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EVALUATION OF POLYSTYRENE BEAD FOAM
AS AN ENCAPSULANT FOR ELECTRONIC PACKAGES

By D. J. Fossey

Published January 1979

Final Report

Prepared for the United States Department of Energy
Under Contract Number DE-AC04-76-DP00613.

**Kansas City
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EVALUATION OF POLYSTYRENE BEAD FOAM AS AN ENCAPSULANT FOR ELECTRONIC PACKAGES

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This experimental stress analysis evaluates polystyrene bead foam (PSBF) as an encapsulant. Direct comparison data are included for polyurethane foam encapsulation. Thermal stresses on solder joints using a thumb tack test are compared for these foam encapsulants and GMB/epoxy. Special transducer designs are used to measure thermomechanical stresses and deflections. Failure criteria for some of the electronic components involved are delineated. The mechanical properties of potting polystyrene bead foam is presented and compared with the properties of structural polystyrene bead foam. The thermomechanical load and deflection data and the transducers developed are aids for making stress analysis in other foam encapsulated units. Polystyrene bead foam is concluded to be a safe encapsulant for certain electronic packages, but polyurethane foam is not.

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SUMMARY

The objective of this project was to evaluate polystyrene bead foam (PSBF) as an encapsulant for electronic packages. The thermomechanical stresses that develop during PSBF encapsulation and thermal cycling were evaluated and compared with those for polyurethane foam (PUF); forces on solder joints in PSBF and other encapsulants were compared, and particular potential problem areas were studied. Other encapsulant investigations have been performed in the past, but this is the first known evaluation of PSBF as an encapsulant for electronic packages.

The tensile and compressive properties of PSBF were determined and potting PSBF and structural PSBF mechanical properties were compared. Axial forces on solder joints were measured for PSBF and PUF encapsulation and thermal cycling and were compared with previous GMB/epoxy data. Failure criteria were determined for pressure loading of ceramic microcircuits and metal covers used in the electronic assembly. A unit without electronic components or interboard wiring was used as a test vehicle to evaluate and compare forces and deflections for PSBF and PUF encapsulation and thermal cycling. Finally, a production equivalent unit (PEU) was used to measure the particular loadings for PSBF and PUF encapsulation and thermal cycling.

The severest loading for PSBF encapsulation is caused by printed circuit board bending, and this is safe. PUF of comparable density causes more severe loadings, especially when the PUF does not bond to printed circuit boards, metal cases, or electronic components. PSBF causes the lowest axial loads, with 0.1, 0.2 and 0.32 g/cm³ PUF, and GMB/epoxy following in order of severity. The pinning points for the encapsulant vitally influence the severity of loading. Voids are more likely when encapsulating a densely packed electronic package in PUF than in PSBF.

As an encapsulant, PSBF was found to be very safe. Axial loading data for solder joints was compared for the first time for GMB/epoxy, for PUF in 0.1, 0.2 and 0.32 g/cm³ densities, and for PSBF. Lateral force and deflection transducers were developed and successfully used; these are available for future applications. A depotting fixture and process, which shortened the depotting time from 3 hours to 30 minutes, was developed.

DISCUSSION

SCOPE AND PURPOSE

Polystyrene bead foam (PSBF) is a new candidate encapsulant material at Bendix. Test units of the first Bendix production unit scheduled to be encapsulated in PSBF were used extensively as test vehicles to evaluate the thermomechanical forces and displacements that PSBF exerts on electronic components, circuit elements, and solder joints in potting and thermal cycling situations. Direct comparison with polyurethane foam (PUF) encapsulation was made. Proven transducing techniques were applied with appropriate adaptation and miniaturization.

PRIOR WORK

Initial feasibility studies concerning potting and depotting characteristics of PSBF were conducted at Sandia Laboratory. This new encapsulating concept was successfully demonstrated on other non-production components.¹ However, behavior of this material and its effect on components in a potting process and subsequent thermal cycling have not been determined, nor have these effects been compared to other popular foam encapsulants.

Some prior work has been done at Bendix in evaluating encapsulation of actual and test components based on reported studies.² Mathematical models have been simultaneously developed so that stress predictions for other specific configurations may be reliably made. Several of these are described and applied in Reference 3. A modified version of one such model which can be applied to solder joints under various thermomechanical loading conditions had previously been developed by Baker.⁴

The mechanical properties of 0.05 g/cm³ and 0.1 g/cm³ PSBF have been reported previously.⁵ Other work has provided limited data about 0.24 g/cm³, 0.3 g/cm³, 0.4 g/cm³, and 0.5 g/cm³ PSBF.^{6,7} Little data have been reported for 0.2 g/cm³ PSBF.

ACTIVITY

Stress Analysis Experiments

The experimental work was divided into four separate categories: the thumb tack tests, the failure criteria tests, the test vehicles, and a Production Equivalent Unit (PEU). All four tests were deemed necessary to provide a comprehensive understanding of PSBF encapsulation stresses and a comparison to stresses found in other popular foam encapsulant materials.

Experience has shown that some types of loadings caused by interaction between encapsulant and electronic component and circuitry are sporadic but perennial problem areas. These include loadings of solder joints which cause movement or lead wire pull out; failure by breaking brittle glass, or by ceramic parts crushing or deforming metal component envelopes or covers so that the internal circuitry shorts or does not function within specifications; and other thermomechanical interactions which load or move the structural or electronic component parts sufficiently to cause a failure to meet the mechanical or electrical specifications.

One new area of investigation for PSBF was lateral forces and displacements. Historically, encapsulant materials have bonded well to most or all surfaces in the electronic units. Because PSBF does not bond to any of these surfaces, bonding was anticipated to be the major area for potential problems. As such, considerable effort was aimed toward collecting quantitative comparison information and evaluating its significance.

The transducers used in each experiment are listed in Table 1, and each transducer is described in Table 2.

Thumb Tack Tests

The thumb tack test technique was designed to evaluate axial loads on a component lead wire soldered normal to a printed circuit board (PCB). The transducers were in the shape of a thumb tack, with a 6.35-mm-diameter steel disc welded to a 0.813-mm-diameter copper lead wire. Strain gages were bonded to the copper lead at 120° spacings about the lead (Figure 1). Each lead was prestressed by stretching with an 11.1 N load and then load calibrated. The lead was then soldered in a PCB segment, and an extensometer (Figure 2) was attached to the lead extension on the PCB side opposite to the tack head to monitor any movement in the solder joint. Thermocouples monitored the temperature at each strain gage location. Each unit was mounted in a metal tube, encapsulated, cured, and thermal cycled. This technique for strain gage application has been published in the open literature.²

The loads resulting after encapsulation and during thermal cycling are compiled in Table 3 and Figure 3. No solder joint movement occurred in the PSBF encapsulation. Figure 3 shows the loads at the high and low temperature ends of each thermal cycle. The GMB/epoxy data of Figure 3 show the effect of continued cure and shrinkage with successive thermal cycles and its appearance as an increased compressive load.

Table 1. Description of Stress Analysis Experiments

Name	Transducer Complement*	Encapsulant
Thumb Tack	3 Strain Gages Around the Lead, 1 Deflectometer	PSBF, 3 Densities of PUF
Failure Criteria	90° Strain Gage Pair	None (Pressurized to failure)
Test Vehicle 1	1 Pressure, 1 Lateral Force, 1 Lateral Deflection, 4 Rosette Pairs on PC Boards	Two Densities of PSBF
Test Vehicle 2	1 Pressure, 1 Lateral Force, 4 Lateral Deflection,** 1 Rosette Pair on PC Board, 3 Vertical PC Board Deflectometers	PSBF and PUF
PEU	1 Lateral Force, 1 Rosette Pair on PC Board, 4 Single Rosettes on Micro-circuit Covers, 3 Single Rosettes on Metal Shields	PSBF and PUF

*A thermocouple was mounted adjacent to each strain gage location.

**This second lateral deflection transducer design operated linearly and reproducibly for all testing.

One tack was potted with PUF densities of 0.10, 0.20 and 0.32 g/cm³. The load during the cure and 10 thermal cycles from -54 to 82°C were monitored. The loads increased with increasing foam density. Only specimen PUF 1 showed a marginally significant bonding strain of 1 mm/m during thermal cycling; the maximum extensometer reading was 0.025 mm for PUF 2 at -54°C. The high load on specimen PUF 3 produced increasing compressive loads with further thermal cycling, perhaps from yielding in the copper lead.

Table 2. Description of Transducers Used in Test Vehicles and PEU

Transducer Type	Quantity Measured	Transducer Description
Pressure	Effective interaction pressure between foam and transistor	Strain gage on TO-5 transistor can, pressure calibrated
Lateral Force	Force components parallel to a PCB surface	Three strain gages about a metal rod, fastened to a TO-5 transistor can as a cover to isolate from the foam
Lateral Deflection	Deflection components parallel to a PCB surface	Three strain gages on a disc with a rod at the center attached to a TO-5 transistor can as a cover, disc edge fastened to a PCB*
Rosette Pair	Biaxial tension and bending of PCBs	Matched pair of strain gage rosettes, bonded to the top and the other to the bottom of a PCB
Board Deflectometer	Movement of PCB relative to metal base	Strain gaged cantilever beam connected to PCB with metal rod
Single Rosette	Biaxial strain on alumina microcircuits and metal covers	Strain gage rosette bonded to microcircuit or metal cover

*This is a description of version 2 which proved to be linear and reproducible for all tests.

Figure 1. Fully Instrumented Thumb Tack Soldered on Printed Circuit Board

Three thumb tacks were encapsulated in 0.20 g/cm^3 PSBF, cured, and thermal cycled seven times through the range from -54 to 82°C . The axial compression loads were 27 to 40 N. No significant nonaxial bending strains were measured, and no lead movement in the solder joint was recorded.

These comparison data for axisymmetric thermomechanical loading of a solder joint in a direction normal to the printed circuit board show that 0.20 g/cm^3 PSBF causes low loading, compared to

Figure 2. Instrumented Extensometer Mounted on Printed Circuit Board and Soldered to Lead Extension

PUF or GMB/epoxy. The PUF of 0.32 g/cm^3 and GMB/epoxy, in contrast, cause large axial loadings during thermal cycling and may cause copper lead wires to yield more with successive thermal cycles ("Thermal Ratchet" according to Reference 4) or else may cause movement in the solder joint. All of the lower density PUF and the PSBF loadings appear safe, with the PSBF causing the lowest force to be transmitted to the solder joints.

For identical joints to these thumb tacks (0.813-mm-diameter copper wire soldered into a 1.270-mm-diameter plated-through hole in a 1.57-mm-thick PCB using 63/37 Sn/Pb solder), a 44 N load will cause failure in 24 hours at 82°C . The breaking load for the copper lead wire itself is 126.5 N. However, small solder joint movement will quickly relieve these thermomechanically generated loads. A movement of 0.0127 mm would relieve about 35 N of load because the PSBF has a much larger area and a much lower elastic modulus than copper.

Table 3: Encapsulated Thumb Tack Loads After Cure and Range for First Thermal Cycle

Specimen Number	Load at 24°C After Cure (N)	Thermal Cycle 1* Load Range (N)	Comments
GMB/Epoxy			
E1-1	-37.4	66.3	No protective coatings
E1-2	-41.8	72.1	No protective coatings
E1-3	-44.9	70.7	No protective coatings
E2-1	-58.3	64.9	Polysulfide foam on PCB
E2-2	-55.2	79.2	Polysulfide foam on PCB
E2-3	-53.8	70.7	and RTV on Lead Wire RTV on Lead Wire
Polyurethane Foam			
PUF 1	-4.4	44.9	0.1 g/cm ³ density
PUF 2	-22.2	64.5	0.2 g/cm ³ density
PUF 3	-32.5	89.0	0.32 g/cm ³ density
Polystyrene Bead Foam			
PSBF 1	-15.6	25.8	0.2 g/cm ³ density
PSBF 2	-17.3	42.3	0.2 g/cm ³ density
PSBF 3	-15.1	24.9	0.2 g/cm ³ density
*Thermal cycle range for GMB/Epoxy was -54 to 74°C; range for foams was -54 to 82°C.			

Failure Criteria Tests

Crushing of ceramic microcircuits and the metal covers was deemed to have the most severe loading potential for PSBF. Even small pressures over the surface could cause failure. Shear loading on the microcircuit leads probably would be the second most severe, but such tests were not conducted, because a small lead movement could relieve much of the load. No other loadings were expected to cause problems. The strains at microcircuit breakage and at yield of the metal covers were needed to help interpret the

SEE TABLE 3 FOR MATERIAL IDENTIFICATION

Figure 3. Thermal Cycle Load Data for Thumb Tacks

significance of the measured strains on the units after encapsulation and during thermal cycling. Two types of tests were performed on the microcircuits. The first was a hydraulic pressurization of two microcircuits in glycerine. Each was instrumented with a right angle pair of strain gages. The pressure and the strains were monitored until each microcircuit cover broke. In the second test, an elastomer pad was used to distribute an unidirectional compression load normal to the largest cross-sectional area of the microcircuit being tested.

The failure strains (Table 4) were lower than the 670 $\mu\text{m}/\text{m}$ estimated from alumina strength data. The measured values could be 20 percent low because each strain gage averages the strain over its length in the strain gradient region at the microcircuit center.

The variation of strains at failure in Table 4 probably reflects the range in strength values representative of brittle alumina ceramic used to make these microcircuit housings. Nominal pressure of failure for all microcircuits tested ranged from 434 to 772 kPa, with the higher pressure required to break the smaller size microcircuits. Figure 4 shows the scatter in microcircuit failure pressure versus the smaller dimension. For a given deflection or pressure, the small dimension had the higher strain and is thus the controlling dimension during failure.

The metal covers were also loaded in unidirectional compression normal to the largest cross section using an elastomer pad for force distribution. The yield points on the load versus strain curves occurred for nominal pressures from 421 to 545 kPa (Table 4). Again, the higher pressure was necessary to cause yielding in the metal cover of the smallest width. The cover yield data are shown as triangles on Figure 4. The smallest and largest metal covers were not rectangular. The smallest was slightly skewed into a parallelogram, and the largest had the two corners along one long side truncated. Note the identical pressures for yielding of two covers of the same size, whereas the alumina microcircuit cover breakage pressures showed scatter for two units of the same size.

These failure criteria also were used to evaluate the significance of loadings developed during encapsulation, curing, and thermal cycling of the test vehicles and of the production equivalent unit.

Test Vehicles

The test vehicle experiments were designed to evaluate forces and deflections other than the axisymmetric variety determined from the thumb tack tests. The special transducers for these experiments were designed to measure pressure, loads, and deflections in the lateral directions (parallel to the PCBs), and also PCB bending and vertical deflection. Pressure loadings were monitored because of crushing of components which has occurred occasionally in the past. The lateral loadings and deflections were important because PSBF does not bond well or at all to internal surfaces of the unit used. Thermal expansion differences between PCBs and PSBF, would then load components parallel to the PCB surface. Bending and vertical deflection of the PCBs were important, based on past experience with other encapsulants.

Table 4. Failure Criteria Test Results

Dimensions (mm)		Failure Pressure (kPa)	Failure Strain ($\mu\text{m/m}$)	Remarks
Width	Length			
22.35	22.35	772	490	*
22.35	45.72	621	590	**
22.35	45.72	531	720	**
26.67	26.67	469	490	*
29.21	29.21	545	300	**
29.21	29.21	434	470	**
25.40	48.26	545	1450	***
26.67	34.29	490	1030	***
26.67	34.29	490	340	***
33.02	48.26	421	510	***
33.02	48.26	421	Bad gage	***

*Ceramic microcircuit under hydraulic pressurization to failure

**Ceramic microcircuit loaded to failure uniaxially using rubber pads

***Metal cover loaded to yield uniaxially using rubber pads

The first test vehicle made use of the case and PCB stack. No components were mounted on the boards. Instead, the transducers for the location shown in Figure 5 were made and mounted to monitor the forces and deflections. Because this unit was less full and less stiff (no components, inter-board wiring, or electrical connectors), this was expected to be a worse case than the production equivalent unit.

The number of transducers was limited by the total number of data recording channels available. The single rosettes were not used in the test vehicles because no microcircuits or metal covers were present. No transducers were placed on the bottom PCB for this test.

Figure 4. Failure Pressures for Ceramic Microcircuits and Metal Covers

The rosette pair locations were chosen to give worst case estimates (rosettes 2 and 4) and other intermediate data (rosettes 1 and 3). The lateral force and deflection transducers are nearly at mirror image positions with respect to the PCB center line and at large distances from the geometrical center. They were expected to measure nearly the maximum lateral force and deflection expected in the entire unit. The unit was encapsulated first with PSBF (0.20 g/cm^3), depotted in toluene, and repotted with PUF (0.21 g/cm^3). Each potting was thermal cycled twice over the range from -54 to 82°C .

The lateral force transducer consisted of a base plate to be epoxied to the PCB. To this was attached a rod with three strain gages mounted at 120° intervals on the surface. A thermocouple was provided for thermal compensation.

TOP PCB

MIDDLE PCB

1 mm

R = ROSETTE PAIR
P = PRESSURE TRANSDUCER
D = LATERAL DEFLECTION TRANSDUCER
F = LATERAL FORCE TRANSDUCER

Figure 5. Transducer Locations for Test Vehicle 1

The other end of the rod was fastened to a "hat" (a TO-5 transistor can). This hat keeps the foam from contact with the strain-gaged rod and allows an unambiguous force measurement both in direction and magnitude. The rod diameter was chosen based on the maximum expected force in this unit. Figure 6 shows the lateral force transducer parts before assembly.

The first lateral displacement transducer design was a modification in the sensing element of the post and hat design described above for the lateral force transducer. Instead of using the stiff central rod for sensing, thin metal strips were fastened to the post on one end, were strain gaged, and were attached to the hat by wire connections from the opposite ends. The strips were thin so that only a small force was required to detect movement of the strips.

The data from Test Vehicle 1 were used in defining the type, number, and locations for transducers to be included in Test Vehicle 2. The general measurement rationale was not changed. The pressure transducer and the lateral force transducer were moved to new locations. Rosette pair 1 was retained as a data consistency check. Four lateral deflection transducers of two revised designs were included to allow larger lateral movement. The spokes are the strain-gaged elements of the first revised-design lateral deflection transducer (Figure 7). The rod, which connects the center of the wheel to the transistor can, has a small diameter to allow large lateral movement and still remain linear elastic with no yielding or permanent set. The rim is thicker than the spokes to allow bending freedom and is bonded to the PCB. The second design (Figure 8) has a full disc connecting the rim and axle instead of the three spokes. This design was expected to have a more uniform calibration with direction. However, the spokes of the first design were wide enough to also provide a uniform calibration with direction. Thus, both designs are of equal accuracy, and the full disc design is easier to make.

A set of PCB deflectometers was mounted at one of the locations expected to deflect most because it was farthest from the PCB mounting posts. This response to PSBF had not yet been monitored. The strain-gaged cantilever beams which served as sensing elements are shown in Figure 9. The support block was bonded with epoxy to the metal base of the test vehicle, and rods connected each beam end to one printed circuit board. The locations of all transducers are shown in Figure 10 except for board deflectometer H_1 , which was connected to the bottom printed circuit board. The arrows show force and deflection directions and PCB maximum tension and bending strain directions relative to the data described below.

Figure 6. Lateral Force Transducer Before Mounting, Cover Attachment, and Calibration

Test Vehicle 2 was potted with 0.20 g/cm^3 PSBF and thermal cycled four times between -54 and 77°C . It was depotted in toluene and repotted with 0.20 g/cm^3 PUF. Five thermal cycles, -54 to 82°C , were monitored with Test Vehicle 2 filled with PUF.

In order to reduce for presentation the large amount of data obtained during the cure and thermal cycles of the test units, only the significant data will be shown in detail. Data from PSBF- and PUF-encapsulated units are presented on the same graph for ease of comparison. To aid in interpretation of the data, a split plot with temperature versus time during the cure of thermal cycle is shown above the transducer data being presented.

Lateral load in Test Vehicle 1 was below 2.2 N at all temperatures. Lateral deflections went well beyond the 0.25 mm calibrated range of the deflectometer. A new transducer with greater lateral movement capability was designed for the second test vehicle. As expected, the largest PCB bending strain was measured in Test Vehicle 1. Rosette pair R_2 recorded 440 and $190 \mu\text{m/m}$ for the two

Figure 7. Three-Spoke Version of Lateral Deflection Transducer Before Mounting, Cover Attachment, and Calibration

principal strains; the largest change with temperature was also by R_2 , with readings of 250 and 130 $\mu\text{m/m}$ for the first and second pottings respectively (see Figure 5 for rosette locations). All readings were essentially the same for both densities of PSBF used to encapsulate Test Vehicle 1.

Figures 11 and 12 show the pressure during the cure and first thermal cycle, respectively, for the PSBF and PUF encapsulation of Test Vehicle 2. The highest pressure recorded for the PSBF was about 2.5 kPa after the cure cycle. A lower pressure of about 1 kPa was recorded after the first thermal cycle. This reduction in pressure was probably caused by loss of pentane during the high temperature side of the thermal cycle. The pressure profiles for thermal cycles 2, 3, and 4 for the PSBF-filled unit were identical to the thermal cycle 1 pressure profile shown in Figure 12.

The pressure slowly increased during the cure cycle of the PUF filled unit; a maximum compressive pressure of 7.5 kPa was reached at the end of the high temperature portion of the cycle. During the first thermal cycle, there was a slight short term decrease in the pressure during the transition from -54 to 82°C. There

Figure 8. Full Disc Version of Lateral Deflection Transducer Before Mounting, Cover Attachment, and Calibration

was an increase in the pressure at 24°C after the first thermal cycle. Thermal cycles 2 to 5 also showed little pressure change with temperature, with only a little progressive pressure increase with successive thermal cycles as the PUF continued to cure during the high temperature portion of each cycle.

The lateral force profiles generated for the cure and thermal cycles of the PSBF- and PUF-filled Test Vehicle 2 are shown in Figure 13 and Table 5, respectively. The PSBF generated, during the cure cycle, a maximum lateral force of 2.2 N and the PUF exerted about eight times the force (18 N). The maximum PSBF lateral force is equivalent to a maximum lateral net pressure on the transducer surface of 103 kPa. This could cause lateral forces on the microcircuits up to 17 N. However, these are relieved readily with lateral movement, because the lateral deflections, as shown in Figure 14 for the cure and Table 6 for the four thermal cycles, of all four lateral deflectometers readily deflected to as much as 0.178 mm. Microcircuit lead strains would then be less than 3 mm/m, or well below yield, and thus very safe. The metal covers should be adequately rigid to resist movement. The final lateral force data point for the PUF-filled unit was recorded the morning after the cure, by which

Figure 9. Printed Circuit Board Deflection Transducer (Rods Connect Each Finger to a Printed Circuit Board)

time the lateral force had increased much more than expected from the small temperature change still remaining before reaching ambient. There was a large increase in force at the middle of cycle 2 and between later cycles. The increase in cycle 2 was from completing the cycle the following morning. A night or a weekend lapse followed between the latter cycles. For cycles 1 and 2 and 3 through 5, there was a progressive increase in force from cycle to cycle, perhaps caused in part by continued cure during the high temperature half of each cycle.

The final lateral force of 98.7 N after five thermal cycles would be equivalent to a maximum lateral pressure on the transducer surface of 4.6 MPa.

A large amount of lateral deflection data is shown in Figure 14 for the cure cycle and Table 6 for the thermal cycles. Deflections are listed at the start, at low and high temperature, and at final room temperature.

R = ROSETTE PAIR
P = PRESSURE TRANSDUCER
H = VERTICAL PCB DEFLECTION TRANSDUCER
D = LATERAL DEFLECTION TRANSDUCER
F = LATERAL FORCE TRANSDUCER

ARROWS SHOW DIRECTIONS OF LATERAL FORCE AND DEFLECTIONS AND OF ROSETTE PAIR MAXIMUM PRINCIPAL STRAINS FOR PSBF (→) AND PUF (---→)

Figure 10. Transducer Locations for Test Vehicle 2

Figure 11. Pressure During Cure of Test Vehicle 2

Figure 12. Pressure During Thermal Cycle 1 for Test Vehicle 2

Figure 13. Lateral Forces During Cure Cycle for Test Vehicle 2

Consider three important observations for the PSBF data. First, the cure is a period of bonding of the individual polystyrene beads to one another. Thereafter, the beads are no longer entities which may act individually to accommodate thermal movement of the transducers and printed circuit boards, but are now part of a bonded whole which has an elastic modulus (temperature dependent). This bonded whole of PSBF now causes forces and generates deflections.

Table 5. Lateral Forces During Thermal Cycles of Test Vehicle 2 and the Production Equivalent Unit (PEU)

Encapsulant	Thermal Cycle	Lateral Force (N)			
		Start, 24°C	Low, -54°C	High*	End, 24°C
Test Vehicle 2					
PSBF	1 to 4	2.22	4.45	0.44	2.22
PUF	1	20.9	29.8	22.7	24.9
PUF	2	25.4	32.4	36.0	36.4
PUF	3	70.3	79.6	72.5	74.3
PUF	4	83.2	92.1	81.4	89.0
PUF	5	95.2	102.3	97.0	98.7
PEU					
PSBF	1	1.56	1.56	0.18	0.84
PSBF	2 and 3	0.58	1.11	0.09	0.67
PUF	1	0.67	1.56	0.40	0.89
PUF	2	0.89	1.56	0.31	0.93
PUF	3	0.89	1.56	0.31	0.93
PUF	4	0.89	1.65	0.40	0.89

*At 77°C for Test Vehicle 2, at 82°C for PEU.

Second, lateral deflectometer D_1 has a low deflection at low temperature and a high deflection at high temperatures, which is opposite to the behavior of D_2 and D_4 . This merely means that D_1 was in a deflected position at the end of the cure and moved toward less deflection at -54°C and more deflection at 77°C. D_2 and D_4 , however, moved toward more deflection at -54°C and less at 77°C, since their positions at the end of the cure were different relative to their equilibrium positions before filling the test vehicle with polystyrene beads.

Third, there was mixed behavior for D_2 , D_3 , and D_4 during cure. Evidently the beads are moving about to accommodate the transducers before the temperature-time conditions have caused bonding. Also, the poorly defined deflection cycles for D_2 and D_3 for the first thermal cycle appear to be caused by the very short hold at -54°C, not really allowing the entire unit to completely equilibrate at temperature sooner, and thus show well defined deflection cycles.

Figure 14. Lateral Deflection During Cure Cycle for Test Vehicle 2

The lateral deflection data for D₁ and D₃ during PUF cure are shown in Figure 14. The five thermal cycles lateral deflection data are listed in Table 6. These are nearly identical to deflection values for D₁ at a given temperature. Lateral deflections D₂ and D₄ followed a similar pattern, but had only half as large deflections at -54°C. D₄ had the lowest deflection of all during PUF cure.

Table 6. Lateral Deflection During Thermal Cycles for Test Vehicle 2

Transducer*	Thermal Cycle	Lateral Deflection ($\mu\text{m/m}$) at Temperature			
		24°C	-54°C	72°C	24°C
PUF/D ₁	1	4.0	8.5	1.4	5.0
	2	5.8	7.0	1.3	4.5
	3	3.5	7.0	1.5	3.3
	4	3.3	7.4	1.6	3.3
	5	3.0	6.5	1.3	3.0
PUF/D ₃	1	4.0	7.5	1.7	6.0
	2	6.0	8.0	3.0	5.0
	3	5.0	9.0	4.0	6.3
	4	6.3	10.5	20.0	19.0
	5	15.0	16.5	22.0	23.0
PSBF/D ₁	1	4.6	0.7	4.0	1.8
	2	2.0	0.8	3.4	1.2
	3	1.3	0.7	3.2	1.1
	4	1.4	0.6	2.7	1.4
PSBF/D ₂	1	2.2	5.0	1.0	1.7
	2	2.0	4.8	0.3	2.8
	3	2.8	5.7	0.1	3.2
	4	3.2	5.8	0.5	3.6
PSBF/D ₃	1	3.0	3.4	2.7	1.6
	2	1.2	4.9	2.4	1.0
	3	1.4	4.5	3.0	1.1
	4	1.6	5.0	2.6	1.2
PSBF/D ₄	1	3.8	5.5	0.5	2.2
	2	1.9	6.9	0.5	4.2
	3	4.4	7.4	0.7	4.6
	4	4.0	7.1	1.4	5.0

*See Figure 10 for locations of transducers.

Lateral deflectometer D₃, however, behaved somewhat differently. The first three thermal cycles appear near normal, even though the deflections at -54°C are larger than expected for an encapsulation such as PUF which is known to adhere well to components,

metals, and printed circuit boards. However, thermal cycles 4 and 5, which were run on the beginning of the next week, behave in an unusual manner during the above-ambient half. Extremely large deflections are indicated, with progressively larger residual deflections at each return to ambient. No reason is known to require disbelief in these data. This lateral deflectometer was not in one of the locations which was expected to produce maximum movement.

The printed circuit board maximum and minimum tension and bending principal strains for rosette pair R_1 for cure and the first thermal cycle for PSBF- and PUF-filled Test Vehicle 2 are shown in Figures 15 through 17. The direction of the maximum principal strains are shown by the arrows on Figure 10. The direction of the corresponding minimum principal strains are at 90° counter-clockwise to the maximum strain. The data for the PSBF-filled unit show very low strains at this location. Data for the other thermal cycles were lost because one strain gage of the rosette pair malfunctioned. The recorded strain values are comparable to those for Test Vehicle 1 at this location.

The PUF strain profiles show larger increases in strain magnitudes occurring during the cure cycle. Only part of this is relieved upon return to ambient after the cure. Figure 18 shows the maximum and minimum tension and bending strains during thermal cycle 3. All thermal cycles showed nearly identical strains at the same temperature, but this cycle is easier to interpret than cycle 1 because of longer hold times at the temperature extremes. Note the nearly equal negative and positive maxima for the cyclical behavior of the maximum principal tension strain in Figure 18. These tension and bending strains are 2 to 3 times as large as for the PSBF encapsulation reported above and would thus provide increased danger to the ceramic microcircuits and to their lead wire attachments to the PCBs.

The printed circuit board deflectometer data for the cure cycles are shown in Figure 19. Note the transient effects which indicate movement and accommodation and stabilization as the polystyrene beads bond to one another. Figure 20 shows the data for thermal cycle 1; cycles 2 to 4 were almost identical. Note that the middle printed circuit board deflection has now moved from its position after cure as shown in Figure 18. Thermal cycle 1 started the morning following the cure, and all Test Vehicle 2 PSBF experiments were completed in one work week. Even the maximum printed circuit board deflection during cure of 0.152 mm, if this causes the board to bend in a circular arc from the corner support posts, will only cause $180 \mu\text{m/m}$ of PCB bending.

Figure 15. Rosette Pair 1 Principal Tension Strain During Cure Cycle of Test Vehicle 2

Figure 16. Rosette Pair 1 Principal Bending Strains During Cure Cycle of Test Vehicle 2

This is within the range of rosette pair 2 for Test Vehicle 1 and less than for rosette 1 as reported above for this run of Test Vehicle 2. This again indicates safety for components in the stiffer production unit. However, no data are available for loads on solder joints of wires which interconnect the PCBs.

Figure 17. Rosette Pair 1 Principal Strains During Thermal Cycle 1 for PSBF in Test Vehicle 2

Figure 18. Rosette Pair 1 Principal Strains During Thermal Cycle 3 for PUF in Test Vehicle 2

Figure 19. Printed Circuit Board Deflections During Cure Cycle of Test Vehicle 2

During the PUF cure, nearly all the activity occurs from accommodation as the unit is heated to the cure temperature, with almost no movement thereafter while curing and returning to room temperature. Comparison of Figures 19 and 20 shows that a change occurred for H_2 (middle board) and H_3 (top board) overnight, since the cure was finished. H_3 returned to a near zero value in a jump

Figure 20. Printed Circuit Board Deflections During Thermal Cycle 1 for Test Vehicle 2

after 25 minutes. H_2 went through a cyclical movement about its zero deflection position, being closer to the base or bowed down (negative deflections) at -54°C and further from the base or bowed up (positive deflections) at 72°C .

Figure 21 shows the PUF-filled unit thermal cycle 3 PCB deflections with a jump in deflections H_2 and H_3 at 250 minutes. These discontinuities in H_2 and H_3 could be explained by debonding of the PUF from the case, the base, and the bottom and middle PCBs such that the middle and top boards jumped closer to one another. This may be a reasonable assumption, as it was found upon disassembly that this PUF did not bond well to any metal surfaces in the unit. Some small voids were seen, but these were not in critical areas relative to the transducer locations. The largest void was near R_1 and may have influenced those readings somewhat. D_3 was mounted on a metallized region of the PCB, which could be the big factor in its very large lateral deflections and unusual behavior. The bottom PCB was quite rigid, and H_1 moved very little.

Table 7 shows the maximum magnitudes of the values for all transducers in Test Vehicle 2 for both PSBF and PUF tests. Remembering the anomalies discussed above and notes to Table 7, the general conclusions are that PSBF is not even dangerous in lateral force or deflection on components. In other words, less danger than expected exists, even though the PSBF does not bond to the case and internal components.

Production Equivalent Unit

The results for Test Vehicles 1 and 2 had not been completely reduced and analyzed when it was necessary to decide on the transducer complement to be included in the production equivalent unit. However, the trends of the raw strain data provided some guidance. Space limitations precluded using any large number of lateral force or deflection transducers. Also, the greater rigidity expected on the PCBs because of inclusion of the microcircuits, metal covers, interconnecting lead wires, and the electrical plug made it less important to include rosette pairs and PCB deflectometers. As it turned out, there was not sufficient space to include even one stack of PCB deflectometers. Also, the straight wires connecting the PCBs to each other were too small in diameter to add strain gages for measuring inter-board forces.

The location of the transducer complement in the PEU is shown in Figure 22 for all three PCBs. The shape of the boards is accurate, but the various components are only near-scale and no electrical circuitry or plated-through holes are shown. One lateral force transducer (F), one rosette pair (R), and seven individual rosettes (r_1 to r_7) were included, and each had a thermocouple immediately

Figure 21. Printed Circuit Board Deflections During Thermal Cycle 3 for PUF in Test Vehicle 2

Table 7. Comparison of Maximum Values for Test Vehicle 2 Data

Quantity Measured	Cure Cycle		Thermal Cycles	
	PSBF	PUF	PSBF	PUF
Pressure, P (kPa)	2.34	7.65	2.14	9.58
Lateral Force, F (N)	2.7	8.0	6.2	36.9 (102.7)*
Lateral Deflection, D ₁ (mm)	0.14	0.09	0.12	0.19
Lateral Deflection, D ₂ (mm)	0.05	0.08	0.15	0.08
Lateral Deflection, D ₃ (mm)	0.12	0.11	0.15	0.34 (0.84)**
Lateral Deflection, D ₄ (mm)	0.03	0.04	0.19	0.08
PC Board Tension, R ₁ (μm/m)	208	469†	170	445†
PC Board Bending, R ₁ (μm/m)	155	435†	179	550†
PC Board Deflection, H ₁ (mm)	0.05	0.03	0.02	0.02
PC Board Deflection, H ₂ (mm)	0.07	0.08	0.05	0.14 (0.18)††
PC Board Deflection, H ₃ (mm)	0.15	0.04	0.07	0.06 (0.13)††

*Maximum value after large change occurred between cycles 2 and 3.

**Occurred from thermal cycles 3 to 5, which behaved in an unusual manner. This transducer was located on a metallized region of the PCB.

†The largest PUF void was near R₁ and above the top PCB.

††Maximum values after anomalous jumps during thermal cycles 3 to 5.

adjacent. Rosettes r_1 and r_3 were mounted on metal covers and r_1 to r_7 were mounted on ceramic microcircuits. The instrumented unit was first encapsulated with 0.20 g/cm^3 PSBF and thermal cycled three times between -54 and 82°C . The unit was then depotted in toluene and repotted in 0.20 g/cm^3 PUF and subjected to four thermal cycles between -54 and 72°C .

In both encapsulations of a PEU with PSBF and PUF, the lateral forces were found to be lower than were measured in Test Vehicle 2. Figure 23 shows the lateral forces generated during the cure cycle. The lateral forces data for the thermal cycles are listed in Table 5. The maximum lateral force generated by the PSBF was about 1.56 N , which is less than 30 percent of that recorded at a different location on the middle PCB in Test Vehicle 2. The data shown for the PUF-generated lateral forces show that the largest forces occurred at -54°C and the lowest at 74°C . A slight decrease in the lateral forces at -54°C occurred from cycle to cycle. All of these forces are well below those measured for PUF in Test Vehicle 2. These lower force values may have been caused by inclusion of the electrical components and the lower temperature used to cure the PUF.

The rosette pair tension and bending principal strains during PSBF and PUF cure are shown in Figures 24 and 25. These data indicate that the PUF-generated strains were slightly higher than those recorded for PSBF, but were much lower than those recorded during the PUF cure in Test Vehicle 2.

Data for the first PSBF thermal cycle are shown in Figure 26; the second and third cycle strain data were nearly identical for the same temperature points. All these strains are lower than those reported for PSBF in Test Vehicle 2. No data are available for the thermal cycles because, of the six strain gages in the rosette pair, two were lost during thermal cycle 1. Note that the strains are much lower than those recorded for PUF cure in Test Vehicle 2. This implies less printed circuit board bending, probably because of lower cure temperature and the stiffening and rigidizing effects of the microcircuits, the wires which interconnect the boards, and the electrical connector. All of these stiffeners were absent in Test Vehicle 2, but were present in the PEU.

Single rosette r_1 was located on the widest metal cover and indeed produced the largest strains for any metal cover during both PSBF and PUF cure (Figure 27) and thermal cycle 1 (Figure 28). The second and third PSBF thermal cycle data were a continuation of thermal cycle 1. Note the strain change during the cure, which indicates a pressure inward on this metal cover. A small translation of the strain values at ambient occurred during

ARROWS SHOW DIRECTIONS OF LATERAL FORCE AND OF ROSETTE PAIR MAXIMUM PRINCIPAL STRAINS FOR PSBF (—→) AND PUF (---→)

Figure 22. Transducer Locations for PEU

Figure 22 Continued. Transducer Locations for PEU

cycle 1 and then stabilized for succeeding cycles. None of these PSBF generated strains come close to the strain for yielding of the metal cover as reported in Table 4.

The maximum principal strain during PUF cure for r_1 shows a rapid increase in negative strain for the triangular data points which levels off near $-800 \mu\text{m/m}$. This metal cover probably yielded from the foam pressure, resulting in a permanent inward depression in the top. Table 4 shows that $800 \mu\text{m/m}$ is sufficient to cause yielding to occur. No unusual behavior was recorded during the first thermal cycle. The second and third thermal cycles were identical, and all cycles are direct continuations of the yielded condition shown in Figure 28 after 175 minutes of cure.

Single rosette r_2 showed the maximum strains for the ceramic microcircuits, even though r_2 was on a slightly wider microcircuit. The strains during both cures are shown in Figure 29 and for thermal cycles 1 and 2 in Figures 30 and 31. The PSBF thermal cycle 3 produced identical results to thermal cycle 2. Note the strain increase at cure and also the transient occurring each time the temperature increase from -54°C is begun. This is probably caused by thermal and stress gradients as a result of the excellent insulating and poor thermal conductivity properties of PSBF. Even these maximum strains are well below the microcircuit failure strains recorded in Table 4.

Figure 23. Lateral Forces During Cure Cycle for the PEU

The principal strains for single rosette r_5 during the PUF cure show the effect of the foam pressure during cure. This pressure and the resulting microcircuit inward bending remain for all thermal cycles (Table 5), with a small progressive decrease in the strain magnitudes occurring from cycle to cycle. And, again, the transient effects during temperature decrease to and rise from -54°C are seen as for PSBF. The maximum inward bending strain is considerably larger for PUF, but still well below the failure criteria of Table 4.

After these tests were completed, the cover was removed from the unit to examine for voids in the PUF. Two fairly large voids were found above the top printed circuit board. The largest of

Figure 24. Rosette Pair Principal Tension Strains During Cure of the PEU

these completely included the microcircuit on which single rosette r_7 was mounted. The other did not touch any transducer area. These were the only two voids visible without taking apart the PCB stack.

The maximum values for each transducer in the PEU are given in Table 8. These data show a minimal difference between PSBF and PUF for the lateral force. The printed circuit board behavior as monitored by R_1 shows PUF to be more severe during cure, with no data for comparison during the thermal cycles. The single rosettes r_1 to r_3 on the metal covers show PUF being much more severe during both cure and thermal cycling. The ceramic microcircuit behavior, as evidenced by r_4 to r_7 , shows PUF to produce more

Figure 25. Rosette Pair Principal Bending Strains During Cure of the PEU

bowing outward or tension. Both the good bonding properties of PUF to ceramic and interaction with the PCBs can contribute to this effect. The magnitudes, however, are considerably larger than might be expected.

The pressure and lateral force data for Test Vehicle 2 and the lateral force data for the PEU show three things. First, PUF loads electronic components more severely than PSBF. PSBF causes

Figure 26. Rosette Principal Strains During Thermal Cycle 1 for PSBF in the PEU

only very low and safe loadings on components. Second, the actual lateral force loading depends on position relative to pinning points in the unit. Third, when PUF does not bond to the lateral surface under the component, then the lateral force (and deflection too) may be very much more severe than when bonding does occur.

Figure 27. Single Rosette, r_1 , Principal Strains During Cure of the PEU

Figure 28. Single Rosette, r_1 , Principal Strains During Thermal Cycle 1 for the PEU

Figure 29. Single Rosette, r_s , Principal Strains During Cure of the PEU

The lateral deflection transducers showed approximately the same range of deflections for PSBF as for PUF, except for D_3 in PUF. This was located on a metallized area of the printed circuit board and the PUF did not bond to it. Very large deflections

Figure 30. Single Rosette, r_s , Principal Strains During Thermal Cycle 1 of the PEU

Figure 31. Single Rosette, r_5 , Principal Strains During Thermal Cycle 2 of the PEU

Table 8. Comparison of Maximum Values for PEU

Quantity Measured	Cure Cycle		Thermal Cycles	
	PSBF	PUF	PSBF	PUF
Lateral Force, F (N)	0.62	0.80	2.00	1.78
PCB Tension, R_1 ($\mu\text{m/m}$)	131	210	118	*
PCB Bending, R_1 ($\mu\text{m/m}$)	119	226	110	*
Metal Cover Strain, r_1 ($\mu\text{m/m}$)	325	795	191	763
Metal Cover Strain, r_2 ($\mu\text{m/m}$)	160	330	156	329
Metal Cover Strain, r_3 ($\mu\text{m/m}$)	211	309	236	357
Microcircuit Strain, r_4 ($\mu\text{m/m}$)	148	101 (563)**	68	85 (251)**
Microcircuit Strain, r_5 ($\mu\text{m/m}$)	91 (141)**	121 (392)**	121 (357)**	93 (370)**
Microcircuit Strain, r_6 ($\mu\text{m/m}$)	41	24 (60)**	31 (45)**	16 (83)**

Table 8 Continued. Comparison of Maximum Values for PEU

Quantity Measured	Cure Cycle		Thermal Cycles	
	PSBF	PUF	PSBF	PUF
Microcircuit Strain, r_7 $\mu\text{m/m}$	32	67 (406)†	182 (328)**	77 (444)†

*Two strain gages were lost during thermal cycle 1; no data exists.

**Indicated to be bowing outward, tension, or both.

†Indicated to be bowing outward, tension, or both; a large PUF void included the entire microcircuit on which r_7 was mounted.

were recorded. This, again, emphasizes the very severe lateral loadings which may occur if the PUF does not bond to case, printed circuit boards, and electronic components.

Biaxial tension and bending of PCBs can and do occur during cure and thermal cycles for these two types of foam encapsulants. The rosette pair and printed circuit board deflectometer data provide direct evidence of these loadings. They also show that sizeable tension and bending strains occur for PUF during cure and that significant changes are caused by thermal cycling. For PSBF, however, the only significant effects seen were the transients in PCB deflection during cure.

Looking at the data for single rosettes mounted on metal covers in the PEU, larger strains than expected from only an effective pressure loading were seen. Test Vehicle 2 pressure data in Table 7 show a range of 2.0 to 9.6 kPa for PSBF and PUF tests. When these are compared with the pressure and strain data from the failure criteria of Table 4, the metal cover strains would be expected to be less than 50 $\mu\text{m}/\text{m}$ even for PUF. One of the few identifiable potential causes of the additional strains is a strain amplification produced by vertical loading on the PCBs and their subsequent bending. Such a hypothesis is also consistent with the unexpected bowing outward or tension strains recorded for most of the single rosettes both for PSBF and PUF. If the bottom PCB were stationary or bowed up slightly, and the middle PCB bowed down relative to it, this would produce a larger apparent pressure on the metal cover. This relative movement was indeed recorded during PSBF cure and thermal cycles and for PUF thermal cycles in Test Vehicle 2. The PUF cure moved only a small amount in this direction at the deflectometer location. No actual board deflection data were obtained on the PEU, and the rosette pair on the top PCB showed one principal bending strain up (positive) and the other down (negative), for an inconclusive reading. The hypothesis is thus reasonable and consistent with the data.

That bending of the PCB is a loading on microcircuits may have further substantiation from the data for single rosette r_7 for PUF in Table 8. Remember that this microcircuit was totally in a PUF void and then notice that the outward bending and tension strains are as large as for r_4 to r_6 , which were fully enclosed in PUF. PUF may thus be forcing the PCBs to bend, and this is seen as strain components on all microcircuits and metal covers.

Mechanical Properties Determination

Test specimens (28.68-mm-diameter by 25.4-mm-high) were used to determine both the tensile and compressive properties. Three 12-cavity molds (Figure 32) were designed and built. The temperature of each mold during the molding cycle was determined. A thermocouple was placed in the center of one corner and another was placed in the center cavity.

Figure 32. Test Specimen Mold

The expandable polystyrene beads were first pre-expanded and then screened using 20 and 30 mesh U.S. Standard screens. The resulting bulk density was 0.20 g/cm³ with a pentane content of 4.39 percent. With one plate bolted to the mold, the 12 cavities were filled with the pre-expanded beads. The molds were then vibrated to obtain maximum packing.

After each cavity was topped with additional beads, the second plate was bolted to the mold. The heat cycle used was 35 minutes at 107°C plus an additional 25 minutes at 100°C. This heat cycle reproduces the temperature profile obtained in the center of the PEU encapsulated using a 60 minute, 100°C heat cycle. The same degree of bead fusion was obtained in both cases.

Seventy-two test specimens were molded and randomly numbered. Each specimen was weighed and measured to calculate density. For tensile testing, 15 specimens were bonded to aluminum bars using an epoxy adhesive. The adhesive was cured for 2 hours at 71°C. Another 15 specimens were compressive tested. Three additional specimens were tested for pentane content determination at the time of tensile and compressive testing. The as-molded pentane content was determined to be 2.5 percent. The pentane content of the specimens at the time they were tested had dropped to 1.4 percent. Another 37 specimens were placed in an air circulating oven at 70°C for 3 weeks, then the oven temperature was raised to 77°C. After 2 additional weeks, these specimens were removed from the oven and reweighed after 24 hours aging at room temperature. The average weight loss during the heat-aging period was 2.3 percent with a corresponding decrease in volume. There was no change in the density of the specimens. The residual pentane in the specimens was determined to be 0.2 percent.

Another set of 12 test specimens was also molded using the same lot of pre-expanded beads, but with a heat cycle of 50 minutes at 107°C plus an additional 10 minutes at 100°C. This heat cycle resulted in a higher degree of fusion between the beads and thus in a stronger foam.

Five of these test specimens were bonded to aluminum tensile bars, and another five were used for compressive testing. The remaining two specimens were used to determine the pentane content of the foam. The pentane content of as-molded and when-tested specimens was determined to be 1.8 and 1.2 percent, respectively. The 12 specimens were tested at ambient temperature only.

The reported tensile data for each tensile specimen tested are shown in Table 9 for both the as-molded and heat-aged 0.2 g/cm³ potting PSBF. Similar data for the compressive-tested specimens are given in Table 10. The average values at each test condition were calculated for both the tensile and compressive results and

Table 9. Tensile Data for 0.2 g/cm³ Potting PSBF

Test Temperature (°C)	Foam Density (g/cm ³)	Yield (kPa)	Modulus (MPa)	Deflection at Yield (Percent)
As-molded PSBF with residual pentane content of 1.4 percent				
-54	0.198	1014	233.0	0.43
-54	0.206	421	222.0	0.20
-54	0.209	875	208.2	0.43
25	0.208	883	210.3	0.42
25	0.214	1111	202.7	0.59
25	0.195	586	179.3	0.40
25	0.196	786	191.0	0.45
25	0.214	469	157.9	0.35
74	0.209	903	119.3	0.78
74	0.216	1179	170.3	0.79
74	0.210	938	160.7	0.71
74	0.210	1103	152.4	0.75
Heat-aged PSBF with residual pentane content of less than 0.2 percent				
-54	0.214	842	256.5	0.30
-54	0.197	448	201.3	0.20
-54	0.186	393	189.6	0.25
-54	0.212	572	233.1	0.25
-54	0.189	303	219.3	0.15
25	0.211	510	155.1	0.30
25	0.202	531	162.7	0.30
25	0.212	324	191.7	0.20
25	0.192	462	160.7	0.30
25	0.208	1027	200.0	0.50
74	0.214	517	153.1	0.35
74	0.193	814	127.6	0.65
74	0.187	538	102.7	0.50
Crosshead speed of 5 mm/min.				

Table 10. Compressive Data for 0.2 g/cm³ Potting PSBF

Test Temperature (°C)	Foam Density (g/cm ³)	Yield (kPa)	Modulus (MPa)	Strength at 10 Percent Stress (kPa)	Deflection at Yield (Percent)
As-molded PSBF with residual pentane content of 1.4 percent					
-54	0.216	4923	205.5	4914	4.3
-54	0.192	3530	151.7	1848	3.8
-54	0.209	4013	183.4	2482	3.3
-54	0.210	4854	205.5	4680	4.7
-54	0.200	4296	183.4	4013	3.7
25	0.218	2675	158.6	1482	2.6
25	0.189	2386	133.8	1937	3.5
25	0.216	3123	166.2	2758	3.5
25	0.220	3296	158.6	2986	3.7
25	0.207	2448	140.0	1151	2.6
74	0.205	1675	140.0	1482	3.0
74	0.212	1620	100.0	1103	2.2
74	0.208	1558	120.0	1151	2.5
74	0.222	1944	145.5	1689	2.5
74	0.207	1724	133.8	1613	2.3
Heat-aged PSBF with residual pentane content of less than 0.2 percent					
-54	0.207	4344	156.5	3916	5.0
-54	0.207	2698	137.9	1379	2.5
-54	0.207	3972	137.9	2551	4.5
-54	0.206	3916	191.7	2179	4.0
-54	0.212	4137	181.3	2068	4.0

Table 10 Continued. Compressive Data for 0.2 g/cm³ Potting PSBF

Test Temperature (°C)	Foam Density (g/cm ³)	Yield (kPa)	Modulus (MPa)	Strength at 10 Percent Stress (kPa)	Deflection at Yield (Percent)
25	0.216	2889	156.5	*	3.0
25	0.184	2386	127.6	*	3.5
25	0.192	2813	132.4	2882	3.3
25	0.195	2986	156.5	3130	3.3
25	0.204	3103	153.1	2351	3.3
74	0.188	1786	115.1	1427	3.5
74	0.202	2234	143.4	2158	4.0
74	0.205	1889	123.4	979	3.0
74	0.199	2055	123.4	1896	3.3
74	0.212	2262	128.2	2103	4.0

*Samples crumbled under load.
Crosshead speed of 1.3 mm/min.

is shown in Tables 11 and 12. These average values are shown graphically as a function of temperature in Figure 33 (yield strength), Figure 34 (modulus), and Figure 35 (deflection at yield). The individual test results for the structural PSBF are given in Table 13; the average values are shown in Tables 11 and 12.

The mechanical properties of PSBF are primarily a function of degree of bead fusion, foam density, temperature, and pentane content. The degree of fusion achieved between the individual polystyrene beads during the fusion cycle will vary, depending on the minimum fusion temperature and length of time the beads are held at fusion temperature. To complicate matters, the minimum fusion temperature varies with the amount of pentane in the polystyrene resin. Previous work indicated there is about a 6°C decrease in the glass transition temperature (T_g) for every 1 percent of pentane in the resin.⁵ Pentane in the polystyrene causes the resin to expand once the T_g has been reached as well as softening the resin, allowing it to fuse together at a lower temperature. The minimum fusion temperature is considered to be about 10°C above the T_g .

All previous applications of PSBF at Bendix required maximum mechanical strength for a given density. Thus, the beads were fused together at a temperature of about 20°C above the T_g . This resulted in a foam structure in which the beads could not be removed intact from the foam. This type of foam was referred to as structural PSBF.

When PSBF is used as an encapsulant for electrical components it does not require maximum mechanical properties. In fact, it may be a better encapsulant if maximum properties are not obtained. With lower mechanical properties, the PSBF would have less effect on the components and solder joints during thermal cycling. When a fusion temperature of about 10°C above the T_g is used, a foam structure is produced in which the individual beads have not completely lost their identity and can be easily removed from the foam. Usually, the beads have not expanded to completely fill the void space around them and are only fused together where they touch. This type of foam was evaluated for this project and is referred to as potting PSBF.

Figures 36 and 37 show the mechanical properties of structural PSBF as a function of density over a range of 0.05 to 0.5 g/cm³. These two graphs were drawn primarily from previously reported data (Table 14).

Figure 38 shows the compressive strength of the potting PSBF for densities ranging from 0.19 to 0.24 g/cm³. These data were obtained from test specimens 55 mm in diameter by 25 mm high molded at the same time units were being encapsulated.

Table 11. Average Tensile Characteristics of
0.2 g/cm³ PSBF

Test Temperature (°C)	Yield (kPa)	Modulus (MPa)	Deflection at Yield (Percent)
-54*	772	221.3	0.35
25*	765	188.2	0.44
74*	1034	150.3	0.76
-54**	510	220.0	0.23
25**	572	173.8	0.32
74**	620	127.6	0.50
25***	1344	203.4	0.68

*Tested at indicated temperature, as-molded, with residual pentane content of 1.4 percent.

**Tested at indicated temperature, heat-aged, with residual pentane content of 0.2 percent.

***Structural foam tested at indicated temperature, with residual pentane content of 1.2 percent.

The effect of elevated temperature on the mechanical properties of most polymers lowers the yield strength and increases the elongation with increasing temperature. Residual pentane, acting as a plasticizer, has the same effect that temperatures does on polymers; as the amount of residual pentane increases, yield strength decreases and elongation increases.

The scatter in the potting PSBF data shown in Tables 9 and 10 and Figure 38 can be caused by different degrees of fusion from specimen to specimen. Conversely, the data for the structural PSBF (Table 13) was not as scattered and appeared to be directly related to the differences in the densities of the specimens.

The effect of temperature on the mechanical properties of the potting PSBF was apparent, as shown in Figures 33, 34, and 35. As expected, the compressive yield strength for both as-molded and heat-aged specimens decreased with an increase in temperature. The tensile yield strength data, however, showed a slight increase with increasing temperature. This was not expected and was probably caused by a higher degree of fusion achieved on the average in the specimens tested at 77°C.

Table 12. Average Compressive Characteristics of 0.2 g/cm³ PSBF

Test Temperature (°C)	Yield (kPa)	Stress at 10 Percent Deflection (kPa)	Modulus (MPa)	Deflection at Yield (Percent)
-54*	4323	3585	186.2	4.0
25*	2786	2062	151.7	3.2
74*	1703	1407	127.6	2.5
-54**	3806	2420	161.3	4.0
25**	2834	2786	145.5	3.3
74**	2048	1710	126.9	3.6
25***	3192	3110	173.1	3.6

*Tested at indicated temperature, as-molded, with residual pentane content of 1.4 percent.

**Tested at indicated temperature, heat-aged, with residual pentane content of 0.2 percent.

***Structural foam tested at indicated temperature, with residual pentane content of 1.2 percent.

Figure 35 shows that the deflection (elongation) at tensile yield increased with increasing temperature, and the deflection at the compressive yield point decreased with increasing temperature. This unexpected trend may be because the compressive yield strength was about 2.5 times greater at -54°C than it was at 77°C, thereby allowing the PSBF to deflect further before yielding and overshadowing the plasticizing effect of temperature.

The effect of the amount of residual pentane in the potting PSBF was different than for structural PSBF. Structural PSBF (0.05 and 0.1 g/cm³) had a 10 percent increase in tensile yield strength for each percent of residual pentane removed. The data reported for the 0.2 g/cm³ potting PSBF showed about a 20 percent decrease in the tensile yield strength at each test temperature. The effect of heat-aging on the compressive yield strength of the 0.2 g/cm³ potting PSBF produced a large decrease at -54°C but increased the strength at 77°C, with essentially the same strength at 25°C. Here again, the degree of fusion apparently masked the plasticizing effect of residual pentane in the potting PSBF.

Figure 33. Yield Strength Versus Temperature for 0.2 g/cm³ Potting PSBF

It was also noted that the degree of bead fusion has more effect on the tensile properties of the foam than on the compressive properties, as would be expected. A low percentage of poorly fused beads would be more effective in causing a lower tensile strength than they would be in causing a compressive failure. This was also apparent in the large increase in the tensile strength and only a moderate increase in the compressive yield strength in going from the potting PSBF to the structural PSBF.

Primer Evaluation

The investigation of primers to promote adhesion of PSBF to the printed circuit boards, metal cover, and base was conducted as follows. Sample discs, 28.7 mm in diameter, of the PCB and nickel-plated aluminum were coated with primers and placed in the cavities of the physical specimen mold. The cavities were filled with pre-expanded beads and then heated to fuse the beads. The resulting specimens were pulled in tension to determine the adhesive strength.

Figure 34. Modulus Versus Temperature for 0.2 g/cm³ Potting PSBF

Five primers were evaluated for promotion of adhesion between PSBF and PCB surfaces. They were a silane compound, three titanates, and a polyurethane. Of the five primers, only the polyurethane promoted adhesion to printed circuit board, solder, and nickel surfaces. All the discs on which the silane and titanate coupling agents were used adhered to the PSBF upon removal from the mold.

The test specimens with polyurethane-primed discs produced a tensile strength of about 100 kPa, with the first layer of beads remaining adhered to the disc after testing; thus, it appeared that the polyurethane weakened the tensile strength of the PSBF and caused it to fail considerably below the expected value of 500 kPa.

No additional evaluation of polyurethane or any other primer was conducted, based on the results of the strain gage evaluation showing that non-adhesion of PSBF to the substrates was not detrimental.

Figure 35. Deflection at Yield Versus Temperature for 0.2 g/cm³ Potting PSBF

Depotting Evaluations

One of the main advantages of PSBF as an encapsulant for electronic packages is that it can be easily removed by dissolution with common hydrocarbon solvents which do not dissolve other plastic components in the unit. Removal of the encapsulant is required when rework of defective components is required. PUF can only be dissolved with strong acidic or basic solvents that attack other polymers and some metals in the unit.

The depotting method used involved submerging the unit, without its cover, in toluene and passing air through the toluene for agitation. The time required to dissolve all the PSBF with this

Table 13. Structural 0.2 g/cm³ PSBF Tensile and Compressive Data Taken at Ambient Temperature

Density	Yield (kPa)	Modulus (MPa)	Deflection at Yield (Percent)	Stress at 10 Percent Deflection (kPa)
Compressive Data*				
0.204	3096	166.2	4.5	3075
0.205	3179	174.4	3.2	3041
0.208	3261	183.4	3.5	3185
0.212	3351	183.4	3.5	3233
0.203	3076	158.6	3.2	3041
Tensile Data**				
0.204	1179	174.4	0.69	
0.210	1393	225.5	0.62	
0.207	1338	188.9	0.75	
0.210	1393	215.8	0.78	
0.209	1413	212.4	0.55	
*Crosshead speed of 1.3 millimeters/minute				
**Crosshead speed of 5 millimeters/minute				
Residual pentane content of 1.2 percent.				

method was 2 to 3 hours. It was felt that the depotting time should be as short as possible to minimize any effect that the solvent may have on components in the unit. A holding fixture was designed which allowed for air agitation between each printed circuit board. The fixture was then evaluated using development production units that required rework.

The first depotting fixture evaluated consisted of four copper tubes, with 0.8-mm-diameter holes spaced 25 mm apart, placed in the bottom of the solvent tanks. Air was passed through the copper tubes, causing agitation of the solvent from the bottom of the unit. This fixture shortened the depotting time to about 1.5 hours. A second depotting fixture was designed to hold the unit vertically and inject air into the space between each printed circuit boards from three layers of circular copper tubes. This fixture had the capability to remove the PSBF in about 1 hour.

Figure 36. Tensile and Compressive Yield Strengths Versus Density of Structural PSBF

A slight modification to the second depotting fixture resulted in a reduction of the depotting time to 20 to 30 minutes. This modification consisted of placing the copper tubing within 12 mm around the perimeter of the unit (Figure 39). This final depotting fixture was turned over to production.

Conclusions

The following significant conclusions may be drawn from the data reported here.

The severest loading for PSBF-encapsulated units arises from printed circuit board bending and from these stresses being transmitted to the ceramic microcircuits. Even this appears quite safe. All other forces and deflections measured are small and safe.

Figure 37. Tensile and Compressive Moduli Versus Density of Structural PSBF

PUF of comparable density is a considerably more severe encapsulant than PSBF. PUF can cause large lateral loadings and deflections when it does not bond to printed circuit boards or metal.

Axial loadings on solder joints are large for GMB/epoxy encapsulation and thermal cycling, are smaller for 0.3, 0.2, and 0.1 g/cm³ PUF in that order, and least for PSBF.

The location, stiffness, and number of lateral motion restraints or pinning points in a particular unit can significantly change the severity of loadings and deflections, especially when the encapsulant does not bond to the various components or the printed circuit boards.

It is more difficult to obtain a void-free filling of complex and densely packed units with PUF than it is with PSBF.

Table 14. Mechanical Properties of Structural PSBF as a Function of Density

Density (g/cm ³)	Tensile Yield (kPa)	Compressive Yield (kPa)	Tensile Modulus (MPa)	Compressive Modulus (MPa)
0.05*	690	345	41	34
0.10*	1241	1034	83	69
0.20**	1379	3172	207	172
0.24***	3034	2068	228	152
0.30†	3792	4137	352	220
0.40†	4826	7585	621	400
0.50†	6688	10549	896	558

*Reference 5

**Table 11

***Reference 6

†Reference 7

ACCOMPLISHMENTS

Several significant accomplishments have resulted from this experimental evaluation of PSBF encapsulation.

PSBF of 0.2 g/cm³ density produces minimal and safe loadings on electronic components and solder joints. PUF of the same density is a much more severe encapsulant.

For the first time, comparison data have been collected for axial loads during cure and thermal cycling of GMB/epoxy, of three densities of PUF, and of PSBF.

Lateral force and deflection transducers were developed, were used successfully, and are now available for future use.

The mechanical properties of 0.2 g/cm³ potting PSBF were determined to be a function of temperature and residual pentane content. The room temperature tensile and compressive yield strengths were determined to be 690 and 2760 kPa, respectively, with corresponding moduli of 186 and 152 mPa. It was also determined that the degree of fusion achieved between the beads has a greater influence on the tensile yield strength of the foam than it does on the compressive yield strength.

Figure 38. Compressive Yield Strength Versus Density of Potting PSBF

The depotting fixture and process developed during this evaluation reduced the time required to remove the PSBF from 3 hours to 30 minutes. This method is presently being used in the production area.

FUTURE WORK

A new project will be initiated to evaluate PSBF as the encapsulant for electronic packages. Besides the thermomechanical effects that were evaluated, the evaluation will be extended to include shock effects, vibration effects, hydrostatic pressure effects, and mechanical properties as a function of density (0.1 to 0.6 g/cm³).

Figure 39. Depotting Fixture

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Fossey, Final, January 1979

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