IMPACT OF STRUCTURAL DESIGN CRITERIA ON FIRST WALL SURFACE HEAT FLUX LIMIT* - S. Majumdar (Argonne National Laboratory)

SUMMARY

The irradiation environment experienced by the in-vessel components of fusion reactors presents structural design challenges not envisioned in the development of existing structural design criteria such as the ASME Code or RCC-MR. From the standpoint of design criteria, the most significant issues stem from the irradiation-induced changes in material properties, specifically the reduction of ductility, strain hardening capability, and fracture toughness with neutron irradiation. Recently, Draft 7 of the ITER structural design criteria (ISDC), which provide new rules for guarding against such problems, was released for trial use by the ITER designers.[1] The new rules, which were derived from a simple model based on the concept of elastic follow up factor, provide primary and secondary stress limits as functions of uniform elongation and ductility. The implication of these rules on the allowable surface heat flux on typical first walls made of type 316 stainless steel and vanadium alloys are discussed.

PROGRESS AND STATUS

Introduction

Austenitic stainless steels have long been known to be embrittled by fission neutron environment.[2-4] Such effects may be further exacerbated by significant generation of transmutation products like He under fusion neutron environment. Typical stress-strain curves for type 316 stainless steel fission reactor irradiated and tested at 250°-270°C are shown in Fig. 1.[5] Note the significant hardening accompanied by losses of strain hardening capability, uniform elongation, and total elongation with fluence. Vanadium alloys (e.g., V-4Cr-4Ti) show similar embrittlement behavior when irradiated and tested at temperatures < 400°C.[6] Traditional design codes are not intended to be applicable to materials with such tensile properties.

Structural design criteria

The basic structural damages (excluding buckling) have been broadly categorized in the ISDC as belonging to either M-type (monotonic) damage, .e.g., necking, gross yielding and fast (brittle) fracture or C-type (cyclic) damage, e.g., ratcheting, fatigue and creep-fatigue, depending on whether they can potentially cause structural failure during the first application of the loading or by repeated application of the loading, respectively. In the traditional design codes as well as ISDC, M-type damage is guarded against by limiting the primary membrane stress intensity to S_m (an allowable stress based on yield and ultimate tensile strengths) and the primary membrane plus bending stress intensity to kS_m, where k is a bending shape factor (k =1.5 for solid rectangular section). However, ISDC considers three additional M-type damages that are generally not considered in the traditional design codes. They are (1) plastic flow localization, (2) local fracture due to exhaustion of ductility and (3) fast (brittle) fracture, all of which are attributable to irradiation effects. To provide safety factors against the first two type of damages, the ISDC includes two new elastic analysis stress limits - S_e limit for primary plus secondary membrane stress intensity and S_d limits for primary plus secondary membrane plus bending stress intensities, with and without peak stress (stress concentration) effects. Note that in the traditional design codes, there is generally no limit on the secondary or peak stress due to M-

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type loading, the assumption being that the material is sufficiently ductile to accommodate these deformation-controlled stresses by local yielding. For unirradiated annealed austenitic stainless steels and vanadium alloys, the numerical values of S_e and S_d are orders of magnitude higher than typical maximum stresses expected in practice and are never controlling. They may become controlling only when the material is sufficiently embrittled by irradiation so that the uniform elongation drops below 2%.

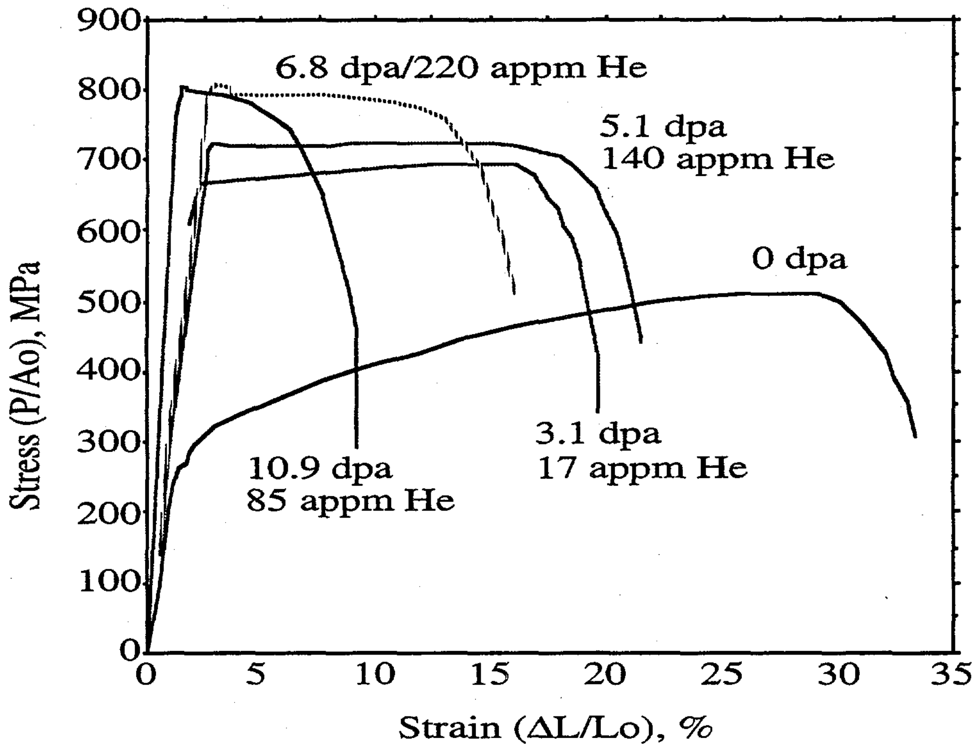


Fig. 1 Typical variation of the uniaxial stress-strain curve of Type 316 LN-IG stainless steel with fluence at 250°-270°C.

In the traditional design codes as well as ISDC, one option for guarding against ratcheting due to C-type loading is the $3S_m$ limit for primary plus secondary stress intensity. However, the $3S_m$ limit is often unduly conservative, particularly for designs with low primary stress. An alternative rule that is usually less conservative than the $3S_m$ rule, is based on the Bree diagram and has been adopted in the ISDC.

Implication of ISDC on allowable surface heat flux

To illustrate the implication of the design rules of ISDC on the surface heat flux capability of irradiated fusion reactor blanket/first wall, we consider a typical first wall geometry, shown in Fig. 2, subjected to a surface heat flux (Q) and coolant pressure (p). Thus, the temperature distribution through the structure is bilinear, being constant in the back wall. In most cases, the boundary condition considered is one of generalized plane strain, i.e., the structure can expand freely in-plane without bending out-of-plane. In one case, we considered the effects of complete constraint to expansion and bending. The design rules considered for setting the surface heat flux limits are (1) the $3S_m$ rule for primary plus secondary stresses, (2) the S_e limit for primary plus secondary membrane stress, (3) the S_d limit for primary plus secondary stress without peak stress, and (4) ratcheting limit based on Bree diagram rule.[1] In addition, we also indicate the limits implied by various maximum material temperature limits. Note that the $3S_m$ limits can be exceeded provided the Bree diagram rule is satisfied. We have not included limits based on fast fracture, creep, fatigue or those due to stress concentration effects at the coolant hole corners. For the design configuration and coolant pressures considered, the primary and secondary membrane stresses are very low and the permissible surface heat fluxes as determined by the S_e limit are never controlling and therefore not reported except in the case of a fully constrained blanket/first wall. Because of the simplicity of the stress analysis model, the surface heat flux limits reported here should be considered for comparison purposes only and should not be viewed as absolute limits.

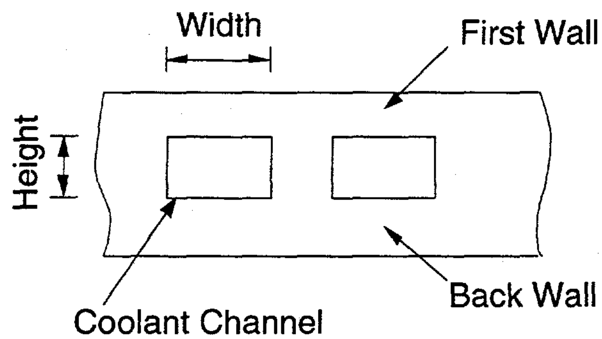


Fig. 2 Typical first-wall/coolant-channel/back-wall geometry considered.

Type 316 stainless steel

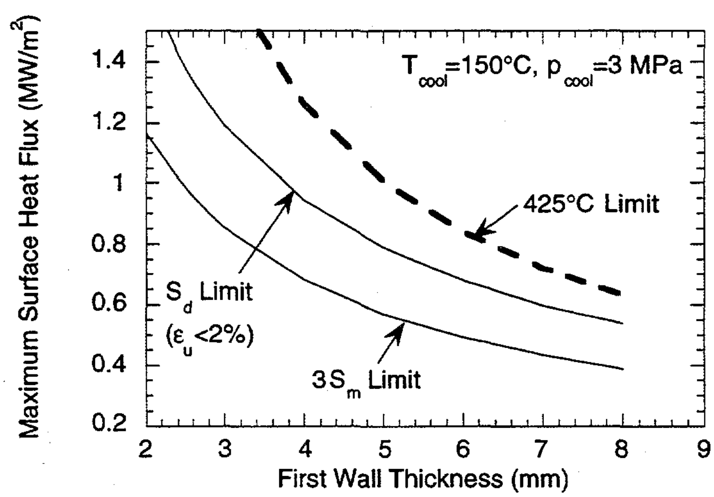
The surface heat flux limits for a low-temperature/low-pressure and high-temperature/high-pressure designs are shown in Figs. 3a and 3b, respectively. Since the Bree diagram ratcheting limit falls above the maximum ordinate value shown, the $3S_m$ limits for the low temperature design (Fig. 3a) can be exceeded up to the T_{max}=425°C limits. Even in the irradiation embrittled condition (ε_u < 2%), the $3S_m$ limits can be exceeded significantly. In the high-temperature/high-pressure design (Fig. 3b), the various allowable surface heat flux curves are shifted differently and the irradiation embrittlement (S_d) limit is never controlling unless the T_{max} = 550°C limit can be exceeded significantly. At small first wall thicknesses, the $3S_m$ limit is above the Bree limit because a small but finite ratcheting strain will occur only during the first cycle. The $3S_m$ limit can be exceeded up to the Bree limit beyond a first wall thickness of 3.5 mm; however, the T_{max} = 550°C limit is violated above a thickness of 4 mm.

Vanadium alloy

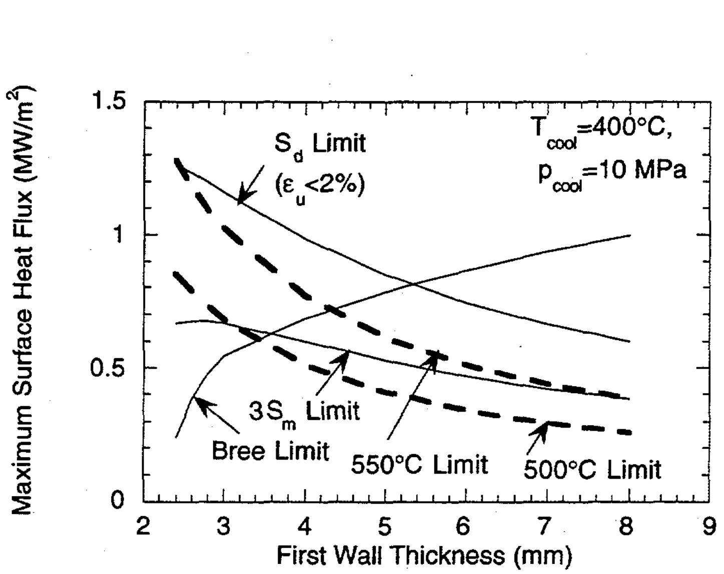
The surface heat flux limits for a V-4Cr-4Ti blanket/first wall design are shown for generalized plane strain and fully constrained conditions in Figs. 4a and 4b, respectively. In both cases, the allowable surface heat flux can exceed the $3S_m$ limit up to the Bree limit or the T_{max} limit, whichever is less. For the generalized plane strain case (Fig. 4a), the surface heat flux limits by irradiation embrittlement (S_d) rule fall below the Bree limits but can exceed the $3S_m$ limits without violating the T_{max} = 700°C limits up to a first wall thickness of 4 mm. For first wall thicknesses ≥ 5 mm, T_{max} = 700°C limit is below even the $3S_m$ limit. For the fully constrained case (Fig. 4b), the $3S_m$ limits, the S_d limits, and the Bree limits are all shifted downwards by about 0.5 MW/m^2. Although the surface heat flux limits due to primary plus secondary membrane stress limits (S_e) fall within the range of the ordinates plotted, they are still much higher than the S_d limits or the $T_{max} = 750°C$ limits.

Conclusions

New rules using the concept of elastic follow up factor (r-factor) have been included in the ISDC to account for the loss of uniform elongation (strain hardening) and true strain at rupture due to irradiation. For designs with low primary stress, the primary plus secondary membrane stress limit (S_e) may never be controlling.

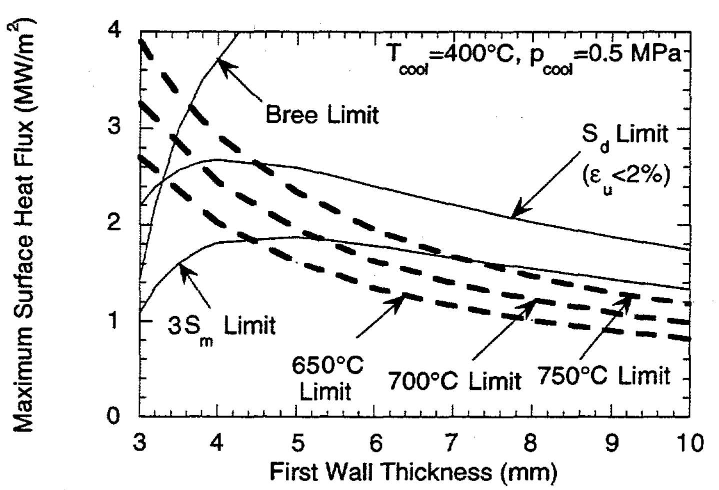


(a)

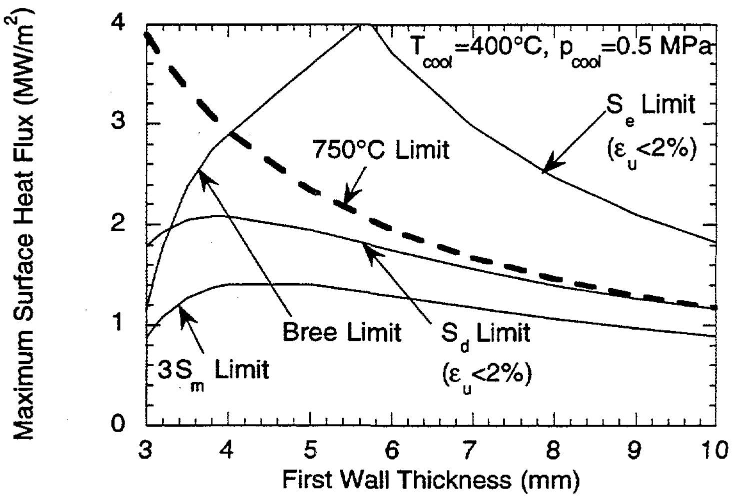


(b)

Fig. 3 Surface heat flux limits as functions of first wall thickness on type 316 stainless steel blankets with a 5 mm thick back wall for a (a) low temperature, low pressure design with 8 mm wide 4 mm high coolant channels and (b) high temperature, high pressure design with 10 mm wide and 20 mm high coolant channels.



(a)



(b)

Figure 4 Surface heat flux limits as functions of first wall thickness on V-4Cr-4Ti blankets with a 5 mm thick back wall, 100 mm wide and 50 mm high coolant channels for (a) generalized plane strain condition and (b) fully constrained condition.

The maximum surface heat flux limits by the various design rules considered here for first wall designs with drilled rectangular coolant channels depend on design variables such as coolant temperature, coolant pressure, material, first wall thickness, degree and type of constraint to deformation. In most cases, the $3S_m$ rule provides the most conservative values of permissible surface heat flux. These limits can be exceeded up to the Bree limits provided the maximum metal temperature limits are not exceeded. For the vanadium alloy blanket, the maximum metal temperature limits can be the controlling criterion for maximum surface heat flux, particularly for first wall thickness > 4 - 5 mm and if a conservative criterion such as T_{max} = 650°C is imposed. Thus, the maximum heat flux capability of vanadium alloy blankets may be significantly increased if the maximum temperature criterion can be relaxed. To emphasize, the surface heat flux limits presented here are not absolute limits, but are used only for comparison purposes.

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