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**A Model for the Mechanical Pellet-Cladding
Interaction During Power Cycles**

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1. INTRODUCTION

The use of solid breeders in blanket components of fusion reactors is necessitated by the need for tritium breeding, with avoidance of problems arising from liquid metal breeders; such as corrosion and MHD pressure drop. However, solid breeders have a relatively low fracture strength and poor mechanical properties. Their ability to withstand mechanical loads and thermal gradients is greatly reduced, leading to intolerable design limits. Another problem with solid breeder materials is the high retention of tritium and helium if the breeder is fully dense. To allow for tritium diffusion, and as a practical solution to their mechanical problems, solid breeders can be produced as porous square cylinders of dimensions on the order of 1-3 cm. Such cylinders, called pellets, are encapsuled in a structural cladding material which provide for a barrier to their interaction with the coolant. Moreover, the cladding material carries existing structural and thermal loads.

Figure (1) shows the blanket configuration, where the material 9-C (low activation equivalent of HT-9) is used for the outside structure of the module, as well as for solid breeder pin cladding. The first wall is cooled with high velocity helium through coolant channels, while the pins are cooled by helium in a cross-flow configuration. The first zone is made up entirely of Beryllium pins for neutron breeding, and then two solid breeder zones follow. The configuration and dimensions of pins in these zones are shown in figure (2).

In order to minimize maintenance time, a satisfactory configuration has to withstand transient phenomena associated with power-ramps and shutdowns while giving optimal thermomechanical performance in reasonable lifetime. These objectives can be reached by selecting suitable geometry and material specifications as well as prescribed temperature histories. Finding the minimal allowable ramp rate for startup is important from the economy of the operation, since overly conservative startup can amount to substantial percentage of the power cycle. In the stage of preliminary design the main concern is failure of the cladding due to high stresses or large total strains. The following analysis provides a simplified tool for design based on macroscopic mechanical interaction between the breeder and the cladding. The next most important effect to include in the analysis is phenomena associated with failure of materials at the micro-scale such as stress corrosion, creep fracture and fatigue. Some of these aspects of pellet-cladding interaction are covered in reference [4].

BLANKET CROSS SECTION

Fig. 1.

PIN STACKING: BREEDER ZONE 1

PIN STACKING: BREEDER ZONE 2

Fig. 2.

2. THEORETICAL FORMULATION

2.1 Assumptions and model restrictions

Since the thermal field (reference [1]) exhibits only a slight azimuthal asymmetry, the problem is formulated based on an axisymmetric analytical solution for the radial temperature distribution. Interaction between the changing geometry and the thermal field has been neglected during the course of the analysis. The size of the developed gap is in the order of hundredth of a millimeter which justifies this simplification.

The large length-radius ratio implies plane strain conditions for most of the pin. This is the result of the different cross-sections constraining each other from axial movement. Plane strain formulation gives a conservative estimate on the radial deformations and the stress field near free surfaces, therefore it can be accepted for design purposes.

Small deformation theory is used throughout the entire analysis. The thickness of the cladding is assumed to be small compared to its diameter, which leads to thin shell formulation in the cladding.

Material models for the pellet include linear elastic behavior, linear thermal expansion and temperature dependent swelling. The cladding material was assumed to exhibit linear elastic behavior, linear thermal expansion, temperature dependent creep. All linear material properties are taken as constants, although temperature dependence, especially in the pellet may have an influence on the results.

Quasi-static solution method is employed, for the frequency of the changes in the thermal field are small compared to the structure's eigenfrequencies. The presence of material and geometrical imperfections is also neglected.

The time dependent temperature field is also represented in a quasi-static manner as follows:

$$T(r,t) = T_{\text{preheat}} + (R(r) - T_{\text{preheat}}) T(\tau) \quad (2.1)$$

where $R(r)$ is the steady state temperature profile. Swelling is assumed to act only at full power, that is, when the temperature profile is fully developed.

For this analysis densification of the pellet material was neglected due to sparsity of available data and in order to simplify the analysis. This material nonlinearity might also be an important component in the interaction. Its effect would lower the contact stresses, therefore the current analysis is conservative as far as analysis of the cladding is concerned.

Fig.3 Geometry, notations

2.1.1 General Solution for the Pellet

The field equations corresponding to the above specified assumptions are as follows:

Strain-displacement relations:

$$\epsilon_r = \frac{u}{r} \quad (2.1)$$

$$\epsilon_t = \frac{du}{dr} \quad (2.2)$$

Strain - stress relations:

$$\epsilon_r = \frac{1}{E} ((1+\nu)\sigma_r - \nu\sigma_{kk}) + \alpha T + \epsilon^{sw}/3 \quad (2.3)$$

$$\epsilon_t = \frac{1}{E} ((1+\nu)\sigma_t - \nu\sigma_{kk}) + \alpha T + \epsilon^{sw}/3 \quad (2.4)$$

$$\sigma_{kk} = \sigma_{rr} + \sigma_{tt} \quad (2.5)$$

where r and t subscripts denote radial and tangential quantities respectively, ϵ^{sw} is the swelling strain, and the temperature measured from

some base value, T_0 . The $1/3$ factor gives dilatational strains from the volumetric strain when infinitesimal strains are assumed.

Equilibrium equations for an axisymmetric stress state reduce to one single equation:

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_t}{r} = 0 \quad (2.6)$$

Substituting the strain-displacement relations 2.1 and 2.2 into the constitutive equations 2.3-2.4, then the stresses in the equilibrium equation we arrive at the displacement form of the equilibrium.

$$\frac{d}{dr} \left[\frac{1}{r} \frac{d(ru)}{dr} \right] = \frac{1+\nu}{1-\nu} \frac{d}{dr} (T\alpha + \epsilon^{SW}/3) \quad (2.7)$$

The solution of this equation for an axisymmetric solid cylinder is:

$$u_r = \frac{(1+\nu)}{r} \int_a^r (\alpha T(r', t) + \epsilon^{SW}(r', t)/3) r' dr' + Cr = \Theta(t) + Cr \quad (2.8)$$

$$\sigma_r = - \frac{E}{r^2} \int_a^r (\alpha T(r', t) + \epsilon^{SW}(r', t)/3) r' dr' + C \frac{E}{1-\nu} = \Phi(t) + CA \quad (2.9)$$

$$\sigma_t = \Phi(t) - E(\alpha T(r, t) + \epsilon^{SW}/3) + CA \quad (2.10)$$

Equation 2.8 represents the radial displacement of the pellet at any given position r while equations 2.9 - 2.10 give the two dimensional stress field within the cross-section of the pellet.

Introduction of auxiliary functions Φ and Θ will make the rest of the equations more compact.

2.1.2 General Solution for the Cladding

Strain-displacement relation:

$$2\epsilon = \frac{2u}{b+d} \quad (2.11)$$

Stress-Strain relation:

$$2\sigma_t = 2E(2\epsilon - 2\alpha T(t) - \epsilon^T - \epsilon^R) \quad (2.12)$$

where the notation is as follows:

ϵ_t : total strain
 ϵ_c : accumulated creep strain
 ϵ^r : residual strain present, zero at initial state

and superscript 2 denotes quantities associated with the cladding in general.

2.1.3 Boundary Conditions

Continuity of displacements:

$$u_r(b,t) - d = {}^2u(t) \quad (2.13)$$

Continuity of tractions.

$$-(p_0 + \sigma_r(b,t)) \frac{b+d}{h} = 2\sigma_t \quad (2.14)$$

where p_0 denotes the coolant pressure which produces compressive stress in the cladding. Since the radial stress in the pellet is negative after contact 2.14 gives the right signs. Equations (2.13) and (2.14) lead to the following integral equation for the unknown function $C(t)$:

$$C(t) = F(t) + \epsilon^c \left(-\frac{b+d}{h} (\Phi(t) + AC(t)), T(t), t \right) \quad (2.16)$$

where

$$\delta = \frac{b+d}{h} A + 2E \frac{b}{b+d}$$

$$F(t) = \frac{1}{\delta} \left[-\frac{b+d}{h} (\Phi(t) + p_0) - 2E \frac{\Theta(t) - d}{b+d} + 2E(2\alpha T(t) + \epsilon^r + \epsilon^{sw}/3) \right] \quad (2.17)$$

and $\epsilon^c(\sigma(t), T(t), t)$, denotes the functional that gives the total creep strain due to a load history $\sigma(t)$ and temperature history $T(t)$. Assuming time-hardening which is identical to strain-hardening for continuous loads the creep strain functional has the following form:

$$\epsilon^c = \int_0^t \left[\frac{\hat{e}(\kappa, \theta, t')}{\delta t'} + \frac{\hat{e}(\kappa, \theta, t')}{\delta \theta} \frac{\delta \theta}{\delta t'} \right] dt' \quad \begin{matrix} \kappa = \sigma(t') \\ \theta = T(t') \end{matrix} \quad (2.18)$$

where $\hat{e}(\sigma, T, t)$ is the uniaxial creep response of the material to constant load σ and temperature T . Equation (2.16) is in the form of the familiar nonlinear Volterra equation of the second kind whose solution procedures are well established.

2.2 Method of Numerical Solution

To simplify the treatment here let us introduce a compact notation for the integral equation (2.17) here as follows:

$$C(t) = F(t) + \int_0^t K(t, \alpha, C(\alpha)) d\alpha \quad (2.19)$$

Now we discretise the time domain and evaluate (2.19) at points $t=nh$, $n=0, 1, \dots, N$.

$$C(nh) = F(nh) + \int_0^{nh} K(nh, \alpha, C(\alpha)) d\alpha \quad (2.20)$$

Equation 2.20 is approximated by using the trapezoidal rule:

$$\begin{aligned} C(nh) = F(nh) + \frac{h}{2} (K(nh, 0, C(0)) + K(nh, nh, C(nh))) \\ + h \sum_{m=1}^{n-1} K(nh, mh, C(mh)) \end{aligned} \quad (2.21)$$

In the last equation $C(nh)$, the unknown quantity appears on the right hand side. Replacing it by $C((n-1)h)$ gives an estimate for $C(nh)$. Subsequent refined values can be obtained by substituting the current estimate in the right hand side of 2.21 in place of $C(nh)$. This process is repeated until $C(nh)$ attains a predefined relative accuracy. It can be shown that the method given here is equivalent to the implicit modified trapezoidal rule discussed in some detail in reference [3]. The order of the method is two, which means that the global error behaves like $O(h^2)$. This scheme works well on stiff systems although several further refinements could be introduced. The present system shows stiffness in the solution, since after the transients due to power variations die out the solution exhibits a slowly varying quasi-steady state behavior. Tracking this part of the curve accurately is important, because it also contributes to the total accumulated strains present at the beginning of the subsequent cycle. This, in turn, defines the behavior during the next transient.

2.3 Effect of the power cycles

To simulate real operational conditions, a typical time history shown in Fig. 4 is used. One cycle consists of a power ramp, operation at full power, shutdown and dwell time at preheat temperature. If creep deformation occurs during the cycle then there will be a residual plastic strain in the clad after it separated from the pellet. This effect is equivalent to a permanent increase in the diameter of the clad and causes it to reach contact in the subsequent startup at a later time within the cycle. Since the formulation

given above is valid only during contact, the residual strains accumulated during contact and, the total time spent under swelling conditions has to be followed carefully in the course of the numerical solution.

Fig. 4. Time history $T(t)$ for assumed cyclic loading

3. MATERIAL CHOICES AND PROPERTIES

Two sets of materials are considered in this analysis. We will first analyze the combination of a Li_2O solid breeder clad with 2.25CrMo steel. Then we present the same analysis for LiAlO_2 and the 9-C martensitic steel. The corresponding material properties are listed below [2].

pellet : Li_2O

Young's modulus : 60 GPa

Poisson's ratio : 0.25

Coefficient of thermal expansion : $26.6 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$

Swelling equation:

$$\epsilon_{\text{sw}} = \left[0.3102 \frac{kT}{\gamma} \frac{fGt}{N^{1/3}} \right]^{3/2}$$

where the volumetric strain is given in (m/m), temperature is in absolute scale and time is measured in seconds.

$$N = 125479.5 \exp(-0.001000826 T) \times 10^{-14} \text{ cm}^{-3} \quad (2.22)$$

$$\gamma = 6.24 \times 10^{14} \text{ eV cm}^{-3}$$

$$G = 5.299 \times 10^{13} \text{ cm}^{-3} \text{ s}^{-1}$$

$$f = 0.035$$

$$k = 8.615 \times 10^{-5} \text{ eV}^\circ\text{K}^{-1}$$

Cladding : 2.25Cr - 1Mo

Young's modulus : 200 GPa

Poisson's ratio : 0.25

Coefficient of thermal expansion: $13 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$

Creep equation:

$$\epsilon^c = \frac{B}{kT} (\sigma - \sigma_0)^3 \exp(-Q/kT) H(\sigma - \sigma_0) \quad (2.23)$$

where the creep strain is given in (m/m) and the temperature dependent "back-stress" is defined as:

$$\sigma_0 = aT + c$$

$$B = 13209.0$$

$$k = 0.0000862$$

$$Q = 2.767$$

$$a = -0.2185$$

$$c = 198.1783$$

Temperature is on the absolute scale and the stress is measured in Mpa.

pellet : LiAlO_2

Young's modulus : 71 GPa

Poisson's ratio : 0.25

Coefficient of thermal expansion : $11.96 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$

The swelling equation is the same as (2.22) with the following parameters:

$$N = (0.0000292T^2 - 0.0292T + 7.71) \times 10^{-14} \text{ cm}^{-3} \quad (2.24)$$

and

$$\gamma = 6.24 \times 10^{14} \text{ cm}^{-3}$$

$$G = 5.299 \times 10^{13} \text{ cm}^{-3} \text{ s}^{-1}$$

$$f = 0.035$$

$$k = 8.615 \times 10^{-5} \text{ eV}^\circ\text{K}^{-1}$$

Cladding : 9-C

Young's modulus : 180.0 GPa

Poisson's ratio : 0.265

Coefficient of thermal expansion : $12 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$

4. RESULTS

Although superposition of the phenomena driving the pellet-cladding

PELLET-CLADDING INTERACTION
SECOND ZONE, FIRST ROW
NO SWELLING
GAP=0.0 m, PREHEATING AT 550 C
MATERIALS:
PELLET: LiAlO_2 , CLADDING: 9-C

Fig. 5.

PELLET-CLADDING INTERACTION
SECOND ZONE, FIRST ROW
NO SWELLING
GAP=0.00015 m, PREHEATING AT 550 C
MATERIALS:
PELLET: Li₂O, CLADDING: 2.25Cr-1Mo

Fig. 6.

PELLET-CLADDING INTERACTION
SECOND ZONE, FIRST ROW
NO SWELLING
GAP=0.00012 M, PREHEATING AT 550 C
MATERIALS:
PELLET: Li₂O, CLADDING: 2.25Cr-1Mo

Fig. 7.

PELLET-CLADDING INTERACTION
SECOND ZONE, FIRST ROW
NO SWELLING
GAP=0.0 m, NO PREHEATING
MATERIALS:
PELLET: LIAIO2, CLADDING: 9-C

Fig. 8.

PELLET-CLADDING INTERACTION
FIRST ZONE, FIRST ROW
NO SWELLING
GAP=0.0 m, PREHEATING AT 550 C
MATERIALS:
PELLET: LiAlO_2 , CLADDING: 9-C

Fig. 9.

PELLET-CLADDING INTERACTION
SECOND ZONE, LAST ROW
NO SWELLING
GAP=0.0 m, PREHEATING AT 550 C
MATERIALS:
PELLET: LiAlO_2 , CLADDING: 9-C

Fig. 10.

PELLET-CLADDING INTERACTION
SECOND ZONE, FIRST ROW
NO SWELLING
GAP=0.0 m, PREHEATING AT 550 C
MATERIALS:
PELLET: LiAlO_2 , CLADDING: 9-C

Fig. 11.

PELLET-CLADDING INTERACTION
SECOND ZONE, FIRST ROW
SWELLING IN THE PELLET
GAP=0.0 m, PREHEATING AT 550 C
MATERIALS:
PELLET: LiAlO_2 , CLADDING: 9-C

Fig. 12.

PELLET-CLADDING INTERACTION
TOTAL AND ACCUMULATED PLASTIC STRAINS
SECOND ZONE, FIRST ROW
SWELLING IN THE PELLET
GAP=0.0 m, PREHEATING AT 550 C
MATERIALS:
PELLET: LiAlO₂, CLADDING: 9-C

Fig. 13.

PELLET-CLADDING INTERACTION
SECOND ZONE, FIRST ROW
SWELLING IN THE PELLET
GAP=0.00015 m, PREHEATING AT 550 C
MATERIALS:
PELLET: Li₂O, CLADDING: 2.25Cr-1Mo

Fig. 14.

PELLET-CLADDING INTERACTION
TOTAL AND ACCUMULATED PLASTIC STRAINS
SECOND ZONE, FIRST ROW
SWELLING IN THE PELLET
GAP=0.00015 m, PREHEATING AT 550 C
MATERIALS:
PELLET: Li2O, CLADDING: 2.25Cr-1Mo

Fig. 15.

interaction is not possible due to their nonlinearity, their effects can be studied qualitatively on separate analyses. In order to gain quantitative data, integrated analysis has to be done. In the following, we present results of calculations illustrating the effects of various important variables on the pellet-cladding mechanical interaction problem.

a: Effect of solid breeder/cladding compatibility

On Fig. 5. and 6. the stresses for different designs under the same thermal operating conditions are shown. Solid lines represent the thermoelastic stresses had plastic strains not developed, while broken lines correspond to the modelled interaction. Swelling of the pellet has been neglected for these runs. Since the coefficients of thermal expansion for the $\text{LiAlO}_2/9\text{-C}$ design are closer, the difference in the displacement of the pellet surface and the cladding is smaller. Consequently, the same elastic stress levels occur at significantly smaller gap sizes, which is advantageous both for thermohydraulics and operation purposes. In fact, for the $\text{LiAlO}_2/9\text{-c}$ design zero initial gap is safe as it will be shown in the integrated analysis.

b: Effect of initial gap thickness

Fig. 7 shows the stress histories in the cladding due to a ramp variation of the center-temperature for $\text{Li}_2\text{O}/2,25\text{Cr-1Mo}$ materials. At larger initial gap thickness contact occurs later, consequently the resulting thermal stresses are much lower. A mere 0.3mm reduction in the gap size resulted in contact at the preheating temperature which is indicated by high tensile stresses initially. This effect seems to drive the whole interaction at a given set of materials, which implies that tolerances will play a crucial role in operation when the breeder and cladding materials are incompatible thermomechanically.

c: Effect of preheating

The third most important effect in the interaction process. Fig. 8. shows the results for the same material choice, steady state temperature profile and geometry as those for Fig. 6. This time the system is not preheated to 550 °C. Since the coefficient of the thermal expansion for the cladding is slightly higher than that for the pellet, initially there is no contact when the pin is preheated. Compressive stress due to the coolant pressure develop in the cladding. Its value is about one third of the critical buckling stress, which represents adequate margin of safety. The advantage of preheating from structural point of view is the interaction occurring at cladding temperature which permits creep. Therefore stress relaxation can act during startup relieving the peak stress significantly. Fig. 9.-10. show the stress relaxation for the characteristic locations of the blanket. Similar stress histories prevail, the first row of the second Li zone showing the highest peak stress. Further cyclic calculations were performed for this particular location.

d: Effect of the temperature ramp

On figures 6.-11. one can observe that the sensitivity of the results to the temperature ramp rate is not significant. When the slope of the temperature ramp is low the cladding can creep more before steady state profile is attained and the resulting displacement helps to accommodate

the thermal expansion of the pellet.

e: Effect of cyclic operation

Fig. 11 shows the effect of the residual strain for $\text{LiAlO}_2/9\text{-C}$ design. In the second cycle contact occurs later, therefore the stress level is lower as compared to the first cycle. For the particular geometry shown here it barely exceeds the value of the "back-stress" defining a threshold for creep, consequently creep strain is very low. The stresses tend to the "back-stress" asymptotically.

f: Effect of pellet swelling - integrated analysis

Fig. 12 illustrates the interaction under cyclic operation when swelling of the pellet is included for the same geometry and material selection as the previous figure. Swelling gradually builds up and instead of the decreasing stresses we see a slight increase and eventually higher stress levels. Another quantity limiting the lifetime of the pin is the accumulated plastic strain. Fig. 13 depicts the plastic strain and the elastic strain over four cycles for the $\text{LiAlO}_2/9\text{-C}$ design. Solid lines indicate the plastic strain, while broken line represents the elastic strain history. The elastic strains are decreasing which reflects the stress relaxation process, while the plastic strains are increasing. The plastic strains stay below 0.5%, and the plastic strain accumulated after the first startup is less than 0.05%. Extrapolating this value for the expected life of three years, the design is safe based on the 1% accumulated plastic strain criterion. On Fig. 15. and 16. the same stress and strain components can be seen for the $\text{Li}_2\text{O}/2.25\text{Cr-1Mo}$ design over one period. In this case swelling of the pellet is stronger, but the creep rate is also higher, therefore stresses remain low. On the other hand, accumulated plastic strain exceeds the 1% value by the end of the first power-cycle, which indicates failure. Because of this last finding and the sensitivity of the peak stress to the gap size, the LiAlO_2 design is recommended based on these structural arguments.

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