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SOLID BREEDER/STRUCTURE MECHANICAL INTERACTION AND THERMAL STABILITY*

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ABSTRACT

Solid breeder/structure mechanical interaction (BSMI) during fusion reactor blanket operation is a potential failure mode which could limit the lifetime of the blanket. The severity of BSMI will generally depend on the materials, specific blanket designs, and blanket operating conditions. Thermomechanical analyses performed for a helium-cooled blanket employing $\text{Li}_2\text{O}/\text{HT}-9$ plates indicate that BSMI could be a serious concern for this blanket.

1. INTRODUCTION

In the Blanket Comparison and Selection Study (BCSS),¹ two helium-cooled solid breeder blankets were included for evaluation. Both blankets consist of radially oriented breeder (Li_2O and LiAlO_2) plates clad with thin sheets (0.25 mm thickness) of ferritic alloy HT-9. Helium coolant at 5.1 MPa enters the blanket through a flow distribution channel, passes the first-wall region (and a beryllium neutron multiplier zone in the LiAlO_2 blanket), then flows radially outward between the breeder plates. Flow gap spacing (1 mm width) is provided by wires wrapped around the exterior of the HT-9 cladding. Tritium recovery from the breeder plates is achieved by a low-pressure (0.1 MPa) helium stream flowing through grooved paths on the breeder surface. Several advantages were mentioned with regard to the above blanket design:

- (1) Since the HT-9 cladding is thin and subjected to a net gas pressure differential of 5 MPa, the cladding will collapse onto the breeder early during blanket operation. This will greatly reduce the uncertainty in the breeder/cladding interface conductance,² hence the uncertainty in the breeder temperatures.

- (2) The coolant pressure of 5.1 MPa will provide sufficient restraint to clamp the cladding against outward movement of the breeder.
- (3) In the event of a loss of coolant pressure, the gas pressure (0.1 MPa) inside the plates will not be high enough to rupture the cladding.

An issue identified for the above blanket design is the occurrence of solid breeder/structure mechanical interaction (BSMI) during blanket operation. The BSMI issue arises because it is a potential failure mode which could cause premature blanket module replacement and safety and environmental concerns. This paper examines the driving forces of BSMI and shows that the $\text{Li}_2\text{O}/\text{HT}-9$ blanket is more susceptible to BSMI than the $\text{LiAlO}_2/\text{HT}-9$ blanket. The remainder of the paper includes two types of thermomechanical analyses of the $\text{Li}_2\text{O}/\text{HT}-9$ blanket: (1) a hub-and-shaft analogy for interface pressure (BSMI) development and the resultant cladding stress and strength comparison, and (2) thermal stability (or instability) of the Li_2O breeder plate. These analyses, though approximate in nature, indicate that BSMI could be a serious concern for the helium cooled $\text{Li}_2\text{O}/\text{HT}-9$ blanket.

II. DRIVING FORCES OF BSMI

Solid breeder/structure mechanical interaction during blanket operation can occur from two sources: differential thermal expansion between solid breeder and structural material, and irradiation-induced swelling in solid breeders. Localized solid breeder/structure mechanical interaction can also occur in regions near breeder grooves, cracks, and interfaces. The differential thermal expansion strain ($\Delta\epsilon_{DTE}$) between solid breeder and structural material may be estimated as follows:

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$$\Delta \epsilon_{DTE} = (\alpha \Delta T)_b - (\alpha \Delta T)_s$$

$$= \bar{\alpha}_b (\Delta T)_b - \bar{\alpha}_s (\Delta T)_s, \quad (1)$$

where α is the thermal expansion coefficient, $\Delta T = T_1 - T_0$ ($i = b$ or s), T_0 is the reference room temperature, subscripts b and s denote solid breeder and structure, respectively, and the bars denote that the terms underneath are volume averaged quantities. Based on the thermal expansion data of Li_2O ,³ LiAlO_2 ,³ and HT-9,² and volume averaged temperatures of 650°C for Li_2O , 700°C for LiAlO_2 , and 500°C for HT-9, the estimated values of $\Delta \epsilon_{DTE}$ are 1.2 and 0.2% for $\text{Li}_2\text{O}/\text{HT-9}$ and $\text{LiAlO}_2/\text{HT-9}$, respectively. These $\Delta \epsilon_{DTE}$ values were obtained assuming that there is zero initial gap between the breeder and HT-9.

Significant irradiation-induced swelling has been observed in Li_2O , not in LiAlO_2 .⁴ The observed Li_2O swelling, at least during the early stages of the experiments, may be described as unconstrained swelling. In those experiments the gaps between the Li_2O pellets and cladding can accommodate the initial swelling without developing significant BSMI. In the $\text{Li}_2\text{O}/\text{HT-9}$ blanket for which there is no gap between the Li_2O and HT-9, however, BSMI will be induced as Li_2O swelling occurs at an estimated diametral swelling rate of $\sim 1.1\%/ \text{at.}\% \text{ } ^6\text{Li}$ burnup.

III. INTERFACE PRESSURE DUE TO BSMI

An elastic analysis is performed below to estimate the interface pressure due to BSMI and the associated cladding stresses in the $\text{Li}_2\text{O}/\text{HT-9}$ plates. The analysis draws an analogy for the contact pressure between a misfitting shaft-and-hub assembly or the so called "shrink-fit pressure". Since the assumed cylindrical geometry is more effective for pressure containment than the rectangular plate geometry, any problem noted in the shaft-and-hub case is an indication of concern for the plate case.

Assume that the radius of the shaft in the unstressed condition is larger than the inner radius of the hub by an amount δ . After assembly a pressure p is produced between the hub and the shaft. The magnitude of p is found from the condition that the increase in the inner radius of the hub plus the decrease in the shaft radius must be equal to δ , i.e.,

$$\frac{b\delta}{E_2} \left(\frac{b}{t} + \nu_2 \right) + \frac{b\delta}{E_1} (1 - \nu_1) = \delta, \quad (2)$$

where b is the shaft radius, t is the hub thickness, E_1 , E_2 and ν_1 , ν_2 are the Young's moduli and Poisson's ratio of the shaft and hub, respectively.

Rearranging Eq. (2) gives

$$p = \frac{\delta}{b} \left[\frac{1}{E_2} \left(\frac{b}{t} + \nu_2 \right) + \frac{1}{E_1} (1 - \nu_1) \right]. \quad (3)$$

The mismatch δ in Eqs. (2) and (3) can result from the differential thermal expansion between Li_2O and HT-9 and/or from the Li_2O swelling. For the following calculations, the shaft is assumed to be Li_2O with $b = 5.5$ mm (half thickness of the plate) and the hub is HT-9 with $t = 0.25$ mm. Mechanical properties used in the calculations are $E_1 = 5.44 \times 10^4$ MPa and $\nu_1 = 0.25$ for 80X-dense Li_2O and $E_2 = 1.62 \times 10^5$ MPa and $\nu_2 = 0.29$ for HT-9.

Since b is the shaft radius (or plate half-thickness), the quantity (δ/b) is the mismatch strain at the breeder/structure interface. The interface pressure can be calculated directly for a given δ/b , after which the cladding stresses can be obtained via thin-shell approximation:

$$\begin{aligned} \sigma_r &= -p/2 \\ \sigma_\theta &= p(b/t) \\ \sigma_z &= p(b/2t) \\ \sigma_e &= (\sqrt{3}/2)p(b/t), \end{aligned} \quad (4)$$

where σ_r , σ_θ , σ_z are the principal stresses in the radial, circumferential, and axial directions of the cladding, respectively, and σ_e is the cladding equivalent stress. The approximation for σ_z is based on the condition that the axial stress is zero when there is no friction between the breeder and cladding, and it approaches $p(b/t)$ when the breeder "sticks" to the cladding. For convenience, an average of these two values is assumed.

Table I lists the interface pressures (p'), circumferential stresses (σ_θ), and equivalent stresses (σ_e) in the HT-9 cladding obtained at three values of δ/b . The interface pressure p' is calculated as p from Eq. (3) and sub-

TABLE I
Interface Pressure and Cladding Stresses Due to $\text{Li}_2\text{O}/\text{HT-9}$ Mechanical Interaction (Shrink-Fit Analogy)

Mismatch Strain, δ/b (%)	p' (MPa)	σ_θ (MPa)	σ_e (MPa)
2.0	127.0	2790	2420
1.0	61.0	1340	1160
0.5	27.9	614	532

tracted from it 5.1 MPa, the counteracting pressure from the helium coolant.

Except for the case of $\delta/b = 0.5\%$, the cladding stress levels are all much higher than the ultimate tensile strength of HT-9 (540 MPa at 500°C).⁴ One would, therefore, expect almost an instantaneous cladding rupture if the mismatch strain of $>1\%$ develops and both Li₂O and HT-9 behave elastically. For $\delta/b = 0.5\%$ the cladding equivalent stress is above the yield strength of HT-9 (450 MPa at 500°C);⁴ hence favoring cladding plastic deformation. Earlier discussion showed that the differential thermal expansion strain between Li₂O and HT-9 is 1.2% and an unconstrained Li₂O diametral swelling up to 3.3% has been noted in the FUBR-1A experiment.⁵ These experimentally observed results more than envelope the δ/b ranges assumed in the above calculations.

The above analysis assumed that both Li₂O and HT-9 behave elastically. With Li₂O swelling gradually increasing during blanket operation, the magnitude of the interface pressure will also be affected by the plastic flow properties of Li₂O. Some credits may be taken for Li₂O hot pressing into the available internal pore spaces in the high temperature region of the Li₂O plates. However, a geometrical limit must be imposed on hot pressing beyond which elimination of breeder internal porosity is no longer possible. An optimistic limit for the sintered Li₂O at 80% TD would be 6.7% in linear dimension assuming isotropic hot pressing. A considerably lower limit (~3%) may be reached sooner when the major fraction of pores become closed pores. In either case, the amount of swelling strains that hot pressing can accommodate at Li₂O/HT-9 interface will be further reduced because hot pressing in Li₂O is not expected near the low-temperature (500°C) region of the plate.

While the tube geometry assumed for the analysis is stiffer than the plate geometry and therefore yields smaller changes in diameter than the anticipated changes in plate thickness due to contact loading, the resulting stresses for the tube geometry are considerably larger than those for the plate geometry. Away from the ends and sides of the plate, the cladding is relatively free to deform by bending with relatively small bending stresses induced. Thus, for the actual breeder plate, deformation limits (e.g. maintaining the coolant gap between plates) may be more important than stress limits.

IV. THERMAL STABILITY OF Li₂O PLATE

For the Li₂O/HT-9 plate design, there is a direct relationship between the coolant flow and the temperature levels in the breeder. Higher breeder temperatures cause thermal

expansion which results in less space for coolant flow. Reduced coolant flow then causes higher breeder temperatures and higher thermal expansion and so on. A problem of thermal instability might exist especially in situations where the coolant passage is narrow as is the case for the Li₂O/HT-9 blanket with helium flow gaps of 1 mm width.

A first-order perturbation analysis has been performed⁶ to study the above thermal instability problem for the Li₂O/HT-9 plate under the following assumptions:

- (1) There is a fixed amount of space available for one breeder plate and one coolant flow channel. That is, an increase in one results in a decrease in the other.
- (2) The pressure drop available for coolant is constant. That is, any decrease in coolant channel width results in reduced coolant flow rate.
- (3) Unconstrained thermal expansion of breeder.

Consider some initial perturbation ϵ_b of the breeder half-thickness d_b (perturbed parameters are denoted by superscript *)

$$d_b^* = d_b(1 + \epsilon_b) \quad (5)$$

As a result, the following parameters are also perturbed:

$$d_c^* = d_c(1 - \epsilon_c) \quad (6)$$

$$(\dot{m}_c^*)^* = \dot{m}_c^*(1 - \epsilon_m) \quad (7)$$

$$(\dot{Q}_{v,a})^* = \dot{Q}_{v,a}(1 - \epsilon_Q) \quad (8)$$

$$h_c^* = h_c(1 - \epsilon_h) \quad (9)$$

where d_c , $\dot{m}_c$, $\dot{Q}_{v,a}$, and h_c are the coolant channel half-width, coolant mass flow rate, average volumetric heating rate, and coolant-side heat transfer coefficient, respectively, and the ϵ 's are the perturbations on each parameter. The perturbations described in Eqs. (5) through (9) yield a further increase in breeder thickness

$$d_b^{\text{calc}} = d_b(1 + \epsilon_{\text{calc}}) \quad (10)$$

and the plate design is unstable if $d_b^{\text{calc}} > d_b^*$. To determine this relation, the following equations are used:

Space Constraint

$$d_b + d_c = \text{constant} \quad (11)$$

Pressure Drop

$$\Delta p = f \frac{L}{d_h} \frac{1}{2} \rho U_c^2 \quad (12)$$

Friction Factor

$$f = 0.00316 / \text{Re}^{1/4} \quad (13)$$

Hydraulic Diameter

$$d_h = 4 \text{ Area/Perimeter} = 4d_c \quad (14)$$

Nusselt Number Relation

$$\text{Nu} = 0.023 \text{ Re}^{0.8} \text{Pr}^{0.33} \quad (15)$$

and the volume-averaged solid breeder temperature T_{avg} is

$$T_{\text{avg}} - T_{\text{in}} = \frac{\dot{Q}_{v,a} d_b^2}{2k_b} q(\zeta) \times \left[\frac{2}{3} + \frac{2k_b}{h_c d_b} + \frac{4k_b L_b}{\dot{a}_c c_{pc} d_b q(\zeta)} \times \int_0^\zeta d\zeta q(\zeta) \right], \quad (16)$$

where T_{in} is the coolant inlet temperature, k_b is the breeder thermal conductivity, L_b is the length of the breeder plate, c_{pc} is the coolant heat capacity, and $q(\zeta)$ is the local nuclear heating rate with the dimensionless parameter ζ defined by z/l_b (coolant flow assumed in the z direction with inlet corresponding to $z = 0$). The particular goal is to determine ϵ_{calc} in terms of ϵ_b . This requires evaluating all ϵ 's. After some manipulations⁶ with Eqs. (5) through (15) and recognizing that ϵ_{calc} is related to the perturbed T_{avg} as $\epsilon_{\text{calc}} = \alpha_{\text{th}}(T_{\text{avg}} - T_{\text{avg}})$, where α_{th} is the breeder thermal expansion coefficient, the following equation is obtained:

$$\frac{\epsilon_{\text{calc}}}{\epsilon_b} = \frac{\dot{Q}_{v,a} d_b^2}{2k_b} \alpha_{\text{th}} q(\zeta) \left[\frac{2}{3} + 0.743 \frac{d_b}{d_c} \frac{k_b}{h_c d_b} + 6.86 \frac{d_b}{d_c} \frac{k_b L_b}{\dot{a}_c c_{pc} d_b q(\zeta)} \int_0^\zeta d\zeta q(\zeta) \right]. \quad (17)$$

With respect to the magnitude of $\epsilon_{\text{calc}}/\epsilon_b$, there are three possible situations:

$$\text{Stable: } \epsilon_{\text{calc}}/\epsilon_b < 1 \quad (18)$$

$$\text{Neutral: } \epsilon_{\text{calc}}/\epsilon_b = 1 \quad (19)$$

$$\text{Unstable: } \epsilon_{\text{calc}}/\epsilon_b > 1. \quad (20)$$

The combination of the stability criterion, Eq. (18), with Eq. (17) gives

$$d_c > \frac{0.743 \frac{k_b}{h_c} + 6.86 \frac{k_b L_b}{\dot{a}_c c_{pc} q(\zeta)} \int_0^\zeta d\zeta q(\zeta)}{\frac{2k_b}{\alpha_{\text{th}} \dot{Q}_{v,a} d_b^2 q(\zeta)} - \frac{2}{3}} \quad (21)$$

If

$$\frac{2k_b}{\alpha_{\text{th}} \dot{Q}_{v,a} d_b^2 q(\zeta)} - \frac{2}{3} > 0. \quad (22)$$

Any coolant channel width smaller than that in Eq. (21) is thermally unstable. An interesting observation is that for the cases that the denominator of Eq. (21) is negative, the breeder is unconditionally unstable, i.e.,

$$\frac{3k_b}{\dot{Q}_{v,a} d_b^2 q(\zeta)} < \alpha_{\text{th}} \quad \text{unconditionally unstable.} \quad (23)$$

It is important to note that the relation in Eq. (23) is rather general and does not depend on the coolant or the coolant channel. It introduces an absolute maximum for the thickness of the solid breeder d_b .

Two general thermal stability criteria, Eqs. (21) and (23), were obtained for a solid breeder plate design. One sets a minimum value for the coolant channel width while the other sets a maximum for the breeder thickness. Numerical calculations for the helium-cooled Li₂O/HT-9 plate indicate that the following should hold in order to maintain thermal stability of the breeder plate:

$$d_c > 0.4 \text{ mm}$$

$$d_b < 74 \text{ mm}$$

The limiting value of $d_c = 0.4$ mm, although very small, is close to the design value of $d_c = 0.5$ mm. The second limit, set by Eq. (23), is far from the design value of $d_b = 5.5$ mm and should not create any problems.

V. CONCLUSIONS

Simple elastic analysis with shrink-fit analogy indicates that solid breeder/structure mechanical interaction can be a serious problem for the helium cooled $\text{Li}_2\text{O}/\text{HT-9}$ blanket. Even in cylindrical geometry, the thin HT-9 cladding cannot sustain much interface pressure without yielding and undergoing large deformation which usually precedes fracture. Plastic deformation of Li_2O , particularly that of hot pressing, will bring about some relaxation of the solid breeder/structure interface pressure. Elastic/plastic analysis is needed to evaluate the effect of Li_2O hot pressing on BSMI which requires mechanical properties of Li_2O . Also, the analysis should be performed for the actual plate geometry with an emphasis on deformation as well as stress.

First-order perturbation analysis of a solid breeder plate has established two criteria for plate thermal stability. For the helium-cooled $\text{Li}_2\text{O}/\text{HT-9}$ plate design, the maximum breeder thickness criterion for thermal stability is amply satisfied, whereas the minimum coolant channel width criterion for thermal stability is only marginally satisfied.

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