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U.S. ITER LIMITER MODULE DESIGN*

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DISCLAIMER

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ABSTRACT

The recent U.S. effort on the ITER (International Thermonuclear Experimental Reactor) shield has been focussed on the limiter module design. This is a multi-disciplinary effort that covers design layout, fabrication, thermal hydraulics, materials evaluation, thermo-mechanical response, and predicted response during off-normal events. The results of design analyses are presented. Conclusions and recommendations are also presented concerning the capability of the limiter modules to meet performance goals and to be fabricated within design specifications using existing technology.

I. INTRODUCTION

The U.S. effort in the area of blanket module design and development has focussed recently on the limiter modules. In addition to accommodating the same operating conditions as the other shield modules, the limiter must also be able to accommodate high heat loads of up to 5 MW/m^2 during start-up and shut-down. This means that the first wall design must be modified to be able to handle the higher heat loads, while the shield portion of the module looks very similar to the other shield modules. The limiter is located at the outboard side of the torus just below the midplane ports and above the baffle modules. The limiter operating parameters are given in Table 1.[1] The following areas are included in the recent design studies:

- Module Design
- Fabrication Approaches
- Thermal-Hydraulics Assessments
- Thermo-Mechanical Assessments
- First-Wall/Plasma Interactions.

Table 1 - Limiter Module Operating Parameters

Parameter	Value
Neutron Wall Load, MW/m^2	1.05
Number of Pulses - BPP, 10^3	13
Number of Pulses - EPP, 10^3	30
Fluence - BPP, MW-a/m^2	0.2
Fluence - EPP, MW-a/m^2	>1
Water Pressure Inlet, MPa	4
Water Inlet Temperature, C	140
Minimum Margin to Critical Heat Flux	2
Maximum Temperature Rise, C	30
Average Heat Flux, MW/m^2	2.4
Peak Heat Flux, MW/m^2	5
Baking Temperature, C	200
Number of Baking Events	200
Total Number of Disruptions - BPP	3000
Total Number of Disruptions - EPP	1000
Energy During Current Quench, MJ/m^2	1
Typical Duration, ms	25
Energy During Thermal Quench, MJ/m^2	1
Typical Duration, ms	25
Peak Heat Load VDE, MJ/m^2	20-60
Maximum Time, ms	300
Runaway Electron Spectrum	$\exp(-E/E_0)$: E_0=12.5 MeV

II. LIMITER MODULE DESIGN

The limiter design is illustrated in Figure 1. Initially, a parallel flow scheme for the first wall and shield block was investigated. Collectors for the first wall and for each tube bank of the shield block were joined with connector pipes, with quantities and dimensions scaled from the figure and modified through discussions with the ITER Joint Central Team. The spacing of the shield block coolant passages increases from the lower to the upper end of the module; this was accounted for by assuming the scaled dimensions were representative of the module's center, with locating dimensions decreasing or increasing proportionately towards the lower and upper ends. Initial, thermo-mechanical analyses showed that a fifth bank of coolant passages was required near the rear of the shield block in order to reduce temperatures and thermal strains to acceptable limits, and the design was modified to incorporate this additional bank.

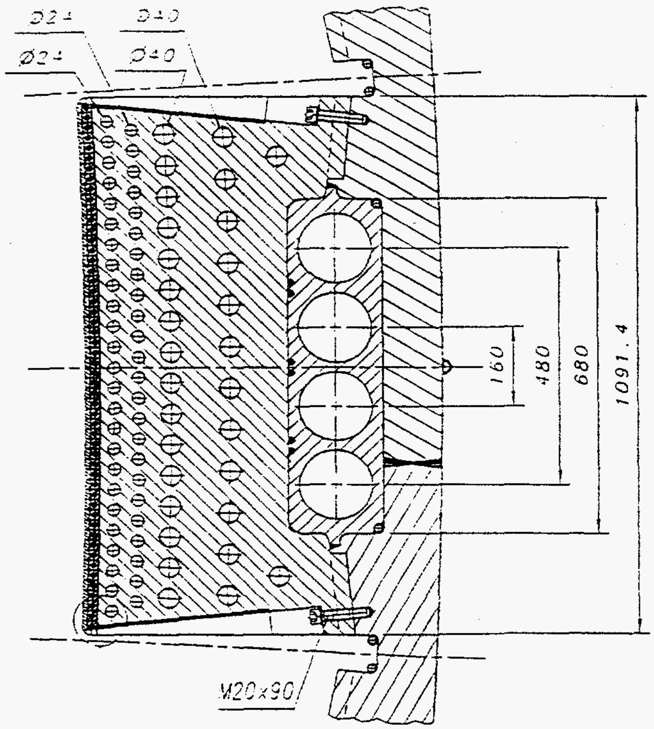

Figure 1. Toroidal cross-section view of limiter module.

During initial evaluations of the baseline design for the module limiter, two concerns arose that pointed to the need for design modification. First, pressure drop analyses indicated that even with parallel flow, the total pressure drop would likely exceed the maximum allowable value of 0.8 MPa. A series flow approach was also considered in order to increase first wall flow velocity and minimize total coolant mass flow rate. For series flow, total pressure drop in the baseline design exceeded the limit by approximately 150%. Losses in collectors and connector pipes were the primary contributors. Second, it was considered that the round cross section collectors located at the poloidal ends of the module would be difficult to fabricate. They would perhaps be feasible in shield block fabrication using either the powder-HIP and cast/HIP approaches being evaluated, but not for the use of a forged/drilled/HIPed approach.

To resolve both these concerns, a modification to the baseline was proposed, that placed the flow collectors at the rear of the shield block. This approach simplifies incorporation of the collectors. Collector and connector cross section shapes and dimensions can be somewhat arbitrary since they are located in a region of low nuclear heating and are easily accessible for detailed machining (before closure by welding or HIPing of closure plate). This approach is amenable to any of the shield block fabrication approaches currently being considered. Pressure drop calculations assuming series flow showed that total pressure drop was well within the allowable value.

III. FABRICATION APPROACHES

There are a number of features in the present baseline limiter design that result in significant complications in fabrication as compared to primary first wall (PFW) modules. Among these are:

- Be armor tiles, 10 mm thick, castellated ~10 mm x 10 mm
- Poloidally-oriented slots (gaps) between adjacent Cu-alloy tubes or blocks (each tube contains a coolant channel)
- Three-dimensional contouring of the plasma-facing surface to tight tolerances
- Stainless steel liners in first wall coolant channels with wall thicknesses ~0.2 to 0.3 mm.

Design limits for structural materials are based on ASME and RCC-MR design codes. In the blanket, only solution annealed 316 stainless steel is assumed to have a structural role. The temperature limits of Be and the Cu-alloy on the first wall are not yet well defined. The allowable peak temperature limit for Be can vary from 500-700°C based on swelling and strength considerations. The peak temperature at the Be/Cu interface should be limited to about 400°C based on possible formation of brittle intermetallic phases during operation.

A. Shield Block

The 316L SS block incorporates internal coolant passages which can be fabricated by casting and then HIPing in a cost effective manner. The casting approach is a near-net-shape method that will minimize the amount of machining necessary. The internal coolant passages can be incorporated by means of cores. Castings of this size and complexity are within the state-of-the-art of the industry. The chemical composition of the castings can be tailored to that desired by ITER. Because of the relatively thick cross-section of the casting, it is recommended that the castings be HIPed after pouring to seal the potential internal porosity.

B. Copper First Wall with Stainless Steel Liners

The nominal 20-mm-thick copper first wall has 10-mm-diameter coolant channels integrated into it. These coolant channels are to be lined with stainless steel. The stainless steel liner is required to be thin (0.2 to 0.3 mm) to meet the predicted lifetime. Three copper alloys are candidates for use. These are GlidCop™ DS AL-25, a dispersion strengthened alloy, and two precipitation hardened alloys, CuNiBe (Hycon™ 3) and CuCrZr.

Several methods were evaluated to attach the copper to stainless steel. HIPing is the reference fabrication procedure, and it offers the advantages of allowing attachment of smaller details to the shield block. Encasing the entire part in a jacket or can is required to provide a pressure boundary between the part and the high pressure of the HIP unit. HIPing is the recommended method for joining the details of the limiter together.

C. Be Attachment to Cu

One method currently being tested is to use individual Be tiles, nominally cubes ~10 mm on each side, to cover the plasma facing surface. These tiles could be placed in a tool to hold several hundred tiles that would have Cu electroplated onto the Be. This electroplating would be continuous at the base of the Be tiles and act as a mechanism to hold the tiles and form a "sheet" of tiles that could be easier to handle for assembly onto the Cu surface of the Cu stainless shield block and first wall. The concept for this approach is the low temperature (<500°C) diffusion bonding of the Be to Cu in a HIP cycle. This low-temperature bonding of Be to Cu is compatible with the other recommended fabrication processes.

D. Recommended Fabrication Sequence

The recommended fabrication sequence would be: (1) the face of the cast shield block would be machined to proper contour, (2) the first Cu plate with grooves for the tubes would be laid in place over the shield block, (3) the stainless steel liners would be laid in place and welded to the manifold at the rear of the shield block, and (4) the top Cu plate would be placed in position over the tubes. At this point the assembly would have the HIP can or jacket put on and the HIP operation performed.

Following HIPing, the front plasma facing surface of the limiter would have the HIP jacket removed. The limiter surface would then be machined to contour to accept the Be tiles. It is still under investigation whether or not to incorporate the slots between the coolant channels at this operation or to make the slots after the Be tiles are joined.

IV. THERMAL-HYDRAULICS ASSESSMENTS

The pressure drop across the limiter is closely related to its design and coolant flow rate requirements. Two designs for the limiter coolant routings were evaluated, the parallel scheme and the series scheme. The pressure drop calculation includes both friction pressure drop and form losses associated with bends and branchings in manifold systems. The correlation employed in evaluating friction loss is provided in Ref. 2, and correlations associated with evaluations of the losses at branches and bends are provided in Ref. 3. All channels were assumed to have a wall roughness of 0.05 mm. In both designs, it is assumed that there are three connectors between the headers of any two layers; i.e., there are three connectors between the exit collector of layer three and the inlet collector of layer two.

A. Parallel Flow

The first wall hydraulic system comprises an inlet collector, an outlet collector, and 43 cooling channels with an inside diameter of 10 mm. The flow rate in the cooling channels, 7 m/s, was used in this calculation. This results in a total flow rate in the first wall of 23.9 liters/s. The inlet conditions are P = 4 MPa and T = 140°C. The pressure drop across the first wall, including those across the inlet connector and collector, outlet connector and collector, and the cooling channels, is about 0.77 MPa. The flow rate across the shield region is about 9.3 liters/s. The pressure drop across the shield region is about 0.81 MPa, including the pressure drop at both inlet and outlet connectors to the main feed and return ducts. Thus the overall pressure drop across the limiter is about 0.81 MPa.

B. Series Flow

Using the same channel dimensions as for the parallel flow scheme, the pressure drop for the series flow was evaluated. The flow rate for the shield region, which by definition is the same as that in the first wall layer for this approach, is about 1.6 times higher than that in the parallel scheme. This large pressure drop is added to that across the first wall channels, resulting in an overall pressure drop about 2.1 MPa. The small connectors between produce a large pressure drop. Thus, one approach to reduce the pressure drop to a satisfactory level is to use larger connectors. By increasing the connector sizes between layers, and keeping other channel dimensions unchanged, the overall pressure drop decreases to 1.08 MPa.

C. Alternate Concept

It is assumed that there are 5 connectors between any two collectors of two layers. The connectors joining collectors of layers 4 and 3 are 40 mm in inside diameter, and all other connectors are 44 mm in inside diameters. The total pressure drop across the limiter is about 0.614 MPa, compared to 1.08 MPa in the series design. Furthermore, the pressure drops across the limiter channels and the main connecting pipes feeding and collecting the coolant to the limiter accounts for about 75% of the overall pressure drop, indicating that only small losses occur in the shield region channels, collectors, and connectors. This result is expected since the improved design provides only one pass in each shield region layer, resulting in a reduction of total flow length and number of connectors necessary.

V. LIMITER THERMO-MECHANICAL ASSESSMENTS

A. 3-D Analysis of Limiter First-wall Temperatures and Stresses

A 3-D finite element analysis of the temperature and stress distribution in the limiter first-wall with surface heat fluxes of 3 and 5 MW/m^2 was conducted. The main object of this analysis was to investigate the effect of the groove depth in Cu on the limiter first-wall stress field. The first wall is composed of 19-mm-thick GlidCop AL-25 with 1 mm slots cut poloidally at the midpoints between adjacent coolant channels. The properties used for the materials are temperature dependent and were taken from the ITER Material Properties Handbook. Figure 2 summarizes the stress analysis results for the assumed surface heat flux of 3 MW/m^2. When the groove is deeper than 6 mm the additional effect on the stress at the interface is negligible, but the maximum stress in Cu continues to be reduced as the groove goes deeper. However, this effect levels off at a groove depth of approximately 13 mm. The maximum temperature for this heat flux is 552°C at the Be surface. The temperature distribution would not vary with groove depth in Cu because of the assumed adiabatic boundary conditions.

The case of the maximum surface heat flux of 5 MW/m^2 currently specified by the JCT was also investigated. For a Cu-groove depth of 13 mm the maximum temperature in the Be is 866°C. The maximum stress in Be for this heat flux equals to 2400 MPa. and in Cu equals 810 MPa, which is about 1.8 times higher than the case of the similar boundary conditions with surface heat flux of 3 MW/m^2. It must be noted that the stress does not scale linearly with the flux. Additional details of the analysis are given in Ref. 4.

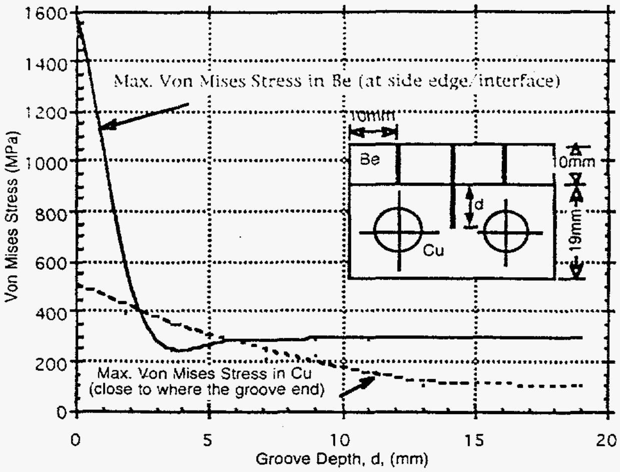

Figure 2. A Summary for the stress analysis for a surface heat-Flux of 3 MW/m^2.

B. Overall Module Evaluations

A finite element analysis of the temperature and stress distribution in the limiter shield during normal operation has been made. The limiter module along with the manifold block and the backplate were modeled. The first wall is composed of 2-cm-thick GlidCop^{TM} DS Cu-AL25 with 1 mm slots cut poloidally between coolant channels. At this point, Be has not been included on the surface. The bulk of the shield is SA 316 LN, and there is a 5-mm-thick layer of Cu on the sidewall to enhance heat transfer. The properties used for the materials are linearly temperature dependent and were taken from the ITER Material Properties Handbook.

This design of the coolant channels represents an optimized design to reduce hot spots. The peak temperature occurs on the surface, as expected, with a maximum of 362°C. Both the manifold block and the backplate remain relatively cold. Within the shield, however, there are some elevated temperatures. The cooling channels in the shield have been distributed to minimize hot spots. The hot spots that occur along the side wall are due to the combination of nuclear heating and the long distance to the nearest cooling channel. It is difficult to move the cooling channels closer to the side wall due to the space needed for cut-outs for the bolted attachment. The presence of the 5 mm Cu helps in distributing the heat, but it does not eliminate the hot spots. The thermal stresses associated with this temperature distribution are within acceptable levels, with the exception of the mechanical attachment between the module and the backplate. The stresses appear to be high here due to the temperature mismatch between the backplate and the module.

The major conclusions of the analysis are:

(1) The sidewall cooling needs to be carefully addressed to insure that temperatures are kept to an acceptable level.
(2) An additional layer of cooling channels improves the temperature distribution towards the rear of the limiter module.
(3) The interface between the shield and backplate could experience high localized stresses and needs to be addressed in more detail.
(4) The peak copper alloy temperature is 362°C at 5 MW/m^2, which is close to the 400°C allowable at the Be/Cu bond. The allowable is based on the growth kinetics of Be-Cu intermetallics.
(5) The time to reach equilibrium will be long at the back of the shield and the backplate. Time dependent calculations should be performed to determine this time.

VI. RESPONSE OF ITER LIMITER TO VERTICAL DISPLACEMENT EVENTS

In the current ITER design, it is projected that plasma instabilities due to vertical displacement events (VDEs) will result in high energy deposition in the range of 10-100 MJ/m^2 over periods of 100-300 ms. Such high energy densities would result in significant plasma-facing material (PFM) surface vaporization and melting. In addition, these long deposition times allow enough time for the deposited energy to diffuse through the coating surface material, into the substrate structural materials, and finally to the coolant channels, where it may cause burnout.

The behavior of different candidate coating PFMs such as beryllium, carbon, and tungsten and structure materials such as copper, due to various plasma instabilities as disruptions, ELMs, and VDEs, is examined using the comprehensive A*THERMAL-S and SPLASH computer codes.[5-7] The thermal analysis of the PFMs prior to plasma instabilities are calculated using the steady state multicomponent computer code HEATSS.[8] A reference case of a VDE in which 20-60 MJ/m^2 energy density deposited in durations of 100-300 ms is used in this analysis. A nominal surface heat flux of 5 MW/m^2 prior to VDE plasma instabilities is assumed unless otherwise stated. This is because it is more likely for VDEs to occur during start-up in which the surface heat flux on the limiter surface is estimated to be 5 MW/m^2.

A. Effects of VDEs on Surface Coating Materials

The effect of VDEs on surface vaporization of W, Be, and C candidate coating materials is shown in Fig. 3 for a VDE energy density of 60 MJ/m^2 deposited in 300 ms. Beryllium has the highest surface vaporization, about a factor of 5 higher than C and W, while both have similar surface vaporization losses. High Be surface vaporization is due to the much higher vapor pressure of Be compared to C and W.

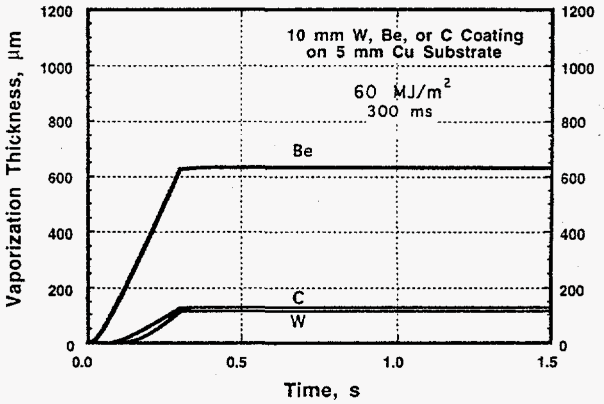

Figure 3. Surface Vaporization Thickness of Candidate Limiter Materials.

Figure 4 shows the Be and W melt-layer thickness developed during VDEs with different energy deposition times. Because of the low melting of Be, its melting thickness is usually larger than W and its melt duration is much longer. Lower energy densities result in lower melt thicknesses, particularly for W. Longer melt-layer durations and larger melt thicknesses can trigger and magnify hydrodynamic instabilities and other melt-layer erosion mechanisms. Carbon has a significant advantage regarding disruption erosion lifetime compared to both Be and W since it does not melt.

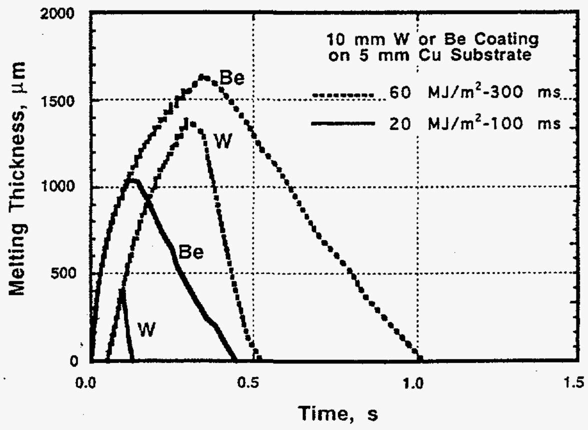

Figure 4. Beryllium and Tungsten Melting Thickness during a VDE.

C. Effects of VDEs on the Structural Material

Figure 5 shows the copper surface temperature rise at the interface for different surface coating materials. Copper surface temperature is the lowest when Be is used as a surface coating material. Both W and C result in high Cu surface temperatures that are probably not acceptable for safe and reliable operation of the structural material. The reason for the low Cu surface temperature rise when using Be coating is because of the high Be surface vaporization losses compared to C and W. Such high surface vaporization rates consume much of the plasma incident energy, leaving little energy to be conducted through and reach the substrate material.

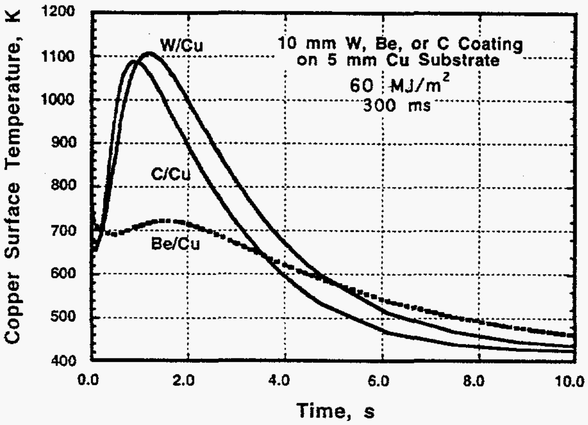

Figure 5. Copper Surface Temperature Rise due to Various Coating Materials.

VII. CONCLUSIONS

The overall design and fabrication of the limiter modules appears workable. A proposed modification of the initial baseline design to locate the coolant collectors at the rear of the shield block allows pressure drop limits to be met and simplifies fabrication. Although further work is needed to work out details of the fabrication approach, it appears feasible to use a cast/HIP approach to create the stainless steel shield block, use HIPing to join the first wall Cu-alloy heat sink to the shield block, and use lower-temperature HIP to join the beryllium armor to the heat sink. Flow stability in the first wall region does not appear to be a major concern, given the present surface heat flux profiles and coolant parameters.

However, the work has identified several key issues where additional effort is required:

- Disruptions, and VDEs in particular, can cause substantial erosion of the plasma facing surface. Beryllium is particularly susceptible because of its relatively low melting point. At this time the design window for beryllium armor appears to be very small at best, given the imposed operating conditions (e.g., numbers of VDEs that must be survived) and constraints on peak temperature allowed during normal startup and shutdown.
- During normal operation, the peak heat loads are very sensitive to the module-to-module alignment accuracy in the toroidal direction as well as to the accuracy of the module surface with respect to the magnetic field profile. It is very important to determine the degree of accuracy that is required in both cases and to then determine what fabrication and installation methods are required to ensure the alignment accuracy.
- A concern the limiter modules have in common with all other blanket modules is accommodation of the electromagnetic forces that accompany the disruptions. The high level of these forces increases the difficulty of identifying an attachment scheme that is both sufficiently strong and easily replaceable during remote maintenance.

ACKNOWLEDGMENT

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