HIGH PERFORMANCE DIVERTOR TARGET PLATE FOR A POWER PLANT: A COMBINATION OF PLATE AND FINGER CONCEPTS

X.R. Wang[a], S. Malang[b], M.S. Tillack[a] and the ARIES Team

[a] *Center for Energy Research, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0417, USA, xrwang@ucsd.edu, mtillack@ucsd.edu*
[b] *Fusion Nuclear Technology Consulting, Fliederweg 3, 76351 Linkenheim, Germany, smalang@web.de*

This paper considers a combination of ARIES modular finger concept and a design with helium channels in a thick plate. Multiple-jet cooling at a back side of a plasma facing surface is employed in this concept. The plasma facing surface is subdivided into a large number of small hexagonal modules, similar to the EU finger concept. Such a modularization reduces thermal stresses and allows therefore maximum surface heat flux of 10 MW/m^2 at least. A solution has been found allowing brazing the fingers made of a W-alloy directly into the W-plate, avoiding in this way the connection of dissimilar materials with largely different thermal expansion coefficients. For an increase in reliability, double walled thimbles are used in the most critical region, providing an additional barrier against leaks of the high pressure helium. Thermal-mechanical calculations confirmed the expected high performance of the concept with the maximum allowable heat flux > 10 MW/m^2 with all the components staying in the elastic regime. Extensive analyses of non-linear materials responses, such as plastic deformation (yield) are performed to allow the materials to be pushed beyond 3S_m in order to determine the maximum allowable heat flux can be.

I. INTRODUCTION

A number of advanced He-cooled W-alloy divertor concepts have been proposed for fusion power plant application within the framework of the ARIES-Pathways Program. The divertor configurations include a larger-scale plate-type divertor design with characteristic dimension of the order of 1 m, taking an advantage of the reduction in number of units and the associated complexity,[1] a mid size T-Tube design with characteristic dimension of the order of 10 cm,[2] the EU finger modular units with characteristic dimension of the order of 1.5 cm,[3] and a modified EU finger-like concept which combined the W-base plate and the finger concepts to minimize the thermal stresses under the high heat flux.[4] All these divertor designs utilize the W or the W-alloy as structural material and impinging-jet cooling scheme, and can be capable of accommodating a high heat flux of 10 MW/m^2. Engineering efforts of the past years were mainly focused on optimizing the divertor configurations and the coolant flow schemes to improve the thermal-hydraulic performance with acceptable material temperature limits and stress limits.

A traditional approach in designing the high heat flux components is to limit the structural behaviors within the elastic regime. However, the 3S_m of the ASME Code for this region is a very conservative design criteria, therefore, "Design by Analyses" will be utilized as the design methods for the heat flux components. Thermal-mechanical calculations confirmed the expected high performance of the concept with the maximum allowable heat flux > 10 MW/m^2 with all the components staying in the elastic regime. Extensive analyses of non-linear materials responses, such as the plastic deformation (yield) are performed to allow the materials to be pushed beyond the 3S_m limit in order to determine the maximum heat flux can be handled.

This paper presents an evolution of the helium-cooled W divertor concept with a combination of the ARIES modular finger concept and the design with large helium coolant channels in the thick W plate. The design details are addressed in this paper, and the results from the supporting analyses are summarized, including the computational fluid dynamic (CFD) thermo-fluid and the finite element (FE) thermo-mechanical analyses with considering both the elastic and the plastic behaviors.

II. DESIGN CONSIDERATIONS

In the EU finger divertor concept, the joining of the W-alloy of the thimbles to the ODS(oxide dispersion-strengthened)-steel of the manifold as necessary in each of the ~550,000 finger-modules is very difficult issue because of small temperature window and the thermal expansion coefficient of the W about 2.5 times smaller than that of ferritic steel. New modifications and improvements to the modular finger design have been made to allow brazing the fingers made of the W-alloy directly into the W plate to avoid the many connections of dissimilar materials with different thermal expansion coefficient inside the high heat flux region. As illustrated in the Fig. 1, the outer diameter of the thimble is enlarged from 15 to 20 mm while keeping the same size of the cartridge. A 1-mm thick cylindrical ring made of the W-alloy is added inside of the W-alloy thimble covering the mantle of the thimble to provide an additional barrier against high-pressure helium leakage. The W armor, the W-alloy thimble and the W-alloy cylindrical ring are brazed together in one step (brazing # 0 and #1) into one armor unit, and then in the second step brazed into the W front plate (brazing # 2 and # 3) as shown in the Fig. 2. In this way, the modified finger design avoids the transition joints between the W-alloy and the steel at the modules, and provides double containment of the high-pressure helium in the most critical regions.

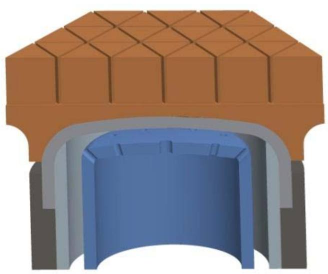


Fig. 1. ARIES Finger unit

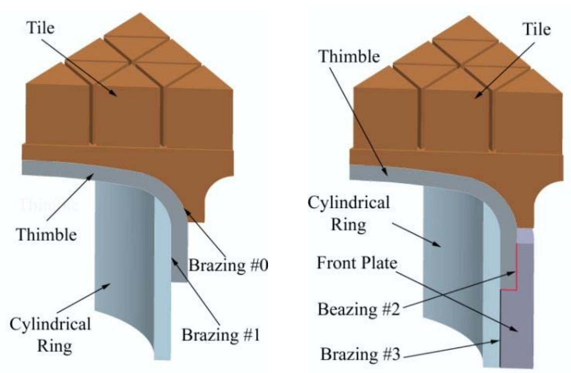
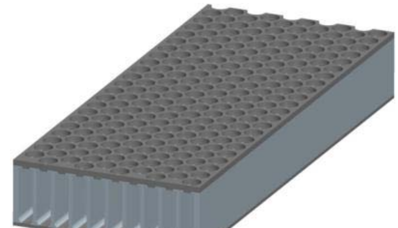
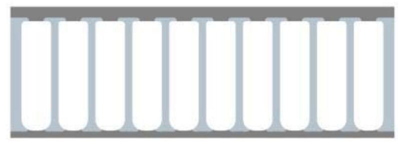


Fig. 2. Fabrication of the finger unit

Fig. 3 shows the W-base plate fabricated by brazing together the front plate, the back plate and the side walls. Fig. 4 illustrates how the inlet manifolds (the steel cartridges) are inserted into the plate. As illustrated in the Fig. 4, the divertor target plate is the combination of the finger concept and the design with helium coolant channels in the thick plate. The jet-cooling at the back side of the plasma-facing surface is employed. Each finger is cooled with the helium at 10 MPa and 600/700 ºC inlet/outlet temperature supplied via the manifold system. The adjacent inlet and outlet manifold channels are oppositely axially tapered in order to generate more uniform coolant velocity along flow direction.



(a)



(b)

Fig. 3. The W-base plate, (a) a bird view, (b) a front view

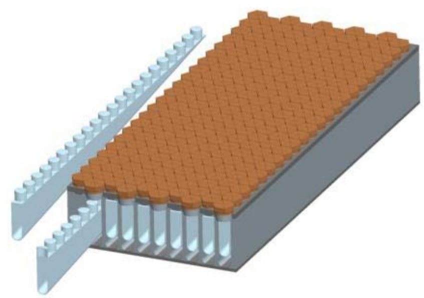


Fig. 4. The divertor target with inserted cooling cartridges

III. W-BASED MATERIAL AND FABRICATION

The compatibility with the plasma as well as the high heat flux density to the target makes the use of the W for the tiles mandatory because of its very high melting point, good thermal conductivity, low sputtering yield and low activation properties. These tiles operate in the temperature range of roughly 1000 ºC to 2000 ºC, and there are no high requirements on the mechanical strength. Therefore, the tiles are designed with a sacrificial layer of ~5 mm giving an expected lifetime of a few years and they may probably be fabricated by powder hipping or injection molding.

The cup-shaped thimble between the tile and the plate are the most difficult elements of the entire concept. Based on the present knowledge and understanding of the W or the W-alloy and their mechanical behaviors, the most promising material for the thin-walled thimble of the finger-concept is Vacuum-Metallized (VM) W which is doped with small amounts (in ppm-range) of aluminum and potassium silicate.[4] The mechanical properties of the

VM-W depend strongly on the wall thickness of the sheets fabricated by rolling with the interesting aspect that thinner is better. The proposed fabrication for the thimble is to start with a 1 mm thick VM-W sheet rolled in alternating direction and to obtain the desired shape of the thimble by deep drawing or press rolling at a sufficiently high temperature.

The plate itself is constructed by brazing together the front and the back plates with the side walls between the parallel helium channels and would function as the major structure for the divertor target plate and serve as the coolant manifold (illustrated in the Fig. 3 and 4). This requires the front-wall thickness of least 6 mm, and the thickness of 4 mm for both the side walls and the back plate. Such thick plates are not possible with the VM-W, therefore, WL10 (W-1%La_2O_3) is one option for all the front-plate, the side and the back plates.

IV. TRANSITION ZONE BETWEEN THE W PLATE AND STEEL MANIFOLD

Designing robust transition joints between the W and the steel manifold are a key for all the tungsten divertor concepts. A concept for the transition from the W-alloy plate to the ODS steel manifolds is proposed to avoid thermo-cyclic plasticization of the W-alloy/steel joints due to a large mismatch of thermal expansion coefficient of the W (4-6 x 10^{-6} K^{-1}) and the ODS steel (10-14 x 10^{-6} K^{-1}).[1,4] It consists of placing a Ta-alloy piece between the W-alloy and the ODS steel because the thermal expansion coefficients of the pure Ta and Ta-alloy are close to those of the W or W-alloy. Detailed thermo-mechanical analysis of the transition from the W plate to the ODS steel manifold at both ends of plate is presented at this conference.[6] The FEA results include thermal cycling loads of the joint fabrication steps and operations with warm and cold shutdown to find out the long-term behavior of such transition zones, taking into account plastic deformation of all the materials in this zone (W-alloy, Ta-alloy, and ODS steel).

V. DESIGN METHODOLOGY

The temperature, stress and pumping power limits are the reason for the heat flux limits on the plasma-facing components. Previous studies on the helium-cooled W-based divertor concepts indicated that the finger unit could handle the surface heat flux up to 10 MW/m^2 without exceeding the temperature, pumping power and 3 S_m stress design limits. Recent efforts were focused on pushing the divertor concepts to the higher performance and higher heat flux. The first of the design approaches is to optimize the impinging-jet cooling to improve and maximize the heat transfer coefficient at the heat-exchange surface behind the plasma side with acceptable pressure drop. The second design approach is to allow the structural behaviors exceeding the elastic regime (yielding) for pushing the structural limits beyond the 3Sm limits and considering stress relaxation of the plastic deformation because the 3S_m limits of the ASME Code are very conservative design criteria, therefore, the "Design by Analyses" were utilized as the design methods for the high heat flux components. Both the elastic and the plastic material responses, such as the stresses, the elastic and the plastic deformations were calculated. Design and computing iteration was performed by Pro/Engineer, CFX and ANSYS Workbench, a state-of-art simulation technology, starting from the thermal-fluid analyses to calculate the material temperature and the fluid pressure drop distribution, then the nodal temperature and the pressure at the interface of the fluid and the solid being mapped to the ANSYS structural model for the elasto-plastic analyses. This coupled thermo-fluid and the thermo-mechanical simulations avoid involving any third computing code and un-accurate data transfer. The work flow chart is illustrated in the Fig. 5.

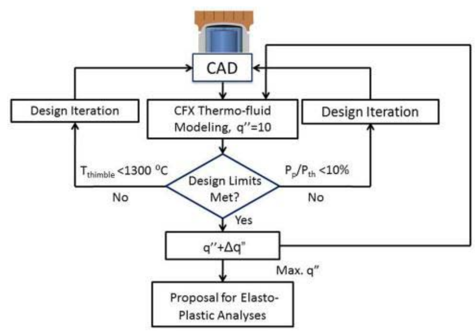


Fig. 5. Design iteration chart

The design criteria for the non-linear structural behavior of the high temperature components is that the maximum plastic strains accumulated over the operating life should be less than 50% of the uniform elongation. The uniform elongation of the W or W-alloy is highly dependent on the material temperature, however very limited dada was found from literatures. For the pure tungsten, the allowable plastic strain is ~0.8% at the temperature of 270 ºC and 1% at the temperature of ~1200 ºC.

VI. FE ANALYSES

Detailed 3-D CFD (using CFX) and 3-D FE thermo-mechanical simulations (using ANSYS Workbench) were performed to explore the allowable heat flux at the divertor target with respect to the temperature, the stress, the deflection and the pumping power limits, and optimize the design configuration. The temperature and the pressure distributions obtained by the CFD code were coupled to the FEA structural model for thermo-mechanical analyses.

VI.A. CFD Thermo-fluid Simulations

Typical parameters utilized in the CFD calculations are summarized in the table I.

TABLE I. Divertor Design Parameters

He pressure, MPa	10
Peak heat flux, MW/m^2	>10
Volumetric heating rate, MW/m^3	17.5
He inlet temperature, ºC	600
He outlet temperature, ºC	700
Nozzle diameter in middle, mm	1.0
Nozzle-to-wall distance , mm	1.2
Tile width over the flat, mm	23.0
Outer diameter of the thimble, mm	20
Outer diameter of the cylindrical ring, mm	18
Outer diameter of the cartridge, mm	13.6
Thickness of the front plate, mm	8.0

Only a 1/6 of the finger module including the armor, the thimble, the cylindrical ring, the cartridge and the fluid was modeled, taking advantages of its periodic symmetry in the geometry and the fluid flows. There are ~1.4 million grids in the fluid model and very fine fluid elements near the wall were used in order to catch the fluid dynamic behaviors accurately and robustly. The temperature-dependent material properties were utilized in the CFD analysis. The heat transfer associated with the jet-impingement cooling was predicted based on a standard turbulent flow model, k-ε with wall enhancement.[8] For the design iteration, the surface heat flux is assumed to start from 10 MW/m^2, then the calculated temperature and pumping power are compared to the design limits. If both the temperature and the pumping power limits are met, a higher heat flux, such as the heat flux of 11.0 MW/m^2 would be assumed for the next iteration. If the calculated temperature or the pumping power did not meet the design limits, the geometry modifications and optimizations would be needed. Fig. 6 shows the velocity distributions for the multiple-jet impinging cooling scheme. The maximum velocity through the jets is about ~332 m/s and corresponding pressure loss is about ~0.26 MPa. As illustrated in the Fig. 7, the corresponding heat transfer coefficient is ~9.26x10^4 W/m^2-K at the heat exchange surface while the pumping power is less than 10% of the removed divertor thermal power. The temperature and pumping power obtained from the CFD calculations indicate that the combined finger and plate concepts can accommodate the surface heat flux up to 15 MW/m^2 without exceeding the temperature and the pumping power limits. The maximum temperature of the W armor is 2243 ºC and the maximum temperature at the interface between the W armor and the thimble (underneath the W armor) is 1295 ºC, which is within the 1300 ºC re-crystallization limit assumed for the VM-W. The minimum temperature of the finger unit is 864 ºC, which is above the 800 ºC for avoiding the embrittlement for the W-alloy.

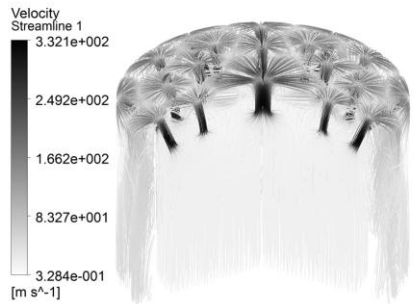


Fig. 6. Velocity distribution in the channel illustrating the jet flow to cool the heated zone

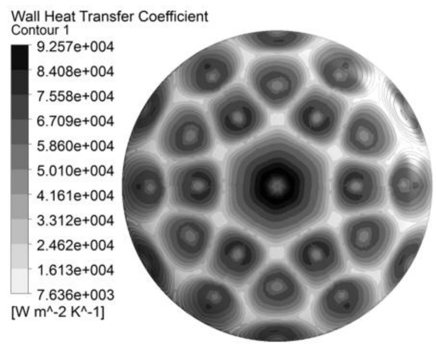


Fig. 7. Heat transfer coefficient distribution

VI.B. FE Thermo-mechanical Analysis

The heat transfer coefficient and the temperature at the interface of the He/W structure were obtained from the CFX thermo-fluid analyses and used as a thermal boundary condition for computing the volumetric temperature and the thermal stresses in the FE model; a coupled thermo-mechanical analysis was then performed. Bilinear isotropic hardening material model was selected from the ANSYS built-in material models for the elasto-plastic analyses to simulate the material responses of both the elasticity and the plasticity. The linear elastic and ideal plastic model was assumed. Thermal creep was not included at the present study. The following mechanical boundary conditions were applied: (1) no channel bending and in-plane back side, and (2) rotational periodic-symmetry condition in the plane of 0 and 60 degree. This resulted in a conservative boundary condition since the entire surface at the back plate was restrained from free bending.

The calculated maximum principal plastic strain is ~0.13% in the W armor and 0.04% in the W-alloy thimble (allowable plastic strain ε_{allow}=1.0% at the temperature of 1200 ºC).[7] The plastic design criteria are met. The SF (safety factor) is defined as the ratio of the 3 S_m stress limits to the maximum combined primary and secondary stresses. For the structural design requirement, the safety factor must be > 1. As shown in Fig. 8, the maximum combined primary and secondary stresses (von Mises) is 481 MPa at the W-alloy thimble, and the corresponding minimum safety factor is ~1.2 after stress relaxation by the plastic deformation. However, without considering the plastic deformation, the minimum safety factor is ~0.4 in the W armor.

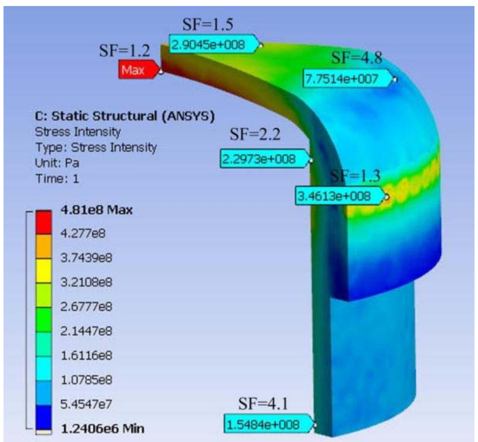


Fig. 8. Combined stress (primary + secondary) distribution after stress relaxation

VII. CONCLUSIONS

The combination of the finger and the plate divertor concepts has been proposed and developed for the fusion power application within the framework of the ARIES-Pathways study. The EU-like finger concept has been improved by (1) avoiding the transition joints between the W fingers and the steel manifolds, (2) adding the cylindrical ring for the double containment in the critical region for decreasing the potential for high pressurized helium leaks.

The calculation confirmed that all material elements of the concept remain in the elastic region for the heat flux up to 10 MW/m^2.

The layout of the impinging-jets has been optimized based on the thermal-fluid analysis for pushing higher heat flux if the plastic deformations are allowed. The design and the computing iteration were performed and the results at the final iteration step indicate that this divertor concept can handle the surface heat flux up to 15 MW/m^2 without exceeding the high temperature and the pumping power limits. With consideration of the material plasticity, the divertor design meets the plastic strain criteria as well as, after the stress relaxation by the plastic deformation, the ASME Code 3 S_m limit.

As the next step, the behavior of the divertor target plate under the cyclic loading condition and the fast transients should be investigated with considerations of the thermal creep, fatigue and fracture.

ACKNOWLEDGMENTS

The work at UCSD was supported under U.S. Department of Energy Grant number DE-FG02-04ER54757.

REFERENCES

1. X.R. WANG, S. MALANG, A.R. RAFRAY, and ARIES TEAM, “Design Optimization of High-Performance Helium-Cooled Divertor Plate Concept,” *Fusion Science and Technology*, **56**, 1023(2009).
2. T. IHLI, R. KRUESSMANN, I. OVCHINNIKOV, P. NORAJITRA, V. KUZNETSOV, and R. GINIYATULIN, “ An Advanced He-cooled Divertor Concept: Design, Cooling Technology, and Thermohydraulic Analyses with CFD,” *Fusion Engineering and Design*, **75-79**, 371(2005).
3. P. NORAJITRA, R. GINIYATULIN, T. IHLI, G.JANESCHITZ, W. KRAUSS, R. KRUESSMANN, V. KUZNETSOV, I. MAZUL, V. WIDAK, I. OVCHINNIKOV, R. RUPRECHT, AND ZEEP, “He-cooled Divertor Development for DEMO,” *Fusion Engineering and Design*, **82**, 2740(2007).
4. M.S. TILLACK, A.R. RAFFRAY, X.R. WANG, S. MALANG, S. ADBDEL-KHALIK, M. YODA, D. YOUCHINSON, “Recent US Activities on Advanced Helium-Cooled W-alloy Divertor Concept for Fusion Power Plants,” *Fusion Engineering and Design*, **86**, 71(2011).
5. A.R. RAFFRAY, L. EL-GUEBALY, T. IHLI, S. MALANG, X. WANG, and the ARIES-CS Team, “Engineering Design and Analysis of the ARIES-CS Power Plant,” *Fusion Science & Technology*, **54**, 725(2008).
6. D. NAVAEI, X.R. WANG, S. MALANG and M.S. TILLACK, “Elastic-Plastic Analysis of the Transition Joint for a High Performance Divertor Target Plate” this Proceedings.
7. X.R. WANG, S. Malang and M.S. TILLACK, “Design and Analysis of an Innovative First Wall Concept for ARIES Power Plant” this Proceedings.