Thermal Expansion of Silicones in Electronic Reliability

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CTE mismatches during temperature cycling can cause significant movement of components and materials relative to one another, which in turn stresses solder joints and wirebonds. Silicones are often used to protect electronic devices, and the large CTE of silicones can be of particular concern, though the very low modulus of these materials tends to greatly mitigate stress. While a few examples of potential damage caused by thermal expansion of silicones do exist, a level of understanding of the magnitude of expansion pressures would be helpful in design, validation, and thermal reliability testing.

A study was begun to measure the pressures developed during thermal expansion of typical silicone encapsulants used in electronic applications. A range of products was evaluated to encompass very soft gels to medium hard elastomers. Harder elastomers were found to generate 0.2 psi/degree C rise in temperature, while soft gels generated <0.01 psi/C and extremely soft gels <0.001 psi/C. Application variables such as part design geometry are discussed and shown to potentially multiply or concentrate the generated pressures. Validation of experimental results was made with a case study.

Introduction

Many applications of electronic devices involve exposure to both very high and very low temperatures. Very high temperatures occur in short durations of seconds during soldering - especially with lead-free processes - and somewhat longer durations of minutes to hours during burn-in and other testing. End uses may have sustained high temperature environments and/or transient thermal spikes. Low temperatures can occur in validation and reliability testing and in any outdoor or avionic applications.

In thermal cycling, all materials will undergo a volume change based on its coefficient of thermal expansion (CTE). Thermal expansion and contraction in CTE mis-matched materials can cause failures in wirebonds and solder joints. Such damage can occur very quickly or can be the accumulation of repeated stresses over time.

The switch to lead-free solders has come at a cost of significantly higher reflow temperatures of 225 – 260C[1,2]. These very high temperatures can degrade materials outright, and can also cause significant stresses due to material expansion and movement.

Silicones are widely used to bond, seal, encapsulate and coat electronics for high temperature applications [3-5]. Standard analytical characterizations of silicones show quite stable properties from -45C to +150C and even to lower and higher temperatures depending on the application and especially to the exposure duration requirements. [6,7]

However, silicones also have very high CTE values, indicating that they expand considerably when heated and contract when cooled. This expansion and contraction can cause stress on wire bonds and solder joints even though the quite low modulus of silicones allows stress to be absorbed and dissipated. In some cases, thermal expansion can result in damage.[8,9]

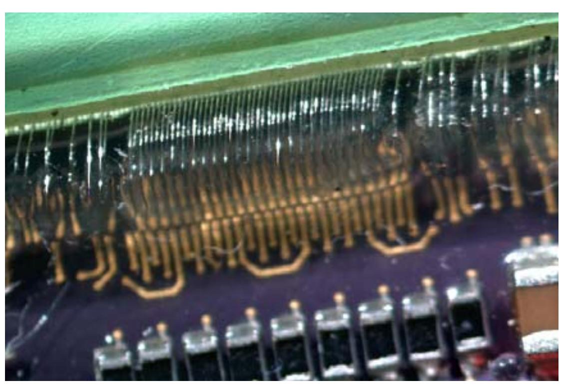

Figure 1 - Silicone Gel Encapsulating Wire Array

Case studies have shown the results of over-stress from thermal expansion, but have not determined any actual stresses produced. The work discussed here attempted to provide a rough measurement of the pressures silicone encapsulants can generate when heated.

Discussion

Common temperature ranges that electronic parts can experience are shown in Table 1.

Table 1 - Typical Application Temperatures and Durations

Application	Max. Temp	Duration
Lead-Free Solder reflow ovens	225-260C	10-90 seconds
Automotive on-engine modules (extended warranty)	175C 150C 150C	5 min. 1000 hrs 3000 hrs
Industrial power devices	250C 200C 175C	hours months years
	Min. Temp	Duration
Consumer and automotive electronics	-40 to -50C	days
Avionics	-65 to -80C	Hours

Thermal cycling/shock is routinely used to estimate reliability with upper temperature limits commonly set to +125 or +150C and lower limits to -40 or -50C.

Silicones are commonly used as protective materials on electronic devices. They are used from 75 micron coatings to several cm thick of encapsulant. For the purposes of this testing, only silicone encapsulants were studied.

Figure 2 - Silicone Conformal Coating Applied to Board

Silicone encapsulants range in hardness from extremely soft gels that begin to blur the distinction between solids and liquids to medium-hard elastomers. Table 2 compiles some of the material characteristics of the products chosen for study.

Table 2 - Silicone Encapsulant Properties

Silicone Encapsulant	1	2	3	4
Description	Soft gel	Firm gel	Tough gel	Clear elastomer
Hardness, Shore A Shore 00	- -	- 25	8 65	50 -
Texture Analyzer Gel Hardness, g	105	1500	9500	28,600
Elastic Modulus, psi	0.15	0.3	17	720
Volumetric CTE, ppm/C	1.20 E-03	9.60 E-04	9.25 E-04	9.30 E-04

Test Methodology
The encapsulants were cured in cylindrical metal cans to a depth of about 10 cm. These containers were then placed within a snugly fitting heating mantle. A Texture Analyzer was used to measure generated pressures. A 1 cm diameter flat bottomed probe was lowered to just contact the surface.

Heat was then applied and a thermocouple placed near the probe was used to monitor actual material temperature. Samples were typically heated from 25C to 80-85C. With the x and y dimensions constrained by the cylindrical container, all expansion movement was forced into the z axis. Once an equilibrium temperature was reached the upward pressure of the expanding silicone was registered on the TA.

Results
Figure 3 displays the results obtained.

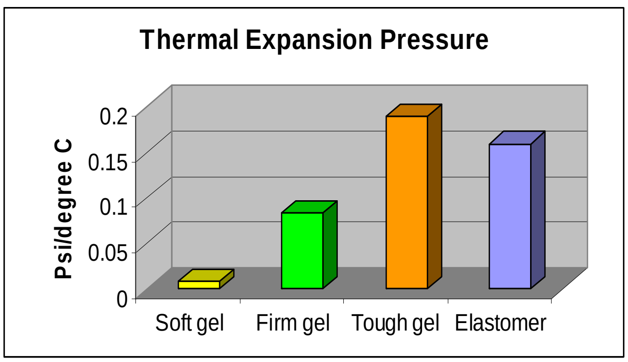

Figure 3 - Thermal Expansion Pressure in Silicone Encapsulants

The data was not found to correlate well to Young's modulus, but did to gel hardness.

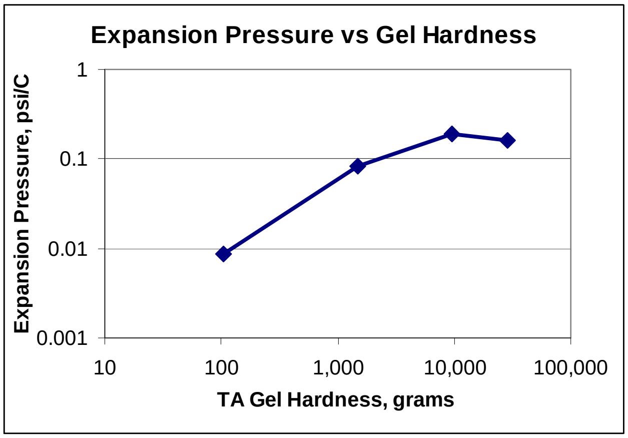

Figure 4 - Expansion Pressure in Silicone Encapsulants as a Function of Gel Hardness

It appeared that a pressure maximum was reached at roughly 10,000 grams TA hardness.

To validate these findings, two additional silicone samples were prepared and tested. One had gel hardness similar to the highest material, while the other was made by lowering the crosslink density in the softest product to achieve a gel hardness of about 27 grams.

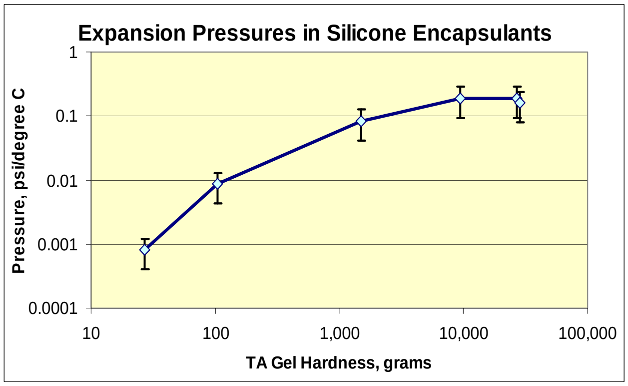

Figure 5 - Expansion Pressure over a Broader Range of Gel Hardness

The predicted pressure for the very soft new gel based on Figure 4 was essentially identical to the actually measured value. The data shows a strong correlation between thermal expansion pressures and TA gel hardness up to a limiting hardness.

For these tests adhesion to the side walls of the container was minimized by applying a release coating. The Tough gel used in this testing is formulated to allow a level of chemical adhesion to develop with surfaces to which it contacts. A second test was run with this product where no release agent was used on its container. Good adhesion was verified – the gel would tear apart before releasing from the side walls of its metal container.

This same product was also tested in thermal contraction where a metal panel was embedded and cured into the gel. This sample was then heated and a tensiometer attached to the metal panel. Downward pressure was measured as the sample cooled. The measured thermal contraction pressure was well within experimental error of the expansion pressure.

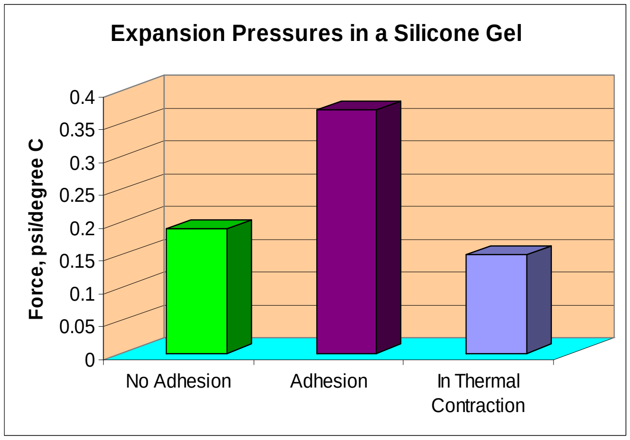

Figure 6 - Expansion & Contraction Pressure With Adhesion

The pressure generated with adhesion to the container side walls was double that with no adhesion. Adhesion effectively locked the vertical dimension of the gel close to the container side walls. All bulk expansion therefore was redirected toward the center of the sample, evidenced by a considerable convex hump.

This shows an element of the complexity when potting a module containing significant component terrain features and/or when adhesion is present. A soft elastic encapsulant may deform easily toward regions of less confinement, creating more complex pressure vectors and regions.

An application example has provided further validity to this work. A detailed investigation of an automotive device failure measured thermal contraction pressure on a solder joint of 50-125 psi over a temperature range of -40 to + 125C. The vertical pressure predicted for the silicone encapsulant based on this work was 31 psi. The actual part geometry was quite complex, with large topographic features. These features were significantly contributing to the pressure on the failing solder joint, focusing a large proportion of the pressure from the silicone movement on that specific joint. The predicted value of 31 psi was well within experimental error for a value that did not take into account any geometric induced multipliers of pressure in localized regions.

Conclusion

Thermal expansion pressures were measured for silicone encapsulants encompassing medium hard elastomers to very soft gels. Pressures were two orders of magnitude lower for extremely soft gels and correlated well with encapsulant hardness as measured by a Texture Analyzer.

Plots were prepared which allow predictive estimates of thermal expansion generated pressure based on encapsulant TA hardness.
Data from a device failure investigation confirmed the magnitude of measured pressures described in this report.

Adhesion was shown to play a significant role to redirect expansion pressure vectors toward less confined areas, thereby creating localized regions of greater movement and subsequent pressure. Device component topography would likewise act to focus encapsulant movement and pressure to specific localized areas.

Understanding the thermal expansion characteristics of silicones and other protective materials used in electronics is an important aspect of module design and reliability.

References

(1) M. Sampathkumar et al., “Effect of Deviating From the Reflow Process Window for Lead-Free Assembly”, SMTA Int. Conference, Sept., 2005.
(2) M. Kelly et al., “Component Temperature Study on Tin-Lead and Lead-Free Assemblies”, SMTA Journal, Vol. 15-4, 2002.
(3) S. Dent, K. Mine, Y. Ushio, M. Watson, “Technology Roadmap for Silicone Adhesives in Thin Multi-Chip Packages”, SMTA Pan Pacific Symposium, Feb., 2003.
(4) C. Wong, J. Segelken, J. Balde, “Understanding the Use of Silicone Gels for Non-Hermetic Plastic Packaging”, Electronic Components Conference, 1989, Proceedings, 39th, p 769-776.

(5) S. Dent, “Development of Microelectronic Grade Silicone Materials for Chip Scale Packages”, SMTA Pan Pacific Symposium, Jan., 2000.
(6) K. Larson, “Low Temperature Reliability Limits of Silicones”, Automotive Electronics Reliability Workshop, May, 2007.
(7) K. Larson “High Temperature Reliability Limits of Silicones”, SMTA/ AIMS Harsh Environment Electronics Workshop, June, 2007.
(8) T. Barcley, P. Berry “Investigation Into the Effect of Gel Hardness on Solder Joints”, SAE 2001 World Congress, Doc. No. 2001-01-0689.
(9) K. Kirchner and D. Nelson, “Conformal Coat Impact on Area Array Package Solder Joint Reliability”, SMTA International Conf., Sept., 2004.

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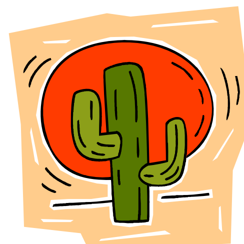
Many electronic devices must operate dependably at both

+150C

+105C

+85C

HIGH



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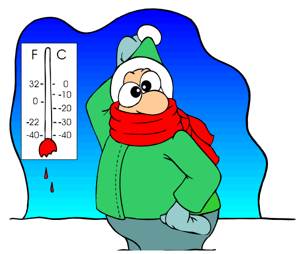


LOW

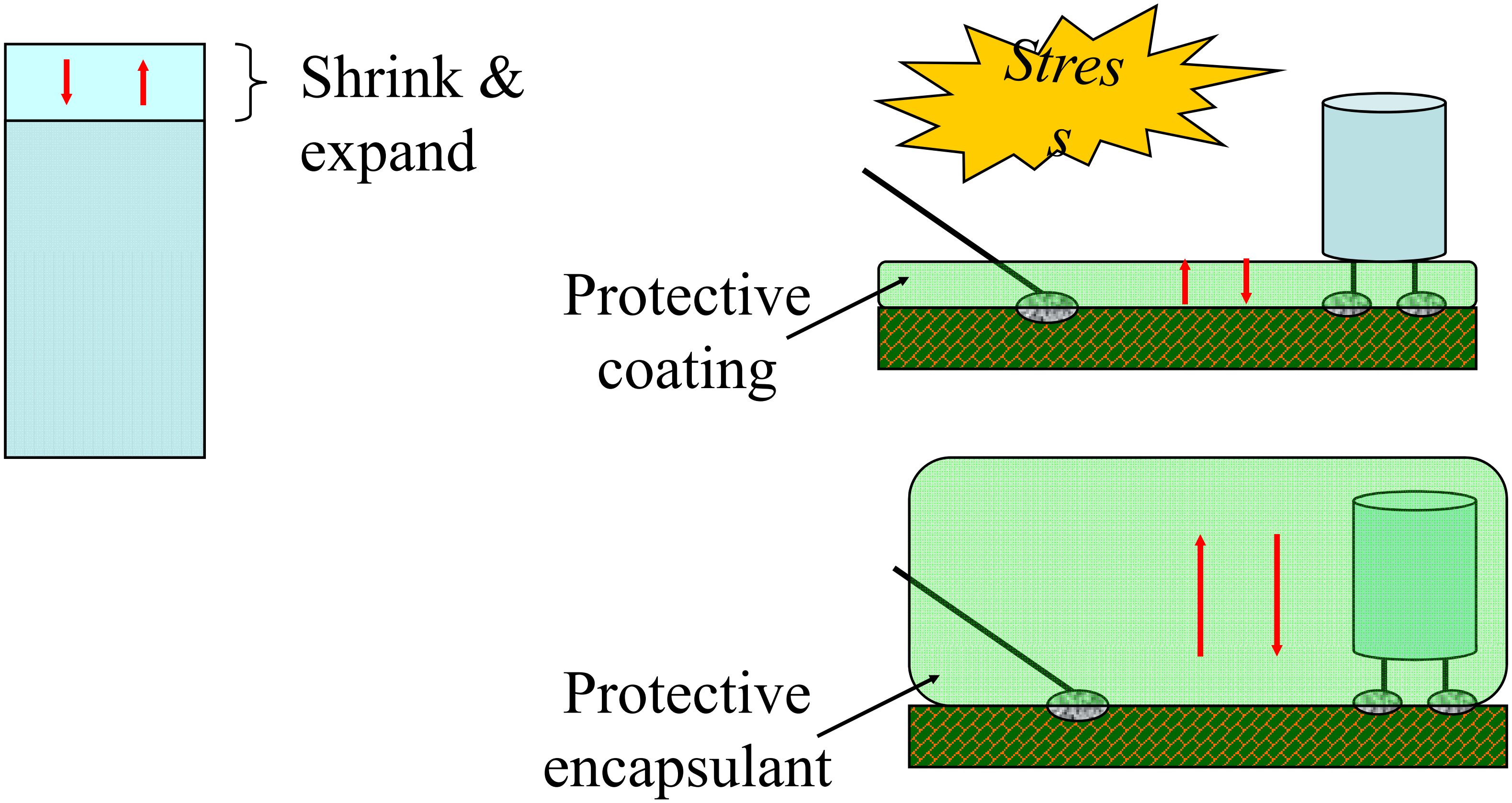
+5C

-20C

-45C

temperature extremes.

As protective materials are thermally cycled …



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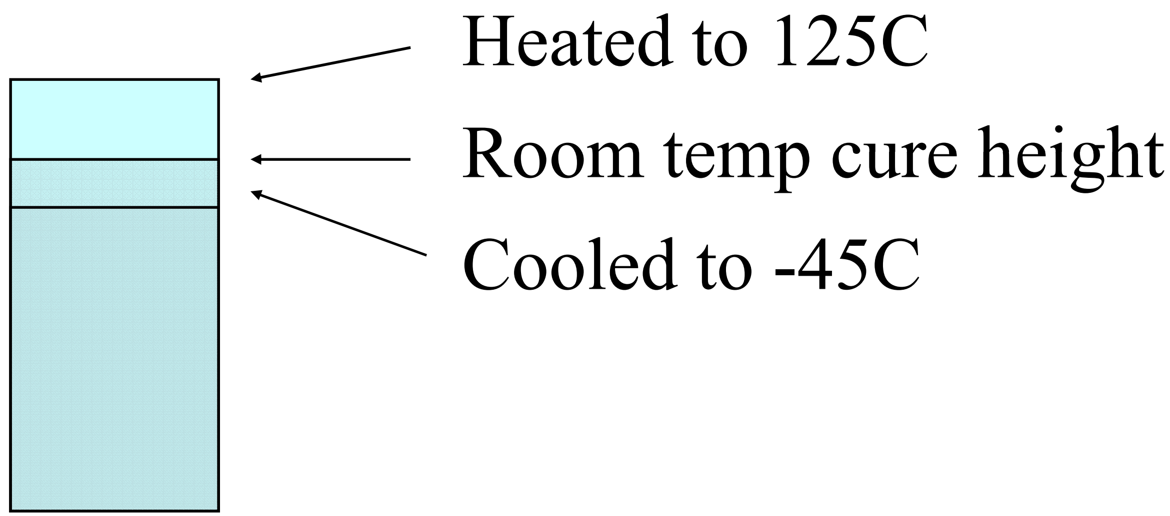
Thermal cycling causes movement in parts due to CTE expansions and contractions

Silicone Linear CTE = 250-400 ppm/C

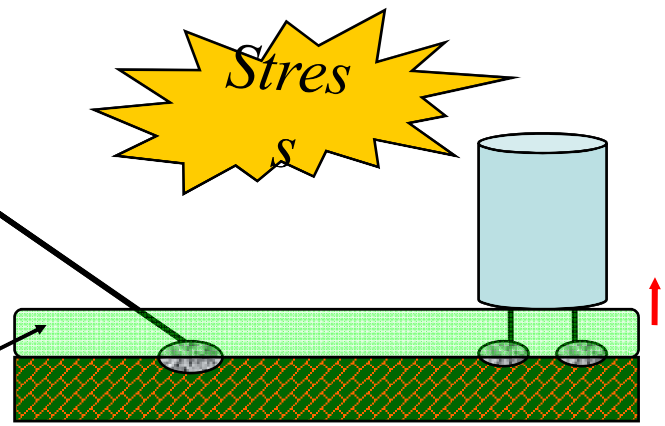
Volumetric CTE = 3X linear = 750-1200 ppm/C

For a 100C temperature rise some silicones may expand 12%

Zero stress is set where the liquid cures into a solid



As protective materials are thermally cycled …

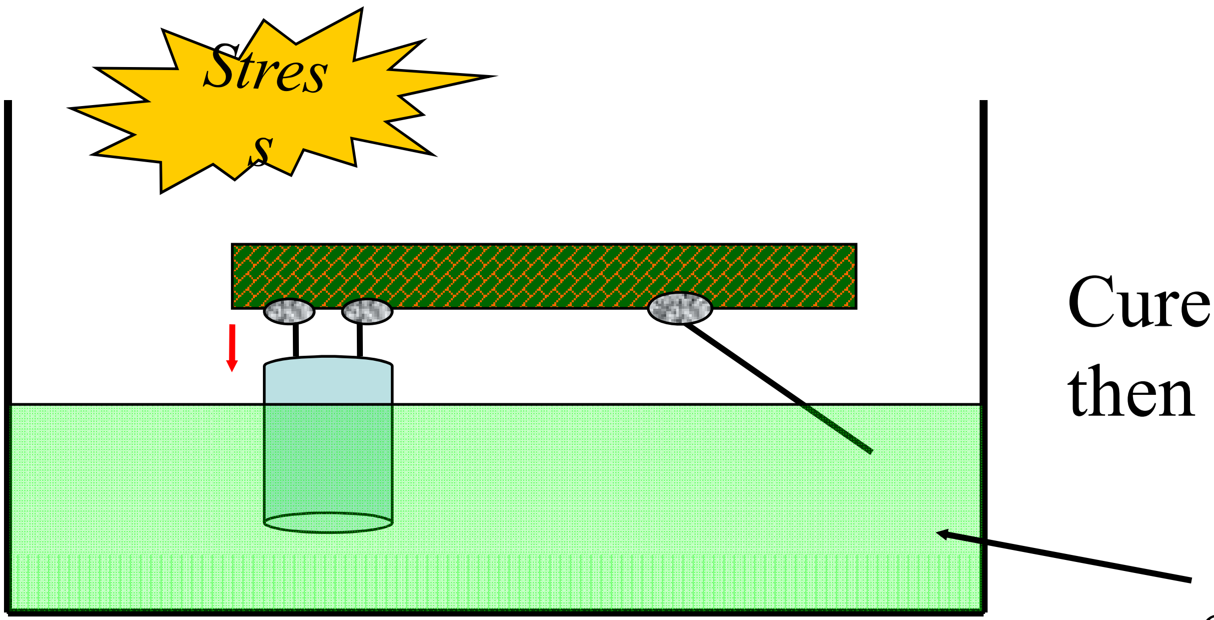


Protective coating

Cured at room temperature and then heated.

Thermal expansion will create pressure under components and stress solder joints and wire bonds.

As protective materials are thermally cycled …



Cured hot and then cooled.

Protective encapsulant

Thermal contraction will create downward pressure and stress solder joints.

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How much pressure can be generated during thermal expansion?

For rigid solids, = CTE x Elastic Modulus x Δ Temp

For contained liquids,

= CTE x Compression Modulus x ΔT

For uncontained liquids = 0

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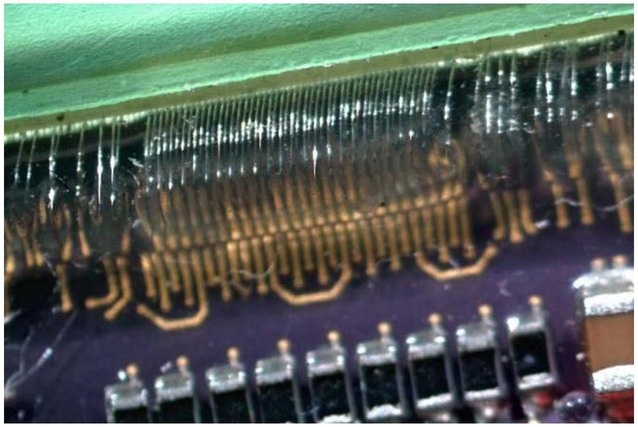
How much pressure can be generated during thermal expansion?

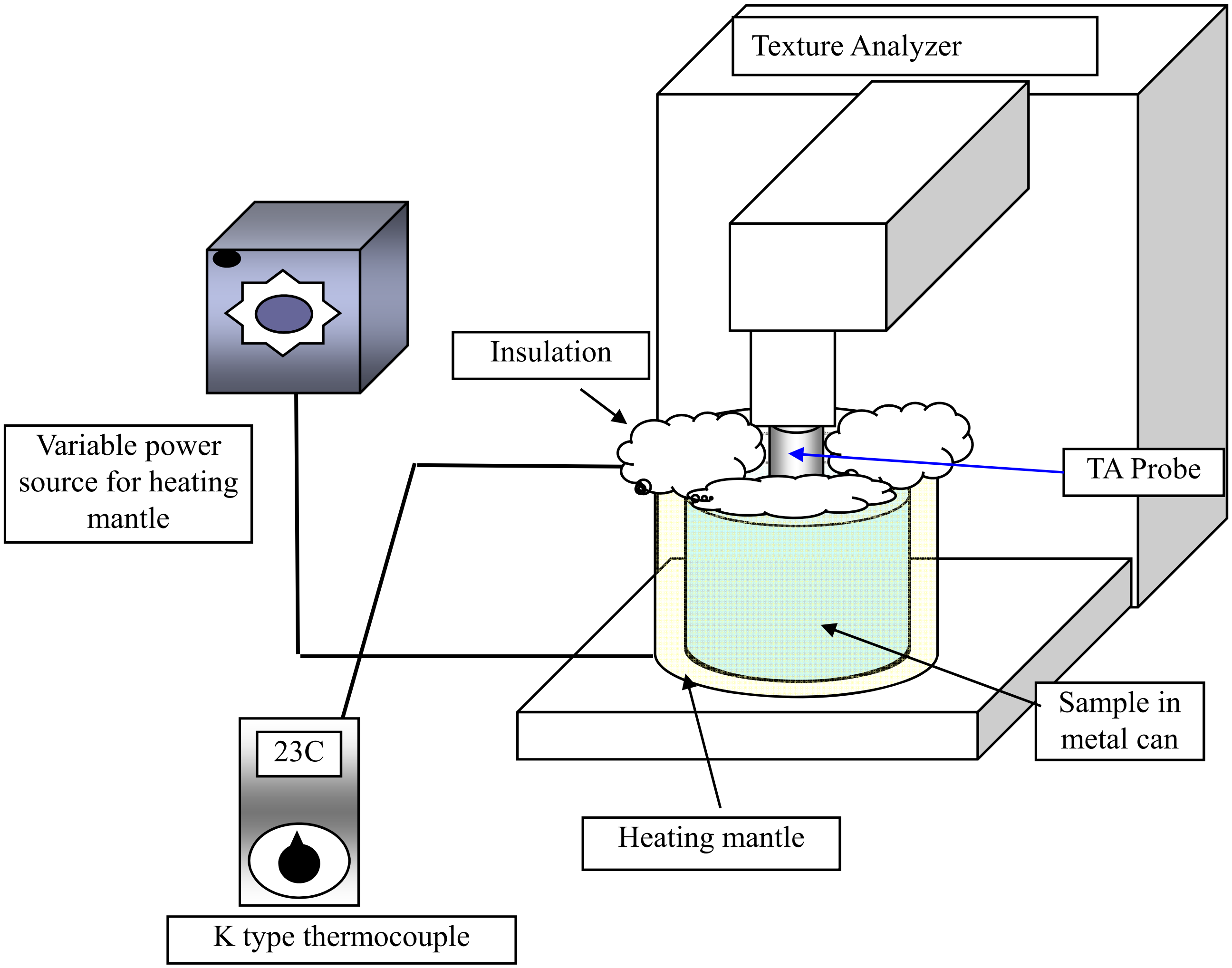
For elastomers, the calculations are not so straightforward.

Silicones have very high CTE's but extremely low modulus and do not tend to fit well to standard calculations.



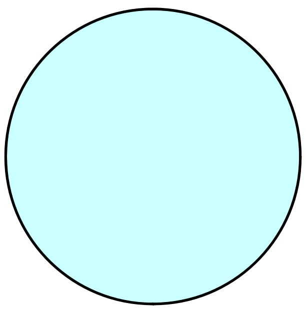
Experiments were designed to directly measure silicone thermal expansion.

Silicone Encapsulant	1	2	3	4
Description	Soft gel	Firm gel	Tough gel	Clear elastomer
Hardness, Shore A Shore 00	- -	- 25	8 65	50 -
Texture Analyzer Gel Hardness, g	105	1500	9500	28,600
Elastic Modulus, psi	0.15	0.3	17	720
Volumetric CTE, ppm/C	1.20 E-03	9.60 E-04	9.25 E-04	9.30 E-04

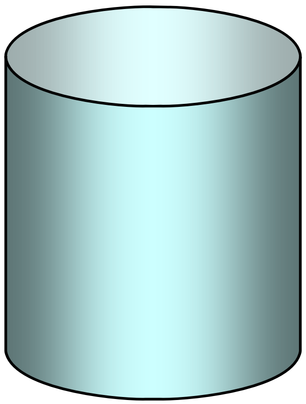

Texture Analyzer
Insulation
Variable power source for heating mantle
TA Probe
Sample in metal can
23C
Heating mantle
K type thermocouple

Thermal Expansion Pressure Measurement

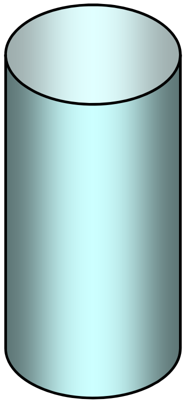
Texture Analyzer Probes



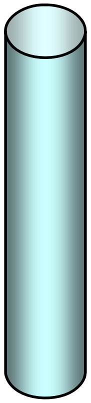
Flat 1.5mm plastic disk
D = 1.34 inches
Area = 1.41 sq.in.
Use D = 1 inch probe



D = 1 inch
Area = 0.785 sq inches

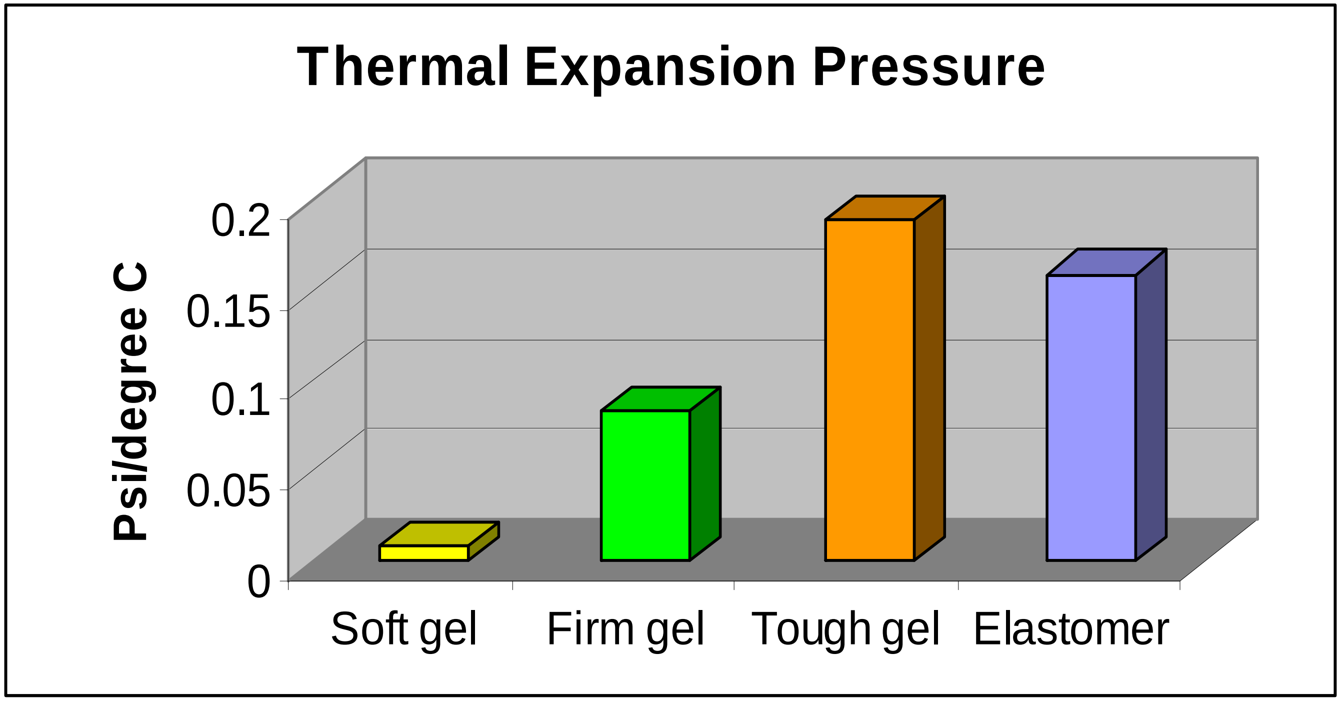


D = 0.51 inch
Area = 0.206 sq inches

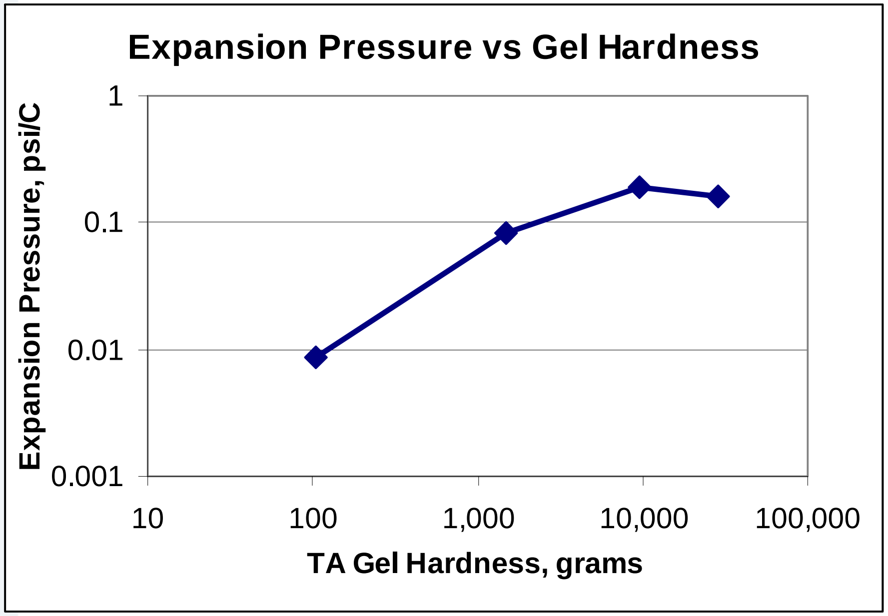


D = 0.254 inch
Area = 0.0506 sq inches

Thermal Expansion Pressure of Silicones

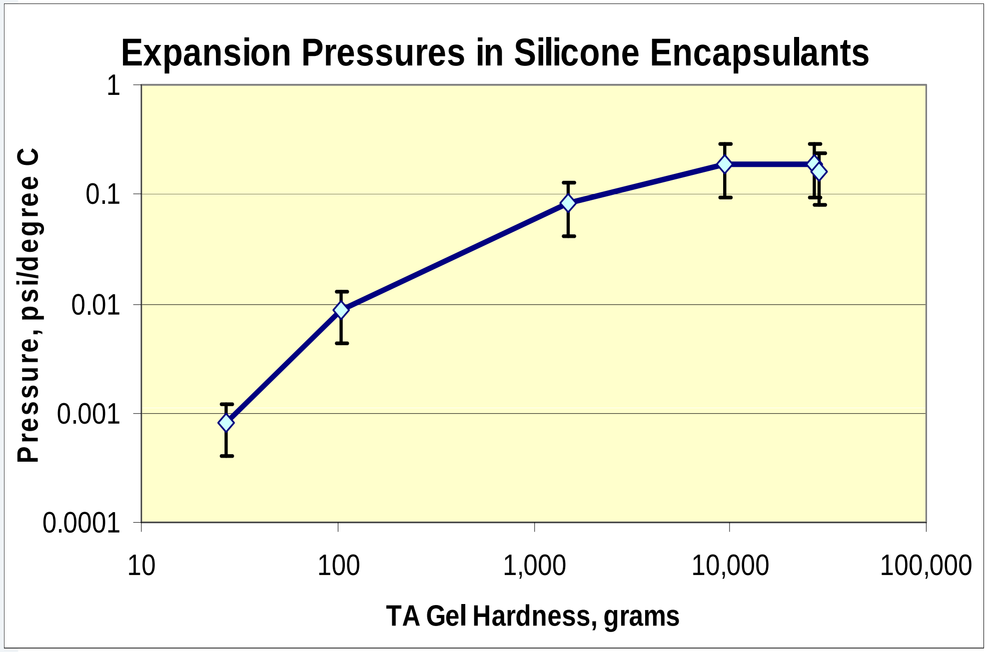


Thermal Expansion Pressure of Silicones



This chart was used to estimate the expansion pressure from a gel with a hardness of about 25 grams. Such a material was then formulated and tested.

Thermal Expansion Pressure of Silicones

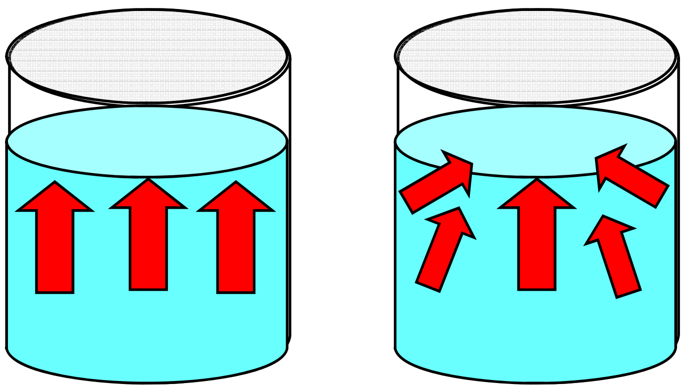


The new extremely soft gel created an expansion pressure exactly predicted from the chart.

Thermal Expansion Pressure of Silicones

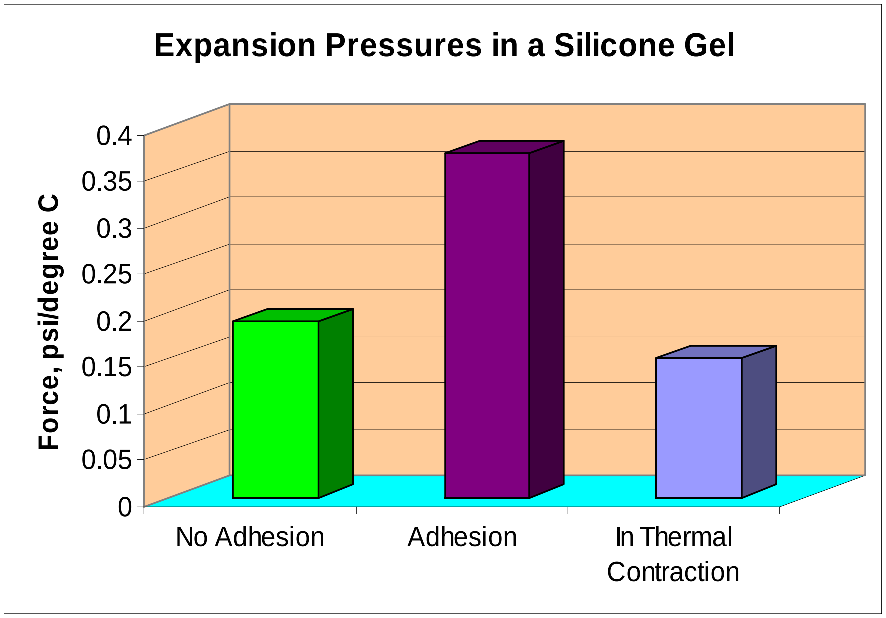
Next, adhesion to container side walls was evaluated.

It was expected that "locking in" the material to the side walls would create a greater pressure as measured in the center of the sample.



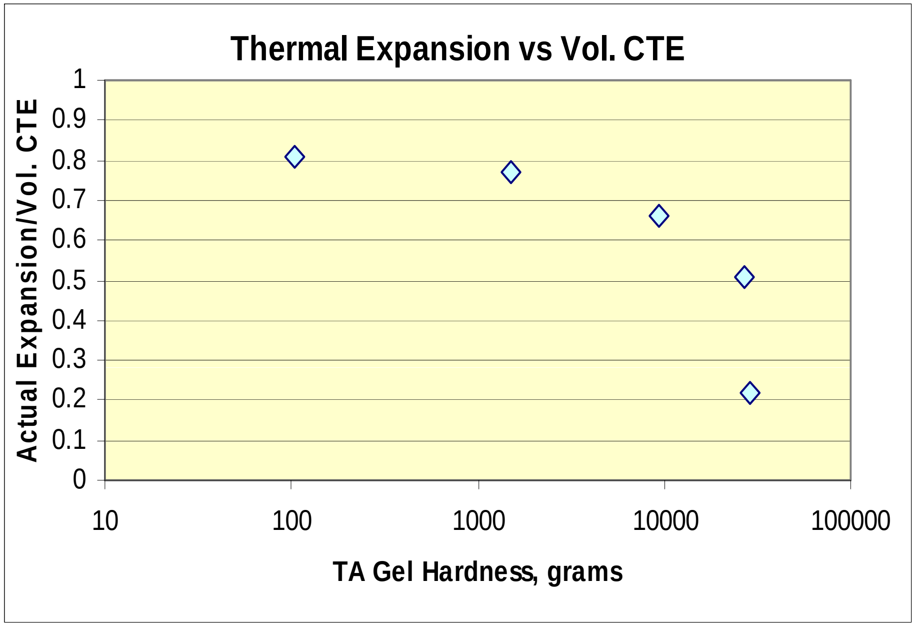
Thermal Expansion Pressure of Silicones

In addition, a test was run in contraction on a tensiometer to validate the results could be obtained in either direction.



Thermal Expansion Pressure of Silicones

Volumetric expansion was measured with samples cured in narrow glass vials with release agent applied to all surfaces.



Unexpectedly, during repeated thermal cycling the harder encapsulants did NOT expand to their CTE predicted height.

Thermal Expansion Pressure of Silicones

During thermal cycling a significant lateral pressure in the harder encapsulants prevented full vertical movement.

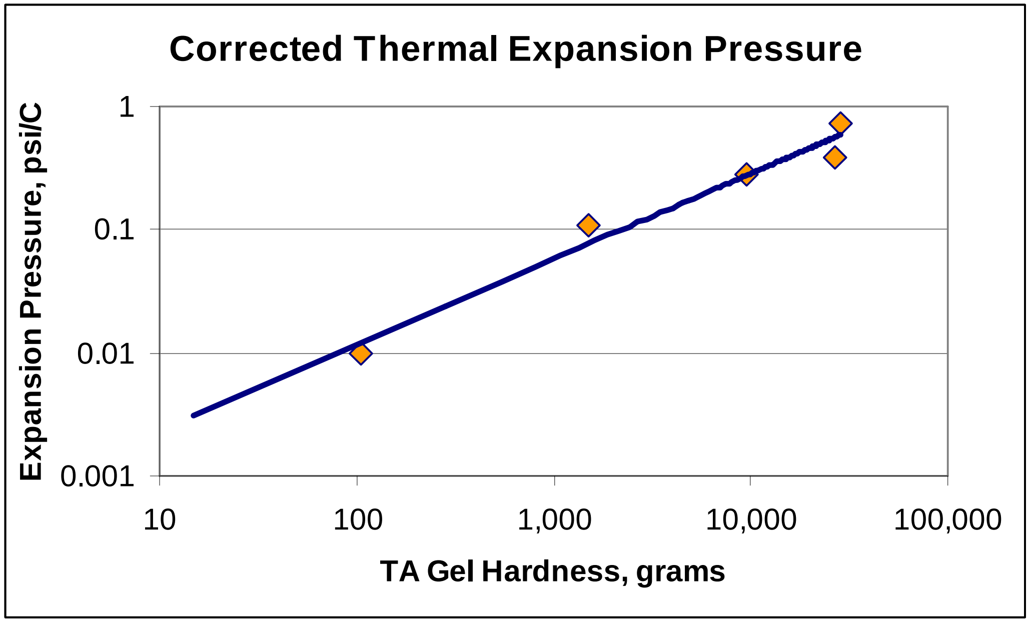
TA Gel Hardness, grams	Vertical Expansion Pressure, psi/C	Horizontal Expansion Pressure, psi/C	Total Expansion Pressure, psi/C
28,600	0.16	0.56	0.72
9500	0.19	0.10	0.29
1500	0.084	0.017	0.11
105	0.0086	0.0014	0.010

"corrected"

Thermal Expansion Pressure of Silicones

Thermal expansion pressure corrected for lateral expansion …

Vertical + Horizontal pressure.



Thermal Expansion Pressure of Silicones

Conclusions

- When heated, silicones expand according to their CTE
- The pressure generated during expansion is proportional to the encapsulant hardness
- Vertical expansion pressure appears to level off in encapsulants with Shore A hardness >5

Thermal Expansion Pressure of Silicones

Conclusions

- Harder encapsulants show a significant lateral x-y component of thermal expansion pressure
- A predictive plot was prepared showing expansion pressures as a function of encapsulant hardness

Thermal Expansion Pressure of Silicones

Conclusions

- Adhesion (and board topography) will affect the magnitude and locations/directions of thermally generated pressures