Thermal Stresses in Annular Glass-to-Metal Seals Under Thermal Shock

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The transient thermal stresses that develop in annular glass-to-metal seals subjected to a thermal shock are evaluated using a two-dimensional axisymmetric model. The results show that large transient maximum radial stresses occur which can cause separation at the interface between glass and metal. The magnitude of this maximum stress is largely dependent on the size configuration, the thermal shock medium used. For certain size configurations the stresses at the interface can be approximated using a plane strain analysis. The results for constant and temperature-dependent thermal expansion coefficients are compared. The effect of material property ratios is analyzed.

Nomenclature

A_b = total outside surface area of the base in contact with the fluid
A_o = outside surface area of lead in contact with fluid
c_g = specific heat of glass
c_k = specific heat of the metal
$\bar{h}_g$ = effective heat transfer coefficient between glass and fluid
$\bar{h}_k$ = effective heat transfer coefficient between metal and fluid
k_g = thermal conductivity of glass
ℓ = axial dimension of glass
N = total number of leads
r_1 = outside radius of glass annulus
r_2 = radius of lead
T_0 = initial temperature of seal
T_∞ = temperature of fluid
V_b = total volume of the base
V_ℓ = volume of the lead
ρ_g = density of glass
ρ_k = density of the metal

I. Introduction

THE thermal shock test is one of many tests used for the screening and qualification of microelectronic devices. Annular glass-to-metal seals are used in such devices to provide a hermetic seal for the internal components which are connected to the outside through electrical leads. The bond at the interface between the glass and the metal is made through the interpenetration of the glass into a layer of intergranular metal oxide. The resistance of this interface to a thermal shock is critical since any failure leads to loss of hermeticity which in turn causes failure of internal components.

The standard thermal shock test procedure as described in Ref. 1 consists of suddenly immersing the device into a cold fluid, followed by a sudden immersion into a hot fluid. Following each immersion, the device is kept in the fluid 5 min, allowing it to reach the temperature of the fluid. The cycling between cold and hot fluids is repeated 15 times. The severity of the thermal shock is varied by changing the temperature of the hot and cold fluid. The different test levels used, as well as the suggested fluids, are shown in Table 1.

In order to use the thermal shock test effectively and knowledgeably, one has to know how the test environment stresses the glass-to-metal seal. An experimental study conducted by Thomas,[2] in which microelectronic devices were submitted to thermal shock, showed that leakage appeared to be directly correlated with the thermal shock. He suggested that thermal stresses in the vicinity of glass-to-metal seals may be large enough to permit leakage during the thermal shock, which might go undetected during subsequent gross leak testing of the device.

In view of these findings, it is important to develop a mathematical model to evaluate the transient thermal stresses that are generated during the thermal shock test. Kokini et al.[3] obtained a first approximation to the solution of this problem by using a one-dimensional generalized plane strain analysis. This was revised by Libove et al.[14] Prior to these studies, thermal stresses in glass-to-metal seals were analyzed by Poritsky[5] and Hull and Burger[6] to determine residual stresses that occur in the glass during the fabrication of the seal. Borom and Giddings[7] evaluated the thermal stresses in a glass-to-metal seal due to a steady-state temperature excursion.

In this paper, the transient thermal stresses that develop in a glass-to-metal seal during thermal shock are evaluated using a two-dimensional axisymmetric model of the seal. The effects of varying the size of the seal, changing the thermal shock fluid (i.e., varying the effective heat transfer coefficient), and changing the materials that form the seal are investigated. The influence of temperature-dependent vs temperature-independent thermal expansion coefficients on the thermal stresses is analyzed. A comparison is made with the plane strain solution of the problem.

II. Formulation

Since microelectronic devices typically have many glass-to-metal seals (cf. Fig. 1) and since the size of such seals varies considerably from one case to another, a typical seal was modeled by considering one lead, one glass annulus, and an annular portion of the base material as three concentric cylinders. Therefore, the model used for the analysis of thermal stresses consists of three concentric cylinders as shown in Fig. 2.

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Temperature Analysis

The solution of the thermal stress problem requires the knowledge of the temperature distribution at every instant of time. For this purpose, a temperature model was developed. In this model, considering that the metal (an iron-nickel alloy) has a thermal diffusivity which is much higher than that of glass, it was assumed that the center lead and base (both made out of metal) conduct heat instantaneously. Therefore, each of these components was assumed to have a uniform temperature distribution at each instant of time.

The heat transfer to or from the glass takes place between the metallic components and the glass by conduction at the interfaces and between the fluid and the glass by convection at the surfaces exposed to the fluid. The amount of base which is exchanging heat with one lead and one glass annulus is assumed to be $1/N$th the amount of base with N being the total number of leads. This enables one to analyze configurations with more than one lead. This heat transfer process is schematically shown in Fig. 3. Therefore, the temperature distribution in the glass varies in the radial and axial directions. Assuming axial symmetry and temperature-independent material properties, the temperature distribution in the glass is governed by the following differential equation given in nondimensional form:

$$\frac{\partial t}{\partial \tau'} = \frac{\partial^2 t}{\partial R^2} + \frac{1}{R}\frac{\partial t}{\partial R} + \frac{1}{L^2}\frac{\partial^2 t}{\partial Z^2} \tag{1}$$

The initial condition is

$$t(R,Z,0) = 1 \tag{2}$$

The boundary conditions are

$$\int_0^1 \left(\frac{\partial t}{\partial R}\right)\bigg|_{R=1} dZ = At\bigg|_{R=1} + B\left(\frac{\partial t}{\partial \tau'}\right)\bigg|_{R=1} \tag{3}$$

$$-\int_0^1 \left(\frac{\partial t}{\partial R}\right)\bigg|_{R=r_1/r_2} dZ = Ct\bigg|_{R=r_1/r_2} + D\left(\frac{\partial t}{\partial \tau'}\right)\bigg|_{R=r_1/r_2} \tag{4}$$

$$-\frac{\partial t}{\partial Z}\bigg|_{Z=1} = Et\bigg|_{Z=1} \tag{5}$$

$$\frac{\partial t}{\partial Z}\bigg|_{Z=0} = Et\bigg|_{Z=0} \tag{6}$$

where

$$t = \frac{T_\infty - T}{T_\infty - T_0} \tag{7}$$

$$\tau' = \frac{\tau k_g}{\rho_g c_g r_2^2} \tag{8}$$

$$R = r/r_2, \qquad Z = z/\ell, \qquad L = \ell/r_2 \tag{9}$$

$$A = \frac{\bar{h}_k A_o}{2\pi\ell k_g}, \qquad B = \frac{\rho_k c_k V_\ell}{2\pi\ell r_2^2 \rho_g c_g}$$

$$C = \frac{\bar{h}_k A_b}{2\pi\ell k_g N}\frac{r_2}{r_1}, \qquad D = \frac{\rho_k c_k V_b}{2\pi\ell r_1 r_2 \rho_g c_g N} \tag{10}$$

Note that because of Eqs. (5) and (6) the temperature distribution is symmetric about a plane perpendicular to the lead axis at lead midheight. This symmetry has not been utilized to enable the analysis to handle the problem of an insulated boundary. This would be true if the lid were to be placed on the base.

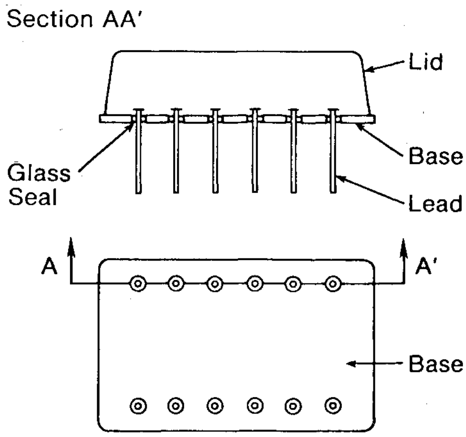


Fig. 1 Microelectronic package showing lead-throughs and glass seals.

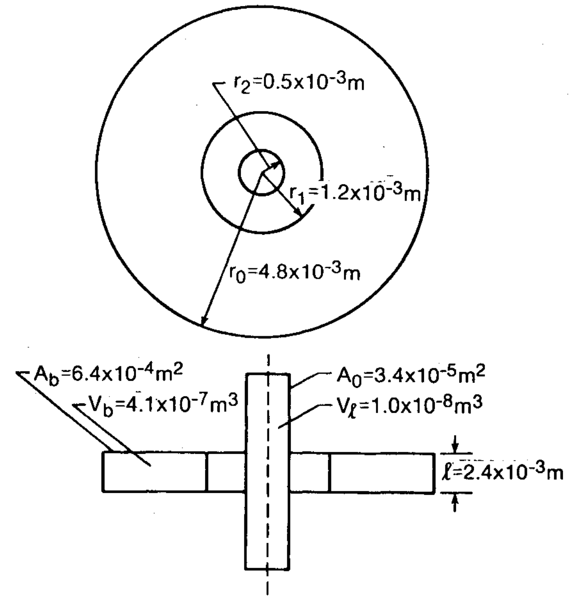


Fig. 2 Configuration and dimensions of glass-to-metal seal subjected to thermal shock.

Equations (1-6) were solved using an iterative, recursive, finite difference solution described in Ref. 8.

Thermal Stress Analysis

The problem of the thermal stresses generated during thermal shock in the lead, the glass, and the base material is treated as a quasisteady, uncoupled, axisymmetric thermoelasticity problem. The temperature distribution at the end of each time step is used to generate static thermal stress solutions.

The materials are assumed to be homogeneous, isotropic, and linearly elastic. All material properties are assumed to be independent of temperature, except for the thermal expansion coefficients of the metal and the glass.

The solution of the thermal stress problem is obtained using a finite element program called ABAQUS.‡ The finite element mesh used to generate the results is shown in Fig. 4. This mesh was obtained by reducing the mesh size until the difference in the results obtained became negligible.

The stresses obtained are nondimensionalized with respect to the lower bound for the strength of the interface which was determined through experiments and is presented in Ref. 9.

‡Developed by Hibbitt, Karlsson, and Sorensen, Inc., Providence, Rhode Island.

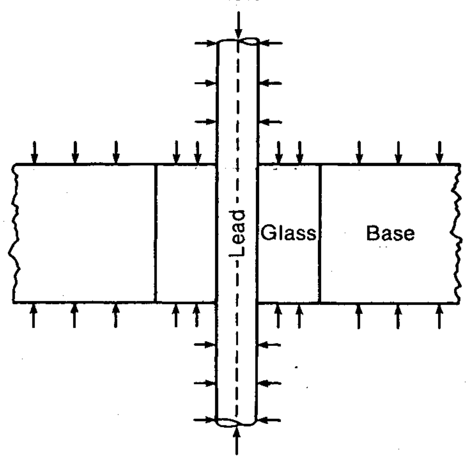


Fig. 3 Schematic representation of heat transfer to the three cylinders.

Thus, the magnitude of this stress thus obtained is 44.79 MPa. Therefore,

$$\{\sigma'\} = \{\sigma\}/\sigma_{\ell b} \tag{11}$$

where

$$\{\sigma\}^T = \{\sigma_r \ \sigma_\theta \ \sigma_z \ \tau_{rz}\}$$

$$\sigma_{\ell b} = \text{lower bound for strength}$$

The material properties are given in terms of the ratios

$$\alpha' = \alpha/\alpha_{gr} \tag{12}$$

$$E' = E_k/E_g \tag{13}$$

where subscripts k and g indicate metal and glass, respectively. α_{gr} is a reference thermal expansion coefficient.

III. Results

The temperature and thermal stress analyses described above are applied to the lead-glass base assembly shown in Fig. 2 which consists of a TO-8 eyelet with a lead sealed at the center. Consequently for this case the number of leads N is one. The material properties for the metal and glass are given in the Appendix.

The thermal shock test for which the results are presented consists of heating the seal from room temperture to 400°C slowly so that only steady-state stresses caused by a mismatch in thermal expansion coefficients develop, and suddenly immersing it in a fluid at room temperature.

The nondimensional radial stresses at three different locations in the glass are plotted as a function of time in Fig. 5. This figure shows that small initial residual stresses develop followed by large transient maximum stresses which are due to the thermal shock. The stresses become zero at room temperature. It should be noted that the largest transient radial stress occurs at the upper surface of the glass where large temperature gradients exist.

A comparison of the radial stresses at midheight of the glass-base and lead-glass interfaces shows that the maximum stress at the lead-glass interface is much larger than the glass-base interface. Thermal shock tests performed on microelectronic packages[2] show that failure in the seal usually occurs by separation of the interface between the glass and the lead. Among the four stresses (radial, hoop, axial, and shear) acting in the glass, only the radial and shear stresses can cause separation at the interface. The results show that the shear

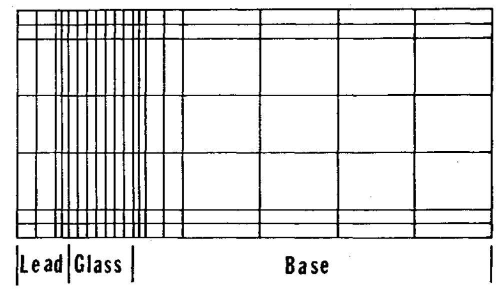


Fig. 4 Finite element mesh used for thermal stress analysis.

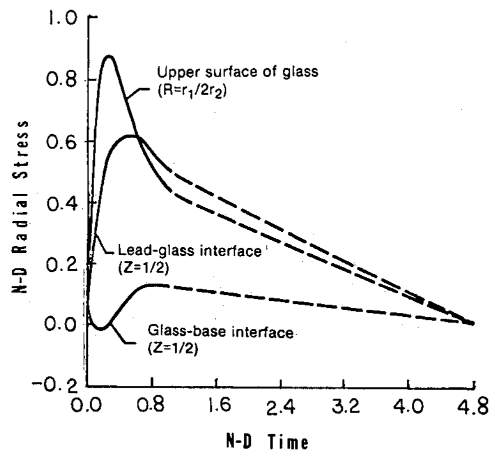


Fig. 5 Nondimensional radial stress vs nondimensional time in the glass seal at the positions shown.

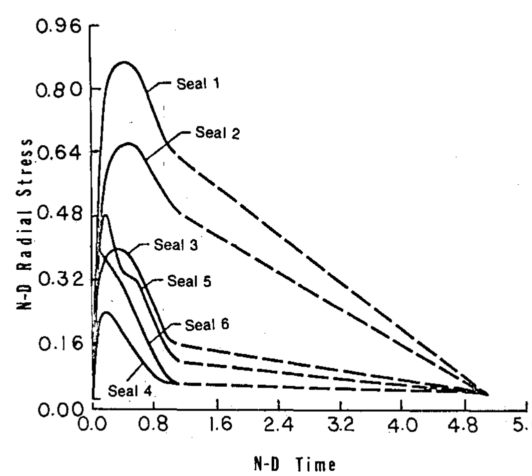


Fig. 6 Nondimensional radial stress vs nondimensional time at the midheight of the lead-glass interface for the six glass-to-metal seals.

stress at the interface is small compared to the radial stress. Consequently, the maximum radial stress at the lead-glass interface is considered to be most damaging to the seal.

Effect of Size

Glass-to-metal seals used in different applications are available in various sizes and configurations. In particular, the radius of the lead and the radius of the glass seal can vary from one case to another. The behavior of the thermal stresses with changing size configurations was investigated by applying the thermal stress analysis to six different glass-to-metal seals whose dimensions and thermal parameters are given in the Appendix. All of the seals are made of the same materials and in all of them the lead, the glass, and the base form three concentric cylinders. The most important difference is that they have leads of different radii and lengths,

Table 1 Standard thermal shock test levels

Condition	A	B	C	D	E	F
Low temperature, °C	0	−55	−65	−65	−195	−195
High temperature, °C	100	125	150	200	150	200
Fluid suggested for low temperature	Water	FC77	FC77	FC77	Liquid nitrogen	Liquid nitrogen
Fluid suggested for high temperature	Water	FC70 or FC40	FC70 or FC40	FC70 or UCON100	FC70 or FC40	FC70 or UCON100

and the outside radius of the glass annulus varies from one to another.

The nondimensional radial stress-time history at the midheight of the lead-glass interface for each seal is shown in Fig. 6. The magnitude of the transient maximum stress varies from one case to another. The largest stress occurs in seal 1 and has a magnitude of 0.821, while the smallest occurs in seal 4 and has a magnitude of 0.216.

This illustrates the effect that a variation in size can have on the magnitude and behavior of thermal stresses in glass-to-metal seals subjected to thermal shock.

The calculation of the thermal stresses in the same seals were performed using a plane strain analysis for which the heat transfer in the axial direction was neglected. The details of this analysis are given in Ref. 8. The maximum radial stress at midheight of the lead-glass interface obtained from the two-dimensional analysis and the maximum radial stress at the lead-glass interface calculated using the plane strain analysis for the six different seals are compared in Table 2. As shown, for cases where the ratio of dimension in the axial direction (ℓ) to the radial thickness $(r_l - r_2)$ is larger than 3.65 the plane strain analysis can be used to predict the maximum radial stress at the lead-glass interface within 5% difference.

Effect of Thermal Shock Fluid

The standard thermal shock test described in the Introduction is performed using different test fluids. In this section, the effect of using different test fluids on the thermal stresses is analyzed.

When different test fluids are used, the heat transfer process between the fluid and the seal is affected. In the mathematical model that describes this heat transfer process, this corresponds to having different heat transfer coefficients $\bar{h}_k$ and $\bar{h}_g$ in boundary condition equations (3-6).

The results presented so far correspond to immersing the seal from a high temperature into an oil bath at room temperature. The heat transfer coefficients were determined experimentally by measuring and recording the temperature-time histories of a TO-8 eyelet and a glass bead and by fitting an exponential curve to the experimental one using a least square fit. The heat transfer coefficients obtained for oil are $\bar{h}_k = 6759$ W/m^2 K and $\bar{h}_g = 1051$ W/m^2 K.

In order to analyze the effects of a different test fluid, the heat transfer coefficients for a fluorocarbon were also determined experimentally. These were $\bar{h}_k = 738$ W/m^2 K and $\bar{h}_g = 613$ W/m^2 K. The nondimensional radial stress at midheight of the lead-glass interface of seals 1 and 2 corresponding to a thermal shock in the two fluids is shown in Fig. 7. The maximum stress in each case occurs at different times and the magnitudes of the two maximum stresses differ by 32% with the maximum radial stress in the fluid which has smaller heat transfer coefficients being smaller. In general, it can be stated that smaller heat transfer coefficients will result in smaller maximum stresses. However, the effect of size should always be taken into consideration. For seal 2, Fig. 7 shows that the maximum radial stresses in the two fluids differ by only 11%.

Table 2 Maximum radial stress at lead-glass interface for six seals using two-dimensional and plane strain models

Seal	$\ell/(r_l - r_2)$	$\sigma'r$ 2-D ($Z = 1/2$)	$\sigma'r$ plane strain	% difference
1	8.45	0.795	0.840	−5.6
2	3.65	0.589	0.557	+5.4
3	2.57	0.348	0.288	+17.2
4	2.33	0.193	0.124	+35.8
5	1.38	0.444	0.169	+61.9
6	1.21	0.370	0.114	+69.2

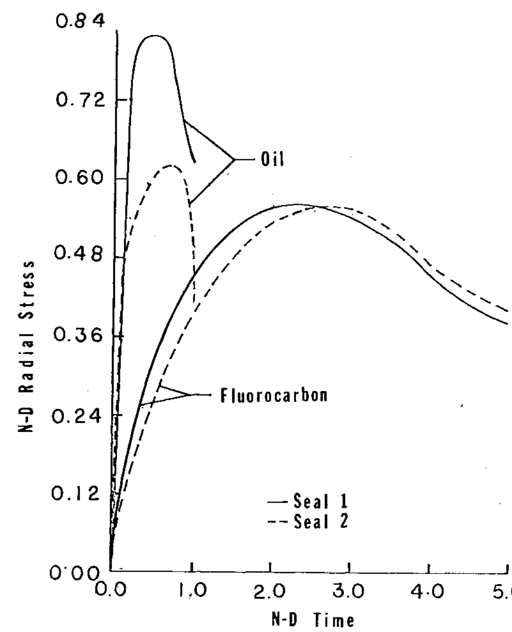


Fig. 7 Nondimensional radial stress vs nondimensional time at the midheight of the lead-glass interface for seals 1 and 2 during thermal shock in oil and fluorocarbon.

Effect of Temperature-Dependent Thermal Expansion Coefficients

The results presented in this paper are obtained using a temperature-dependent thermal expansion coefficient for glass and metal. The temperature extremes for the thermal shock test were 400°C and room temperature. The corresponding $\alpha = \alpha(T)$ relationship is given in the Appendix. These thermal expansion coefficients were obtained using the thermal expansion curve given for 7052 Corning glass and Kovar by their respective manufacturers. As an example, the thermal expansion curve for glass is shown in Fig. 8. The thermal expansion coefficient corresponding to 400°C was obtained by calculating $\epsilon_{400}/\Delta T_{400}$ and in a similar manner for the other temperatures.

In this section, the results obtained by using a constant thermal expansion coefficient will be compared with the

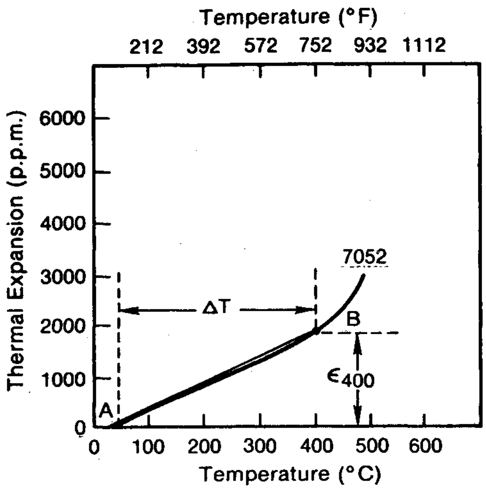


Fig. 8 Thermal expansion vs temperature curve for Corning 7052 glass.

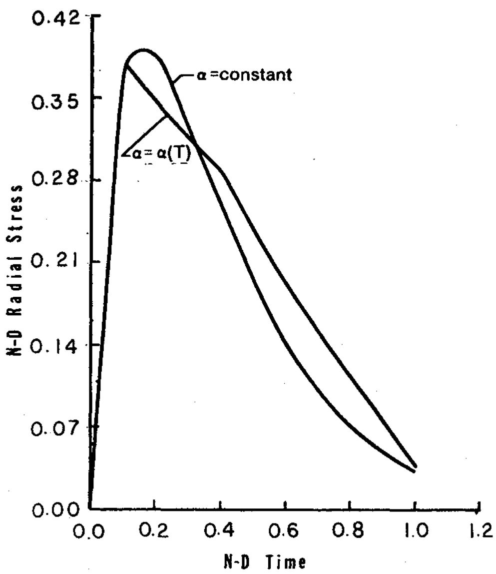


Fig. 9 Nondimensional radial stress vs nondimensional time at the midheight of the lead-glass interface for seal 2, evaluated with constant and temperature-dependent thermal expansion coefficients.

results obtained using a temperature-dependent α. Thus, the thermal strains generated will follow the straight line AB rather than the $\epsilon(T)$ curve.

The nondimensional radial stress at midheight of the lead-glass interface for seal 2 is plotted against time in Fig. 9 for the cases of constant and temperature-dependent thermal expansion coefficients. The difference in the maximum stresses is only 1.7%.

In order to examine the effect of size, a similar calculation was performed for seal 6 and the results are shown in Fig. 10. The difference in the maximum stresses between the two cases is 2.8%.

Therefore, for the given temperature range and materials, the maximum radial stresses at the lead-glass interface would not be affected significantly if a constant thermal expansion coefficient were used.

Effect of Different Materials

The materials used for glass-to-metal seals can be different than the ones described in the preceding sections. It is important to analyze the way different material property ratios affect the maximum tensile stresses.

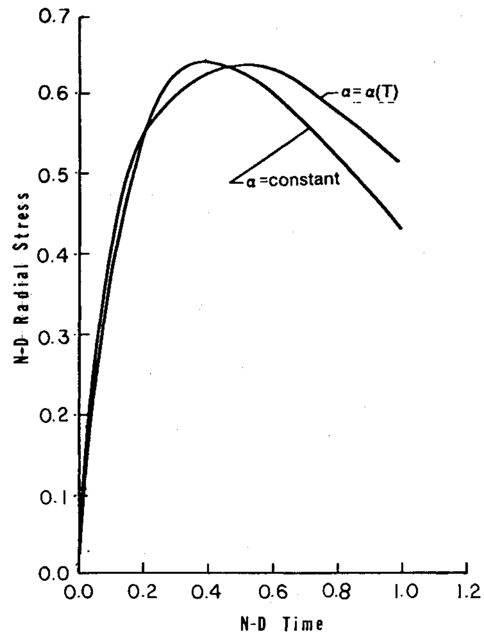


Fig. 10 Nondimensional radial stress vs nondimensional time at the midheight of the lead-glass interface for seal 6, evaluated with constant and temperature dependent thermal expansion coefficients.

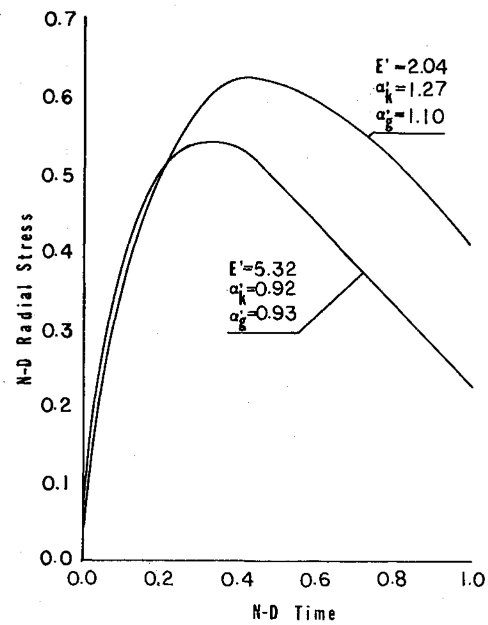


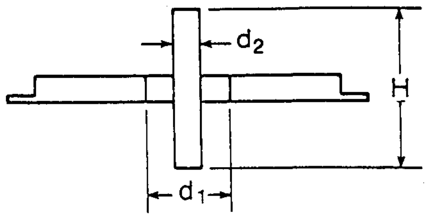
Fig. 11 Nondimensional radial stress vs nondimensional time at the midheight of the lead-glass interface for seal 2 with different material property ratios.

The thermal stress analysis therefore was applied to a glass-to-metal seal made of a different glass and tungsten. It was assumed that both the thermal expansion coefficient ratios α' and modulus of elasticity ratio E' were constant. In this case α_k' was 0.92 compared to 1.27 in the preceding results, α_g' was 0.93 compared to 1.1, and E' was 5.319 compared to 2.04. The Poisson ratios for the metal and the glass were 0.39 and 0.19, respectively, instead of 0.30 and 0.22. The thermal parameters A,B,C,D corresponding to seal 2 for this case were respectively 15.1314, 3.1914, 125.2125, and 57.1813.

The nondimensional radial stresses at the lead-glass interface are plotted as a function of nondimensional time in Fig. 11. It can be noted that the second material combination results in a lower maximum stress. The difference between the two cases is 15%. This indicates that the materials that make

Table A1 Seal configurations

Seal	d_2, m $\times 10^{-3}$	d_1, m $\times 10^{-3}$	H, m $\times 10^{-2}$	A_b, m^2 $\times 10^{-4}$	V_b, m^3 $\times 10^{-7}$	A	B	C	D	E
1	1.016	1.515	1.250	6.432	4.261	15.13	4.44	185.06	118.38	2.43
2	1.016	2.311	1.250	6.387	4.100	15.13	4.44	125.21	79.63	2.43
3	1.524	3.556	1.588	6.323	4.100	30.80	6.47	118.38	43.23	2.43
4	1.346	3.175	1.819	6.277	3.933	30.47	5.65	119.88	33.37	2.43
5	1.524	5.436	1.588	6.135	3.769	19.52	4.52	73.91	28.98	2.43
6	1.270	4.699	1.270	6.019	3.605	30.47	5.65	75.20	20.12	2.43



the glass-to-metal seal have an important effect on the stresses caused by a thermal shock.

IV. Conclusions

The transient two-dimensional temperature and thermal stress analysis presented in this paper provide the means to investigate the behavior of annular glass-to-metal seals subjected to a thermal shock test. In this analysis the assumption of instantaneous conduction can be relaxed to make the solution more general and applicable to any material with a similar configuration.

The results show that, among the stresses that affect the lead-glass interface (i.e., the radial and shear stress), the largest stresses which will cause separation when tensile, are radial stresses. Despite the fact that larger stresses occur at the surface of the glass in contact with the fluid failure has been observed to happen at the interface. This indicates that the strength of the interface should be lower or comparable to the strength of glass. Thus, if the interfacial seal is not made properly, the thermal shock test will lead to loss of hermeticity.

The effect of different size configurations on the magnitude and behavior of thermal stresses has been shown to be an important one. The results of thermal shock tests should be evaluated, taking into account the sizes of different glass-to-metal seals.

The effect of using different thermal shock test fluids has also been shown to cause different thermal stresses. In terms of testing, this means that a seal may fail under the action of a given level of thermal shock test and may not fail in an equally or more severe thermal shock level that uses a different test fluid with a different heat transfer coefficient.

Therefore, the severity of a thermal shock test can be established in terms of temperature extremes only if all other conditions, such as size and thermal shock test fluid, are the same. Otherwise, a larger difference between the high-temperature and low-temperature extremes of the thermal shock test does not necessarily mean a more severe test condition.

Appendix

Material properties

$k_g = 1.02$ W/m K $\qquad \nu_g = 0.22$

$\rho_g = 2269.97$ kg/m^3 $\qquad E_g = 56.65$ GPa

$c_g = 962.32$ J/kg K $\qquad \nu_k = 0.30$

$\rho_k = 8360.13$ kg/m^3 $\qquad E_k = 137.9$ GPa

$c_k = 439.32$ J/kg K $\qquad \alpha_{gr} = 4.6 \times 10^{-6}$ m/m/K

Room temperature to

T, °C	α_g, m/m/°C, $\times 10^{-6}$	α_k, m/m/°C, $\times 10^{-6}$
100	5.10	5.87
200	4.81	5.20
300	4.89	5.13
400	4.91	5.06

Acknowledgment

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