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Oxford Sigma Recent Development on Liquid Metals for Fusion Breeding

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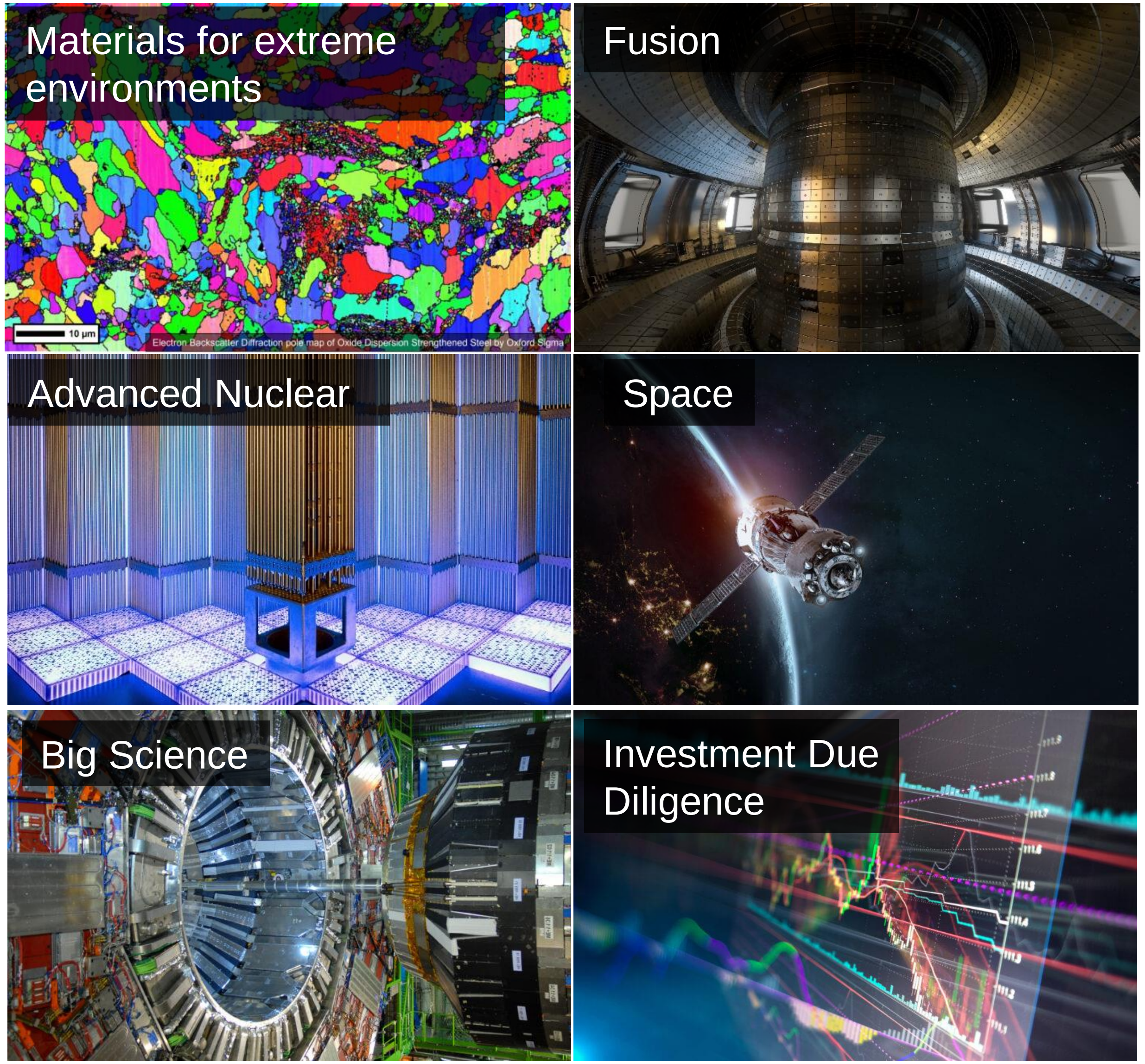
20/10/2022 – NIA Fusion Event

Company Introduction

The company's aim is to develop innovative nuclear technology to withstand extreme environments, provide nuclear materials expertise, and advise the advanced nuclear and fusion energy industries in their quest to achieve commercialisation.

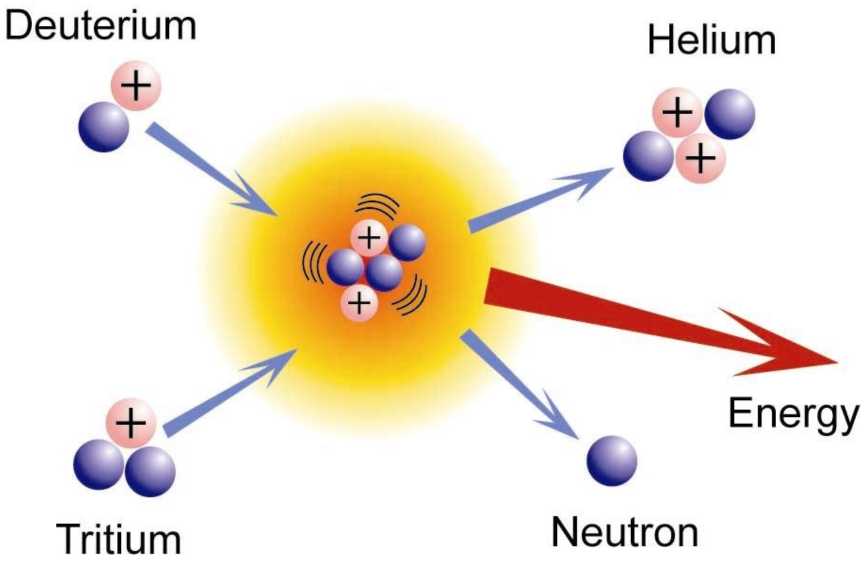
Based on Harwell Campus, Oxfordshire, UK

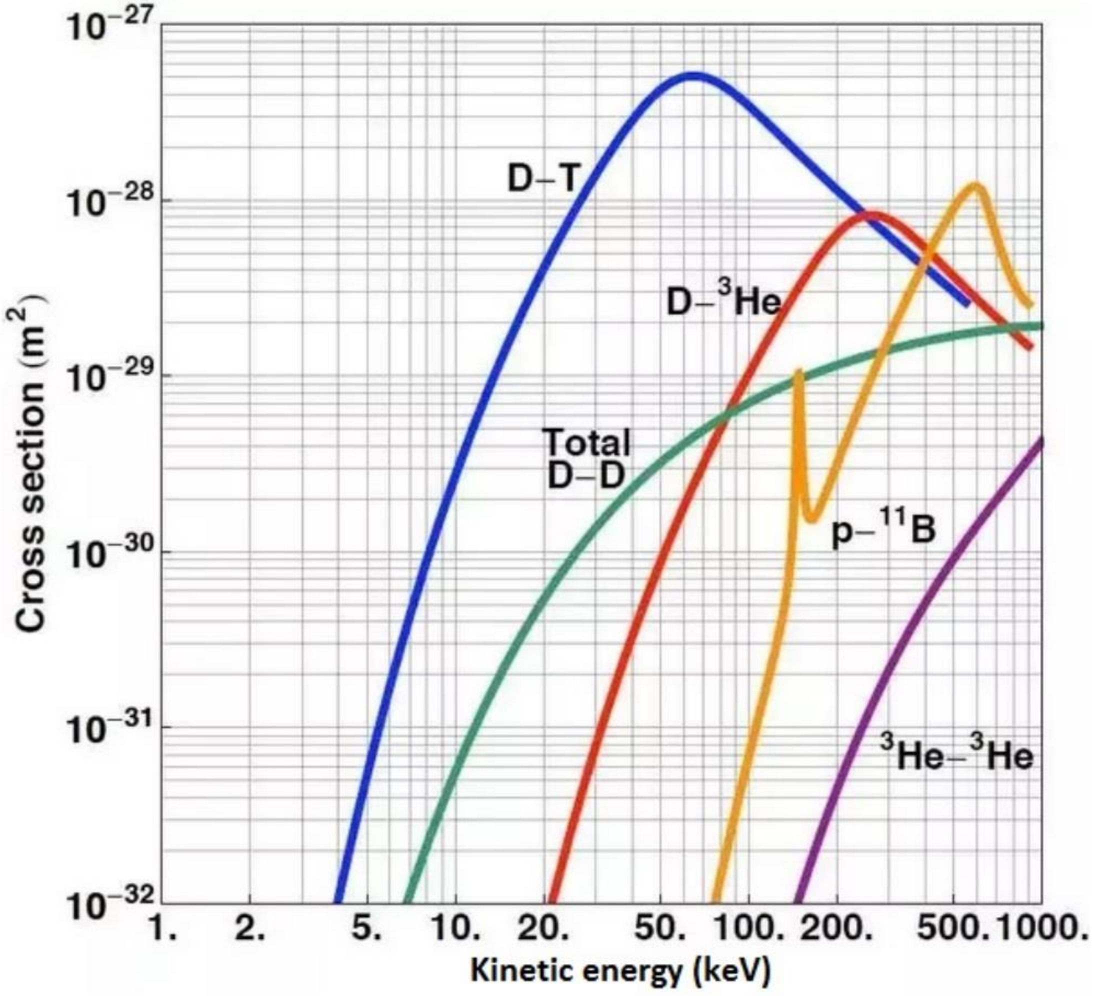


Nuclear Fusion

- Most favourable fusion reaction:

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}He(3.5MeV) + n(14.1MeV)$$





Fusion Physics, chapter 1. International Atomic Energy Agency, 2012.

Tritium breeding

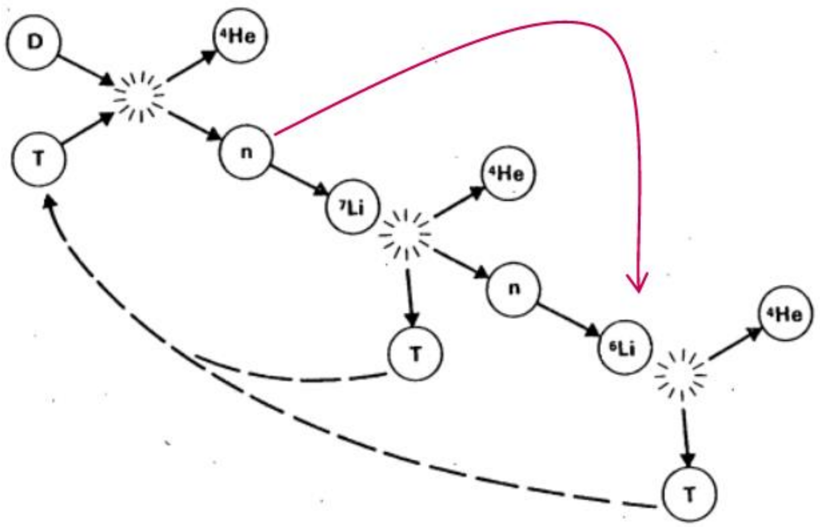
- Deuterium can be extracted from seawater (~33g per 1t)
- Tritium is difficult to source due to its short half-life (~12.3 years)

Tritium is proposed to be bred inside the fusion reactor

$$n + {}^{6}_{3}Li \rightarrow {}^{3}_{1}T + {}^{4}_{2}He$$

$$n + {}^{7}_{3}Li \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + n$$

DEUTERIUM-TRITIUM FUEL CYCLE



J. Ongena and G. Van Oost. Energy for Future Centuries - Prospects for Fusion Power as a Future Energy Source. Fusion Science and Technology, 53(2T):3–15, 2008.

Tritium self-sufficiency

- Tritium Breeding Ratio

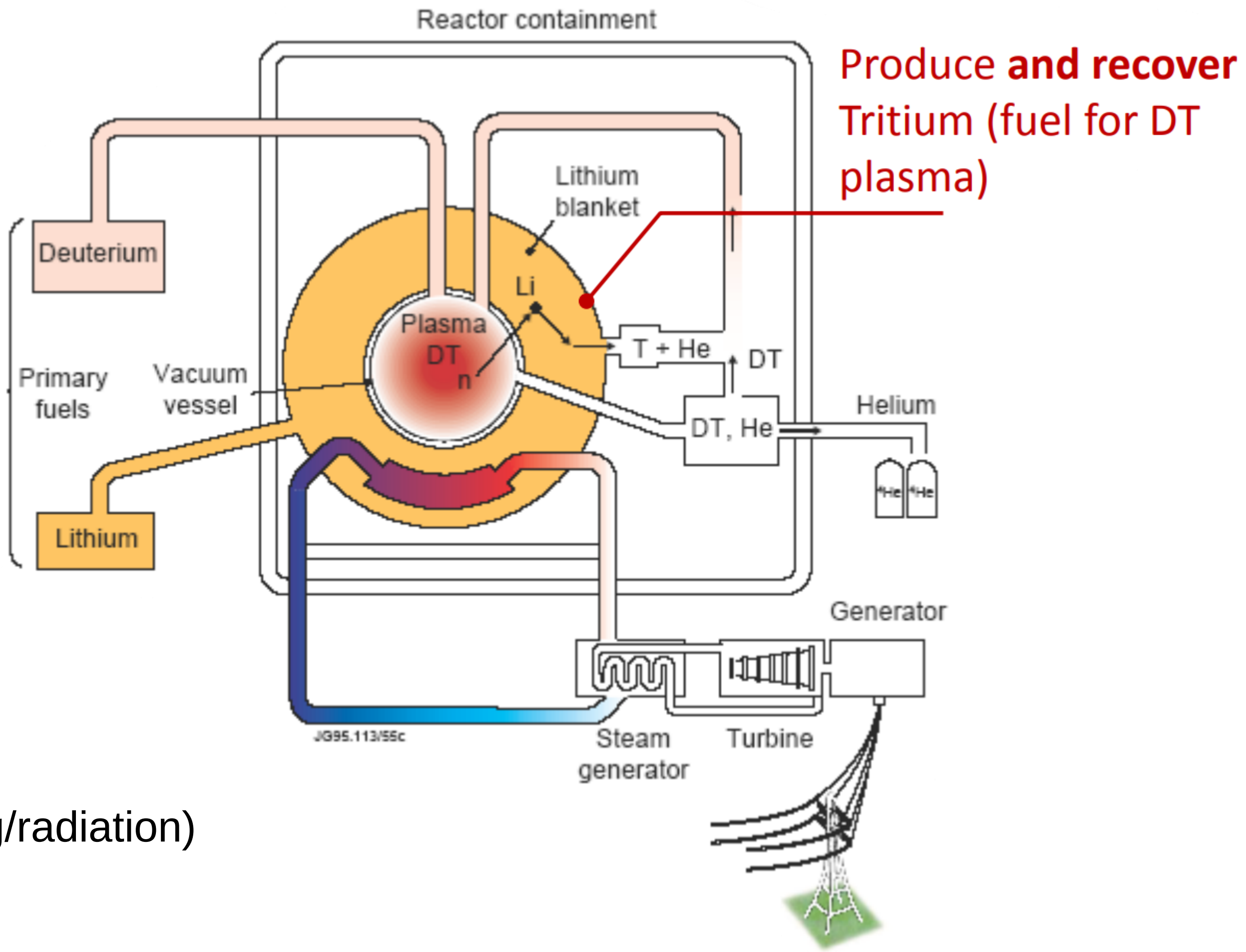
$$TBR = \frac{tritium\ produced}{tritium\ consumed\ in\ the\ reactor}$$

TBR > 1.15

- Tritium extraction efficiency and radioactive decay (5.47% per year)
- Supply tritium inventory for start-up of other fusion reactors
- “Reserve” inventory for continued reactor operation in case of tritium production failure

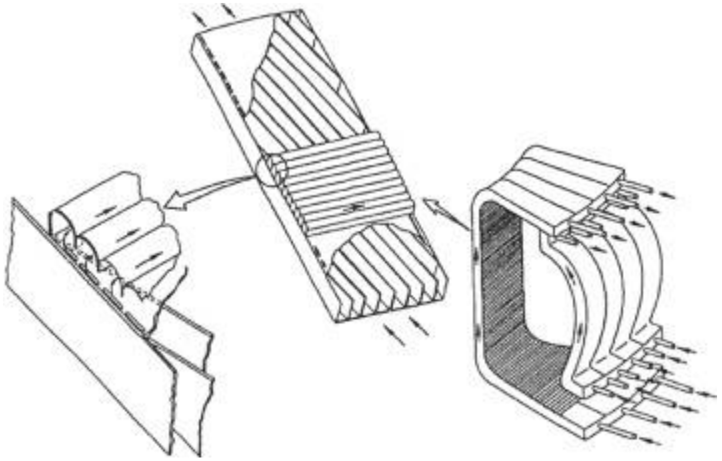
What is needed in a breeder blanket?

- Any breeding blanket consist of:
  - Breeding material (Li bearing)
  - Neutron multiplier
  - Structural material
  - Coolant
- Any combination has to comply with:
  - Safety
  - Performance
- Main tasks are:
  - Produce and recover tritium
  - Protect vacuum vessel and coils (heating/radiation)
  - Convert neutron energy into heat



Breeder blanket concepts

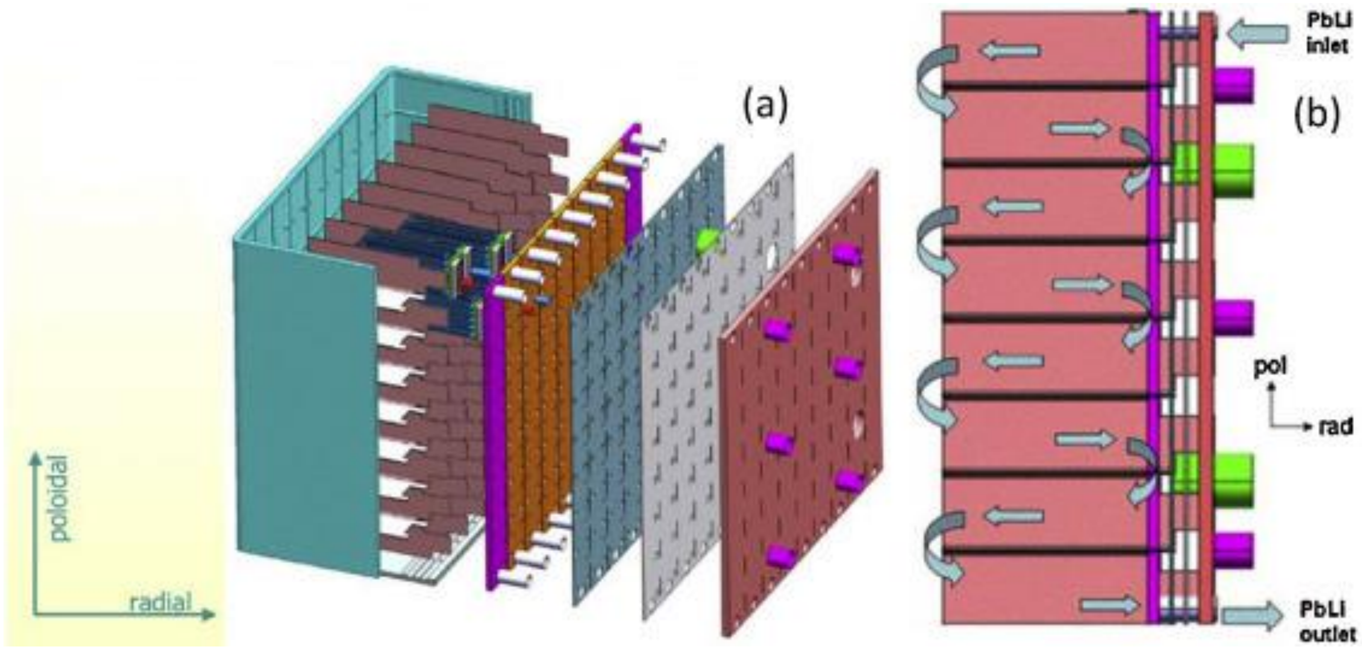
- Self-cooled liquid metal blankets
  - “Discontinued” unacceptably high MHD pressure drop☹



Self-cooled lithium/vanadium blanket (poloidal/toroidal flow)

Breeder blanket concepts

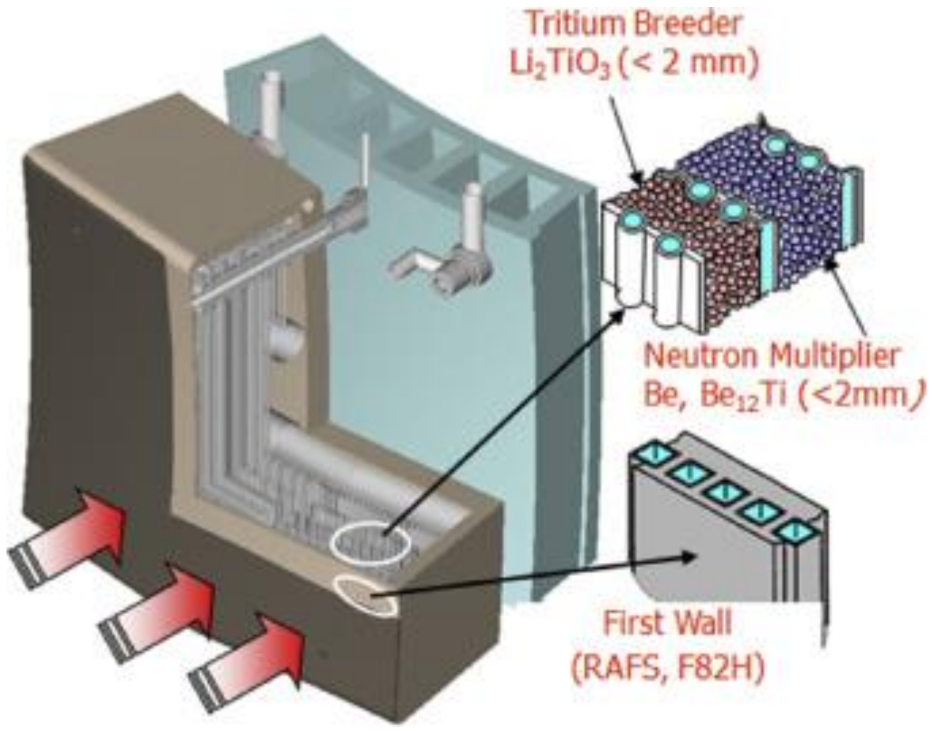
- Self-cooled liquid metal blankets
  - “Discontinued” unacceptably high MHD pressure drop☹
- Separately-cooled liquid metal blankets
  - Heat removal by He ☺
  - Tritium permeation from PbLi into He ☹



EU Helium-Cooled Lithium/Lead (HCLL) blanket: (a) general view, (b) PbLi flow path

Breeder blanket concepts

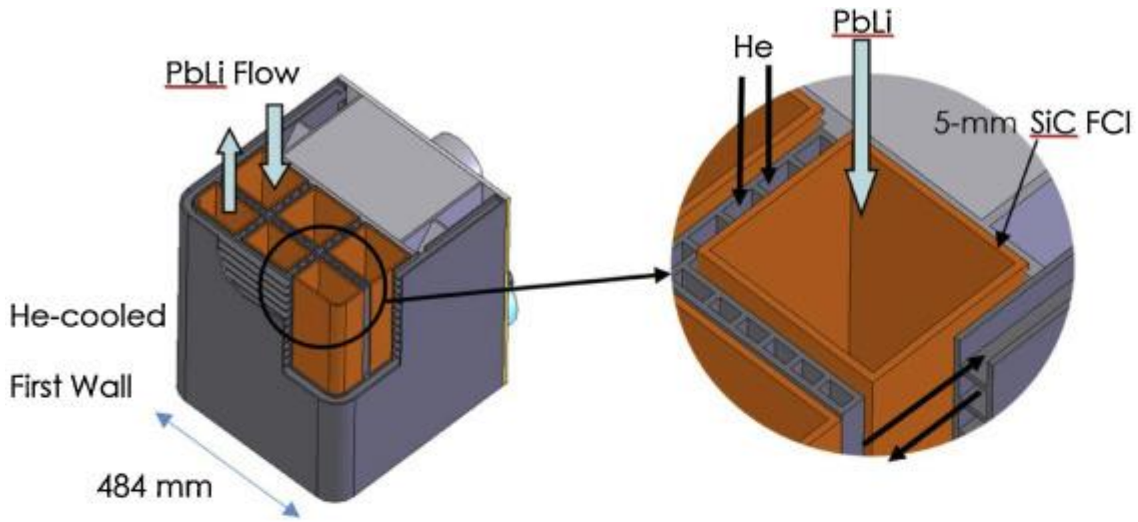
- Self-cooled liquid metal blankets
  - “Discontinued” unacceptably high MHD pressure drop☹
- Separately-cooled liquid metal blankets
  - Heat removal by He ☺
  - Tritium permeation from PbLi into He ☹
- Water-cooled ceramic breeder blanket
  - High-temperature, high-efficiency ☺
  - Temperature-limited RAFM ☹



Water cooled ceramic breeder blanket concept proposed by Japan

Breeder blanket concepts

- Self-cooled liquid metal blankets
  - “Discontinued” unacceptably high MHD pressure drop☹
- Separately-cooled liquid metal blankets
  - Heat removal by He ☺
  - Tritium permeation from PbLi into He ☹
- Water-cooled ceramic breeder blanket
  - High-temperature, high-efficiency ☺
  - Temperature-limited RAFM ☹
- Dual-coolant lead-lithium blanket
  - Electrical and thermal insulation to allow higher PbLi exit temperature☺
  - Requires better understanding of PbLi-SiC interaction under strong magnetic fileds ☹



Sketch of a DCLL blanket design, including a poloidal duct with SiC FCI and He and PbLi flows.

Benefit of liquid metals

- Breeder: pure Li

Sufficient TBR ☺
High thermal conductivity (~10^1W/mK)☺
Low viscosity (~$10^{-7}$$m^2$/s)☺
Excellent for heat removal☺

More reactive with water, air and concrete☹

- Breeder: eutectic LiPb

Same benefits of pure Li ☺
Lower chemical reactivity with water, air and concrete ☺

- More corrosive (?), denser ☹
- Undesirable activation products ☹

- ↑power densities and ↓ radiation damage ☺
- Magnetohydrodynamic (MHD) interactions☹

- Lithium interaction with surrounding materials??

Liquid lithium corrosion

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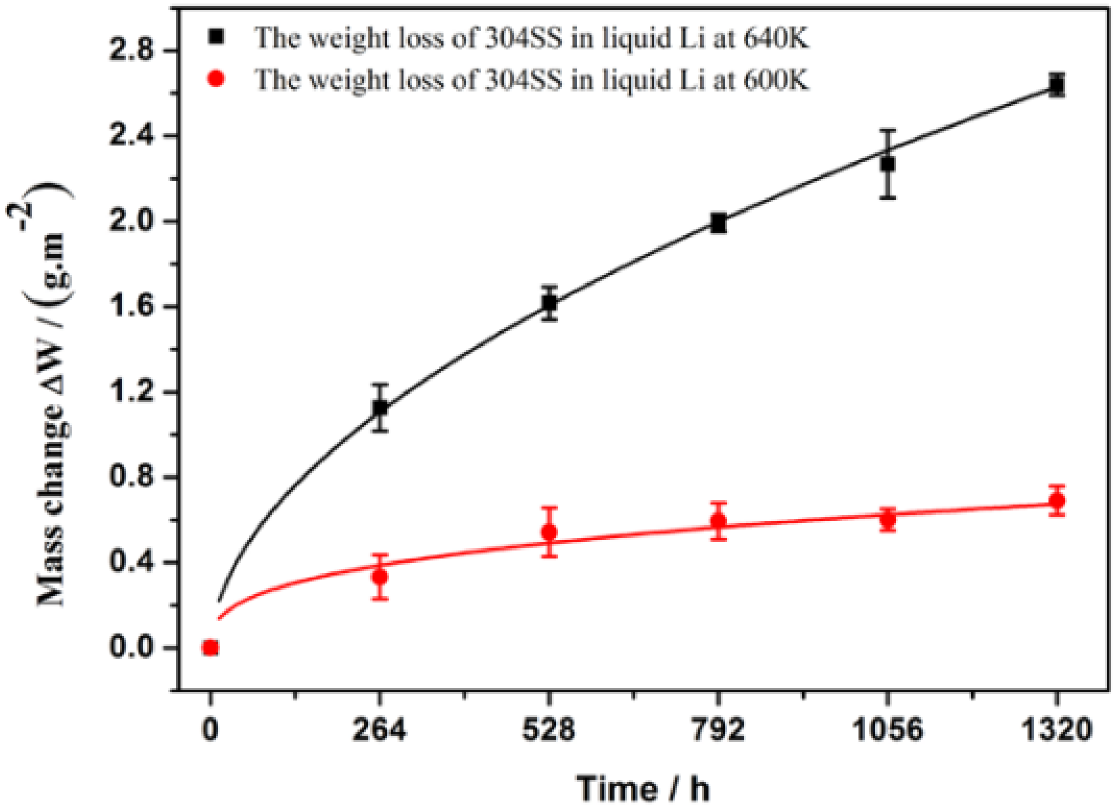
- Variables affecting liquid metal corrosion

- Temperature
- Temperature gradient
- Cyclic temperature fluctuation
- Surface-area-to-volume ratio
- Purity of liquid metal
- Flow velocity or Reynolds number
- Surface condition of container material
- Number of materials in contact with the same liquid metal

Effect of temperature on the corrosion behaviors of 304 stainless steel in static liquid lithium



Meng, X. et al. Effect of temperature on the corrosion behaviors of 304 stainless steel in static liquid lithium. Fusion engineering and design, 75-81, 2018.

Liquid lithium corrosion

- Proposed mechanism for Li corrosion
  - Dissolution of the oxide layer and cementite from the bulk

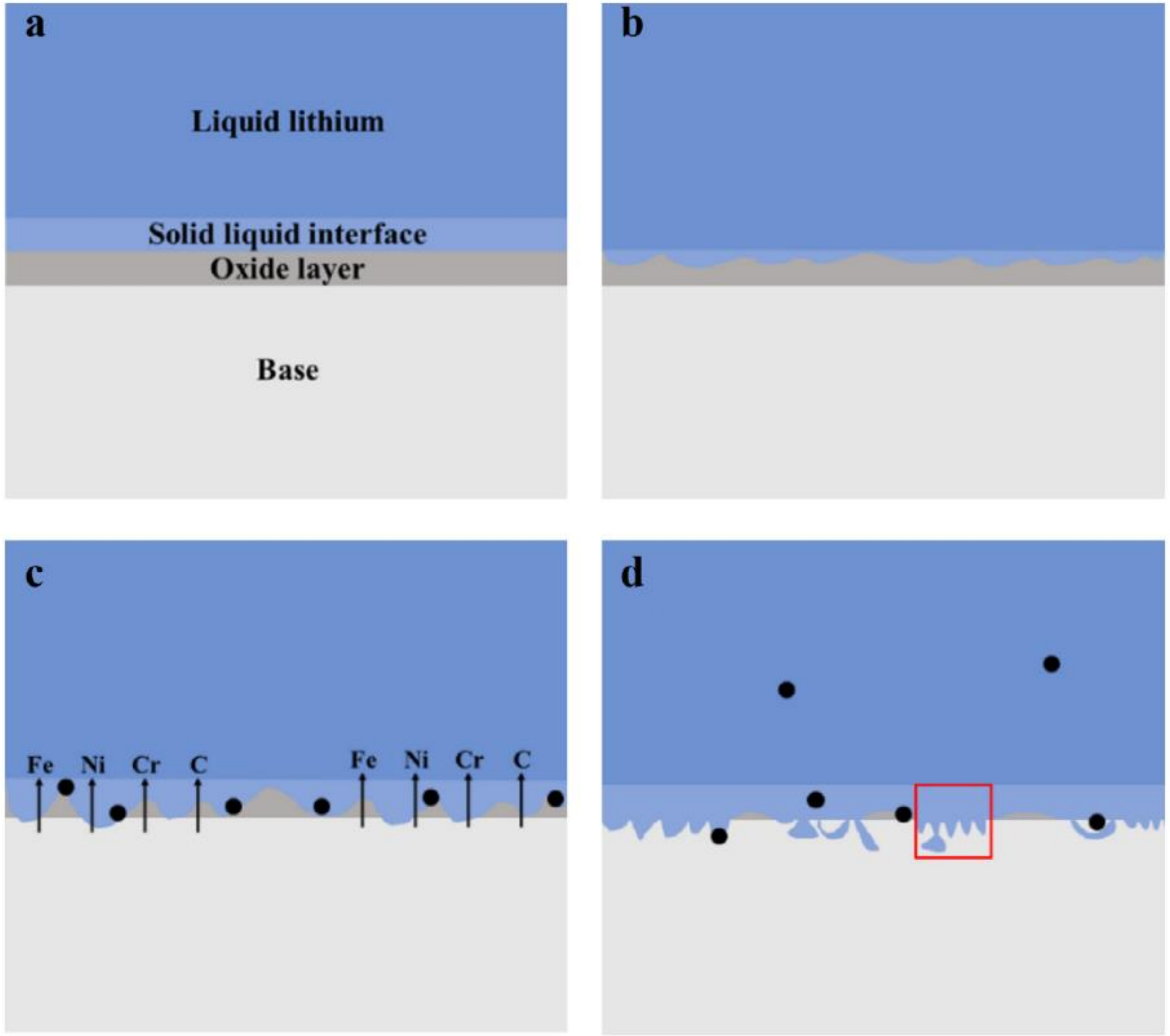
$$Cr_2O_3 + 6\,Li = 3\,Li_2O + 2\,Cr(600K,\ \Delta G = -599.3KJ),$$

$$2Fe_3C + Li = 6\,Fe + Li_2C_2\,(600\,K,\ \Delta G = -78.4\,KJ),$$

  - C dissolves into Li and forms Li_2C_2 and form Cr carbides

$$23Cr + 3Li_2C_2 = Cr_{23}C_6 + 6\,Li(600K,\ \Delta G = -201.5\,KJ),$$

$$14Cr + 3\,Li_2C_2 = 2Cr_7C_3 + 6\,Li(600\,K,\ \Delta G = -158.6\,KJ),$$



Probable corrosion mechanism of SS in liquid Li

Zhang et al., Study of the corrosion characteristics of 304 and 316L stainless steel in the static liquid lithium, Journal of Nuclear Materials (553) 153032, 2021

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