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Effect of ELMS and disruptions on FNSF plasma-facing components

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ABSTRACT

Previous work has addressed the thermomechanical and electromagnetic effects of ELMs and disruptions on plasma-facing components in conceptual, commercial fusion reactors. Given that the proposed Fusion Nuclear Science Facility (FNSF) will have different geometry and plasma parameters, it is necessary to address similar issues in that context. Hence, this paper presents two key results: the thermomechanical response of the first wall and divertor to expected FNSF ELMs and disruptions, and the electromagnetic response of all structures inside the FNSF vacuum vessel to a plasma current quench. Structures considered in the electromagnetic analyses include the vacuum vessel, blankets, structural ring (which supports many of the internal components), and all internal shells used for plasma stability and control. The first wall is a ferritic steel structure with a thin tungsten coating and the divertor is all tungsten. Properties used for the divertor are those of pure tungsten, though it is quite possible that some alloy or nanostructured material would be employed at some point. Both the first wall and divertor are gas-cooled, so coolant pressures are quite high (8–10 MPa). The finite element code ANSYS is used to carry out all analyses and parametric studies are employed in order to identify parameters for which uncertainties will have a significant effect on the predicted performance. The ELM and disruption loads are found to be substantially smaller than those expected in a commercial reactor, so the component designs have more margin.

1. Introduction

Plasma-facing components (PFCs) in future fusion devices pose substantial challenges, due primarily to large anticipated and unanticipated thermal and particle fluxes. During normal operation, PFCs will be subject to a large time-averaged heat flux, which is accompanied by transients due to edge localized modes (ELMs). There are also substantial particle fluxes from the plasma. In addition to these anticipated loads, there will be the potential for substantial thermal and electromagnetic loads resulting from disruptions. In this paper, we attempt to address the severity of these issues by predicting the loads expected in a Fusion Nuclear Science Facility (FNSF) device and then calculating the thermomechanical response.

The FNSF design is a relatively small ($R < 5$ m) tokamak with superconducting coils ($B > 15$ T), long pulses, and power plant prototypic structure temperatures [1]. Transient heat loads on the PFCs are determined using a methodology previously described by Kessel [2]. These loads are then used to determine the expected temperatures, stresses, and strains in the first wall and divertor. The divertor is a plate-type, all-tungsten design that employs gas cooling in a jet configuration to enhance heat transfer. Properties for pure tungsten are used in the simulations. The first wall is reduced activation ferritic steel with a thin tungsten coating. For the electromagnetic effects of disruptions, a plasma quench is assumed to occur via a linear decay of the plasma current. Induced currents in all in-vessel components are determined and then a mechanical analysis is carried out to determine the ability of the structures to withstand the load.

2. Thermal loads from edge localized modes (ELMs)

Edge localized modes (ELMs) are very fast, repetitive thermal transients. ELMs are associated with the H-mode plasma confinement regime and provide periodic release of energy from the plasma. Although this is desirable for sustaining this plasma regime, the ELMs disperse large heat loads to the plasma facing surfaces. Predicted ELMs loads for ARIES-ACT1, ITER, and FNSF are Contained in Table 1. For FNSF, each ELMs event releases 14 MJ with one half of that energy going to the divertors and the other half to the outboard region of the first wall. This energy is deposited in a triangular pulse lasting about 1.5 ms at a frequency of 3.75 Hz. The repeated large energy releases present a design challenge for the plasma facing surfaces. For example, analysis of the thermal response of the ARIES-ACT1 outboard divertors

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Table 1
Predicted ELMs heating levels for ARIES-ACT1, ITER and FNSF.

	ARIES-ACT1	ITER	FNSF
DW_{ELM}^{large}, MJ	23.4	21	14.1
$Dt_{ELM,rise}$, ms	0.44	0.5	0.63
$Dt_{ELM,fall}$, ms	0.88	1	0.95
f_{ELM}, Hz	12	3.5	3.75
$q_{div,OB}^{peak}$ (ELM), MW/m^2	8350	5449	1102[a]

[a] Includes reduction factor of 4, per Ref. [4].

to a single ELMs thermal transient indicated the considerable melting would occur at the surface of the tungsten armor [3].

For the FNSF concept, the expected ELMs loads are reduced both in magnitude and frequency as compared to ARIES-ACT1. For the divertor, the peak heat flux has been reduced by nearly a factor of eight which is in part the result of an assumed area expansion factor of four that has been observed experimentally. For these analyses, the ELMs loads are delivered in the form of a triangular pulse with a rise time of 0.63 ms and a fall time of 0.95 ms at a frequency of 3.75 Hz. For the outboard divertor, the peak ELMs heat flux is 1102 MW/m^2, and the steady flux between ELMs events is 7.55 MW/m^2. The heating on the inboard divertor plates are predicted to be significantly lower; peak ELMs flux of 398 MW/m^2 and steady flux between ELMs of 2.76 MW/m^2. In this paper, only the more severe heating of the outboard divertor is examined. For the first wall, only the outboard region is subjected to ELMs loadings and the peak heat flux is predicted to be 163 MW/m^2.

2.1. *Thermostructural analysis of the FNSF divertor during ELMs*

As mentioned previously the baseline divertor concept for FNSF is the all tungsten plate type divertor developed for the ARIES program. This concept, as illustrated in Fig. 1, employs jet impingement cooling to enhance heat transfer and castellated surfaces to reduce thermal stress. Extensive analysis, design, and optimization efforts [5–11] have been made to ensure that the temperature and stress design requirements at steady surface heating rates exceeding 10 MW/m^2 are satisfied. The concept is constructed primarily of pure tungsten surface tiles and tungsten alloy structures. The high temperature capability and thermal conductivity of tungsten along with the castellations of the plasma facing surface enable the divertors to withstand high surface heat fluxes and make the structure tolerant to large transients, such as those caused by ELMS.

Thermal and structural analyses were carried out using ANSYS 3-D elements. The analyses used temperature dependent thermal and structural properties for tungsten taken from the ITER Material Properties Handbook [12]. We acknowledge that radiation damage and transmutation will alter these properties, but addressing those changes is beyond the scope of this paper. A smaller representative section of the component, representative of areas not near an edge, was modeled employing appropriate boundary conditions to simulate the effects of the surrounding structure and coolant flows. For the thermal analysis, this meant the external boundaries were adiabatic. For the structural analysis, one pair of edges were given symmetry constraints, while the other pair were constrained to remain plane but allowed to translate and rotate. ELM loads, as described in the previous section, were applied to the tile surface while spatially varying internal convection conditions gleaned from more complex fluid flow analyses [6] were applied to the internal coolant channels. The helium coolant was assumed to be at a temperature of 600 °C and a pressure of 10 MPa. Additionally, a 14 MW/m^3 volumetric body load was applied to the entire structure. The mesh was further refined near the plasma surface to better capture the localized transient thermal and stress gradients, and because these models were also used for fracture mechanics analysis extensive studies were performed to ensure mesh convergence near the surface. Contours of divertor temperatures between ELMs are plotted in Fig. 2. These results are after a number of cycles where a thermal equilibrium has been reached and there is little temperature change from cycle to cycle. Additionally, the loads considered here are for the outboard divertor which has the more severe loading relative to the inboard. Transient temperatures near the plasma facing surface are plotted as a function of time in Fig. 3. The surface temperature reaches a maximum of 3200 °C, rising nearly 1400 °C with each ELM heat pulse. For the predicted FNSF ELMs loads, the surface stays below the tungsten melting temperature of 3410 °C, but given the uncertainty in the material properties and load predictions the approximately 200 °C margin should be reexamined as the design and testing processes proceed. The large temperature extremes are localized to the surface of the tile. At a depth of 0.1 mm the temperature rise is 900 °C, while the rise

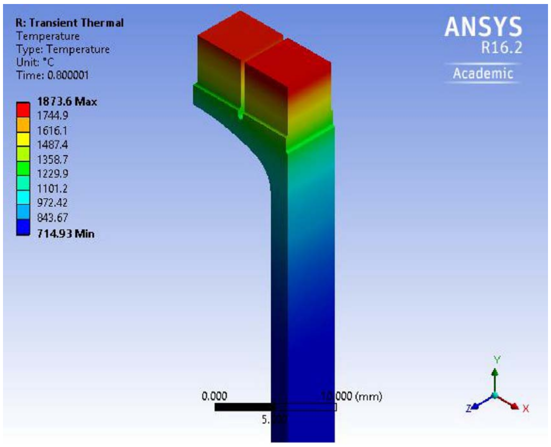

Fig. 2. Divertor temperature contour between ELMs events.

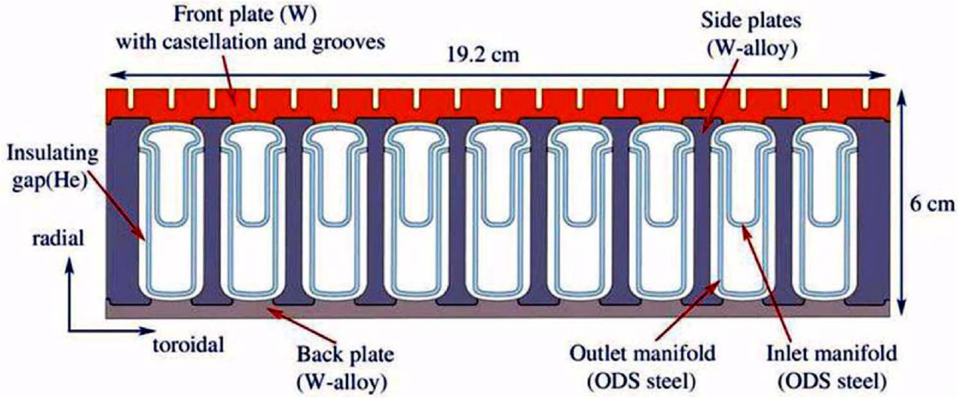

Fig. 1. Schematic of the ARIES plate divertor cross section.