OAK RIDGE National Laboratory

June 8, 2026

Let's get cozy with some blankets!

PRESENTED BY

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R&D Blanket Engineer

Oak Ridge National Laboratory

U.S. DEPARTMENT OF ENERGY

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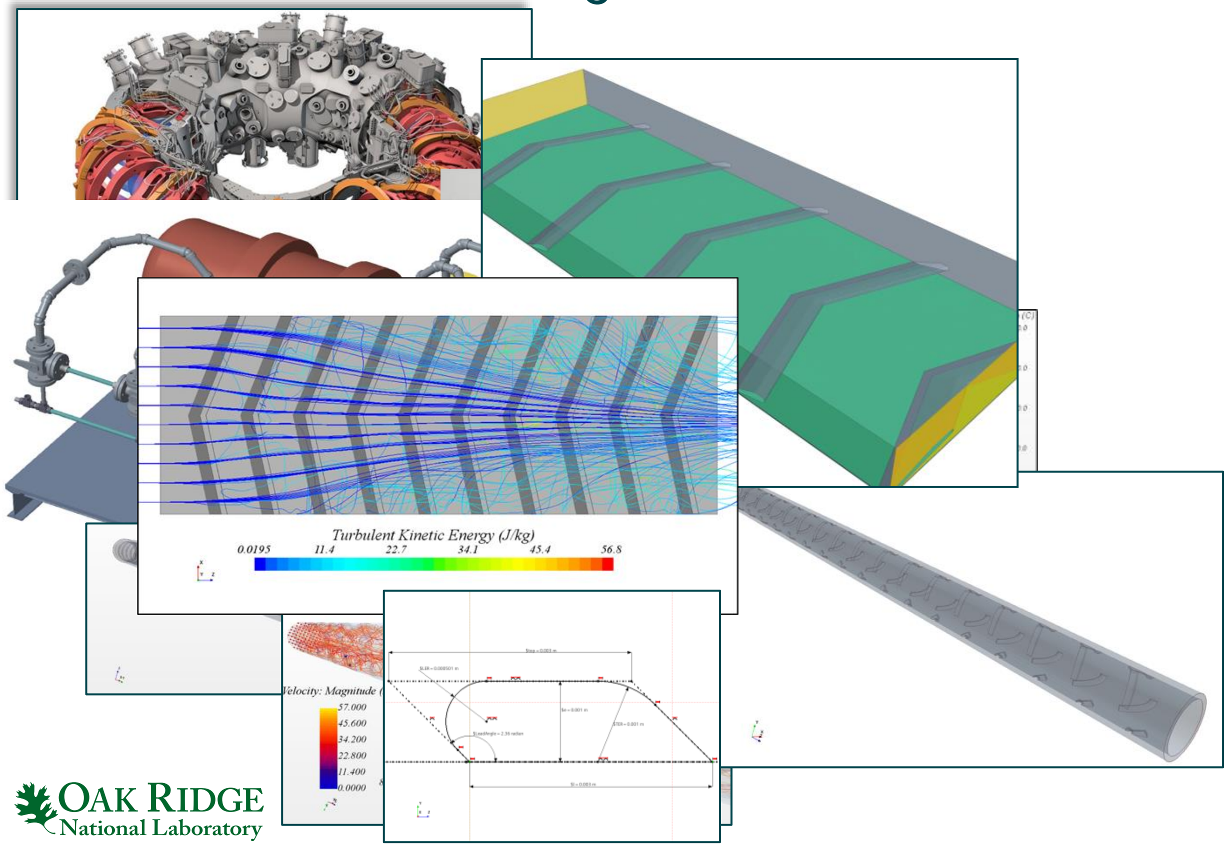
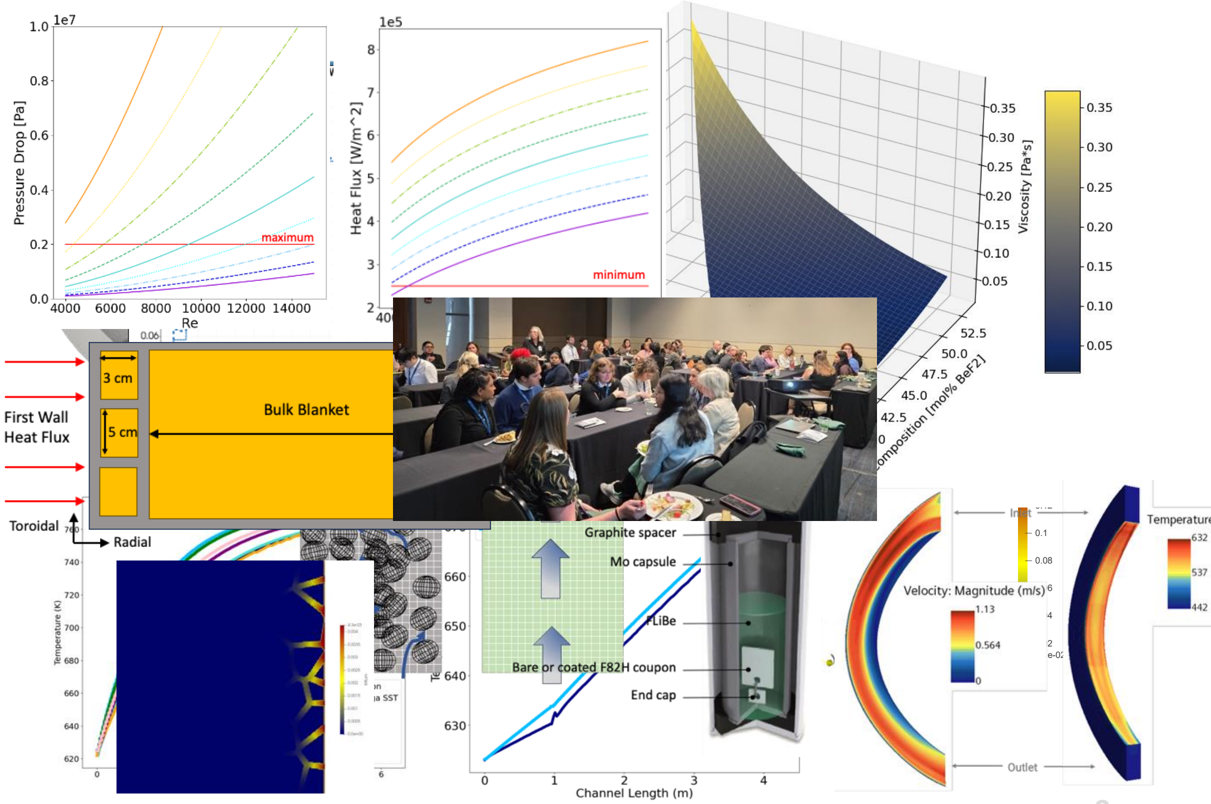
Introductions…

- BS in Nuclear Engineering Missouri S&T (2013 – 2017)
- PhD in Nuclear Engineering Missouri S&T (2017 – 2022), advised by Dr. Gary Mueller and Dr. Joshua Schlegel
- DOE Fusion Energy Sciences Postdoctoral Participant (2022 – 2023), mentored by Dr. Paul Humrickhouse
- R&D Blanket Engineer (2023 – Present)

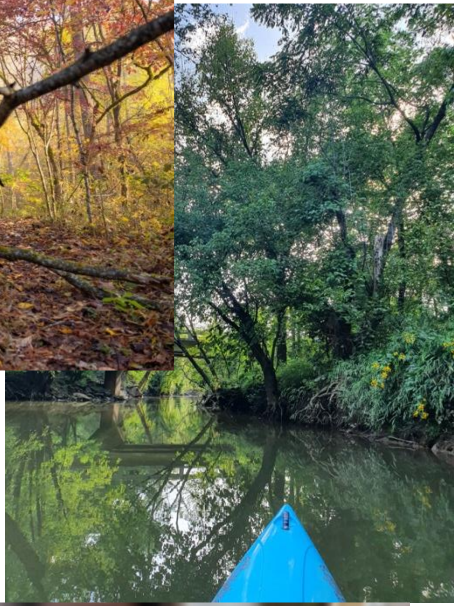




Monica, the Human Being

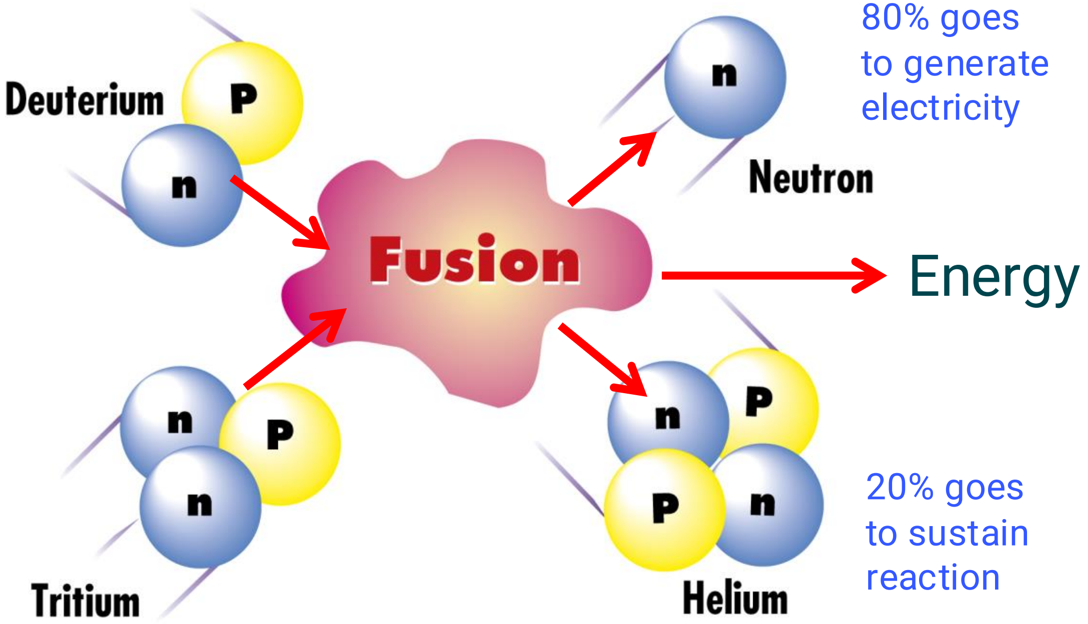







Fusion – The Basics

In a fusion reaction, two hydrogen-like nuclei fuse to produce helium …Releasing large amounts of energy

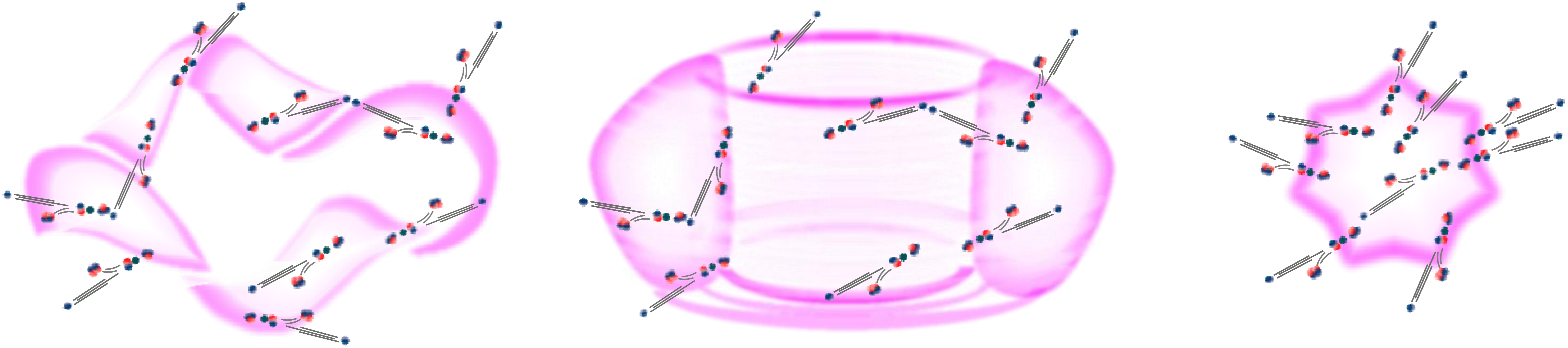


80% goes to generate electricity

20% goes to sustain reaction

Fusion as an energy source

D+T → He (3.5 MeV) + n (14.1 MeV)

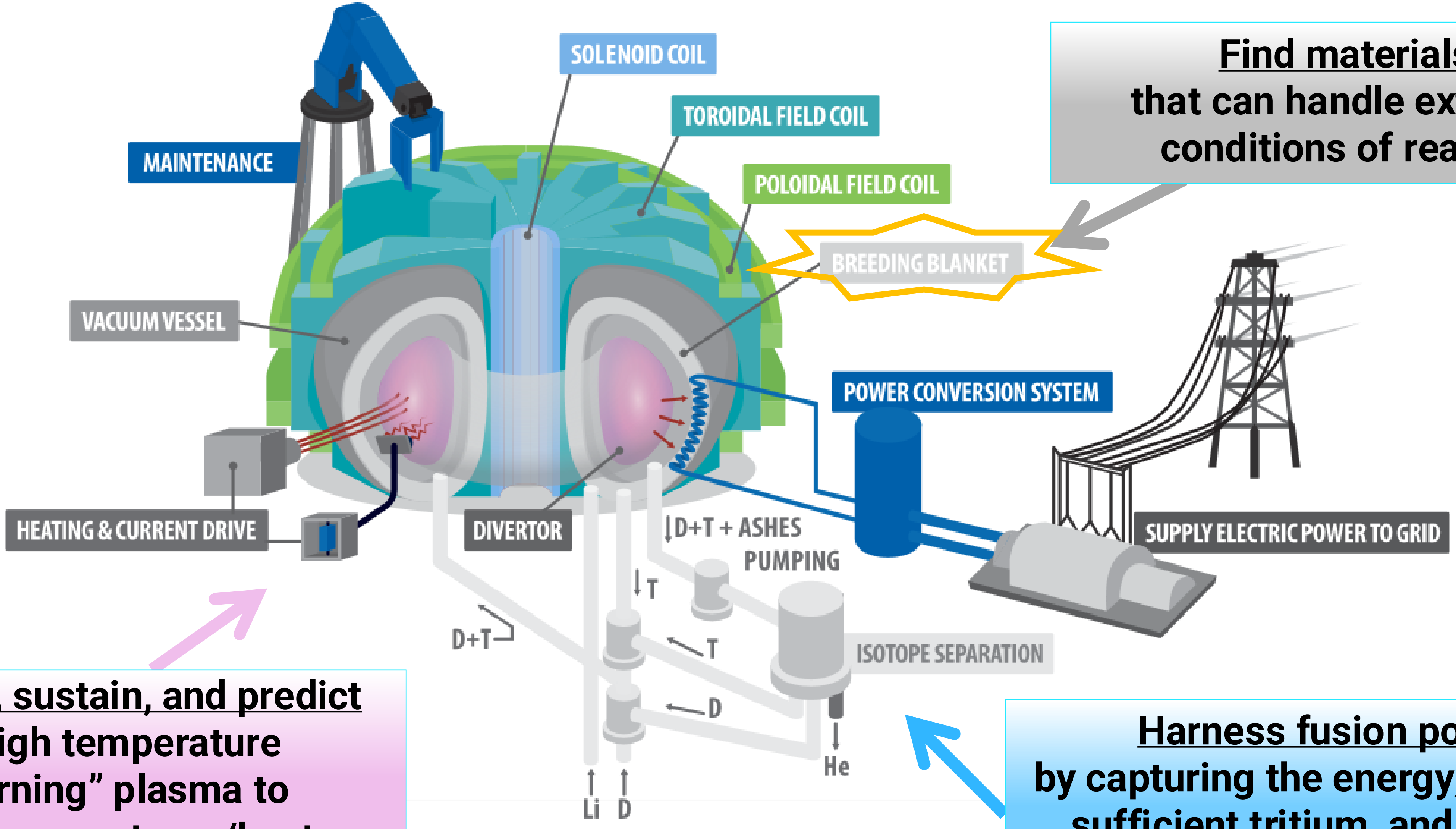


How do we get energy from fusion?

How do we sustain energy from fusion?

What are some key challenges in tritium breeding blankets?

Generating Electricity from Fusion Energy Requires Meeting Three Scientific/Technological Challenges

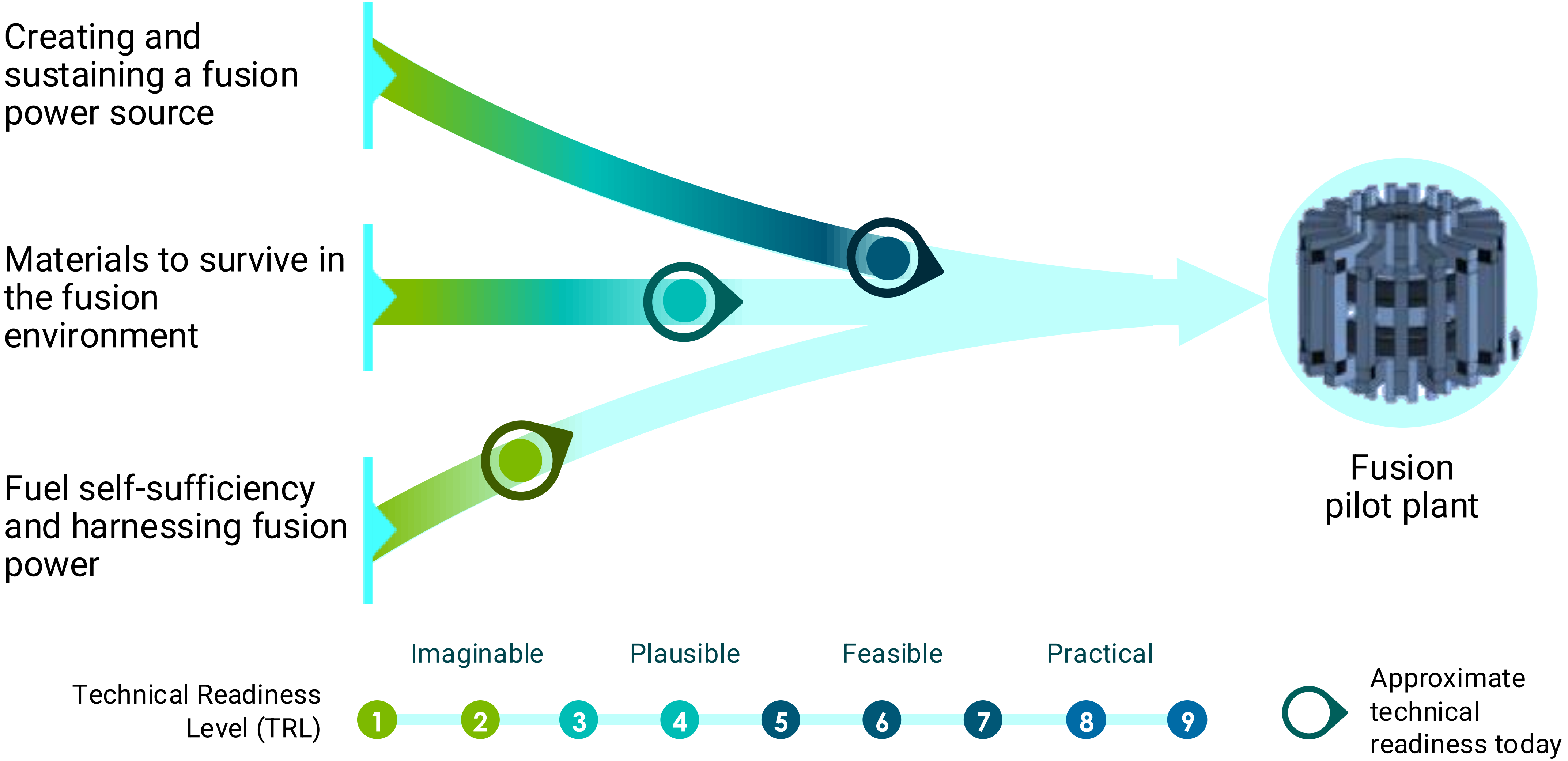


Find materials
that can handle extreme conditions of reactor

Control, sustain, and predict
a high temperature "burning" plasma to produce neutrons/heat

Harness fusion power
by capturing the energy, breeding sufficient tritium, and reliably producing net electricity

Technical readiness must be advanced rapidly to meet goals



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Blanket Components

Structural Material Selection

Tritium Breeding Material Selection

Neutron Multiplier Material Selection

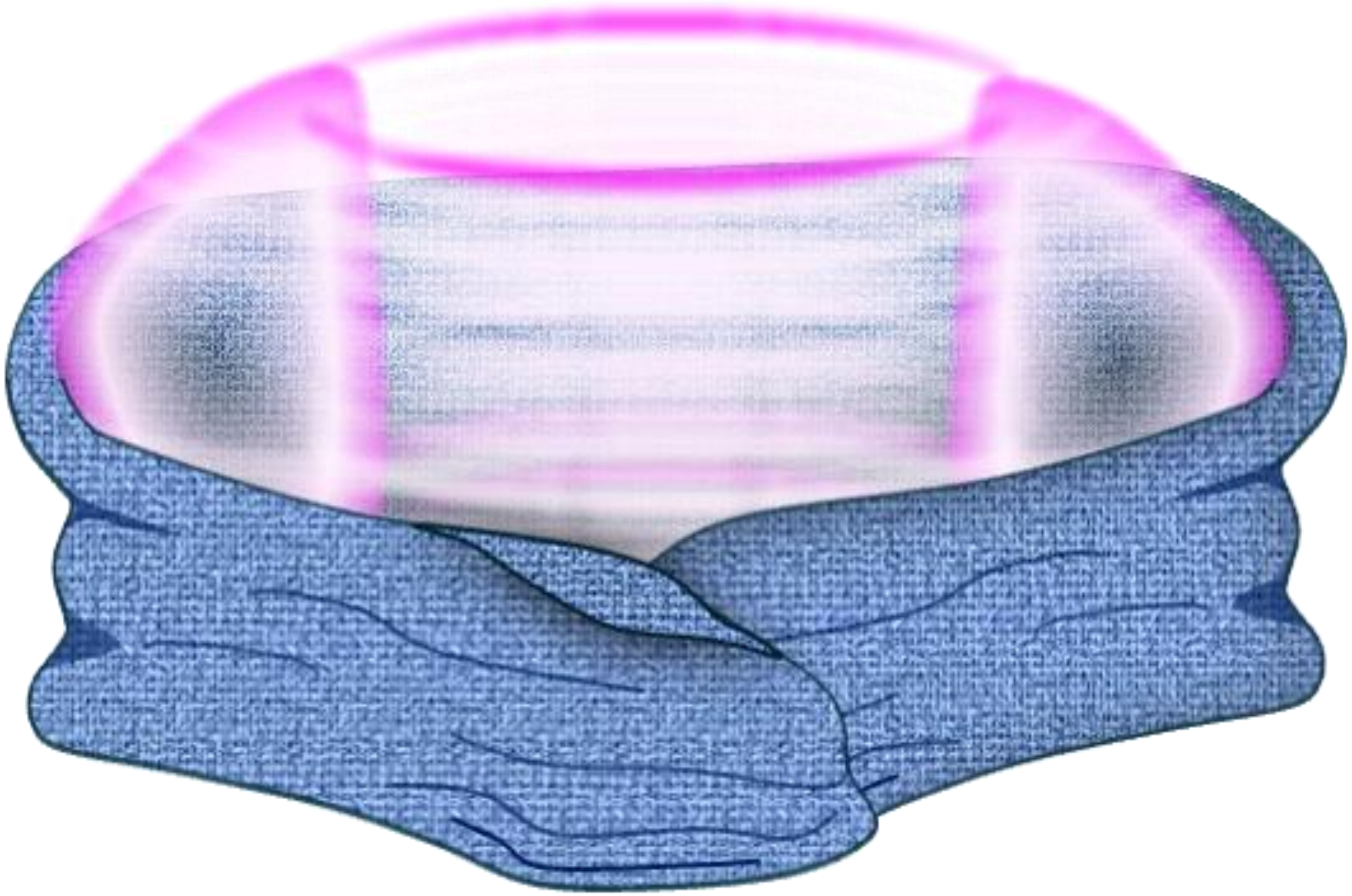
Coolant Material Selection

General Challenges

What is a blanket?

Functions

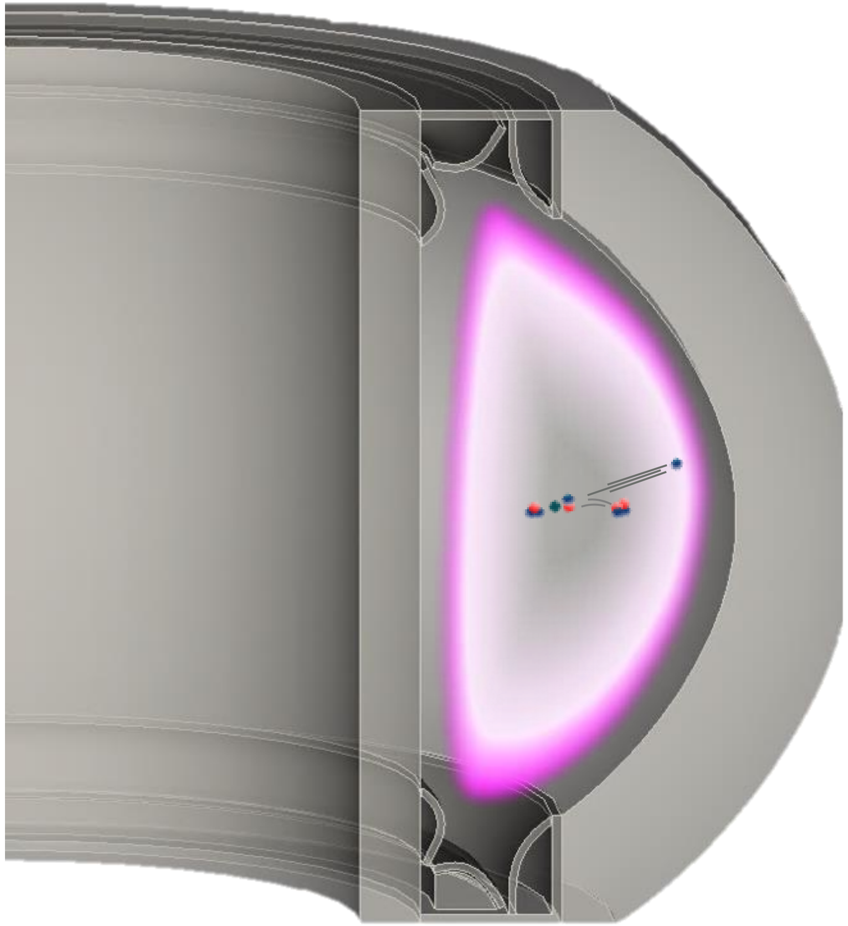
- Tritium breeding
- Heat generation/removal
- Shielding
  - magnets
  - diagnostics
- Structure



What is a blanket?

Components

- Structural Material
  - Materials that don't become highly radioactive
- Tritium breeding material
  - $n + {}^{6}Li \rightarrow {}^{4}He + T + 4.785\ MeV$
    - Large probability of interaction at lower neutron energies
    - Exothermic: produces additional energy!
  - $n + {}^{7}Li \rightarrow {}^{4}He + T + n' - 2.5\ MeV$
    - Produces tritium *and* a neutron
- Multiplier material
  - Elements that produce more neutrons when hit with a neutron
  - Elements that don't absorb neutrons
- Coolant



What is a blanket?

Components

- **Structural Material**
  - Reduced activation materials
- Tritium breeding material
  - $n + {}^{6}Li \rightarrow {}^{4}He + T + 4.785\ MeV$
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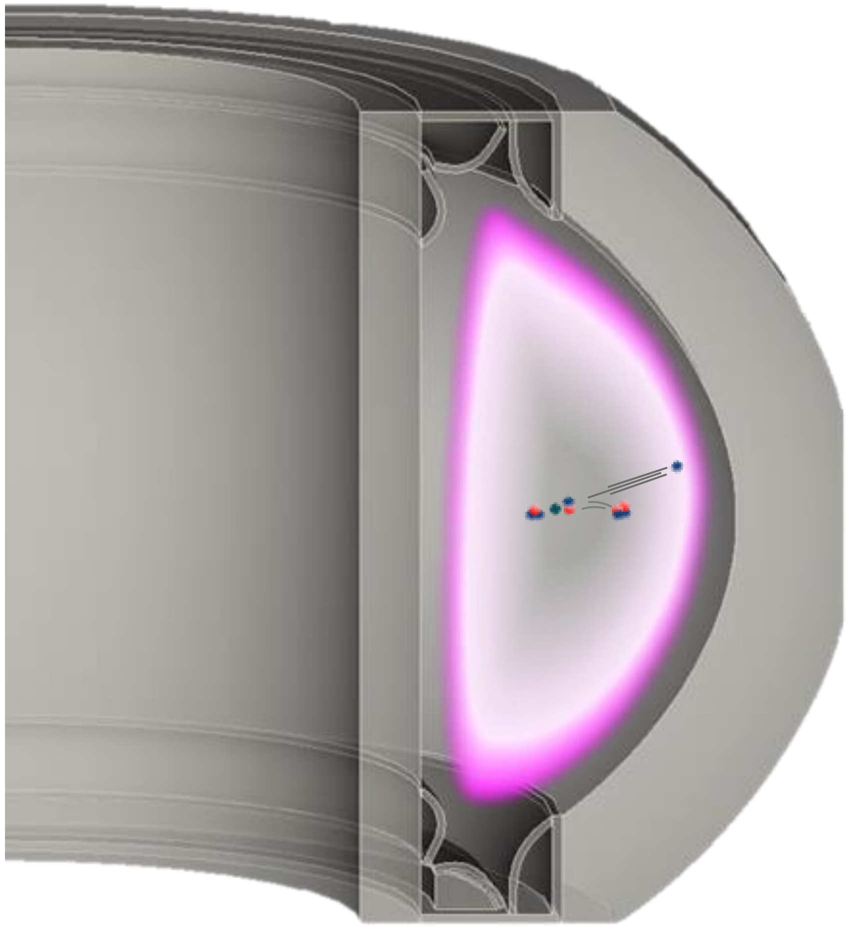
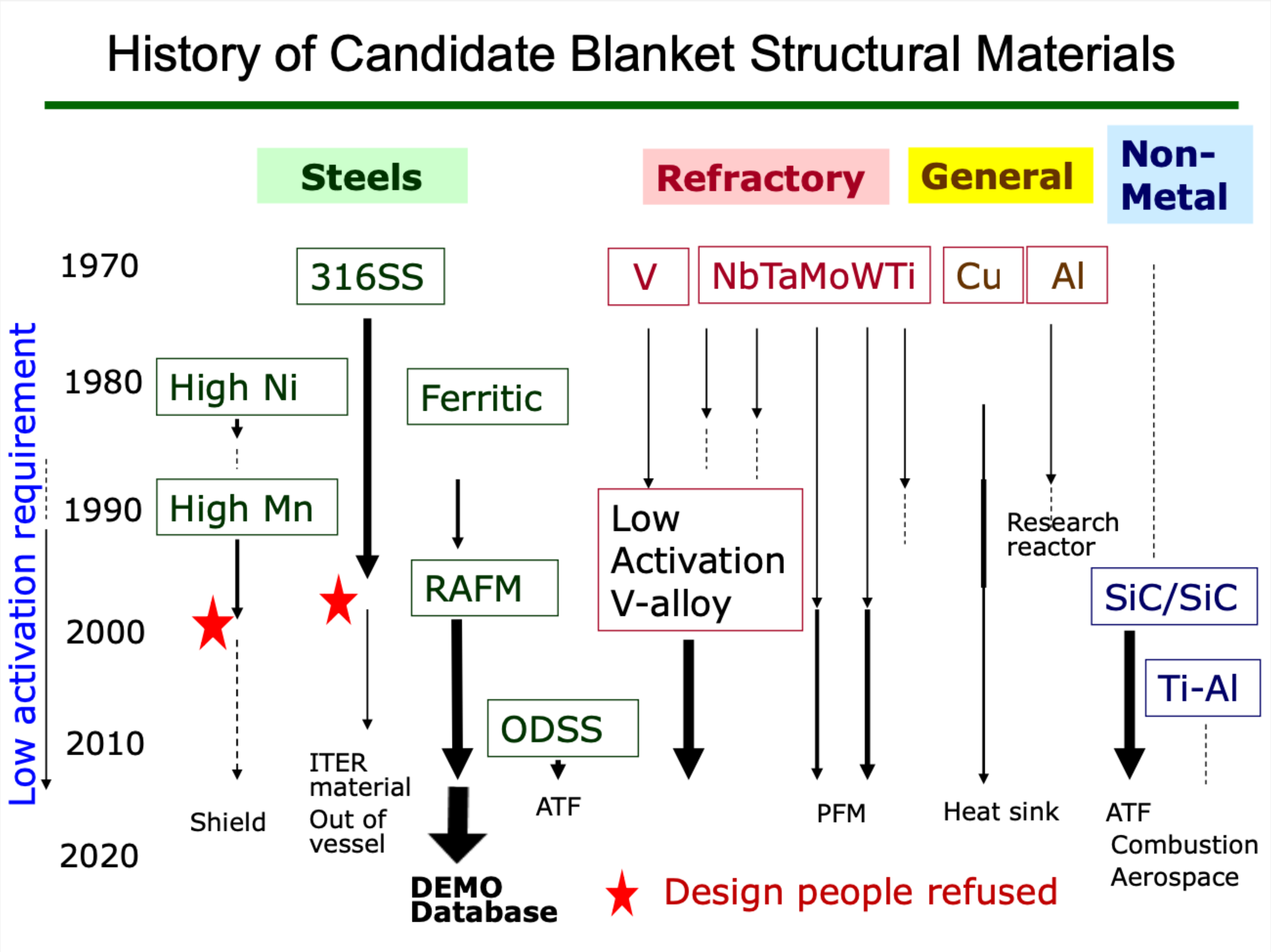


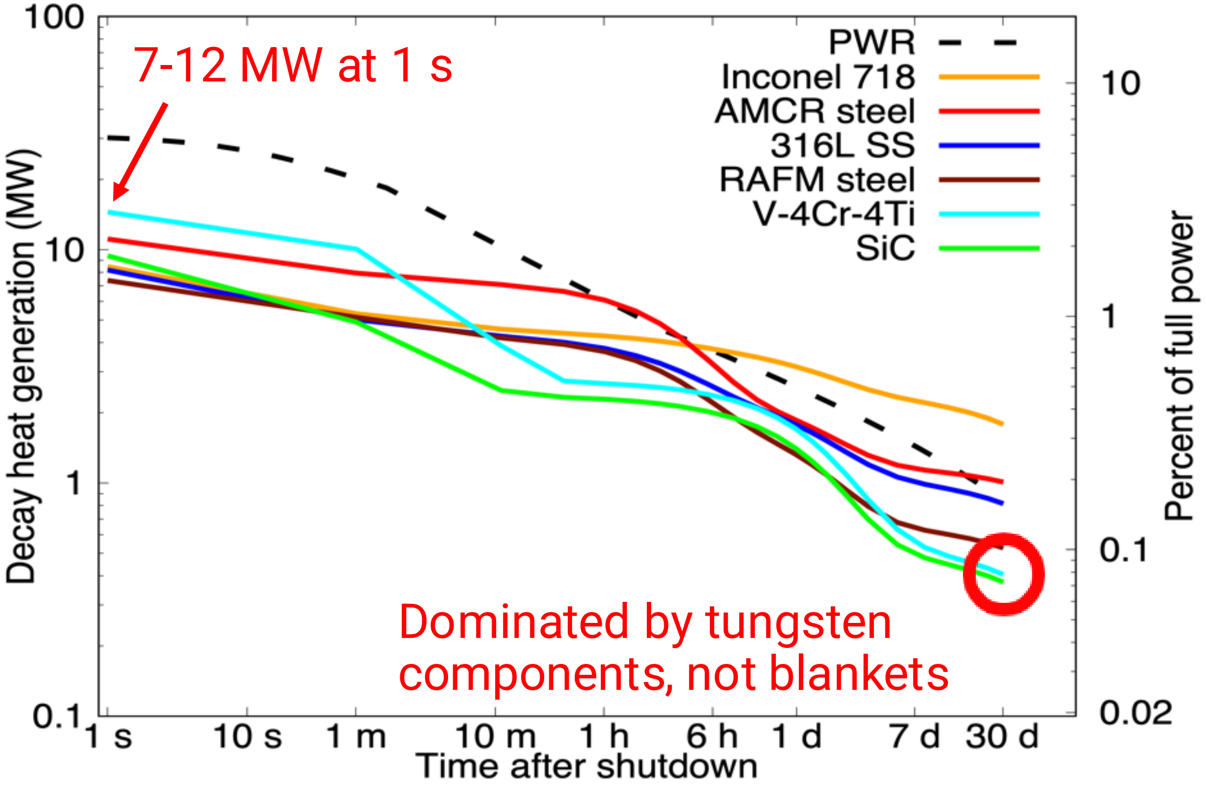
Structural Materials



T. Muroga, 3/29/2022

Activation of Structural Materials

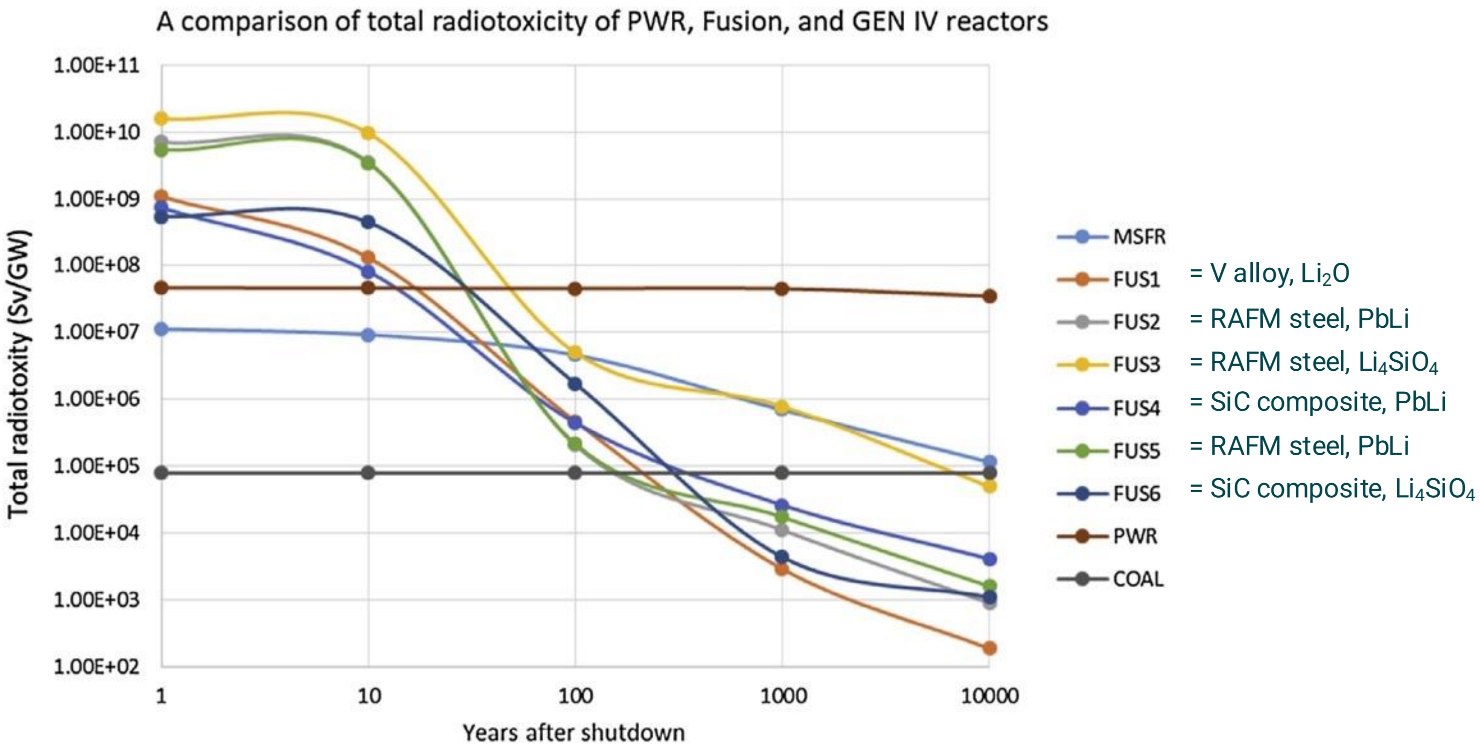
- D-T fusion creates waste
  - Goal: Below Class C Low-Level Waste
- Common alloying elements with long-lived radioisotopes
  - Avoid Ni, Co, Mo, Nb, etc.



P. W. Humrickhouse, *Fusion Science and Technology* (2024, submitted)

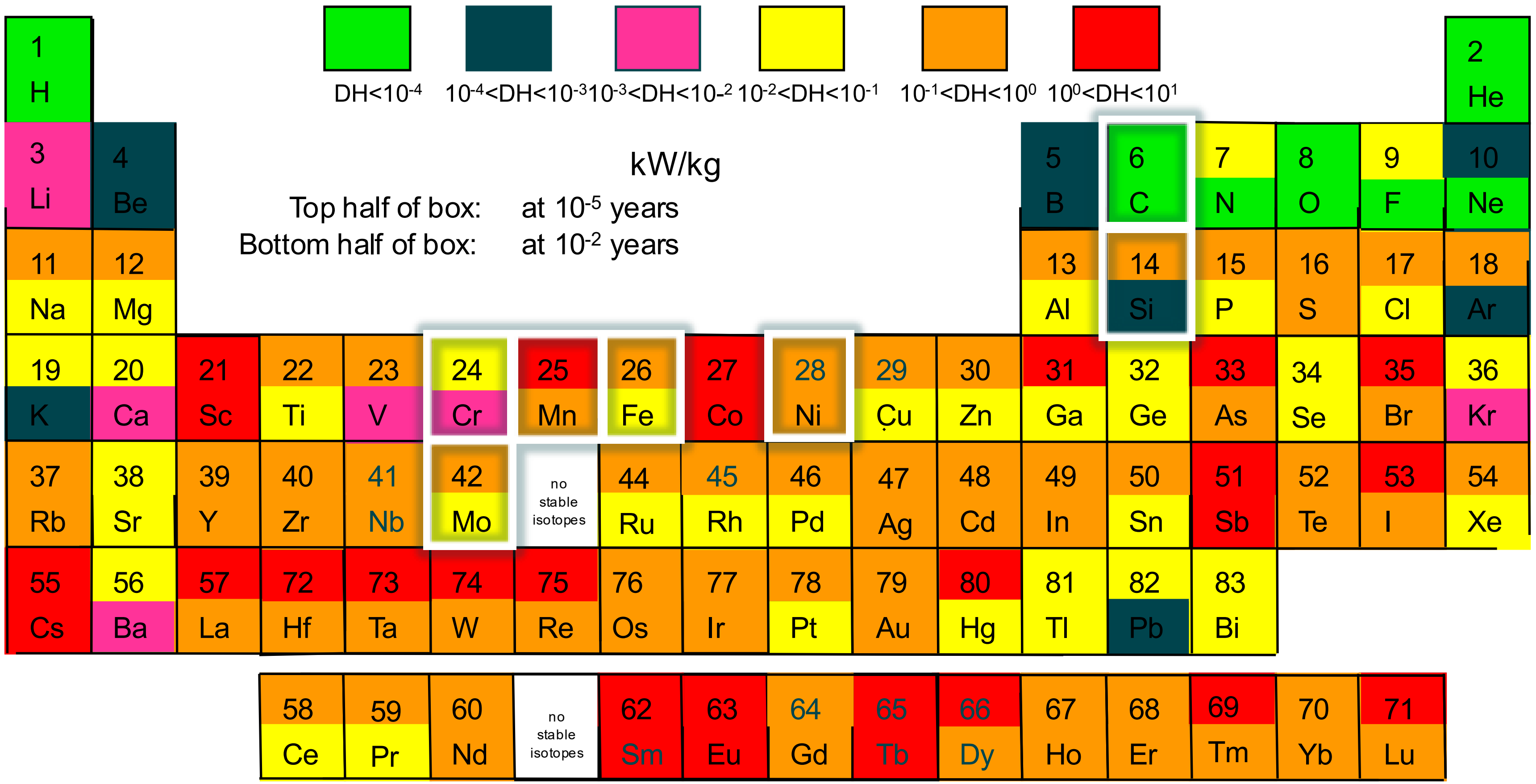
Activation of Structural Materials

- Low-activation Materials
  - Reduced-Activation Ferritic/Martensitic Steel – most mature fusion material
  - Vanadium Alloys – need development
  - Silicon Carbide – need development



M. Zucchetti, *Fusion Engineering and Design* **136** (2018) 1529-1533.

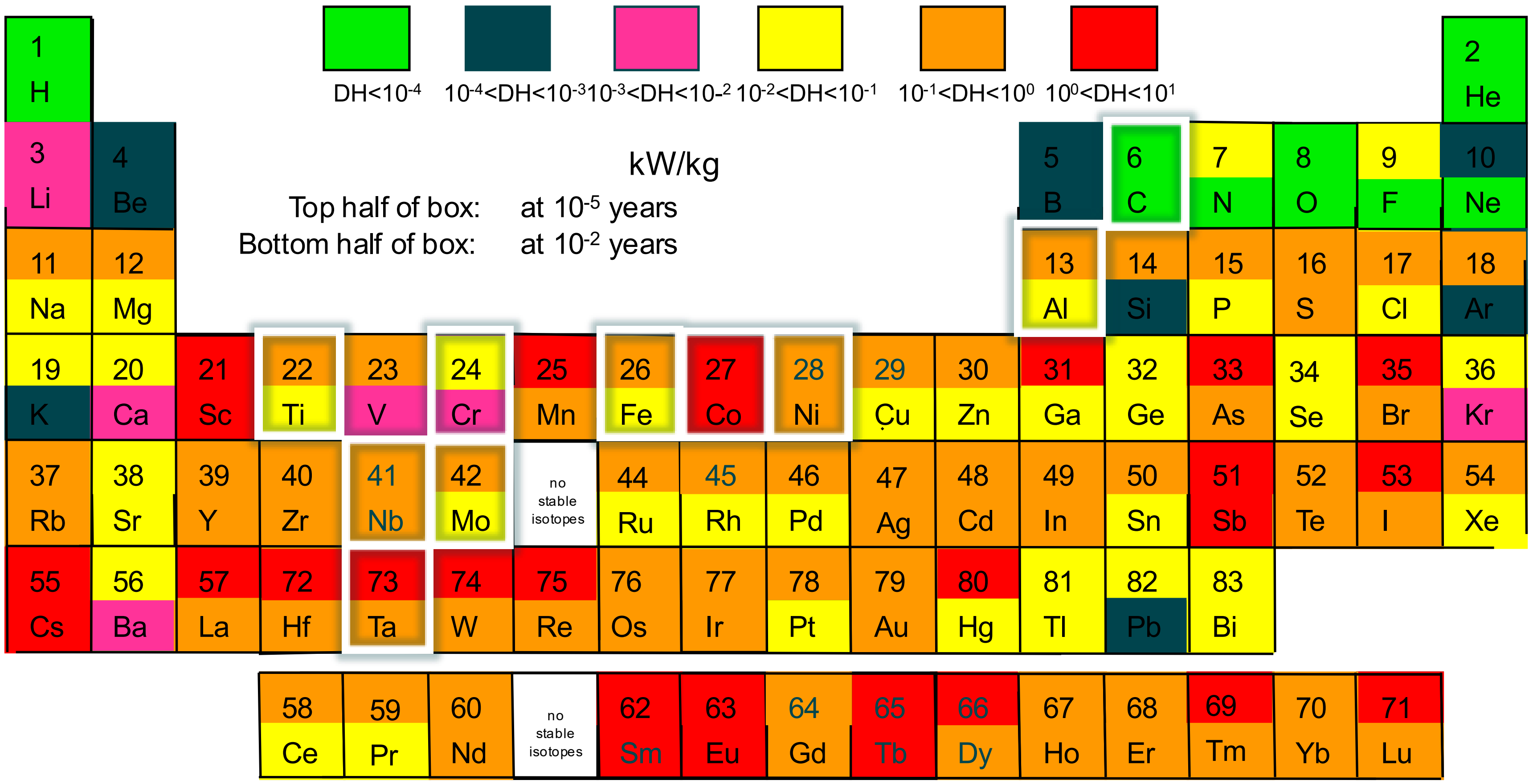
Decay Heat



316 Stainless Steel

Based on C. B. A. Forty, et al., Handbook of Fusion Activation Data; Part 1. Elements Hydrogen to Zirconium, AEA FUS 180, May, 1992. Assumes 4.15 MW/m^2 for 25 years

Decay Heat



Inconel 718

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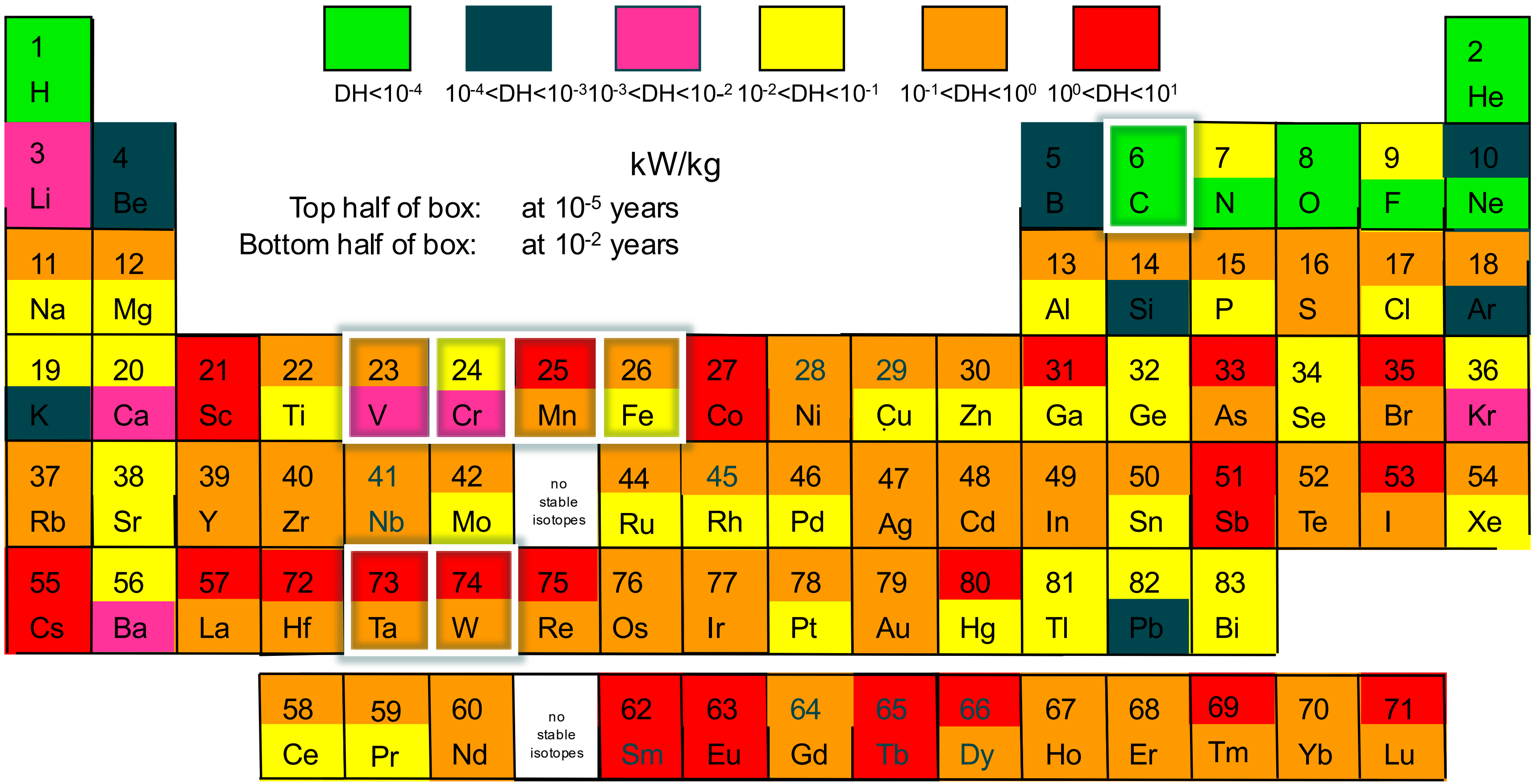
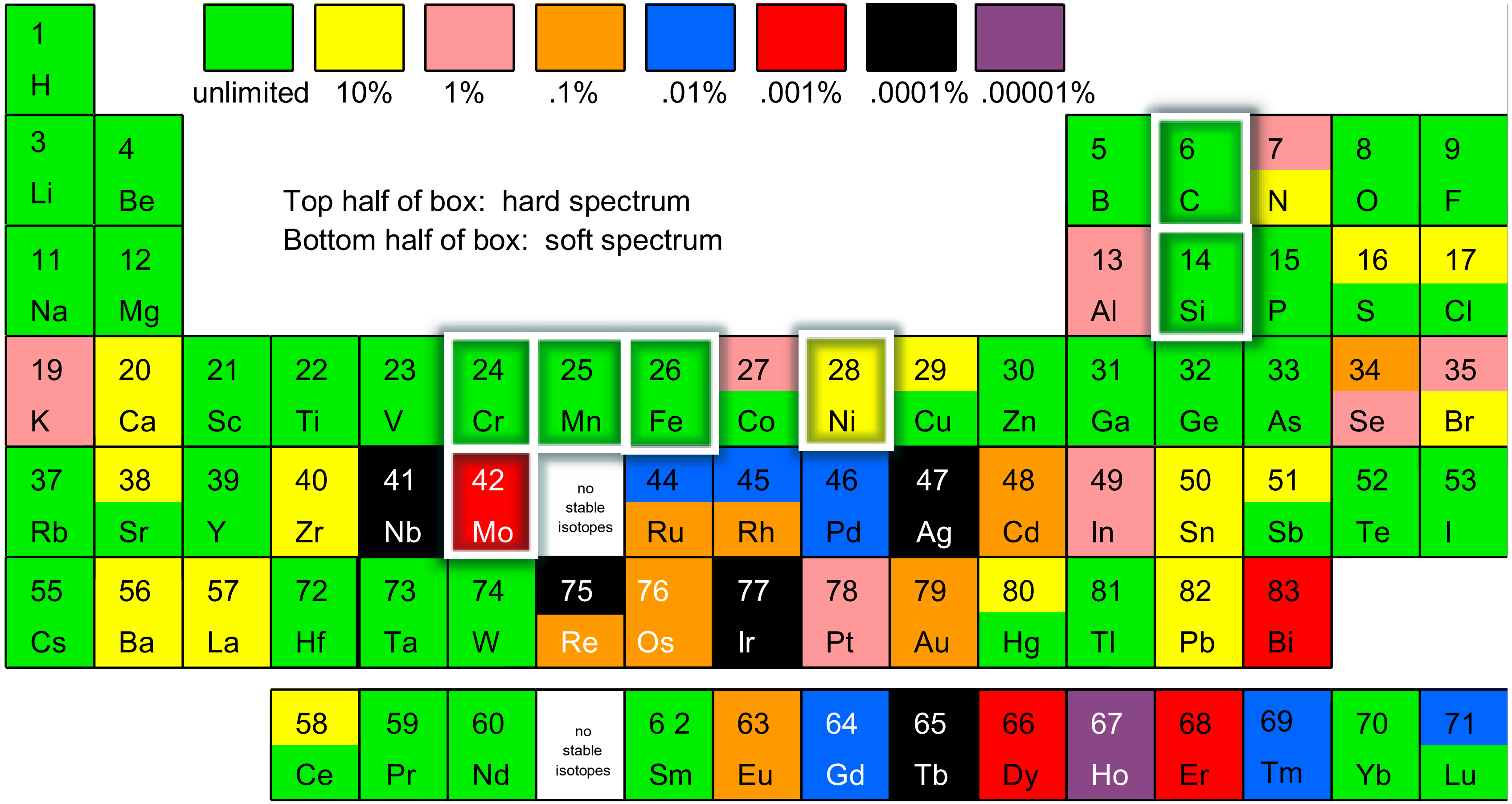


RAFM Steel

Based on C. B. A. Forty, et al., Handbook of Fusion Activation Data; Part 1. Elements Hydrogen to Zirconium, AEA FUS 180, May, 1992. Assumes 4.15 MW/m^2 for 25 years

Alloy concentrations to meet Class C disposal



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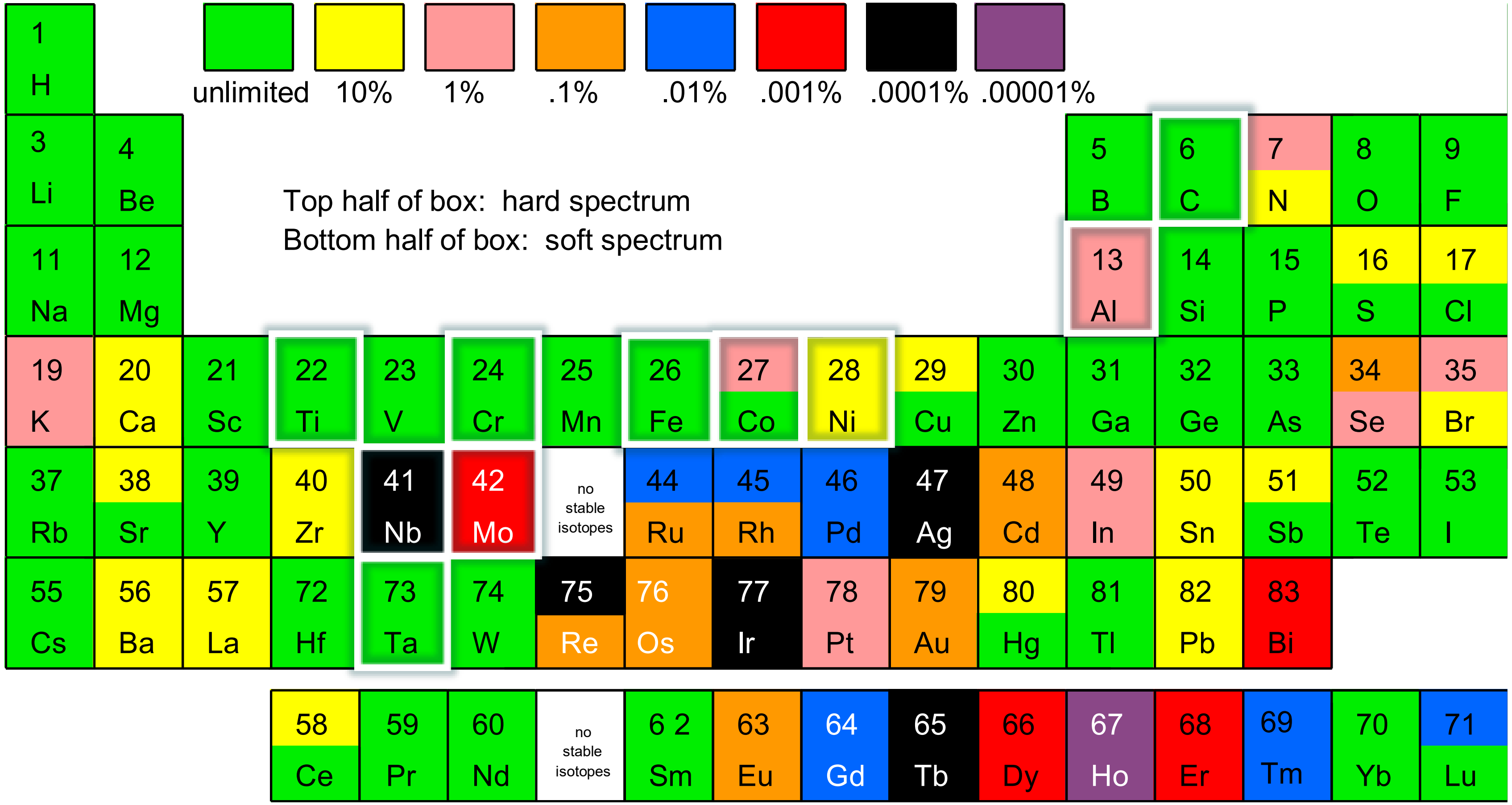

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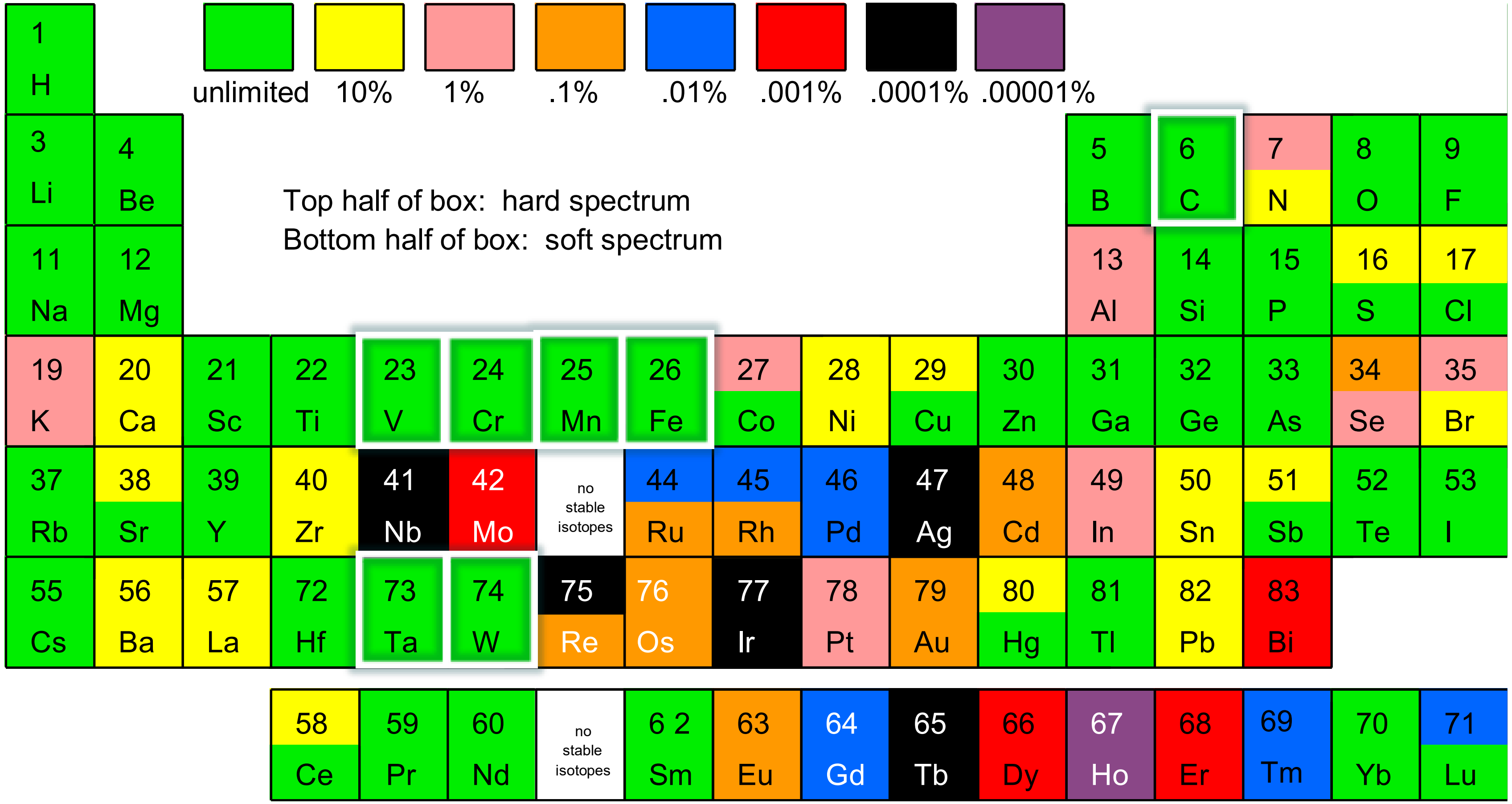

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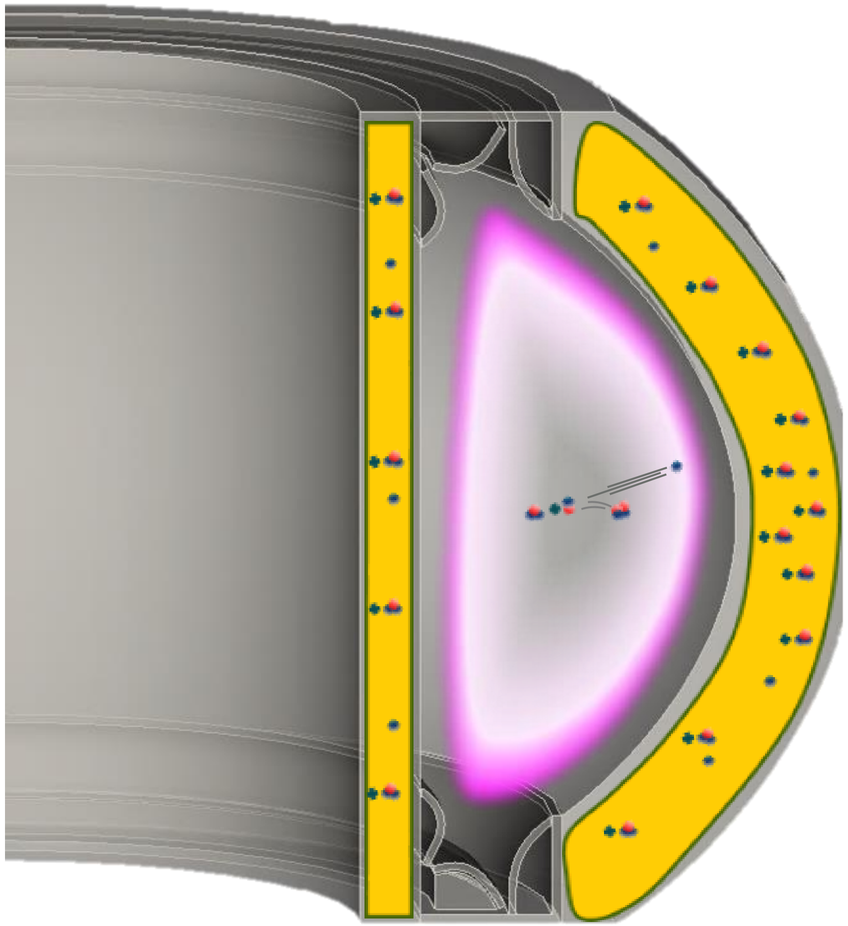
What is a blanket?

Components

- Structural Material
  - Reduced activation materials
- **Tritium breeding material – Tritium Breeding Ratio >1**
  - n + ^{6}Li → ^{4}He + T + 4.785 MeV
    - Large cross section at thermal energies
    - Exothermic: produces additional energy
  - n + ^{7}Li → ^{4}He + T + n’ - 2.5 MeV
    - Produces tritium *and* a neutron
- Multiplier material
  - Elements that undergo (n,2n) reactions
  - High (n,2n) cross section and low total absorption cross section
    - Be and Pb are best
- Coolant



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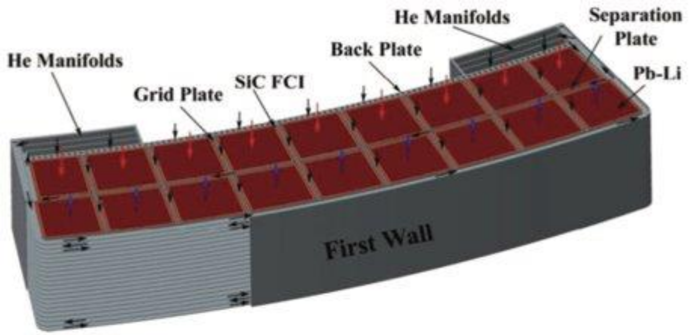
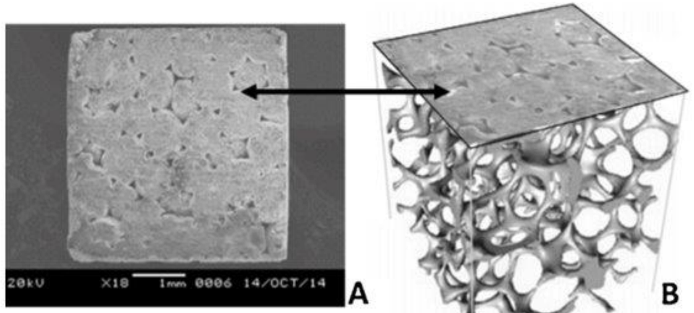
Tritium Breeding Materials



X. R. Wang *et al.*, *Fusion Science and Technology*, vol. 67, no. 1, (2017) 193-219

- Liquid Metals ← **Magnetohydrodynamic challenges**
  - Li
  - PbLi

  Relatively low melt temperature ✓

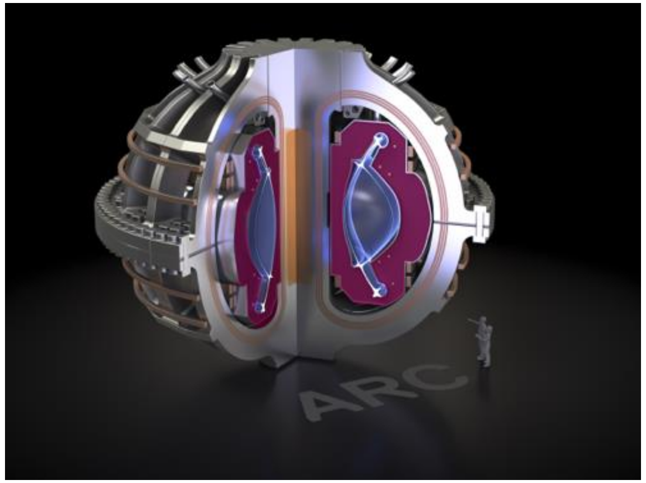


S. Sharafat et al., *Fusion Engineering and Design* **109-111** (2016) 119-127

- Solid Ceramics ← **More structure required**
  - Li_2TiO_3, Li_4SiO_4, and many others possible
- Molten Salts ← **Highly Corrosive ✕**
  - FLiBe (2LiF + BeF_2)
  - FLiNaBe (LiF + NaF + BeF_2)

  High melt temperature ✕

  Lower TBR ✕



https://www.psfc.mit.edu/news/2022/turning-neutrons-into-fusion-fuel

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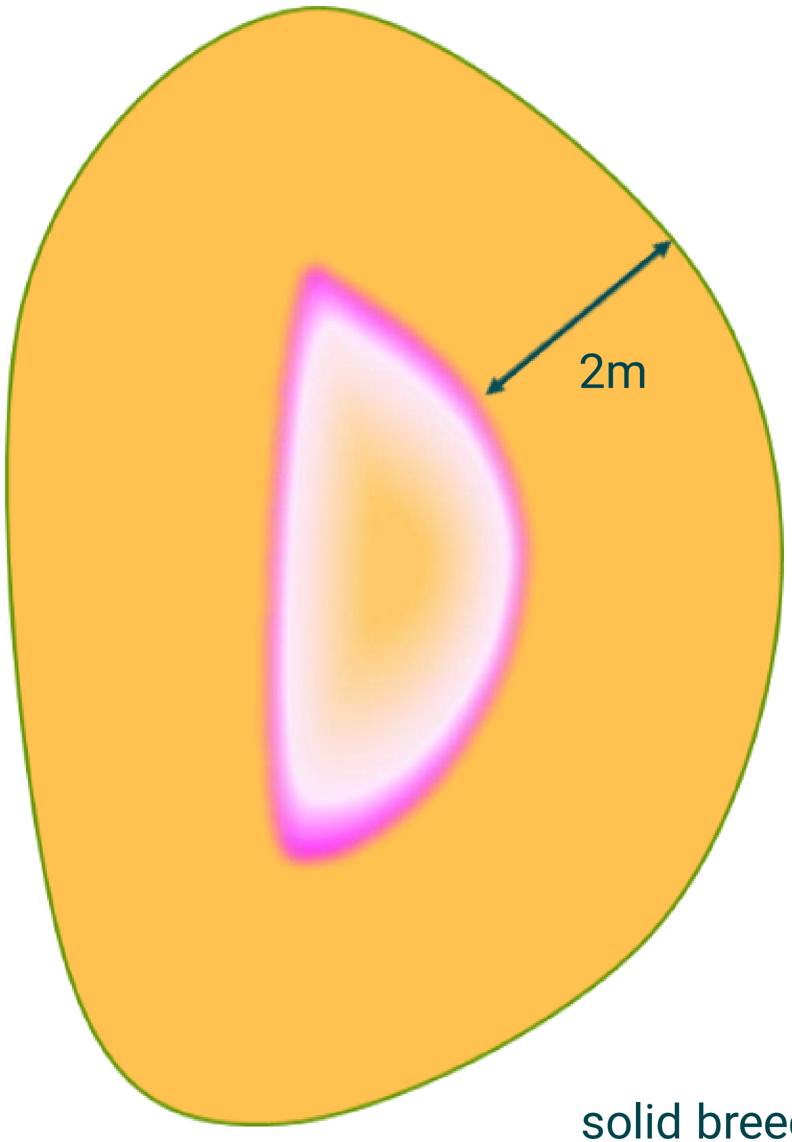
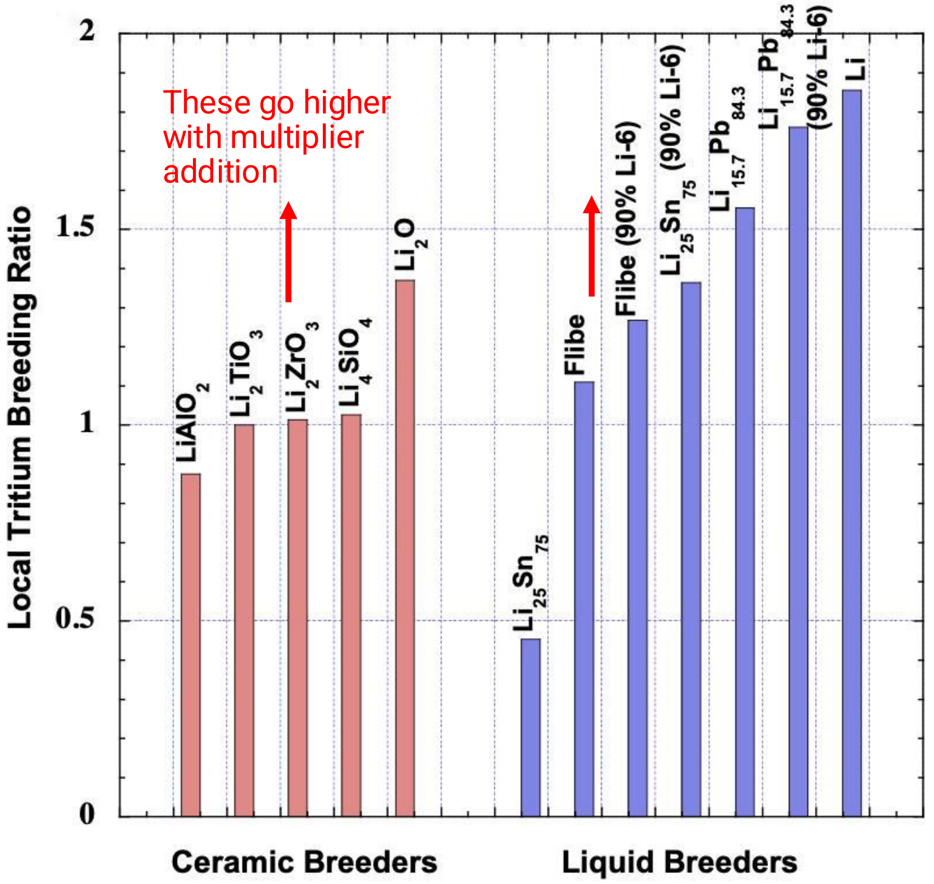
Tritium Breeding Ratio for Different Materials





L. El-Guebaly, in "Fusion Energy and Power: Applications, Technologies and Challenges" (2015)

solid breeder: helium is separate from coolant stream

Lithium Enrichment

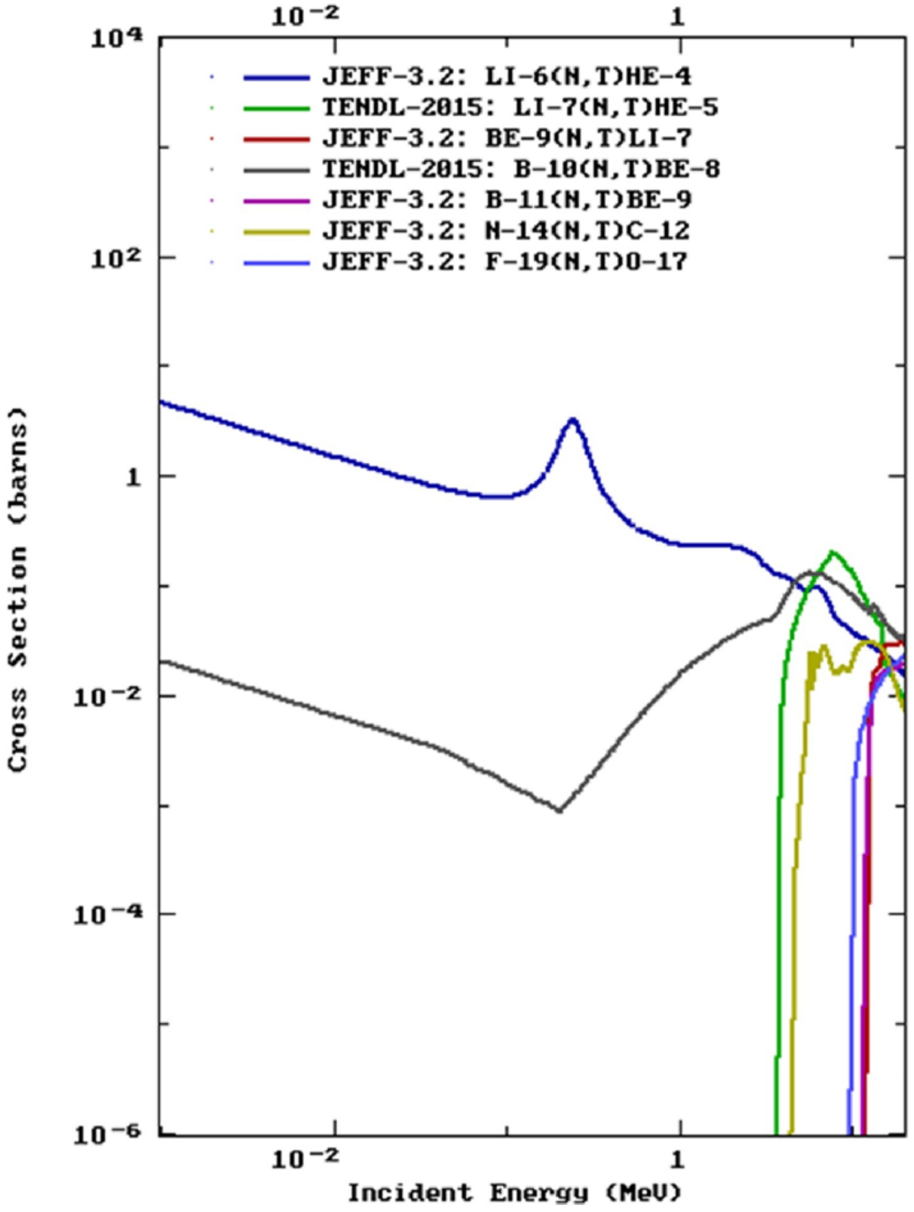
n + ^{6}Li → ^{4}He + T + 4.785 MeV

- Large cross section at thermal energies
- Exothermic: produces additional energy
- **Li^6 is only 7.5% of natural lithium**

n + ^{7}Li → ^{4}He + T + n’ - 2.5 MeV

- Produces tritium *and* a neutron

How do you get desirable quantities of Li^6?
→ Enrichment!



Methods of Breeding Tritium

Liquid Metal - Li

- Good TBR; may not need ^{6}Li enrichment
- Low T_{melt} = 180 °C
- Traditionally paired with Vanadium alloy or RAFM steel structure
- Very high chemical reactivity with H_2O and air (safety issue)
- High tritium solubility/inventory, different extraction techniques needed
- Electrical insulators required for MFE

Liquid Metal - PbLi

- Good TBR, but with ^{6}Li enrichment
- Low T_{melt} = 235 °C
- Traditionally paired with RAFM steel or SiC structure
- Much lower chemical reactivity than pure Li
- Low T/high T design options
- Material compatibility at high T may require coatings
- Electrical insulators required for MFE

Solid Ceramic

- Good TBR requires Be multiplier addition, structure minimization
- Traditionally paired with RAFM steel structure and He or H_2O coolant
- Better material compatibility than liquids
- Simpler & more mature tritium extraction
- Require replacement
- Evolution under irradiation important

Molten Salt - FLiBe

- Good TBR may require Be multiplier addition
- High T_{melt} = 460 °C
- Corrosion a significant concern
- Structural material solution unclear
- Low electrical conductivity
- High heat capacity
- Low thermal conductivity
- High viscosity

What is a blanket?

Components

- Structural Material
  - Reduced activation materials
- Tritium breeding material
  - $n + {}^{6}Li \rightarrow {}^{4}He + T + 4.785$ MeV
    - Large cross section at thermal energies
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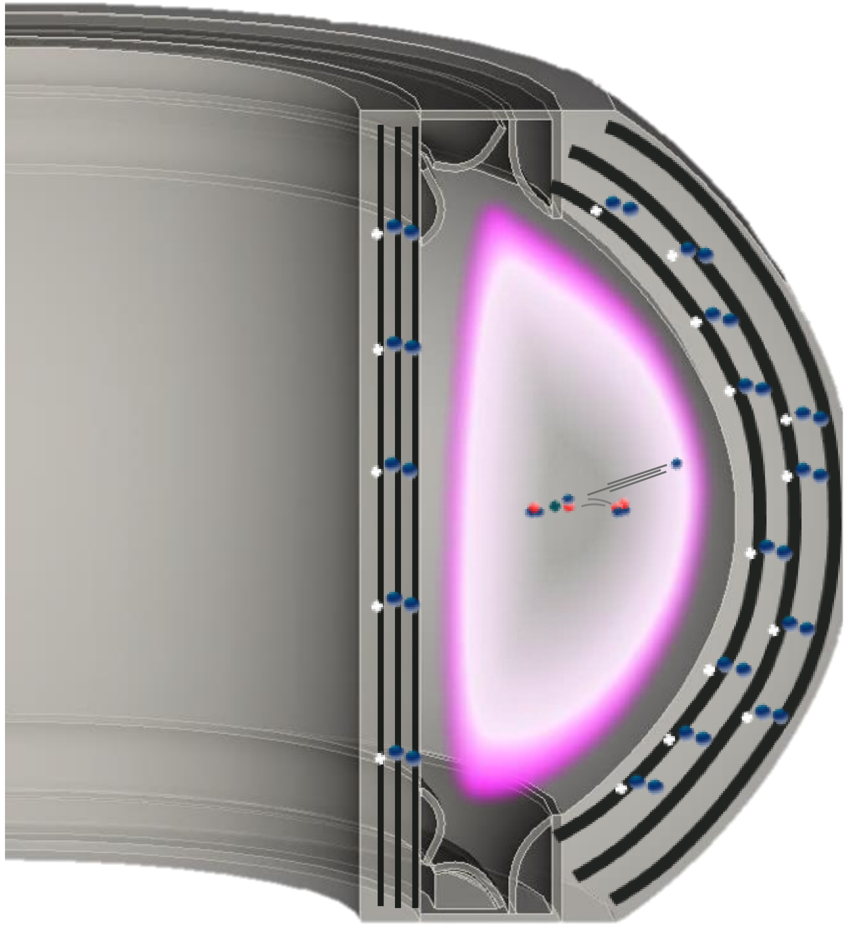
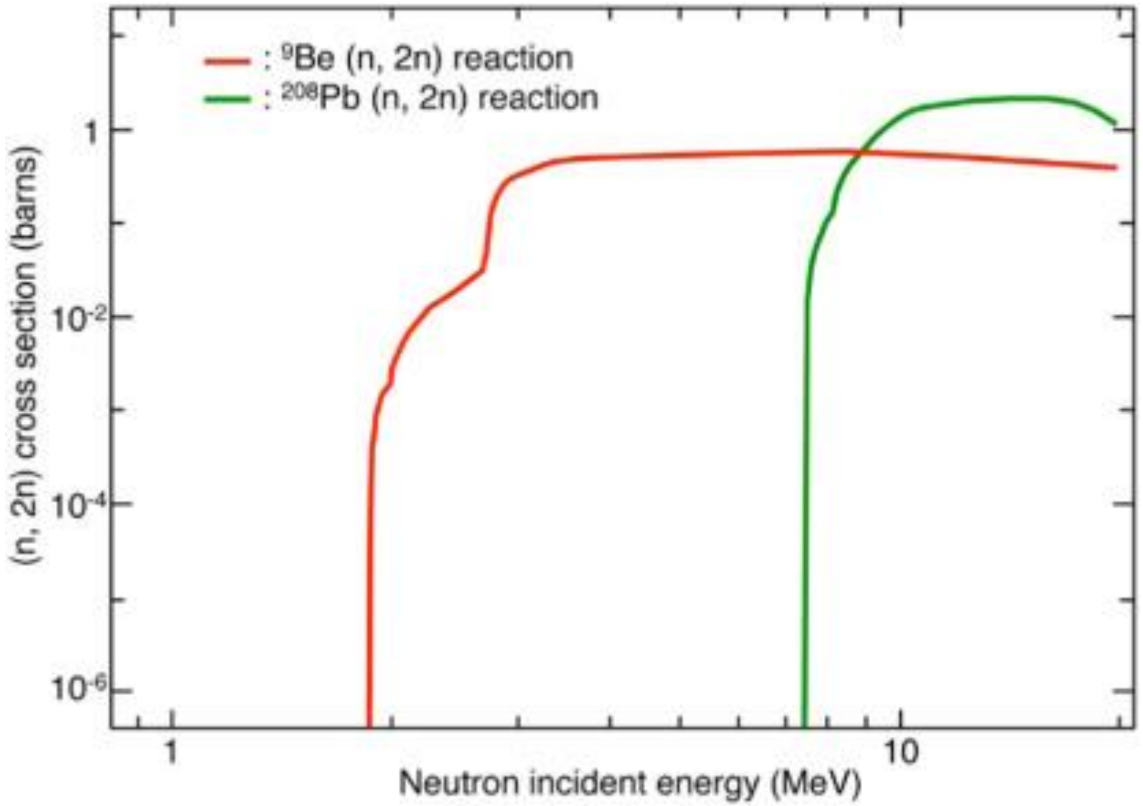
- **Multiplier material**
  - Elements that undergo (n,2n) reactions
  - High (n,2n) cross section and low total absorption cross section
    - Be and Pb are best
- Coolant

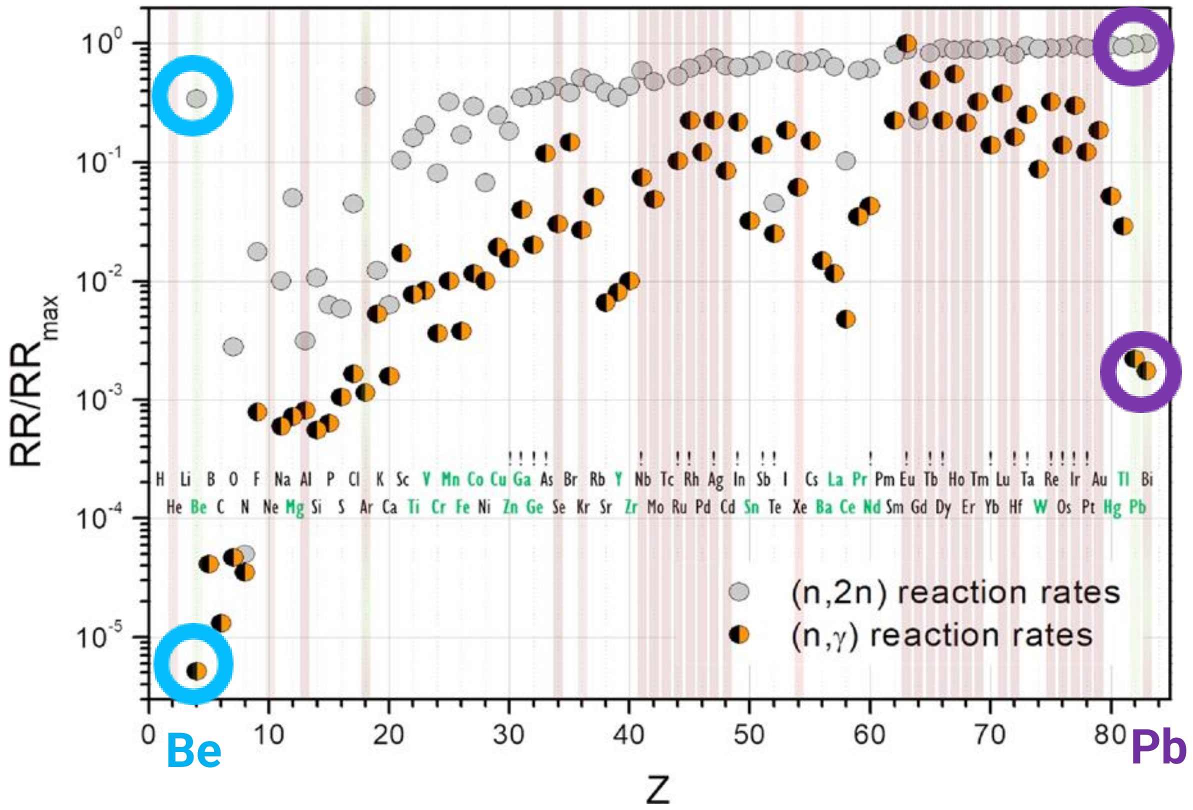


Multiplier Materials

- TBR = 1 → every fusion neutron produces tritium (unlikely)
  - Need more neutrons!



M. Nakamichi, in *Comprehensive Nuclear Materials* 2nd ed (2020).



F. Hernandez, *Fusion Engineering and Design* **137** (2018) 243-256.

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Lead, Beryllium and Beryllides

Lead

Must be in liquid form

Low radiation damage

Toxic

Impurities (Bismuth)

- Activation products

High (n, 2n) cross section

Relatively high total absorption cross section

Beryllium

Solid – high melt temperature

Toxic

Swelling due to irradiation

Tritium breeding; low tritium diffusivity (retention)

Highly exothermic reaction with air and water

Impurities (Uranium)

High (n, 2n) cross section

Low total absorption cross section

Beryllides (eg, $Be_{12}Ti$)

Solid – high melt temperature

Toxic

Limits swelling

Limits chemical reactions

Tritium breeding; no retention

Large number of different beryllide compounds; some hard to work with

Impurities (Uranium)

Higher total absorption cross section than Be

Decreased atom density of Be

What is a blanket?

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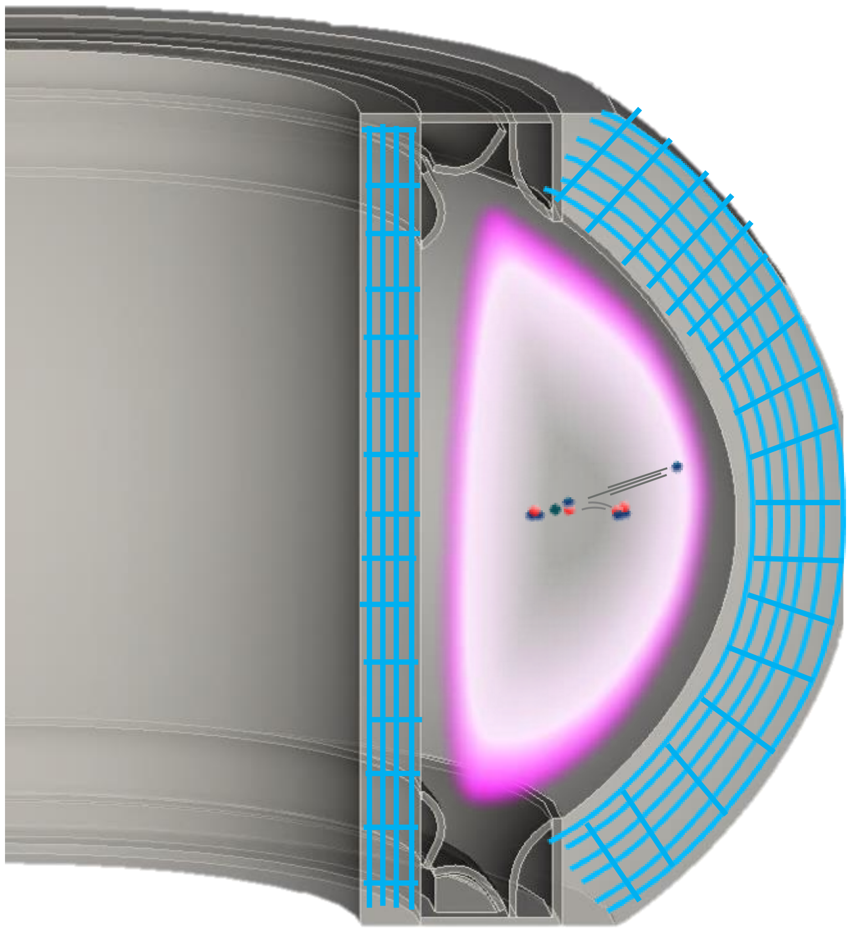
- **Coolant**



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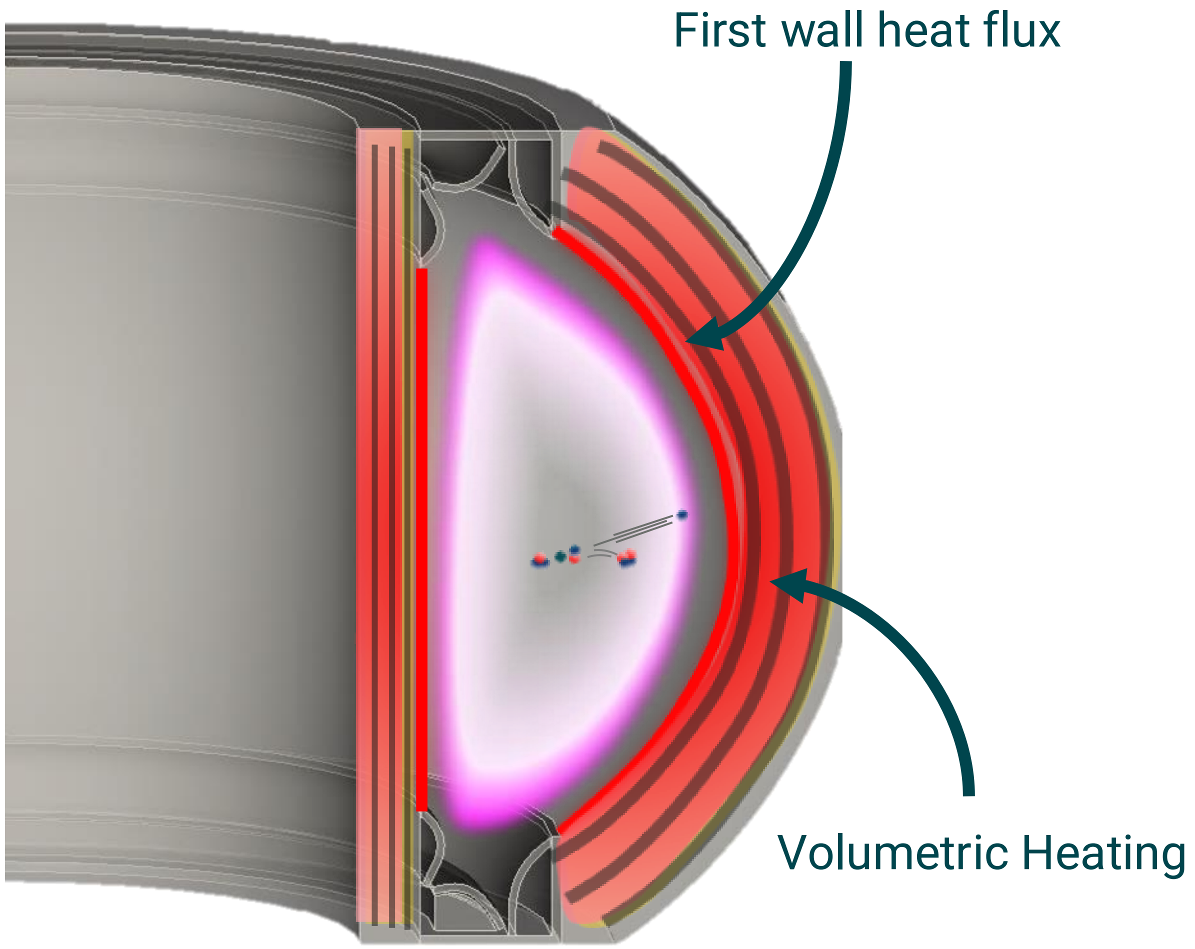
Blanket Cooling

Heat Removal

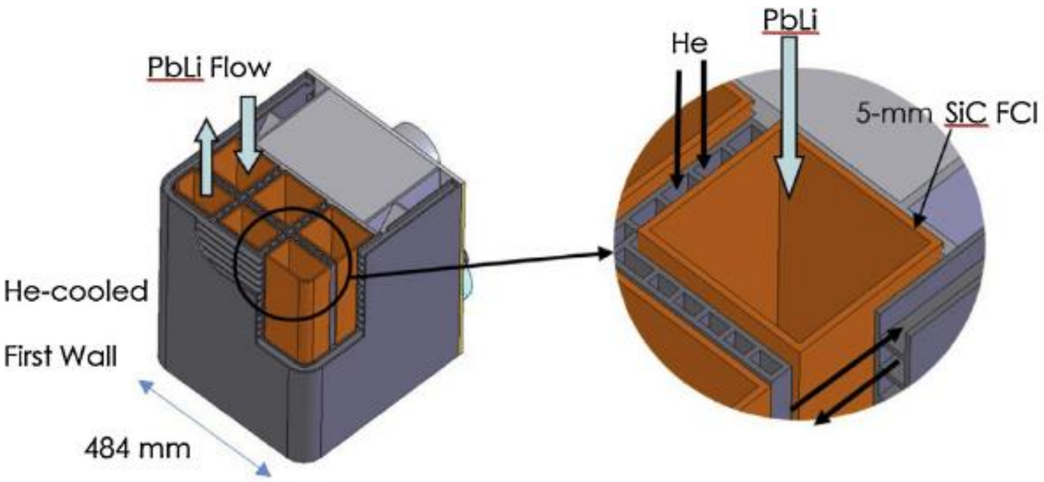
- Remove heat from First Wall
  - plasma
  - neutrons
- Remove heat due to volumetric heating
  - heating in structural materials
  - heat produced in exothermic reactions
  - decay heat
- Use for power conversion



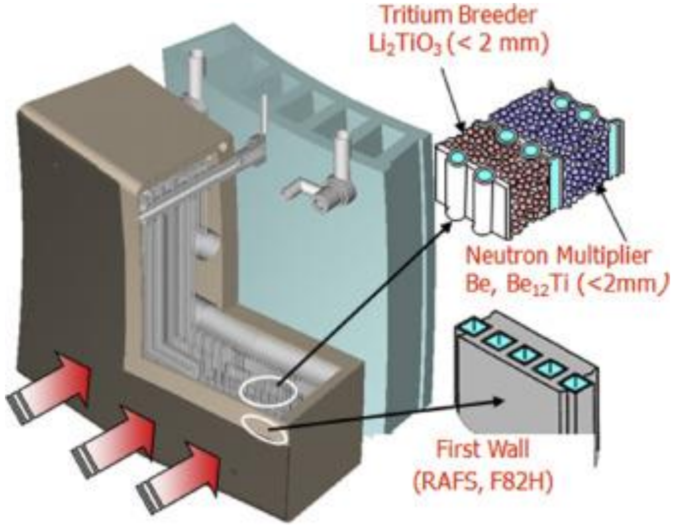
Cooling mechanisms

Dual-Cooled

- Uses a separate coolant and breeding material
- Examples:
  - Dual-Cooled Lead Lithium (DCLL)
  - Helium-Cooled Ceramic Breeder (HCCB)
  - Water-Cooled Ceramic Breeder (WCCB)

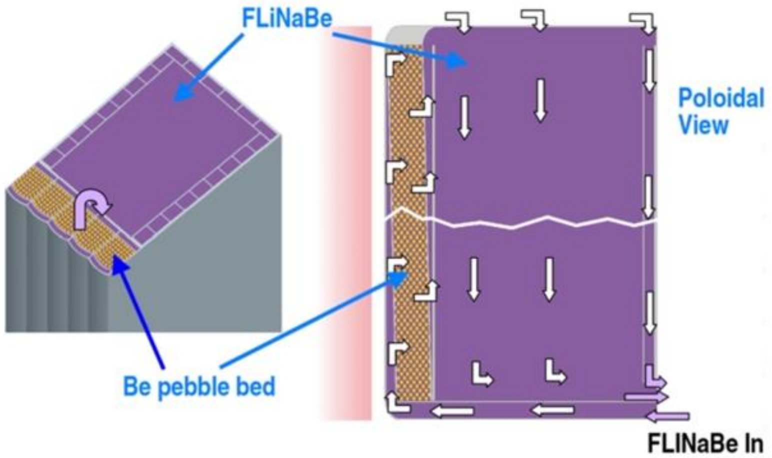


M. S. Tillack and S. Malang, "High performance PbLi blanket," *17th IEEE/NPSS Symposium Fusion Engineering*



M. Abdou (2015). Blanket/first wall challenges and required R&D on the pathway to DEMO. Fusion Engineering and Design.

Cooling mechanisms



C. Wong, *Fusion Eng. Des.* **72** (2004) 245-275.

Self-Cooled

- Uses the same coolant and breeding material
- Examples
  - Self-Cooled Lead Lithium (SCLL)
  - Self-Cooled Molten Salt

Coolants and Their Challenges

Helium

(+) Inert

(-) Low thermal conductivity

(+) High specific heat capacity

(-) High pressure system

(-) Bad neutron shield

Water

(-) Steam reactions bad

(-) Tritiated water bad

(-) High pressure system

(+) High specific heat capacity

(+) Well-known pumping systems

(+) Neutron shield

Liquid Metal

(-) MHD pressure drop

(+) High thermal conductivity

(-) Corrosive

(+) Reasonable melt temperature

Reactivity

- (-) Lithium highly reactive with water and air
- (+) PbLi Less reactive

Specific Heat Capacity

- (-) Low specific heat capacity (PbLi)
- (+) High specific heat capacity (Li)

(+) Breeding Material

Molten Salt

(-) High viscous pressure drop

(-) Somewhat poor thermal conductivity

(-) Highly Corrosive

(-) High melt temperature

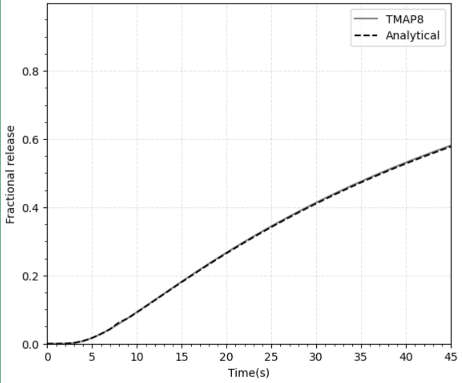
(+) High specific heat capacity

(+) Breeding material

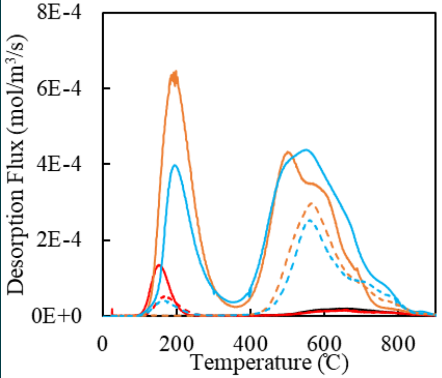
(+) Neutron shield

As we are making tritium, tritium migration is occurring

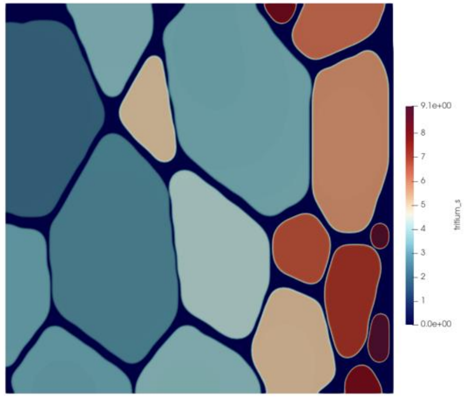
Tritium management is a key challenge in fusion reactors



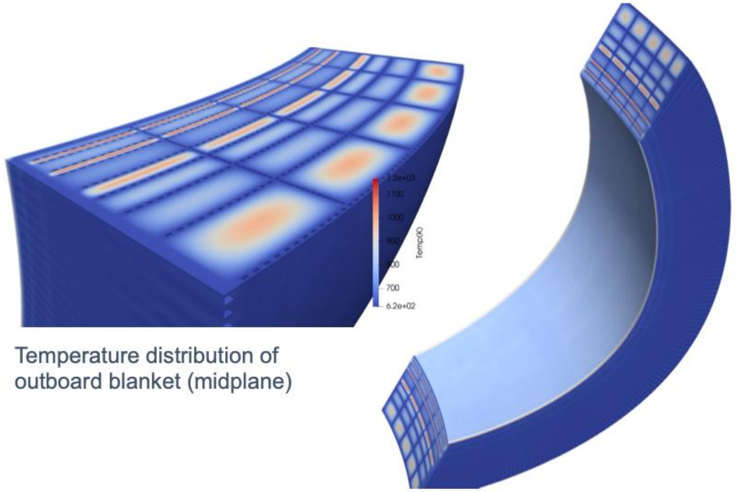
Tritium retention and transport in materials affects fuel cycle and safety



Use tools such as TMAP8 to model tritium permeation through materials



Use component-scale modeling to understand tritium transport conditions



Temperature distribution of outboard blanket (midplane)

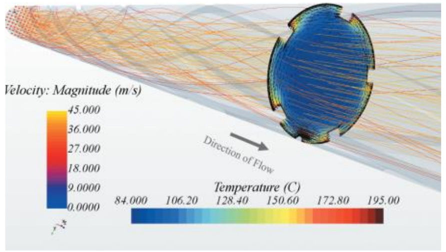
How do we get and sustain energy from fusion?

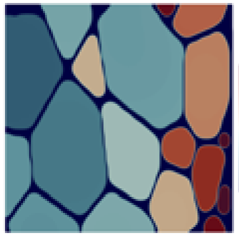
- Breeding tritium from lithium
  - solid ceramic
  - liquid metal
  - molten salt
- Make more neutrons with neutron multipliers
  - Pb
  - Be/Beryllides
- Heating for power conversion

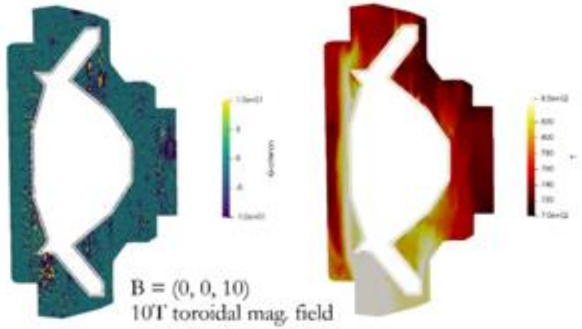
What are some main challenges?

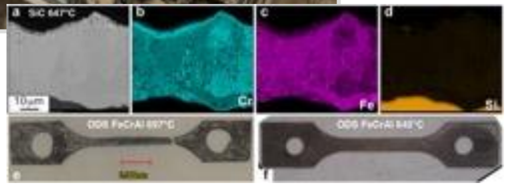
- Material activation and decay heat
  - Requires careful material selection
- Damage to solid structures
  - need to shield sensitive components
- Large heat load
  - Careful selection of Breeding/Multiplier/Coolant material combinations
  - Magnetohydrodynamic effects with electrically conductive liquids
- Tritium management

ORNL is working on these problems









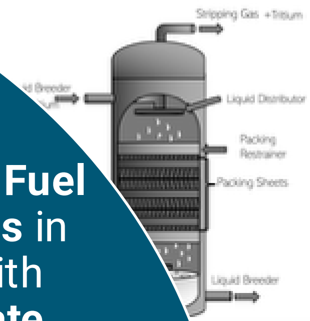
Leverage **design expertise** and world-leading **computation** to advance private sector FPP desi

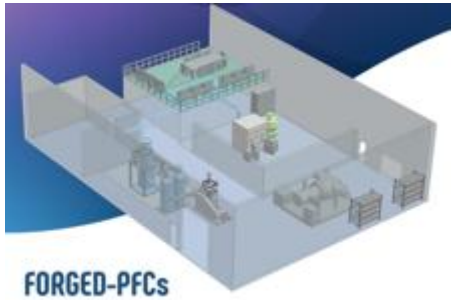
Build **Blanket and Fuel Cycle Test Stands** in collaboration with **public** and **private sector partners** to support a **Blanket and** **uel Cycle Test Facility**

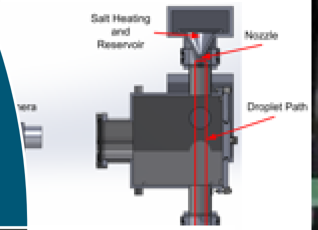
Knowledge Transfer

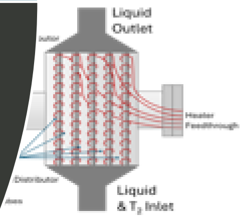
Coordinate wi **foundational R&D** issues through **experiments** and **simulation**

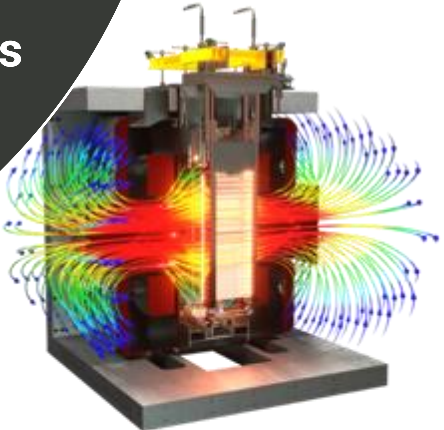
Resolve key **feasibility** and **integration** issues through **integral scale experiments**











Questions?

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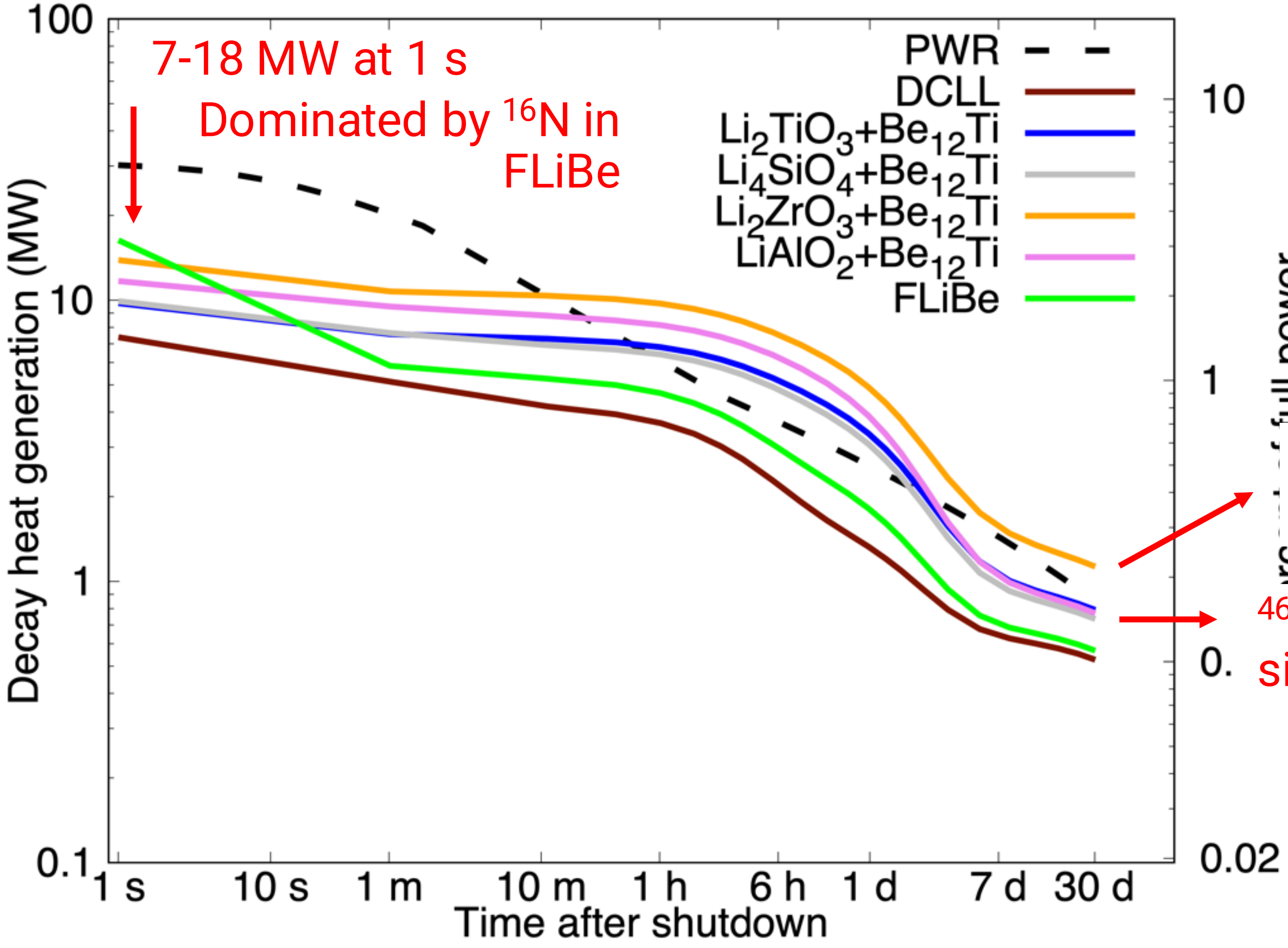
U.S. DEPARTMENT OF ENERGY

Decay heat dependence on blanket concept

- FNSF with PbLi replaced with other breeder/multiplier materials:



Blankets with high beryllium content lead to increased activation of FW and Divertor tungsten through multiplication, moderation of the neutron flux

^{95}Zr, ^{95}Nb add significantly in Li_2ZrO_3 breeder

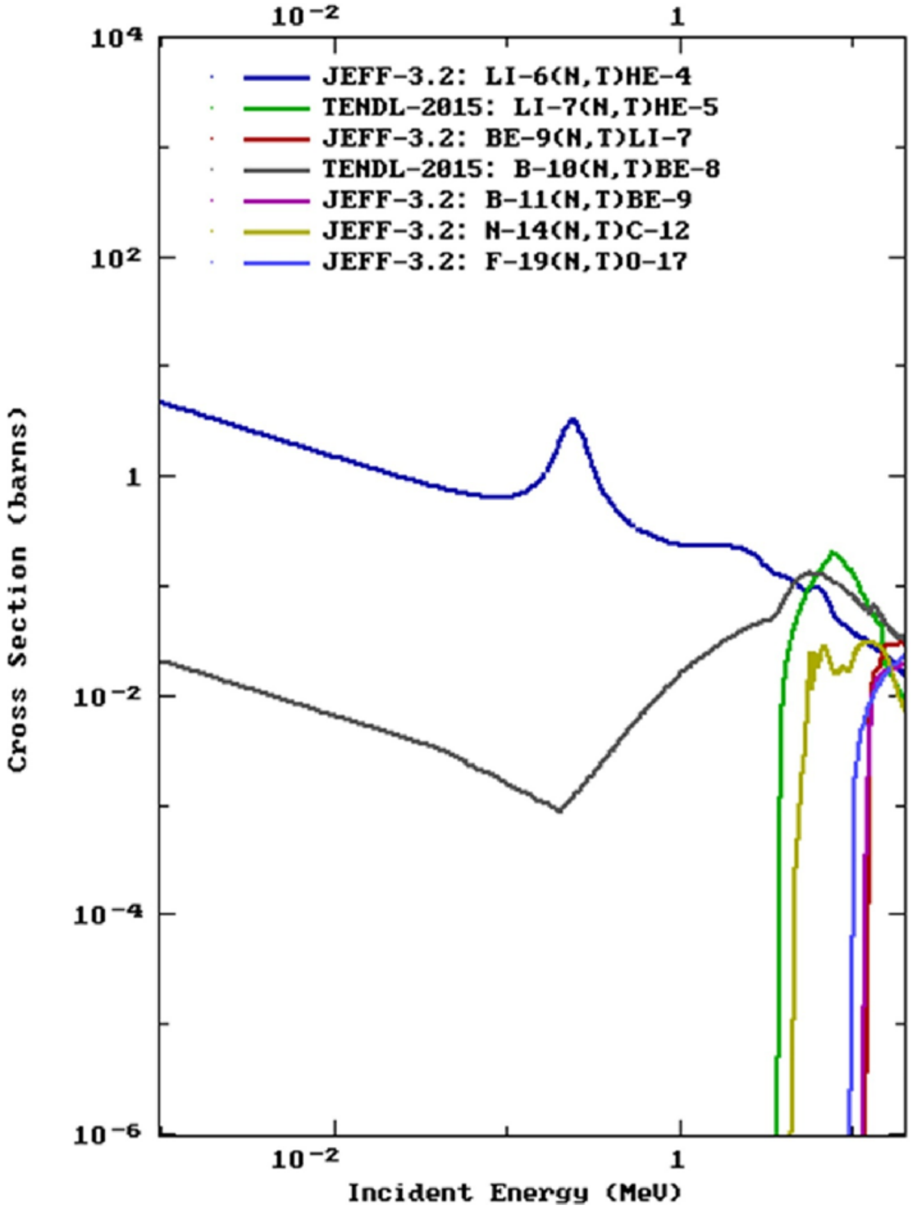
^{46}Sc (from Ti in multiplier) adds significantly in solid breeders

Lithium is the only solution

- Lithium is the only element that can achieve a TBR > 1:
  - $n + {}^{6}Li \rightarrow {}^{4}He + T + 4.785$ MeV
    - Large cross section at thermal energies
    - Exothermic: produces additional energy!
  - $n + {}^{7}Li \rightarrow {}^{4}He + T + n' - 2.5$ MeV
    - Produces tritium *and* a neutron
- A D-T fusion is essentially fueled with deuterium and lithium:

$$T + D \rightarrow {}^{4}He + n$$

$$T + {}^{4}He \leftarrow Li + n$$



F. Hernandez, *Fusion Engineering and Design* **137** (2018) 243-256.

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Beryllium as a multiplier

Pb and Be are the only viable multipliers

Pure Be has a number of shortcomings as a multiplier material (aside from toxicity and resultant difficulty in manufacturing):

- High swelling under irradiation, especially at high temperature (> 600 °C)
- High tritium retention (40% at 600 °C)
  - A small but significant (<1%) amount of tritium is bred in beryllium
    - $^{9}Be(n,\alpha) \rightarrow {}^{6}He \rightarrow {}^{6}Li + \beta^{-}$
    - $^{9}Be(n,T) \rightarrow {}^{7}Li$
  - Diffusivity of tritium in beryllium metal is low (it would be a decent permeation barrier)
- High chemical reactivity…

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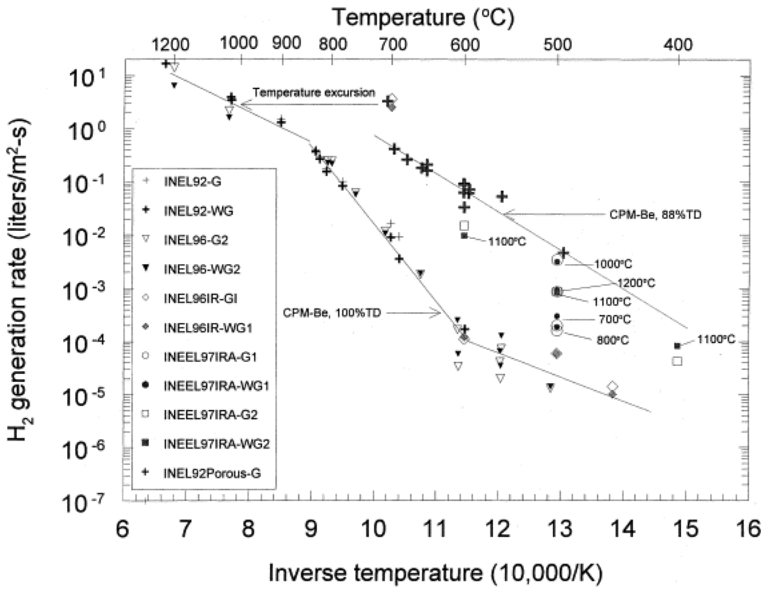
F. A. Hernández, *Fusion Engineering and Design* **137** (2018) 243-256.
F. A. Hernández, *Fusion Science and Technology* **75** (2019) 352-364.

Beryllium Oxidation

R. A. Anderl, *Journal of Nuclear Materials* **258-263** (1998) 750-756.

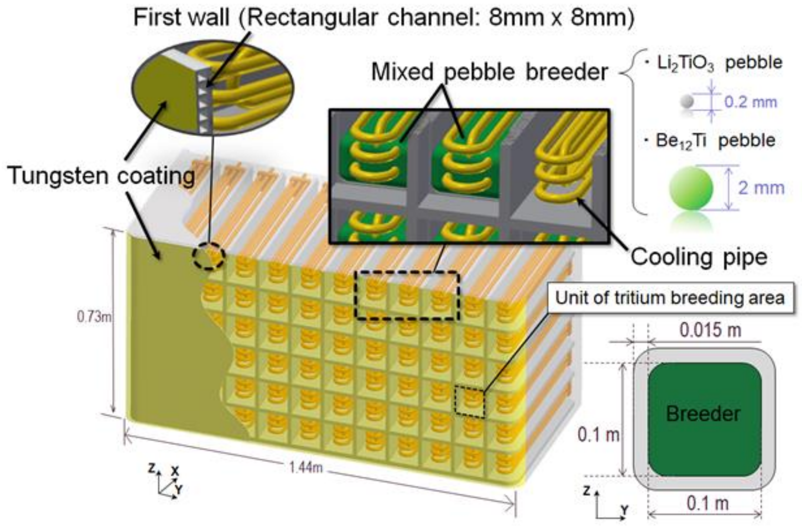


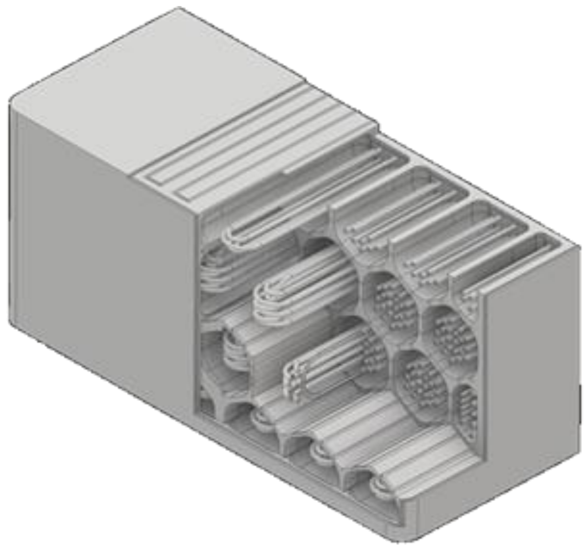
Beryllium reacts exothermically with steam and air; at high temperature the possibility for “runaway” reactions exists

For water-cooled ceramic breeder designs, this is a significant safety issue

So also for ITER (water cooling and beryllium PFCs)

- Helium cooling avoids steam reactions, hydrogen generation
- But should consider the event of air ingress, e.g. as a result of ex-vessel helium pipe break





Y. Someya, 2018 US-JA Workshop

Beryllides

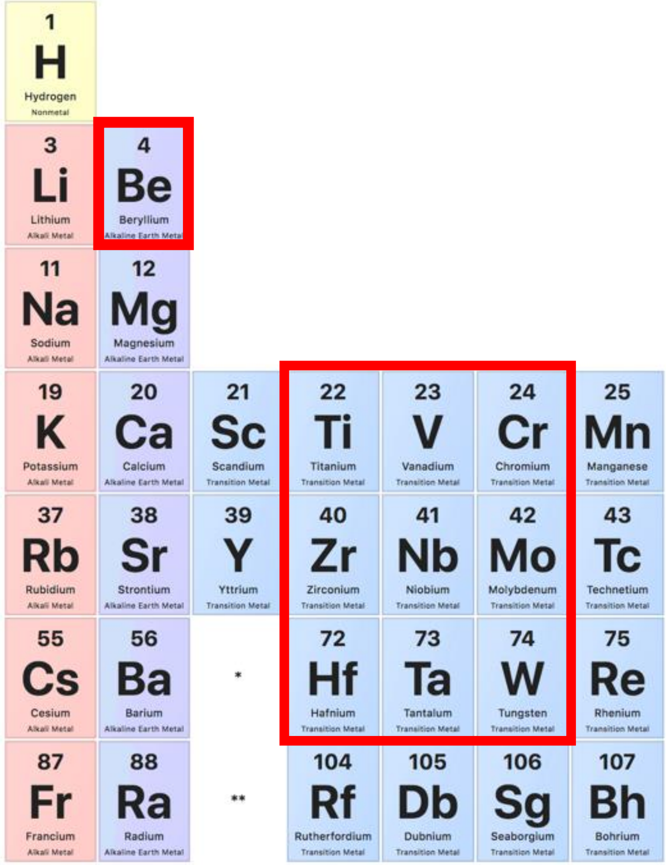
Need to inhibit oxidation led to a search for alternate materials with high beryllium content but better oxidation resistance

Focus on group 4-6 transition metal beryllide intermetallic compounds

- Be_XM, where X=12 or 13; >92% beryllium
- Hard, brittle, high melt temperature (1500-1900 °C)

Early research performed by Brush Wellman (now Materion), funded by the air force, in search of new oxidation-resistant high temperature materials

None apparently found widespread application at that time, but high beryllium density, high temperature, oxidation resistant behavior makes them potentially attractive multipliers for ceramic breeder blankets



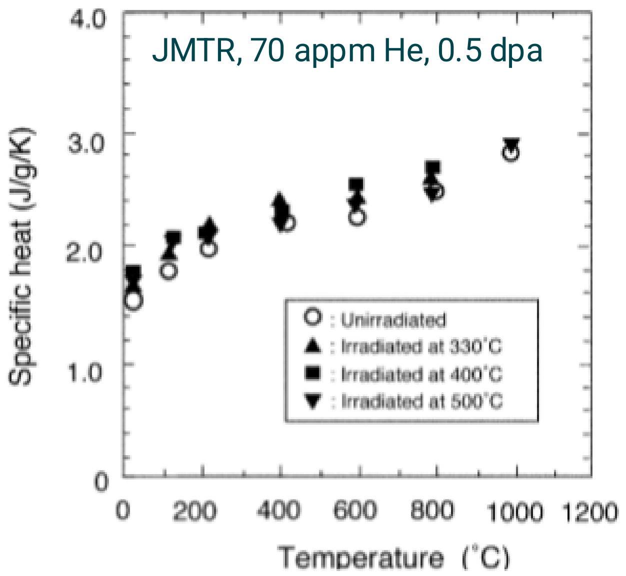
Titanium Beryllide

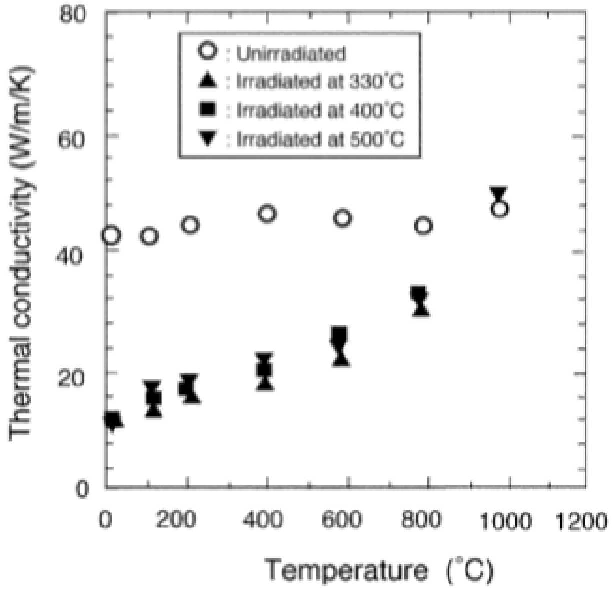
Titanium beryllide, $Be_{12}Ti$, is the first and most extensively studied beryllide for fusion applications

- Best neutron multiplier among the beryllides[1]

$$\rho = 2.26\ \mathrm{g/cm^3},\ T_{melt} = 1538\ \mathrm{°C}$$

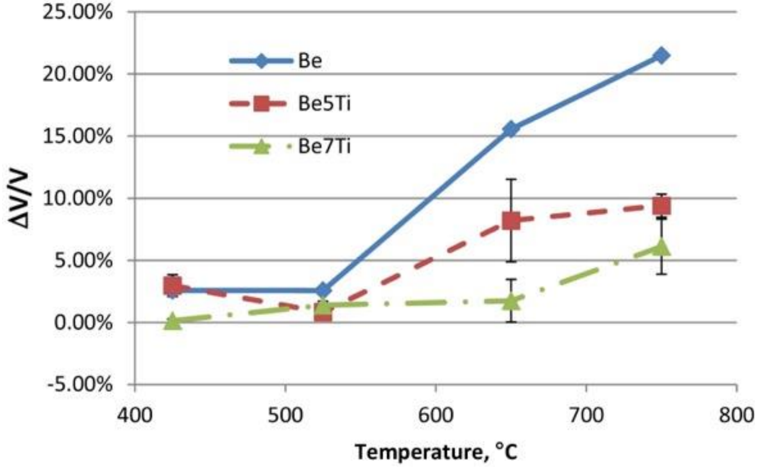
Irradiation to 19.5 dpa, 2740 appm He in HIDOBE-01 revealed much lower swelling and tritium retention compared to pure Be

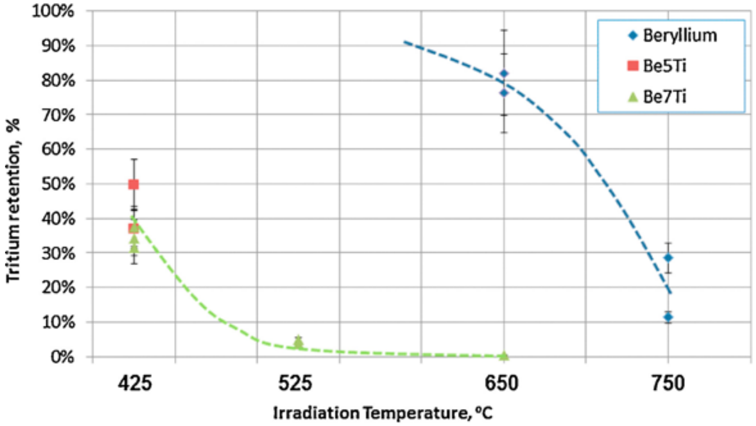




M. Uchida, *Fusion Engineering and Design* **69** (2003) 499-503.

A. V. Fedorov, *Fusion Engineering and Design* **102** (2016) 74-80.





[1] C. Dorn, *Fusion Engineering and Design* **84** (2009) 319-322.

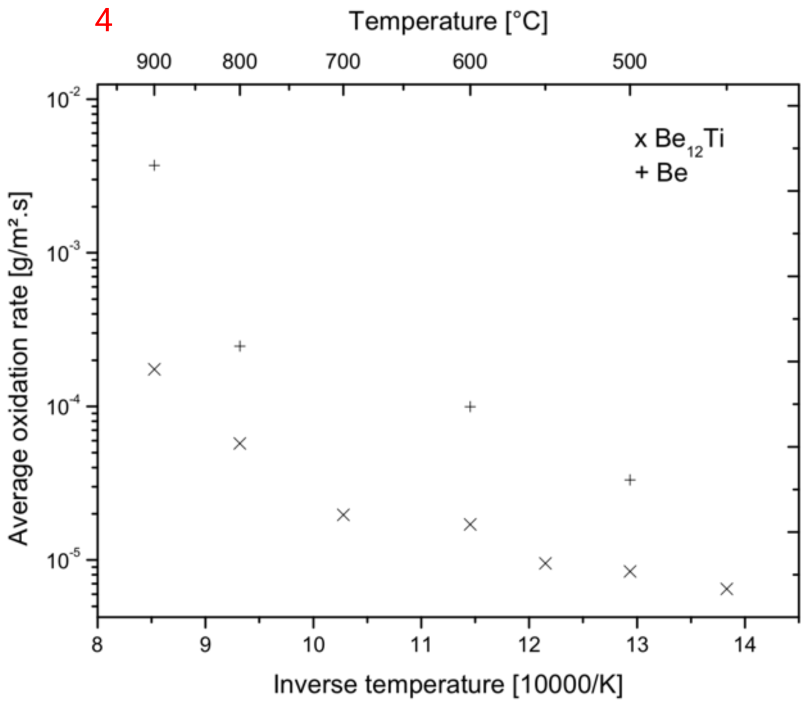
Titanium Beryllide Oxidation

Titanium beryllide ($Be_{12}Ti$) amongst those characterized in early work by Brush Wellman[1]; not as extensively characterized as other beryllides, which outperformed it[3]

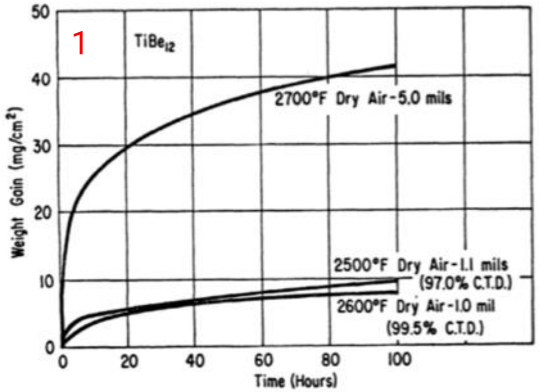
Complete oxidation: $Be_{12}Ti + 7O_2 \rightarrow 12BeO + TiO_2$

TiO_2 not observed in more recent air oxidation work; Be expected to reduce TiO_2[2]

Multiple studies suggest lower oxidation rates than pure Be; 6-20x lower in SCK-CEN studies[4]



[1]R. M. Paine, *Corrosion* **20** (1964) 307t-310t.
[2]P. Kurinsky, *Fusion Engineering and Design* **86** (2011) 2454-2457.
[3]C. Dorn, *Fusion Engineering and Design* **84** (2009) 319-322.
[4]F. Druyts, https://www.osti.gov/etdeweb/servlets/purl/20658771.



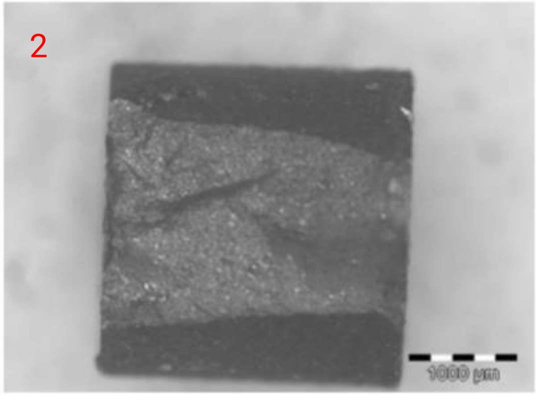


Fig. 2. $Be_{12}Ti$ cylindrical sample after loading at 800 °C.

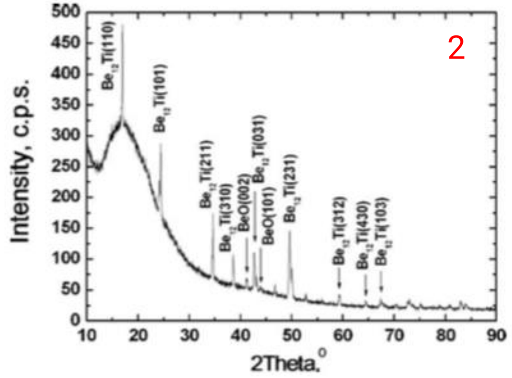


Fig. 8. X-ray diffraction pattern of $Be_{12}Ti$ specimen annealed at 800 °C in air.