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ABSTRACT

The Fusion Engineering Research Experiment (FIRE) device is designed for high power density and advanced physics operating modes. Due to the short distance of the divertor from the X–point, the connection lengths are short and the scrape off layer thickness is small. A relatively high peak heat flux of 25 MW/m^2 is expected on the divertor.

The FIRE divertor engineering design is based on the design approaches developed for International Thermonuclear Experimental Reactor (ITER). The geometry of the FIRE divertor consists of water cooled copper fingers and a tungsten brush armor as plasma facing material. The divertor assembly consists of modular units for remote handling. A 316 stainless steel back plate is used for support and manifolding. The backing plate is joined to the copper fingers by pins. The coolant channel diameter is 8 mm at a pitch of 14 mm. The total power flow to the outer divertor is 35 MW. A water at an inlet temperature of 30°C, 1.5 MPa and a flow velocity of 10 m/s is used with two channels in series. A margin of about 1.6 is obtained on the critical heat flux.

A three dimensional thermal stress finite element (FE) analysis of this geometry was performed. Thermal hydraulic correlations derived for ITER were used to perform the thermal analysis. Design changes were implemented to reduce the stresses and temperatures to acceptable levels.

1. INTRODUCTION

The FIRE is being designed for high power density and advanced physics operating modes [1]. The FIRE tokamak has a major radius of 2 m,a minor radius of 0.525 m, and liquid nitrogen cooled copper coils. The aim is to produce a pulse length of 20 s with a plasma current of 6.6 MA and with alpha dominated heating.

The FIRE has a double-null divertor configuration. The outer divertor is water cooled. The inner divertor has a low heat flux and is cooled by conduction to the copper shell inside the vessel wall. Figure 1 shows the cross section of the FIRE with location of outer upper divertor.

The purpose of this task was to determine temperatures and stresses under worst power flow conditions and choose flow rates, flow direction, inlet coolant conditions, and diameter and pitch of the attachment pins.

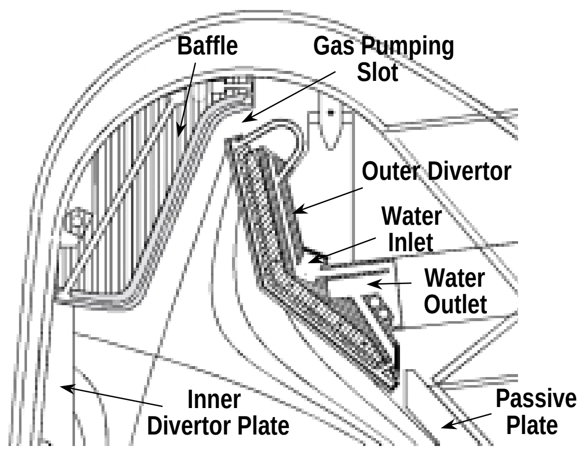

Fig. 1. Cross section through FIRE divertor and baffle.

2. DIVERTOR GEOMETRY

The divertor design of the FIRE is based on technologies developed for ITER [2,3]. There are 32 modules of the divertor (16 upper and 16 lower). Each module is divided into 24 copper (Cu-Cr-Zr) plates across the front surface. The copper plates include a tungsten-brush armor as a plasma-facing component (PFC) and coolant channels. The tungsten rods are 3 mm in diameter arranged on a triangular pitch of 3.1 mm. The rods of the brush have a conical tip of 1 mm length on the heat sink side. The tungsten rods are joined to the copper with HIP-bonding process [4]. A 5 mm thickness of the PFC gives an adequate lifetime under the expected disruption conditions. The use of tungsten brush reduces the pre-stresses in the PFC. This is one of the designs for the ITER divertor PFC in the highest heat flux region. Each divertor module is 0.67 m in the toroidal direction and 0.55 m in the poloidal direction. The coolant water inlet is at a temperature of 30°C and a pressure of 1.5 MPa. The copper fingers are joined to the support structure made of 316 N stainless steel by 4.5 mm pins at pitch a pitch of 12 mm (Fig. 2).

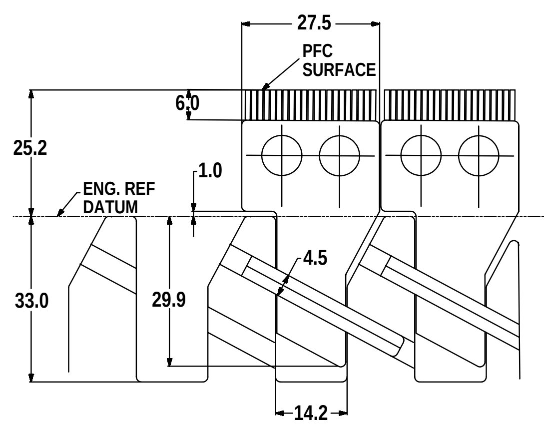

Fig. 2. Attachment concept to join copper fingers to support structure.

3. POWER FLOWS

The FIRE tokamak is planned to be operated in four modes: 1) Base line D-T (20s), 2) An advanced physics D-D (215 s), 3) A long burn D-T mode (31 s), and 4) A high field operation D-T (12 T, 8 MA, 12 s). The heat loads on the outer divertor and baffle are highest during the base line D-T operation with power flows as shown in Table 1. The poloidal distribution of heat flux is shown in Fig. 3.

Table 1. The power flows during baseline D-T mode

	Outer Divertor
Total Power (MW)	34.3
Peak Power/module (MW)	2.32
Peak Heat Flux (MW/m^2)	25.0
Nuclear heating in Tungsten (W/cm^3)	42
Nuclear heating in Cu (W/cm^3)	16

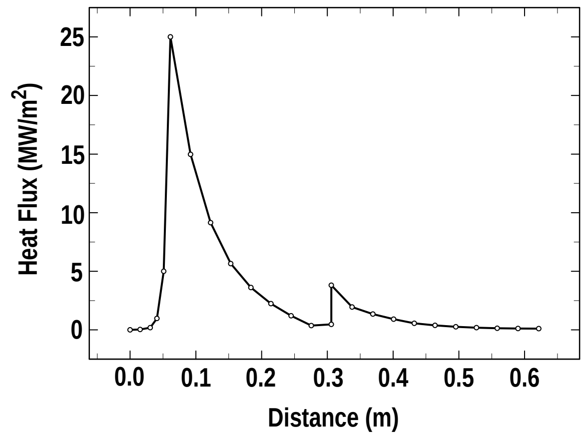

Fig. 3. Axial distribution of heat flux on divertor surface.

4. THERMAL STRESS MODEL

A 3-D thermal stress analysis of a segment of the FIRE divertor was performed using a finite element model input to the COSMOS code [5]. Since only 20 cm of the divertor of the total length of 55 cm is subjected to the high heat flux, only a 20.4 cm length is modeled. The support pins are spaced every 1.2 cm along the length of the divertor segment and assumed to be made from 316 LN stainless steel. The resultant reaction loads at the support locations are used to calculate the shear stress in the pins.

It is assumed that the divertor segment is free from residual stresses due to fabrication. A study of flow direction on coolant temperature at the location of highest heat flux indicated that the flow direction did not make a significant difference. Hence, an inlet at high heat flux end, which was suitable for manifolding was chosen. The coolant temperature varies from 30°C to 95°C along the channel. The convection film coefficient varies as a function of film temperature (average of coolant channel surface and coolant) and was calculated by correlations developed for ITER [6–8]. The material property data was assigned as a function of temperature [9,10].

5. THERMAL HYDRAULIC ANALYSIS RESULTS

In order to remove an incident peak heat flux of 25 MW/m^2, a very large flow velocity (> 20 m/s) is required if smooth channels are used. The flow velocity and flow rate required to cool the divertor can be reduced by using a heat transfer enhancement in the flow channels. A review of enhancement methods [8] shows that a swirl tube (ST) is the best available method. The ST is easy to fabricate and has a large reliable database. For a ST with a tape thickness of 1.5 mm and a twist ratio of 2 in the divertor channels of 8 mm diameter, a flow velocity of 10 m/s gives sufficient safety margin on critical heat flux (CHF) for the divertor. If two adjacent channels are connected in series, the maximum outlet temperature is 95°C and minimum exit pressure is 1.05 MPa, resulting in a minimum subcooling of 87°C.

A 2-D FE analysis of a divertor cell has been previously performed for these flow conditions [11]. This analysis was refined by a 3-D model, with the axial heat flux profile shown in Fig. 3. The heat transfer coefficient in the coolant channel is calculated as function of film temperature over forced convection and nucleate boiling region by methods described in Refs. [7] and [8]. The pressure drop is calculated by Lopina-Bergles correlation 12].

A steady-state condition is reached in about 6 s. Figure 4 shows the temperature distribution after steady-state is reached. The peak surface temperature is 1362°C and the peak heat flux on the coolant channel wall (WHF) is 29.75 MW/m^2. Since the calculated wall critical heat flux under these conditions is 48 MW/m^2 (this CHF value is much higher than calculated for ITER due to much lower coolant temperature for FIRE), we have a safety margin of about 1.61. The maximum copper temperature is 406°C. The flow per module is 9 ℓ/s.

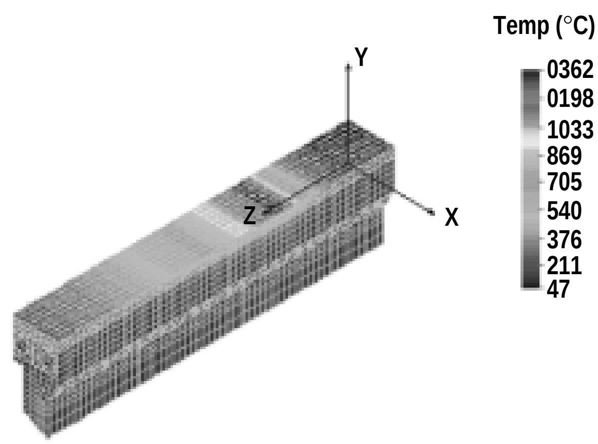

Fig. 4. Temperature distribution on surface of the divertor.

6. STRESS ANALYSIS RESULTS

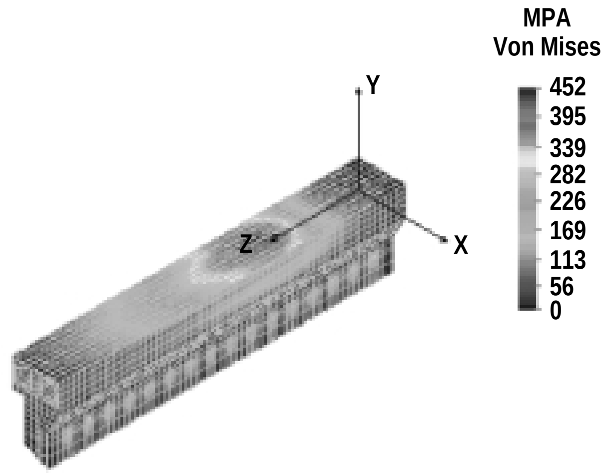

Fig. 5. Stress distribution in the heat sink.

A plot of the Von Mises stress in the heat sink due to thermal loads is shown in Fig. 5. The peak Von Mises stress in the heat sink is seen to be 452 MPa. This calculated thermal stress in the heat sink therefore exceeds the $3S_m$ limit for elastically calculated thermal stresses. However, maximum Von Mises stress is due to compressive components and that an elastic-plastic fatigue stress analysis may show acceptability due to a lack of stress concentration features at this location. Such an analysis is in progress. Also, thermal testing of this divertor design has been performed at Sandia National Laboratory at Albuquerque and shown to be successful for a large number of cycles of the prescribed heat flux [4]. Testing of a prototype is planned. The maximum tensile stress on the surface of a coolant channel is 307 MPa which is acceptable.

An analysis of the shear stress in the pins <u>without</u> axial sliding of the heat sink causes a shear stress of 954 MPa in the pins, which is not acceptable. The reaction forces on the support pins is due to the restrained lateral expansion and the loads restraining the bowing to the divertor segment. This stress can not be reduced to acceptable level by use of larger pins or by reducing the pitch. Hence the design was modified so that the pins can slide in the axial direction in slotted holes. The pins will be coated with electrically insulating material. This is an arrangement developed for ITER [2]. The maximum resultant pin reaction is 3450 N with this arrangement, resulting in a stress intensity of 433 MPa. For 316 LN stainless steel, the allowable thermal stress intensity is 441 Mpa up to temperatures of 150°C [11].

7. CONCLUSIONS

A satisfactory thermal and stress design of the FIRE divertor can be achieved with existing technology.

1. At an inlet of 30°C, 1.5 MPa and a flow velocity of 10 m/s in a swirl tube, water cooling provides a safety margin of 1.6 on the CHF to remove 25 MW/m^2 of peak heat flux. The total flow rate required for outer divertor is 288 ℓ/s. The peak PFC temperature is 1362°C and peak copper temperature is 406°C.
2. The flow direction does not have a significant impact on peak temperatures and stresses. The calculated thermal stress on the heat sink surface exceeds the allowable limit. However, similar heat sinks have been tested under expected heat flux conditions and have survived the required number of cycles. An elastic plastic analysis is in progress to insure acceptance of the design.
3. The maximum calculated thermal stress in the coolant channel is below the limit.
4. The copper heat sink is allowed slide in the axial direction relative to the support structure. This reduces the stress in the support pins from to 984 MPa to an acceptable value of 433 MPa.

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