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**Transient Thermal and Dynamic Stresses in
Strongback-Design Blankets ***

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Submitted to Third International Symposium on Fusion Nuclear Technology, June 27- July 1, 1994, Los Angeles.

* Work supported by the U.S. Department of Energy, Office of Fusion Energy, under Contract W-31-109-Eng-38.

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Transient Thermal and Dynamic Stresses in Strongback-Design Blankets *

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Abstract

Transient thermal stresses of the first wall are compared for strongback-design blankets that contain stainless steel, ferritic steel, or a vanadium alloy as structural materials.

Transient dynamic stresses due to plasma disruptions are computed on a parametric basis. Disruption loading characteristics, for which transient effects are important, are identified. Also explored are the relative merits of supporting the blanket at the top versus the bottom from the standpoint of dynamic stresses.

1 INTRODUCTION

To resist high electromagnetic forces created during plasma disruptions, blankets for fusion reactors such as ITER often employ a thick, toroidally continuous strongback structure. In addition, to avoid generating large radial currents during plasma disruptions, the first wall is made toroidally continuous (electrically) by welding adjacent segments at the first wall. Therefore, in this paper, adjacent blanket segments are considered structurally continuous in the toroidal direction.

In breeding blankets, the presence of significant nuclear bulk heating in the strongback region can help reduce the maximum thermal stress in the first wall during steady-state burn by minimizing the temperature difference between the strongback and the first wall. However, because the thermal-response time of the strongback is long

* Work supported by the U.S. Department of Energy, Office of Fusion Energy, under Contract W-31-109-Eng-38.

relative to that of the first wall, high transient thermal stresses may develop in the first wall during plasma on-off cycles and thus limit its fatigue life.

Plasma disruption events create electromagnetically induced radial pressure on the first wall. The response of the blanket structure to this dynamic pressure loading depends on the spatial and temporal variation of the pressure and the dynamic characteristics of the blanket. A strongback in the blanket design is necessitated by the consideration of stresses during disruptions. Relative merits of supporting the inboard blanket at the bottom versus supporting it at the top are considered for two rise times of the pressure loading.

The materials that were considered are Type 316 austenitic stainless steel, HT-9, and V-5Cr-5Ti. The allowable primary membrane stress intensity (twice the maximum shear stress), S_m , which is defined as the lesser of 1/3 ultimate and 2/3 (90% for 316SS) yield strengths at temperature, is shown for the three materials in Fig. 1.

2 PLASMA ON-OFF CYCLES

To illustrate the effects of a thick strongback on transient thermal stresses, a typical inboard blanket segment (Fig. 2) was considered for analysis. Because of symmetry, only one-half of a toroidal section was analyzed. Both the first and the second walls were considered curved (Fig. 2) because, without curvature, the toroidal thermal stresses were unacceptably high. Transient thermal and elastic stress analyses were conducted with the finite element code ANSYS.

2.1 Thermal Analysis

For present purposes, a plasma burn time of 1000 s, interspersed between 300-s rest periods was used. The heat deposition was assumed to start and end instantaneously with the onset and completion of ignition, respectively. The surface heat flux on the first wall is shown in Fig. 2. The bulk nuclear heating rate in the strongback region depends on the shielding provided in the blanket. Calculations were made with two values of bulk nuclear heating rate, 1 and 2 MW/m³. The coolant temperatures (T_c) in the first wall and the strongback regions for the three structural materials are shown in Fig. 2. The heat transfer coefficient was taken as 10,000 W/m²/°C in all cases. The thermal conductivity and heat capacity of all three materials were input as functions of temperature.

The variations of the peak temperatures in the first wall and the strongback with time during the first plasma burn cycle are shown in Fig. 3. For all three materials, the first wall responded very quickly when compared with the strongback. Figure 4 shows a similar plot for the peak strongback temperature over a plasma on-off-on cycle when the bulk nuclear heating rate was 2 MW/m^3 . The strongback did not cool down to the coolant temperature in 300 s of rest period for any of the three materials. More than one cycle was necessary to set up a steady cyclic temperature field. For all three materials, the maximum temperature difference between the strongback and the first wall occurred during the early part of the transients and not at the end of the plasma burn time, when steady-state conditions prevailed.

2.2 Analysis of Thermal Stress

Because the strongback and the first wall were assumed to be toroidally continuous, radial symmetry was used in all stress analyses, i.e., the side walls, after deformation, were assumed to remain in their respective original radial-poloidal planes. In addition, all thermal stress analyses were conducted under the assumption of a generalized plane strain deformation of the blanket, i.e., the blanket was free to expand but constrained from bending in the poloidal direction. A detailed three-dimensional thermal stress analysis of a blanket segment has confirmed that away from the top and bottom ends of the blanket, the generalized plane strain assumption is quite accurate.

Fig. 5 shows the effects of the bulk nuclear heating rate of the strongback on the time variation of maximum stresses in the strongback and the first wall of a Type 316 stainless steel blanket. The poloidal stress in the first wall at the plasma edge was highly compressive ($\approx -600 \text{ MPa}$) early ($\approx 20 \text{ s}$) during the plasma burn, and moderately tensile ($\approx 300 \text{ MPa}$) early ($\approx 20 \text{ s}$) during the rest period. Both of these peak stresses relaxed with time as the strongback temperature responded transiently and approached the steady state level. The peak transient stress was reduced during the second plasma burn cycle because the strongback did not cool down to the coolant temperature during the preceding 300-s rest period. Thus, the duration of the rest period may significantly affect the fatigue life of the first wall.

As expected, both transient and steady-state maximum stresses in the first wall during plasma burn were reduced when the bulk nuclear heating rate of the strongback was increased. However, the maximum transient stresses in the strongback throughout the cycle and those in

the first wall during the rest period varied directly in proportion to the bulk nuclear heating rate. Consequently, the maximum stress-range in the first wall, which controls its fatigue life, was not reduced by the bulk nuclear heating of the strongback.

Figures 6 and 7 show the variations of the maximum stresses in the first wall and the strongback, respectively, for the three structural materials. The maximum thermal stress ranges in both V-5Cr-5Ti and HT-9 blankets were within the $3S_m$ limit for the respective materials. On the other hand, the maximum thermal stress ranges in the Type 316 stainless steel blanket (both the strongback and the first wall) exceeded the $3S_m$ limit, indicating a potential for large cyclic plastic strain in this material for this design with plasma on-off cycles.

2.3 Conclusions from Thermal Stress Analysis

Transient thermal analysis should be conducted for blanket designs that use a thick strongback with significant bulk nuclear heating so that the maximum thermal stress range in the blanket can be calculated conservatively. Because the maximum stress range in the blanket can be underestimated, fatigue life may be significantly overestimated if life prediction is based on steady-state thermal analysis.

The higher the nuclear bulk heating rate in the strongback, the greater the maximum transient thermal stresses developed in the strongback (throughout the cycle) and the first wall during the rest period. On the other hand, the transient stresses in the first wall during plasma burn are reduced with increasing bulk nuclear heating of the strongback. As a result, although the maximum stress range in the strongback is increased, that in the first wall is relatively unchanged. Thus, an increase in the bulk nuclear heating rate of the strongback will decrease the fatigue life of the strongback but will not significantly influence the fatigue life of the first wall.

During plasma on-off cycles, cyclic plastic strains will not occur for V-5Cr-5Ti and HT-9 but are likely to occur for Type 316 stainless steel. The thermal-stress problem for Type 316 stainless steel can be mitigated by protecting the first wall from alpha heating by providing a heat-sink material (cooled), e.g., a copper alloy, on the plasma side.

3 PLASMA DISRUPTION EVENTS

During disruptions, toroidal electrical currents are induced in the blanket first wall. These currents interact with the poloidal magnetic field to create a radial pressure on the first wall. For centered disruptions, the poloidal variation of the pressure on the inboard first wall is approximately linear, with a maximum at the midplane. Toroidal variation of pressure at any poloidal location was assumed to be uniform. Two rise times, 5 and 25 ms, for the pressure were considered. The assumed temporal and spatial distributions of the pressure on the inboard blanket first wall are shown in Fig. 8. These pressure distributions may not be entirely realistic, because peak pressure generally decreases with increasing rise time. The purpose here is to explore, for a given peak pressure, the effects of rise time on the transient dynamic stresses.

A full three-dimensional analysis of a blanket segment (out of a total of 144 such segments) was conducted. As in the thermal analysis, the blanket segments were considered structurally continuous in the toroidal direction. The cross section of the blanket at midplane is the same as shown in Fig. 2, with the exception that the second wall was omitted. The poloidal geometry of the blanket was taken as the same as that of the ITER. Because of symmetry, only one-half of a blanket segment in the toroidal direction was modeled using shell elements. Two types of vertical support for the blanket strongback were considered: first, at the bottom of the blanket and second, at the top, both without constraint in the radial direction.

3.1 Quasistatic stress analysis

Figure 9 shows maximum membrane stress intensities in the strongback and the first wall for the two vertical support conditions. In both cases, the peak membrane stress intensity (primarily toroidal) of the strongback occurred at the midplane (where the pressure was highest) and was within the allowable limit S_m for all three materials. On the other hand, the maximum membrane stress intensity (primarily poloidal) in the first wall occurred away from the midplane region, toward the bottom (when supported at the bottom) and top (when supported at the top) of the blanket. The maximum stress intensity for the case where the blanket was supported at the bottom was still within the allowable limit for all three materials. However, for the case where the blanket was supported at the top, the maximum membrane stress intensity, although within the allowable limit for HT-9, exceeded the allowable limits for Type 316 stainless steel and V-5Cr-5Ti.

3.2 Dynamic analysis of blanket

In the dynamic analyses, the mass of the coolant and the shielding material in the blanket (assumed to be 50% volume fraction stainless steel) were included with that of the strongback. Because damping effects for an all-welded blanket structure (like ITER) are expected to be modest, the effects of damping were ignored during dynamic stress analysis.

3.2.1 Natural frequencies

The fundamental and fifth natural frequency modes of a blanket supported at the bottom are shown in Fig. 10. The frequencies for these two modes are ≈ 20 Hz and ≈ 70 Hz, respectively, for all three materials. Thus dynamic response of the blankets for the three materials is expected to be similar, and results from this point on are presented for Type 316 stainless steel only.

The same natural frequency modes when the blanket was supported at the top are shown in Fig. 11. Although the fundamental frequency was reduced to 9 Hz, the fifth natural frequency remained approximately the same as in the previous case.

3.2.2 Transient dynamic analysis

The transient dynamic analyses were conducted for the temporal and spatial distributions of disruption pressure shown in Fig. 8. The full method (i.e., using the full system matrices) of transient dynamic analysis with automatic time-stepping was used.

Blanket supported at the bottom. The poloidal variation of the maximum membrane stress intensity at the toroidal midspan location of the strongback is shown in Fig. 12, which also shows the times during the transient at which the maximum stresses occurred. The predominant component of the membrane stress intensity is the toroidal (hoop) tensile stress. A comparison of Figs. 9 and 12 shows that the magnification factors (defined as the ratio of the maximum transient dynamic membrane stress intensity to the maximum quasistatic membrane stress intensity) for the maximum membrane stress intensity in the strongback were 1.10 and 1.55 for 25- and 5-ms rise times, respectively. The location of the peak stresses remained at the midplane, where the applied pressure was also the highest. Time variation of the maximum stress showed that, for a rise time of 5 ms, the peak stress oscillated at the fundamental frequency

of the blanket, i.e., ≈ 20 Hz. For a rise time of 25 ms, higher modes were also excited.

A similar plot for the first wall is shown in Fig. 13. A comparison of this figure with Fig. 9 shows that although the location of the peak stress is unchanged, the magnification factors for the membrane stress intensity are 1.70 and 2.25 for 25- and 5 ms rise times, respectively. As in the quasistatic case, the predominant component of the membrane stress intensity was a poloidal compressive stress induced by overall poloidal bending of the blanket. These large increases in the maximum stresses may be reduced if significant damping effects are present.

Blanket supported at the top. A comparison of the membrane stress intensity in the strongback for a blanket supported at the top with that for a blanket supported at the bottom, for a rise time of 5 ms, is shown in Fig. 14. Although the maximum stresses for the two support conditions are approximately equal, a comparison of Fig. 14 with Fig. 9 shows that the magnification factor for the strongback, when the blanket was supported at the top, is 1.20 (cf. 1.55 for the case when the blanket was supported at the bottom) if the rise time is 5 ms. For a rise time of 25 ms, the magnification factor is 0.90 (cf. 1.10 for the case when the blanket was supported at the bottom).

A similar comparison of the maximum membrane stress intensity in the first wall of a blanket supported at the top with one supported at the bottom for a rise time of 5 ms is shown in Fig. 15. When the blanket was supported at the top, the magnification factor was only 1.03 (cf. 2.25 for the case when the blanket was supported at the bottom). For a rise time of 25 ms, the magnification factor was 1.25 (cf. 1.70 for the case when the blanket was supported at the bottom). However, in absolute terms, the maximum membrane stress intensities in the first wall of a blanket that was supported at the bottom were either equal to or less than those of a blanket that was supported at the top.

3.3 Conclusions from dynamic analyses

A quasistatic analysis showed that, for the assumed peak disruption pressure of 1.5 MPa and excluding stresses due to coolant pressure, the maximum membrane stress intensities in both the first wall and the strongback were within the allowable limits for all three materials if the blanket was supported at the bottom. On the other hand, if the blanket were supported at the top, the maximum membrane stress

intensity of the first wall exceeded the allowable limits for Type 316 stainless steel and V-5Cr-5Ti.

The fundamental natural frequency of vibration for a blanket supported at the bottom is ≈ 20 Hz, whereas that for a blanket supported at the top is reduced to ≈ 9 Hz.

If the blanket was supported at the bottom, the magnification factors for the strongback and the first wall increased as rise time decreases from 25 to 5 ms. The magnification factors for the first wall were greater than those for the strongback.

If the blanket was supported at the top, the magnification factor for the strongback increased but that of the first wall decreased as rise time decreased from 25 to 5 ms. The magnification factors for both the first wall and the strongback were generally lower than those when the blanket was supported at the bottom. However, in absolute terms, the maximum membrane stress intensities for cases where the blanket was supported at the top always equalled or exceeded those for the cases where the blanket was supported at the bottom.

If damping is ignored, the maximum transient membrane stress intensities in the strongback were within the allowable limits for all three materials for rise times between 5 and 25 ms, irrespective of the vertical support condition. For a rise time of 5 ms, the maximum membrane stress intensity limit for the first wall was satisfied for HT-9 but exceeded that for Type 316 stainless steel and V-5Cr-5Ti, irrespective of the vertical support condition. On the other hand, for a rise time of 25 ms, the maximum transient membrane stress intensity for the first wall was within the allowable limit for all three materials if the blanket was supported at the bottom, was within the allowable limit for HT-9 but exceeded that for V-5Cr-5Ti and 316 stainless steel if the blanket was supported at the top.

Fig. 1 Allowable primary membrane stress intensities for 316 stainless steel, HT-9, and V-5Cr-5Ti at various temperatures.

Mater.	T_c
316 SS	100°C
HT-9	250°C
V-5Cr-5Ti	250°C

Fig. 2 Geometry and thermal loading used for analysis. The strongback was subjected to an additional bulk nuclear heating rate. A total of 192 toroidal segments were assumed. First-wall angle ϕ was assumed = 120°.

Fig. 3 Variations of short-term transient peak temperature of first wall and strongback, made of three structural materials, for surface heat flux of 0.4 MW/m^2 and bulk nuclear heating of strongback of 1 MW/m^3 .

Fig.4 Variations of transient peak temperature of strongback, made of three structural materials, when strongback was subjected to a bulk nuclear heating of 2 MW/m^3 .

Fig. 5 Time variations of maximum toroidal stress in strongback (coolant edge) and maximum poloidal stress in first wall (plasma edge) of Type 316 stainless steel blanket as functions of bulk nuclear heating rate of strongback and when surface heat flux was 0.4 MW/m².

Fig. 6 Time variations of maximum poloidal stress in first wall for surface heat flux of 0.4 MW/m^2 and bulk nuclear heating rate of strongback of 1 MW/m^3 .

Fig. 7 Time variations of maximum toroidal stress in strongback for surface heat flux of 0.4 MW/m^2 and bulk nuclear heating rate of strongback of 1 MW/m^3 .

Fig. 8 (a) Time variations of peak disruption pressure on first wall assumed for rise times of 5 and 25 ms. (b) Spatial distribution in the poloidal direction was assumed to be linear, with maximum value at the midplane. Toroidal pressure distribution at any poloidal location was assumed to be uniform and radial (i.e., normal to first wall).

Fig. 9 Poloidal distribution of maximum membrane stress intensity in first wall and strongback due to peak disruption pressure applied statically. Poloidal locations 1 and 43 correspond to bottom and top of blanket, respectively.

Material	Vibration Mode 1	Vibration Mode 5
316SS	20.3Hz	69.6Hz
HT-9	20.8Hz	70.1Hz
V-5Cr-5Ti	19.4Hz	71.4Hz

Fig. 10 (a) First and (b) fifth natural modes of vibration for inboard blanket supported vertically at strongback at bottom.

(a) Mode 1 (8.8 Hz)

(b) Mode 5 (67.8 Hz)

Fig. 11 (a) First and (b) fifth natural modes of vibration for Type 316 stainless steel inboard blanket supported vertically at strongback at top.

Fig. 12 Poloidal distribution of membrane stress intensity in strongback when its maximum corresponded to two rise times of disruption pressure. Element locations 1 and 43 correspond to bottom and top of blanket, respectively. Blanket was supported vertically at bottom.

Fig. 13 Poloidal distribution of membrane stress intensity in first wall when its maximum corresponded to two rise times of disruption pressure. Element locations 1 and 43 correspond to bottom and top of blanket, respectively. Blanket was supported vertically at bottom.

Fig. 14 Poloidal distribution of membrane stress intensity in strongback of blankets supported at bottom and top at times corresponding to their maximum values, for a disruption pressure with 5-ms rise time.

Fig. 15 Poloidal distribution of membrane stress intensity in first wall of blankets supported at bottom and top at times corresponding to their maximum values, for a disruption pressure with 5-ms rise time.

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