No failures in 187 accumulated years of space operations but many lessons learned on the ground!

Steve's Failures… on the Ground

1982 AMPTE- *Loose transformer gap adjuster resulted in frequency shift.*

1988 EUVE IPS- *Thermal breakdown at potted transformer wire termination.*

1995 SOHO- *Hidden crack on potted side of ceramic output connector.*

1995 IMAGE- *Vibration failure at transistor heat sink mount.*

1995 FUSE- *Arc-induced oscillator latch-up.*

1998 HST-COS- *Broken wire on high voltage multiplier.*

1999 GP-B- *Detached wire on high voltage capacitor during vibration.*

2005 AIM- *Backwards tantalum capacitor.*

2005 TEGA- *Cracked high voltage resistor after potting.*

2005 TEGA- *Light sensitivity on high voltage opto-couplers.*

2009 SAM- *Control loop instability due to wrong part.*

2009 SAM- *Broken transformer wire after potting and thermal cycling.*

Moving on to Detailed Element Design Approaches…

- *We are now (finally!) going to move on to the real engineering stuff where most of the guide documents don't go.*
- *The discussions will be centered around the "focus areas" discussed yesterday. Some areas are not covered in detail:*
  - *High Power and high frequency designs.*
  - *RF generation and injection techniques.*
  - *Impulse generators and pulse forming methods.*
  - *Insulator design approaches.*
  - *Frequency synchronized designs.*
  - *Resonant regulation techniques.*

Cleaning and Contamination… 1

- *Proper cleaning and processing methods in tandem with approaches to prevent re-contamination are essential to achieve reliable and predictable high voltage system performance.*
- *Develop "certified" plastic and metal cleaning and storage processes that are consistent with all of the material you use.*
- *Always assure parts are dried and baked out prior to bagging and **NEVER use a metalized bag for storing parts used in the high voltage areas unless they are pre-wrapped** in a plastic material that does not contain plasticizers.*

Cleaning and Contamination… 2

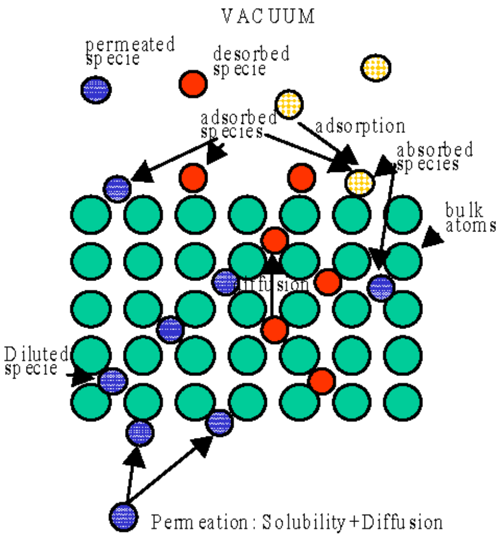
- *Pure Nylon (Zytel 101 trade name), FEP and PTFE Teflon, and Mylar (polyester) sheet or film have no plasticizers.*
- ***2 mil Teflon film material is a good choice**.*
- *Never handle plastic parts or ceramic parts with bare fingers.*
- *Protect against re-introduction of plastic or metal particles (or dust) into open high voltage cavities that are to be coated or encapsulated.*
- *Always **protect high voltage connectors and output insulators from contamination or metalized surface contact.***

Venting Considerations… 1

- *Rapid and effective venting through known pathways is essential to any high voltage system used in space.*
- *Design must accommodate de-pressurization (and re-pressurization) and efficient release of desorbed outgassing products consisting of volatiles chemical species and adsorbed water.*
- *Typically, a high voltage system needs to operate in the range of at 10E-5 torr pressure although operation in the range of 10E-4 is possible. The problem immediately after launch is that the external pressure might also be in the range of 10E-5 to 10E-6 which restricts the effective pumping rate.*
- *If possible, a properly vented system should wait several days (often 1-2 weeks is specified for scientific systems with exposed high voltages) before turning on unless the outside pressure is well known via design plus analysis and/or direct measurement.*

Venting Considerations… 2

- *In general a properly sized outgassing vent is large enough to also meet de-pressurization requirements.*
- *If you want to avoid detailed analysis, gas effusion from a contained volume through a pin-hole into a vacuum gives a simple way of calculating the ratio of required vent area for a given volume.*
- *A good rule of thumb sizing formula for the sizing of outgassing vents is to use a Volume (cm^3)/Area (cm^2) ratio in the range of 2000 to 20,000 (typically 10,000) for simple volumes with simple vent designs.*
- *For example a 1000 cm^3 volume would require in the range of 0.1 cm^2 of vent area (~ 4 mm hole).*



Venting Considerations… 3

- *Note that hot temperatures that increase the outgassing rate or a poor external vacuum can affect the V/A ratio.*
- *Make vents re-entrant to prevent radiation leaks and minimize re-contamination risk. Also, it is best to distribute the vents in ways that are related to the critical high voltage circuit locations.*
- *Make sure to vent all screw holes and be sure that you don't accidentally coat over the holes. Vented screws can also be used.*

Venting Considerations... 4 (and finally!)

- *Remember that venting can also allow for the introduction of particulate contaminants.*
- *Make sure that vent holes for screws cannot allow chips to enter electronic cavities (punctured Kapton tape works well in many applications!).*
- *You can also use a fine mesh filter or a similar mitigation method if fast re-pressurization cannot be avoided.*

Choice of Insulating Media…

- *This area has already been discussed from a physics perspective by Eric. Now we are going to talk about key engineering parameters and choices.*
- *The key design choice comes down to open construction vs. encapsulation or some combination of both.*
- *Aside from solid potting materials such as epoxy, urethanes and silicones, there are many available materials including engineering plastics, Parylene, greases, gels, plastics, Boron nitride, alumina, beryllia, mica, ruby, sapphire, dielectric liquids and dielectric gasses.*
- *Choice(s) depends on operating voltage, required lifetime, temperature, operational pressure, serviceability, mass and volume.*
- *Choice(s) also depend on qualification of the material for the specific operating environments in combination with the process expertise of the user.*

Steve's List... *of Proven Materials and Process Methods*

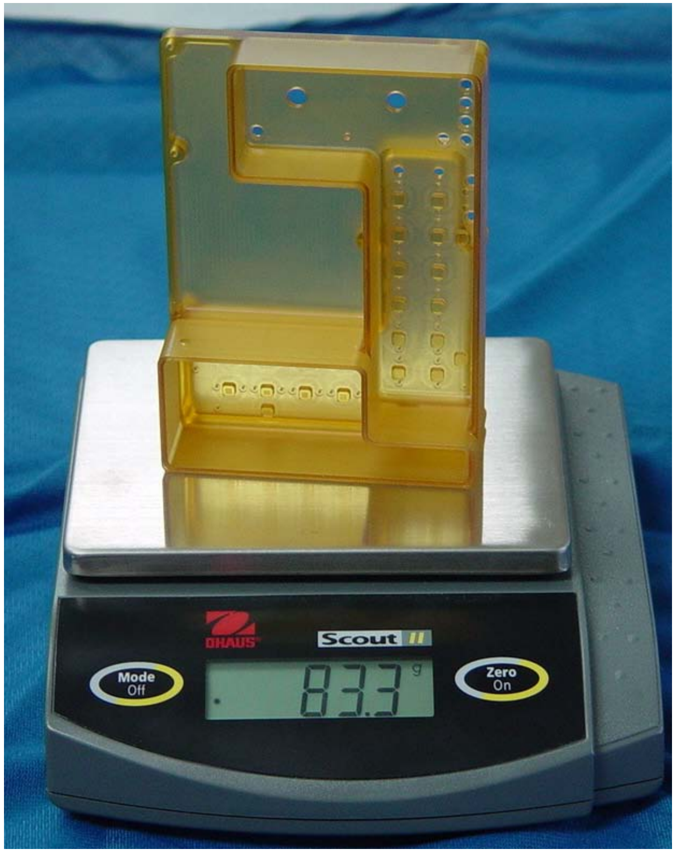
Commercial Ident.	Material/ Spec.	Manuf.	Processing Parameters	Application
Kapton Tape CHR K102	Polyimide	CHR	Tape Insulation	
Uralane 5750-A/B (LV)	Polyurethane Conf. Coating	Huntsman	2 part mix; thin with Tolulene+MEK Per GSFC MPD-313-008	PC Board Coating
Uralane 5753-A/B (LV)	Polyurethane Thixotropic	Huntsman	2 part mix; 15% Cab-o-Sil Fill (M-5) Per GSFC MPD-313-008	PC Board Staking
Scotchweld 1838B/A	Struct. Epoxy	3M	2 part mix; 1:1 BW	General Adhesive Not Used for High Voltage
EN-4-A/11-B	Polyurethane	Cytec	100A/55B mix; Amb + 60Cpost Per BE/999/94/248A	Adhesive Bonding
EN-4-A/11-B	Polyurethane Thixotropic	Cytec	100A/55B mix; 7% Cab-O-Sil Fill (M-5) Per BE/999/94/059B	Transformer Wire Staking/Coating
EN-4-A/11-B	Polyurethane	Cytec	100A/55B mix; Amb + 60Cpost or 60C cure Per BE/999/94/057C	HV Section Encapsulant
EN-4-A/11-B	Polyurethane	Cytec	100A/55B mix + 20% BW Boron Nitride; 24 hrs 60C Per BE/999/92/184B	Thermal Staking Thermal Potting
STYCAST 2850FT/Cat24LV	Filled Epoxy	EC	Cat24LV; 60C cure Per BE/999/97/149	HV Connector Encapsulant
STYCAST 2850FT/Cat9	Filled Epoxy	EC	Cat9; 82C cure Per BE/999/94/061B	HV Staking
Epon 828/V125	Unfilled Epoxy	Shell	CatV125; Amb + 82C cure Per BE/999/94/249A	Pre-pot Wire Primer
Scotchcast 280	Unfilled Epoxy	3M	2 part 2:3 mix; 120C cure Per BE/999/95/550	Magnetics Impregnation
ULTEM 1000	Polyetherimide	GE	Sheet Stock	Stiffeners, HV Insulators, Enclosures
PEEK	Polyetherketone	Dupont	Sheet Stock	HV Insulators
Vespel	Polyimide	Dupont	Sheet Stock	HV Insulators
Parylene C	Poly-para-xylylene	Specialty Coatings	Per standard dimer Vapor deposition process.	High voltage coating.
G-10 Laminate	MIL-P-13949G	QPL	.010, .020, .062	Insulator
Epo-Tek H22	Conductive Epoxy Silver Filled	Epoxy Technology	20 part-A; 0.9 part-B BW Per BE/999/98/115; 80C Cure	HV Connections Ground Connections

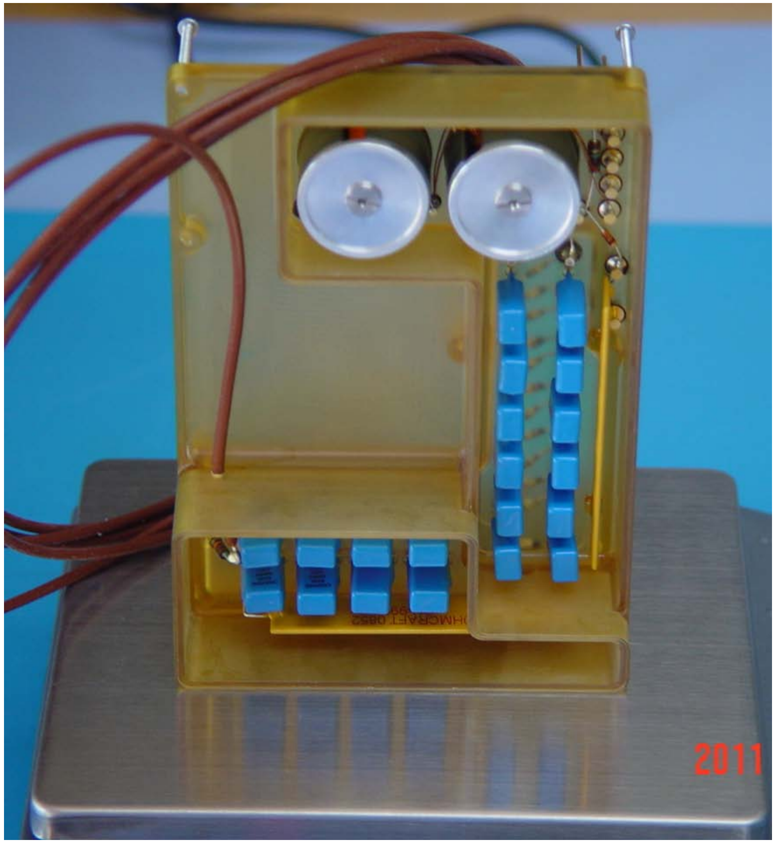
Preferred Engineering Plastics…

- *There are many engineering plastics although a few stand out as proven for use in flight applications. A combination of high service temperature, strength, low outgassing, surface bond strength and electrical properties are the determining factors in selection.*
  - ***G10- Useful for structural supports and intermediate grade insulation. Can be processed as a PC board for shield and related field control applications.***
  - ***ULTEM- Most useful combination of electrical and mechanical properties for enclosures, insulators and standard insulating parts. Good bonding and can be plated. Poor IZOD notch performance.***
  - ***PEEK- Good match to metals in structural applications. Bondable and can be made into screws. Also takes threads well.***
  - ***VESPEL- Best high voltage properties and good structural toughness but challenging to bond reliably.***
  - ***Kapton- Good bonding and electrical properties when used for tubing and spacers. Arc tracking is an issue in some applications.***

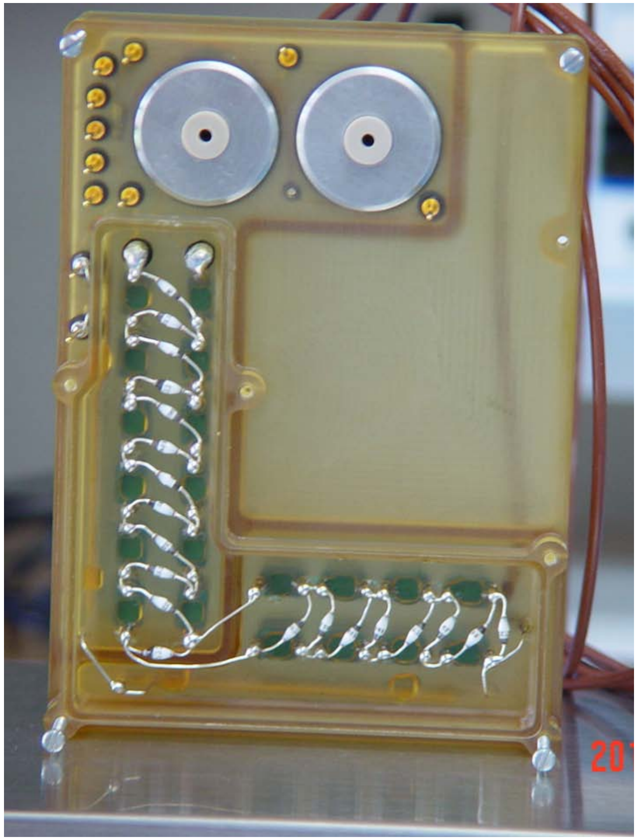
Never use oil when machining plastic materials. The surface is also porous so always wear gloves when handling.

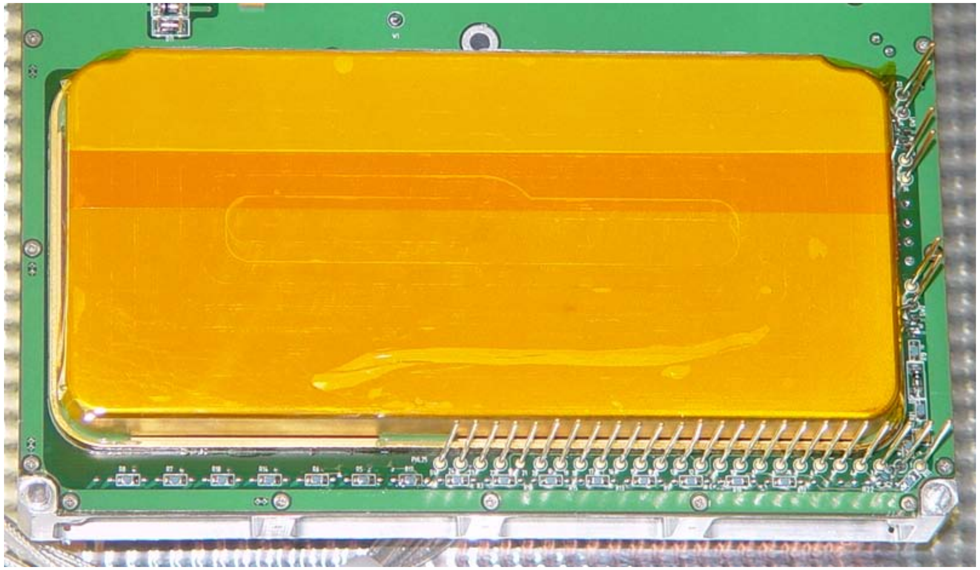
ULTEM Enclosure Example…





PEEK and ULTEM Applications…





ULTEM is readily gold plated making it especially useful in applications where triple-junctions must be avoided. This cover is also covered with Kapton tape.

Other Solid Insulating Materials… 1

- *Alumina (99.9% pure) and Beryllium Oxide (99% pure) have good thermal conductivity and can be plated to make excellent flat insulators or standoffs.* ***Glazing of alumina depends on the application but should not be used when potting or high performance coating is required****. High dielectric constant of alumina limits some applications.*
- *Sapphire and Ruby make great insulators especially as "ball" spacers. Can be ground into various shapes.*
- *MICA comes in many grades but is excellent as a very thin high performance insulator with good high temperature characteristics.* ***Use V-1 grade or synthetic for the best properties****.*
- *Macor is a machinable glass ceramic with reasonable properties. Generally harder to bond in potted cavities.*

Other Solid Insulating Materials… 2

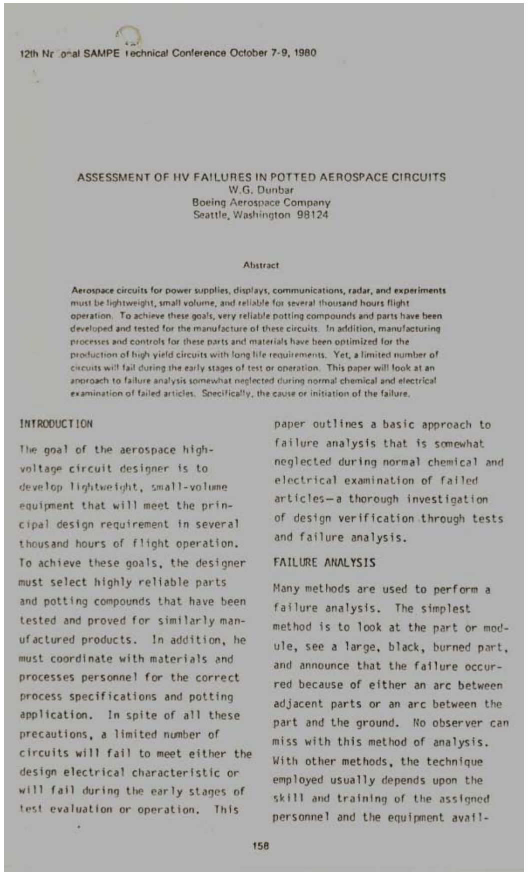
- Boron-Nitride is a hot-pressed material that can be machined or ground. Difficult to bond to. Exceptional electrical insulating properties and relatively low dielectric constant (~4) combined with very high thermal conductivity make it a superior insulator for ultra-high voltage and high power applications.
- Boron-Nitride powder can also be used as a thermally conductive electrically insulating filler in urethane and epoxy casting and potting applications. Difficult to bond and metalize so requires careful design.
- Castings using Stycast 2850 epoxy can be made with good properties.
- Polyimide (Kapton) has the best combined properties as an insulating film.
- Mylar film has superior insulating properties and has good conformal characteristics but has limited applicability due to temperature limitations.
- For GSE applications, Delrin and Teflon are commonly used due to their high performance at reasonable cost.

Epoxy Choices…

- *There are many preferred types of epoxy and epoxy manufacturers. Be a "GOO ROO" and make to know your materials. Also, make sure the supplier does not change the formulation.*
- *One important consideration is that structural epoxies like 3M 1838 or 2216 are not good high voltage epoxies due to the type of fillers used to achieve the combination of properties.*
- *Stick to unfilled epoxies (for impregnation or coating) and/or epoxies such at EC 2850FT that use an alumina filler.*
- *I generally use 2850FT with Cat 9 as for high voltage staking where high compliance is not required.*
- *3M 280 is an excellent unfilled low viscosity epoxy for transformer impregnation. Baking at 120C eliminates outgassing issues.*

Encapsulation Materials and Methods… 1

- *Requirement for reliable full voltage operation in air, very high voltages and/or volumetric efficiency (traded against mass) often forces a move to encapsulation.*
- *Hard epoxy encapsulation is possible in some applications but compliant insulation systems using urethanes or silicones are preferred.* ***Working temperature range of urethane is typically from -55C to +70C. Silicones can be used over a much wider range if properly formulated and applied.***
- *Work by Dunbar and other in the late 1970's led way to urethanes with EN-11 "Conathane" being the preferred material in most NASA systems (via Ruitberg at NASA and others).*



12th Nr onal SAMPE Technical Conference October 7-9, 1980

ASSESSMENT OF HV FAILURES IN POTTED AEROSPACE CIRCUITS

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Abstract

Aerospace circuits for power supplies, displays, communications, radar, and experiments must be lightweight, small volume, and reliable for several thousand hours flight operation. To achieve these goals, very reliable potting compounds and parts have been developed and tested for the manufacture of these circuits. In addition, manufacturing processes and controls for these parts and materials have been optimized for the production of high yield circuits with long life requirements. Yet, a limited number of circuits will fail during the early stages of test or operation. This paper will look at an approach to failure analysis somewhat neglected during normal chemical and electrical examination of failed articles. Specifically, the cause or initiation of the failure.

INTRODUCTION

The goal of the aerospace high-voltage circuit designer is to develop lightweight, small-volume equipment that will meet the principal design requirement in several thousand hours of flight operation. To achieve these goals, the designer must select highly reliable parts and potting compounds that have been tested and proved for similarly manufactured products. In addition, he must coordinate with materials and processes personnel for the correct process specifications and potting application. In spite of all these precautions, a limited number of circuits will fail to meet either the design electrical characteristic or will fail during the early stages of test evaluation or operation. This paper outlines a basic approach to failure analysis that is somewhat neglected during normal chemical and electrical examination of failed articles—a thorough investigation of design verification through tests and failure analysis.

FAILURE ANALYSIS

Many methods are used to perform a failure analysis. The simplest method is to look at the part or module, see a large, black, burned part, and announce that the failure occurred because of either an arc between adjacent parts or an arc between the part and the ground. No observer can miss with this method of analysis. With other methods, the technique employed usually depends upon the skill and training of the assigned personnel and the equipment avail-

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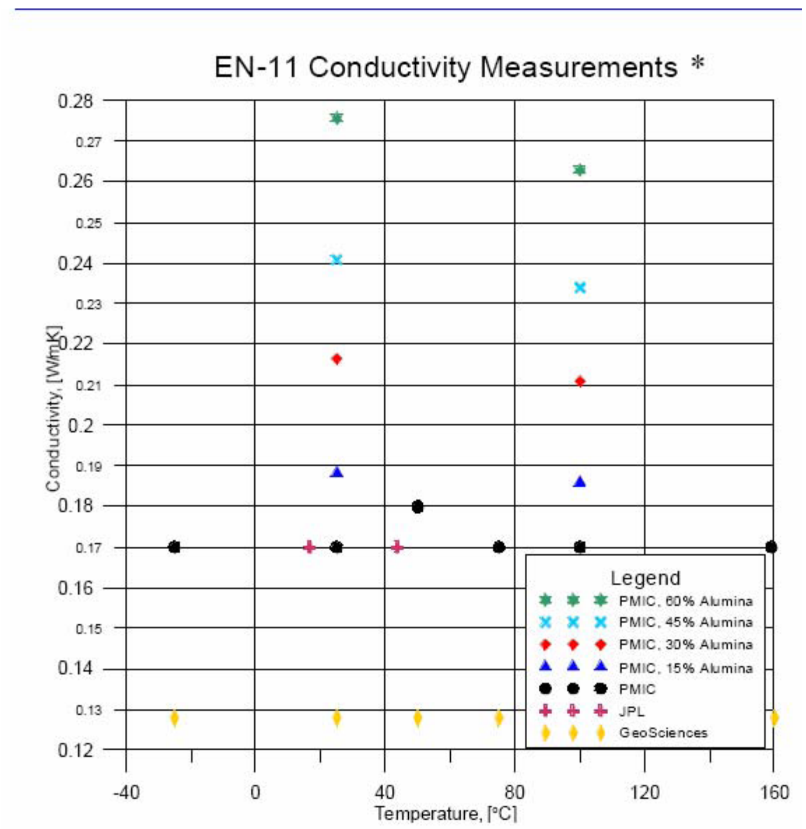
Encapsulation Materials and Methods… 2

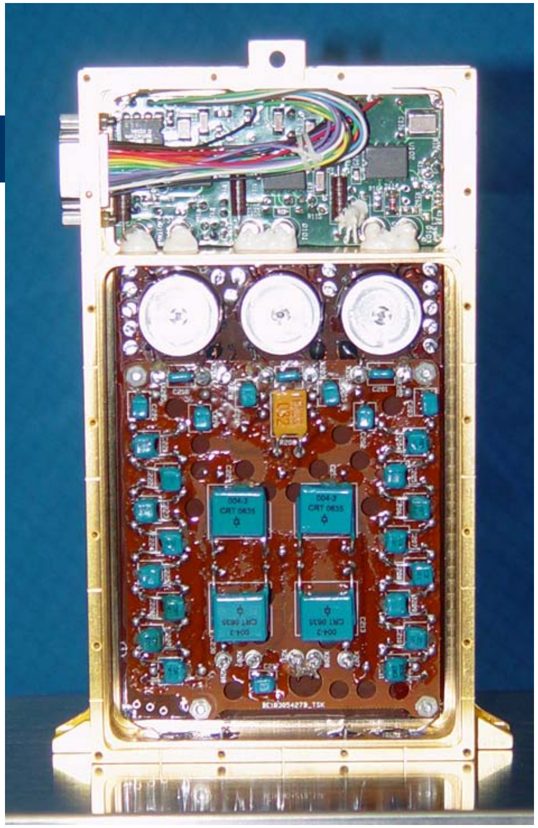
- *"Super" electrical insulators also turn out the usually be super thermal insulators leading to possible thermal problems in potted assemblies unless low power or mitigated through the use of thermal leaks or shunts.*
- *BN (30-40% BW)and other fillers such as Alumina add mass but can provide an effective thermal leak path.*
- *Aside from normal field dependent life effects, "hot spots" or thermal gradients can cause local field enhancements that lead to thermal breakdown or premature dielectric breakdown.*



Encapsulation Materials and Methods… 3

Encapsulation with EN-11 or any urethane material is a bargain with the devil- but is a devil that you know!

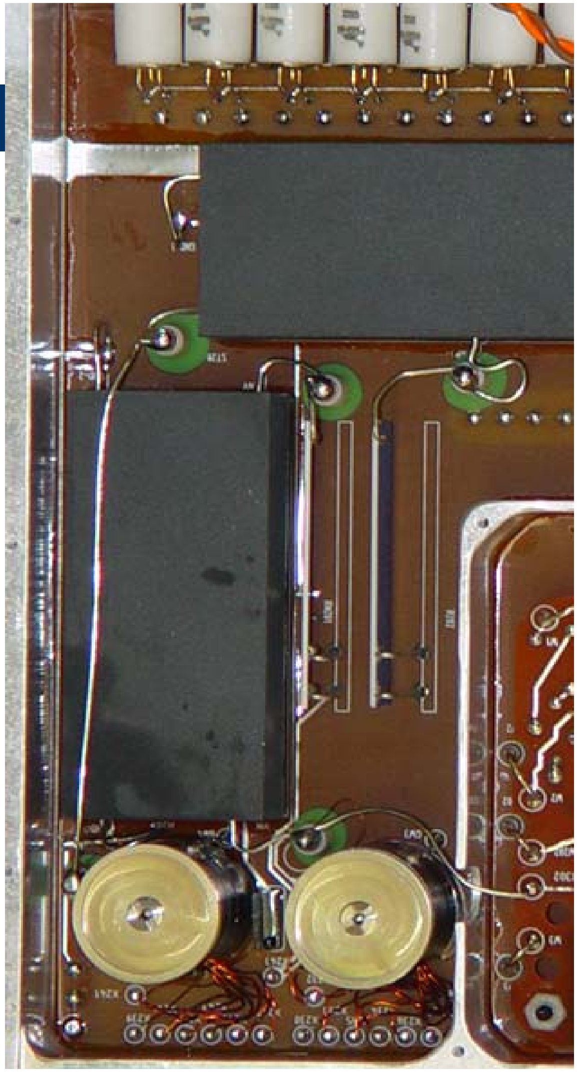
- Biggest challenges for most potting operations using EN-11 are achieving adhesion, preventing bubbles, curing for best properties plus minimizing impact of temperature and vacuum expansion.
- Urethane materials require careful surface preparation especially for bare metals (walls should be abraded) including wires and solder joints. Generally an epoxy primer is used.
- I generally brush apply Epon 828 with V25 catalyst. Use a pre-cleaned #1 camelhair brush. Apply only to metal surfaces taking care to not "freeze" small wires. Cure over night at ambient followed by 2-4 hours at 82C. Pot right afterwards for best adhesion due to cross-linking between epoxy and urethane.



Note the holes in the PC board to improve penetration and bubble removal. Plastic nuts are also removed on spacers to allow board to float in the potting.

Encapsulation Materials and Methods… 4

- *Beyond priming, an important part of the encapsulation process is to pre-align, bond and stake wires and components as required to assure that intended design spacing's are maintained.*
- *Wires should have strain relief to allow flexing in the unconstrained potting direction. Potting material will swell and apply pressure on wires, components and attachment points. Motion will be low deep in the potting and greatest near the surface.*



Note pre-screened high voltage multiplier modules used in this design.

Encapsulation Materials and Methods… 5

- *Bubble formation must be carefully managed through a combination of design to avoid deep cavities and virtual leaks, proper cleaning to ensure adhesion and bakeout to eliminate adsorbed water and residual solvents.*
- *Vacuum potting is always preferred but is not always possible (and is not perfect either). Since bubbles can form under any potting scenario, it is important to space components with at least 2 mm parallel or diverging gaps to assure bubbles will evolve upwards and not be trapped.*
- *If residual bubbles do occur and become frozen in the potted assembly, many times they are in areas that are not important. IF a bubble occurs that is a problem, it is possible to use a syringe injection method to fill the void (remember to make an exit hole!).*

Encapsulation Materials and Methods… 6

- *Once encapsulation is complete, a proper cure process is critical to achieving optimal electrical and mechanical properties.*
- *In general the best electrical properties occur with a 7 day room temperature cure followed by a 24 hour post-cure at the maximum temperature the unit will ever see.*
- *A high temperature cure at 60C (do not go higher) is also possible for some applications where mechanical properties including adhesion are dominant or where the resulting shrinkage can help with applying compression to certain components. The main issue with high temperature cures is that stresses are frozen into the material that tend to affect the cold temperature properties.*
- *If a hot cure is used, it is generally a good idea to use a progressive cure in 5C steps to prevent uneven curing where the outer walls cure ahead of the more insulated middle. A variable sure can result in an insulator with graded stresses.*

Encapsulation Materials and Methods… A few other helpful hints 1

- *Always do a leak test on a potted volume **prior** to the potting operation! Also take care to mask accounting for the bubble rise.*
- *Make sure to strip off any masking and do a careful cleanup prior to curing.*
- *Don't overfill the potting cavity. Swelling under vacuum and at hot temperatures will result in the material sticking to the lid!*
- *Think of the curing material as a crystal. Take care to not jiggle the unit curing cure and make sure the unit is level.*
- *Never use solder mask in a potted area.*
- *Inks can interfere with potting adhesion so limit the ink placement especially in critical areas or where the voltage gradient is high.*
- *In mass critical applications, it is possible to introduce intentional voids or use vented hollow elements to eliminate potting in unneeded areas.*
- *If there are outgassing concerns, the exposed potted surface can be shielded (also necessary for E-Field control in some applications) or Parylene coated (basically impermeable and very effective).*

Encapsulation Materials and Methods… *A few other helpful hints 2*

- *Always use fresh material for critical encapsulation processes. Even fresh material can come in looking milky so inspect your material carefully at each use. Never use a suspect batch and always do a material test run for critical potting operations.*
- *Since material generally comes in big cans, I generally break down a new batch into smaller cone top cans (minimized air volume) that are fully filled and then sealed with Teflon film under the cap. Make sure to mix each part thoroughly prior to breaking down into smaller batches.*
- *Each use will be from one can that is discarded unless used within 1-2 days.*
- *You can procure cans from House of Cans at* *http://www.houseofcans.com/cone_top_cans.html*

Encapsulation Example…

25 kV 6 Watt potting application using hot cured EN-11