High Voltage Engineering Techniques For Space Applications

Day 2 of 2

Steven Battel
NESC-Battel Engineering
www.battel-engineering.com

April 2-3, 2012

2 Day Timeline

Start time	DAY 1 TOPIC
0830	INTRODUCTORY STUFF
0845	GROUNDWORK FOR DISCUSSIONS
0900	APPROACH TO HIGH RELIABLE HIGH VOLTAGE SYSTEM DESIGN- PART 1
0955	**BREAK**
1005	APPROACH TO HIGH RELIABLE HIGH VOLTAGE SYSTEM DESIGN- PART 2
1120	**QUESTIONS/DIALOGUE**
1200	**LUNCH**
1300	OVERVIEW OF HIGH VOLTAGE COMPONENTS AND TECHNOLGIES
1330	HIGH VOLTAGE CAPACITOR TUTORIAL
1350	HIGH VOLTAGE RESISTOR TUTORIAL
1405	HIGH VOLTAGE CONNECTORS AND CABLES
1440	**BREAK**
1450	**QUESTIONS/DIALOGUE**
1535	HIGH VOLTAGE INSULATORS AND ELECTRIC FIELD CONTROL TECHNIQUES
1635	E-FIELD ANALYSIS METHODS AND SOFTWARE
1700	**QUESTIONS/DIALOGUE**
1730	**RECEPTION**
1900	**ADJOURN**

Start time	DAY 2 TOPIC
0830	INTRODUCTORY STUFF
0840	LEIDECKER ON WIEBULL METHODS
0900	HENNING LEIDECKER'S GALLERY OF FAILURES
0915	SYSTEM DESIGN CHOICES- PART 1 - CLEANING AND CONTAMINATION - VENTING CONSIDERATIONS - CHOICE OF INSULATING MEDIA - PREFERRED ENGINEERING PLASTICS - OTHER SOLID INSULATING MATERIALS - ENCAPSULATION METHODS
1015	**BREAK**
1025	SYSTEM DESIGN CHOICES- PART 2 - SHIELDING APPROACHES - INSULATING COATINGS - GROUNDING APPROACHES - PC BOARD DESIGN CONSIDERATIONS - HIGH VOLTAGE SOLDER JOINTS - PACKAGING AND CONSTRUCTION
1135	ELEMENTAL DESIGN APPROACHES- PART 1 - OSCILLATOR DESIGN
1200	**LUNCH**
1240	ELEMENTAL DESIGN APPROACHES- PART 2 - MAGNETICS DESIGN AND MANUFACTURE - HIGH VOLTAGE MULTIPLIER DESIGN - MONITOR AND FEEDBACK APPROACHES - REGULATORS AND MODULATORS - OUTPUT FILTER DESIGN APPROACHES - OUTPUT TERMINATION APPROACHES - HIGH VOLTAGE CABLES - MATCHING UP TO THE "USER" END - "SHRINKING" A DESIGN
1515	**BREAK- EARLY ADJOURN POINT**
1530	**QUESTIONS/DIALOGUE**
1600	MEASUREMENT METHODS
1630	OTHER IMPORTANT STUFF - RADIATION EFFECTS - GSE AND SIMULATOR DESIGN - SAFETY IS ALWAYS FIRST - SUMMARY THOUGHTS - PLANNING FOR OCTOBER
1730	**QUESTIONS/DIALOGUE**
1800	**ADJOURN**

Introducing Dr. Henning Leidecker on the Use of Weibull Methods to Quantify System Reliability

Use of Weibull Methods to Quantify System Reliability

- Three definitions of Reliability: R-1, R-2, R-3
- Failure measures: cumulative, density, hazard
- The Weibull distribution: definitions
- The Weibull distribution: why?
- The Weibull distribution: how?
- The Weibull distribution: literature?
- The Weibull distribution: examples

Three definitions of Reliability

- Reliability-1: The system *CANNOT* fail – this would be ideal, but it is "un-obtainium".

- Reliability-2: The probability that the system meets its specifications for the entire mission. This is the definition used by most professionals.

- Reliability-3: The system supports a "probability" approach. But this is not the case for one-off systems, or for many COTS systems.

Failure measures -- Reliability-2: pt A

- The probability of failure between "t=0" and "t" is the **cumulative failure distribution**:

  $F(t) = \int_0^t f(t') \, dt'$, where
- The **density** of failure at "t" is $f(t) = dF/dt$.
- The probability of NO failure between the starting time "0" and the time "t" is

  $P(t) = 1 - F(t)$.
- The normalized rate of failures at "t" is the **hazard**, also called simply the failure rate:

  $H(t) = f/P = (dF/dt)/P = - d\,[\ln(P)]/dt$.

Failure measures -- Reliability-2: pt B

- These measuring functions can each be computed from any other:

  $f = dF/dt = - dP/dt = H \cdot \exp[-\int_0^t H(t')\, dt']$,

  $F = \int_0^t f(t')\, dt' = 1-P = 1-\exp[-\int_0^t H(t')\, dt']$,

  $P = 1-\int_0^t f(t')\, dt' = 1-F = \exp[- \int_0^t H(t')\, dt']$,

  $H = f/[1-\int_0^t f\, dt'] = (dF/dt)/(1-F) = - d[\ln(P)]/dt$.

- Therefore, each of these measuring functions contains the same information as any other.

Failure measures : a generalization to other stresses, and two commonly-met distributions -- Weibull and log-normal

- The time “t” in the failure distribution can often be replaced by some other measure of “stress”, such as: temperature, voltage, mechanical load, or the number of cycles of application of the loading stress.
- “About 85%-95% of all life data are adequately described with **Weibull probability plots**. About 85%-95% of all repair times are adequately described by **log normal probability plots**.” Quoted from:

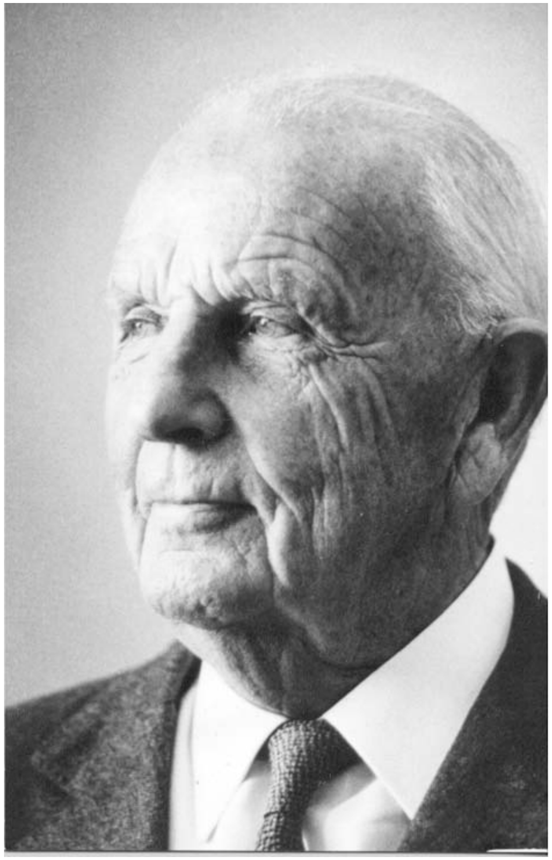
  http://www.barringer1.com/tnwhb.htm

The Weibull distribution: definitions

- $P(t) = \exp[- (t/\eta)^{\beta}]$
- $F(t) = 1 – \exp[- (t/\eta)^{\beta}]$
- $f(t) = (\beta/\eta)\cdot(t/\eta)^{[\beta-1]}\cdot\exp[- (t/\eta)^{\beta}]$
- $H(t) = (\beta/\eta)\cdot(t/\eta)^{[\beta-1]}$

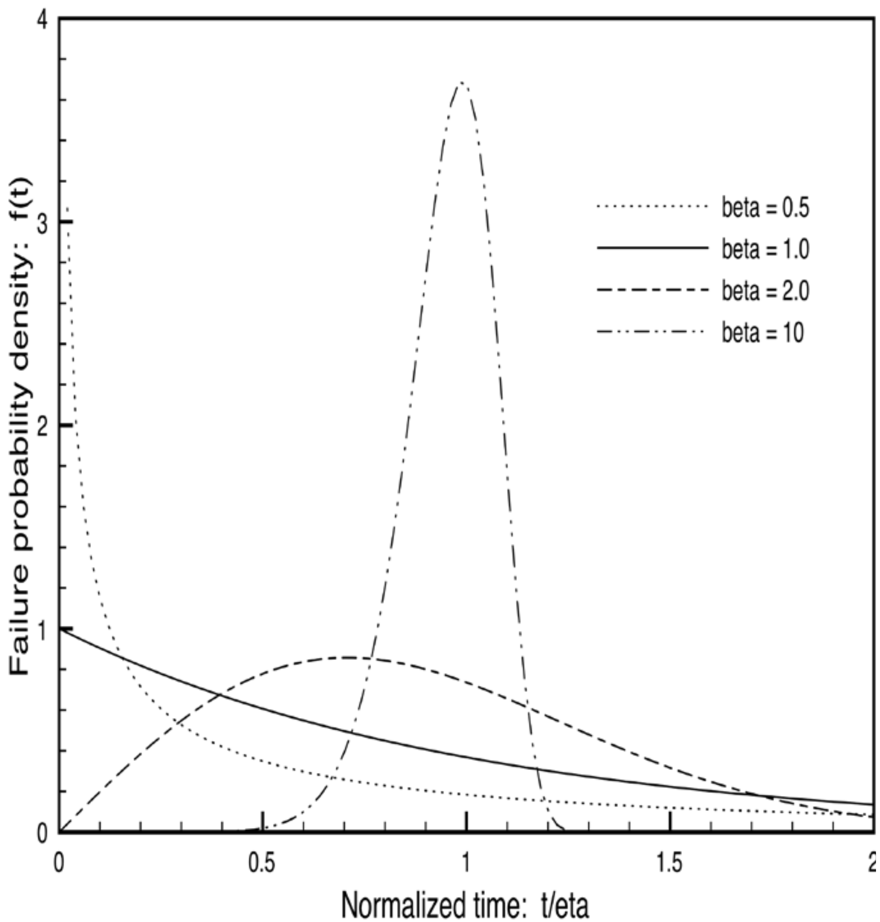
where

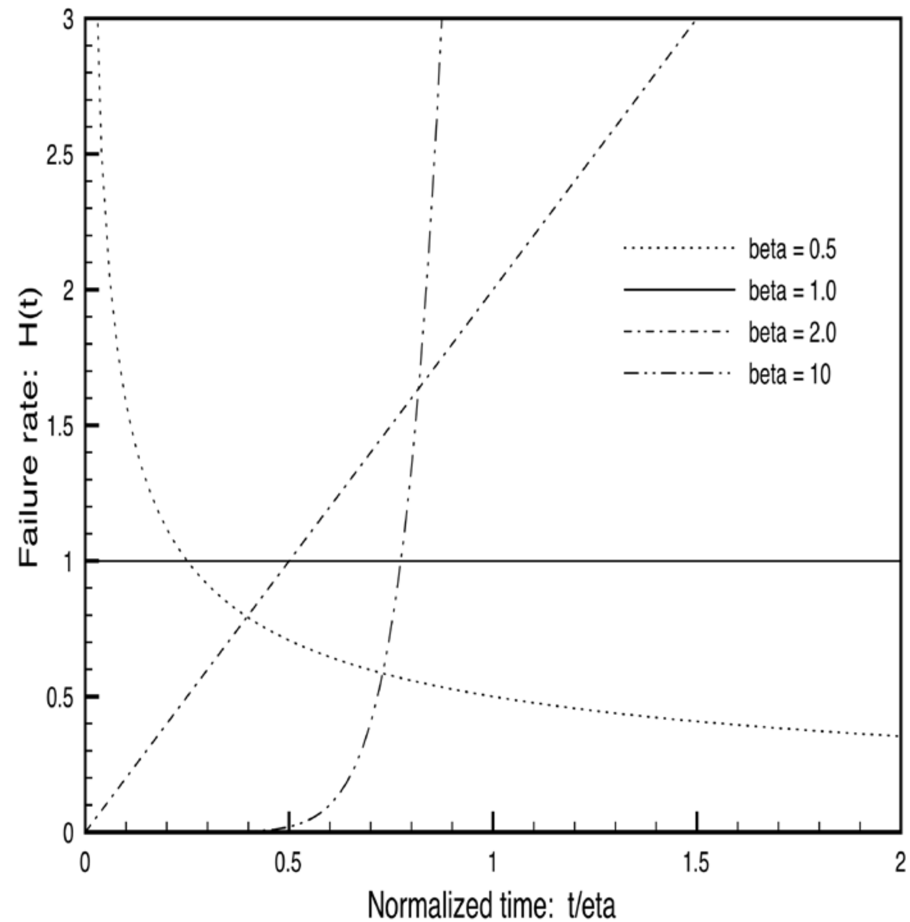
η is the 'time-scale' parameter, and
β is the 'shape' parameter.



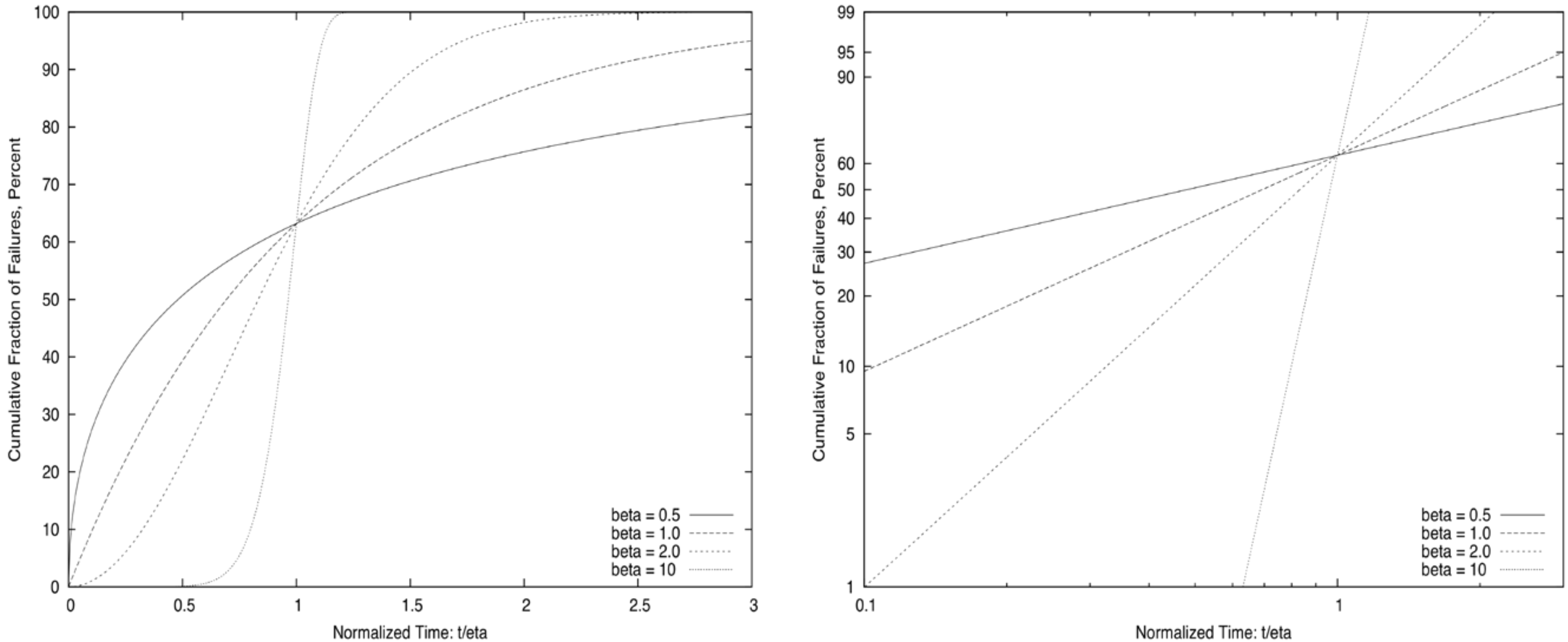
Dr. E. H. Waloddi Weibull

The Weibull distribution: plots A





The Weibull distribution: plots B



Who does not like a straight line?
But we have to plot “log(-log(1-C)) versus log(t)” to get that straight line.

The Weibull distribution: **β**

- β -- the shape parameter -- tends to have about the same value when the same physical process is causing failures, even when the stress level changes so that the time-scale factor η changes.
- β < 1: ‘infant mortality’, allowing such practices as ‘established reliability’ parts, such as solid tantalum capacitors.
- β = 1.0: Constant Failure Rate – the base assumption of MIL-HDBK-217 and of some major aerospace companies.
- β = 2.0: approximately ‘normal’ distribution – now used for time-to-burnout of W-lamps
- β > 2: strong ‘wear out’ – dielectric breakdown, HST gyros.

The Weibull distribution: **η**

- η is the time-scale parameter. It directly gives the time at which the cumulative number of failures reaches ~ 63%, and it allows computation of the other measures of the "typical" time-to-failure. It increases as the applied stress-level decreases, and reciprocally.

- Mean = $\eta \cdot \Gamma(1 + 1/\beta)$
  where Γ is the gamma function.

- Median = $\eta \cdot [(\ln 2)^{(1/\beta)}]$ = the time when the cumulative number of failures reaches 50%.

The Weibull distribution: Why?

- “A statistical distribution function of wide applicability”, W. Weibull, 1951.

  This is the paper, with its seven distinct failure examples, each well-fit by a Weibull distribution, that launched the present recognition of its usefulness. It has wide applicability because it has two wisely-chosen fitting parameters, η and β.

- “On the probability distribution of the maximum deviation”, M. Frechet, 1927.

  This shows the reason for the wide applicability of the Weibull distribution: it applies to situations in which a system of many parts fails when its weakest part fails; thus, it applies to the failure of a chain made of many link. Canonical example: a chain of many links.

The Weibull distribution: How?

- Collect the time-to-failure list: t(i) for i=1 to N.
- Sort into ascending order: t(j) for j=1 to N.
- Make Bernard's correction: k = (j-0.3)/(N+0.4).
- Plot "log(-log(1-k))" versus "t": I use "octave", but many **use "Weibull-smart" software**.
- Interpret the plot. **Experience helps.**

The Weibull distribution: learning!

- “The New Weibull Handbook” 5th edition, 2006 with updates in ‘07, ’08, ‘09, & ’10; by Dr R. Abernethy. I urge you to get a copy! See http://www.barringer1.com/tnwhb.htm
- Visit http://www.weibullnews.com

  or send Email to Wes Fulton at Wes@weibullnews.com

  Wes writes WinSMITH Weibull and WinSMITH Visual software to support “The New Weibull Handbook”.
- Visit http://www.weibull.com/ which has some 6,000 pages for you to explore.

More: Henning Leidecker on "High Voltage Lessons Learned"

Alternative Title:
"Why I Will Always have a Job at NASA!"

Some Power Supply Adventures…

Why a failure analyst will always have a job!

Factors that affect Reliability-2

- **Design intent** as hoped for, and as claimed in the **product specifications**.
- **Architecture** chosen to get the design intent.
- Choice of **materials**.
- Choice of **assembly methods**.
- Choice of **checking** materials & assembly
- Performance: **qualifications** & **screens**.
- Checking the performance that has been demonstrated ‘**in the field**’.

Thermal Runaway

- Thermal runaway of diodes, caused by a "reverse recovery time" that was large, and grew larger with increased temperature has destroyed three power supplies that I know of, but not until exposure to Thermal-Vaccum testing, very close to launch!
- Landsat 7 had to replace several hundred diodes.
- An earth-observing satellite had to replace all the ladder-diodes in a high-voltage supply.
- A high-voltage supply designed to power an ion-thruster had to replace its ladder-diodes.

Delayed failure of pw-boards

- The slow growth of conductive filaments within pw-boards has destroyed two power supplies that I know of.
- The Fermi Gamma-ray Space Telescope – badly made pw-boards got eliminated by a perceptive screen; then, the manufacturing process got improved. No further failures, up to now, four years after launch.
- A communications satellite for NASA: total destruction followed shorting, with a 50 V bus driving about 1,000 A thru a metal vapor arc. Placing ground and power planes next to each other, with 5 mil-thick polyimide laminate (dropping to 3.9 mil in places) did not provide enough margin against flaws induced in the construction of the pw-boards, that allowed conductive filaments to grow into bridging shorts.

Paschen Effects

- Bubbles in potting material!
- CALIPSO laser shorted as the pressurized container leaked down – lost the extra life it was otherwise capable of delivering.
- Three of six of the ICESat photomultiplier tubes shorted to death during vacuum testing: the potting material applied to the pins was shaped as a cap, rather than being solid, and provided pin-to-pin shorting paths as the air pressure slowly dropped.

Metal Whiskers of Tin, Zinc, and Cadmium have caused shorting events and arcing events!

- Several com-sats have lost all power thru metal vapor arcs caused by metal whiskers: some of tin and some of zinc.
- A possible cause of the ‘soft shorts’ seen in the CAPS instrument on the CASSINI spacecraft
- Space Shuttle OV-105, Endeavour.
- Electrostatic attraction is important.
- See also FM-08 style fuses.

Deep-level Dielectric Charging

- WMAP: plasma events in transmission lines with Teflon dielectric, having some length outside hull, and connected to the 2,000 within-hull FETs, each with 0.75 V breakdown. The multiple trips thru Van Allen belts needed to get to L2 presented a risk of plasma-events within the cables, that could destroy the FETs.
- Lichtenberg figures induced in clear dielectric materials used as lenses: fused silica, others.

Unscreened Parts, thought to be screened.

- Schottky diodes were obtained as die, screened for acceptable forward current at selected values of forward voltage, and at selected values of reverse voltage, and for an acceptbly robust value of “reverse breakdown”.
- However, the urgently-important “reverse energy test”, which screens out the ~ 0.1% to 1% of the die with crystalline defects, cannot be applied at the die level; rather, it can only be applied after solid metal tabs are firmly attached.
- The need for, but the absence of, this “reverse energy test” was not recognized by the manufacturer, and **so the customer was the one to carry out these screens**.

Silver-loaded Epoxy "out of place"

- A power supply manufacturer mounted an opto-coupler using conducting epoxy (silver-loaded). This mixed with the staking epoxy applied under the part: the silver particles almost bridged (perhaps there were units where this happened by burn-in, and these units were eliminated).
- Over months to several years, silver-migration under the steady E-field completed the shorting, and disabled the voltage-regulation of the unit, whose output went from a regulated 15 V to the 28 V rail.

Bulging Lids

- Package-lids were welded onto package-boxes: this sealed in dry nitrogen at an atmosphere of pressure.
- The lid had a few mils of clearance with the tops of magnetics and other devices, and PIND testing would excite collisions between the vibrating lid and these 'tall poles', prodding a PIND-failure. So blobs of resin were applied to tops of the 'tall poles' to prevent banging together.
- When the units were placed into vacuum, the lids bulged upward, and applied an upward pull on these tall poles: sometimes, this ruptured elements. In some cases, the ferrite cores would be separated, reducing magnetic coupling efficiency, and causing the regulator in the unit to call for more drive (inducing a substantial increase in current required by the unit); in other cases, solder joints were ruptured.
- These events were seen in ground testing, and subsequent de-lidding showed this mechanism operated.
- This also happened to a unit powering the HST Advanced Camera System, and was confirmed when astronauts returned the power unit and it was inspected.
- One fix has been to bond a 'doubler' lid onto the original: this has worked.
- Another fix has been to apply a Teflon liner to the inside of the lid so that an upward motion will separate the lid from the resin-pads on the 'tall poles': this Teflon lid has been seen to curl its ends about, and break an internal bond wire.

Misbehaving Capacitors

- Various instances of output filter capacitors shorting -- some solid tantalums, some plastic film dielectrics, and various choices of stacked capacitors killed by frame-stresses.
- GSFC experienced two solid tantalum capacitor failures in the same month: different projects, but same supplier. This “could not happen”, and mandated an inspection of the manufacturer, which showed that the screening used to establish the reliability had mis-carried, and was not eliminating weaklings! There have been no failures after establishing a correct screen.
- A line of commercial power supplies showed a 20% failure rate during our burn-in. Repeating the burn-in on the survivors showed (again) a 20% failure rate. A review of the company’s own burn-in yield of this lot showed a 20% failure rate. Hence, these supplies showed a constant failure rate under burn-in: the screen was not helping! DPA showed shorted filter capacitors, probably from soldering these into place at too-high a temperature for the particular plastic used as the dielectric.
- Stacked ceramic capacitors, when “home built”, have a history of failing from the stresses imposed by the rigid “stacking” frame and the CTE effects of the soldering.

Negative Resistance → Oscillations

- We have encountered “front-end” oscillations of regulated power supplies that are induced by a bad combination of 'negative dynamic input impedance' and 'too much inductance' in regulated supplies.
- The regulation means that the input current has to increase as the input voltage decreases, and so the dynamic input resistane R_dynamic = dV/dI is negative.
- In an input circuit with inductance and capacitance, this negative dynamic resistance can cause an oscillation: this has happened on numerous occasions, often on the launch pad when the spacecraft is supplied thru 1,000 foot long cables.

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

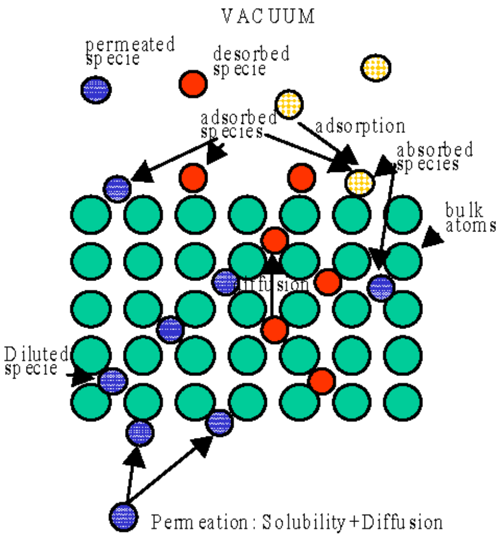
- *Pure Nylon (Zytel 101 trade name), FEP and PTFE Teflon, and Mylar (polyester) sheet or film have no plasticizers.*
- ***2 mil Teflon film material is a good choice**.*
- *Never handle plastic parts or ceramic parts with bare fingers.*
- *Protect against re-introduction of plastic or metal particles (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.*

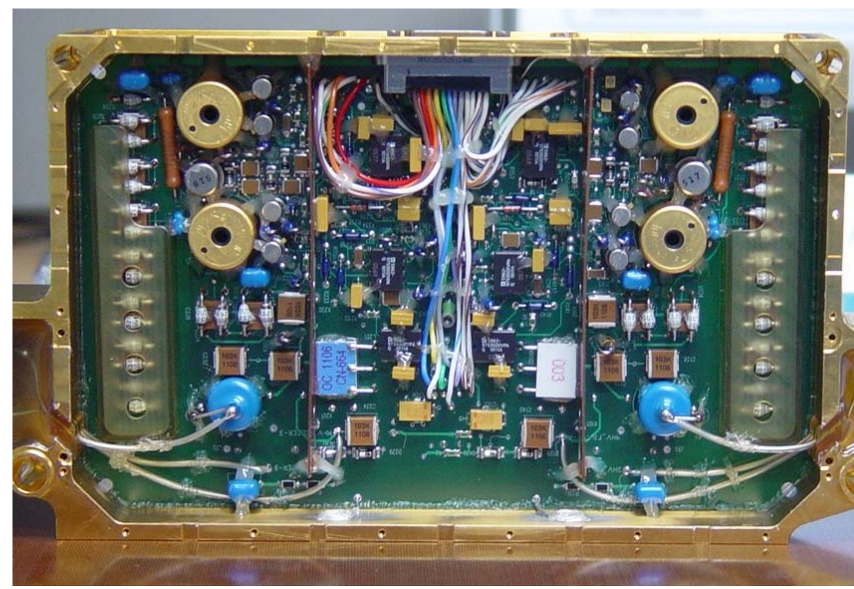
Venting Considerations… 2

- *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*

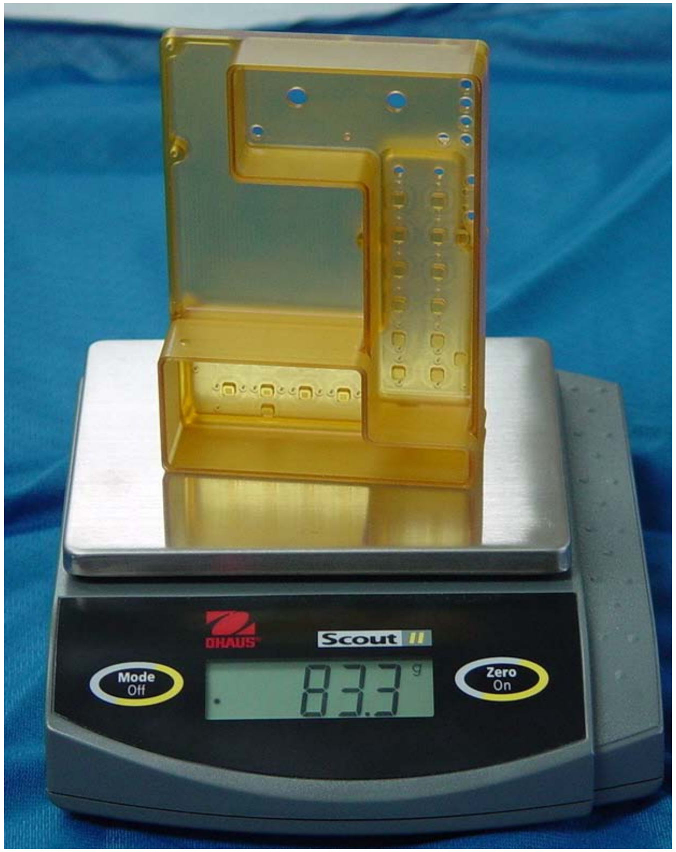
Commercial Ident.	Material/ Spec.	Manuf.	Processing Parameters	Application
Kapton Tape CHR K102	Polyimide	CHR	Tape Insulation	
Uralane 5750-A/B (LV)	Polyurethane Conf. Coating	Huntsman	2 part mix; thin with Tolulene+MEK Per GSFC MPD-313-008	PC Board Coating
Uralane 5753-A/B (LV)	Polyurethane Thixotropic	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

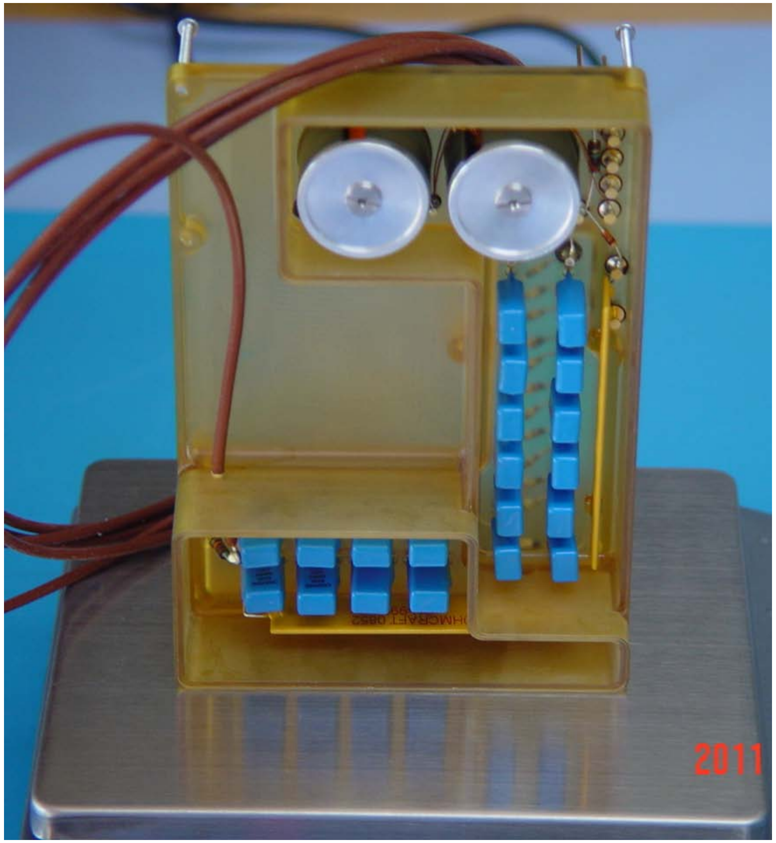
Preferred Engineering Plastics…

- *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.***

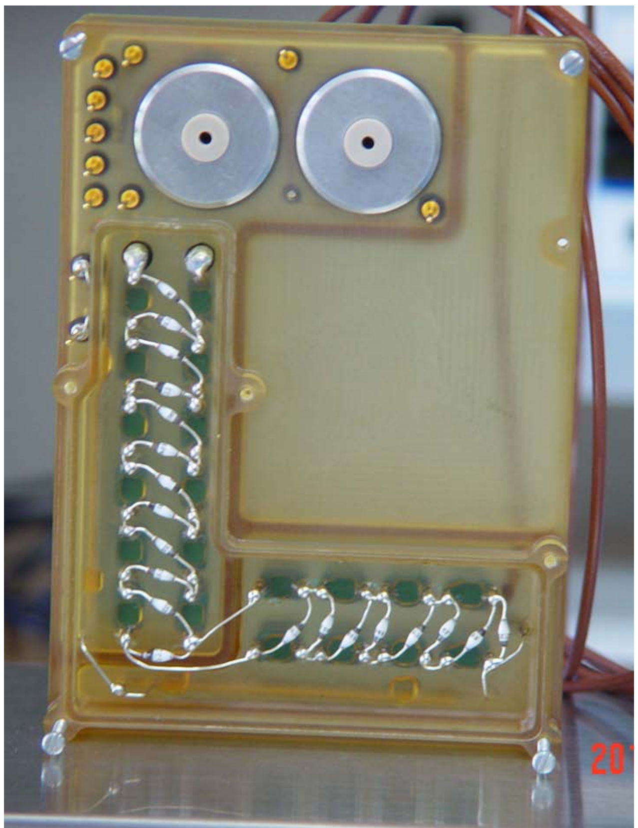
Never use oil when machining plastic materials. The surface is also porous so always wear gloves when handling.

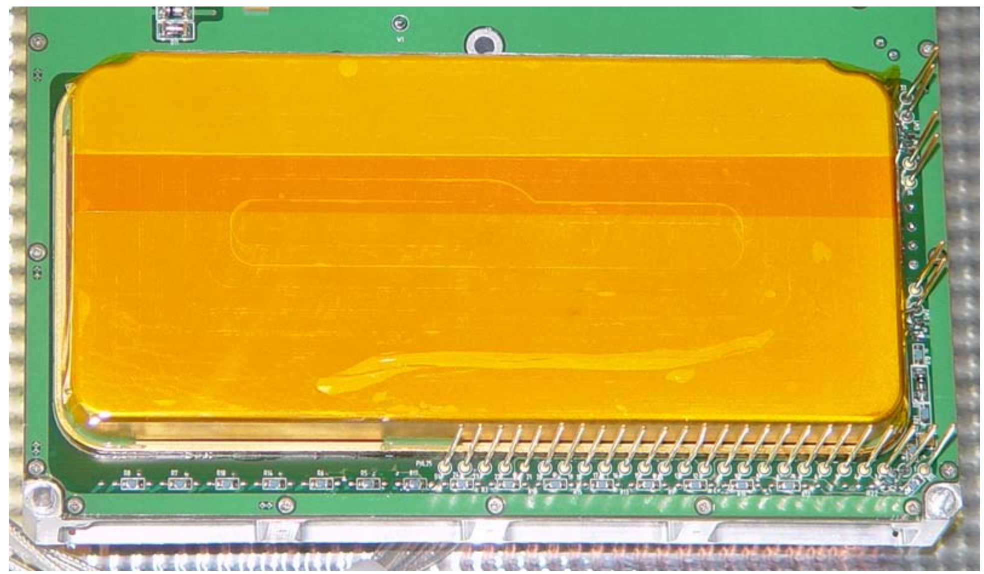
ULTEM Enclosure Example…





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

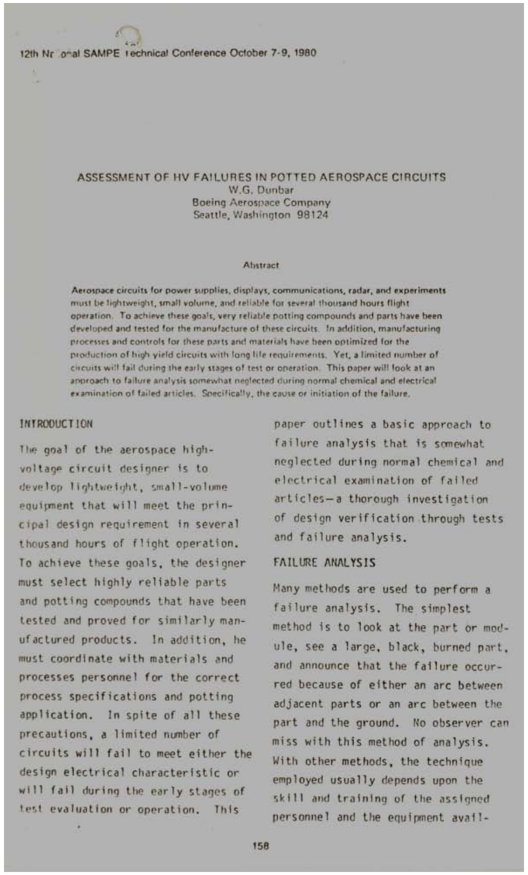
- *Boron-Nitride is a hot-pressed material that can be machined or ground. Difficult to bond to. Exceptional electrical insulating properties and relatively low dielectric constant (~4) combined with very high thermal conductivity make it a superior insulator for ultra-high voltage and high power applications.*
- *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 o al SAMPE echnical Conference October 7-9, 1980

ASSESSMENT OF HV FAILURES IN POTTED AEROSPACE CIRCUITS

W.G. Dunbar
Boeing Aerospace Company
Seattle, Washington 98124

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.

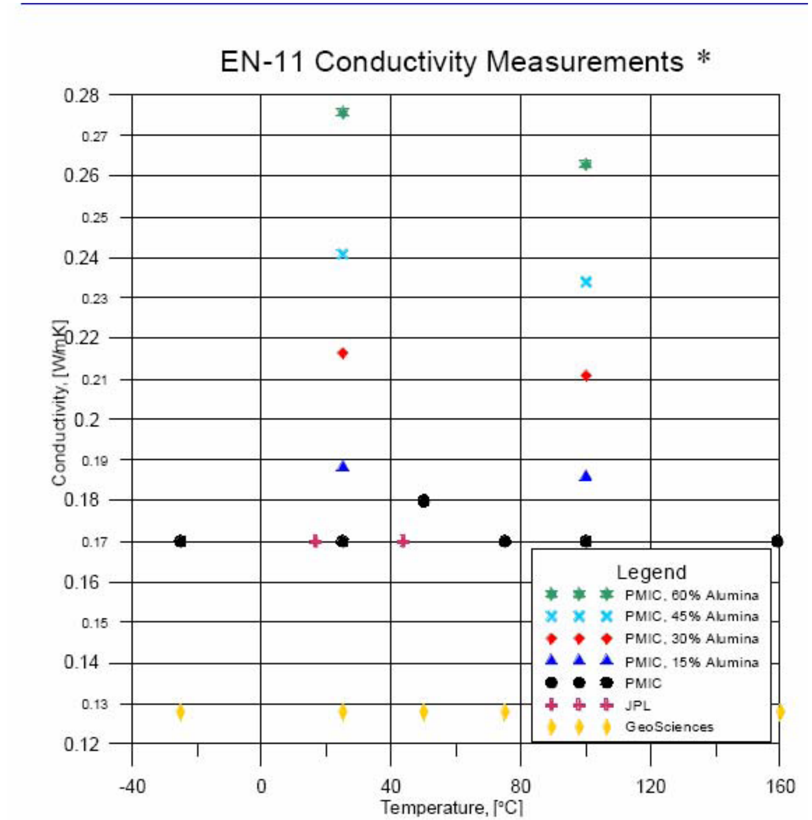
FAILURE ANALYSIS

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-

158

Encapsulation Materials and Methods… 2

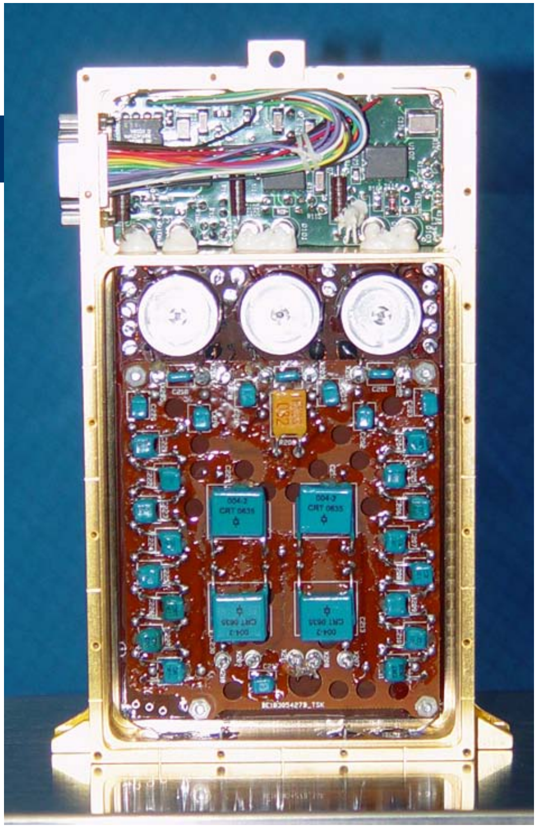
- *"Super" electrical insulators also turn out the usually be super thermal insulators leading to possible thermal problems in potted assemblies unless low power or mitigated through the use of thermal leaks or shunts.*
- *BN (30-40% BW)and other fillers such as Alumina add mass but can provide an effective 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!

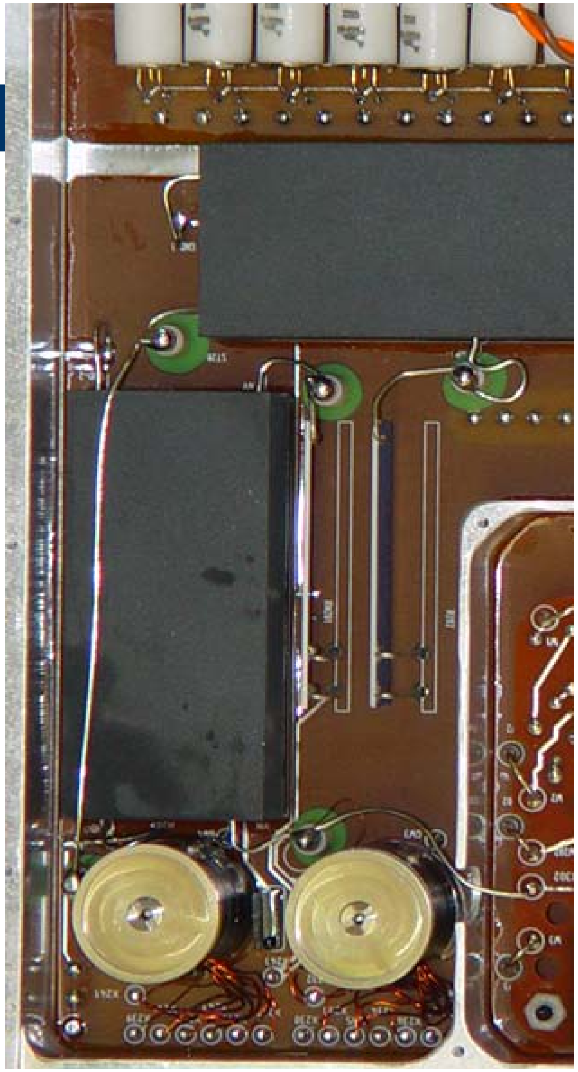
- *Biggest challenges for most potting operations using EN-11 are achieving adhesion, preventing bubbles, curing for best properties plus minimizing impact of temperature and vacuum expansion.*
- *Urethane materials require careful surface preparation especially for bare metals (walls should be abraded) 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

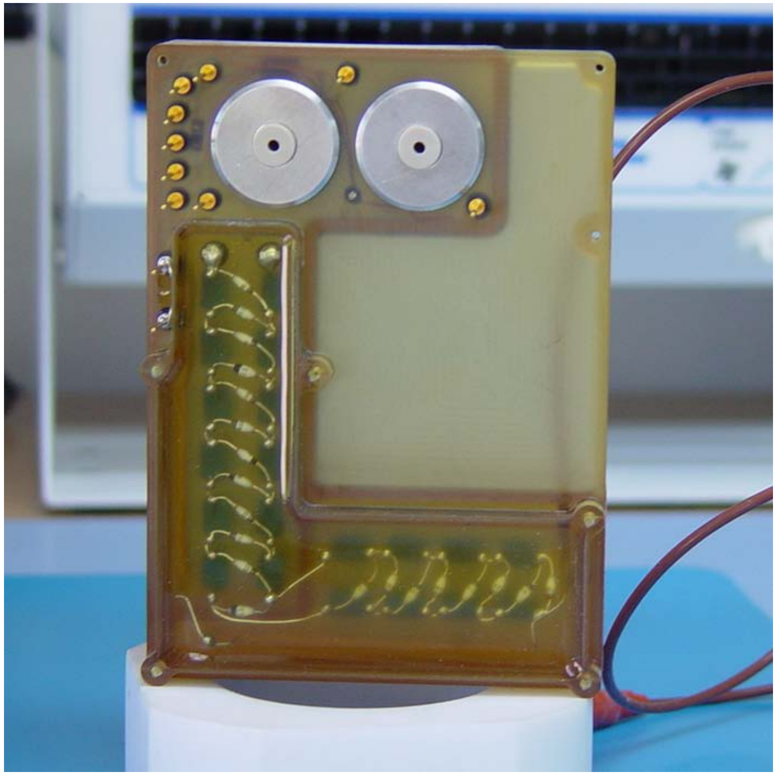
- *Always do a leak test on a potted volume **prior** to the potting operation! Also take care to mask accounting for the bubble rise.*
- *Make sure to strip off any masking and do a careful cleanup prior to curing.*
- *Don't overfill the potting cavity. Swelling under vacuum and at hot temperatures 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).*

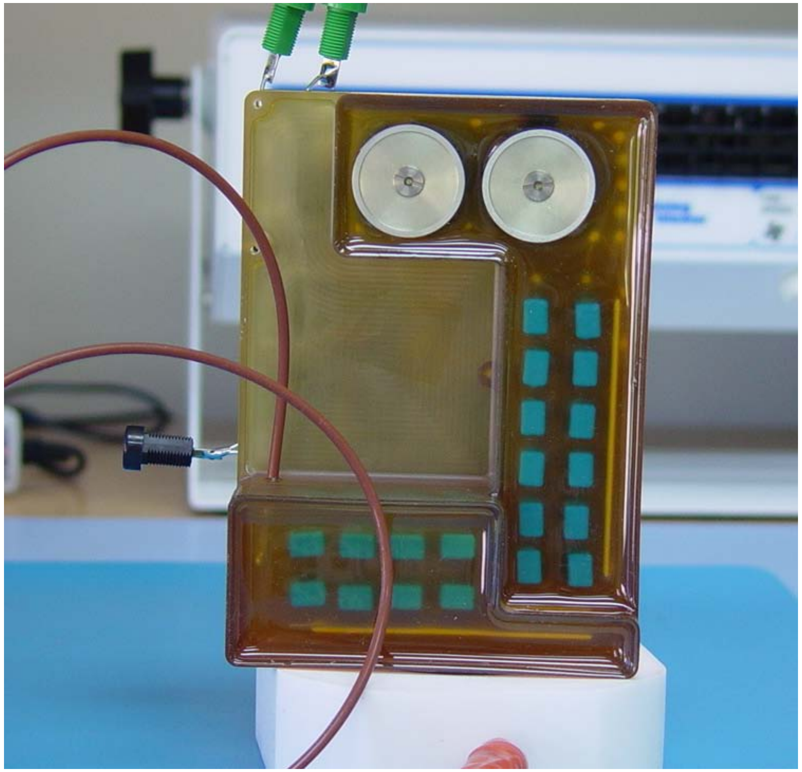
Encapsulation Materials and Methods… *A few other helpful hints 2*

- *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…

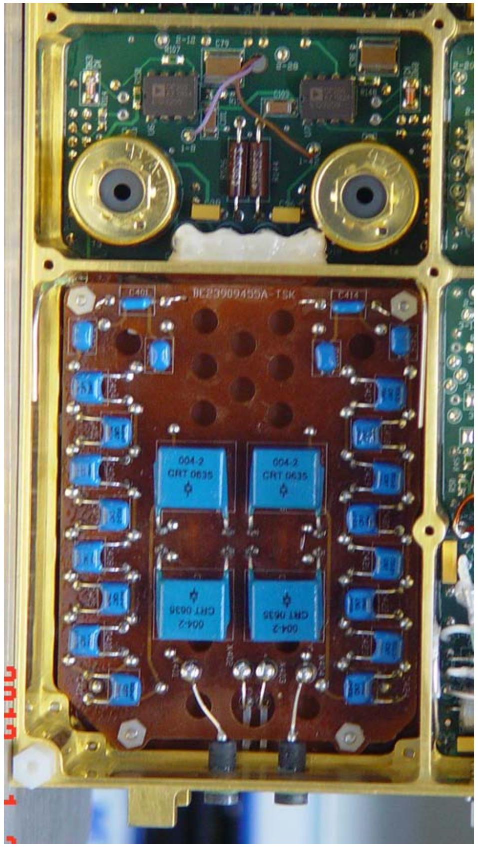
25 kV 6 Watt potting application using hot cured EN-11

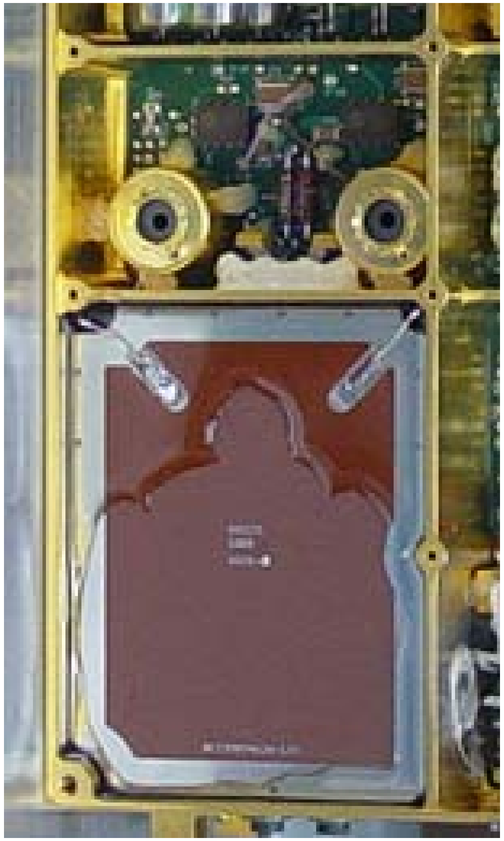




Shielding Example…

- *Many applications require a shield installed over the potted area for E-Field control and/or environmental isolation.*
- *This application for MAVEN shows the primed unit in Phase-1 test and the final potted and shielded unit in Phase-2 test.*
- *For this application the shield is applied after the initial pot and cure.*

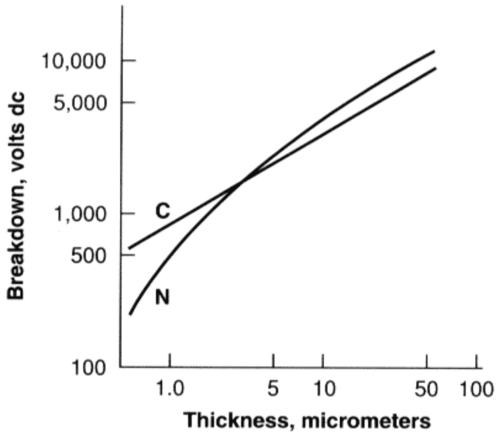




Insulating Coatings… 1

- *Solder mask is NOT a high voltage coating since there is no process control of voids and pin holes. It does offer the advantage of doing testing in air without supplementary insulation for parallel traces with voltages under 1000 volts and can be used if the insulation properties are not critical in the application.*
- *In critical applications it is better to leave the board bare in high voltage trace areas and then use a brush-on coating. Solder mask can be used under Parylene although in most cases I prefer to coat the bare board for high voltage applications.*
- *If properly applied, conformal coating can be effective in many applications for both field reduction at the surface of a conductor and to prevent both corona and flashover. I prefer using un-thinned EN-11 in one coat applied by brush to pre-baked surface although 2-3 Arathane coatings of surfaces also works okay.*
- *Parylene-C and -N (–C is the best all around coating except for exceptional high voltage applications) applied via gas deposition is the absolute best dielectric coating due to its 50L/1D penetrating ability, hydrophobic nature, void-free deposition, good adhesion and superior insulating properties.*

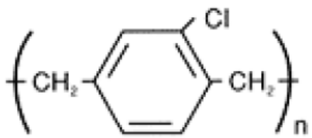
Insulating Coatings… 2



Properties (1)	Parylene N	Parylene C	Parylene D	Epoxides (2)	Silicones (2)	Urethanes (2)
Dielectric Strength, dc volts/mil short time, 1 mil films[a]	7,000	5,600	5,500	-	-	-
corrected to 1/8 in	630	500	490	400-500	550	450-500
Volume Resistivity, ohm-cm, 23 °C, 50% RH[b]	1.4×10^{17}	8.8×10^{16}	1.2×10^{17}	10^{12}-10^{17}	10^{15}	10^{11}-10^{15}
Surface Resistivity, ohms, 23 °C, 50% RH[b]	10^{13}	10^{14}	10^{16}	10^{13}	10^{13}	10^{14}
Dielectric Constant[c] 60 Hz / 1 KHz / 1 MHz	2.65 / 2.65 / 2.65	3.15 / 3.10 / 2.95	2.84 / 2.82 / 2.80	3.5-5.0 / 3.5-4.5 / 3.3-4.0	2.7-3.1 / 2.6-2.7 / 2.6-2.7	5.3-7.8 / 5.4-7.6 / 4.2-5.2

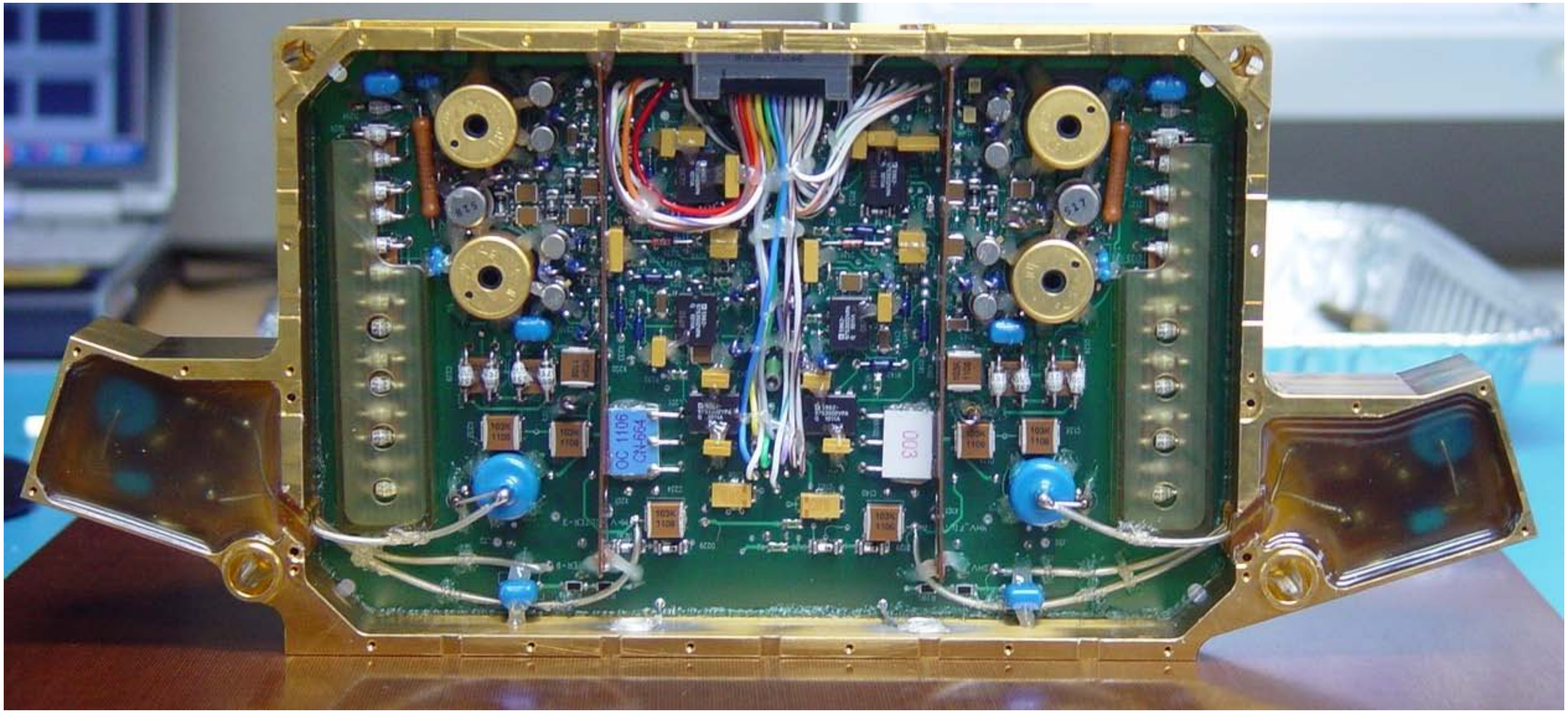
1 mil is 25 um
1.5 mils is 37 um

Parylene Coating Design Considerations… 1

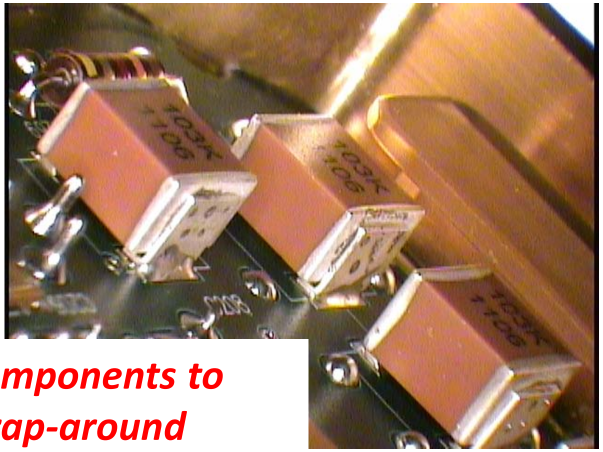


- *Note that Parylene is NOT a way to save a mediocre design but does provide an opportunity for achieving designs that can operate in air and vacuum at higher voltages than is possible using standard non-potted techniques.*
- *-N has modestly better electrical properties but –C is easier to apply, is pinhole-free and is the most hydrophobic. Thus, -C is preferred for most applications, especially if good properties are desired in air operation as well as vacuum.*
- *Parylene coatings require special design considerations to assure proper coating and expected performance. Most important is to design parts with spacing's that assure full coating around the entire part.*
- *Careful and absolutely impermeable masking is essential due to the penetrating ability of Parylene. The design must build in the ability to implement masking that can be successfully applied and removed without impacting the high voltage reliability.*
- *Staking is typically done prior to coating. Typically the thickness is controlled in the range of 1.4 to 2.0 mils (I prefer around 1.5 mils). An organic silane primer is typically used ahead of application to improve adhesion.*

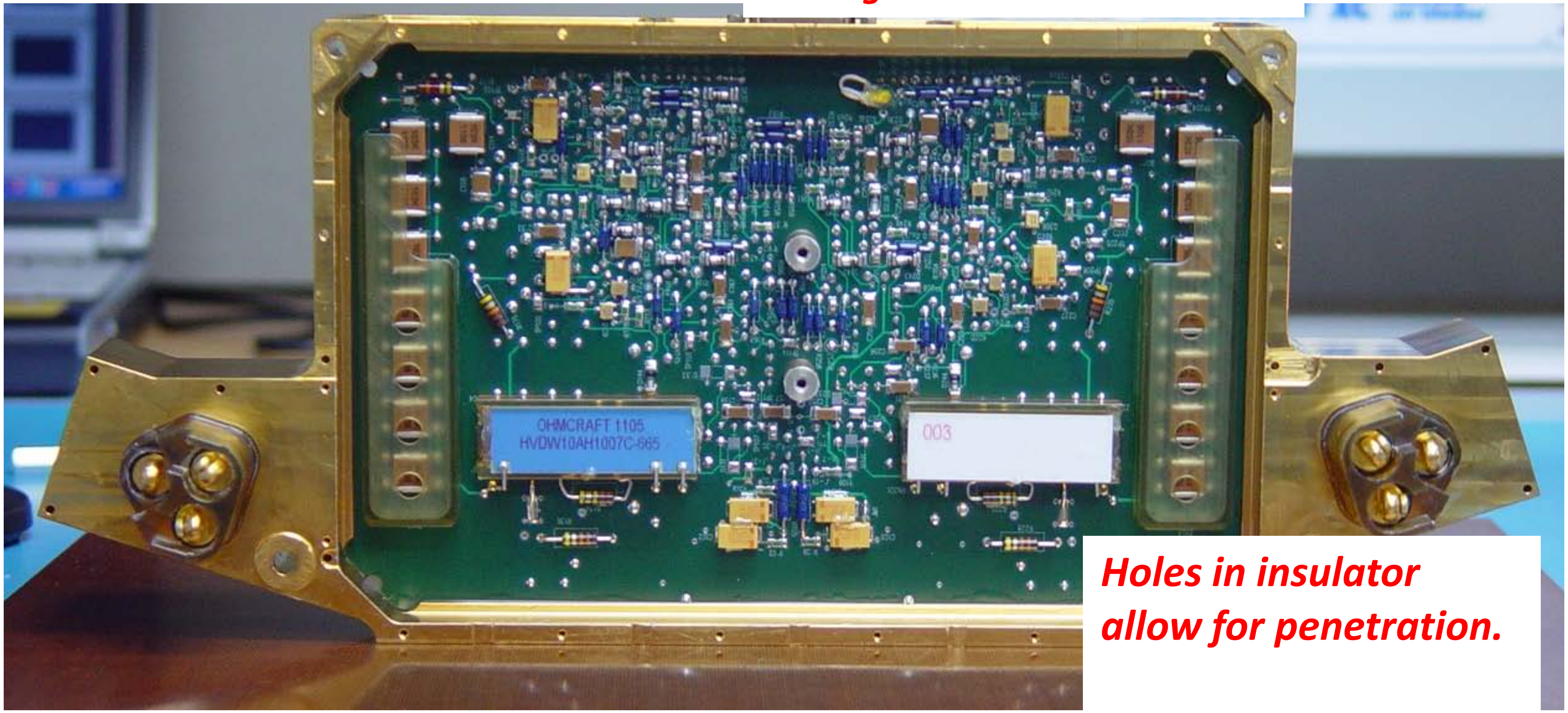
Parylene Coating Design Considerations… 2



Parylene Coating Design Considerations… 3



Space critical components to allow for full wrap-around coating.



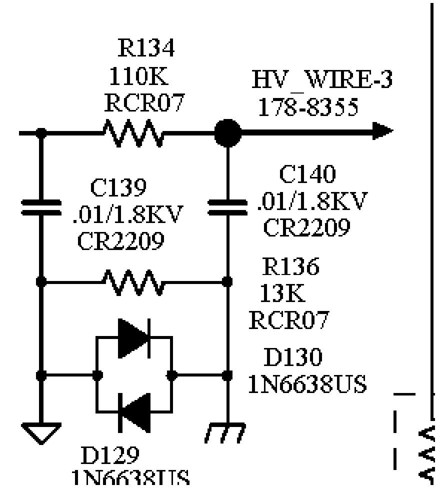
Holes in insulator allow for penetration.

Grounding Approaches… 1

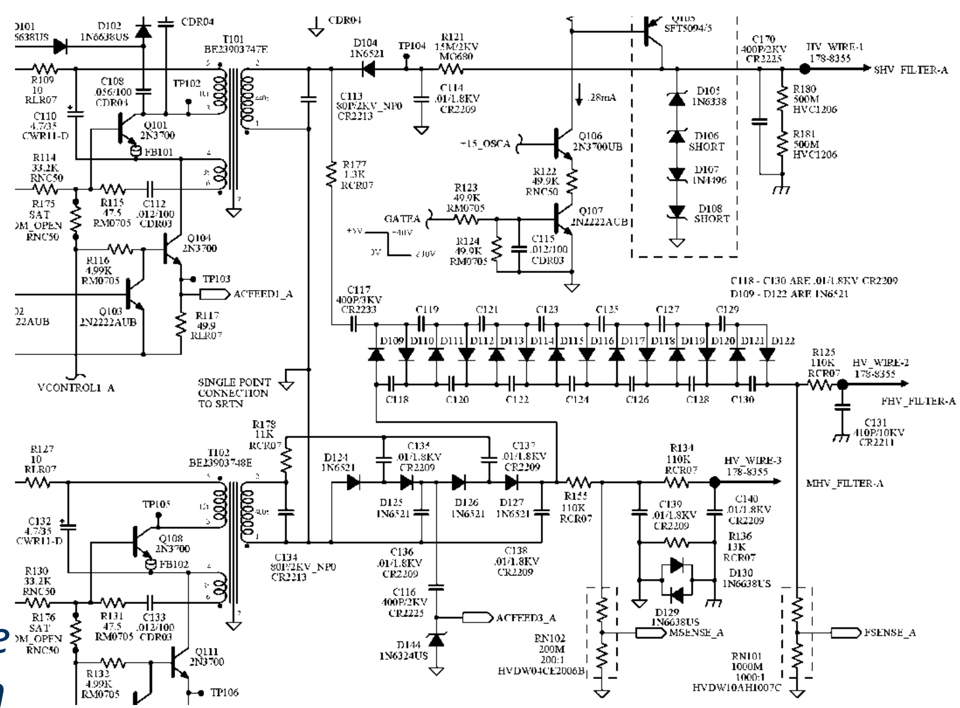
- Recognize that the HVPS system, if designed and shielded correctly, is actually very quiet as a stand-alone system AND typically has a direct connection to your detector or some other sensitive sensor element. Thus, incorporating digital functions or other power functions is likely to make the HVPS a noise transmitter despite the most careful engineering approaches.
- Building a high voltage system is already challenging and can get even more challenging from a noise and performance perspective if rational grounding principles are not carefully followed.
- For low power systems, a KIS (Keep it Simple) rather than DIS (Design it Stupid) approach is strongly advised. KIS principle K1 is that the HVPS system should be designed without primary-secondary isolation such that the entire system runs at signal return potential.
- Principle K2 follows from K1 with the recommendation that power bus isolation and the first level of regulation occur some place else in order to suppress noise, better manage thermal dissipation and simplify packaging.

Grounding Approaches… 2

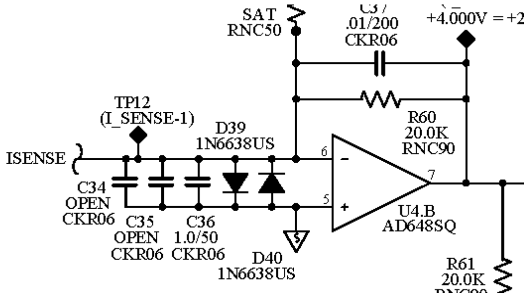
Use a "zap-trap" at all key structure to ground return locations to ensure safe bypassing of an arc.



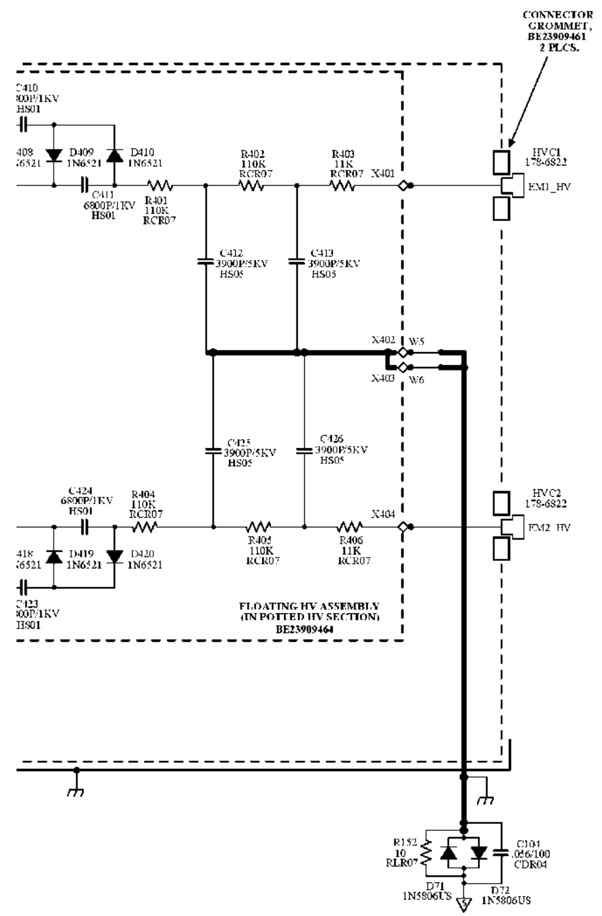
- *Although you are not isolating grounds for the HVPS, the step-up transformer does allow for flexibility on how the grounding is implemented (more on this later).*
- *The most important thing to recognize that an inadvertent high voltage arc will almost always occur to structure in the supply or downstream in the user element.*
- *Therefore, structure must be (and typically should be) treated as the primary high voltage return for an arc with associated mitigation approaches.*



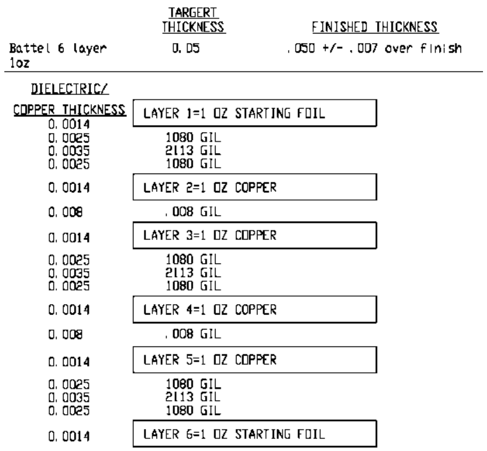
Grounding Approaches… 3



- *Despite what the Golden Rules might say, resist trying to design the system to either isolate the signal return from structure. Also, do not make the principle return a wire or the cable shield unless you take arc suppression measures.*
- *Always use arc suppression resistors and protection diodes configured as "zap traps" to protect circuits and manage ground faults.*
- *Use "zap traps" in multiple locations if necessary to assure local protection against ground faults.*
- *Low capacitance diodes can be used in critical applications although standard diodes are generally good enough.*
- *Zener diodes are also useful in some cases where the sensing junction is not at zero potential.*



PC Board Design Considerations… 1



- *Except for very specialized designs, PC boards are the way most high voltage system designs are implemented.*
- *Like all other elements exposed to high voltage, it is essential to control all aspects of the board design and manufacturing process.*
- *Work with your trusted vendor to design a simple and reliable board structure that they can process reliably.*
- *If possible limit to 4-6 layers using stacked up clad laminate cores in order to minimize pre-preg build-ups. For pre-made cores you can go to 100 volts per mil if the fields are controlled. For pre-preg structures you are safer using 50 or 75 volts per mil (or lower).*
- *1 oz copper gives the most repeatable build-up of high voltage layers. Talk to your vendor and try not to go too thick or too thin.*
- *Maintain your manufacturing documentation so that you can repeat the process in the future. Also, keep one of the boards for reference!*

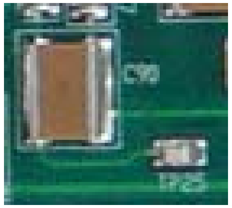
PC Board Design Considerations… 2

	Tg °C	UL-94	Key Feature(s)	Td (5%)	Z-Expansion 50-260°C (%)	Tc W/m-K
Polyimide						
85N Pure Polyimide	250	HB	Best Thermal Stability	407	1.2	0.20
84N Filled Polyimide	250	HB	Crack-resistant Fill	407	1.0	0.25
35N GP Fast Cure	250	V1	General Purpose Poly Fast Cure	407	1.2	0.20
35NQ Quartz Reinforced	250	V1	Low Dk and Loss Tangent	407	1.1	0.20
33N GP UL-94 V0	250	V0	Best Flame Retardant Polyimide	389	1.2	0.20
37N Low Flow	200	V0	Low Flow For Polyimide Rigid-Flex	340	2.3	0.30
38N Low Flow	200	V0	Enhanced Process Poly Low Flow	330	1.5	0.30
85NT Non-woven Aramid	240	HB	CTE Control for SMT Application	426	2.3	0.20

- *We have had very good success with GI polyimide laminates so try to stick with proven materials and processes unless there are special issues that force special engineering considerations.*
- *Main trade with your vendor is to achieve good laminating in combination with good drilling and plating, especially in areas with high voltage.*
- *Generally 35N material gives the best processing and 85N gives the best performance. In general, the ability to reliably process is usually more important than the slightly better properties so make sure that your vendor understands your priorities.*
- *Also remember that you can make multi-layer stack-up thicknesses that are “non-standard in order to save mass or achieve a particular insulation build-up. I tend to prefer a 6-layer .050 or .062 structure.*

PC Board Design Considerations… Some useful rules and suggestions 3

- *Try to balance your layers and have thicknesses of at least 8-10 mils in high voltage areas. Thin layers in the range of 3-4 mils that are used in low voltage systems are prone to defects that can break down under E-field stress.*
- *Wicking, cracks and other problems due to drilling damage occur in any type of PC board system but have a greater impact on high voltage systems. Minimize vias or penetrations in the PC board that have high voltage unless you specifically design to control the local E-field.*
- *If you use swage turrets for high voltage connections be very gentle with the swage to minimize cracks.*
- *Use "standard" test points only in non-high voltage areas and design the attachment trace to be a "spur" from a pad rather than being in line with the main signal. This will minimize the impact of a test point delamination.*

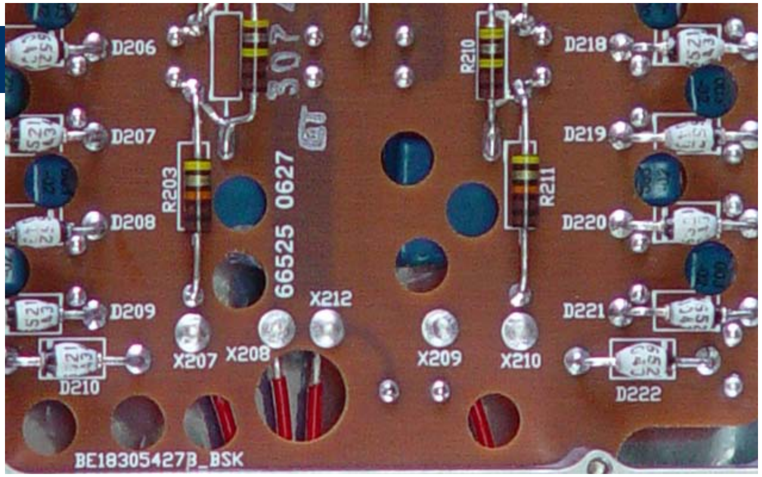


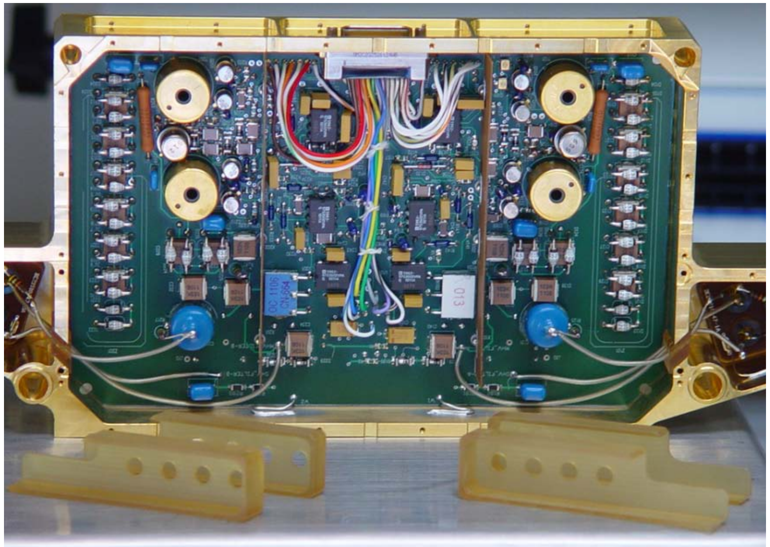
PC Board Design Considerations… *Some useful rules and suggestions 4*

- *There are many opinions and “standards” related to safe trace spacing on a board surface. The key thing to remember that one serious flashover should mean a permanent compromise of the insulation. Thus, you want to be conservative especially if you do initial testing uncoated.*
  - ***Flashover depends on many factors but tends to run around 50 volts per mil** in air**.***
  - ***Commercial Class III safety standards require around 19 volts per mil.***
  - ***The NASA standard is 8 volts per mil which is probably conservative.***
  - ***My general rule of thumb for parallel traces is 100 mils for 1000 volts (10 volts per mil) if you coat the traces. In reality the best rule is DON’T run parallel traces if it can be avoided!***
  - ***I also allow at least 100 mils (and generally more if possible) for any trace near the edge of the board or near the wall of an enclosure.***
- *Buried parallel traces can be run around 30 volts per mil for long life and 50 volts per mil for shorter life.*

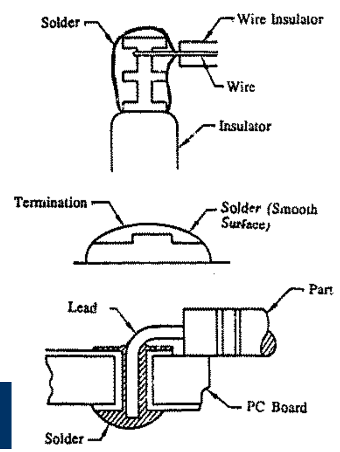
PC Board Design Considerations… *Some useful rules and suggestions 5*

- *The most important thing to remember is that the best designs are ones where you specifically design to control the local E-field.*
- *Sharp corners are the enemy so make sure to shape pads with high voltage and design smooth bends.*
- *Grooves or cuts in the PC board can help with high voltage isolation but they weaken the board and often do not help with flashover since they can act as source of "jumping" electrons.*
- *Shields work better and can also act as stiffeners if properly implemented.*



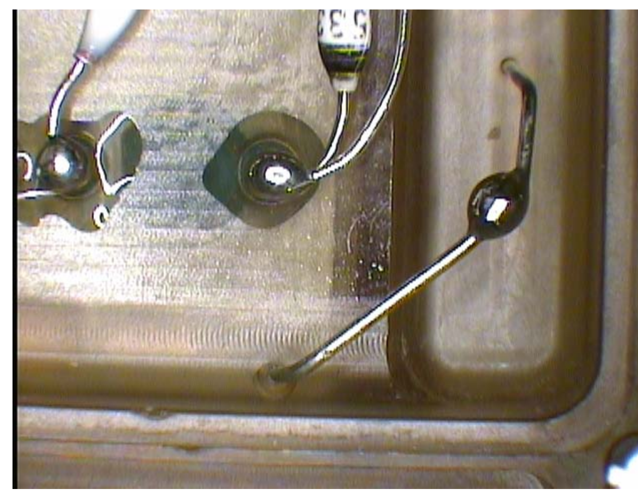


High Voltage Solder Joints… 1



- *As we have discussed, high voltage reliability fundamentally comes down to controlling the local E-Field to acceptable values at each point in each element of a system design.*
- *We also know that soldering as a process is also a critical contributor to achieving electronic system reliability.*
- *The key challenge of soldering in high voltage systems is to merge the above 2 process demands into an approach to making joints that possess inspectable criteria while also being reliable and immune to breakdown.*
- *There are generally two types of joints with spherical “balls” being used for floating joints (either on a PC board on in a potted assembly) and “flattened balls” used for pads with protruding wires on PC boards.*

High Voltage Solder Joints… 2



- *The "ball" solder joint is typically floating so must be both a solid mechanical joint as well as acceptable high voltage joint.*
- *Making a good joint is challenging and required good technician experience along with some practice in matching solder amount, tip-time, tip temperature.*
- *Rework almost never improves a joint so successful first time results are very important for flight reliability.*
- *A finished joint must be smooth and in the range of 2.0 to 3.0 mm in diameter. If bigger joints are required due to voltage requirements, it is possible to use conductive caps or dielectric layering to reduce the local E-field gradient.*

High Voltage Solder Joints… 3

- *Most high voltage joints on PC boards are assumed to be at voltages where a semi-flat joint is possible.*
- *The key is to trim and then reflow without overheating the joint.*
- *If too hot, it is possible to introduce an internal crack or defect that can ultimately result in failure.*

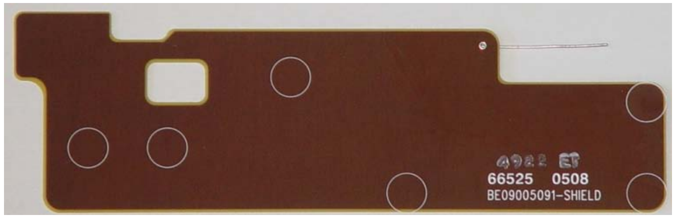
PROCEDURE

.010" LEAD TRIMMING AND HV SOLDERING

Note: This procedure is to be used in applications where high voltage (in excess of 300 volts) is applied to leads that protrude through the bottom of a PC board. In such cases, high electric fields can be induced by the sharp points created by the leads. Because this approach reduces the strength and inspectability of the solder joint, it should only be used in applications specifically called out in the assembly procedure. It should not be used in applications where the parts are potted and/or subjected to unusually high tensile stress.

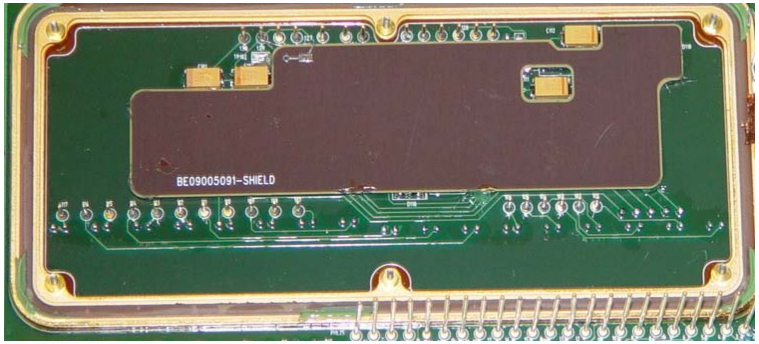
1. Pre-tin parts and Install using normal techniques for spacing and holding in place.
2. Solder using standard procedures but with a lighter than normal application of solder.
3. Inspect joint for integrity and solder pull-through.
4. Trim leads to <0.010 such that the lead is trimmed almost flush to the PC board.
5. Apply flux and apply more solder from the bottom side such that the joint is completely covered and takes on a rounded "ball" type appearance. (A lower soldering iron temperature often helps with this step. Some practice may be required to achieve the desired solder ball effect.)
6. Clean joint thoroughly with an approved solvent.
7. Inspect soon after completion of work to minimize time between initial soldering and any rework. (When properly accomplished the solder joint should look round and smooth. There should be little or no evidence of the lead sticking through the solder.)

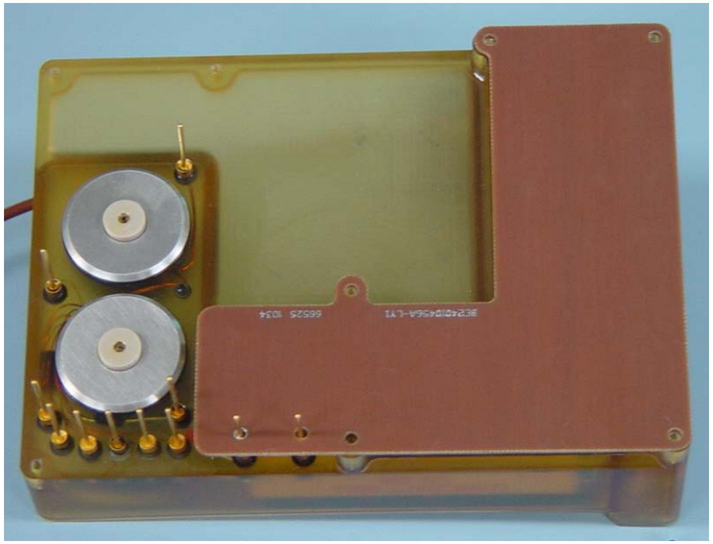
The circles are Ultem bumper locations glued on to the shield.

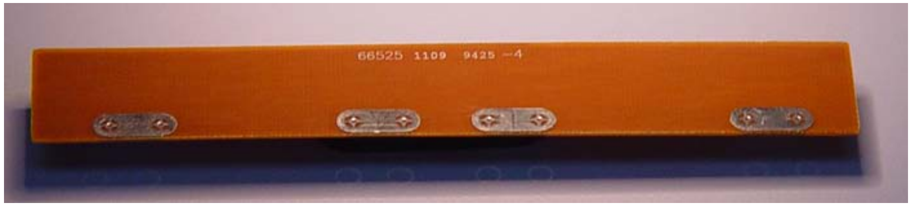


Electrical Shield Designs…

- *High voltage systems generate both high AC and DC fields that need to be managed in order to achieve accurate performance and low noise.*
- *I typically make .020 thick shields with an internal copper layer and outside insulating layer.*
- *Horizontal and vertical shields are both possible. Vertical shields can be supported using bifurcated turrets.*



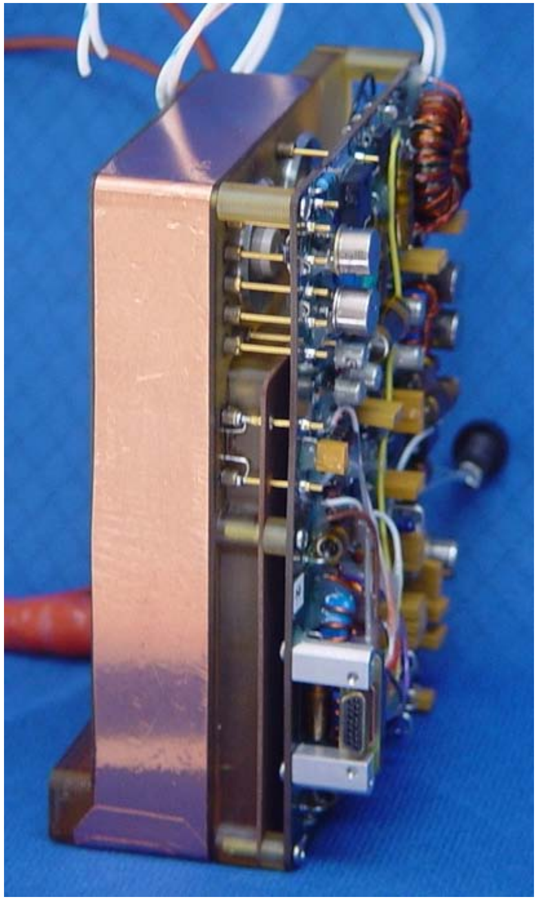




Packaging and Construction… 1

- *The reliability of high voltage systems is determined by many factors. One constant factor for higher voltages is to have the package contribute to the system reliability by functioning as a deterministic "wrap" for the system that controls the T-E-M-P aspects of the design.*
- *Over time, my personal preference has moved toward "board in frame" (BIF) designs plus plastic enclosure approaches for the more challenging applications.*
- *Single layer planar designs and vertical designs using "plug in" boards are both practical allowing for adaptable E-field management as well as reliable coating and encapsulation.*
- *Mating pin-socket approach allows for simple and reliable interconnects with less management of spacing. Typically use 0.040 swageable Concord pins with a Tyco-AMP mating socket.*
- *Other approaches are certainly possible if properly managed. Just make sure you have a solid qualified process that manages all key parameters.*

Packaging and Construction… 2



Oscillator Design… 1

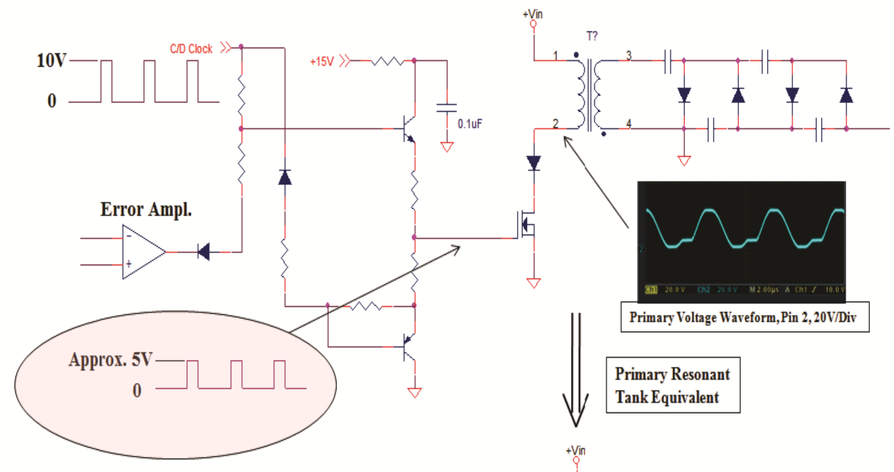
- *The beauty of oscillator options for high voltage systems is truly in the eye of the beholder/user.*
- *The most important criteria for the selection of an approach is confidence in the stability and reliability of the design choice.*
  - ***Power range and application.***
  - ***Sine vs. Square vs. Flyback.***
  - ***Driven vs. Self-Oscillating.***
  - ***Frequency synchronization.***
- *When considering an oscillator design, it is important to see the oscillator and transformer as coupled system with respect to performance and reliability.*

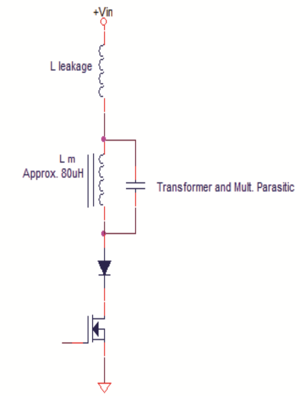
Oscillator Design… 2

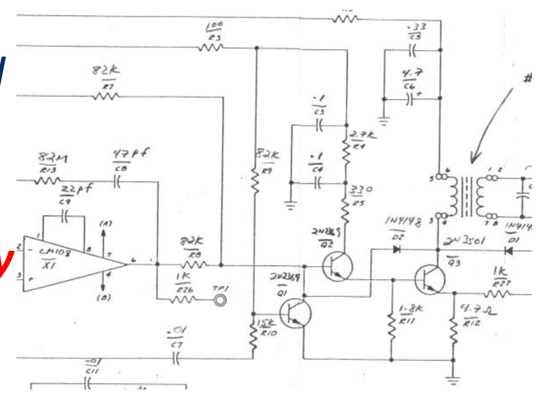
- *Many designs have moved to driven systems since easier to design and understand. Frequency synchronization is also simpler when demanded by the application or to manage multiple oscillators within the system.*
- *Although more complex, driven systems, if correctly implemented, have an excellent flight history.*
- *With the permission of the designers, I will do a quick description of two types developed by GSFC (Ruitberg et al.) and SwRI (Casey et al.), each with more than 20 years of flight development history.*
- *Note that both design approaches are also tied to a specific magnetic design and qualified manufacturing process.* ***You must implement both matched to the application in order to achieve a reliable system.***

Oscillator Design… *GSFC Design Approach 3*

- *The GSFC design uses a 25% drive duty cycle that can be synchronized using a PLL.*
- *The oscillator is designed to be primary resonant.*
- *Control of the system gain is achieved via linear control of the gate voltage on the MosFet drive stage.*
- *The design requires a special transformer that will be discussed later.*



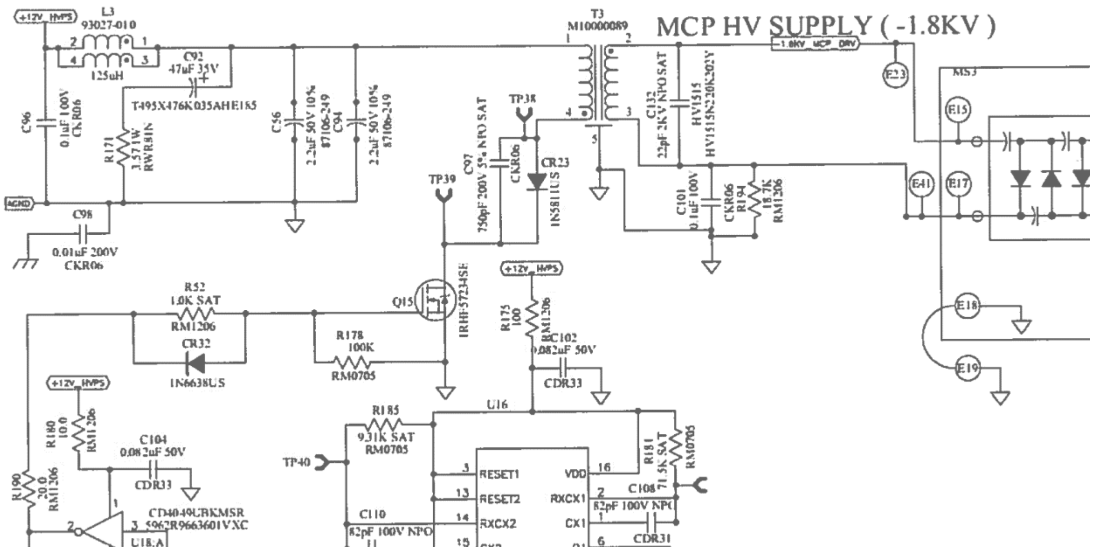




My notes show a similar secondary resonant design developed by Rosenbauer in the 1970's for ISEE.

Oscillator Design… *SwRI Design Approach 4*

- ***The SwRI design is similar in drive approach to the GSFC design but uses a triggerable multi-vibrator to manage the duty cycle and achieve regulation.***
- ***The oscillator is also designed to be secondary resonant.***

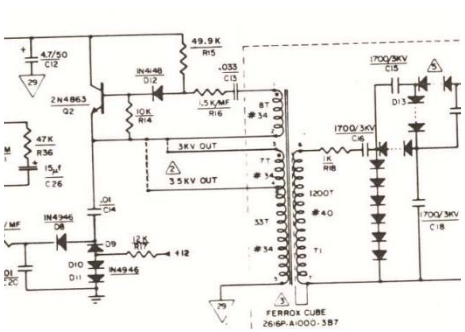


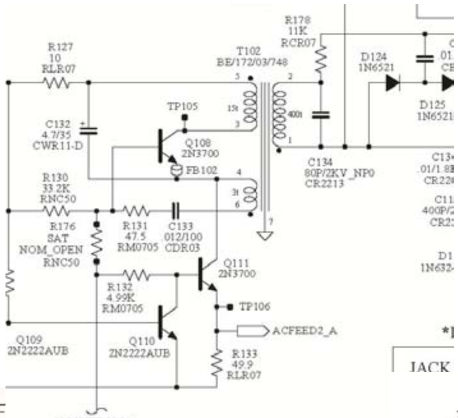
Oscillator Design… 5

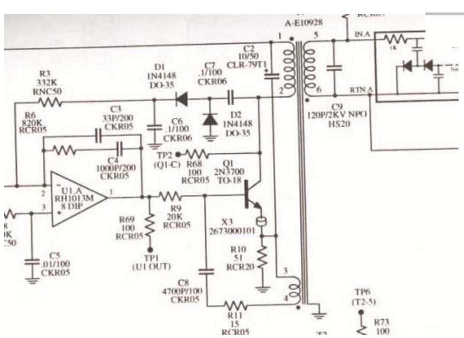
- *I prefer self-resonant oscillators since they are much simpler, more robust, immune to aging effects and lower noise.*
- *2 basic oscillator types have been evolved over the past 35 years.*
- *Type 1 is a single transistor gain controlled amplifier for low power applications in the <1 watt range. There is a 40 year story of its evolution!*
- *The Type 2 design is actually based on a Ruitberg current-fed push-pull oscillator than can operate efficiently in applications up to 6+ watts. The Type 2 evolution story is only 35 years!*
- *Both designs being self-resonant are functionally intertwined with their associated magnetic devices.*

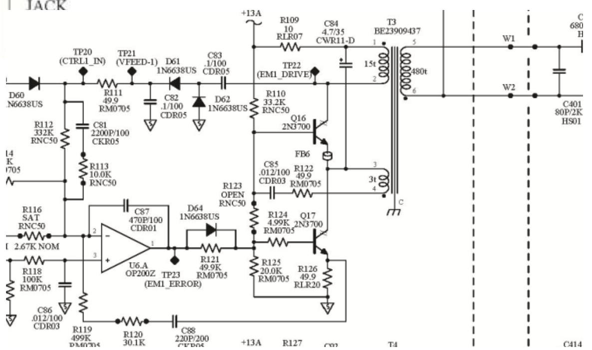
Oscillator Design… *Single-Ended 6*

The 40 year story of the low power oscillator starts with the AE mission in an unbroken string through DE – Galileo – Cassini- IMAGE - AIM all the way to SAM and MAVEN.





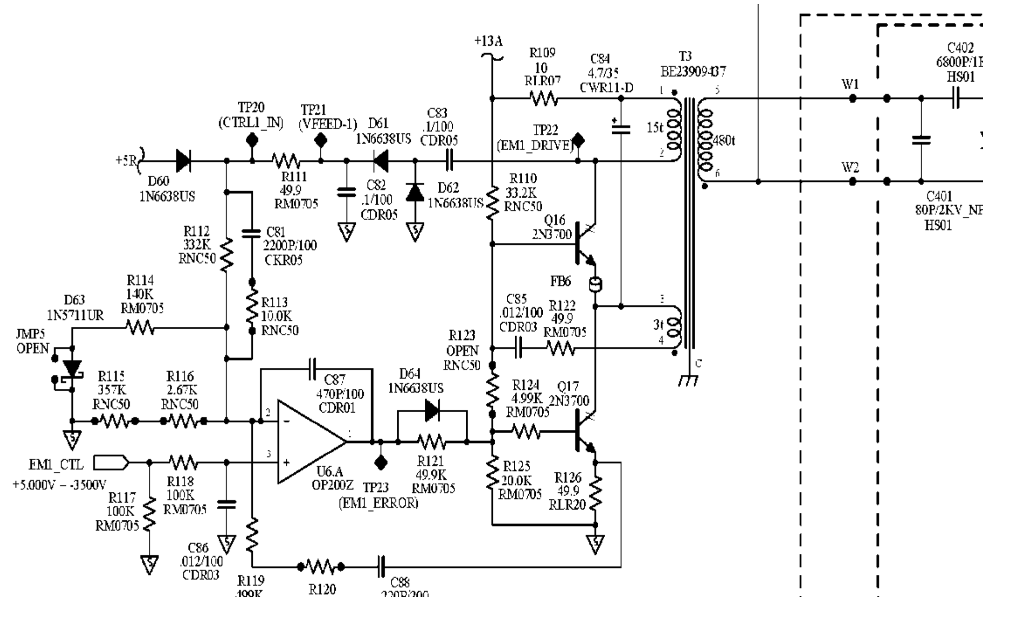




Developed by S. Battel and J. Maurer (at the University of Michigan) in the mid-1970's, this circuit was first used on the Dynamics Explorer and Galileo missions and has subsequently flown in 36 applications on 11 missions including Cassini and Huygens. The design show uses primary feedback without a connection to the secondary.

Oscillator Design… *Single-Ended 7*

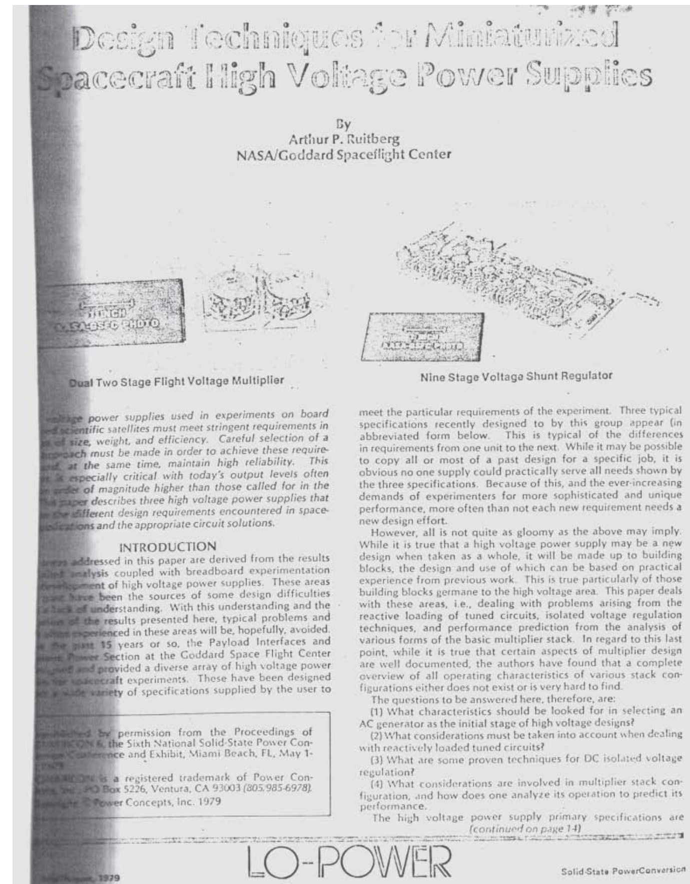
- ***The basic low power oscillator used for most designs is capable of operating down to 5 volts with start-up at less than 1 volt.***
- ***Oscillator is a single-transistor self-resonant Hartley-Armstrong derivative using a resonant secondary.***
- ***Develops a harmonically pure sine wave output and is essentially immune to radiation and temperature induced gain reduction in the drive circuit.***
- ***Inherently very low power through the using a dual feedback loop with AC coupled "tickler" feedback combined with proportional cascode control of the DC current drive to set the operating point.***



The "Ruitberg" oscillator described in 1979 was modified by S. Battel at Lockheed in the early 1980's to incorporate the use of Darlington drive transistors for higher efficiency and wider dynamic range. It has been used in 18 applications on 12 missions including Cassini, SOHO, IMAGE, FUSE, GALEX, HST and Mars-Phoenix.

Oscillator Design… *Current-Fed Push-Pull 8*

- ***The basic medium power push-pull oscillator used for most designs is capable of operating down to 5 volts with start-up at less than 2 volts. Best operation in regulated applications occurs when operated at 8 volts or higher.***
- ***Oscillator is a current-fed push-pull self-resonant design using a resonant primary and loosely coupled secondary.***
- ***Develops a harmonically pure sine wave output and is basically immune to radiation and temperature induced gain reduction in the drive circuit.***



Design Techniques for Miniaturized Spacecraft High Voltage Power Supplies

By
Arthur P. Ruitberg
NASA/Goddard Spaceflight Center

Dual Two Stage Flight Voltage Multiplier

Nine Stage Voltage Shunt Regulator

[illegible] power supplies used in experiments on board [illegible] scientific satellites must meet stringent requirements in [illegible] size, weight, and efficiency. Careful selection of a [illegible] approach must be made in order to achieve these require[illegible] at the same time, maintain high reliability. This [illegible] especially critical with today's output levels often [illegible] of magnitude higher than those called for in the [illegible] paper describes three high voltage power supplies that [illegible] different design requirements encountered in space[illegible] applications and the appropriate circuit solutions.

INTRODUCTION

[illegible] addressed in this paper are derived from the results [illegible] analysis coupled with breadboard experimentation [illegible] of high voltage power supplies. These areas [illegible] been the sources of some design difficulties [illegible] of understanding. With this understanding and the [illegible] results presented here, typical problems and [illegible] experienced in these areas will be, hopefully, avoided. [illegible] past 15 years or so, the Payload Interfaces and [illegible] Power Section at the Goddard Space Flight Center [illegible] and provided a diverse array of high voltage power [illegible] spacecraft experiments. These have been designed [illegible] variety of specifications supplied by the user to meet the particular requirements of the experiment. Three typical specifications recently designed to by this group appear (in abbreviated form below. This is typical of the differences in requirements from one unit to the next. While it may be possible to copy all or most of a past design for a specific job, it is obvious no one supply could practically serve all needs shown by the three specifications. Because of this, and the ever-increasing demands of experimenters for more sophisticated and unique performance, more often than not each new requirement needs a new design effort.

However, all is not quite as gloomy as the above may imply. While it is true that a high voltage power supply may be a new design when taken as a whole, it will be made up to building blocks, the design and use of which can be based on practical experience from previous work. This is true particularly of those building blocks germane to the high voltage area. This paper deals with these areas, i.e., dealing with problems arising from the reactive loading of tuned circuits, isolated voltage regulation techniques, and performance prediction from the analysis of various forms of the basic multiplier stack. In regard to this last point, while it is true that certain aspects of multiplier design are well documented, the authors have found that a complete overview of all operating characteristics of various stack configurations either does not exist or is very hard to find.

The questions to be answered here, therefore, are:

(1) What characteristics should be looked for in selecting an AC generator as the initial stage of high voltage designs?

(2) What considerations must be taken into account when dealing with reactively loaded tuned circuits?

(3) What are some proven techniques for DC isolated voltage regulation?

(4) What considerations are involved in multiplier stack configuration, and how does one analyze its operation to predict its performance.

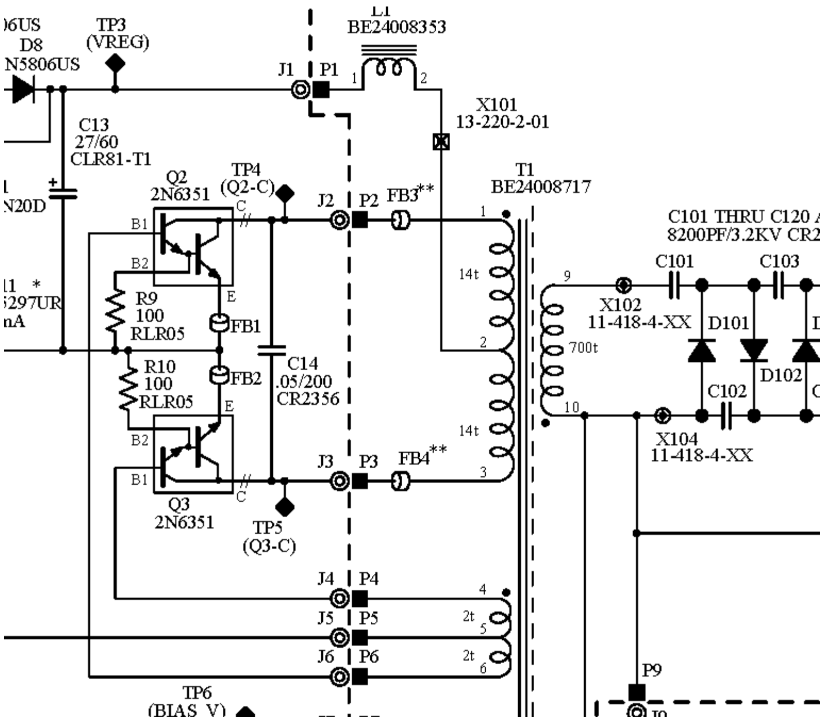
The high voltage power supply primary specifications are

(continued on page 14)

[illegible] by permission from the Proceedings of [illegible] 6, the Sixth National Solid-State Power Con[illegible] Conference and Exhibit, Miami Beach, FL, May 1- [illegible]
[illegible] is a registered trademark of Power Con[illegible] PO Box 5226, Ventura, CA 93003 (805/985-6978).

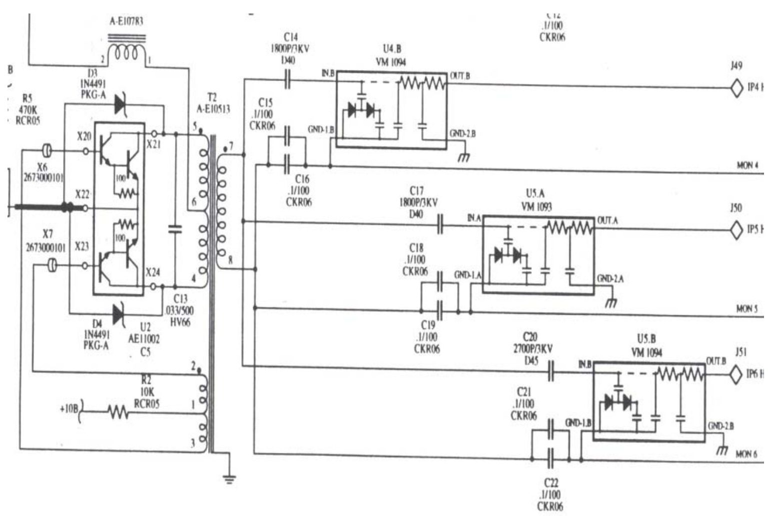
Oscillator Design… *Current-Fed Push-Pull 9*

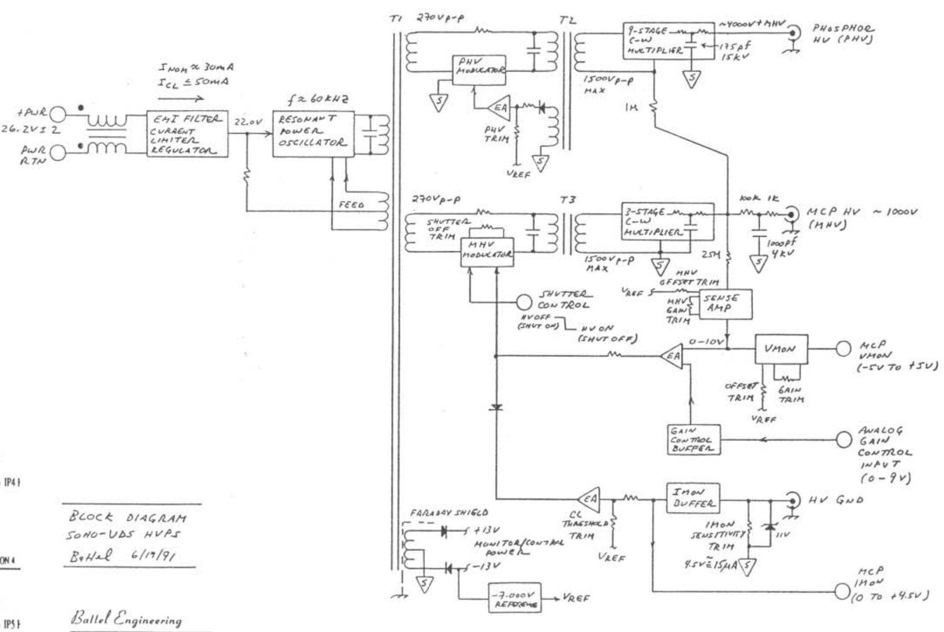
- ***Design required both a transformer and a resonating inductor although both can be stacked into a single assembly.***
- ***Aside from simplicity and efficiency over a wide dynamic range, 3 major advantages of this oscillator approach are scalability, the boosted drive voltage at the center-tap to 1.57 time the supply voltage, ability to use primary resonance.***
- ***Circuit also has low ripple current and is very quiet if properly designed and shielded.***



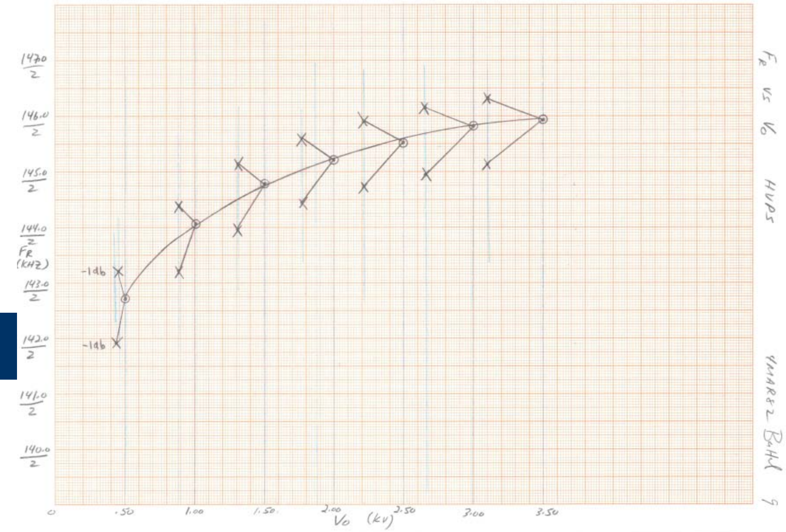
Oscillator Design… *Current-Fed Push-Pull 10*

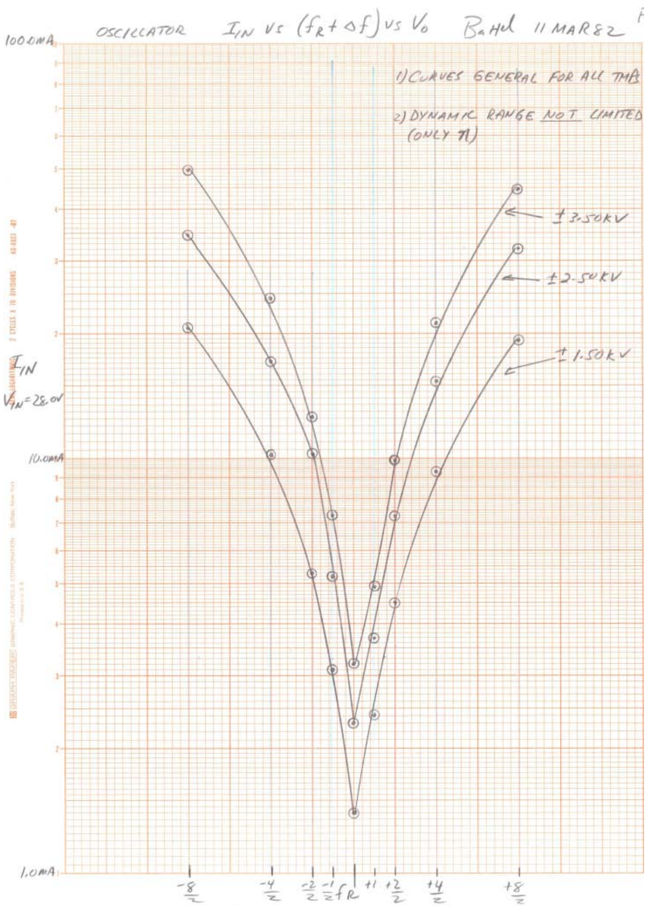
- ***The push-pull design's dynamic range and stability under wide loads also makes it useful in applications with multiple secondary outputs.***

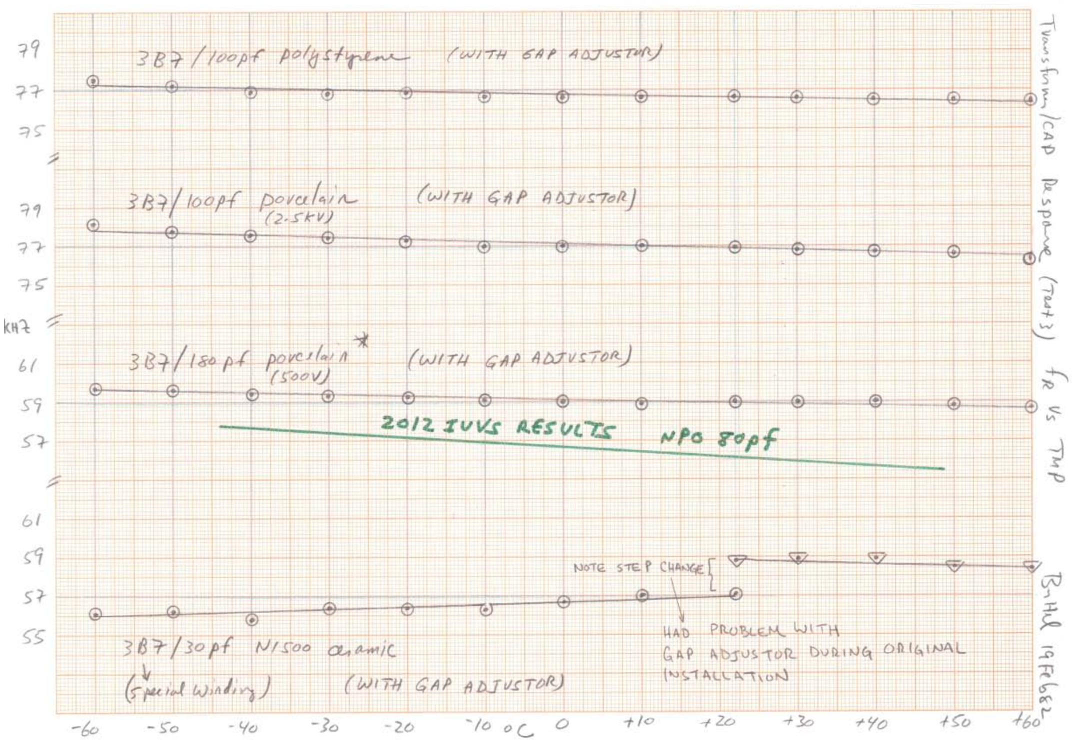




Oscillator Frequency Stability…

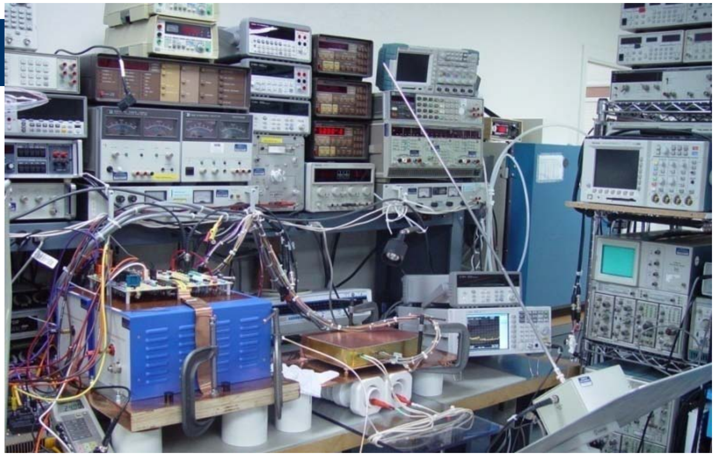




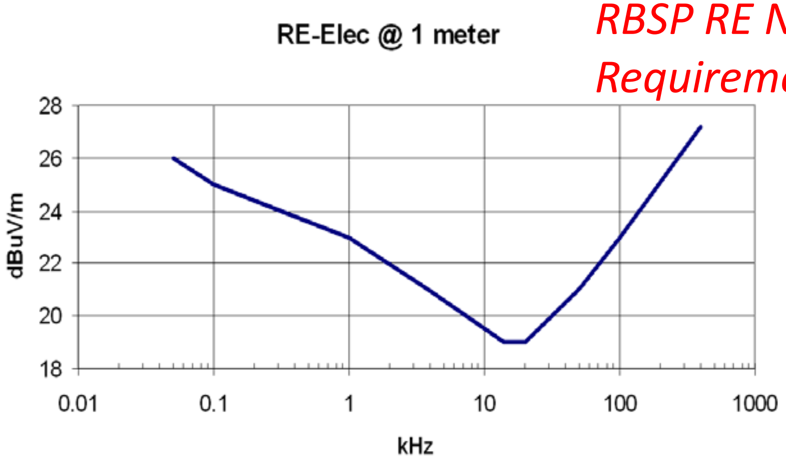


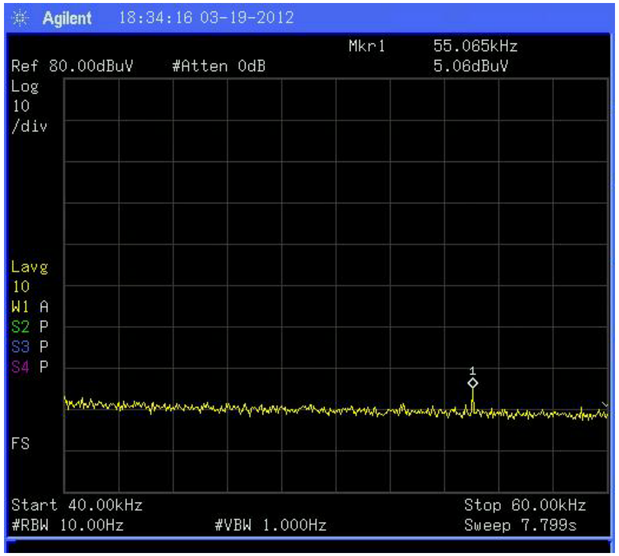
The Oscillator Noise Story… 1

Self-Oscillating systems are harmonically pure and actually quieter than driven and/or synchronized systems. The measured E-Field value for MAVEN unit is 5.06 dBuV/m.

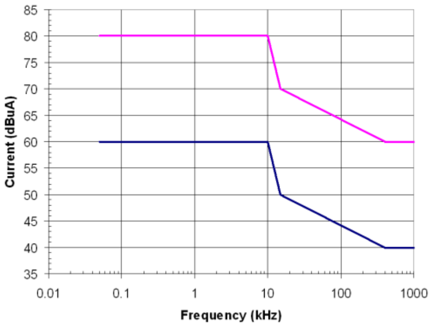


RBSP RE Noise Requirement

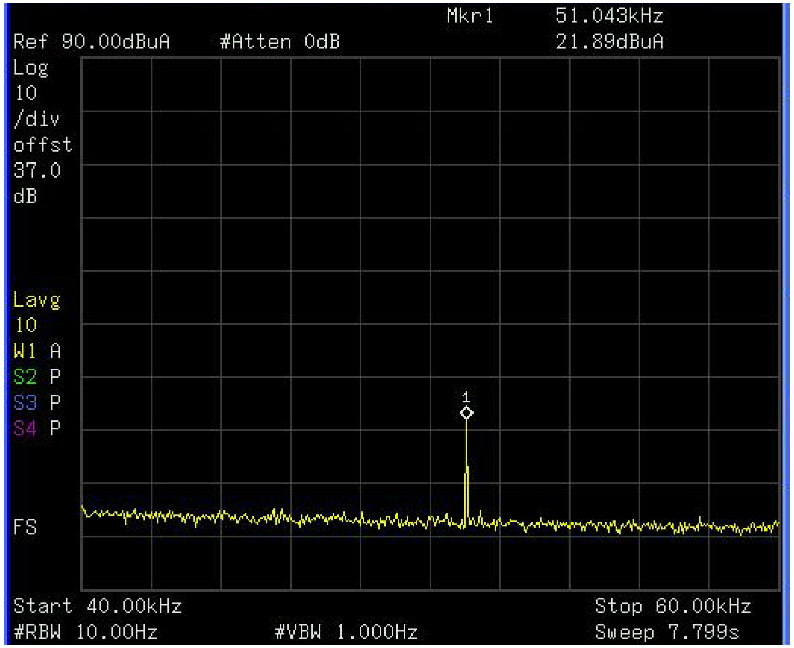




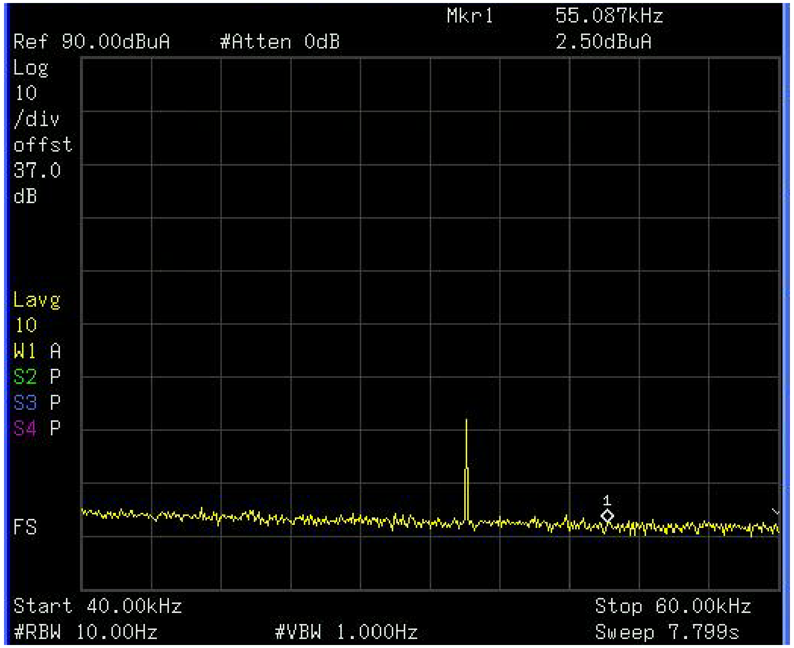
RBSP C-M Noise Requirement



The Oscillator Noise Story… 2



CE-01 C-M MAVEN measurement with LVPS on and HVPS off = 21.9 dBuA



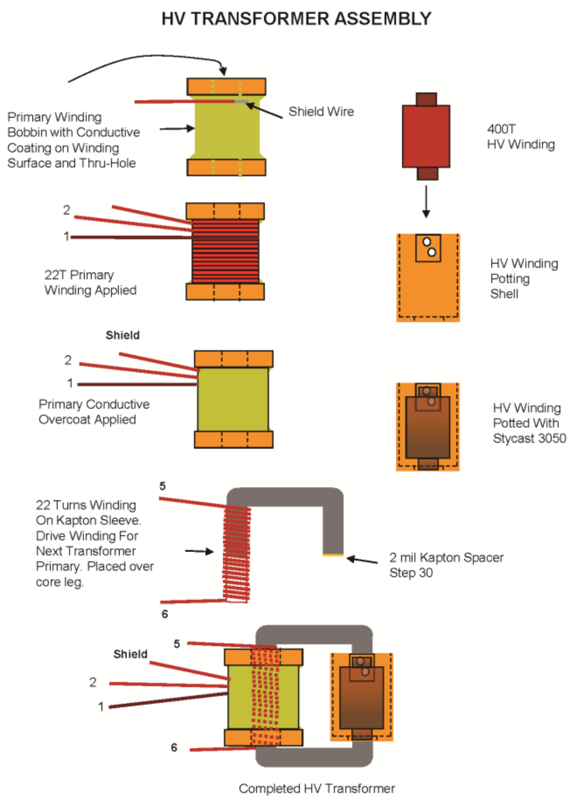
CE-01 C-M measurement with LVPS on and HVPS on- not measurable at HVPS oscillator frequency.

Magnetics Overview…

- *Magnetics are typically the design limiter on high voltage power supply designs.*
  - ***Most vendor sensitive element.***
  - ***Most expensive element.***
  - ***Least stress-controlled element.***
  - ***Most process and material sensitive element***
- *I try to use standardized designs in each type of oscillator application that have evolved into trusted elements through a long history of testing, process improvements and flight experience.*
  - ***Processes and manufacturing continuity for 30+ years.***
  - ***Have developed my own qualification and screening capability.***
- *One helpful thing about a transformer is that it can be tested to failure using accelerated methods.*

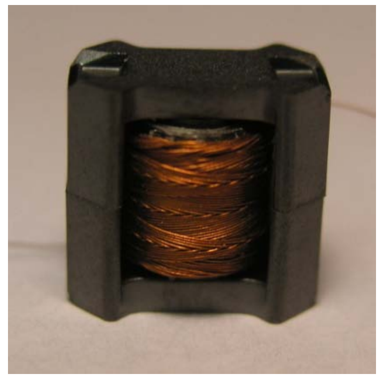
Ruitberg Lattice Wound Transformer… 1

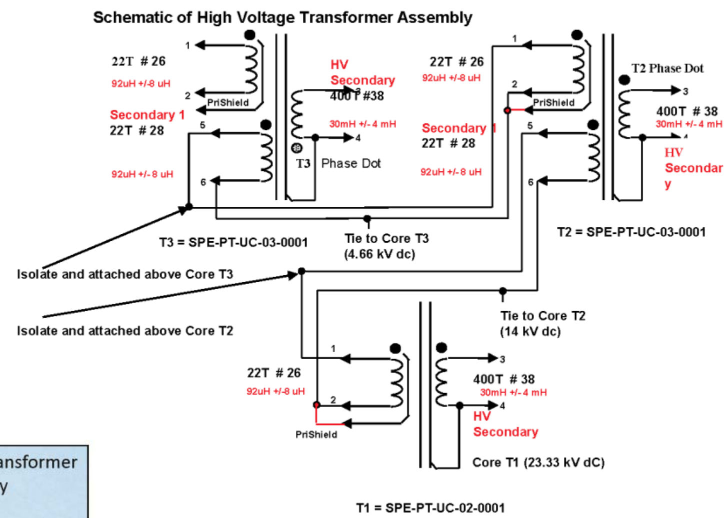
- WINDING IS SELF SUPPORTING. NO BOBBINS OR INNER INSULATION LAYERS REQUIRED.
- ADJACENT WINDING TO WINDING VOLTAGE CAN BE PRECISELY CONTROLLED IN LATTICE STYLE CONSTRUCTION.
- WINDING PITCH CAN BE VARIED TO ADJUST INTERWINDING SPACING (AND ASSOCIATED PARASITIC CAPACITANCE.)
- WINDING PARASITIC PROPERTIES VERY REPEATABLE.
- TECHNIQUE LESS PRONE TO OPERATOR ERROR THAN MANUAL METHODS.
- BARRIER-FREE CONSTRUCTION AND LARGE INTERWINDING SPACING ALLOWS FOR VOID-FREE SOLID ENCAPSULATION. TRANSFORMER CORE AND PRIMARY WINDING LEFT UNPOTTED.

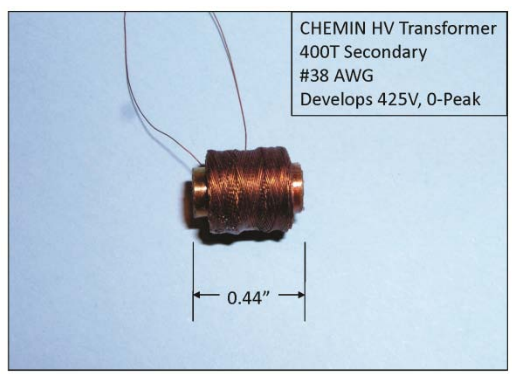


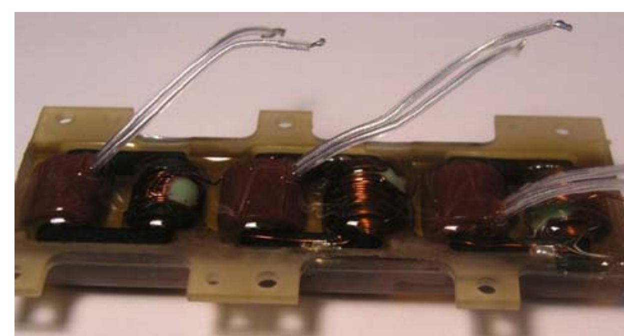
Ruitberg Lattice Wound Transformer… 2

- ***IN MANY APPLICATIONS, LATTICE HV WINDING CAN BE USED "UNPOTTED."***
- ***ALSO, VERY COMPATIBLE WITH PARYLENE COATING. PARYLENE WILL COMPLELETY PENETRATE WINDING AND MECHANICALLY " LOCK" WINDINGS TOGETHER, VOID FREE.***



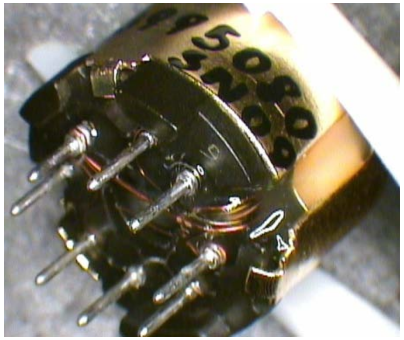


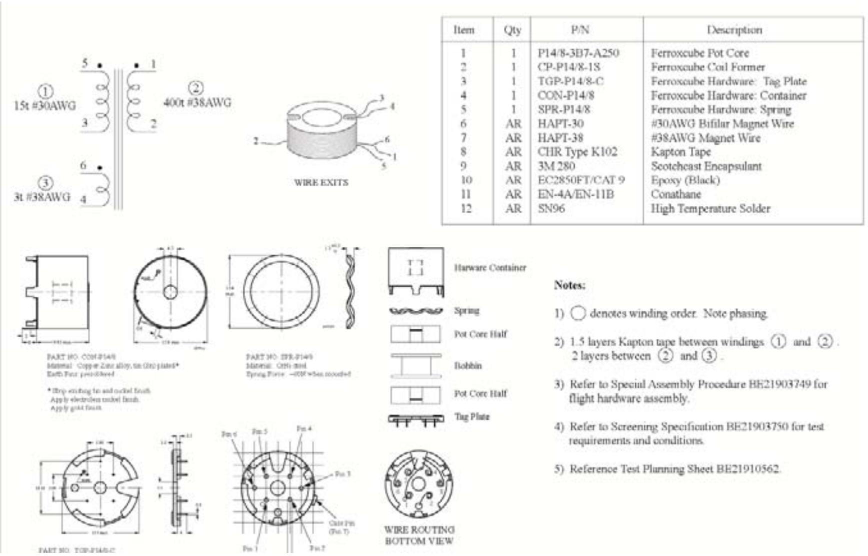




Resonant Transformer Construction… 1

- “Standard” transformer designs for most high voltage oscillators use gapped potcore magnetics and standard spring mounting hardware to allow a -55C to +120C processing temperature range.
- Typically use Ferroxcube 3B7 material due to relatively linear temperature coefficient.
- Cores should be carefully inspected and diamond filed to smooth sharp edges. Do not scratch, drop or chip cores during handling or use one that have cracks or chipouts.
- Cans should be stripped and gold plated.
- Windings should be implemented to minimize internal gradients.

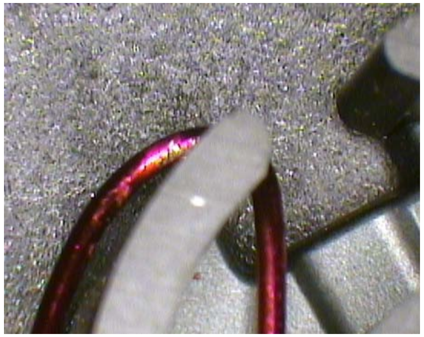




Item	Qty	P/N	Description
1	1	P14/8-3B7-A250	Ferroxcube Pot Core
2	1	CP-P14/8-1S	Ferroxcube Coil Former
3	1	TGP-P14/8-C	Ferroxcube Hardware: Tag Plate
4	1	CON-P14/8	Ferroxcube Hardware: Container
5	1	SPR-P14/8	Ferroxcube Hardware: Spring
6	AR	HAPT-30	#30AWG Bifilar Magnet Wire
7	AR	HAPT-38	#38AWG Magnet Wire
8	AR	CHR Type K102	Kapton Tape
9	AR	3M 280	Scotchcast Encapsulant
10	AR	EC2850FT/CAT 9	Epoxy (Black)
11	AR	EN-4A/EN-11B	Conathane
12	AR	SN96	High Temperature Solder

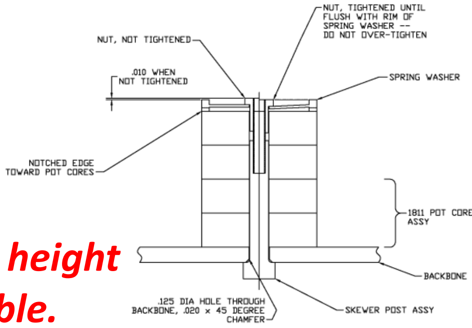
Notes:

1) ◯ denotes winding order. Note phasing.
2) 1.5 layers Kapton tape between windings ① and ②. 2 layers between ② and ③.
3) Refer to Special Assembly Procedure BE21903749 for flight hardware assembly.
4) Refer to Screening Specification BE21903750 for test requirements and conditions.
5) Reference Test Planning Sheet BE21910562.



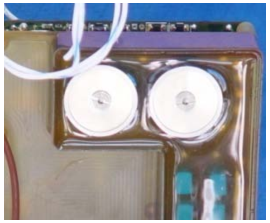
Resonant Transformer Construction… 2

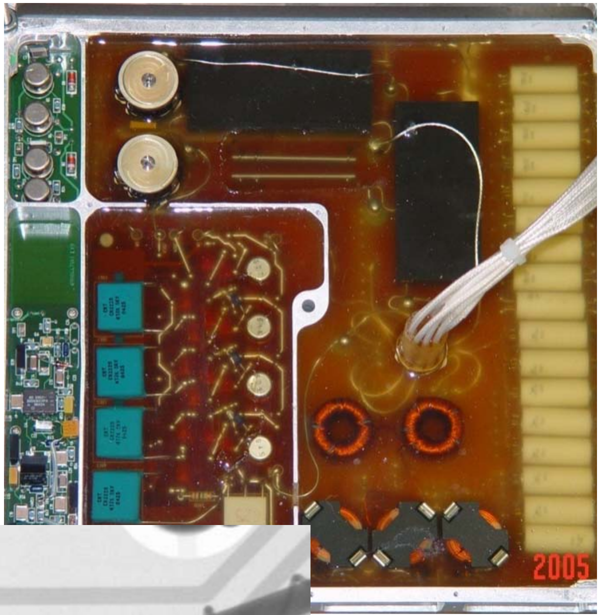
A single height or dual height stacked design is possible.

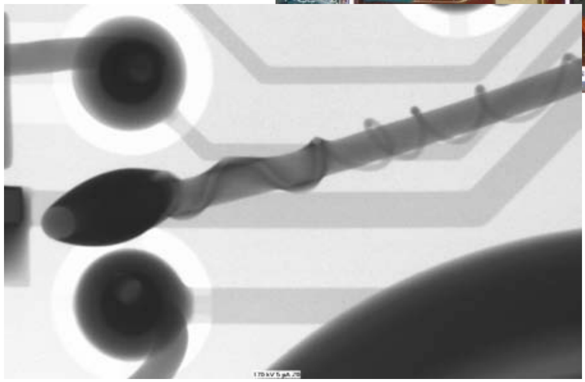


POT CORE STACK ASSY

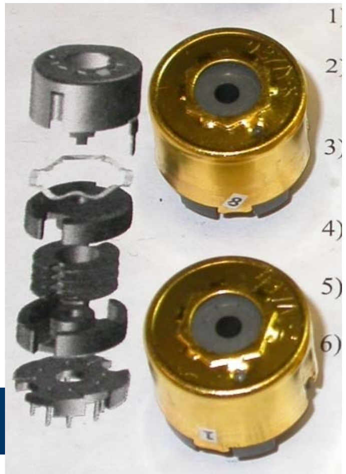
- *Designs intended to be potted (such as Mars applications) are implemented using a "Hertzberg Spring" that has controlled mechanical properties matched to the core thermal expansion properties.*
- *RM cores with standard clamps have also been qualified less critical resonant or non-resonant applications where the operating properties are less critical. Note that they are not fully shielded as are potcores.*
- *Routing and soldering of fine wires smaller than 34 AWG is much more critical when the transformer is potted.*







Magnetics Design and Manufacture… 1

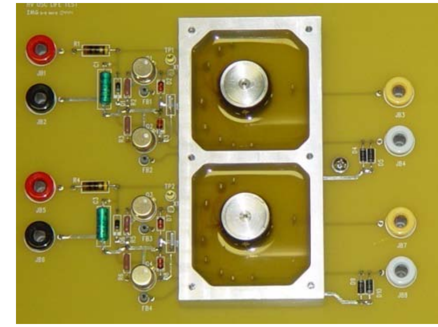


- *Once you achieve a proven and qualified design for a resonant transformer, each application comes down to a choice of core size, gap choice, primary winding turns and secondary step-up ratio.*
- *Proven potcore sizes are 1408, 1811, 2213 and 2616 with 1811 being the preferred starting point for most low power and medium power designs. In higher step-up applications, a 2213 core gives more room for larger wires and managing spacing. For higher power (up to 6-8 watts) a 2616 core is preferred although the resonant characteristics require a little more management.*
- *For most applications a transformer works best with around 1 volt per turn on the primary. Secondary turns up to 750 have been successful with output voltages as high as 1250 volts peak.*
- *With lower voltages (~450 volts peak) coupling and efficiency are best with the windings layered on top or each other. Above that voltage, custom split bobbins made of Ultem are typically used.*

Magnetics Design and Manufacture… 2

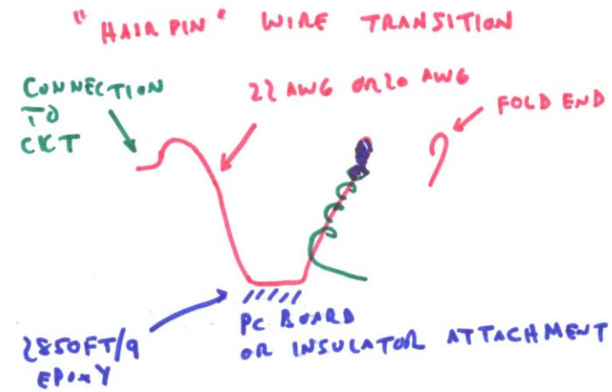
- *The resonant frequency "sweet spot" tends to be in the range of 40 kHz in higher power applications and 55 kHz to 80 kHz in lower power applications depending on the turns ratio and parasitic capacitance. In general, the driver on frequency is the size of the tank capacitor with the frequency chosen to eliminate higher frequency resonances.*
- *In nearly all applications resonant designs, if properly constructed, result in very little heat rise within the device. In most cases the temperature rise is less than 5C.*
- *Process control is essential in low volume production manufacturing spread over many years. The manufacturing technicians have not changed in almost 30 years of production. Procedures evolve based on engineering results, discoveries, material changes AND feedback from the technicians.*

Magnetics Design and Manufacture… 3



- *Design, manufacturing and test are fundamentally based on 981 criteria but have been adapted to achieve high voltage reliability. Most important (and a great advantage) in resonant designs is to test using a simple oscillator circuit similar to the flight application.*
- *Generally, I test magnetics from -55C to +100C operating in the resonant circuit. Note that REAL operating applications are generally limited to +70C due to limitations on potting materials and coatings.*
- *Faraday shields within the transformer are possible but tend to add complexity and reduce reliability. They can be helpful, however, in some designs by allowing for better field control between windings.*

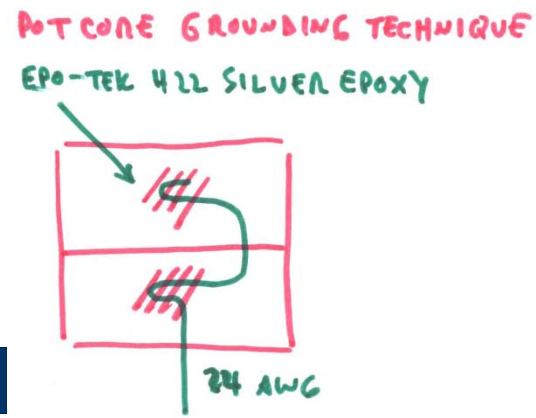
Magnetics Design and Manufacture… 4



- *Special bobbins are also possible to manage the construction and internal fields. Except for split bobbins, I tend to avoid complicated assemblies but nested Ultem cores, gold plating and other techniques are certainly possible and have been successful.*

- *Wire sizing has a big impact on the E-field. In general, the wire-wire voltage and layer-layer voltages can be controlled by how the windings are constructed. However, the wire egress and transition segment are a challenge that must be managed.*
- *In general breakdown in air is a good indicator of the effective electric field around the wire. Thus, if you can operate with the bare wire in air you are likely to be sized okay. In nearly all practical cases 36 AWG works okay up to 1200 volts peak. Splicing or spiral wrapping at the point of egress can improve on these numbers.*

Magnetics Design and Manufacture… 5



- *Core grounding occurs automatically when a core is mounted in a standard can (assuming the can grounding pin is used) but grounding is not guaranteed when other mounting schemes are used. There are also floating applications where the core is not at ground potential. In these cases, if the core is properly abraded, a hair pin 24 AWG wire can be attached to each core half using silver epoxy.*
- *As noted previously, special care must be taken to make sure that there is no tin plating on the cans or on other parts. The magnetic materials we use are fundamentally commercial parts so they are cheap but also subject to manufacturing "improvements" and RoHS requirements.*

Magnet Wire Considerations… 1

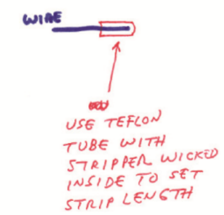
- *There are several types of magnet wire and many people try to go for the heaviest built (H4) and highest temperature (220C) under the largely false assumption that these characteristics increase reliability. The assumption turns out to be fundamentally true in motors and transformers operating at very hot temperatures but not for small high voltage wires operating as low temperatures.*
- *For greatest process uniformity and best wire lay-up of small wires, I prefer HAPT (Heavy Armored Poly-Thermaleze) which is a dual coated wire consisting of a base coat of cross-linked modified polyester resin and a top coat of amide-imide polymer.*
- *I usually procure from MWS Wire Industries using the JW 1177/12B CL-180 H2 spec. There are other manufacturers but I have 30 years of experience working with MWS and they have always delivered a good product at a fair cost.*

Magnet Wire Considerations… 2

- *MWS mostly re-spools Essex wire for standard applications like HAPT so make sure to ask them to provide material less than 1 year old. I have had not problem recertifying wire more than 1 year old if it has been stored in a cool dry place but I always try to use new wire for each mission.*
- *Magnet wire insulation may be crazed or otherwise degraded by exposure to polar solvents (such as water or alcohol). As well, acrylic adhesive dissolves in alcohol and many epoxy bonds may be damaged by even short exposure (>1 min) to trichloroethane vapors.*
- *Due to crazing problems, alcohol or other solvents should be used locally and controlled procedurally with respect to* ***where and how****. Any time solvents are used,* ***an annealing step shall follow afterwards unless otherwise specified. This annealing step consists of baking at 120C (do not exceed 128C) for 1 hour.***

Magnet Wire Considerations… 3

48	Trim wire to allow for a transition to the stripped section of wire. Strip the wire insulation using InsulStrip acid allowing for 4 turns of wrap at the point of soldering. Use Teflon tubing to hold the acid and set the strip length. Apply stripper multiple times until the wires are fully stripped.

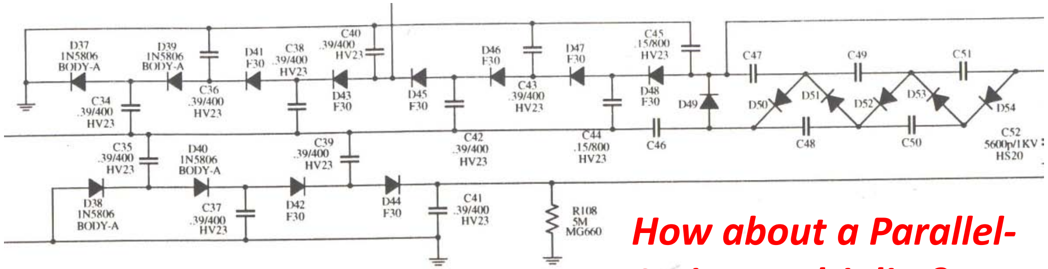


49	Thoroughly wipe off acid with moistened swab followed with IPA or ethyl alcohol swab rinse.

Using InsulStrip

- *I prefer 3M 281 Scotchcast epoxy for bobbin impregnation due its low viscosity and excellent penetration in combination with its good thermal shock characteristics over the temperature range of -65C to +150C. Standard outgassing tests tend to show it a little above the 0.1% CVCM spec but the transformer hot temperature post-cure processing results in-spec outgassing.*
- *Stripping of fine magnet wires is always a challenge. Over many years and many attempts to find alternatives to chemical stripping,* ***Ambion "InsulStrip" gel*** (AMBION CORPORATION, *NAUGATUCK , CT) remains the method of choice for the tougher magnet wire coatings. . This stuff is very dangerous so make sure to prepare properly and handle safely.*
- *For solder terminations on pins that will be re-soldered to a PC board, you want to use a higher temperature solder (I prefer Sn96) that will not re-melt during the later installation process. Note that it has a gray appearance that tends to confuse inspectors so you want to make sure the inspection criteria are clearly noted in the processing procedure.*

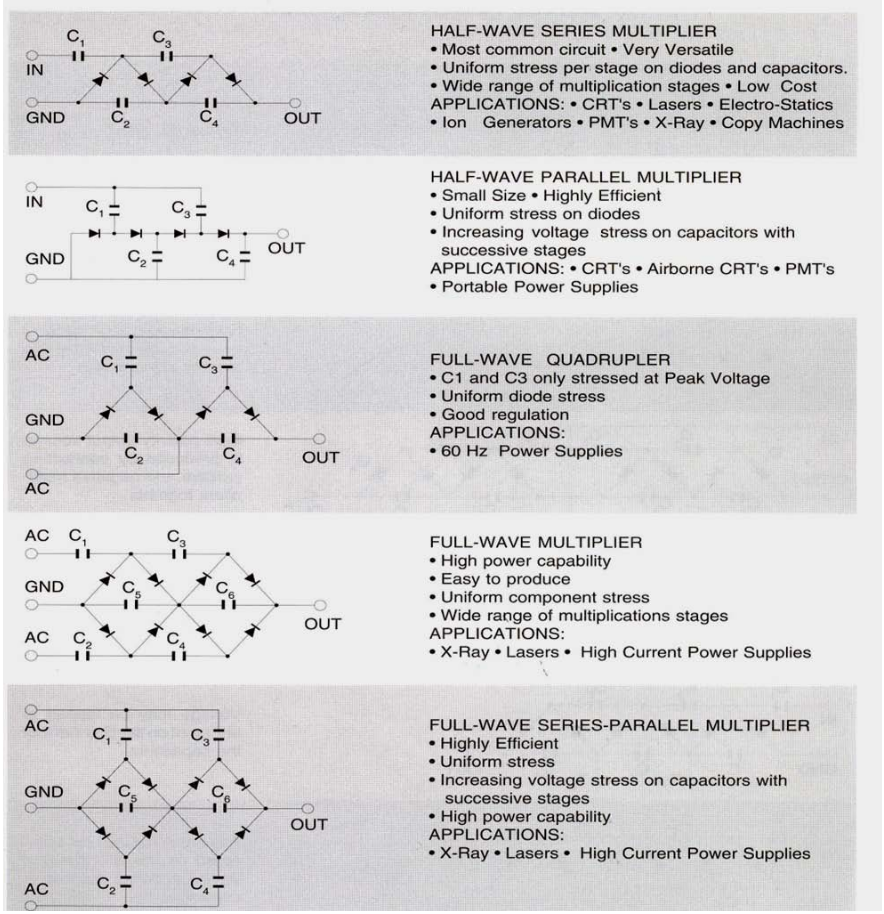
High Voltage Multiplier Design… 1



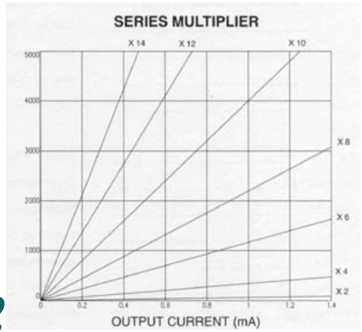
How about a Parallel-Series Multiplier?

Figure provided courtesy of Voltage Multipliers Inc.

- *Most designers prefer a half-wave Cockroft-Walton voltage multiplier (proper name is actually a Greinacher cascade) implementation because of its simplicity and equal voltage per stage.*
- *There are many types of half-wave and full-wave designs each possessing advantages and dis-advantages. Parallel multipliers are more efficient but require higher voltages for progressive stages.*



High Voltage Multiplier Design… 2



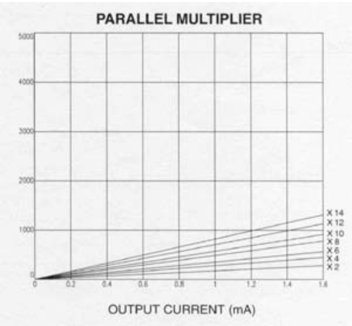
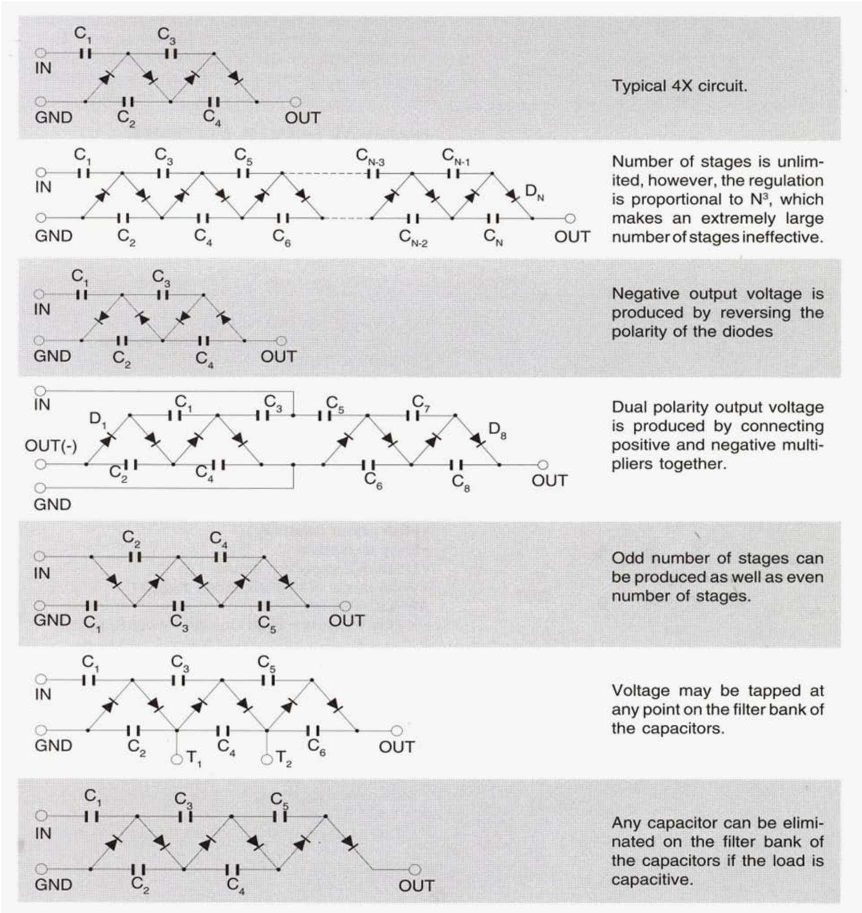


Figure provided courtesy of Voltage Multipliers Inc.

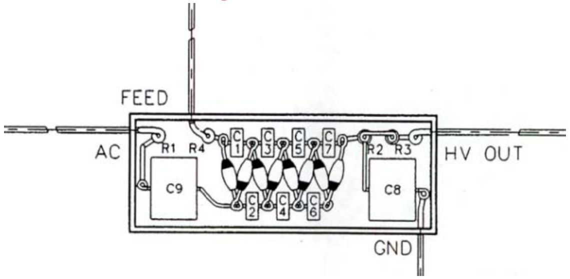
- *The key to understanding a multiplier is to recognize the problem of charge transfer per stage.*
- *A series multiplier must move all of the charge through every stage while a parallel design injects along the length of the stack.*
- *In the end the size due to the CV constraint is about the same for each type but the voltage loss is less on a parallel design.*
- *Designs can be optimized by using larger capacitors and/or progressive staging to limit the loss per stage.*

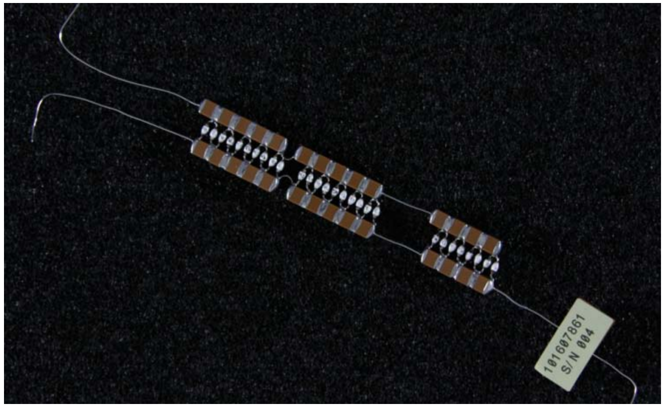


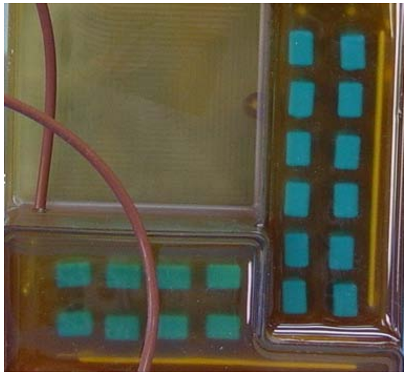
High Voltage Multiplier Design… 3

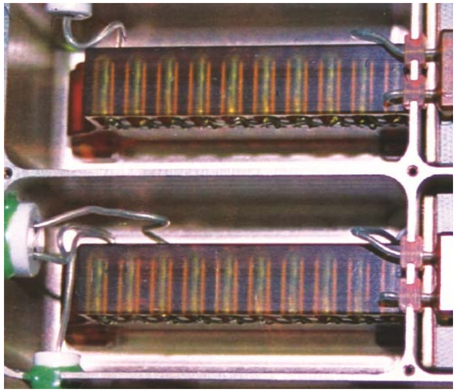
With thanks to VMI, SwRI and Art Ruitberg

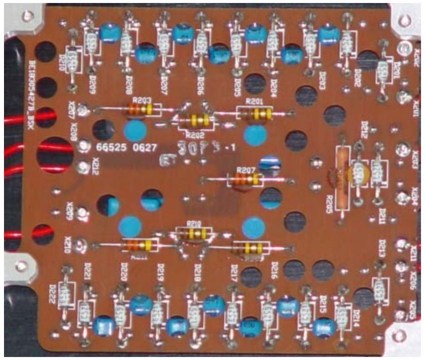
Multipliers can be made in all shapes, sizes and ratings using many different assembly methods.





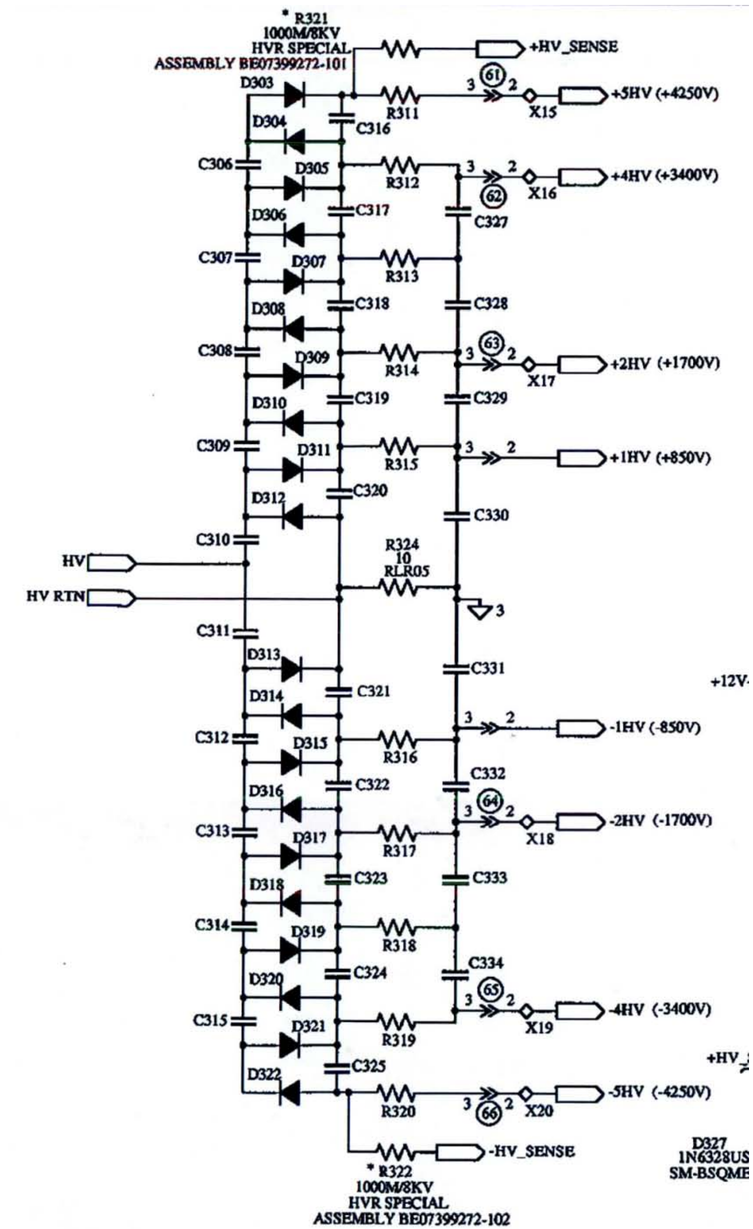






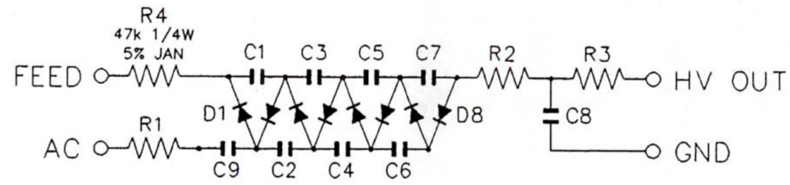
High Voltage Multiplier Design… 4

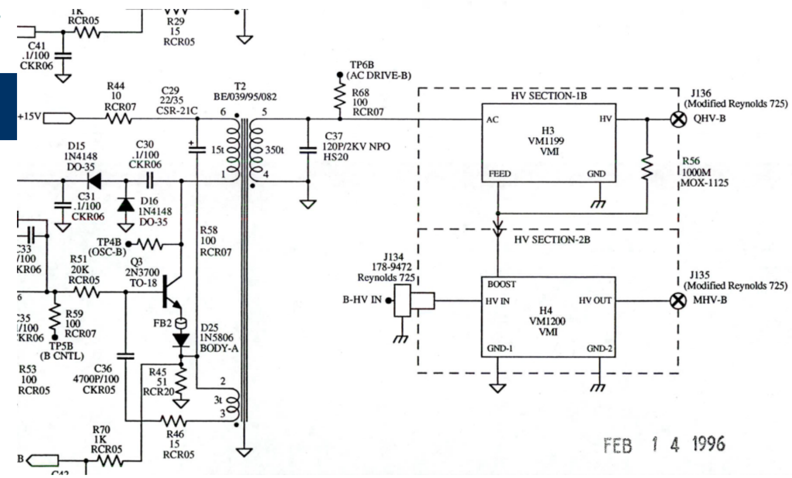
- *In "bulk supply" where the voltage on the overall stack is held relatively constant, **voltage taps** can be implemented.*
- *Depending on the bulk application and regulation requirements, it is also possible to regulate the stack of one of the lower taps with the benefit of requiring a lower voltage rating on the feedback resistor.*
- *As will be discussed later, it is also possible to use a lower tap for AC feed-forward in the control loop.*

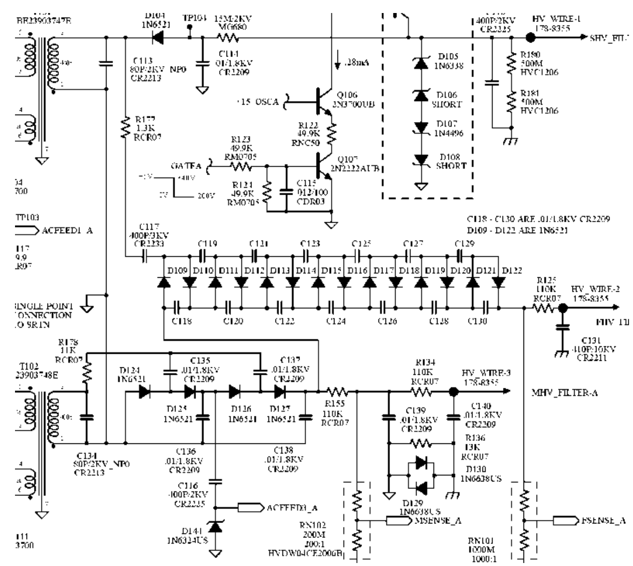


High Voltage Multiplier Design… 5

- *You have seen that transformers can be stacked in specialized applications.*
- *Multipliers can be AC coupled and stacked as well.*
- *In noise-sensitive applications it is usually helpful to implement shields to isolate the multiplier from the output filter.*
- *Remember that multipliers exhibit light sensitivity and can become leaky if they do not have an opaque cover.*

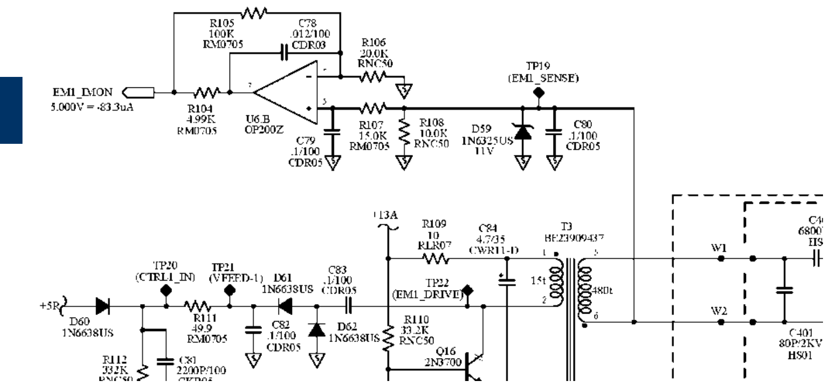


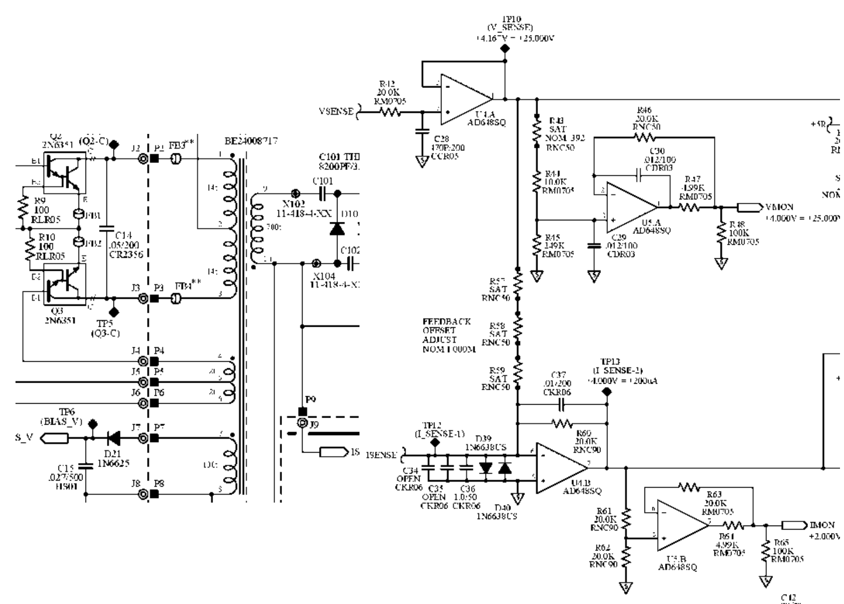




Current and Voltage Monitor Approaches… 1

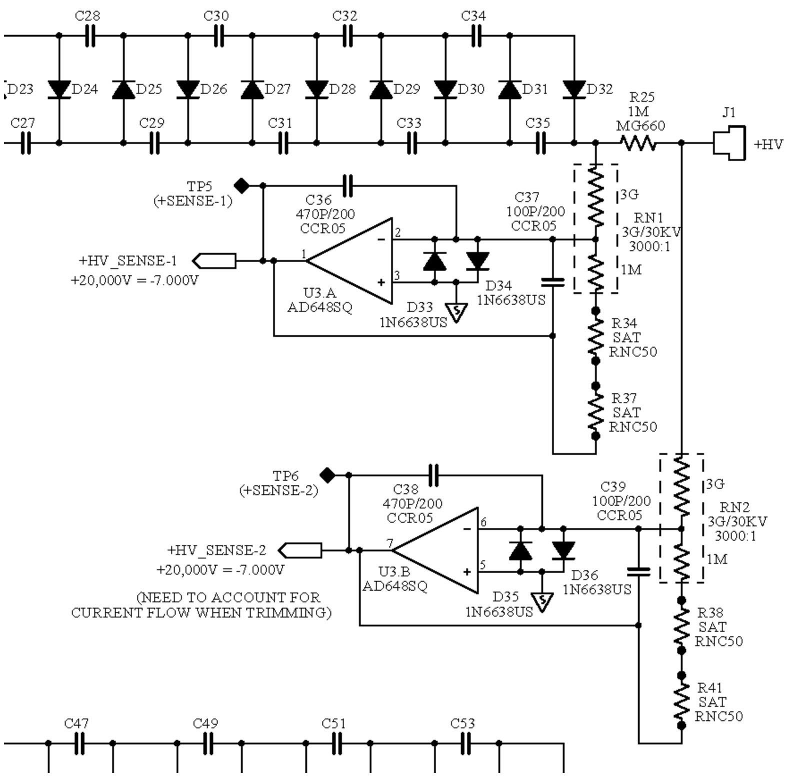
- *The 2 key rule of designing monitors is first, “do no harm” and second, keep it simple.*
- *A properly designed monitor should never affect the main circuit function or add a failure mode to that function.*
- *For current monitors, I always prefer a ground-leg approach where the current is sensed at the return point of the monitor. ALWAYS include clamping protection on the input that accommodates a fault condition.*
- *Feedback current can also be corrected for by coupling the voltage and current monitors.*





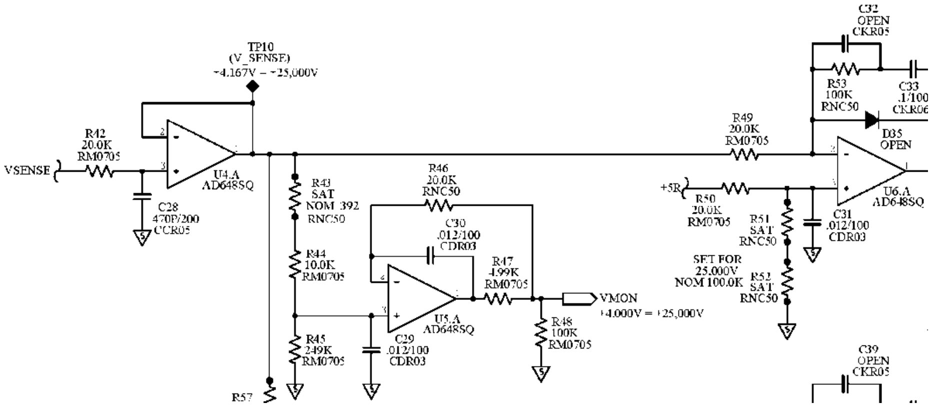
Current and Voltage Monitor Approaches… 2

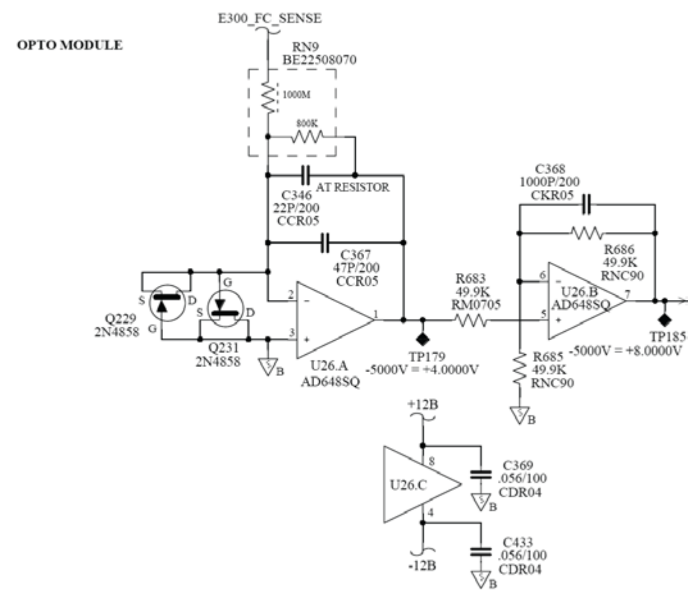
- *High-side current monitors generally add risk and complexity due to the need to sample parallel voltage outputs across a sense resistor.*
- *When designing a high side monitor work hard to get sense resistors that are matched for resistance as well as for Tc and Tc of Vc. It also helps if you only need to match at the operating point over a narrow voltage range.*
- *It is also worth noting that in many application the primary side input current is very closely coupled to the output current.*



Current and Voltage Monitor Approaches… 3

- Voltage monitors also have their challenges, especially if linearity, accuracy and speed are required over a wide voltage range and/or temperature range.
- The challenge is made greater in cases where the feedback system and monitor are inter-connected since there is a trade between power dissipation and bandwidth that must be managed.
- Although a little more complicated, I generally prefer to use a higher impedance with a sense amplifier followed by a separate monitor amplifier and error amplifier.

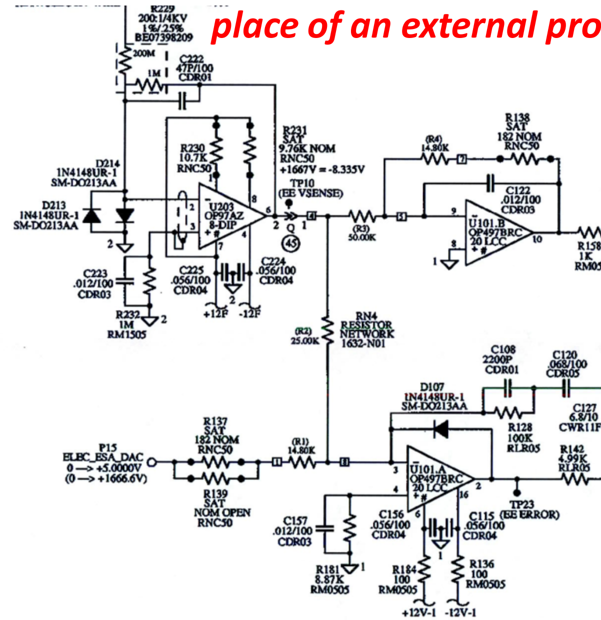


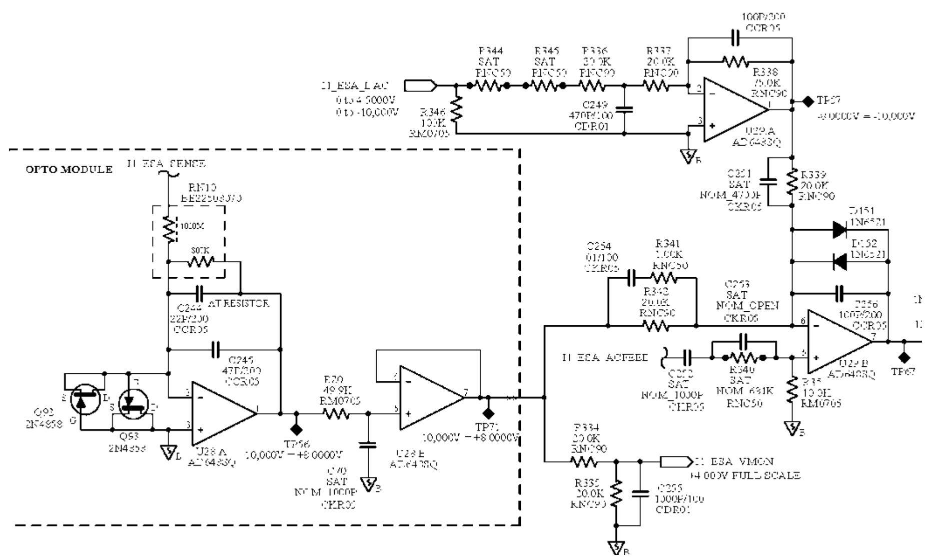


If you trust the sense amp, once it is calibrated you can use it for many tests in place of an external probe.

Feedback and Sense Amp Methods… 1

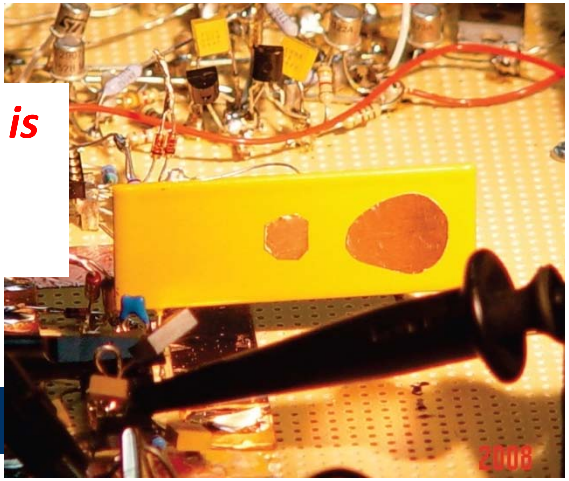
- *Following from the monitor discussion, using a sense amplifier allows matching the feedback resistor to the unique requirements of the monitor and error amplifier.*
- *Loading considerations are also important depending on power, speed and accuracy requirements.*
- *Make sure that the sense amplifier has arc protection.*
- *Feed-forward and Speed-up methods should be integral to the design approach.*
- *V/10 or some means of reduced voltage testing is should also be considered.*





Feedback and Sense Amp Methods… 2

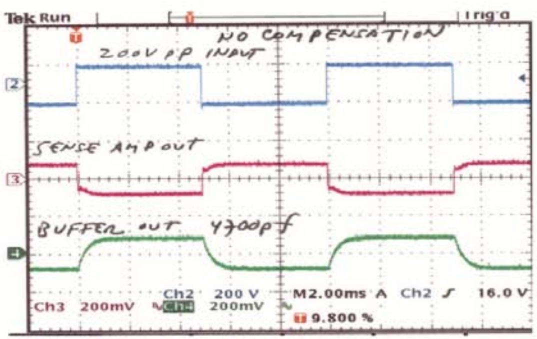
The resistor shown is operating at 10 kV.



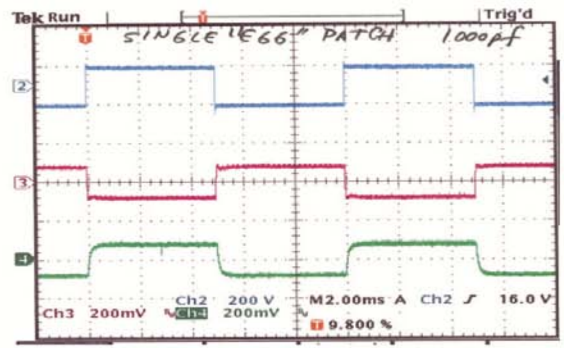
- *For high speed applications, some means of overcoming the distributed capacitance of the sense resistor is generally required unless the resistor is made an unrealistically low value.*
- *The traditional speed-up approaches, are to use a capacitor to bypass the resistor or use a series of resistors that can be impedance matched. Unfortunately, both methods add complexity and can degrade reliability.*
- *An alternate approach that is usable with flat high voltage resistors is **the "egg" method** where patches are attached to back side of the alumina.*
- *It can be seen on the next page, that it is possible through a bit of trial and error to effectively match the distributed impedance of the sense resistor in a way that corrects the response.*
- *Ohmcraft indicates that it should be possible to mask on a backside semiconductive coating that can match the "egg" response.*

Feedback and Sense Amp Methods… 3

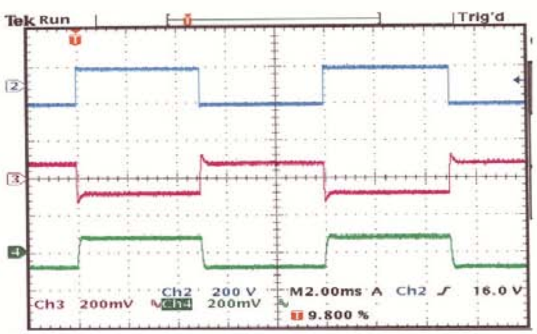
Progressive adjustment of phase response in using a wideband 200 volt peak-to-peak signal injected by a Krohn-Hite 7500 power amplifier.



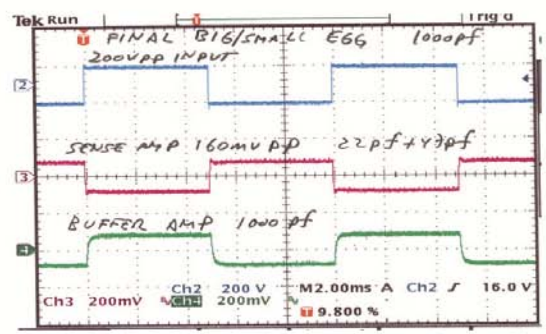
PIC5- Uncompensated
4700 pf on Buffer Amp (DN227)



PIC6- Single Patch
1000 pf on Buffer Amp (DN232)

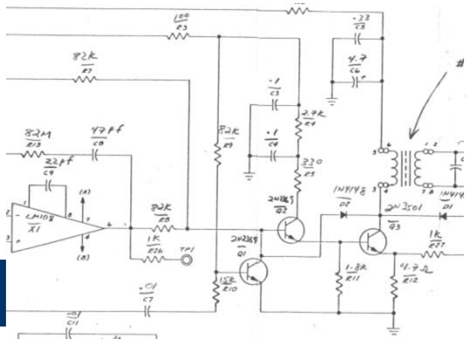


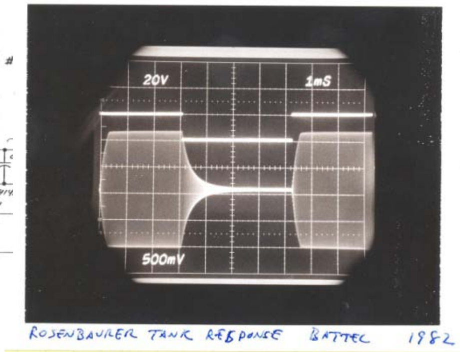
PIC7- "Double Egg" Patches
1000 pf on Buffer Amp (DN233)



PIC8- Final "Big Egg–Small Egg"
Compensation; 1000 pf on Buffer Amp
22pf + 47pf on Resistor (DN234)

Pre-Modulator Approaches…

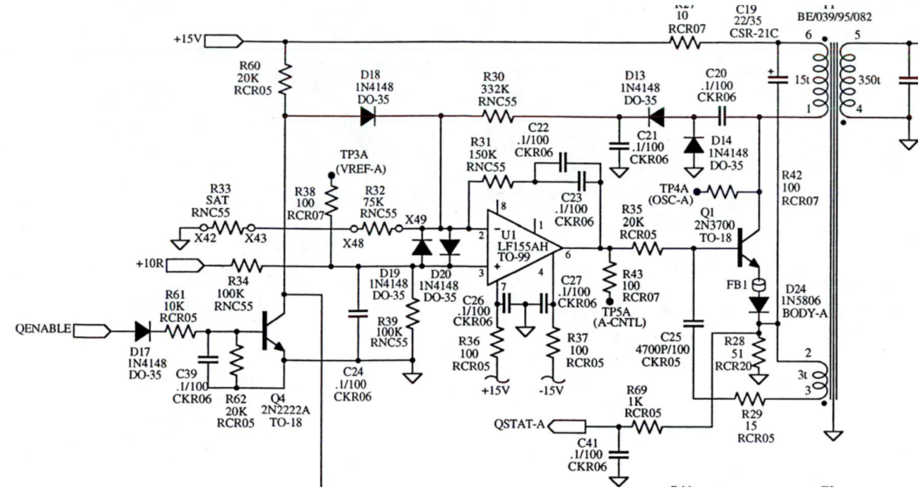


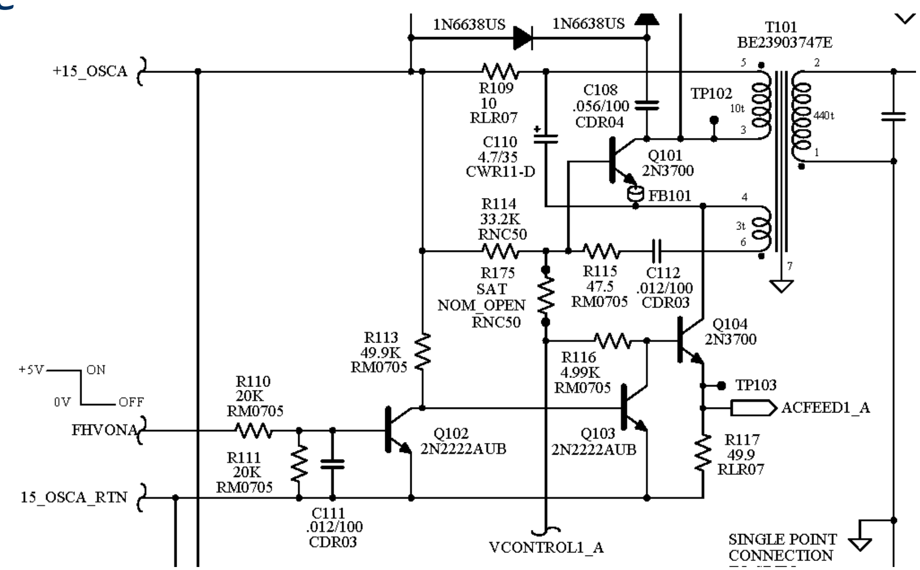


- *Pre-modulator approaches include both pre-regulator and intermediate-stage modulation control methods.*
- *To achieve accurate DC control, linear pre-regulator approaches are nearly always best.*
- *If fast transitions are required, speed is dominated by the combination of stored energy in the tank circuit energy and the high voltage multiplier. In general, the oscillator transistor is both DC gain controlled and On/Off modulated in these applications.*
- *Most fast transition designs, such as for stepping spectrometer applications with multiple outputs, have moved to post-modulator approaches.*

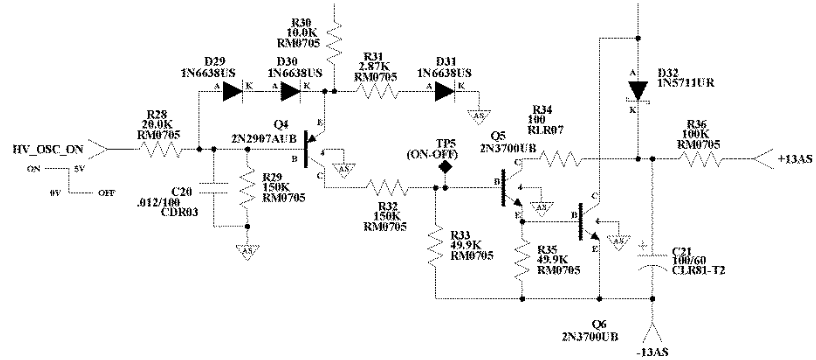
DC Regulation Approaches… 1

- *There are many ways of doing DC control based on experience and design preferences. The main issue to consider is that the loop response of most high voltage systems is very slow. Thus, some means of improving noise rejection is usually valuable.*
- *The single-ended oscillator is operated as a current source so generally the loop control is implemented using either direct control of the oscillator transistor or via cascode control.*

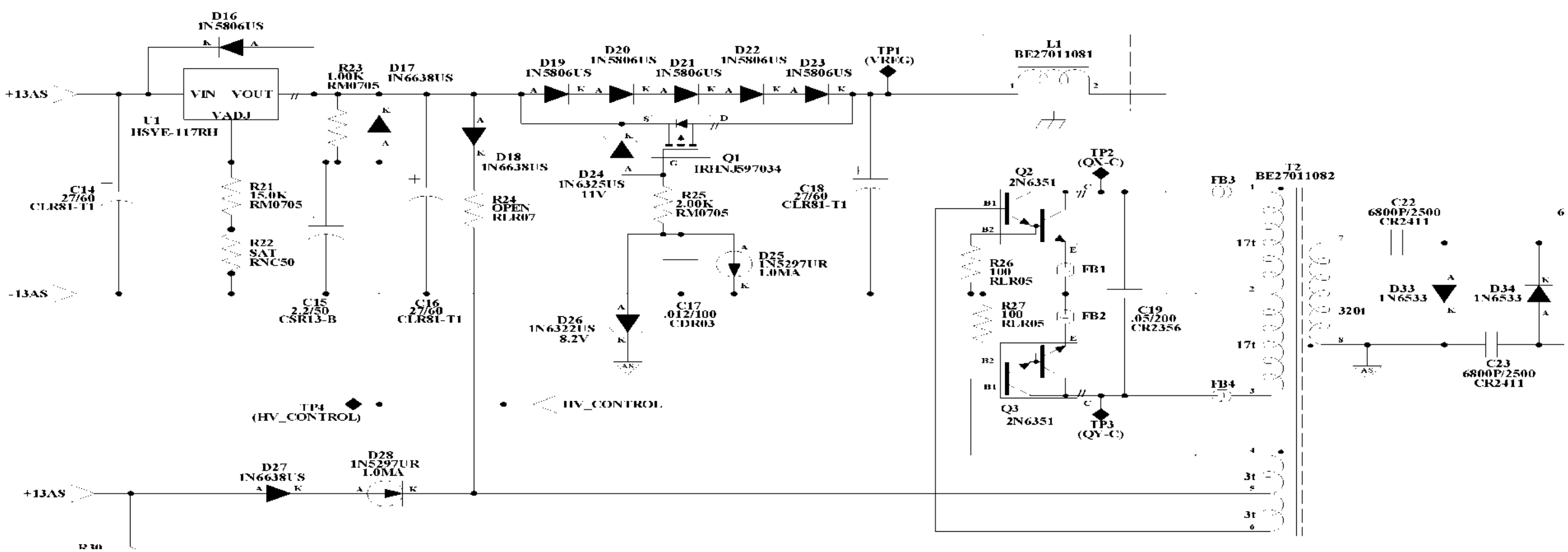




DC Regulation Approaches… 2

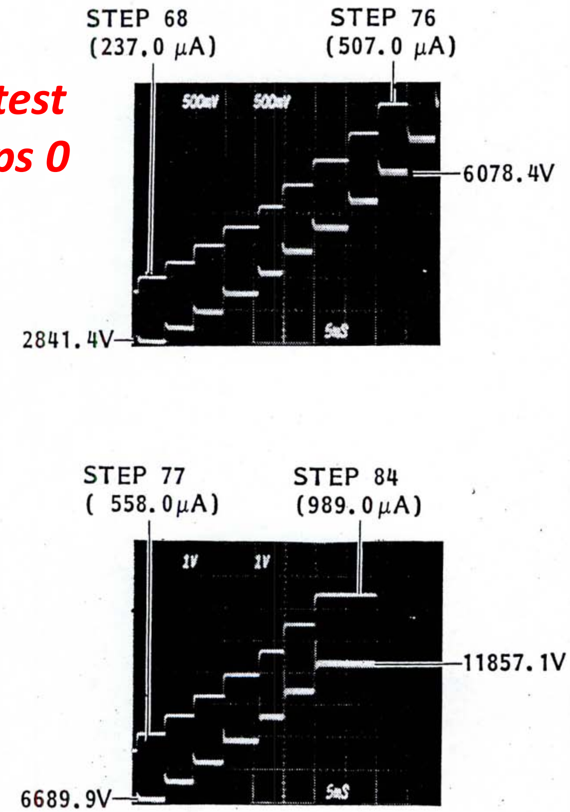


- *The push-pull oscillator is also current-fed but I generally employ a pre-regulator in a dual-loop configuration due to its simplicity and high level of noise rejection.*
- *A soft start approach is also a good idea at power application to reduce the high voltage stress at turn-on, eliminate overshoot and reduce the turn-on current transient.*

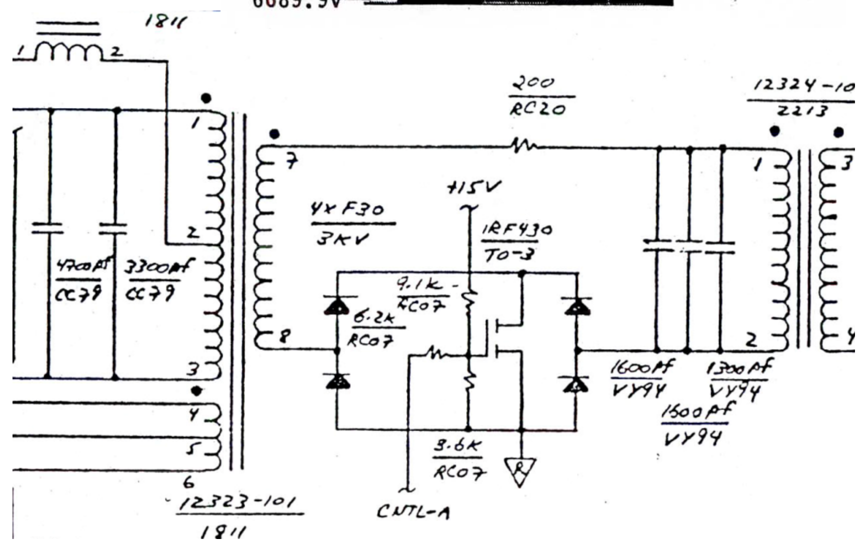


Intermediate Modulator Approach…

EAPS prototype test results. 5 ms steps 0 to 12 kV (1984)



- *An intermediate modulator generally is implemented using 2 transformers and an intermediate diode bride modulator.*
- *The approach allows for a larger total step-up ratio distributed between the two transformers in combination with tank energy stored in the second modulated stage.*
- *The performance can be very fast and accurate if properly implemented.*
- *The big disadvantage is the need to match the resonance between the 2 transformers.*

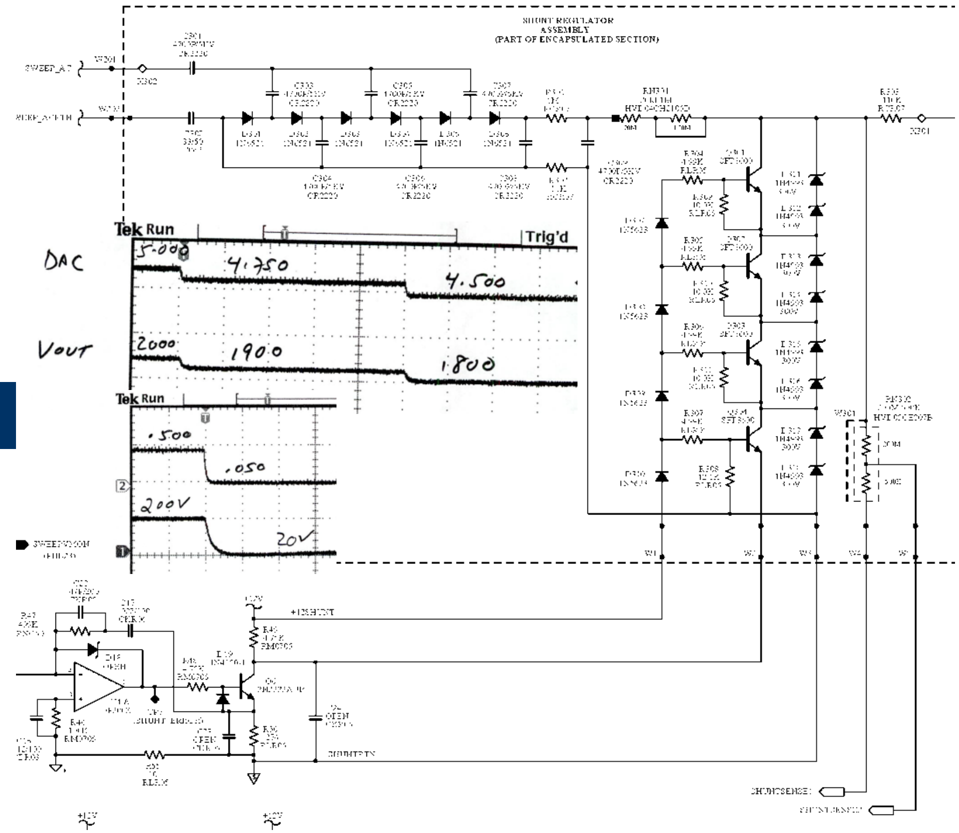


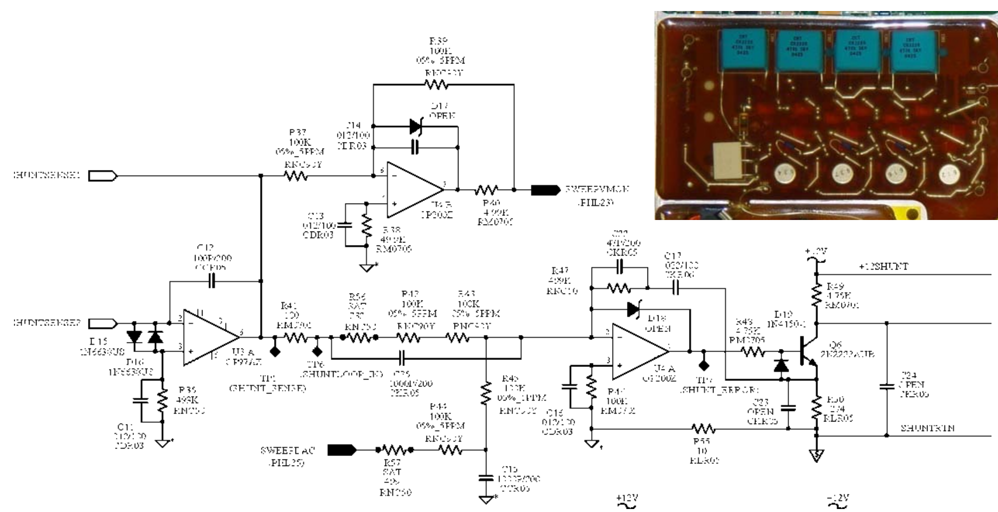
Post-Modulator Approaches… 1

- *Post-modulation approaches have the great advantage of being after the resonant tank circuit and multiplier. They can also be implemented off of voltage taps and in many different combinations from a single bulk supply.*
- *There are two general approaches with many variants. The first uses stacked transistors in a shunt configuration. The second approach uses an LED optically coupled to a high voltage diode operated as a current-controlled-current- source.*
- *The first space LED opto-coupler modulators were done by Rosenbauer at MPI on the Giotto ion analyzer systems. In the early 1990's the Amptek HV601 (followed by other designs) came on the scene and became the dominant approach for most space physics instrumentation requiring output voltage modulation.*

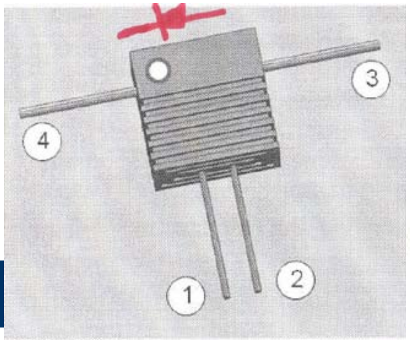
Post-Modulator Approaches… 2

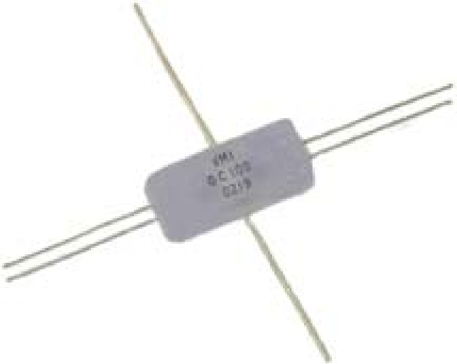
- *The shunt approach is well-proven and can be very fast and efficient when operated in its active direction.*
- *Approach is especially effective in applications that require filtering and have a large output capacitance.*
- *The approach also works really well near zero volts.*
- *I generally prefer cascode control of the stack in order to the manage the overall circuit gain.*





Post-Modulator Approaches… 3

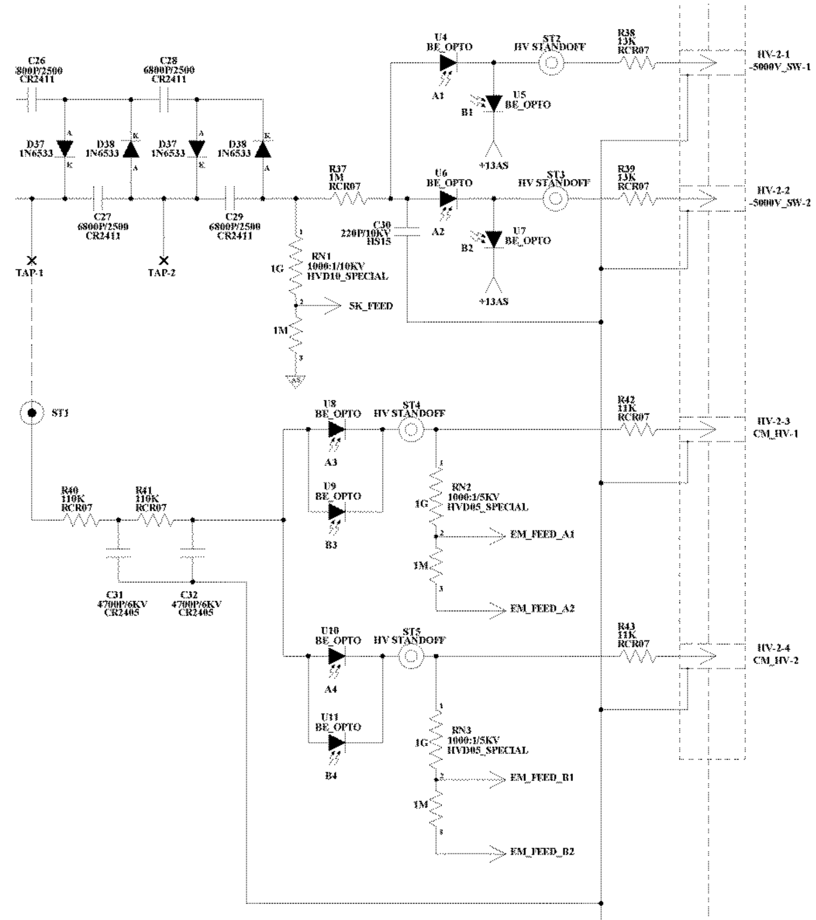




- *The Amptek HV801 and variants such as the VMI OC100HG/150HG and Micropac 66353-XXX are now in common use in high voltage applications requiring fast stepping of high voltages.*
- *In general, the devices are operated off of a "bulk" supply to allow for multiple outputs from a single supply. Devices are fairly small and can be configures in series with a load or as a shunt if the device gain is sufficient and the power dissipation is managed.*
- *Most applications drive electrodes and cables as a capacitive load in combination with the DC resistance of a feedback resistor. Since the device operates as a current source, the speed of transition in these applications is proportional to LED drive current and inversely proportional to load capacitance.*
- *Devices can also be configured single-ended (working against a resistor or current source), in a push-pull configuration or, if you are really clever, in combination with a transistor shunt to achieve better low voltage performance.*

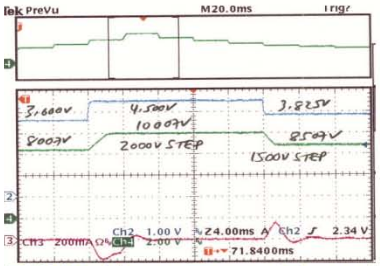
Post-Modulator Approaches… 4

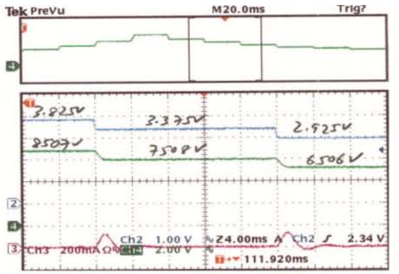
- *The application to the right shows a -5000 volt shutter switch at the output plus a series regulator application for a detector of a selectable multiplier tap.*
- *Applications where the device is used in series with the load are usually the most stressful and must be carefully managed since both the LED and diode need to be on continuously.*
- *For example a 100 uA load through the high voltage diode with a 1000 volt drop results in 100 mW of dissipation.*
- *Remember that the devices are well insulated thermally as well as electrically!*

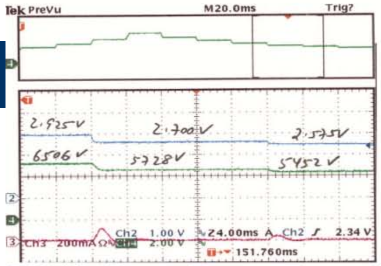


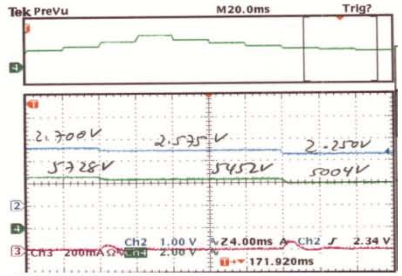
Post-Modulator Approaches… 5

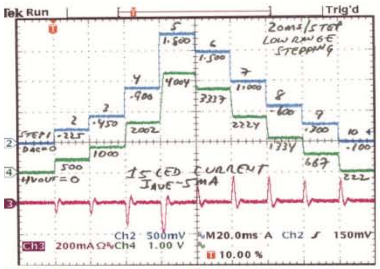
- *Stepping applications require attention to many design factors if performance is to be accurate and stable over temperature and other environmental factors such as radiation.*
- *LED wearout will occur with time so the LED current should be managed within constraints that are consistent with both proper derating lifetime requirements.*
- *Switching speed and settling is dominated by LED current and load capacitance in combination with the sense amplifier frequency response and error amplifier slew rate.*

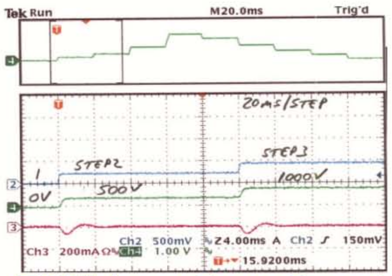

PIC17- Upper Range Expanded (DN368)

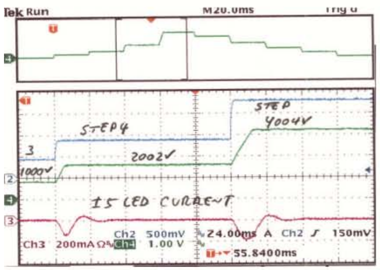

PIC18- Upper Range Expanded (DN369)

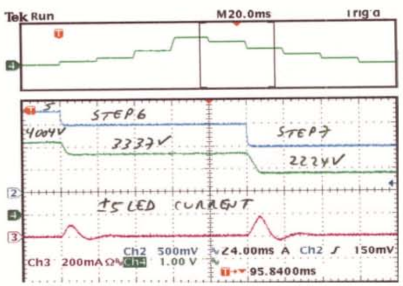

PIC19- Upper Range Expanded (DN370)


PIC20- Upper Range Expanded (DN371)

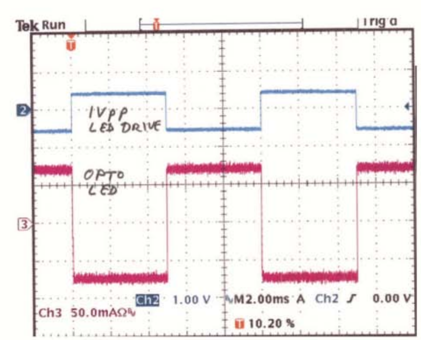

PIC21- Lower DAC Range Stepping; +52/-50 mA (DN352)


PIC22- Lower Range Expanded (DN358)

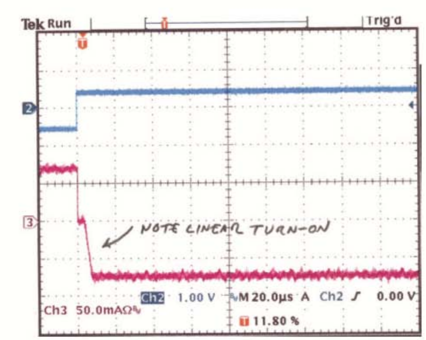

PIC23- Lower Range Expanded (DN359)


PIC24- Lower Range Expanded (DN360)

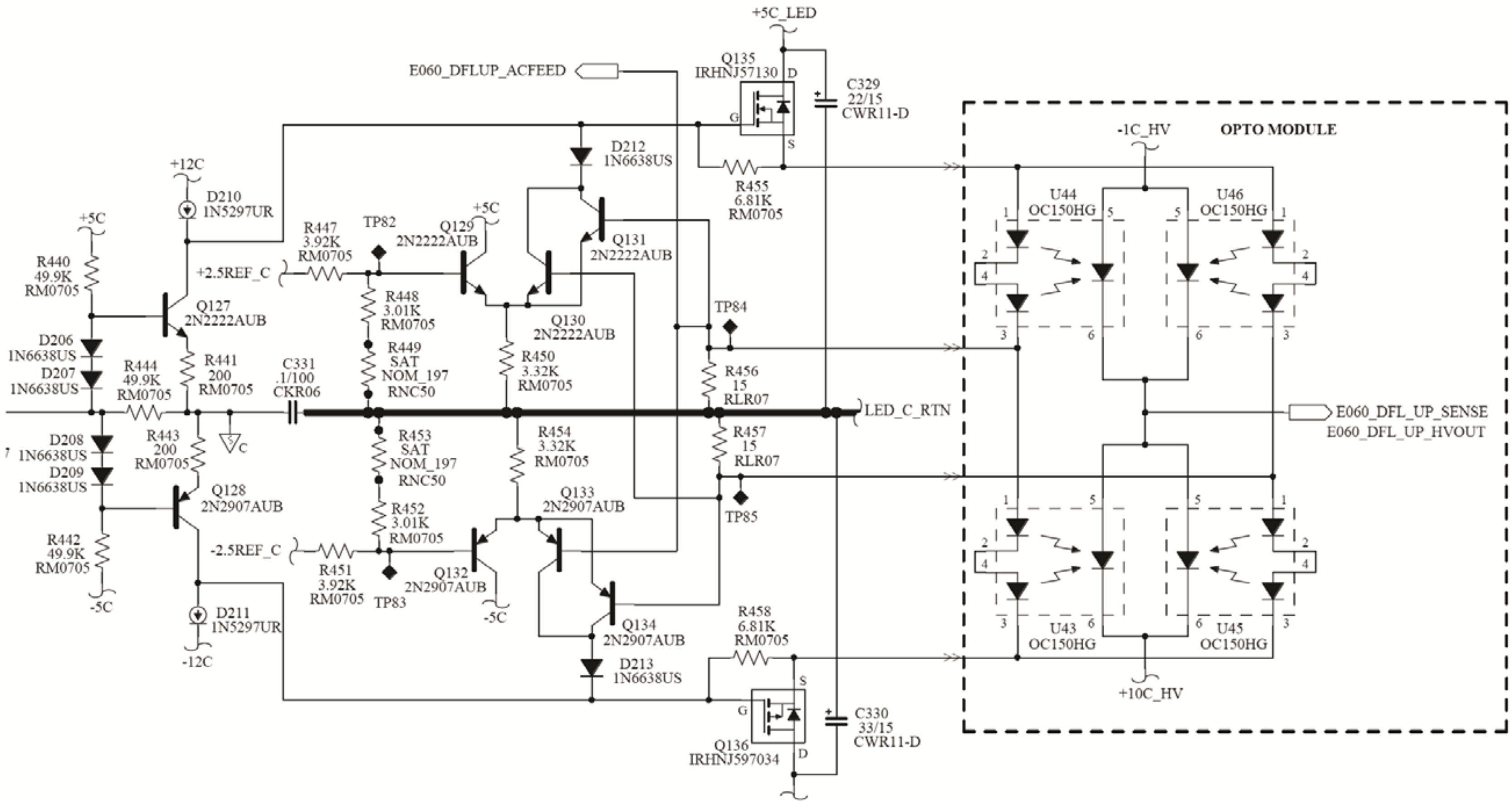
Post-Modulator Approaches… 6



PIC9- +/-500 mV Drive
Active 75 mA CL (DN319)



PIC10- Active Control Range
Narrow for Rapid Capture (DN320)

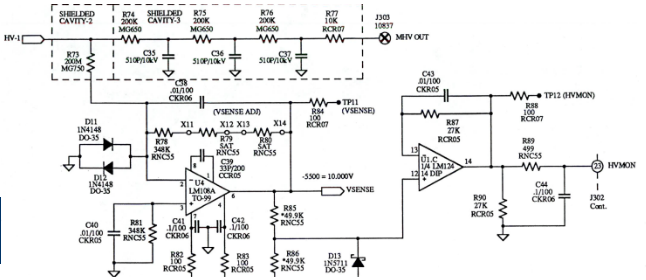


A Few More High Voltage Opto-Coupler Notes…

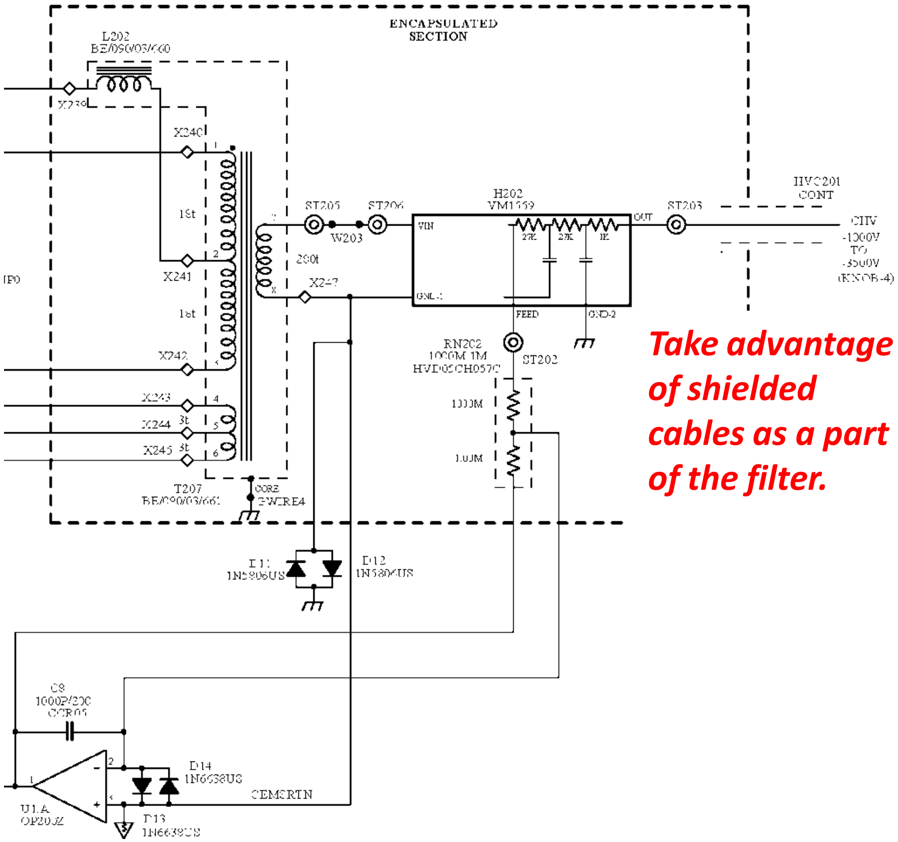
- *Remember that the device is a low volume production hybrid. Each lot will be different so design to accommodate parametric variation.*
- *Devices WILL be damaged if you exceed temperature range, thermal limits or voltage derating so take care with the design and with your test approach.*
- *Device reliability will be affected by the mounting and termination method so take care to design with assembly in mind.*
- *LED life and radiation effects mean the EOL gain will be lower than BOL. Adaptive designs that can adjust speed are helpful.*
- *Floating designs where the LED can operate at the high voltage potential puts a lot of stress on the device. The stress cannot be avoided in most applications so take the precaution of designing the drive circuit to be tolerant do an arc or breakdown problem.*

Output Filter Design… 1

HST-COS multi-pole filter



- High voltage filters designs must combine acceptable performance with absolute reliability.
- If you have the room, multiple smaller stages are more effective than a single stage.
- Feedback should , if possible, be on the inside of the filter for minimum phase shift.
- Use "zap traps" at strategic points to control ground faults.
- Isolate the source end with a resistor and connect the output capacitor to the structure to create a proper arc return path.

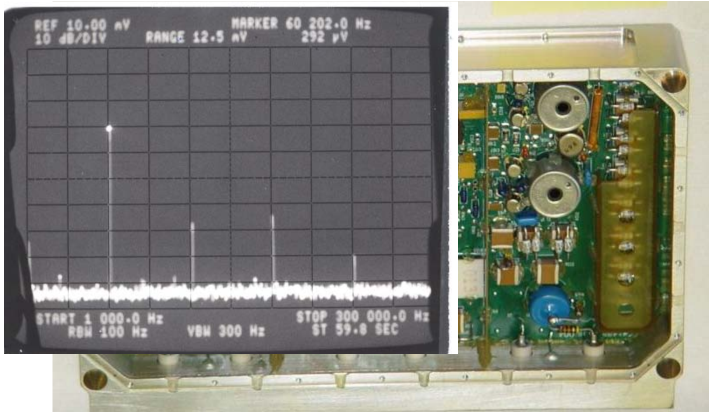


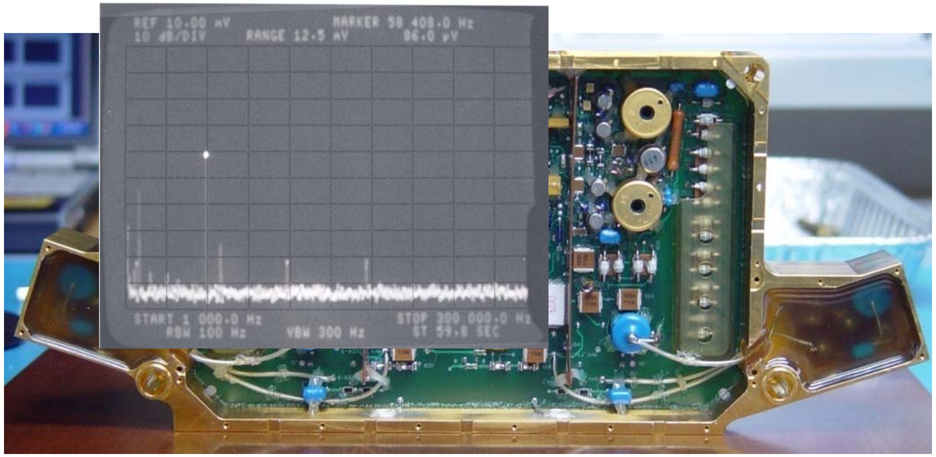
Take advantage of shielded cables as a part of the filter.

Output Filter Design… 2

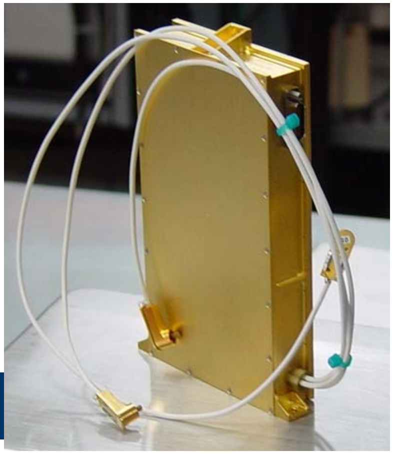
Noise reduction from AIM (2005) design (292 mV) to IUVS (2012) design (86 mV) due to separation into isolated "ear".

- *Separation and/or isolation from the high voltage multiplier is essential if you need good filtering.*
- *Parasitic capacitance (especially in potted sections) can reduce filter effectiveness.*
- *Axial lead capacitors make great a filtered standoff if implemented properly.*
- *Use only carbon resistors or film resistors specifically designed for arc tolerance.*
- *Filtering at the user end is more effective than at the source end.*

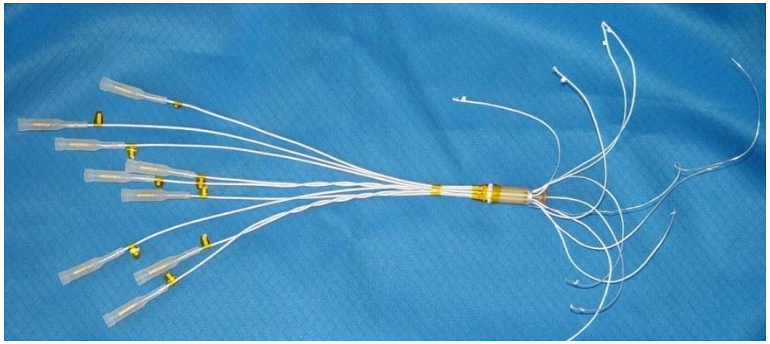




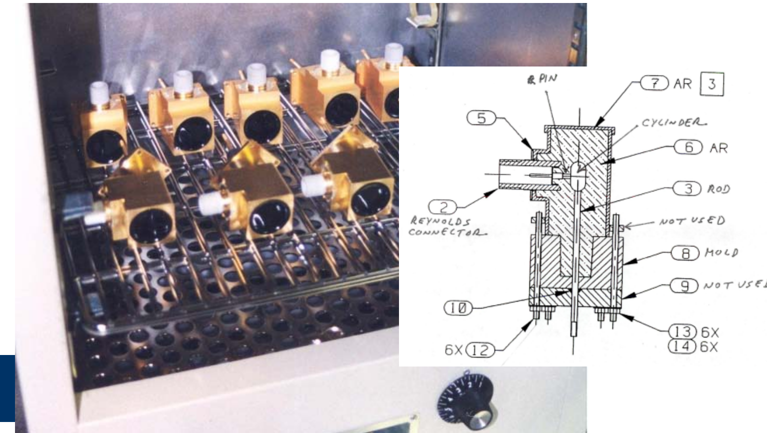
Output Termination Approaches… 1



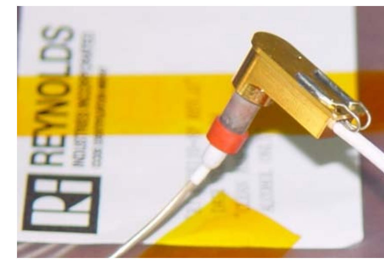
- *Output terminations are often overlooked with respect to their effect on performance and reliability. If not properly selected and implemented they can be the weak point in an otherwise good design.*
- *Basic connection types are umbilicals, connectors and custom terminations using screw or caps.*
- *Umbilicals are the easiest and have been very successful in applications where a connection can be conveniently made at the user end (or vice versa).*

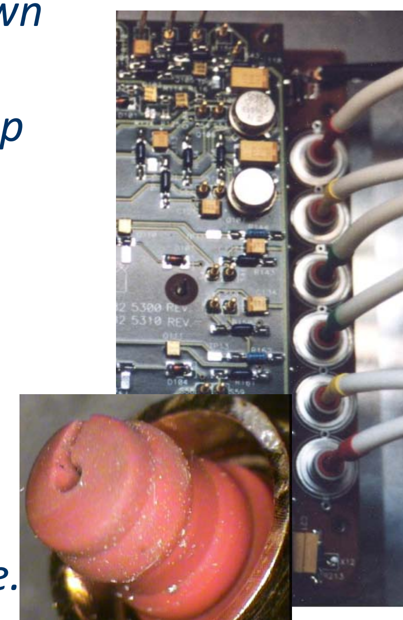


Output Termination Approaches… 2

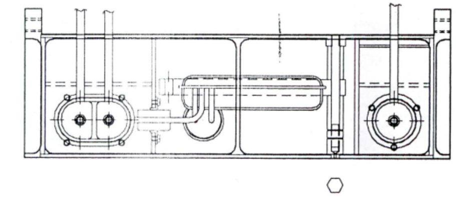


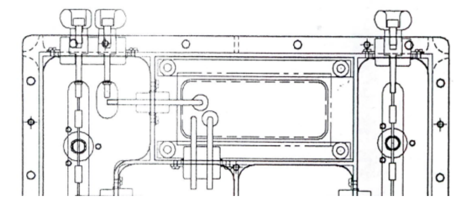
- *Teledyne Reynolds makes a standard set of spaceflight rated connectors that can be reliably used is properly applied. My preferred connectors for space applications are the PeeWee and 725 series. The 600-S series is also good at lower voltages.*
- *A key issue with any connector is managing the internal field gradient while voids or gas pockets that can slowly pump down over time in vacuum.*
- *Well sealed connectors can take as long as 4-6 weeks to pump down into the Paschen region.*
- *Depending on voltage and application a light coating of Bray 601 grease can eliminate voids and increase connector reliability.*
- *Custom connectors are almost always derived from standard connectors.*
- *Another issue is avoiding metal or dielectric particle contamination or damage to the boot at the mating interface.*



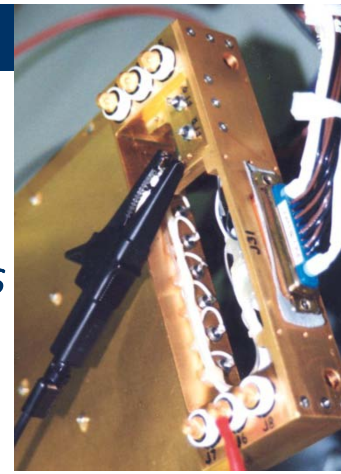


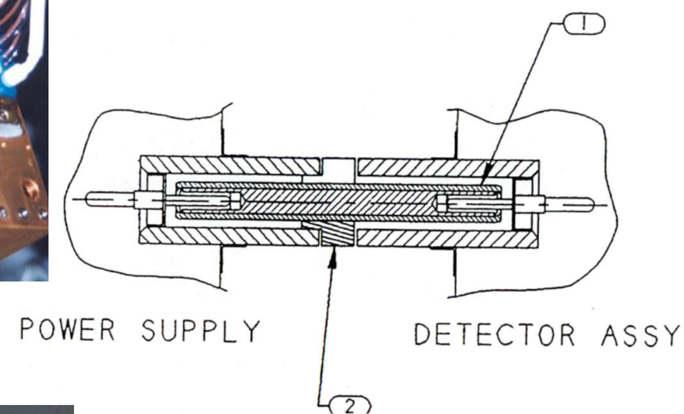
Output Termination Approaches… 3

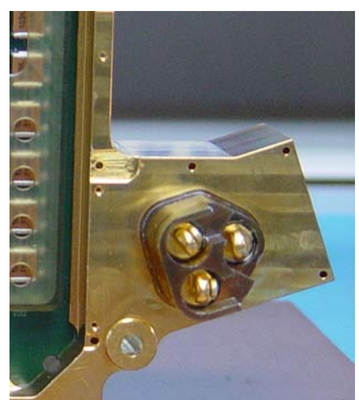


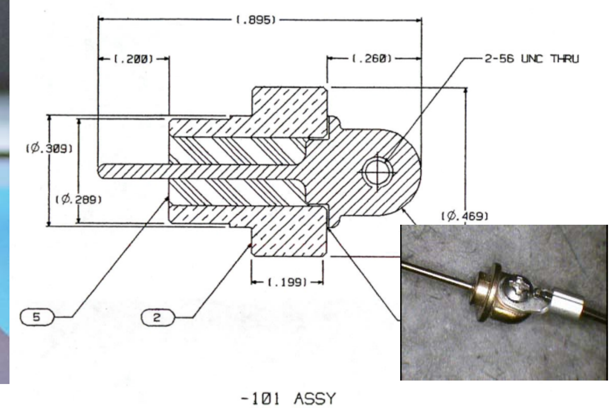


- Custom terminations can be made very reliable and should be considered in applications where connectors or umbilicals are not well suited.
- Generally require field shaping at point of attachment so best applied to unshielded applications.
- Ceramics and plastics are both useful but ceramics offer unique metallization options.
- Screws or toroidal caps are generally used for wire connections.









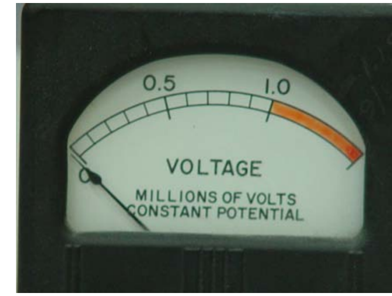
High Voltage Cables…

- *Teledyne Reynolds makes excellent quality high voltage cables in both shielded and unshielded versions.*
- *Unique cable constructions using semiconducting coatings are also possible in special applications.*
- *Coaxial cables have the advantage of both shielding and controlled E-field properties but are more complex to handle and terminate.*
- *Reliability is dependent on proper cable handling including compression, cut damage and/or improper bend radius.*
- *Biggest problem with unterminated coaxial cables is field controlled separation of shield from surface of inner conductor. Triple-junction can form unless approach is "gap-free" using an insert or filler.*
- *An O-ring is often a useful means of pealing away shield in a controlled manner.*

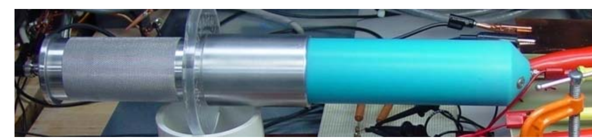
What to do on the other end…

- *It is important to treat the "user end" as part of the high voltage system.*
- *Try to design the terminations, shields and grounding to be consistent and equally reliable on both ends.*
- *Incorporate "zap traps" and ensure both internal grounding and structural pathways can safely sustain an arcing event.*
- *As noted previously, filtering at the user end is more valuable than at the source end.*

Voltage Measurement Approaches… 1

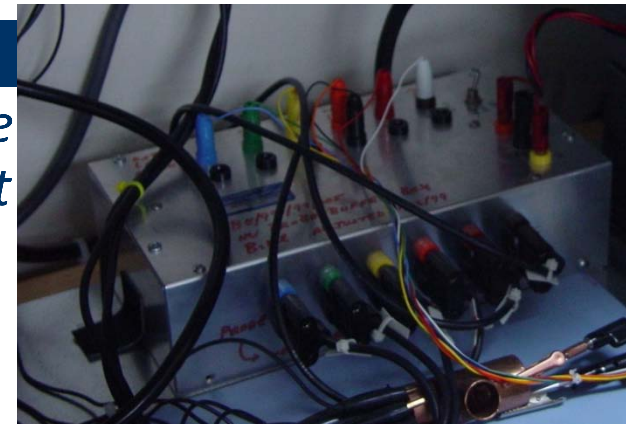


- *There are many types of voltmeters for high voltage measurement applications.*
- *For **direct DC measurement**, the Fluke 80K-40 1000M 40 kV probe is inexpensive but precise, stable with age and repeatable up to ~20 kV with very little voltage coefficient (accuracy will be discussed shortly).*
- *Accurate AC measurements requires special impedance matched probes and dividers.*
- *Probe shields are easy to make with PVC pipe and are highly recommended to maintain a safe setup.*
- *Custom probes make sense in some applications.*



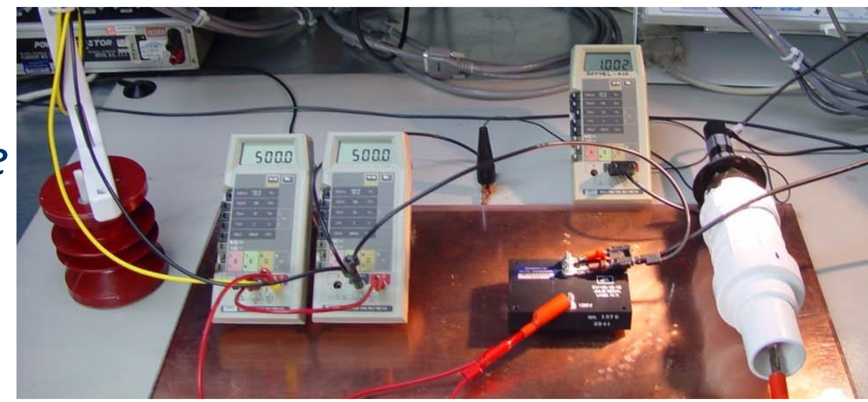
Voltage Measurement Approaches… 2

- *Measurement precision with a Fluke probe is in the 13 to 15 bit range if measurement conditions are properly controlled (0.2 to 0.7 volts per 10,000 volts).*
- *Measurement accuracy depends on DVM input matching and tends to be in the 9-bit range (I match probes to meters and get ~11-bit accuracy)*
- *14 bit performance is routinely possible if matching electronics are built and tuned to each probe. The 6 probe array shown with its matching electronics has maintained 0.1 volt accuracy for over 10 years.*



Probe Calibration…

- *The sad truth is that the only time I have calibrations problems is after equipment returns from calibration! Precision high voltage measurement devices do not go out of calibration if they are kept clean, dry and stored properly.*
- *Rather than calibrate probes, I maintain a testable secondary standard (Julie Research KV-VB-10-10) that can be used to verify calibration at 1000.0 volts using a calibrated combination of DVM's. of probes and setups as part of each test procedure.*

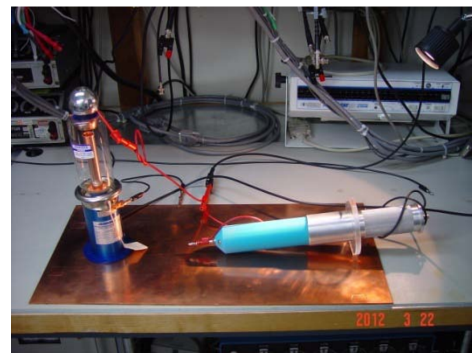


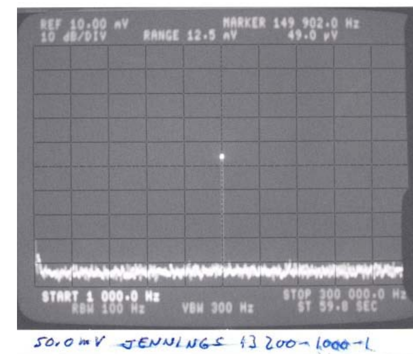
Output Noise Measurements… 1

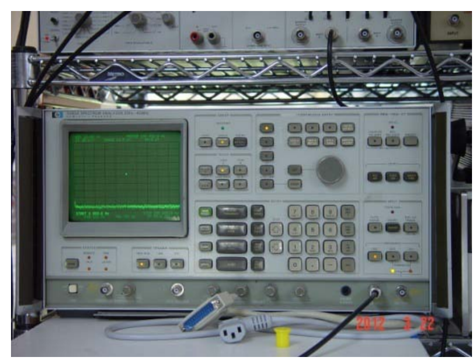
- *Output noise measurements on high voltage systems serve multiple purposes.*
- *Direct measurements of noise are essential to the design verification process as well as to the quantify performance margins between the source and user.*
- *Partial Discharge (Pd) measurements on components (especially transformers during development and capacitors during screening) gives insight into the quality of the design and manufacturing processes.*
- *Partial Discharge measurements at the system level give good insight into the expected reliability and are also an indicator of possible noise problems in sensitive detection equipment.*
- *Corona detection capability (beyond your eyes, ears and nose!) is also helpful for troubleshooting problems during development and test.*

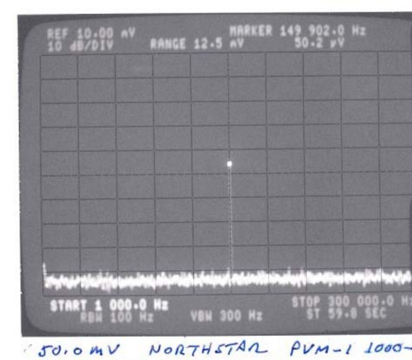
Output Noise Measurements… 2

- *Probe calibration is essential for making accurate and meaningful measurements of output noise on system.*
- *I prefer a direct DC measurement using a Northstar PVM-1 1000:1 probe IF the unit can tolerate a 1000M load.*
- *If the unit cannot tolerate a load, the Jennings 13200-1000-1 vacuum capacitor divider is a little harder to use but also makes an accurate measurement.*

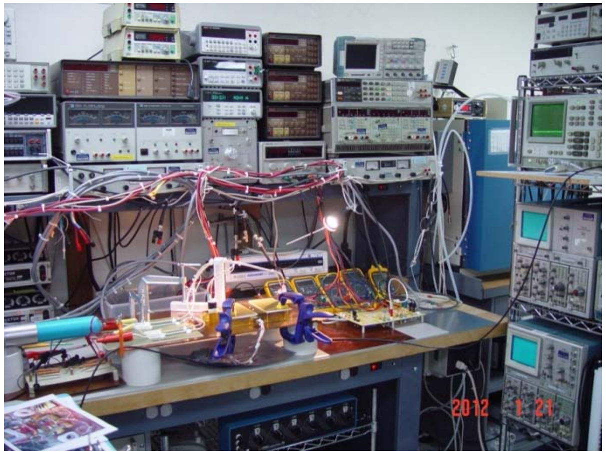


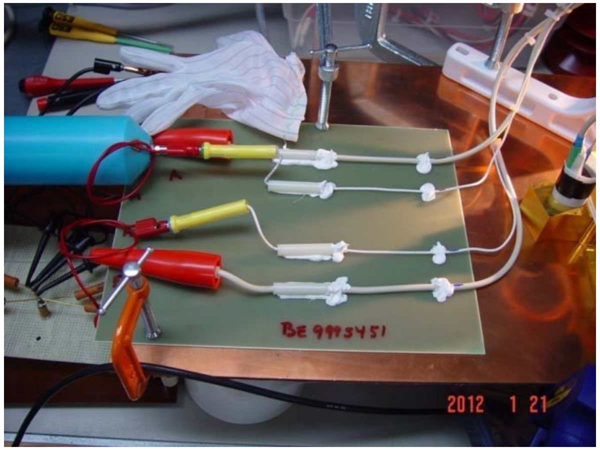


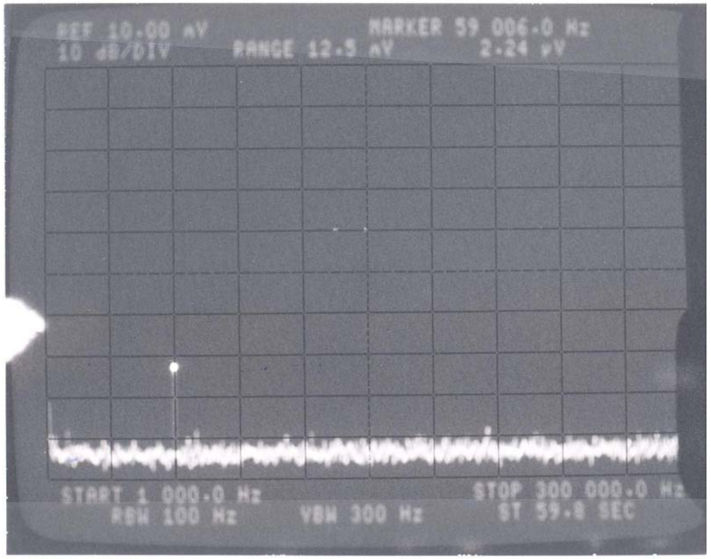




Output Noise Measurements… 3



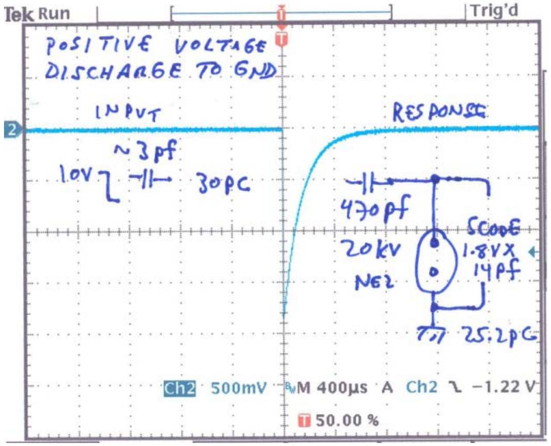


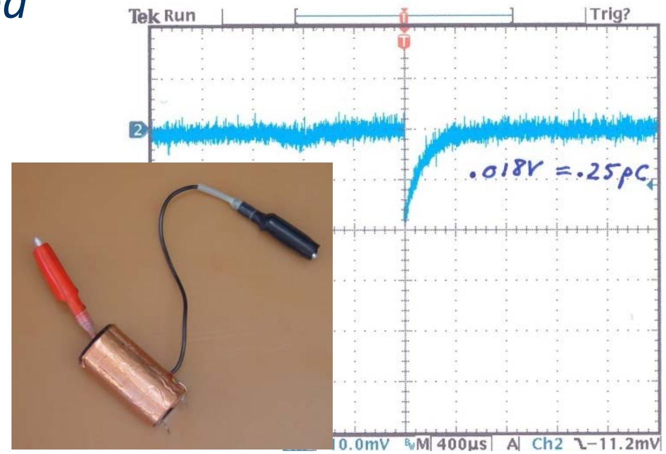


With a good spectrum analyzer measurements down to <500 uV are possible even with the 1000:1 attenuation of the probe.

Pd Measurement…

- *Biddle testers are the traditional means of making Partial Discharges. They use an AC drive signal and are really focused on commercial production market for motors and power equipment.*
- *A simple DC measurement can be made using a capacitive coupler capable of holding off the DC voltage. I prefer the "trigger and count" method where the scope trigger is calibrated for a 50% trigger rate at the measurement threshold.*
- *1 pC is the traditionally accepted threshold for long term damage although numbers up to 2-5 pC are typical and don't seem to have a big effect on reliability.*



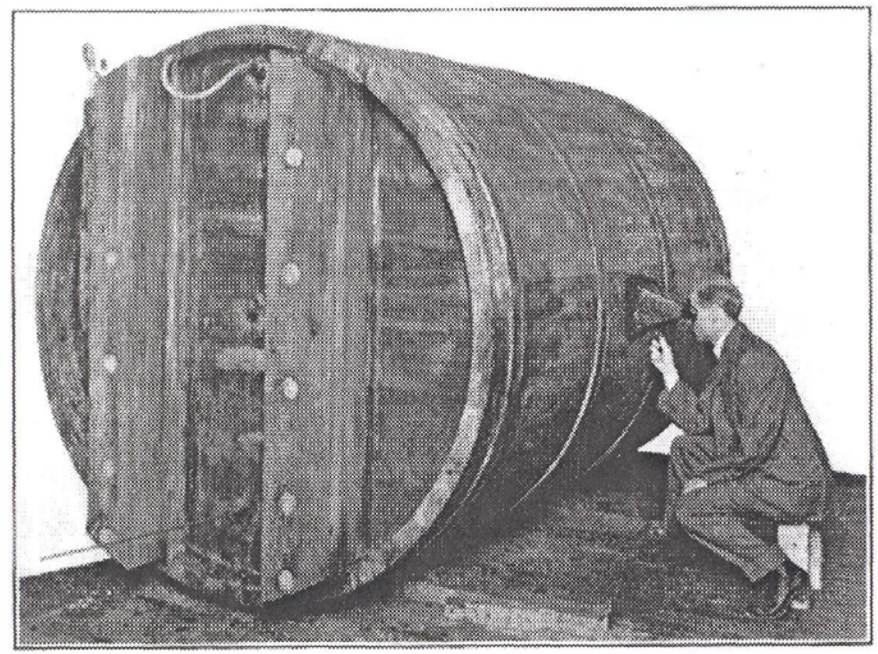


High Voltage Isolation Measurements…

- *Like Pd measurements, most high voltage isolation measurement equipment is geared for the power generation market.*
- *For dielectric measurements I prefer to use DC and make the measurement in a representative test condition.*
- *I mostly use the AEMC 5070 Megohmmeter for step voltage testing although my one and true love is the venerable GR 1863.*

Corona Measurements…

- *Methods have not changed too much since the famous 1912 studies by Peck and others.*
- *If corona does occur, troubleshooting is typically done with a combination of visual observation, photography, gas quenching, RF sensing and analysis.*
- *Low level corona (as opposed to sustained arcing) generally has a damage rate low enough to allow for reasonable troubleshooting.*

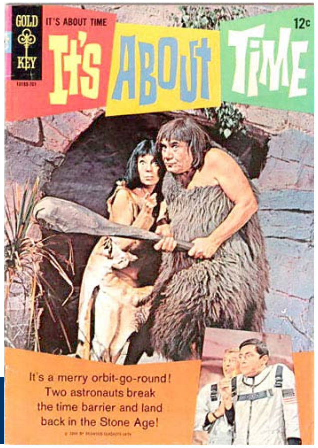


. 96.—Cask for the study of the variation of spark-over and cor voltages with air pressure.

Radiation Effects…

- *Parts issues are well managed by other experts and there is not much I can add other than the fact that there are not many substitutes for some of the key devices. The design and test approach should allow for graceful degradation.*
- *LET and associated upsets need to be carefully manages since a crash of the control circuitry can truly result is a catastrophic failure.*
- *The many excellent dielectrics make charging in the space environment a more interesting issue although one that can typically be managed.*
- *Radiation effects on insulators are usually not a problem since the dose rates need to be really high. However, there are cases such as cables where the surface and penetrating effects need to be carefully evaluated.*
- *The one area worth some discussion is the ability to both partition designs and use potting or other insulators as a radiation shield. The components in the transformer, multiplier and filter are not strongly radiation sensitive. Thus, the shield can be substantially less in these areas.*

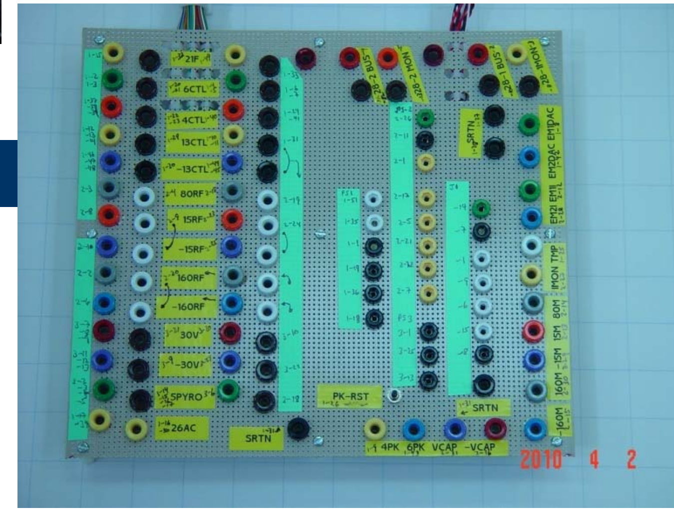
“Shrinking” a Design…



…”*It's about time, it's about space it’s about, strange people in the strangest place”…*

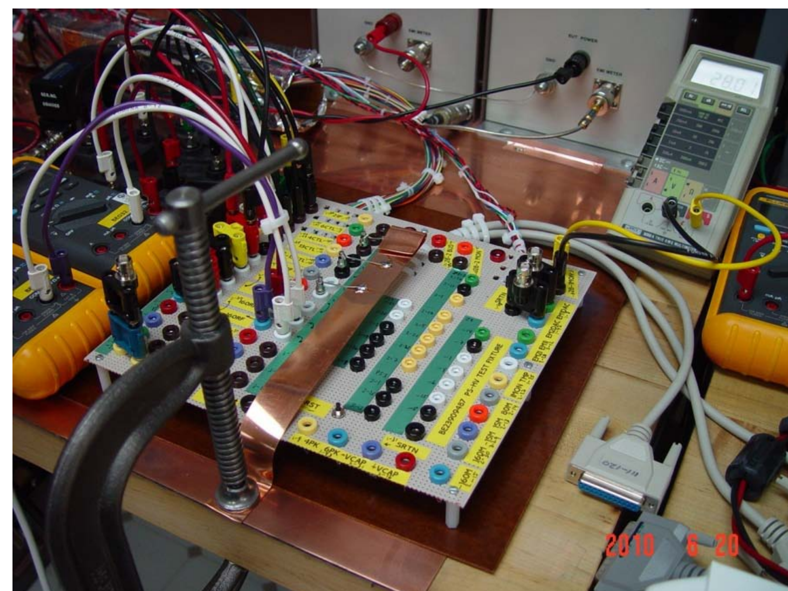
- *People can make up all the requirements they want, but engineers must consider the physics of failure when trying to make a high voltage system substantially more compact than allows for using standard design factors.*
- *The key driver in an optimal design will always be about managing the time dependent dielectric failure mechanism.*
- *The 4 way trade will be between complexity, field spacing (volume), density and operating life.*
- *My approach is to first attack the requirements and then attack the key elemental drivers such at the magnetics or multipliers that can be subjected to accelerated testing.*

Make your GSE simple enough that a 4th grader and (possibly) even your manager can run a test on flight hardware!



GSE Design… 1

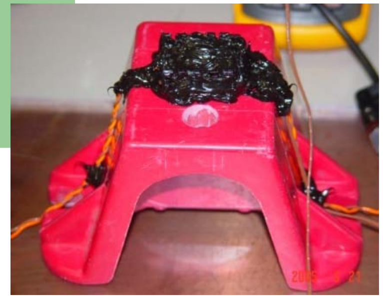
- *GSE design is a place where institutional preferences come into play.*
- *Since I am often asked to resurrect old brassboards or test units many years after their production, I greatly prefer simple "direct connect" designs that have no active circuits or intermediate electronics between the unit and the test equipment.*
- *This approach is dependent on maintaining a "standard" test bench setup but does allow for full visibility in order to fully understand everything that happens during the test activity.*

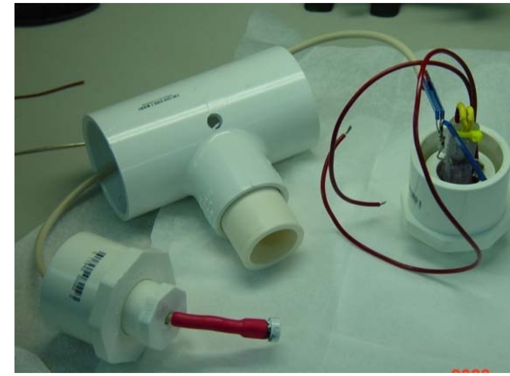


The test problem can still be hard even when the GSE is simple. But, at least you will know the problem is with the hardware!

GSE Design… 2

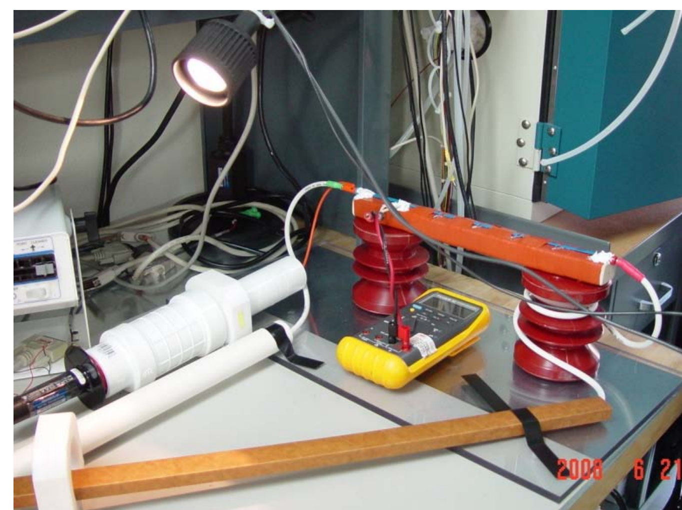
- *A secondary advantage of a direct connect GSE approach is that you also achieve a simple and clean test setup that is easy to analyze and validate prior to connecting the flight hardware.*
- *I always certify the test setup prior to use including performing secondary calibration on the key measurement equipment.*
- *One important lesson learned over many years is to maintain continuity in the test setups. I store every test setup and maintain it for future use.*





Simulator Design…

- *Simulators for high voltage systems can come in all shapes and sizes.*
- *I find that building simulators and then certifying them for the application is actually the most fun part of the overall job.*
- *Keep your simulator simple and robust.*
- *Test your simulator carefully and completely.*



Tools of the Trade…

Use gas tube "equipment savers to protect your equipment!

- It is important to recognize the "real work" happens in the early stages of design when the various elements are laced together as a proof of concept.
- Having a big junk box of insulators, wires, spacers etc. enables rapid setups and investigations.
- Also don't overlook the value of the "the equipment saver". Gas tubes are a great way to protect the input to your meters and other sensitive equipment.

Safety is Always First… 1

- *These notes are simply a supplement to your Institutional Safety Standards. Make sure you are familiar with them and that they are consistent with proper operation of the flight hardware.*
- *Safety considerations are part of the engineering process and should be incorporated into the design.*
- *If the work area has a mixed use, barriers and marking should be employed to assure the area is safe and free of distractions.*
- *Support equipment should be certified and clearly marked.*
- *Only people with proper training in the fundamentals of safe high voltage operation should be in proximity to equipment.*

Safety is Always First… 2

- *Proper grounding is essential. I prefer floating setups with clear simple point grounding paths to a facility ground bar.*
- *I use mats and heel straps rather than wrist straps to keep metal away from the work area.*
- *We have already discussed arc protection and V/10 design approaches. Safe fault-tolerant methods for ON/OFF switching operational control should also be implemented.*
- *Units, test equipment and procedures should also be consistent with safe operation and test.*

Summary Thoughts…

- *By now you have probably concluded that you know the engineering and understand the physics. That is why I have been trying to teach the "art".*
- *You have also figured out the approach I have been trying to teach where there are three fundamentals to developing reliable high voltage systems:*
  - ***Push back on requirements in order to find the optimal middle.***
  - ***Own every element of the design, process and product.***
  - ***Adapt proven and reliable techniques to successfully solve new problems.***
- *Thanks again for your time and your patience. I hope to see you in October at JPL!*