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Journal of Nuclear Materials 283–287 (2000) 716–720

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Performance limits for fusion first-wall structural materials

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Abstract

Key features of fusion energy relate primarily to potential advantages associated with safety and environmental considerations and the near endless supply of fuel. However, high-performance fusion power systems will be required in order to be an economically competitive energy option. As in most energy systems, the operating limits of structural materials pose a primary constraint to the performance of fusion power systems. In the case of fusion power, the first-wall/blanket system will have a dominant impact on both economic and safety/environmental attractiveness. This paper presents an assessment of the influence of key candidate structural material properties on performance limits for fusion first-wall blanket applications. Key issues associated with interactions of the structural materials with the candidate coolant/breeder materials are discussed.

1. Introduction

Key features of fusion energy relate primarily to potential advantages associated with safety and environmental considerations and the near endless supply of fuel. However, it is generally concluded that high-performance fusion power systems will be required in order to be economically competitive with other energy options. As in most energy systems, structural materials' operating limits pose a primary constraint to the performance of fusion power systems. It is also recognized that, for fusion power, the first-wall/blanket system will have a dominant impact on both the economic and safety/environmental attractiveness of fusion energy. The first-wall blanket structure is particularly critical since it must maintain high integrity at relatively high temperatures during exposure to high radiation levels, high surface heat fluxes and significant primary stresses.

The performance limits of the first-wall/blanket structure will be dependent on the structural material properties, the coolant/breeder system and the specific design configuration. Key factors associated with high-performance structural materials include high-temperature operation to provide for high power conversion efficiency, a large operating temperature window to accommodate high surface heating and high power density and a long operating lifetime of the structure to improve system availability and minimize waste disposal. The performance of a fusion first-wall/blanket structure will be limited by both the inherent properties of the candidate structural materials and by factors imposed by the fusion system environment. The physical and neutronic properties of most candidate materials are characteristic of the base alloy system. For example, the thermal conductivity and thermal expansion coefficients of transition metals such as vanadium alloys and ferritic steels are insensitive to composition variations, thermochemical treatment and even irradiation effects. Similarly, the neutronic properties of the base materials cannot be changed except by isotopic tailoring, which is probably not a realistic solution. Notable exceptions include the thermal conductivity of SiC/SiC composites. Fabrication constraints such as welding and joining are important since joints are typically more susceptible to failure than the base material. However, significant modifications to the mechanical properties of most materials can be made by modest variations of composition, microstructure or thermomechanical treatment.

Limits imposed by the fusion system environment include such factors as the hydrogen plasma, the coolant/breeder system, the high-energy neutron environment and the magnetic field effects. Primary issues related to the hydrogen plasma include hydrogen (D–T)

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interactions involving solubility and permeability and surface heat flux deposition. Coolant/breeder compatibility issues include chemical interactions, coolant system pressure and coolant/breeder temperature constraints. The high-energy neutrons from the plasma cause displacement damage to the structural materials and significant transmutations. In most materials, the helium and hydrogen produced by nuclear interactions are the most important; however, transmutations of higher-Z atoms are important for some materials. The primary magnetic field effects relate to stresses associated with ferromagnetic materials, magnetohydrodynamic interactions of conducting liquid coolants and stresses associated with currents induced in the structure interacting with the magnetic field during disruptions.

2. Candidate first-wall structural materials

Three classes of first-wall materials are listed in Table 1. The primary candidate structural materials for advanced fusion system application are ferritic steels, vanadium alloys and SiC/SiC composites [1,2]. Copper alloys and austenitic steels are proposed for near-term applications [3]. Refractory metal alloys of tungsten, tantalum, niobium and molybdenum were considered as possible candidate structural materials in the early stages of the fusion program but were dropped for various reasons. These alloy systems are being re-evaluated with the current emphasis on high performance. The possibility of using free surface liquid walls for high surface heat fluxes has been suggested [4]; however, the potential of this approach for first-wall applications in magnetic fusion applications appears to be quite remote. The emphasis of this paper is limited primarily to the three candidate materials proposed for advanced fusion power systems.

Table 1
Candidate first-wall materials for fusion systems

Primary candidate structural materials	Refractory metals suggested for high performance	Free surface liquid wall
Ferritic steels	Tungsten alloys	Lithium
Vanadium alloys	Tantalum alloys	Li_2BeF_4 (Flibe)
SiC/SiC composites	Niobium alloys	
Copper alloys[a]	Molybdenum alloys	
Austenitic steels[a]		

[a] Primarily for near-term devices.

3. Factors affecting operating limits of materials

Since space limitations preclude a comprehensive assessment of all issues, this paper attempts to highlight some of the key factors affecting the performance limits of the candidate structural material issues for the various material options. Table 2 presents a summary of the neutronic responses of the candidate materials. Values given are only approximate since precise values are dependent on the specific design configuration and the combination of materials. Primary observations from this table include (1) the very high He and H transmutation rates for the SiC/SiC composite, (2) the relatively low He and H transmutation and displacement damage rates for the tantalum and tungsten alloys, (3) the very high dose rate and decay heat for tantalum and (4) the relatively low dose rate and decay heat for the SiC/SiC composite and vanadium alloy. Based on these data alone, the use of a tantalum alloy appears unacceptable because of dose rate considerations. The lifetime of the SiC/SiC composite with the high helium generation rate is a major concern regarding the feasibility of this material. This issue will in all likelihood be exacerbated by the high hydrogen transmutation rate and the fact that hydrogen diffusion/permeation in SiC is very low. The relatively high He generation rates for all materials compared to those in a fission reactor spectrum represent one of the major lifetime issues for a fusion first-wall system. The high-Z materials, Ta and W, exhibit

Table 2
Neutronic responses of first-wall/blanket structural materials[a]

Alloy	dpa[b] (15 MWy/m^2)	He Transmut[b] (15 MWy/m^2) appm	H Transmut[b] (15 MWy/m^2) appm	Dose rate[c] (Sv/h)	Decay heat[c] (W/kg)
Austenitic steel (316)	170	2400	8550	4000	3
Ferritic steel (9Cr–1Mo)	170	1800	7350	1000	1
Vanadium alloy (V–4Cr–4Ti)	170	855	4050	0.3	0.0005
SiC/SiC composite	135	19 500	13 350	0.0001	0.00003
Niobium	95	495	1725	4000	4
Molybdenum	95	525	5250	500	0.3
Tantalum	51	45	135	1 000 000	1000
Tungsten	45	51	135	1000	10
Copper	210	1500	8700	2000	1

[a] Approximate values; actual values depend on specific design. [b] Approximate values at first wall after 15 MW y/m^2. [c] Approximate values one month after 3 yr at 5 MW/m^2.

relatively low He and H transmutation rates. Of the three primary candidate materials, the vanadium alloys exhibit the lowest He and H transmutation rates; however, even for the vanadium alloys, the He is expected to have an impact on the operating lifetime.

The inherent physical properties of the structural materials will also influence performance limits. Table 3 presents the calculated temperature gradient through a characteristic wall for surface heat fluxes of 1 and 2 MW/m^2, which correspond approximately to neutron wall loadings of 5 and 10 MW/m^2. The wall ΔTs for the ferritic steel and vanadium alloy are similar, but both materials require a rather wide operating temperature range to accommodate a 2 MW/m^2 surface heat flux plus a reasonable coolant temperature change ($T_{out} - T_{in}$). This issue is much more complex for the SiC/SiC composite. The thermal conductivity of SiC is strongly influenced by temperature, microstructure, impurity level and irradiation [5,6]. Commercially available SiC/SiC composites exhibit fairly high (40–60 W/m K) thermal conductivities with fiber direction. However, thermal conductivity across the fibers is lower by a factor of five or more [5] and further reductions by factors of up to five are observed at lower temperatures after irradiation. Recent in-reactor measurements on so-called improved SiC/SiC composites also exhibit substantial reductions in thermal conductivities to ~10 W/m K at temperatures of 500°C and lower [6]. One might expect that the high He and H transmutation rates would cause additional reductions in the thermal conductivity. The values shown in Table 3 indicate that the surface heat flux for a SiC/SiC first wall would be limited to relatively low values based on the reductions to the thermal conductivity during irradiation and the assumed temperature limits for this material.

Structural material design criteria for fusion applications have been developed as part of the ITER engineering design activity [7]. In certain cases, the ITER structural design criteria (ISDC) allow higher surface heat flux limits than values based on the simple design stress criteria, $3S_m$, used in the past [7]. Structural design stress criteria based on the ISDC have been extended to include radiation-induced embrittlement and thermal creep (but not fatigue) for vanadium-base alloys [8]. Fig. 1 shows the time-independent maximum surface heat flux as a function of wall thickness for the V–4Cr–4Ti alloy properties. The $3S_m$ limit indicates a maximum surface heat flux of ~1.2 MW/m^2 for a wall thickness of 5–6 mm. The new design criteria allow the maximum surface heat flux to be set by the Bree limit for ductile materials ($\varepsilon_u > 2\%$) [7]. The Bree limit is projected for vanadium alloys above ~425°C [9]. For the case of a 750°C maximum temperature limit, the allowable surface heat flux is ~2.5 MW/m^2 for a 4.2-mm thick wall. This surface heat flux would correspond to a neutron wall loading of ~10 MW/m^2. For the case where the uniform elongation is reduced below 2%, the maximum heat flux is set by a material ductility limit S_d, which is ~1.8 MW/m^2. In either case, substantially higher wall loads are allowable for the vanadium alloy with the new criteria compared to the $3S_m$ criteria. The new design criteria have not yet been applied to the ferritic steels, but a similar set of criteria should apply, albeit with a lower T_{max}. However, since the uniform elongation of irradiated F82H ferritic steel is less than 2% [10], the S_d limit would apply. Since similar design criteria for the SiC/SiC composite have not been developed, estimates of surface heat flux limits cannot be made with any certainty. Although these types of design criteria have not yet been applied to tungsten and molybdenum alloys, the relative advantages of these characteristically low ductility materials may be significantly less than previously assumed.

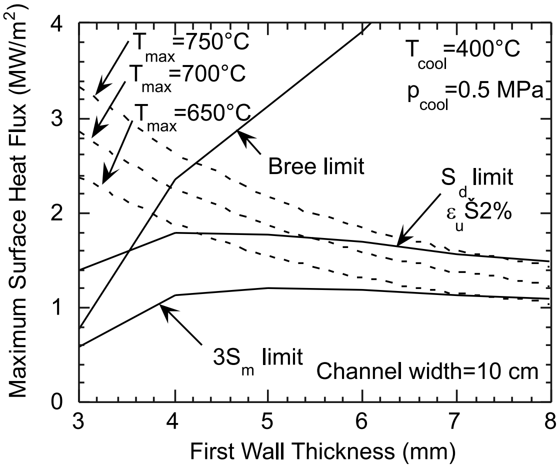

Fig. 1. Time-independent maximum surface heat flux as a function of wall thickness for vanadium alloy structure.

At high temperatures, thermal creep will become a factor and creep properties become more important as the design lifetime increases. Low-pressure coolants provide significant advantages since coolant pressure is the dominant contributor to primary stress. For example, for characteristic designs with a vanadium alloy

Table 3
Calculated temperature gradient through first wall for surface heat fluxes of 1 and 2 MW/m^2

Structural material	ΔT, °C	
	1 MW/m^2	2 MW/m^2
Ferritic steel (4 mm wall)	140	280
Vanadium alloys (4 mm wall)	120	240
SiC/SiC (6 mm wall)		
$K_t = 30$ W/m K	200	400
$K_t = 20$ W/m K	300	600
$K_t = 10$ W/m K	600	1200

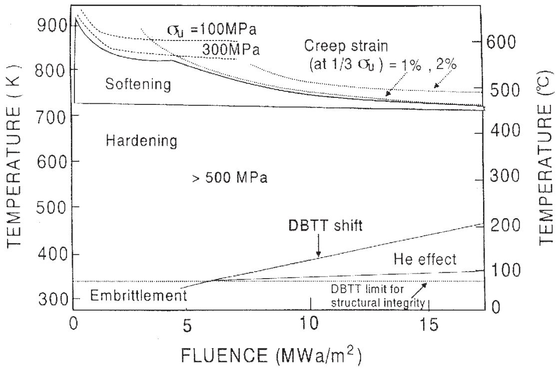

Fig. 2. Schematic design window for a tokamak-type fusion reactor with a ferritic steel first-wall structure [11].

structure, the maximum temperature for a primary stress of 120 MPa is ∼650°C, compared to a maximum temperature of ∼750°C for a primary stress of 40 MPa, which is typical of a lithium-cooled system. Similar type behavior is derived for the ferritic steels. Fig. 2 is a temperature/neutron fluence map for the F82H ferritic steel with water coolant presented by Hishinuma et al., [11]. At temperatures above ∼450°C, this steel exhibits a reduction of yield strength or softening with neutron damage. The reduction in allowable temperature is also indicated for creep strains of 1% and 2%. The lower temperature limit is affected by the ductile–brittle-transition temperature (DBTT). This figure projects a significant increase in the DBTT due to irradiation; however, for both the ferritic steel and the vanadium alloy, the effects of He on mechanical properties are highly uncertain. The shift in the DBTT may, in fact, be significantly greater than indicated if the effects of He and H transmutations are included. Further research on He (and H) effects on properties of both ferritic steels and vanadium alloys is of critical importance.

Neither the database nor the design criteria for the SiC/SiC composite are sufficiently developed to provide a similar assessment of the performance limits of this material. However, key constraints for SiC/SiC appear to be related to substantial reductions in thermal conductivity with irradiation, effects of the high He and H transmutation rates on the mechanical integrity and swelling, concerns related to fabrication and hermeticity and possible tritium retention.

As mentioned previously, the coolant/breeder system will have an impact on the acceptability and performance limits of candidate materials. It is beyond the scope of this paper to present a comprehensive assessment of all structure/breeder/coolant constraints; however, selected critical issues are presented. Clearly, the use of water coolant with lithium breeding material is not acceptable. Compatibility issues associated with hydrogen or tritium are important for several systems. The approximate tritium pressure corresponding to tritium generation resulting from a single pass of the breeder/coolant is $\sim 10^{-13}$ Pa for lithium, ∼0.1 Pa for PbLi alloy and ∼5 Pa for the flibe salt (assuming that T is not in the reduced form) in order to provide adequate breeding. For a self-cooled breeder system, only a few percent of the coolant system will be diverted to the tritium processing system. Therefore, tritium pressure in the breeder/coolant will approach values one to two orders of magnitude higher than those listed. Lithium is a special case with an extremely low tritium partial pressure, which should not impact any of the candidate structural materials. However, PbLi and Flibe (assuming that T is not in the reduced form) will exhibit tritium pressures that may lead to excessive tritium inventories in V, Nb and SiC/SiC. This does not appear to be a problem for the ferritic steel, Mo or W alloys. For the case of a Li-ceramic breeder, the tritium pressure per pass of helium purge is ∼5 Pa, assuming that T is in the reduced form. Additional hydrogen, typically ∼100 Pa, is added to the helium purge to facilitate tritium desorption from the lithium ceramic. Therefore, the hydrogen/tritium considerations for ceramic breeder systems are similar to those for PbLi and Flibe.

Compatibility limits associated with oxygen impurity in helium coolant are of particular importance for all refractory metals. It is clear that none of these alloys (V, Nb, Ta, Mo and W) can be exposed to air or oxygen at elevated temperatures. However, the oxygen level in He coolant must also be maintained at extremely low levels to be acceptable for use with the refractory metals. This issue has been addressed for the Group V metals (V, Nb, Ta), but has not been emphasized for Mo and W alloys. The calculated oxygen concentrations in high pressure (100 atm) He required to avoid oxidation of Mo and W are $\sim 10^{-8}$ ppm for MoO_2 and $\sim 10^{-7}$ for WO_2 at 700°C. The oxidation kinetics of Mo and W are also very high and oxides are even volatile at temperatures above 700–800°C. An extremely leak-tight system is required to maintain oxygen levels in He at acceptable levels even for Mo and W alloys. However, the issue is further complicated by tritium containment considerations. The preferred approach for containing tritium in a high temperature He-cooled system is by oxidizing it to reduce the tritium pressure and, hence, the permeation rates. However, oxidation of tritium will also lead to oxidation of the refractory metals. Adequate control of both oxygen and tritium remains a question for the He-cooled refractory metal systems.

4. Summary of structural material limits

The following general conclusions can be drawn regarding the performance limits of candidate structural materials.

Ferritic steels

- The key issue for ferritic steels relates to irradiation embrittlement, including effects of He and H transmutations.
- Energy conversion efficiency and wall load limits with He coolant are severely constrained by the upper temperature limits imposed by radiation softening and thermal creep.
- Temperature limits for ferritic steels are not compatible with the operating temperatures of Flibe.
- The current hope for a high-performance system is placed on ODS ferritic steels, which are quite different from the conventional ferritic steels and will require extensive development.

Vanadium alloys

- An operating temperature window of ~350°C (400–750°C) at a neutron wall loading of 5–10 MW/m^2 with a power conversion efficiency of >40% appears feasible with low-pressure Li coolant if a reliable insulator coating can be developed. In addition to the insulator coating requirement, key issue involves the effects of He transmutation on performance limits.
- Use with He coolant remains a question because of the combination of oxidation and tritium containment.
- Use with Flibe is questionable because of considerations related to tritium pressure/inventory, compatibility and the high melting temperature of Flibe.

SiC/SiC composites

- SiC/SiC composites are at an early stage of development and still present a number of unresolved issues such as joining, hermeticity and cost.
- The projected high operating temperatures (to ~1000°C) offer potential for high power conversion efficiency with He coolant.
- The reduction of thermal conductivity by irradiation poses a serious limitation to the surface heat load capability of SiC/SiC. This effect will probably be exacerbated by the high He and H transmutation rates.
- The effects of very high He and H transmutations on swelling and the mechanical properties are major concerns. High operating temperature limits may be imposed by multiplier/breeder temperature limits or compatibility considerations.

Refractory alloys (*Ta, Nb, Mo, W*)

- Ta alloys are considered unacceptable based solely on neutronic properties.
- Key issues for Nb alloys relate to the minimum temperature for radiation-induced embrittlement (possibly >500°C) and the concern related to long-term activation.
- Compatibility issues are similar to those for vanadium alloys. Key issues for Mo alloys relate to the minimum temperature limit for radiation-induced embrittlement (estimated to be >600°C), welding and fabrication difficulties and long-term activation. Issues related to oxidation and tritium containment for He-cooled systems remain a question.
- Key issues for W alloys are similar to those for Mo alloys, except the temperature for embrittlement is higher (possibly >700°C) and welding/fabrication is even more difficult and probably prohibitive.

5. Conclusion

This paper presents an assessment of the influence of key candidate structural material properties on the performance limits for fusion first-wall/blanket applications. Key issues associated with interactions of structural materials with candidate coolant/breeder materials are addressed. The dominant uncertainties regarding the performance limits for the primary candidate first-wall/blanket structural materials relate to effects of fusion-relevant He and H transmutation rates on structural material properties. Of particular significance is the extension of the ITER structural material design criteria to advanced structural materials and power system conditions. The new criteria indicate that significantly higher performance (wall load and high temperature) may be allowable for certain conditions than were projected based on older structural design criteria.

Acknowledgements

This work was supported by the Office of Fusion Science, US Department of Energy, under contract W-31-109-Eng-38.

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