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THERMAL SHOCK CONSIDERATIONS FOR THE TFCX LIMITER AND FIRST WALL*

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Abstract: Resistance to thermal shock fracture of limiter and first wall surface material candidates during plasma disruption heating conditions is evaluated. A simple, figure-of-merit type thermal shock parameter which provides a mechanism to rank material candidates is derived. Combining this figure-of-merit parameter with the parameters defining specific heating conditions yields a non-dimensional thermal shock parameter. For values of this parameter below a critical value, a given material is expected to undergo thermal shock damage. Prediction of thermal shock damage with this parameter is shown to exhibit good agreement with test data. Applying this critical parameter value approach, all materials examined in this study are expected to experience thermal shock damage for nominal TFCX plasma disruption conditions. Since the extent of this damage is not clear, tests which explore the range of expected conditions for TFCX are recommended.

Introduction

The Tokamak Fusion Core Experiment (TFCX) represents the next tokamak device to be built in the U.S. fusion program. The mission of this device is to achieve long-duration, ignited-burn operation. Based on past operation of experimental tokamak devices, a significant number of plasma disruptions are expected during the lifetime of the TFCX device. A disruption frequency of three disruptions per 100 burn cycles is set as a design guideline.

The intense heating conditions experienced by the TFCX inboard wall and limiter surfaces during plasma disruptions will cause intense thermal shock (a sudden transient temperature change) of the surface material. This thermal shock leads to high, localized thermal compression stresses. If these thermal stresses exceed a critical value, failure of the near-surface structure will occur.

Other investigators have performed numerous studies to predict resistance to thermal stress fracture. Many of these previous studies are reviewed [1,2]. These investigators proposed a series of figure-of-merit type thermal-stress fracture parameters which apply to particular types of heating or cooling conditions. Several of these parameters are discussed in Ref. 1 and are useful for material selection and screening studies.

Most of the previous thermal shock studies were concerned with sudden quenching (cooling) of a hot material in a liquid bath. The type of heat transfer processes and thermal stress conditions for this situation are quite different from those experienced in a plasma disruption. In the quenching (cooling) process, heat is transferred from the liquid to the material by convection. Therefore, the heat transfer rate depends on the surface temperature, which changes during the process. Thermal stresses at the surface are tensile because the surface is cooler than the bulk material. For the plasma disruption process, the surface is subjected to a heat flux that is independent of the surface temperature, and the thermal stress at the surface is compressive since the bulk material is cooler than the surface.

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DISCLAIMER

Thermal stress resistance parameters previously used in fusion reactor studies [3,4] for material screening or comparison are:

$$R = \frac{\sigma(1-\mu)}{\alpha E}$$

and

$$R' = \frac{\sigma(1-\mu)k}{\alpha E}$$

where

σ = material strength
μ = Poisson's ratio
α = Coefficient of thermal expansion
E = Young's modulus
k = thermal conductivity.

The parameter R can be interpreted to be a measure of the temperature difference between the surface and bulk material that will cause thermal stress fracture. The parameter R′ is a figure-of-merit type thermal stress parameter which is only valid for steady-state heat transfer. Because of the transient nature of the plasma disruption heating process, the parameter R′ is irrelevant.

The purpose of this paper is to establish the thermal shock parameter relevant for the plasma disruption environment. The leading TFCX first wall and limiter candidate materials are low-atomic number ceramic materials. The ability of these brittle materials to withstand intense heating rates is assumed to be limited by fracture at excessive compressive strain. An expression for the temperature distribution that leads to a compression stress that exceeds the compression strength of the material is derived and used to develop the thermal shock parameter. The validity of this parameter is shown by a comparison of predicted results to previous experimental results [5]. First wall and limiter material candidates are then ranked on the basis of this parameter. The likelihood of thermal shock damage of TFCX first wall and limiter surfaces and the need for experimental investigations of this phenomena in support of the design and development of TFCX first wall and limiter materials are also discussed.

Thermal Shock Parameter for Plasma Disruption Conditions

The thermal stresses induced in a material subjected to intense plasma disruption heating will depend on the material properties and specific heating conditions. The material properties are temperature dependent, and the surface heat flux may vary during the disruption process. Several simplifying assumptions are made to facilitate the establishment of a simple figure-of-merit type thermal shock parameter. The temperature dependence of the material properties is neglected, and the heat flux is assumed to be constant during the disruption. Material properties are evaluated at 1000 K.

For the configuration shown in Fig. 1, the transient temperature response is given by:

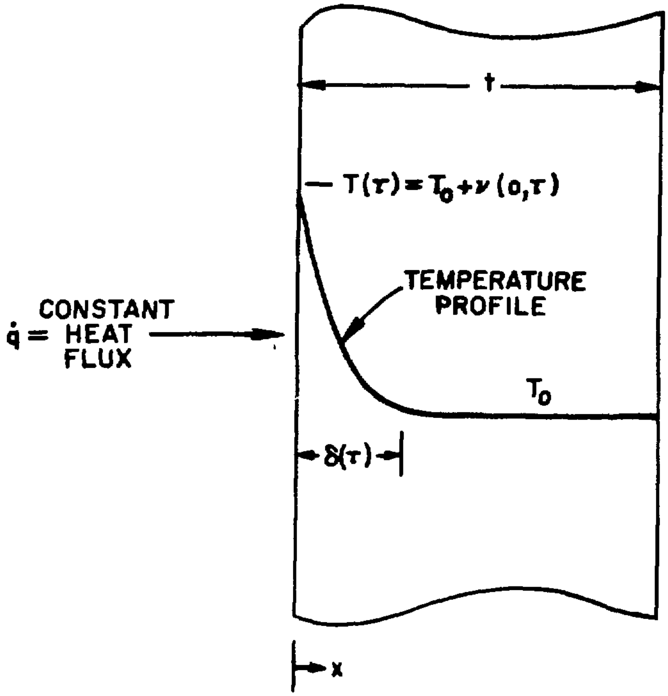

Fig. 1. First wall and limiter surface configuration

$$\nu(x,\tau) = \frac{q}{k}\sqrt{\frac{4D\tau}{\pi}}\left(e^{-x^2/4D\tau} - x\sqrt{\frac{\pi}{4D\tau}}\ \mathrm{erfc}\ \frac{x}{\sqrt{4D\tau}}\right) \quad (1)$$

where

x = distance from heated surface
τ = time from start of heating pulse
$\nu(\chi,\tau)$ = temperature rise above the initial temperature
q = heat flux
k = thermal conductivity
D = thermal diffusivity = $k/\rho C$
ecrf = complimentary error function
ρ = density
C = specific heat.

Equation (1) is valid for a semi-infinite slab. The semi-infinite approximation is valid if the penetration depth [6] (δ = depth to which thermal effects are felt) is less than the material thickness (t). The penetration depth is approximated by [6]:

$$\delta(\tau) = 2.8\sqrt{D\tau} \tag{2}$$

Therefore, the semi-infinite approximation is valid if:

$$\tau_f < \frac{1}{D}\left(\frac{t}{2.8}\right)^2 \tag{3}$$

where τ_f is the heating pulse duration. The heating duration at which this approximation breaks down is shown in Fig. 2 for a range of thicknesses and for several materials. For the first wall and limiter surface materials considered for TFCX, the duration at which this approximation is no longer valid is about 1 s for a 10-mm-thick layer of material. This duration is much greater than the nominal TFCX disruption duration of 10 ms. Therefore, the semi-infinite approximation is valid for TFCX disruption conditions.

Neglecting the $\sqrt{4/\pi}$ factor in Eq. (1), the rise of the surface temperature $\nu(o,t)$ is:

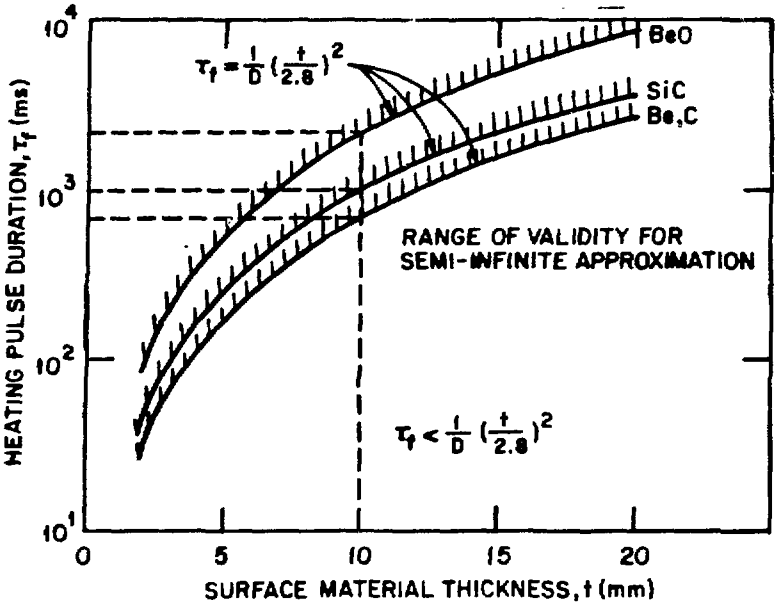

Fig. 2. Range of validity for semi-infinite slab approximation

$$\nu(o,\tau) = \frac{\dot{q}}{k}\sqrt{D\tau} \tag{4}$$

The maximum thermal stress, S, occurs at the surface and is simply:

$$S(o,\tau) = \frac{E\alpha\nu(o,\tau)}{(1-\mu)} \tag{5}$$

Substituting Eq. (4) into Eq. (5):

$$S(o,\tau) = \frac{E\alpha\dot{q}\sqrt{D\tau}}{(1-\mu)k} \tag{6}$$

$$= \frac{E\alpha\dot{q}}{(1-\mu)}\sqrt{\frac{\tau}{\rho c k}} \tag{6a}$$

Using Eq. (6a), the thermal shock figure-of-merit parameter for plasma disruption-type heating conditions is:

$$P = \frac{\sigma_c(1-\mu)}{E\alpha}\sqrt{\rho c k} \qquad (7)$$

where σ_c = compressive strength.

This new thermal shock parameter P depends only on material properties and differs from the steady-state thermal stress parameter R′ by a factor of $D^{-1/2}$.

A non-dimensional thermal shock parameter P′ formed from Eq. (6a) is:

$$P' = \frac{\sigma_c(1-\mu)}{E\alpha\,\dot{q}}\sqrt{\frac{\rho c k}{\tau_f}} \qquad (8)$$

The parameter P′ can be used to estimate whether a particular set of heating conditions will lead to thermal shock damage of a material. If P′ is less than unity, thermal shock fracture is expected.

Material Candidates and Properties

Materials considered for use as inboard first wall or limiter surface materials for TFCX are Be, BeO, C (graphite), and SiC. Material properties relevant to characterization of thermal shock resistance are listed in Table 1. Properties for several materials considered in previous experimental studies [5] are also shown in the table. The figure-of-merit parameter P provides a means for ranking the material candidates based on resistance to thermal shock damage. High values of P indicate a high resistance to thermal shock during disruptions. Graphite is more than a factor of two better than any of the other materials listed in the table.

Table 1. Material properties and thermal shock parameters

Material	ρ (Mg/m^3)	c (kJ/kg-K)	k (W/m-K)	E (GPa)	α (10^{-6}/K)	ν	σ_c (GPa)	P ($MW\text{-}s^{1/2}/m^2$)	R (K)
Beryllium (Be)	1.85	2.6	85.	130.	16.	0.03	0.2	1.9	93
Beryllium Oxide (BeO)	3.0	2.0	35.	365.	9.0	0.34	0.55	1.6	110
Boron Carbide (B_4C)	2.52	1.7	16.	450.	5.2	0.21	2.8	7.8	950.
ATJS Graphite (C)	1.83	1.8	60.	10.	6.0	0.2	0.1	19.	1300.
Silicon Carbide (SiC)	3.2	1.1	46.	360.	5.0	0.19	1.4	8.0	630.
Titanium Carbide (TiC)	6.56	0.86	38.	370.	8.6	0.19	2.1	7.8	530.
Zirconium Carbide (ZrC)	4.92	0.51	35.	360.	7.7	0.26	17.	4.3	450.

In addition to the parameter P, the parameter R is also listed in Table 1 for each material. If the parameter R is large, the thermal shock fracture of a material is less likely because a large portion of the heat will be dissipated by either reradiation from the surface or by vaporization and/or melting of the surface before the surface temperature reaches the critical temperature, defined by R, necessary for thermal shock fracture. As demonstrated in experiments [5], the relatively large value of R and P for graphite leads to such a situation. Sublimation of graphite acts as a heat sink and thus prevents the surface temperature from reaching the level required for thermal shock fracture. The parameters P and P′ along do not include this consideration. Therefore, the parameter R can also be important in evaluating the thermal stress resistance of materials.

Comparison with Experimental Results

Ulrickson [5] performed screening tests related to thermal shock resistance for several materials considered for use on TFTR limiters and first wall armor. Electron beams were used to heat test specimens with heat fluxes up to 180 MW/m^2 for pulse lengths up to 1.0 s. Although these heating conditions are significantly different from those expected for TFCX disruptions, these test results provide a reasonable basis for comparing the analytically determined thermal shock parameter P' with experimental results.

The experimental conditions (heat flux and duration) at which thermal shock fracture occurred are shown in Table 2 for several materials. Many more materials were examined in tests [5]; however, a full set of properties was not located for other materials. Therefore, these materials are not listed in Table 2. Recalling that a thermal shock parameter P' value of <1 should result in thermal shock fracture, remarkably good agreement is exhibited between the parameter P' and test results. Based on these results, it appears that the non-dimensional thermal shock parameter P' provides a reasonably accurate means to predict whether or not thermal shock fracture will occur under a specific set of heating conditions.

Table 2. Comparison of test results [5] with predictions

Material	q Limiting heat flux* MW/m^2	τ_f heating pulse duration* (s)	P (MW-s$^{1/2}$/m^2)	Non-dimensional thermal shock parameter* $P' = P/(q\tau_f^{1/2})$
SiC	25	0.5	8.0	0.45
B_4C	24	0.5	7.8	0.46
TiC	25	0.5	7.8	0.44
ZrC	20	0.5	4.3	0.30
ATJS graphite**	70	0.5	19.	0.38

*Values at which the test specimen fractured.

**Sublimation occurred rather than fracture.

Plasma Disruptions for TFCX

Plasma disruption heating conditions for TFCX are highly uncertain. Nominal values of the disruption parameters are listed in Table 3. The range of values which represent the degree of uncertainty in each parameter are also shown in the table. The disruption scenario consists of a thermal quench phase, followed by a current quench phase.

Table 3. TFCX disruption parameters

	Nominal value	Range of values
Thermal quench		
Time - ms	1	0.2 to 5
Energy - MJ	69	60 to 77
To limiter	75%	50 to 100%
To first wall	25%	0 to 50%
Peaking factor		
Limiter	Same as opr. power distribution	--
First wall	1 (uniform)	--
Energy density - MJ/m^2		
Limiter	6.1	--
First wall	0.075	--
Current quench		
Time - ms	10	5 to 100
Thermal energy - MJ	17	9 to 26
Magnetic energy - MJ	35	0 to 70
Region of deposition	Inboard and limiter	--
Extent of region	20%	10 to 30
Peaking factor	2	1 to 3
Energy density - MJ/m^2	4.5	--

The thermal quench phase is characterized by a voltage spike and a general expansion of the plasma minor radius. Most of the plasma thermal energy (80% for the nominal case) is released during the thermal quench phase, with most of this energy (75% nominally) deposited on the limiter surface.

The subsequent current quench phase is characterized by a reduction in plasma current and a movement of the plasma toward the inboard first wall surface or the limiter, thus depositing the remaining 20% of the original plasma thermal energy. A significant fraction (50% nominally) of the magnetic energy in the plasma is converted to plasma thermal energy and also is deposited on the inboard first wall or limiter surface.

Nominal energy densities and heating durations are 6.1 MJ/m^2 to the limiter and 0.025 MJ/m^2 to the first wall during the 1-ms-long thermal quench phase and 4.5 MJ/m^2 to either the limiter or inboard first wall during the 10-ms-long current quench phase. Based on the degree of uncertainty listed in Table 3 for each parameter, energy densities from 0.05 MJ/m^2 to 10 MJ/m^2 and heating durations from 0.2 to 100 ms are a possibility.

Using the non-dimensional thermal shock parameter P' [Eq. (8)], the energy density that causes thermal shock damage of the surface is plotted as a function of heating duration in Fig. 3 for the TFCX first wall and limiter surface candidate materials (Be, BeO, C, SiC). As shown in Fig. 3, the nominal disruption parameters are much greater than the threshold value ($P' = 1$) for thermal shock damage for any of the candidate materials. Therefore, thermal shock damage of the first wall and limiter surfaces subjected to plasma disruption heating is expected. However, this damage may not necessarily result in catastrophic fracture. For short-duration disruptions, only a thin layer of material will be subjected to large thermal stresses; and thus the effects may be *localized* (e.g., spalling). Tests are required to examine the characteristics of the thermal shock damage for candidate materials at disruption-type heating conditions.

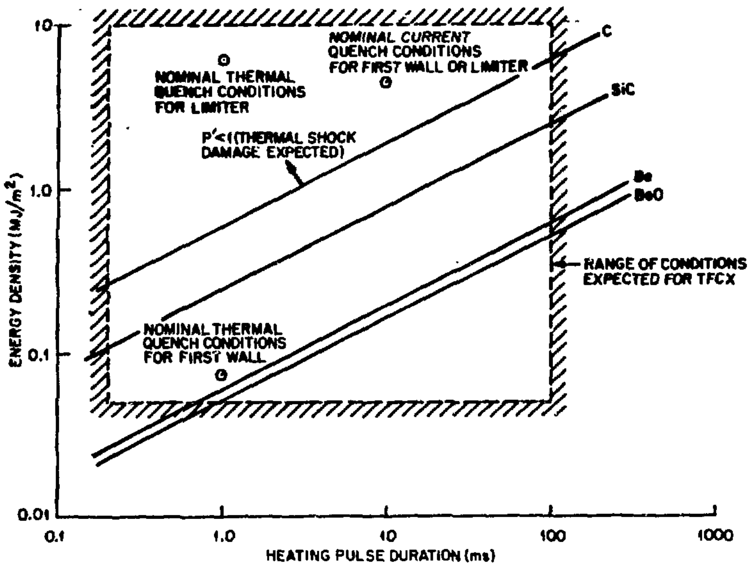

Fig. 3. Disruption heating limits for thermal shock damage.

Conclusions

The analysis procedure and resulting thermal shock parameters outlined in this paper provide a means to determine the relative resistance to thermal shock damage for TFCX candidate limiter and first wall materials. A method to estimate whether thermal shock damage is expected for a particular set of disruption-type heating conditions and a specific material was also developed.

Although this method facilitates the prediction of whether thermal shock damage occurs for particular heating conditions, the impact of thermal shock damage on the integrity of candidate tile materials must be evaluated with tests. Heating conditions that produce catastrophic fracture, as opposed to localized spalling of the surface, must be determined by tests with each of the candidate materials.

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