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PROTECTION OF GLASS TUBES IN
EPOXY ENCAPSULATION

Topical Report

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PROTECTION OF GLASS TUBES IN EPOXY ENCAPSULATION

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March 1974

Prepared by J. W. Steele, D/814.

A glass electron tube was breaking during a thermal cycle test after being potted in glass microballoon filled epoxy. Encasement requirements were established, experiments were designed, and information accumulated. After data from experiments was studied, two proposed designs were evaluated and one, a closed cell silicone rubber sponge extruded sleeve, was found to provide the required tube protection.

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Atomic Energy Commission

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SUMMARY

An electronic assembly contains a spraytron tube within its assembly PWA-5. Each lot of 50 spraytron tubes is qualified by D-testing five tubes which are assembled into PWA-5s, potted, thermal cycled, fired, and subjected to postmortem examination.

Spraytron tube failures occurred during the qualification of Lot 2 specimens. Postmortem of the D-tested units revealed a broken glass envelope. A deterioration of the tube protective encasement system was apparent in all depotted specimens.

The protective envelope failed when the epoxy resin under vacuum potting conditions impregnated or collapsed the foamed Thiokol at the tip of the tube and impregnated the polyurethane foam wrapped around the sides of the tube. Attempts to salvage the urethane foam-polysulfide sponge protective system by sealing the surface were successful but the urethane and polysulfide had too high a modulus at the low temperature test condition. The failure to salvage the tube protection system design prompted a study to develop a new tube protection system.

The following tube protection design criteria were re-established. The leads must be able to move a minimum of 0.010 inch (0.25 mm) in push or pull with a maximum force of 10 pounds (4.5 kg). The protection system must remain functional over the entire temperature range of -65°F (-54°C) to +160°F (+71°C). The tube encasement system must, after potting, permit the tube to move longitudinally a minimum of 0.005 inches (0.13 mm) in response to a maximum pull on a cathode lead or push on the tube base of 10 pounds (4.5 kg).

Stress relief lead configurations were evaluated. Data presented in the activity section of this report show that the design criteria is met by various stress-relief configurations in 0.025 inch (0.635 mm) diameter Dumet leads provided the relief configuration is contained in a low modulus coating and not potted directly in the epoxy glass microballoon potting system.

Room temperature, -65°F (-54°C), and +160°F (+71°C) shear and compressive property data were produced on candidate encasement materials. Based on results, Rubatex EPT rubber sponge and polysulfides were dropped as candidates because of their lack of low temperature flexibility.

Twenty-four tubes were encased, potted, and tested to determine the ability of various encasement systems to meet the difficult tube mobility criterion.

The strain gage work associated with the sprytron breakage was used to show the cause of failure of the original system and to demonstrate the acceptability of proposed new encasement systems.

Initial experiments showed the glass tube envelope to be a satisfactory transducer. Two tubes were broken under hydraulic pressures of 8900 psi (62.2 MPa) and 11500 psi (80.3 MPa). Tubes containing strain gages were assembled into Lot 2 and Lot 3 configurations, potted, and thermocycled from -65° to +160°F (-54° to +71°C).

Gage readings were compared to readings previously obtained during hydraulic deformation calibration and correlated to equivalent hydraulic pressure loads. Data show that the urethane foam-polysulfide sponge system failed to isolate the sprytron tube from potting stresses, that the loading on the tube was not a simple hydraulic load, and that strains occurred corresponding to hydraulic pressures in the range of 2500 to 3000 psi (17.5 to 20.9 MPa). Curves generated during the cure of the potting compound show non-uniform strains develop as polymerization progresses and appear to show a wave of polymerization moving from the center of the mass past the tube base and on toward the tube tip.

One specimen exhibited a repeatable high circumferential load occurrence equivalent to a hydraulic strain of 6000 psi (41.9 MPa) during the warmup cycle after stabilization at -65°F (-54°C). Thus in this one experiment a tube was close to breaking as a result of potting stresses and thermal expansion stresses at -65°F and as a result of differential thermal expansion caused by a transient large thermal gradient during warmup from -65°F.

The strain gage effort was directed toward evaluating new candidate tube encasements. Four tubes were gaged with 13 gages each. After thermal and hydraulic calibration, the tubes were assembled into PWA-5 configurations. Before assembly two tubes were encased in the silicone sponge extrusion system and two were encased in the internally ribbed silicone rubber boot system.

The four assemblies were potted in the PWA-5 production molds. The longitudinal and circumferential strain data accumulated during potting, cure, and thermal cycling show that the sponge sleeve was a satisfactory encasement for the protection of the tube. Tensile and compressive strains on the sponge sleeve protected tubes never exceeded 200 microunits per unit during the strain gage investigation.

Both of the ribbed silicone rubber boot protected tubes demonstrated exceptional tensile strains occurring in longitudinal and circumferential directions at gage locations on the tube cylinder close to the tube tip. Since the tensile strain at this location occurred only during the high temperature cycle the longical explanation is that the strain was the result of a compressive force at or close to the tube tip caused by an expansion of an excess of tube boot material in that area. The compressive force must be large to cause such a ballooning of the cylinder, and the force must be pressing at or close to the point at which the tube is necked down and sealed where the tube wall thickness variation is the greatest.

These results caution against the incorporation of design changes or new design concepts without thorough evaluation, and point out that careful consideration must be given to dimensioning parts designed from high bulk modulus high thermal expansion materials such as silicone rubbers.

No evaluation of a redesigned boot was made because the silicone sponge system was shown to be a more than adequate system with strain levels so low that incorporating the silicone sponge into the assembly could be made with confidence in its function.

The strain gage investigation proved to be a valuable tool in the evaluation of protective encasements for sensitive components in a rigid potting environment.

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DISCUSSION

SCOPE AND PURPOSE

Printed Wiring Assembly 5 (PWA-5) used in an electronic assembly failed Lot 2 acceptance tests. Postmortem of D-tested units disclosed failure of the protective encasement around a broken glass sprytron tube. A task force was assigned the mission of determining the cause of sprytron tube failure and supplying a new protection system to correct the problem. This report presents data developed while carrying out specific tasks within this assignment.

ACTIVITY

Definition of PWA-5

The electronic assembly contains an assembly designated PWA-5. The PWA-5 consists of a capacitor, sprytron tube, E-1 and E-2 output terminals, and associated circuitry. A sample number of PWA-5s are potted and tested separately to gain confidence in new components and the package design without increasing D-test rates on the much more expensive complete assembly.

Five of each lot of 50 PWA-5s are thus potted separately, electrically tested, and depotted for inspection in the postmortem laboratory. The remaining 45 PWA-5s are assembled into complete assemblies.

Postmortem of PWA-5 D-test units revealed that the urethane foam and polysulfide sponge protection system around the sprytron tube had collapsed and necked down around the tube tip.

Further examination revealed that the urethane foam on both the capacitor and tube was substantially impregnated with potting epoxy and that the polysulfide sponge at the tube tip had become partially impregnated with epoxy in addition to collapsing. Depotted tubes containing the collapsed polysulfide sponge in place and with the urethane foam removed are shown in Figure 1. Figure 2 shows a PWA-5 Lot 3 tube before potting. Figure 3 shows the PWA-5 D-test unit potted in a glass microballoon-epoxy potting system according to PS9927066.

Following discovery of the apparent failure of the tube protection system, several electrical failures, and several broken tubes, experiments to find a satisfactory tube protection system began. Initial experiments were directed toward using the urethane foam sheet material and polysulfide sponge system

Figure 1. Depotted Tubes With Urethane Foam Removed

which was failing but which, with some modification, would prevent the system from malfunctioning.

Figure 2. PWA-5 Lot 3 Configuration Before Potting

The Tufcote urethane material used was a 0.023-inch-thick (0.584 mm) open cell foam foamed between a 0.0015-inch-thick (0.038 mm) cast Korel urethane film outside skin and a 0.002-inch-thick (0.051 mm) polypropylene film carrying a contact adhesive on both sides. The tube was covered with two layers of Tufcote as shown in the illustration taken from the traveler (Figure 4). The cylindrical cavity at the tube tip end was filled with polysulfide sponge prepared according to SS293089. All edges of the urethane foam were coated with polysulfide (Figure 5).

Figure 3. PWA-5 Potted in Glass Microballoon Epoxy Showing Position of Test Thermocouples

Attempts to Salvage Existing Design

To avoid stopping production, design changes were made in Lot 3 of the PWA-5. These changes included polysulfide coating, stress relief of the tube leads, and removal of the spacer board.

The Tufcote urethane material with the Korel film was thought to be impervious to vacuum impregnation. As a result polysulfide was used to seal only the exposed edges of the foam. When the Korel skin was found not to be impervious to resin, the first design change made to the Lot 3 build of PWA-5 was the incorporation of a polysulfide dip coating over the entire urethane foam-polysulfide sponge assembly.

Examination of a broken tube from Lot 2 suggested that a probable mode of failure was tension or compression on a tube lead. With this in mind stress relief loops were incorporated into the Lot 3 PWA-5 design, and all leads

were coated with RTV Silicone Rubber 3140 to allow some lead movement within the potting matrix.

Figure 4. Tube Being Covered With Tufcote

Another mode of tube breakage suggested from Lot 2 postmortem was that the small spacer board in which terminals E1 and E2 were located was positioned with a protruding corner very close to the bottom of the tube and may have exerted a force on the tube during thermal cycling. The board was deleted in the Lot 3 design.

Experiments with aluminum rods to simulate the tubes later showed that the polysulfide rubber was inadequate to protect the polysulfide foam from collapse. Without exception the polysulfide foam would vent through the polysulfide rubber coating at a point of intersection with the thermoplastic adhesive.

Figure 5. Finished Protected Tube, Lot 2 Configuration

A number of specimens were prepared using aluminum rods to simulate tubes. Various methods were employed to protect the urethane and polysulfide foam from impregnation during the potting operation. After potting, the specimens were sectioned for examination. In analyzing the results of these experiments it became apparent that polysulfide foam prepared according to SS292089, Issue B, was not fully cured and its use in electronics assemblies was dropped. Coating the urethane foam skin with polysulfide rubber did appear to offer some protection from impregnation of the foam. The polypropylene contact adhesive carrier was a barrier to the epoxy and therefore protected the bulk of the inside layer of the two-layer wrap-around foam construction.

Under stress the thermoplastic contact adhesive released and allowed buckling of the urethane foam. The use of contact thermoplastic adhesive in electronic assemblies is not recommended, particularly if it must function during the elevated temperature evacuation cycle used in potting procedures.

All schemes which totally enclosed the urethane-polysulfide sponge prior to exposure to the hot (185°F) (85°C) vacuum potting process were successful in protecting the system. These included constructions contained within a latex fingercot bonded in place with polysulfide, and prepotting the construction in glass microballoon (GMB) potting compound using no vacuum.

An analysis of experiments was made to select the method of providing tube protection for Lot 4 production. Three systems survived the must category of a Kepner Tregoe type analysis:* the Tufcote urethane and polysulfide sponge system used in the Lot 2 build, unchanged except prepotting in the GMB potting formulation without vacuum; the Tufcote urethane with the tip constructed with plain polysulfide containing a disc of closed cell rubber foam; and a closed cell silicone rubber sponge sleeve used in place of the urethane sponge wrap-around. A disc of silicone sponge was bonded in place over the end of the tube.

Continuing the analysis of adverse consequences, as prescribed by Kepner-Tregoe, it was concluded that a combination of two systems: a closed cell sponge in polysulfide to protect the tube tip, and a no-vacuum prepot to protect the Tufcote urethane, would offer the best solution.

Thus the polysulfide sponge of questionable stability was replaced with a manufactured closed cell material of known dimensional displacement capacity.

Five sprytron tubes were potted using the no-vacuum prepot method. Sectioning the tubes showed packages in which the urethane foam was free from impregnation.

Following the recommendation of the no-vacuum prepot method utilizing the Tufcote urethane foam and a Rubatex EPT rubber sponge pad at the tube tip, a stop order was issued and this technique became one of the many to be more widely evaluated.

Following the discovery of tube failures in Lot 3 D-test units a stop order was released which stopped production of the PWA-5 until the cause for breakage of the Sprytron Tube was identified and corrective steps could be taken. A task force was established to handle various aspects of this investigation. This report attempts to distribute data generated and report on the specific tasks assigned to the author for coordination. Data from other task assignments is included when it affects, supports, and interrelates with the total effort.

*C. H. Kepner and B. B. Tregoe, The Rational Manager. New York: McGraw-Hill, 1965, p 24.

Tube Mechanical Limitations

The expanded program included tests to determine the mechanical limitations of the glass tube and its lead-to-glass interface seal. The following data were established in an attempt to develop mechanical specifications for tube packaging.

At room temperature a tensile pull of approximately 23 pounds (10.4 kg) on individual anode or cathode leads causes the lead-to-glass seal to yield.

Anode and cathode seals did not fail with a 30 pound (13.6 kg) compressive force applied to leads cut to within 0.030 to 0.050 inch (0.762 to 1.270 mm) of the tube base. At room temperature and at -65°F (-54°C), lead buckling occurred at compressive forces higher than 30 pounds (13.6 kg). One sample tested developed a deep crack around the anode lead caused by lead bending.

One-quarter-inch long (6.35 mm) anode and cathode leads of 0.025 diameter (0.635 mm) Dumet buckle at an average compressive force of 19.5 pounds (8.8 kg) at room temperature and 23 pounds (10.3 kg) at -50°F (-46°C).

When subjected to a lead tensile pull at a 45 degree angle (0.765 radians) to the tube base the lead-glass seal yields and cracks initially at a tensile force as low as 2.5 pounds (1.1 kg). This test was performed at room temperature.

In tests performed at Sandia Albuquerque, two tubes cracked in the second cycle of a hot water and ice water thermal shock with a change in temperature of 180°F (ΔT 100°C).

Two tubes were imploded under hydraulic pressure in water. The implosions occurred at 8900 and 11500 psi (61.3 and 79.4 MPa). The second tube was under the additional stress of 10 pounds (4.5 kg) tensile load on one cathode lead at the start of the experiment.

Figures 6 through 10 were used to analyze the failure of a tube removed from one of the PWA-5 units.

Most proposed explanations for this fracture involve a tensile force on the cathode lead centering the three-pronged fracture of the base. This tube was from a PWA-5 that contained a corner of the terminal spacer board which had penetrated the RTV rubber on the base of the tube.

Lead pull tests were conducted on five tubes. Failure occurred at 33 pounds (15 kg) by pulling on a cathode lead in one of the five tubes prepared in the evaluation which preceded the stop order. This test was conducted at -65°F (-54°C). The tensile tester crosshead movement was not stopped at the instant of failure and therefore the failure was not analyzed.

Figure 6. Fracture Cones and Tilted Cathode

Figure 7. Failed Cathode Spacer

Figure 8. View of Tube Base

Figure 9. Failed Tube

Figure 10. Lead Orientation

A cathode lead was pulled at room temperature on one new tube and two tubes potted in Lot 1 configuration and partially depotted for testing. Failure occurred at 26, 51, and 27 pounds respectively (11, 23, and 12 kg). In each of these three tubes the glass in the base of the tube had cracked starting at the cathode and running in three directions across the base and up the side of the tube. The ceramic spacer inside the tube was also cracked on the tube that failed at 27 pounds (12 kg). A fifth tube was tested by pulling on the green trigger lead. The lead which contains no ceramic sleeve broke loose from the glass at 17 pounds (8 kg).

Stress Relief of Leads

In view of evidence pointing to lead stress involvement in tube breakage, it was determined that stress relief loops covered with RTV silicone rubber should be incorporated into any new package design. Based on data showing anode and cathode glass to lead seal yield at 23 pounds (10 kg) in straight tensile pull at room temperature, and calculated maximum tube base movement of 0.0080 inches (0.20 mm) based on thermal expansion mismatch over the +160 to -65°F (+71 to -54°C) temperature range, an arbitrary target requirement of 0.010 inch (0.25 mm) minimum movement from a compressive

or tensile force of 10 pounds (4.5 kg) maximum, was established. An experiment designed to measure the ability of various lead configurations to meet the target requirements was conducted.

Each specimen consisted of two leads soldered to a printed wiring board chip and shaped to one of five different configurations as illustrated in Figure 11 and described in Table 1 and Table 2.

The chips were then each bonded approximately in the center of aluminum weighing dishes and potted to a depth of approximately 0.5 inch (13 mm). One half of the specimens were coated from the board up the lead for about 0.5 inch with RTV 3140 silicone rubber which was cured before potting. Dumet 0.025-inch-diameter (0.635 mm) wire was used for all leads. Configuration 1 with its short length of sleeving simulated the cathode lead used in PWA-5 Lots 1 and 2. Configurations 2, 3, and 4 are various potential cathode relief loops. Configuration 5 with the double wire, double sleeve construction represents the anode configuration.

Using a universal test machine, specimens were mounted and individual wires were pulled to a load of 10 pounds (4.5 kg) or until a point on the wire approximately 1 inch (25.4 mm) above the potting surface had moved 0.010 inch (0.25 mm) from the surface indicating that the wire was pulling out of the potting by a corresponding amount. The elongation of 0.025 inch diameter (0.635 mm) Dumet wire at 10 pounds (4.5 kg) was first determined to be negligible.

Following the accumulation of pull test data at room temperature and at -65°F (-54°C) a fixture was constructed to permit pushing individual leads without buckling, in a rigid column which terminated 0.050 inches (1.270 mm) above the potting surface. Room temperature push data was obtained on the few remaining specimens. The data obtained are presented in Tables 1 and 2.

The results show that stress relief loops in tension only lock the lead in the epoxy potting material unless they are contained in a low modulus matrix such as RTV 3140. When encased in a low modulus matrix, stress relief configurations in 0.025 inch diameter (0.635 mm) Dumet will yield in tension in excess of 0.010 inch (0.254 mm) at 10 pounds (4.5 kg).

Less force is required to obtain a compressive yield of 0.010 inch (0.254 mm) and the low modulus matrix facilitates movement at much lower pressures.

Two questions appear in the data: one, a low reading on Configuration 5 with RTV at -64°F (-54°C) may have resulted from the extensometer riding up on the sleeving as it pulled from the potting; and the one low reading for Configuration 2 with RTV at -65°F (-54°C) is unexplained, although the results indicate

CONFIGURATION 1

CONFIGURATION 2

CONFIGURATION 3

CONFIGURATION 4

CONFIGURATION 5

Figure 11. Configurations of Five Specimens for Pull Test Data

Table 1. Stress Relief Loop Pull Test Experiment

Configuration	Strain (Inches) (mm) at Room Temperature Without Coat- ing 10 Pounds (4.5 kg) Stress	Strain (Inches) (mm) at Room Temperature With RTV Coat- ing at 10 Pounds (4.5 kg) Stress	Strain (Inches) (mm) at -65°F (-54°C) With- out Coating at 10 Pounds (4.5 kg) Stress	Strain (Inches) (mm) at -65°F (-54°C) With RTV Coating at 10 Pounds (4.5 kg) Stress
1	0.0025 (0.0635)	0.0050 (0.1270)	0.0016 (0.0406)	0.0050 (0.1270)
1	0.0016 (0.0406)	0.0006 (0.0152)	0.0010 (0.0254)	0.0025 (0.0635)
1	0.0030 (0.0762)	0.0010 (0.0254)		
1	0.0045 (0.1143)	0.0020 (0.0508)		
2	0.0044 (0.1118)	0.0180 (0.4572)	0.0020 (0.0508)	0.0012 (0.0305)
2	0.0042 (0.1067)	0.0160 (0.4064)	0.0010 (0.0254)	
2		0.0140 (0.3556)	0.0031 (0.0787)	
2		0.0050 (0.1270)	0.0017 (0.0432)	
2		0.0130 (0.3302)		
2		0.0130 (0.3302)		
3	0.0020 (0.0508)	0.0270 (0.6858)	0.0014 (0.0356)	0.0190 (0.4826)
3	0.0009 (0.0229)	0.0420 (1.067)	0.0020 (0.0508)	0.0200 (0.5080)
3	0.0036 (0.0914)	0.0293 (0.7442)		
3	0.0018 (0.0457)	0.0293 (0.7442)		
4	0.0040 (0.1016)	0.0280 (0.7112)	0.0018 (0.0458)	0.0200 (0.5080)
4	0.0038 (0.0965)	0.0295 (0.7493)	0.0035 (0.0889)	0.0140 (0.3556)
4	0.0018 (0.0457)	0.0350 (0.8890)		
4	0.0020 (0.0508)	0.0332 (0.8433)		
5	0.0030 (0.0762)	0.0220 (0.5588)	0.0030 (0.0762)	0.0020 (0.0508)
5		0.0170 (0.4318)	0.0034 (0.0864)	
5		0.0230 (0.5842)		
5		0.0250 (0.6350)		

Table 2. Stress Relief Loop Push Test Experiment at Room Temperature

Configuration	Strain (Inches) (mm) Without Coating	Stress (Pounds) (kg) Without Coating	Strain (Inches) (mm) RTV Coating	Stress (Pounds) (kg) With RTV Coating
1	0.010 (0.254)	6.9 (3.13)	0.010 (0.254)	4.2 (1.9)
1	0.010 (0.254)	7.7 (3.49)	0.010 (0.254)	6.0 (2.72)
2	0.0052 (0.1321)	10 (4.54)		
2	0.010 (0.254)	5.6 (2.54)		
3	0.010 (0.254)	4.2 (1.91)	0.010 (0.254)	2.1 (0.95)
3	0.010 (0.254)	6.1 (2.77)	0.010 (0.254)	1.6 (0.73)
4	0.010 (0.254)	4.0 (1.81)	0.010 (0.254)	0.5 (0.22)
4	0.010 (0.254)	9.7 (4.40)	0.010 (0.254)	0.4 (0.18)

that perhaps the RTV was not applied to the loop. The moduli of both the high modulus Dumet and low modulus RTV increased only slightly at -65°F (-54°C).

Shear and Compressive Properties of Candidate Cushion Materials

Candidates for the tube protection system must function in both compression and shear throughout the temperature range of thermal cycle of -65 to 160°F (-54 to 71°C). An experiment was set up to determine property values of various potential tube protection materials at the temperature extremes and at room temperature. A balanced shear specimen was prepared by bonding 1-inch-square samples of material on each side of a 1- by 4- by 0.06-inch (25 by 100 by 1.5 mm) aluminum 2024 alloy T-3 standard shear specimen and placing them between two more aluminum specimens. For proper alignment, holes were drilled after the specimens were cured.

Silicone Rubber Foam

RTV Silicone Foam 511, 3110, and TBS 757 test specimens were foamed in place against SS-4155 primed aluminum. The RTV foam formulations were as follows:

RTV 511 or DC 3110, 100 pbw;
RTV 921 blowing agent, 10 pbw;
Diluent (silicone fluid), 12 pbw; and
Catalyst (T-9) stannous octoate, 1 pbw.

Ethylene Propylene Terpolymer Rubber Closed Cell Sponge

Rubatex EPT rubber sponge S481-T soft and 483-T medium test specimens were bonded with Epon 828 catalized with 25 parts-per-hundred Epon U curing agent and room temperature cured.

Silicone Rubber Closed Cell Sponge

Samples cut from silicone rubber sponge sleeving were bonded to DC1203 primed aluminum specimens with RTV 3140. The sleeving used in this investigation was designated AMS 3195 sponge tubing by the manufacturer.

Ribbed Silicone Boot

Specimens cut from a ribbed silicone rubber boot molded from SE5211 silicone rubber were prepared so that the smooth sides were bonded to the two outside aluminum specimens and only the 0.020 inch (0.508 mm) flat portions

of the teeth were bonded on each side of the center aluminum specimen. The shear specimen prepared from the ribbed boot does not simulate the manner in which it would function in tube protection because it would not be bonded to the tube. The specimens were prepared, however, to allow the boot design to participate in the compression test.

Polysulfide

Polysulfide specimens were prepared from MS4115060 material processed according to PS 9905101 and cast in place between vapor blasted aluminum tabs.

Specimens were mounted in a universal test machine and stressed at various temperatures. The target shear property requirement was established at 10 pounds (4.5 kg) maximum pull to achieve a minimum displacement of 0.010 inch (0.25 mm). Thus, if leads to the tube were fixed at terminals E1 and E2 and the stress relief configurations were totally inoperative then the tube protection system would permit tube movement with less than 10 pounds (4.5 kg) stress on the tube leads. Shear data presented in Tables 3 and 4 show that EPT rubber sponge and polysulfide rubber were unsuccessful as low temperature shear candidates. The shear modulus was calculated according to the following formula and Figure 12.

$$E_s = \frac{\Delta P/A}{\Delta L/L} = \frac{\Delta PL}{A \Delta L}$$

where:

A = Area = ab

ΔP = change in load

L = gage length = thickness

ΔL = strain

Example:

$$\text{TBS-757 at -65 (Sample 2)} = \frac{20 \times 2}{0.0025/193} = \frac{40}{0.0129} = 3100 \text{ psi (21.374 MPa)}$$

Figure 12. Balanced Shear Specimen

Table 3. Shear Stress-Strain Data on Candidate Encasement Materials

Material and Sample Number	Strain (Inches) (mm) at -65°F (-54°C)	Stress (Pounds) (kg) at -65°F (-54°C)	Strain (Inches) (mm) at Room Temperature	Stress (Pounds) (kg) at Room Temperature	Strain (Inches) (mm) at 160°F (71°C)	Stress (Pounds) (kg) at 160°F (71°C)
Rubutex-Soft 1	0.0000 (0.0000)	20 (9.07)				
2	0.0000 (0.0000)	20 (9.07)				
3	0.0002 (0.0051)	20 (9.07)				
Rubutex-Medium 1	0.0001 (0.0025)	20 (9.07)				
2	0.0001 (0.0025)	20 (9.07)				
TBS 757 1	0.0032 (0.0813)	20 (9.07)	0.0026 (0.0660)	10 (4.54)	0.0040 (0.1016)	10 (4.54)
1	0.0028 (0.0711)	20 (9.07)				
2	0.0025 (0.635)	20 (9.07)	0.0030 (0.0762)	10 (4.54)	0.0036 (0.0914)	10 (4.54)
2	0.0024 (0.610)	20 (9.07)				
3	0.0024 (0.610)	20 (9.07)	0.0032 (0.0813)	10 (4.54)	0.0029 (0.0737)	10 (4.54)
3	0.0029 (0.737)	20 (9.07)				
Silicone 1	0.010 (0.254)	6.2 (2.81)	0.010 (0.254)	4 (1.81)	0.010 (0.254)	3.7 (1.68)
Rubber 1		6.5 (2.95)				
Sponge 2		4.8 (2.18)	0.010 (0.254)	3.6 (1.63)	0.010 (0.254)	2.8 (1.27)
Extrusion 2		5.7 (2.58)				
3		6.9 (3.13)	0.010 (0.254)	3.9 (1.77)	0.010 (0.254)	3.7 (2.54)
3		8.1 (3.67)				
RTV 511 1		1.8 (0.82)	0.010 (0.254)	1.9 (0.86)	0.010 (0.254)	1.9 (0.86)
Silicone 2		2.0 (0.91)		2.2 (1.00)	0.010 (0.254)	2.2 (1.00)
Foam 3		2.0 (0.91)		2.2 (1.00)	0.010 (0.254)	2.4 (1.09)
RTV 311D 1		2.2 (0.99)		2.3 (1.04)	0.010 (1.04)	2.7 (1.22)
Silicone 2		2.5 (1.13)		2.3 (1.04)		
Form 3	0.010 (0.254)	2.0 (0.91)	0.010 (0.254)	2.3 (0.91)	0.010 (1.04)	2.3 (1.04)
Polysulfide 1	0.0000 (0.0000)	20 (9.07)	0.0013 (0.0330)	10 (4.54)	0.0040 (0.10160)	10 (4.54)
2			0.0020 (0.0508)	10 (4.54)	0.0039 (0.09906)	10 (4.54)
3			0.0017 (0.0432)	10 (4.54)	0.0044 (0.11178)	10 (4.54)

Table 4. Shear Modulus Data on Candidate Encasement Materials

Material	Sample	Shear Modulus (psi) (MPa)		
		-65°F (-54°C)	Room Temperature	160°F (71°C)
TBS 757	1	2424 (16.712)	1492 (10.286)	966 (6.660)
	2	3100 (21.373)	1290 (8.894)	1075 (7.411)
	3	3226 (22.242)	1212 (8.356)	1333 (9.190)
	Average	2917 (20.112)	1331 (9.177)	1125 (7.750)
Silicone Rubber Sponge Extrusion	1	242 (1.669)	149 (1.027)	133 (0.951)
	2	193 (1.331)	145 (1.000)	113 (0.779)
	3	261 (1.800)	147 (1.014)	140 (0.965)
	Average	232 (1.600)	147 (1.014)	130 (0.896)
RTV 511 Silicone Foam	1	181 (1.250)	191 (1.317)	191 (1.317)
	2	205 (1.413)	226 (1.558)	226 (1.558)
	3	201 (1.386)	221 (1.524)	241 (1.662)
	Average	196 (1.351)	213 (1.517)	219 (1.510)
RTV 3110 Silicone Foam	1	217 (1.496)	227 (1.565)	266 (1.834)
	2	246 (1.696)	227 (1.565)	266 (1.834)
	3	197 (1.358)	227 (1.565)	227 (1.565)
	Average	220 (1.517)	227 (1.565)	253 (1.744)
Polysulfide	1		2817 (1.943)	917 (6.322)
	2		1802 (12.424)	922 (6.357)
	3		2150 (14.824)	877 (6.116)
	Average		2256 (15.555)	887 (6.265)

Following tensile shear testing, the same specimens were used in testing compressive properties. Compressive stress-strain and modulus data presented in Table 5 and 6 show the lack of required compressibility of the non-silicone materials when tested at low temperature.

Tube Mobility Evaluation

The primary experiments used to evaluate potential tube encasement systems were the push-pull tests conducted on sprytron tubes encased in various protective systems and potted in GMB-epoxy. Initially tubes were potted so that the bottom of the tube was flush with the surface of the potting material. These are referred to as Style 1. As the experiment progressed, it became apparent that the Style 1 configuration did not represent the potted sprytron tube and that false information might be obtained through failure to enclose the tube base in potting material. The potting technique was then changed to a Style 2 configuration which captured the sleeved anode leads and two trigger leads in the potting material which extended about 0.5 inch (12.7 mm) beyond the tube base. The two cathode leads were brought out of the potting through a 0.25 inch (6.55 mm) diameter Teflon tube. RTV 3140 silicone rubber was applied to all leads in the Style 2 potting configuration and the Teflon tubing protecting the cathode leads was embedded in the 3140 at the tube base.

The pottings were mounted in universal test machine and a tensile stress was applied to the cathode leads. The extensometer was mounted on the potting and contacted the tube base by means of a needle which penetrated the RTV 3140 applied to the base of the tube. The tube encasement and RTV in the cathode lead channel were removed to permit free passage of the extensometer needle.

The first configuration tested was the five tubes prepared before the stop order described earlier in this report was issued. These were tested in tension only in advance of other candidate systems evaluated in this series. Figure 13 illustrates the average movement of these tubes in response to a tensile pull on a cathode lead. The rigidity of the urethane foam as demonstrated by the almost complete lack of tube movement at -65°F (-54°C) caused the Tufcote urethane to be dropped as a candidate for tube protection, and redirected the scope of this effort to one of finding new encasement systems rather than one of salvaging the existing system.

Following the pull tests, leads were clipped at the tube base and push tests were conducted using the same extensometer arrangement. The specimens were constructed as shown in Figures 14 through 27. Data from these tests is presented in Tables 7 and 8.

Text continued on page 42.

Table 5. Compressive Stress-Strain Data on Candidate Encasement Materials

Materials	Sample	Strain (Inches) (mm) -65°F (-54°C)	Stress (Pounds) (kg) -65°F (-54°C)
Tube Boot Section (GE 5211)	1	0.0191 (0.4851)	20 (9.07) ↑
	2	0.0174 (0.4420)	
	3	0.0222 (0.5639)	
	4	0.0174 (0.4420)	
TBS 757 (Foam) (GE)	1	0.0050 (0.1270)	↓
	2	0.0052 (0.1321)	
	3	0.0050 (0.1270)	
Silicone Rubber Sponge (Extruded)	1	0.0510 (2954)	20 (9.07) ↓
	2	0.0540 (3716)	
	3	0.0520 (3208)	
RTV 511 (Foamed)	1	0.027 (0.6858)	5 (2.27) ↑
	2	0.025 (0.6350)	
	3	0.024 (0.6096)	
RTV 3110 (Foamed)	1	0.0220 (0.5588)	↓
	2	0.0220 (0.5588)	
	3	0.0230 (0.5842)	5 (2.27)
Polysulfide Seal	1	0.0024 (0.0610)	20 (9.07)
	2	0.0019 (0.0483)	20 (9.07)
	3	0.0026 (0.0660)	20 (9.07)

Strain (Inches)(mm) at Room Temperature	Stress (Pounds) (kg) at Room Temperature	Strain (Inches) (mm) at 160°F (71°C)	Stress (Pounds) (kg) at 160°F (71°C)
0.0068 (0.1727)	20 (9.07)	0.0070 (0.1778)	20 (9.07)
0.0072 (0.1829)	20 (9.07)	0.0070 (0.1778)	20 (9.07)
0.0073 (0.1854)	20 (9.07)	0.0060 (0.1676)	20 (9.07)
0.0265 (0.6731)	10 (4.54)	0.254 (0.6452)	10 (4.54)
0.0275 (0.6985)	↑	0.0286 (0.7264)	10 (4.54)
0.0278 (0.7061)		0.0286 (0.7264)	10 (4.54)
0.0490 (1.2446)		0.0240 (0.6096)	5 (2.27)
0.0440 (1.1176)		0.0220 (0.5588)	↑
0.0460 (1.1684)	↓	0.0220 (0.5588)	
0.0390 (0.9906)		0.0180 (0.4572)	
0.0390 (0.9906)		0.0180 (0.4572)	
0.0420 (1.0668)	10 (4.54)	0.0180 (0.4572)	5 (2.27)
0.0065 (0.1651)	20 (9.07)	0.0080 (0.2032)	20 (9.07)
0.0062 (0.1575)	20 (9.07)	0.0052 (0.1321)	20 (9.07)
		0.0065 (0.1651)	20 (9.07)

Table 8. Compressive Modulus Data on Candidate Encasement Materials

Material	Sample	Compressive Modulus at 20 Percent Deflection (psi)(MPa)		
		-65°F(-54°C)	Room Temperature	150°F (71°C)
TBS 757 (Foam) (GE)	1	772 (5.322)	536 (3.695)	551 (3.799)
	2	742 (5.115)	567 (3.909)	584 (4.026)
	3	772 (5.322)	528 (3.640)	551 (3.799)
	Average	762 (5.253)	544 (3.743)	562 (3.874)
Silicone Rubber Sponge (Extruded)	1	73 (0.503)	71 (0.489)	73 (0.503)
	2	75 (0.517)	73 (0.503)	70 (0.482)
	3	73 (0.503)	68 (0.468)	67 (0.461)
	Average	74 (0.508)	70.6 (0.497)	70 (0.448)
RTV 511 (Foamed)	1	88 (0.606)	102 (0.703)	102 (0.703)
	2	102 (0.703)	116 (0.799)	118 (0.813)
	3	112 (0.772)	109 (0.751)	114 (0.786)
	Average	101 (0.694)	109 (0.694)	111 (0.767)
RTV (Foamed)	1	114 (0.786)	126 (0.868)	132 (0.910)
	2	112 (0.772)	126 (0.868)	128 (0.882)
	3	112 (0.772)	117 (0.806)	126 (0.868)
	Average	113 (0.777)	123 (0.847)	129 (0.887)
Polysulfide Seal	1	1164 (11.472)	691 (4.764)	938 (6.467)
	2	3584 (24.711)	1627 (11.217)	1234 (8.508)
	3	2587 (17.837)	1294 (8.921)	1035 (7.136)
	Average	2612 (18.007)	1204 (8.301)	1069 (7.370)
RTV 3140 (DC)		2500 (17.236)	1800 (12.411)

Figure 13. Tube Movement Versus Applied Force (Average of Five Samples) for Configuration 1, Style 1

Tube Protection Configuration 1 (Figure 14) was constructed with two layers of Tufcote urethane foam sheet wrapped around the tube. The tip area was filled with plain polysulfide but contained a disc of Rubatex EPT closed cell rubber sponge. The urethane foam was unimpregnated because of a no-vacuum prepotting of the encasement in GMB-epoxy potting compound. Five specimens were prepared.

Figure 14. Tube Protection Configuration 1 (Style 1)

Configuration 2 (Figure 15) was a tube assembly removed from a lot 1-type engineering-evaluation-potted PWA-5 and contained the semi-impregnated urethane and collapsed polysulfide sponge.

Configuration 3 (Figure 16) was prepared by curing TBS-757 silicone rubber foam fire barrier material around the tube in a cotton-phenolic sleeve. Both the tube and sleeve were printed with GE-4155. The sleeve used in this and subsequent configurations was NEMA-LE with an outer diameter of 1.000 ± 0.005 inches (25.4 ± 0.127 mm) and an inner diameter of 0.950 ± 0.005 inches (24.13 ± 0.127 mm).

Configuration 4 (Figure 17) was prepared similar to Configuration 3 except it was a Style 2 specimen with the trigger and anode leads captured in GMB epoxy potting.

Figure 15. Tube Protection Configuration 2

Figure 16. Tube Protection Configuration 3

Figure 17. Tube Protection Configuration 4 (Style 2)

Configuration 5 (Figure 18) was prepared by curing TBS-757 molded around the tube in a mold made by cutting to size a 32 by 162 mm polycarbonate test tube which was subsequently removed leaving the TBS-757 skin exposed to as was the Style 2 configuration.

Configuration 6, not shown, was the same as Configuration 5 except that it was a Style 1 specimen.

Configuration 7 (Figure 19) employed an internally ribbed boot molded from SD 5211U silicone rubber. The boot was molded to a designated old boot design as shown in Figure 20. The tube-base to boot interface was sealed with Sylgard 186 cast in place over the RTV 3140 on the tube base as received from the tube manufacturer. The boot was bonded inside a phenolic-cotton sleeve with Sylgard 186 before potting in the Style 1 configuration.

Tube Configuration 8 was the same as Configuration 7 except that the RTV 3140 applied to the base of the tube was removed and became replaced with Sylgard 186 at the time the boot was sealed to the tube base.

Tube Configuration 9 was the same as Configuration 7 except that it was potted according to Style 2 configuration.

Figure 18. Tube Protection Configuration 5

Figure 19. Tube Protection Configuration 7

Figure 20. Comparison of Old and New Boot Designs

Configuration 10 (Figure 21) utilized a silicone rubber extruded closed cell sponge designated AMS-3195 by the manufacturer, Chase-Walton Elastomers Incorporated. The tube was bonded into the tube with RTV 3140 after being primed with DC 1203. Sponge discs and washers were cut from the sleeving and fitted over the tube tip and the base and bonded in place with RTV 3140.

Configuration 11 (Figure 22) was encased in extruded silicone sponge sleeving similar to Configuration 10, except the sleeving was not bonded to the tube. The sponge sleeved and capped tube assembly was bonded with RTV 3140 into a phenolic-cotton sleeve which had been primed with DC 4094. Style 2 was used.

Configuration 12 (Figure 23) was primed with GE 4004 and placed in an extruded silicone sponge sleeve with no adhesive. The base and the tip of the tube were foamed with RTV 511 and cured in place. The foam was bonded to the tube and the sponge sleeve. Style 2 potting configuration was used. The formulation of the RTV 511 foam was the same as previously described.

Configuration 13 (Figure 24) was enclosed in an internally ribbed molded silicone rubber boot of the old boot design similar to Configuration 7, except that an extruded sponge disc punctured for lead passage was bonded with RTV 3140 to the base of the boot-tube interface. Style 2 was used.

Figure 21. Tube Protection Configuration 10

Figure 22. Tube Protection Configuration 11

Configuration 14 (Figure 25) was primed with DC 4094 cured 30 minutes in air and bonded inside an extruded silicone sponge sleeve with RTV 3140. The exposed RTV 3140 at the tip end was primed with GE 4155 and the tube tip cavity was filled with TSB 757 and cured for 1 hour at 250°F (121°C).

Figure 25. Tube Protection Configuration 14

Configurations 15 and 16, (Figure 26) were encased in extruded silicone rubber sponge sleeving similar to Configuration 11 (Figure 22) except that they were bonded to the sleeve with RTV 3140. The encasement was then bonded inside a phenolic-cotton retainer sleeve with RTV 3140. Style 2 potting configuration was used.

Configuration 17, not shown, was the same as Configurations 15 and 16 except it was potted to Style 1 configuration. This specimen was constructed to obtain data on movement in response to a side thrust on leads. It was not tested in pull and push.

Configuration 18 and 19 (Figure 27) were enclosed in the new-design internally ribbed molded silicone rubber boots. New-design (Figure 20) refers to changes which include 0.020 inch (0.508 mm) inch flats on the inside ribs contacting the tube and lengthening the boot by 0.090 inch (2.29 mm) to allow the insertion

Figure 26. Tube Protection Configurations 15 and 16

Figure 27. Tube Protection Configurations 18 and 19

Table 7. Tube Mobility Evaluation Pull Test Results

Specimen and Style	Strain (in.) (mm) at -65°F (-54°C)	Stress (lb) (kg) at -65°F (-54°C)	Strain (in.) (mm) RT	Stress (lb) (mm) RT	Strain (lb) (kg) 160°F	Stress (lb) (kg) 160°F (71°C)
1-1	0.000	10 (4.54)	0.003 (0.076)	10 (4.54)	0.010 (0.254)	7 (3.17)
2-1	0.000	20 (9.08)	0.001 (0.025)	20 (9.08)	0.002 (0.051)	20 (9.08)
3-1	0.000	10 (4.54)	0.001 (0.025)	10 (4.54)	0.0012 (0.030)	10 (4.54)
4-2	0.000	10 (4.54)	0.0026 (0.066)	10 (4.54)	0.0012 (0.030)	10 (4.54)
5-2	0.000	10 (4.54)	0.0019 (0.048)	10 (4.54)	0.0011 (0.028)	10 (4.54)
6-1	0.001 (0.025)	10 (4.54)	0.0012 (0.030)	10 (4.54)	0.0016 (0.041)	10 (4.54)
7-1	0.044 (1.118)	5 (2.27)	0.010 (0.254)	2.7 (1.22)	0.010 (0.254)	4.4 (1.99)
8-1	0.032 (0.815)	8 (3.62)	0.010 (0.254)	3.4 (1.54)	0.010 (0.254)	4.3 (1.95)
9-2	0.001 (0.025)	10 (4.54)	0.009 (0.228)	10 (4.54)	0.010 (0.254)	9.0 (4.07)
10-2	0.010 (0.254)	4.2 (1.90)	0.0059 (0.150)	10 (4.54)	0.0051 (0.127)	10 (4.54)
11-2	0.0093 (0.236)	10 (4.54)	0.010 (0.254)	7.2 (3.60)	0.010 (0.254)	5.4 (2.44)
12-2	0.010 (0.254)	7.2 (3.26)	0.010 (0.254)	3.5 (1.59)	0.010 (0.254)	4.5 (2.04)
13-2	0.0040 (0.102)	10 (4.54)	0.0082 (0.208)	10 (4.54)	0.0087 (0.221)	10 (4.54)
14-2	0.000	10 (4.54)	0.0010 (0.025)	10 (4.54)	0.0020 (0.051)	10 (4.54)
15-2	0.0020 (0.051)	10 (4.54)	0.0054 (0.137)	10 (4.54)	0.0056 (0.142)	10 (4.54)
16-2	0.0097 (0.246)	10 (4.54)	0.0077 (0.196)	10 (4.54)	0.0076 (0.193)	10 (4.54)
18-2	0.0090 (0.228)	10 (4.54)	0.010 (0.254)	8.1 (3.67)	0.010 (0.254)	8.7 (3.94)
19-2	0.0076 (0.193)	10 (4.54)	0.0096 (0.244)	10 (4.54)	0.0091 (0.231)	10 (4.54)

Table 8. Tube Mobility Evaluation Push Test Results

Specimen and Style	Strain (in.) (mm) at -65°F (54°C)	Stress (lb) (kg) at -65°F	Strain (in.) (mm) RT	Stress (lb) (kg) RT	Strain (in.) (mm) 160°F (71°C)	Stress (lb) (kg) 160°F
1-1						
2-1	0.001 (0.025)	20 (9.08)	0.0010 (0.0254)	20 (9.08)	0.002 (0.051)	20 (9.08)
3-1	0.0005 (0.0127)	10 (4.54)	0.0008 (0.0203)	10 (4.54)	0.0008 (0.0203)	10 (4.54)
4-2	0.0006 (0.0152)	10 (4.54)	0.0002 (0.0051)	10 (4.54)	0.0005 (0.0127)	10 (4.54)
5-2	0.0072 (0.183)	10 (4.54)	0.0005 (0.0127)	10 (4.54)	0.0003 (0.0076)	10 (4.54)
6-1	0.0006 (0.0152)	10 (4.54)	0.0011 (0.0279)	10 (4.54)	0.0010 (0.0254)	10 (4.54)
7-1	0.010 (0.254)	4 (1.82)	0.010 (0.254)	4.8 (2.18)	0.010 (0.254)	6.3 (2.86)
8-1	0.010 (0.254)	3.1 (1.54)	0.010 (0.254)	4.4 (2.00)	0.010 (0.254)	6.3 (2.86)
9-2	0.010 (0.254)	7.1 (3.22)	0.010 (0.254)	7.8 (3.54)	0.010 (0.254)	9.2 (4.16)
10-2	0.0017 (0.0432)	10 (4.54)	0.0040 (0.1016)	10 (4.54)	0.0043 (0.1092)	10 (4.54)
11-2	0.010 (0.254)	3.3 (1.50)	0.010 (0.254)	3.8 (1.72)	0.010 (0.254)	4.2 (1.90)
12-2	0.010 (0.254)	4.3 (1.95)	0.010 (0.254)	4.3 (1.95)	0.010 (0.254)	6.3 (2.86)
13-2	0.010 (0.254)	9.1 (4.13)	0.010 (0.254)	6.7 (3.04)	0.010 (0.254)	5.8 (2.63)
14-2	0.002 (0.051)	10 (4.54)	0.002 (0.051)	10 (4.54)	0.0034 (0.0863)	10 (4.54)
15-2	0.0092 (0.2337)	10 (4.54)	0.010 (0.254)	8.1 (3.68)	0.0097 (0.2464)	10 (4.54)
16-2	0.010 (0.254)	9.3 (4.08)	0.010 (0.254)	8.4 (3.82)	0.010 (0.254)	10 (4.54)
18-2	0.010 (0.254)	9.5 (4.30)	0.010 (0.254)	6.7 (3.04)	0.010 (0.254)	7.2 (3.26)
19-2	0.010 (0.254)	8.3 (3.63)	0.010 (0.254)	7.1 (3.22)	0.010 (0.254)	9.4 (4.25)

of an extruded silicone sponge disc between the tube base and the boot lip. The sponge was bonded in place and the boot sealed with RTV 3140.

An arbitrary minimum acceptable mobility requirement was established at 0.005 inch (0.127 mm) movement with 10 pounds (4.54 kg) pull or push. Tube protection Configuration 12 performed well but was dropped from consideration because the RTV 511 foam used was hydrogen blown. Because of leak potential in the lead to glass seal area the use of hydrogen in the vicinity of a sprytron tube is to be avoided. Data indicated that either the molded ribbed boot or the extruded silicone rubber sponge should adequately protect the sprytron tube.

Tube Strain Measurements

Initial experiments indicated that the glass tube envelope was a good transducer responding well to hydraulic pressure. To establish base line data for correlating potted tube strain gage data to hydraulic loading, a tube with nine strain gages positioned as shown in Figure 28 was exposed to hydrostatic loading. Figures 29 and 30 are graphical plots of strain distribution of longitudinal and circumferential gages under hydrostatic pressures of 100, 200, 300, and 400 psi (689, 1378, 2068, and 2756 MPa). Figure 31 extends, assuming a straight line, the calibration data to corresponding higher pressures. The tube was assembled into a Lot 3 PWA-5 configuration and potted in the production mold according to PS9927003.

The gage readings when the potted unit returned to room temperature (Figures 32 and 33) show the stress applied to the tube at room temperature by the potting cure shrinkage and thermal expansion properties of the potting material. The data show that the urethane foam-polysulfide protection system used in Lot 3 production failed to isolate the sprytron tube from potting stresses, that the loading was not a simple hydraulic load, and that the strains were not destructively high. The longitudinal compressive strain of 1050 micro units per unit at Gage 55 corresponds to a hydraulic pressure of about 2500 psi (17237 KPa).

Figures 34 and 35 show that the longitudinal strain at both Gages 56 and 57 rose to about 1300 microunits for each unit when the potted unit temperature was reduced to -65°F (-54°C). The corresponding hydraulic load at those locations of 3000 psi (20680 kPa) is significant but much lower than the 8900 psi (61363 kPa) hydraulic load known to have broken a tube.

Six more tubes were strain gaged. Each of the six tubes contained three gages (Figure 36) so that circumferential, longitudinal, and diaphragm or base plate strains could be monitored. Comparison of the hydraulic deformation calibration curves showed the data was similar enough to consider the data transferable among the six tubes.

The six tubes were assembled into PWA-5 configurations, two each Lot 2 worst case, Lot 2 best case, and Lot 3. Lot 2 worst case specimens differed from Lot 2 best case specimens only in that the worst case specimens were so assembled that one corner of the spacer board protruded into the RTV at the base of the tube. The board was at a right angle to the tube base, simulating the location of the laminate in one of the Lot 2 D-test units which contained a broken tube. Each of the Lot 2 configurations contained an additional strain gage on the spacer board.

The assemblies were potted in production molds according to PS9927003 and strains were monitored on two units throughout the 24-hour potting cycle. Figures 37 and 38 present the strain data taken during the cure. Unfortunately the base gage was lost on one unit.

The curves show that the urethane-polysulfide envelope failed to protect the tube from the compressive forces of potting gellation and cure. They show nonuniform strains develop as polymerization progresses. They also show what appears to be a wave of polymerization progressing from the center of the mass past the tube base and on toward the tip.

Figure 28. Strain Gage Layout of Nine Gages

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Figure 29. Longitudinal Deformation of Tube Under Hydrostatic Pressures

Figure 30. Circumferential Deformation of Tube Under Hydrostatic Pressures

Figure 31. Calibration of Strain Versus Hydrostatic Pressure

Figure 32. Circumferential Deformation at Room Temperature of Lot 3 Configuration Potted in Epoxy GMB

The curves from the gages on the spacer boards show about the same compressive strain developing during cure; however, upon cooling to room temperature following cure, the strain on one of the Lot 2 worst case spacer boards moved to 3000 microunits per unit as compared to about 1900 and 1500 microunits per unit on two Lot 2 best case boards. The readings from one of the Lot 2 worst case specimens were lost during potting.

Much of the information from these six units was lost because of broken leads at the potting-mold interface. Leads were broken during removal of the castings from the mold. Additional data were lost because of equipment problems. Signals were recorded on a 24-point recorder through a signal conditioner.

The Lot 2 worst case specimen exhibited a high load occurrence* during a warm up from -65°F (-54°C) during thermal cycling. About 45 minutes after

*C. Thompson, "Failure Analysis of Sprytron Tube." LTR, Bendix Kansas City: October 1972.

Figure 33. Longitudinal Deformation at Room Temperature of Lot 3 Configuration Potted in Epoxy GMB

the hold cycle at -65°F (-54°C), after the specimen began its move back to room temperature, the circumferential gage moved to a sharply increased strain which is equivalent to a hydraulic strain of 6000 psi (41369 MPa) at that location. The gage readings returned to their original post potting readings after stabilization at room temperature. The high load phenomena occurred again on the next -65°F (-54°C) warm up cycle.

Based on the reading it appears that the tube was close to breaking because of a compressive load occurring during a transient thermal wave. Since no

Figure 34. Circumferential Deformation at -65°F (-54°C) of Lot 3 Potted in Epoxy GMB

transient high load phenomena was noted in other units during thermal cycle, it would appear that the presence and location of the spacer board was a significant contributor to the strain.

To determine a thermal distribution from the capacitor to the tip of the sprytron tube during thermal cycle, a PWA-5 assembly was instrumented with ten chromel alumei thermocouples as shown in Figure 3. Thermocouple 1 was positioned 0.730 inch (18.542 mm) under the surface of the epoxy GMB against the metal stud. Number 2 was positioned at the base of the tube to a

Figure 35. Longitudinal Deformation at -65°F (-54°C) of Lot 3 Potted in Epoxy GMB

depth of 0.660 inch (16.764 mm). Numbers 3, 4, 6, and 7 were against the tube wall at depths of 0.400 inch (10.160 mm), 0.370 inch (9.398 mm), 0.360 inch (9.144 mm) and 0.320 inch (8.128 mm), respectively. Numbers 5, 8 and 10 were positioned alongside the tube at depths of 0.750 inch (10.050 mm), 1.550 inch (39.370 mm), and 0.630 inch (16.002 mm) respectively. Number 9 was positioned at the center surface of the capacitor 1.100 inch (27.940 mm) deep.

Figure 39 is a time-temperature plot of Thermocouples 1, 7, and 9. From a stable 75°F (24°C) room temperature, the environment was abruptly changed to -65°F (-54°C). After 45 minutes at -64°F a temperature differential of 50°F (28°C) existed between the tube surface and the center of the capacitor surface.

Figure 36. Strain Gage Layout of Three Gages

After stabilization at -65°F (-54°C) the tube surface temperature once again returned to room ambient before the capacitor surface, developing a maximum temperature differential of 35°F (19°C). Thus, the thermal distribution data appears to support involvement of a transient thermal wave in stress occurrence.

Further efforts to show cause for Lot 2 and Lot 3 tube breakage were discontinued as the strain gage effort was redirected to the evaluation of new designs for tube encasements.

Four more tubes were gaged with 13 gages each. After thermal and hydraulic calibration the tubes were assembled into PWA-5 configurations. Two of the tubes were encased in extruded silicone sponge extrusions as detailed in Configurations 15 and 16 in the tube encasement push-pull section of this report. The other two tubes were encased in internally ribbed silicone rubber boots as described for Configurations 18 and 19.

The assemblies were potted in the PWA-5 production molds with epoxy-GMB according to PS9927003. The gage leads were sleeved to prevent damage at the potting mold interface. Figures 40 through 55 present the logitudinal and circumferential strain data accumulated during potting cure and thermal

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Figure 37: Curing and Residual Strains of Sprytron Tube

Figure 38. Curing and Residual Strains of Sprytron Tube Lot 2

Figure 39. Encapsulated Sprytron Thermal Cycle

cycling of these 4 units. The data show that the extruded sponge sleeve was a satisfactory encasement for the protection of the tube. Strains on the sponge sleeve protected tubes never exceeded about 200 microunits per unit during the strain gage investigation.

Both of the ribbed silicone rubber boot protected tubes demonstrated exceptional tensile strains in both longitudinal and circumferential directions at gage locations on the tube cylinder close to the tube tip. Since the tensile strain at this location occurs only at the high temperature cycle the logical explanation is that it is the result of a compressive force at or close to the tube tip caused by expansion of an excess of tube boot material in that area. The compressive force must be quite large to cause such a ballooning of the cylinder, and that force must be pressing at or close to the point at which the tube is necked down and sealed--the area at which tube wall thickness variation is the greatest.

The results of the strain gage experiments do not discredit the use of the molded boot protective envelope but the strains which developed at 160°F do indicate that some redesign of the molded boot is needed. Further, these results caution against the incorporation of design changes or new design concepts without thorough evaluation and point out that careful consideration must be given to dimensioning parts designed from high-bulk modulus high-thermal-expansion materials such as silicone rubbers.

No evaluation of a redesigned boot was made because the silicone sponge system was shown to be a more than adequate system with strain levels so low that its incorporation into the assembly could be made with confidence in its function. The strain gage investigation proved to be a valuable tool in the evaluation of protective encasements or sensitive components in a rigid potting environment.

ACCOMPLISHMENTS

The objectives of this program were met, the cause for tube breakage in the production design was reasonably shown, and a new protective package was supplied along with data to permit its incorporation into production with a high confidence in its functional capability.

By carrying the work to completion and obtaining strain data on tubes employing the developed packaging systems in the production PWA-5 potted mode, this project avoided recommending two alternate encasement systems when one system was found to require further development.

The molded internally ribbed silicone rubber boot which fell out of competition at this final stage of the program was not found to be a poor system for tube protection. The strain gage data did show, however, that redesign of the boot was needed and additional gaged tube investigations would be required to evaluate a redesigned boot.

The silicone sponge sleeve protective encasement design has been incorporated into production and no sprytron tube failures have occurred to date in subsequent testing.

The methodology used in this problem solving endeavor is believed to be unique in the study of encapsulated assemblies. The results were such that this technique is recommended for future investigations of potted components.

Figure 40. Circumferential Strain Versus Curing and Temperature Cycles for Tube 1 With Extruded Silicone Rubber Sponge

Figure 41. Circumferential Residual Strain and Tube Deformation Versus Temperature Cycling for Tube 1 With Extruded Silicone Rubber Sponge

Figure 42. Longitudinal Strain Versus Curing and Temperature Cycles for Tube 1 With Extruded Silicone Rubber Sponge

Figure 43. Longitudinal Residual Strain and Tube Deformation Versus Temperature Cycling for Tube 1 With Extruded Silicone Rubber Sponge

Figure 44. Circumferential Strain Versus Curing and Temperature Cycles for Tube 2 With Molded Silicone Rubber Boot

Figure 45. Circumferential Residual Strain and Tube Deformation Versus Temperature Cycling for Tube 2 With Molded Silicone Rubber Boot

Figure 46. Longitudinal Strain Versus Curing and Temperature Cycles for Tube 2 With Molded Silicone Rubber Boot.

Figure 47. Longitudinal Residual Strain and Tube Deformation Versus Temperature Cycling for Tube 4 With Extruded Silicone Rubber Boot

Figure 48. Circumferential Strain Versus Curing and Temperature Cycles for Tube 3 With Molded Silicone Rubber Boot

Figure 49. Circumferential Residual Strain and Tube Deformation Versus Temperature Cycling for Tube 3 With Molded Silicone Rubber Boot

Figure 50. Longitudinal Strain Versus Curing and Temperature Cycles for Tube 3 With Molded Silicone Rubber Boot

Figure 51. Longitudinal Residual Strain and Tube Deformation Versus Temperature Cycling for Tube 3 With Molded Silicone Rubber Boot

Figure 52. Circumferential Strain Versus Curing and Temperature Cycles for Tube 4 With Extruded Silicone Rubber Sponge

Figure 53. Circumferential Residual Strain and Tube Deformation Versus Temperature Cycling for Tube 4 With Extruded Silicone Rubber Sponge

Figure 54. Longitudinal Strain Versus Curing and Temperature Cycles for Tube 4 With Extruded Silicone Rubber Sponge

Figure 55. Longitudinal Residual Strain and Tube Deformation Versus Temperature Cycling for Tube 2 With Molded Silicone Rubber Sponge