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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439-4801

INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER) DIVERTOR
PLATE PERFORMANCE AND LIFETIME CONSIDERATIONS

by

R.F. Mattas

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**INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER) DIVERTOR
PLATE PERFORMANCE AND LIFETIME CONSIDERATIONS**

Richard F. Mattas

ABSTRACT

The ITER divertor plate performance during the technology phase of operation has been analyzed. High-Z materials, such as tungsten and tantalum, have been considered as plasma side materials, and refractory metal alloys, Ta-10W, TZM, Nb-12Zr, and V-15Cr-5Ti, plus copper alloys have been considered as the structural materials. The fatigue lifetime have been predicted for structural plates and for duplex plates with the plasma side material bonded to the structure. The results indicate that refractory alloys have a comparable or improved performance to copper alloys. Peak allowable heat fluxes for these analyses are in the range of 15-20 MW/m² for 2 mm thick structural plates and 7-11 MW/m² for 4 mm thick duplex plates.

1.0 INTRODUCTION

1.1 General Consideration

Extended operation of the divertor plate represents a critical area for ITER operation, particularly in the technology phase with long burn times and increased availability. The severe operating conditions in the divertor mean that materials will be pushed to their limits to meet design objectives. At this time, it is by no means obvious that a suitable combination of materials and plate design exists to satisfy all these objectives. The purpose of this section is to assess the capability of candidate materials for the divertor and to determine approximate operating limits for the divertor in the technology phase.

The nominal operating conditions at the divertor plate are presented in Table 1-1. The combination of high heat loads, radiation damage, and surface erosion make it extremely difficult to operate for extended periods. The plasma edge conditions also place constraints on the choice of surface material. High-Z materials, e.g., tungsten, are favored at low edge temperatures, below ~75 eV [1], because of their low sputtering erosion rates, whereas low-Z materials are favored at higher edge temperatures where high-Z materials exceed a self-sputtering coefficient of unity. The impact of impurities in the plasma on radiation losses also favors low-Z materials. Unfortunately, the candidate low-Z and high-Z materials, such as C, Be, W, and Ta, are not considered to be suitable structural materials, so that duplex structures, consisting of a plasma side material bonded to a structural material, are usually considered for divertor plate designs.

Table 1-1. Operating Conditions for the ITER Divertor Plate [2]

Parameter	Physics Phase	Technology Phase
Peak Heat Flux (no safety factor)	10 MW/m ²	11 MW/m ²
Neutron Wall Load	0.7 MW/m ²	0.5 MW/m ²
Total Neutron Fluence	0.05 MW-y/m ²	1.0 M-y/m ²
Burn Time	200 s	1200 s
Number of Burn Cycles	7,000	50,000
Peak Plasma Temperature	50 eV	50 eV

Considering the severe conditions and the numerous choices for candidate materials and plate designs, it is a formidable task to find an optimum solution. Since there is no precedent for components operating under these conditions, procedures for designing and analyzing divertor plates are still in the process of being developed. In particular, there are no established design criteria for fusion components. Existing design codes, such as the ASME Boiler and Pressure Vessel Code, have been developed for components that are expected to last for a 30 year design life whereas the design life of the ITER divertor is anticipated to be approximately one year. In addition, the potential for irradiation degradation of material properties, the inherently pulsed nature of ITER operation, and the unique problems associated with plasma disruptions mean that existing design codes cannot be directly applied to ITER in-vessel components [3]. The safety factors built into the ASME code are necessarily conservative, and such conservatism could severely limit the predicted performance of ITER components. Less conservative safety factors are probably warranted in many cases, but appropriate factors for ITER design have yet to be established. For the cases considered in this section, no safety factors have been included. Safety factors can be easily incorporated into the analyses when they are established, however.

1.2 Overview of Analysis Procedures

The materials properties of both plasma side materials and divertor structural materials have been collected and then used as input for divertor plate stress and lifetime analyses.

The ITER first wall and divertor collector plates have been examined with the FLIP computer code [4]. 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.

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, 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.

A simple thermal-hydraulics subroutine calculates the temperature distribution through the plate during the burn cycle. The temperature distribution is then used to calculate the thermal strain distribution, which is used as input to calculate the stress distribution. The stresses can be determined for a plate which is either totally constrained from expansion or allowed to expand but not bend. These two conditions span the possible range of component constraint in the reactor.

Once the temperature, stress, and strain distributions are determined, the long term response of the material to the reactor environment can be evaluated. The code determines the swelling change, creep change, fatigue damage, and crack growth for a time increment Δt . The swelling and creep which occurs during the period Δt results in a modified strain distribution that is used to calculate the changes in the stresses. The code also determines the amount of surface erosion during the time increment. The reduction in plate thickness results in a modified temperature distribution. The property change calculations are then repeated using the modified distributions until either the failure criteria are met or the component reaches the goal lifetime. For calculational purposes, the temperature and

stresses are assumed to remain constant during the time increment. Therefore, Δt must be chosen such that the stress change is small compared with the total stresses in order for this approach to reasonably approximate in reactor behavior.

2.0 MATERIALS PROPERTIES

2.1 Selection Criteria

2.1.1 Structural Materials

The divertor must be able to withstand high surface heat fluxes under cyclic operating conditions. During the technology phase the influence of neutron irradiation also has a significant impact on divertor performance. In order to successfully survive in this environment, there are a large number of desirable properties for divertor structural materials as shown in Table 2-1. The list of desirable properties over-specifies the problem so that there is no single material which meets all the requirements. For example, high thermal conductivity in materials is usually coupled with high electrical conductivity which is in conflict with the desirable characteristics. Therefore, a compromise must be made in the selection of the divertor structure.

The ability to operate under cyclic conditions involves several properties that interact with each other. The level of thermal stress for a specific heat flux depends upon the thermal expansion coefficient, thermal conductivity, elastic modulus, and Poisson's ratio. Under cyclic loading conditions, fatigue and crack growth behavior are important along with these other properties. In choosing a structural material, it is important to find the material with a combination of desirable properties that best meets the needs for ITER conditions.

The candidate materials considered for the divertor are copper based alloys and refractory metal alloys. The advantages and disadvantages of these alloys are listed in Table 2-2. The copper alloys exhibit the highest thermal conductivity, but they also have the highest thermal expansion. The refractory metal alloys generally have low thermal expansion combined with relatively high thermal conductivities. With the exception of the V-15Cr-5Ti

alloy, all the alloys are considered to be high activation. A comparison of the specific thermophysical and mechanical properties of the candidate alloys are shown in Figs. 2-1 to 2-7. For comparison, the properties of stress relieved tungsten, which is the leading candidate plasma facing material for the technology phase, are also shown.

Table 2-1. Desirable Properties for Divertor Structural Materials

Property	Basis
High Thermal Conductivity	Reduce peak temperature. Reduce thermal gradient and stresses.
Low Thermal Expansion Coefficient	Reduce thermal strains and stresses.
Low Elastic Modulus	Reduce thermal stresses.
Low Electrical Conductivity	Reduce currents and stresses during disruptions.
High Yield Stress & Ultimate Stress	Increase normal and transient stress capacity.
High Ductility	Maximize capability to survive transients that produce plastic deformation.
High Fracture Toughness	Maximize capability to survive transients that produce plastic deformation.
High Melting Point	Increase normal operating and transient temperature window.
Low Radiation Swelling	Minimize dimensional change.
Low Radiation Creep	Minimize dimensional change.
High Resistance to Hydrogen Embrittlement	Minimize effect of D/T implantation and diffusion on mechanical properties.
Coolant Compatibility	Reduce corrosion loss and transport. Reduce stress corrosion cracking.
Good Fabrication Characteristics	Increase potential for fabrication of complex shapes and joining.
Low Impact of Neutron Radiation on Mechanical Properties	Increase long-term capability and lifetime.
Low Afterheat and Activation	Enhanced safety and waste disposal.
High Fatigue Resistance	Increase lifetime for cyclic operation.
Low Crack Growth Rate	Increase lifetime for cyclic operation.

Table 2-2. Structural Material Candidates for the ITER Technology Phase

Alloy	Advantages	Disadvantages
Dispersion Strengthened Copper	High thermal conductivity. Resistance to hydrogen embrittlement. High ductility.	High electrical conductivity. Low melting point. High thermal expansion coefficient. High activation.
Annealed Copper	High thermal conductivity. Resistance to hydrogen embrittlement. High ductility. Good fabricability.	High electrical conductivity. Low melting point. Poor mechanical strength. High thermal expansion coefficient. High activation. High radiation swelling.
TZM (Mo alloy)	Low thermal expansion. High strength. High melting point. Good thermal conductivity.	High elastic modulus. Poor fatigue properties. High activation. Poor fabricability. Low radiation ductility/fracture toughness. High activation.
Nb-12r (Nb alloy)	Low thermal expansion High melting point. Good fabricability. High fatigue resistance. High ductility. Low elastic modulus.	High activation. Poor mechanical strength.
V-15Cr-5Ti	Good fabricability. High ductility. High fatigue resistance. Low activation.	Low thermal conductivity. High thermal expansion.

Figure 2-2. Diverter materials thermal conductivity.

Figure 2-1. Diverter materials thermal expansion.

Figure 2-3. Divertor materials Young's modulus.

Figure 2-4. Divertor materials yield strength.

Figure 2-6. Diverter materials

Figure 2-5. Diverter materials ultimate tensile strength.

Figure 2-7. Divertor materials fatigue.

3.0 RELATIVE PERFORMANCE OF DIVERTOR STRUCTURAL MATERIALS FOR THE ITER TECHNOLOGY PHASE

3.1 Conditions Used for Analyses

The performance of candidate structural materials has been analyzed in order to obtain a relative ranking of their capabilities for ITER. The FLIP code was used to make the calculating and the conditions used for the analyses are shown in Table 3-1. The combined effects of radiation swelling, creep, hardening, and embrittlement are included in the analysis along with the more usual considerations of thermal stress and fatigue damage. The inclusion of radiation effects should provide a more realistic assessment of structural material performance than thermal stress analysis alone. It should be noted that the conditions with no safety factor for fatigue and with a plate allowed to expand but not bent should yield optimistic values for allowable heat flux limits. As stronger mechanical constraints plus safety factors are added, the allowable heat flux will be reduced.

Table 3-1. Parameters Used for Comparison of Structural Materials

Parameter	Value/Condition
Geometry	flat plate
Plate Thickness	2 mm
Constraints	free to expand but not bend total constraint
Surface Heat Flux	5, 10, 15, 20, 25 MW/m ²
Neutron Flux	0.5 MW/m ²
Burn Time	1200 s
Number of Cycles	50,000
Coolant Temperature	100°C
Heat Transfer Coefficient	40,000 W/m ² K
Fatigue Safety Factor	none
Integrated neutron fluence	1 MW-y/m ²

3.2 Results of Structural Analyses

Nb-1Zr

A complete set of graphs showing the changes in properties, swelling and creep behavior, temperature distribution, stress distributions during the burn and dwell periods, and finally the level of fatigue damage presented over the 50,000 cycle lifetime are given in Figs. 3-1 to 3-9 for a surface heat flux level of 15 MW/m². The temperature distribution shown in Fig. 3-1, indicates a peak temperature of ~1250 K at the side facing the plasma which decreases linearly to a temperature of ~725 K at the coolant side. Over the course of the technology phase, the strength of Nb-1Zr will increase and the ductility will decrease as illustrated in Figs. 3-2 to 3-4. The initial yield strength is quite low at ~150 MPa, but it is predicted to increase to 300-350 MPa after 50,000 cycles. The uniform elongation will decrease, but it is predicted to remain in the range of 3-8%.

Dimensional changes that occur over the lifetime are a result of radiation swelling and creep. Figure 3-5 shows that the peak swelling is predicted to remain below 0.5%, and Fig. 3-6 shows that radiation creep will remain below -0.1%.

Even though the dimensional changes are small they can have large effects on the stress distribution, as illustrated in Figs. 3-7 and 3-8 for the stress during the burn and stress during the dwell, respectively. At the beginning of life the stress during the burn will be compressive on the plasma side and tensile on the coolant side. The yield stress is exceeded at both surfaces. The influence of radiation creep is to relax the stresses towards zero over time. In this particular case, however, radiation swelling acts to counteract stress relaxation so that the overall stress distribution during the burn is not predicted to change substantially over the lifetime. The effect of swelling on the stress distribution is more apparent during the dwell cycle, as shown in Fig. 3-8. At the start of life, the stresses are near zero at the center of the plate, but they rise at both surfaces as a result of the yield stress being exceeded during the burn cycle. Over time, an area of compressive stress is produced in response to the radiation swelling. Overall, the peak stresses remain reasonably low during the 50,000 cycle lifetime.

The difference in stresses and strains between the burn cycle and dwell cycle can then be used to predict the fatigue lifetime of the plate. Fatigue damage accumulation is calculated using a simple linear damage summation law.

$$\text{Fatigue damage} = \sum_{i=1}^I \frac{n_i}{N_{f_i}}$$

where n_i is number of cycles for the i th time interval and N_{f_i} 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.

The fatigue damage for Nb-12Zr is presented in Fig. 3-9. As expected, the level of fatigue damage is greatest at either surface because these are the locations that experience the largest stress differences between the burn and dwell cycles. The increase in fatigue damage is not linear with time due to the changes in stress distribution that occur from swelling and creep. In this case, the peak level of fatigue damage is -0.23, and therefore, fatigue cracking is not predicted.

When the surface heat flux is raised to 20 MW/m^2 , fatigue cracking is predicted to occur at both surfaces, as shown in Fig. 3-10. Fatigue damage in the middle of the plate is predicted to remain low. It is not clear from this analysis whether or not the plate has failed. A detailed crack growth analysis is required to see if the fatigue cracks at the surface will propagate to failure. For now, the heat flux limit will be set by the point where fatigue damage reaches unity anywhere in the plate. Thus the heat flux limit for Nb-1Zr is estimated to be $17\text{-}18 \text{ MW/m}^2$.

Fatigue Damage for Other Structural Materials

Similar calculations to those for Nb-1Zr were performed for dispersion strengthened copper, V-15Cr-5Ti, TZM, and Ta-10W alloys. Representative fatigue damage graphs are shown in Figs. 3-11 to 3-14. These graphs represent the heat flux levels where fatigue crack initiation is first predicted. The V-15Cr-5Ti alloy has the lowest allowable heat load at $\sim 7 \text{ MW/m}^2$ due largely to its relatively poor thermal conductivity and high coefficient of thermal expansion. The Ta-10W alloy is predicted to have the highest limit at $\sim 22\text{-}23 \text{ MW/m}^2$. Table 3-2 summarizes the heat load limits for the various alloys.

Table 3-2. Predicted Surface Heat Flux Limits
for the Conditions Given in Table 3-1

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

Figure 3-1. Temperature distribution - Nb-12r - 2mm - 15 MW/m².

Figure 3-2. Yield stress - Nb-12r - 2 mm - 15 MW/m² - burn.

Figure 3-3. Ultimate strength - Nb-12r - 2 mm - 15 MW/m² - burn.

Figure 3-4. Uniform elongation - Nb-12r - 2 mm - 15 MW/m² - burn.

Figure 3-5. Swelling - Nb-1Zr - 2 mm - 15 MW/m².

Figure 3-6. Radiation creep - Nb-1Zr - 2 mm - 15 MW/m².

Figure 3-7. Burn stress - Nb-1Zr - 2 mm - 15 MW/m^2 - burn. Expand but not bend.

Figure 3-8. Dwell stress - Nb-1Zr - 2 mm - 15 MW/m^2 - burn. Expand but not bend.

Figure 3-9. Fatigue damage - Nb-12r - 2 m - 15 MW/m² - burn. Expand but not bend - no safety factor.

Figure 3-10. Nb-12r - 20 MW/m²

Figure 3-11. Fatigue damage - Dis. Str. Cu - 15 MW/m^2 - no safety.

Figure 3-12. Fatigue damage - V - 10 MW/m^2 - no safety.

Figure 3-13. Fatigue damage - TZM 20 MW/m² - no safety.

Figure 3-14. Fatigue damage - Ta-10W - 25 MW/m² - no safety.

4.0 PERFORMANCE OF DUPLEX STRUCTURE

4.1 Conditions Used for Analysis

The complexity of the analysis of duplex structures is increased because of the additional combinations of conditions that need to be considered. There are a large number of possible combinations of plasma side materials and structural materials, and the initial stress state of the duplex structure depends on the temperature and fabrication procedures used for bonding. In order to keep the total number of cases down to a reasonable number, a limited number of conditions were considered, as shown in Table 4-1. These conditions are similar to those used in previous section on structural materials performance. The plasma side materials are high-Z materials since they are expected to exhibit greatly reduced sputtering erosion compared with low-Z materials. The reduced erosion should result in extended lifetimes during the technology phase.

Table 4-1. Nominal Operating Conditions Used for Analyses of Duplex Structure Divertor Plates

Parameter	Value/Condition
Geometry	flat plate
Plate Thickness	4 mm (2 mm plasma side material and 2 mm structural material)
Constraints	Free to expand but not bend total constraint
Surface Heat Flux	11.7 MW/m ²
Neutron Flux	0.5 MW/m ²
Integrated Neutron Fluence	1.0 MW-y/m ²
Burn Time	1200 s
Number of Cycles	50,000
Coolant Temperature	100°C
Heat Transfer Coefficient	40,000 W/m ² K
Fatigue Safety Factor	none
Plasma Side Materials	W, Ta-10 W
Structural Materials	T2M, Nb-1Zr dispersion strengthened copper

4.2 Results of Duplex Structure Analyses

4.2.1 Stress Relieved Tungsten Bonded to Nb-1Zr

A complete series of graphs showing the changes in properties and stresses for a 4 mm thick W/Nb-1Zr plate is given in Figs. 4-1 to 4-10. For this particular case, it has been assumed that the plate is allowed to expand but not bend.

The peak temperature for a heat flux of 11 MW/m^2 is $\sim 1170 \text{ K}$, as shown in Fig. 4-1. The increased temperature gradient towards the coolant (structural) side of the plate reflects the lower thermal conductivity in Nb-1Zr compared with tungsten.

The changes in the tensile properties are shown in Figs. 3-2 to 3-5. The strength of both materials increases with time due to radiation hardening, but the rate of increase is faster in Nb-1Zr because of its low initial strength. Along with the hardening comes a decrease in ductility (Figs. 3-4 and 3-5). The drop-off in uniform elongation is faster in tungsten. During the burn, ductility of both materials is expected to remain at acceptable levels. However, the uniform elongation in tungsten is predicted to reach levels of only $\sim 0.2\%$ during the dwell (Fig. 3-5). Loss of ductility in the plasma side material is not itself a concern for failure, but a brittle plasma side material could crack, and the cracks could then propagate into the structural material. Further analysis is needed to assess crack propagation from the plasma side material to the structure.

The levels of swelling and radiation creep are illustrated in Figs. 3-6 and 3-7. The greatest level of swelling is predicted in the tungsten with an insignificant amount predicted in Nb-1Zr. The peak swelling is only $\sim 0.3\%$. The levels of radiation creep remain below $\sim 0.1\%$ over the 50,000 cycle lifetime.

The resulting stress distributions during the burn and dwell are shown in Figs. 3-8 and 3-9, respectively. Initially during the burn, the stresses in the plasma side material are generally compressive and the stresses in the Nb-1Zr are generally tensile. There is jump in the stress levels across the interface between the materials which reflects the differences in the materials properties. The difference in the stresses across the interface is also dependent on the fabrication procedures, e.g., the stress free

Figure 4-1. Temperature distribution - W/Nb-12r - 11 MW/m².

Figure 4-2. Yield stress during burn - W/Nb-12r - 11 MW/m².

Figure 4-3. Ultimate stress during burn - W/Nb-12r - 11 MW/m^2 .

Figure 4-4. Uniform Elongation during burn - W/Nb-12r - 11 MW/m^2 .

Figure 4-5. Uniform elongation during dwell - W/Nb-12r - 11 MW/m^2 .

Figure 4-6. Radiation creep strain - W/Nb-12r - 11 MW/m^2 . Expand but not bend.

Figure 4-7. Swelling - W/Nb-12r - 11 MW/m^2 .

Figure 4-8. Burn stress - W/Nb-12r - 11 MW/m^2 - 750k sft. Expand but not bend.

Figure 4-9. Dwell stress - W/Nb-12r - 11 MW/m^2 - 750k sft. Expand but not bend.

Figure 4-10. Fatigue damage - W/Nb-12r - 11 MW/m^2 . Expand but not bend. No fatigue safety factor.

temperature or lock up temperature for bonding. In this case, the stress free temperature is assumed to be 750 K. Different fabrication procedures can result in significantly different initial stress distributions and could therefore have an influence on performance and lifetime. Future analyses of duplex structures need to include the effects of fabrication on initial stress distributions.

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, shown in Fig. 3-10, 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 previous section with a single material where the rate of fatigue damage is always greatest at the plasma side or coolant surface.

The effects of total constraint on the plate at 11 MW/m^2 and 7 MW/m^2 on the stresses and fatigue damage are shown in Figs. 4-11 to 4-16. With total constraint at 11 MW/m^2 , the stresses are always compressive during the burn cycle. In this case, both the tungsten and Nb-1Zr are predicted to plastically deform due to thermal stresses. The absolute values of the peak stresses are significantly higher for total constraint of the plate, and these higher stresses result in a significantly higher rate of fatigue damage, as shown in Fig. 4-13. At 11 MW/m^2 , fatigue cracking is predicted at an early stage through the tungsten and partly into the Nb-1Zr. Therefore, a heat flux of 11 MW/m^2 exceeds the allowable limit for these conditions. A heat level of 7 MW/m^2 was also considered to see whether the level of fatigue damage was acceptable. The results shown in Figs. 4-14 to 4-16 indicate an improvement in fatigue damage through the plate, but fatigue cracking is still predicted at the surface of the tungsten and in the Nb-1Zr at the interface.

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 $\sim 12 \text{ MW/m}^2$ when the plate is allowed to expand but not bend, but it is only $\sim 6 \text{ MW/m}^2$, when the plate is totally constrained.

Figure 4-11. Burn stress - W/Nb-12r - 11 MW/m^2 - total constraint 750k sft.

Figure 4-12. Dwell stress - W/Nb-12r - 11 MW/m^2 . Total constraint 750k sft.

Figure 4-13. Fatigue damage - W/Nb-1Zr - 11 MW/m² - 750 k sft. Total constraint. No fatigue safety factor.

Figure 4-14. Burn stress - W/Nb-1Zr - 7 MW/m² - 750k sft. Total constraint.

Figure 4-15. Dwell stress - W/Nb-12r - 7 MW/m^2 - 750k sft. Total constraint.

Figure 4-16. Fatigue damage - W/Nb-12r - 7 MW/m^2 . Total constraint. No fatigue safety factor.

4.2.2 Tungsten on Other Structural Materials

Other duplex structures, consisting of 2 mm of tungsten bonded to either TZM or dispersion strengthened copper have also been analyzed, and the calculated stresses and levels of fatigue damage are illustrated in Figs. 4-17 to 4-25. 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/m^2 , the level of fatigue damage exceeds unity, and thus fatigue cracks are predicted in both the W and TZM (Fig. 4-22).

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/m^2 , the copper is predicted to fail rather quickly.

4.2.3 Ta-10W on Nb-1Zr

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 it has superior fabrication capabilities. As shown in Figs. 4-26 to 4-34, 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 be considered as alternates to pure tungsten.

5.0 CONCLUSIONS

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-1Zr, 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

Figure 4-17. Burn stress - W/T2M - 11 MW/m^2 . Expand but not bend. 750 sft.

Figure 4-18. Dwell stress - W/T2M - 11 MW/m^2 . Expand but not bend. 750 sft.

Figure 4-19. Fatigue damage - $W/T2H - 11 \text{ MW/m}^2$. Expand but not bend. No fatigue safety factor.

Figure 4-20. Burn stress - $W/T2H - 11 \text{ MW/m}^2$. Total constraint - 750 sft.

Figure 4-21. Dwell stress - W/TZM - 11 MW/m^2 . Total constraint 750 sft.

Figure 4-22. Fatigue damage - W/TZM - 11 MW/m^2 . Total constraint. No fatigue safety factor.

Figure 4-23. Burn stress - W/dis Cu - 11 MW/m^2 . Expand but not bend - 700k sft.

Figure 4-24. Dwell stress - W/dis Cu - 11 MW/m^2 . Expand but not bend - 700k sft.

Figure 4-25. Fatigue damage - W/dis Cu - 11 MW/m^2 . Expand but not bend. No fatigue safety factor.

Figure 4-26. Burn stress - Ta-10W/Nb-12r - 11 MW/m^2 . Expand but not bend. 750k sft.

Figure 4-27. Dwell stress - Ta-10W/Nb-12r - 11 MW/m^2 . Expand but not bend. 750k sft.

Figure 4-28. Fatigue damage - Ta-10W/Nb-12r - 11 MW/m^2 . Expand but not bend. No fatigue safety factor.

Figure 4-29. Burn stress - Ta-10W/Nb-1Zr - 11 MW/m^2 . Total constraint - 750k sft.

Figure 4-30. Dwell stress - Ta-10W/Nb-1Zr - 11 MW/m^2 . Total constraint - 750k sft.

Figure 4-31. Fatigue damage - Ta-10W/Nb-12r - 11 MM/m². Total constraint. No fatigue safety factor.

Figure 4-32. Burn stress - Ta-10W/Nb-12r - 7 MM/m². Total constraint - 750k sft.

Figure 4-33. Dwell stress - Ta-10W/Nb-1Zr - 7 MW/m^2 . Total constraint - 750k sft.

Figure 4-34. Fatigue damage - Ta-10W/Nb-1Zr - 7 MW/m^2 . Total constraint. No fatigue safety factor.

permeation/embrittlement. Based on a wide variety of considerations, Nb-12r 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 problem 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 15-20 MW/m² 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 10-12 MW/m² 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. For duplex structures, the maximum allowable heat flux is estimated to be 10-12 MW/m² 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.

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 to include complex materials behavior, particularly radiation damage behavior.

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