# Considerations of Primary Heat Exchangers Materials for Fusion Reactors with sCO$_2$ for Power Conversion

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# Scope of the paper

Candidate materials, opportunities and challenges for different primary working fluids - fusion reactor coolants and supercritical carbon dioxide ($sCO_2$) as the power generation working medium

The focus is on the materials of construction of primary heat exchangers, exemplifying the challenges and opportunities for development

In addition, the presentation includes

High level summary of the fusion technology and plant development

High level power cycle design and opportunities $sCO_2$ cycles present

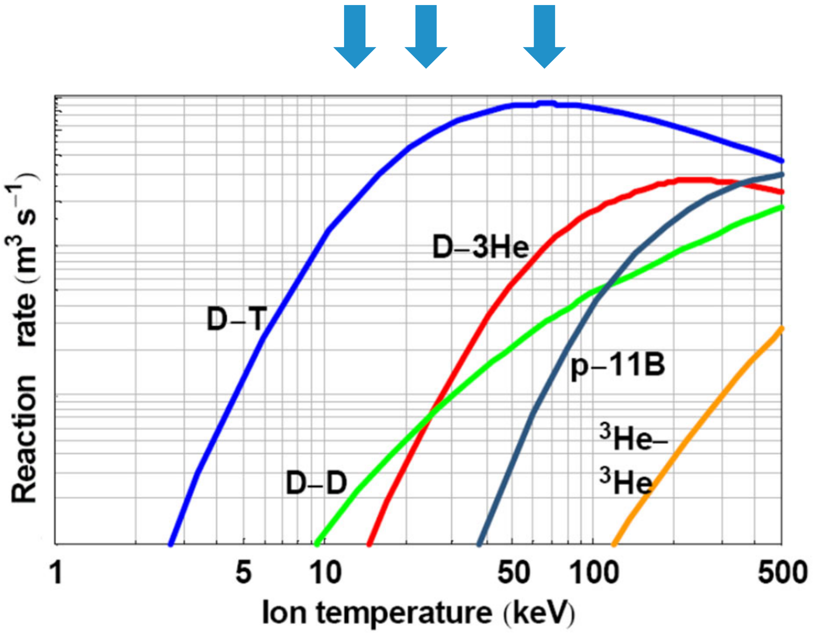
High level fusion environment materials consideration

# Background to Nuclear Fusion

Fusion Fuels

“To obtain viable fusion energy, deuterium–tritium (D–T) fuel is the most common choice for future fusion power plants and the majority of fusion development activities continue in variation of this design.”

At temperature below 300 million K Deuterium Tritium reaction provides at least 2 orders of magnitude more energy than other fusion reactions.

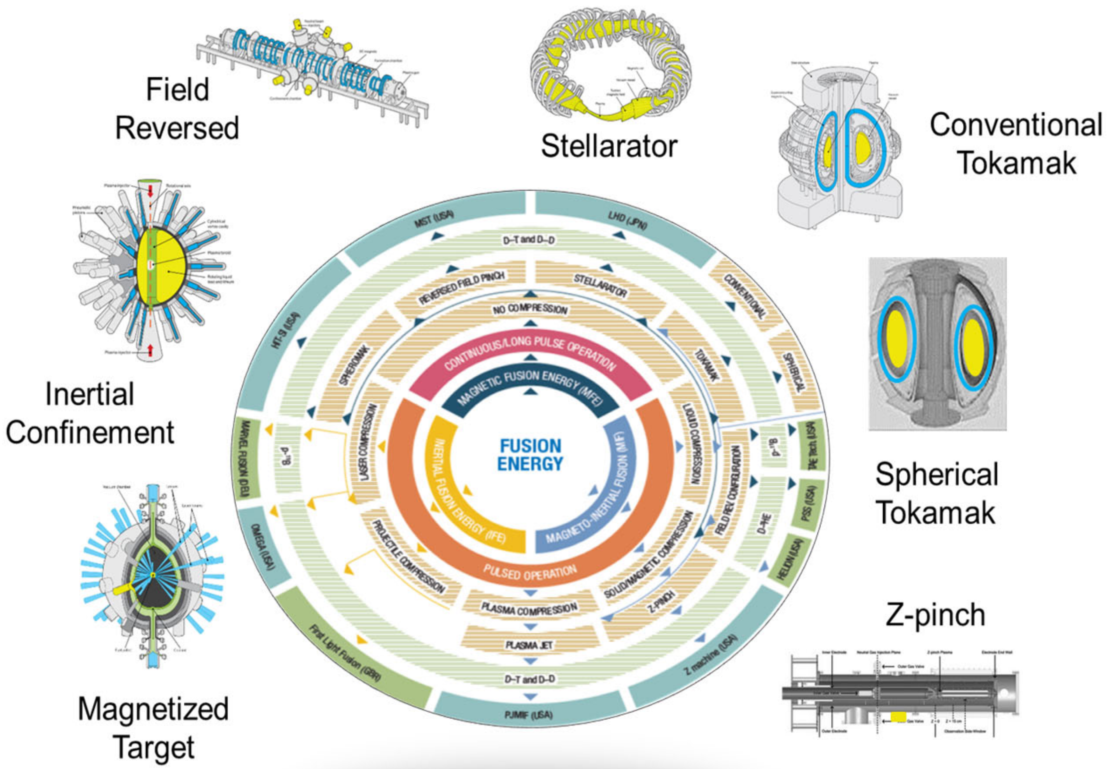


150 300 800 Million K

**IAEA World Fusion Outlook 2023**, © IAEA, 2023, page 46
https://doi.org/10.61092/iaea.ehyw-jq1g

# General Confinement Methods

Fusion Power Plant design is highly complex & requires integrated engineering approach

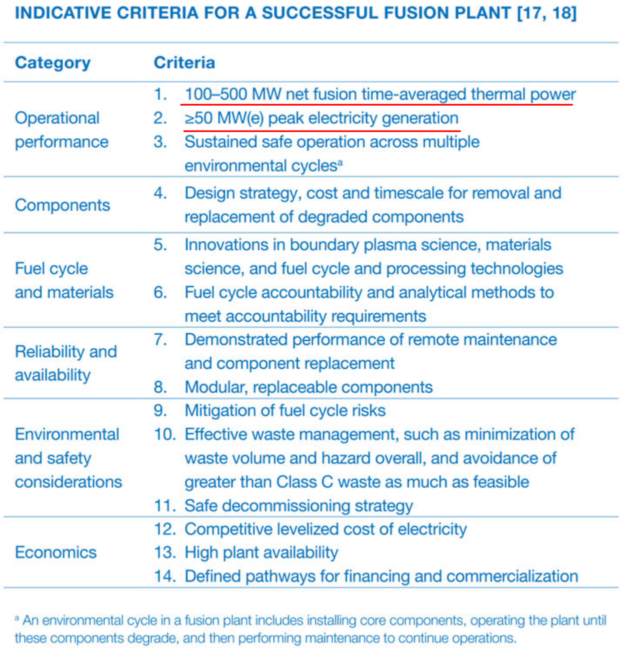


“The vast majority of past fusion plasma experience is from magnetic confinement in a tokamak design using deuterium–deuterium (D–D) fuel.”

**IAEA World Fusion Outlook 2023**, © IAEA, 2023, page 18
https://doi.org/10.61092/iaea.ehyw-jq1g

# Fusion plant timescale

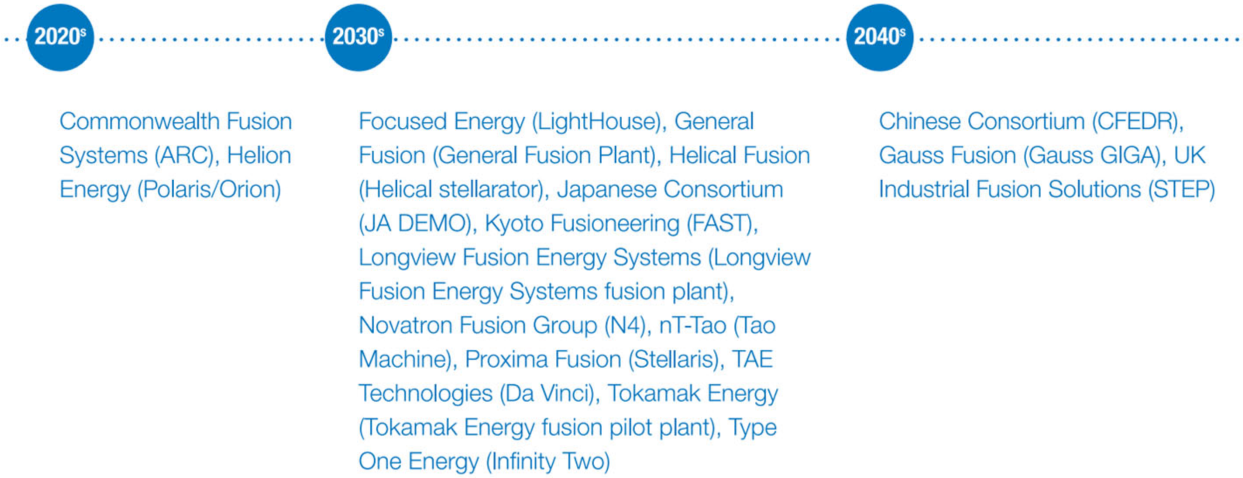
*“The fusion era is thus no longer just an aspiration it is a reality within our grasp and presents the opportunity for low carbon, sustainable and dispatchable thermal and electrical energy production.”*



**INDICATIVE CRITERIA FOR A SUCCESSFUL FUSION PLANT [17, 18]**

| Category | Criteria |
|---|---|
| Operational performance | 1. 100–500 MW net fusion time-averaged thermal power |
| | 2. ≥50 MW(e) peak electricity generation |
| | 3. Sustained safe operation across multiple environmental cycles[a] |
| Components | 4. Design strategy, cost and timescale for removal and replacement of degraded components |
| Fuel cycle and materials | 5. Innovations in boundary plasma science, materials science, and fuel cycle and processing technologies |
| | 6. Fuel cycle accountability and analytical methods to meet accountability requirements |
| Reliability and availability | 7. Demonstrated performance of remote maintenance and component replacement |
| | 8. Modular, replaceable components |
| Environmental and safety considerations | 9. Mitigation of fuel cycle risks |
| | 10. Effective waste management, such as minimization of waste volume and hazard overall, and avoidance of greater than Class C waste as much as feasible |
| | 11. Safe decommissioning strategy |
| Economics | 12. Competitive levelized cost of electricity |
| | 13. High plant availability |
| | 14. Defined pathways for financing and commercialization |

[a] An environmental cycle in a fusion plant includes installing core components, operating the plant until these components degrade, and then performing maintenance to continue operations.



**2020s**

Commonwealth Fusion Systems (ARC), Helion Energy (Polaris/Orion)

**2030s**

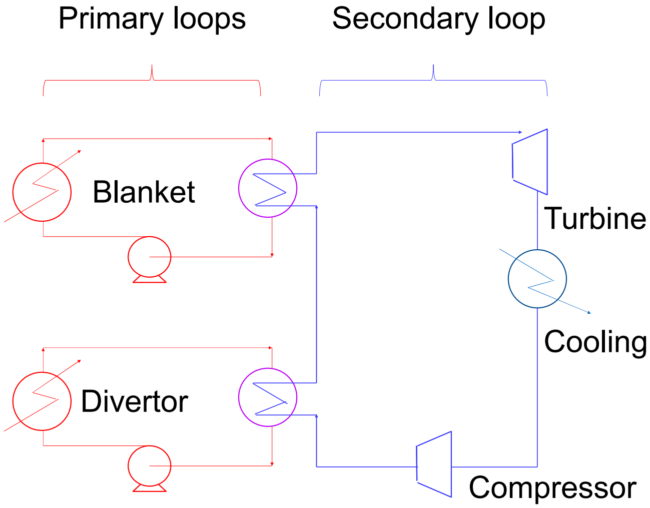
Focused Energy (LightHouse), General Fusion (General Fusion Plant), Helical Fusion (Helical stellarator), Japanese Consortium (JA DEMO), Kyoto Fusioneering (FAST), Longview Fusion Energy Systems (Longview Fusion Energy Systems fusion plant), Novatron Fusion Group (N4), nT-Tao (Tao Machine), Proxima Fusion (Stellaris), TAE Technologies (Da Vinci), Tokamak Energy (Tokamak Energy fusion pilot plant), Type One Energy (Infinity Two)

**2040s**

Chinese Consortium (CFEDR), Gauss Fusion (Gauss GIGA), UK Industrial Fusion Solutions (STEP)

**IAEA World Fusion Outlook 2025**, © IAEA, 2025, page 25
25-02871E_PUB_WorldFusionOutlook_LO29_CMYK.indd

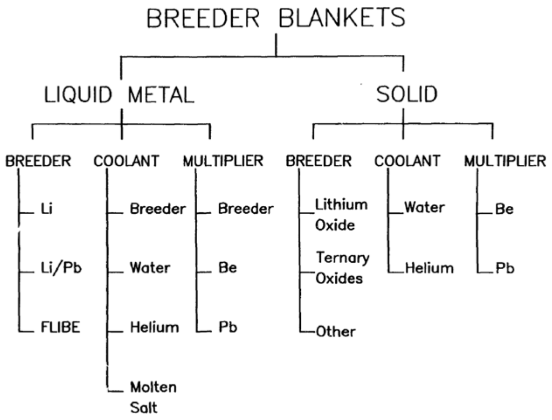
# Power cycles – optioneering



There are a diverse range of thermal fluid options, but these will be constrained by materials of construction

| Location | Grade of heat | EU DEMO | UKIFS STEP |
|---|---|---|---|
| Blanket | High | 86% | 75% |
| Outboard first wall | Medium | | |
| Inboard build | Low | | 10% |
| Divertors | Low | 10 | 13% |
| Vacuum vessel | Low | 4 % | 2% |

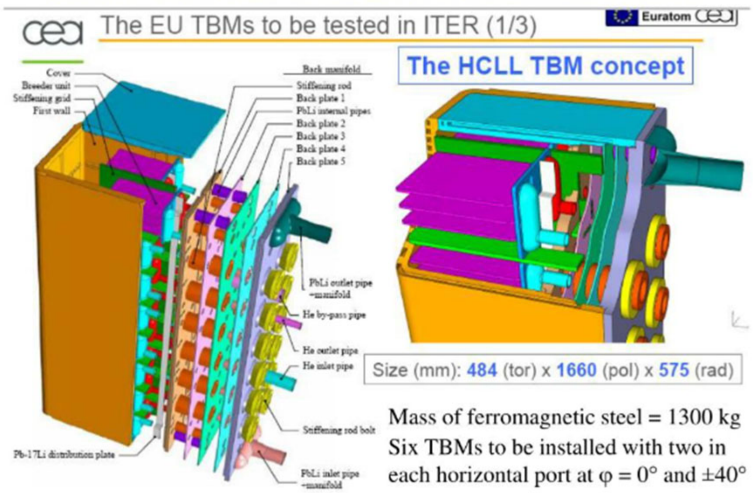
# Breeder blanket



<u>Function</u>

To breed tritium, convert the neutronic energy into heat and shield sensitive components from neutrons.

Helium Cooled Lithium-Lead Test Blanket Module

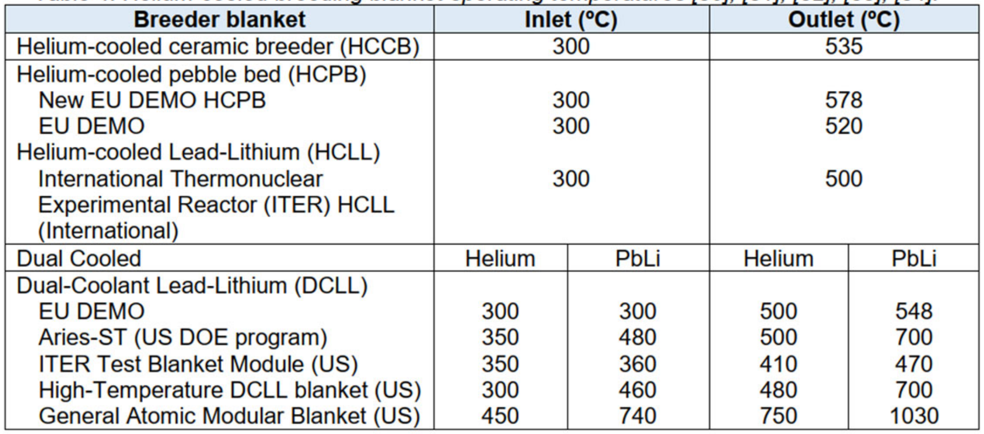

The EU TBMs to be tested in ITER (1/3)

**The HCLL TBM concept**

Size (mm): 484 (tor) x 1660 (pol) x 575 (rad)

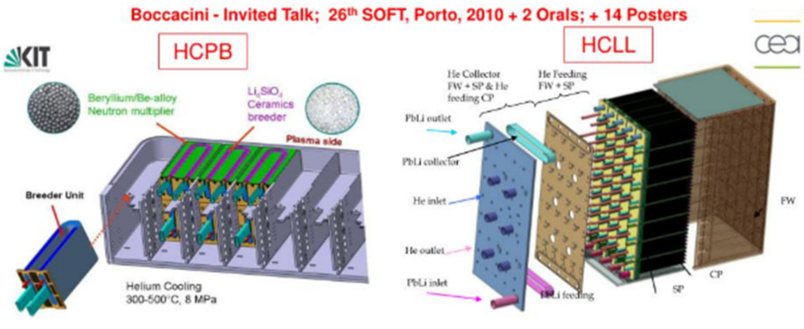
Mass of ferromagnetic steel = 1300 kg
Six TBMs to be installed with two in each horizontal port at φ = 0° and ±40°

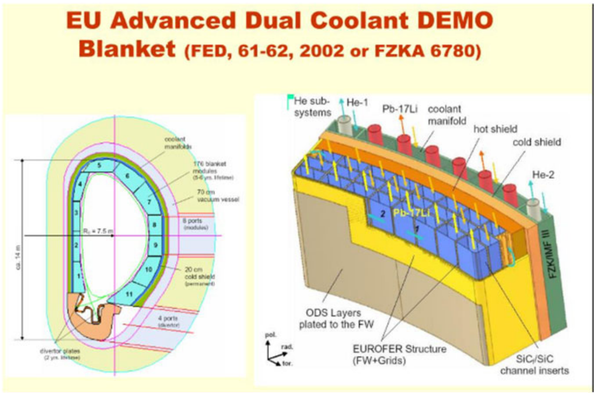
*Table 4. Helium-cooled breeding blanket operating temperatures [30], [31], [32], [33], [34].*

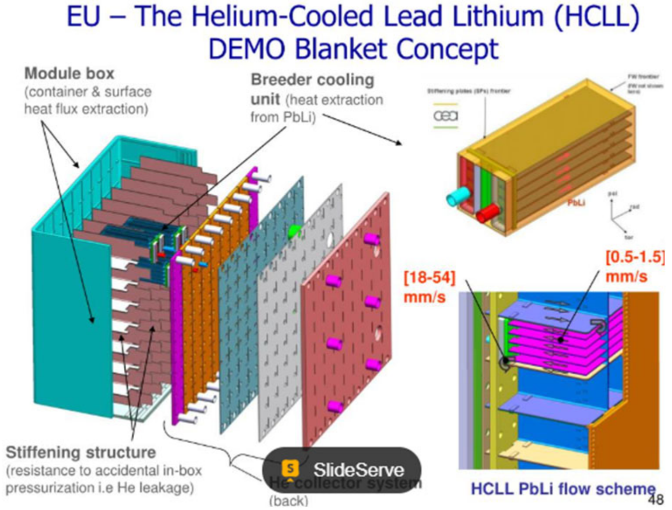


| Breeder blanket | Inlet (ºC) | | Outlet (ºC) | |
|---|---|---|---|---|
| Helium-cooled ceramic breeder (HCCB) | 300 | | 535 | |
| Helium-cooled pebble bed (HCPB) | | | | |
| New EU DEMO HCPB | 300 | | 578 | |
| EU DEMO | 300 | | 520 | |
| Helium-cooled Lead-Lithium (HCLL) | | | | |
| International Thermonuclear Experimental Reactor (ITER) HCLL (International) | 300 | | 500 | |
| Dual Cooled | Helium | PbLi | Helium | PbLi |
| Dual-Coolant Lead-Lithium (DCLL) | | | | |
| EU DEMO | 300 | 300 | 500 | 548 |
| Aries-ST (US DOE program) | 350 | 480 | 500 | 700 |
| ITER Test Blanket Module (US) | 350 | 360 | 410 | 470 |
| High-Temperature DCLL blanket (US) | 300 | 460 | 480 | 700 |
| General Atomic Modular Blanket (US) | 450 | 740 | 750 | 1030 |

# Additional divertor and blanket images


Boccacini - Invited Talk; 26th SOFT, Porto, 2010 + 2 Orals; + 14 Posters


EU Advanced Dual Coolant DEMO Blanket (FED, 61-62, 2002 or FZKA 6780)


EU – The Helium-Cooled Lead Lithium (HCLL) DEMO Blanket Concept

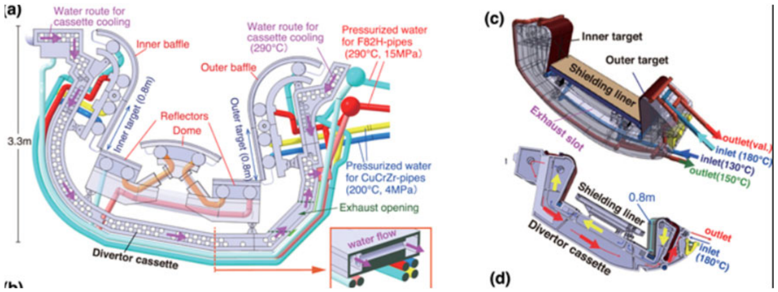
**Module box** (container & surface heat flux extraction)

**Breeder cooling unit** (heat extraction from PbLi)

**Stiffening structure** (resistance to accidental in-box pressurization i.e He leakage)

**He collector system** (back)

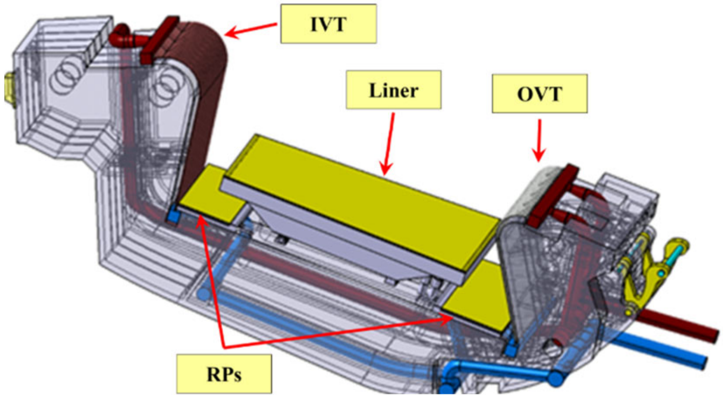
HCLL PbLi flow scheme

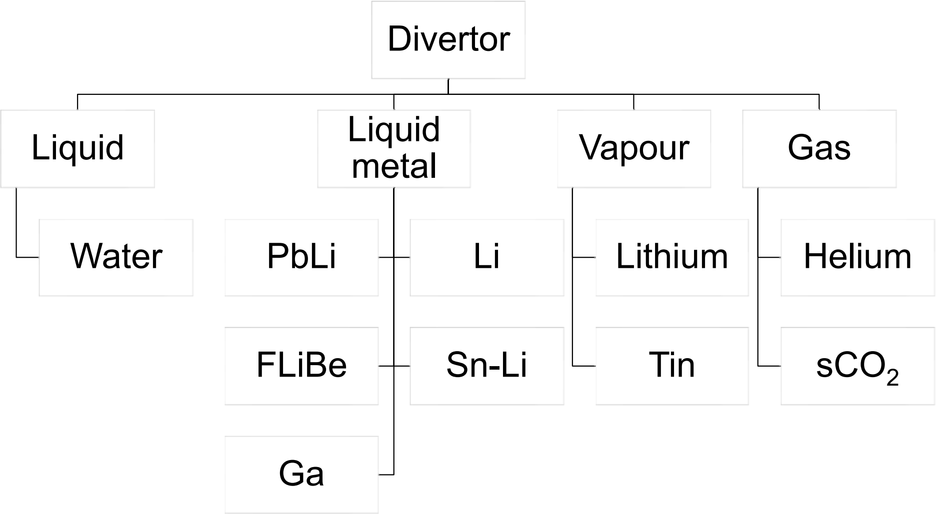


# Divertor

<u>Function</u>

To extract heat and removed waste particles from the plasma





- Divertor
  - Liquid
    - Water
  - Liquid metal
    - PbLi
    - Li
    - FLiBe
    - Sn-Li
    - Ga
  - Vapour
    - Lithium
    - Tin
  - Gas
    - Helium
    - $sCO_2$

*Table 5. Water- and liquid metal-cooled divertors [41].*

| Divertor system (cooling-material) | Pressure (bar) | Coolant Inlet Temperature (°C) | Coolant Outlet Temperature (°C) |
|---|---|---|---|
| WCD-CuCrZr | 42 | 140 | ~166 |
| WCD-RAFM | 155 | 300 | ~325 |
| LMCD | Hydro-static | 600 | ~900 |

# Case for the $sCO_2$ Cycle in Fusion Plants

- High recirculating power requires high efficiency for significant net output
- Ability to integrate diverse grades of heat from different systems
- Responsiveness
- Reduced power cycle equipment footprint
- Enhanced Tritium barrier over steam

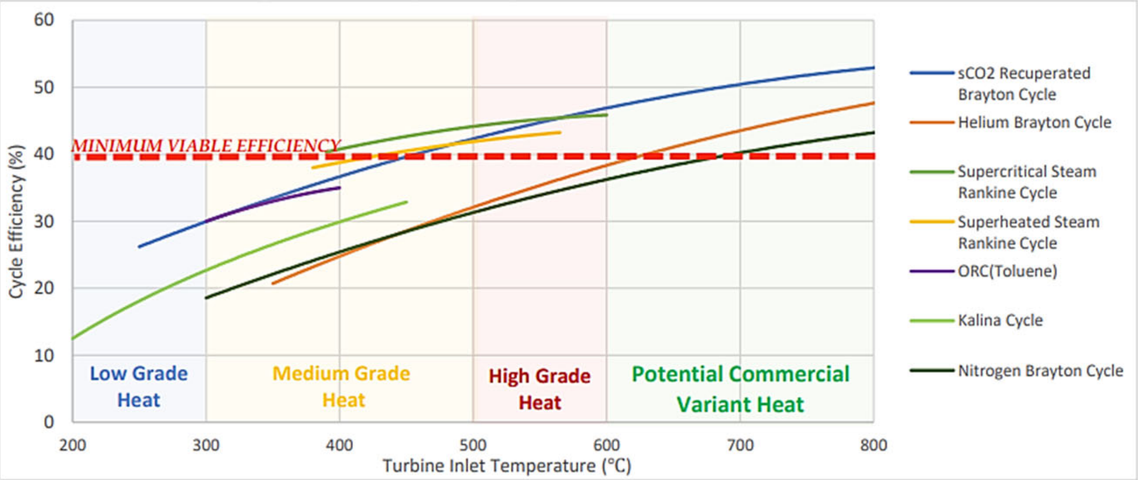


*Figure 3: Efficiencies vs Temperatures of state-of-the-art thermodynamic cycles*

*From Acres et al., Philos Trans A Math Phys Eng Sci* (2024) 382 (2280): 20230404
https://doi.org/10.1098/rsta.2023.0404

# Primary Heat Exchangers Materials Challenges

- Diverse fusion plant designs
  - Different thermal sources, operating cadences, grades of heat and working fluids.
- Interaction between the in-vessel materials of construction and working fluids ($sCO_2$) creates challenging environments
- Each coolant presents a distinct material compatibility challenges and imposes limits on the operating temperatures of the heat exchanger
- Need to optimize and integrate all of the thermal energy entering the sCO2 power cycle(s)
- Unprecedented challenge for the materials of construction, but possibly some learning from SFR

Necessitate a careful balance in material selection to ensure long-term performance, corrosion resistance, and mechanical integrity.

Need to engineer fusion energy conversion systems - Now

# Heat Exchanger Requirements for Materials of Construction

- Structural integrity at operational conditions
- Environmental resistance to corrosion particularly from lithium-bearing coolants
- Resistance to carburisation and high-temperature oxidation
- Thermal properties
- Manufacturing readiness
- Impurities management

# Material Compatibility – $sCO_2$

### Ferritic <500°C

- Carburisation issue – formation of unprotective Fe-rich oxide scale rather than protective chromia layer

### Austenitic - 550°C

- Ductility retained at 550°C, but then C ingress causes embrittlement

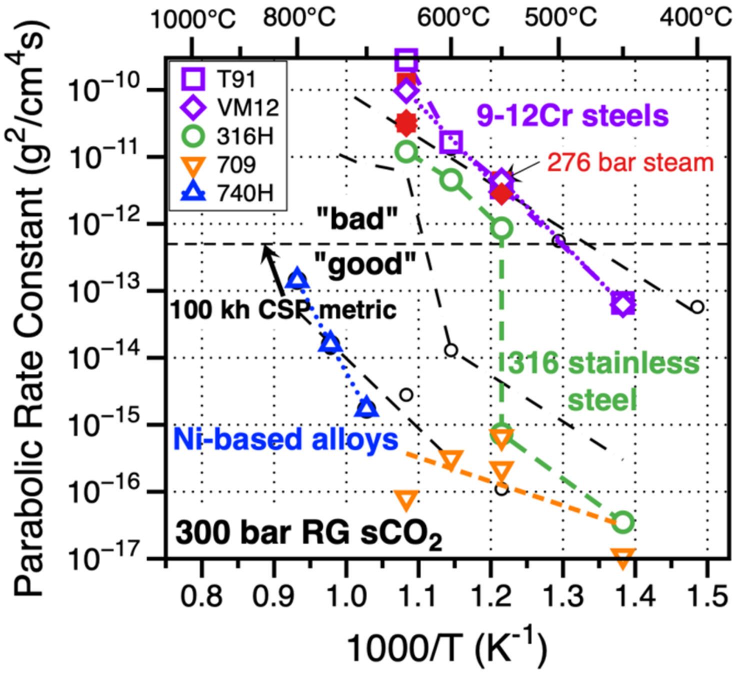
### Advanced austenitic steels - 650°C

- Carburisation issue mitigated by higher Cr content
- Ductility retained at 650°C

### Ni-based alloys: 650 - 800°C

- Not affected by carburisation
- Little pressure effect, but composition matters at higher temperatures

### SiC and SiCf/SiC: Up to 1000°C



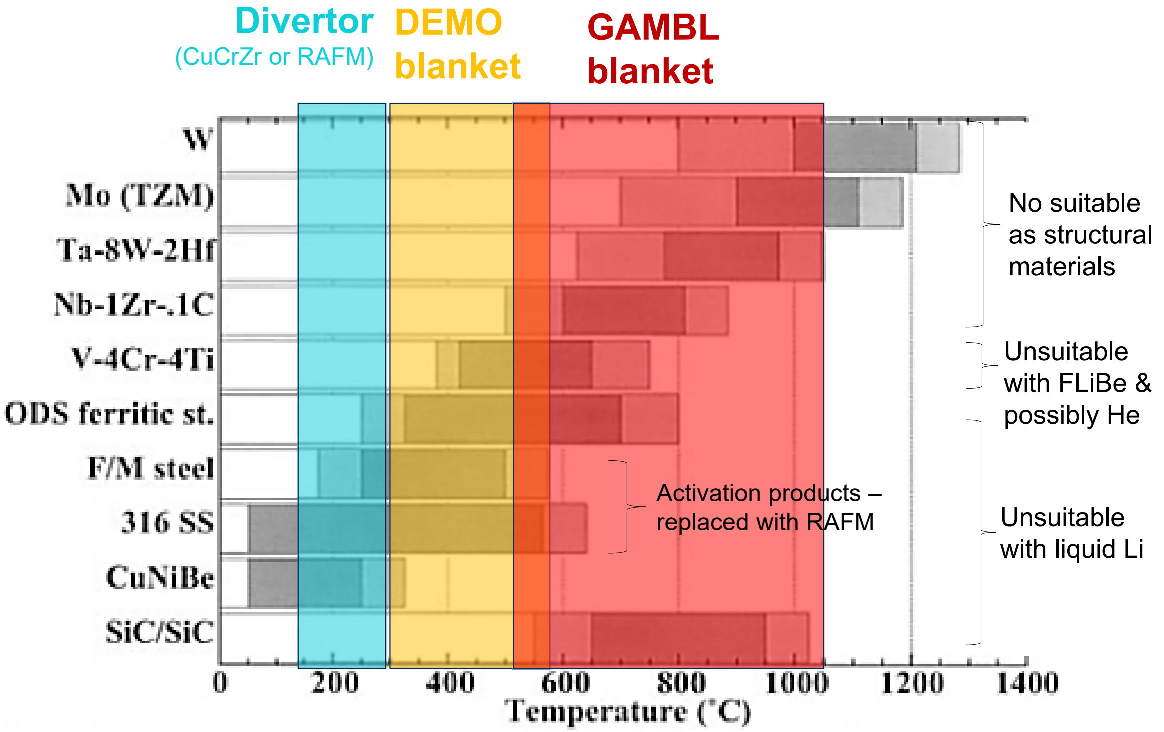
From Pint et al. *Effect of Impurities on Supercritical Carbon Dioxide Compatibility (FWP-FEAA144)*,
Gordon Research Conference on High Temperature Corrosion, 2023

**But all steels limited to 550°C when $H_2O$ and $O_2$ impurities are added to $CO_2$ in addition to a ductility reduction.**

# Material compatibility – coolants from in-vessel components

General material requirements:

- High-temperature capability: strength retention and creep resistance
- No embrittlement at lower (high) temperatures due to neutron (helium)
- Corrosion resistance to aggressive lithium-bearing species (PbLi, Li, FLiBe) and water
- Low tritium inventory
- Manufacturability and supply availability
- No or reduced production of long-lived radionuclides when irradiated with neutrons: e.g., Co, Ni, Mo, Nb (although not transuranic)



No suitable as structural materials

Unsuitable with FLiBe & possibly He

Unsuitable with liquid Li

Activation products – replaced with RAFM

Adapted from Zinkle et al. Fus. Eng. Des., vol. 51–52, pp. 55–71, Nov. 2000, https://doi.org/10.1016/S0920-3796(00)00320-3

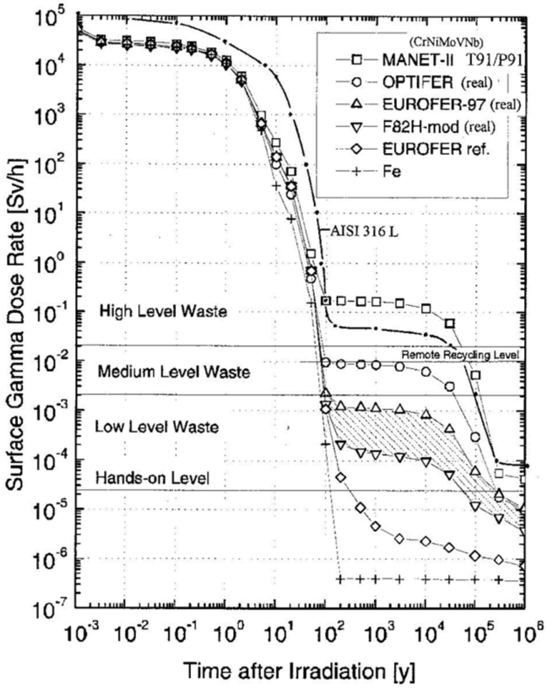
# Reduced Activation Ferritic Martensitic (RAFM) Steels

*Advantages*

- Low activation characteristics, achieved by replacing long-lived radioactive elements (Ni, Co, Mo, Nb) with W, Ta, and V
- radiation resistance with minimal shift in the ductile-to-brittle transition temperature under neutron irradiation;
- Proven fabrication and joining techniques, enabling faster technological maturation compared to other low-activation materials
- Compatible with PbLi, helium, water, and potentially FLiBe up to 550°C, limited by corrosion and creep resistance.

*Disadvantages*

- Not compatible with liquid lithium and limited to 550°C
- More importantly, they contain 8–9 wt.% chromium, which is insufficient to resist carburization in $sCO_2$ environments.



From Rieth et al., "EUROFER 97 Tensile, Charpy, Creep and Structural Tests [PDF]." Forschungszentrum Karlsruhe Gmbh, Karlsruhe in Germany (2003).

# Oxide Dispersion-Strengthened (ODS) Steels

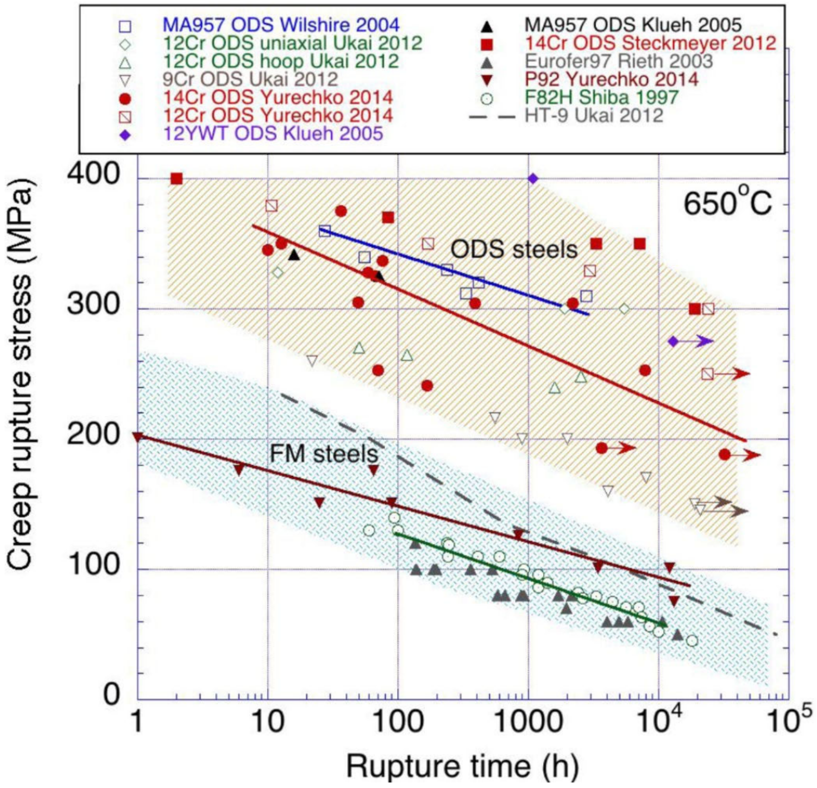
*Advantages*

- Excellent strength and creep resistance at temperatures up to 650°C and superior irradiation tolerance

*Disadvantages*

- Lower readiness due to non-standardised production methods and variable quality.
- The traditional joining method presents difficulties
- ODS steels typically contain 8–9 wt.% Cr, which poses similar carburisation challenges in $sCO_2$

- High-Cr ODS alloys (up to 16 wt.%) ODS offer better creep resistance but lower toughness,
- UPM2000 ODS steel (20 wt.% Cr) outperformed austenitic and Ni-based alloys in $sCO_2$ at 650°C and 20 MPa over 3000 hours



From S. J. Zinkle et al., Nuclear Fusion, vol. 57, no. 9, Jun. 2017, https://doi.org/10.1088/1741-4326/57/9/092005

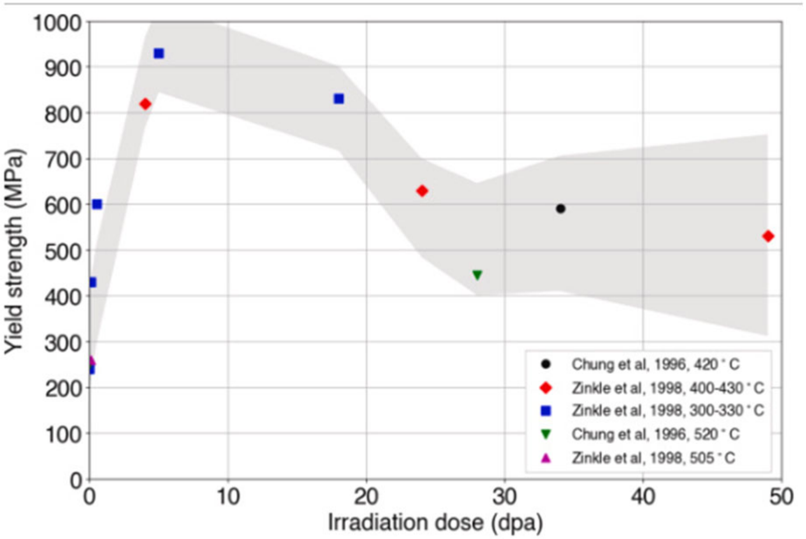
# Vanadium Alloys

*Advantages*

- Vanadium alloys, e.g., V-4Cr-4Ti, offer superior corrosion resistance in liquid lithium up to 650°C
- High creep strength and low thermal expansion for extended component lifetime

*Disadvantages*

- Highly susceptible to embrittlement due to interactions with non-metallic impurities (N, C, O) (at few ppm level)
- Unsuitable with FLiBe (tritium solubility higher in Vanadium than salt)



Butt et al., Fusion Engineering and Design Volume 210, January 2025, 114739
https://doi.org/10.1016/j.fusengdes.2024.114739

# SiCf/SiC Ceramic Matrix Composites

SiCf/SiC composites have been investigated in fusion programs such as ARIES-ACT2, UNITY, and GAMBL due to their high-temperature corrosion resistance, especially to PbLi and FLiBe

*Advantages*

- Low activation, low thermal expansion and high creep resistance.
- Resilient to $H_2O$ and $O_2$ impurities and He embrittlement*
- Resist He embrittlement up to 1000°C
- Not expected to be susceptible to carburisation
- Available knowledge based from monolithic SiC heat exchangers

*Disadvantages*

- High cost of SiC fibres (~$10,000/kg),
- Complexity manufacturing, limited production capabilities and scarce supply chain
- In general, not a structural material

- From General Atomics, SiGA SiC Composite
- From Pearson et al. Overview of Kyoto Fusioneering's SCYLLA© ("Self-Cooled Yuryo Lithium-Lead Advanced") Blanket for Commercial Fusion Reactors, IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 50, NO. 11, 2022
- From Mersen, CORRESIC® silicon carbide block heat exchangers

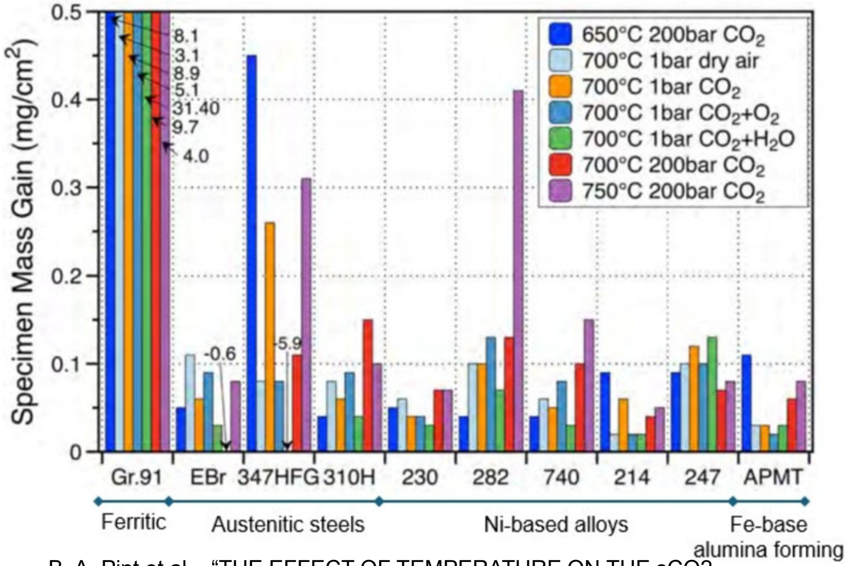
# Ni-based alloys

*Advantages*

- Used in FLiBe testing loops as they resist corrosion in molten salts like up to 700°C.
- Ni-based alloys also possess high creep resistance
- Established manufacturing techniques
- Benchmark for the $sCO_2$ power cycle balance of plant.

*Disadvantages*

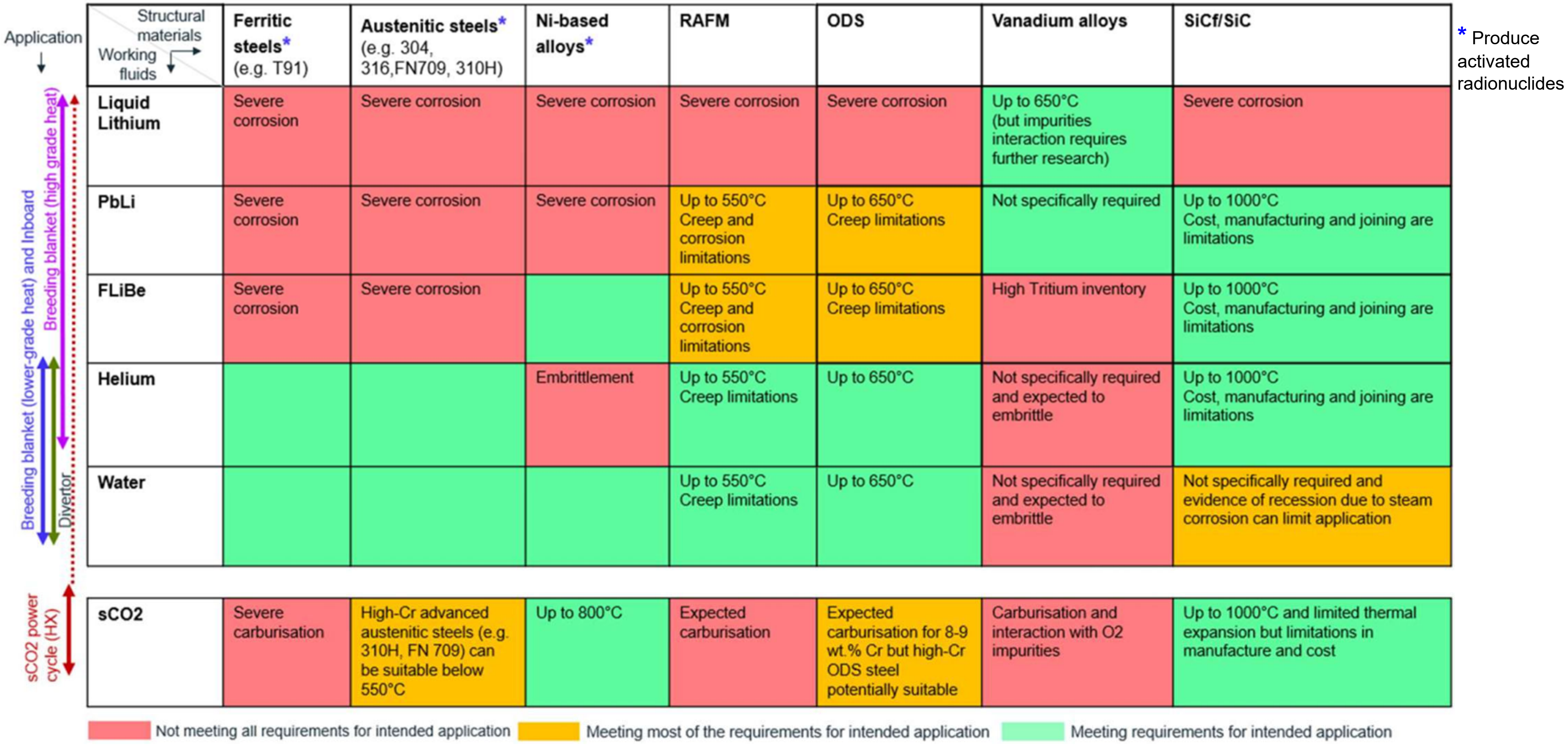
- Unsuitable in PbLi and liquid lithium and likely He
- Formation of long-lived radionuclides makes them a non-Fusion material



B. A. Pint et al. , "THE EFFECT OF TEMPERATURE ON THE sCO2 COMPATIBILITY OF CONVENTIONAL STRUCTURAL ALLOYS," *The 4th International Symposium - Supercritical CO2 Power Cycles*, 2014

Ni-based alloys may be viable for heat exchangers in fusion plant using FLiBe as coolant/breeder, provided activation concerns are managed.

# Compatibility of structural materials with breeding blanket coolants and $sCO_2$



| Structural materials → / Working fluids ↓ | **Ferritic steels*** (e.g. T91) | **Austenitic steels*** (e.g. 304, 316,FN709, 310H) | **Ni-based alloys*** | **RAFM** | **ODS** | **Vanadium alloys** | **SiCf/SiC** |
|---|---|---|---|---|---|---|---|
| **Liquid Lithium** | 🟥 Severe corrosion | 🟥 Severe corrosion | 🟥 Severe corrosion | 🟥 Severe corrosion | 🟥 Severe corrosion | 🟩 Up to 650°C (but impurities interaction requires further research) | 🟥 Severe corrosion |
| **PbLi** | 🟥 Severe corrosion | 🟥 Severe corrosion | 🟥 Severe corrosion | 🟧 Up to 550°C<br>Creep and corrosion limitations | 🟧 Up to 650°C<br>Creep limitations | 🟩 Not specifically required | 🟩 Up to 1000°C<br>Cost, manufacturing and joining are limitations |
| **FLiBe** | 🟥 Severe corrosion | 🟥 Severe corrosion | 🟩 | 🟧 Up to 550°C<br>Creep and corrosion limitations | 🟧 Up to 650°C<br>Creep limitations | 🟥 High Tritium inventory | 🟩 Up to 1000°C<br>Cost, manufacturing and joining are limitations |
| **Helium** | 🟩 | 🟩 | 🟥 Embrittlement | 🟩 Up to 550°C<br>Creep limitations | 🟩 Up to 650°C | 🟥 Not specifically required and expected to embrittle | 🟩 Up to 1000°C<br>Cost, manufacturing and joining are limitations |
| **Water** | 🟩 | 🟩 | 🟩 | 🟩 Up to 550°C<br>Creep limitations | 🟩 Up to 650°C | 🟥 Not specifically required and expected to embrittle | 🟧 Not specifically required and evidence of recession due to steam corrosion can limit application |
| **sCO2** | 🟥 Severe carburisation | 🟧 High-Cr advanced austenitic steels (e.g. 310H, FN 709) can be suitable below 550°C | 🟩 Up to 800°C | 🟥 Expected carburisation | 🟧 Expected carburisation for 8-9 wt.% Cr but high-Cr ODS steel potentially suitable | 🟥 Carburisation and interaction with O2 impurities | 🟩 Up to 1000°C and limited thermal expansion but limitations in manufacture and cost |

🟥 Not meeting all requirements for intended application 🟧 Meeting most of the requirements for intended application 🟩 Meeting requirements for intended application

* Produce activated radionuclides

# Recommendations for future research

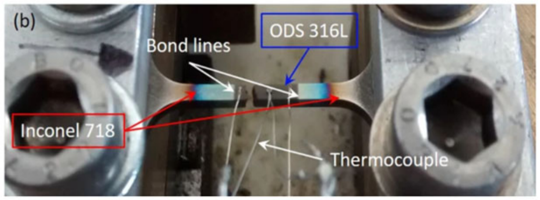
Materials of construction research

- Materials testing with $sCO_2$ (food-grade)
- Advanced manufacturing and joining of dissimilar materials
- Deployment of coatings (for example permeation barriers)
- Optimising the use of elements which can form long-lived radionuclides

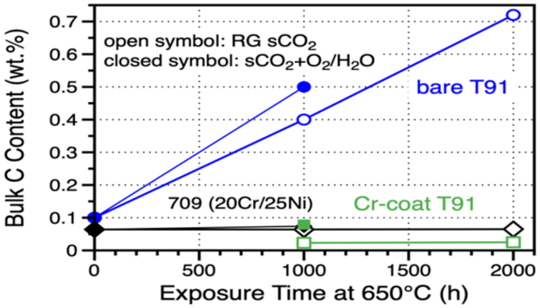
Heat exchanger research / collaboration

- Design and assessment of heat exchangers with a wide array of working fluids.

Primary Heat Exchangers ‘a la Heatric’, 2024
Supercritical CO2 Power Cycles Symposium



Leo et al., Metall Mater Trans A **55**, 827–838 (2024). https://doi.org/10.1007/s11661-023-07288-2



Effect of Impurities on Supercritical Carbon Dioxide Compatibility (FWP-FEAA144), 2023
, 2023 Gordon Research Conference on High Temperature Corrosion

# Summary

No Single “Preferred” Materials Solution for Fusion Systems

- Ni-based alloys
  - Strong performance in $sCO_2$ and compatible with water and FLiBe coolants.
  - Challenges: long-lived activation products; limited compatibility with PbLi and liquid lithium.

- High(er)-Cr RAFM & ODS steels
  - Needed to resist corrosion (Li-bearing) and carburization in $sCO_2$.

- Vanadium alloys & SiC/SiC
  - Vanadium alloys have carburisation issues in $sCO_2$.
  - Vanadium alloys & $SiC^f/SiC$ faces manufacturing readiness, cost, and supply-chain constraints.

- First-generation breeding blankets
  - Operate at relatively low temperatures (~550 °C).
  - Potential for advanced austenitics or coated RAFM in primary heat exchangers.

- $sCO_2$ power cycles for fusion
  - Require improved materials performance and validation under fusion-relevant conditions.

- Architecture implications
  - Adding an intermediate loop simplifies materials selection but reduces efficiency and increases plant footprint and cost.