

Considerations of Primary Heat Exchanger Materials for Fusion Reactors Utilizing sCO₂ for Power Conversion

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ABSTRACT

The integration of supercritical carbon dioxide (sCO₂) Brayton cycles into fusion power plants presents a promising pathway to enhance thermodynamic efficiency, reduce plant footprint, and accommodate the dynamic nature of plasma operations. However, the deployment of sCO₂ cycles in fusion environments introduces unprecedented challenges, particularly in the selection of materials for primary heat exchangers that must interface with diverse and chemically aggressive in-vessel coolants such as liquid lithium, eutectic lead-lithium alloy (PbLi), lithium-fluoride beryllium-fluoride salt (FLiBe), helium, and water. This paper explores the compatibility of candidate structural materials with both sCO₂ and fusion reactor coolants, focusing on the complex interplay between corrosion resistance, mechanical integrity, activation concerns, and manufacturing challenges.

Considerations include the performance of reduced activation ferritic martensitic (RAFM) steels, oxide dispersion-strengthened (ODS) steels, vanadium alloys, SiC_f/SiC composites, and Ni-based alloys under typical sCO₂ conditions. While Ni-based alloys offer superior resistance to carburization and high-temperature creep, their activation under neutron irradiation limits their use in in-vessel components. Conversely, RAFM and ODS steels, though suitable for fusion environments, exhibit poor durability in sCO₂ due to carburization and corrosion. SiC_f/SiC composites show good compatibility with sCO₂ and in-vessel component coolants but face significant manufacturing and joining challenges. These challenges are typical of vanadium alloys, which are the only metallic alloys compatible with liquid lithium, but are believed to be unsuitable for sCO₂ environments.

Safety considerations, including failure scenarios involving interactions between sCO₂ and lithium-bearing species arising from potential leaks, must be addressed. Ultimately, the findings underscore that no single material currently satisfies the operational and safety requirements. Thus, further research into hybrid design solutions, advancements in manufacturing and joining, coatings, and novel materials are required to enable the successful deployment of sCO₂ cycles in fusion power plants.

INTRODUCTION

As evidenced by the recently released US Department of Energy's (US DOE) Fusion Science & Technology Roadmap [1], the momentum behind fusion energy today is undeniable and investing in fusion energy research and its commercialization promises significant economic benefits. 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 [2].

As several approaches to generate fusion-derived power are being investigated, magnetic confinement fusion using tokamak and stellarator devices are the most developed. Several other experiments and programmes developing Fusion Pilot Plants (FPP) [3], [4], [5], [6], [7], [8], [9] are under development with the ultimate goal to achieve (or show the pathway towards) net energy output, which is a precursor to demonstrating the commercial sustainability of fusion.

To generate electricity, a thermodynamic power cycle is used to convert the heat extracted from the tokamak reactor into electrical output. Thermal energy from the fusion reaction is transferred from the tokamak subsystems and components such as the breeder blanket and diverter to one or more primary coolant loops. From there, the heat is transferred through primary heat exchangers to the power cycle, where the working fluid is expanded through a turbine to generate electricity.

Several thermodynamic power cycles have been explored for application in fusion prototype power plants, each presenting distinct advantages and limitations. A common consensus is that maximizing heat utilization from the tokamak is essential to enhance the operational efficiency and to demonstrate the commercial viability of fusion energy. The safety case for coolant selection must be robust—especially given the potential use of exotic combinations within the reactor—and must also support operational flexibility to accommodate the dynamic nature of plasma behaviour and pulsed operation modes. Achieving high efficiency further necessitates operating at elevated temperatures, which in turn demands significant advancements in materials capable of withstanding the complex and extreme conditions inherent to fusion environments.

This paper highlights the candidate materials, opportunities and challenges for different primary working fluids (fusion reactor coolants and supercritical carbon dioxide (sCO₂) as the power generation working medium). This paper specifically focuses on the materials of construction of primary heat exchangers, exemplifying the challenges and opportunities for development.

The paper assumes that the high-energy neutronic fields and activated products are not transferred into the power conversion working fluid using an efficient system of hot and cold traps for removal of radioactive and other impurities and an effective tritium removal/detrification system. It must be noted however, that these factors present even more significant risks if a steam Rankine cycle is selected because of the formation of tritiated water.

Also, outside the scope of this paper are considerations regarding the number and types of heat exchangers, and their architectures and geometries – even as we recognize the future interactions necessary between the mechanical, thermal, and materials disciplines to specify these features.

THERMODYNAMIC POWER CYCLES LANDCAPE

Several thermodynamic cycles and combinations thereof have been considered for fusion power plants, including steam Rankine cycles (supercritical and superheated), helium and sCO₂ Brayton cycles.

Table 1 provides a comparison of the main advantages and disadvantages of the candidate thermodynamic cycles.

Table 1. Overview of thermodynamic cycles for fusion powerplant [10], [11].

Thermo-dynamic power cycle	Operating Temp. (°C)	Advantages	Disadvantages
Superheated Steam Rankine	280–565	<p>Commercially mature technology</p> <p>Readily available equipment with low technical risk</p> <p>Reduced material compatibility risk between primary and secondary loops</p>	<p>Low thermodynamic efficiency, requiring larger thermal input from heat source to achieve net power/plant capacity, increasing cost and risk</p> <p>Increased plant capital cost and large footprint</p> <p>Tritiated water can be formed and needs to be managed</p>
Supercritical Steam Rankine	565–620	<p>Higher efficiencies than superheated steam cycles</p> <p>Commercial maturity and equipment availability</p>	<p>Increased capital cost and requirement for advanced materials</p> <p>Tritiated water can be formed and needs to be managed</p>
Helium Brayton	350–950	<p>Chemically inert and non-corrosive coolant</p> <p>Limited formation of activated by-products</p> <p>Low energy requirement for detritiation because no or limited tritiated water is formed</p>	<p>Experimental and demonstrational projects underway, not an established technology</p> <p>High helium leak rate necessitates frequent resupply, presenting supply chain and op. cost risks</p> <p>Lower overall efficiency power cycle at lower temperatures</p>
sCO ₂	350–1000	<p>Reduced footprint compared with above cycles.</p> <p>Better suited for flexible, non-continuous operation due to smaller equipment and less thermal mass</p> <p>Low detritiation energy requirements because no or limited tritiated water is formed.</p> <p>Working fluid is stable across a wide operating range</p> <p>Commercially available at low cost</p>	<p>Immature technology, though roadmaps and supply chains are under development</p>

Steam Rankine cycles remain a cornerstone of modern thermal power generation, with operating conditions progressively advancing as new high-performance alloys become commercially viable. Utilizing fusion energy as the sole thermal input to a Steam Rankine cycle introduces several critical challenges (some of which could be mitigated with the inclusion of an intermediate loop with thermal storage, but at increased cost and complexity). Steam turbines can take hours to start up, introducing a considerable discrepancy with the relatively instantaneous start of the fusion reactor and the pulsed operations of the fusion power plant. Rapid fluctuations in thermal load and operating conditions can lead to the formation of excessive wet steam in the final stages of the turbine, posing risks to mechanical integrity and efficiency. The initial fusion power plants must also manage the complex task of integrating multiple thermal sources (at different temperatures and heat quantities) into a cohesive and efficient thermodynamic cycle. In a steam Rankine cycle, a significant portion of thermal energy is transferred at a constant temperature during steam generation. This temperature may not be optimal for the specific design requirements of a tokamak system.

Additionally, the presence of tritium in the working fluid necessitates effective detritiation strategies while minimizing the parasitic load. For instance, the Canada deuterium uranium (CANDU) pressurized heavy-water fission reactor incorporates commercial systems for tritium extraction from thermal working fluids. The CANDU reactors generate approximately 0.13 kg of tritium annually [12], whereas a continuously operating 1 GW_{th} deuterium–tritium fusion reactor would require extraction of around 52.5 kg of tritium per year. Scaling the parasitic load does not present a viable method for net energy production.

OVERVIEW OF SUPERCRITICAL CO₂ POWER CYCLE FOR FUSION POWER PLANT

Power cycles based on sCO₂ offer significantly higher thermal efficiencies compared to conventional cycles such as steam Rankine cycle or helium Brayton cycle, particularly when operating at higher turbine inlet temperatures and pressures [10], [11]. The upper bounds for temperature are especially relevant for applications in concentrated solar power and direct fossil fuel heating [13], [14]. However, for nuclear applications, including fusion, the operating conditions are typically more conservative, with maximum temperatures around 700°C and pressures between 20–30 MPa [15].

Research has shown that sCO₂ Brayton cycles offer significantly enhanced responsiveness, with the working fluid remaining in a single phase throughout operation, thereby reducing the risk of turbine damage associated with phase transitions [16].

Above its relatively low critical point of 73.77 bar and 30.98°C, sCO₂ has nearly 1.5-times the density of steam at its critical point of 220.64 bar and 373.95°C. The high density and volumetric heat capacity of sCO₂ makes it more energy-dense, resulting in reductions in turbomachinery size. These benefits also lead to a smaller plant footprint and possibly lower capital costs. Near the critical point, CO₂ becomes nearly incompressible and requires less energy to pressurize the fluid. This reduces the compression power required compared to other gas-based (e.g., He) — yielding higher cycle efficiency.

The efficiency advantages of sCO₂ vs. Helium Brayton and Steam Rankine (shown in Figure 1) is what first brought the important potential of the sCO₂ power cycle to the attention of GTI Energy (GTI). Work performed in 2006 by GTI's technology predecessor, a division of Pratt & Whitney Rocketdyne, independently confirmed the efficiency analysis and incorporated results from the model used for the analysis (the coloured symbols in Figure 1 below [17]). The sCO₂, Helium Brayton and steam cycles are being considered for fusion power plants. The plot shows

the efficiency of the sCO₂ cycle exceeded that of subcritical-superheated steam cycles at ~450°C turbine inlet temperatures and of the single-reheat supercritical cycles at ~550°C. The most advanced steam cycle systems (double reheat configuration) can exceed sCO₂ cycle efficiency through maximum material limits of ~600°C, though with higher capital cost and very few commercial deployments. The Helium Brayton cycle efficiency is predicted to be significantly lower than sCO₂ over the full range of possible temperatures. It is this efficiency advantage that continues to drive our interest in planning for using the sCO₂ cycle on upcoming fusion power plants and exploring the potential mitigation measures for potential issues involved with its use.

Regarding the detritiation of operating fluids, tritium removal from CO₂ has been effectively demonstrated in Advanced Gas-cooled Reactors [18].

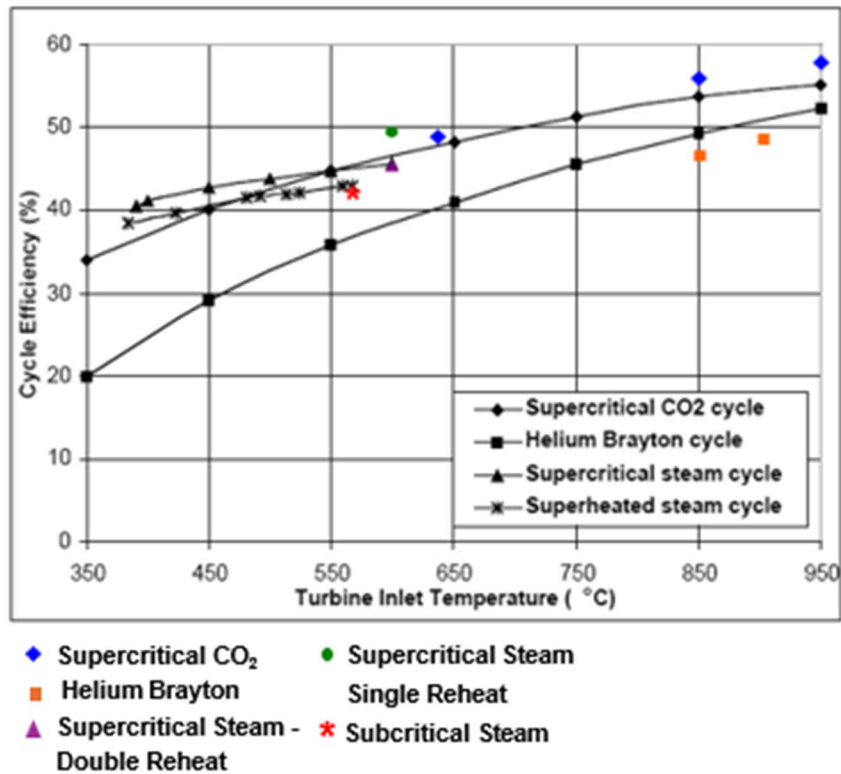


Figure 1. Plot from [19]. Coloured symbols represent the modelling results obtained at GTI. CHEMCAD was used to model sCO₂ and Helium Brayton cycles; and GateCycle used to model steam cycles.

Heat Sources in Fusion Power Plants

An aspect that must be considered in developing the power cycle and the Balance of Plant architecture of the tokamak is the presence of a range of heat sources contributing to different cooling fluids at different temperatures. These heat sources from within the tokamak include the breeding blanket, the divertor (including plasma-facing component and cassette), the inboard walls and shield, and the vacuum vessels (Figure 2). Depending on the geometries of the tokamak, plasma operating scenarios, coolants and materials of construction, the amount of heat available (and grade or temperature) from each source can vary.

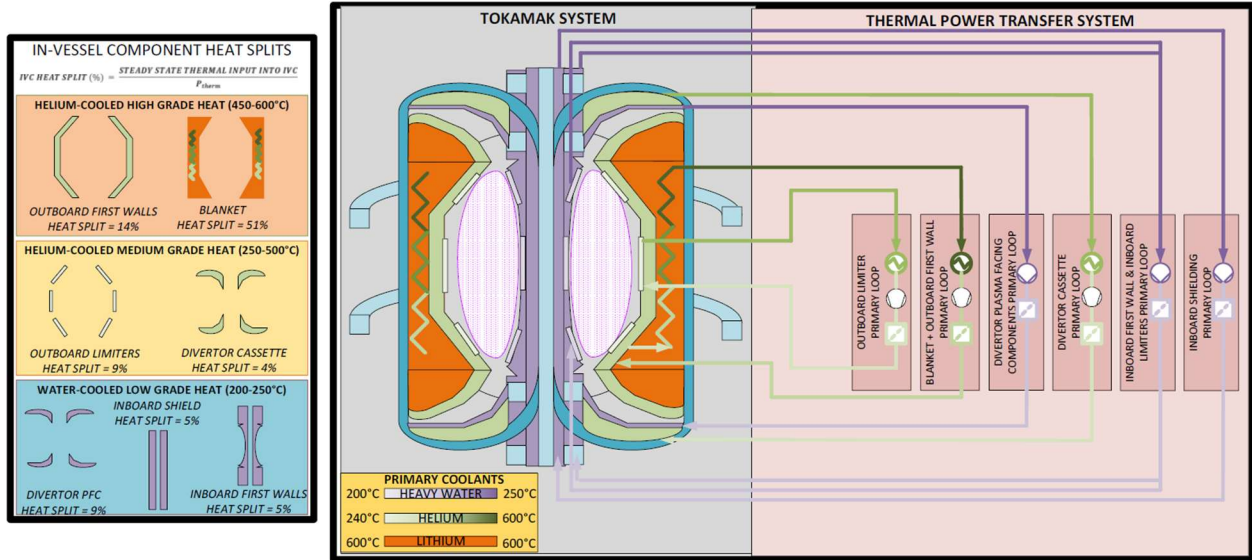


Figure 2. Overview of the primary coolant and tokamak component's heat splits[11].

Table 2 indicates how the energy distributions change for different conceptual designs of the European Union DEMONstration power plant (EU DEMO) and the United Kingdom Energy Authority (UKAEA)'s Spherical Tokamak for Energy Production (STEP).

Table 2. Comparison of sources of heat in magnetically confined tokamaks [20], [21].

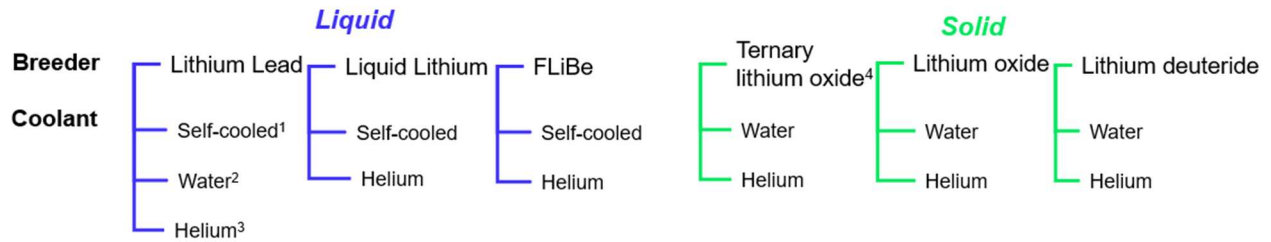
	EU DEMO	UKAEA STEP
Blanket and outboard first wall	86%	75%
Inboard build		10%
Divertors	10%	13%
Vacuum vessel components	4%	2%

In general, it is accepted that the two major heat sources in a tokamak that ultimately will determine the power cycle architecture are the breeding blanket and the divertor.

Breeding Blanket Component

Breeding blankets have two functions, first to transfer the kinetic energy from the neutrons into heat, and second to breed tritium. Typically, breeding blanket designs provide the greatest quantity of heat with a heat flux 0.1 to 5 MW/m² [22]. There is currently no global consensus on the optimal choice of tritium breeding material, tritium carrier gas, or coolant. Depending on the breeder/coolant pairing, several distinct blanket configurations may be identified, as shown in Figure 3.

Breeding blanket



Notes:

¹ Self-Cooled = breeder acts as a coolant and is the only cooling fluid; commonly referred as Self-cooled Lithium Lead (SCLL) blanket

² Commonly referred as Water-cooled Lithium Lead (WCLL) blanket; it can be referred as Dual-Coolant Lithium Lead (DCLL) blanket if both breeder and water function as coolants

³ Commonly referred as Helium-cooled Lithium Lead (HCLL) blanket; it can be referred as Dual-Coolant Lithium Lead (DCLL) blanket if both breeder and water function as coolants

⁴ when the ceramic is in the form of pebbles, they are referred as water-cooled pebble bed (WCPB) and helium cooled pebble bed (HCPB) blankets

Figure 3. Breeding blanket types.

The operating temperature for each design is determined from the breeder material, coolant type and materials of construction. For breeding blanket designs using a liquid breeder, the power generation relies on the higher outlet temperatures of the liquid metal or molten salts rather than the structural component coolant (helium and water) which is generally at lower temperatures. For blanket concepts using a solid breeder the heat source for power generation is helium or water, with the former being more commonly explored.

The coolant operating pressures are influenced by heat transfer coefficient, structural material constraints, and operational load. Table 3 and Table 4 indicate operating ranges for both the breeder material and coolant type. Helium cooling notionally operates around 80 bar, similar to a high temperature gas-cooled fission reactor [23], [24]. In breeding blankets using water as coolant, such as the water-cooled lithium lead blanket concept of the EU DEMO Power Plant, the temperatures are lower (295–330°C) but operate at higher pressures 155 bar [25]).

Table 3. Liquid metal breeder physical properties (1 atm) [26], [27], [28], [29].

	Melting point (°C)	Boiling point (°C)
Lithium	180.5	1,342
Lithium 17 at. % / Lead 83 at. % (eutectic PbLi)	235	–
Lithium fluoride-beryllium fluoride molten salt (FLiBe)	459	1,430

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

Breeder blanket	Inlet (°C)		Outlet (°C)	
Helium-cooled ceramic breeder (HCCB)	300		535	
HCPB				
New EU DEMO HCPB	300		578	
EU DEMO	300		520	
Helium-cooled Lead-Lithium (HCLL)				
International Thermonuclear Experimental Reactor (ITER) HCLL	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

sCO₂ is being considered as the cooling fluid for structural components of the breeding blanket under development for the Chinese Fusion Engineering and Test Reactor, namely COOLed Lithium-Lead (COOL) blanket [35], [36], [37]. It must be noted that this is a dual-coolant breeding blanket concept, with PbLi circuit being the high-grade heat source for the power cycle (up to 800°C) and sCO₂ being an additional heat source for the power cycle with a temperature below 400°C.

Divertor component

The divertor designs typically provide the second largest quantity of heat, even with a higher heat flux of 5 to 20 MW/m² [38] compared to breeder blankets. Divertors can deliver a significant amount of heat to the power cycle (12.9% in the study of Linares et al. for EU DEMO DCLL [39]).

The divertor is a key in-vessel component carrying out critical functions: removing heat produced from particle bombardment, as well as radiation and volumetric nuclear heating. It also acts as the plasma exhaust, removing the helium “ash” and unburnt deuterium-tritium fuel. The final function is to shield the vacuum vessel and magnets, while being physically compatible with the plasma [40]. There are a variety of designs. Table 5 shows the pressure and inlet/outlet temperatures for the water-cooled divertor (WCD) and liquid metal-cooled divertor (LMCD) for the EU power plant conceptual studies [41].

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

Table 6 shows the conditions for the helium-cooled divertor designs

Table 6. A selection of Helium-cooled divertor designs [41].

Material	Pressure (bar)	Coolant Inlet Temperature (°C)	Coolant Outlet Temperature (°C)
Porous medium	80	632	800
Multi-channel	140	500	550
Eccentric swirl	140	600	800
Slot	140	600	800
T-tube (ARIES-CS)	100	600	680

HEAT EXCHANGERS

General

Special attention ought to be paid to the primary heat exchangers due to their relevant role in the cycle efficiency. A particular challenge in the design of the power cycle of a fusion plant is that the highest-grade heat is coming from the reactor coolant, which is typically the liquid metal/molten salt or helium for solid breeding blanket. Thus, the heat exchanger(s) would have the additional challenge to withstand an unprecedented combination of harsh environments due to the lithium-bearing metal/molten salt coolant and sCO₂ power cycle working fluids, or helium coolant and sCO₂ power cycle working fluids. The closest knowledge base for sCO₂ power cycle for fusion plant lies in the experimental and numerical works carried out at Argonne National Laboratories (US) and CEA (France) on sodium fast reactors coupled with sCO₂ cycle [42], [43]. Under these conditions, the pool of viable candidate materials for the heat exchanger becomes significantly restricted.

As stated in the introduction, the design and configuration of the heat exchanger is not being evaluated as part of this current scope, which would impact the materials selection. It will be an essential part of our future work.

Requirements for Materials of Construction

The materials of construction significantly influence the device's operation and impact the operational loads. The operating window for materials deployed in sCO₂ turbomachinery, and specifically the heat exchanger in sCO₂ power cycle of fusion power plant, would need to account for the following factors:

1. High-temperature capability: alloys are to retain strength at elevated temperatures where the efficiency of sCO₂ cycles can be maximized.
2. Structural integrity: Materials are to resist creep, fatigue, and mechanical degradation over long operational lifetimes.
3. Environmental resistance to corrosion: Particularly from lithium-bearing coolants, helium, and water; of these, water can be highly reactive under operating conditions.
4. Resistance to carburisation and high-temperature oxidation: sCO₂ environments can lead to carburisation, while impurities such as H₂O and O₂ may cause high-temperature oxidation.

5. Environmentally Assisted Cracking (EAC): Materials exposed to flowing sCO₂ under tensile stress may experience EAC, creep, or a combination of both. Understanding the dominant failure mechanism, whether fatigue, creep, or stress corrosion requires careful analysis of load conditions, microstructure, and stress concentration zones.
6. Surface Fouling and Heat Transfer Degradation: The formation of carbonaceous deposits and localized oxide growth can induce overheating and accelerate degradation. Detached deposits may also pose a blockage/fouling risk in compact heat exchanger geometries and damage risk to turbomachinery.
7. Thermal properties: A low thermal expansion coefficient helps minimize stress accumulation, while a high heat transfer coefficient supports efficient thermal exchange.

Aspects related to the sCO₂ power cycle technology maturity and manufacturing must be accounted for in material selection:

1. Manufacturability readiness: Including considerations for joining techniques, machinability, and overall ease of fabrication. Material selection is closely tied to the design architecture of the heat exchanger. Compact designs such as Printed Circuit Heat Exchangers (PCHEs), diffusion-bonded plate-fin exchangers, and microtube heat exchangers require materials with excellent machinability and fabrication compatibility [44].
2. Design for manufacture: Thin-walled heat exchangers may exhibit non-linear mechanical behaviour. For example, Pint et al. observed that Ni-based alloy foils (e.g., 282 and 602CA) with 500 μm thickness had shorter lifetimes than 200 μm foils, but longer than 100 μm foils, indicating a complex relationship between thickness and durability [45]. Design space is highly impacted by material selection.
3. Manufacturing route options: Flexibility in processing methods to accommodate different design and performance requirements.
4. Cost, supply chain maturity, and options: Availability of materials and components at scale, with reliable sourcing and logistics.

Material Compatibility – sCO₂

While mechanical strength is a fundamental criterion, the long-term durability of materials is often governed by their resistance to creep, fatigue-induced crack propagation, and environmental factors. At elevated temperatures, CO₂ environments pose challenges due to bulk carburization and formation of carbonaceous deposit at the surface [46], [47]. Pioneering studies have been conducted to evaluate corrosion resistance of ferritic/martensitic steels (e.g. Gr 22, T91), austenitic steels (SS201, SS316L, 304H, SS310, SS347FHG Fe-based alumina-forming alloys (AFA) (e.g. APMT, PM2000) and Ni-based alloys (alloy 625, Alloy 617, Alloy 600, Alloy 718, Alloy 740, HR214) in high-purity sCO₂ at different temperatures and pressures [15], [45], [48], [49]. The studies have shown that low-chromium steels (e.g., Gr22, T91, <12 wt.% Cr) are particularly susceptible to internal carburization while high-chromium alloys (e.g., FN709, >20 wt.% Cr) demonstrate improved resistance (see Figure 4).

The reduced corrosion resistance appears to be related to the formation of non-protective, Fe-rich oxide scales, (rather than the desired thin, protective Cr-rich chromia layers) [50]. The

proposed degradation mechanism involves CO₂ promoting internal carburization of chromium, forming chromium carbides that deplete surface chromium and inhibit the formation of protective oxide layers. These carbides can form both within grains and along grain boundaries, reducing resistance to thermal cycling and increasing the risk of crack formation due to volumetric expansion.

In addition, the presence of impurities such as H₂O, O₂ and SO₂ in the sCO₂ stream can compromise the performance of the construction materials. Mahaffey et al. compared the effect of industrial grade CO₂ and pure CO₂ on corrosion and found the presence of impurities in the industrial grade CO₂ enhance the corrosion of alloys that typically resist corrosion [51]. Similar conclusions were reported from Kung et al [52]. Pint et al. [45] reported the addition of 1% O₂ + 0.1% H₂O to sCO₂ makes the steels (even advanced austenitic steel such as 709) unsuitable for applications in sCO₂ power system at temperature as low as 550°C.

Nickel-based alloys generally offer superior resistance to carburization compared to stainless steels, primarily due to the lower solubility of carbon in nickel [53]. They are considered the material of choice for turbomachinery in sCO₂ operating above 650°C due to the compatibility with sCO₂ and are creep resistance when compared to the majority of steels. Studies such as those by Pint et al. have investigated the mass change of various stainless steels and Ni-based alloys after 2000 hours of exposure to sCO₂ under varying temperatures and impurity levels (see [45]). Ni-based alloys withstand carburization to acceptable levels (according to metrics developed for concentrated solar power systems) up to 800°C, compared to 650°C for advanced austenitic steels (e.g. 709), 550°C for austenitic steels (e.g. 316H), and ferritic-martensitic (e.g. T91) at temperatures as low as 500°C. Nevertheless, the presence of alloying elements in Ni-based alloys that form brittle carbides introduces concerns regarding mechanical integrity [15], [49]. While favouring selection of Ni-based alloys with less mass-gains under sCO₂ environments, findings from Pint et al. [15] underscored that there is a complex interplay between Ni-based alloy composition, environmental conditions, and degradation mechanisms.

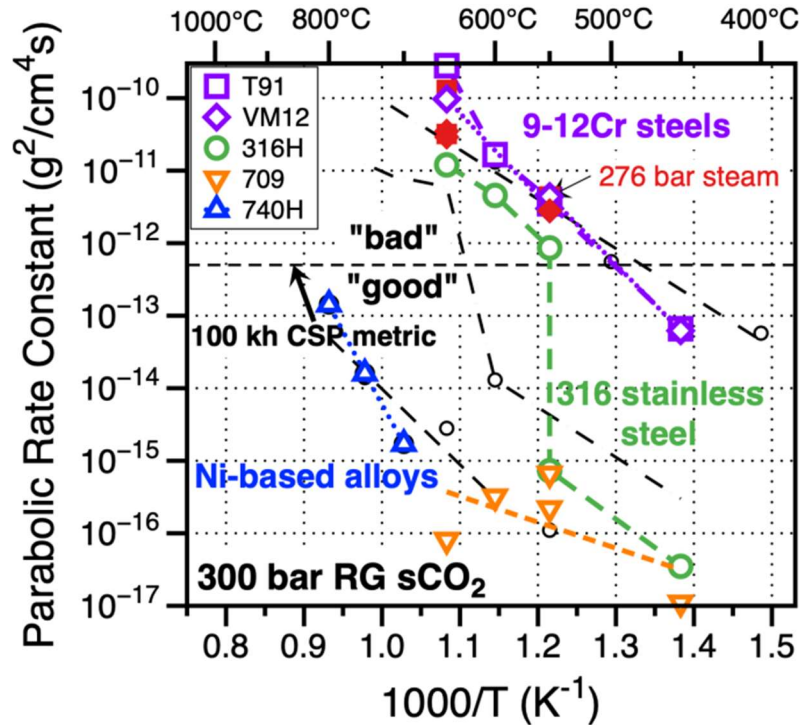


Figure 4. Parabolic rate constant for different grades of steels and Ni-based alloys exposed for 2,000 hours in sCO₂ at 300 bars. From [45].

Material compatibility – coolants from in-vessel components

Coolants from the in-vessel components introduce distinct material compatibility challenges and imposes limits on the maximum operating temperature of the heat exchanger. For example, liquid metals (PbLi, Li) and molten salts (FLiBe) tend to operate at lower pressures, but can be chemically aggressive, especially at high temperatures. Helium and water coolants typically require higher operating pressures, which impose additional mechanical stress on the heat exchanger materials but are less chemically challenging.

These variations in temperature, pressure, and chemical reactivity necessitate a careful balance in material selection to ensure long-term performance, corrosion resistance, and mechanical integrity. Additionally, the development of materials for the in-vessel components has been driven by the fusion community's resistance to neutron irradiation and the related induced radioactivity that generates undesirable activation products.

The volume of material contained within the pipework located outside the tokamak envelope is expected to be substantially greater than that within, introducing additional considerations.

Figure 5 provides an overview of the operational temperature window for the in-vessel fusion materials [54]. It must be noted the Ni-based alloys and many austenitic steels are not present in the diagram of Figure 5 because the formation of relatively long-lived (but not transuranic) radionuclides when irradiated with neutrons. This causes the material selection of a sCO₂ heat exchanger to become a complex task. By utilizing the current state of the art, the best material options for sCO₂ balance of plant components (i.e. Ni-based alloys and advanced austenitic alloys) are materials excluded for in-vessel components but may still be considered for the heat

exchanger.

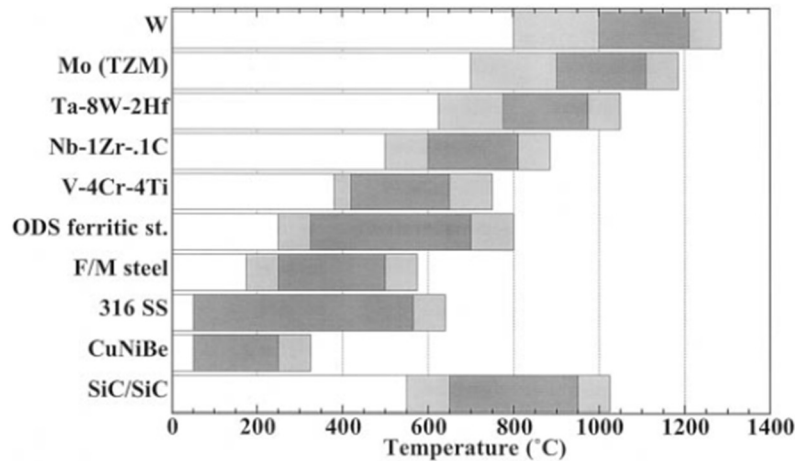


Figure 5. Window of operating temperature based on radiation damage and thermal creep considerations. Dark grey bars represent optimal working range, while lighter grey bars represent potential working range, limited by radiation and helium embrittlement or thermal creep. From [54].

Reduced Activation Ferritic Martensitic (RAFM) Steels

RAFM steels have been developed as promising structural materials for fusion applications, building on the knowledge base of conventional ferritic/martensitic steels such as T91 [55]. RAFM steels have been developed across several regions: EUROFER 97 (Europe, Fusion for Energy), F82H (Japan, JAEA), 9Cr-2WVT (USA, Oak Ridge National Laboratory) and CLAM (China, INEST) [56].

Their appeal lies in the radiation resistance with minimal shift in the ductile-to-brittle transition temperature under neutron irradiation; the proven fabrication and joining techniques, enabling faster technological maturation compared to other low-activation materials (like vanadium alloys or SiCf/SiC composites); and the low activation characteristics, achieved by replacing long-lived radioactive elements (Ni, Co, Mo, Nb) with W, Ta, and V [56], [57], [58], [59].

RAFM are suitable for use with PbLi, helium, water, and potentially FLiBe up to 550°C, limited by corrosion and creep resistance. They are not compatible with liquid lithium, which causes premature corrosion [60]. In addition, they contain 8–9 wt.% chromium, which is insufficient to resist carburization in sCO₂ environments.

Oxide Dispersion-Strengthened (ODS) Steels

ODS steels represent a high-risk, high-reward class of materials, produced via powder metallurgy to achieve excellent strength and creep resistance at temperatures up to 650°C (Figure 6). They have superior irradiation tolerance due to nanoclusters acting as sinks for point defects [59], [61], [62].

However, ODS manufacturing readiness is low due to non-standardized production methods and variable quality [59]. The traditional joining method (welding) presents difficulties as it degrades mechanical properties by disrupting nanoscale particles. Advanced techniques like

friction welding or diffusion bonding are needed but not yet mature [63].

ODS steels typically contain 8–9 wt.% Cr, which poses similar carburization challenges in $s\text{CO}_2$ as RAFM steels. High-Cr ODS alloys (up to 16 wt.%) offer better creep resistance but suffer from lower toughness, especially at 300–500°C [59].

A study at the University of Wisconsin-Madison showed that PM2000 ODS steel (20 wt.% Cr) had superior corrosion resistance in $s\text{CO}_2$ at 650°C and 20 MPa over 3000 hours, outperforming austenitic and Ni-based alloys [64].

Despite promising creep performance and potential resistance to carburization, if new grades are developed, the brittleness, joining limitations, and high manufacturing complexity make ODS steels challenging for use in compact, high-efficiency heat exchangers.

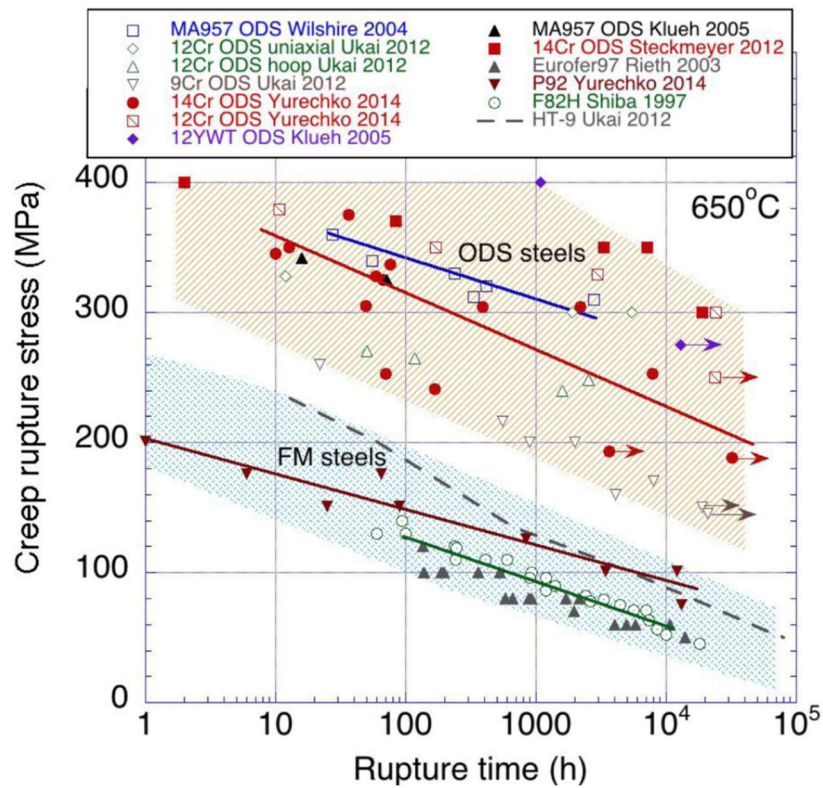


Figure 6. Comparison of the thermal creep behaviour at 650°C for ODS versus conventional ferritic/martensitic steels. From [59].

Vanadium Alloys

Vanadium alloys, such as V-4Cr-4Ti, are considered for liquid lithium-cooled breeding blankets operating up to 650°C [65], [66], [67], [68], [69]. They offer superior corrosion resistance in liquid lithium compared to RAFM, ODS, and austenitic steels [54], [70]. They possess high creep strength at elevated temperatures and long durations. Low thermal expansion reduces thermal stress and extends component lifetime [66].

However, vanadium alloys are highly susceptible to embrittlement due to interactions with non-metallic impurities (N, C, O) in the coolant. Liquid lithium scavenges oxygen, degrading their

mechanical properties [65], [67], [68], [71], [72]. Thus, vanadium alloys are unsuitable for coolant transport and sCO₂ heat exchangers because of their extreme sensitivity to oxygen and water impurities that are contained in the sCO₂; embrittlement occurs even at ppm-levels of impurities.

SiC_f/SiC Ceramic Matrix Composites

SiC_f/SiC composites have been investigated in fusion programmes such as ARIES-ACT2, UNITY, and GAMBL due to their high-temperature corrosion resistance, especially to PbLi and FLiBe [73], [74], [33], [75], [76]. SiC_f/SiC possesses low activation, low thermal expansion ($4.5\text{--}5.5 \times 10^{-6} \text{ K}^{-1}$), and high creep resistance [74].

A protective silica layer forms in oxidising environments (up to 1450°C), making them resilient to certain allowable concentrations of H₂O (though not in a 100% steam environment unless barrier coatings are applied), and O₂, [77], [78] and sCO₂ impurities. It is not expected to be a material severely susceptible to carburization and the commercial availability of monolithic SiC heat exchangers constitutes an additional advantage of this material [79].

However, SiC_f/SiC presents some noticeable challenges such as high cost of SiC fibers (~\$10,000/kg), complexity in the manufacturing, including machining and limited joining options [80]. Supply chain is scarce and specialised production capabilities are required (limited transferable skills from metallurgy). Additionally, even the highest-performing grades of SiC_f/SiC have lower fracture toughness compared to steels, raising safety concerns in high-pressure systems.

Ni-based alloys

As mentioned above, Ni-based alloys are generally unsuitable for fusion reactor internal structures due to the formation of relatively long-lived radioactive activation products, which is conflicting with the fusion industry's goal of low radioactive waste production [81]. However, Ni-based alloys are widely used in corrosion testing loops (e.g., LiBRA experiment [81], [82], [83]) due to their excellent corrosion resistance in molten salts like FLiBe up to 700°C. Ni-based alloys also possess high creep resistance as shown in Figure 7 [48]. Established manufacturing techniques are available across the aerospace and oil and gas sectors, and they can be considered the benchmark for the sCO₂ power cycle balance of plant. Ni-based alloys may be viable for heat exchangers in fusion plant using FLiBe as coolant/breeder, provided activation concerns are managed. In molten salts, Ni-based alloys containing Mo and W and with low percentage of chromium and aluminium are preferred because of the preferential corrosion of these elements in chlorides and fluorides [84]. Contrarily, in sCO₂ service, a high chromium content is preferred for carburization resistance. In general, there is a more complex relationship between Ni-based alloy composition and in-service conditions, as different oxide scales may be formed and evolve at different temperatures, pressures and duration [15].

In liquid lithium and PbLi, as reported by several authors, the solubility of nickel is higher than Fe and Cr (one and two orders of magnitude respectively), which makes Ni-based alloys unsuitable for use with these liquid metal coolants [85], [86].

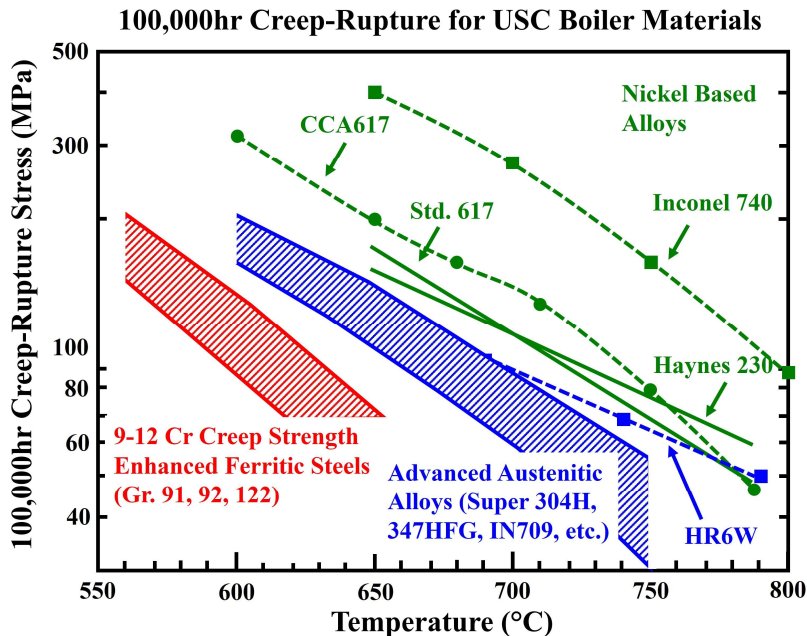


Figure 7. Comparison of the creep behaviour of advanced alloys under consideration for applications in ultra-supercritical steam boiler applications, and also applicable to supercritical CO₂ turbomachinery. From [87].

Divertor material compatibility

Divertors are typically cooled with water or heavy water, although helium-cooled divertor design and integration studies in EU DEMO have been carried out [88]. A separate heat exchanger for the divertor loop with sCO₂ would require the joining of CuCrZr alloy pipes to an alloy compatible with the sCO₂ power cycle. It has been reported the successful joining of CuCrZr to SS 316L, and separately to Cu-alloyed ODS steels, constitutes a knowledge base/precedent for the joining of CuCrZr alloys with steels in general. Advanced divertor loops operating at higher temperatures would require more exotic combinations such as W/Cu laminate pipes [88].

RECOMMENDATIONS FOR CONTINUED RESEARCH

As shown in Table 7, the current material options for sCO₂ heat exchangers are largely limited to Ni-based alloys and advanced austenitic steels. While these materials offer excellent performance in sCO₂ environments, they are not compatible with most fusion blanket structural materials due to activation concerns. In addition to material compatibility study with coolants, five areas of further research for materials of construction have been identified:

1. Heat exchanger design and materials
2. Advanced manufacturing techniques
3. Joining of dissimilar materials
4. Coatings
5. Safety considerations

Table 7. Compatibility of structural materials with breeding blanket coolants and sCO₂ in a RAG (red-amber-green) matrix representation. *In-vessel materials that produce activated radionuclides.

Application Working materials fluids	Structural materials	Ferritic steels* (e.g. T91)	Austenitic steels* (e.g. 304, 316, FN709, 310H)	Ni-based alloys*	RAFM	ODS	Vanadium alloys	SiC/SiC
Breeding blanket (lower-grade heat) and Inboard Breeding blanket (high grade heat) Diverter	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 Creep and corrosion limitations	Up to 650°C Creep limitations	Not specifically required	Up to 1000°C Cost, manufacturing and joining are limitations
	FLiBe	Severe corrosion	Severe corrosion		Up to 550°C Creep and corrosion limitations	Up to 650°C Creep limitations	High Tritium inventory	Up to 1000°C Cost, manufacturing and joining are limitations
	Helium			Embrittlement	Up to 550°C Creep limitations	Up to 650°C	Not specifically required and expected to embrittle	Up to 1000°C Cost, manufacturing and joining are limitations
	Water				Up to 550°C 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
sCO ₂ power cycle (HX)	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 O ₂ 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

Heat Exchanger design and materials

The advantage of sCO₂ power cycle is small footprint of its machinery components. The advantage can be enhanced by adopting a compact heat exchanger instead of a conventional shell and tube heat exchanger [89]. Compact heat exchangers for sCO₂ cycles include printed circuit heat exchangers (PCHE), plate-fin heat exchangers, micro shell-and-tube, and additive manufactured heat exchangers. Each of these designs has important correlations with candidate materials. For instance, PCHE requires diffusion bonding which works well for 316 stainless steels, but not SS347 and Ni-based alloys such as Inconel 617 [90]. Diffusion bonding could be challenging for ODS steels because of the oxides dispersed in the steel; similar challenges are applicable to vanadium alloys and SiC_f/SiC composites. High-temperature designs and microtubes would need to consider the limitations dictated by thermal creep and hence shifting the selection to high-Cr ODS or some types of Ni-based alloy such as Inconel 625 and 617 (rather than Alloy 600 and austenitic steels) [90]. Materials that easily form carbonaceous deposits at the surface or oxidation reactions with the coolant may lead to heat exchangers prone to fouling.

Advanced Manufacturing techniques

High efficiency PCHEs for sCO₂ Brayton cycles are manufactured using diffusion bonding where 2D channels are etched into plates, which are aligned and diffusion bonded into a block [91]. This precision manufacturing approach has reached regulatory maturity and is included in the ASME boilers and pressure vessel codes [92]. Operating envelopes of approximately 250 bar and 700°C have been achieved using such designs. More recently, there has been research and prototyping efforts on using additive manufacturing (AM) for development of topologically optimized geometries (pin-fins and lattices) for compact heat exchangers [93], [94]. While the AM heat exchangers can offer higher thermal efficiency and power density for a smaller footprint,

surface roughness of micro-channels can result in larger pressure drop and challenges with fatigue/creep of the alloys [95]. Further, this technology does not have regulatory maturity today and further work is needed in terms of pressure testing, sCO₂ corrosion and materials qualification.

Joining

As shown in Table 7, high-chromium ODS steels and SiCf/SiC composites are potentially compatible with sCO₂, PbLi and Helium. However, both face significant challenges in terms of manufacturing readiness, cost, and fabrication complexity, especially for large-scale or intricate heat exchanger geometries.

If 8–9 wt.% Cr ODS steels are selected as the structural material for the breeding blanket, advanced joining technologies will be required to connect them to Ni-based alloys. While steels can be joined to Ni-based alloys, this is not necessarily true for ODS.

Joining RAFM steels to Ni-based alloys may be less challenging, given the existing knowledge base in welding and filler materials for steel/nickel interfaces. A possible option is the use of an intermediate material to facilitate the transition between the heat source coolant and the power cycle working fluid. Assuming this region is free from neutron activation and tritium contamination, the intermediate material can include nickel and other alloying elements, significantly expanding the pool of viable options. Depending on the inlet temperature of the breeding blanket coolant into the primary heat exchanger, this intermediate material could be a conventional austenitic steel such as SS 316. Notably, SS 316 has shown resistance to PbLi corrosion below 450°C [96], and SS 316H has demonstrated carburisation resistance for up to 60,000 hours at 450°C [88], making it a viable candidate for intermediate segments [45]. It must be noted this solution is viable if the operating temperatures are significantly reduced and, in turn, the thermodynamic efficiency compromised.

A special case is represented by Liquid Lithium Blankets. Vanadium alloys are the only materials known to withstand corrosion under relevant conditions. This necessitates joining vanadium alloys to Ni-based alloys, which introduces a significant risk: welding promotes the uptake of non-metallic impurities (e.g., N, C, O), which can increase embrittlement of vanadium alloys. Resulting welds may be mechanically compromised, posing safety and reliability concerns.

Metallic and Ceramic Coatings

Coatings offer a potential solution to improve corrosion resistance in sCO₂ environments. Pint et al. demonstrated that Cr-coated T91, which performs poorly when uncoated, showed no carbon ingress after 2000 hours at 650°C, even in the presence of O₂ and H₂O impurities [45]. Cr-coated SS 316H exhibited even higher performance under similar conditions [45]. Chromium coatings on RAFM and 8–9 wt.% Cr ODS steels could significantly enhance carburization resistance. Copper, which is non-reactive with CO₂, has shown the ability to eliminate inward oxidation and of SS 316 to a point that the SS 316 has carburisation performance similar to that of Ni-Based alloys.

Ceramic oxide coatings are under development in fusion blankets as tritium permeation barriers (e.g., Al₂O₃, Er₂O₃) [97] and are established as environmental barrier coatings in gas turbines. [98], [99]. Alumina coatings on vanadium alloys may resist carburization in sCO₂ environments. However, oxide coatings may impair heat transfer due to low thermal conductivity; pose challenges with differential thermal expansion, risking delamination; are difficult to repair and

apply on complex geometries; and can restrict design flexibility and influence the choice of heat exchanger architecture.

Safety considerations

Typically, the balance of plant of the power cycle is in a neutron- and tritium-free environment. This simplifies the design, material selection, operations, maintenance, and decommissioning. A “cold trap” purification system is designed to remove impurities and corrosion products dissolved in the tokamak coolants via upper concentration limits imposed by temperature-dependent solubility constraints. These impurities (including those activated with consequential induced radioactivity), if not trapped, could be transported within the heat exchanger circuit with subsequent deposition on the heat exchanger interior surfaces. While such effects will unlikely affect the integrity of the material itself, they will be of consequence in maintaining, inspecting, and repair of the structures (e.g., requiring remote tools vs. manual).

Preventing tritium ingress into the primary loop is preferred, as it prevents the reduction in tritium inventory in the tokamak and it avoids the parasitic energy cost of detritiating the working fluid. To prevent tritium transfer from the primary to the secondary loop, two strategies are commonly employed: 1) effective detritiation within the primary loop and 2) the use of barrier coatings in the primary-to-secondary heat exchangers. Barrier coatings such as alumina, erbium oxide, and silicon carbide can reduce tritium permeation by several orders of magnitude. However, the coating thickness needs to be carefully optimized to ensure sufficient permeation resistance without significantly degrading the heat exchanger’s overall heat transfer coefficient. In general, the coating of a metallic substrate with a ceramic coating requires a material design study as the materials need to be compatible to have good adhesion and thermal stability.

Another specific challenge in the heat exchanger for fusion plant is the interaction of sCO₂ with liquid lithium, PbLi, or FLiBe in case of accidents such as tube failure. It is well known about the high reactivity of lithium-bearing species with oxygen sources and water, but there is limited knowledge about possible failure scenarios with sCO₂. Applicability of the experience of CO₂ reactions with sodium under fast reactor operating conditions producing exothermic reactions and forming solid species, primarily with carbonates and carbon should be evaluated [100]. In view of this, specific studies are also required to assess the energy release during the reaction and formation of intermediate products between sCO₂ and lithium-bearing species.

SUMMARY

sCO₂ Brayton power cycles can ensure the highest thermodynamic efficiencies with the available heat from fusion reactor systems. Added benefits are the ability of more-rapidly adapting to the dynamic operation of the plasma volume and a reduced power cycle equipment footprint. However, there are some design challenges related to the integration of heat from different in-vessel heat sources at different temperatures and pressures, and operating with different coolants (i.e., liquid lithium, PbLi, molten salts, water, helium). The combination of in-vessel coolants and sCO₂ create a complex and challenging environment for the balance of plant, particularly for the primary heat exchanger. While there are precedents of sodium fast reactor designs coupled to sCO₂ power cycles, fusion power plants represent an unprecedented challenge for the materials of construction. Each coolant introduces distinct material compatibility challenges and imposes limits on the operating temperatures of the heat exchanger and, in turn, on the performance of the overall power plant.

The variations in temperature, pressure, and chemical reactivity described in this paper

necessitate a careful balance in material selection to ensure long-term performance, corrosion resistance, and mechanical integrity. Based on these elements, **Error! Reference source not found.** summarizes our assessment of material compatibility for primary heat exchangers.

It appears that there is not a “preferred” material solution. Ni-based alloys are the materials that offer the best performance in sCO₂ at high temperatures. Currently they appear to be the best option for sCO₂ turbomachinery and to withstand in-vessel coolants such as water and FLiBe. However, they generate relatively long-lived activation product isotopes and are not compatible with PbLi and liquid lithium. Therefore, their use for the in-vessel components would be very specific to FLiBe-cooled breeding blankets provided the activated waste concern is resolved. RAFM, and to an extent ODS steels, cannot offer the temperature capabilities (creep and corrosion limitations) of vanadium alloys, and they would suffer from carburization in sCO₂ environment. Manufacturing readiness, cost, and supply chain barriers exist for SiC_f/SiC.

It must be noted the first generation of breeding blankets (see ITER and EU DEMO operating temperatures in

Table 4) operate at relatively low temperatures of approximately 500°C. However, most of the data collected on material compatibility with sCO₂ are at temperatures above 600°C. Thus, the onset of deteriorating performance for steels is believed to start at 550°C. As such, steels ought to be used in primary heat exchangers for only for such “low temperature” breeding blankets.

Therefore, the development of sCO₂ power cycles for fusion power plant heat exchangers requires advancements in materials performance and their assessment and/or design solutions that would mitigate challenges and risks of the current materials offered. Alternatively, a secondary loop could be utilized to decrease the materials selection complexity for the primary heat exchanger, but this would likely decrease efficiency and increase plant footprint and costs.

REFERENCES

- [1] US Department of Energy, "The U.S. Department of Energy's (DOE) Fusion Science & Technology (FS&T) Roadmap." Accessed: Nov. 06, 2025. [Online]. Available: <https://www.energy.gov/fusion-energy>
- [2] International Atomic Energy Agency, "IAEA WORLD FUSION OUTLOOK 2024," 2024. Accessed: Oct. 24, 2025. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/p15777-24-02766E_WFO_web.pdf.
- [3] ITER, "The machine." Accessed: Oct. 22, 2025. [Online]. Available: <https://www.iter.org/machine>
- [4] EUROfusion Consortium, "DEMO - EUROfusion." Accessed: Oct. 22, 2025. [Online]. Available: <https://euro-fusion.org/programme/demo/>
- [5] Commonwealth Fusion Systems, "SPARC®: Proving commercial fusion energy is possible." Accessed: Oct. 22, 2025. [Online]. Available: <https://cfs.energy/technology/sparc>
- [6] Proxima Fusion, "Building stellarators to power the future." Accessed: Oct. 22, 2025. [Online]. Available: <https://www.proximafusion.com/>
- [7] Tokamak Energy, "Fusion energy and high temperature superconducting magnets." Accessed: Oct. 22, 2025. [Online]. Available: <https://tokamakenergy.com/about-us-fusion-energy-high-temperature-superconducting-magnets/#roadmap>
- [8] "Home - Type One Energy." Accessed: Oct. 24, 2025. [Online]. Available: <https://typeoneenergy.com/>
- [9] Gauss Fusion, "Leading European Industries to build Fusion Power Plants." Accessed: Oct. 24, 2025. [Online]. Available: <https://gauss-fusion.com/>
- [10] V. Dostal, P. Hejzlar, and M. J. Driscoll, "The Supercritical Carbon Dioxide Power Cycle: Comparison to Other Advanced Power Cycles," *Nucl Technol*, vol. 154, no. 3, pp. 283–301, 2006, doi: 10.13182/NT06-A3734.
- [11] J. Acres, I. Antoniou, F. Christie, D. Blackburn, and S. Knight, "Staying positive: producing net power," *Philosophical Transactions A*, vol. 382, no. 2280, Aug. 2024, doi: 10.1098/RSTA.2023.0404.
- [12] M. Ni, Y. Wang, B. Yuan, J. Jiang, and Y. Wu, "Tritium supply assessment for ITER and DEMOnstration power plant," *Fusion Engineering and Design*, vol. 88, no. 9–10, pp. 2422–2426, Oct. 2013, doi: 10.1016/J.FUSENGDES.2013.05.043.
- [13] X. R. Zhang, H. Yamaguchi, D. Uneno, K. Fujima, M. Enomoto, and N. Sawada, "Analysis of a novel solar energy-powered Rankine cycle for combined power and heat generation using supercritical carbon dioxide," *Renew Energy*, vol. 31, no. 12, pp. 1839–1854, Oct. 2006, doi: 10.1016/j.renene.2005.09.024.
- [14] G. E. Rochau, "Supercritical CO₂ Brayton Cycle Development."
- [15] B. A. Pint and J. R. Keiser, "THE EFFECT OF TEMPERATURE ON THE sCO₂ COMPATIBILITY OF CONVENTIONAL STRUCTURAL ALLOYS," in *The 4th International Symposium - Supercritical CO₂ Power Cycles*, 2014.
- [16] M. T. White, G. Bianchi, L. Chai, S. A. Tassou, and A. I. Sayma, "Review of supercritical CO₂ technologies and systems for power generation," *Appl Therm Eng*, vol. 185, p. 116447, Feb. 2021, doi: 10.1016/J.APPLTHERMALENG.2020.116447.
- [17] M. McDowell, "Rocketdyne Development of the Supercritical CO₂ Power Conversion System," in *The 2nd International Symposium - Supercritical CO₂ Power Cycles*, 2007. Accessed: Oct. 23, 2025. [Online]. Available: <https://www.sco2symposium.com/papers2007/8-mcDowell.pdf>
- [18] British Electricity International, "Modern Power Station Practice: Nuclear Power Generation," 1990.
- [19] V. Dostal, M. J. Driscoll, and P. Hejzlar, "A Supercritical Carbon Dioxide Cycle for Next

- Generation Nuclear Reactors,” 2004. [Online]. Available: <http://web.mit.edu/canes/>
- [20] I. Moscato *et al.*, “Progress in the design development of EU DEMO helium-cooled pebble bed primary heat transfer system,” *Fusion Engineering and Design*, vol. 146, pp. 2416–2420, Sep. 2019, doi: 10.1016/J.FUSENGDES.2019.04.006.
- [21] D. Blackburn, J. Acres, and I. Antoniou, “Investigating dynamic scenarios of a spherical tokamak fusion power plant,” *Fusion Engineering and Design*, vol. 216, p. 115062, Jul. 2025, doi: 10.1016/J.FUSENGDES.2025.115062.
- [22] D. P. Jackson *et al.*, “A Review of Fusion Breeder Blanket Technology Part 1 / Review and Findings CFFTP Report Number Cross Reference Report,” 1985.
- [23] A. Froio, “Dynamic thermal-hydraulic modelling of the EU DEMO HCPB breeding blanket cooling loops - EUROFUSION WPPMI-PR (16) 16027,” 2016. Accessed: Oct. 27, 2025. [Online]. Available: https://scipub.euro-fusion.org/wp-content/uploads/eurofusion/WPPMIPR16_16027_submitted-2.pdf
- [24] J. M. Beck and L. F. Pincock, “High Temperature Gas-Cooled Reactors Lessons Learned Applicable to the Next Generation Nuclear Plant,” 2011.
- [25] E. Martelli *et al.*, “Advancements in DEMO WCLL breeding blanket design and integration,” in *International Journal of Energy Research*, John Wiley and Sons Ltd, Jan. 2018, pp. 27–52. doi: 10.1002/er.3750.
- [26] N. Narayana and D. R. J. Burgess, “Melting points and boiling points for the alkali metals,” Feb. 2024. doi: 10.6028/NIST.TN.2273.
- [27] B. Garcinuño, R. Fernández-Saavedra, T. Hernández, M. B. Gómez, A. Quejido, and D. Rapisarda, “Establishing technical specifications for PbLi eutectic alloy analysis and its relevance in fusion applications,” *Nuclear Materials and Energy*, vol. 30, p. 101146, Mar. 2022, doi: 10.1016/j.nme.2022.101146.
- [28] K. Baral, S. San, R. Sakidja, A. Couet, K. Sridharan, and W. Y. Ching, “Temperature-Dependent Properties of Molten Li₂BeF₄ Salt Using Ab Initio Molecular Dynamics,” *ACS Omega*, vol. 6, no. 30, pp. 19822–19835, Aug. 2021, doi: 10.1021/ACSOMEGA.1C02528.
- [29] D. Ying *et al.*, “Activation of FLiBe coolant in the molten salt reactor,” *Ann Nucl Energy*, vol. 129, pp. 62–66, Jul. 2019, doi: 10.1016/j.anucene.2019.01.038.
- [30] F. Hernandez, “A new HCPB breeding blanket for the EU DEMO fusion reactor: design evolution, rationale and preliminary nuclear, thermo-hydraulic and thermo-mechanical performances - EUROFUSION WPBB-CP (16) 15535,” 2016. Accessed: Oct. 27, 2025. [Online]. Available: https://scipub.euro-fusion.org/wp-content/uploads/eurofusion/WPBBCP16_15535_submitted.pdf
- [31] G. Zhou *et al.*, “The European DEMO Helium Cooled Pebble Bed Breeding Blanket: Design Status at the Conclusion of the Pre-Concept Design Phase,” *Energies (Basel)*, vol. 16, no. 14, Jul. 2023, doi: 10.3390/en16145377.
- [32] S. Smolentsev, N. B. Morley, M. A. Abdou, and S. Malang, “Dual-coolant lead–lithium (DCLL) blanket status and R&D needs,” *Fusion Engineering and Design*, vol. 100, pp. 44–54, Nov. 2015, doi: 10.1016/j.fusengdes.2014.12.031.
- [33] M. S. Tillack, S. A. Binguier, I. Holmes, L. Holland, F. Santos-Novais, and G. I. Maldonado, “GAMBL – A dual-cooled fusion blanket using SiC-based structures,” *Fusion Engineering and Design*, vol. 180, Jul. 2022, doi: 10.1016/j.fusengdes.2022.113155.
- [34] F. Cismondi *et al.*, “Progress in EU Breeding Blanket design and integration,” *Fusion Engineering and Design*, vol. 136, pp. 782–792, Nov. 2018, doi: 10.1016/J.FUSENGDES.2018.04.009.
- [35] L. Chen *et al.*, “Progress in the Conceptual Design of the Supercritical CO₂ Cooled Lithium-Lead Blanket and the Power Conversion System for CFETR,” in *15th International Symposium on Fusion Nuclear Technology (ISFNT)*, 2023.
- [36] K. Jiang *et al.*, “Thermal hydraulic assessment on the full banana model of COOL blanket

- for CFETR,” *Nuclear Fusion*, vol. 64, no. 4, Apr. 2024, doi: 10.1088/1741-4326/ad2385.
- [37] L. Chen *et al.*, “Design and Multi-physical Performance Analysis of the WCCB and COOL Blanket for CFETR IAEA Technical Meeting on Tritium Breeding Blankets and Associated Neutronics,” in *IAEA Technical Meeting on Tritium Breeding Blankets and Associated Neutronics*, 2025.
- [38] R. Behrisch and G. Venus, “Heat removal by the divertor plate and limiter materials in fusion reactors,” *Journal of Nuclear Materials*, vol. 202, no. 1–2, pp. 1–9, Jun. 1993, doi: 10.1016/0022-3115(93)90023-R.
- [39] J. I. Linares, L. E. Herranz, I. Fernández, A. Cantizano, and B. Y. Moratilla, “Supercritical CO₂ Brayton power cycles for DEMO fusion reactor based on Helium Cooled Lithium Lead blanket,” *Appl Therm Eng*, vol. 76, pp. 123–133, Feb. 2015, doi: 10.1016/J.APPLTHERMALENG.2014.10.093.
- [40] J. H. You *et al.*, “Divertor of the European DEMO: Engineering and technologies for power exhaust,” *Fusion Engineering and Design*, vol. 175, p. 113010, Feb. 2022, doi: 10.1016/J.FUSENGDES.2022.113010.
- [41] P. Norajitra *et al.*, “Divertor conceptual designs for a fusion power plant,” *Fusion Engineering and Design*, vol. 83, no. 7–9, pp. 893–902, Dec. 2008, doi: 10.1016/j.fusengdes.2008.05.022.
- [42] C. Craig Gerardi, C. and Carl Youngdahl, and C. G. Grandy, “AFR-100 Sodium-CO₂ Reaction Analysis Nuclear Engineering Division,” 2011.
- [43] H. Pham *et al.*, “Supercritical CO₂ cycle coupling to sodium cooled fast reactors recent R&D achievements at CEA Supercritical CO₂ Cycle Coupling to Sodium Cooled Fast Reactors: Recent R&D Achievements at CEA,” 2016, Accessed: Oct. 22, 2025. [Online]. Available: <https://cea.hal.science/hal-02441969v1>
- [44] L. Chai and S. A. Tassou, “Recent Progress on High Temperature and High Pressure Heat Exchangers for Supercritical CO₂ Power Generation and Conversion Systems,” *Heat Transfer Engineering*, vol. 44, no. 21–22, pp. 1950–1968, Dec. 2023, doi: 10.1080/01457632.2022.2164683.
- [45] B. A. Pint, Y.-F. Su, M. J. Lance, R. Pillai, and J. R. Keiser, “Effect of Impurities on Supercritical Carbon Dioxide Compatibility (FWP-FEAA144),” in *Gordon Research Conference on High Temperature Corrosion*, 2023. Accessed: Oct. 27, 2025. [Online]. Available: https://netl.doe.gov/sites/default/files/netl-file/23FECM_18_Pint.pdf
- [46] H. E. McCoy, “Type 304 Stainless Steel vs Flowing CO₂ At Atmospheric Pressure and 1100-1800F,” *Corrosion*, vol. 21, no. 3, pp. 84–94, Mar. 1965, doi: 10.5006/0010-9312-21.3.84.
- [47] “Environmental Damage at High Temperature,” in *High Temperature Deformation and Fracture of Materials*, Elsevier, 2010, pp. 330–348. doi: 10.1533/9780857090805.2.330.
- [48] L. Tan, M. Anderson, D. Taylor, and T. R. Allen, “Corrosion of austenitic and ferritic-martensitic steels exposed to supercritical carbon dioxide,” *Corros Sci*, vol. 53, no. 10, pp. 3273–3280, Oct. 2011, doi: 10.1016/j.corsci.2011.06.002.
- [49] V. Firouzdor, K. Sridharan, G. Cao, M. Anderson, and T. R. Allen, “Corrosion of a stainless steel and nickel-based alloys in high temperature supercritical carbon dioxide environment,” *Corros Sci*, vol. 69, pp. 281–291, Apr. 2013, doi: 10.1016/j.corsci.2012.11.041.
- [50] F. Rouillard, F. Charton, and G. Moine, “Corrosion Behavior of Different Metallic Materials in Supercritical Carbon Dioxide at 550°C and 250 bars,” *CORROSION*, vol. 67, no. 9, pp. 095001-095001–7, Sep. 2011, doi: 10.5006/1.3628683.
- [51] J. Mahaffey, M. Anderson Research Professor, A. Kalra, and K. Sridharan Research Professor, “MATERIALS CORROSION IN HIGH TEMPERATURE SUPERCRITICAL CARBON DIOXIDE,” in *The 4th International Symposium - Supercritical CO₂ Power Cycles*, 2014.

- [52] S. C. Kung, J. P. Shingledecker, I. G. Wright, and B. M. Tossey, "Oxidation and Carburization of Alloys Exposed to Impure Supercritical CO₂," Mar. 26, 2017, *OnePetro*. Accessed: Oct. 22, 2025. [Online]. Available: <https://dx.doi.org/>
- [53] P. Becker and D. J. Young, "Carburization resistance of nickel-base, heat-resisting alloys," *Oxidation of Metals*, vol. 67, no. 5–6, pp. 267–277, Jun. 2007, doi: 10.1007/s11085-007-9058-x.
- [54] S. J. Zinkle and N. M. Ghoniem, "Operating temperature windows for fusion reactor structural materials," *Fusion Engineering and Design*, vol. 51–52, pp. 55–71, Nov. 2000, doi: 10.1016/S0920-3796(00)00320-3.
- [55] A. Möslang *et al.*, "Towards reduced activation structural materials data for fusion DEMO reactors," *Nuclear Fusion*, vol. 45, no. 7, pp. 649–655, Jul. 2005, doi: 10.1088/0029-5515/45/7/013.
- [56] H. Tanigawa *et al.*, "Development of benchmark reduced activation ferritic/martensitic steels for fusion energy applications," *Nuclear Fusion*, vol. 57, no. 9, p. 092004, Jun. 2017, doi: 10.1088/1741-4326/57/9/092004.
- [57] M. Rieth, G. Aiello, and M. Zmitko, "Status of European reduced activation ferritic/martensitic steel EUROFER97," *Fusion Energy Technology R and D Priorities*, pp. 27–46, Jan. 2025, doi: 10.1016/B978-0-443-13629-0.00004-6.
- [58] L. Tan, L. L. Snead, and Y. Katoh, "Development of new generation reduced activation ferritic-martensitic steels for advanced fusion reactors," *Journal of Nuclear Materials*, vol. 478, pp. 42–49, Sep. 2016, doi: 10.1016/j.jnucmat.2016.05.037.
- [59] S. J. Zinkle *et al.*, "Development of next generation tempered and ODS reduced activation ferritic/martensitic steels for fusion energy applications," *Nuclear Fusion*, vol. 57, no. 9, Jun. 2017, doi: 10.1088/1741-4326/57/9/092005.
- [60] United Kingdom Atomic Energy Authority, "UK FUSION MATERIALS ROADMAP 2.0," 2025. Accessed: Oct. 22, 2025. [Online]. Available: <https://www.ukaea.org/wp-content/uploads/2025/09/uk-materials-roadmap-2-0.pdf>
- [61] R. Lindau *et al.*, "Present development status of EUROFER and ODS-EUROFER for application in blanket concepts," *Fusion Engineering and Design*, vol. 75–79, no. SUPPL., pp. 989–996, Nov. 2005, doi: 10.1016/J.FUSENGDES.2005.06.186.
- [62] S. Ukai and M. Fujiwara, "Perspective of ODS alloys application in nuclear environments," *Journal of Nuclear Materials*, vol. 307–311, no. 1 SUPPL., pp. 749–757, Dec. 2002, doi: 10.1016/S0022-3115(02)01043-7.
- [63] B. W. Baker and L. N. Brewer, "Joining of Oxide Dispersion Strengthened Steels for Advanced Reactors," *JOM*, vol. 66, no. 12, pp. 2442–2457, Nov. 2014, doi: 10.1007/S11837-014-1206-6/METRICS.
- [64] V. Firouzdor, G. P. Cao, K. Sridharan, M. Anderson, and T. R. Allen, "Corrosion resistance of PM2000 ODS steel in high temperature supercritical carbon dioxide," *Materials and Corrosion*, vol. 66, no. 2, pp. 137–142, Feb. 2015, doi: 10.1002/MACO.201307223.
- [65] L. Butt, A. Dickinson-Lomas, M. Freer, J. Lim, and Y. L. Chiu, "Research and development on vanadium alloys for fusion breeder blanket application," *Fusion Engineering and Design*, vol. 210, p. 114739, Jan. 2025, doi: 10.1016/J.FUSENGDES.2024.114739.
- [66] R. Bullough, "Factors involved in the use of vanadium alloys and ferritic steels for the ITER first wall/blanket and divertor," 2009. Accessed: Oct. 13, 2025. [Online]. Available: <https://scientific-publications.ukaea.uk/wp-content/uploads/UKAEA-FUS-554FINAL.pdf>
- [67] T. Muroga, P. F. Zheng, and Y. Yang, "History, present status, and future directions of vanadium alloys for fusion reactors," *Curr Opin Solid State Mater Sci*, vol. 36, p. 101224, May 2025, doi: 10.1016/J.COSSMS.2025.101224.
- [68] D. L. Smith, B. A. Loomis, and D. R. Diercks, "Vanadium-base alloys for fusion reactor

- applications — a review,” *Journal of Nuclear Materials*, vol. 135, no. 2–3, pp. 125–139, Oct. 1985, doi: 10.1016/0022-3115(85)90070-4.
- [69] T. Sparks *et al.*, “Mechanical characterisation of V-4Cr-4Ti alloy: Tensile tests under high energy synchrotron diffraction,” *Journal of Nuclear Materials*, vol. 569, p. 153911, Oct. 2022, doi: 10.1016/J.JNUCMAT.2022.153911.
- [70] L. Giancarli *et al.*, “Test blanket modules in ITER: An overview on proposed designs and required DEMO-relevant materials,” *Journal of Nuclear Materials*, vol. 367–370, no. SPEC. ISS., pp. 1271–1280, Aug. 2007, doi: 10.1016/J.JNUCMAT.2007.03.234.
- [71] K. Natesan, “Influence of nonmetallic elements on the compatibility of structural materials with liquid alkali metals,” *Journal of Nuclear Materials*, vol. 115, no. 2–3, pp. 251–262, Apr. 1983, doi: 10.1016/0022-3115(83)90316-1.
- [72] M. Li, D. T. Hoelzer, and M. L. Grossbeck, “The Influence of lithium environment on tensile behavior and microstructure of V–4Cr–4Ti,” *Journal of Nuclear Materials*, vol. 392, no. 2, pp. 364–370, Jul. 2009, doi: 10.1016/J.JNUCMAT.2009.03.026.
- [73] B. W. Lamm, T. Koyanagi, J. J. Lee, J. R. Keiser, H. Gietl, and Y. Katoh, “Corrosion characteristics of silicon carbide fiber-reinforced composites in beryllium-bearing molten fluoride salt,” *Corros Sci*, vol. 244, p. 112635, Mar. 2025, doi: 10.1016/J.CORSCI.2024.112635.
- [74] T. Koyanagi *et al.*, “Recent progress in the development of SiC composites for nuclear fusion applications,” *Journal of Nuclear Materials*, vol. 511, pp. 544–555, Dec. 2018, doi: 10.1016/J.JNUCMAT.2018.06.017.
- [75] L. El-Guebaly, “Final Radial/Vertical Builds for ARIES-ACT-SiC Power Core”, Accessed: Oct. 13, 2025. [Online]. Available: <http://fti.neep.wisc.edu/UWNeutronicsCenterOfExcellence>
- [76] R. Pearson, C. Baus, S. Konishi, K. Mukai, A. D’Angio, and S. Takeda, “Overview of Kyoto Fusionengineering’s SCYLLA© (‘Self-Cooled Yuryo Lithium-Lead Advanced’) Blanket for Commercial Fusion Reactors,” *IEEE Transactions on Plasma Science*, vol. 50, no. 11, pp. 4406–4412, Nov. 2022, doi: 10.1109/TPS.2022.3211410.
- [77] M. Steinbrueck, M. Grosse, U. Stegmaier, J. Braun, and C. Lorrette, “Oxidation of Silicon Carbide Composites for Nuclear Applications at Very High Temperatures in Steam,” *Coatings 2022, Vol. 12, Page 875*, vol. 12, no. 7, p. 875, Jun. 2022, doi: 10.3390/COATINGS12070875.
- [78] R. R. Naslain, “SiC-Matrix Composites: Nonbrittle Ceramics for Thermo-Structural Application,” *Int J Appl Ceram Technol*, vol. 2, no. 2, pp. 75–84, Mar. 2005, doi: 10.1111/J.1744-7402.2005.02009.X.
- [79] MERSEN, “SiC heat exchangers.” Accessed: Oct. 13, 2025. [Online]. Available: <https://www.mersen.co.uk/products/anticorrosion-equipment/heat-exchangers/silicon-carbide-heat-exchangers>
- [80] R. H. Jones *et al.*, “Promise and challenges of SiCf/SiC composites for fusion energy applications,” *Journal of Nuclear Materials*, vol. 307–311, no. 2 SUPPL., pp. 1057–1072, Dec. 2002, doi: 10.1016/S0022-3115(02)00976-5.
- [81] B. A. Pint, E. Kiosidou, D. Sulejmanovic, and P. Humrickhouse, “Materials Assessment for FLiBe Fusion Blankets,” 2024. [Online]. Available: www.osti.gov
- [82] A. Sagara, “Flibe/Flinabe blanket,” *Fusion Energy Technology R and D Priorities*, pp. 217–223, Jan. 2025, doi: 10.1016/B978-0-443-13629-0.00028-9.
- [83] S. E. Ferry, K. B. Woller, E. E. Peterson, C. Sorensen, and D. G. Whyte, “The LIBRA Experiment: Investigating Robust Tritium Accountancy in Molten FLiBe Exposed to a D-T Fusion Neutron Spectrum,” *Fusion Science and Technology*, vol. 79, no. 1, pp. 13–35, 2023, doi: 10.1080/15361055.2022.2078136.
- [84] J. Zhang *et al.*, “Redox potential control in molten salt systems for corrosion mitigation,” *Corros Sci*, vol. 144, pp. 44–53, Nov. 2018, doi: 10.1016/J.CORSCI.2018.08.035.

- [85] J. Jun and P. F. Tortorelli, "Corrosion in Other Liquid Metals (Li, PbLi, Hg, Sn, Ga)," *Comprehensive Nuclear Materials: Second Edition*, pp. 515–527, Jan. 2020, doi: 10.1016/B978-0-12-803581-8.11627-3.
- [86] T. Gnanasekaran, R. K. Dayal, and B. Raj, "Liquid metal corrosion in nuclear reactor and accelerator driven systems," *Nuclear Corrosion Science and Engineering*, pp. 301–328, Jan. 2012, doi: 10.1533/9780857095343.3.301.
- [87] S. Sridhar, P. Rozzelle, B. Morreale, and D. Alman, "Materials challenges for advanced combustion and gasification fossil energy systems," *Metall Mater Trans A Phys Metall Mater Sci*, vol. 42, no. 4, pp. 871–877, Apr. 2011, doi: 10.1007/S11661-011-0627-X/FIGURES/2.
- [88] B.-E. Ghidersa, J. Reiser, Y. Chen, J.-S. Lim, N. Lee, and H. Cho, "Helium-cooled Divertor: Design and DEMO Integration Studies", Accessed: Oct. 13, 2025. [Online]. Available: <http://www.euro-fusionscipub.org>.
- [89] J. S. Kwon, S. Son, J. Y. Heo, and J. I. Lee, "Compact heat exchangers for supercritical CO₂ power cycle application," *Energy Convers Manag*, vol. 209, p. 112666, Apr. 2020, doi: 10.1016/J.ENCONMAN.2020.112666.
- [90] S. R. A. Graduate, R. Assistant, I. W. J. Graduate, and M. H. A. Research, "Nuclear code case development of printed-circuit heat exchangers with thermal and mechanical performance testing".
- [91] L. Chai and S. A. Tassou, "A review of printed circuit heat exchangers for helium and supercritical CO₂ Brayton cycles," *Thermal Science and Engineering Progress*, vol. 18, p. 100543, Aug. 2020, doi: 10.1016/J.TSEP.2020.100543.
- [92] ASME, "ASME/BPVC - 2437-1 - 2437-1 Rules for Diffusion Bonded, Flat Plate, Microchannel Heat Exchanger Section VIII, Division 1 SUPP 6 | GlobalSpec." Accessed: Oct. 23, 2025. [Online]. Available: <https://standards.globalspec.com/std/475777/2437-1>
- [93] M. Marshall, M. Akbari, J. C. Zhao, and K. Hoopes, "Design of an Additively Manufactured Recuperator With 800 °C Inlet Temperature for sCO₂ Power Cycle Application," *J Eng Gas Turbine Power*, vol. 145, no. 2, Feb. 2023, doi: 10.1115/1.4055723.
- [94] I. N. Tano *et al.*, "A Scalable Compact Additively Manufactured Molten Salt to Supercritical Carbon Dioxide Heat Exchanger for Solar Thermal Application," *J Sol Energy Eng*, vol. 146, no. 1, pp. 11007–11008, Feb. 2024, doi: 10.1115/1.4063081.
- [95] M. Searle, A. Roy, S. Ramesh, and D. Straub, "Surface Roughness Effects on Heat Transfer in Additively Manufactured sCO₂ Cycle Heat Exchangers," Sep. 2021, doi: 10.2172/1819281.
- [96] H. U. Borgstedt, G. Frees, and G. Drechsler, "Corrosion of stainless steel in flowing PbLi eutectic," *Journal of Nuclear Materials*, vol. 141–143, no. PART 2, pp. 561–565, Nov. 1986, doi: 10.1016/0022-3115(86)90054-1.
- [97] G. W. Hollenberg, E. P. Simonen, G. Kalinin, and A. Terlain, "Tritium/hydrogen barrier development," *Fusion Engineering and Design*, vol. 28, no. C, pp. 190–208, Mar. 1995, doi: 10.1016/0920-3796(95)90039-X.
- [98] A. G. Evans, D. R. Clarke, and C. G. Levi, "The influence of oxides on the performance of advanced gas turbines," *J Eur Ceram Soc*, vol. 28, no. 7, pp. 1405–1419, Jan. 2008, doi: 10.1016/J.JEURCERAMSOC.2007.12.023.
- [99] L. Kang, "Coatings for Superalloy Components," in *The gas turbine handbook*, vol. 4.4.2, 2006, pp. 419–437. Accessed: Oct. 24, 2025. [Online]. Available: <https://www.netl.doe.gov/sites/default/files/gas-turbine-handbook/4-4-2.pdf>
- [100] S. Miyahara, H. Ishikawa, and Y. Yoshizawa, "Experimental investigation of reaction behavior between carbon dioxide and liquid sodium," *Nuclear Engineering and Design*, vol. 241, no. 5, pp. 1319–1328, May 2011, doi: 10.1016/J.NUCENGDES.2010.08.006.