13. Summary of Materials Considerations and Data Base (S.J. Zinkle, S. Majumdar and N.M. Ghoniem)

13.1 Introduction

The list of structural materials originally considered for the APEX project includes conventional materials (e.g., austenitic stainless steel), low-activation structural materials (ferritic-martensitic steel, V-4Cr-4Ti, and SiC/SiC composites), oxide dispersion strengthened ferritic steel, conventional high temperature refractory alloys (Nb, Ta, Mo, W alloys), Ni-based super alloys, ordered intermetallics (TiAl, Fe_3Al, etc.), various composite materials (C/C, Cu-graphite and other metal-matrix composites, Ti_3SiC_2, etc.), and porous-matrix metals and ceramics (foams). In order to provide maximum flexibility in the design (and to increase the possibility for significant improvements in reactor power density), low long-term activation was not used as a defining “litmus test” for the selection of candidate materials.

Due to limitations in resources and time, the materials analysis for APEX quickly focused on refractory alloys due to their higher thermal stress capacity and higher operating temperature capabilities compared to conventional structural materials. However, it should be emphasized that conventional materials may work satisfactorily in some of the APEX concepts (e.g., austenitic stainless steel located behind a thick wall of Flibe). Other promising advanced structural materials (e.g., ODS alloys, intermetallics) should be considered in future analyses.

Numerous factors must be considered in the selection of structural materials, including

- unirradiated mechanical and thermophysical properties
- chemical compatibility and corrosion
- material availability, cost, fabricability, joining technology
- radiation effects (degradation of properties)
- Safety and waste disposal aspects (decay heat, etc.)

Work by the APEX team focussed on the first four items in this list during initial 18 months of the project, and the key findings are summarized below.

13.1.1 Material costs and fabrication issues

The APEX materials team gathered information on the costs of many of the candidate structural materials. This raw material cost information is summarized in Table 13.1. The fabrication costs for producing finished products of refractory alloys (particularly W) is known to be much higher than for steels. The Group V refractory metals (V, Nb, Ta) are relatively easy to fabricate into various shapes such as tubing, whereas the Group VI refractory metals (Mo, W) are very difficult to fabricate. A further issue with all of the refractory metals is joining, particularly in-field repairs. Satisfactory full-penetration welds have not been developed for W, despite intensive efforts over a >25 year time span (1960-1985). The main issue associated with fusion zone welding of the Group V alloys is the pickup of embrittling interstitial impurities (O, C, N, H) from the atmosphere. Experimental studies are in progress in the US to develop satisfactory fusion welds for vanadium alloys.

Table 13.1 Costs for simple plate products (1996 prices)

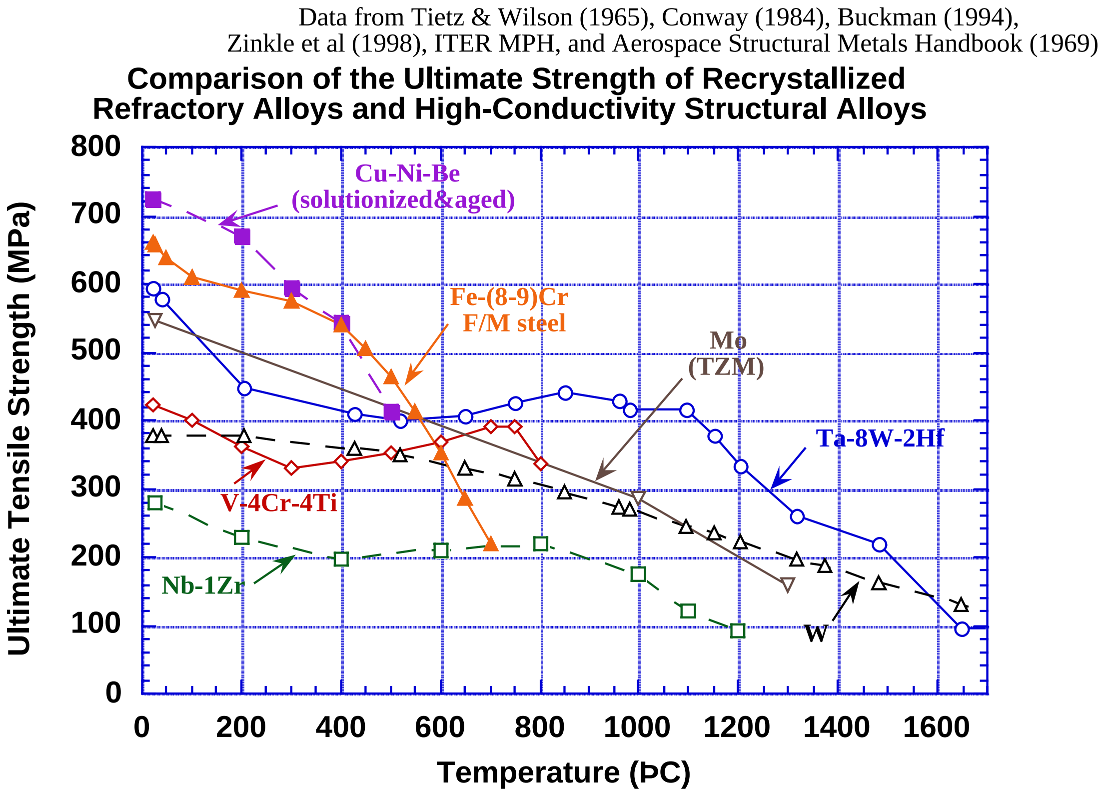
Material	Cost per kg
Fe-9Cr steels	$\leq$\$5.50 (plate form)
SiC/SiC composites	>\$1000 (CVI processing) ~\$200 (CVR processing of CFCs)
V-4Cr-4Ti	\$200 (plate form--average between 1994-1996 US fusion program large heats and Wah Chang 1993 "large volume" cost estimate)
Nb-1Zr	~\$100
Ta	\$300 (sheet form)
Mo	~\$80 (3 mm sheet); ~\$100 for TZM
W	~\$200 (2.3 mm sheet); higher cost for thin sheet

13.1.2 Overview of thermal stress capabilities of various alloys.

The key mechanical and physical properties of high-temperature refractory alloys and low-activation structural materials are summarized in Section 13.3. A thermal stress figure of merit convenient for qualitative ranking of candidate high heat flux structural materials is given by $M=\sigma_U k_{th}(1-\nu)/(\alpha_{th}E)$, where σ_U is the ultimate strength, E is the elastic modulus, ν is Poisson's ratio, k_{th} is the thermal conductivity, and α_{th} is the mean linear coefficient of thermal expansion. In addition, temperature limits (usually determined by thermal creep considerations) can be used for additional qualitative ranking of materials. A rigorous quantitative analyses of candidate materials requires the use of advanced structural design criteria such as those outlined in section 13.2.

The mechanical properties for recrystallized refractory alloys have been used as the reference case for purposes of APEX designs. The mechanical properties of stress-relieved (non-recrystallized) refractory alloys are superior to those of recrystallized specimens, with increases in strength of up to a factor of 2 being typical. However, the possibility of stress- or radiation-enhanced recrystallization of these alloys (along with the likely inclusion of welded joints in the structure) does not allow this strength advantage to be considered for conservative design analyses.

The thermal stress figures of merit varies from ~57 kW/m for a high strength, high conductivity CuNiBe alloy at 200˚C [14] to ~2.0 for SiC/SiC at 800˚C. Copper alloys are not attractive choices for high thermal efficiency power plants due to their high thermal creep at temperatures above 400˚C. The low thermal stress resistance of SiC/SiC is mainly due to the low thermal conductivity in currently available composites (primarily due to a combination of poor quality fibers and imprecise control of the CVI deposition chemistry). The two major classes of low-activation structural alloys, V-Cr-Ti and Fe-8-9Cr martensitic steel have figures of merit of ~6.4 (450-700˚C) and 5.4 (400˚C), respectively. The refractory alloys offer some advantage over vanadium alloys and ferritic-martensitic steel, even in the recrystallized condition. For example, pure recrystallized tungsten has a figure of merit of M=11.3 at 1000˚C, and TZM (Mo-0.5Ti-0.1Zr) has a value of M=9.6 at 1000˚C. The alloy T-111 (Ta-8W-2Hf) has the best thermal stress figure of merit among the (non-copper) alloys considered, with a value of M=12.3 at 1000˚C.


Data from Tietz & Wilson (1965), Conway (1984), Buckman (1994), Zinkle et al (1998), ITER MPH, and Aerospace Structural Metals Handbook (1969)

Comparison of the Ultimate Strength of Recrystallized Refractory Alloys and High-Conductivity Structural Alloys

Fig. 13.1. Temperature-dependent ultimate tensile strengths of recrystallized refractory alloys and high-conductivity structural alloys.

13.2 Structural Design Criteria

Most advanced blanket design concepts require the first wall to operate in temperature regimes where thermal creep effects may be important. Therefore, in addition to the usual low-temperature design rules, high-temperature design rules may also have to be applied. We have adopted the ITER Structural Design Criteria (ISDC) as a basis for the design rules to be used in APEX.

Since the design studies under APEX are preliminary in nature, only elastic analysis design rules are included. The design rules are divided into a high temperature section and a low temperature section, depending on whether thermal creep effects are or are not important. The low temperature rules are always applicable. High temperature rules are also applied if thermal creep may be significant. The low temperature design rules include limits associated with 1) necking and plastic instability, plastic flow localization, ductility exhaustion, brittle fracture, ratcheting (cyclic loading), and fatigue. The high temperature design rules include limits associated with creep damage, creep-ratcheting, and creep-fatigue.

13.3 Summary of thermophysical properties (unirradiated and irradiated)

Analytical expressions for the temperature-dependent mechanical and thermophysical properties for five of the structural materials considered for APEX have been derived from least-squares fits of experimental data (Fe-8-9Cr ferritic/martensitic steel, V-4Cr-4Ti, SiC/SiC, Ta-8W-2Hf, and W-10Re). Radiation-induced void swelling is not anticipated to be a lifetime-limiting issue in the refractory metals due to their BCC structure, although there are insufficient experimental studies to fully establish the void swelling behavior. Radiation hardening and associated embrittlement can have a major impact on all of the refractory alloys. The amount of radiation hardening at low temperatures ($<0.3T_M$) is pronounced in all of the refractory alloys, even for damage levels as low as ~1 displacement per atom. The amount of radiation hardening typically decreases rapidly with irradiation temperature above $0.3T_M$, and radiation-induced increases in the ductile to brittle transition temperature (DBTT) may be anticipated to be acceptable at temperatures above $\sim 0.3\ T_M$ (although experimental verification is needed). Very little information is available on the fracture toughness of irradiated or unirradiated refractory alloys.

13.4 Coolant/structure chemical compatibility

In general, the refractory alloys have very good compatibility with the liquid metals and salts of interest for fusion applications (Li, Pb-Li, Sn-Li, Flibe). Impurity pickup (O, C, N, etc.) is the key engineering issue in most cases for refractory alloys in contact with these coolants as well as for He-cooled concepts.

Formation of volatile oxides can lead to pronounced surface erosion of Group VI metals (Mo, W) at elevated temperatures. The evaporation rate increases rapidly up to ~2000K in both Mo and W. The high-temperature oxidation of Mo and W was analyzed using a thermodynamic model. If boundary layer scattering effects are ignored, the evaporation rate exceeds 100 μm/y at ~1500 K in both materials for 1 ppm oxygen in He at a pressure of 10 MPa. Boundary layer effects may reduce the evaporation rate by several orders of magnitude. The calculations suggest that limitations on mass transport through the boundary layer may reduce the erosion rate to less than 10 μm/y at wall temperatures up to 2600 K in both Mo and W. Although the model does not take into account many of the physical features of real wall-coolant interactions, such as roughness, bends, and temperature variations along the flow, it is reasonable to assume that the evaporation rate of W and Mo will be below a few microns per year, when operated at temperatures as high as 1200 to 1300^{o}C.

Oxygen pickup in the Group V metals (V, Nb, Ta) causes matrix hardening, which in turn produces an increase in the ductile-to-brittle transition temperature (DBTT). The matrix oxygen content must be kept below ~1000 wt. ppm in order to keep the Charpy V-notch DBTT below room temperature. Due to the high affinity of the Group V metals for oxygen, it is not realistic to avoid oxygen pickup from non-lithium coolants on the basis of thermodynamics. However, the kinetics of the oxygen pickup can be kept acceptably low either by maintaining the temperature below $\sim 0.4\ T_M$ or by keeping the oxygen partial pressure sufficiently low so as to prevent significant impingement of oxygen on the metal surface. A conservative analysis indicates that an oxygen partial pressure of ~10^{-10} torr would be sufficient to keep oxygen pickup to acceptably low levels in Group V metals for expected structural material lifetimes (10 to 50 years).

The experimental database on corrosion of structural alloys in contact with liquid metals and Flibe was reviewed. The refractory alloys have excellent compatibility with liquid lithium up to very high temperatures. The maximum operating temperatures of various alloys in Li, Pb-Li and Flibe is summarized in Table 13.2. There is a strong need for experimental data on the chemical compatibility of the various structural alloys with Sn-Li and Flibe although several materials appear to be compatible with these coolants at temperatures of interest for APEX. The refractory alloys do not appear to have good compatibility with Sn-Li.

Table 13.2. Maximum allowable temperatures of structural alloys (bare walls) in contact with high-purity liquid coolants, based on a 5 µm/yr corrosion limit. The Sn-Li corrosion limits are based on experimental studies conducted with liquid Sn.

	Li	Pb-17 Li	Sn-Li (Sn)	Flibe
F/M steel	550-600°C	450°C	400-500˚C	700°C ? 304/316 st. steel
V alloy	~700°C	~650°C	?	?
Nb alloy	>1300°C	>600°C (>1000°C in Pb)	600-800˚C	>800°C
Ta alloy	>1370°C	>600°C (>1000°C in Pb)	600-800˚C?	?
Mo	>1370°C	>600°C	<800˚C?	>1100°C?
W	>1370°C	>600°C	~800˚C	>900°C?
SiC	~550°C ?	>800°C ?	>760˚C?	?

13.5 Summary and conclusions

The estimated minimum and maximum temperatures for several of the structural materials considered for APEX are summarized in Fig. 13.2. The lower temperature limit is based on radiation hardening/ fracture toughness embrittlement (K_{1C}<30 MPa-$m^{1/2}$) due to low temperature irradiation. This embrittlement effect would be expected to occur for damage levels above ~1 dpa. There is a large uncertainty in the lower temperature limit for radiation embrittlement in W due to lack of mechanical properties data at irradiation temperatures above 700˚C. The upper temperature limit is based on thermal creep considerations (1% creep in 1000 h for an applied stress of 150 MPa). Depending on the choice of coolant, this upper temperature limit could be reduced due to corrosion issues. On the other hand, even higher temperatures might be conceivable for applications which have very low applied stress. The corresponding minimum and maximum temperature limits for Fe-8-9%Cr ferritic/martensitic steel are ~250 and ~550˚C. The upper temperature limit could be increased by using oxide dispersion strengthened ferritic steel, which has good creep strength to temperatures in excess of 650˚C. The recommended minimum and maximum temperature limits for SiC/SiC composites are ~600˚C (due to radiation-induced thermal conductivity degradation effects) and ~900˚C (due to void swelling concerns), although additional irradiation data are needed to firmly establish these temperature limits.

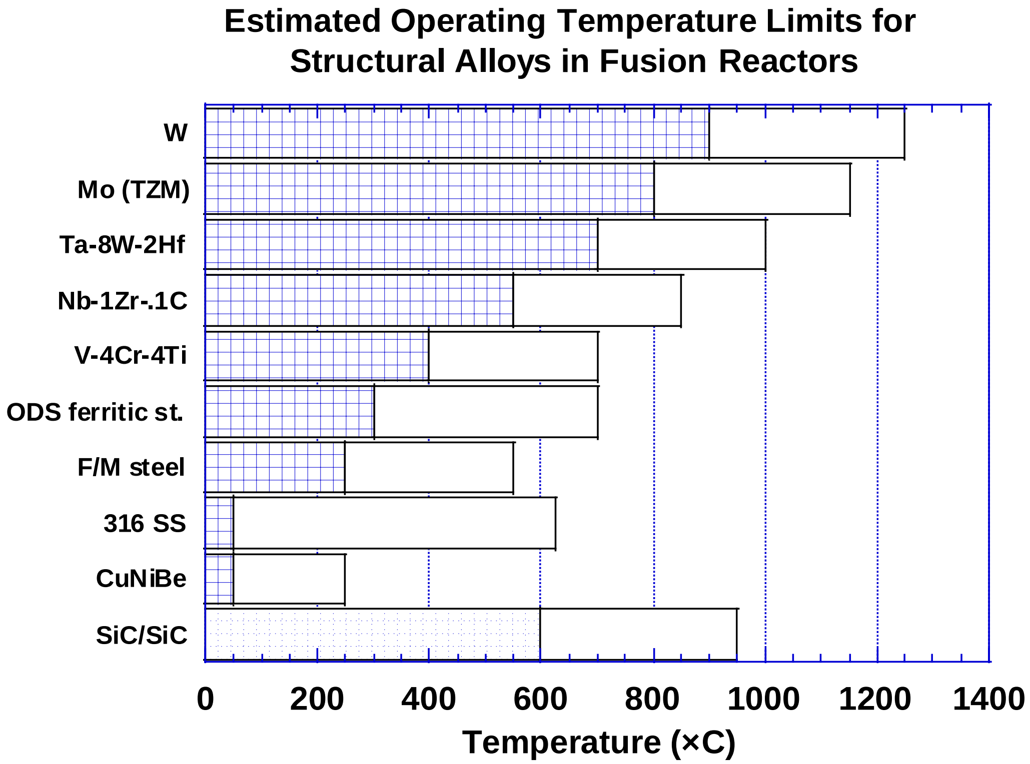


Fig. 13.2. Estimated operating temperature limits for structural alloys in fusion reactors.