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A robust water-cooled divertor target plate solution for DEMO has to date remained elusive. Common to all contemporary concepts is an interlayer at the boundary between the tungsten armour and the cooling structure. In this paper we show by design optimisation that an effectively designed interlayer can produce dramatic gains in power handling. CCFE has proposed a promising target concept termed “Thermal Break”, and associated design studies indicate that an effective interlayer should have a relatively low thermal conductivity and a very low elastic modulus. A design is proposed which passes linear-elastic code rules up to an applied heat flux of 18MW/m^2.

Keywords: DEMO, divertor target, interlayer, design optimization.

1. Introduction

The engineering of the divertor target remains a major challenge in the design of DEMO (a demonstration fusion power reactor). The target structure must survive an environment of extremely high heat fluxes (tens of MW/m^2), intense neutron radiation and aggressive surface sputtering, while also satisfying plant low activation criteria. The European fusion Roadmap foresees a ‘near-term’ DEMO, a long-pulsed device capable of several hundred MW electricity generation with technology based on realistic extrapolation from ITER [1]. In this device low-temperature water is used as the baseline divertor coolant as it can achieve much higher heat transfer rates than a gas-cooled system.

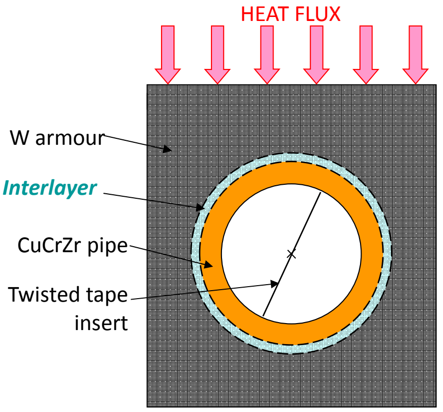

Fig. 1. Generic water-cooled divertor target concept.

Contemporary water-cooled target concepts are based on the ITER design, and comprise a CuCrZr structural pipe surrounded by a tungsten monoblock as the plasma facing material (Figure 1) [2]. CuCrZr suffers softening under irradiation and has a narrow operating temperature window but is thought to be an acceptable material in the low neutron fluence divertor region. Tungsten is considered the most suitable armour material due to its refractory nature, good conductivity and low sputter yield. Between these two materials is an interlayer, which in ITER is pure copper. This interlayer facilitates joining of the parts and is often regarded as a compliance layer. Although it is not seen as a structural component, the interlayer is pivotal to the structural performance of the target. In this paper a new concept termed “Thermal Break” is proposed and it is shown by design search and optimisation that an effectively engineered interlayer can produce dramatic gains in power handling.

2. A Divertor Target with a “Thermal Break”

In a divertor target element as shown in Figure 1, there are three sources of stress in the structural (pipe) material: (1) the internal pressure of the water coolant; (2) the temperature gradient due to the applied heat flux; (3) the difference in thermal expansion between the CuCrZr pipe and the tungsten armour. At low temperature (100-200°C) and pressure the third source of stress, i.e., mismatch in thermal expansion, dominates by more than a factor of ten. It is therefore vitally important that this component of stress is reduced.

If one makes the assumptions of two concentric thin-walled pipes, uniform heat flux on the outer circumference and plane stress, the mismatch stress between the two pipes $\sigma_{mismatch}$ can be expressed as

$$\sigma_{mismatch} = \frac{\alpha_2(T_{2,average} - T_0) - \alpha_1(T_{1,average} - T_0)}{{(1-\nu_2)t_1}/{t_2 E_2} + {(1-\nu_1)}/{E_1}} \qquad (1)$$

where α is the coefficient of thermal expansion, t is wall thickness, T is temperature (average across t, or reference T_0), ν is Poisson’s ratio, E is Young’s modulus and subscripts 1 and 2 denote the two materials in contact. This model illustrates two points. First, if 1 denotes the CuCrZr pipe and 2 denotes the interlayer, the mismatch stress is reduced if the interlayer thickness and elastic modulus (t_2 and E_2) are reduced. This increased compliance is widely adopted and in ITER-like designs is embodied by the soft Cu interlayer.

Second, if 1 denotes CuCrZr and 2 denotes tungsten, then because α_2 (4µε/°C at 150°C) is much lower than α_1 (17µε/°C), the compressive mismatch stress is reduced by increasing the tungsten temperature T_2 while reducing (or limiting) the CuCrZr temperature T_1. This step in temperature or “Thermal Break” between the two

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materials can be realised by using an interlayer with a low thermal conductivity. The principal of using this Thermal Break is illustrated graphically in Figure 2.

The Thermal Break concept is quite unintuitive, since it reduces the overall conductance of power exhausted into the coolant. However, the idea of an interlayer with limited conductance is not new; Li-Puma et al. [2] have in the past proposed a carbide “thermal barrier” interlayer, although the purpose of this was as a “heat flux repartition” layer rather than a direct means of reducing stress in the structure.

The potential benefits of a Thermal Break interlayer are: (1) reduced structural stress brought about by a large temperature rise between the CuCrZr and tungsten; (2) reduced stress if the interlayer is also compliant; (3) more favourable material properties if the Thermal Break is designed such that the CuCrZr and tungsten are operating close to their recommended temperature windows; (4) reduced peak heat flux upon the coolant channel (pipe) as a result of power flowing deeper around the W monoblock, giving a greater margin to critical heat flux (CHF).

In this design study, we vary the interlayer stiffness, thermal expansion coefficient and thermal conductivity as well as geometric variables in an automated design search and optimisation process.

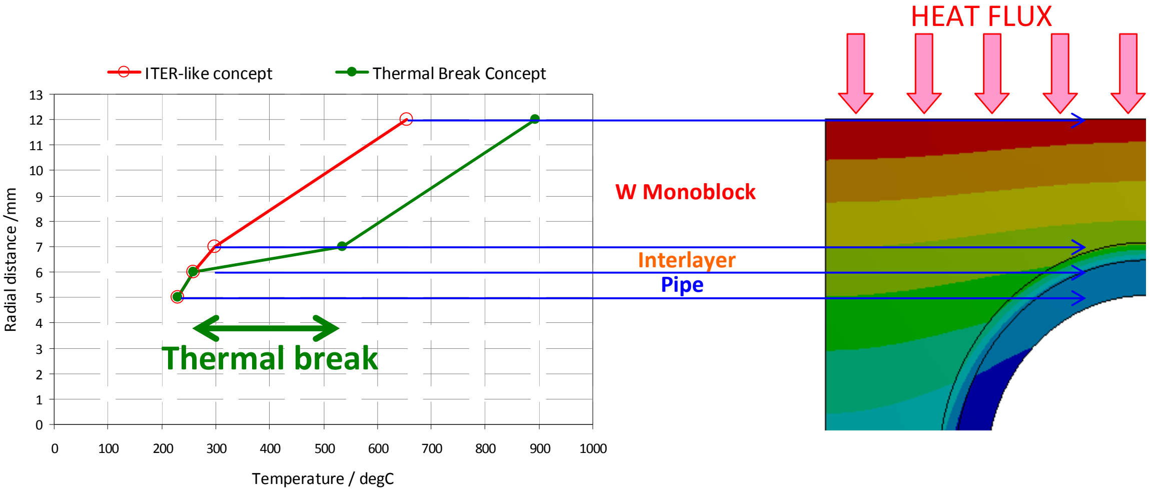


Fig. 2. Illustration of the Thermal Break concept: temperature vs. radial distance vertically through the divertor target.

3. Design Optimisation Procedure

Below is an overview of the computational design search procedure used in this work; for more detail the reader is referred to a report by the Authors [3].

3.1 Finite Element Model

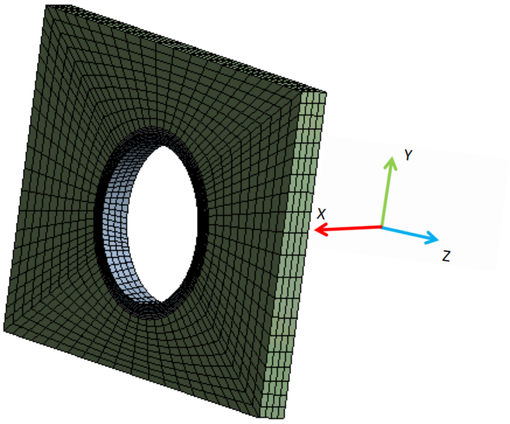


Fig. 3. Finite element model used in the design studies.

The optimisation of designs requires an analysis method to calculate a metric of performance. The divertor target is analysed using a thermo-structural finite element sub-model (Figure 3) of one-half a monoblock with a symmetry plane on the cut (*y*-*z*) plane. Half an inter-monoblock gap is modelled, giving a stub of pipe on the end of which the nodes have a coupled displacement constraint in the *x* (axial) direction. The underside of the monoblock is fixed in the transverse (*y* and *z*) directions. The thermal solver takes an applied surface heat flux (10MW/m^2 in all design studies), coolant temperature and uses spatially varying wall heat transfer coefficient (CEA and Tong75 [4,5]) to calculate a temperature field for input to the structural solver which calculates the stress and strain field. In all analyses the structural/pipe material is CuCrZr-IG, the monoblock is tungsten, and the interlayer is pure copper but the E, α and k are variables of the design process. All materials are in perfect bonded contact with properties (un-irradiated and irradiated) taken from the ITER SDC-IC and Material Properties Handbook [6,7].

3.2 Objective Function Calculation

The ITER SDC-IC [6] linear elastic design criteria are used to calculate a design metric which the optimiser uses in the search for better designs. In each call of the analysis model (Section 3.1), nine radial paths are defined spanning the pipe wall which are spaced equally around 180° from top to bottom. Linearized stresses are calculated on each path, which are compared to stress allowables (a function of path mean temperature) to calculate a reserve (safety) factor for each failure mode assessed. The lowest reserve factor of all failure modes and of all nine paths in each analysis is termed the minimum reserve factor and this quantity is maximised by the optimiser. This method helps to ensure that unanticipated failure modes are accounted for in the automatic design search.

3.3 Optimisation Methodology

The optimisation strategy employed is the method of response surfaces. The design space is initially populated with an efficient spread of design points using design of experiments. A surface is then fitted to these points, which is used as a surrogate of the true objective function, allowing a thorough search of the design space using a global optimizer. The surface model used is the Kriging method due to its ability to assess confidence in the response surface and expected improvement in areas away from design points. Typically we refine the response surface using new design points until the level of predicted error is below 5%. A multi-objective genetic algorithm is used to search the response surface. The primary objective is the maximisation of the minimum reserve factor (Section 3.2), with additional constraints being the CuCrZr temperature limit of 350°C [1] and an assumed temperature limit of tungsten (to avoid re-crystallisation) of 1300°C.

4. Design Optimisation Results

The design studies involved a number of response surfaces of varying size and dimensionality with the results of each study informing the next. For brevity only the final optimisation study is reported here.

The design study variables and their bounds as well as fixed parameters are listed in Table 1. The interlayer Thermal Break properties (E, α and k) are controlled using a single design variable, termed "interlayer copper fraction", which is a linear scale factor of the properties for pure copper. Certain parameters such as pipe diameter, tungsten "top" thickness (above the pipe) and coolant parameters are fixed at practicable values as we find the optimiser always chooses them to be on the bounds of the design space.

Table 1. Design optimisation variables and final design values.

Parameter	Lower bound	Upper bound	Design
Surface heat flux [MW/m^2]			10
Coolant velocity [ms^{-1}]	-	-	20
Coolant bulk pressure [MPa]	-	-	8
Coolant bulk temperature [°C]	-	-	200
Interlayer thickness [mm]	0.25	0.5	0.5
Interlayer copper fraction	0.01	0.3	0.03
Tungsten side thickness [mm]	3	7.5	4.04
Tungsten depth [mm]	2	6	3.66
Pipe thickness [mm]	0.5	1	0.52
Pipe inside diameter [mm]	-	-	10
Tungsten top thickness [mm]	-	-	5
Tungsten bottom thickness [mm]	-	-	3.5

The 'optimal' design parameters resulting from the design optimisation are also listed in Table 1. The chosen design has a thick interlayer with a very low interlayer copper fraction, i.e., poorly conducting and compliant. The response surface shows little sensitivity to tungsten monoblock (axial) depth but a strong correlation between monoblock width and pipe diameter. Figure 4 displays contours of Von Mises stress in the new design. The maximum stress in the pipe is 120MPa, occurring at the bottom of the pipe. The stress field is relatively symmetric, suggesting that loads have been well distributed through the structure by the optimiser. The peak stress in the tungsten (600MPa) is a concern but is not design driving in this study.

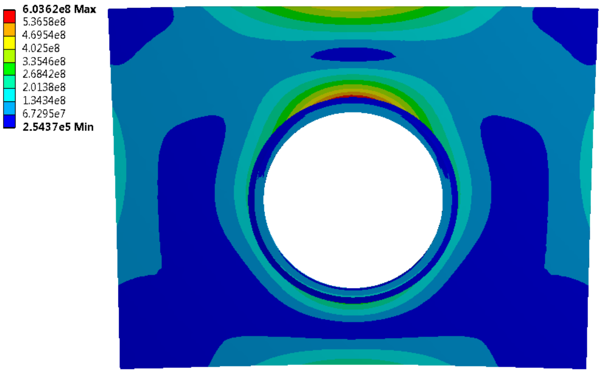
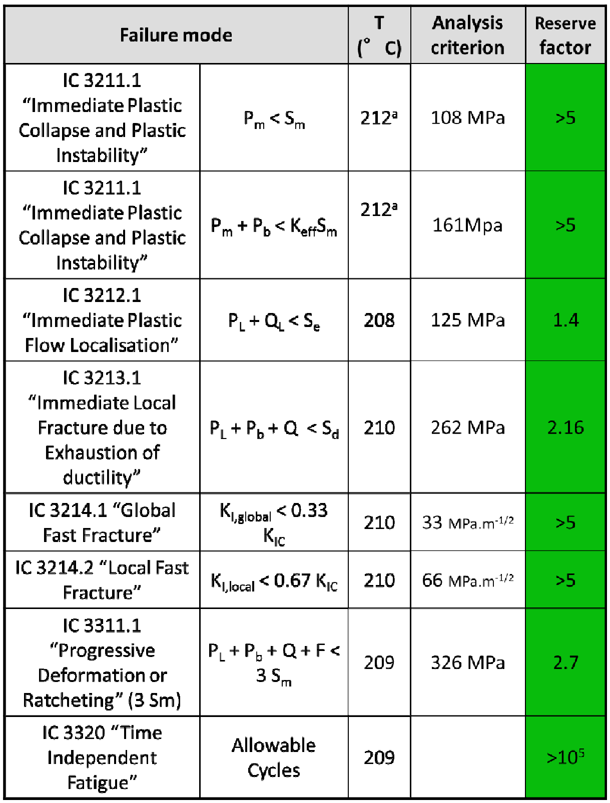


Fig. 4. Equivalent (Von Mises) stress contours in an 'optimised' Thermal Break divertor target.

Table 2. Summary of ITER SDC-IC design assessment.



Failure mode		T (° C)	Analysis criterion	Reserve factor
IC 3211.1 "Immediate Plastic Collapse and Plastic Instability"	$P_m < S_m$	212[a]	108 MPa	>5
IC 3211.1 "Immediate Plastic Collapse and Plastic Instability"	$P_m + P_b < K_{eff}S_m$	212[a]	161Mpa	>5
IC 3212.1 "Immediate Plastic Flow Localisation"	$P_L + Q_L < S_e$	208	125 MPa	1.4
IC 3213.1 "Immediate Local Fracture due to Exhaustion of ductility"	$P_L + P_b + Q < S_d$	210	262 MPa	2.16
IC 3214.1 "Global Fast Fracture"	$K_{I,global} < 0.33\ K_{IC}$	210	33 MPa.m$^{-1/2}$	>5
IC 3214.2 "Local Fast Fracture"	$K_{I,local} < 0.67\ K_{IC}$	210	66 MPa.m$^{-1/2}$	>5
IC 3311.1 "Progressive Deformation or Ratcheting" (3 Sm)	$P_L + P_b + Q + F < 3\ S_m$	209	326 MPa	2.7
IC 3320 "Time Independent Fatigue"	Allowable Cycles	209		>10^5

[a] Analysis at 22°C , criterion evaluated at local operating temperature 212°C.

Table 2 gives a summary of the assessment of the design against the ITER SDC-IC rules. At the design heat flux of 10MW/m^2, all criteria are passed and the minimum reserve factor is 1.4. The peak wall heat flux is 12.3MW/m^2 which is a margin to CHF of 2.2. Critically, the maximum tungsten temperature is 1298°C, i.e., on the limit of the imposed constraint. However, if we ignore this constraint on tungsten temperature and consider only the CuCrZr structural integrity, by ramping the applied heat flux we find the first structural failure at 18MW/m^2 (by plastic flow localisation). This very promising result invites further study to understand the importance of the Thermal Break effect.

5. Exploring Interlayer Parameter Sensitivity

Instead of grouping the interlayer properties as a single parameter, the design optimisation has been run with the interlayer E, α and k separately parameterised. Each is expressed as a fraction of the values for copper, with bounds $0.001<E/E_{cu}<1$, $0.1<\alpha/\alpha_{cu}<1$, $0.01<k/k_{cu}<1$. However, since we now know that very smaller interlayer fractions are beneficial, the variables are expressed on a log scale. As before, all designs are analysed for 10MW/m^2 surface heat flux.

By treating the three interlayer variables independently, the optimiser finds a large area of the design space where minimum structural reserve factors above 2 are found. From the response surfaces it is seen that the designs are broadly insensitive to α, but strongly dependent on E and k. Figure 5 shows the response surface for varying E and k with all other variables fixed at their optimal values. This response surface features two distinct plateaus. If $E/E_{cu}>0.01$, i.e., the interlayer E is greater than roughly 1GPa, the designs are very dependent on interlayer k and only designs with $k/k_{cu}<0.03$ can achieve a minimum reserve factor above unity (as reported in Section 4). However, at very low $E/E_{cu}<0.01$ the Thermal Break is relatively ineffective, and minimum reserve factors above 1.6 can be achieved with conductivity approaching that of copper. Such designs would have the advantage of keeping the tungsten cooler. Indeed, in this region of the surface a design was identified which passes all the SDC-IC rules and satisfies the 1300°C tungsten temperature limit, up to a maximum surface heat flux of 16.5MW/m^2. Using an 'ultra compliant' interlayer structurally decouples the monoblock and CuCrZr, and the structure effectively only experiences the thermal gradient stress.

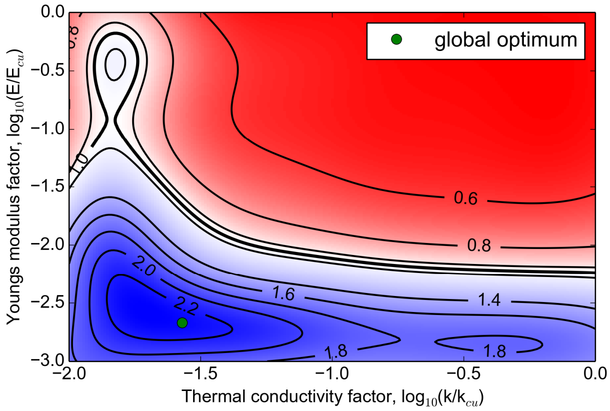


Fig. 5. Response surface showing contours of minimum reserve factor as a function of the interlayer Young's modulus and thermal conductivity.

6. Implementing a Compliant Thermal Break

In this work it is shown that engineering the properties of the interlayer can greatly enhance divertor power handling. Clearly, an important next step is to try to realise our ideal interlayer parameters in a practical divertor target design. A low conductivity interlayer is likely to be straightforward to implement and this alone would yield promising gains. However, the pursuit of a material with ultra-compliance which is suitable for the DEMO environment is more challenging. A true structural decoupling could be achieved with a liquid-metal interlayer, but this would require substantial R&D. The Authors are experimenting with practical Thermal Break materials as detailed in a companion paper [8].

7. Conclusion

The potential for enhancing water-cooled divertor target power handling by engineering the interlayer has been demonstrated by use of a design search and optimisation procedure. The principal of a Thermal Break interlayer has been introduced, which can dramatically improve structural performance by reducing the thermal mismatch stress at the armour interface and increasing the margin to CHF. Designs which pass the ITER SDC-IC linear elastic design rules up to an applied heat flux of 18MW/m^2 have been found.

If a practical design can be devised, perhaps more important is an ultra-compliant interlayer which structurally decouples the tungsten armour and CuCrZr cooling structure. The response surface models presented here suggest that the interlayer elastic modulus should be less than 1GPa. This alone effectively eliminates the thermal mismatch stress and lessens the need for a Thermal Break. This may be essential if a maximum tungsten temperature limit must be respected.

Further design studies and experimental trials are underway to develop practical materials to realise this potential.

Acknowledgments

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References

[1] D. Stork et al., Fus. Eng. Des. **89** (2014), pp1586-94.

[2] A. Li-Puma et al., Fus. Eng. Des. **88** (2013), pp1836-43.

[3] T. R. Barrett et al., *Water-Cooled Divertor Target Design Study – Alternative CuCrZr Concepts*, WP13-DAS-02-T02 report for EFDA ref. EFDA_D_2AQ5UZ (2013).

[4] E. Rabaglino et al., *Prediction of Heat Transfer in Water Actively Cooled Plasma facing Components*, 18th UIT National Heat Transfer Conference, Como, Italy, 2000.

[5] L. S. Tong, *A phenomenological study of critical heat flux*, ASME, 75-HT-68.

[6] *ITER Structural Design Criteria for In-vessel Components (SDC-IC)*, (internal project document distributed to the ITER Participants), 2012.

[7] V. Barabash, *ITER Materials Property Handbook (baseline)*, ITER_D_29DDBF, 2009.

[8] D. Hancock et al., *Testing candidate interlayers for an enhanced water-cooled divertor target*, 28th SOFT, San Sebastian, Spain, 2014.