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THERMAL SHOCK ANALYSIS OF STANDARD HARDWARE MODULES

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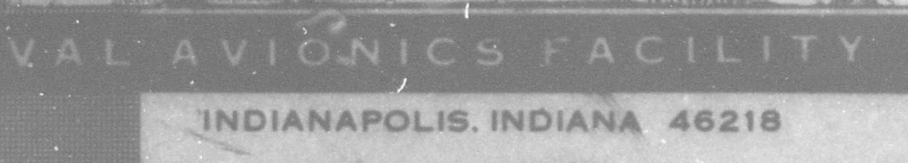

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ABSTRACT

This report is a theoretical analysis of stresses exerted on connector pin solder joints of NAFI Standard Hardware Modules, Style 1-A, during thermal shock due to varying coefficients of expansion between adjacent materials. An estimate is also made of the solder joint strength and a comparison made between the two. Although both sets of calculations are worst case analyses (maximum thermal stress vs. minimum joint strength for temperature extremes of -55°C. to + 125°C.) it appears that the solder joint will always withstand forces equal to several times those induced by thermal elongation.

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PREFACE

An infrequent though peculiar cause of failure in NAFI Type 3, Standard Hardware Modules is rupturing of the solder joint between the insulator contact pins and the copper lands. This is puzzling because previous experience, both here at NAFI and in other printed circuit applications,* has shown that the mechanical strength of the solder fillet is generally much greater than that of the surrounding components or the board itself. This would indicate that other factors, perhaps thermal stresses, are at work and must be taken into account.

This report attempts a theoretical worst case analysis of the stresses produced during thermal shock as well as the strength of the solder joint. The work was performed under the sponsorship of Special Projects Office, SP-23.

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I. CONCLUSIONS AND RECOMMENDATIONS

A comparison of calculated solder joint strength and applied force along each of the three mutually orthogonal axes (Fig. 1) is presented in Table 3. On the basis of these figures it is safe to conclude that acting alone, thermal stresses experienced during shock (-55°C. to +125°C.) can be easily withstood by the solder joint with no loss in mechanical integrity. Even at the higher temperature, joint strength is sufficient to provide a comfortable margin of safety. Although no data was available for calculating strength at the cold extreme, it should prove to be even greater than that at room temperature.[5]

Consequently, the present design configuration of the solder joint appears adequate, and if poor electrical/mechanical contact is encountered, factors other than thermal shock should be investigated as the primary cause. These might include externally applied stresses, poor wetting of the joint, insufficient solder, etc., none of which were taken into account in this study.

II. TECHNICAL DISCUSSION

A. ASSUMPTIONS

It must be emphasized here that in the theoretical analysis of thermal stresses experienced in the Type 3 modules, many simplifying assumptions must necessarily be made in order to arrive at any conclusions in a reasonable time. No attempt has been made here to arrive at the one "right" answer for such does not exist due to the multitude of variables involved. The stresses obtained should be taken only as "ballpark" approximations and as such are useful primarily as rough estimates for comparisons or preliminary design work.

The calculations are divided into two main sections, the first dealing with the forces required to rupture the solder joint along each of three mutually orthogonal axes (see Fig. 1), and the second covering the thermal forces exerted on the joint in each of these directions. Since this is intended to be a worst case analysis, in making the simplifications every effort was made to minimize the strength of the joint while maximizing the thermal stresses. Following are some of the major underlying assumptions:

1. Entire assembly always exists in a state of uniform temperature (either -55°C. or +125°C.)

2. All thermal elongations are additive in the same direction and independent in transverse planes, as well as reversible.

3. We are dealing with essentially a two-dimensional problem; i.e., no attempt is made to include the restraining effects of the module guide strips or the other thirty-nine possible pins in the assembly except where explicitly stated.

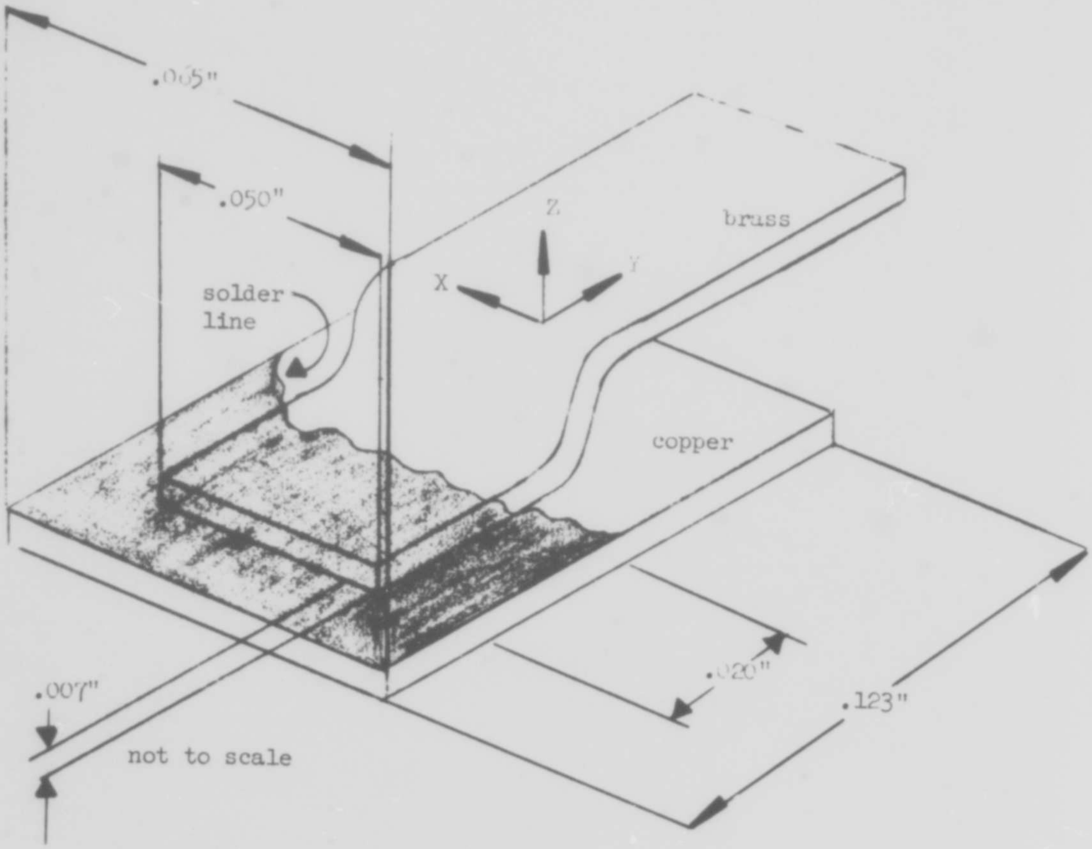

Figure 1 Typical Pin Solder Joint Configuration

4. The module is in a stress-free state at the initial temperature; i.e., when taken from -55°C. to +125°C. none of the tensile stresses produced by thermal expansion are neutralized by compressive stresses produced in going down to -55°C.

5. The primary source of stress relief in the module during either heating or cooling is the Sylgard 184 bonding material, due to its low modulus of elasticity and resulting high flexibility. The actions of thermal expansion and stress relief in the Sylgard 184 are taken to be independent processes.

6. The solder joint where the connector pin makes contact with its copper pad satisfies all specification requirements (WS6611B)[13] in regards to mechanical integrity.

7. For lack of better data, the linear coefficient of thermal expansion for the various materials is taken as constant over the entire range -55°C. to +125°C.

8. It should be pointed out that the mechanism of thermal creep may have an appreciable effect on joint strength not taken into account here. This is a time dependent phenomena in the solder itself which can produce a drastic decrease in strength if the joint remains in a stressed state for periods of days or weeks at a time, especially at elevated temperatures. However, no reliable quantitative theory has been presented to either explain or predict this behavior.

9. Stresses exerted on the pins by the encapsulant (Sylgard 182) are negligible due to the fact that it has a free upper surface, allowing it to flow up and around the joint. Even if this

were not the case and the Slygard 182 resin was assumed to be "stiff", preliminary calculations indicate that the maximum forces it might exert would be in the neighborhood of very small fractions of a pound.

Other simplifications of not so broad a nature will be mentioned later on along with the calculations, as they would not be clear here when taken out of context.

B. STRENGTH OF SOLDER JOINT

A diagram giving the configuration of a typical solder joint is shown in Fig. 1, in which are labeled the three directions to be considered. The various interfaces between solder and joined pieces are taken to have the minimum surface area possible and still meet specifications. The joint itself is assumed to have no imperfections i.e., air gaps or poor wetting. For want of a better figure the strength of the solder-metal interface is assumed equal to that of the bulk solder (60/40 Sn-Pb) as given in Table 1. If anything, this will minimize the joint strength since in most cases the combined mechanical-chemical nature of the bond is the strongest region in the assembly. Further, thermal stresses produced in the joint itself are neglected since the similar coefficients of expansion of the brass and copper (Table 2) would tend to lessen any tendency of the metals to pull away from one another.

Strength figures were computed at both room temperature and 125°C. No data could be found for the solder strength at -55°C. Since no experimental data was available on the solder shear strength at elevated temperatures, it was artitrarily approximated by assuming the same percentage decrease as that suffered by the tensile strength, i. e.: (see Table 1)

$$\tau_s \text{ @ } 125°C = \frac{2,500}{7,600} \times 5,600 = 1,840 \text{ psi}$$

Table 1 Strength of Bulk 60/40 Solder vs. Temperature[4]

TEMP. °C.	TENSILE STRENGTH psi	SHEAR STRENGTH psi
19	7300	—
25[1]	7600	5600
50	6000	—
75	5400	—
100	4000	—
125	2500	—
150	1600	—

Table 2 Material Properties

MATERIAL	THERM. COEF. OF EXPANS. IN./IN.-°C x 10^{4}	THERM. COND. $\frac{\text{BTU-FT.}}{\text{°F-HR.-FT.}^2}$	TENSILE STRENGTH LBS./IN^2
5052 ALUMINUM	.232	79.83	33,000
CORNING 7740 PYREX GLASS	.036	.59	10,000
SYLGARD 182	3	.213	900
SYLGARD 184	3	.228	900
BRASS ½ HARD	.180	104-67	35,000
COPPER	.176	226	32,000
DIALLYL PHTHALATE	.470	————	5,500-9,500

SYLGARD 184, 182:

ELASTIC MODULUS: 160 psi
SHEAR MODULUS: 60 psi

The formulas used in the calculations are:

$$F\ [\text{lbs}] = \sigma_s\ [\text{lbs/in}^2] \cdot A\ [\text{in}^2] \quad \text{for surfaces in normal stress}$$

$$F\ [\text{lbs}] = \tau_s\ [\text{lbs/in}^2] \cdot A\ [\text{in}^2] \quad \text{for surfaces in shear stress}$$

where F = maximum acceptable force in direction considered

A = interface area experiencing stress

σ_s, τ_s = tensile strength and shear strength, respectively; the choice of which to use for a certain area is determined by the relative orientation of that surface to the direction of applied force.

1. Strength in Y-Direction

@ Room Temperature (25°C)

$$\begin{aligned}
\sigma_s &= 7{,}600 \text{ psi} \\
\tau_s &= 5{,}600 \text{ psi} \\
F_y &= (.007)(.05)\ \sigma_s + 2(.007)(.02)\ \tau_s + 2(.05)(.02)\ \tau_s \\
&= (3.5 \times 10^{-4})\ 7{,}600 + (2.8 \times 10^{-4})\ 5{,}600 + (20 \times 10^{-4})\ 5{,}600 \\
&= 2.7 + 1.6 + 11.2 \\
\underline{F_y} &\underline{= 15.5 \text{ lbs}}
\end{aligned}$$

@ 125°C

$$\begin{aligned}
\sigma_s &= 2{,}500 \text{ psi} \\
\tau_s &\quad 1{,}840 \text{ psi} \\
F_y &= (3.5 \times 10^{-4})\ 2{,}500 + (2.8 \times 10^{-4})\ 1.840 + (20 \times 10^{-4})\ 1.840 \\
&= .875 + 4.20 \\
\underline{F_y} &\underline{= 5.08 \text{ lbs}}
\end{aligned}$$

2. **Strength in Z-Direction**

@ Room Temperature (25°C)

$$\sigma_s = 7{,}600 \text{ psi}$$
$$\tau_s = 5{,}600 \text{ psi}$$
$$F_z = [(.007)(.05) + 2(.007)(.02)]\ \tau_s + (.05)(.02)\ \sigma_s$$
$$= (3.5 \times 10^{-4} + 2.8 \times 10^{-4})\ 5{,}600 + (10 \times 10^{-4})\ 7{,}600$$
$$= 3.53 + 7.60$$
$$\underline{F_z = 11.13 \text{ lbs}}$$

@ 125°C

$$\sigma_s = 2{,}500 \text{ psi}$$
$$\tau_s = 1{,}840 \text{ psi}$$
$$F_z = (3.5 \times 10^{-4} + 2.8 \times 10^{-4})\ 1{,}840 + (10 \times 10^{-4})\ 2{,}500$$
$$= 1.16 + 2.50$$
$$\underline{F_z = 3.66 \text{ lbs}}$$

3. **Strength in X-Direction**

@ Room Temperature (25°C)

$$\sigma_s = 7{,}600 \text{ psi}$$
$$\tau_s = 5{,}600 \text{ psi}$$
$$F_x = [(.007)(.05) + 2(.05)(.02)]\ \tau_s + (.007)(.02)\ \sigma_s$$
$$= (3.5 \times 10^{-4} + 20 \times 10^{-4})\ 5{,}600 + (1.4 \times 10^{-4})\ 7{,}600$$
$$= 13.15 + 1.06$$
$$\underline{F_x = 14.21 \text{ lbs}}$$

@ 125°C

$$\sigma_s = 2{,}500 \text{ psi}$$
$$\tau_s = 1{,}840 \text{ psi}$$
$$F_x = (3.5 \times 10^{-4} + 20 \times 10^{-4})\ 1{,}840 + (1.4 \times 10^{-4})\ 2{,}500$$
$$= 4.32 + .35$$
$$\underline{F_x = 4.67 \text{ lbs}}$$

C. THERMAL ELONGATIONS AND STRESSES

The elongation experienced by a member subjected to a change in temperature is linearly proportional to both ΔT and its initial length. This is expressible as:

$$\Delta L\,[\text{in}] = \alpha\,[\text{in/in-}^\circ\text{C}] \cdot L[\text{in}] \cdot \Delta T\,[^\circ\text{C}]$$

where ΔT = change in temperature of the material

L = initial dimension of the member in direction of interest

α = experimentally determined constant of proportionality. This is usually referred to as the linear coefficient of thermal expansion; values for the various materials we are considering are presented in Table 2 along with other thermo-physical properties.

In reality, the relation is not really linear since it is dependent on the temperature and state of stress in the material, as well as other variables. For our purpose, it is assumed constant over the entire range -55°C. to 125°C. The temperature at which all dimensions in the module may be considered nominal is somewhat ambiguous. We will in all cases use the dimensions as shown on the applicable drawing (ref. 14, 15) as the "initial" figure regardless of the direction of thermal shock. This may seem a rather drastic supposition, but since Δ L's are orders of magnitude smaller than the L's, it is acceptable for our purpose. Note that this implies that the thermal stresses induced from 125°C. to -55°C. (compressive) are equal in magnitude but opposite in sign to those experienced in going from -55°C to 125°C. (tensile).

In computing the resulting stresses, the familiar Hooke's Law is used for elastic materials:

$$\sigma\,[\mathrm{lbs/in^2}] = E\,[\mathrm{lbs/in^2}] \cdot \epsilon$$

$$\tau\,[\mathrm{lbs/in^2}] = G\,[\mathrm{lbs/in^2}] \cdot \gamma$$

where

σ, τ = normal, shear stresses, respectively

E, G = modulus of elasticity, shear modulus

ϵ, γ = normal, shear strain

In attacking the problem, we add up all the appropriate length changes which occur above the bonding material and those which occur below it and use the resultant difference to compute the strain and stress exerted on the Sylgard 184 bond. Then a simple multiplication by contact area will provide the force transmitted to the solder joint. Here it has been assumed that there is enough "give" in the Sylgard 184 layer to enable it to absorb enough deflection so as to make any additional thermal stresses in other layers negligible; in other words, everything but the bonding material remains "stiff".

1. Exerted Force in Y-Direction
   Refer to Fig. 2.

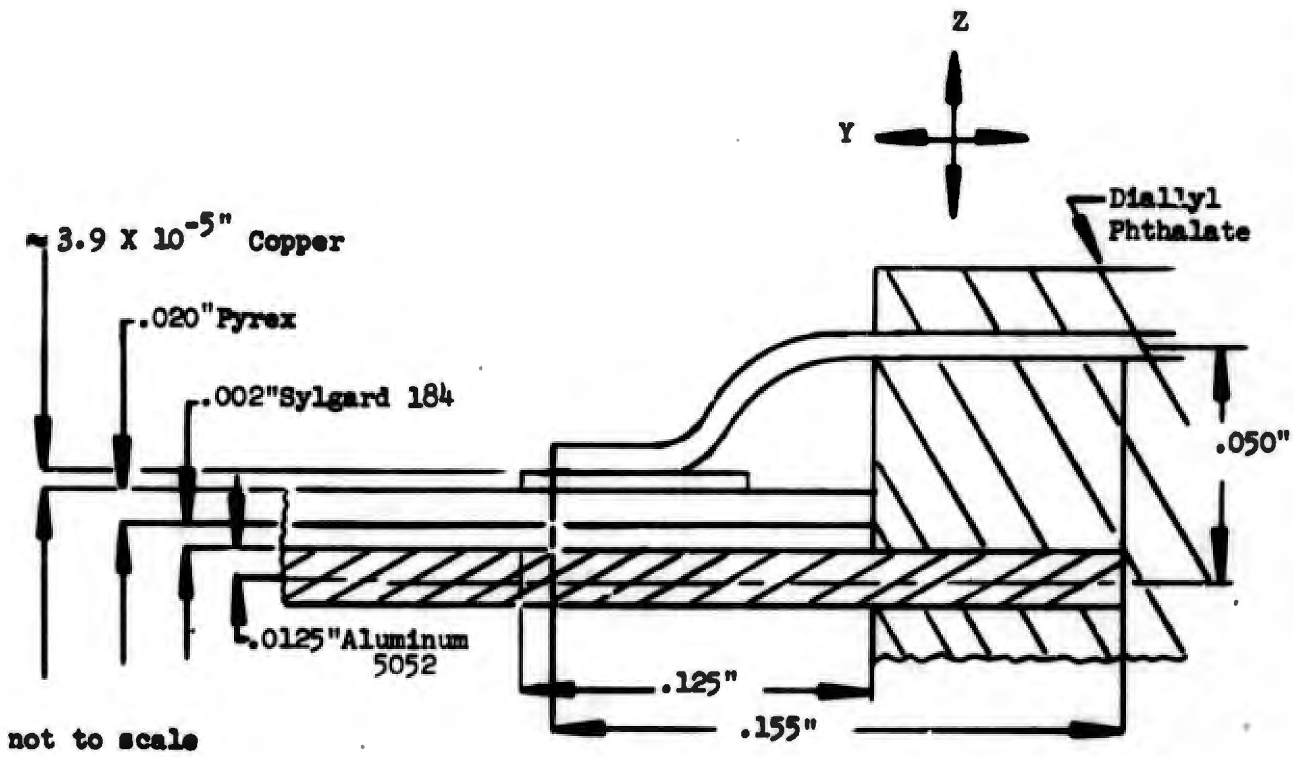

Figure 2 Style 1-A Module Cross-Section
(Only top half shown due to symmetry)

On top of bond

Brass contact pin

$$\Delta Y = (.180 \times 10^{-4})(.155)(125 + 55) = .0502 \times 10^{-2} \text{ in.}$$

Copper pads

$$\Delta Y = (.176 \times 10^{-4})(.123)(125 + 55) = .0390 \times 10^{-2} \text{ in.}$$

Pyrex substrate

$$\Delta Y = (.036 \times 10^{-4})(.125)(125 + 55) = \underline{.0081 \times 10^{-2} \text{ in.}}$$

$$\text{Total} \quad .0973 \times 10^{-2} \text{ in.}$$

On bottom of bond

Aluminum heat sink

$$\Delta Y = (.232 \times 10^{-4})(.155)(125 + 55) = .0646 \times 10^{-2} \text{ in.}$$

Sylgard 184 bonding material

$$\Delta Y = (3 \times 10^{-4})(.125)(125 + 55) = \underline{.6750 \times 10^{-2} \text{ in.}}$$

$$\text{Total} \quad .7396 \times 10^{-2} \text{ in.}$$

Actually, of course, the Sylgard 184 thermal expansion doesn't rightly belong in either the "bottom" or "top" column; however, since we are concerned here with only relative deflections between the two interfaces and the other changes are far smaller, the choice is arbitrary.

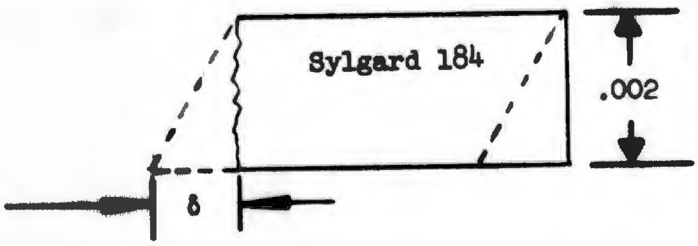

Figure 3 Shear Deformation of Bond in Y-Direction

The shear deflection experienced by the Sylgard 184 (Fig. 3) is the difference of the above totals:

$$\delta \quad = \quad (.7396 - .0973) \times 10^{-2} \quad = \quad .6423 \times 10^{-2} \text{ in}$$

$$\gamma \quad = \quad \frac{.6423 \times 10^{-2}}{.2 \times 10^{-2}} \quad = 3.21$$

$$\tau \quad = \quad G\gamma \qquad\qquad G = 60 \text{ psi}$$

$$= \quad 60 \times 3.21$$

$$\tau \quad = \quad 192 \text{ psi}$$

If P denotes the force applied to the solder joint:

$$P_y \quad = \quad \tau \cdot A$$

$$= \quad 192 \cdot (.065)(.123)$$

$$= \quad 192 \cdot 8 \times 10^{-3}$$

$$\underline{P_y \quad = \quad 1.54 \text{ lbs}}$$

Note that where some of the elongations may be negligible in comparison to others, they have been included for the sake of clarity.

2. <u>Exerted Force in Z-Direction</u> (Refer to Fig. 2)

<u>On top of bond</u>

Diallyl Phthalate insulation

$$\Delta Z = (.47 \times 10^{-4})(.050)(125 + 55) = .04230 \times 10^{-2} \text{ in}$$

Brass contact pin

$$\Delta Z = (.180 \times 10^{-4})(.007)(125 + 55) = .00227 \times 10^{-2} \text{ in}$$

Copper pads

$$\Delta Z = (.176 \times 10^{-4})(3.9 \times 10^{-5})(125 + 55) = .00001 \times 10^{-2} \text{ in}$$

Pyrex substrate

$$\Delta Z = (.036 \times 10^{-4})(.020)(125 + 155) = \underline{.00130 \times 10^{-2}} \text{ in}$$

$$\text{Total} \qquad .04588 \times 10^{-2} \text{ in}$$

On bottom of bond

Aluminum heat sink:

$$\Delta Z \;=\; (.232 \times 10^{-4})(.0125)(125 + 55) \;=\; .0052 \times 10^{-2} \text{ in}$$

Sylgard 184 bonding material:

$$\Delta Z \;=\; (3 \times 10^{-4})(.002)(125 + 55) \;=\; .0108 \times 10^{-2} \text{ in}$$

$$\text{Total} \qquad .0160 \times 10^{-2} \text{ in}$$

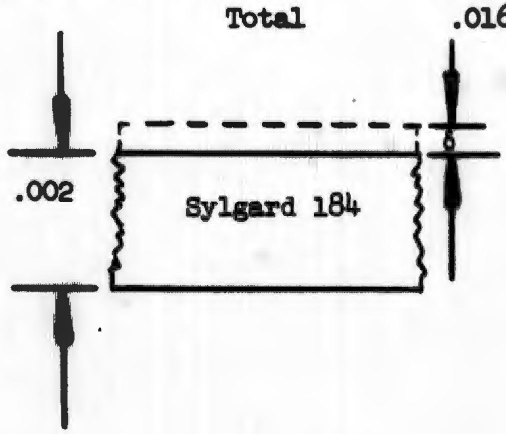

Figure 4 Normal Elongation of Bond in Z-Direction

The normal deflection (Fig. 4) is:

$$\delta \;=\; (.0459 - .0160) \times 10^{-2} \;=\; .0299 \times 10^{-2} \text{ in}$$

$$\epsilon \;=\; \frac{.0299 \times 10^{-2}}{.2 \times 10^{-2}} \;=\; .150$$

$$\sigma \;=\; E \cdot \epsilon \qquad E = 160 \text{ psi}$$

$$\sigma \;=\; 160 \times (.150) = 24$$

$$P_z \;=\; \sigma \cdot A \;=\; 24 \times 8 \times 10^{-3}$$

$$\underline{P_z \;=\; .192 \text{ lbs}}$$

3. <u>Exerted Force in X-Direction</u>

Here an attempt is made to estimate the thermal forces experienced by one of the four pins located farthest from the module center line, i.e., in the 1 or 20 position. When looking down on the printed circuit board, the module appears as in Fig. 5 where only the essential parts of the assembly are shown. In this direction, the Sylgard 184 is constrained between the guide strips mounted on the heat sink at the sides of the module. Thus, the elongation below the bond in this case is limited to that occurring in the aluminum.

<u>On top of bond</u>

Diallyl Phthalate insulation

$$\Delta X = (.47 \times 10^{-4})(.950)(125 + 55) = .8040 \times 10^{-2} \text{ in}$$

Brass contact pin

$$\Delta X = (.180 \times 10^{-4})(.050)(125 + 55) = .0162 \times 10^{-2} \text{ in}$$

Copper pads

$$\Delta X = (.176 \times 10^{-4})(.065)(125 + 55) = .0206 \times 10^{-2} \text{ in}$$

Pyrex substrate

$$\Delta X = (.036 \times 10^{-4})(.950)(125 + 55) = \underline{.0616 \times 10^{-2}} \text{ in}$$

$$\text{Total} \qquad .9024 \times 10^{-2} \text{ in}$$

<u>On bottom of bond</u>

Aluminum heat sink

$$\Delta X = (.232 \times 10^{-4})(.950)(125 + 55) = \underline{.396 \times 10^{-2}} \text{ in}$$

$$\text{Total} \qquad .396 \times 10^{-2} \text{ in}$$

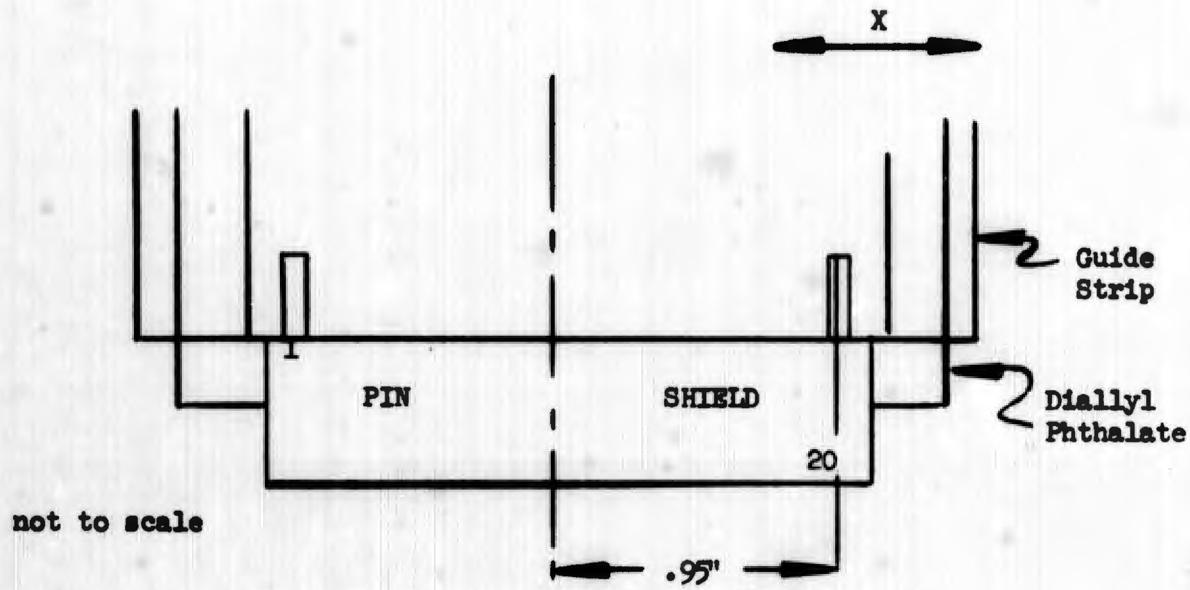

Figure 5 <u>Style 1-A Module Frontal View</u>

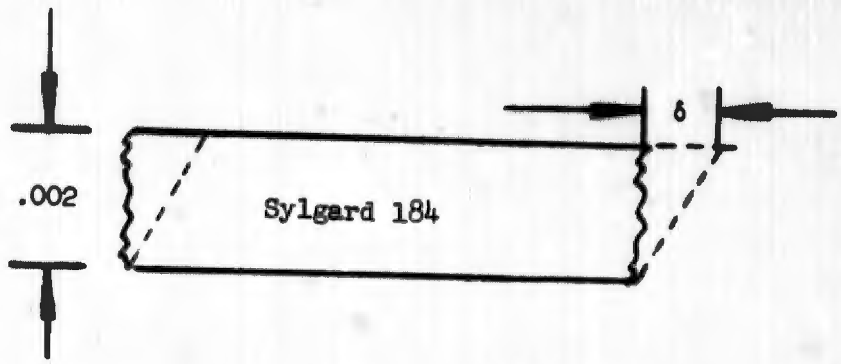

Figure 6 Shear Deflection of Bond in X-Direction

The 184 resin experiences a shear deformation of Fig. 6:

$$\delta = (.9024 - .396) \times 10^{-2} = .5064 \times 10^{-2}\text{in}$$

$$\gamma = \frac{.5064 \times 10^{-2}}{.2 \times 10^{-2}} = 2.53$$

$$\tau = G \cdot \gamma \qquad G = 60 \text{ psi}$$

$$= 60 \times 2.53$$

$$\tau = 152 \text{ psi}$$

$$P_x = \tau \cdot A = 152 \cdot 8 \times 10^{-3}$$

$$\underline{P_x = 1.22 \text{ lbs}}$$

These results, as well as the calculated values of joint strength, are tabulated in Table 3. The last column gives the ratio of joint strength over applied force as an indication of the margin of safety.

Table 3 Comparison of Joint Strength of Applied Thermal Forces

Direction	Applied Force (lbs)	Joint Strength (lbs) 25°/125°C	Ratio of $\frac{\text{Joint Strength}}{\text{Applied Force}}$ 25°/125°C
Y	1.540	15.5/5.08	10.0/3.30
X	1.220	14.2/4.67	11.6/3.83
Z	.192	11.1/3.66	57.8/19.1

REFERENCES

1. Manko, Howard H., Solders and Soldering, McGraw-Hill Book Company, 1964.

2. Faupel, Joseph H., Ph.D., Engineering Design, John Wiley and Sons, 1964.

3. Juvinall, Robert C., Stress, Strain, and Strength, McGraw-Hill Book Company, 1964.

4. Lewis, W. R., Notes on Soldering, Tin Research Institute, 4th Edition reprinted 1964.

5. Bester, M. H., and Borland, M. B., A Review of Some Metallurgical Factors Affecting Reliability of Interconnections, North American Aviation/Autonetics, Research & Engineering, May 1964.

6. Lyman, Taylor, editor, Metals Handbook, Vol. I, American Society for Metals, 8th ed., 1961.

7. Materials Engineering, Materials Selector Issue, Vol. 66 No. 5, Mid-October, 1967, Reinhold Publishing Corp.

8. Coombs, Clyde F., Jr., editor, Printed Circuits Handbook, McGraw-Hill Book Company, 1967.

9. Schlabach, T. D., and Rider, D. K., Printed and Integrated Circuitry, McGraw-Hill Book Company, 1967.

10. 1958 Book of ASTM Standards-Non-Ferrous Metals, Electronic Materials, American Society for Testing Materials, 1958.

11. Electronic Materials Notebook, Dow Corning Corp.

12. Technical Reports 781, 503; Technical Papers 202, 311 (Rev. 1); Materials Test Reports 47-64, 78-64, 50-64; Naval Avionics Facility, Indianapolis.

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