STRUCTURAL DESIGN METHODS FOR CERAMICS IN FUSION REACTORS

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SUMMARY

A feasibility study is made of constructing fusion reactors with materials that have very low neutron activations or very rapid after-heat decay. Certain ceramic materials such as graphite and silicon carbide deactivate many orders of magnitude faster than most metals, and have good high-temperature capabilities as well. The major disadvantage of these ceramics is that they are brittle. The problem is to identify the design, fabrication, and attachment technologies that will be required in order to make structural ceramics feasible in fusion reactors, in spite of intrinsic brittleness.

A probabilistic design approach based on the Weibull weakest link concept is used to characterize the scatter in strength, the size effect, and the probability of failure of ceramic fusion reactor structures. Life prediction for constant stress and cyclic stress loading is based on strength degradation due to subcritical crack growth. The design methodology has some basic implications for ceramic fusion reactor designs. The volume of the first wall for a tokamak reactor could be more than $10^7$ times the volume of a typical bend specimen used to determine the material strength. Thus, to overcome the size effect, materials with high strength and Weibull modulus and negligible strength degradation must be identified. Also, modular design and proof testing are essential.

A series of first wall/blanket modules for confinement systems such as tokamaks and mirrors have been analyzed. One modular design consists of a SiC container 1 m long and 0.5 m in diameter with a hemispherical end facing the plasma and the cylindrical end attached to a support structure. Finite element thermal and stress analysis was performed to provide the framework for an optimization of the thickness as a function of internal pressure and thermal loading. The usefulness of the probabilistic ceramic design approach is demonstrated by optimizing the thickness based on minimizing the probability of failure.
1. Introduction

Ceramic materials such as silicon carbide and graphite are being considered for fusion reactor applications [1]. These materials offer the advantages of high temperature capability and abundant raw materials as well as low induced radioactivity and low plasma impurity effects. To account for the brittle characteristics of these materials, new design techniques must be developed. A Weibull statistical design approach can be used to predict the probability of failure of the structure and to account for the scatter in the strength and the size effect [2]. Strength degradation during constant stress and cyclic stress loading can be included in the design technique [2]. The objectives of this paper* are (1) to briefly describe the design methodology and required material properties and (2) to present the results of the analysis of ceramic first wall/blanket conceptual designs [3].

2. Design Methodology and Material Considerations

In order to develop a design technique for brittle materials, the failure mechanism must first of all be characterized. The strength of ceramic material depends on the stress required to propagate small inherent flaws which are distributed throughout the ceramic material. The fracture stress, \( \sigma_f \), is related to the flaw size, \( a \), by the fracture mechanics relation \( K_c = \sigma_f Y \sqrt{a} \) where \( Y \) is a geometric factor and \( K_c \) is the fracture toughness, a constant. For ceramic materials there is a wide range of strength controlling flaw sizes and thus a wide variation in the fracture strength from one specimen to another. Also, the average strength of a group of specimens with a small volume of stressed material is higher than the average strength of specimens with a large volume of stressed material. This size effect is due to the higher probability of encountering a larger critical flaw with increasing volume of stressed material. The variation in fracture stress can be characterized by a weakest link model due to Weibull [4] where the risk of rupture is defined as \( R = \int (\sigma/\sigma_c)^m \, d\sigma \), and the probability of failure is \( P = 1 - \exp(-R) \), where \( \sigma \) is the stress, \( V \) is the volume (surface area could also be used for fracture controlled by surface flaws), \( \sigma_c \) is a normalizing constant, and \( m \) is the Weibull modulus. The Weibull modulus is a measure of the scatter in the strength distribution and the size effect, a small \( m \) value indicating a large amount of scatter and a large size effect. These relationships can be used to correlate the fracture behavior of specimens and to predict the probability of failure of structures. Thus, in addition to the average fracture strength, the unique material property that is required is the Weibull modulus. The risk of rupture is computed using the finite element method [2].

The effects of strength degradation due to subcritical crack growth must be considered in a design methodology for ceramic structures operating at high temperature. For stress intensities less than \( K_c \), subcritical crack growth is commonly described for many ceramic materials as \( v = A \sigma^n \) where \( v \) is crack velocity, \( K \) is stress intensity and \( A \) and \( n \) are constants that depend on environment and temperature. By assuming that the time-to-failure, \( t_f \), consists entirely of the time required for the subcritical crack growth of a preexisting flaw, the crack velocity expression can be integrated for constant stress (\( \sigma_f \)) and cyclic stress (\( 0 < \sigma_f \)) loading. For constant stress loading \( \sigma_f t_f = \frac{C_1}{A} \), a constant. For cyclic loading \( \sigma_f n t_f = \frac{C_1}{A} (n + 1) \) where \( t_c \) is the number of cycles multiplied by the period of the cycle. Thus, strength degradation due to subcritical crack growth can be incorporated into the design methodology where the material property that is required is \( n \), the strength degradation exponent.

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Three types of material data are necessary fracture input to a design methodology: the Weibull modulus, the fracture stress as a function of temperature, and the strength degradation exponent (n). The risk analysis assumes that the Weibull modulus is a material parameter which does not vary from specimen to structure. This means that the fabrication of the specimen and the structure should be the same, or that specimens should be prepared from some of the components. For fracture controlled by surface flaws, the surface preparation of the specimens and the structure should be the same. Thus the Weibull modulus is not a parameter that can simply be specified for a particular material. Data for the fracture strength as a function of temperature must be accompanied by the test configurations. The size of the specimen and the type of loading must be specified along with the time-to-failure and load condition -- constant stress rate or constant stress. The strength degradation exponent, n, can be determined from subcritical crack growth rate measurements or from constant stress rate tests over a range of loading rates. A more complete description of the design methodology is contained in Reference [2].

One problem which must be examined in all first wall material candidates is the effect of high fluence fast neutrons (E > 1 MeV) and ions on the mechanical and thermal properties. Thus, certain mechanical, electrical and structural properties of SiC and graphite at high temperature (~1200°C) were investigated after fast neutron irradiation [5]. Test samples of nominal dimension 2.5 mm x 2.5 mm x 25 mm (0.1" x 0.1" x 1") were fabricated from self-bonded SiC (Norton NC-430) and graphite (POCO AXF-SQ) and irradiated in the Brookhaven high flux beam reactor. Experiments were performed to obtain three types of data: the Weibull modulus, the fracture stress, and the strength degradation parameter. The observed decrease in Weibull modulus with increasing fluences for graphite at 25°C and SiC at 25°C and 1200°C indicates increased scatter in the fracture strength data and increased probabilities of failure of structures (Fig. 1). At 25°C the fracture strength of graphite increases with increasing fast neutron fluences while the fracture strength of SiC decreases (Fig. 2). At high temperature the fracture strengths of graphite (1100°C) and SiC (1200°C) are unaffected by irradiation indicative of high temperature recovery of irradiation damage. Additional details are given in [5].

3. Implications for Fusion Reactor Ceramic First Wall and Blanket Designs

The design methodology discussed previously has some basic implications for ceramic first wall designs for fusion reactors [6]. They concern the size effect and the life aspects of such designs. The size of the first wall is far larger than any of the volumes of the existing high temperature ceramic components under development today except possibly reactor graphite moderator elements. For example, a tokamak reactor with a first wall of major radius 13 m (43 ft.) and minor radius 5 m (16 ft.) would have an area of roughly 4π² Rmin Rmaj = 2500 m² (27000 ft²). If the thickness is assumed to be 5 mm (0.2 in.), the volume of the total wall is approximately 12.8 m³ (450 ft³). Individual modules of the first wall, as discussed previously, might well be of the order of 1 m (3.3 ft.) x 1 m (3.3 ft.) in dimension. Their volume would be of the order of .005 m³ (0.18 ft³). The results in Fig. 3 illustrate this size effect. The fracture strength of the material determined by a laboratory bend specimen is divided by the maximum stress in the structure and displayed as a function of the volume. It has been assumed that the load factor for bending is the same as the load factor for the structure. A first wall module is an order of magnitude larger than a "large" gas
turbine component, although well within the range of potential capability for one single component. The difficulty in assuring high probability of success (or low probability of failure) is that so many modules might be required for the complete first wall - of the order of 2500. Thus, materials of high strength and high Weibull modulus will have to be identified. It will have to be shown also that the Weibull modulus (an important parameter in the probabilistic considerations) does not significantly deteriorate with irradiation. There is some evidence [5] that the Weibull modulus does decrease with irradiation, and this observation may have profound ramifications in ceramic designs.

A further initial conclusion (based on the large volumes of ceramics which may be involved in the first wall designs) is that extensive proof testing of each module may have to be made. Figure 4 shows that for a probability of failure of the first wall of $10^{-6}$, the fracture strength of a small bond specimen must be 40 times the maximum stress for a Weibull modulus of seven. This would, of course, be nearly impossible. However, if each first wall module were proof tested where 1 in 10 failures would be allowed, the fracture strength would need to be only 5 times the maximum stress (Fig. 4). This proof test could be carried out by a laboratory thermal shock test that would reproduce the magnitude and distribution of the service stresses as nearly as possible.

Strength degradation due to subcritical crack growth would tend to shift the curves in Fig. 4 to higher fracture strengths or higher probabilities of failure (Fig. 5). The magnitude of this shift would depend on the strength degradation exponent ($n$) and the load history (Fig. 5). Since the fusion reactor will exhibit cyclic phenomena, the number of thermal cycles multiplied by the period of the cycle could provide a significant amount of time. A large amount of degradation (small $n$) can have a significant effect. Again, however, proof testing could be employed in order to attain a reasonable ratio of fracture strength to maximum service stress. The level of stress in the proof test would be of such a level to assure a certain given lifetime.

4. Application to Specific Ceramic First Wall/Blanket Designs

A series of design concepts for ceramic first wall/blanket structures have been developed [2]. These design concepts include the following:
1. A modular design consisting of a cylinder with a hemispherical end.
2. A radiating first wall consisting of an assembly of interlocking "cartons".
3. A radiating panel with cooling holes.
4. Tube and cylinder based concepts.
5. Falling sphere first wall/blanket concept.

The results of the analysis of the first concept will be discussed in detail below. Results for the other concepts are given in [7]. The temperature distributions were calculated with a finite element heat transfer program. With the temperature distributions and pressure loadings, a finite element stress analysis program was used to calculate the stress distributions. The stress distributions are transferred to a Weibull statistical analysis program [2] which calculates effective volumes and effective areas and the probability of failure. The use of these three coupled programs provides the probabilistic structural analysis of the design concepts.

The material properties of silicon carbide (SiC) and graphite vary with temperature, irradiation, microstructure, processing, and fabrication. Because of these wide variations and
since, except for the elastic modulus, the properties are nearly the same for SiC and graphite, the analyses used values of 3.5 J/cm$^3$K for specific heat * density, 43.2 W/m$^3$K for thermal conductivity, 4.0/°K for coefficient of thermal expansion, and 0.15 for Poisson’s ratio. The elastic modulus of graphite and SiC were 14 GPa (2 × 10$^6$ psi) and 372 GPa (54 × 10$^6$ psi), respectively.

The SiC module consists of a container (cylinder with a hemispherical end) to hold the breeding material. For coolant, pressurized helium would flow through lithium oxide or through a smaller thimble region surrounded by liquid lithium. In the first case, the ceramic container would provide the pressure vessel for the helium while a central coolant exit tube could provide attachment support for the module. In the second case, the ceramic container would not be pressurized but would support the liquid lithium. In either case, these modules would be mounted on a wall to surround the plasma regions of a tokamak reactor. The critical attachment region at the wall could be made with a shear joint. The module is 1 m long with a diameter of 0.5 m. Details are shown in Fig. 6 along with volumetric and surface heat loadings. Thickness of the ceramic was optimized as a function of pressure load and thermal loading (total wall loading) to 1 MW/m$^2$.

For the surface heat load the maximum temperature difference through the thickness (ΔT) was three times the ΔT resulting from the volumetric heat load. However, in all subsequent analysis, both heat loadings were used. For a heat transfer coefficient of 1100 W/m$^2$°K on the inside of the ceramic wall, the maximum wall temperature reached about 950°C at the tip of the hemisphere where the coolant was 650°C. The stresses for this case were about 25% lower than for the case where the heat transfer coefficient is very high and the inside wall temperature is the coolant temperature. In all of the following analyses 1100 W/m$^2$°K was used as the heat transfer coefficient.

The results of finite element analysis of various thermal and pressure loading situations were used to provide the frame work of an optimization of the ceramic wall thickness. These optimizations were obtained by procedures outlined in Fig. 7. The probability of failure is calculated as a function of thermal load and pressure and is shown in Fig. 8. The maximum stress is larger for optimum thicknesses found by minimizing the probability of failure than for optimum thicknesses found by minimizing the maximum stress. However the probability of failure is lower. This situation occurs because of the uniform pressure distribution in the cylinder and the localized thermal stress distribution in the hemisphere. The probability of failure calculation accounts for the uniformity of the stress distribution. This optimization demonstrates the usefulness of the probabilistic ceramic design approach.

In general, for a pressure of 5.07 MPa (50 atm.) and high thermal loads, a high strength SiC such as sintered SiC is necessary. However, the probability of failure can be reduced by lowering the heat load or reducing or eliminating the pressure load. The heat load could be reduced by a factor of 1/4 by eliminating the surface heat load with an independent first wall. The pressure load is eliminated with the liquid lithium system but the ceramic container must support the liquid lithium. Also, the diameter of the module could be reduced with a decrease in the pressure stress. All of these probabilities have been quantified and will be compared to other designs in the summary.

5. Summary and Conclusions

As a consequence of the scatter and size effect in the fracture strength of ceramics,
large ceramic first wall/blanket structures should be modular and each module should be proof tested. The use of a ceramic material with a high fracture strength, a high Weibull modulus (minimal strength scatter and size effect), and a high strength degradation exponent (minimal subcritical crack growth) is desirable. Finite element heat transfer and stress analysis can be coupled with a Weibull statistical analysis and effectively used to optimize the geometry of the ceramic structure and to produce minimum probability of failure for various pressure and thermal loading conditions. Design concepts with acceptable probabilities of failure can be produced. A number of designs would perform satisfactorily from a thermal-stress standpoint in the environments considered. However, other factors, particularly attachment concepts and performance, must be considered. In any case, the probability of failure of basic configurations such as the radiating first wall, tubes and cylinders, and spheres was low for typical loading conditions. The results for the complete first wall/blanket concepts - the module and a radiating panel are summarized in Table I. It should be noted that the probability of failure would be for the proof test while the probability of failure in service would be lower.

6. References

Table I. Summary of Results

<table>
<thead>
<tr>
<th>BLANKET DESIGN</th>
<th>LOADING CONDITION</th>
<th>THICKNESS (cm)</th>
<th>MAXIMUM STRESS (MPa (ksi))</th>
<th>PROBABILITY OF FAILURE**</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODULE</td>
<td>*</td>
<td>1.5</td>
<td>135 (20)</td>
<td>2 x 10^-2 (+)</td>
</tr>
<tr>
<td></td>
<td>NO SURFACE HEAT</td>
<td>2.2</td>
<td>60 (9)</td>
<td>1 x 10^-2</td>
</tr>
<tr>
<td></td>
<td>NO PRESSURE</td>
<td>1.0</td>
<td>56 (8)</td>
<td>2 x 10^-3</td>
</tr>
<tr>
<td></td>
<td>HALF DIA.</td>
<td>0.8</td>
<td>85 (12)</td>
<td>5 x 10^-2</td>
</tr>
<tr>
<td>RADIATING PANEL</td>
<td>*</td>
<td>2.0</td>
<td>62 (9)</td>
<td>1 x 10^-2</td>
</tr>
<tr>
<td></td>
<td>NO SURFACE HEAT</td>
<td>2.0</td>
<td>18 (3)</td>
<td>3 x 10^-7</td>
</tr>
<tr>
<td></td>
<td>HALF THICK.</td>
<td>1.0</td>
<td>41 (6)</td>
<td>1 x 10^-4</td>
</tr>
</tbody>
</table>

*Pressure = 5.07 MPa (50 atm.); surface heat load = 0.2 MW/m²; internal heat generation = 4 W/g.

**Fracture strength = 275 MPa (40 ksi) - typical for self-bonded SiC's which have good large size fabrication characteristics - except (+) where fracture strength = 550 MPa (80 ksi) - typical of sintered SiC - was used, Weibull modulus = 10.
Fig. 1. Weibull modulus vs. neutron fluence for graphite and silicon carbide at room temperature.

Fig. 2. Mean fracture strength vs. neutron fluence for graphite and silicon carbide. Also shown are the results of Matthews [8].

Fig. 3. Size effect in terms of the Weibull modulus, \( m \).

Fig. 4. Failure probabilities and proof test considerations.
Fig. 5. Effect of strength degradation exponent n on the probability of failure.

Fig. 7. Thickness optimization technique.

Fig. 8. Probability of failure for optimum thickness.

Fig. 6. Module - finite element mesh, thermal load, and coolant flow.