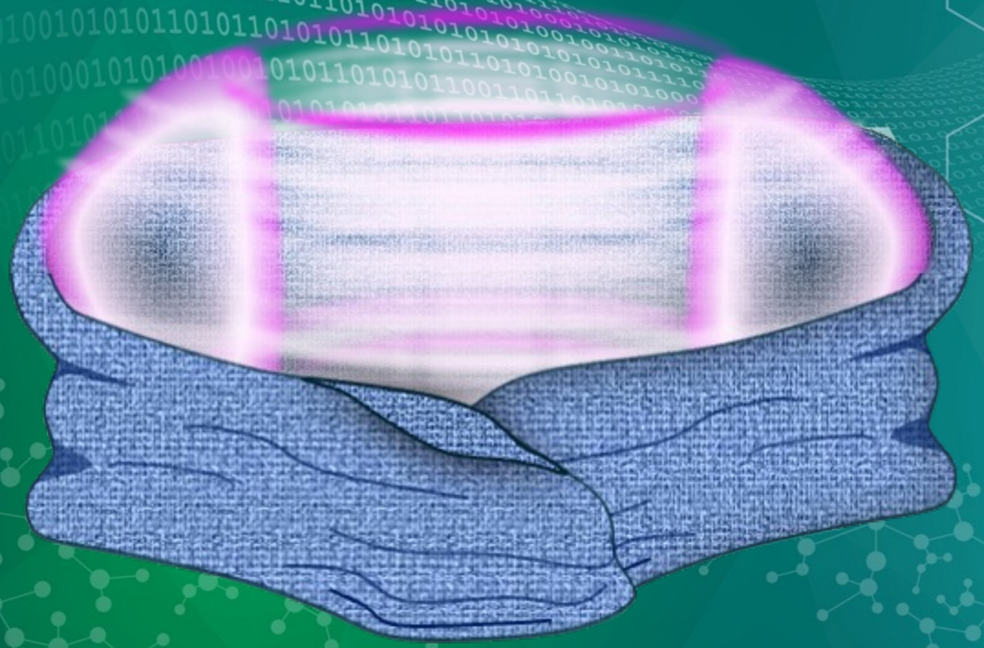
Oak Ridge National Laboratory

Tritium Breeding Blankets for Nuclear Fusion Reactors



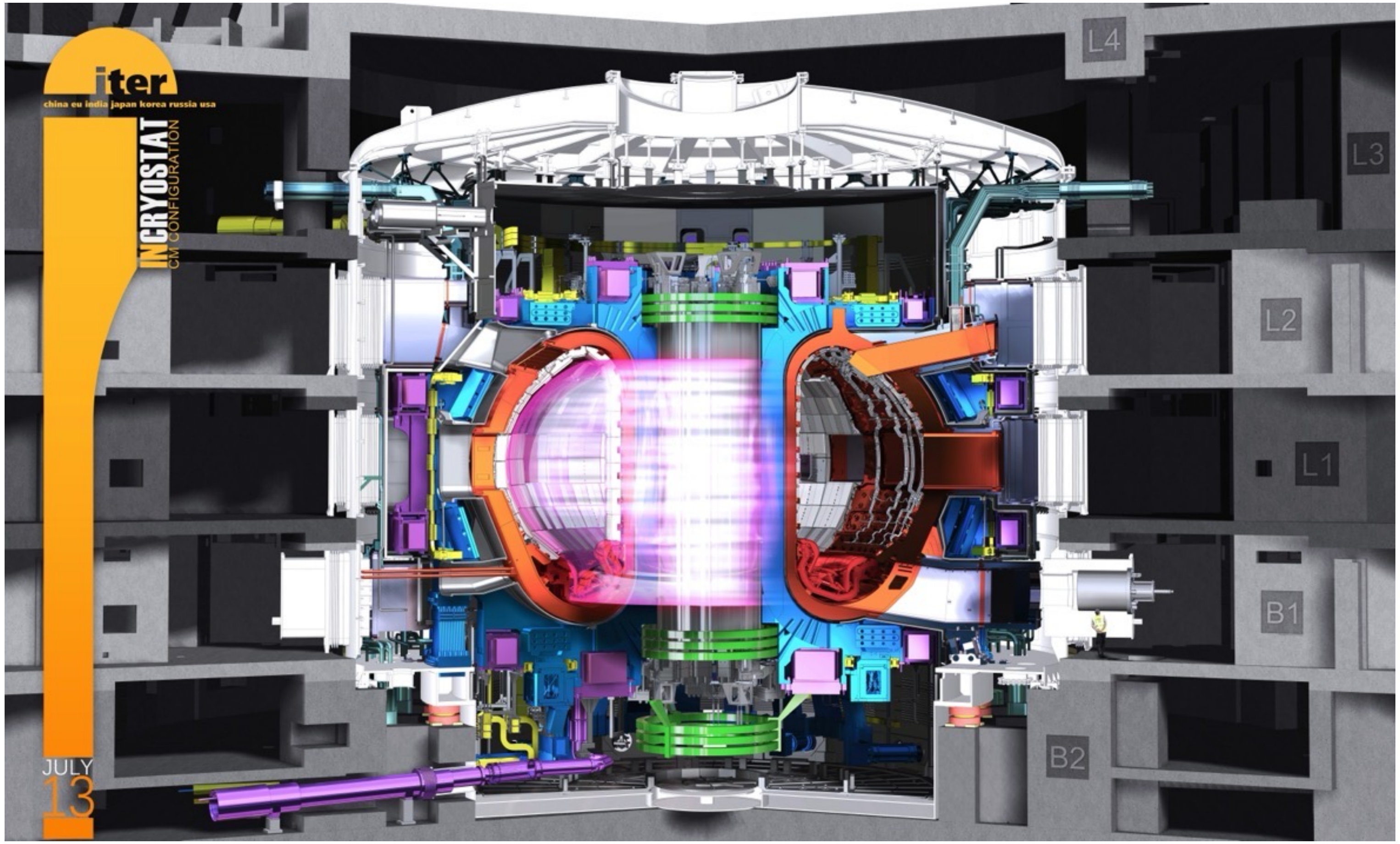
Monica Gehrig, PhD

Paul Humrickhouse, PhD

Blanket and Fuel Cycle Group

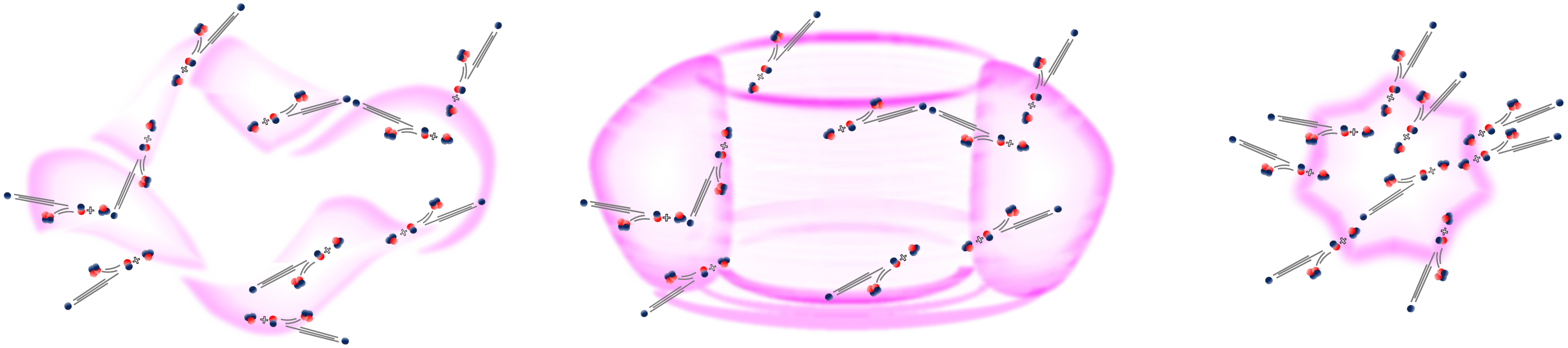
Fusion Energy Division

A lot goes into making fusion work



Fusion produces high energy neutrons

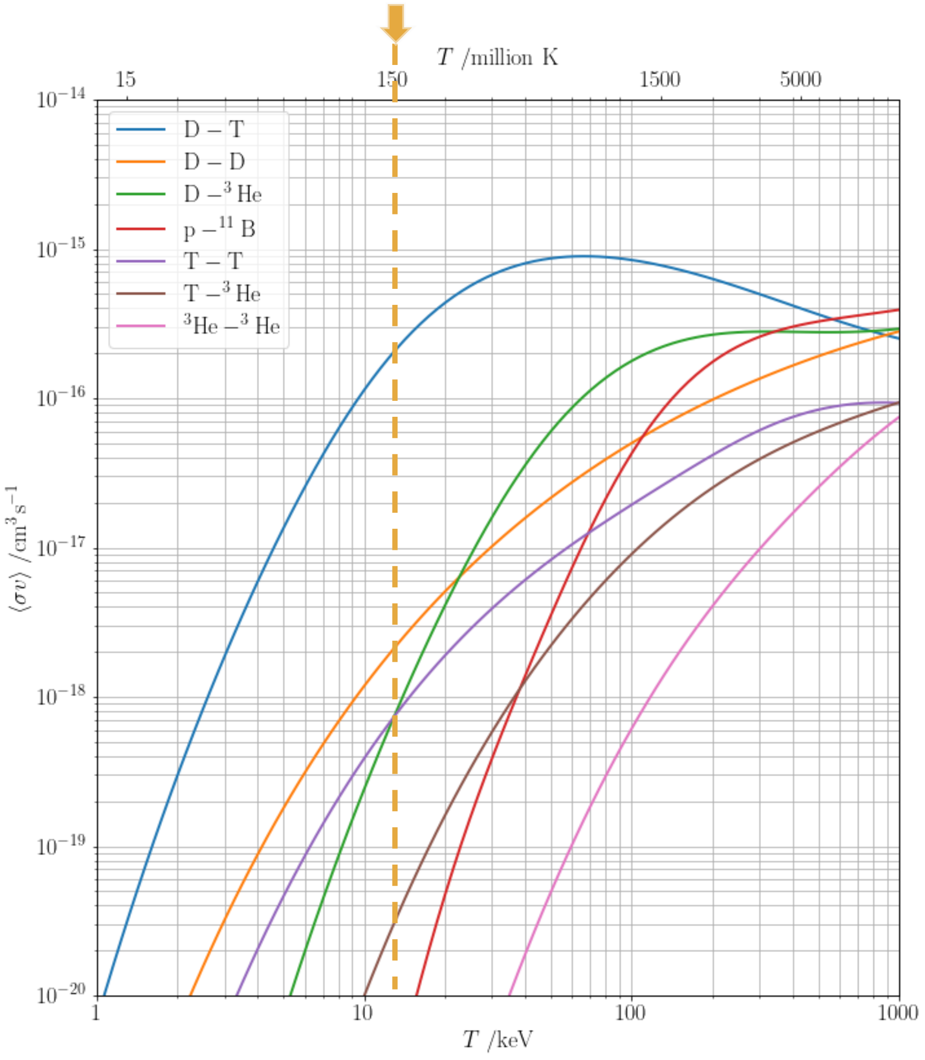
D+T → He (3.5 MeV) + n (14.1 MeV)



How can we use those neutrons?

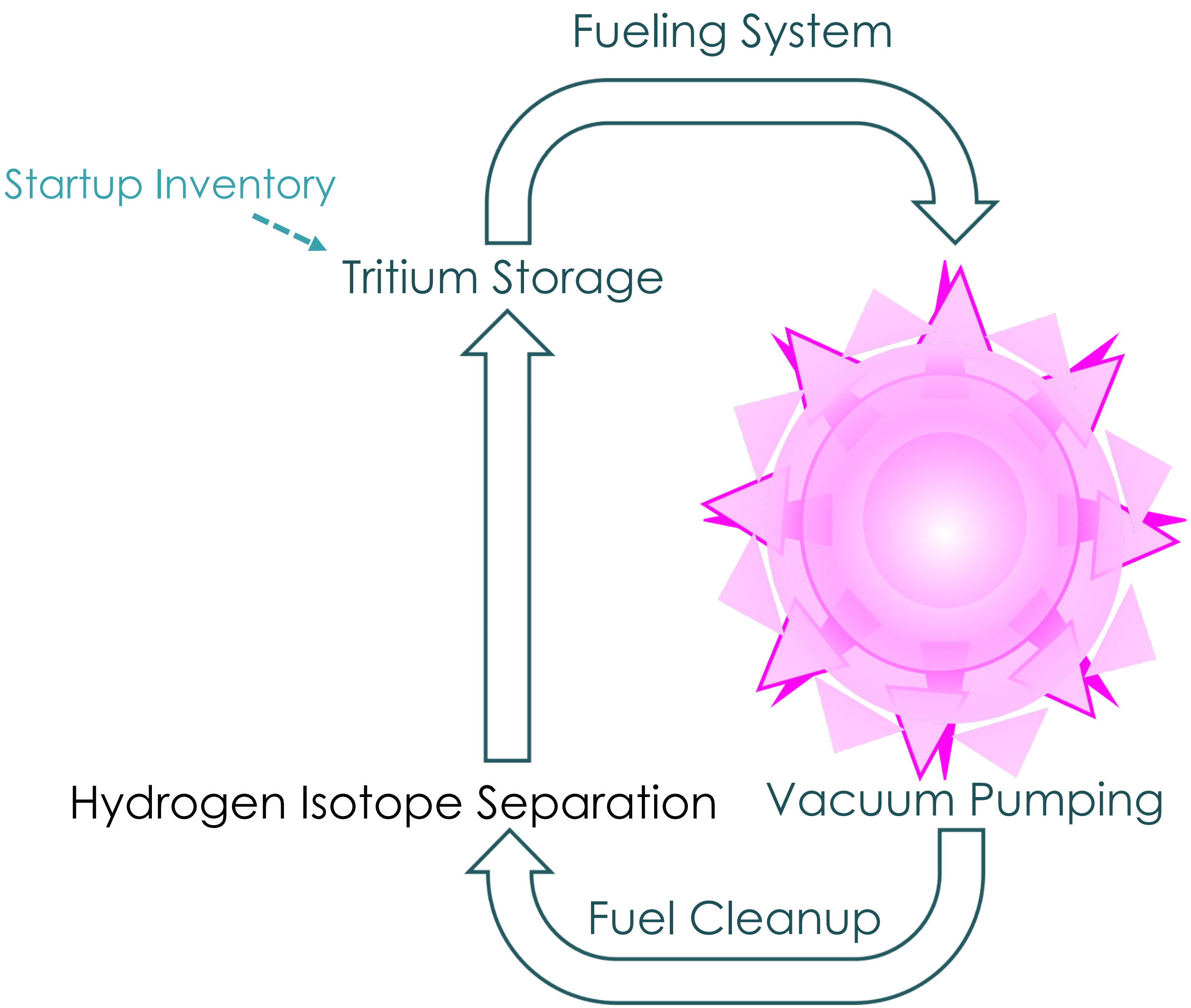
What challenges do those neutrons present?

The need for tritium breeding



- The D-T fusion reaction is most attainable
- Tritium has a (relatively) short half-life
- Small amounts produced by fission reactors
- Need tritium supply, with a tritium breeding ratio (TBR) > 1*

Fuel Cycle and Blanket Overview



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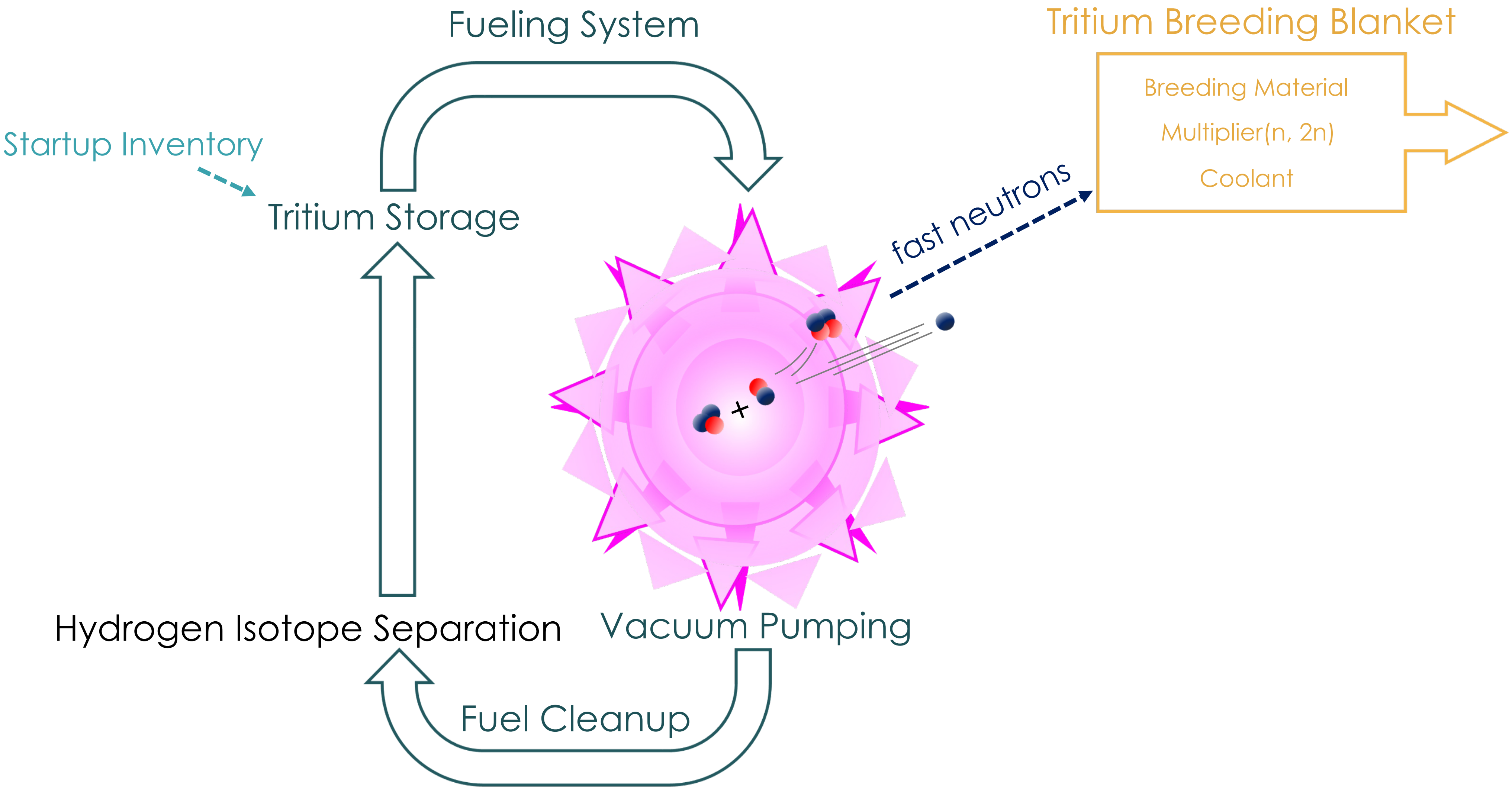

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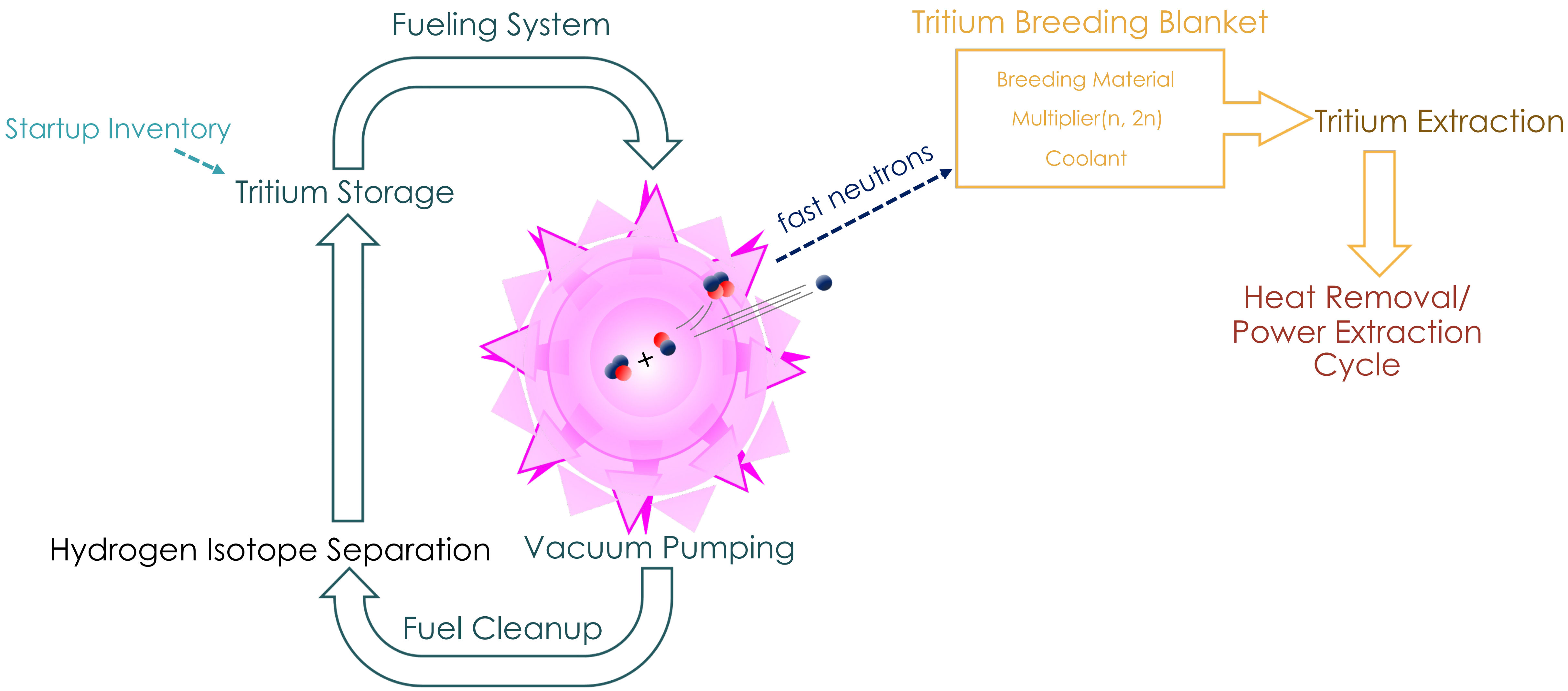

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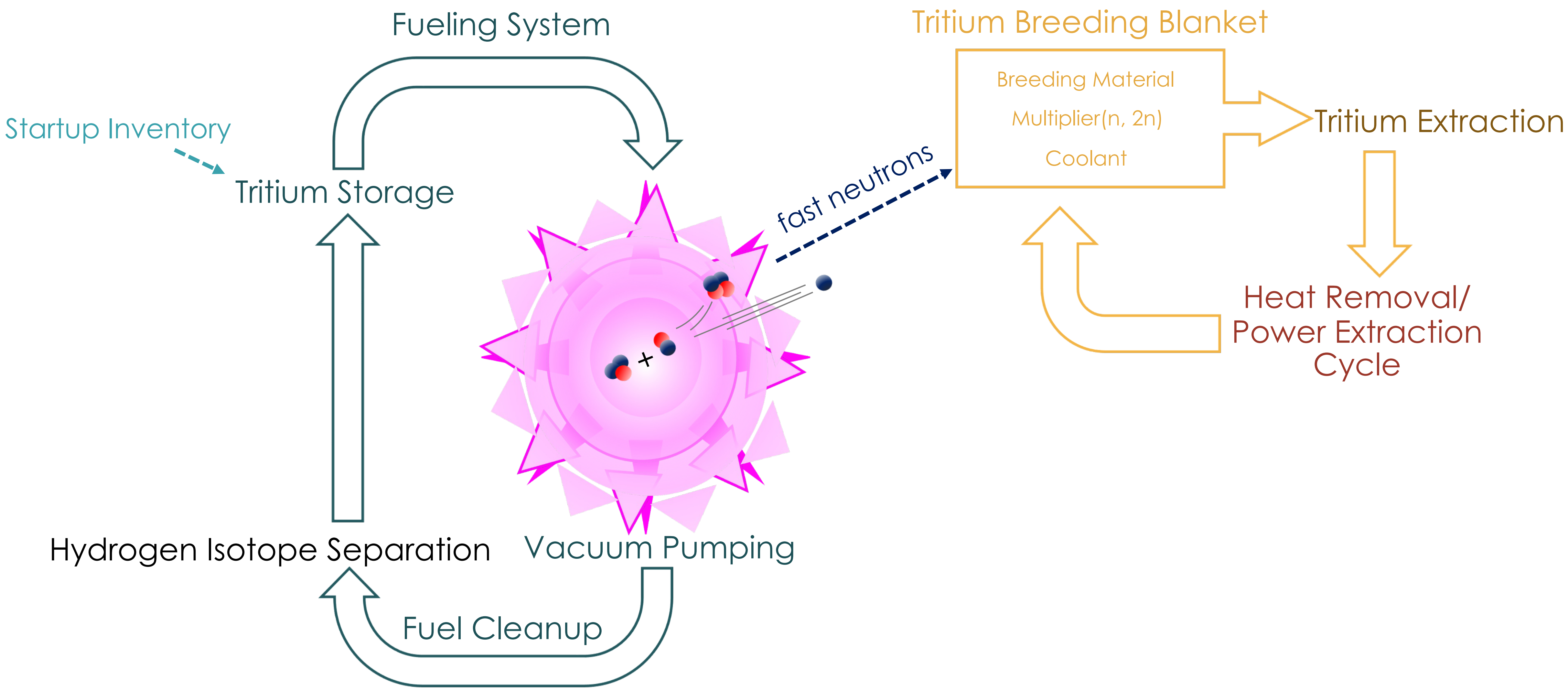

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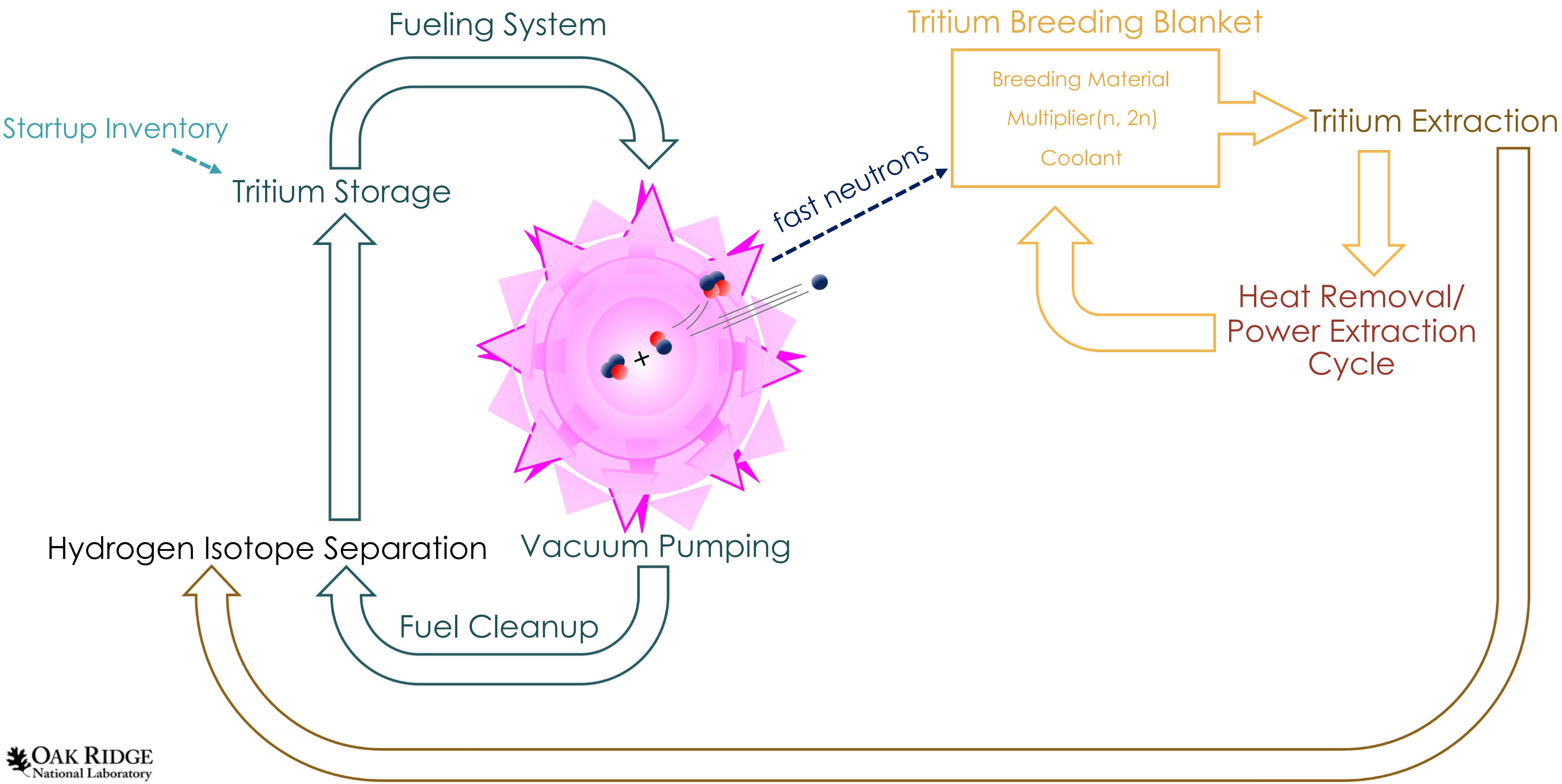

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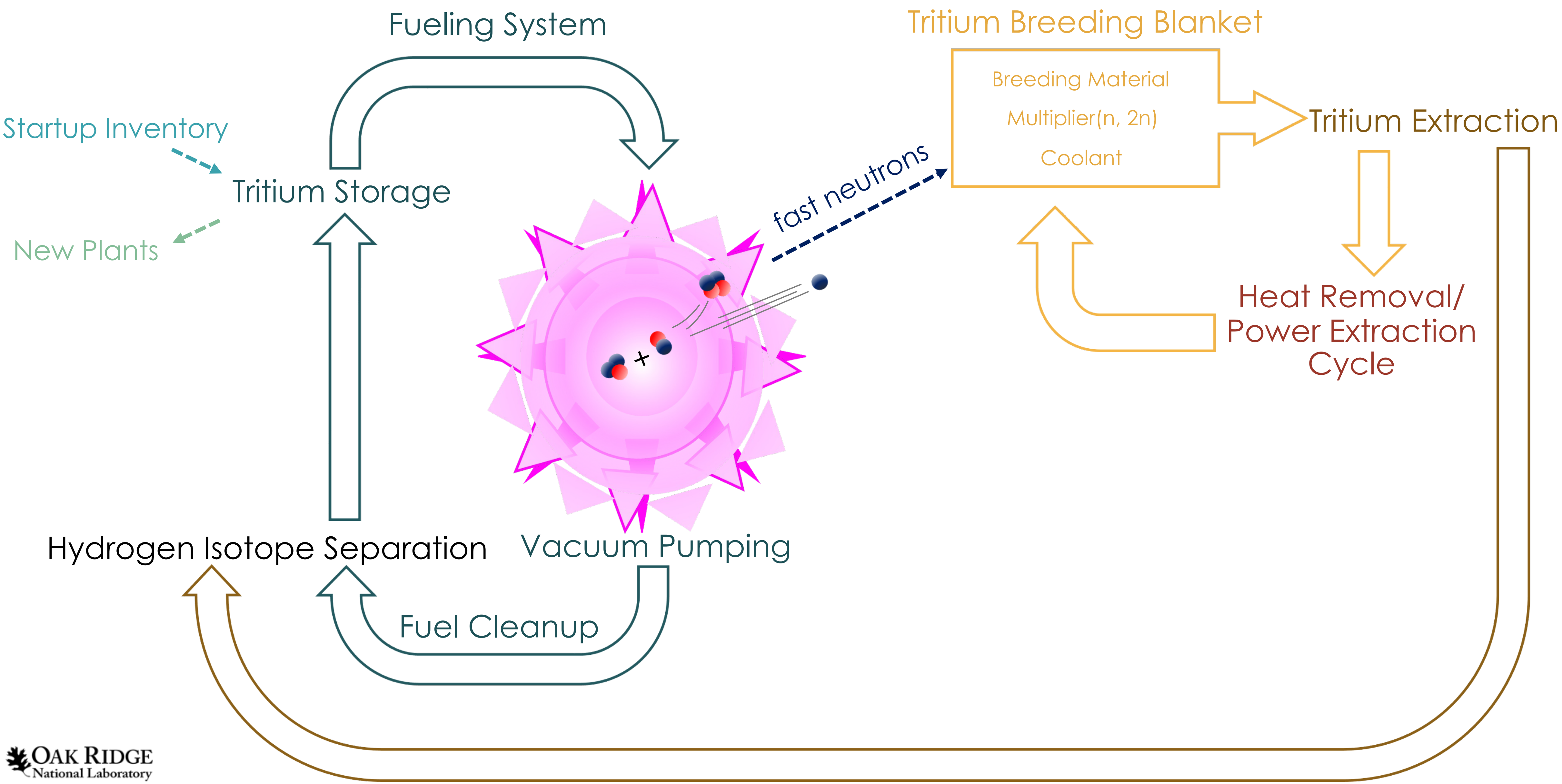

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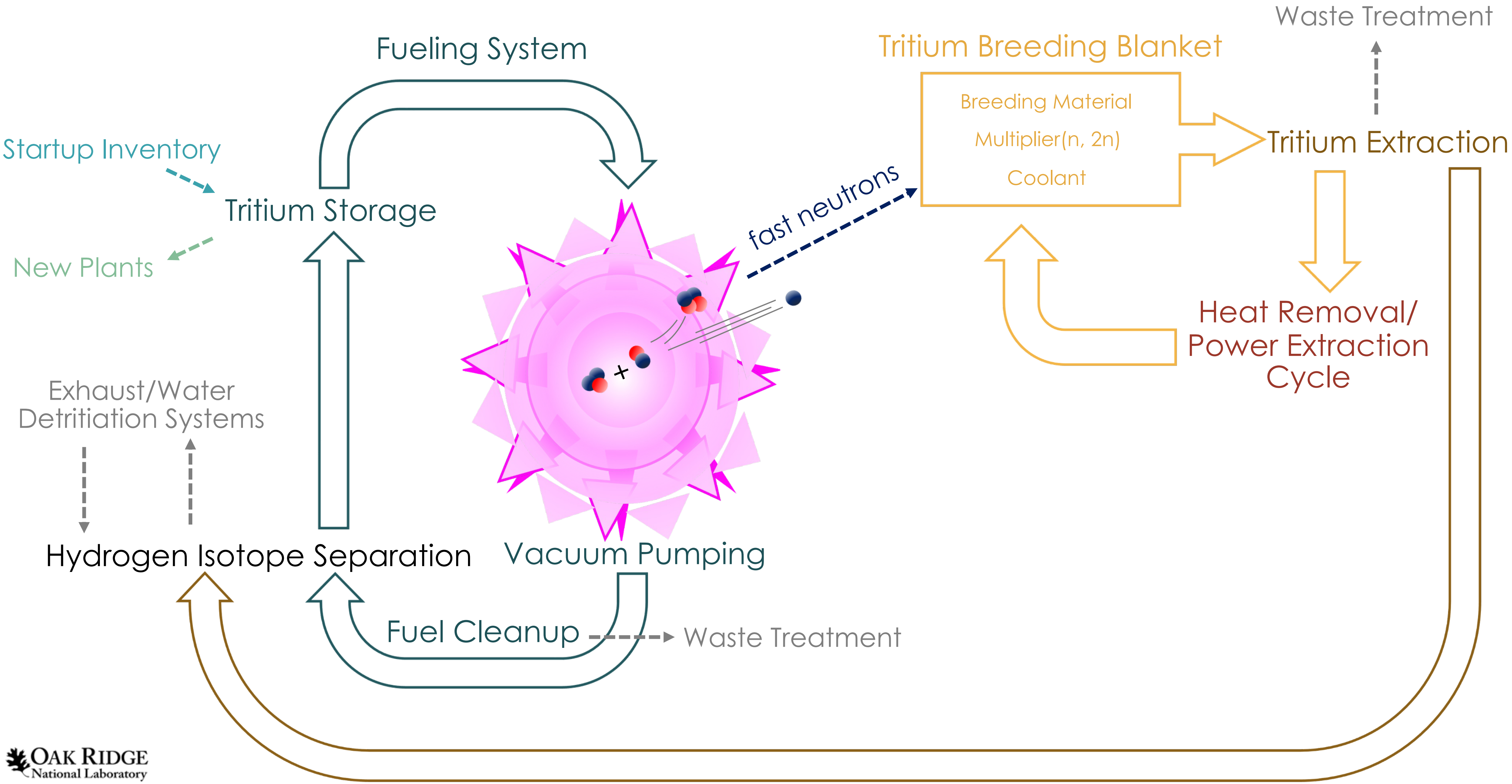

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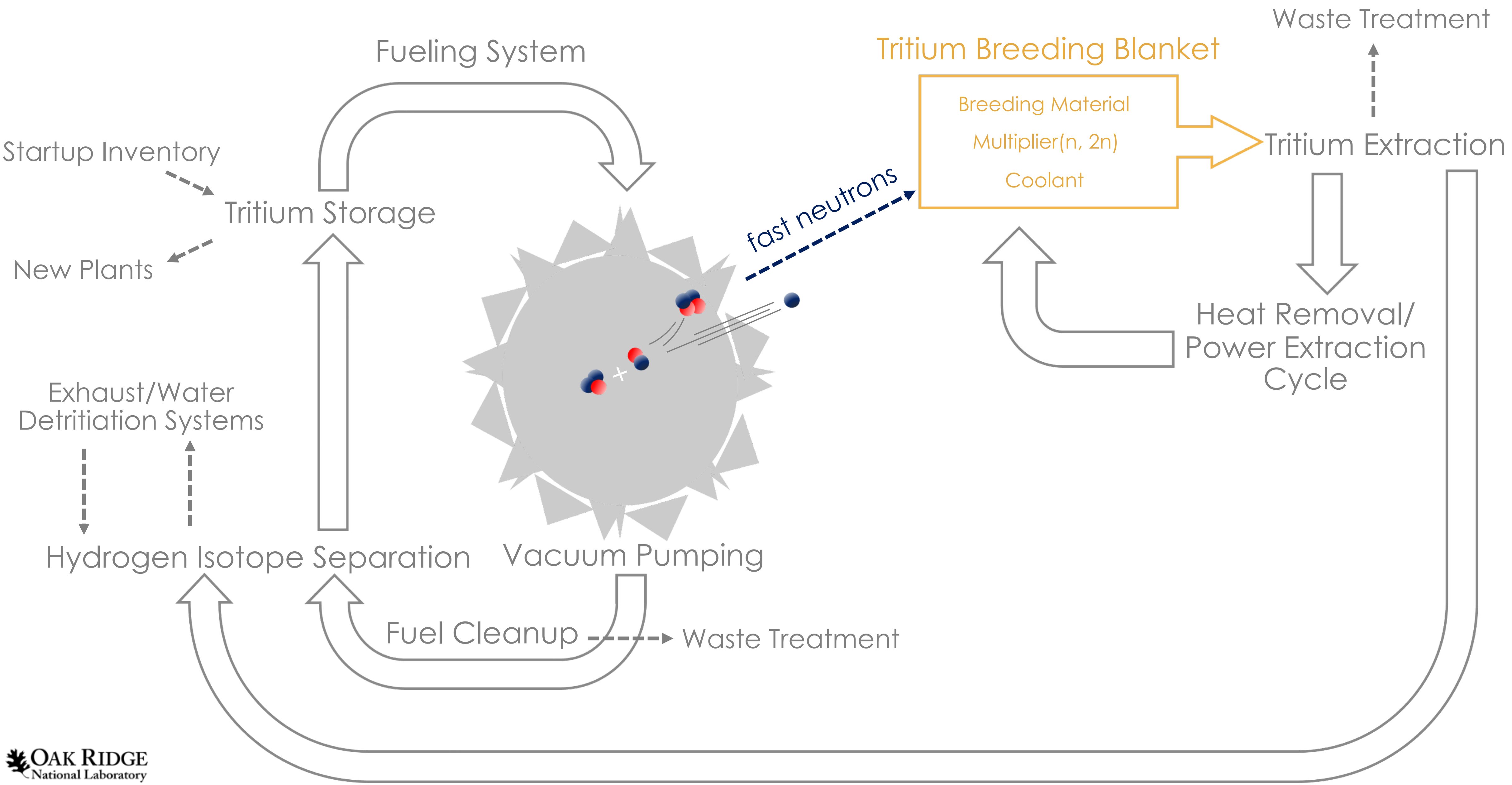
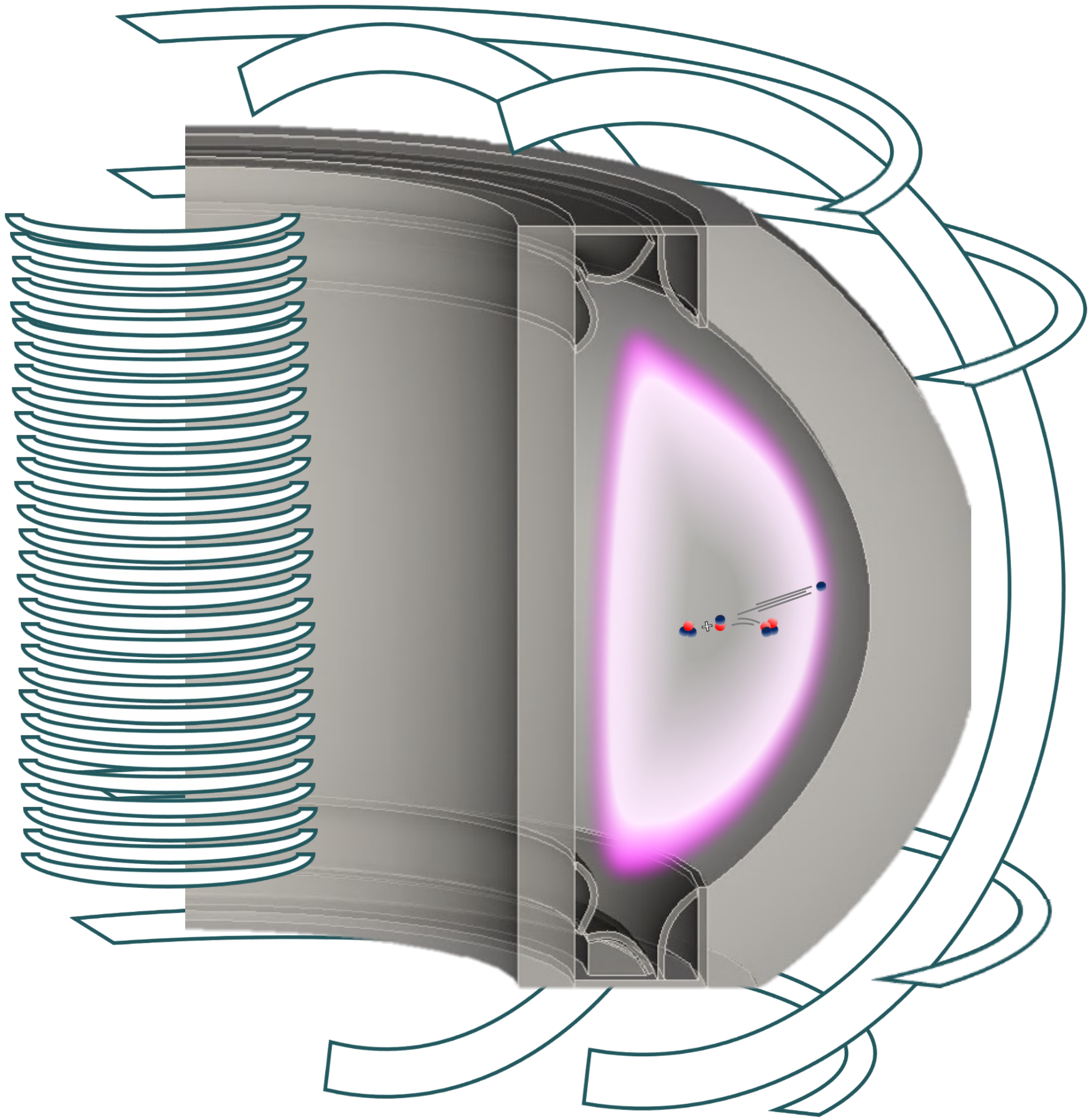


What is a blanket?

Functions

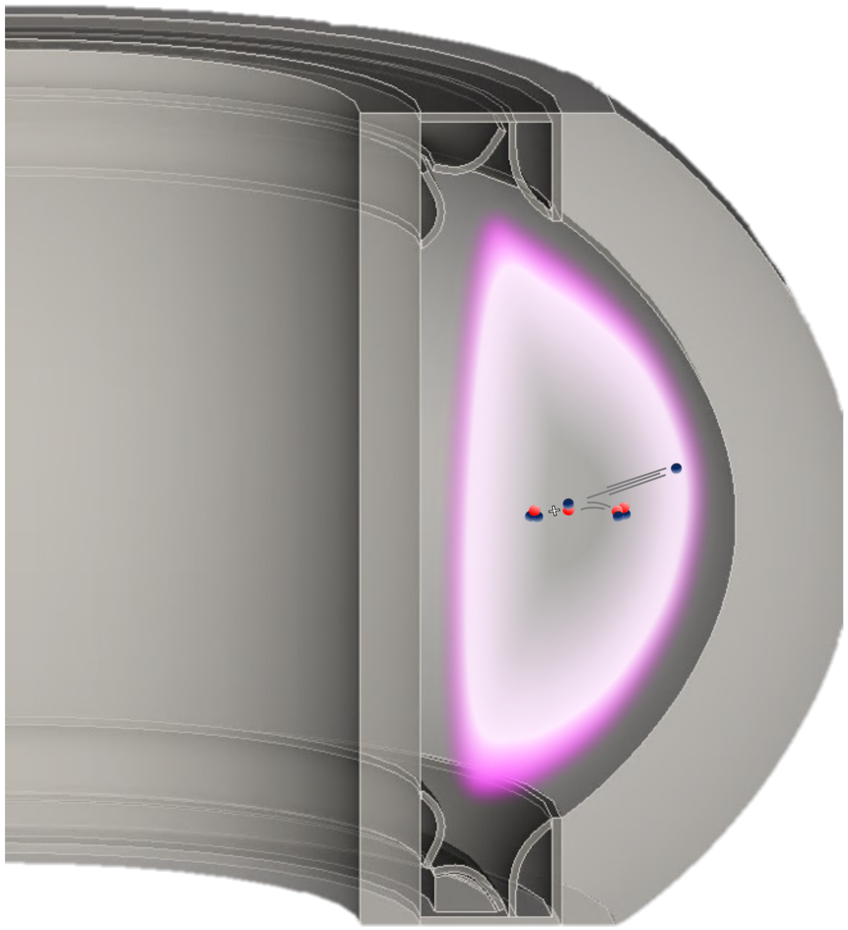
- Tritium breeding
- Heat generation/removal
- Shielding
  - magnets
  - diagnostics
- Structure



What is a blanket?

Components

- Structural Material
  - Reduced activation materials
- Tritium breeding material
  - 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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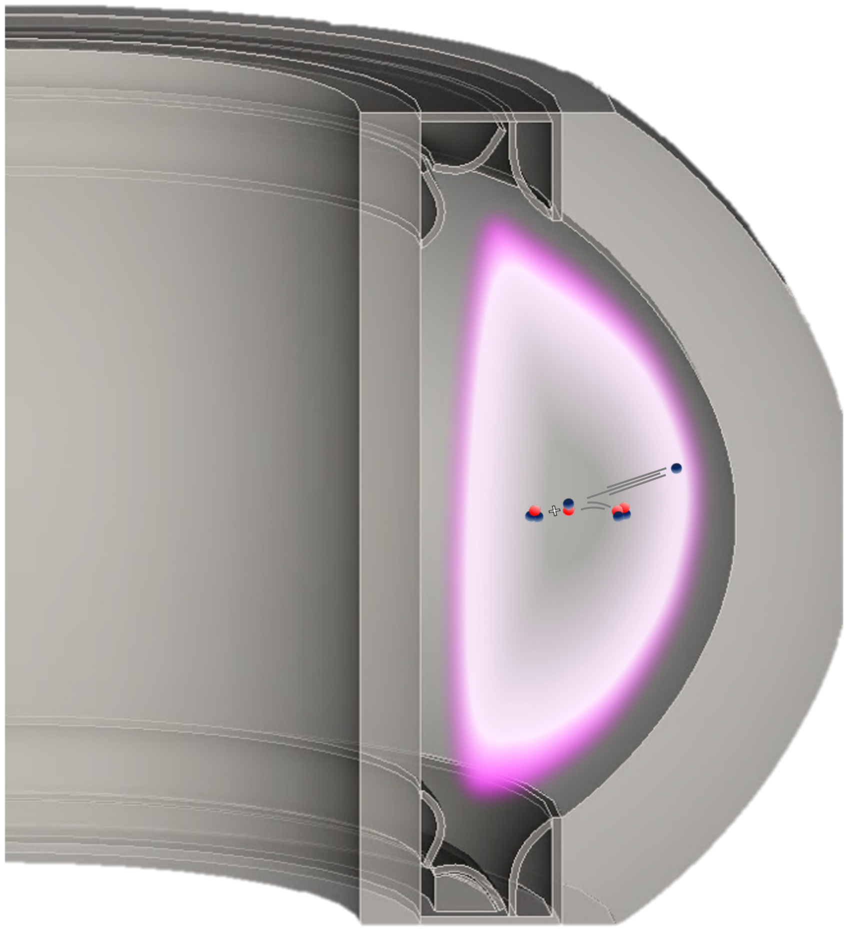
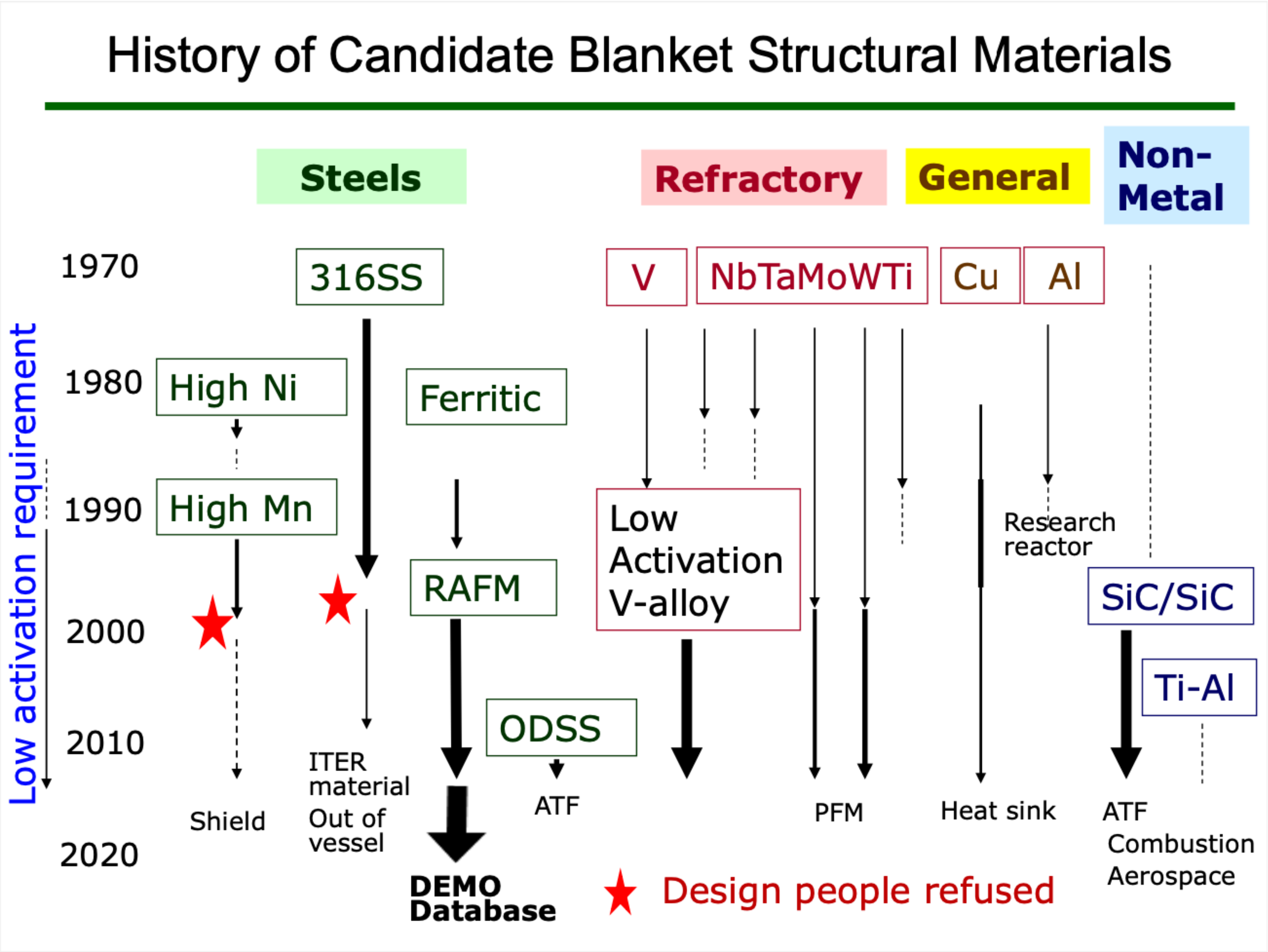


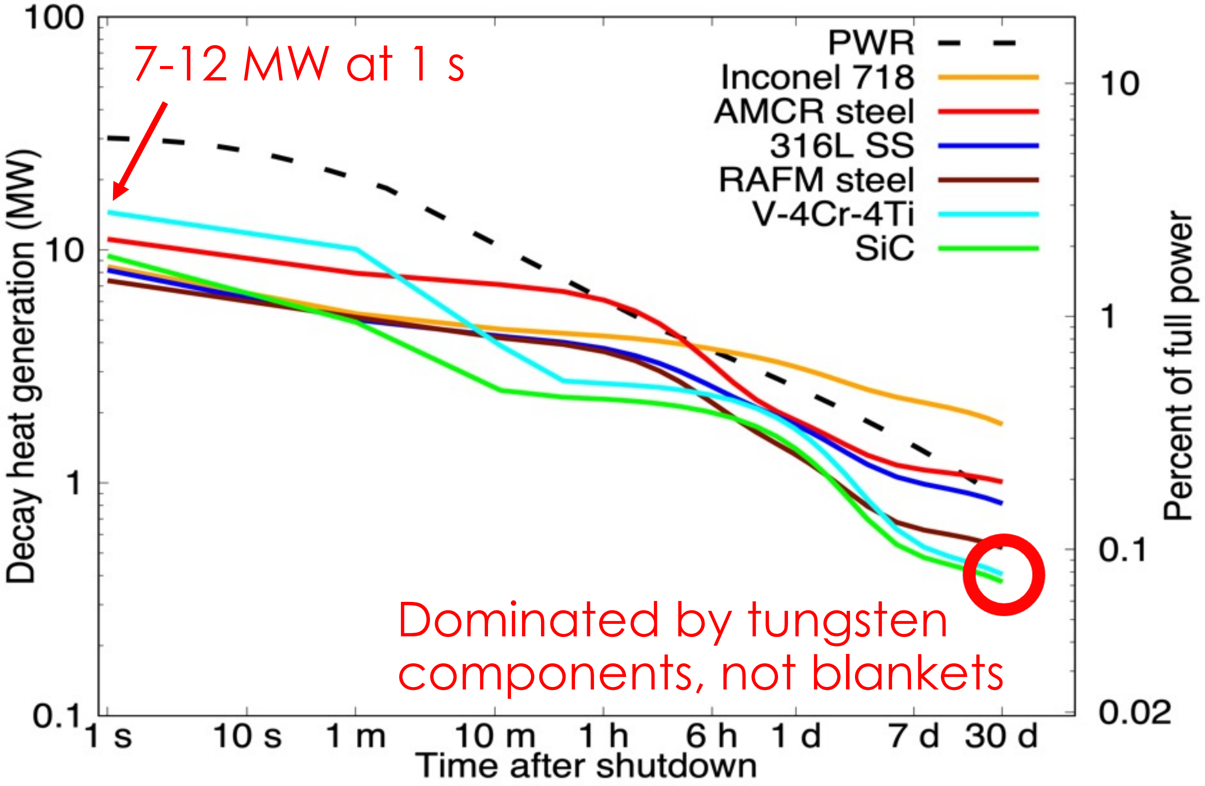
Structural Materials



T. Muroga, 3/29/2022

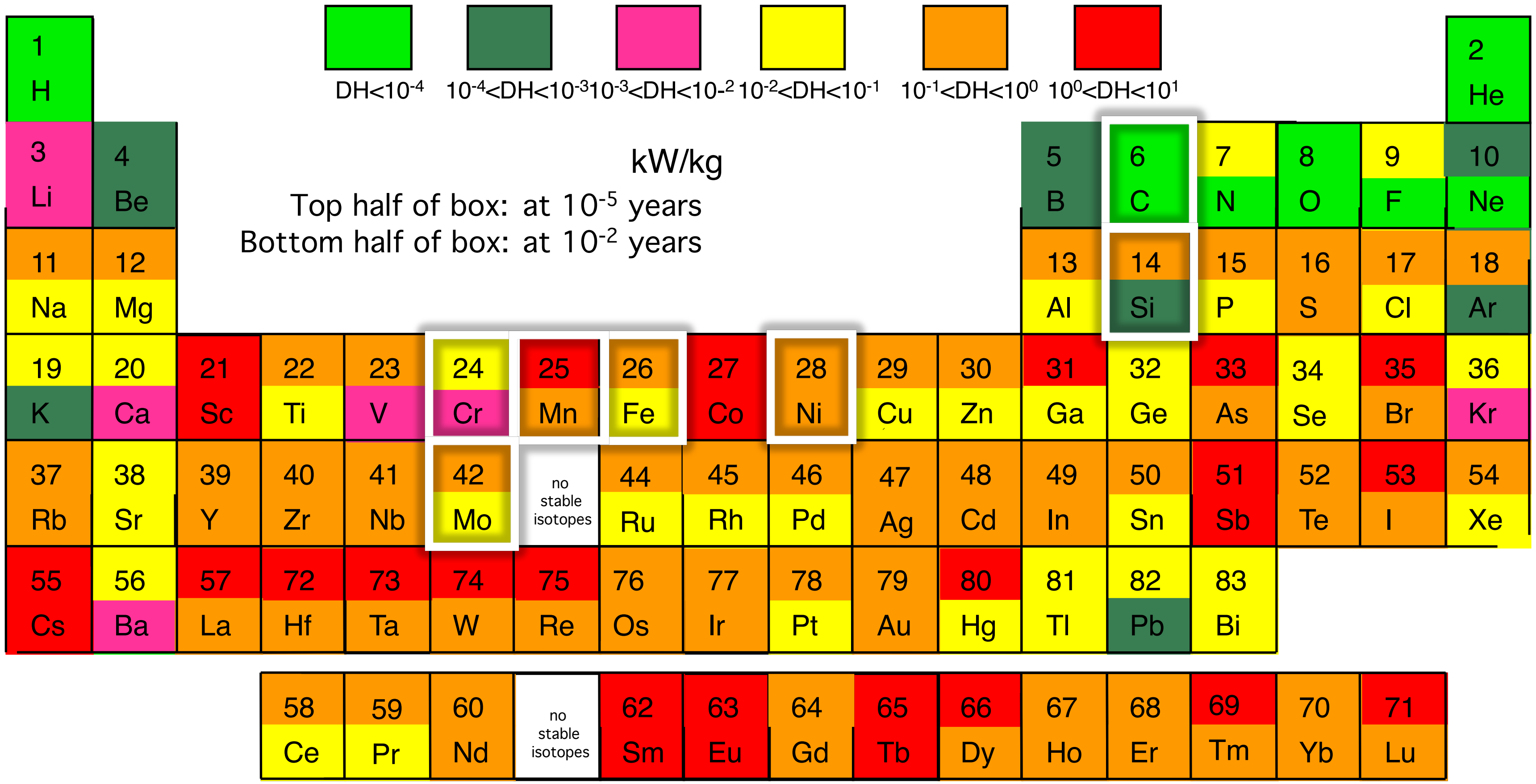
Activation of Structural Materials

- 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)

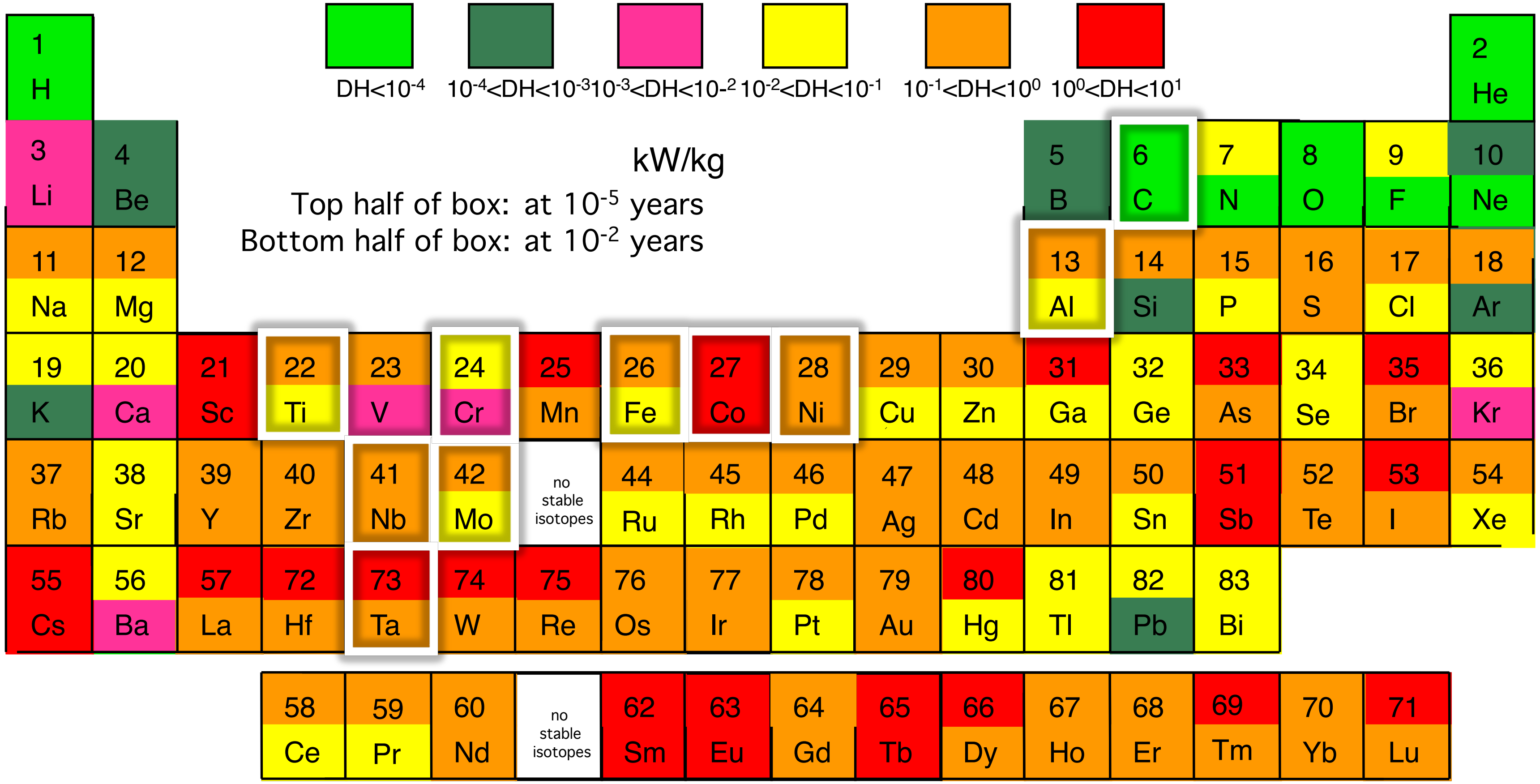
Decay Heat



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

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

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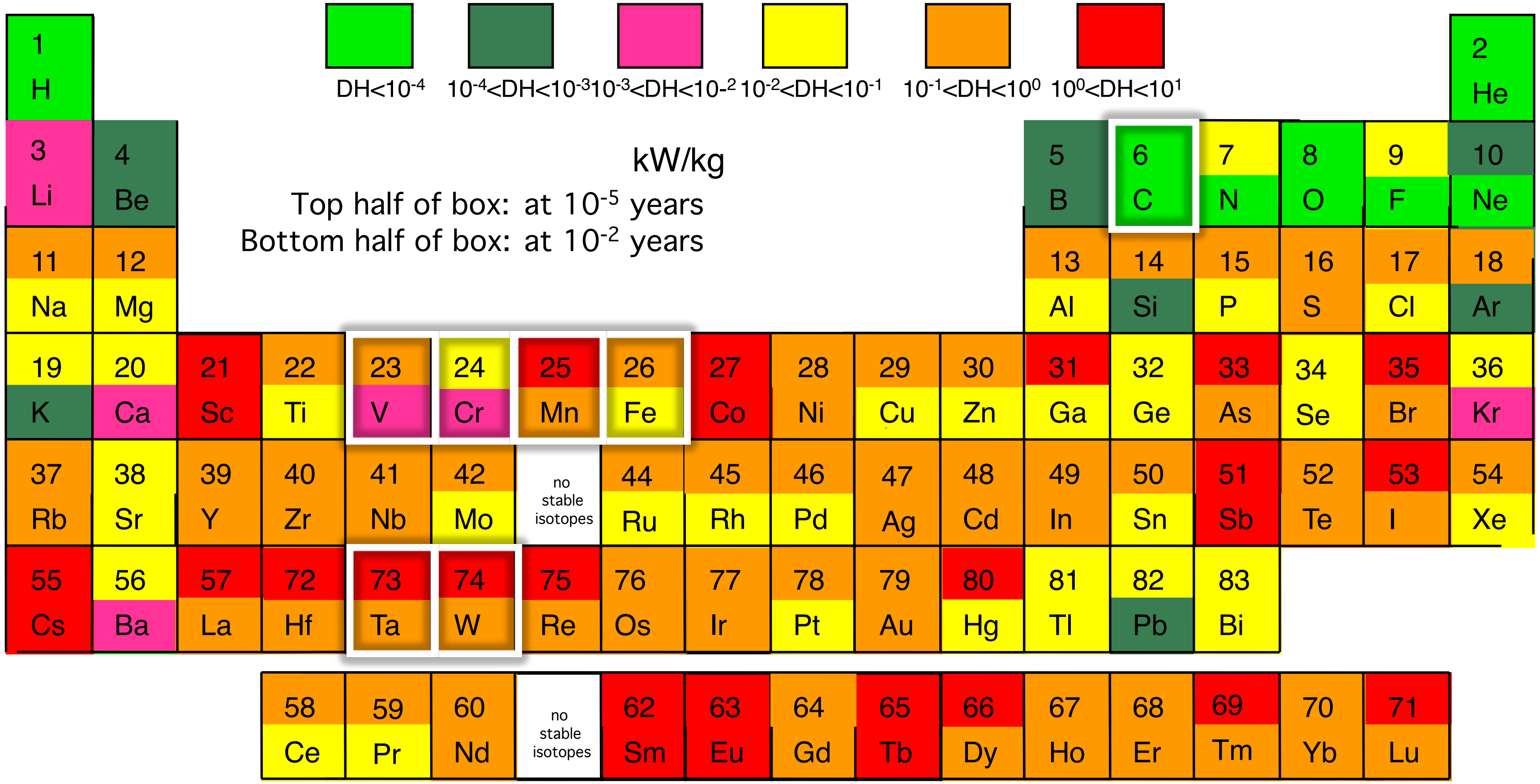

RAFM Steel

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

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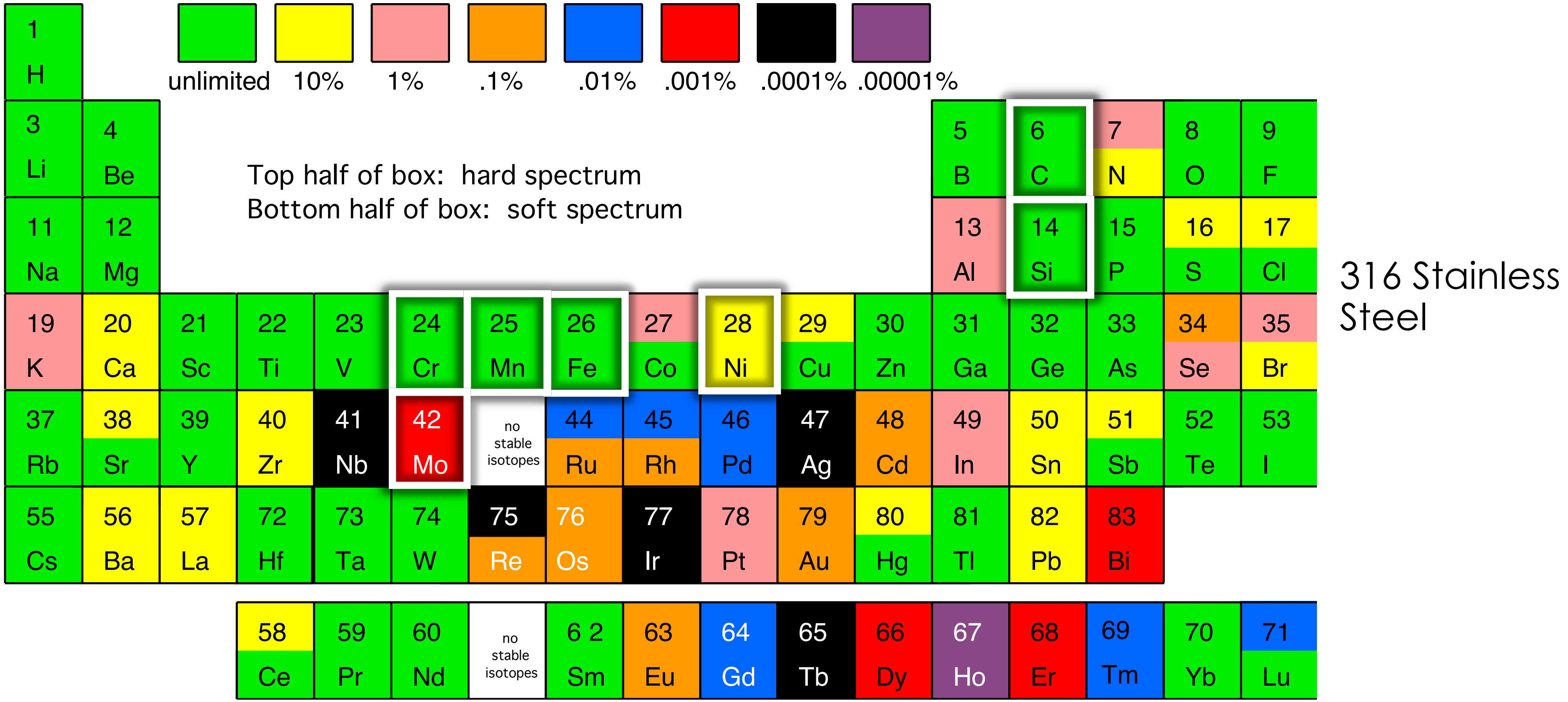
Alloy concentrations to meet Class C disposal



From: Piet, et al., "Initial Integration of Accident Safety, Waste Management, Recycling, Effluent, and Maintenance Considerations for Low-Activation Materials", **Fusion Technology**, Vol. 19, Jan. 1991, pp. 146-161. Assumes 5 MW/m^2 for 4 years; and E. T. Cheng, "Concentration Limits of Natural Elements in Low Activation Materials", **presented at ICFRM-8, Sendai, Japan,October 1997**

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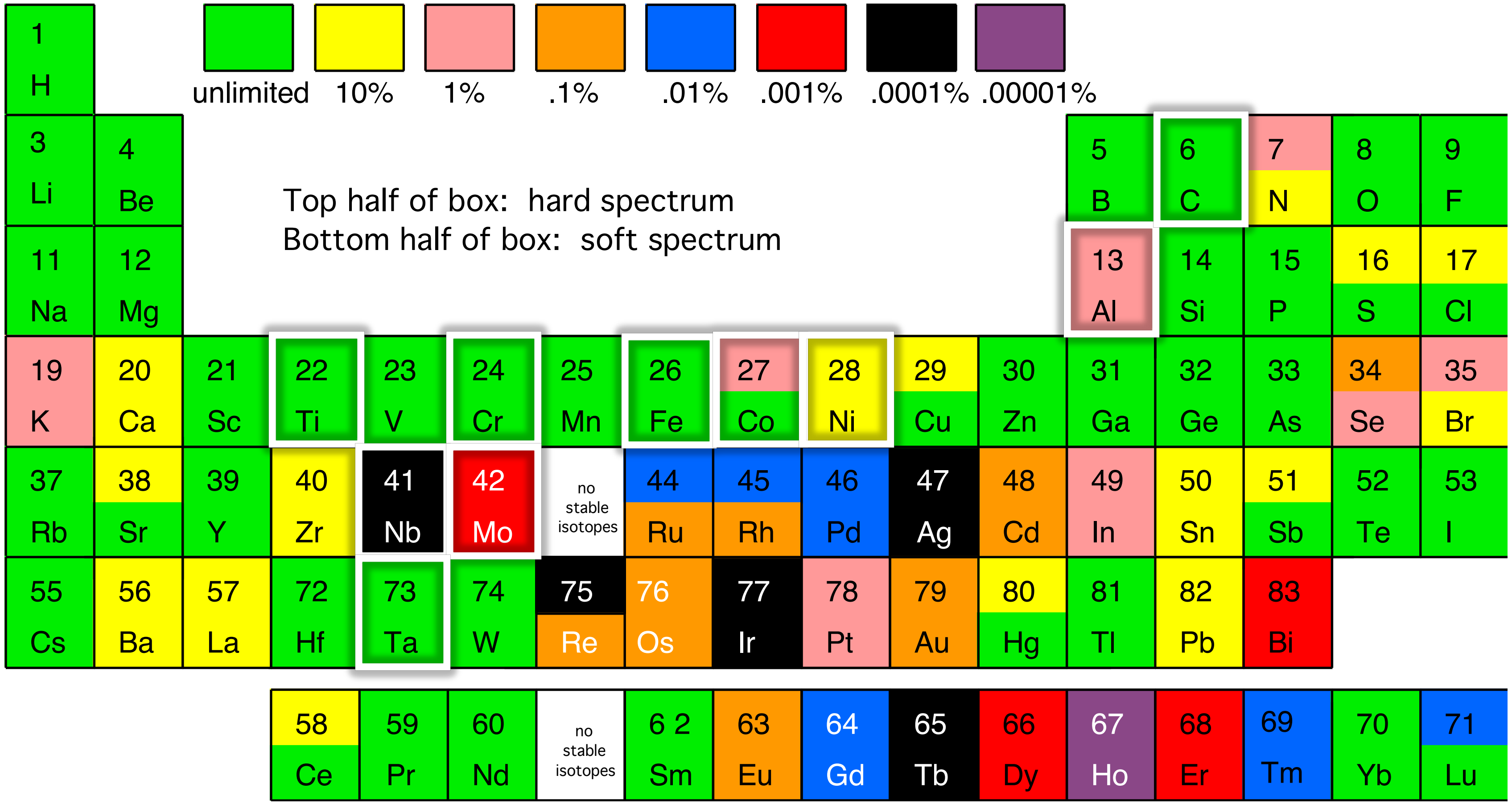

Inconel 718

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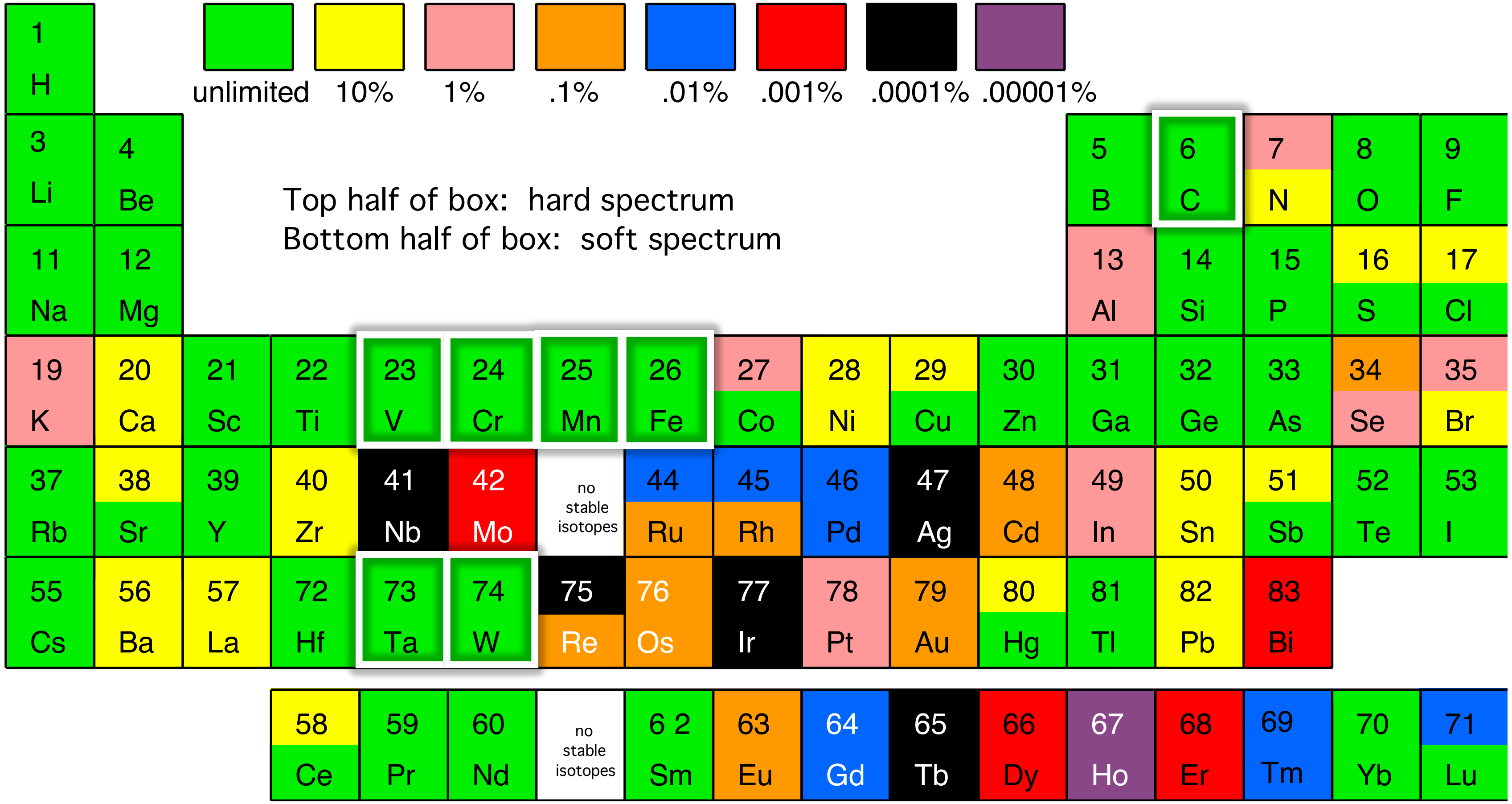

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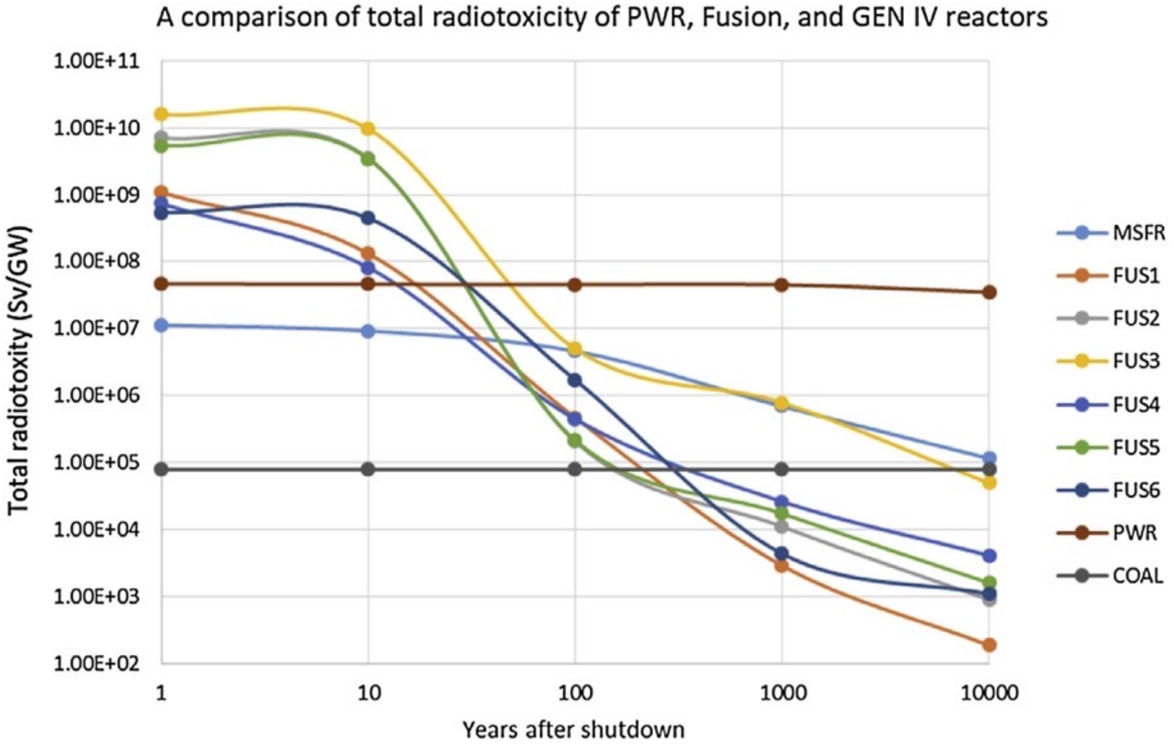
Activation of Structural Materials

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



FUS1 = V alloy, Li_2O
FUS2 = RAFM steel, PbLi
FUS3 = RAFM steel, Li_4SiO_4
FUS4 = SiC composite, PbLi
FUS5 = RAFM steel, PbLi
FUS6 = SiC composite, Li_4SiO_4

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

What is a blanket?

Components

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- **Tritium breeding material**
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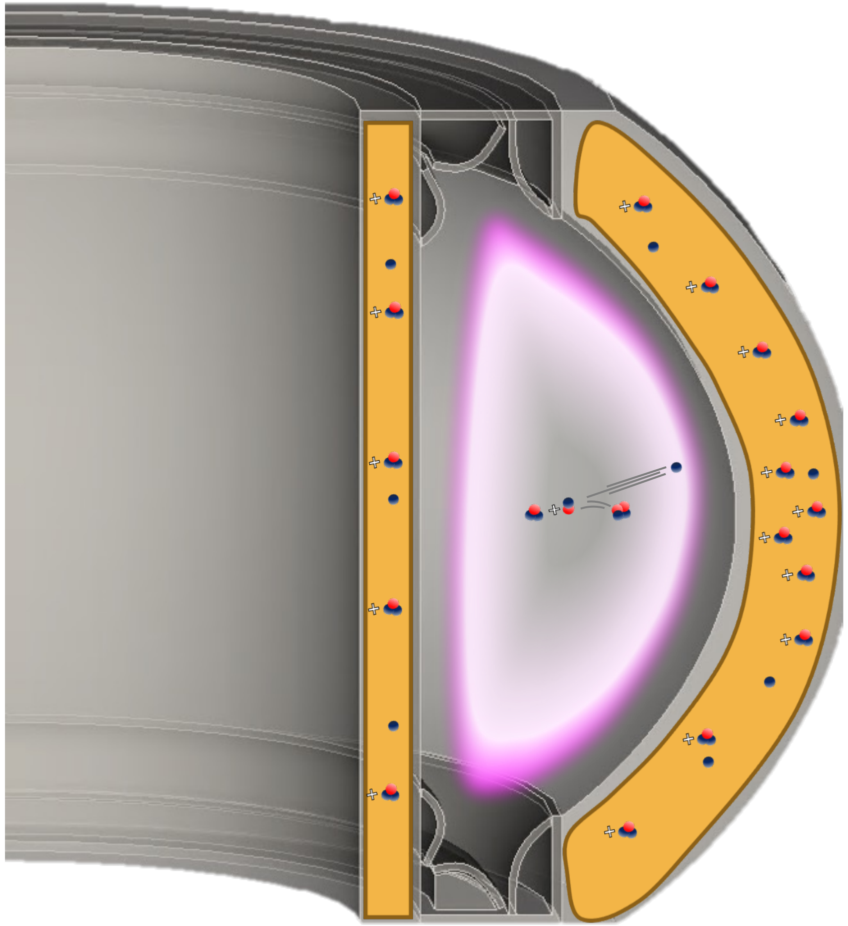
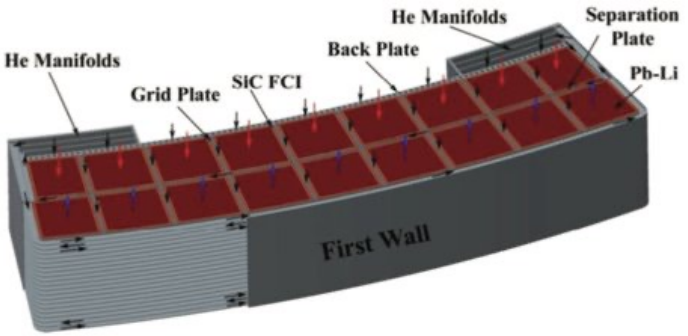
    - Large cross section at thermal energies
    - Exothermic: produces additional energy
  - n + ^{7}Li → ^{4}He + T + n' - 2.5 MeV
    - Produces tritium *and* a neutron
- Multiplier material
  - Elements that undergo (n,2n) reactions
  - High (n,2n) cross section and low total absorption cross section
    - Be and Pb are best
- Coolant



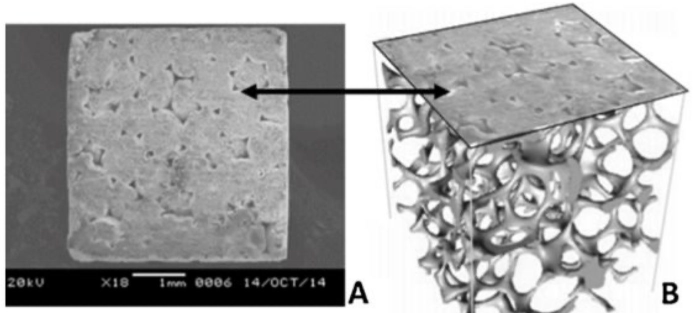
Tritium Breeding Materials



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

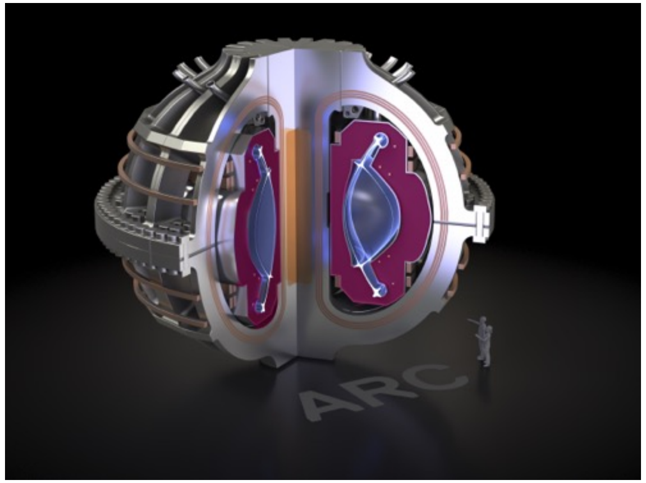
- Liquid Metals ← **Magnetohydrodynamic challenges**
  - Li
  - PbLi

  Relatively low melt temperature ✓



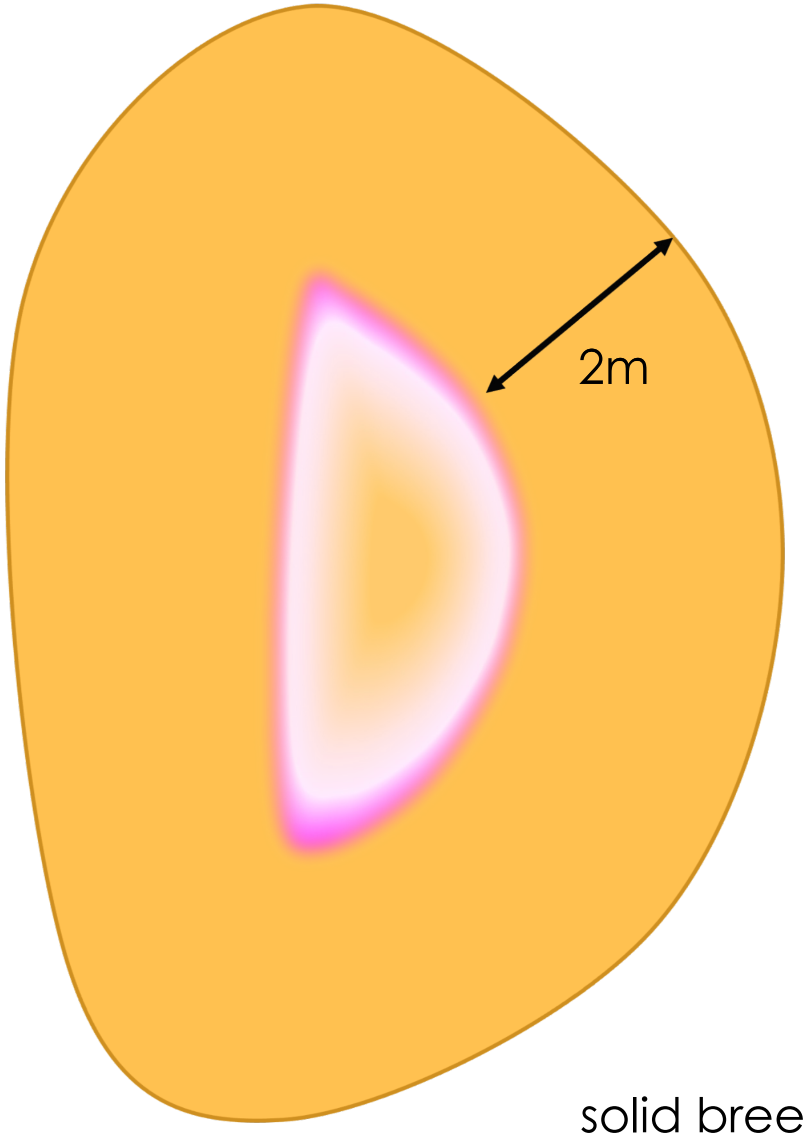
S. Sharafat et al., *Fusion Engineering and Design* **109-111** (2016) 119-127

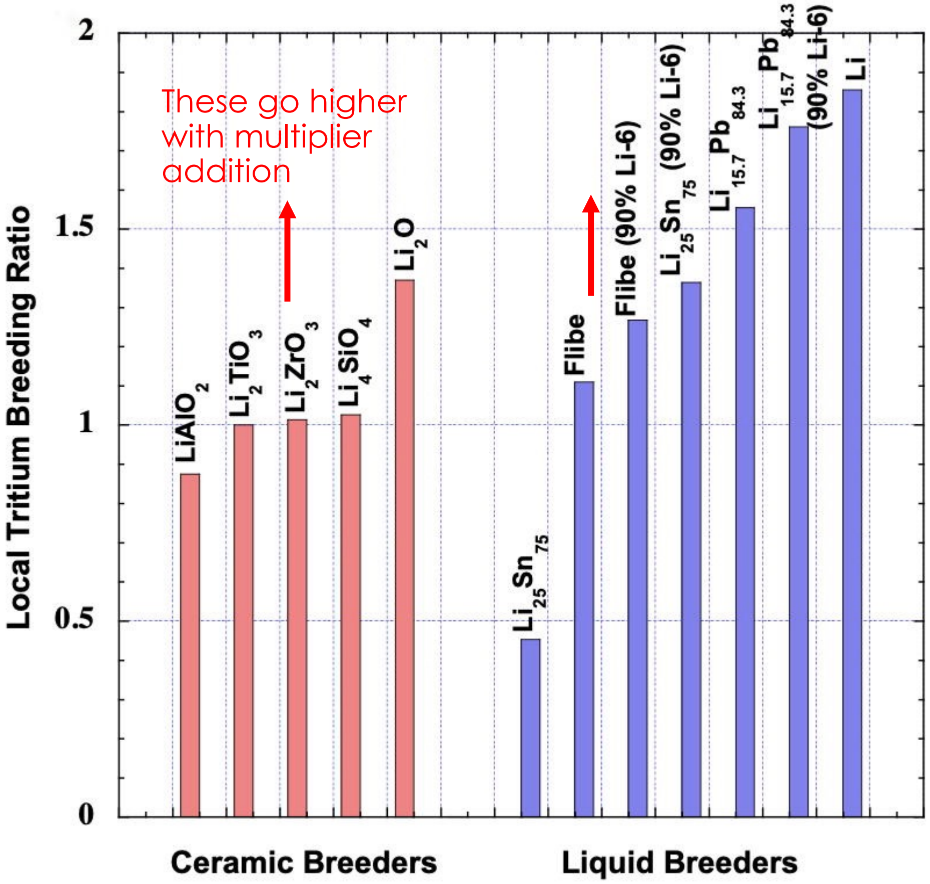
- Solid Ceramics ← **More structure required**
  - Li_2TiO_3, Li_4SiO_4, and many others possible
- Molten Salts ← **Highly Corrosive ✕**
  - FLiBe (2LiF + BeF_2) High melt temperature ✕
  - FLiNaBe (LiF + NaF + BeF_2) Lower TBR ✕



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

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

$n + {}^{6}Li \rightarrow {}^{4}He + T + 4.785$ MeV

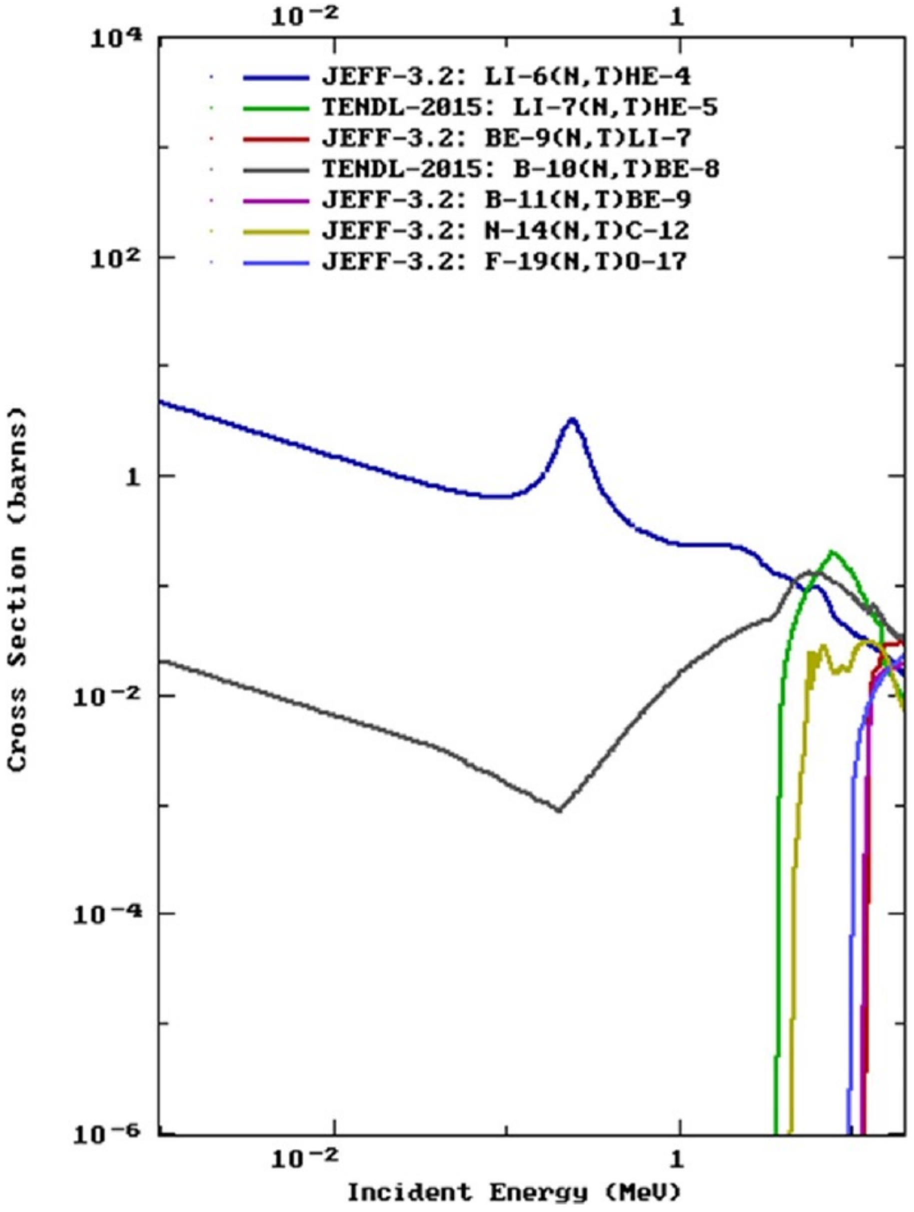
- Large cross section at thermal energies
- Exothermic: produces additional energy
- **Li^6 is only 7.5% of natural lithium**

$n + {}^{7}Li \rightarrow {}^{4}He + T + n' - 2.5$ MeV

- Produces tritium *and* a neutron

How do you get desirable quantities of Li^6?

→ Enrichment!



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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

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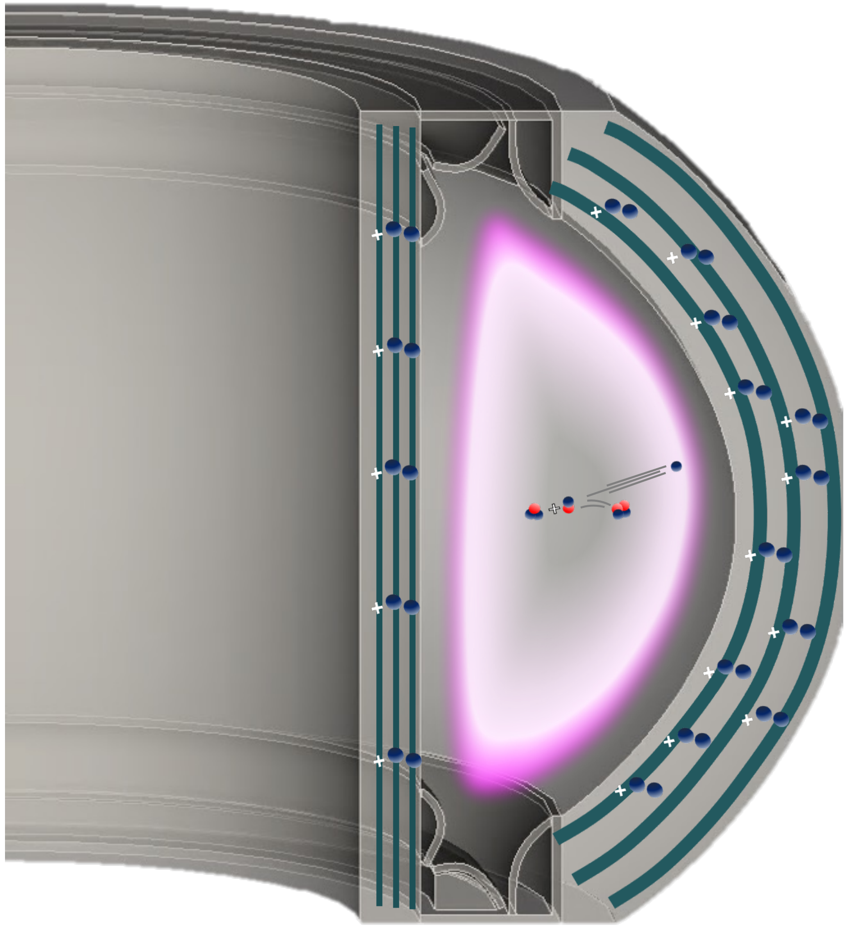
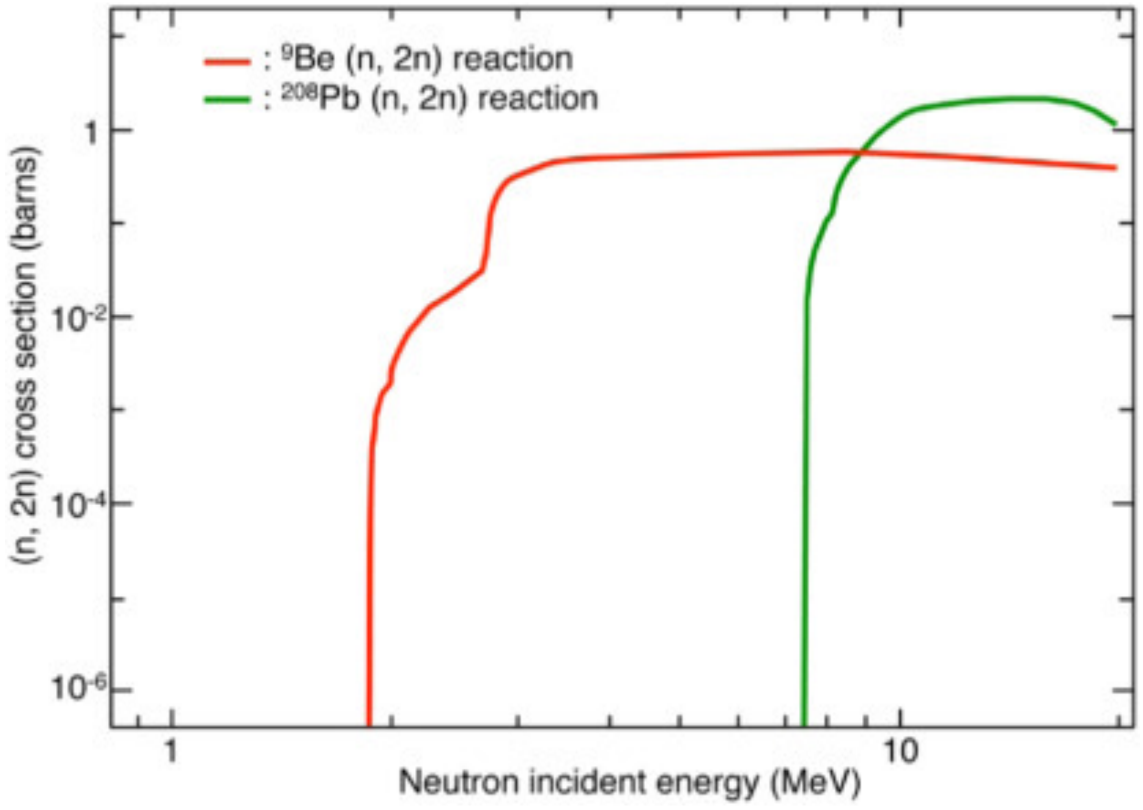
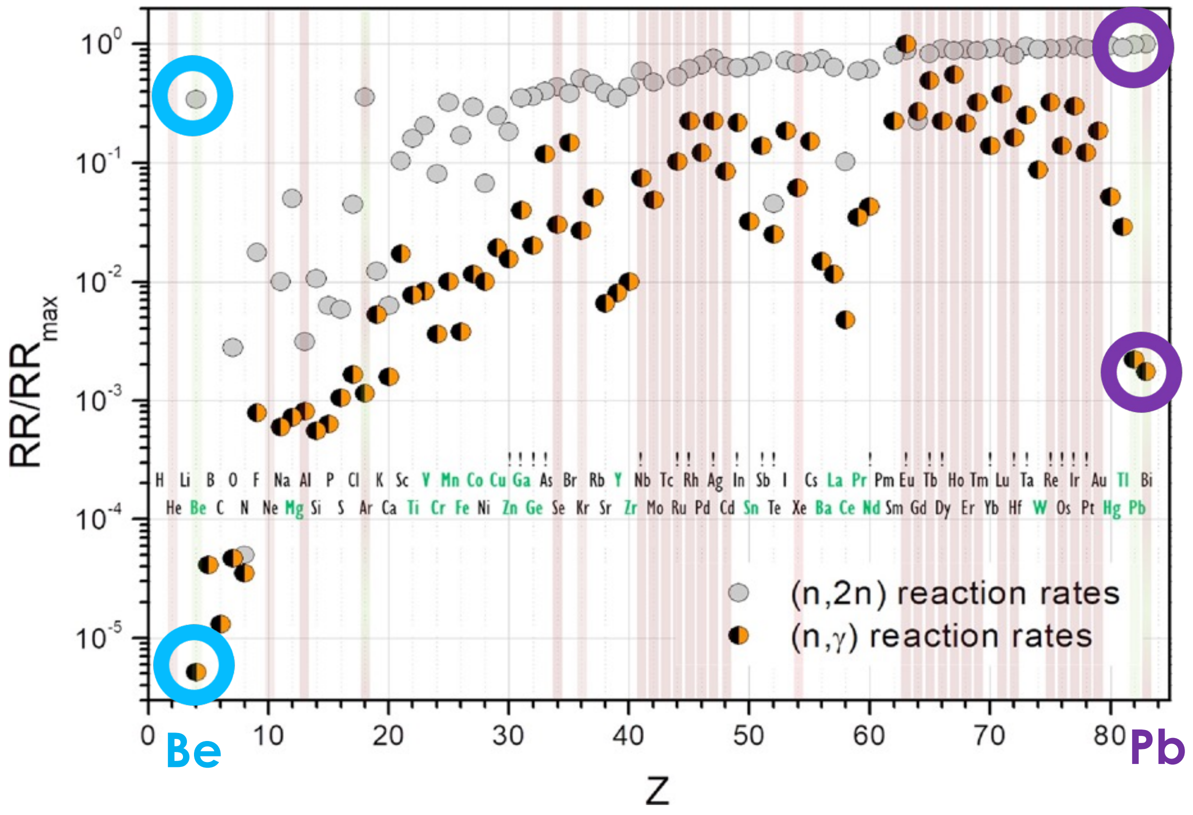


Multiplier Materials

- 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.

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

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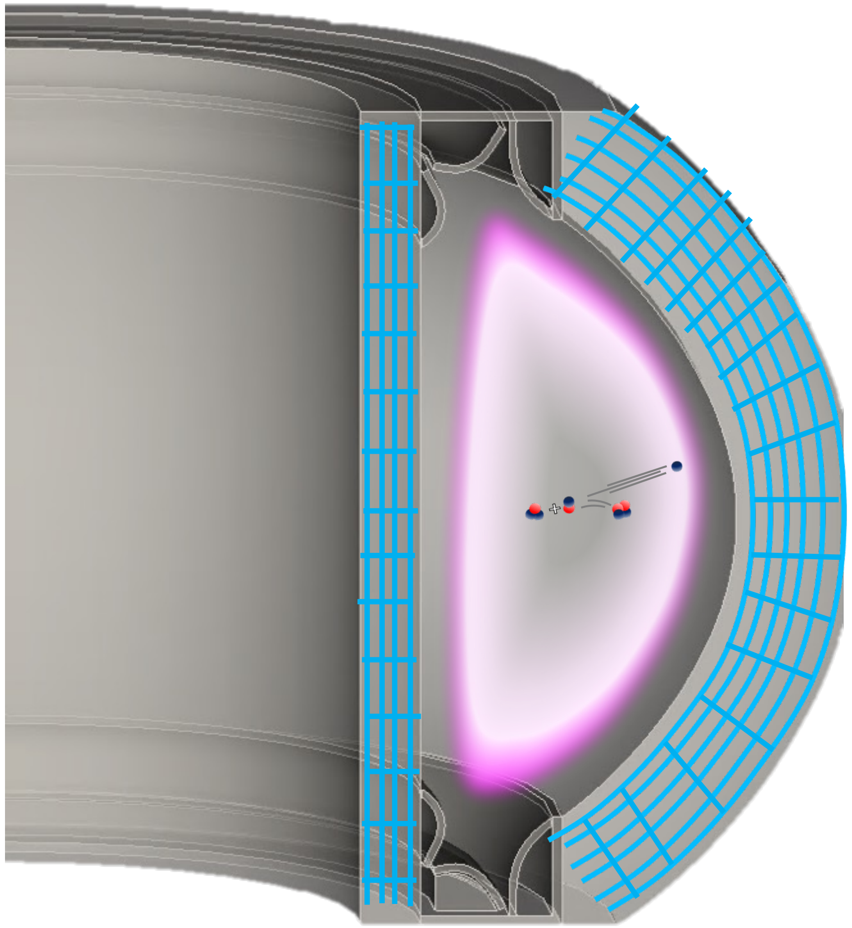
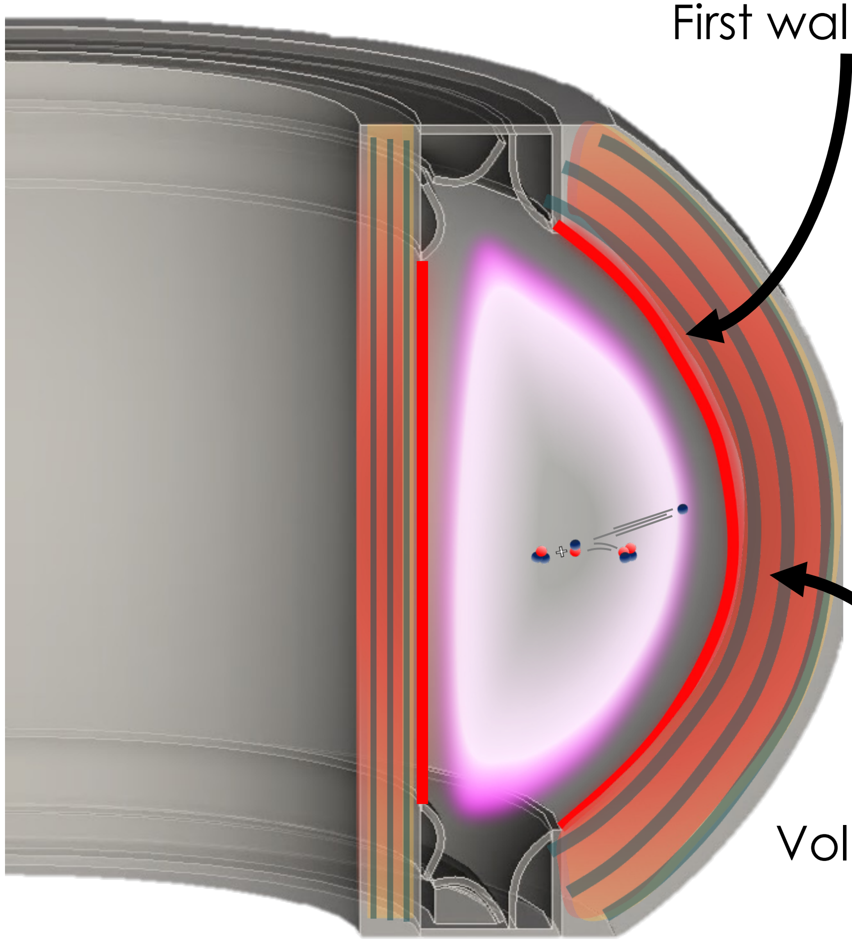


Blanket Cooling

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 conversation



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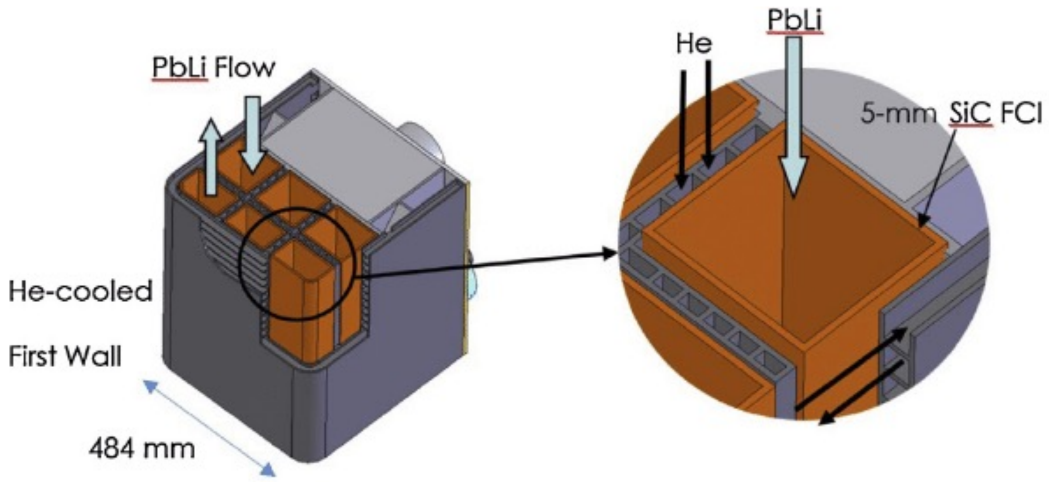
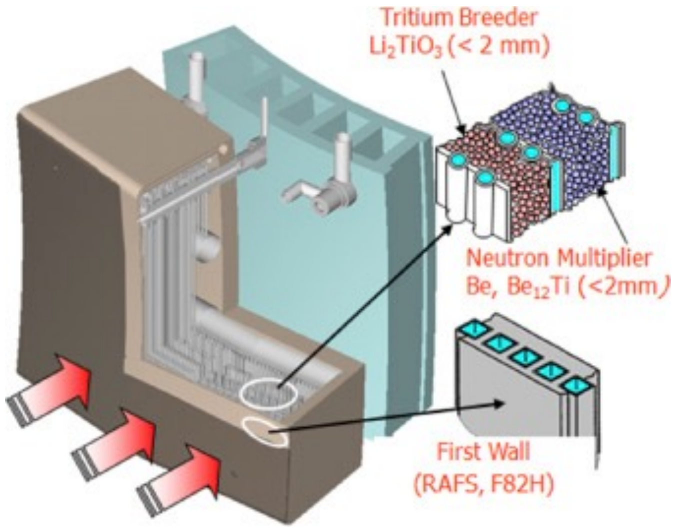
Cooling mechanisms

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.

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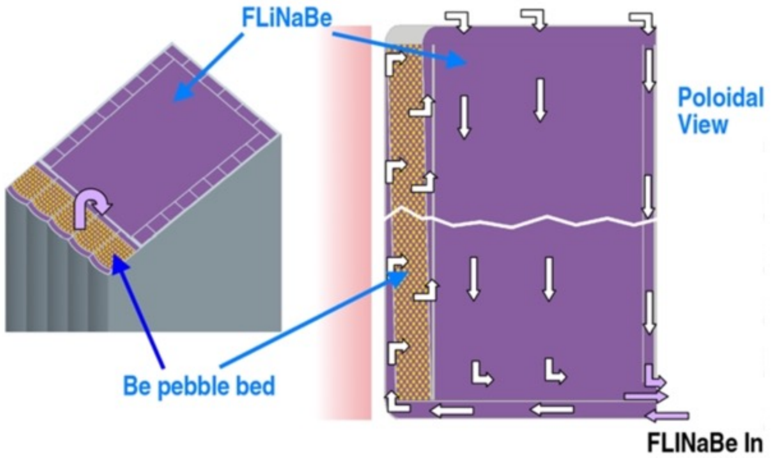
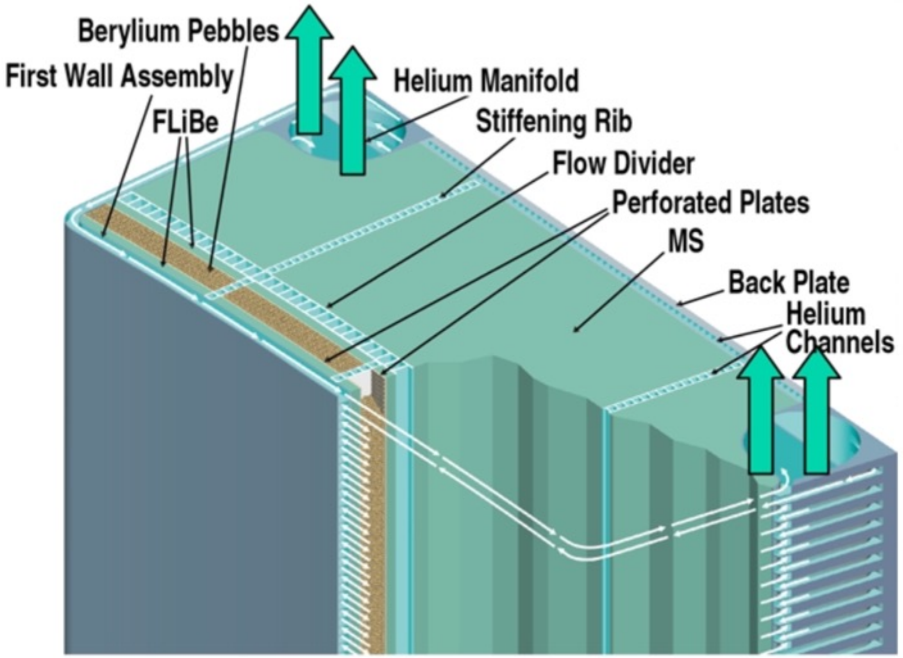
Cooling mechanisms

Self-Cooled

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





C. Wong, *Fusion Eng. Des.* **72** (2004) 245-275.
C. Wong, *Fusion Sci. Technol.* **47:3** (2005) 502-509

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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

Conclusion

How can we use those neutrons?

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

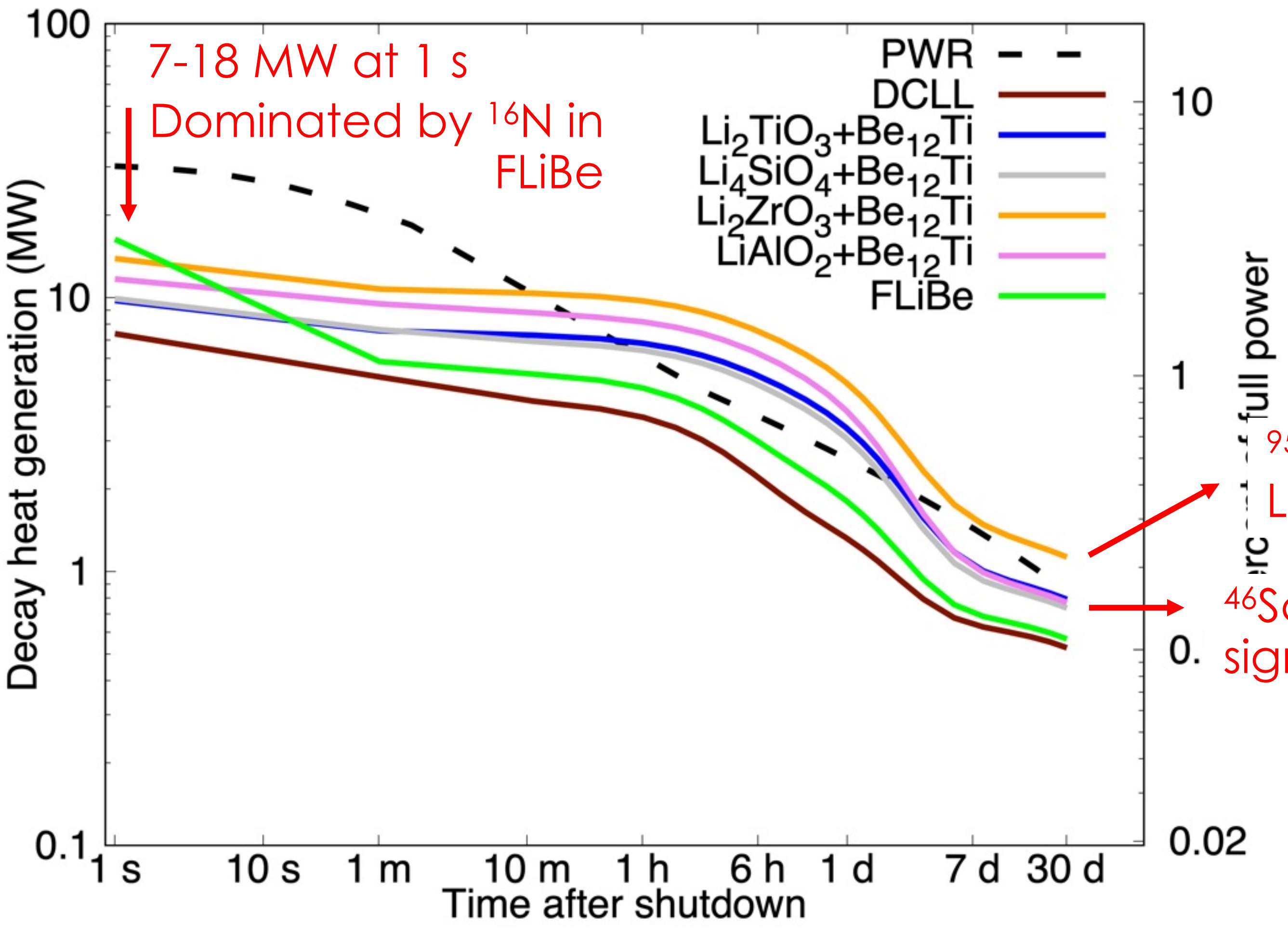
What challenges do those neutrons present?

- 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

Extra Slides

Decay heat dependence on blanket concept

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



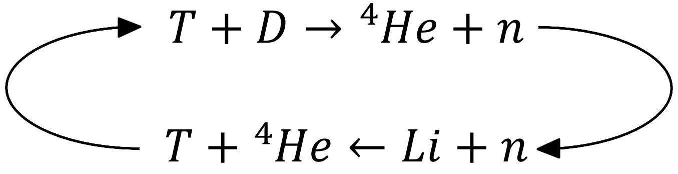
Blankets with high beryllium content lead to increased activation of FW and Divertor tungsten through multiplication, moderation of the neutron flux

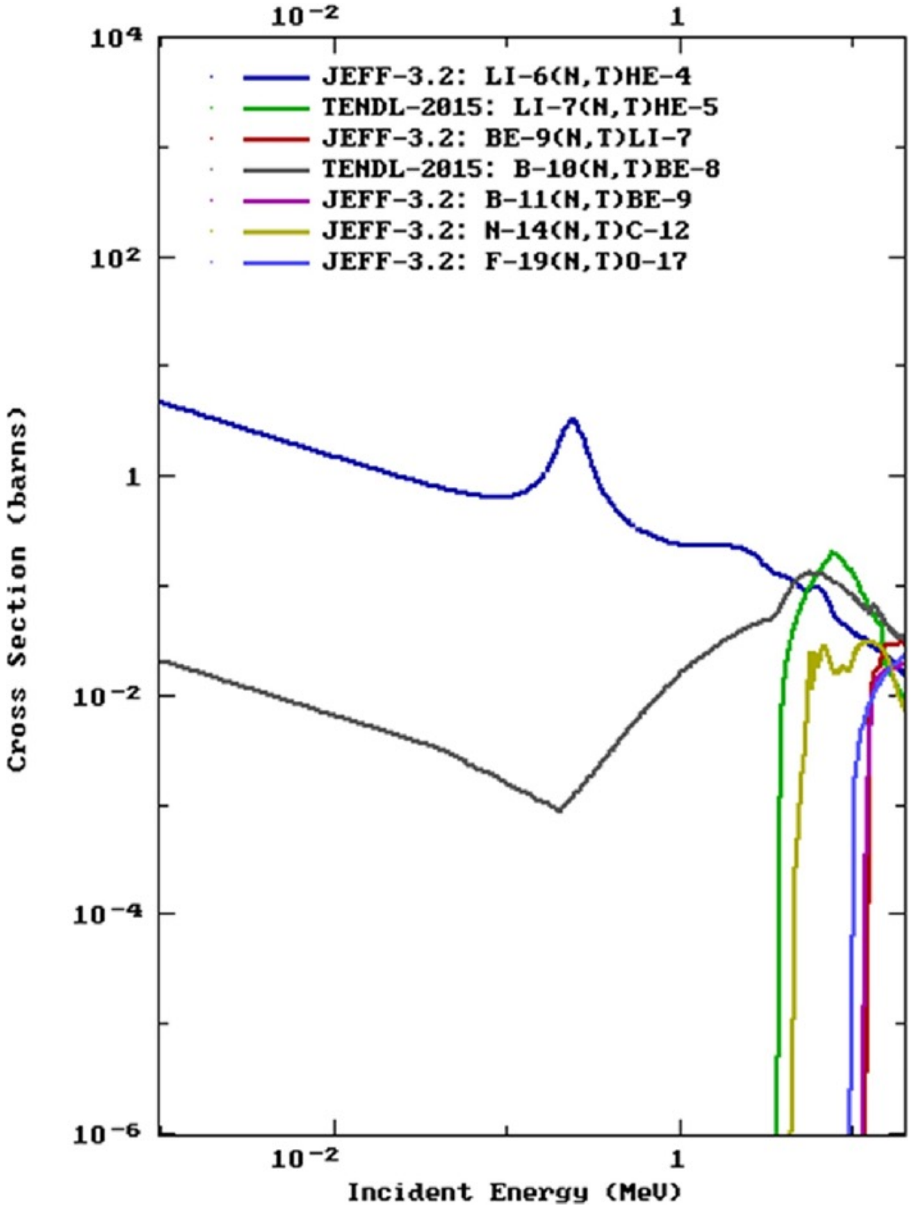
^{95}Zr, ^{95}Nb add significantly in Li_2ZrO_3 breeder

^{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:





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

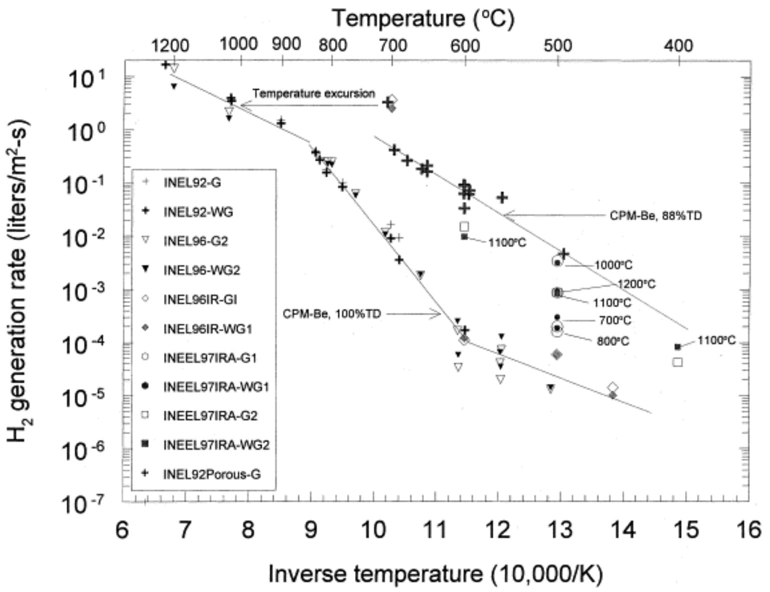
Beryllium as a multiplier

- 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…

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

Beryllium Oxidation

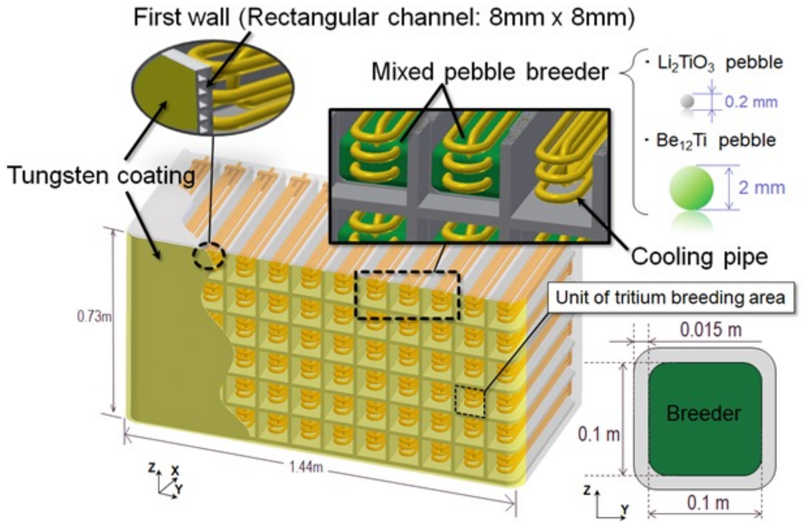
R. A. Anderl, *Journal of Nuclear Materials* **258-263** (1998) 750-756.

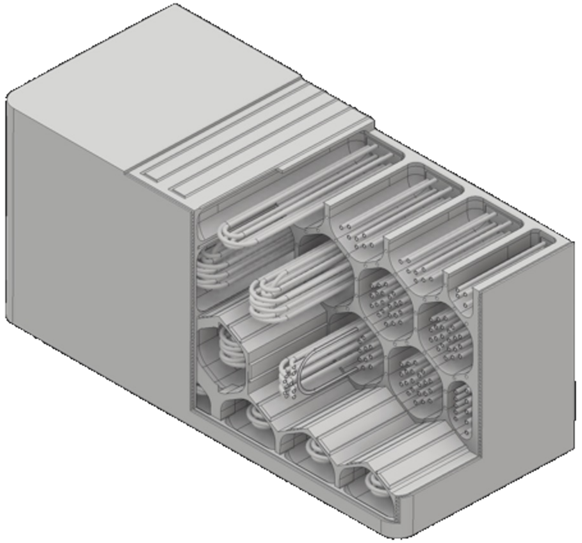


- Beryllium reacts exothermically with steam and air; at high temperature the possibility for "runaway" reactions exists
- For water-cooled ceramic breeder designs, this is a significant safety issue
- So also for ITER (water cooling and beryllium PFCs)

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

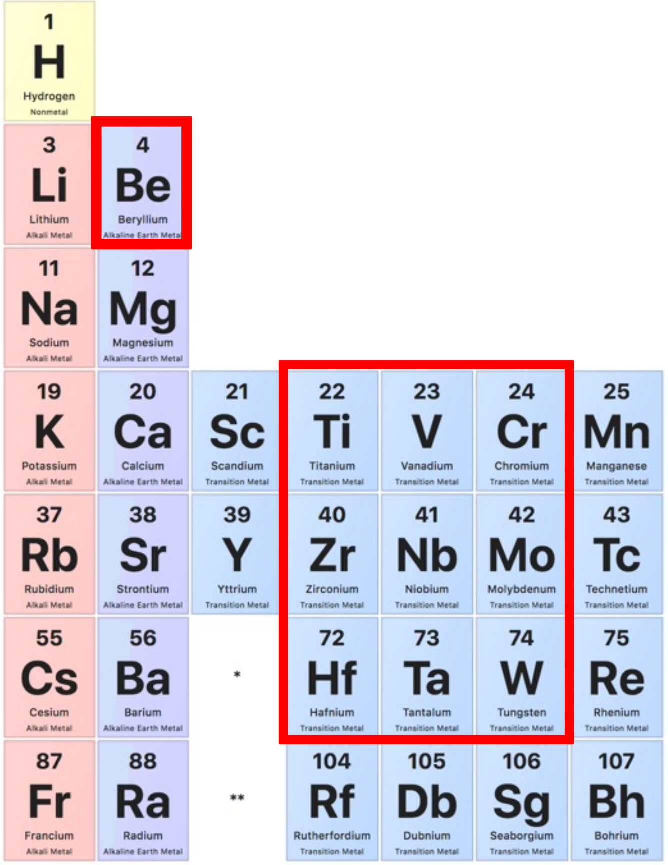




Y. Someya, 2018 US-JA Workshop

Beryllides

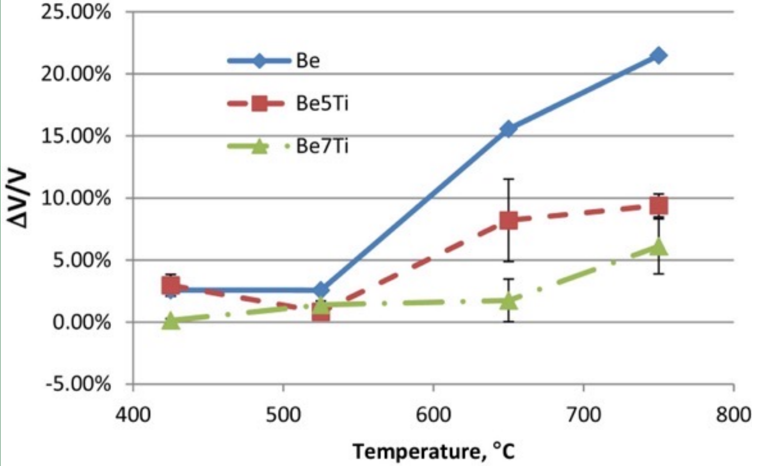
- Need to inhibit oxidation led to a search for alternate materials with high beryllium content but better oxidation resistance
- Focus on group 4-6 transition metal beryllide intermetallic compounds
  - Be_XM, where X=12 or 13; >92% beryllium
  - Hard, brittle, high melt temperature (1500-1900 °C)
- 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

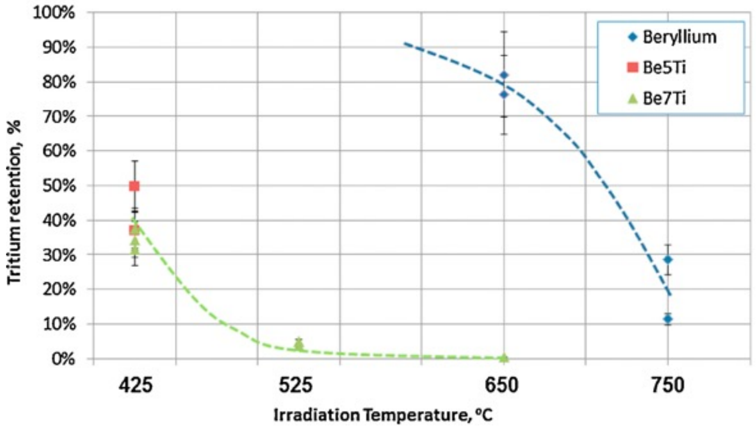


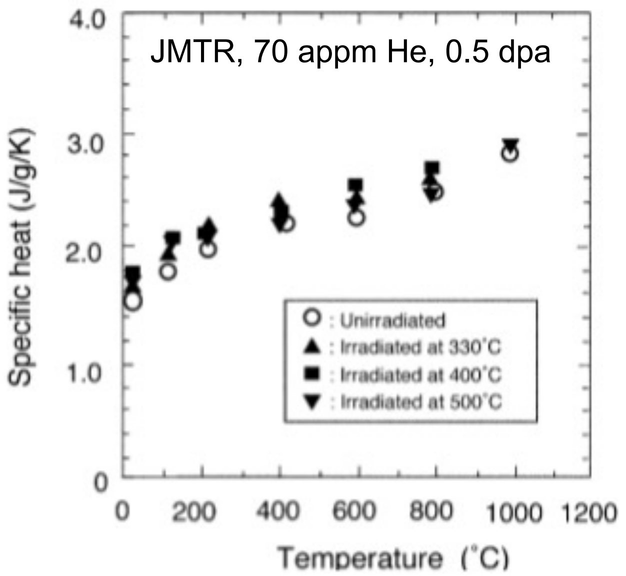
Titanium Beryllide

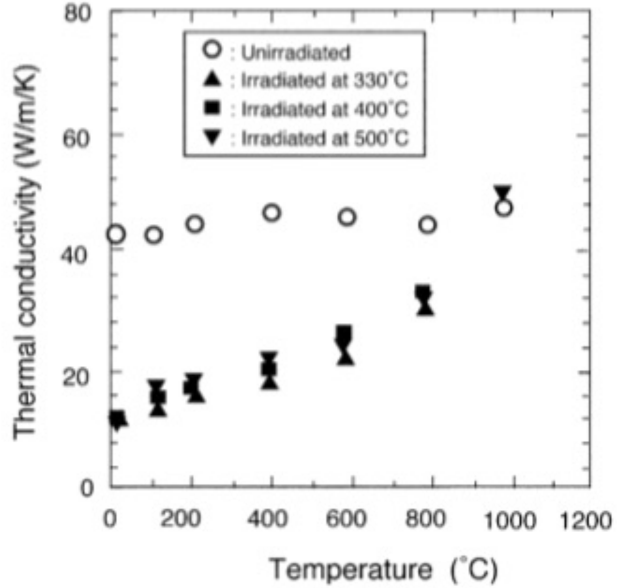
- Titanium beryllide, $Be_{12}Ti$, is the first and most extensively studied beryllide for fusion applications
  - Best neutron multiplier among the beryllides[1]
- $\rho = 2.26\ \mathrm{g/cm^3},\ T_{melt} = 1538\ °\mathrm{C}$
- Irradiation to 19.5 dpa, 2740 appm He in HIDOBE-01 revealed much lower swelling and tritium retention compared to pure Be

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





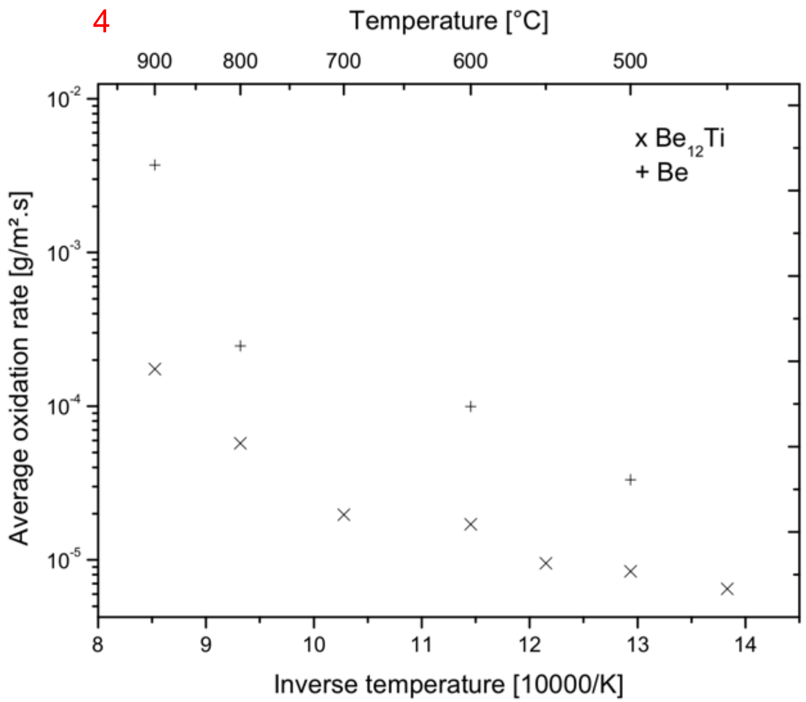




M. Uchida, *Fusion Engineering and Design* **69** (2003) 499-503.

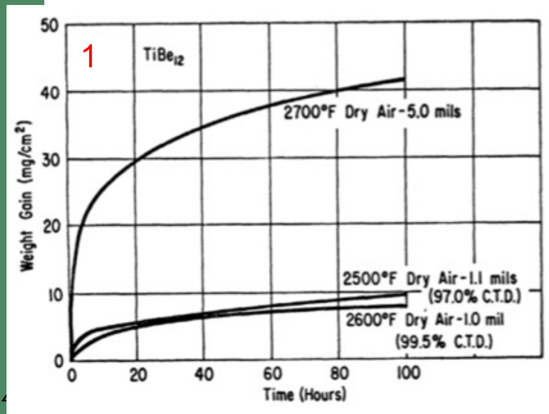
[1]C. Dorn, *Fusion Engineering and Design* **84** (2009) 319-322.

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.



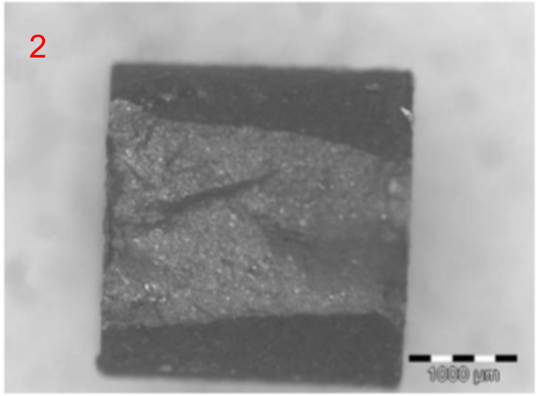


Fig. 2. $Be_{12}Ti$ cylindrical sample after loading at 800 °C.

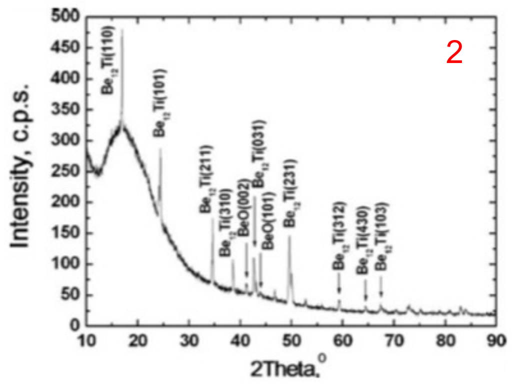


Fig. 8. X-ray diffraction pattern of $Be_{12}Ti$ specimen annealed at 800 °C in air.