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FIRST WALL AND DIVERTOR PERFORMANCE AND LIFETIME ANALYSIS
FOR THE U.S. ITER DESIGN*

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FIRST WALL AND DIVERTOR PERFORMANCE AND LIFETIME ANALYSIS
FOR THE U.S. ITER DESIGN*

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ABSTRACT

The performance of the ITER first wall and divertor have been analyzed using the Fusion Lifetime Prediction (FLIP) code. The code is a one-dimensional finite difference code which calculates the changes in properties, stress, strain, and temperature overtime for plate structures. The results indicate that the first wall should be able to accommodate up to -0.6 MW/m^2 heat flux for the reference operating conditions. At much higher levels, fatigue and cracking are predicted to lead to rapid failure. The loss of ductility in irradiated austenitic stainless steel at low temperatures is a concern which may limit operating life. The results of the divertor analysis show that a bare, 2 mm thick plate of Nb-12r or TZM can accommodate fluxes of 15-20 MW/m^2 for the ITER conditions. Duplex structures composed of 2 mm of tungsten on 2mm of Nb-12r or TZM are limited to 8-10 MW/m^2 .

I. GENERAL CONSIDERATIONS

The ITER first wall and divertor collector plates have been examined with the FLIP computer code.¹ The code first calculates the temperature, stress, and strain distribution through a plate based upon the selected operating and design parameters. Property changes are then determined for a specific time increment, and the effects of those changes on the initial distributions are evaluated. This process is repeated until failure occurs or the desired lifetime is reached.

For the first wall, the code has been modified to model a plate constrained by a back plate which is closer to the geometry expected for the first wall. The plate configuration is illustrated in Fig. 1. The entire structure is allowed to expand but not bend. The program considers a 1-D plate analysis through the top plate and back plate, and the back plate is considered a single element

at a uniform temperature in the analysis. The code has the flexibility to vary the thickness of the top plate and the back plate, the heat flux to the top plate and the temperature of the back plate. A thin back plate with respect to the top plate results in a minimum constraint whereas, a very thick back plate results in essentially total constraint from expansion for the top plate.

Program considers 1-D plate analysis through section A-A including constraint from back plate adjacent to blanket.

Figure 1. First Wall geometry & constraint.

The basic inputs to the code are the operating and design parameters. The design parameters include component material(s) selection, plate thickness, coolant characteristics, primary stress level, initial crack length, and plate constraint. The operating parameters include the burn cycle characteristics (ramp time, burn time, dwell time), and down period duration and frequency, surface heat flux, neutron wall loading, and surface erosion rate. Finally, the failure criteria for swelling, deformation, and ductility are also provided.

Either a single or dual material plate can be analyzed by the code. The dual material plate is representative of impurity control components which are likely to have a low-Z or high-Z material bonded to a structural material. The materials properties which are considered are the thermophysical, mechanical,

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swelling, and neutronic properties. Temperature is the primary parameter considered for the thermophysical properties. Radiation effects are also considered in the cases of the thermal conductivity and the elastic modulus. The mechanical properties considered are the tensile, crack growth, fatigue, and creep properties. A bi-linear, elastic-plastic behavior is assumed for the tensile properties. Temperature, stress, fluence, flux, stress and strain ranges, and stress intensity are the parameters included in determining the mechanical behavior. Radiation swelling is dependent on the temperature and fluence, and the neutronic properties depend on the neutron flux and fluence.

Since there is no precedent for components operating under these conditions, procedures for designing and analyzing the first wall and divertor plate are still in the process of being developed. In particular, it is not clear what safety factors in the materials performance should be employed for the lifetime assessment. The ASME code has been used in the past as a guide for engineering design, but the safety factors built into the ASME code are generally conservative, and such conservatism could severely limit the predicted performance of ITER components. For the cases considered in this paper, no safety factors have been included in the materials data. Safety factors can easily be incorporated into the analyses when they are established, however.

The operating conditions for the first wall are given in Table 1. The primary variables are the surface heat flux, ranging from 0.1 to 1.0 MW/m² and the starter crack length, ranging from 0.1 mm to 1.0 mm. The burn cycle times and number of cycles are taken from Ref. 1. During the physics phase the burn length is 400 S, and it is 2300 S during the technology phase.

The conditions used for the analyses of the divertor plates are shown in Table 2 for bare structural materials and for duplex structures. The heat flux for bare structures was analyzed up to 25 MW/m², while it was limited to 11 MW/m² for duplex structures. The total integrated fluence is 1.0 MW-y/m².

II. FIRST WALL RESULTS

The temperature distributions for surface heat fluxes from 0.1 to 1.0 MW/m² are shown in Fig. 2. The peak surface temperatures range from -355 K to -570 K.

An illustration of the behavior of the first wall is presented in Fig. 3 for a heat flux level of 0.2 MW/m². At the start of operation the top surface is under a compressive stress and the back plate will operate

under a tensile stress. During the dwell or down period, the stress is virtually at a zero stress through the entire plate. Note that the stress distribution during the burn is approximately linear, which reflects purely elastic deformation. The influence of radiation creep during the burn will tend to relax the stresses towards zero. When the stresses reach zero during the burn, they will be highly tensile at the top surface during the dwell. This shift in stress will then influence the fatigue and crack growth behaviors which depend on the magnitude and sign of the stresses.

Table 1

Parameter	Value	
	Physics	Technology
Geometry	Flat top plate constrained by a flat back plate	
Top plate	4 mm SA 316 SS	
Back plate	4 mm SA 316 SS	
Overall constraint	Allowed to expand but not bend	
Surface heat flux	0.1, 0.2, 0.4, 0.6, 0.8, 1.0 MW/m ²	
Neutron flux	1.0 MW/m ²	0.8 MW/m ²
Burn time	400 s	2300 s
# of cycles	5,000	17,500
Integrated neutron fluence	.06 MW-y/m ²	1.0 MW-y/m ²
Coolant temp.	60°C	
Heat transfer coefficient	20,000 W/m ² K	
Fatigue/crack growth safety factor	none	
Starter crack length	0.1, 0.2, 0.4, 1.0 mm	
Effective heat flux from blanket	0.3 MW/m ²	

Neutron irradiation will also increase the yield stress and reduce the ductility as shown in Fig. 4. Over the ITER operation, the

yield stress will increase to a level of ~720 MPa, and the ductility will decrease to below 1%. The loss of ductility is a concern, particularly towards the end of the technology phase, because of the potential for a catastrophic failure. This loss of ductility raises the issue of whether it is possible to operate ITER up to a level of 3 MW-y/m².

Table 2.
Parameters Used for Divertor Analyses

Parameters	Value Condition	
	Duplex Structures	Bare Structures
Geometry	flat plate	flat plate
Plate Thickness	4 mm (2 mm plasma side material & 2 mm structural material)	2 mm
Constraints	free to expand but not bend total constraint	
Surface Heat Flux	11.7 MW/m ²	5, 10, 15, 20, 25 MW/m ²
Neutron Flux	0.5 MW/m ²	0.5 MW/m ²
Integrated Neutron Fluence	1.0 MW-y/m ²	1.0 MW-y/m ²
Burn Time	1200 s	1200 s
Number of Cycles	50,000	50,000
Coolant Temperature	100°C	100°C
Heat Transfer Coefficient	40,000 W/m ² K	40,000
Fatigue Safety Factor	non	none
Plasma Side Materials	W, Ta-10 W	-----
Structural Materials	TZM, Nb-12r dispersion strengthened copper	

The life limiting phenomena for the first wall operation will likely be by fatigue and crack growth. The overall effects of crack

growth on the life of the first wall are summarized in Fig. 5. The two curves shown are for assumptions of no heat flux from the blanket side and for an equivalent of 0.3 MW/m² from the blanket side. Since the first wall is integral with the blanket, the back plate side will experience an effective heat flux from the high temperature multiplier. The level of effective heat flux has been estimated to be 0.3 MW/m².³ For 0.3 MW/m², the average temperature of the back plate is estimated to be ~375 K rather than the coolant temperature of 323 K. For a 1 mm starter crack, the heat flux limit is predicted to be ~0.6 MW/m² without considering the effective heat flux from the blanket, and the limit is 0.8 MW/m² when the effective heat flux from the blanket is considered. With shorter starter cracks, the allowable heat flux will increase. If the starter crack length can be kept below 0.2 mm, a heat flux limit of ~1.0 MW/m² is predicted.

Figure 2. First wall temperature distribution - SA 316 SS.

Figure 3. Burn stress through first wall - 0.2 MW/m² - SA 316 SS.

Figure 4. Uniform elongation through first wall- .2MW/m² - SA 316 SS.

Figure 5. Maximum allowable starter crack lengths ITER first wall- 4 mm thick and 4 mm back plate.

III. DIVERTOR PLATE RESULTS

Surface heat flux limits, based upon fatigue damage limits, have been calculated for several potential divertor plate structural materials. The stress and strain distribution determined with the FLIP code are used as inputs to calculate the level of fatigue damage. Fatigue damage accumulation is calculated using a simple linear damage summation law

$$\text{Fatigue damage} = \sum_{i=1}^t \frac{n_i}{N_{fi}}$$

where n_i is the number of cycles for the i th time interval and N_{fi} is the calculated cycles to failure for the i th time interval. Fatigue cracking is assumed to occur when the sum from the above equation exceeds unity.

As an example of the stress distribution over time, the burn stress for a 2 mm, Nb-12r plate at 15 MW/m² is shown in Fig. 6. This stress distribution yields a level of fatigue damage accumulation shown in Fig. 7. The predicted limits for several materials is shown in Table 3. Only the vanadium alloy has a limit clearly below the reference level of ITER (~15 MW/m²).

Figure 6. Burn stress- NB-12r - 2 mm - 15 MW/m² allowed to expand but not bend.

Figure 7. Fatigue damage- Nb-12r - 2 mm - 15 MW/m² - allowed to expand but not bend - no safety factor.

Similar calculations were performed for duplex structures. The stress distribution for 2 mm of tungsten bonded to 2 mm of Nb-12 is illustrated in Fig. 8. Initially during the burn, the stresses on the plasma side are generally compressive, and the stresses in the

Nb-Zr are generally tensile. There is a jump in the stress levels across the interface between the materials which reflects the differences in the material properties. The difference in the stresses across the interface is also dependent on the fabrication process, e.g., the stress free temperature or lock-up temperature for bonding. In this case, the stress free temperature is assumed to be 750 K. Different fabrication processes can therefore have an influence on performance and lifetime.

Table 3.
Predicted Surface Heat Flux Limits for the
Divertor Plate Structural Materials

Material	Heat Flux Limit Expand but not Bend
Nb-1Zr	17-18 MW/m ²
Dispersion Strengthened Copper	~14 MW/m ²
V-15Cr-5Ti	~7 MW/m ²
TZM	~20 MW/m ²
Ta-10 W	~23 MW/m ²

Figure 8. Burn stress - W/Nb-1Zr - 11 MW/m²,
750k sft. Expand but not bend.

The stresses tend to decrease over time with radiation creep relaxation. The stresses in the tungsten remain within the elastic regime, but the front and back surfaces of the Nb-1Zr are predicted to plastically deform due

to a relatively low initial strength. The stresses in the tungsten during the dwell period remain compressive largely as a result of the higher swelling in the tungsten. For these conditions, the level of fatigue damage is predicted to remain at an acceptable level. In the case of duplex structures, however, the level of fatigue damage could become significant at the interface. This is in contrast to the results with a single material where the rate of fatigue damage is always greatest at the plasma side or coolant surface.

When the effects of total constraint are considered, the allowable heat flux is predicted to be reduced. At 11 MW/m², fatigue cracking is predicted at an early stage. At 7 MW/m², the stresses are reduced, but fatigue cracking at the surface of the tungsten and at the interface is still predicted. The basic conclusion of the analysis of W on Nb-1Zr is that the constraint of the plate is crucial to the level of heat flux that can be accommodated. For ITER conditions the allowable level is ~12 MW/m² when the plate is allowed to expand but not bend, but it is only ~6 MW/m², when the plate is totally constrained.

Other duplex structures, consisting of 2 mm of tungsten bonded to either TZM or dispersion strengthened copper have also been analyzed. For the case of W on TZM where the plate is allowed to expand, the plate behavior is similar to that of W on Nb-1Zr. The major difference is that the initial stresses in TZM do not exceed the yield stress and they are higher than in Nb-1Zr because of the high tensile strength of TZM. However, the level of fatigue damage also remains acceptable for TZM. For total constraint at 11 MW/m², the level of fatigue damage exceeds unity, and thus fatigue cracks are predicted in both the W and TZM.

In contrast to the refractory alloys, the fatigue performance of dispersion strengthened copper is rather poor. For the case of a plate allowed to expand but not bend at 11 MW/m², the copper is predicted to fail rather quickly.

A tantalum alloy, Ta-10W, was also considered as a plasma side material because it is expected to have similar sputtering properties compared with pure tungsten, but is has superior fabrication capabilities. The behavior of Ta-10W on Nb-1Zr is similar to that of tungsten for a plate that is allowed to expand but not bend. When the plate is totally constrained, the fatigue damage is predicted to be lower than the same case using tungsten. It is concluded, therefore, that tantalum alloys could be considered as alternates to pure tungsten from the thermomechanical viewpoint.

IV: CONCLUSIONS

A. First Wall

Solution annealed 316 SS has been analyzed for the ITER first wall. The results indicate that thermal stresses will exceed the yield stress at a level of $\sim 0.3 \text{ MW/m}^2$. Since the peak heat flux limits of ITER are estimated to be 0.6 MW/m^2 , part of the first wall will be operating in the plastic regime. Radiation damage will act to increase the strength and decrease the ductility of the steel. There is a concern that the rapid decrease in ductility predicted in the technology phase could limit the operating lifetime of the first wall. Lifetime limits based upon fatigue and crack growth were also evaluated. The results indicate an upper limit of $\sim 0.6 \text{ MW/m}^2$ in order to operate through the technology phase to a fluence of 1 MW-y/m^2 . Different burn cycle scenarios would be expected to alter these limits, e.g., fewer cycles with longer burn times would tend to increase the lifetimes.

B. Divertor Plate

A general comparison of structural materials for the technology phase indicates refractory metals have comparable capabilities to copper alloys. In some cases, refractory metals have superior performance over copper alloys. Of the alloys analyzed, three systems, Nb-12Zr, TZM, and Ta-10W, have similar capabilities for accommodating high heat fluxes. The selection of a primary candidate alloy will likely be determined by capabilities in other areas such as fabrication, activation/afterheat, radiation embrittlement, and hydrogen permeation/embrittlement. Based on a wide variety of considerations, Nb-12Zr is recommended as the lead option for the divertor structural material. Ta-10W has a high level of activation which restricts its use, and TZM has been shown to be severely embrittled by neutron irradiation.

High-Z materials are favored as the plasma facing materials during the technology phase because of the reduced level of sputtering erosion. The present analyses indicate that either pure W or Ta-10W perform well structurally, but pure W is recommended primarily because of the activation with Ta-10W.

The heat flux limits for the technology phase based upon fatigue damage considerations indicate that the materials will be pushed to their performance limits. For a thin plate, 2 mm thick, the heat flux limits are estimated to be $15\text{-}20 \text{ MW/m}^2$ when the plate is allowed to expand but not bend and when no safety factors are included for fatigue. These limits could be reduced by a factor of two when additional stress constraints and safety factors are

imposed. For duplex structures, the maximum allowable heat flux is estimated to be $10\text{-}12 \text{ MW/m}^2$ for a plate that is allowed to expand but not bend without fatigue safety factors. Again, this limit is likely to be reduced when additional stress constraints and safety factors are imposed. For duplex structures, the maximum allowable heat flux is estimated to be $10\text{-}12 \text{ MW/m}^2$ for a plate that is allowed to expand but not bend and without fatigue safety factors. Again, this limit is likely to be reduced when additional stress constraints and safety factors are imposed.

V. A FINAL NOTE

It is important to note that these conclusions are preliminary, and they are based upon rather meager materials data, particularly for the refractory metals. Clearly, an improved materials data base would improve the validity of performance analyses. Specific data which are desirable include radiation creep behavior, fatigue behavior with and without neutron damage, tensile properties with neutron damage, and swelling behavior. There is also a need for information on the interactions between properties, e.g., the effect of stress on swelling, and the relationship between radiation creep and swelling. The other major area where work is needed is modelling development. Specific items that need to be explored are the modelling of fatigue damage and crack growth. In addition there is a need to couple the materials behavior with 2-D and 3-D finite element in their capabilities and to include complex materials behavior, particularly radiation damage behavior.

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