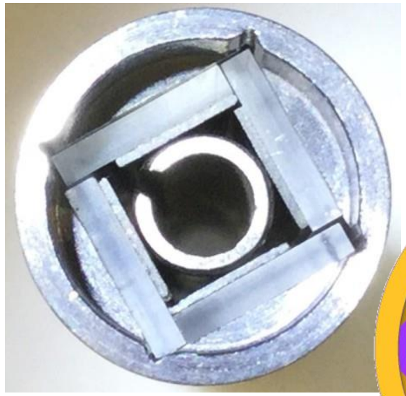
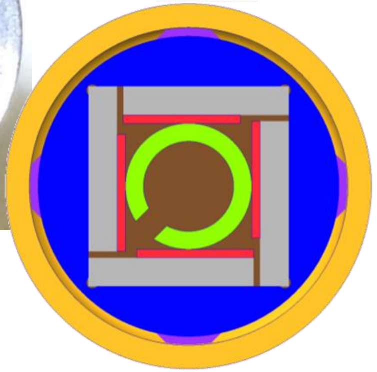
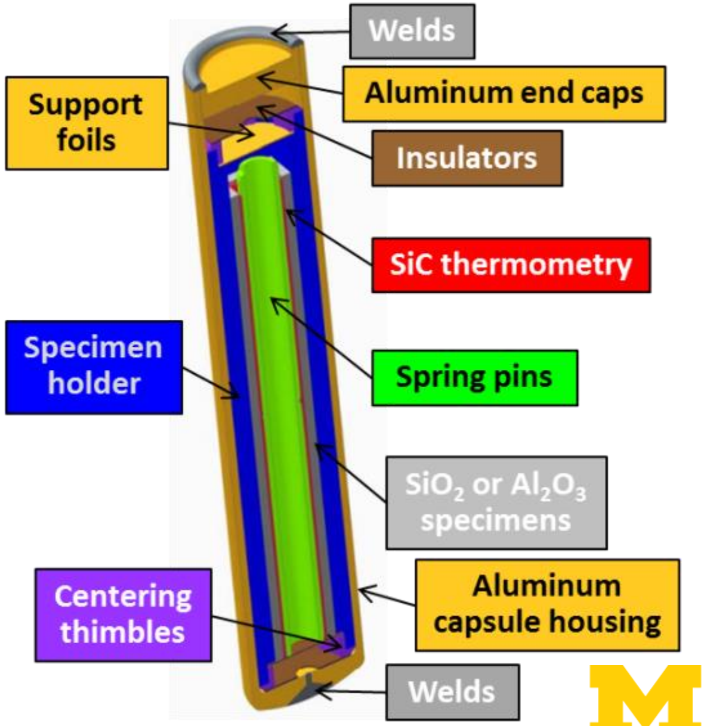
Irradiation Experiment Design

A basic approach is followed to complete the design:

1. Mechanical design of experiment with Computer Aided Design (CAD) software to produce engineering drawings
2. Neutronics analysis to determine heat generation rates
   - Substantial neutron/gamma heating: ~10 to >100 W/g
3. Thermal analysis to size insulating gas gap and choose fill gas to achieve desired temperatures
   - Very small gas gaps: 0.02 to 0.5 mm
     - Requires thermal/structural coupling to consider thermal expansion, radiation swelling, etc.
     - Multi-body heat transfer with small gaps that open/close due to differential expansion







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Passive capsules vs. active (instrumented) capsules

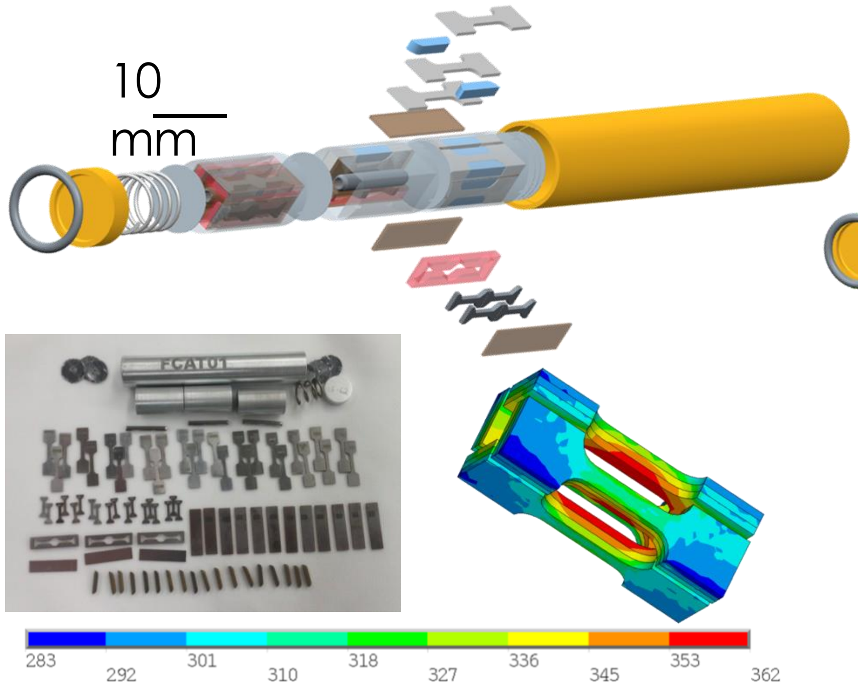
- Passive capsules reach design conditions by means of passive control
  - Gas gap optimization
  - Set fill gas composition
  - Reactor heating
- Active, or instrumented, capsules use control logic as well as passive means to reach design conditions
  - Thermocouples
  - Control software
  - Constant gas gap
  - Variable fill gas composition
- Passive capsule are generally less complex and expensive compared to instrumented experiments
  - Passive capsules also generally have more uncertainty

Standard vs. Unique capsule designs

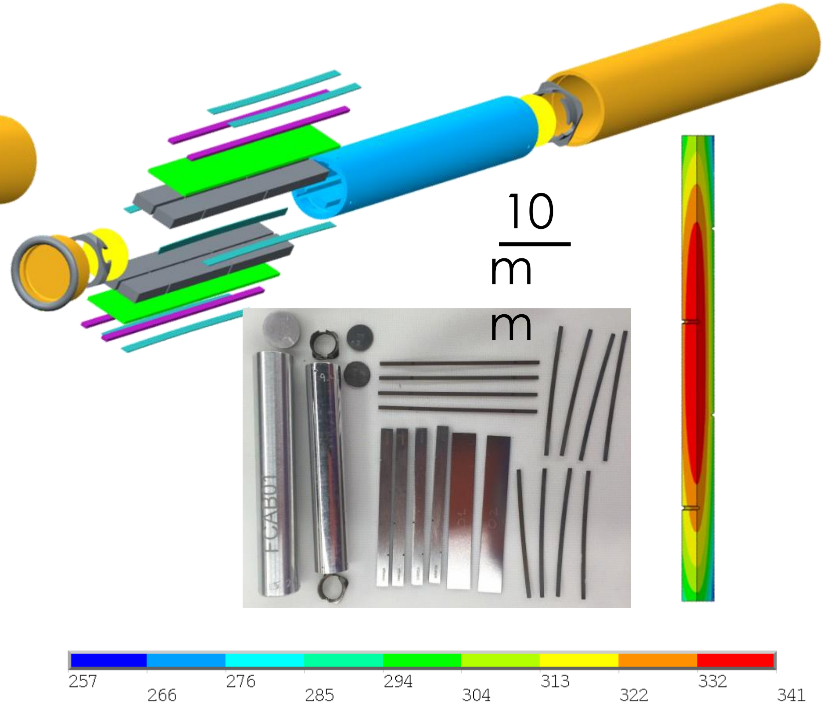
Examples of standard rabbit capsules

- Flexible sealed designs for irradiation of common metals with nuclear applications
- Steels, ferritic alloys, nickel alloys, etc.
- Applicable temperatures: 200°C to 1000°C

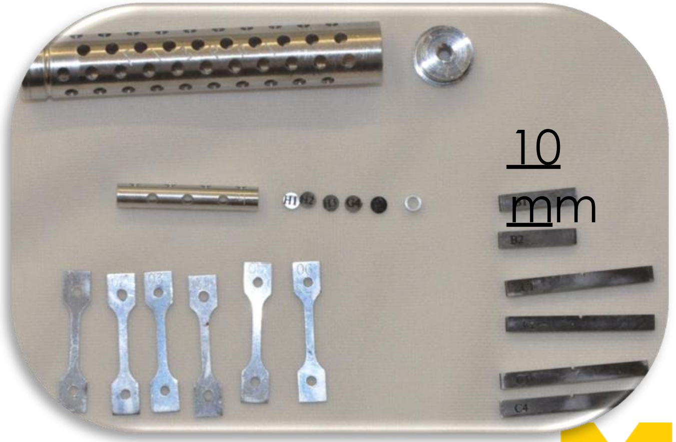
Tensile Specimens: SS-J2, SS-J3, SS-2E



Fracture Toughness: M4-PCCVN



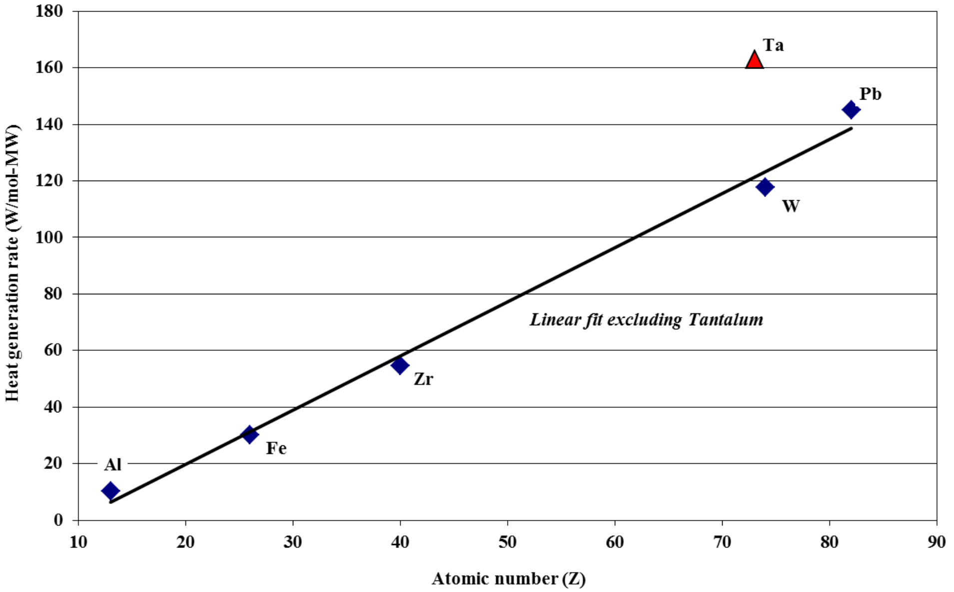
- Perforated Rabbit format
- Specimens exposed to reactor coolant (~60°C)
- Relatively inexpensive
- Ceramics, concrete, steels, metal alloys (Al, Cu, Ti, V, Zr, and Ni based), and refractory metals (Mo, W)



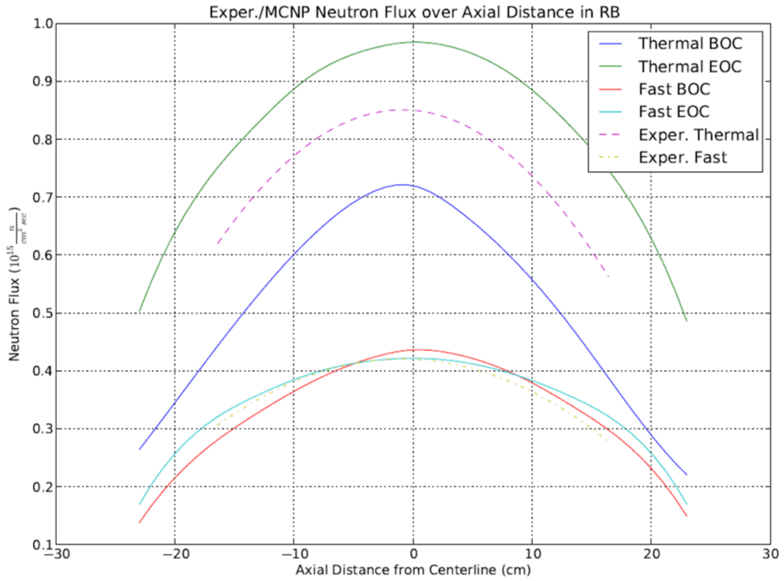
Getting the ”right” temperature requires classic engineering

Estimating nuclear heating is achieved through comparison or simulation.

- Reactor Power ∝ neutron flux ∝ fission gamma emission
- Gamma absorption ∝ material Z
- Gamma heating rates can be estimated through comparison with a material with known heating rate Z
- Neutron and activation heating are calculated with particle transport simulations (like MCNP)



Measured Heat Generation Rates for Various Materials in HFIR



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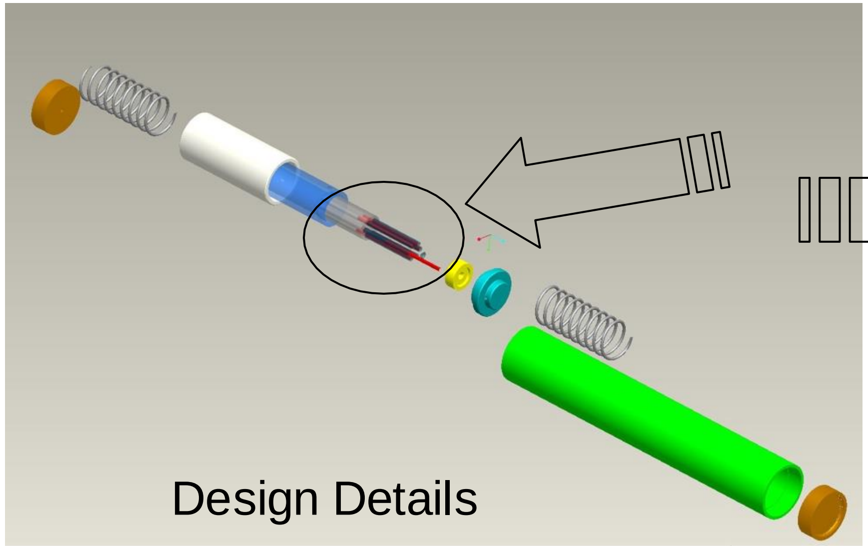
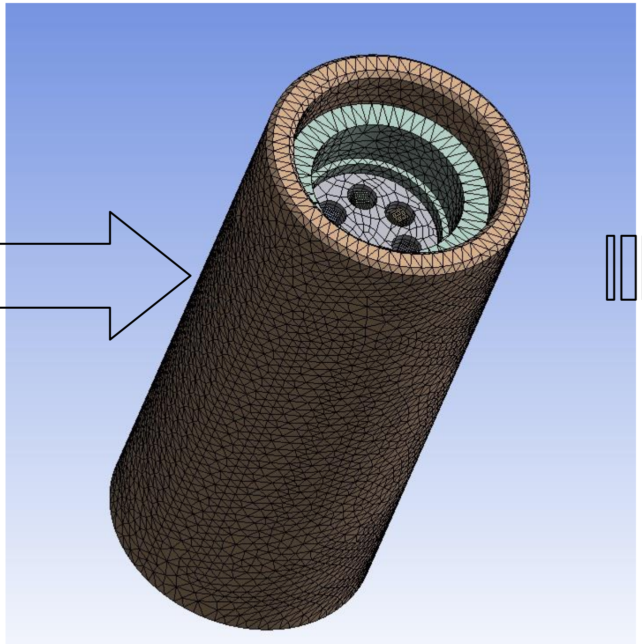
Getting the "right" temperature requires classic engineering

Establish boundary and input conditions

HFIR MCNP

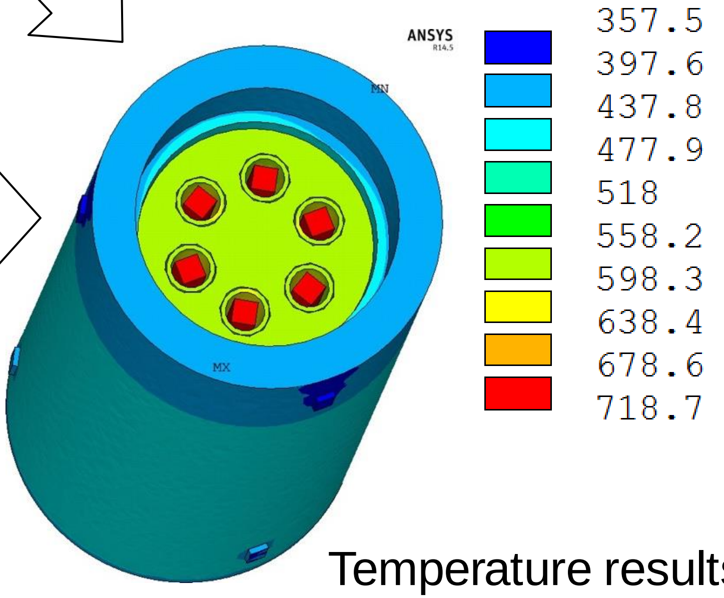
CAD Model





Prepare the thermal model

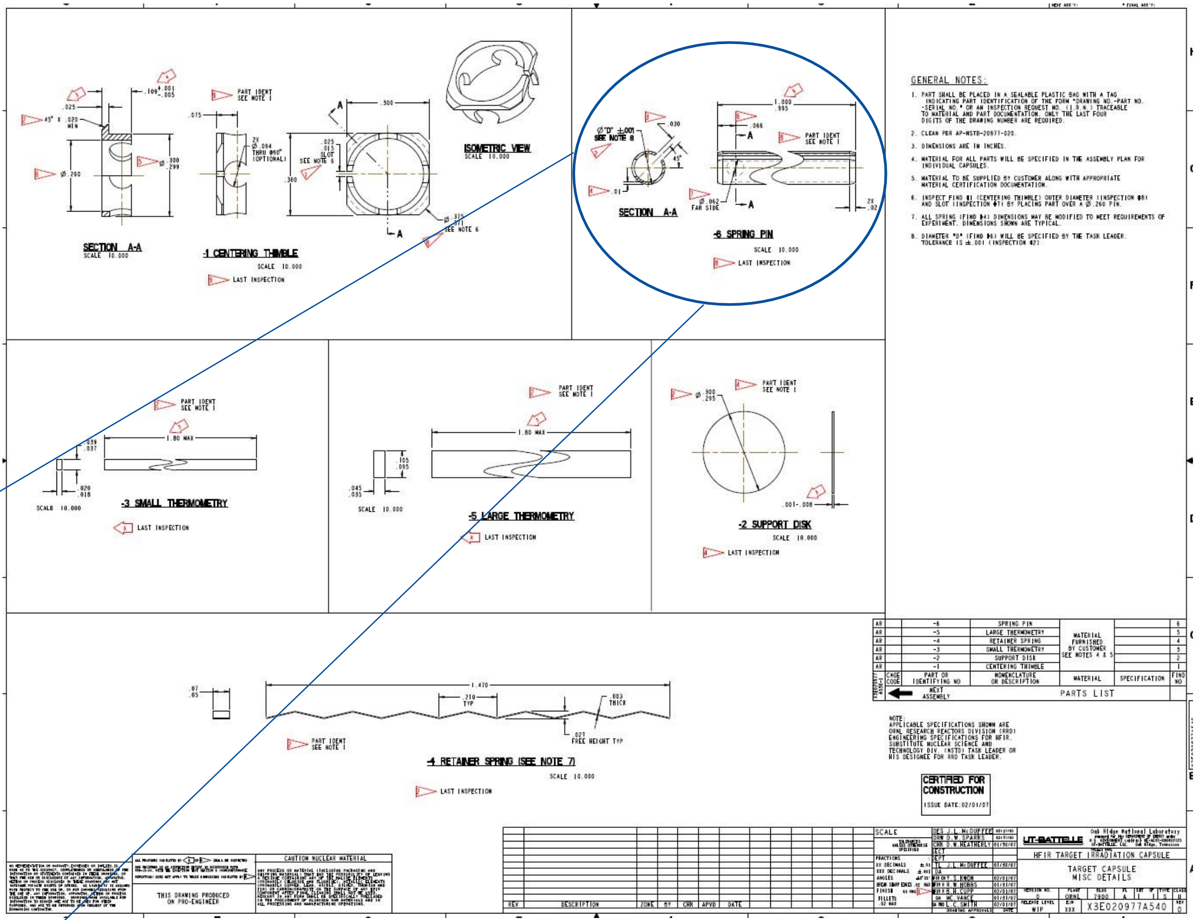
Finite element analysis

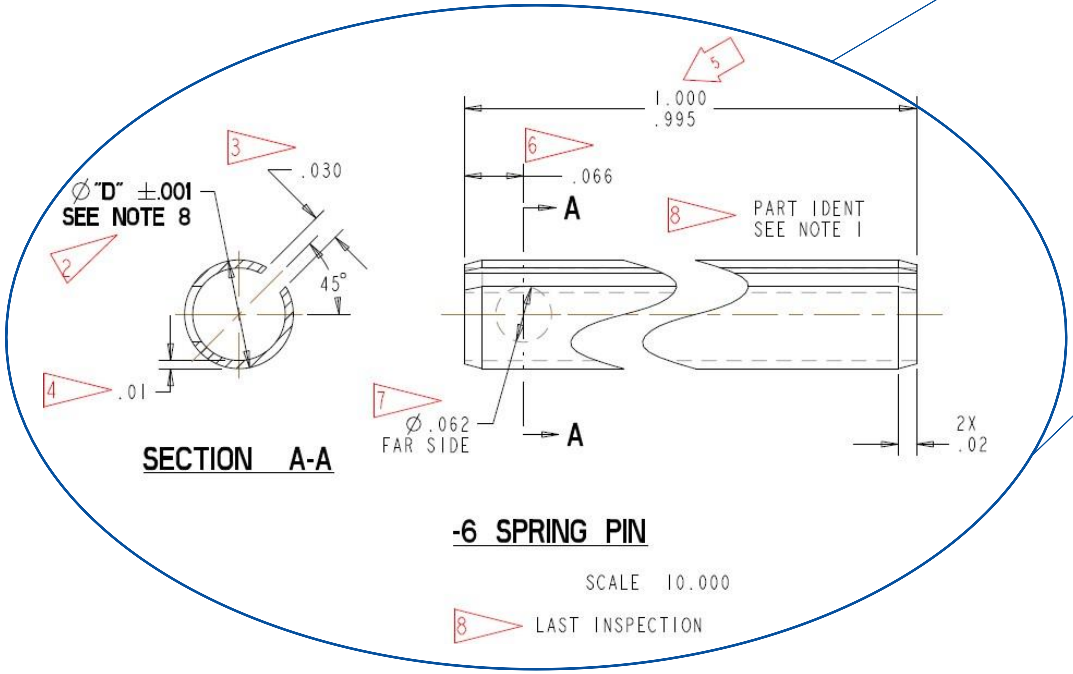


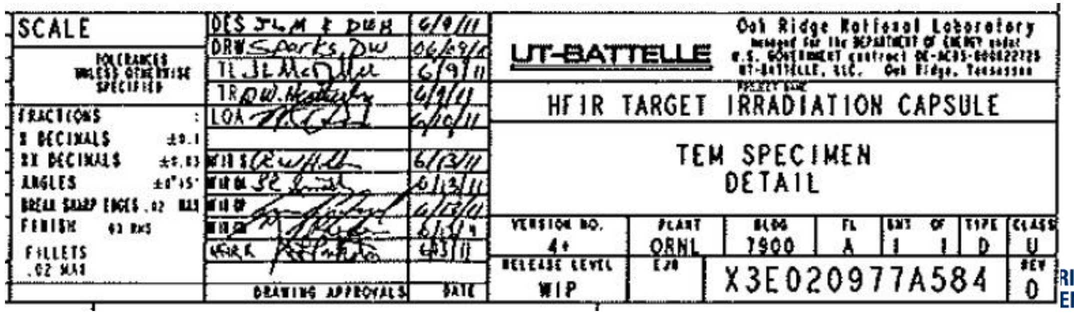
Temperature results

Getting the "right" temperature requires classic engineering

- Optimized parameters are recorded in the CAD model and engineering drawings are created and issued
- Critical dimensions that ensure proper capsule performance are designated on the drawings and recorded during part fabrication



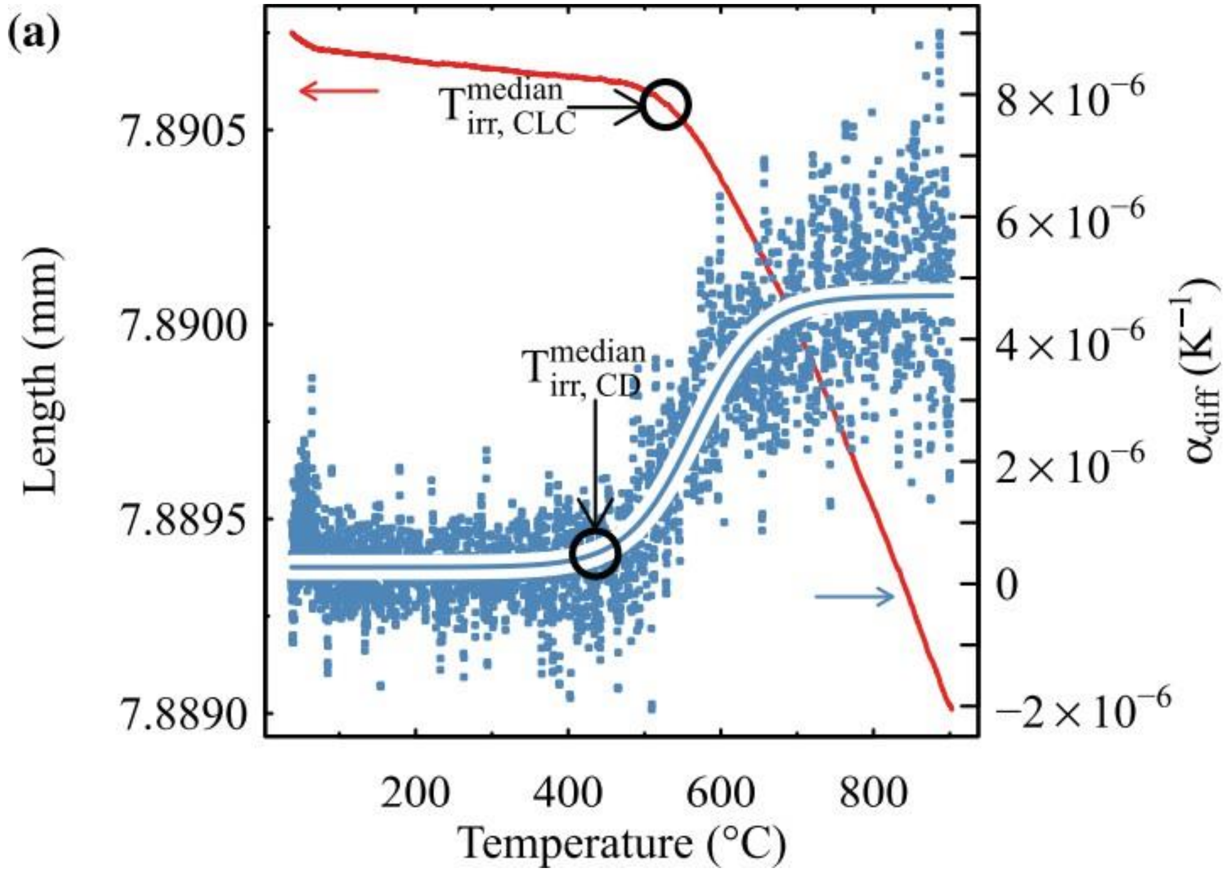




Thermal and performance validation

Thermometry data provide information on how passive experiments perform thermally

- SiC samples embedded into passive experiments can provide post-irradiation indication of operating temperature
- Instantaneous coefficient of thermal expansion is measured during heat-up and subsequent cool-down
- Annealing of radiation-induced defects occurs as the sample is heated beyond the irradiation temperature
- CTE will be different during cool-down than on heat-up



[1] K. G. Field, et al., "Evaluation of the continuous dilatometer method of silicon carbide thermometry for passive irradiation temperature determination," DOI 10.1016/j.nimb.2019.02.022

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Post-irradiation examination (PIE)

- Hot cell operations must be performed remotely due to experiment radioactivity
  - Master-slave manipulators are the primary interface
  - Assistance from modern electronics is limited
  - Hot cells can be crowded places
- Experiments use sub-size specimens to keep radioactivity under control
  - Small parts are difficult to manage in a hot cell
  - Identifying parts within the cell can be challenging
- Testing is performed to gather scientific data

In cell microscope image of tensile halves

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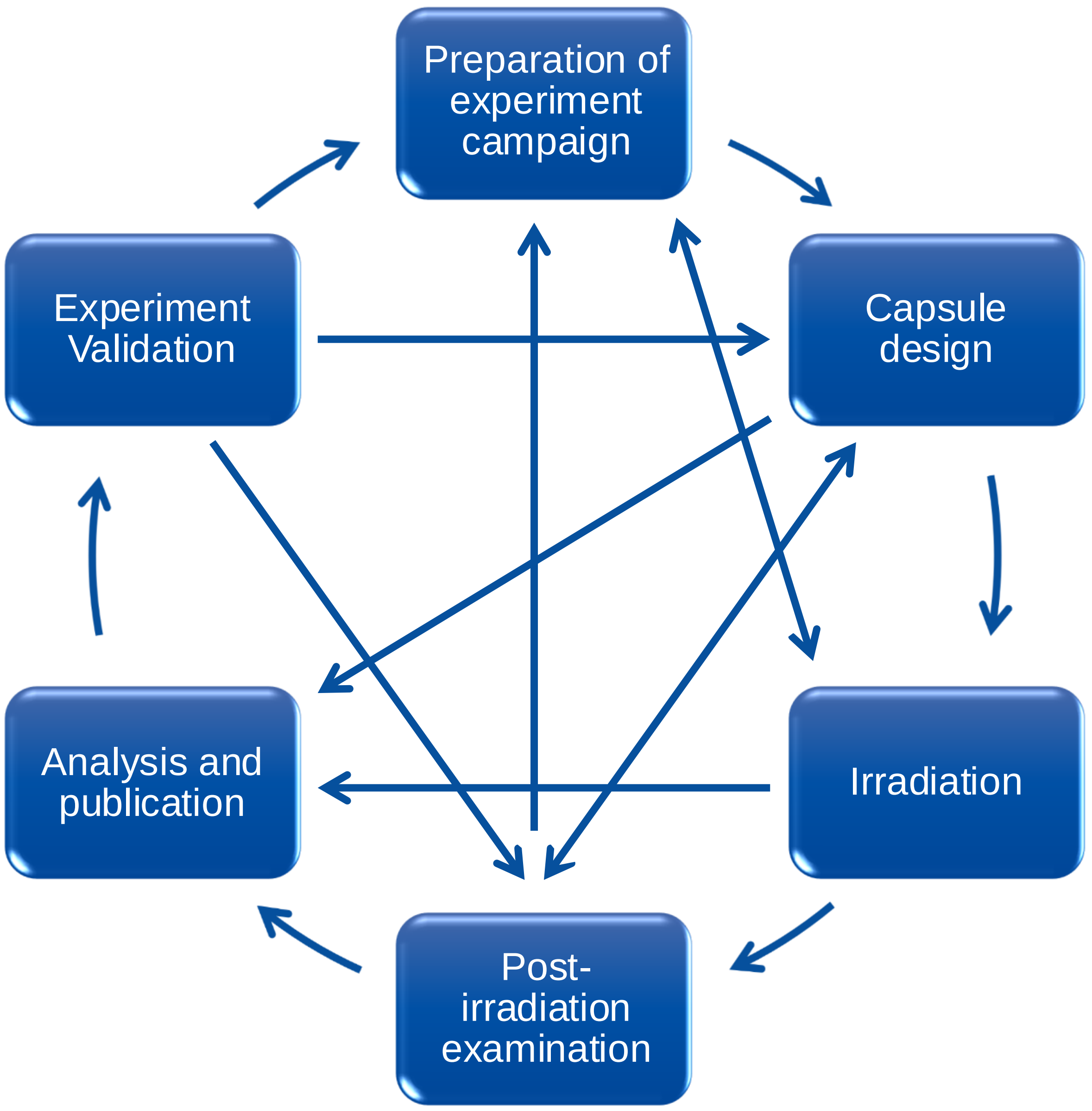
Capsule design discussion - Design philosophy



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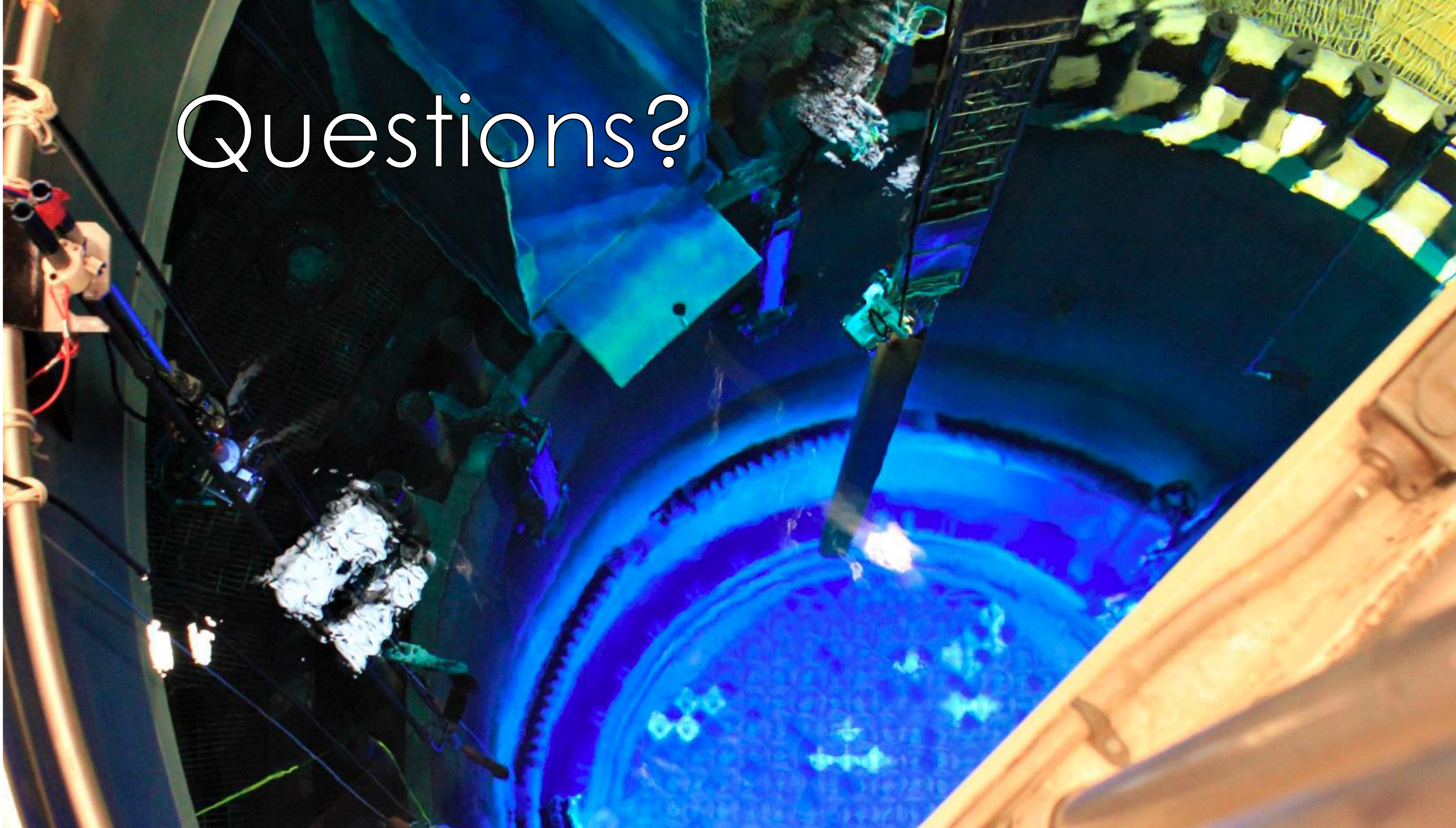
Questions?