Expandable Bio-based Polymers: A Lightweight Future for Electronics Ruggedization

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ABSTRACT

Lightweight materials continue to add value to engineering, design, and technology, particularly as more organization's vocalize their pledge to a sustainable future. The ability to do more with less affords numerous competitive advantages, lighter materials minimize waste through material saving, reduce consumption of finite resources, reduce environmental footprint, and achieve cost saving. Automotive design engineers reap considerable benefits when the weight of electronic components is reduced, lowering fuel consumption, reducing emissions, and improving the range of vehicles. Traditionally, encapsulation resins are used as part of circuit board assembly to meet the performance challenges in a variety of electronic applications, such protective polymer materials are deemed essential to ruggedize electronic devices and give long lasting protection from harsh external environments and reduce negative impacts from long term wear-and-tear such as shock and vibration. Encapsulation resins are typically thermoset materials derived from crude oil and contain a significant amount of inorganic filler and thus have a high density and contribute significantly to the weight of the overall encapsulated device. This paper presents a novel, bio-based, expandable, thermoset solution, a low density, light weight method to effectively encapsulate and protect electronic components.

Numerous accelerated life tests were conducted to evaluate the performance of such light weight, expandable solutions alongside standard synthetic grades. Bare and reflowed TB33A test coupons were coated, and the Surface Insulation Resistance was recorded at 85°C (+185°F), 85% Relative Humidity, to understand the impact high temperature high humidity has on electrical resistivity. Test assemblies with a variety of surface mount components were subject to short term Condensation Testing, the Insulation Resistance was recorded. A novel Foam Topcoat ruggedization solution was evaluated to highlight the value proposition of a hybrid ruggedization method that achieves considerable weight and material savings but still achieves a perfect score in a liquid water immersion test, equivalent to a high-density general-purpose encapsulation resin. Potted polycarbonate junction boxes were immersed in deleterious substances, to evaluate long term chemical resistance. This comparative study concludes that the proposed bio-based, expandable polymer acts as a lightweight solution to effectively protect an electronic device subject to harsh operating conditions, including high temperature high humidity, underwater and temperature cycles, and contributes to a significant weight reduction, greater than 80% weight saving is obtained when compared to traditional encapsulation resins.

Key words: Encapsulation Resin, Ruggedization, Lightweight.

INTRODUCTION

Encapsulation resins and potting compounds are designed to protect and insulate printed circuit boards and other electronics components from the numerous threats afforded by harsh operating environments, including moisture, vibration, general contaminating, thermal and physical shock forming a complete barrier against such environments offering superior performance under extreme conditions. They are used in a plethora of weird and wonderful applications including transducers, power distribution modules, high voltage insulation, rail bonds and sensors. They can be applied in tiny shot sizes through to multiple gallons per unit. This variety goes some way towards explaining the complexity behind the market space.

Irrespective of the chemistry type, encapsulation resins are formulated as a mixture of an organic polymer, normally derived from crude oil, inorganic powder, normally refined mineral rocks and other additives such as catalysts. Powders are added for a variety of reasons including structural reinforcement and flame retardance, the addition of such solid materials outlines the problem context for encapsulation resins, high loading of inorganic powders generates ruggedization materials with high densities, this means they contribute significant additional weight when used to protect an electronic device. The weight gain could be negligible for applications with small shot sizes, but where large potting volumes are necessary, and devices are used in moving parts excess weight can be a huge hinderance to the overall economics of performance.

In a changing globalized world, management of finite resources is essential. The need to reduce fossil fuel dependency in the chemical industry has led to the emergence of bio-based alternative products to achieve a more innovative and lower emission economy. Bio-based chemicals are chemical products wholly or partially derived from materials of biological origin. In the future more radical policies could be implemented to make fossil-fuel counterparts less desirable and more expensive. Such future incentives would boost the demand for bio-based alternatives across all market segments. It is possible to utilize bio-based polymer materials to formulate expandable foams with low densities. Such materials can be used in small amounts to fill large volumes and create structural reinforcement, vibration resistance, general protection from the external environment and give other value-added properties such as flame retardance.

Expandable foams can be formulated from hydrophobic building blocks and can have a closed cell structure this limits their ability to interact with water. The purpose of this study is to evaluate such materials in common tests used for ruggedization materials and suggest appropriate methods that could be employed to ensure they outperform materials already available on the market.

The aim of this paper is to answer the question, can we do more with less?

DISCUSSION OF METHODOLOGY

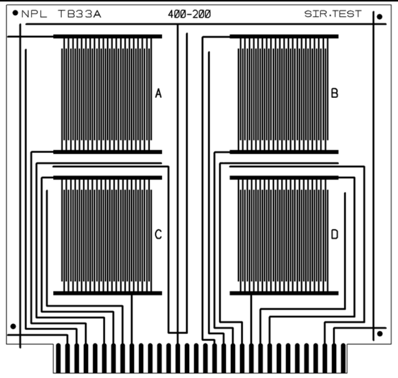
Surface Insulation Resistance

Surface Insulation Resistance (SIR) was conducted by the National Physical Laboratory (NPL). 3 TB33A test assemblies were left bare (no solder paste) – Bare PCB. 2 TB33A test assemblies were reflowed with CVP-390 solder paste – Paste.

Encapsulation Resin, Foam and Solvent Based Coating were sprayed onto TB33A test assemblies. The wet thickness was measured using a thickness gauge and the and cured / dry thickness was measured using a micrometer.

SIR was acquired at 50V, 85°C (185°F) /85% RH for 1000 hours.

The data presented is a mean average of each data set. Error bars presented represent the standard deviation across each data set.



Layout of TB33A

Figure 1. SIR Test Assembly

Condensation Test

Condensation Testing was conducted by the NPL using a novel set up. Populated test assemblies were coated with Encapsulation Resin, Foam and Solvent Based Coating. The wet thickness was measured using a thickness gauge and the and cured / dry thickness was measured using a micrometer on a flat section of the test assembly.

Test Assemblies are mounted on a platen within a humidity chamber. The temperature of the chamber is kept constant at 41°C. The platen temperature is independently controlled to control condensation level, by incrementally increasing the temperature difference below the dew point more condensation forms on the surface of the test assembly. There are 8 levels of increasing condensation, these last 6 hours each.

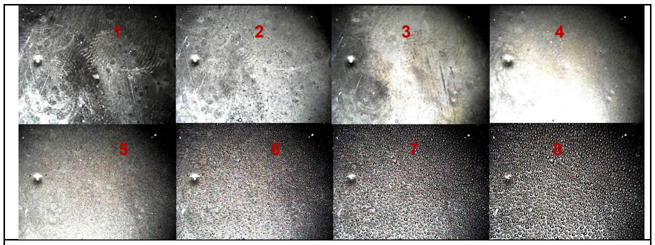


Figure 2. Showing 8 Levels of Increasing Condensation

Insulation Resistance (IR) was acquired at 10V, for 48 hours.

The data presented is a mean average of each data set. Error bars presented represent the standard deviation across each data set.

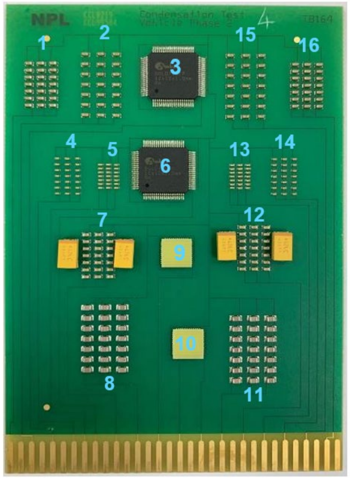


Figure 3. Condensation Test Assembly

Table 1. Surface Mount Components

Code	IR Pattern
1	C0603, 0.8mm space
2	C0603, 1.6mm space
3	QFP 80 0.5mm pitch
4	C0402, 1.0mm space
5	C0402, 0.5mm space
6	QFP 80 0.5mm pitch
7	C0603, 0.8mm space + Tantalum
8	C0805, 1.25mm space
9	QFN48
10	QFN48
11	C0805, 1.25mm space
12	C0603, 0.8mm space + Tantalum
13	C0402, 0.5mm space
14	C0402, 1.0mm space
15	C0603, 1.6mm space
16	C0603, 0.8mm space

Foam Topcoat

A theoretical study to consider the potential weight and material saving opportunities when using a foam and foam with different thickness layers of topcoat to encapsulate different size units.

The materials considered are:

- General Purpose Epoxy Encapsulation Resin.
- Foam
- Foam + 250µm (9.8mil) General Purpose Epoxy Encapsulation Resin topcoat.
- Foam + 500µm (19.7mil) General Purpose Epoxy Encapsulation Resin topcoat.

The weight of each ruggedization material combination required to completely pot different housing volumes is calculated and compared.

Water Immersion

Polycarbonate junction box potted with different combinations of ruggedization materials completely immersed in water monitored to evaluate weight change associated with water absorption over a 1000-hours.

General Purpose Epoxy Encapsulation Resin, Foam, Foam + 250µm (9.8mil) General Purpose Epoxy Encapsulation Resin, Foam + 500µm (19.7mil) General Purpose Epoxy Encapsulation Resin. 3 repeats of all material combinations were tested. All materials applied with a PVA VPX-2K dual component spray valve.

The data presented is a mean average of each data set. Error bars presented represent the standard deviation across each data set.

RESULTS

Surface Insulation Resistance

SIR is the electrical resistance between a pair of conductors, SIR testing is used to evaluate a 'systems' ability to resist failure, identified by current leakage or electrical shorting.

Table 2. Material Thickness Details

Material	Wet (µm)	Cured / Dry (µm)
Encapsulation Resin	2000	2000
Foam	300	2000
Solvent Based Coating	350	75

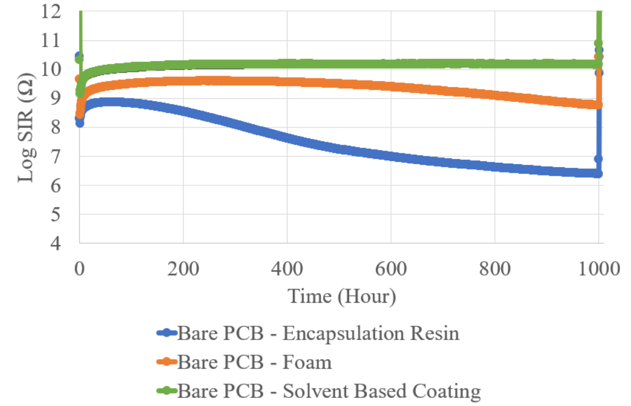


Figure 4. Bare PCB SIR

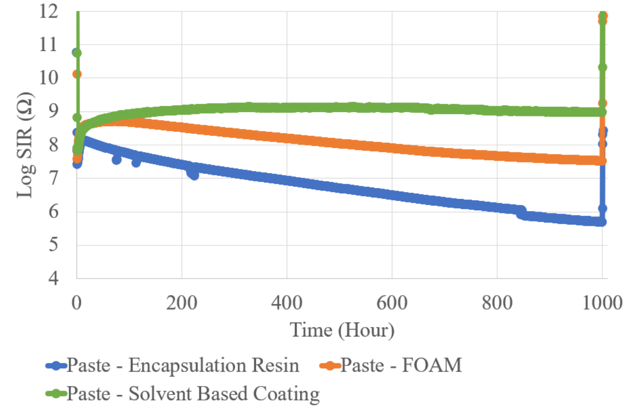


Figure 5. Paste SIR

The SIR values for the Encapsulation Resin containing paste are approximately one decade lower than that of bare PCBs. Test assemblies cannot be visually inspected after SIR testing due to the opaque nature of the Encapsulation Resin. It is likely that corrosion products have formed around anode. Such corrosion products could cause significant SIR failure.

Encapsulation resins are typically not subject to high temperature high humidity SIR testing as they typically contain a high proportion of inorganic powders acting as a flame retardant powder. Flame retardant powders include Ammonium Polyphosphate (APP), an inorganic salt of polyphosphoric acid and ammonia are typically inorganic salts and can be sensitive to hydrolysis under hot humid conditions this can explain the observed downward trend of the Encapsulation Resin SIR over time.

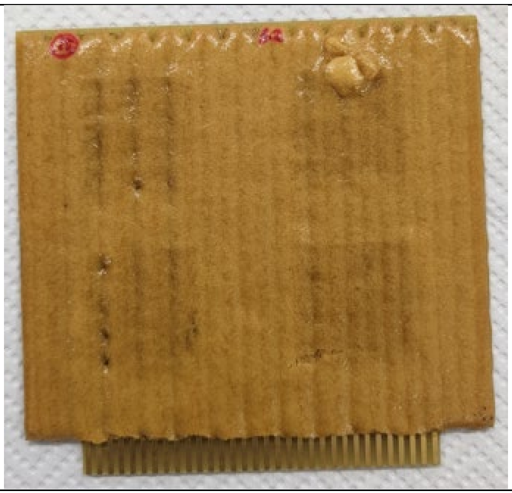


Figure 6. Image of Paste – Foam after SIR

The SIR values for the Foam on paste printed PCBs are approximately one decade lower than that of bare PCBs. Test assemblies cannot be visually inspected after SIR testing due to the opaque nature of the Foam, the Paste comb patterns have significantly discolored after 1000H testing, indicative of corrosion products.

The proposed Foam shows superior electrical performance to the Encapsulation Resin in hot humid conditions. The Foam formulation appears to be hydrolytically stable on a Bare PCB across the entire 1000-hour test period.

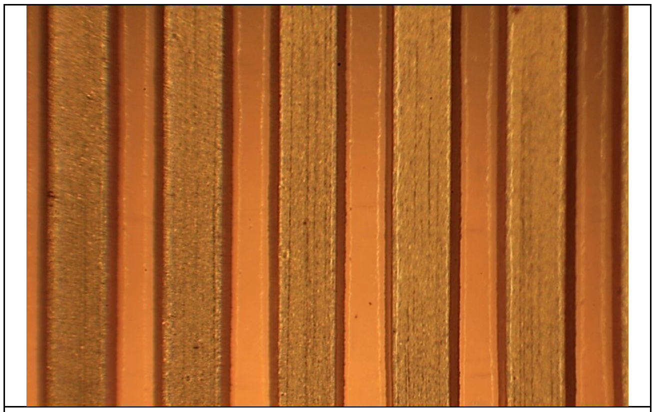


Figure 7. Image of Bare PCB – Solvent Based Coating after SIR

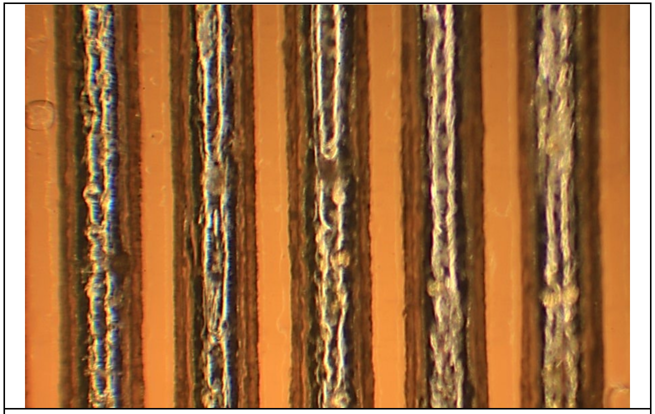


Figure 8. Image of Paste – Solvent Based Coating after SIR

The SIR values for the Solvent Based Coating on paste printed PCBs are approximately one decade lower than that of bare PCBs. There was no significant visual change observed on both bare PCB and printed PCB after 1000 hours of SIR testing, no visual indicators of corrosion products.

The Solvent Based Coating is an acrylic system designed to be hydrolytically stable towards water vapor when applied on a flat unencumbered test assembly.

Condensation Test

Wet ruggedization materials typically do not have the same electrical insulation properties as dry.

Table 3. Material Thickness Details

Material	Wet (µm)	Cured / Dry (µm)
Encapsulation Resin	2000	2000
Foam	300	2000
Solvent Based Coating	350	75

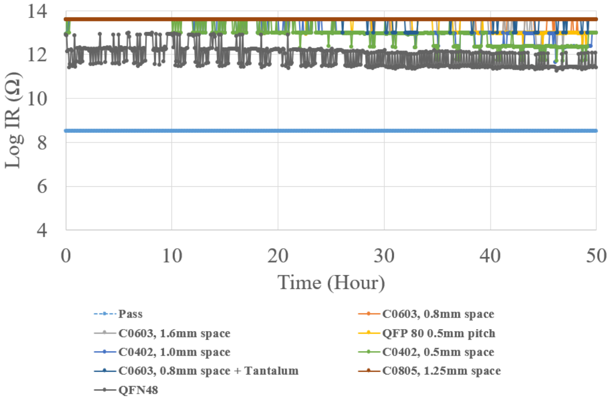


Figure 9. Encapsulation Resin Condensation IR

Figure 10. Encapsulation Resin Image after Condensation IR test

The Encapsulation Resin shows outstanding electrical insulation over all surface mount components and is considered hydrolytically stable in these test conditions. The encapsulation resin is impervious to water under the parameters of the temperature conditions. The rheology and thickness of 80mil means that there is sufficient material to protect the topologies of all the different surface mount components.

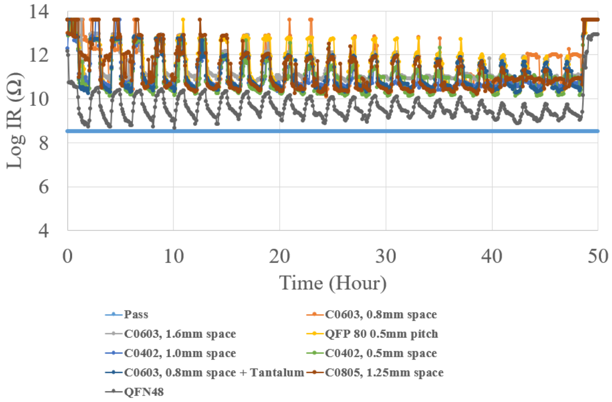


Figure 11. Foam Condensation IR

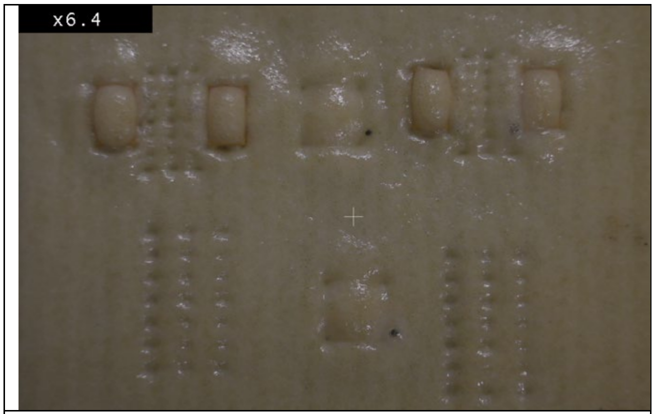


Figure 12. Foam Image after Condensation IR test

The Foam encapsulant provided sufficient electrical insulation over all surface mount components and is categorized as a hydrolytically stable material within the test conditions of this experiment. The use of hydrophobic bio-based materials to create expandable foams means the water absorption at room temperature is low when exposed to short periods of condensation. The ability to apply a thin film of material that expands to approximately 8x the applied thickness means that there is sufficient material to protect the topologies of all the different surface mount components. The IR values for the QFN component are approximately 2 orders of magnitude lower than that of the other surface mount components. Visual inspection of the test assembly after testing shows a small defect within the Foam around the QFN.

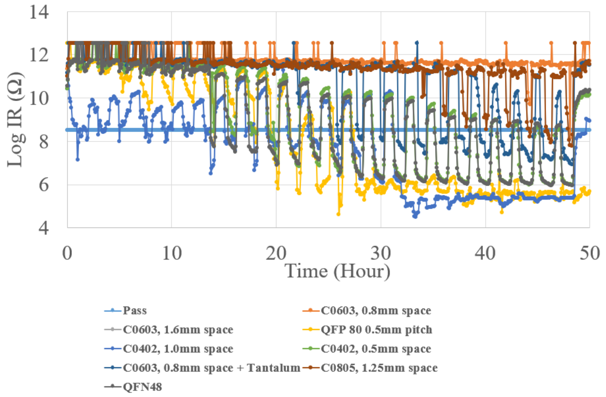


Figure 13. Solvent Based Coating Condensation IR

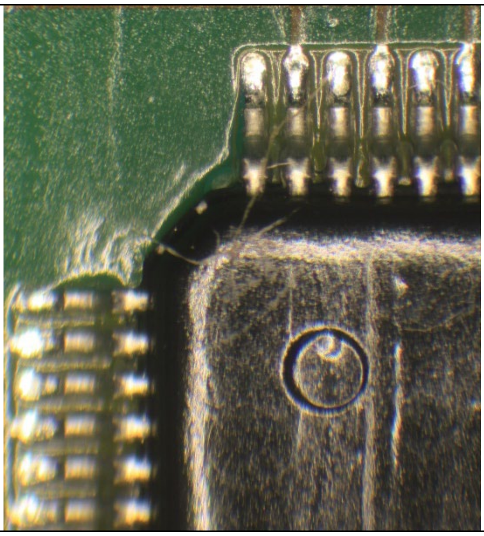


Figure 14. FOD on Solvent Based Coating Image after Condensation IR test

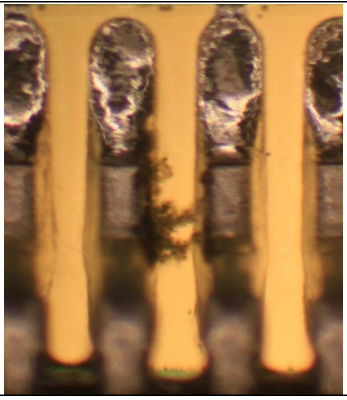


Figure 15. Corrosion Products on Solvent Based Coating Image after Condensation IR test

The solvent-based coating shows poor performance in the Condensation IR test. The overall IR values are poor in comparison to the other materials considered in this study. There are numerous surface mount components that have failed this test and are not categorized as hydrolytically stable. The poor performance of such Solvent Based Coating is linked to the higher level of relative liquid water absorption, thin layers have a lower resistance to thick layers, lack of crosslinking from the drying of the liquid coating and the poor edge coverage means surface mount components are left exposed to water, it is likely that conductive bridges could form between conductors. Corrosion products and hydrophilic FOD were observed both can cause significant failure within devices.

Foam Topcoat

The purpose of this section is to discuss the value proposition of a novel solution to achieve a perfect scoring, lightweight ruggedization material, suitable for liquid water immersion conditions, a **Foam Topcoat** material. The bulk of the ruggedization material is made up of a low-density Foam, with a thin layer of an impervious polymer applied as a Topcoat.

Table 4. Ruggedization Materials

Property	Encapsulation Resin	Foam
Bio-based Content	0	60
Flame Retardancy UL-94	V0	V0
Density	1.8	0.3

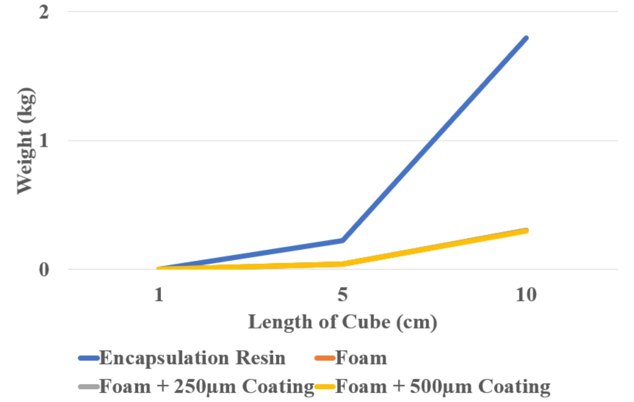


Figure 16. Weight of Ruggedization Material vs Length of Cube

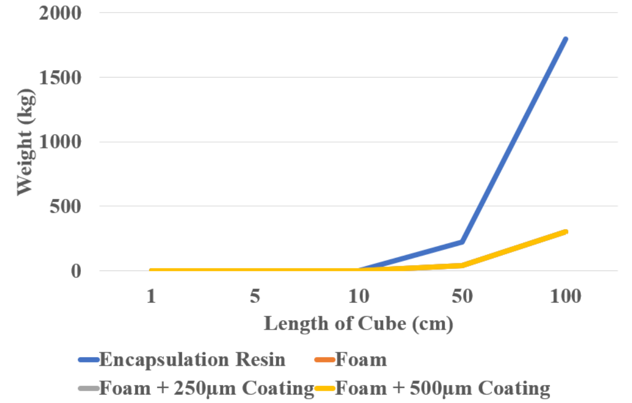


Figure 17. Weight of Ruggedization Material vs Length of Cube

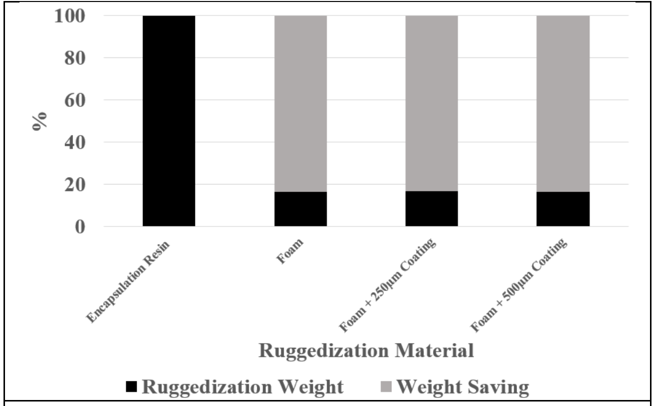


Figure 18. Weight and Weight Saving

The additional weight attributed to a 250µm (9.8mil) and a 500µm (19.7mil) topcoat is negligible to the overall weight of the entire ruggedization system. Utilizing the Foam concept with or without a Topcoat gives weight savings of approximately 80%. Using low density foams with 60% bio-based sustainable content affords significant weight saving opportunities compared to using high-density general-purpose encapsulation resins, weight saving also means material cost saving.

Water Immersion

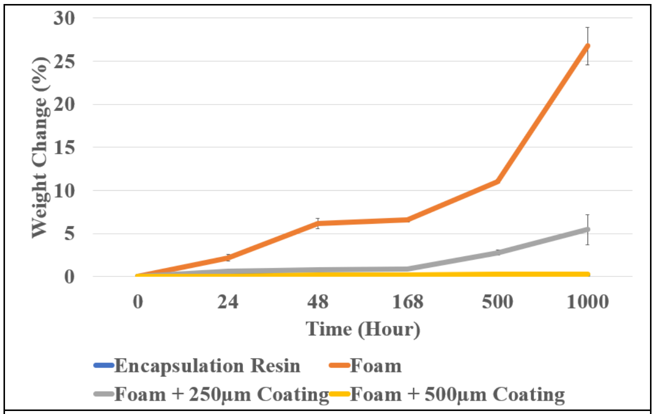


Figure 19. % Weight Change of Ruggedization Material with Continuous Immersion in Water, lower resolution

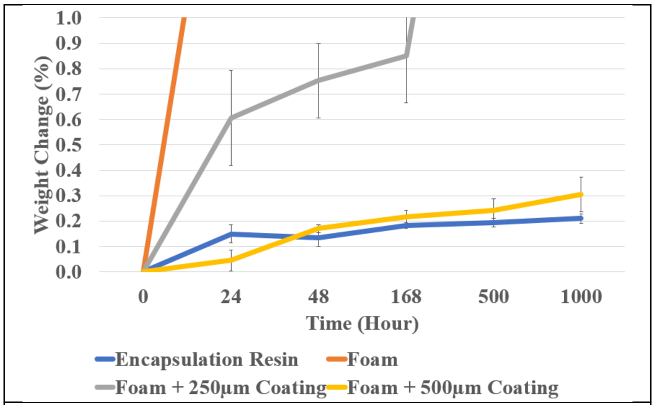


Figure 20. % Weight Change of Ruggedization Material with Continuous Immersion in Water, higher resolution

A 250µm (9.8mil) layer of Topcoat material provides a vast improvement to the water absorption rate compared to the Foam. A 500µm (19.7mil) layer of Topcoat material provides a sufficient barrier towards liquid water. Over a 1000-hour test period a unit potted with Foam containing a 500µm (19.7mil) layer of Topcoat performs equivalently to a unit potted with a high-density general-purpose resin. The measured weight change for both was less than 0.5%. This suggests a PCBA embedded within the unit housing would be adequately protected from liquid water in long term immersion.

Conclusion

Humid conditions drive corrosion products, monolayers of water can form on the surface of a PCBA and act as a carrier solution for any ionic contaminants that could be a residual artefact from any surface mount assembly such as paste reflow, or from environmental conditions such as salt-spray or corrosive gases, such factors along with dissimilar metals and bias cause corrosion products, any detrimental reaction is accelerated as the temperature increases. All polymers are permeable to water in its vapor phase. Water vapor permeability reduces the insulation resistance of a ruggedized assembly. The impact of paste contamination is observed in this study, all ruggedization materials considered have a SIR one decade lower. Most general-purpose encapsulation resins contain inorganic powders that can be sensitive to hydrolysis in hot humid conditions, and such typically have poor performance in SIR testing. The bio-based expandable foam shows far superior protection and is considered hydrolytically stable on a Bare-PCB across a 1000-hour test period. This shows that we can provide more protection against hot humid conditions with 80% less material when comparing the SIR of the Foam with the Encapsulation Resin.

Liquid water, condensation brings about many of the same issues as corrosion, in addition liquid water can bridge conductors and lead to electrical shorting. Solvent based coatings perform poorly when exposed to short periods of condensation, the thin layers of non-crosslinking thermoplastic polymer have a lower resistance towards water absorption. Poor edge coverage on surface mount components can leave devices vulnerable to corrosion products. The Foam provides sufficient protection against condensation and is considered hydrolytically stable in this condensation test method. Expandable materials do a good job at protecting the intricacies of the complicated geometries of different surface mount components.

The Encapsulation Resin achieved a near perfect score in the condensation test but performed poorly in the SIR test under hot humid conditions. The Foam performed much better in the SIR test, it is considered hydrolytically stable in the conditions of the condensation test and shows far superior performance to the Solvent Based Coating when faced with different levels of short cycles of surface contamination of liquid water.

By considering the material consumption and weight of ruggedization material used to completely pot different volumes, it is potentially possible to get the 'best of both worlds' if the bulk of the volume is potted with a Foam and an impervious Topcoat layer applied to seal a unit, a significant 80% weight saving could be achieved, such monumental savings could be game changing to the overall economics of performance of ruggedization materials.

When monitoring the weight change attributed to water absorption of units potted with Foam and different thickness layers of Topcoat shows that a 500µm (19.7mil) layer of Topcoat material provides a sufficient barrier towards moisture and shows equivalent water absorption to a unit completely potted with a high-density general-purpose resin clearly displaying that the same barrier protection properties can be achieved with 80% less material.

Future Work

The work presented in this paper highlights numerous opportunities into this this field of bio-based expandable polymer materials for use in electronics. Any future work should seek to quantify what the water absorption value means in terms of electrical performance, Water Absorption vs Insulation Resistance. This relationship could also be studied under different temperatures and in different deleterious mediums.