

Swelling Tolerant Design for a Fusion Blanket Structure

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ABSTRACT

Neutron-induced swelling is the largest dimensional change expected in the blanket structure of a fusion reactor. Most reactor blanket candidate materials are known or expected to swell and embrittle during irradiation; thus, the oft-suggested reliance on creep to relieve stresses is less acceptable in the design of a reactor blanket than in the design of nonirradiated structures. The desirability of avoiding the use of creep as a design tool is equivalent to a requirement that the blanket structure remain in the elastic regime. Such a design is examined and its performance, using various materials, is evaluated.

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1. Introduction

In the design of structures where deflection is not part of the purpose, dimensional changes due to operation are commonly of two forms: structural deflection under the applied load, where 0.1% dimensional change is a typical value, and thermal expansion effects in heated applications, where 0.05% is typical. The blanket structure of a fusion reactor will be subject to both of these dimension change effects. In addition, it will be exposed to a very large flux ($\sim 10^{19}$ n/m²/s) of fast neutrons and will experience radiation-induced swelling. The current perception is that in neutron fluences of the order of 10^{27} n/m², typical of a fusion reactor, the various materials will undergo a linear dimensional increase ranging from an extreme of around 10% for beryllium to ~5% for stainless steel, to perhaps 0.5% for some of the swelling-resistant structural candidates [1,2,3].

It appears that the functional properties of the material strength will stay within acceptable limits during this irradiation. Indeed, in several materials, the early effect of irradiation is to increase the strength and the hardness, although possibly at the expense of ductility and fracture toughness [2,4]. Thus, the completely serviceable blanket structural materials will be subject to conventional thermal and function-related strains and in addition, to radiation-induced swelling effects which are approximately an order of magnitude greater than the conventional effects. The swelling effects will therefore completely dominate the concept of the structural elements in the blanket, and consequently, solutions must be sought by means of the structural configurations used.

2. Blanket Structural Configuration

The configuration herein described has been evolved over the past few years with the purpose of developing swelling-tolerant designs in fusion reactors. Blankets of this type are described for a mirror in [7] and in a tokamak machine in [8]. The basic configuration consists of a ring of lobes under pressure held by a strong outer shell. This allows a comparatively thin first wall because of the reduced radius associated with the lobe. Figure 1 shows an embodiment of this which has been examined for a mirror machine.

The major task in the mechanical design is the containment of the helium gas coolant at a design pressure of 50 atm. Figure 2 shows the structure designed to fulfill this function. An end of one lobe is illustrated showing the lobed, semi-cylindrical first wall, the pressure balanced deep sides which tie the lobes to the outer shell, and the submerged tie structure built onto the sides which holds the end plates. Table 1 provides the specifications of the design.

The logic of the components is as follows. The lobe construction enables high pressures to be carried with a very thin first wall. A simple cylindrical module first wall would be about sixteen times as thick. The first wall swells in all directions. Though the thickness change is not significant, the change in radius caused by swelling must be accommodated by flexure. This flexure engenders stresses which mix with the simple tension due to coolant pressure, and this mixing is an important design consideration. Longitudinal swelling of the

first wall is accommodated by its bellows-like form and, thus, the stresses induced by bellows flexure do not mix with the major support system load paths or stresses.

Since the first wall must be of bellows form, it cannot contribute by axial tension to carrying the lobe end plate pressure loads. The lobe end plates are restrained axially by the plate which is built into the tieback panel and stretches the length of the module. Careful positioning of this plate can minimize the swelling stresses both in the tieback panels which are considerably affected by the exponential spatial variation of the neutron fluence, and in the first wall, which has simpler but more severe effects. This configuration shows the potential for tolerating 1.1% linear swelling without relief or assistance from creep, and without exceeding the allowable stresses which are well within the elastic limit.

The reference material for the first wall and structure in this application is Inconel 718. This is not the lowest swelling material available, however, its swelling tolerance is excellent. Swelling tolerance involves Young's Modulus at temperature, the allowable stress at temperature, and the swelling itself. Some comparatively low swelling materials are often disqualified by these interactions. To assess this, a revised version of a parameter proposed in 1982 [5] is suggested:

$$T_s = \frac{(S_{all})^2}{E} \times \frac{n}{\delta} \quad (1)$$

where T_s is a swelling tolerance indicator, high numbers reflecting superiority. n is fluence, E is Young's modulus, δ is the actual linear swelling, and S_{all} is the permissible working stress in the environment using all considerations in the calculation.

The outer shell sees essentially no neutron swelling and hence, is of conventional design. A number of swelling tolerant configurations are possible for the blanket contents. An example for solid breeder material is presented in [6]. The treatment of the radial tieback panels appears to be amenable to the methodology, if not the specific design features set out in that paper, which related to radially oriented fuel plates. The analysis of the swelling-tolerant first wall and blanket pressure boundary design is discussed in more detail below.

3. Analytical Work

First-wall temperature stresses with a through-wall ΔT of between 5° and 50°C and in-plane variations about the same were considered small enough to ignore in exploratory work of this nature. Swelling-temperature coupling was thus also ignored. Dimensional changes due to temperature are about 3% of the major swelling effects.

The corrugation form was selected so that the bellows flexural stress in its conventionally compressed mode would, at the end of life, equal the major lobe generated pressure stress plus the swelling induced additive flexural stress at right angles to the conventional bellows stress. This was an iterative procedure, the result of which is shown in Fig. 3.

In view of the fact that the corrugation is 6 mm high and the final major radius to which it is bent is 130 mm, these calculations are essentially accurate in a prismatic analysis, especially since the bellows length change is only 1.1%.

For a prismatic shape of the form shown in Fig. 3, the stress due to flexure is:

$$S_f = \frac{\Delta l}{l} \left(\frac{E \cdot t}{10.83 \cdot h} \right) \quad (2)$$

where l = the length of the bellows, t and h are per the figure, and E is Young's modulus.

The stress due to pressure is

$$S_p = \frac{Pd^2}{2t^2} \quad (3)$$

where d is per the figure.

As presented, it may appear that the above process led the design integration; however, it should be noted that iterations were required to match the stresses on each axis. The starting point was virtually a decision made jointly with the neutronic and thermal hydraulic designers that the first wall should be no more than 3.5 mm (0.14 in.) thick neutronically, and 1 mm thick thermally. This led directly to the design shown where every attempt was made to minimize the "beam depth" of the first wall which, at 6 mm, is very important to the elastically achieved swelling tolerance. The iterative process is expected to be replaced in later work by a procedure of direct synthesis, but in this case, time was not available.

Figure 4 shows the relationship of material choice and a key geometric parameter to the amount of swelling required to overstress the first wall region where the lobe faces join the tieback structures. Given a known pressure, the stress in a fixed design thin first wall containing that pressure as part of a cylinder, is simply derivable and is a direct function of radius:

$$S = P \times \frac{R}{t} \quad (4)$$

It should be noted that the t (thickness) is the total amount of material per unit length considered. Thus, stress clearly increases with radius.

A direct relationship can also be observed between the amount a given lobe is transversely compressed by swelling and the swelling characteristics of the material. This in fact, says that strain of the geometry is identical to the swelling. An equation from [9] can be used to derive the stress when the swelling based deflection is imposed. This is

$$S_B = \frac{\partial_x E y}{0.4304 R^2} \quad (5)$$

where ∂_x is the dimension the lobe diameter would have enlarged without restraint (% swelling \times diameter), E is Young's modulus, y the wall half-thickness as a beam, and R the wall radius. Thus, as the radius is made smaller, the swelling stress rises.

Figure 4 illustrates the fact that as the radius alone is changed, the combination of these two effects gives an optimum geometry. This geometry represents an optimum solution of the combined stress equations:

$$f_{\text{total}} = \frac{P \cdot R}{t} + \frac{\partial_x \cdot E \cdot y}{0.4304 R^2} \quad (6)$$

The factors ∂_x and E are descriptive of the materials available, and Fig. 4 shows a characteristic selection. The fact that y is not t/2 is of interest in the corrugation design as mentioned above.

Figure 5 shows the relationship of the material choice and lobe radius to the fluence required to overstress the blanket and resulted from the conversion of the swellings back to fluences in a linear relationship. The equation used was $\Delta l/l = f(\text{fluence}) = \text{constant} \times \text{fluence}$.

From published data [2], 0.1% linear swelling had associated fluences of 3.33×10^{27} N/m² for Inconel, 0.75×10^{27} N/m² for 20CW316, and 10×10^{27} N/m² for HT9.

In a situation where a detailed design was being studied rather than a broad selection made, the nonlinearity of the swelling curve could be important.

4. Discussion of Analysis

The above serves as an indication of the performance of various materials in the swelling tolerant blanket structural configuration. It is expected that the trend of the results will also be applicable to other configurations. All blanket structures must share available working stress between swelling and operating functions. The design shown has simple, and thus, clear elements; others will be more obscure but will nonetheless contain all of the above factors.

What is clearly indicated is that the swelling tolerance parameter proposed is emerging as a practical evaluation criterion. It is worth repeating that swelling, modulus, and allowable working stress are required to describe with exactness how any considered material will perform in a radiation environment. Calculation of this parameter gives the following values:

| <u>Material</u> | <u>Swelling Parameter</u> |
|-----------------|---------------------------|
| Inconel 718 | 3.26×10^{27} |
| 20CW-316 SS | 0.15×10^{27} |
| HT-9 | 1.66×10^{27} |

The swelling parameter units are newtons/m⁴. The structural analysis follows these values closely in assigning merit to the materials.

This is believed to be the first mechanical design attempt to limit swelling and operating stresses to normal working levels in a blanket design. Its necessity is based upon two precepts. The first is that creep relief is not an acceptable design tool, since it does not explicitly appear as a tool in any other engineering field. Second, the use of creep as a design tool invalidates the elastic stress strain relationships essential for the prediction of buckling structure performance (either compressive or shear). Thus, these much downgraded functions become of very limited use in the design and in any case, make many configurations fundamentally unacceptable, unless a new descriptive theory can be generated.

5. Conclusions

It may be concluded that swelling is an important consideration in a blanket structure, and that the above identifies one structural form with useful life within elastic stress constraints. It may further be concluded that material performances in the swelling environment are not simply dependent upon how much the given material swells but also upon its strength and stiffness, and that this is a factor of major importance in material selection.

Competitive selection will ultimately be made by cost, consequently, radiation resistance is not the absolute criterion. As this and other designs develop, cost of fabrication and changeout must be factored into the decisions.

References

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- [9] ROARK, R. J., Formulas for Stress and Strain, McGraw-Hill Book Co., New York, 1954, Table VIII, Case 1, p. 156.

TABLE 1
BLANKET STRUCTURAL SPECIFICATIONS

| | |
|--|---|
| Working pressure | 50 atm |
| Maximum temperature | 550°C |
| Material | Inconel 718 |
| Maximum working stress | 345 MPa (50 ksi) |
| Design-allowable swelling at maximum stress (derived figure) | 1.1% linear at a fluence of $3.6 \times 10^{23} \text{ n/cm}^2$ |

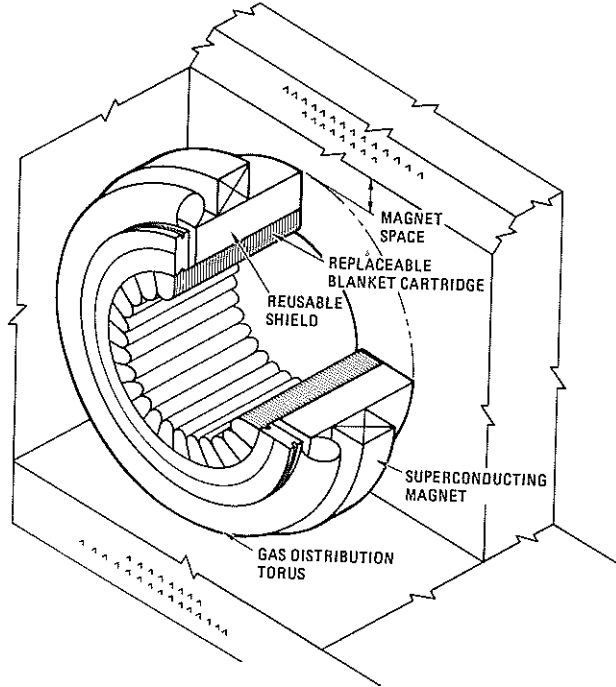


Fig. 1. Helium-cooled blanket modules.

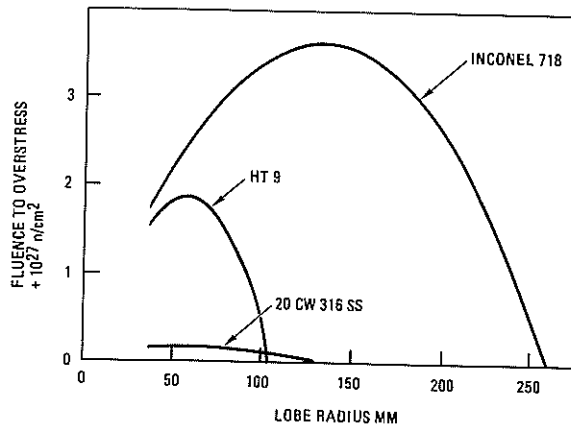


Fig. 2. Structural representation of lobe.

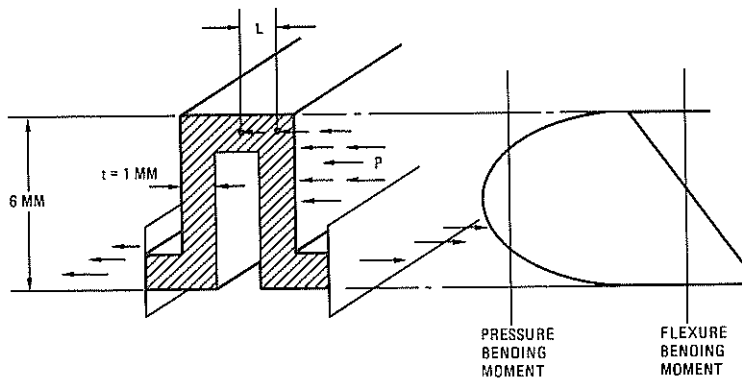


Fig. 3. Method of assessment of conventional bellows stress in prismatic form.

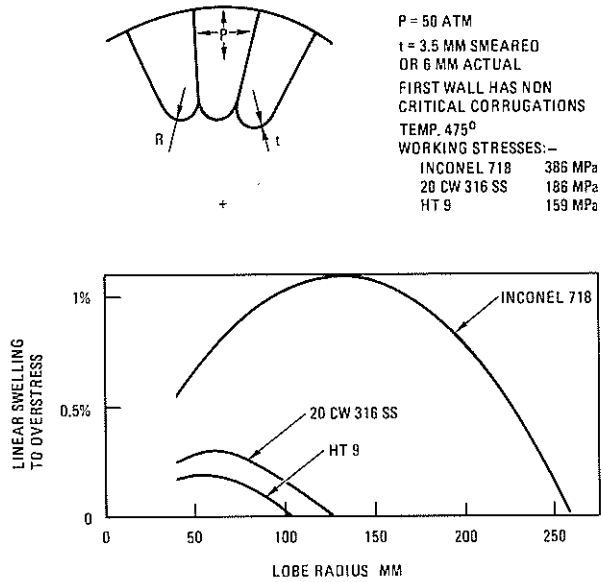


Fig. 4. Overstressing of candidate materials and geometries by swelling.

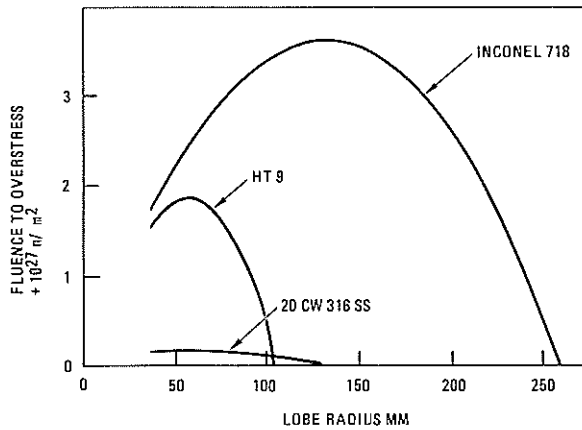


Fig. 5. Overstressing of candidate materials and geometries by swelling from neutronic irradiation.