ELSEVIER

Journal of Nuclear Materials 283–287 (2000) 1424–1428

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

ITER structural design criteria and their extension to advanced reactor blankets ☆

S. Majumdar [a,*], G. Kalinin [b]

[a] Fusion Power Program, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA

[b] ITER Garching JWS, Max-Planck-Institut für Plasmaphysik, Boltzmannstrasse 2, 85748 Garching bei München, Germany

Abstract

Applications of the recent ITER structural design criteria (ISDC) are illustrated by two components. First, the low-temperature-design rules are applied to copper alloys that are particularly prone to irradiation embrittlement at relatively low fluences at certain temperatures. Allowable stresses are derived and the impact of the embrittlement on allowable surface heat flux of a simple first-wall/limiter design is demonstrated. Next, the high-temperature-design rules of ISDC are applied to evaporation of lithium and vapor extraction (EVOLVE), a blanket design concept currently being investigated under the US Advanced Power Extraction (APEX) program. A single tungsten first-wall tube is considered for thermal and stress analyses by finite-element method.

1. Introduction

A primary purpose of any structural design criteria is to provide adequate design margins against postulated failure mechanisms that the structure could experience during its design lifetime. The ITER structural design criteria (ISDC) [1,2], which were developed collaboratively by the four home teams of Europe, Japan, the Russian Federation, and the United States, adopted many of the rules of existing national codes (e.g., ASME Code [3] and RCC-MR [4]) that consider conventional failure mechanisms such as necking and plastic collapse. The ISDC includes new rules to account for radiation embrittlement. The new low-temperature-design rules of ISDC are illustrated for copper alloys that, according to recent data [1], are particularly prone to irradiation embrittlement at relatively low fluences at certain temperatures. Allowable stresses are derived, and the impact of the embrittlement on allowable surface heat flux of a first-wall/limiter design is demonstrated.

To enhance the economic attractiveness of fusion power, many of the currently proposed advanced blanket concepts envision operation of the first wall in a high-temperature regime, where time-dependent deformation and damage processes associated with thermal creep are active. The high-temperature-design rules of ISDC are applied to EVOLVE [5], a blanket design concept currently being investigated under APEX. One such concept envisions the use of a series of parallel tungsten tubes (first wall) that are cooled internally by lithium vapor, typically at 1200°C. A low Li vapor pressure (0.035 MPa) that results in a low primary stress is an attractive feature of the design. For purposes of this paper, a single tungsten first-wall tube is considered for thermal and stress analyses by finite-element method.

2. ISDC rules

A few of the important design rules for low- and high-temperature applications are briefly reviewed below.

2.1. Low-temperature rules

In addition to the usual design rules prescribed in the ASME Code and RCC-MR, two new rules [2] were

☆ Work supported by Office of Fusion Energy, US Department of Energy, under Contract W-31-109-Eng-38.

* Corresponding author. Tel.: +1-630 252 5136; fax: +1-630 252 4798.

E-mail address: majumdar@anl.gov (S. Majumdar).

0022-3115/00/$ - see front matter
PII: S0022-3115(00)00324-X

incorporated into ISDC for irradiated materials with reduced strain-hardening capability (uniform elongation) and ductility (%RA or total elongation). First, to prevent failure by plastic flow localization, the elastically calculated primary plus secondary membrane stress intensity ($\overline{P_L + Q_L}$, bar denotes effective stress) is limited to S_e, where

$$S_e = \begin{cases} \frac{1}{3} S_u & \text{if } \varepsilon_u < 0.02, \\ \frac{1}{3}\left[S_u + \frac{E(\varepsilon_u - 0.02)}{2r}\right] & \text{if } \varepsilon_u > 0.02. \end{cases} \quad (1)$$

S_u is irradiated minimum ultimate tensile strength, ε_u the minimum uniform elongation, E the Young's modulus, and r is an elastic follow-up factor. In a similar fashion, to prevent local failure due to exhaustion of ductility, the primary membrane plus bending plus secondary stress intensity ($\overline{P_L + P_b + Q}$) is limited to S_d, where

$$S_d = \begin{cases} \frac{2}{3} S_u & \text{if } \frac{\varepsilon_f}{\mathrm{TF}} < 0.02, \\ \frac{2}{3}\left[S_u + \frac{E((\varepsilon_f/\mathrm{TF}) - 0.02)}{r}\right] & \text{if } \frac{\varepsilon_f}{\mathrm{TF}} > 0.02, \end{cases} \quad (2)$$

where ε_f is minimum true strain at rupture (or total elongation if ε_f is unavailable), and TF is a stress triaxiality factor [1] whose value is 2 for equibiaxial loading. In Eqs. (1) and (2), the elastic follow-up factor r is given by [2]

$$r = \begin{cases} 4 & \text{if } \varepsilon_u \geqslant 0.02, \\ \infty & \text{if } \varepsilon_u < 0.02. \end{cases} \quad (3)$$

Eq. (2) is slightly modified from that given in the ISDC [1] in order to make the variation of S_d with the ductilities more continuous. An additional rule that guards against local failures at zones of stress concentrations is not considered here.

2.2. High-temperature rules

To guard against thermal creep damage, the following limits (in addition to the usual time-independent S_m limits for primary membrane and bending stresses) must be satisfied:

$$\overline{P_L} \leqslant S_t(T_m, t), \quad (4a)$$

$$\overline{P_L + P_b/K_t} \leqslant S_t(T_m, t), \quad (4b)$$

where t is the design lifetime, $K_t = (K+1)/2$, K is bending-shape factor, and S_t is a time (t) and thickness-averaged temperature (T_m)-dependent allowable primary stress intensity. It is customary to denote the lesser of S_t and S_m as S_{mt}. S_t is defined in terms of stresses (with safety factors) to cause rupture, onset of tertiary creep and 1% thermal creep strain (or $\varepsilon_C/5$ if creep ductility ε_C <5%).

An additional rule at high temperature is used in the ISDC to avoid failure due to creep ratcheting [1,6].

3. Results

3.1. Low-temperature applications

Copper alloys have been proposed as heat sink materials for first wall and limiter applications. However, copper alloys show large losses in uniform and total elongations at fluences $\geqslant$0.3 dpa at low temperatures. The variations of mechanical properties of irradiated Cu–Cr–Zr with average first-wall temperature are shown in Fig. 1(a). Minimum uniform elongation is near zero until a temperature of 200°C beyond which it increases rapidly. As a result, the stress allowable S_e, also shown in Fig. 1(a), increases rapidly above 200°C, even though ultimate tensile strength decreases with temperature. A similar increase in allowable stress S_d occurs above

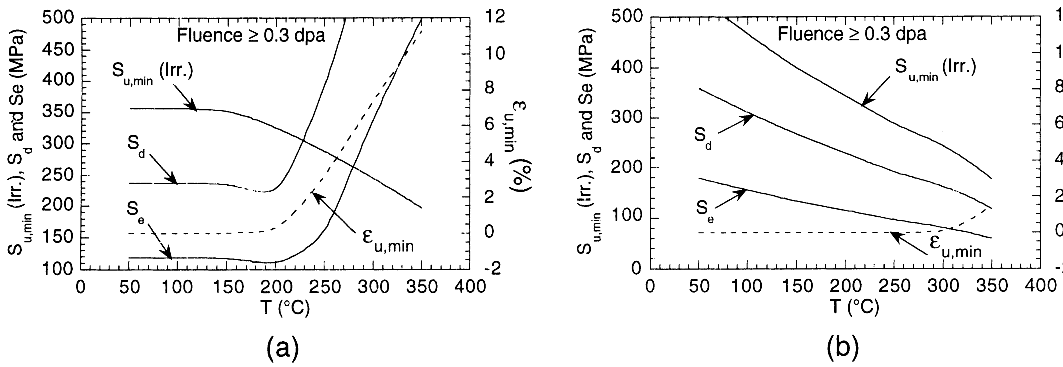

Fig. 1. Estimated minimum ultimate tensile strength, minimum uniform elongations and stress allowables S_d and S_e for irradiated: (a) Cu–Cr–Zr and (b) DS Cu (CuAl-25).

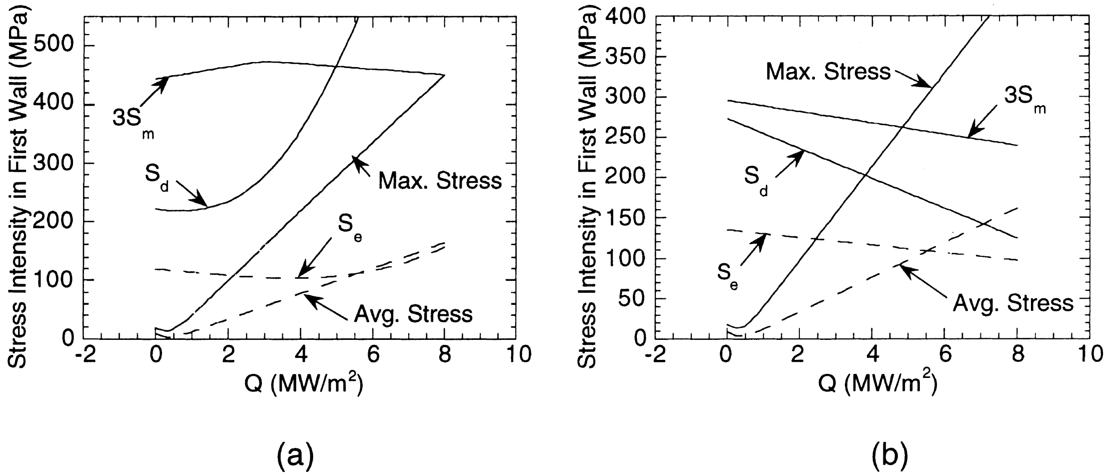

Fig. 2. Calculated average and maximum stresses (assuming a stress-free temperature = 300°C) and stress allowables S_e and S_d for irradiated cooled first wall (5 mm thick) made of: (a) Cu–Cr–Zr, (b) and DS Cu (CuAl-25) brazed to a thick internally cooled stainless steel structure.

200°C. In contrast to Cu–Cr–Zr, the uniform and total elongations of DS Cu (Glidcop® CuAl25) show large scatter (with low minimum values) up to 300°C (Fig. 1(b)). As a result, the S_d and S_e values of DS Cu (CuAl25), although greater than those of Cu–Cr–Zr at lower temperatures (because of higher ultimate tensile strengths), do not benefit from improved ductilities with increasing temperature.

The impact of the irradiated-material properties and the new design rules on allowable surface heat flux on the first-wall and limiter is demonstrated by considering a first-wall/limiter design consisting of 5 mm thick first wall and back wall separated by 10 mm high rectangular coolant channels. The coolant temperature is 150°C (primary stress due to coolant pressure is assumed to be negligibly small), heat transfer coefficient is 0.06 W/mm^2/°C, and an end-of-life fluence >0.3 dpa. The copper-alloy first wall is brazed to an internally cooled stainless steel block, which is assumed to be 50 cm thick radially. A 4-mm-thick beryllium coating is bonded at the plasma edge. A steady-state thermal heat conduction analysis of the first wall is used for the startup transient, while the temperature of the stainless steel block is assumed to be constant at 160°C during the transient. Stresses generated during fabrication and cooldown can be relaxed significantly because Cu can relax stresses by thermal creep down to relatively low temperatures. For present purposes, the stress-free temperature of the Cu/SS structure is assumed to be 300°C and the structure is assumed to be free of any externally applied mechanical constraint. Assuming that the coating is slotted, the influence of the coating on the first wall stress is neglected.

The variations of the average first-wall stress and the maximum stress (occurring at the Cu/Be interface) with surface heat flux for Cu–Cr–Zr and DS Cu (CuAl25) first-wall structures are shown in Figs. 2(a) and (b), respectively. Also shown are the various allowable stresses (S_e for average stress and S_d for maximum stress) for these materials. For the Cu–Cr–Zr first wall (Fig. 2(a)), the new design rules do not limit the allowable surface heat flux up to 8 MW/m^2. However, for the DS Cu (CuAl25) first wall (Fig. 2(b)), the S_d rule limits the surface heat flux to 4 MW/m^2. Note that the $3S_m$ rule would be unconservative for the first-wall design considered. Also, fatigue and the high temperature design rules may introduce further limits on the surface heat flux.

3.2. High-temperature applications

To demonstrate the use of the high-temperature rules, consider the EVOLVE concept which utilizes the exceptionally high heat of evaporation of lithium (about 10 times higher than that of water) to remove the entire heat deposited in the first wall and blanket [5]. A reasonable range of boiling temperatures of this alkali metal is 1200–1400°C, corresponding to a saturation pressure of ≈0.035 MPa. Such high temperatures would require the use of refractory metals, i.e., molybdenum, tantalum, or tungsten as structural material. These metals have sufficient strength, compatibility with lithium at these temperatures, and high thermal conductivity. The first wall is composed of U-shaped tubes in a radial-toroidal-radial arrangement. Inside each tube is a smaller feed tube with an array of nozzles that generate liquid-metal jets striking the back of the first wall. The diameter of each feed tube has a maximum at the entrance and goes to nearly zero at the exit where the entire space within the first-wall tube is utilized for vapor flow.

For purposes of this paper, thermal and stress analyses were conducted for a single tungsten tube of radius 2 cm and wall thickness of 3 mm subjected to a surface heat flux of 2 MW/m^2, a coolant temperature of 1200°C, and a coolant pressure of 0.05 MPa. The tube is assumed to deform under generalized plane strain conditions. For the heat conduction analysis, a cosinusoidal heat flux profile on the first wall is assumed.

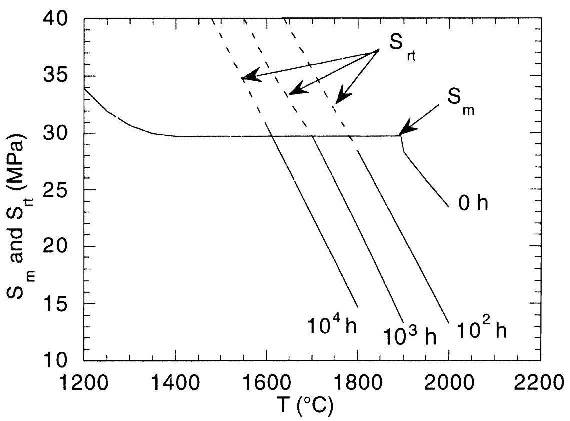

Fig. 3. Time-independent primary membrane stress intensity allowable S_m and time-dependent primary membrane stress intensity allowable S_{rt} for annealed tungsten.

The variation of primary stress allowable S_m with temperature for annealed tungsten is shown in Fig. 3. Note that the value of S_m at $\geqslant$1200°C is constant at 30 MPa up to 1900°C and is >20 MPa at 2000°C. Because only the creep rupture time data for tungsten were available, the allowable stress intensity is denoted by S_{rt} and is given in Fig. 3. Note that as long as the average first-wall temperature is <1400°C, S_m determines the value of S_{rt}. Since the primary membrane stress due to the coolant pressure is only 0.33 MPa, creep rupture damage is not of concern over any reasonable lifetime. If there is a drastic reduction in creep rupture properties of tungsten due to irradiation/helium embrittlement, the stress allowable S_{rt} values could be lower than those shown in Fig. 3.

Fig. 4 shows the temperature distribution in the first wall for a peak surface heat flux of 2 MW/m^2. The plasma side peak temperature is 1317°C. A maximum through-thickness temperature drop of $\approx$60°C occurs at the top of the tube, and a significant fraction of the heat is conducted circumferentially to the cooler part of the tube in the back. A maximum stress intensity of 158 MPa occurs at the location of the peak temperature. An inspection of Fig. 3 shows that this stress exceeds the $3S_m$ limit at the cross-section-averaged temperature of 1225°C. However, it would be extremely conservative to apply the $3S_m$ rule

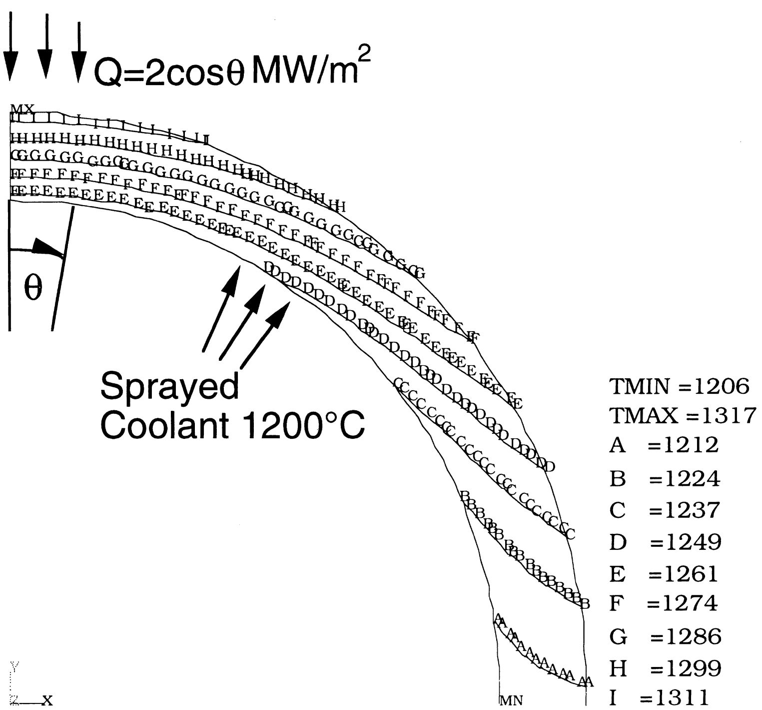

Fig. 4. Temperature contours in W first wall due to peak surface heat flux of 2 MW/m^2, coolant temperature of 1200°C, and coolant/first-wall heat transfer coefficient of 0.04 W/mm^2/°C. The surface heat flux is assumed to vary cosinusoidally.

to a case in which the primary stress is so low. An application of the high-temperature ratcheting rule [6] shows that the ratcheting limit is easily satisfied for this low pressure and 2 MW/m^2 surface heat flux.

To this point, we have ignored embrittlement of tungsten due to either irradiation or helium embrittlement. No relevant data on embrittlement of tungsten are currently available. If we assume conservatively that either the uniform elongation is <2% or the ductility (i.e., %RA) of tungsten is reduced to zero, then the S_d limit for this material at 1200°C is 150 MPa, which is slightly less than the peak stress 158 MPa. However, very little ductility is needed to raise the S_d limit to a relatively high value. For example, if uniform elongation remains higher than 2%, the S_d value, corresponding to a ductility of $\%RA = 1$, is raised to >300 MPa.

4. Conclusions

The stress allowables S_e and S_d of two irradiated copper alloys were derived and compared with each other. The allowable surface heat flux on a Cu/SS first-wall/limiter design with a low coolant pressure has been determined for Cu–Cr–Zr and DS Cu (CuAl25) heat sinks. According to the elastic design rules, the surface heat flux limit is >8 MW/m^2 when Cu–Cr–Zr is used and 4 MW/m^2 when DS Cu (CuAl25) is used. However, these surface heat flux limits can be exceeded if the inelastic analysis rules of the ISDC are satisfied after detailed elastic–plastic analyses of the structure using irradiated stress–strain curves.

Low primary stress in the tungsten first-wall tube of the EVOLVE design allows the high-temperature creep rupture limit to be easily satisfied. Heat conduction and elastic stress analysis of the tungsten first-wall tube were conducted by a finite-element method. Because of the low primary stress, the high-temperature creep-ratcheting limit is also easily satisfied. If it is conservatively assumed that tungsten is totally embrittled (i.e., zero uniform and total elongations) by irradiation and He embrittlement, a maximum surface heat flux of 2 MW/m^2 can still be allowed if an effective heat transfer coefficient of $\geqslant 0.04$ $W/mm^2/°C$ can be achieved.

References

[1] ITER structural design criteria for in-vessel components (ISDC), ITER IDoMS S74MA1 97-12-12 R0.2, Appendix A IDoMS G74MA2 98-06-26 F1, 1998.
[2] S. Majumdar, P. Smith, in: Proceedings of the Fourth International Symposium on Fusion Nuclear Technology (ISFNT-4), Tokyo, 6–11 April 1997.
[3] ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsections NB and NH, Edition July, 1995.
[4] RCC-MR Design and Construction Rules for Mechanical Components of FBR Nuclear Islands, Section I, Subsection B: Class 1 components, Edition 1985.
[5] R.F. Mattas et al., in: Presented at the Fifth International Symposium on Fusion Nuclear Technology (ISFNT-5) in Rome, 19–24 September 1999.
[6] S. Majumdar, in: Presented at the Fifth International Symposium on Fusion Nuclear Technology (ISFNT-5) in Rome, 19–24 September 1999.