ASSESSMENT OF THE DCLL TBM THERMOSTRUCTURAL RESPONSE BASED ON ITER DESIGN CRITERIA

Shahram Sharafat, Aaron T. Aoyama, Nasr Ghoniem

University of California Los Angeles, Los Angeles, CA, 90095-1597, shahrams@ucla.edu

The U.S. Dual Coolant Lead Lithium (DCLL) ITER Test Blanket Module (TBM) is under development for operation in the ITER reactor. The DCLL TBM must satisfy the Structural Design Criteria for ITER In-vessel Components (SDC-IC), which provides rules for the design evaluation and stress analyses of in-vessel mechanical components of ITER with the purpose of ensuring that required safety margins are maintained relative to the types of mechanical damage which might occur as a result of imposed loadings.

Primary stresses on the blanket structure come from the pressurization of coolants, the weight of the blanket element, and any electromagnetic forces due to plasma disruptions events. Secondary stresses in the materials due to thermal stress resulting from temperature gradients also contribute to the stress state of the structure. The response to primary stresses will depend on the distribution of loads, the blanket support, as well as material thermo-physical properties, which depend on operating temperatures, loads, fabrication and heat treatment and changes caused by neutron irradiation effects.

A detailed structural and thermal analysis of the DCLL TBM under typical loading conditions was performed. Highly stressed locations in the TBM were identified and the stress was broken down into membrane, bending, secondary, and peak stress for evaluating local stress intensities and equivalent stress in order to apply the SDC-IC design rules. Both low- and high temperature damage rules were evaluated to show lack of excessive deformation and negligible thermal creep.

I. INTRODUCTION

A primary mission of ITER is to test DEMO reactor relevant breeding blanket mockups called Test Blanket Modules (TBMs). The U.S. ITER TBM is a Dual Coolant Lead Lithium (DCLL) concept, which uses reduced activation ferritic-martensitic steel, F82H as structural material, a helium-cooled first wall (FW) and liquid Pb-17Li as self-cooled breeder for power conversion and tritium breeding. Details of the US ITER DCLL TBM design are elaborated in references[1, 2].

Although TBMs are not classified as safety important ITER components, they must fulfill all required ITER codes and standards for reliable and safe operation of ITER. Therefore, as an in-vessel component the TBM must follow the ITER SDC-IC design rules (SDC-IC: Structural Design Criteria – In-vessel Components[3]). The ITER structural design criteria (SDC-IC) were developed collaboratively by the ITER home teams adopting many of the rules of national codes (e.g., ASME Code[4] and RCC-MR[5]).

A detailed thermo-structural analysis of the DCLL TBM was performed and high- and low temperature SDC-IC design rules were applied to ascertain the DCLL anticipated performance under ITER normal operating conditions.

II. DESIGN CODE PURPOSE

The primary purpose of structural design rules is to assess if a structure has adequate design margins against postulated failure mechanism, which the structure could experience during lifetime operation. A number of important design rules for low- and high temperature applications are reviewed here.

II.A. Failure Modes

Failure modes of fusion reactor first wall/blanket (FW/B) components, such as the TBM can be immediate at the start of operations, or delayed by prolonged damage accumulation due to thermal stress and radiation effects on the microstructure. In qualifying FW/B components, one must therefore consider the following possible modes of failure:

1. M-type (monotonic) damage induced failure
   - (a) Immediate plastic collapse.
   - (b) Immediate plastic instability (due to large deformation or to plastic flow localization).
   - (c) Immediate fracture (brittle or with exhaustion of ductility).
   - (d) Thermal creep cavitation and rupture.

2. C-type (cyclic) damage induced failure:
   (a) Progressive deformation (ratcheting).
   (b) Progressive cracking (fatigue).
   (c) Fatigue-creep type failure.
3. Irradiation accelerated and induced failure:
   (a) Irradiation-induced immediate plastic instability due to flow localization.
   (b) Irradiation-induced immediate fracture due to hardening, loss of ductility, and embrittlement due to helium and phase instabilities.
   (c) Irradiation-accelerated thermal creep cavitation and rupture.
   (d) Dimensional instabilities due to irradiation-induced creep and swelling.

These failure mechanisms must be considered when determining the reliability of TBM structures for ITER.

III. THE SDC-IC DESIGN CODE

III.A. SDC-IC Definitions

The SDC-IC design rules relate deformation/failure mechanisms to design criteria. To understand design criteria, we first list here some of the main definitions:

1. *Primary stress* is defined as that portion of the total stress which is required to satisfy equilibrium with the applied loading and which does not diminish after small scale permanent deformation.
2. *Secondary stress* is that portion of the total stress (minus peak stresses, as defined below), which can be relaxed as a result of small scale permanent deformation. The basic characteristic of a secondary stress is that it is self-limiting.
3. *Total stress* (*strain*) is the stress (strain) under the effect of all the loadings to which the component is subjected.
4. *Membrane stress (strain)* tensor is the tensor whose components are equal to the mean value of stresses through the thickness.
5. *Bending stress (strain)* tensor is that tensor whose components vary linearly through the thickness.
6. *Peak stress* is the increment of stress which is additive to the membrane- plus-bending stresses by reason of local discontinuities or local thermal stresses including the effects, if any, of stress concentrations.
7. *Stress intensity* (denoted by a bar) at any given point is a scalar derived from the stress tensor at that point, using the maximum shear or Tresca criterion.
8. Effective stress: the effective stress used for creep calculation is based on von-Mises effective stress
9. *Stress intensity range* is the maximum of the stress intensities of the tensor differences between the stress tensors and for every pair of times t and δt within a cycle.
10. *Allowable primary membrane stress intensity* (S_m) is a temperature (T) and fluence (Φt) dependent allowable stress intensity defined as the least of the quantities:

$$S_m = Min\begin{bmatrix} \frac{1}{3}S_u,\min(RT,0), \frac{1}{3}S_u,\min(T,0), \frac{1}{3}S_u,\min(T,\Phi t), \\ \frac{2}{3}S_y,\min(RT,0), \frac{2}{3}Sy,\min(T,0), \frac{2}{3}S_y,\min(T,\Phi t) \end{bmatrix}$$

    where $S_{y,min}$ and $S_{u,min}$ are the minimum yield and ultimate tensile strengths, respectively, and RT is room temperature.
11. *Uniform elongation* is defined as the plastic component of the engineering strain at the time when necking begins in a uniaxial tensile test.
12. *Elastic follow-up factor(r)* provides a simplified inelastic analysis approach by which the peak inelastic strain and stress in a structure can be estimated from elastic analysis results. An r value of 4 is used in SDC-IC as a conservative estimate for many structures made of ductile alloys with adequate strain-hardening capability.
13. *Allowable primary plus secondary membrane stress intensity* (S_e) is a temperature (T) and fluence (Φt) dependent allowable stress intensity for a material with severe loss of uniform elongation due to irradiation and is defined as follows:

$$S_e = \left[\frac{1}{3}S_u,\min(T,\Phi t) + \frac{E\alpha_1}{r_1}[\varepsilon_u(T,\Phi t) - 0.02)]\right] \quad if \;\; \varepsilon_u > 2\%$$

$$and \quad S_e = \frac{1}{3}S_u,\min(T,\Phi t) \quad if \;\; \varepsilon_u < 2\%$$

    where E is the Young's modulus, $\alpha_1 = 0.5$, and $r_1 = \infty$ for $\varepsilon_u < 2\%$ and $r_1 = 4$ for $\varepsilon_u > 2\%$.
14. *Allowable total stress intensity (S_d)* is a temperature (T), fluence (Φt),and r-factor dependent allowable stress intensity for total primary plus secondary stress in radiation embrittled materials, defined as:

$$S_d = \frac{2}{3}\left(S_u,\min(T,\Phi t) + \frac{E\varepsilon_{tr}(T,\Phi t)}{r \times TF}\right)$$

    where *TF* = triaxiality factor [6] to account for the effect of hydrostatic stress on ductility: $TF = (\sigma_1 + \sigma_2 + \sigma_3)/\sigma_e$, where σ_e is the equivalent stress, *r* = elastic follow-up factor, and ε_{tr} is the strain at rupture.
15. *Time-dependent allowable primary stress intensity (S_t)* is a time and temperature-dependent allowable primary stress intensity defined as the least of the following: (1) two thirds of the minimum stress corresponding to average creep rupture time *t* at temperature *T*, (2) 80% of the minimum stress corresponding to time *t* and temperature *T* for onset of tertiary creep, and (3) minimum stress to cause a creep strain of min[1%, ε_C/5] in time *t* and temperature *T*, where ε_C is the minimum creep ductility.

III.B. SDC-IC Criteria

The SDC-IC design rules are divided into a low temperature-, high temperature-, and all temperature criteria, depending on whether thermal creep effects are or are not important:

LOW TEMPERATURE CRITERIA:

- Limit load collapse, under a single load application.
- Excessive displacement and/or deformation, limiting functionality, under a single load application, below the limit load.
- Structural instability or buckling, under a single load application.
- Progressive collapse by ratcheting under cyclic load.
- Fracture by the initiation and/or propagation of a crack under a single load application.
- Fatigue failure under cyclic loading.
- Breach of the pressure boundary, or structural collapse caused by corrosion induced loss of section.

HIGH TEMPERATURE CRITERIA:

- Excessive deformation - loss of functionality, due to creep deformation under essentially steady load.
- Creep buckling - time dependent structural instability leading to catastrophic collapse or loss of function.
- Cyclically enhanced creep deformation (Creep Ratcheting) - Accelerated creep deformation caused by repeated resetting of stresses by cyclic plastic strain, due to cyclic loads superimposed on a sustained load history.
- Accelerated creep rupture - Accelerated creep damage caused by repeated resetting of stresses by cyclic plastic strain, due to cyclic loads superimposed on a sustained load history.
- Creep/fatigue interaction - Failure under cyclic conditions in a period, usually less than fatigue due to the cyclic condition alone, or creep rupture due to time-at-stress alone, the mechanism for which may include other time/temperature related phenomena, such as oxide layer cracking, and may be material specific.

ALL TEMPERATURES CRITERIA:

- Corrosion, oxidation, and mass transport phenomena.
- Irradiation induced failure mechanisms

IV. SDC-IC DESIGN RULES

The low temperature rules are always applicable. To determine whether the high temperature rules are also to be applied, the following negligible creep test should be used. Thermal creep is negligible over the total design lifetime of a component if the following summation limit is satisfied:

$$\sum_{i=1}^{N}\left(\frac{t_i}{t_{ci}}\right) \le 1 \qquad (1)$$

where the total lifetime is divided into N intervals of time; for each interval i, of duration t_i. The negligible thermal creep time t_{ci} at a temperature T_i is calculated as the time required to accumulate a thermal creep strain of 0.05% in a uniaxial creep specimen subjected to a constant stress of 1.5 $S_m(T_i)$. The maximum temperature is denoted by T_i. If the inequality in Equation 1 is satisfied, then only low temperature design rules need be applied. The following is a list of the design rules that must be met for components made of any structural material, and that we will apply to the DCLL TBM.

- *LOW-TEMPERATURE DESIGN RULES:*

1. Necking and plastic instability limit to prevent failure by necking and plastic instability, the following limits must be satisfied at all times:

$$\overline{P_m} \le S_m; \qquad \overline{P_L + P_B} \le K S_m(T_m, \Phi t_m) \qquad (2)$$

where a bar denotes effective stress. P_m is the general primary membrane stress, P_L is local primary membrane stress, P_B is primary bending stress, K is bending shape factor (= 1.5 for solid rectangular cross sections), and S_m is evaluated at the thickness-averaged temperature (T_m) and fluence (Φt_m).

2. Plastic flow localization limit: To prevent cracking due to plastic flow localization (in a material with significant loss of uniform elongation due to irradiation), the elastically calculated primary plus secondary membrane stress intensity is limited to S_e:

$$\overline{P_L + Q_L} \le S_e(T_m, \Phi t) \qquad (3)$$

and Q_L is the secondary membrane stress intensity.

3. Ductility exhaustion limit: To prevent local fracture due to exhaustion of ductility (embrittlement) the total stress, including peak stress, is limited to S_d:

$$\overline{P_L + P_b + Q + F} \le S_d(T, \Phi t, r_2) \qquad (4)$$

where F is the peak stress (e.g., due to stress concentration), r_2 = max[K_T & 4] (K_T is the elastic stress concentration factor), is Q is the secondary stress intensity, and the total stress, excluding peak stress, is limited by (and $r_3 = r_1$; see definition #13) :

$$\overline{P_L + P_b + Q} \le S_d(T, \Phi t, r_3) \qquad (5)$$

4. Brittle fracture limit: To prevent brittle fracture initiating from severe flaws or notches, the maximum mode I stress intensity factor, K_I, due to all primary and secondary loadings, including peak

stress (P_L+P_b+Q+F), must be limited by the following:

$$K_I \le K_C(T_m, \Phi t) \quad (6)$$

where K_C is the linear-elastic fracture toughness evaluated at the thickness-averaged temperature and fluence. The stress intensity factor K_I has to be determined from the analysis of a postulated surface flaw of depth a_0, length $4a_0$, where $a_0 = max[4a_u, h/4]$, a_u = largest undetectable crack length, and h = section thickness.

5. Ratcheting limit: To prevent ratcheting due to cyclic loading, either one of the following two limits should be satisfied at all times:
   (a) $3S_m$ limit: $\overline{(P_L+P_b)_{\max}} + \Delta\left[\overline{P}+\overline{Q}\right]_{\max} \le 3S_m(T_m, \Phi t_m)$
   where Δ denotes the range of primary (P) and secondary (Q) stress due to cyclic loading.
   (b) Bree-diagram limit:

$$Y \le \begin{cases} \dfrac{1}{X} & for \quad 0 \le X \le 0.5 \\ 4(1-X) & for \quad 0 < X \le 1 \end{cases} \quad (7)$$

where $X = \dfrac{\overline{P_m}}{S_y}$ or $X = \dfrac{\overline{P_L + \frac{P_b}{K}}}{S_y}$ and

$Y = \dfrac{\Delta\left[\overline{P_m}+\overline{Q}\right]}{S_y}$, as applicable

and the yield stress S_y is evaluated at the average of the thickness-averaged temperatures at the 'cold' and 'hot' ends of the cycle and ΔP an ΔQ are the primary and secondary stress intensity ranges.

- *HIGH-TEMPERATURE DESIGN RULES:*

1. Creep damage limit: To guard agains creep damage the following limit must be satisfied:

$$\overline{P_m} \le S_t(T_m, t)$$
$$\overline{P_L + P_b / K_t} \le S_t(T_m, t) \quad (8)$$

where t is the design lifetime, and $K_t = (K+1)/2$. If the lifetime involves variable stress and temperature history, these equations, should be replaced by limits on usage fraction sums.

2. Creep-ratcheting limit: If the negligible creep test (Eq. 1) is not satisfied, then in addition to satisfying the low temperature ratcheting limit based on Bree diagram, the high temperature ratcheting limit should be satisfied by first calculating an effective core stress σc for creep calculations as follows:

$$\sigma_c = ZS_{yL} \quad (9)$$

where S_{yL} is the S_y value at the 'low' temperature extreme of the cycle and Z is a creep stress parameter defined in terms of *S* and *Y* as follows:

$$\begin{aligned} &Z = X && for\ X + Y \le 1 \\ &Z = Y + 1 - 2\,(1-X)Y && for\ 1-X \le Y < 1/(1-X) \\ &Z = XY && for\ Y > 1/(1-X) \end{aligned} \quad (10)$$

The total creep strain accumulated during the lifetime due to a stress $1.25\sigma_c$ should be less than min[1%, $\varepsilon_C/5$] where ε_C is the minimum creep ductility during the cycle. If the lifetime involves more than one type of cycle of stress and temperature, the criterion is satisfied by the use of usage fraction sums.

The rules for fatigue limit and creep-fatigue limit were not included in this work and are not listed. Table 1 summarizes and lists all low- and high temperature SDC-IC design criteria that were used to assess the DCLL TBM.

V. SDC-IC MATERIAL PROPERTIES

The physical and mechanical properties required for SDC-IC design rules applications are presented in a document called 'Appendix A: Materials Design Limit Data [7]. However, it is written mainly for austenitic stainless steels and deal with low temperatures and low neutron doses. They do not include at present rules and data for reduced activation ferritic/martensitic steel, F82H. Tavasolli et al. [8, 9] published a database for F82H (IAE Heat) properties with derived correlations for modulus of elasticity, density, thermal conductivity, thermal diffusivity, specific heat, mean and instantaneous linear coefficients of thermal expansion versus temperature.

Based on these data bases we developed a set of design data for F82H as a function of temperature and fluences. In particular, at end of life (EOL) the ITER DCLL TBM structural material will have an accumulated neutron damage of 3.7 dpa.

The design criteria as outlined in Section II require correlations for average tensile yield strength ($S_{y(av)}$), average ultimate tensile strength ($S_{u(av)}$) as well as the irradiated counterparts, $S_{y(irr)}$ and $S_{u(irr)}$. The average yield strengths and ultimate strength of F82H are reported in Ref. 8 and 9, however only a limited correlation for $S_{y(irr)}$ were developed. Here we report on the development of correlations for the irradiated average yield and tensile strengths, $S_{y(irr)}$ and $S_{u(irr)}$ based on irradiation data. The correlation for $S_{y(av)}$ as a function of temperature was given as:

$$S_{y(av)}(T) = 558.76 - 0.81574\,T + 2.7621\times10^{-3}T^2 - 3.476\times10^{-6}T^3 \quad (11)$$

TABLE 1: Summary of Applied SDC-IC Design Criteria [6,7]

	Design Criteria
LOW TEMPERATURE DESIGN RULES:	
Necking and Plastic Instability Limit-Primar membrane stress (imm-ediate plastic collapse & plastic instability)	$\overline{P_m} \leq S_m(T_m, \phi t_m)$
Necking and Plastic Instability Limit-Primar membrane and bending stress	$\overline{P_L + P_b} \leq K_{eff}\, S_m(T_m, \phi t_m)$
Local primary membran stress–(immediate plasti collapse & plastic instability)	$\overline{P_L} \leq \min\left[1.5\, S_m(T_m, \phi t_m),\ S_{y,min}(T_m, \phi t_m)\right]$
Local primary membran stress–(immediate plastic collapse & plasti instability)	$\overline{P_L} \leq 1.1\, S_m(T_m, \phi t_m)$
Plastic Flow Localizatio Limit - Primary plus secondary membrane str (immediate plastic flow localization)	$\overline{P_L + Q_L} \leq S_e(T_m, \phi t_m)$
Ductility Exhaustion Limit - (Local fracture, exhaustion of ductility)	$\overline{P_L + P_b + Q + F} \leq S_d(T, \phi t, r_2)$
Ductility Exhaustion Limit – Without peak stress (Local fracture, exhaustion of ductility)	$\overline{P_L + P_b + Q} \leq S_d(T, \phi t, r_3)$
HIGH TEMPERATURE DESIGN RULES:	
Creep Damage Limit	$P_L + {P_b}/{K_t} \leq S_t$
Ratcheting Limit-Progressive de-formation or ratcheting	$X \cdot Y \leq 1 \quad for \quad 0 \leq X \leq 0.5$
Ratcheting Limit - Progressive de-formation or ratcheting	$\frac{Y}{4(1-X)} \leq 1 \quad for\ 0.5 \leq X \leq 1.0$
Ratcheting Limit-Progressive deformation/ratcheting	$X + Y \leq 1$

where T is temperature in Celsius and strength is in MPa. To estimate the yield strength as a function of neutron damage (dpa), irradiation data of F82H IAE Heats 9741, 9753 (Ref. 10) along with recent irradiation data of IAE Heat 974 (Ref. 11,12) were reviewed and are shown in Fig.1.

Based on the average yield strength (Eq. 11) and the irradiation data [11,12] we developed a correlation for the average irradiated yield strength of F82H as a function of damage (dpa) and temperature, which is given by Eq. 12 and also shown in Fig. 1.

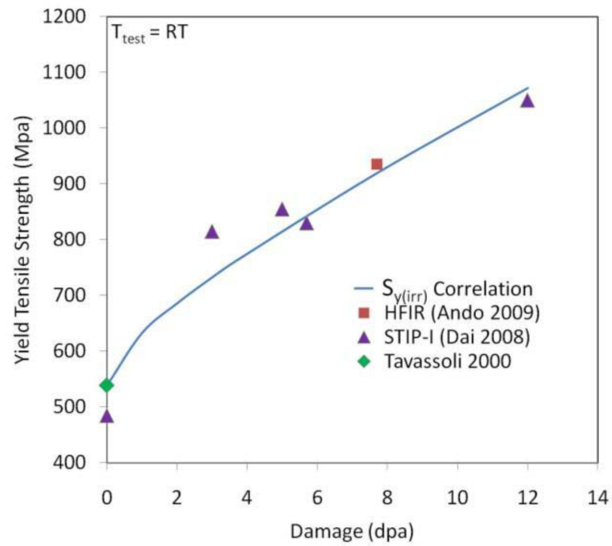

Fig. 1: Yield tensile strength (YTS) for F82H as a function of damage (HFIR: $T_{irr} = 300^oC$; STIP-I: $T_{irr} = 90\ ^oC$ to $375\ ^oC$ – HFIR/Tavassoli: IEA Heat 9741, 9753; STIP-I: IEA Heat 974)

$$S_{y(irr)}(\text{dpa}, T) = S_{y(av,unirr)}(1 + 0.045 \times \varphi + 0.13\varphi^{0.5}) \quad (12)$$

where φ is damage in dpa, T is temperature in Celsius, and the strength is in MPa. Fig. 2 shows the correlation (Eq. 12) evaluated at 1, 2, and 3.7 dpa as well as the RT tested irradiation data points for un-irradiated and irradiated yield strength of F82H. The damage level of 3.7 dpa represents the end of life (EOL) for the ITER TBM structure. The reported irradiation hardening data by Dai et al. [12] also contains the effects of helium content.

Similarly, the ultimate strength of F82H IAE Heat 9741 and 9753 was reported by [8] as:

$$S_{u(av)} = 666.44 - 0.84514\, T + 2.1019 \times 10^{-3} T^2 - 2.617 \times 10^{-6} T^3 \quad (13)$$

where the T is temperature in Celsius and strength is in MPa. Ando et al.[11] reported the RT measured irradiated ultimate tensile strength (UTS) of F82H (IAE Heat 9741, 9753) at 7.7 dpa and T_{irr} of 300 ^oC. He showed a 51% increase in UTS (un-irradiated UTS 621.6 MPa; irradiated UTS_{irr} 938.9 MPa; tested at RT). Furthermore, Dai et al. [12] reported results of irradiated ultimate tensile strength for F82H (IEA Heat 974) irradiated between 90 ^oC and 375 ^oC up to 12 dpa using spallation neutrons in the SINQ Target Irradiation Program (STIP-I). To correlate effects of neutron damage on the UTS of F82H, we developed an equation similar to irradiated yield strength (Eq. 12):

$$S_{u(irr)}(\text{dpa}, T) = S_{u(av,unirr)}(1 + 0.02 \times \varphi + 0.13\varphi^{0.5}) \quad (14)$$

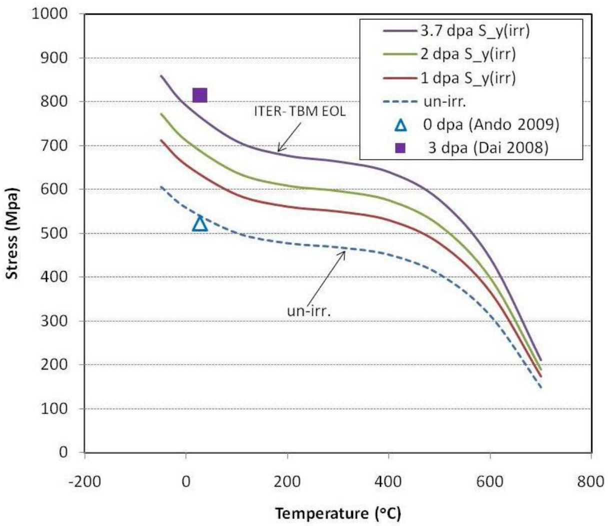

Fig. 2: Average and irradiated yield strength of F82H (IAE Heats 9741, 9753) as a function of temperature based on correlations given by Eqs. 11 and 12 (Dai 2008: 3 dpa at T_{irr} = 85 –100 ^{o}C and 180 He-appm).

where φ is damage in dpa and the strength is in MPa. UTS as a function of temperature is shown in Fig. 3.

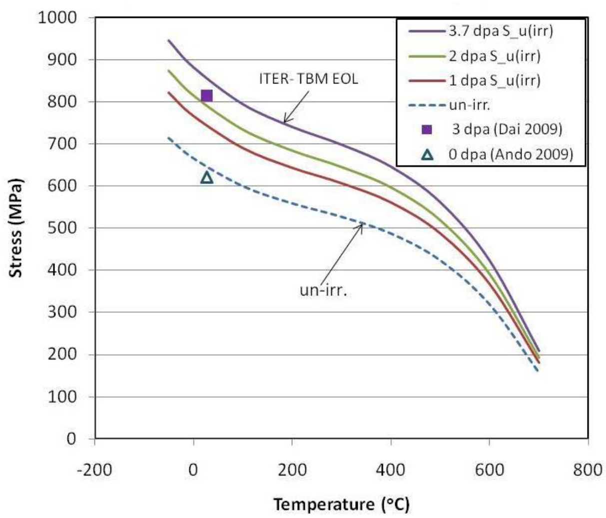

Fig. 3: Irradiated ultimate tensile ($S_{u(irr)}$) strength of F82H (IAE Heats 9741, 9753) as a function of temperature based on the correlation given by Eq. 14 (Ref. 11,12) : 3 dpa at T_{irr} = 85 – 100 ^{o}C and 180 He-appm).

Based on the irradiated strength correlations for $S_{y(irr)}$ and $S_{u(irr)}$ expressions for the allowable primary membrane stress intensity (S_m), allowable primary plus secondary membrane stress intensity (S_e), and allowable total stress intensity (S_d) can be evaluated as a function of temperature and neutron irradiation damage.

To evaluate the TBM structure response to a postulated surface flaw following neutron damage, it is necessary to have correlations that relate K_{IC} to neutron damage and corresponding irradiation temperature (T_{irr}), the operating temperature (T), the shift in ductile to brittle transition temperature (DBTT), and the width of the temperature transition region between the upper and lower shelf energies (ΔT_{trans}). We developed a complex relationship of the fracture toughness on the aforementioned variables and irradiation induced damage by a correlation for $K_{IC(irr)}$, the result of which is shown in Fig.4.

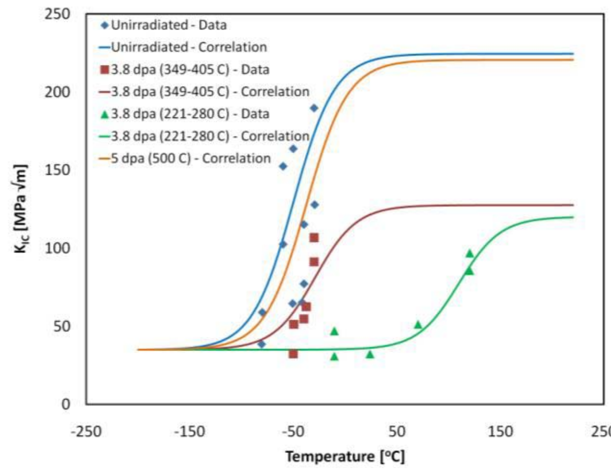

Fig. 4: The $\mathbf{K_{IC(irr)}}$ correlation based on experimental conditions listed in reference [13].

VI. APPLICATION OF SDC-IC DESIGN RULES

Prior to applying the design rules, a detailed structural analysis of the most recent DCLL TBM design including FW cooling channels, internal helium-cooled support structures and top and bottom lids, helium- and PbLi supply and return manifolds, and flexible joints was performed and are presented in these proceedings [14]. The cited thermo-mechanical analysis only serves as a "design screening" and thus we use a simple elastic analysis, with 8 node-brick elements, flexible joints, and simulating steady-state normal TBM operating conditions.

VI.A. Path Average Stresses

In order to determine the stress across critical 'paths' through the TBM structure, first we identified 13 path. Figure 5 shows the location of 6 of the 13 paths we chose for applying the SDC-IC rules.

In selecting the paths we identified locations of highest stress and highest- as well as lowest temperatures throughout the TBM structure. Average temperatures along each of the 13 paths were determined, and using the property correlations outlined in Section III, the following stress along the paths were calculated for non-irradiated $S_{y,av}$, $S_{y,min}$, $S_{u,av}$, $S_{u,min}$, $S_{m,min}$, $S_{d,min}$, $S_{r,av}$, $S_{r,min}$, $S_{t,av}$, $S_{t,min}$, and for irradiated $S_{y,irr}$, $S_{u,irr}$, $S_{m,irr}$, $S_{d,irr}$ conditions. Table 2 shows sample results for all 13 paths.

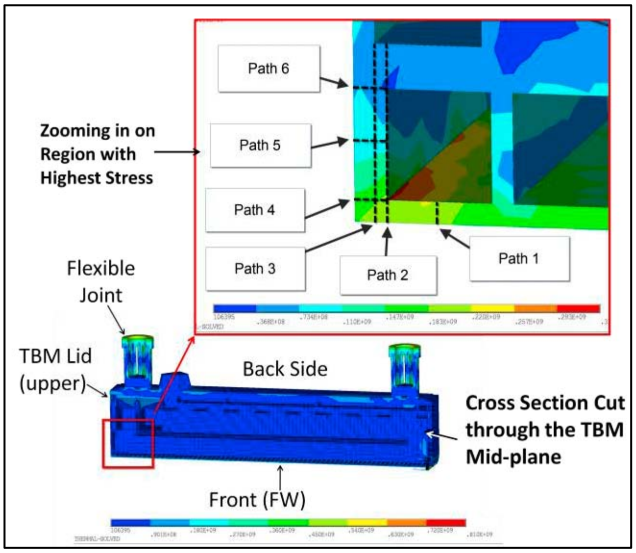

Fig. 5: Cross sectional view of the DCLL TBM, showing stress contours; the inset shows a blowup view of the upper TBM corner flow channel and chosen paths (dotted lines) with high stress along the edge inside a FW coolant channel and the upper TBM lid [14] [note: print copy is b&w, but color online].

VI.B. Path Applied Design Criteria Results

Following the ITER Design Criteria, stresses along the 13 chosen paths were extracted from the ANSYS FEA solutions. Linearized uniaxial stresses were extracted from the multiaxial FEM stresses and processed according to the ITER design criteria and compared to material property data for F82H steel for the unirradiated, and 3.7 dpa irradiated cases[14]. Matlab and Excel were used to linearize all required stress components, and to calculate the stress expressions required for failure evaluation via the design criteria. When stress intensity values were necessary, both the Tesca and Von Mises equivalent stress methods are used. All design rules listed in TABLE 1 were applied to each of the 13 paths for both un-irradiated and irradiated operating conditions.

Table 3 shows an example of results using 3.7 dpa irradiated F82H properties applied to the Necking and Plastic Instability Limit - Primary membrane stress (immediate plastic collapse & plastic instability). As expected the factor of safety (FoS) using Tesca was somewhat smaller than for using Von Mises.

VI.C. Factor of Safety

The 12 SDC-IC design criteria were applied to all 13 paths and the factor of safety (FoS, ratio of LHS versus RHS of expressions in Table 1) using irradiated and un-irradiated material properties were determined. Table 4 compares the FoSs for irradiated and un-irradiated materials, showing the lowest FoS for each of the 12 SCD-IC criteria and the associated path.

TABLE 2: Path Average Temperatures and Stresses

Path	Average T [°C]	$S_{y,irr}$ [MPa]	$S_{u,irr}$ [MPa]	$S_{m,irr}$ [MPa]	$S_{d,irr}$ [MPa]
1	452.62	582.07	616.05	205.35	410.70
2	456.62	579.60	612.57	204.19	408.38
3	461.60	576.41	608.15	202.72	405.43
4	522.25	525.47	544.16	181.39	362.77
5	447.42	585.16	620.47	206.82	413.64
6	430.63	594.20	633.93	211.31	422.62
7	439.40	589.65	627.04	209.01	418.03
8	413.18	602.21	646.75	215.58	431.17
9	413.22	602.20	646.73	215.58	431.15
10	451.50	582.75	617.01	205.67	411.34
11	392.14	610.20	660.79	220.26	440.53
12	391.30	610.49	661.32	220.44	440.88
13	374.45	615.69	671.52	223.84	447.68

TABLE 3: Path Average Primary Membrane Stress

$\overline{P_m} \leq S_m(T_m, \phi t_m)$				
Path	$\overline{P_m}$ [MPa]		Factor of Safety	
	Tesca	Von Mises	Tesca	Von Mises
1	31.66	27.42	6.49	7.49
2	19.15	18.11	10.66	11.28
3	20.69	18.74	9.80	10.82
4	27.00	23.73	6.72	7.64
5	24.49	21.36	8.45	9.68
6	17.12	16.01	12.34	13.20
7	52.67	47.40	3.97	4.41
8	19.20	17.68	11.23	12.19
9	19.31	17.74	11.16	12.15
10	29.42	27.74	6.99	7.41
11	40.48	37.14	5.44	5.93
12	6.87	6.29	32.11	35.03
13	38.25	37.42	5.85	5.98

VII. SUMMARY AND CONCLUSIONS

Table 4 lists the lowest factor of safeties (FoSs) along the 13 paths through the DCLL TBM structure for Beginning of Life (BOL) and EOL (3.7 dpa). Based on these results, the only design criteria that is not met is the ‘primary plus secondary membrane stress, or immediate plastic flow localization’, which occurs along Path-1 with BOL material properties (FoS = 0.71). Path-1 is across the upper corner of the DCLL TBM structure near the FW facing the plasma (Fig. 5). It is interesting to note that following irradiation the material hardens sufficiently to prevent immediate local plastic flow. The current elastic FEM analysis of the TBM [14] serves the purpose of design screening and either the DCLL TBM structural design near the upper lid has to be modified, or an elastic-plastic analysis needs to be performed to show that secondary stress relaxation due to plastic deformation can result in reliable TBM performance.

TABLE 4: Minimum Factor of Safety for 12 SDC-IC Design Criteria along 13 Paths across the TBM Structure

Design Criteria	Irradiated		Non- Irr.	
	FOS	Path	FOS	Path
$\overline{P_m} \le S_m(T_m,\phi t_m)$	3.97	7	2.77	7
$\overline{P_L + P_b} \le K_{eff} S_m(T_m,\phi t_m)$	4.34	7	3.03	7
$\overline{P_L} \le \min\left[1.5 S_m(T_m,\phi t_m), S_{y,min}(T_m,\phi t_m)\right]$	5.95	7	4.16	7
$\overline{P_L} \le 1.1 S_m(T_m,\phi t_m)$	4.37	7	3.05	7
$\overline{P_L + Q_L} \le S_e(T_m,\phi t_m)$	1.02	1	0.71	1
$\overline{P_L + P_b + Q + F} \le S_d(T,\phi t,r_2)$	1.86	4	1.3	4
$\overline{P_L + P_b + Q} \le S_d(T,\phi t,r_3)$	1.9	4	1.33	4
$P_L + P_b \le KS_m$*	4.46	8	3.12	8
$P_L + {P_b}/{K_t} \le S_t$	3.57	10	3.57	10
$X \cdot Y \le 1 \;\; for \;\; 0 \le X \le 0.5$	33.12	7	14.94	7
$\frac{Y}{4(1-X)} \le 1 \;\; for \; 0.5 \le X \le 1.0$	8.99	1	5.87	1
$X + Y \le 1$	2.1	1	1.41	1

*This is the usual ASME limit (no embrittlement) for combination of primary & membrane bending stress, and K is the bending shape factor.

ACKNOWLEDGMENTS

This work is supported by the U.S. Department of Energy, Office of Fusion Energy Sciences through grant #DE-FG02-03ER54708 with UCLA.

REFERENCES

1. C.P.C. WONG, et al., “An overview of the US DCLL ITER-TBM program,” Fus. Engr. Des., **85** (2010) 1129-1132
2. N.B. MORLEY, et al., “Recent research and development for the dual-coolant blanket concept in the US,” Fus. Engr. Des., **83** [7-9] (2008) 920-927
3. Structural Design Criteria for ITER In-vessel Components (SDC-IC), ITER Document G 74 MA 8 R0.1, July 2004.
4. ASME Boiler and Pressure Vessel Code, Section III, Division 1: - Rules for Construction of Nuclear Facility Components, Subsections NB and NH, Edition July, 1995.
5. RCC-MR, Design and Construction Rules for Mechanical Components of FBR Nuclear Islands, Section I, SubsectionB: Class1 components, Ed 1985.
6. ITER structural design criteria for in-vessel components, ITER IDoMS S74MA1 97-12-12 R0.2, Appendix A IDoMS G74MA2 98-06-26 F1, 1998.
7. SDC-IC, Appendix A Materials Design Limit Data, ITER, G 74 MA 8 R01, July 2004
8. A.F. TAVASSOLI, J.W. RENSMAN, M. SCHIRRA, K. SHIBA, “Materials design data for reduced activation martensitic steel type F82H,” Fusion Engineering and Design **61-62** (2002) 617-628
9. F. TAVASSOLI, et al., J. Nucl. Mater. 329–333 (2004) 257–262
10. K. SHIBA, et al., “Properties of Low Activation Ferritic Steel F82H IEA Heat,” JAERI-Tech 97-038, JAERI, 1997.
11. M. ANDO, H. TANIGAWA, E. WAKAI, R.E. STOLLER, “Effect of two-steps heat treatments on irradiation hardening in F82H irradiated at 573 K, ” J. Nucl. Mater. 386–388 (2009) 315–318
12. Y. DAI, B. LONG, Z.F. TONG, “Tensile properties of ferritic/martensitic steels irradiated in STIP-I,” J. Nucl. Mater. 377 (2008) 115–121
13. R.L. KLUEH, et al., “Embrittlement of reduced-activation ferritic/martensitic steels irradiated in HFIR at 300°C and 400°C,” J. Nucl. Mater. 283-287 (2000) 478-482.
14. A. T. AOYAMA, S. SHARAFAT, N. GHONIEM, M. DAGHER, C.P.C. WONG, “Thermo-mechanical Analysis of the Revised U.S. ITER DCLL Test Blanket Module,” in ANS 19th Topical Meeting of Fusion Energy (TOFE), Las Vegas, NV., U.S.A. Nov. 7 – 11, 2010; these proceedings.