Structural Materials for Fusion Reactors

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Princeton Plasma Physics Laboratory SULI Summer Course
June 23, 2020

About me

https://commons.wikimedia.org/wiki/File:Map_of_USA_with_state_names.svg

Masters and PhD in Nuclear Engineering-University of Wisconsin-Madison

SULI-Fermilab

Undergraduate degree, Nuclear engineering-University of Illinois

High School-Charleston, IL

Job-Oak Ridge National Laboratory

Internship at GEMICO Nancy, France

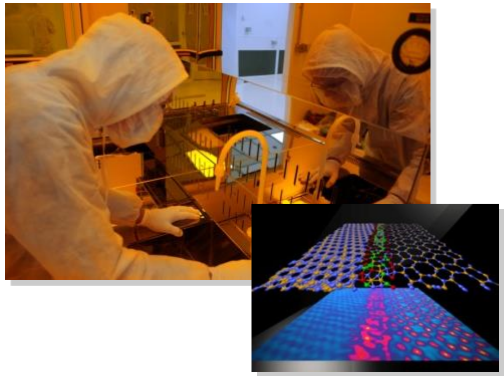
ORNL Has Six Main Research Areas

Clean Energy

High-Performance Computing

Nuclear Science

Advanced Materials



Neutron Science

National security

…and interns, both undergraduate and graduate, work in all of these areas!

www.orau.org/ornl

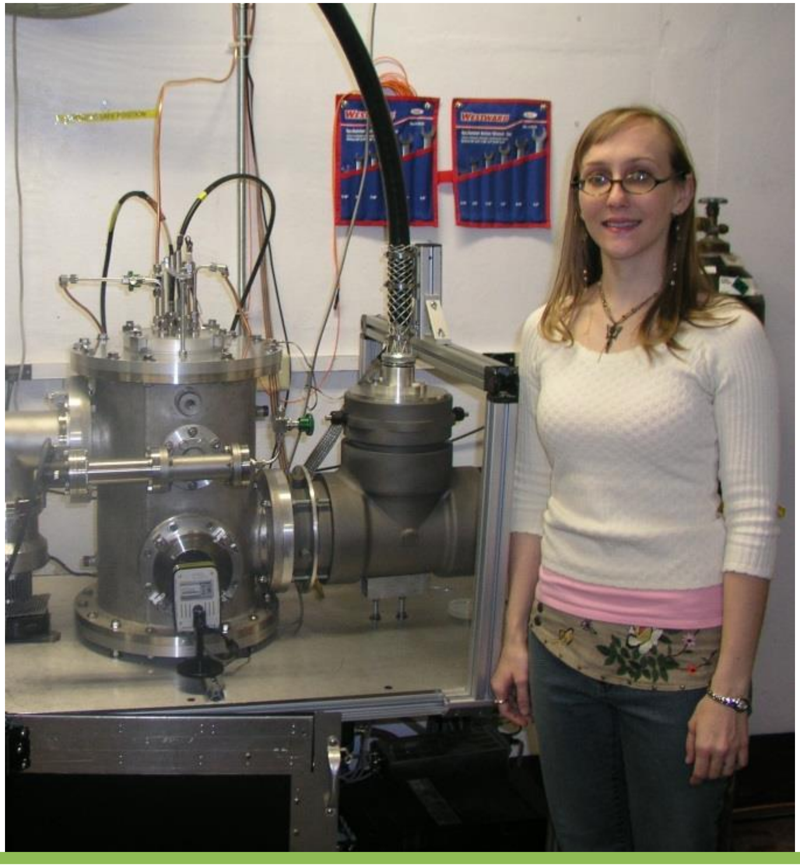
Fusion structural materials

Requirements for Fusion

- For fusion
  - High enough energy
  - High enough confinement time
  - High enough particle density

Small scale devices are easily capable of causing fusion reactions

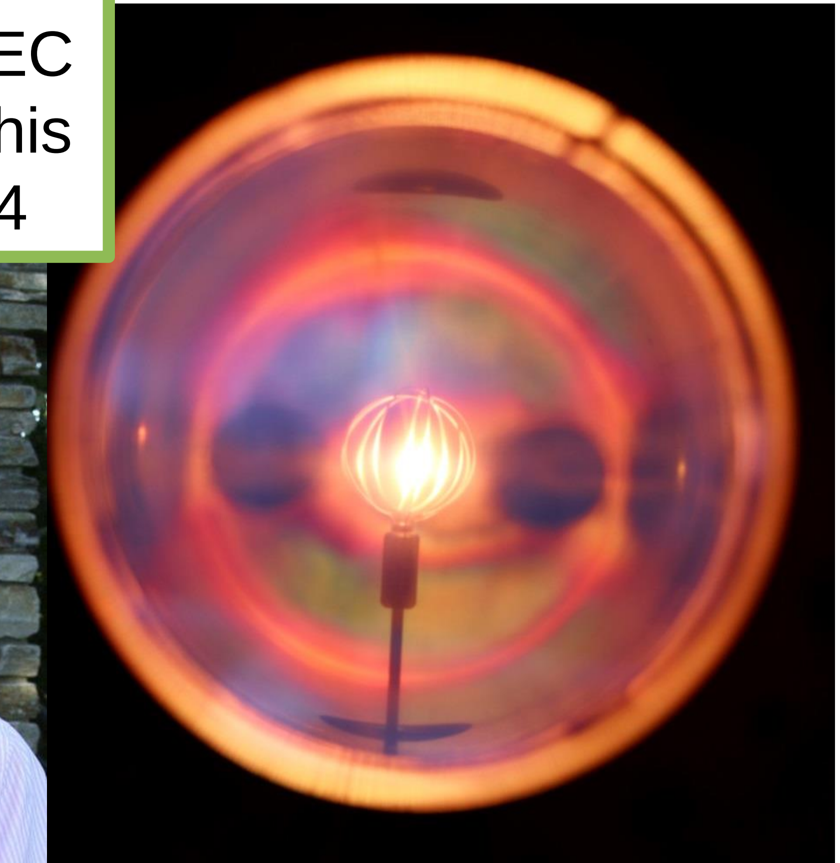
IEC=inertial electrostatic confinement is one method of creating fusion reactions in a lab



Me as a graduate student next to a fusion-producing device at the University of Wisconsin

Taylor Wilson

-Started making IEC fusion devices in his garage at age 14



http://www.sciradioactive.com/fusiongallery/

Requirements for Fusion

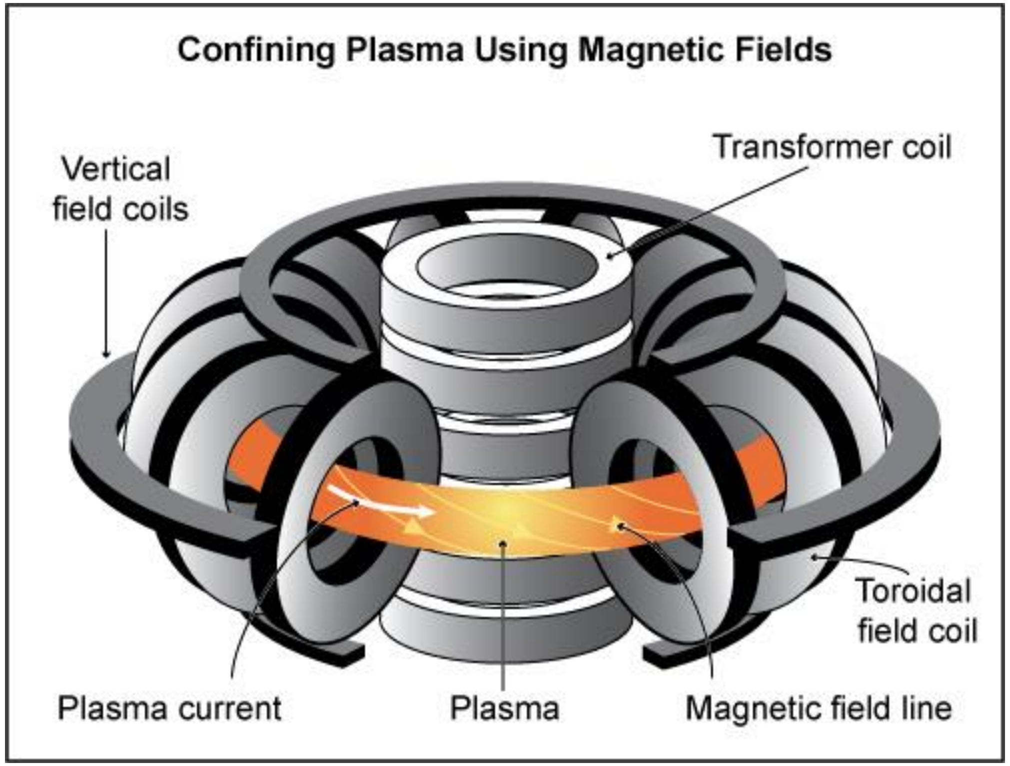
- For fusion
  - High enough energy
  - High enough confinement time
  - High enough particle density

  } Easy

- For power reactor, additionally
  - Create fusion efficiently so that (power in)<(power out)
  - Sustain the fusion reaction (steady state or pulsed) over ~years with minimal maintenance periods
  - Capture the generated energy to produce electricity

All these challenges require materials innovation

Conceptual Idea of a Tokamak

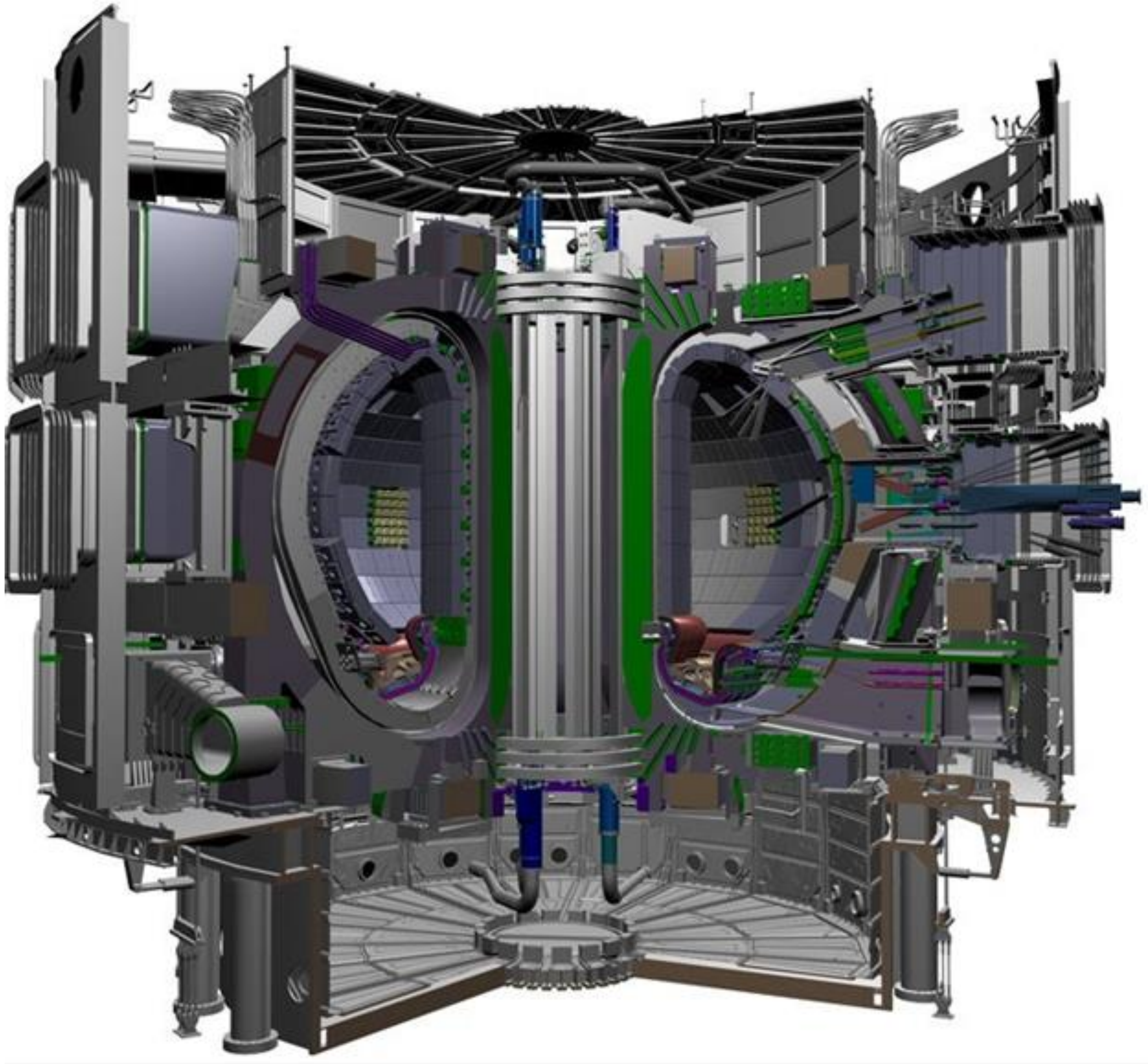


https://eswrenewableenergystudy.wordpress.com/2012/04/

A real experiment reactor is much more complicated than the concept

- A power reactor will have even more systems and more harsh conditions than ITER

I visited the ITER site



http://www.iter.org/mach

Fusion Materials: Fact or Fiction

- Iron Man's arc reactor
  - https://www.youtube.com/watch?v=5Rb9hAHifFA
  - ~0:50-2:52

Arc Reactor

- The arc reactor is a miniaturized fusion power source
- From the movie:
  - ~~Needs palladium~~
  - ~~Generates "3 GJ/s" of power = 3 GW of~~ power
  - Has wires wrapped around the torus—magnets?
  - Has a magnetic field, to stop the metal shrapnel in Tony's body from moving and reaching his heart
  - ~~Fits in the palm of a hand~~
  - ~~No fuel that we see~~
  - Sand casting molten metal

How much power is 3 GW?

- A current full power plant might produce 1000 MW electric=1 GW

Could something so small withstand that power?

- Assume 3" major radius, 1" minor radius
  - 0.076 m^2 surface area
  - 39,000 MW/m^2
- Surface of the sun, ~63 MW/m^2
- Iron Man's arc reactor has approximately 619 sun's worth of heat flux
- Real plasma facing components have been designed to withstand ~20 MW/m^2

Need to use materials science to design a real reactor

Oak Ridge National Laboratory

What is Materials Science and Engineering?

What is Materials Science and Engineering?

MSE encompasses the research and application of natural and human-made materials.

It includes:

- Making raw materials from ore (extraction),
- Combining materials in useful ways (synthesis),
- Turning materials into finished goods (processing),
- Using specialized equipment to view materials (characterization), and
- Studying how materials behave (properties).

Everything is made of materials

Everything around us is made of materials, so knowledge of materials gives you an understanding of everything.

dishes, shoes, windows, couches, books, etc.

Every cool piece of technology everywhere is based on materials

https://www.gizmotimes.com/what-how/dual-tri-and-quad-band-cell-phones/19220

https://spaceflight.nasa.gov/gallery/images/shuttle/sts-120/hires/sts120-s-028.jpg

https://www.amazon.com/Oculus-Touch-Virtual-Reality-System-pc/dp/B073X8N1YW/ref=asc_df_B073X8N1YW/?tag=hyprod-20&linkCode=df0&hvadid=309892766843&hvpos=1o2&hvnetw=g&hvrand=5742625851061306037&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9022196&hvtargid=aud-466360936450:pla-541346611872&psc=1

https://en.wikipedia.org/wiki/Ballistic_face_mask#/media/File:Mounted_Soldier_System_cropped.jpg

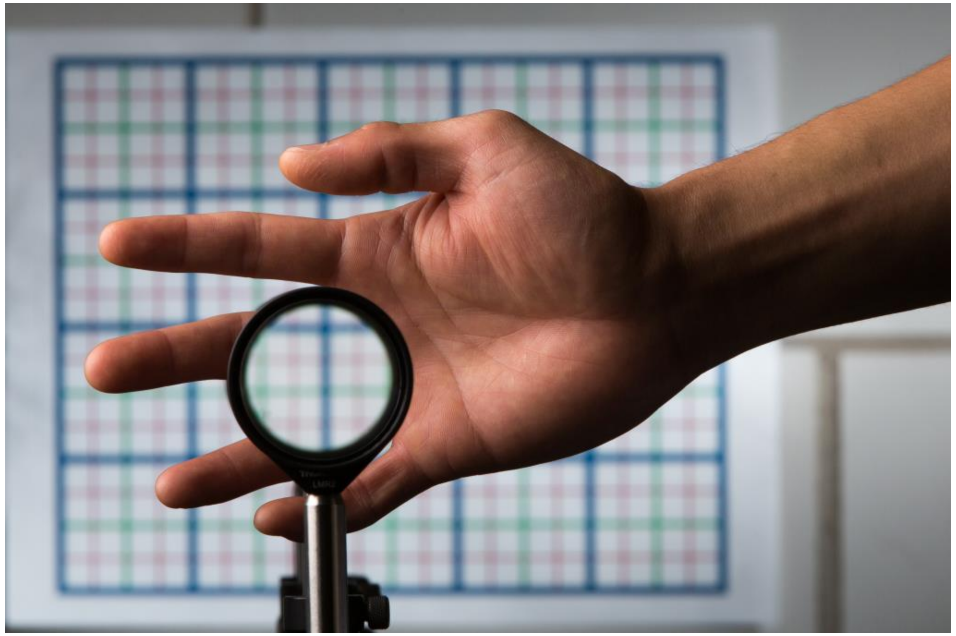
https://en.wikipedia.org/wiki/Bridge#/media/File:Akashi-kaikyo_bridge3.jpg

https://en.wikipedia.org/wiki/LED_lamp#/media/File:LED_bulbs_2012.jpg

https://web.ornl.gov/sci/manufacturing/shelby/

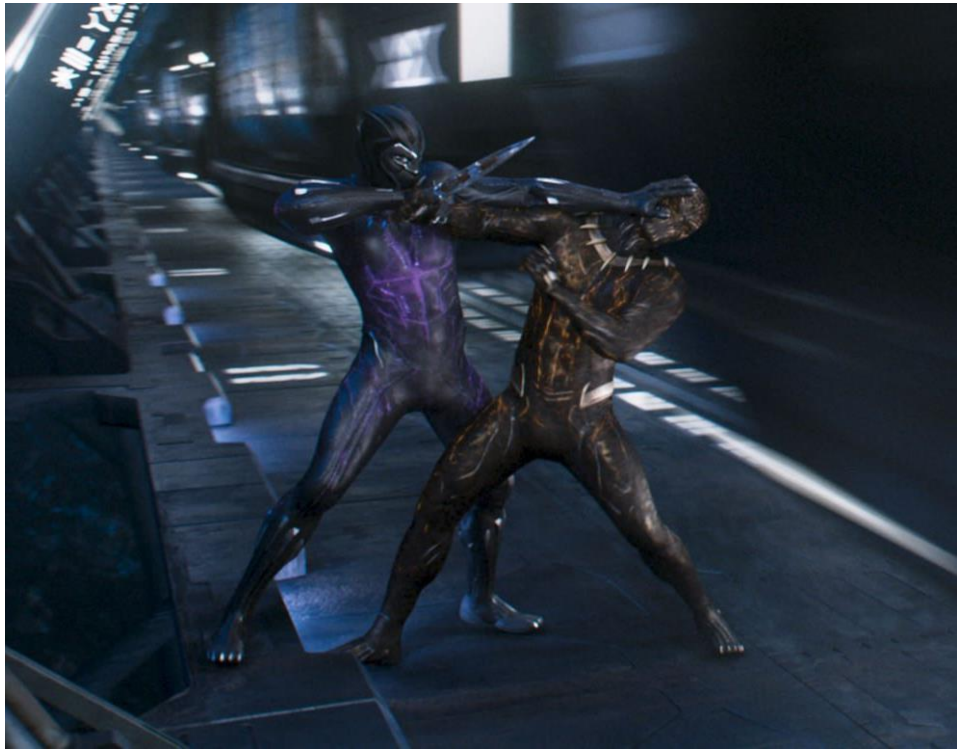
Wonder Woman's Invisible Plane

Wonder Woman Annual vol. 5, #1 (July 2017). Art by Nicola Scott and Romulo Fajardo, Jr.



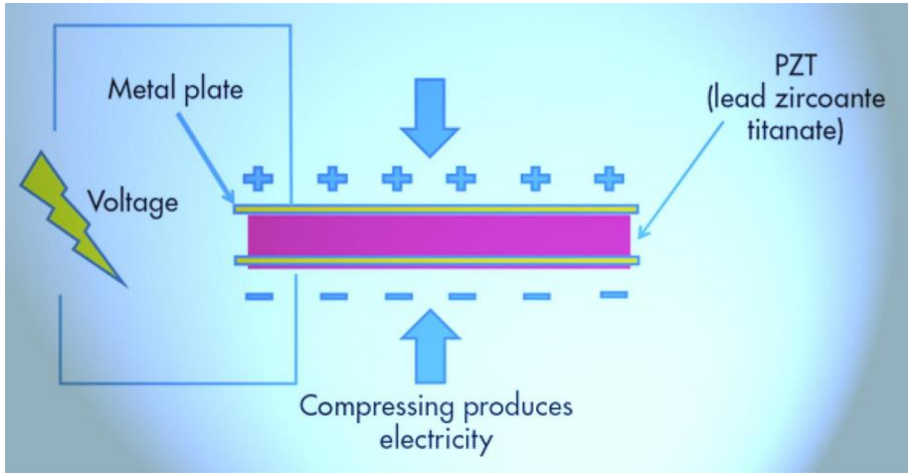
http://www.rochester.edu/newscenter/watch-rochester-cloak-uses-ordinary-lenses-to-hide-objects-across-continuous-range-of-angles-70592/

Black Panther’s Suit



https://www.mpaa.org/2018/05/how-black-panthers-visual-effects-team-infused-the-panther-suits-with-vibranium-technology/

Piezoelectric Materials

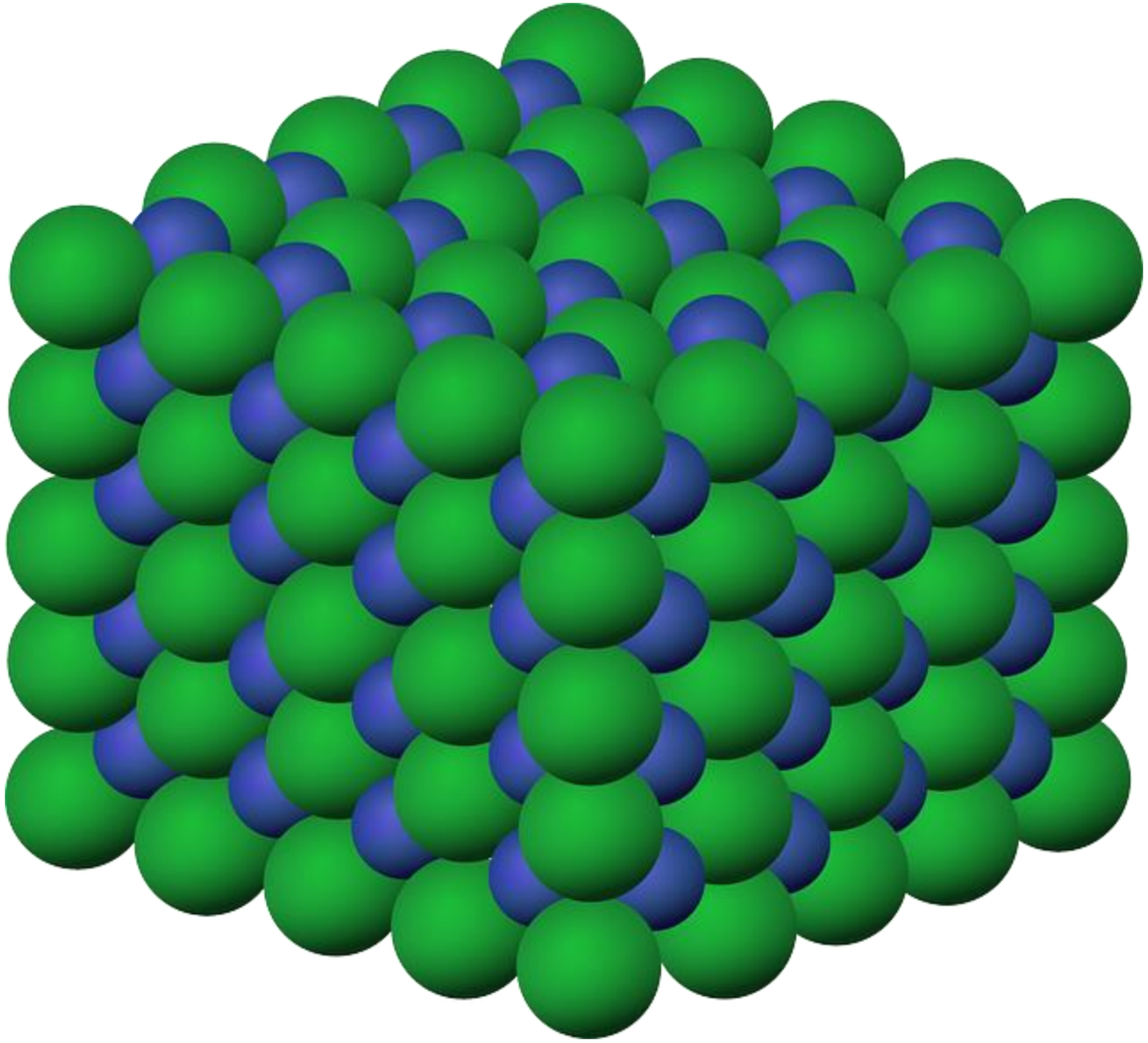


https://www.electronicdesign.com/power/what-piezoelectric-effect

Materials Science Basics

Crystal Structure

- Unique arrangement of atoms in a crystalline material
  - Solid materials; all metals, many ceramic materials, and certain polymers
- Composed of repeating unit cells
  - Small entities with defined atomic positions
- In a three dimensional lattice



https://upload.wikimedia.org/wikipedia/commons/e/e9/Sodium-chloride-3D-ionic.png

http://ww1.prweb.com/prfiles/2006/11/14/478461/eXpert2611.jpg

Tensile Testing

- Tensile stress applied uniaxially on a sample
- Sample deformed, generally to fracture
- Output is load vs. elongation
- Determine strength and ductility of material

https://www.youtube.com/watch?v=BHZALtqAjeM

~0:35 – 2:00

Tensile Testing

During the whole test

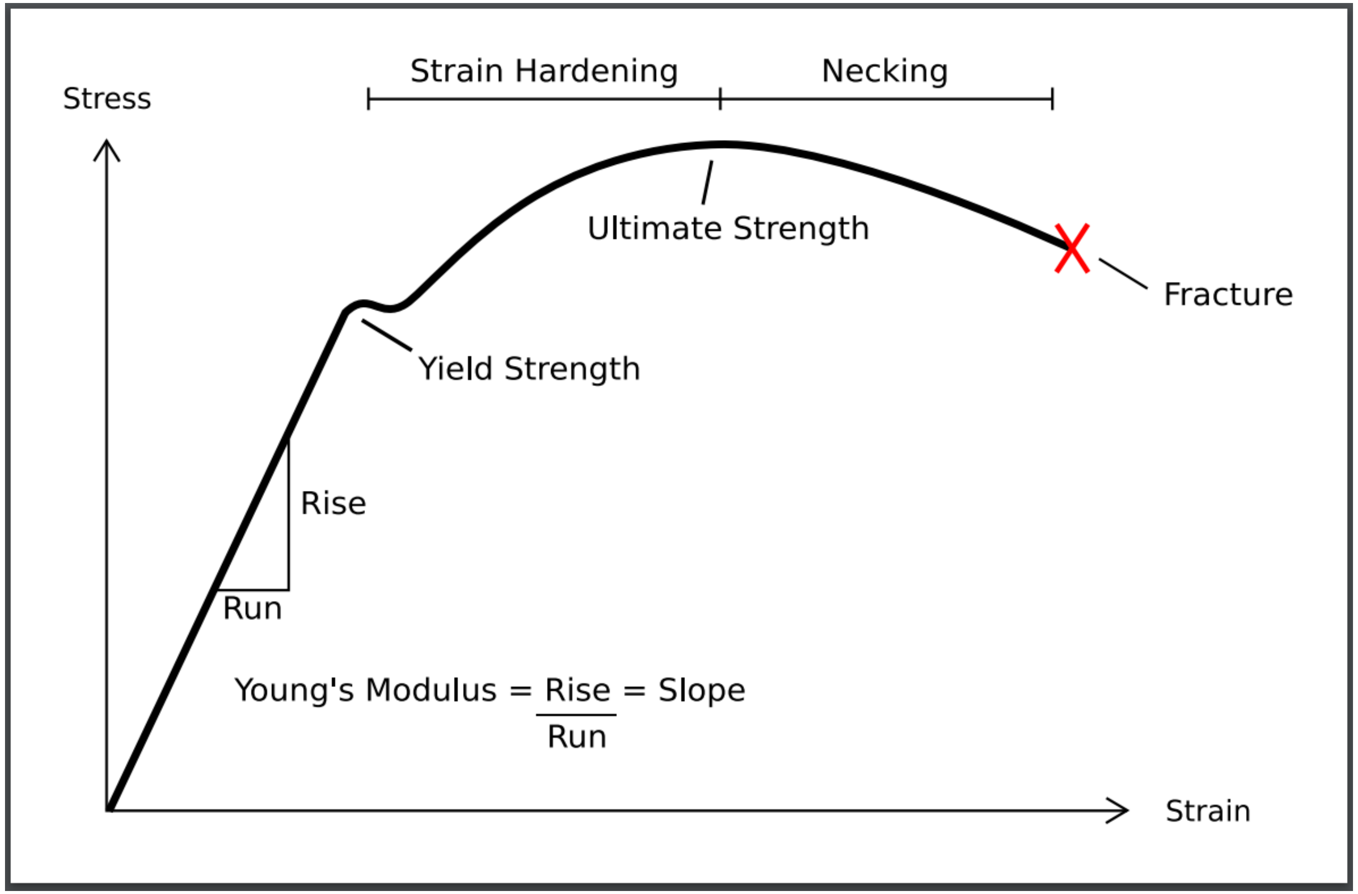
Stress=σ=Force/Area (MPa)

Strain=ε= $\frac{change\ in\ length}{original\ lengh}$=Δl/l (%)

In the elastic region

σ=Eε

E=Young's Modulus

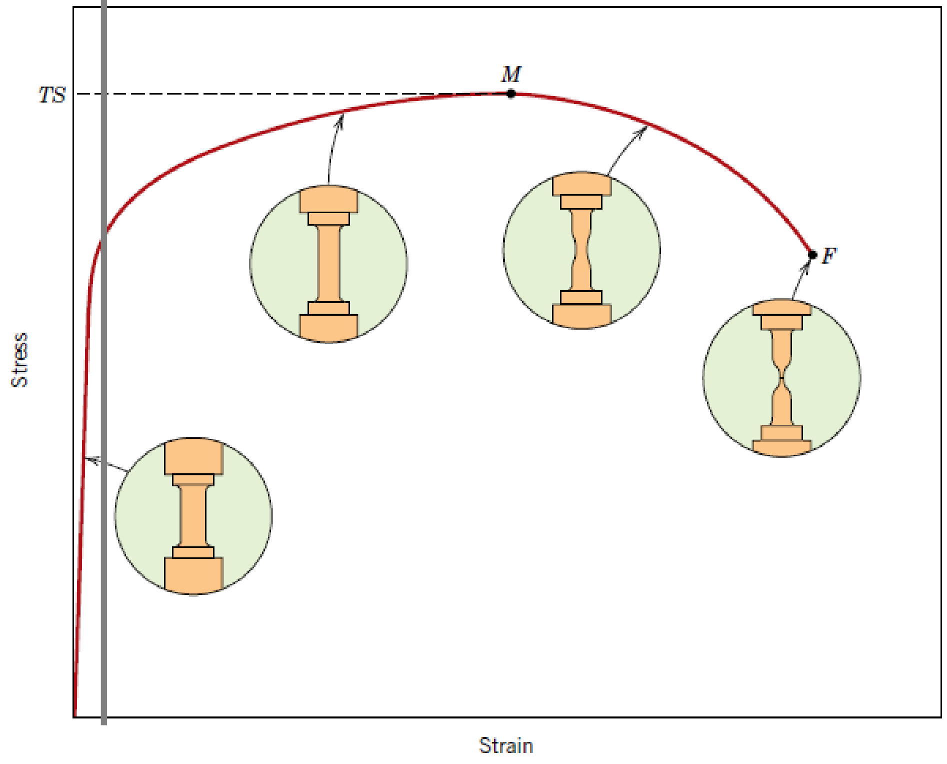


https://commons.wikimedia.org/wiki/File:Stress_Strain_Ductile_Material.pdf

Materials "stretch" and deform by dislocation motion

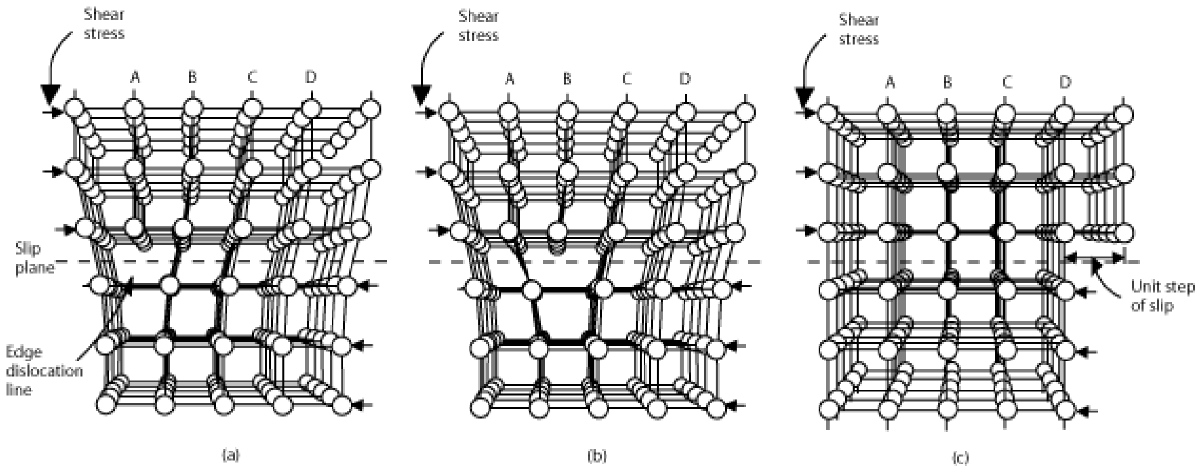
In the elastic region, atomic bonds are stretched but atoms don't move

In the plastic region, atomic bonds are broken and atoms move by dislocation motion

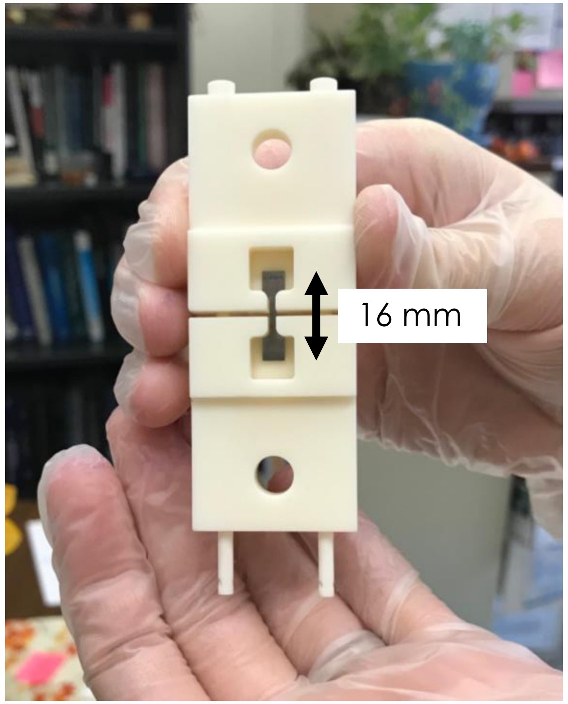


Callister and Rethwisch "Materials Science and Engineering" 9th ed. Wiley 2014

Dislocation Motion



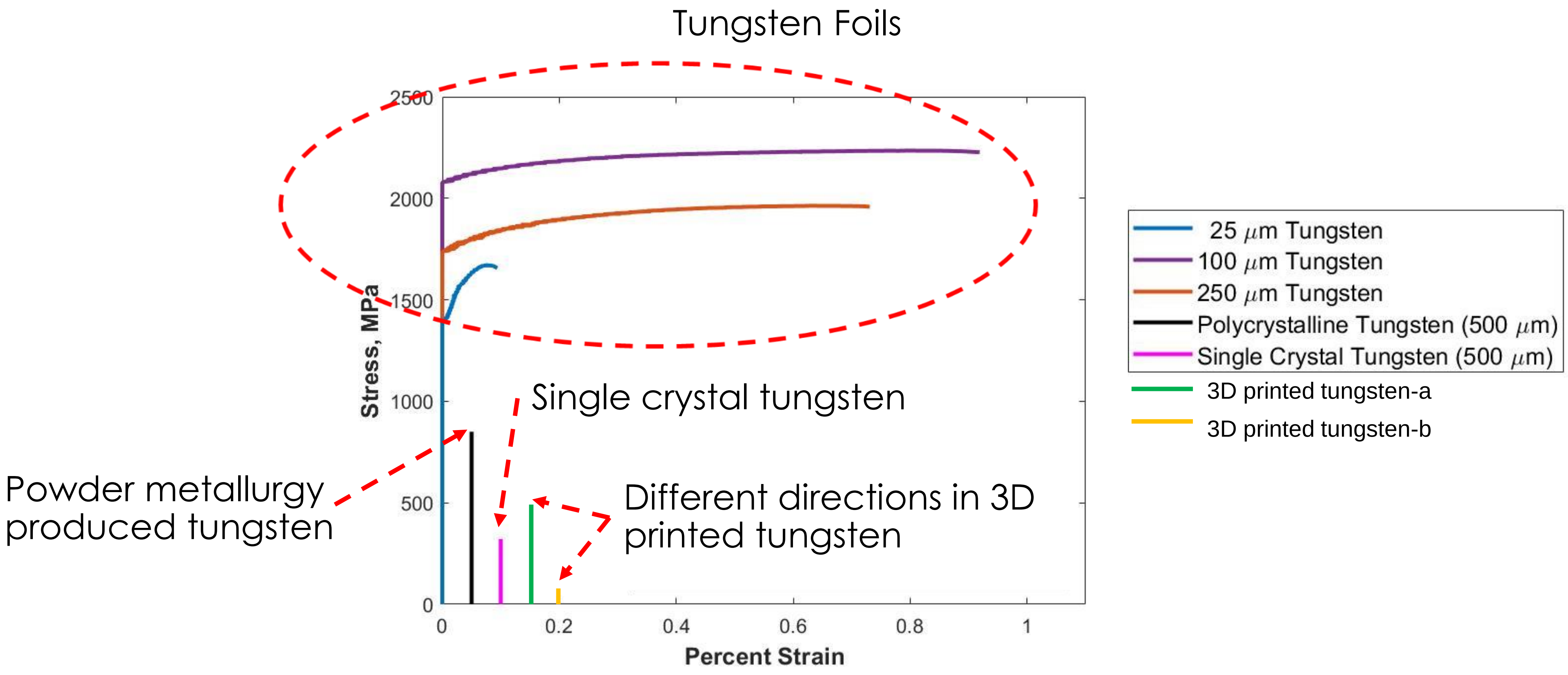
I tensile test very small, neutron irradiated samples



US quarter coin
24.26 mm

→Ask me in the hallway why our samples are so small
→Ask me in the hallway about working with radioactive samples

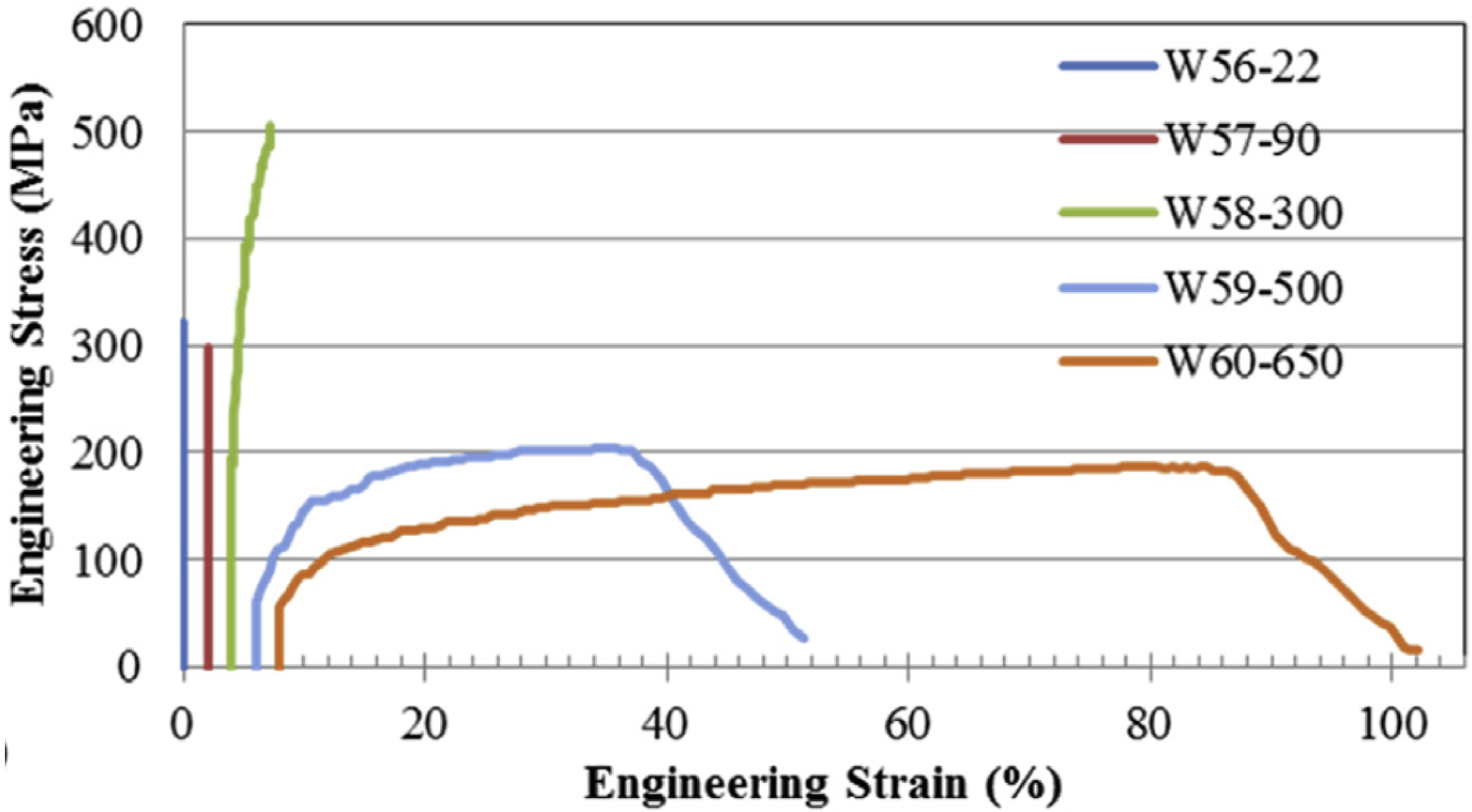
Tungsten is tungsten is tungsten, right?



All tensile tests at room temperature in air

Material Properties Change with Temperature

Single crystal <110> tungsten at different test temperatures



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Material properties change

- Material properties depend on
  - What elements
  - Composition
  - How the atoms are distributed (grain size and structure)
- Material properties change with
  - Temperature
  - Time
  - Fabrication method
  - Surrounding chemistry
  - And neutron exposure

Material Properties that Matter for Design (not exhaustive)

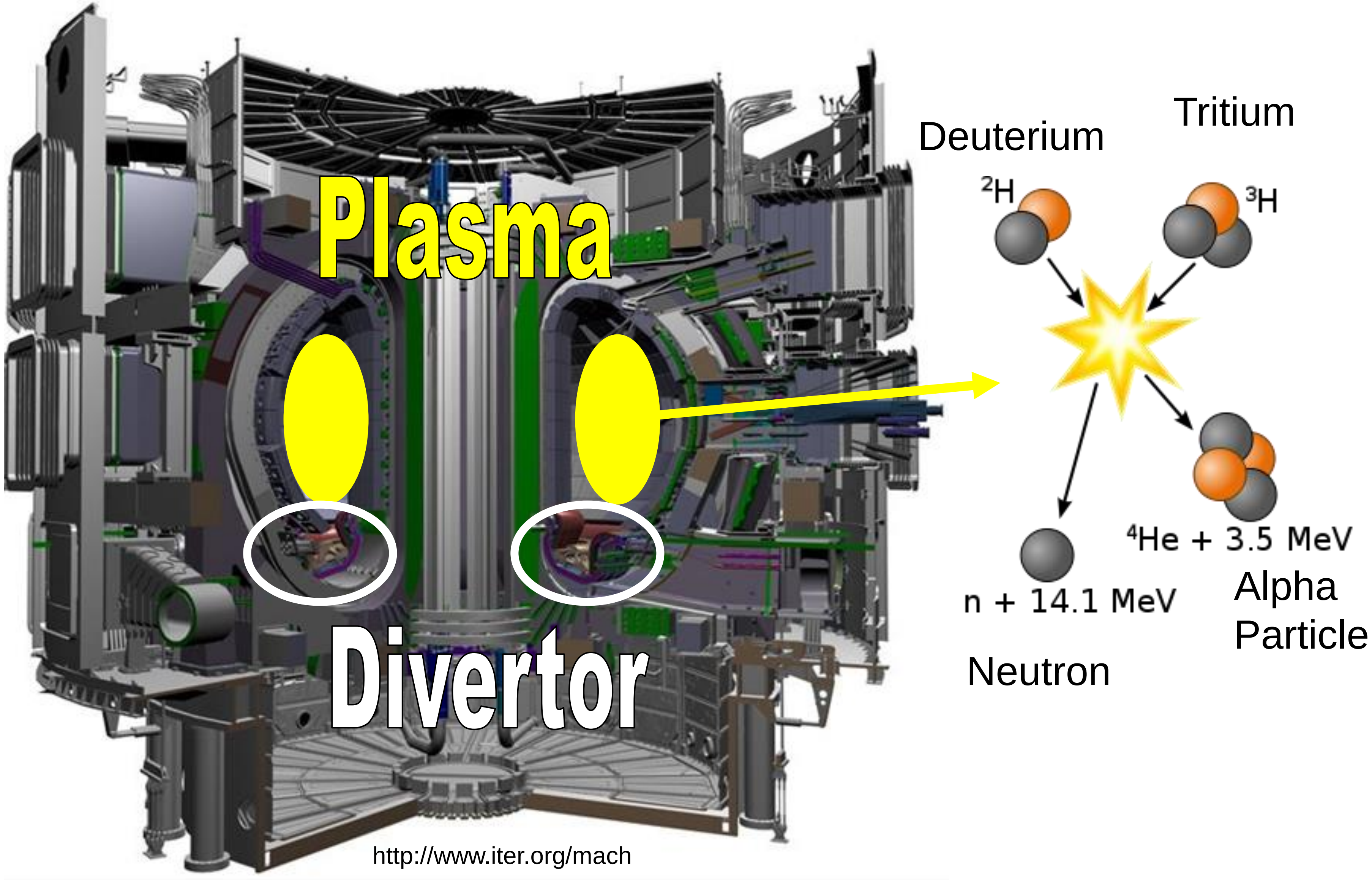
- Thermal properties
  - Thermal conductivity
  - Thermal expansion
- Chemistry/Elemental content
- Mechanical properties
  - Tensile and compression strength
  - Fatigue lifetime
  - Fracture toughness
  - Flexibility
- Manufacturability
- Weldability
- Compatibility with coolants
- And more

What is special about studying materials for fusion reactors?

- Neutrons
- High temperatures
- Exotic coolants
- Gradients of all the conditions (temperature, stress, chemistry, etc.)

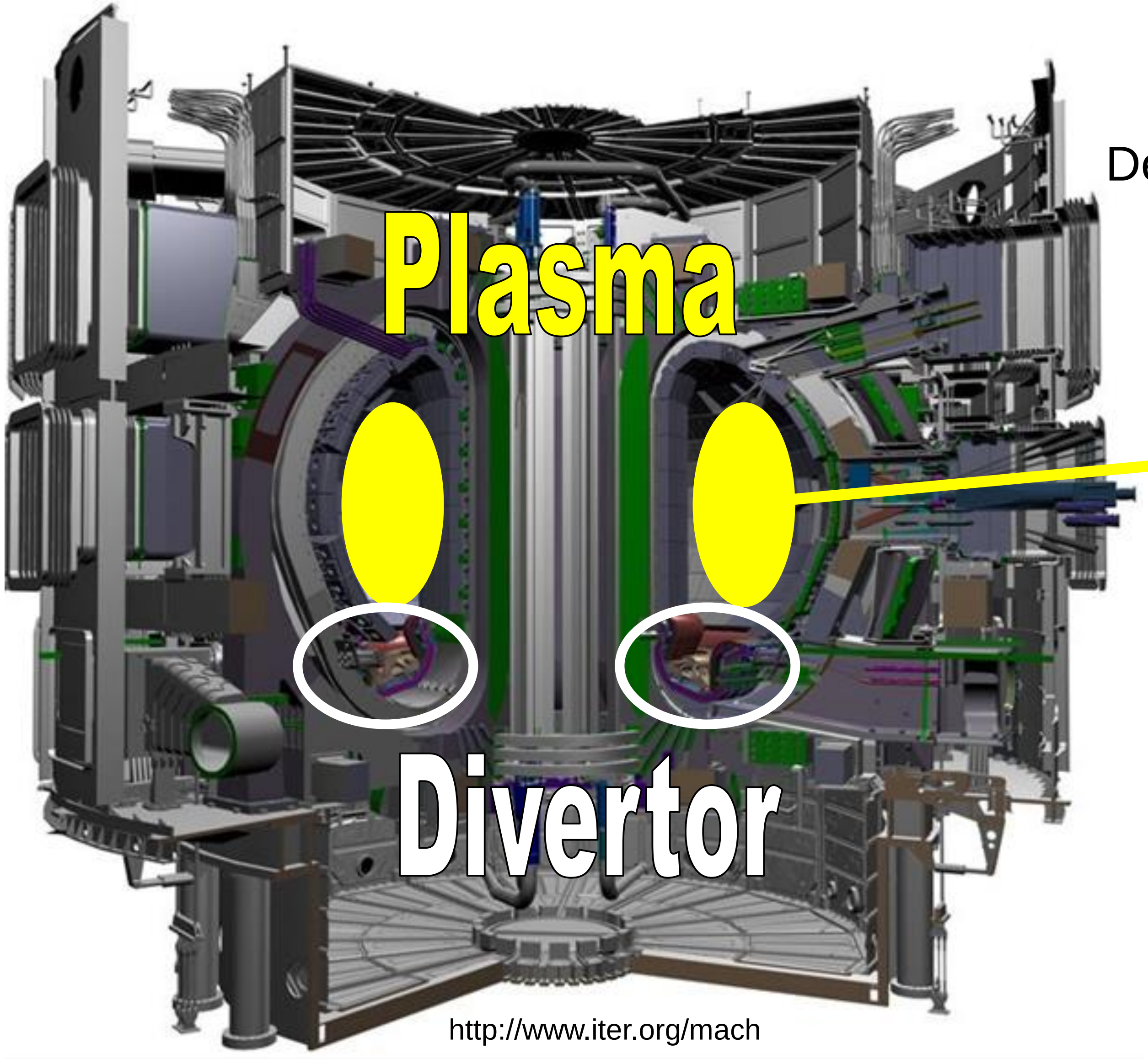
- Neutrons plus high temperatures and exotic coolants and gradients

A Real Reactor is much more complicated than the concept

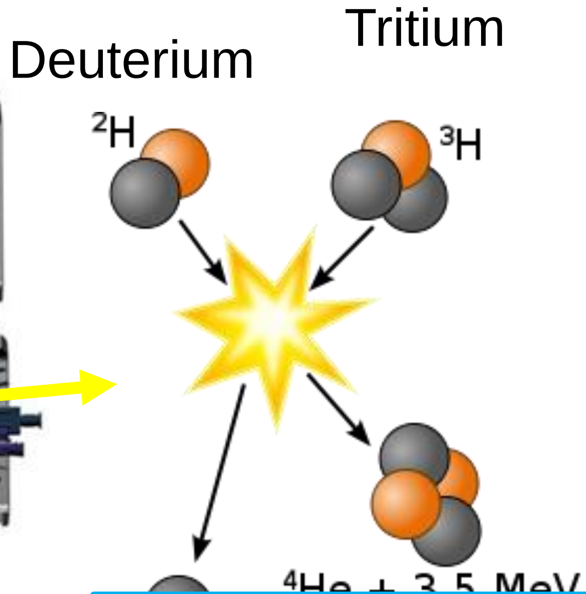


http://www.iter.org/mach

A Real Reactor is much more complicated than the concept



http://www.iter.org/mach



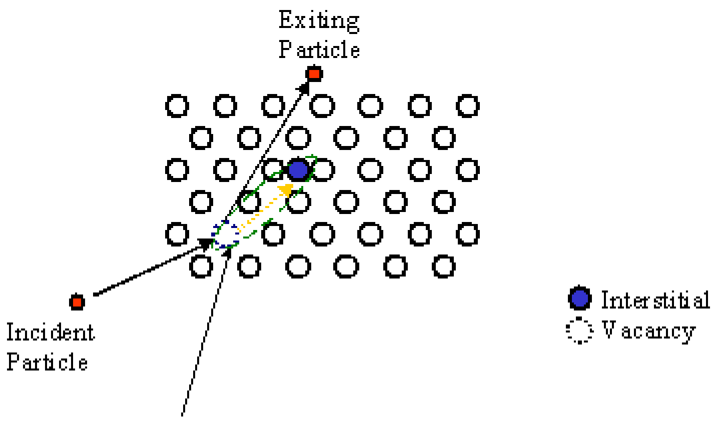
→See Dr. Lasa's presentation for more detail on solid PFMs
→See Dr. Allain's presentation for more detail on liquid PFMs
→See Dr. Kessel's presentation for more information on the complicated structure in the blankets

Effects of neutron damage

- Ballistic damage
- Transmutation

What do neutrons do to materials?

- 1. Ballistic Damage
  - Create individual defects in the lattice



A Frenkel pair consists of a vacancy and an interstitial atom.

http://holbert.faculty.asu.edu/eee560/tiondose.html

- Many of these defects are created very quickly when one neutron enters the material
  - VIDEO: https://www.doitpoms.ac.uk/tlplib/nuclear_materials/damage_mechanism.php
- These can accumulate to form large defects in the material

Overview of Basic Radiation Damage Events

- To calculate energy transferred from incident particle collision assume
  - Binary
  - Elastic
  - Non-Relativistic
- Energy most efficiently transferred between objects of similar mass
- Cross sections for interaction
  - Total scattering
  - Differential Energy Transfer
  - Differential Angular

$$T = \frac{1}{2}\Lambda E_0(1 - \cos\vartheta)$$

$$\Lambda = \frac{4mM}{(m + M)^2}$$

T: Recoil Energy
E_0: Incident Particle Energy
ϑ: Center of mass scattering angle
m: Mass of incident particle
M: Mass of target particle

How do we measure ballistic damage?

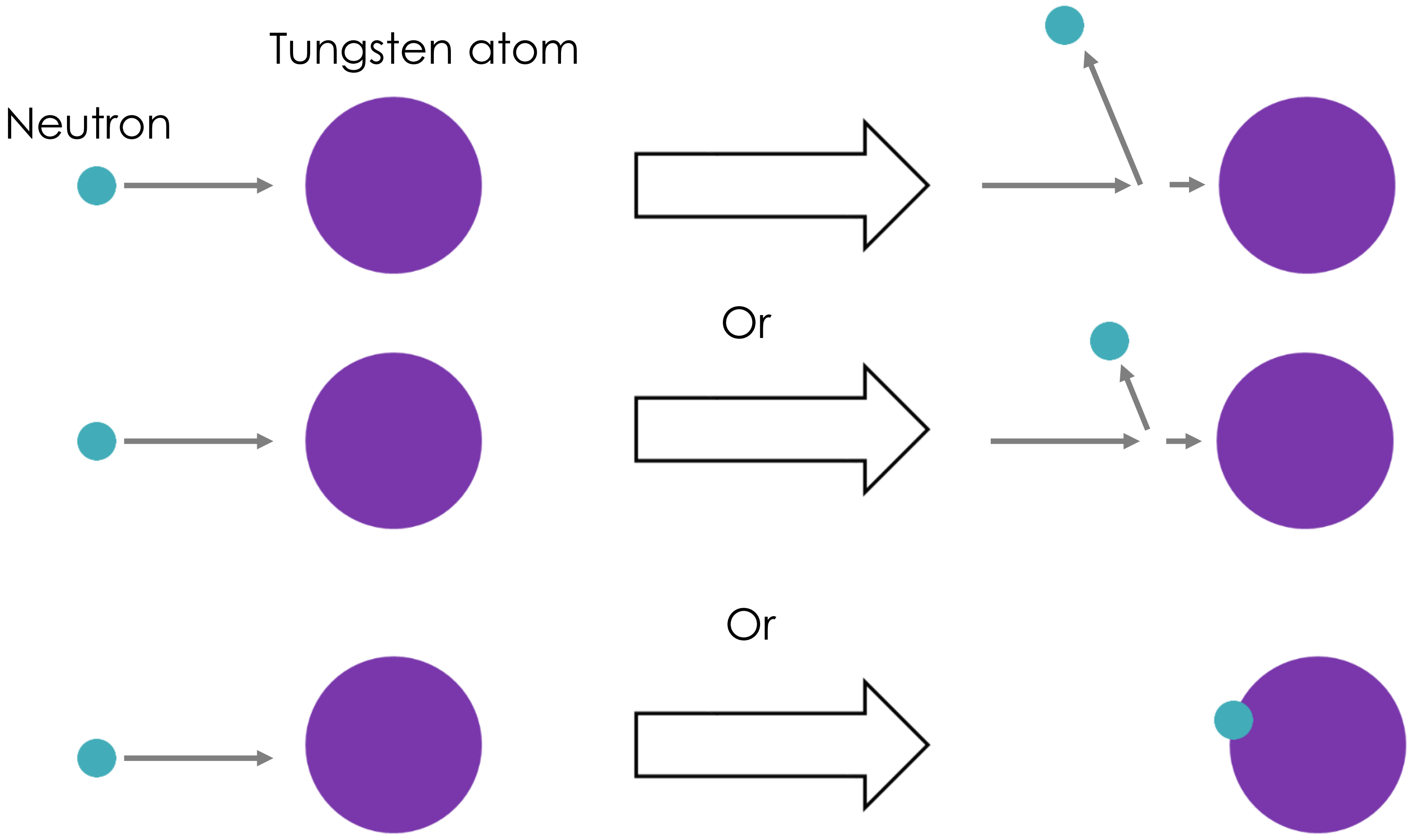
- Displacements per atom (dpa)
  - This is a common way that we discuss how much neutron dose a material has experienced
  - It is a measure of how many times each atom was removed from its lattice site during a period of neutron exposure

What do neutrons do to materials?

- 2. Transmutation
  - Neutrons have a probability to be captured by the nucleus of an atom
  - If that addition of a neutron makes the atom unstable, it has a probability to transmute, which means decaying to a new element

Opus Medico-Chymicum (The medical-chemical work), Johann Mylius, 1618. From https://www.nlm.nih.gov/exhibition/sciencemagicmedicine/exhibition1.html#!

Neutron interactions with matter



Elastic collision=Bounces off and kinetic energy conserved, tungsten may be displaced from it's lattice (dpa)

Inelastic collision=Bounces off but some kinetic energy converted to another form, tungsten may be displaced from it's lattice (dpa)

Absorption/capture= Neutron is incorporated into the nucleus

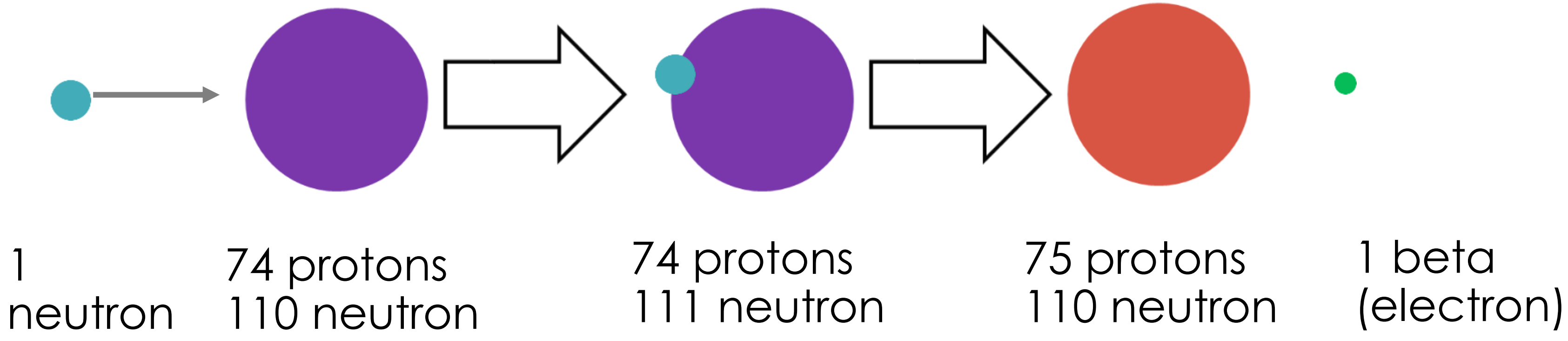
Transmutation-Tungsten

Stable Isotopes of Tungsten

Isotope	abun-dance
^{180}W	0.12%
^{182}W	26.50%
^{183}W	14.31%
^{184}W	30.64%
^{186}W	28.43%

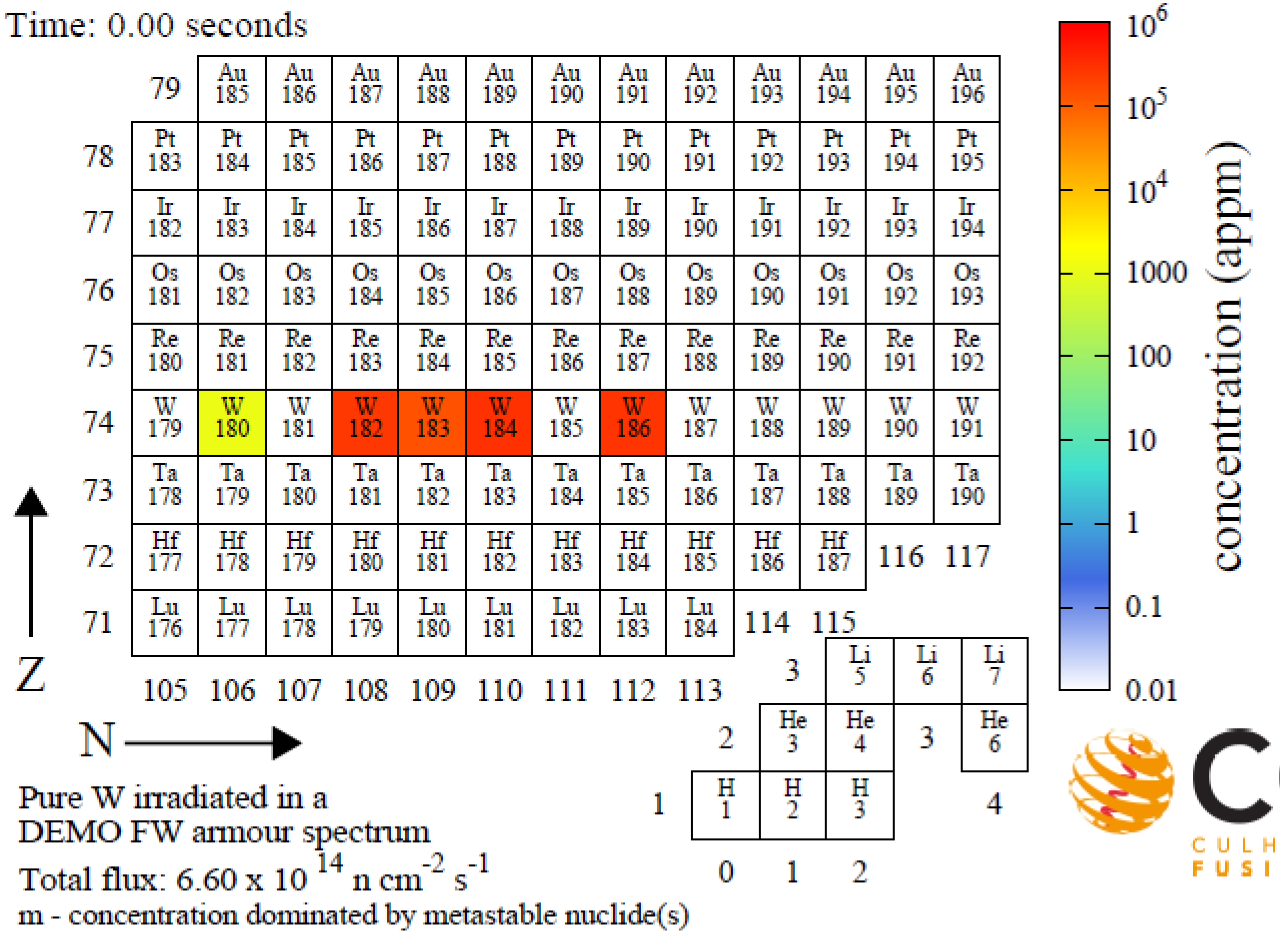
Radioactive isotope of tungsten with 75.1 day half life

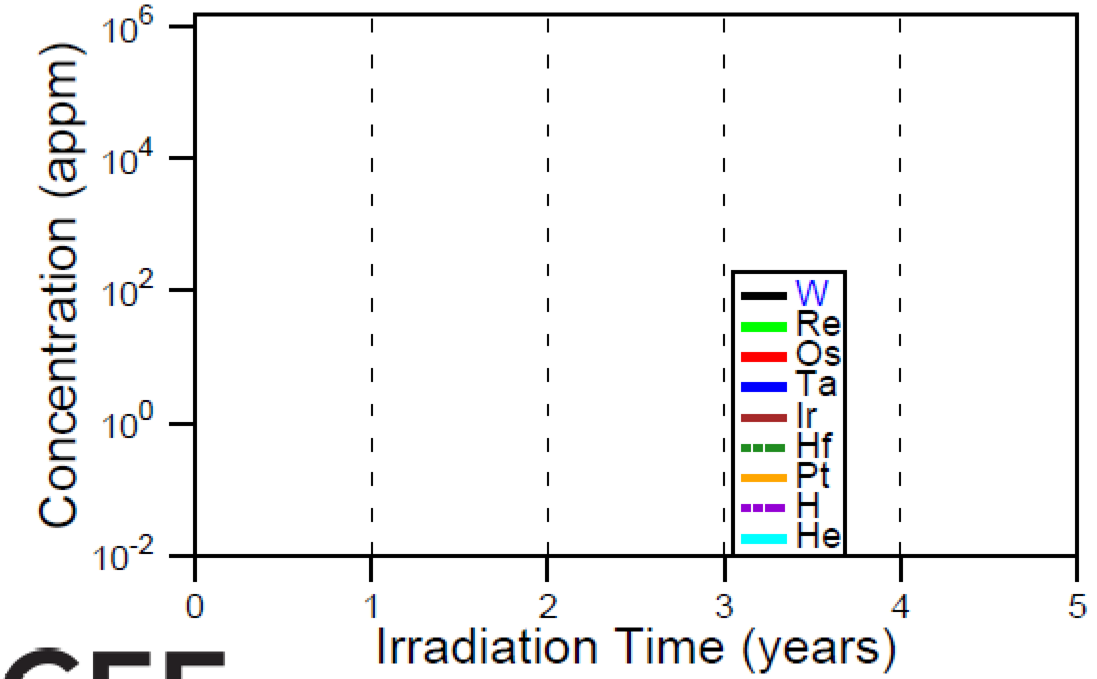
$$n + {}^{184}W \rightarrow {}^{185}W \rightarrow {}^{185}Re + \beta$$



This has higher probability to happen when the neutron is low energy

Video of transmutation-starting condition contains stable isotopes of tungsten

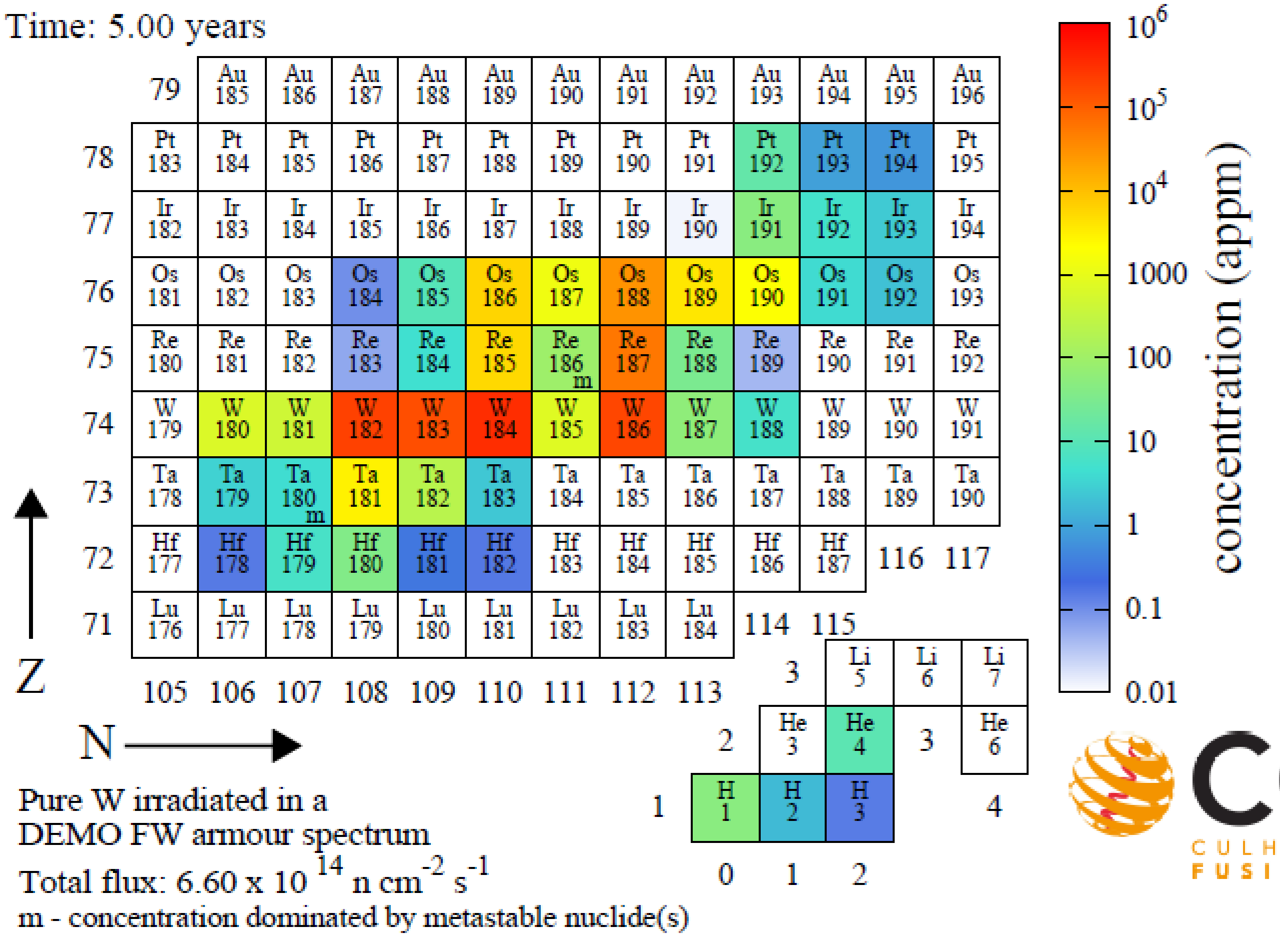


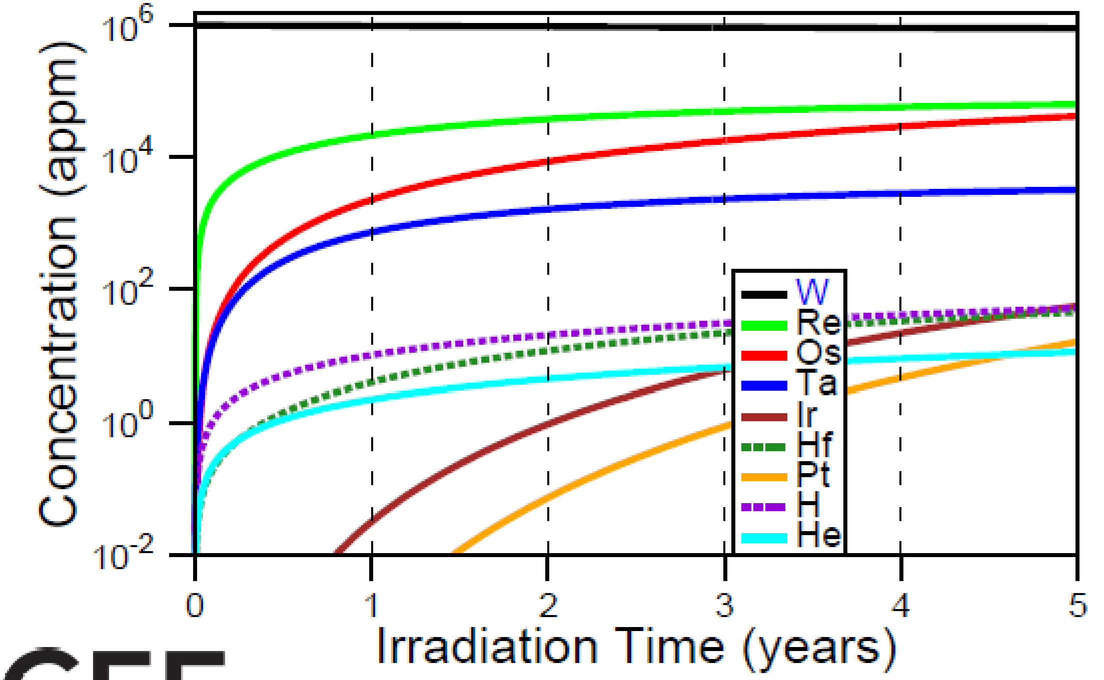


M. R. Gilbert et al., *Nucl. Sci. Eng* (2014)

M.R. Gilbert et al., *Nucl. Fusion* **51** (2011) 043005 & **52** (2012) 083019

Video of transmutation-After 5 years irradiation, we have many different elements in our "tungsten"





CCFE CULHAM CENTRE FOR FUSION ENERGY

M. R. Gilbert et al., *Nucl. Sci. Eng* (2014)
M.R. Gilbert et al., *Nucl. Fusion* **51** (2011) 043005 & **52** (2012) 083019

Transmutation-Iron

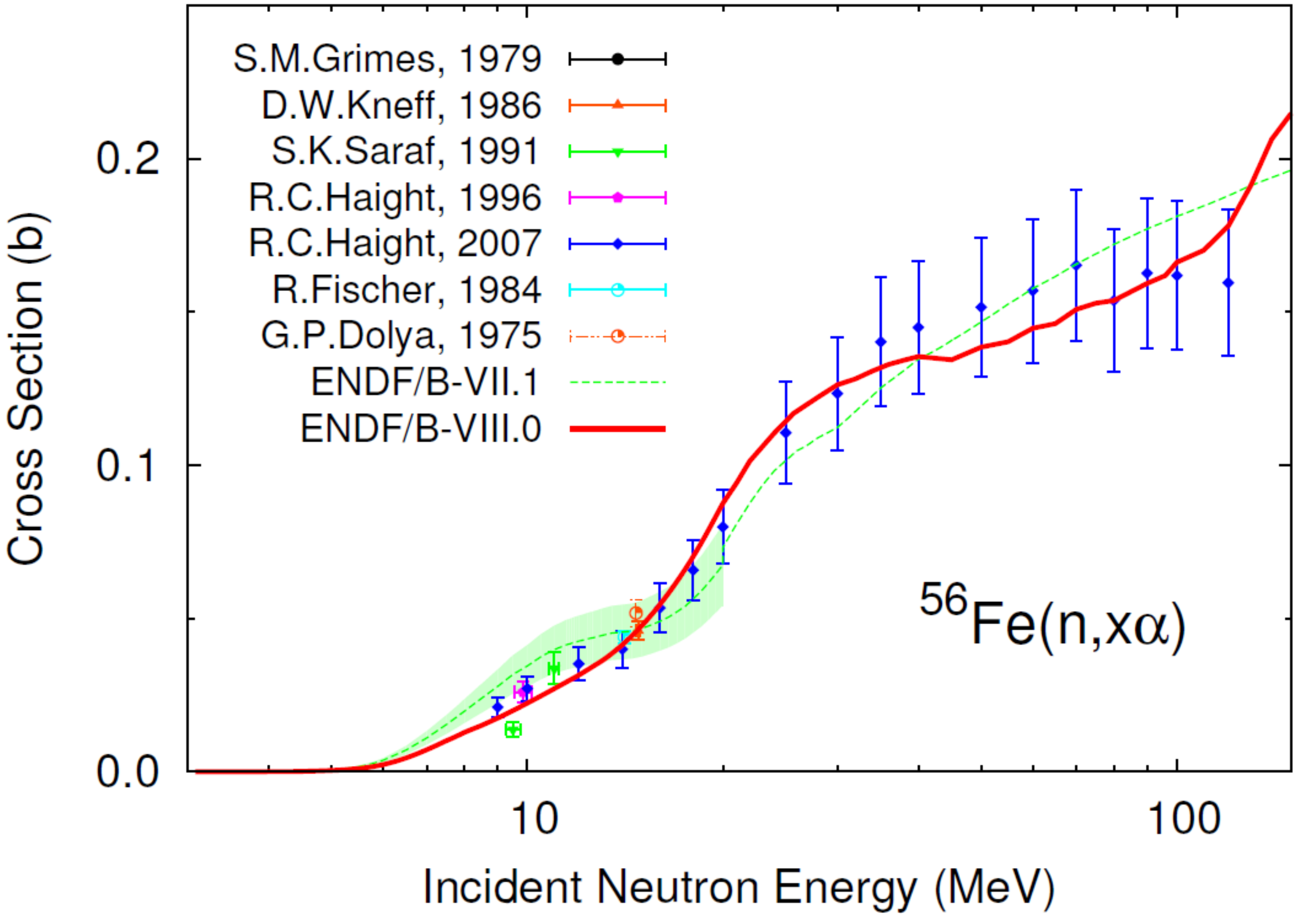
$n + {}^{56}Fe \rightarrow {}^{57}Fe \rightarrow {}^{53}Cr + \alpha$

Alpha= helium nucleus

As iron is exposed to neutrons, helium gas is created throughout the material.

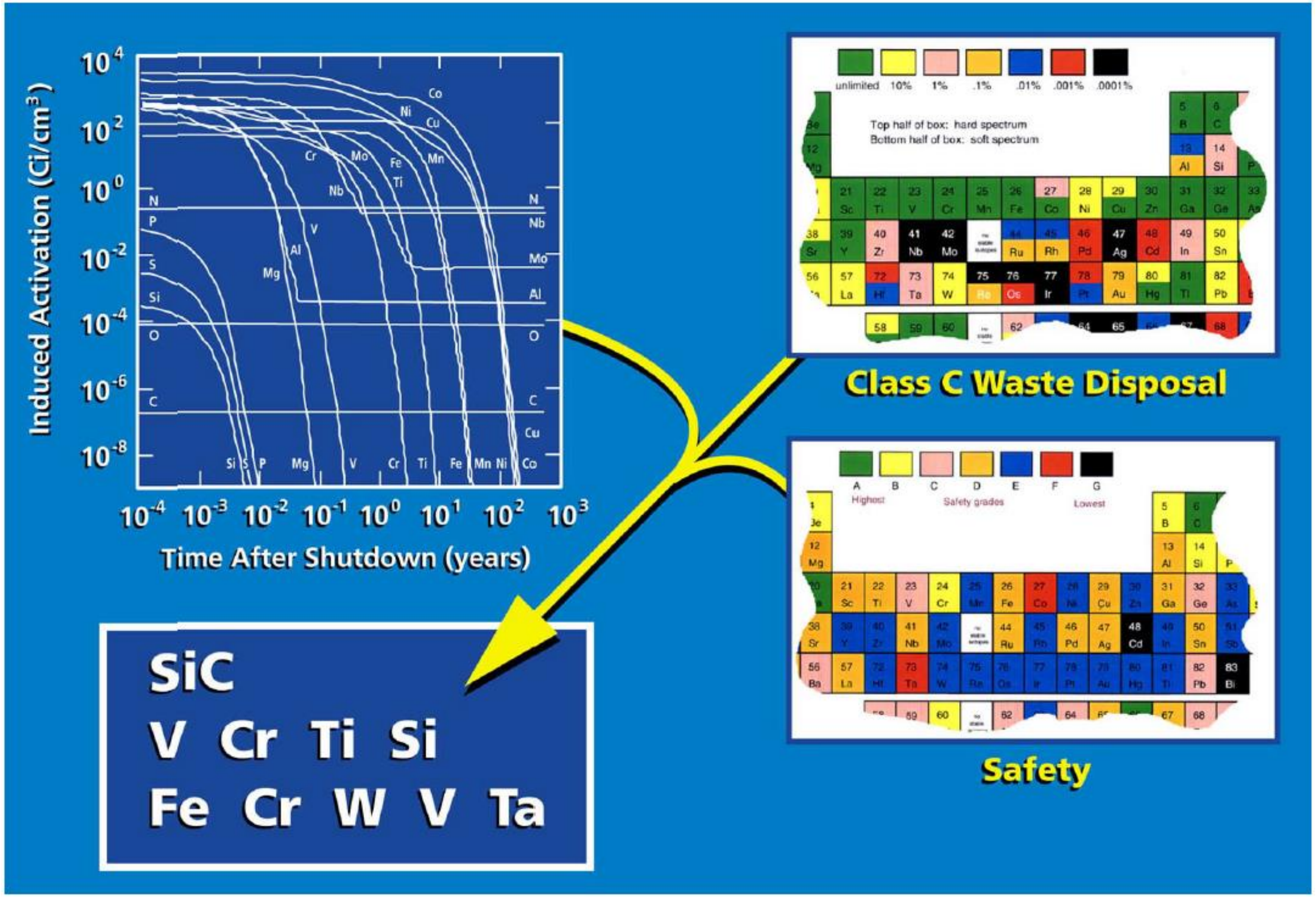
The higher the energy neutrons, the more likely the helium production.

We have to design iron based materials (i.e. steels) to keep their mechanical integrity when they start filling up with gas.



Herman et al. Nuclear Data Sheets 148 (2018) 214-253

Transmutation limits the elements we can use in fusion structural materials because of material properties and safety



Steve Zinkle. FUSION SCIENCE AND TECHNOLOGY VOL. 64 AUG. 2013

Overall Radiation Effects

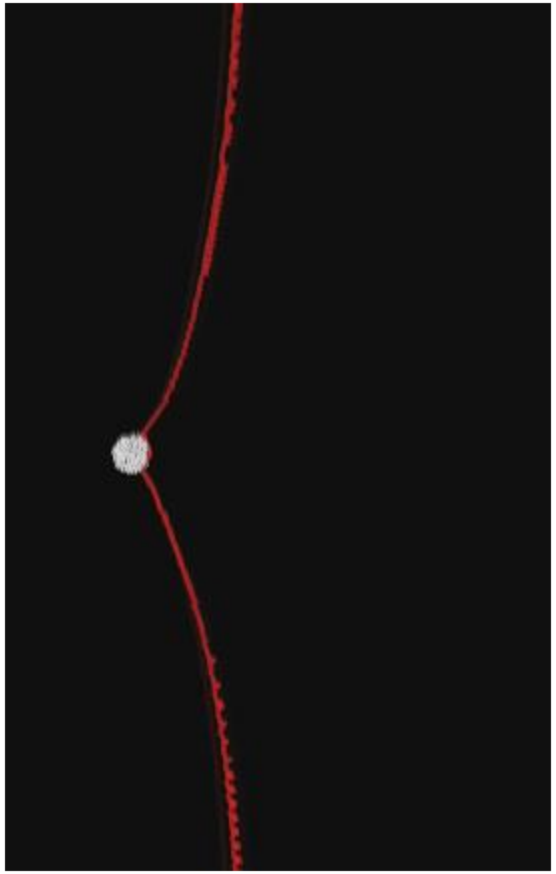
Neutron damage changes almost all materials properties.

- Thermal properties
  - Thermal conductivity
  - Thermal expansion
- Physical properties
  - Swelling
  - Thermal creep
  - Irradiation creep
- Mechanical properties
  - Tensile, compressive
  - Fracture toughness
  - Hardness

- Microstructural information
  - Precipitate
  - Void
  - Bubble
  - Grain sizes
- Elemental information
  - Transmutation elements
  - He appm
  - Segregation
  - Precipitate composition
  - Phase
- And more

Closer look: How does radiation damage change tensile properties of a material?

- Radiation induced defects such as voids, precipitates and other defect clusters pin down dislocations and prevent them from moving
- This decreases the ductility of the material
- Increases the stress required to push dislocation past an obstacle



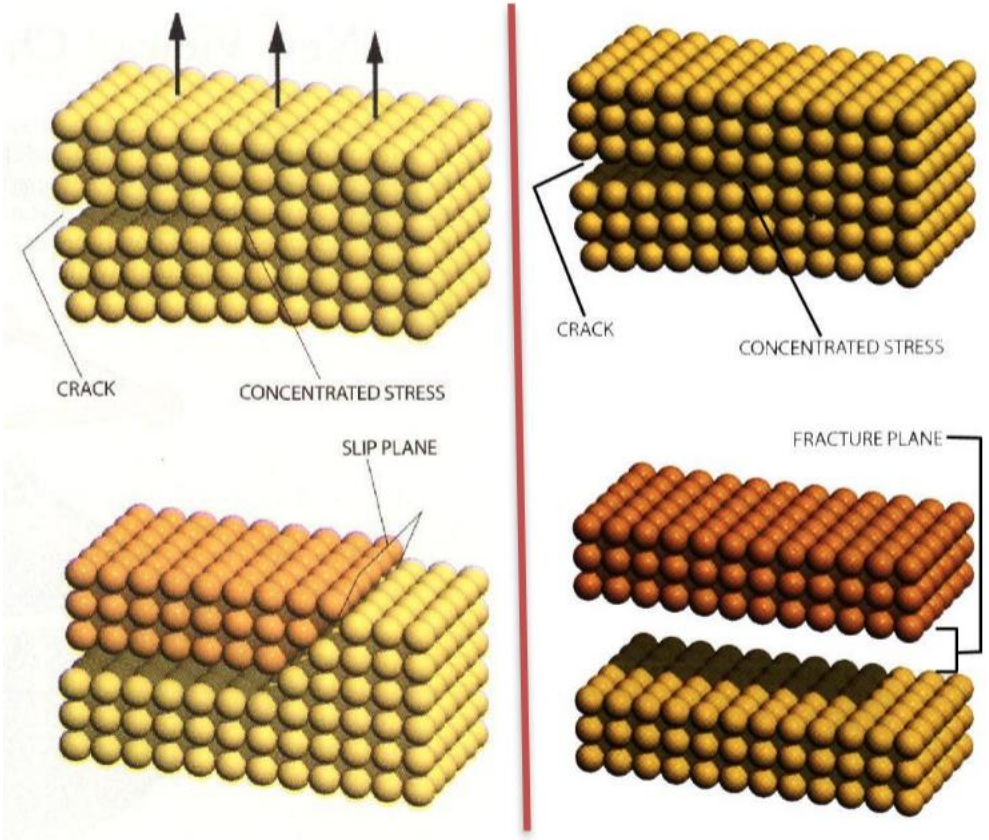
Interaction between an edge dislocation and a void in iron.

Movie 12-6 from Was “Fundamentals of Radiation Materials Science” http://www-personal.umich.edu/~gsw/movies.html

Closer look: How does radiation damage change tensile properties of a material?

- When dislocations can't move, they pile up at obstacles causing stress concentrations and allowing cracks to propagate through the material

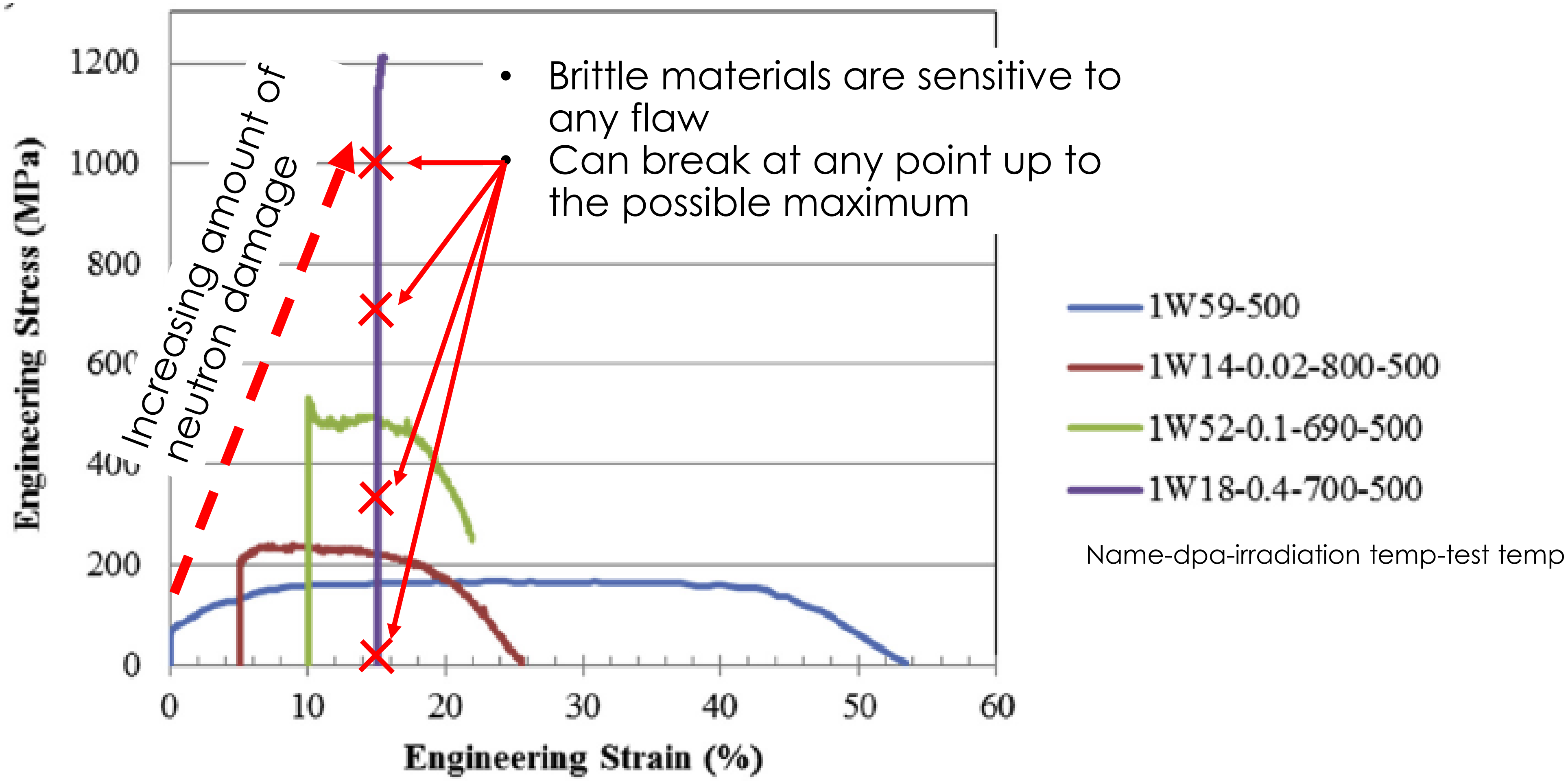
→ Brittle fracture



Example: Neutron irradiated tungsten tensile properties

Single crystal <110> tungsten, tensile tested at 500C and different neutron doses

- Brittle materials are sensitive to any flaw
- Can break at any point up to the possible maximum



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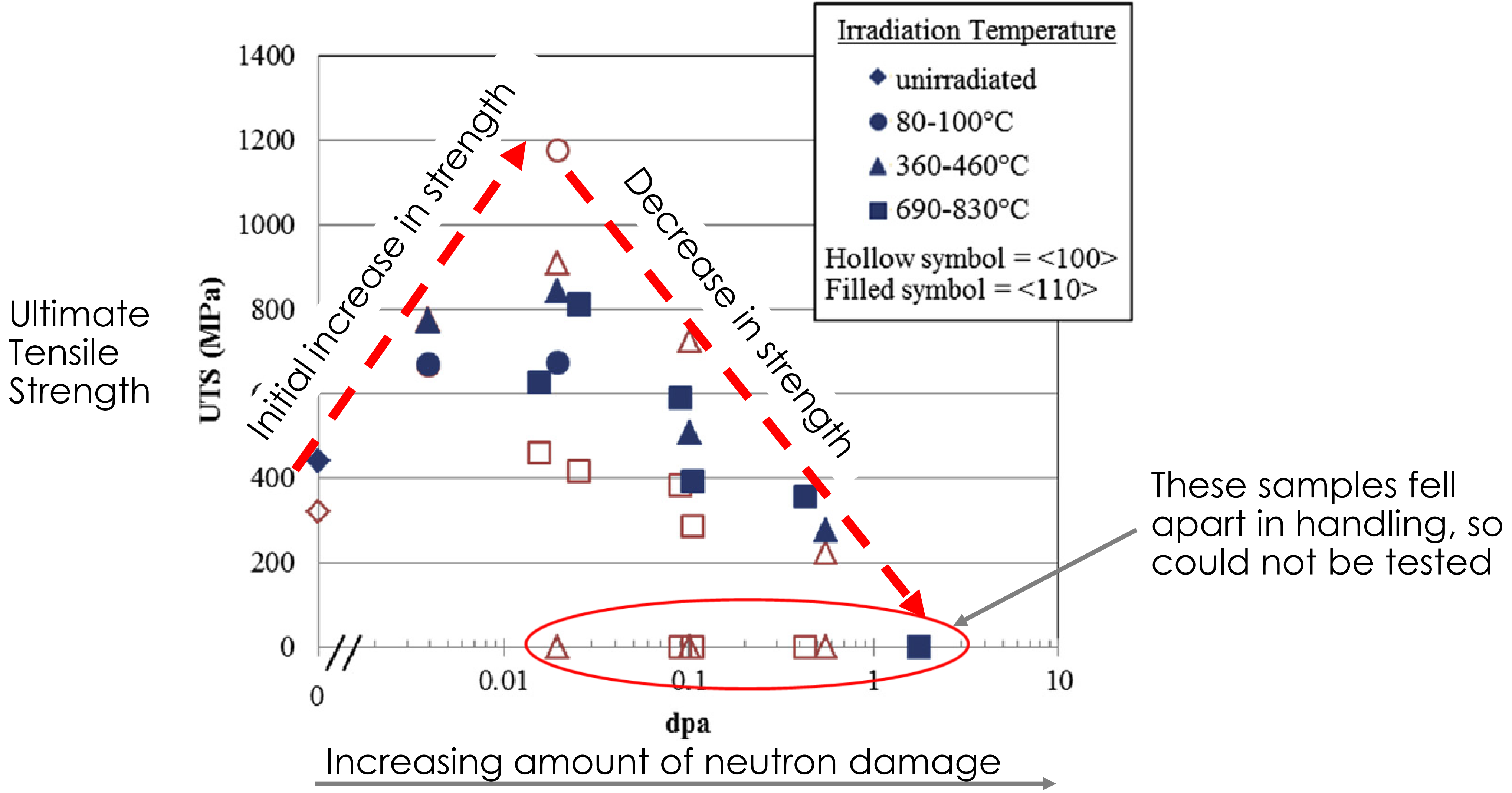
Example: Neutron irradiated tungsten tensile properties



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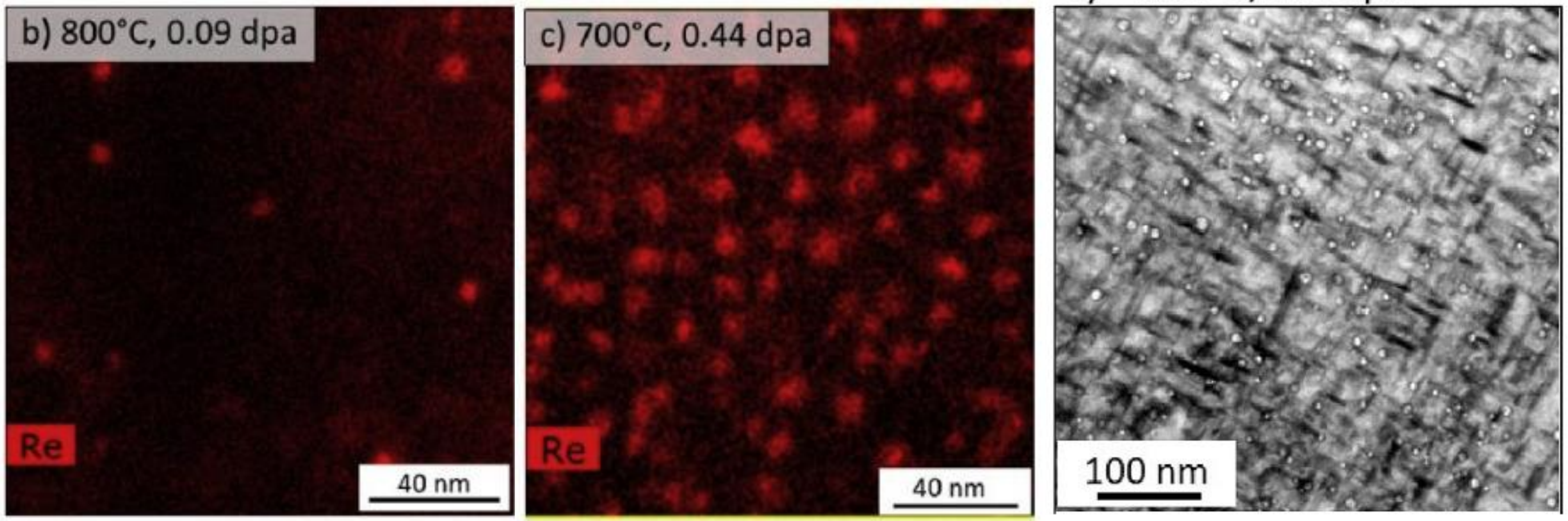
What happens at the atomic level that causes these bad mechanical properties?

Increasing amount of neutron damage

Start with pure, single crystal tungsten. No Rhenium

f) ~800°C, 1.5 dpa



Transmuted Re starts to gather

Transmuted Re are in clusters

Many needle-shaped precipitates of Re (and Os) and voids are seen throughout. This sample broke in handling.

STEM/EDS images, black is W, red is Re

TEM image, dark black dashes are precipitates, white round circles are void

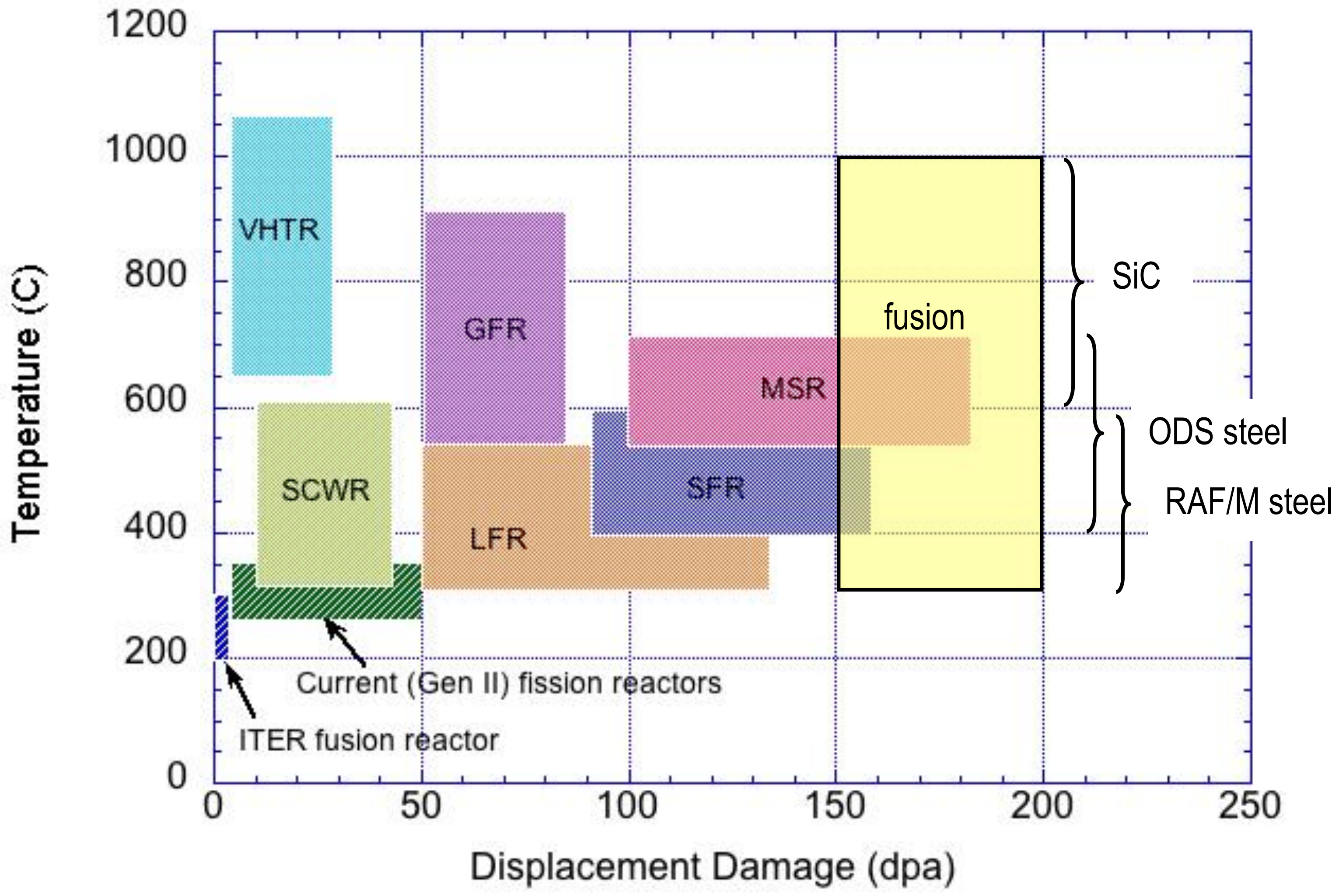
→Ask me in the hallway why the Re forms clusters

OAK RIDGE National Laboratory

Y. Katoh et al. / Journal of Nuclear Materials 520 (2019) 193–207

Why can't we use materials from fission reactors for fusion reactors?

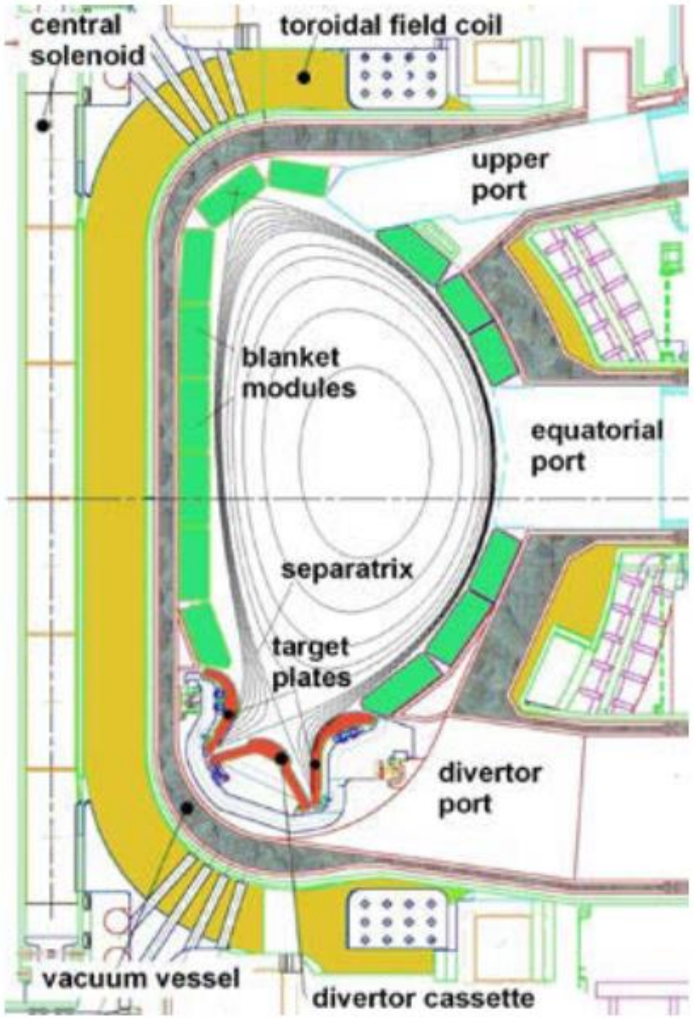
- Compared to fission reactors, fusion reactors will have
  - higher operating temperatures
  - higher neutron damage
  - Much more He transmutation (~1500 appm versus <10 appm)
  - Different coolants (Pb-Li or He versus water)



S.J. Zinkle ,OECD NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007

Neutrons everywhere!

- Remember, neutrons are going to interact with almost every material in the fusion device.
- The specific transmutation and material properties changes is going to be different for every material.
  - Structural materials
  - Plasma-facing materials
  - Superconducting magnet materials
  - Breeder blanket materials
  - Diagnostic and sensing materials



Samm, U., *Plasma-wall interaction in magnetically confined fusion plasmas.* Fusion Science and Technology, 2012. **61**(2T): p. 193-198

Tokamak pictured here, but any fusion system that uses the D-T reaction, will produce neutrons and have to consider this.

Greeting cards Material Scientists send to Reactor Designers

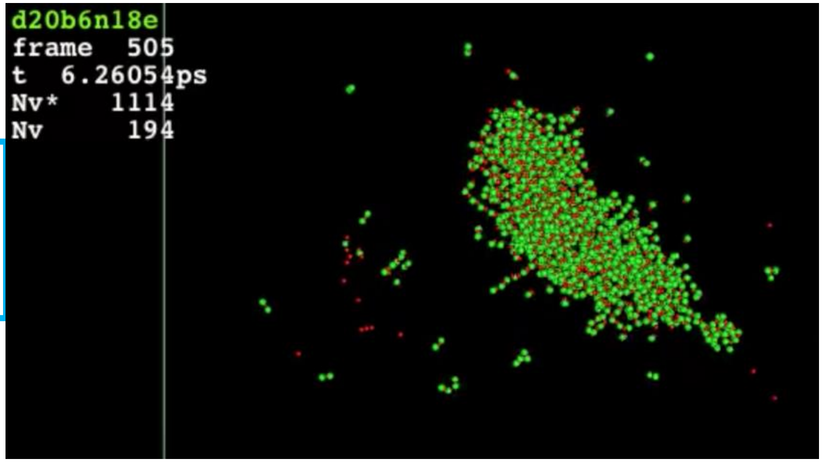
F minus comics by Tony Carrillo

How can we design materials for fusion reactors?

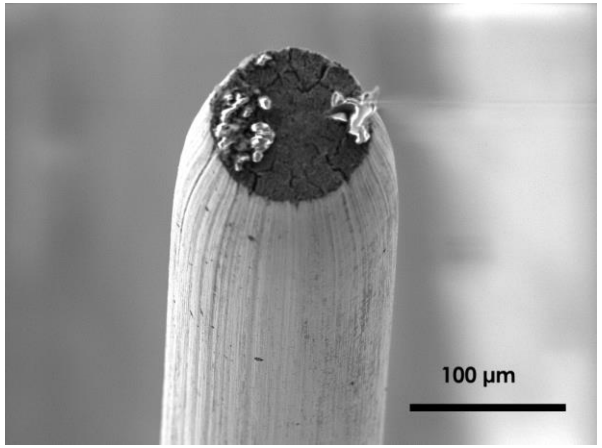
How are we solving the challenges of materials for fusion reactors?

Composites

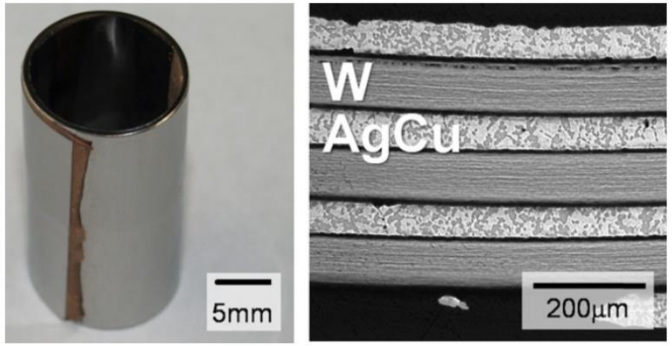
Theory and modeling of materials



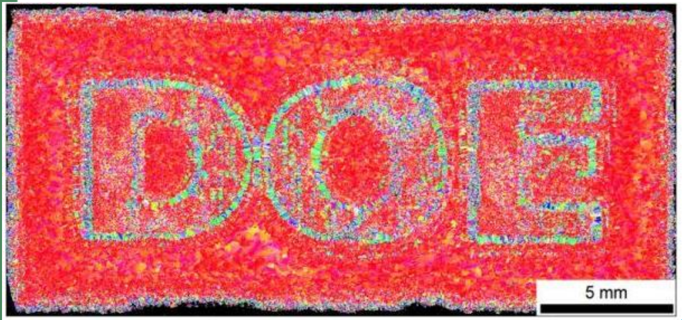
Andy Calder https://www.youtube.com/watch?v=0btHd_8JFV4



Garrison TMS 2020

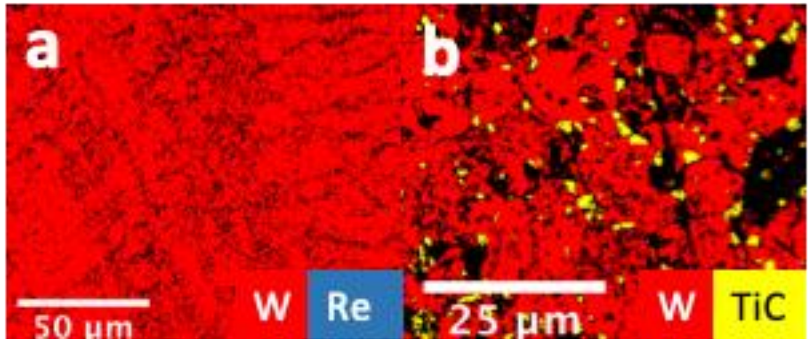


J. Reiser, M. Rieth, B. Dafferner, A. Hoffmann, J. Nucl. Mater., 423 (2012) 1-8



Additive manufacturing
Texture tailoring
Grain Boundary engineering

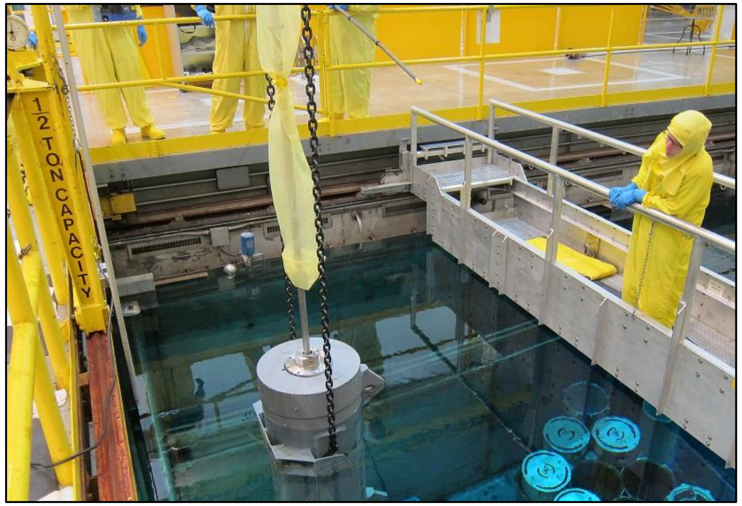
https://www.architectmagazine.com/technology/oak-ridge-national-laboratory-refines-metal-3d-printing_o



New alloys

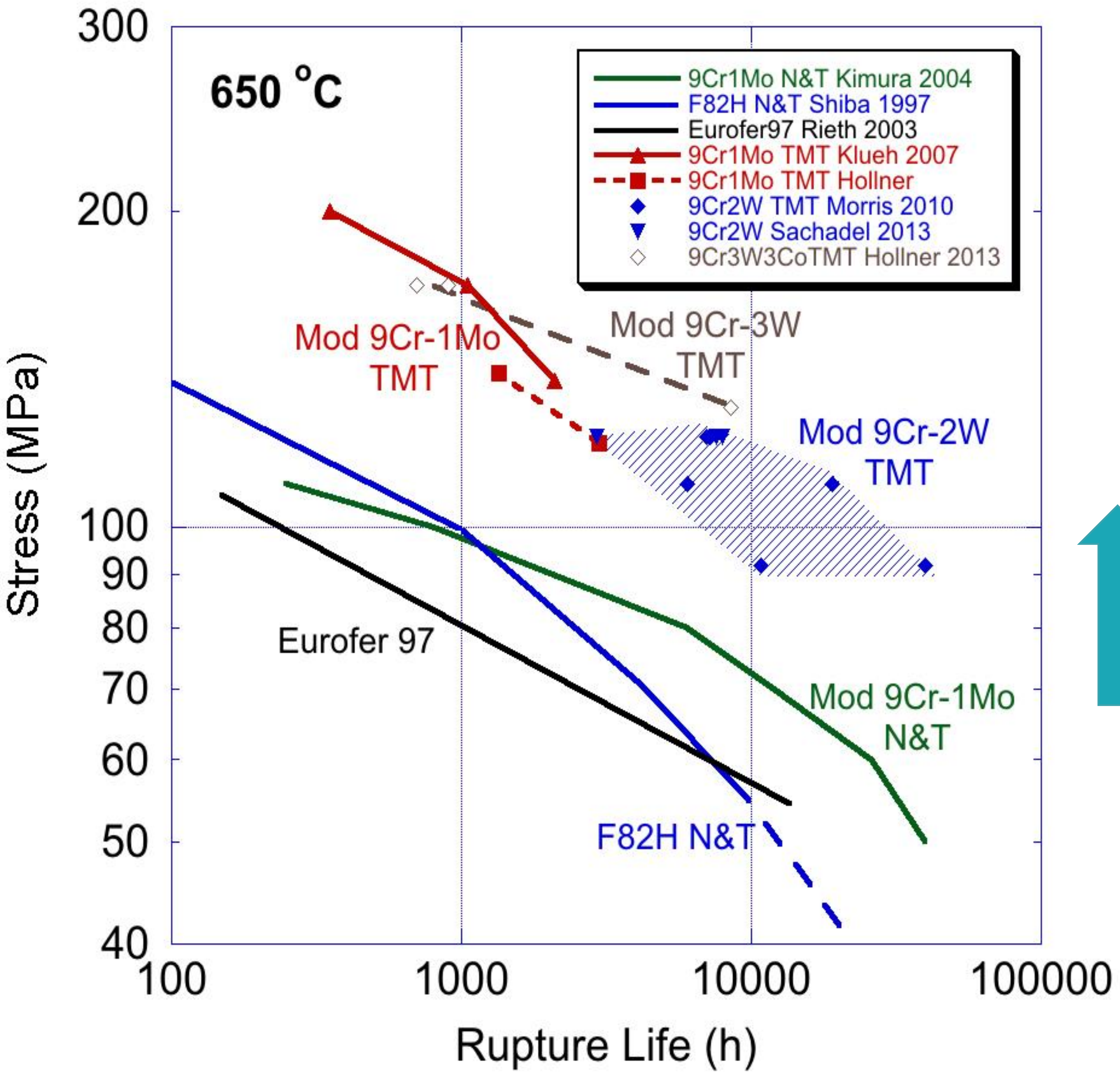
Particle additions

Lang. Fusion Science and Technology 75 (2019) 533-541



Testing under extreme conditions

Example: We Can Design Better Materials Using Modern Tools



50-100% improvement in creep rupture strength for newly designed reduced activation steels

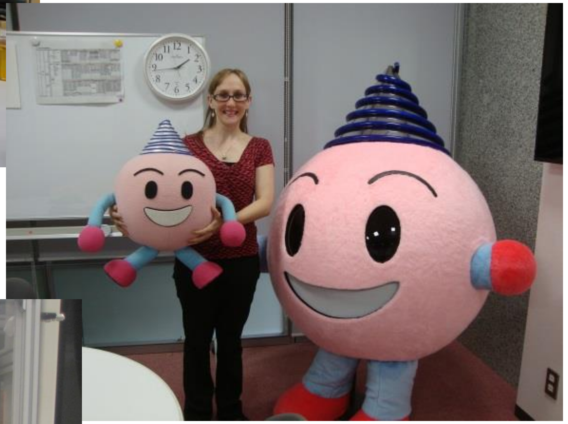
S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005

Being a Nuclear Materials Scientist is Awesome!

Conferences!

Travel!

Collaborating with scientists all around the world!

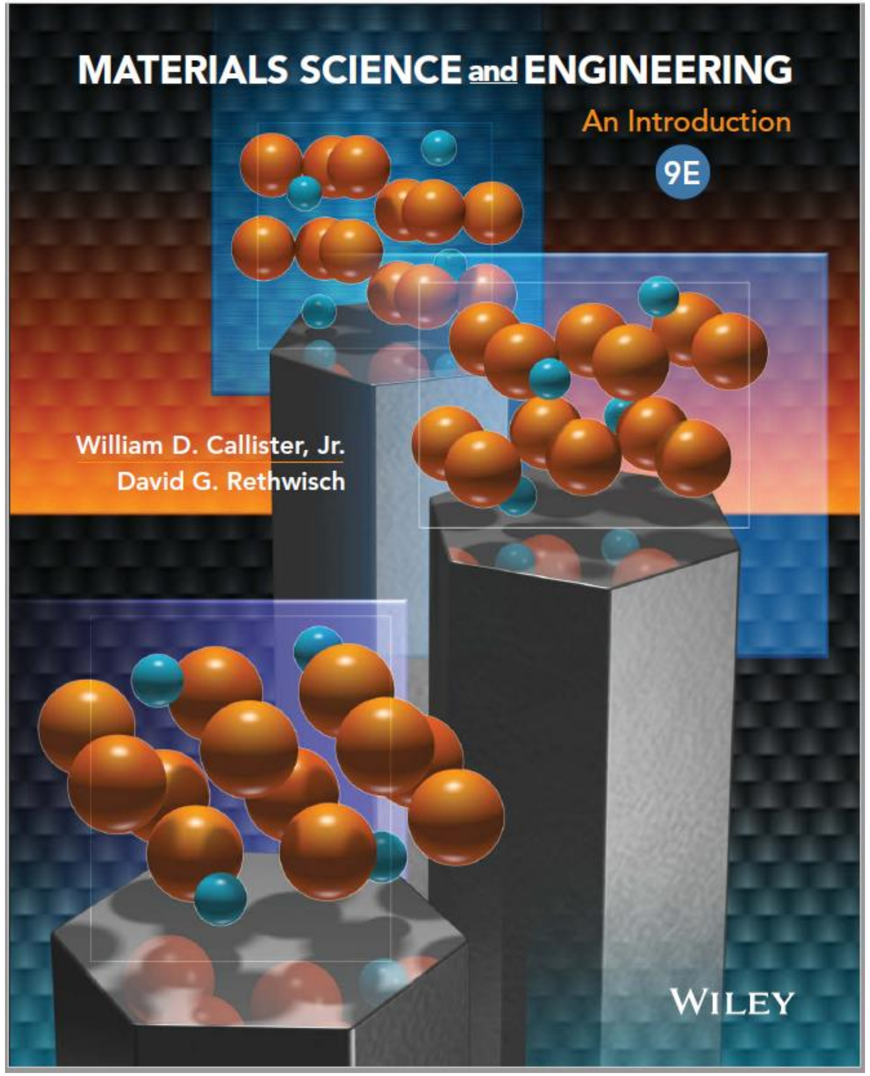


Meeting Mr. Plasma at NIFS in Japan!

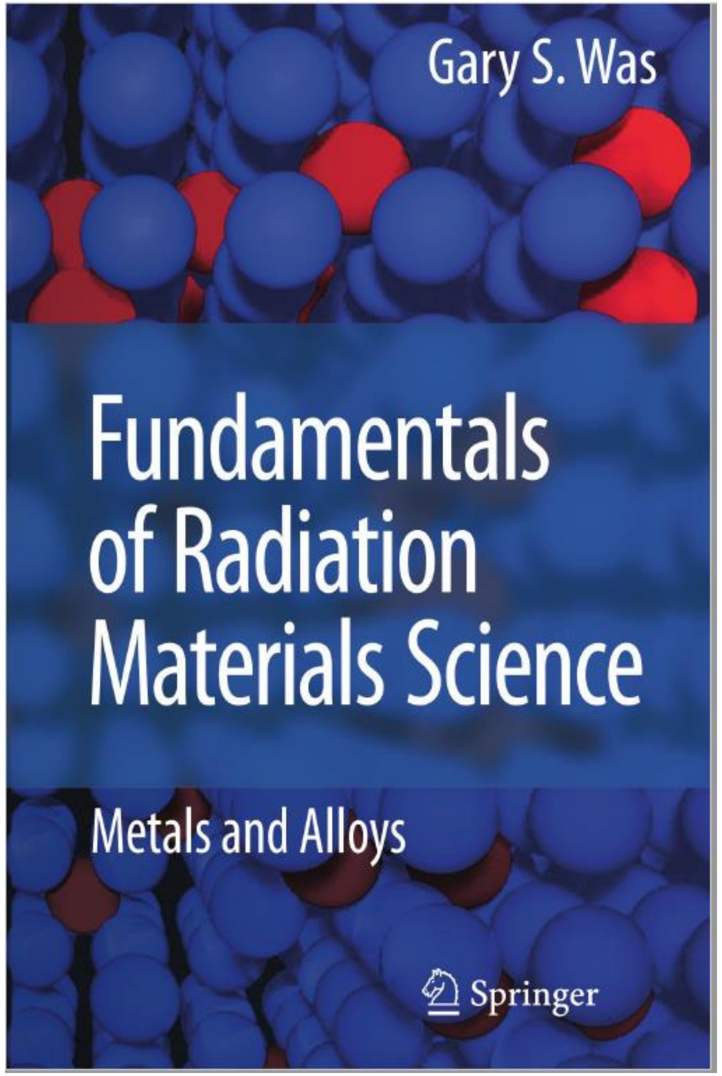
Mentoring students!

Solving really challenging problems to make fusion energy a reality!

Further Reading



A good introduction to materials science topics



The textbook for radiation damage in materials

Questions?

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