IN COMPLIANCE™

THE COMPLIANCE INFORMATION RESOURCE FOR ELECTRICAL ENGINEERS

THE 2013

ANNUAL REFERENCE

GUIDE

A Compliance Handbook for Electrical Engineers

It's Not Bragging Whe

Lots of suppliers claim to have "The Best Products", but do they ha
AR has been proving it for over 43 years. We've built a reputation
Products that are more powerful, faster, smaller, and more efficient. Produ
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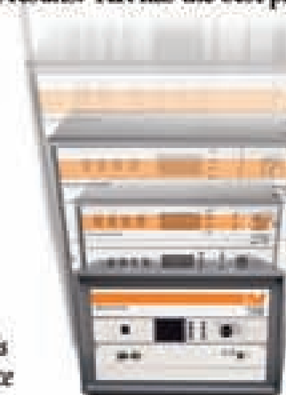

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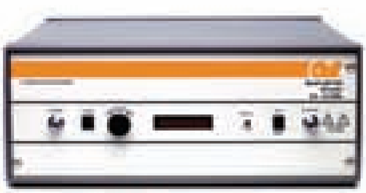
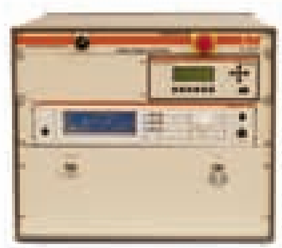


1.0 to 2.5 GHz Solid State Amplifiers
The solid state alternative to TWTA's. Improved harmonics, lower noise, superior linearity and reliability and now featuring 1,000 watts CW.



RF Conducted Immunity Test Systems
These self contained systems driven by our proprietary software; simplify calibration, testing, troubleshooting and reporting. They allow accurate, sensitive and repeatable measurement in one unit. And did we mention incredible speed with outputs up to 150 watts and 400 MHz.

A Special Family of Antennas for High Intensity Radiated Field (HIRF) Testing
High-gain, high-power microwave horn antennas. Typically 20 dBi over isotropic. Suitable for DO 160 HIRF testing.

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rf/microwave instrumentation

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for reliable products that go the distance… and then some.
ucts that outlast, outperform, and outrun any of our competitors.
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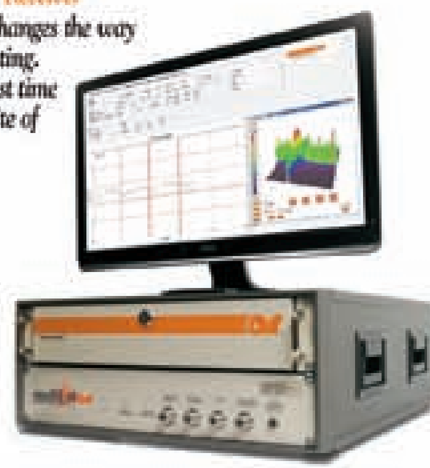
multi star Precision DSP Receiver
This 18 GHz EMI receiver changes the way you think about emissions testing. Data is more accurate and test time is reduced. Testers have a suite of new mitigation tools.



Series amplifiers
ter, more portable, and 50% smaller. Available all the power you need 1200 watts.

multi star Multi-Tone Tester
This incredible system cuts RF Radiated Immunity testing from days down to hours by testing multiple frequencies simultaneously, reducing product development cost and time to market.

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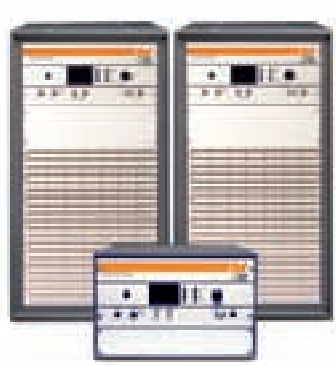
All-in-one test systems for any EMC application, DC to 50 GHz. Our systems make testing more efficient, accurate, and affordable.



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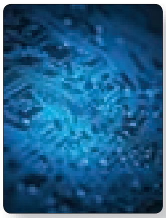
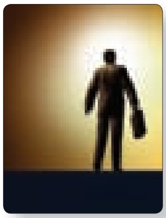
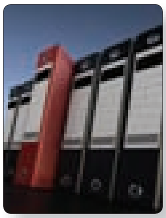
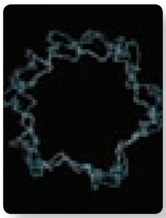
DEPARTMENTS

EMC









EMC (continued)

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We have what you need.
Rohde & Schwarz provides EMC customers with state-of-the-art test solutions for all requirements:
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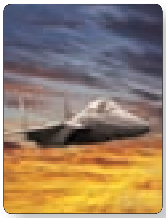

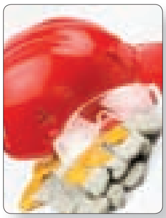

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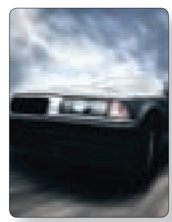


YOU'LL BE IN CHARGE OF THIS PROJECT.
WHAT'S MY BUDGET?
I'LL NEED TO APPROVE ALL EXPENSES.
WHO WILL REPORT TO ME?
YOUR TEAM WILL REPORT TO ME AND I'LL TELL THEM WHAT TO DO.
I'LL START ON THE PROJECT PLAN.
UM...
SKIP THAT PART. I ALREADY HAVE A PLAN IN MY HEAD.
HYPOTHETICALLY, WHO WOULD TAKE THE BLAME IF THIS PROJECT FAILED?
WELL, YOU'RE IN CHARGE...

Letter from the editor

Welcome to the 2013 Annual Reference Guide

Dear Readers,

In your hands, you hold *In Compliance Magazine's 2013 Annual Reference Guide*. We welcome you to our fourth edition of this annual compliance engineering handbook. With each passing issue, *In Compliance* continues to reinforce our commitment to this community of compliance engineering professionals we are pleased to call our readers.

The *2013 Annual Reference Guide* presents a collection of articles which have been selected to provide new (and not-so-new) engineers with current reference materials to navigate challenges you encounter in your daily work. These articles span multiple subject areas: EMC, Product Safety, ESD, Telecom and Wireless and focus on standards, design and emerging technology.

For easy navigation of the 2013 Annual Reference Guide, here's a quick run-down of what you'll find inside. Beginning on page 12, our Compliance Solutions section highlights 10 companies who present in-depth profiles highlighting their areas of expertise. Technical articles span by subject area from page 32 to page 194. Note the black subject tabs located on the side of the book for quick access to your favorite subject. As you near the back of the book beginning on page 195, don't miss the Product Showcases, Consultants Directory and Product Spotlights. Beginning on page 204 you'll find an extensive Buyer's Guide of industry suppliers. These resources are presented in print to assist you in locating service and product suppliers in an easy-to-use (alphabetical) and easy-to-access medium.

We understand that today's engineer needs to be able to access information at the fingertips, be it in print or online. You will find the full content of this print edition on our website at www.incompliancemag.com where you can also sign-up to receive our e-newsletters, read the latest industry news, participate in reader surveys and contests, and renew your subscription.

As always, we welcome commentary on the contents of *In Compliance*. Send your feedback to editor@incompliancemag.com.

We hope you enjoy this year's Guide!

Until next time,

Lorie Nichols, Editor
editor@incompliancemag.com

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Verifying EMC performance is one thing. Diagnosing the cause of EMI is quite another.

When you find a device out of EMI compliance, now you can also understand why. Because the new Agilent receiver is also an X-Series signal analyzer, loaded with diagnostics to show what's happening.

That's thinking ahead. That's Agilent.

Agilent N9038A MXE EMI Receiver

- CISPR 16-1-1 2010 compliant
- Built-in X-Series analyzer runs applications
- Intuitive interface and graphical displays
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Compliance Worldwide, Inc.

Test Locally, Sell Globally and Launch Your Products Around the World!

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Compliance Worldwide is an independent regulatory compliance testing laboratory founded in 1996. We provide testing and certification services for domestic and international markets. We are A2LA Accredited under ISO Guide 17025-2005 and provide EMC, EMI/RFI, CE Marking, Product Safety, Wireless and Wireline Telecommunications Testing and FCC/Industry Canada approval Liaison Services for manufacturers of Electronic Equipment.

Our testing expertise and core technologies we serve include ITE, Audio/Video, Consumer, Telecommunications, Laboratory, Medical, Security and Wireless products. We work with organizations around the world and also cater to very specific product categories, such as, Automotive Radar, Ground Penetrating Radar, Ultra Wideband (UWB), DECT (UPCS - Un-licensed PCS), Cellular / PCS / LTE (AWS) 4G Amplifiers, 802.11 b/g/a/n Access Points and Client Devices, 802.15.4 Zigbee, 802.15 Bluetooth, and VoIP.

We continue to grow and expand, with the completed upgrade to our anechoic chamber we can measure 9 kHz to 40 GHz in an ambient and reflection free environment. The addition of a second OATS site with scheduled completion by the end of 2012 will double our daily capacity for wireless/emissions testing. We also added a 3 Meter ground penetrating radar (GPR) Test Site to the rear of our enclosed 10 Meter site. Our continued success over the last 16 years can also be measured by our innovation to better serve our clients. Over the last decade we have developed one of the fastest radiated emission pre-scanning capabilities in the country, providing excellent correlation to final measurements made on our 10 Meter OATS. We offer reliable and repeatable data, meaning you can debug your product quickly, saving time and money for your company. Today, customers want maximum flexibility and seamless solutions. Whether you are a start-up or Fortune 500 company, now more than ever, demand for quicker time-to-market continues to grow. We offer a timely lab schedule with options the same day the inquiry is made, and our veteran engineers work closely with you throughout the entire testing process and are always available for consultation.

At Compliance Worldwide, our success is driven by our people and their commitment to excellence. We fully understand our customer's challenges with global compliance. We think from the client's perspective and work as a team to ensure total customer satisfaction and support. This has always been our driving force and will continue to set us apart from our competitors. ■

Compliance Worldwide

Compliance Worldwide, Inc.
357 Main Street
Sandown, NH 03873

Tel: (603) 887-3903

Fax: (603) 887-6445

sales@ComplianceWorldwide.com

www.ComplianceWorldwide.com

Year company was founded: 1996

Number of employees: 10

Number of facilities: 1 - 5000 square feet, includes two open area test sites, 3 meter compact semi anechoic chamber and two ground-planes.

Compliance Worldwide

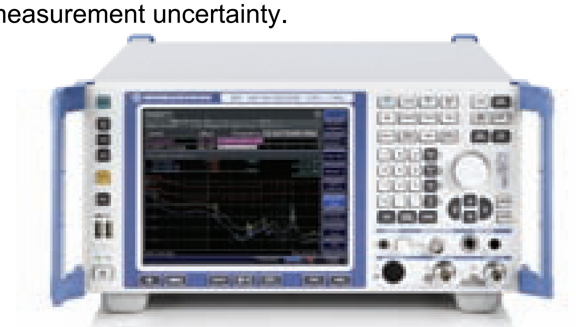
OUR NEW 3 METER OATS FOR TESTING WIRELESS DEVICES IS COMPLETE

EMISSIONS • IMMUNITY • TELECOM • WIRELESS

CW Emissions & Wireless Testing Services
Providing the Latest Advances in Regulatory Testing

Quality Regulatory Testing – Quality Service – Delivered

Compliance Worldwide, Inc. continues to expand its emissions and wireless capability with the purchase of the NEW Rohde & Schwarz ESR7 EMI Receiver and FSV40 Spectrum Analyzer with K54 EMI Measurement Application. We have the fastest, most accurate and fully compliant CISPR 16-1-1 measurement capability available, providing the lowest measurement uncertainty.



Our continuing investment into low noise preamplifiers, low loss cables and EMC antennas allow us to test at the recommended distances typically 10 or 3 meters for a given standard, providing you with the best possible results. Our Rohde & Schwarz SMB 100A 40 GHz signal generator allows us to quickly verify operation of high frequency cables and special purpose notch filters for testing wireless devices.

The upgrade to our 3 meter semi anechoic chamber with Panashield HYB-NF Hybrid Absorber, allows us to measure from 9 kHz to 40 GHz in an ambient free environment with minimal reflections, and our state of the art, impressive weather enclosed 10 Meter Open Area Test Site (OATS) ensures you receive the most accurate numbers available. Of course if you need to go higher, we have all the necessary mixers and horns to get you to 110 GHz and in the future 200 GHz.

Our veteran team of RF engineers and experienced technicians provide complete customer service before, during and after your testing is completed. We stay up to date with the new editions of the standards, upgrading our facility as the ever changing requirements occur. Over the last decade we have developed one of the fastest radiated emission pre-scanning capabilities in the country, providing excellent correlation to final measurements made on our 10 Meter OATS, meaning you can debug your product quickly saving time and money for your company.

An additional purchase of the Rohde & Schwarz SMBV100A Vector signal generator allows us to simulate the latest technologies such as 802.11n, WiMax, LTE and other complex modulations to 6 GHz and generate Dynamic Frequency Selection (DFS) Radar pulses for the US (FCC), Canada (IC), Europe (ETSI), Australia / New Zealand (AS/NZS), Japan (TELEC) and South Korea (KCC). The flexibility and support from R&S to create new waveforms and future technology requirements, allows us to always be up to date with the latest standards and current wireless technology.

Photographs Reproduced with Permission, Courtesy of Rohde & Schwarz, Inc.

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Providing Solutions for EMC Test and Measurement

ETS-Lindgren is one of the world's largest vertically integrated manufacturers of EMC systems and components. We are engaged in every aspect of the EMC industry; engineering, manufacturing, sales and support, calibration and repair. We are also committed to wireless, microwave, acoustic and medical technologies.

Company Roots

We trace our earliest roots to the 1930's when the Ray Proof Company began producing x-ray shielding for the medical market. In 1995, EMCO, Rantec and Ray Proof joined together to form EMC Test Systems, known then as ETS. Later, other companies were acquired; Euroshield Oy, Lindgren RF Enclosures, Holaday Industries, and Acoustic Systems. Today our company is known as ETS-Lindgren.

Global Scope

Headquartered in Cedar Park, Texas, ETS-Lindgren conducts business around the globe.

Our diverse and highly skilled global workforce consists of approximately 750 employees in North America, South America, Europe, and Asia. We have four manufacturing facilities in the US, and one each in Great Britain, Finland, and China.

Our sales network of more than 60 independent representative and distributor organizations provides knowledgeable sales, service and support around the world.

Commitment, Growth and Investment

ETS-Lindgren is committed to our industry and encourages our employees to participate in standards committees, as speakers and session chairs at symposiums, and as authors and lecturers. It would be difficult to attend a symposium and not see an ETS-Lindgren team member in front of a podium, or read a journal or trade magazine without reading something authored by one of our engineers.

Our growth is propelled by meeting our customer's need for systems and components that provide reliable service, repeatable results, and value at a fair price. Our history of success and proven track record virtually eliminates risky outcomes for our customers.

ETS-Lindgren believes in making investments that enable us to serve our customers better. Our manufacturing facilities use efficient, cost reducing systems. Our engineers work with modern equipment. We continue to expand our locations to better service our customers, such as our newest office in Bengaluru, India.

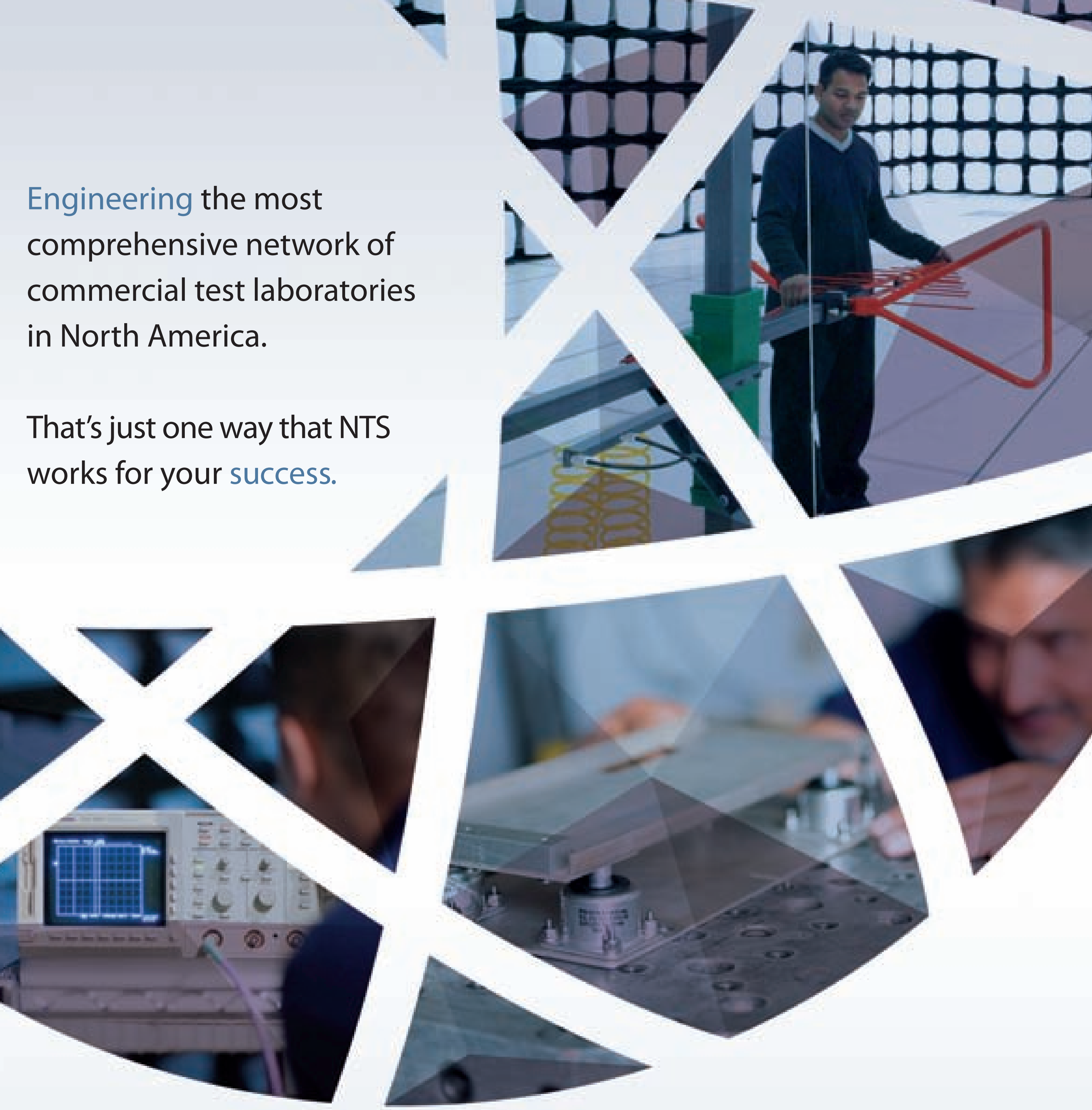
Environment and Safety

As a company and as individuals, ETS-Lindgren take great pride in contributing to the communities where we live and work. Our efforts include the support of local charities, one of which benefits children with hearing disabilities. We also care about the environment and are proud of the many ways in which our employees work to safeguard it.

Our persistent efforts to improve on our safe work environment continue to pay off. We provide ongoing safety training and awareness, and a safe place to work.

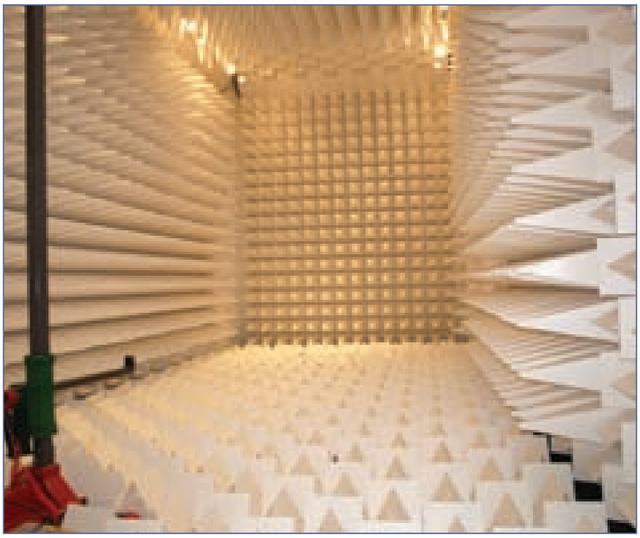
Our Work Ethic

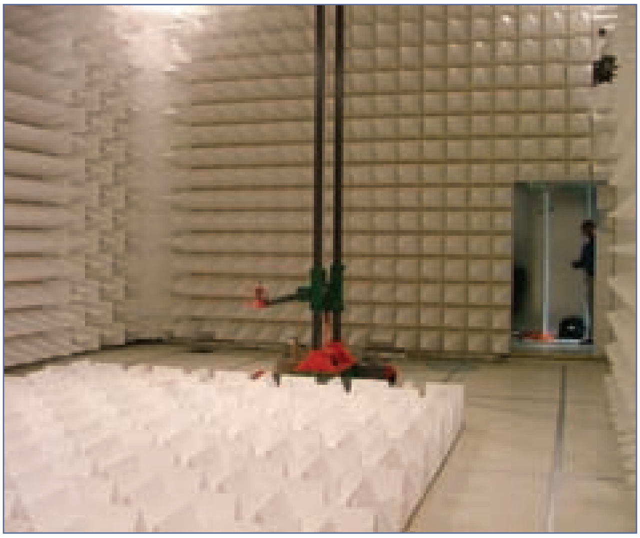
ETS-Lindgren recognizes the importance EMC has in a world increasingly dependent on electronic devices operating safely and compliance with regulatory standards. That's why our employees work daily to design, manufacture and support the systems and components our customers can depend on.

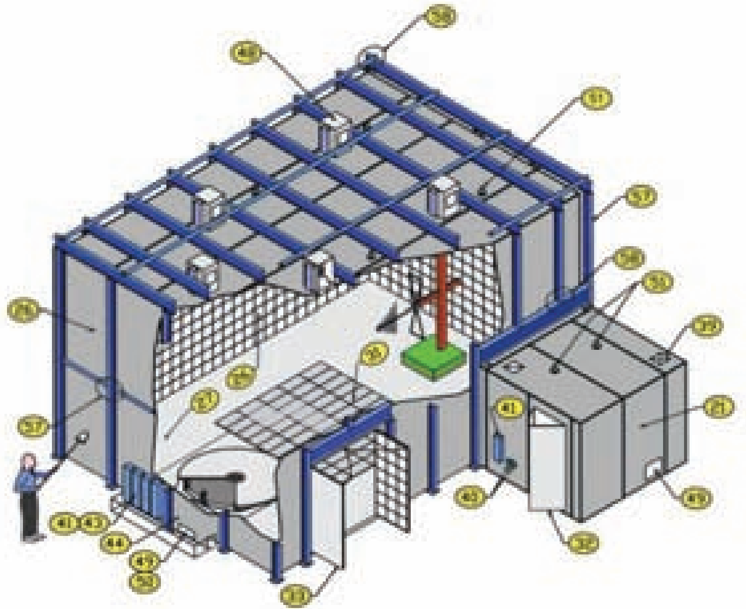


Facilities Designed with Compliance to Multiple International EMC Testing Standards are an EMC Engineer's Essential Asset

EMC engineers have a daunting task to stay knowledgeable of current international EMC testing standards in order to get their company's products globally compliant and ready for market in record time. In addition to being knowledgeable, the engineer's most essential asset to meet this task is an EMC facility designed to meet the needs of global compliance testing standards, with capability for upgrading various key components as the standards change. Whether the engineer's product is hard-wired or wireless, commercial, military, aerospace, medical or security, products can be designed for differing market applications, and may need to be tested for compliance over a wide range of standards. The EMC facility design should be current to meet the latest requirements, and also allow for upgrades in size, absorber treatment, and cross-market test usage. Another important part of the design should be the ability for relocation when corporate real estate demands change. Contact the designers at Panashield to guarantee the continued success of the most essential asset – the EMC test facility.







To interact with this facility design, visit www.panashield.com

Supporting Technological Advances with Testing, Consulting & Engineering Services

What was once just a small EMC laboratory, Professional Testing has grown into a one-stop shop of testing, consulting and engineering services supporting manufacturers in some of the world's most technologically advanced industries.

Medical

Caring for the world of human life is a challenge in today's health and medical market. Professional Testing is passionate about its support of products needing EN 60601-1-2 EMC and Electrical Safety evaluations and provides expertise on the comprehensive FDA submittal requirements and European Medical Device Directive.

Military

Military forces are constantly working with smarter and more sophisticated equipment. Professional Testing has the capability to test this equipment to the MIL-STD-461 EMC requirements and ruggedized environmental requirements of MIL-STD-810.

Aviation

Electronic devices are everywhere and have made notable changes to our transportation systems. Making sure that these devices are compatible with a plane's crucial radio and navigation systems is the utmost concern of the RTCA DO-160 EMC and Environmental services provided by Professional Testing.

Wireless

Wireless communication and control are a part of our everyday lives. Demonstrating compliance with worldwide RF and wireless regulations can be challenging. Professional Testing overcomes that challenge for its customers by providing not only the required testing for the latest 802.11, Bluetooth and other low power radio devices, but also the worldwide homologation to enable these devices to be used worldwide.

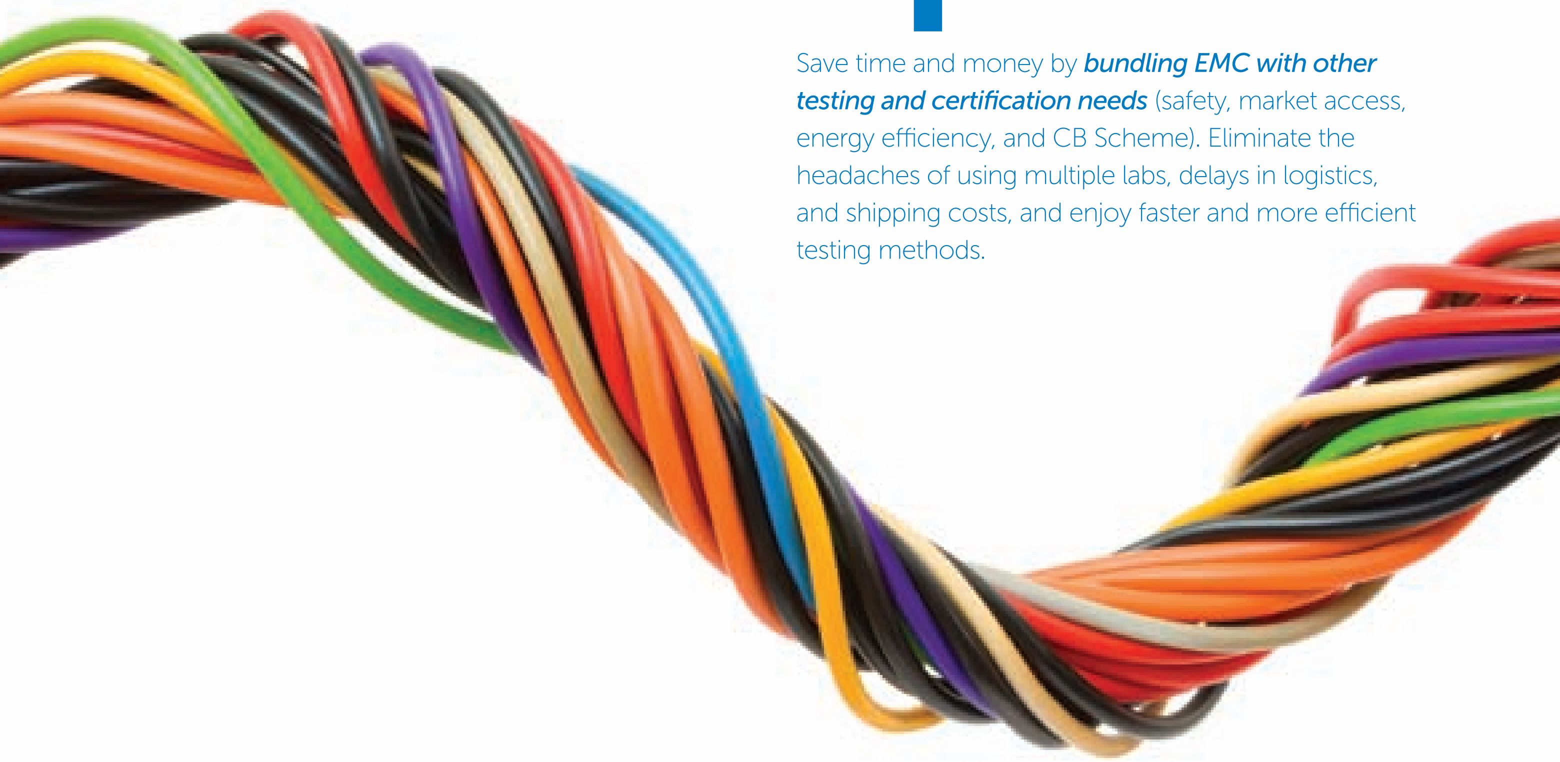
Information Technology

The world of information technology touches every segment of society and brings technology to every human being around the globe. Nestled in Austin's Silicon Hills, Professional Testing provides services in EMC, Electrical Product Safety and Reliability testing to enable products to be sold in markets worldwide.

Test Measurement & Control

Electronic equipment is used everywhere in the oil and gas industry as well as other similar industries including exploration, subsea control, drilling and refinement. Professional Testing is a responsible partner, ensuring the safe and effective use of this equipment in potentially hazardous and explosive environments through EMC, Electrical and Machinery Safety and Hazardous Location testing.

Bundle **Up**



Save time and money by ***bundling EMC with other testing and certification needs*** (safety, market access, energy efficiency, and CB Scheme). Eliminate the headaches of using multiple labs, delays in logistics, and shipping costs, and enjoy faster and more efficient testing methods.

Product Safety Testing and Certification

Product safety testing assures consumers what they are buying is safe and compliant with applicable requirements. We offer expert third-party testing to almost any product safety standard, including ANSI/UL, ASTM, CSA, EN, IEC, ISO, and NFPA. Our laboratories are recognized by major accreditation bodies, including OSHA (NRTL), Standards Council of Canada, IECEE, FCC and more.

EMC Testing

TÜV Rheinland provides the capacity, proximity and engineering resources to streamline your EMC compliance testing process for any market you want to reach. Our Mobile EMC truck can perform in-situ testing at your site for larger, complex systems.

Market Access

Gain quicker access to global markets with our streamlined and timely solutions. Our International Approval experts will get you through the mryiad of complex regulations, regional interpretations and any obstacles presented by a regulatory authority. We will obtain all the necessary certifications for you.

For 140 years, TÜV Rheinland has been helping its clients meet their test and compliance needs quickly, efficiently and reliably. We have the experience, resources and talented professionals you need, as a one-stop testing partner, for all your EMC, Telecom, Market Access or Product Safety needs.

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The Basic Principles of Shielding

BY GARY FENICAL

Today's electrical and electronic devices are subject to mandatory EMC requirements throughout the world. Many devices operate at high frequencies and are very small. They are placed in nonconductive plastic cases providing no shielding. Essentially, all these devices cannot meet these mandatory requirements or they may cause interference to other devices or receive interference causing susceptibility problems without a proper program of EMI control. This program consists of identifying the "suspect" components and circuits that may cause or be susceptible to EMI. This is completed early on in the program to allow for an efficient design in keeping the cost of dealing with EMI as low as possible. A complete EMC program consists of proper filtering, grounding and shielding. This article will discuss the latter, but the other factors cannot and will not be ignored or given insufficient priority.

The article will look into what EMI is and how to design to control it using shielding in conjunction with proper design. Various shielding materials and their uses will be discussed.

WHAT IS EMI?

EMI (Electromagnetic Interference) is a process by which disruptive electromagnetic energy is transmitted from one electronic device to another via radiated or conducted paths, or both. In electronic components, devices and systems, EMI can adversely affect their performance. The goal of all electronic designers is to achieve EMC (Electromagnetic Compatibility) in their designs. Not only to assure proper operation, but to meet the various mandatory EMC requirements imposed by legislation around the world.

EMI can simply be a nuisance such as static on a radio, or it can manifest itself as dangerous problems such as interference with aircraft control systems, automotive safety systems, or medical devices.

Remember, it is always more efficient and less expensive to deal with EMI at its source. The farther away you get from the source or the farther down the design chain you are, the more difficult and expensive it is to mitigate the problems.

THE PROBLEMS

The trend in today's electronic devices is faster, smaller, and digital rather than analog. Most equipment of today contains digital circuits. Today's digital designer must create a circuit board that has the lowest possible EMI, combined with the highest possible operating and processing speeds; generally keeping it as small as possible. Design of the printed circuit board (PCB) is the most critical EMC influencing factor for any system, since virtually all active devices are located on the board. It is the changing current (accelerating electron movement) produced by the active devices that result in EMI.

The faster the digital speed, the greater the required circuit bandwidth, and the more difficult it is to control both radiated emissions and susceptibility. In this regard, it is useful to first consider the relationship between operating frequencies and radiated emissions. The fundamental frequency for

each active device and its associated circuitry must be considered. But the harmonics of these devices can be 10 to 100 times greater in frequency than their fundamentals. The odd harmonics, 3, 5, 7, 9, etc. times the fundamental, are especially troublesome. As a result, increases in EMI with the evolution from analog to high speed digital circuits have been dramatic. RF energy levels at the higher frequency harmonics of analog devices are negligible. The harmonics of an ideal Gaussian wave shape, albeit more a mathematical concept than a practical reality, fall off very quickly at the higher frequencies.

A cosine-squared wave shape, approximately equivalent to that produced by a linear power supply or other analog continuous wave (CW) source having some harmonic distortion, exhibits high frequency harmonic amplitude falloff of 60 dB per decade of frequency. Moving from analog circuits to low speed digital circuits has no significant effect at the fundamentals level, but RF amplitudes increase at the higher harmonic frequencies because falloff occurs at 40 dB per decade rather than 60 dB. In moving from low speed to high speed digital operation, high frequency radio frequency (RF) levels increase even more as harmonics fall off at just 20 dB rather than 40 dB per decade. Given today's extremely fast rise times, one can see that the high frequency harmonics are much greater than in the past.

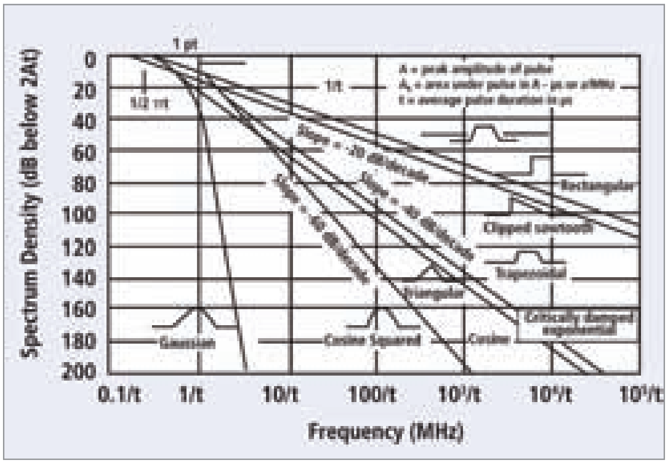


Figure 1: This chart compares the EMI characteristics of analog, low speed digital, and high speed digital logic.

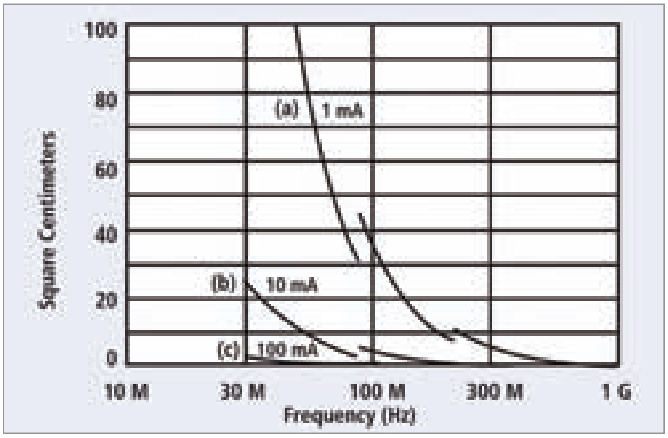


Figure 2: This chart correlates maximum loop area in square centimeters and the FCC Part 15B(B) limit for radiated RF at 1 mA (a), 10 mA (b), and 100 mA (c) of current. The measurement distance is 3 meters.

SOME SIMPLIFIED MATH

Radiation emitted by electronic devices results from both differential and common mode currents. In semiconductor devices, differential mode currents flowing synchronously through both signal and power distribution loops produce time variant electromagnetic fields which may be propagated along a conducting medium or by radiation through space. On simple one- or two-layer PCBs, loops are formed by the digital signals being transferred from one device to another that return by means of the power distribution traces. Loops are also created by PCB traces that supply power to these devices. Common mode radiation results from voltage drops in the system that create common mode potential with respect to ground. In addition, parasitic capacitive coupling, a hard-to-control phenomenon that occurs between all conductive materials, makes external cables act like antennas.

The radiated EMI levels created by the active circuit loops on the board are proportional to the square of the highest created frequencies. These frequencies are determined by the data pulse rise time, and contain significant RF energy at typically 10 to 15 times the operating speed. The rise time also determines the circuit bandwidth. For small circuits whose dimensions are less than the dimensions at resonance, the plane wave emission levels generated by these loops may be calculated by the following equation:

$$E = 1.3\,AIF^2/(DS)$$

Where:

- E = microvolts/meter
- A = radiating loop area in cm^2
- I = current in amps
- F = frequency in MHz
- D = measurement distance in meters
- S = shielding effectiveness ratio

Radiated susceptibility, on the other hand, increases linearly with the offending frequency. For small circuits whose dimensions are less than the dimensions at resonance, the maximum voltage induced into the circuit by a narrowband incident plane wave within its passband is given by:

$$V_i = 2\pi\varepsilon s A B_{pb}/\lambda S$$

Where:

- V_i = volts induced into the loop
- ε = field strength of incident wave in V/m

A = circuit capture area in square meters

B_{pb} = passband bandwidth response

λ = wavelength in meters of incident wave

S = shielding effectiveness ratio

Outside of the circuit passband, narrowband signal effects will be determined by the circuit attenuation response. Broadband signal effects will be determined by both the attenuation response and the circuit bandwidth. Of course, circuit attenuation can be increased with the installation of shielding.

By examining the two formulae, we can draw some conclusions. For emissions, the field strength is controlled by the specification that must be met or by the highest allowable emissions for the environment in which the device must operate. The distance is set either by the specification, such as three meters for the FCC part 15 requirements, or by the distance from the source to the receptor of the radiated energy. Generally, these factor on beyond the control of the device designer. Of course, 1.3 is a constant and cannot be changed. We now come to factors that the designer can control. We see that frequency is squared; therefore, emissions increase exponentially as frequency increases. This explains why high frequency devices and circuits are the most troublesome. Emissions also increase lineally with current. Therefore, one must place high frequency and high current circuits at the top of the EMI suspect list. However, emissions also increase with loop area. By far, large uncontrolled and even unknown loop areas have proven to be the biggest reason for emission failures.

We see that the designer must control the loop area once the frequency and current have been established. Especially for high frequency and high current circuits, the loop area must be kept to a minimum. This must be done at the beginning of the design. It is far too difficult and expensive to do this once the PCBs are designed, and even manufactured.

Once the frequency, current, and loop area have been set, and the circuit does not meet its emissions requirements, we now see that there is only one factor left in the equation that can bring the circuit into compliance: shielding!

For susceptibility, we see that the same good design practices as for emissions apply. In this case, the voltage induced into the circuit is a function of field strength which is controlled either by the specification or the circuit's environment. The bandpass bandwidth response is controlled by the choice of components and other circuit design components such as the choice of the active components, and inactive components such as ferrite chip beads or filters. Again, we see that loop area is a factor. The larger the loop area, the more efficient the pickup of the circuit and generally, the more susceptible it will be. Finally, we see again that once the circuit design is finalized, if it is still susceptible, the only factor left in the formula is shielding!

SHIELDING

Shielding is a conductive barrier enveloping an electrical circuit to provide isolation. The "ideal" shield would be a continuous conductive box of sufficient thickness, with no openings. Shielding deals almost exclusively with radiated energies. Shielding Effectiveness (SE) is the ratio of the RF energy on one side of the shield to the RF energy on the other side of the shield expressed in decibels (dB).

For sources outside of the shield, the absorption and reflection of the shielding material, in dB, are added to obtain the overall SE of the shield. For sources within the shield, roughly only the absorption of the shield can be considered.

The absorption of the shielding material at frequencies of concern is controlled by:

- Conductivity
- Permeability
- Thickness

The reflectivity of the material at the frequencies of concern is controlled by:

- Conductivity
- Permeability

However, this is only true for our "ideal" shield. Two other major factors are:

- "Apertures" - holes or slots in the enclosure.

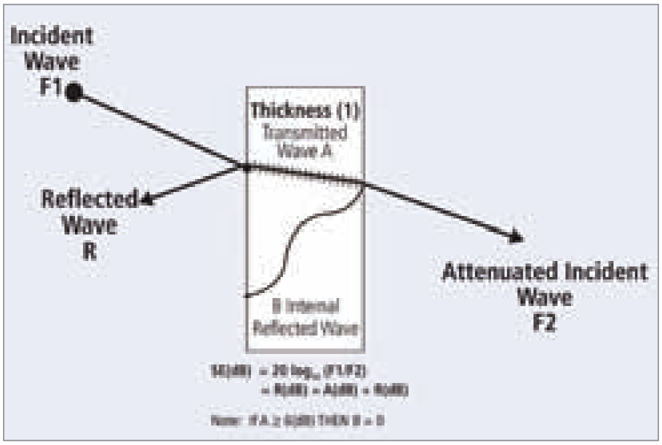


Figure 3: Graphical representation of shielding

- The mechanical characteristics and effectiveness of the gaskets used on the enclosure.

"Mechanical characters" is pointed out because the biggest reason that RF gaskets do not perform as specified is because of improper installation, such as "putting a gasket where a gasket was never meant to go." This is because many times, an RF gasket is used as a "fix" after the design has been set. As we saw in the formulas, shielding is necessary after all other factors in the circuit have been established. Sadly, it is also viewed that way. Rather than design in shielding and gasketing, it is used as a last desperate effort to get the device into compliance; adding the reason for so many failures in shielding and gasketing efforts.

Shielding, which is noninvasive and does not affect high-speed operation, works for both emissions and susceptibility. It can be a stand-alone solution, but is more cost-effective when combined with other suppression techniques such as filtering, grounding, and proper design to minimize the loop area. It is also important to note that shielding usually can be installed after the design is complete. However, it is much more cost-effective and generally more efficient to design shielding into the device from the beginning as part of the design process. It is important to keep in mind that the other suppression techniques generally cannot be added easily once the device has gone beyond the prototype stage.

The use of shielding can take many forms ranging from RF gaskets to board-level shields (BLS). An RF gasket provides a good EMI/EMP seal across the gasket-flange interface. The ideal gasketting surface is conductive, rigid, galvanically-compatible and recessed to completely house the gasket.

A device housed in a metal case is generally a good candidate for RF gasketing materials. When electrical and electronic circuits are in nonconductive enclosures, or when it is difficult or impossible to use RF gasketing, BLS provides the best option for EMI suppression. A properly designed and installed BLS can actually eliminate the entire loop area because the offending or affected circuit will be contained within the shield.

APERTURES

Apertures, or holes, have SE. The SE of an aperture and ultimately the entire electronic enclosure is determined by the size, shape and number of the apertures. The formula is:

$$SE_{db} = k \log_{10}\left(\frac{\lambda}{2L}\right)$$

Where:

λ = Wavelength

k = 20 for a slit or 40 for a round hole

L = Longest dimension of the aperture

If there is more than one hole, we subtract from the original formula: the total number of holes within half a wavelength.

Apertures are placed in electronic enclosures for many reasons. Apertures are required for viewing, controls, meters, wire entry, etc. One reason is simply the seam around the perimeter of the cover(s). To maintain the conductivity across the seam, we generally need to use RF gasketing. RF gasketing is also used around display panels, shielded connectors, and other apertures in the enclosure.

RF GASKETS

Although there are hundreds of gasket varieties based upon geometry and materials, there are four principle categories of shielding gaskets: beryllium copper and other metal spring fingers, knitted wire mesh, conductive particle filled elastomers and conductive fabric-over-foam. Each of these materials has distinct advantages and disadvantages, depending upon the application. Regardless of the gasket type, the important factors to be considered when choosing a gasket are RF impedance (R + jX, where R = resistance, jX = inductive reactance), shielding effectiveness, material compatibility corrosion control, compression forces, compressibility, compression range, compression set, and environmental sealing. However, many other factors may come into the selection decision.

Below is a comprehensive list of selection factors.

- Operating frequency
- Materials compatibility
- Corrosive considerations
- Mandatory compliance
- Operating environment
- Load/forces
- Cost
- Attenuation performance
- Fastening/mounting methods
- Storage environment
- Nuclear, biological, chemical (NBC)
- Cycle life
- Shielding/grounding/other
- Electrical requirements
- Materials thickness/alloy
- Space/weight considerations
- Product safety
- Recyclability

Metal RF Gaskets (Fingerstock) and Spring Contacts

Metal RF gaskets are made from various materials. They generally have the largest physical compression range and high shielding effectiveness holding steady of a wide frequency range. CuBe is the most conductive and has the best spring properties. They can be easily plated for galvanic corrosion considerations.

Fingerstock and spring contact products are ideal for high cycling applications requiring frequent access, with hundreds of standard shapes available as well as cut-to-length and modified standards.

Wire Mesh and Knitted Gaskets

Wire mesh gaskets can be made from a variety of metal wires, including monel, tin plated-copper clad-steel or aluminum. They are cost-effective for low cycling applications and offer high shielding effectiveness over a broad frequency range. They are available in a wide variety of sizes and shapes with the knit construction providing long lasting resiliency with versatile mounting options.

Conductive cloth knit offers close-knit stitch of the metalized nylon, providing a highly effective EMI shield, as well as a smooth, soft surface. Copper Beryllium (CuBe) Mesh offers superb resiliency for consistent, point-to-point contact requiring the lowest compression forces.

Elastomer Core Mesh combines excellent shielding performance with a high degree of elasticity.

Oriented Wire

Oriented wire is a conductive elastomer in which individual conductive wires of either Monel or aluminum are impregnated into solid or sponge silicone. Oriented wire provides EMI protection and seals against moisture or rain on cast or machined surfaces.

Fabric-over-Foam (FoF)

FoF EMI gaskets offer high conductivity and shielding attenuation and are ideal for applications requiring low compression force. Typical FoF EMI gasket applications include shielding or grounding of automotive electronic equipment seams and apertures. There are a wide range of shapes and thickness to meet any design need.

Electrically Conductive Elastomers

Conductive elastomers are ideal for applications requiring both environmental sealing and EMI shielding. They provide shielding effectiveness up to 120dB at 10GHz with a wide choice of profiles to fit a large range of applications. Conductive fillers include, but are not limited to:

- Carbon (C)
- Passivated aluminum (IA)
- Silver-plated aluminum (Ag/Al)
- Silver-plated copper (Ag/Cu)
- Silver-plated glass (Ag/G)
- Silver-plated nickel (Ag/Ni)
- Nickel-coated carbon (Ni/C)
- Silver (Ag)
- Elastomer options include:
- Silicone rubber
- Fluorosilicone rubber
- Ethylene propylene diene monomer (EPDM)
- Fluorocarbon rubber, Viton, or Fluorel

Form-in-Place (FiP)

Form-in-Place (FiP) EMI gaskets can be dispensed onto any conductive painted, plated, or metallic surface of an electronics enclosure that requires environmental sealing, has complex or rounded surfaces, or has miniature devices requiring a precision gasket; thus, protecting the enclosure against internally and externally radiated interference and environmental elements.

Board-Level Shielding (BLS)

If done well, PCB level shielding can be the most cost-efficient means of resolving EMI issues. As a low cost, and most common shielding method, a variety of board-level metal can-type shields have been used to eliminate EMI radiation from entering or exiting sections of a PCB. This method has primarily employed solder-attached perforated metal cans being attach and soldered to the ground trace on a PCB directly over the electrical components that need to be shielded.

The can-type-shields are often installed in a fully automated fashion via a surface mount technology process at the same time the components themselves are installed onto the PCB using wave soldering, or solder paste and a reflow process. Such cans offer very high levels of shielding effectiveness, are typically very reliable, and are widely used in the industry.

Board-level shielding metal cans can consist of tin or zinc plated steel, stainless steel, tin-plated aluminum, brass, copper beryllium, nickel silver or other copper alloys.

Combination Shielding Products

Combination shields offer two or more technologies combined into one convenient form. These shields are made by molding conductive elastomer walls onto metal shield cans to provide any compartment geometry needed. In addition, even more complex applications involve welding spring contact/fingerstock to shield cans to seal compartments in ultra-low profile applications.

CONCLUSION

Basic shielding theory is really not so basic. A comprehensive knowledge of EMI control, circuit design, mandatory specifications, environmental issues and other factors must be considered. Shielding requires a conductive enclosure around a circuit, device, apparatus, or even entire buildings to control EMI. The most cost effective shielding is applied at the source of the problem. However, that is not always possible.

Once the design is established and there are EMI issues, many times, shielding is the only solution. Today there are a myriad of choices for shielding materials from BLS to metal and/or “conductive plastic” enclosures. In most cases, when shielded enclosures are required, RF gasketing is also necessary to provide a conductive interface across the enclosure’s apertures.

Simply trying to pick off-the-shelf shielding materials is not an option. There are many factors involved in the selection of RF shielding materials and RF gaskets. In fact, if one is not intimately familiar with the materials and mechanics of shielding, then it is best left to the experts in the shielding industry. ■

REFERENCES

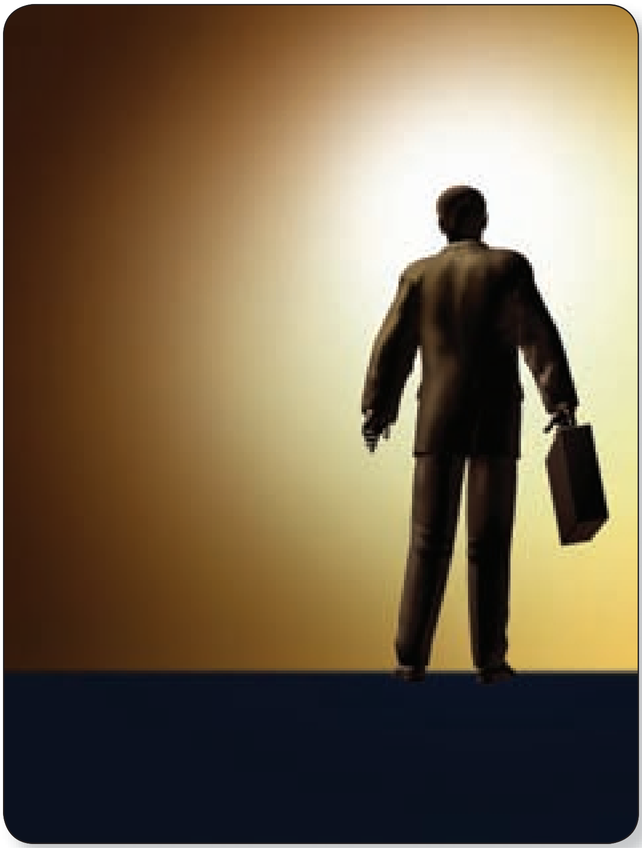
- Instrument Specialties’ Engineering Design and Shield Product Selection Guide: 2000
- Laird Technologies’ Web Site: 2010

__Gary Fenical__ is an EMC Technical Support Engineer with Laird Technologies, as well as an NARTE Certified EMC Engineer. Mr. Fenical has been with Laird Technologies for 26 years. He is a specialist in RF shielded enclosures and has been responsible for the design and/or measurement and quality control of hundreds of large-scale shielded enclosures as well as a number of shielded equipment cabinets and housings. He was instrumental in the design and construction of Laird Technologies’ state-of-the-art World Compliance Centers. Mr. Fenical has authored many articles on EMC Requirements for Medical Devices, Mutual Recognition Agreements and Guidelines to meet the essential requirements if the EU EMC Directive. He has also authored several seminars on the EU EMC Directive, International Compliance, and Designing for EMC and EMC Requirements for Medical Devices which have been presented worldwide. He holds the patent for the invention of heat-treated beryllium-copper knitted wire mesh gasket.

So You Are a New EMC Engineer...

Now what?

BY DARYL GERKE, PE, AND BILL KIMMEL, PE



It's been said that nobody grows up wanting to be an EMC engineer. Rather, it usually just happens. Maybe you had incriminating information on your resume, such as being a radio ham. "You've created interference, so you must know how to stop it, right?" Maybe you showed a knack for EMC troubleshooting, and suddenly you're now the company expert - whether you want to be or not.

Or maybe you just zigged when you should have zagged. In any event, you're now in the EMC trenches. In this article, we'll discuss what to do next. It won't happen overnight, but with a plan (and some work), you can move from EMI-novice to EMI-expert.

FIRST, FIND A MENTOR...

If you are in a big company with an established EMC group, this may be your boss or a colleague. You need someone who has experience and who is willing and able to share it. Fortunately, most EMC engineers are happy to help - particularly the older guys, so don't be afraid to approach the more senior members of your engineering staff.

If you are in a smaller company, identifying a mentor may be more difficult, particularly if you are the sole EMC practitioner. In this case, you may need to look outside the company. Good candidates for mentors are your local EMC test lab, or perhaps an EMC consultant. Since both sell their time, fees may or may not be involved, but your company should be willing to invest in your education. After all, they put you in this position, and they want you to do well.

GET SOME EXPERIENCE - FAST...

If you are responsible for the front end design work, get to know the design teams. Participate in design reviews even if you don't feel you know a lot about EMC. Trust us, this is a quick way to accelerate learning, particularly if you are a young engineer.

Be curious, and ask questions. Don't worry that you don't know the answers - you are in learning mode. And don't limit yourself to EMC engineers. Designers in specialized areas like power electronics, RF or analog circuits often have valuable insights applicable to EMC issues.

Witness EMC tests. If you are hired into an EMC lab, you'll be doing this anyway under the supervision of an experienced EMC test engineer. If you're doing design work, get in as much test time as you reasonably can. It is amazing how much you can learn by just watching an EMC test. An added advantage - you'll also get to know the good folks at the test lab.

START ON YOUR SELF-EDUCATION...

Unfortunately, undergraduate engineering classes on EMC are few and far between. Graduate programs are even more rare, and those that do exist usually focus on specific research. As a result, you may need to set up your own self-training program. Here are some ideas.

Books

While we have over a hundred EMC books on our bookshelves, there are four we regularly recommend for newcomers to EMC.

EDN Magazine Designer's Guide to EMC written by us as a beginner's guide for non-EMC engineers. Simple explanations and recommendations, with no equations or complex math. A good place to start if you are new to EMC. Published by Kimmel Gerke Associates.

Electromagnetic Compatibility Engineering - written by Henry Ott as a major update to his previous book (*Noise Reduction Techniques in Electronics Systems*). Well written, with all the equations you need without field theory or complex calculus. Published by Wiley & Sons.

Introduction to Electromagnetic Compatibility, 2nd Edition - written by Clayton Paul, primarily as a college text, so it has lots of technical depth with all the field theory details. At the same time, very readable and practical. Published by Wiley Interscience.

High Speed Digital Design - A Handbook of Black Magic - written by Howard Johnson as the definitive guide on Signal Integrity. Easy to read, with all the great design advice applies to EMC too. Published by Prentice Hall.

Magazines

There are several publications serving the EMC community. The good news is that two are free, and both are filled with practical articles. We've also included a third publication, a specialty newsletter that is not free but quite useful for industry events and insights.

In Compliance (you are reading it now) - monthly, with an annual buyers guide. Design, test and regulatory issues. Focus on commercial electronics, blanketing compliance related topics. Free on-line, free hard copy in North America. Same Page Publishing Co.

Interference Technology (formerly ITEM) - annual buyers guide with two additional guides throughout the year. Primarily test and regulatory issues, with an emphasis on EMC. Free. ITEM Publications.

Electromagnetic News Report (*ENR*) - bi-monthly publication on EMC issues. Good coverage of EMC community news, products, and events. Paid Subscription. Seven Mountains Scientific.

Courses

These are an excellent way to gain focused practical information in a short time. They typically run from 2-5 days in duration and are offered throughout the US. In house classes are another option. Here are three major providers of EMC training.

Kimmel Gerke Associates (us) - EMC Design classes (2-day), plus an optional EMC Troubleshooting class (1-day). Typically, 15-20 public classes are offered per year throughout the US in selected cities. Also provides in-house training classes. Has offered training for 20+ years.

Henry Ott Consultants - EMC Design classes (2-day). Typically, several public classes offered per year. Also provides in-house training classes. Has offered training for 30+ years.

WL Academy - various EMC issues (length varies), with an emphasis on regulatory topics. Classes throughout the year at Washington Labs in Maryland. Offers a unique and very popular class on MIL-STD-461F testing.

REGULATIONS

Last, but not least, you will want to get copies of the EMC regulations applicable to your industry. Most are copyrighted and have a fee, but government regulations such as MIL-STD-461 and MIL-STD-464 are in the public domain and are free. The latter also have detailed appendices that are great tutorials on the "why" along with the ''how" of the various tests. (Recommended reading.)

Here are the main EMC requirement by industry (with web sites.) Many of these are tailored by individual companies as internal EMC requirements.

- *Military* - MIL-STD-461F & MIL-STD-464 (www.assist.daps.dla.mil)
- *Avionics* - RTCA DO-160F (www.rtca.org)
- *Automotive* - SAE J551 & SAE J1113 (www.sae.org)
- *Commercial/Industrial* - FCC Part 15, EN55022/55011, EN61000-4-x (www.fcc.gov, www.ansi.org)
- *Telecommunications* - Telecordia (formerly Bellcore) GR-1089 (www.telecorida.com)
- *Medical* - EN60601-1-2, FDA "Reviewer Guidance" (www.ansi.org, www.fda.gov)

PARTICIPATE IN THE EMC COMMUNITY...

The community is small, but tight. Don't worry - fresh recruits are always welcome. Maybe it is a case of "misery likes company", but you will find most EMC folks are friendly to newcomers.

This is especially true of many EMC old-timers. Most of us have enjoyed the journey and are happy to share what we have learned. Since little of this is taught in schools, most of us learned (and continue to learn) directly from colleagues and those before us. So if you are a new EMC engineer, don't hesitate to ask for help.

The IEEE EMC Society is probably the biggest community resource. Among the smallest of the IEEE professional societies, the EMC Society is very active. It hosts chapters throughout the world, along with annual symposiums. Both provide excellent opportunities for ongoing education and professional networking.

Join an EMC Chapter

Our first recommendation is to join your local IEEE EMC chapter. Go to www.emcs.org for a list of chapters, many with links to their local pages. Most chapters host at least four meetings a year, and usually include a speaker discussing a technical topic. Finally, you don't need to be an IEEE member to attend - if you are interested in EMC, you are always welcome.

If you don't have a local chapter, consider forming your own. When Daryl moved to Phoenix fifteen years ago, he missed the camaraderie of the Minnesota chapter. He and two other EMC engineers reactivated the local chapter, which had been defunct for years. It is still active fifteen years later. And, again, you are not alone. The EMC Society will help with its *Angel* and *Distinguished Lecturer* programs.

Attend EMC Symposiums

Our next recommendation is to attend an IEEE EMC Symposium. These are held annually around the US, with additional international symposiums around the world. A word of caution - you may need to convince your management of the value of attending. Trade shows are often seen as a boondoggle, but this can be an excellent educational opportunity. Even after 40+ years in this business, we both learn something new from every show.

Here are some suggestions for attending the symposium:

- Attend all five days. While the main technical sessions are Tuesday through Thursday, tutorial sessions are held on Monday and Friday. These tutorials sessions are often aimed at the new EMC engineer, but we find them useful too.

- The Tuesday through Thursday technical sessions are usually heavy on analysis and modeling, so make these a lower priority. Now this may irk the academics, but you can always read the papers later. If a particular paper interests you, by all means attend. Sometimes there are special sessions, and we've found those to be very useful. The point is - don't spend all your time in the meeting rooms.

- Spend time on the show floor. Talk with the vendors to find out about new products, and attend the special tutorial demos. Both can be particularly beneficial to the new EMC engineer.

- Attend the social events. Remember, "All work and no play..." Besides, this is a chance to rub shoulders with those in the business. Although many engineers are introverts, try to mingle, meet and ask questions. Most of those you meet will be fellow engineers.

Use LinkedIn

Finally, use your on-line resources. At this time, LinkedIn is the preferred venue for professional activities. There are several EMC special interest groups which you can join. Your participation can be as much or as little as you prefer. These are also great places to post those perplexing EMC questions.

MAKE A PLAN, AND THEN WORK IT...

First, be patient. It may take a couple of years until you feel like you have really mastered the craft. If you are new, there is a lot to learn. Often this learning is piecemeal, like working a puzzle. But if you study, learn and participate, one day in the not too distant future the overall picture will make sense. At that point, you'll realize you are finally there - you're no longer an EMC-novice, but have become an EMC-expert.

A final piece of advice. When you reach that point, don't stop learning. Even after 40+ years each, we are still learning about EMC. Actually, this keeps us in the game. What weird problem will we see next? Welcome to the wild and wacky world of EMC!

Daryl Gerke, PE *and* ***Bill Kimmel, PE*** *are the founding partners of Kimmel Gerke Associates, Ltd. The firm specializes in EMC consulting and training, and has offices in Minnesota and Arizona. The firm was founded in 1978 and has been in full time EMC practice since 1987.*

Daryl and Bill have solved or prevented hundreds of EMC problems in a wide range of industries - computers, medical, military, avionics, industrial controls, vehicular electronics and more. They have also trained over 10,000 designers through their public and in-house EMC seminars.

Daryl and Bill are both degreed Electrical Engineers, registered Professional Engineers, and NARTE Certified EMC Engineers. Between them, they share over 80 years of industry experience. For more information and resources, visit their web site at www.emiguru.com.

A Primer on Global Regulatory Requirements for ITE

BY JOHN MAAS

Sellers and importers of Information Technology Equipment (ITE) must comply with a vast array of hardware regulations when marketing their products in today's world. The scope of hardware regulations includes the following basic disciplines:

- Product Safety
- Electromagnetic Compatibility (EMC)
- Homologation of wired and wireless telecommunication devices
- Energy Efficiency
- Environmental
- Chemical

Such regulations are established at many levels, including national, regional, state, province and even individual cities or towns. In many case, hardware regulations carry the force of law. Hence, a complete and in-depth understanding of the regulations applicable to any particular product is needed to avoid running afoul of the law. Being aware of all the regulations that apply to a product can be challenging enough, even before understanding all the details.

REGULATORY FUNDAMENTALS

Regardless the discipline, all hardware regulations encompass a common set of basic elements.

- Technical evaluation, which may include testing or engineering analysis
- Documentation of results, often in the form of a test report
- Conformity assessment procedures, including Declaration of Conformity (DOC), verification and certification
- Product and packaging marking
- Information to the user
- Market surveillance and on-going compliance

It should be noted that some regulations may not require explicit action on some of these elements. For example, certain regulations do not require a statement of compliance to be included in the documentation provided to the end user of the product. Other elements may be included as well, such as an audit of procedures and capabilities of manufacturing factories.

The technical evaluation typically includes either testing a sample of the product against some defined standard or set of standards or an engineering analysis or assessment. Restrictions or rules on who can perform the testing or evaluation vary. In some cases, the test or assessment may be performed by the product's manufacturer, while other regulations for the same basic discipline may require the use of an independent third party. If testing to standards is required, the lab performing the testing may need to be accredited by the regulatory agency or through a designated lab accrediting agency. With the wide possibility of requirements on who can perform the evaluation and what specifically is required or allowed, it is easy to see why

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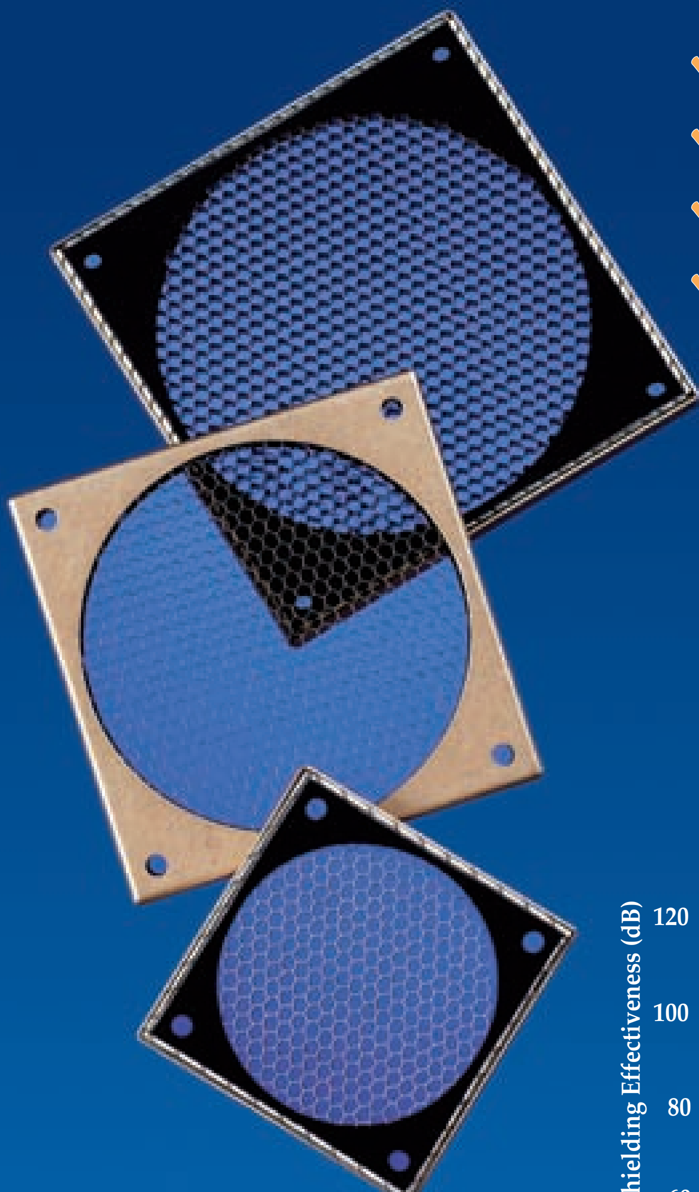

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- *Patented Honeycomb "Blending" Process*
- *Up to 80dB of Shielding at 1GHz*
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- *Compatible with 40, 60, 80, 92 and 120mm fans or custom sizes*

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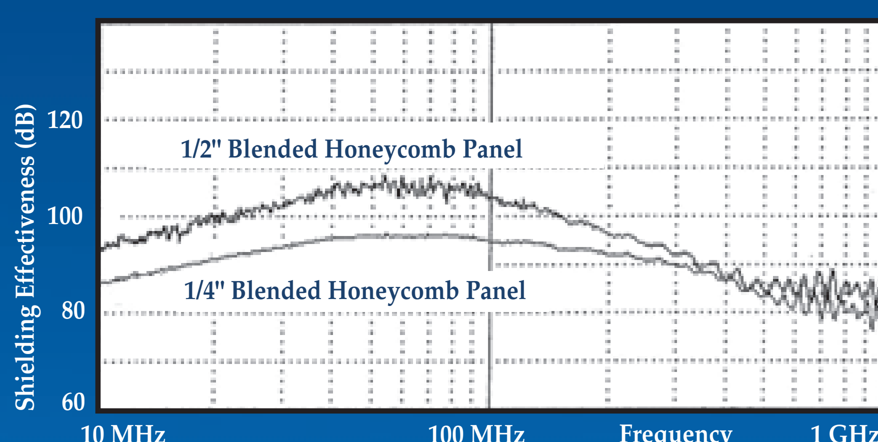

Typical Shielding Effectiveness Test Data of Spira Honeycomb Fan Filters

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EMC

The old adage of the work not being done until the paperwork is completed definitely applies in hardware compliance. Without adequate documentation of the evaluation, one cannot truly demonstrate compliance with the requirements.

in-depth knowledge of the applicable regulations is essential for successful compliance.

Once the technical evaluation is completed, the results must be documented. The old adage of the work not being done until the paperwork is completed definitely applies in hardware compliance. Without adequate documentation of the evaluation, one cannot truly demonstrate compliance with the requirements. What product was evaluated? How was the evaluation performed? Who did the work, and were they properly qualified to do it? The list of content that must be included in a test report can be quite extensive. Consider the following example.

1. Test Report Cover Page stating the regulation the report encompasses
2. Test standard and test method that were applied and any deviations from the specified procedures
3. Classification of the product with respect to the regulation (for example, Class A or Class B for EMC emissions test results)
4. Description of the device being tested for approval, including marketing designation or model number
5. Product specification sheet describing its functions and capabilities
6. Functional block diagram
7. Specific identification of the device that was tested, including serial number and detailed list of all hardware content
8. Description of software used to exercise the unit being tested
9. Measuring equipment used in performing the test, including make, model, serial number and calibration details
10. Test results
11. Description of any changes made to the device during testing to meet the test limits
12. Photographs of the test setup
13. Photographs of the device being tested
14. Diagram of the physical arrangement and configuration of the unit tested
15. Drawing or photograph of the product label showing required marking(s) and location of label on the device

The conformity assessment procedures define the specific process steps that must be followed to satisfy the regulation and include things such as filing a report with an agency versus keeping it on file to be made available if requested These procedures can be placed into three basic categories:

- Certification
- Suppliers Declaration of Conformity
- Verification

Certification generally requires filing specific documentation (such as the test report) with the agency and receiving a certificate in return.

In a Suppliers Declaration of Conformity procedure, the supplier (typically the product's manufacturer) completes a form attesting, or declaring, that the device complies with the required regulation. The method used for demonstrating compliance is often listed on the declaration. In same cases, the declaration is distributed with the product to the end user, while in other cases, it is kept on file to be made available upon request.

Verification is the simplest form of conformity assessment in which the supplier creates documentation to verify that the product meets the requirements. Typically, this documentation would be a test report that is kept on file and made available upon request.

Type of Test	Base Standard
Conducted and Radiated Emissions	CISPR 22
	FCC Part 15 Rules
Power Line Harmonic Emissions	IEC 61000-3-2
	IEC 61000-3-12
Voltage Fluctuations and Flicker	IE C 61000-3-3
	IEC 61000-3-11
Immunity	CISPR 24

Table 1: Common standards serve as the basis for global EMC regulations

Product marking involves placing a mark or statement on the product. Most often the marking is added to the product's information label. Some regulations allow alternatives of placing the product marking on the packaging (such as the cardboard box) or in the user manual, but most require the marking on the product.

Information to the user is generally a statement that the product complies with the regulation. It may also include caution or warning statements describing types of locations where the device is, or is not, allowed to be used.

Market surveillance includes any activities undertaken by the authorities to verify that products being sold do, in fact, comply with all applicable regulations. Market surveillance activities take many forms and may include checking products at retail outlets to ensure proper labeling; requesting copies of test reports, DoCs or certificates from the manufacturer or importer; or performing the tests defined by the standards or regulations on samples acquired from manufacturers, importers or retail outlets.

Compliance verification by Customs officials at the time of importation is another form of market surveillance. Verification by Customs typically involves document inspection to see if all the paperwork accompanying a shipment is in order. Noncompliances discovered during Customs verification typically result in delayed product deliveries to customers, as the noncompliant product (or suspected noncompliant product) will likely be held by Customs until compliance can be demonstrated or obtained. Even simple errors in documentation, such as the model number shown on the commercial invoice not matching the information on the certificate issued for the product, can create problems at the time of importation. Therefore, attention to detail is very important.

EMC

Let us now explore EMC regulations around the globe.

A device's ability to exist in its intended operating environment without causing electromagnetic interference with other electronic equipment (emissions) or without suffering undue interference from other equipment (immunity) is regulated in some 50 countries.

Fortunately for manufacturers, importer and other responsible parties, these regulations reference a much smaller set of common standards, as shown in Table 1.

> Depending on the changes introduced in subsequent editions of a standard, the effect of nonuniform implementation schedules can range from simply referencing the correct edition in test reports to testing a single product multiple times to accommodate the technical differences between versions.

This referencing of common standards substantially reduces the testing burden, although changes and revisions to the reference standards are not always adopted on uniform schedules by the various regulations. A recent example of the variations that can happen in adoption is the roll out of the CISPR 22 limits on radiated emissions between 1 and 6 GHz. Compliance with these limits became mandatory in October 2010 for the Republic of China (Taiwan), in March 2011 for the Peoples Republic of China, and October 2011 in Australia, the European Union and Japan. Depending on the changes introduced in subsequent editions of a standard, the effect of nonuniform implementation schedules can range from simply referencing the correct edition in test reports to testing a single product multiple times to accommodate the technical differences between versions of the standard.

Geography	Test Type	Conformity Assessment Procedure	Submit Test Report	Product Label	User Manual Statement	Lab Accreditation or Approval
Australia	Emissions	DoC	No	Yes	No	Recommended
Brazil	Emissions Immunity	Certification	Yes	Yes		Yes
Canada	Emissions	Verification	No	Yes	Yes	No
China	Emissions Harmonics Flicker	Certification	Yes	Yes	Yes	Yes
European Union	Emissions Immunity Harmonics Flicker	DoC	No	Yes	Yes	No
Japan	Emissions	DoC	No	Yes	Yes	Yes
South Korea	Emissions Immunity	Certification	Yes	Yes	Yes	Yes
New Zealand	Emissions	DoC	No	Yes	No	Recommended
Russia	Emissions Harmonics Flicker	Certification	Yes	Yes	Yes	Yes
Taiwan	Emissions	Certification DoC	Yes	Yes	Yes	Yes
Turkey	Emissions Immunity Harmonics Flicker	DoC	No	Yes	Yes	No
USA	Emissions	Verification Certification DoC	No Yes No	Yes	Yes	No No Yes
Vietnam	Emissions	DoC	Yes	Yes	No	Yes

Table 2: Sampling of compliance details for EMC regulations

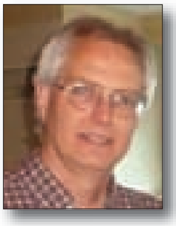
Now that the new CISPR 32 standard for emissions from multimedia equipment has been published, it will be interesting to see how the various jurisdictions incorporate the standard into their requirements.

Even with the use of these common standards to establish the test conditions and limits that must be met, the industry must understand and correctly apply differences in the conformity assessment details between various global EMC regulations. A sampling of these details is summarized in Table 2. Note that some regulations include multiple conformity assessment procedures, usually based on the type of product or product classification.

CONCLUSION

Many countries around the world have hardware regulations that must be met before ITE is marketed, sold or imported into those countries. These regulations exist for valid reasons and generally are intended to protect something: people, other equipment or the environment. Meeting the technical details of hardware regulations is only one step in satisfying the regulations. Satisfying the administrative elements of the conformity assessment process that need to be completed after the technical analysis or testing is finished can be more challenging and time consuming than the test or analysis itself.

Effective regulatory compliance engineers must have a solid technical background to understand the intricate details of product design and the related test standards. They must also stay current on the ever-evolving test and analysis standards, related test equipment, laboratory performance and approval criteria, accreditation requirements, import rules and the rules for the declaration and certification regimes of many regulatory agencies throughout the world.



John Maas *is Corporate Program Manager for EMC for IBM Corporation and has responsibility for IBM's worldwide EMC regulatory compliance program. He has over 25 Years of EMC experience including hardware design and test. He has been involved in international standardization for much of his career and currently is active in IEC SC77B/WG10 and the US advisory groups for IEC TC77, SC77A and SC77B and CISPR/I.*
Mr. Maas can be reached at johnmaas@us.ibm.com.

Administrative Compliance

Your Achilles Heel?

BY NICK WAINWRIGHT

This article outlines the administrative obligations contained in the European EMC Directive, 2004/108/EC, with particular reference to the Declaration of Conformity (DoC). It considers the mounting evidence, including that resulting from European market surveillance campaigns, that insufficient attention is paid to ensuring that the supporting documentation is not only in place, but also up to date.

The requirements of the EMC Directive, like all New Approach directives, can be broadly split into two;

- the technical requirements and
- the administrative requirements

Compliance with the technical requirements is demonstrated (in most cases) by assessing a product against the relevant harmonised European standards and compliance with the administrative requirements is demonstrated by ensuring that the requisite documents and paperwork are available and up to date. In the case of the EMC Directive, the requisite paperwork is normally Technical Documentation and a valid DoC.

Only by meeting both the technical and the administrative obligations should the CE Marking be affixed to a product and the product placed on the market.

ADMINISTRATIVE REQUIREMENTS

Whilst concerns regarding the number (or suspected number) of non-compliant products on the market is nothing new, historically many of these concerns have tended to relate to the technical aspects of compliance.

Deficiencies in administrative compliance have, with the exception of market surveillance activities, only tended to come to light when a DoC has been requested by a potential customer and the manufacturer has been unable to supply one in a reasonable time frame.

Under both 89/336/EEC and 2004/108/EC, there is a stated requirement to produce a valid DoC and the minimum requirements of what it should contain are clearly stated as follows:

- reference to the Directive
- identification of the apparatus to which it refers
- name and address of the manufacturer and, where applicable, the name and address of his authorized representative in the Community
- dated reference to the specifications under which conformity is declared to ensure the conformity of the apparatus with the provisions of this Directive


Cables & Connectors
Circuit Boards
Telecom
Automotive Electronics
Your Next Solution Here
Datacom
Satcom
Defense
Medical

- date of the declaration
- identity and signature of the person empowered to bind the manufacturer or his authorized representative

MARKET SURVEILLANCE ACTIVITIES

The EMC Administrative Co-operation Working Group (ADCO) carried out the 4th EMC Market Surveillance Campaign during 2011.

The primary purpose of the campaign was to assess the compliance of a range of LED lighting products with the administrative and technical requirements of the EMC Directive. Administrative compliance included checking of the DoC.

The results of the surveillance activities were published towards the end of 2011 [1]. The overall administrative compliance was found to be only 28.8% with the main deficiencies relating to the CE marking and the DoC.

Declarations of Conformity were available for only 74.4% of the assessed LED lighting equipment, meaning that 1 in 4 assessed products did not have a DoC available. It is possible that some of those products may have been technically compliant, however as they were not administratively compliant, they did not meet the requirements of the EMC Directive.

Almost half of DoCs presented had major deficiencies including:

- missing reference to the Directive
- incorrect Directive referenced
- inadequate identification of the product
- incorrect standards
- not issued by the manufacturer and/or authorised representative

Overall, only 39.9% of the assessed products were presented with an acceptable Declaration of Conformity. In other words 61.1% of the assessed products were not presented with an acceptable Declaration of Conformity, either because one did not exist or because it had major deficiencies.

Previous EMC Market Surveillance Campaigns raised similar concerns about compliance levels generally and administrative compliance specifically.

FURTHER EVIDENCE

The ADCO market surveillance results of 2011 reflect the compliance position of the LED market; a fast growing and fast changing industry.

Are the deficiencies identified in DoCs for LED lighting products representative of those commonly found elsewhere?

At York EMC Services (YES) we see a significant number of DoCs each year, either via our DoC Checking Service or as part of our wider consultancy work and therefore an answer to the question above is readily available. And that answer is an emphatic “yes”; all the issues identified in the market surveillance activities for LED lighting are commonly observed by YES across a wide range of different industry sectors.

Probably less than 10% of DoCs that arrive at YES for assessment could be classed as being anywhere approaching correct with the other 90% containing a range of deficiencies, many of which would be considered as major.

Directives Complied with:	Low Voltage Directive 2006/95/EEC Electro Magnetic Compatibility Directive 2004/108/EEC
References to Harmonised Standards used:	All equipment contained within the system satisfies the requirements when installed and operated according to the supplied instructions: EN6100-4-2 – ESD EN6100-4-4 – Electrical Fast Transients / Burst EN6100-4-5 – Voltage Surges EN6100-4-6 – Conducted RF Fields EN6100-4-11 – Voltage Dips and Interruptions

Figure 1: References to basic standards are commonplace

BS EN 50081-1 : 1994	Electromagnetic Compatibility Generic Emission Standard Part 2: Industrial Environment
BS EN 50082-2 : 1995	Electromagnetic Compatibility Generic Immunity Standard Part 2: Industrial Environment

to demonstrate compliance with Council Directive 89/336/EEC (amendments 92/31/EEC and 93/68/EEC).

Figure 2: References to old generic standards are still commonplace

Given the copious number of sources of information for what should be included on a DoC; specialist training providers, consultants, industry websites and even the EMC Directive itself this is a disappointing state of affairs.

As regards deficiencies, there are a number of recurring themes, of which the top 3 are:

1. The standards are incorrectly applied, out of date or undated
2. The reference to the Directive is incorrect
3. Identification of the apparatus covered by the DoC is inadequate

Each of these will now be considered in turn including typical examples of where and how the requirements have not been met.

STANDARDS

The most common issues, by some distance, relate to the presentation of standards on a DoC. These issues break down into a number of subcategories which will be considered in more detail.

Perhaps to start off on a positive note, it is worth stating that it unusual to see a DoC where the manufacturer has selected completely incorrect product specific or generic standards. No doubt these do exist but, it seems, not in significant numbers.

Listing Basic Standards

It is relatively common to see a DoC which lists basic standards as opposed to product specific or generic standards. Figure 1 shows a typical example.

CE Marking is based on the correct application of harmonised European standards which includes product specific and generic standards. In lay terms, basic standards, which contain details of the test methods, are the support acts to product specific and generic standards. They are not "CE Marking" standards and are not listed in the OJ. A DoC should be made against product specific and/or generic standards as appropriate.

In relation to Figure 1, there are several questions that the DoC does not answer:

- Against which standards is the product being declared for EMC? The answer to this question is that we simply don't know. EN61000-4-X immunity standards are referenced by virtually every product specific and generic standard published in recent years. Conspicuous by its absence is reference to EN61000-4-3 for radiated immunity.
- What about emissions? There are no emission standards listed at all.
- Against which standards is the product being declared for electrical safety? The Low Voltage Directive is listed on the DoC but it contains no safety standards, so again the answer is that we simply don't know.

Correct Versions of Standards

By far the most common issue relating to standards occurs when the product has been correctly assessed against a particular version of a standard, but that standard has subsequently been updated and either an amendment and/or a new version has been published. The transition period has then passed and as a result the DoC has become invalid.

Two examples of recently reviewed DoCs are shown in Figure 2 and Figure 3 (page 54). There is plenty of other potential discussion relating to the information contained in both Figures 2 and 3.

More specifically, and what can't be seen from the snippet used in Figure 3, is that the DoC was signed in 2003. Therefore all of the standards listed were considerably out of date even at the time the DoC was signed!

Undated Standards

All standards change on a regular basis either by amendment or publication of a new version. The newer standard may contain different tests or test limits/levels or other changes that affect how the product is assessed.

A standard listed on a DoC without an associated date means that is not possible to identify the precise version of the standard to which the product is being declared and by association the actual test requirements that have been met. Figure 4 (page 56) shows an example of where undated standards have been included on the DoC.

In addition (and leaving aside the fact that most of the standards are undated) Figure 4 shows a DoC for a product meeting an impressively long list of EMC standards.

This must certainly be an interesting product; a cross between Information Technology Equipment (ITE) and a household appliance which is also Industrial, Scientific and Medical (ISM) Equipment and used in an industrial environment!

Upon further investigation, it transpired that the product covered by this DoC was in fact a piece of measurement equipment falling within the scope of EN61326-1; which isn't actually listed!

REFERENCE TO THE DIRECTIVE

When doing presentations on the subject of DoCs I have often found myself anecdotally stating that I am as likely to review a DoC which references 89/336/EEC on as I am one which references 2004/108/EC. Several years since the passing of 89/336/EEC this still seems to be the case.

When researching for this paper, I picked 10 of the most recently assessed DoCs to check the frequency at which 89/336/EEC still appeared. Sure enough the 10 DoCs were split exactly 50/50; 5 referring to 89/336/EEC and 5 referring to 2004/108/EC.

Most of the examples used in this paper to illustrate other issues also make reference to 89/336/EEC.

DESCRIPTION OF THE APPARATUS

One of the key information requirements for a DoC is that the product(s) included should be able to be clearly identified. For manufacturers having a large number of products this can be a challenge but an important one to undertake. It should be possible to uniquely trace each product to a DoC; without ambiguity.

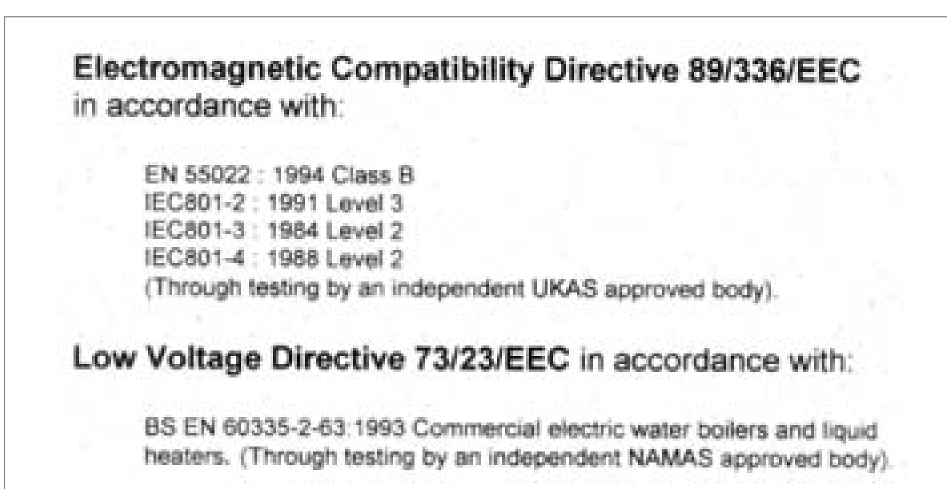
Figure 5 (page 56) illustrates a common issue where the manufacturer is inadequately describing the scope of the DoC.

The phrase "a range of" only defines the scope of the DoC in general terms. What products, types, models and/or variants are included in this range? The answer is that it is impossible to tell without additional information and furthermore it is highly likely that "the range" will change over time further reducing the traceability.

Figure 6 (page 57) shows a good example of how to identify products within the scope of the DoC. In this example the actual product numbers can be identified clearly and unambiguously.

CONCLUSION

There is clear evidence that many products placed on the market are not compliant with the administrative requirements of the EMC Directive and therefore not compliant with the EMC Directive.


Electromagnetic Compatibility Directive 89/336/EEC
in accordance with:

EN 55022 : 1994 Class B
IEC801-2 : 1991 Level 3
IEC801-3 : 1984 Level 2
IEC801-4 : 1988 Level 2
(Through testing by an independent UKAS approved body).

Low Voltage Directive 73/23/EEC in accordance with:

BS EN 60335-2-63:1993 Commercial electric water boilers and liquid heaters. (Through testing by an independent NAMAS approved body).

Figure 3: References to IEC801-X standards still exist but are fortunately not that commonplace

A DoC should be a living document that is regularly reviewed to ensure that it accurately reflects the state of compliance of the product to which it refers. There should be a valid DoC for each day that the product is placed on the market.

A recurring theme, when assessing DoCs, is that many were clearly valid when issued but have become invalid over time through not being maintained. This is demonstrated by the number of out of date standards that are often encountered.

What this reveals is that the issuing of a DoC is perceived by many manufacturers to be a one-off, isolated event rather than part of a compliance process.

Relevant EC Directives:	Low Voltage Directive 73/23/EEC EMC Directive 89/336/EEC
Harmonized Standards:	EN 61010-1 EN 61010-1:1990+A1 EN 61010-1:1990/A2 EN 61010-2-051
	EN 50081-1 EN 50081-2 EN 50082-1:1992 EN 50082-2 EN 55011:1991 EN 5514-1 EN 5514-1/A1 EN5514-2 EN 55022:1994 EN61000-3-2 EN61000-3-3 EN61000-6-2

Figure 4: Keeping options open!

The range of conforms to the CE marking directive 93/68/EEC through compliance with the following standards:

Figure 5: The statement "a range of" on a DoC is far too commonplace

In practice, issuing a DoC is simply one event in a whole series of events that when brought together form the compliance process for the product from concept to retirement from sale.

Ensuring on-going compliance (both technical and administrative) after the product is placed on the market is one phase of this process and the one that includes maintenance of the DoC.

A DoC should be a living document that is regularly reviewed to ensure that it accurately reflects the state of compliance of the product to which it refers. There should be a valid DoC for each day that the product is placed on the market.

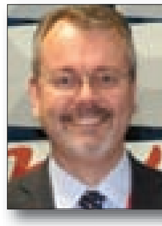
Often an invalid DoC is just the tip of the iceberg and inevitably raises other questions about the technical compliance of the product.

- Is it simply the case that the DoC hasn't been updated or is there more to it?
- Is it also the case that the changes to the standards have not been assessed for their technical significance to the product in question?
- If the DoC is invalid, what is the likelihood that the Technical Documentation is also invalid?
- If the DoC hasn't been updated for several years, is it also the case that the product has changed in the meantime and that an EMC assessment carried out previously is no longer valid?

In other words could an invalid DoC be an indication that the product is actually neither administratively nor technically compliant….?

REFERENCE

1. 4th EMC Market Surveillance Campaign, EMC Administrative Co-operation Working Group, 2011



Nick Wainwright *has been involved with EMC all his working life, starting as an EMC test engineer in the telecommunications industry before moving into commercial testing.*

He joined York Electronics Centre, the predecessor to York EMC Services, in 1990 as an EMC Test Engineer and worked his way up the organization until this year he was given the task of running the 40 strong company as Chief Operating Officer.

Nick takes a very hands-on approach to the roles he undertakes and has specified and designed EMC test facilities and implemented quality systems within laboratories to enable them to achieve accreditation to ISO17025.

Nick is a regular speaker at EMC conferences, courses and workshops on subjects ranging from CE Marking and standards to testing, ISO17025 and measurement uncertainty.

Product family	Detector and ancillaries
Product description	Part Number
Optical Smoke Detector	55000-600
EMC Optical Smoke Detector	55000-620
Optical Detector	55000-660
Heat Detector	55000-400
EMC Heat Detector	55000-420
High Temperature Heat Detector	55000-401
Ionisation Smoke detector	55000-500
EMC Ionisation Smoke detector	55000-520
Ionisation Smoke detector	55000-560
Multisensor Detector	55000-885
Isolating Base	45681-284
Isolator	55000-720
Intelligent Low Power Relay Base	45681-242
MiniDisc Remote Indicator	53832-070

Figure 6: Robust identification of the products covered by a DoC

EMC

Conductors and "Conductive Paths"

What Is Really Happening (And why should anyone care?)

BY MARK STEFFKA

When people are asked what is the most commonly used component in electrical or electronic circuits, the typical answers are "Well, of course everyone knows its resistors", or "It must be capacitors", and even sometimes "Nothing operates without transistors".

In fact, none of those answers are correct; the *real* answer is that *conductors* are *the* most common type of component. Obviously, without conductors there would be no such thing as circuits. Even though conductors are the basic component of electrical circuits, there is surprisingly little consideration of the physics involved in conductors (outside of textbooks) and there seems to be even less emphasis on considering the characteristics of conductive structures (such as "chassis grounds") when those conductors and conductive assemblies are used for the critical current return paths in a circuit. Perhaps this is because wires just don't seem that exciting! Ironically, successful EMC engineering requires just such an understanding!

This article will refresh (or perhaps initiate) the reader's knowledge and understanding of key aspects of conductors and conductive paths by looking at a number of topics, including:

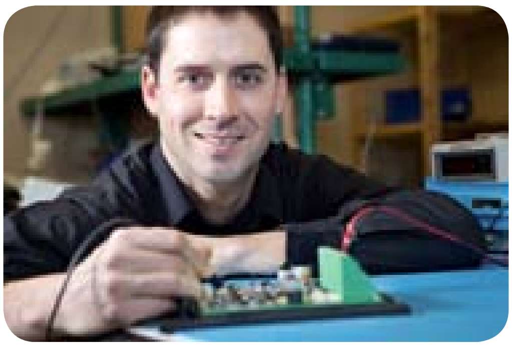
- history of conductors.
- fundamentals of electrical energy propagation.
- types of wire conductors.
- models and characteristics of transmission lines.
- use of assemblies as conductive paths.

HISTORY OF CONDUCTORS

Although wire made from conductive materials (such as iron or copper) has been in use for perhaps thousands of years, it was used as a mechanical component. It was not until a few hundreds of years ago (during the 1700s) that it was first used as a method to define a path for electrical current flow. Some of those first electrical uses were for protection of wooden structures in colonial America by the attachment of the conductive wire to iron "rods" placed on buildings to (hopefully!) provide a path for lightning strikes to be safely conducted to the earth instead of across the structure (which many times caused fires). The use of wire for this purpose (and the invention of the associated lightning rods) has been attributed to Benjamin Franklin.

During the early 19th century, as interest and worldwide fascination into "electrical flow" grew, Michael Faraday was among the first to perform empirical experiments to understand properties of conductors.

As the 1800s progressed, more uses for electricity were developed, including power distribution and communication (telegraph systems). As these systems became more complex, physically large, and capital intensive, there was an increasing desire to more fully understand these interconnection methods. As a result, Oliver Heaviside developed a number of important concepts and inventions during the 1880s, including transmission line theory and the "coaxial" style cable that we see today.



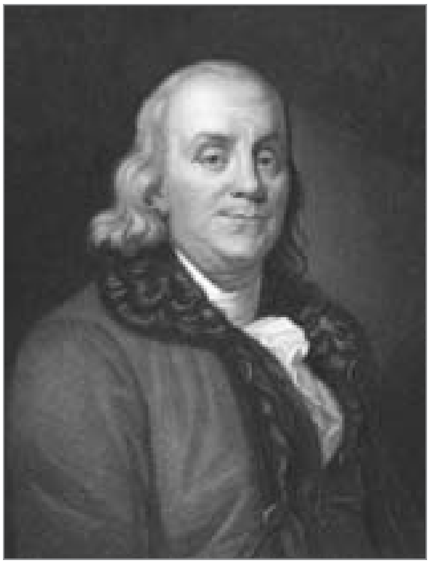


Figure 1: Pioneers in the use of conductors, Benjamin Franklin, Michael Faraday and Oliver Heaviside

WHAT IS THE PURPOSE OF A CONDUCTOR?

From the evolution of wires for lightning protection to power and signal distribution, and even to today, it can be seen that there is only one purpose of a conductor. That purpose is to provide an intended path for propagation of electromagnetic energy.

Therefore, a conductor is used to:

- provide power or signal(s) to where it's needed.
- divert energy from where it's NOT desired (such as in lightning grounds or surge suppression).

That intended path of electromagnetic energy is via "conduction", as described by Professor Maxwell (in addition to his theory of "displacement current", such as the current that "flows" through a capacitor).

In order to understand how energy is conducted from a source to a load, we start with the concept of the *"idealized" energy transfer loop* (as shown in Figure 2).

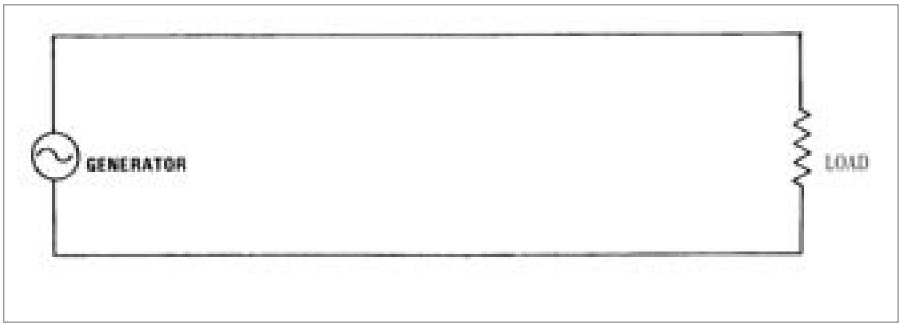


Figure 2: Schematic of basic or "ideal" energy transfer loop

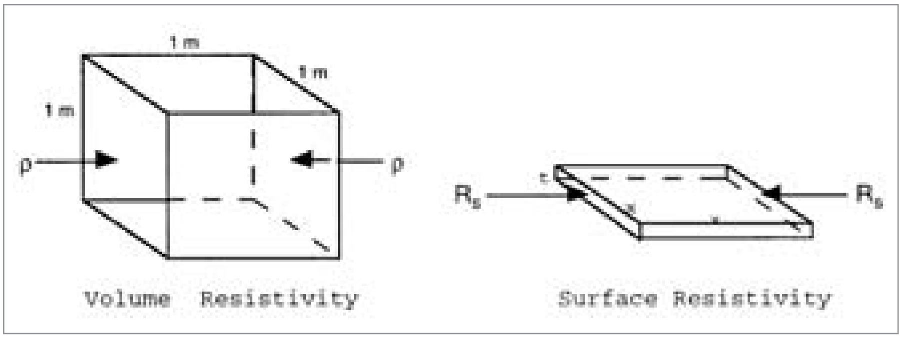


Figure 3: Defining the actual relevant volume and surface resistivity of a conductor

"IDEALIZED" ENERGY TRANSFER LOOP

The figure shows the source of the power (or signal), represented by the "generator". On the other side of the figure is the load (which can be represented by an impedance). The process of transferring the energy from the source to the load is via the conduction path, defined by the solid lines on the diagram). This transfer is typically explained as being similar to a current in water, in that there is a "current flow" along one conductor, while the other conductor functions as a "current return". While this view is not incorrect, sometimes it is better to visualize the energy as an electromagnetic wave being guided from the source to the load.

CONNECTION PATH IMPEDANCE

Using the idealized energy transfer loop leads (unfortunately) to assumptions in system and circuit design that the conductive path is always characterized by a simple zero impedance connection. The problem is that in actual circuit construction, although conductive materials are used, these materials in reality have "non-zero" physical parameters (such as thickness, width, and material resistivity). Depending upon the physical size of the conductor(s), these actually need to be defined as having relevant volume or surface resistivity as shown in Figure 3. For volume resistivity, it is common to utilize a unit volume, such as a cube of equal dimensions in the X, Y, and Z directions. For surface resistivity (when the thickness of the material is significantly less than the other dimensions) an X and Y dimension is used.

The way we typically establish conductive paths from sources to load is to use wires of various diameters (called "gauges"). Figure 4 shows various wire geometries and the common method for identifying the wire diameter. The resistance of wire is a function of both its material and physical dimension (typically diameter is expressed in "MIL", which is equal to 0.001 inch).

By using physical dimensions and material characteristics, it becomes a straightforward process to determine the resistance of any wire. This is shown below.

Calculation of the Resistance of Wires

- Resistance (R), is determined by ρ (rho), length (L), and cross sectional area (A).
- Example showing resistance for 1,000 feet of wire of 10,400 circular mils.

Given: $\rho = 10.37$ ohms

$L = 1{,}000$ ft

$A = 10{,}400$ circular mils

Solution:

$$R = \rho \frac{L}{A} = 10.37 \times \frac{1000}{10{,}400}$$

$= 1$ ohm (approximately)

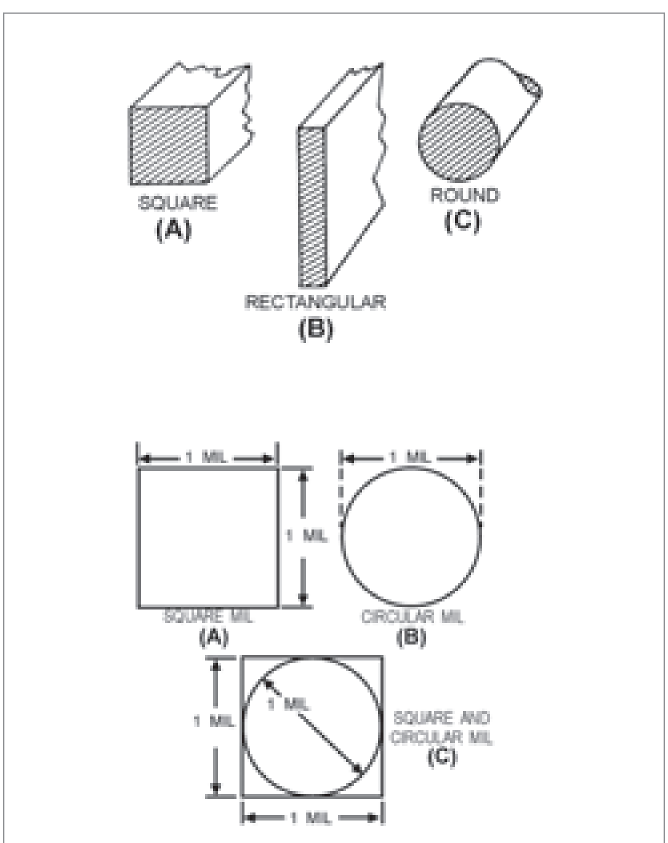


Figure 4: Various geometries of wire and methods for determining gauge

In this example, the 1,000-foot wire has a resistance of 1 ohm. It can be seen that if the length is doubled, the resistance will also double. This makes sense. An interesting observation can be made at this point, however, and that is if the cross-sectional area of the wire decreases (gets smaller), the resistance of the wire increases!

WIRE SIZE ("GAUGE")

In order to provide consistency in wire selection and application, it is typically manufactured in sizes numbered according to the American Wire Gauge (AWG) tables. These tables show wire sizes from 0000 gauge (which is a 460.0 mil diameter for solid wire) to 40 gauge (3.1 mil diameter for solid wire). Of particular note is the fact that, according to these tables, a *wire* is a single rod or filament of drawn metal. Of course another type of wire is actually a number of solid wires bound together to function as a single wire. This more correctly is known as a *stranded conductor* or a cable. Table 1 shows DC parameters of typical cables of various AWG sizes. Figure 5 shows the difference between a single conductor wire and a stranded-conductor "wire".

Why do we have both solid and stranded "wires" (conductors)? It turns out that each has its own advantages that would make the selection of one or the other optimum for a particular application.

In the case of solid wires, they have the following attributes:

- cost-effective.
- high mechanical integrity (keeps form).
- smaller diameter for equivalent "gauge".

Stranded wires, on the other hand would be used when the following characteristics are desired:

- flexibility.
- reduced "noise" (due to lower inductance compared with a similar length of solid wire).

DC Parameters of Some Standard Cables

Size (AWG)	Diameter (mils)	DC Resistance (Ohms/1000 ft)
No. 12	80.81	1.588
No. 8	128.5	0.6282
No. 2	257.6	0.1563
1/0	324.9	0.09827

Table 1: Table showing DC reistance of different wires by gauge and diameter

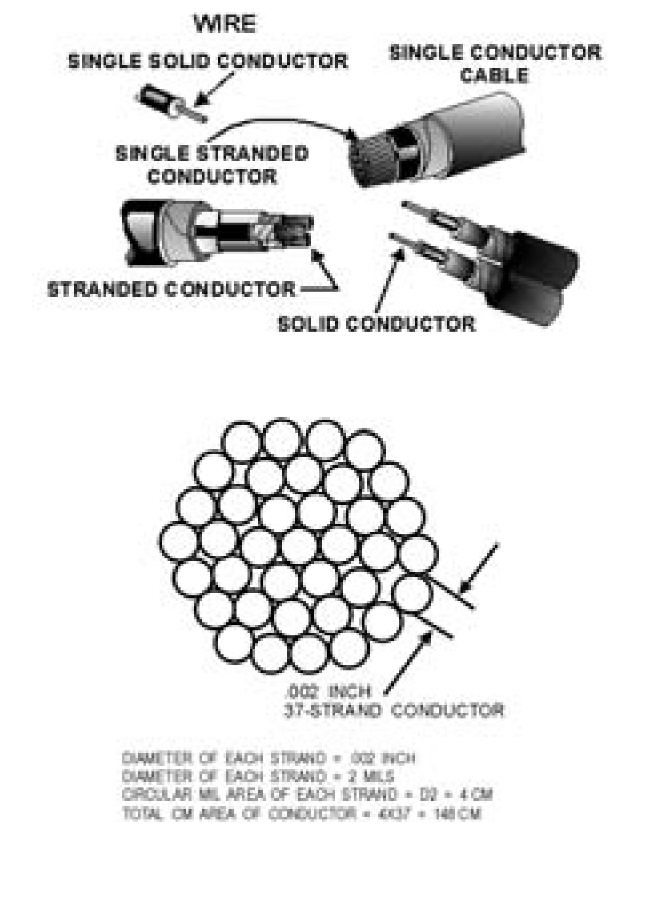


Figure 5: Illustration of both wire and cable conductors

Wire Gauge	Wire Diameter (mils) Solid	Stranded
4/0	460.1	522.0 (427 × 23)
		522.0 (259 × 21)
3/0	409.6	464.0 (427 × 24)
		464.0 (259 × 23)
2/0	364.8	414.0 (259 × 23)
		414.0 (133 × 20)
1/0	324.9	368.0 (259 × 24)
		368.0 (133 × 21)
1	289.3	328.0 (2109 × 34)
		328.0 (817 × 30)
2	257.6	292.0 (2646 × 36)
		292.0 (665 × 30)
4	204.3	232.0 (1666 × 36)
6	162.0	184.0 (1050 × 36)
		184.0 (259 × 30)
8	128.5	147.0 (655 × 36)
10	101.9	116.0 (105 × 30)
		115.0 (37 × 26)
12	80.0	95.0 (165 × 34)
		96.0 (7 × 20)

Table 2: Table equating solid wire gauge to stranded cable

- redundancy (some broken solid wires will not affect functionality).

In the same way we can define solid wire sizes, we also define physical dimensions for stranded conductors. *An interesting point is that the diameter for "gauge equivalent" solid and stranded conductors are NOT the same!* This is due to the fact that the stranded wires have some amount of open space between them when contained in one bundle (because the wires are circular). This can be seen in the cross-section of the stranded conductor in Figure 5.

Shown is a table for examples of both solid and stranded wires (Table 2). The table is used in the following manner:

- the entry for the wire gauge 12shows a SOLID wire diameter of 80.0 mils.
- Stranded wire with a 12 gauge can be obtained by combinng either 165 solid wires of 34 gauge (165 x 34) or 7 wires of 20 gauge (7 x 20).

EMC ASPECTS OF WIRES

While important, DC characteristics of wires are not the primary characteristics of concern in EMC work. The important elements to consider are:

- lines on a schematic (or connections in SPICE) that represent the "ideal" characteristics.
- frequencies of interest in EMC work that require an understanding of "non-ideal" behaviors.

A key consideration when using wires (or any type of conductor) with non-DC current is that there is AC impedance that increases with frequency due to the skin effect phenomenon. The skin effect causes a reduction in the cross-sectional area through which the current flows and, as we saw in a previous equation, the cross-sectional area decreases when the resistance increases. The same condition is a contributor to AC impedance. This is shown in the following figure and equation (Figure 6).

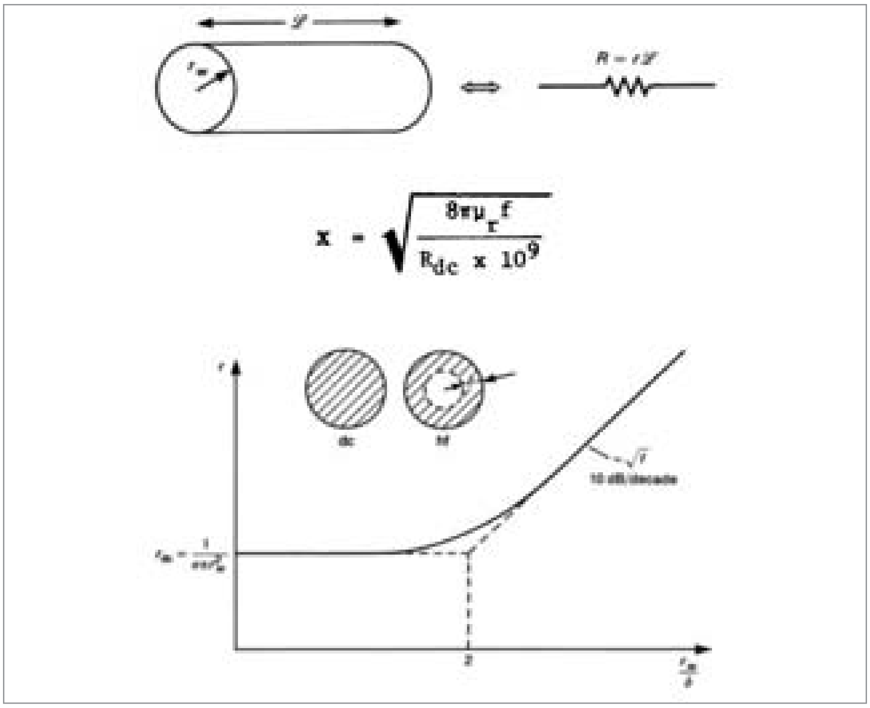


Figure 6: AC impedance of a conductor is composed of two parts: the DC resistance and the AC resistance (once the wire radius exceeds approximately two skin depths)

Size AWG	Length (Ft)	R_{dc} (Ω)	R_{ac} (Ω)	L (μH)	X_L (Ω)	Z (Ω)
No. 12	100	0.1588	1.23	60.9	382.65	382.65
No. 2	100	0.0156	0.387	53.8	338.03	338.03
1.0	100	0.0098	0.307	52.44	329.49	329.49

Table 3: Comparison of AC resistance, DC resistance and inductive reactance (due to partial inductance) for different wire gauges

In addition, both the AC resistance and reactance of a conductor vary with frequency as a result of the skin effect, and are reflected in the resistance ratio factor (X).

DC RESISTANCE, AC RESISTANCE, AND INDUCTIVE REACTANCE

If the fact that AC resistance can dominate DC resistance isn't bad enough, since the wires are part of a current loop, they also have self-inductance and result in even higher impedance.

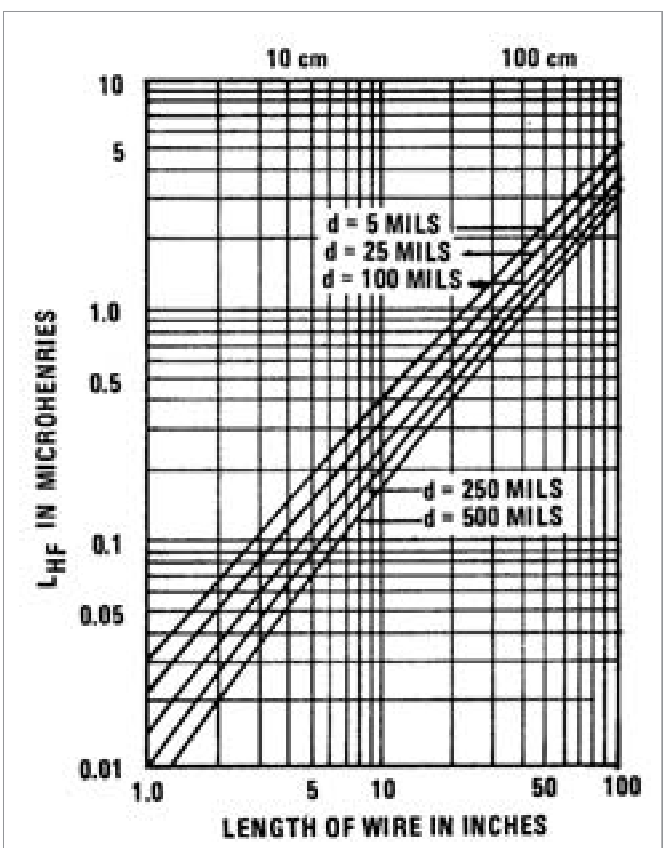


Figure 7: Relationships between wire length, diameter, and its partial inductance

Table 3 summarizes these effects. It may even be startling that at only 1 MHz, *the AC resistance is an order of magnitude greater than the DC resistance and the inductive reactance (XL) due to the wire partial inductance as described in* Inductance: The Misconceptions, Myths, and Truth *(page 72) is hundreds of times the AC resistance!*

Figure 7 also shows the relationship between wire length, diameter, and its partial inductance. We can see that even "small" values of inductance (a few micro-Henries) have high impedance at EMC frequencies (due to X = jωL).

Now that we have investigated the properties of single-strand wires, let's look at the characteristics of stranded wires.

It turns out that an approximation can be made in that the resistance (and to a certain degree, self inductance -- ignoring the effects of mutual inductance) of the stranded wire can be modeled as the resistance (inductance) of each strand divided by the number of strands (as each strand is effectively in parallel with the others). Interestingly, this was first empirically observed by Michael Faraday making the simple observation of "sparks" created in a circuit. When the same parallel wires were spread out, the "sparks" were less – without any change to the length of the wire bundle. Of course, we now know that fewer "sparks" mean less series inductance. Faraday's observation is recorded as follows:

Copper wire [illegible] of inch in diameter. Six lengths of five feet each, soldered at ends to piece of copper plate so as form terminations, and these amalgamated. When this bundle was used to connect the electro-motor it gave but very feeble spark on breaking contact, but the spark was sensibly better when the wires are held together so as to act laterally than when they were opened out from each other, thus showing la'eral action.

Made a larger bundle of the same fine copper wire. There were 20 lengths of 18 feet 2 inches each and the thick terminal pieces of copper wire 6 inches long and ¼ of inch thick.

This bundle he compared with a length of 19 feet 6 inches of a single copper wire ¼ inch in diameter,

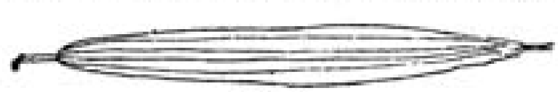
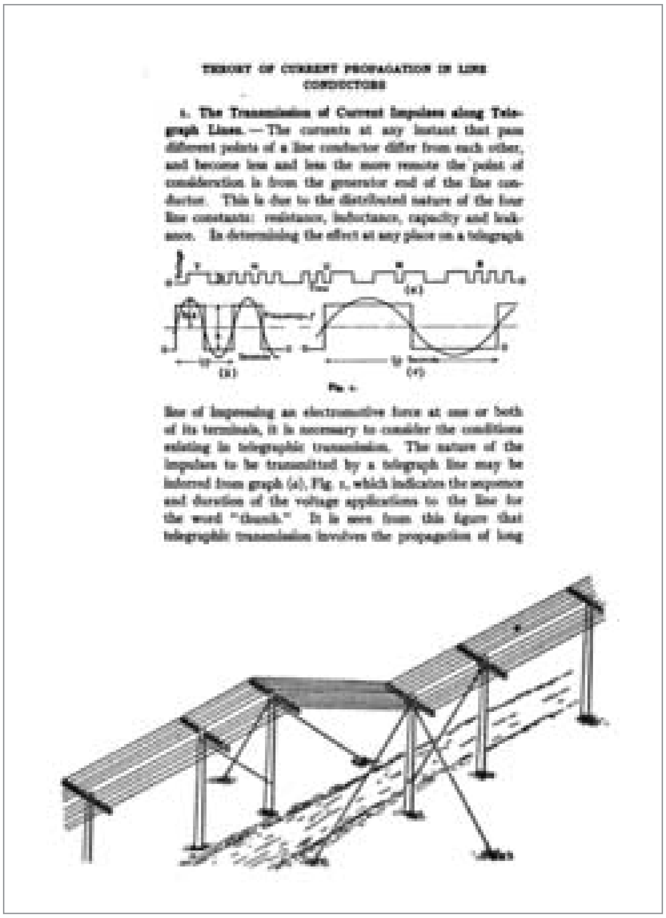


Fig. 13.

having about equal sectional area. The latter gave decidedly the largest sparks on breaking circuit.



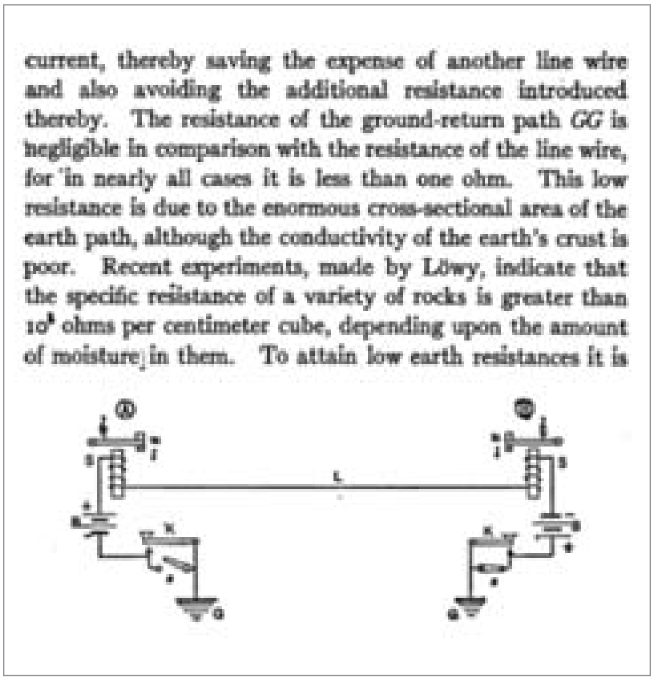
THEORY OF CURRENT PROPAGATION IN LINE CONDUCTORS

1. **The Transmission of Current Impulses along Telegraph Lines.**—The currents at any instant that pass different points of a line conductor differ from each other, and become less and less the more remote the point of consideration is from the generator end of the line conductor. This is due to the distributed nature of the four line constants: resistance, inductance, capacity and leakance. In determining the effect at any place on a telegraph

Fig. 1.

line of impressing an electromotive force at one or both of its terminals, it is necessary to consider the conditions existing in telegraphic transmission. The nature of the impulses to be transmitted by a telegraph line may be inferred from graph (a), Fig. 1, which indicates the sequence and duration of the voltage applications to the line for the word "thumb." It is seen from this figure that telegraphic transmission involves the propagation of long

Figure 8: Requirements of early electronic communications led to new understanding of conductors



current, thereby saving the expense of another line wire and also avoiding the additional resistance introduced thereby. The resistance of the ground-return path *GG* is negligible in comparison with the resistance of the line wire, for in nearly all cases it is less than one ohm. This low resistance is due to the enormous cross-sectional area of the earth path, although the conductivity of the earth's crust is poor. Recent experiments, made by Löwy, indicate that the specific resistance of a variety of rocks is greater than 10^8 ohms per centimeter cube, depending upon the amount of moisture in them. To attain low earth resistances it is

Figure 9: Early reference of the term "ground-return"

WIRING FOR COMMUNICATION

As the 1800s continued, the "state-of-the-art" communications systems became the telegraph, and later the telephone, systems. As the infrastructure was developed and built for these, there became a need to understand, in detail, the physics of conductors (which were now called transmission lines). It was discovered that long distance communication paths had unique characteristics that hadn't been seen before (Figure 8). This was because these installations were the first widespread development of large systems utilizing interconnecting conductors (wiring). This led to the development of the "Telegrapher's Equations" (discussed later) that became the basis for transmission line theory.

….AND THEN IT HAPPENED – THE FIRST (AND STILL THE ONLY TRUE) GROUND CONNECTION!

As the telecommunications boom of the 1800's continued, more and more wire was needed to construct the systems. From this need, one fundamental of all electrical engineering procedures was born, the discovery that by using the earth as a current return path, only half the amount of wire was needed! *Thus, the term "ground" was coined for electrical connections* (Figure 9)*!*

ANALYSIS OF THE GROUND RETURN

This practice for long distance telephone and telegraph connection was possible due to a unique physical relationship of the geometry and conductivity of the earth. It turns out that, rather than being a return path with a significant variation in impedance, the resistance reached an asymptotic limit just over 4 ohms (Figure 10).

This was due to the large area through which current could flow (similar to parallel wires) and, ironically, the resistance

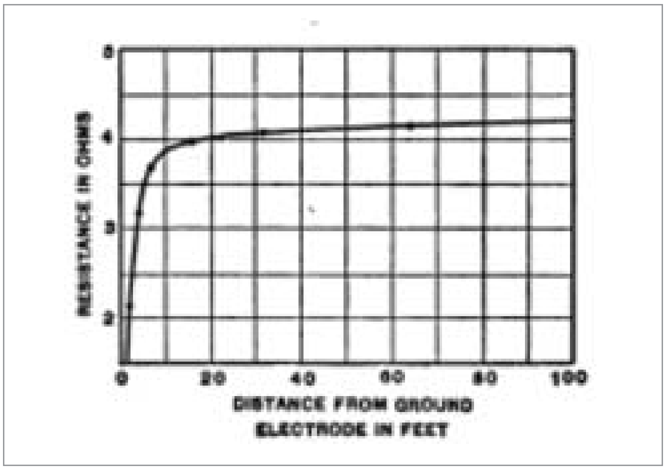


Figure 10: Graph showing the leveling off of resistance in a ground connection

of the ground connection was much lower than the long signal wires. This further established the belief that a ground connection was a low impedance path (compared to the rest of the circuits).

HEAVISIDE'S DISCOVERIES: THE TELEGRAPHER'S EQUATIONS

An interesting phenomenon then occurred as the (telegraph) message signal speeds increased. It was discovered that some of the transmission lines caused signals to be affected and changed at the receiving end from their original characteristics at the sending end.

Heaviside then investigated Faraday's observations of inductance, referenced Maxwell's work, and from that work he developed the "Telegrapher's Equations" which revealed how line characteristics affected signal propagation. This became the basis for all transmission line engineering.

This was amazing an insight. Heaviside realized that the use of two conductors in the telegraph transmission line resulted in the capacitive and inductive properties of the line. (This had not been recognized before.) He correctly understood that the capacitance and inductance are continuous along the length of the pair of conductors and therefore could be represented as either lumped or distributed components along the transmission line (Figure 11).

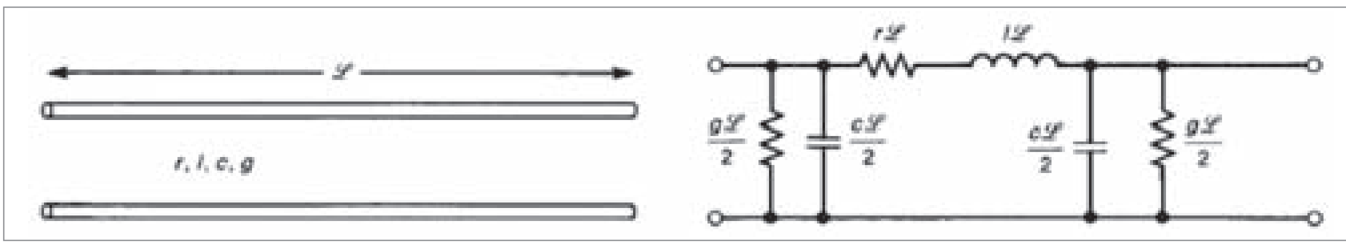
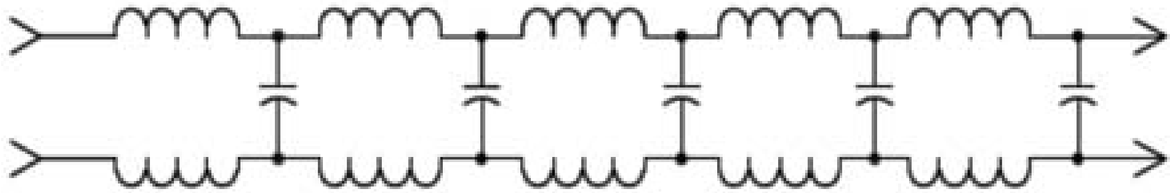


Figure 11: Heaviside realized that capacitance and inductance are continuous along the length of a pair of conductors , and can be represented as "lumped" or "distributed"



$$Z_0 \approx \sqrt{\frac{L}{C}}$$

Figure 12: Diagram and equation for the Transmission Line Model

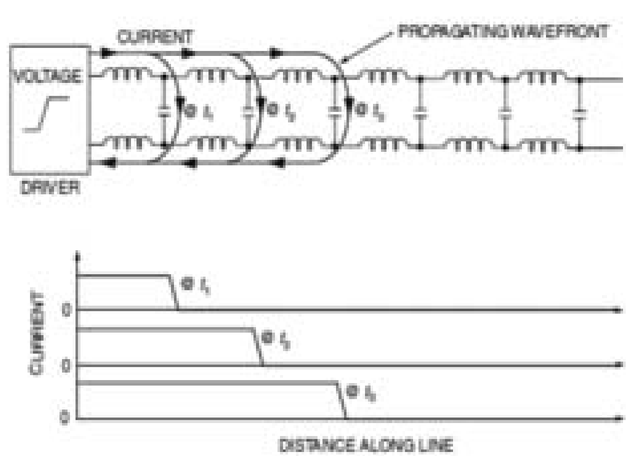


Figure 13: Illustration of how energy propogates along a line (courtesy of Henry Ott, page 218 of *Electromagnetic Compatiiblity Engineering*)

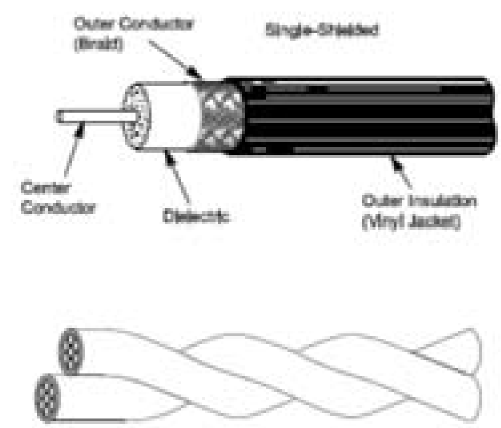


Figure 14: A coaxial line is shown on the top and a twisted wire pair is shown on the bottom.

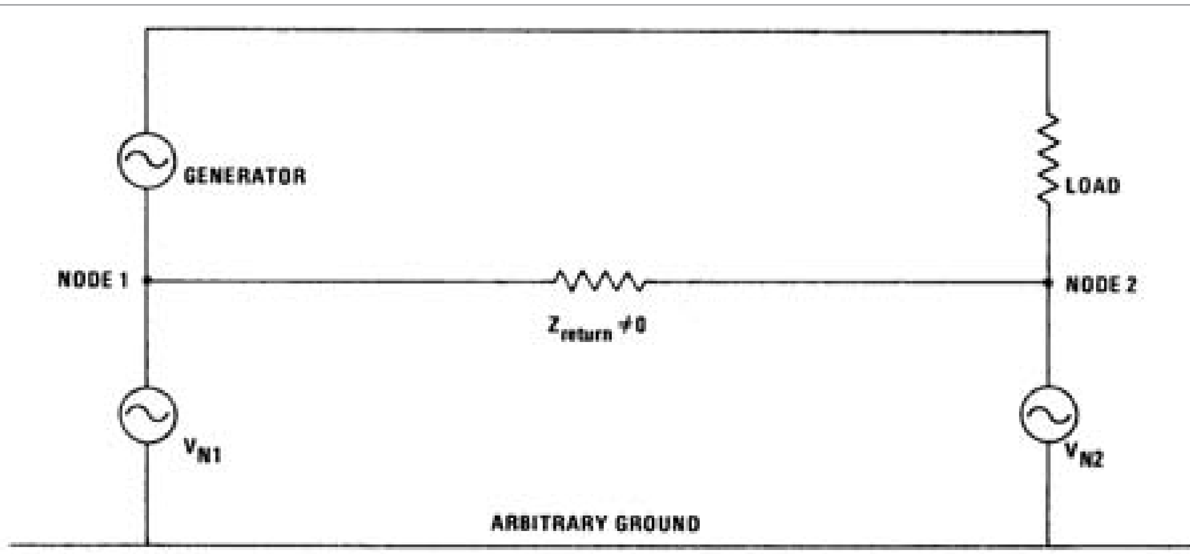


Figure 15

We now refer to Heaviside's work as the discovery of the Transmission Line Model (Figure 12). Most importantly, this discovery allowed for the describing of a transmission in term of its characteristic impedance (Zo), which is a function of the distributed inductance and capacitance along the line and which makes it independent of line length!

THE TRANSMISSION LINE MODEL

- Model that utilizes a line of distributed inductance and capacitance.
- Model that shows a line can be represented by a surge (or characteristic) impedance, ignoring small dielectric losses.

TRANSMISSION LINE SIGNAL PROPAGATION

Key to transmission line theory is the ability to understand how energy, whether it's "power" or "signal", propagates along the line. A very good visualization of this is shown in Figure 13.

As can be seen, the propagation essential takes place by the current flow through the line series inductance and the "charging" of the effective parallel capacitors. Since there is a time constant associated with the charging of the capacitors, this causes the propagation speed to be reduced compared to the traditional "speed of light" electromagnetic wave propagation through air/vacuum. The effect of this reduction in propagation speed is known at "velocity factor" and varies based upon the values of the inductance and capacitance (which is determine both by transmission line geometry and material used in the transmission line construction.

EXAMPLES OF COMMON TRANSMISSION LINES

Today's transmission lines are typically either coaxial or "twisted wire pair" (TWP) (Figure 14). Coaxial cable is used for shielding electrical fields and TWP is used for magnetic field shielding from emissions from either the transmission lines or from external interference.

OTHER TYPES OF CONDUCTIVE PATHS

A common practice is to utilize the metal chassis or enclosure as a conductive path (typically called "case grounding") for either signal or power return. There are a number of reasons that this is done including:

- minimization of wiring costs (similar to telegraph "grounding").
- resolve of component/system EMC problems.

Unfortunately, due to the fact that the impedance of the "ground" path is unknown, this results in the actual energy transfer loop being quite different from the "idealized" (previously discussed). The actual loop is shown in the Figure 15.

Implications of Practice

From that figure, it is easily seen that using the chassis or enclosure as an electrical return path would result in "ground" impedance being undefined and something other than the assumed zero (0) ohms. This impedance is comprised of two terms, the resistance (due to material and frequency) and inductance (due to geometry). Unfortunately, this would *not* be evident from looking at the schematic for the system and result equivalent circuit from this practice is shown in Figure 16 (page 70).

Actual "Grounding"!

Since the chassis conductive path is very small (compared to earth) – there may be significant path impedance (Figure 16), *resulting in unexplained "ground shift" conditions.*

Signal "Grounding"

Connecting the signal return to the conductive chassis can cause undesired results due to impedance in the signal current path and/or the presence of other return currents (Figure 17, page 70).

Signal Return – Best Practice

The best solution is to isolate the signal return from conductive paths that are not well controlled or may have interfering currents on them (Figure 18).

SUMMARY

There are undeniable realities of conductors that we need to be conscious of when working with circuits:

- Real conductors have properties of resistance and inductance that need to be considered.
- Conductors are the defined paths for the propagation of electrical energy.
- Wires can be either solid or stranded, with each having advantages and disadvantages.
- Transmission lines have inductance and capacitance that determine their characteristics.

And the moral is that any conductive path needs to be evaluated – not just assumed!

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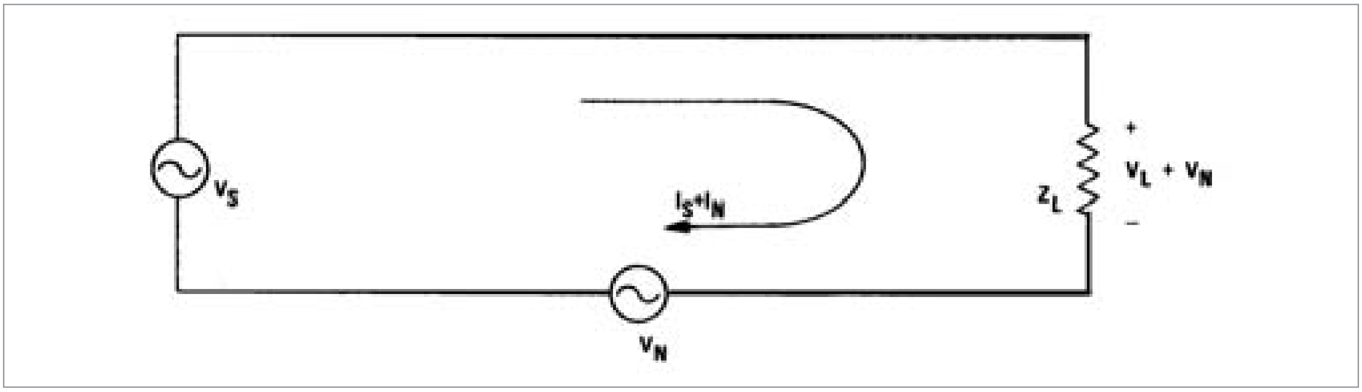

Figure 16

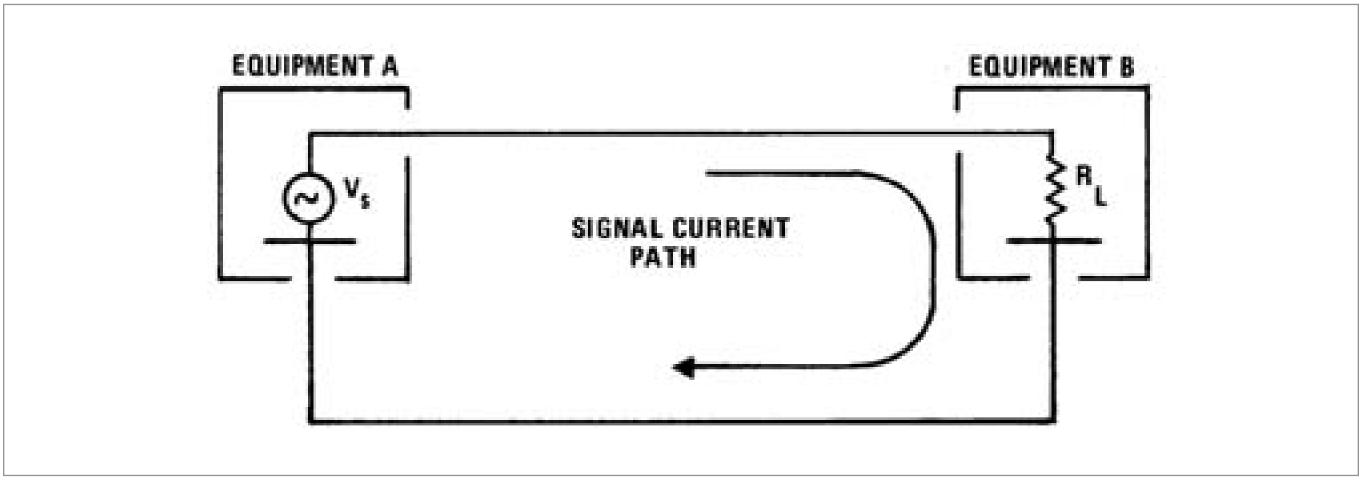

Figure 17: Schematic of a signal return

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This article is based on a presentation made during the "Fundamentals" workshop at the 2011 IEEE EMC Symposium and is an example of the type of material discussed at Fundamentals sessions.

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Mr. Steffka is the author and/or co-author of numerous technical papers and publications on EMC presented at various Institute of Electrical and Electronics Engineers (IEEE) and Society of Automotive Engineers (SAE) conferences. He has also written about and has been an invited conference speaker on topics related to effective methods in university engineering education. He is an IEEE member, has served as a technical session chair for SAE and IEEE conferences and has served as an IEEE EMC Society Distinguished Lecturer. He holds a radio communications license issued by the United States' Federal Communication Commission (FCC) and holds the call sign WW8MS.

EMC

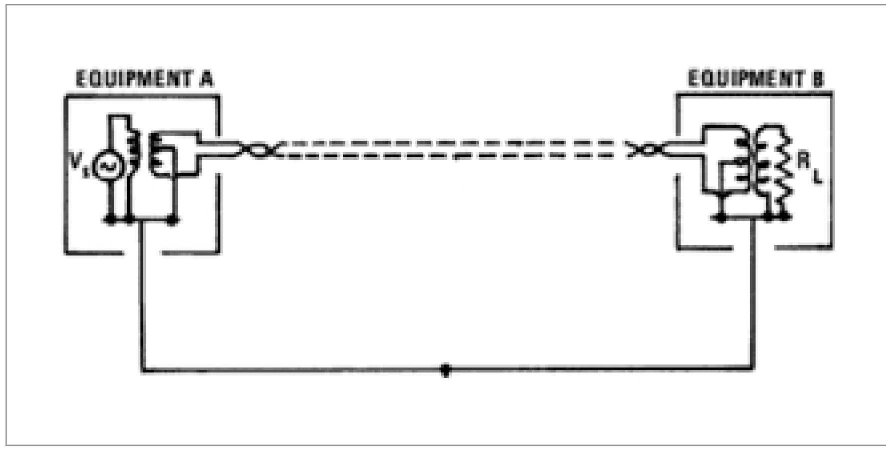
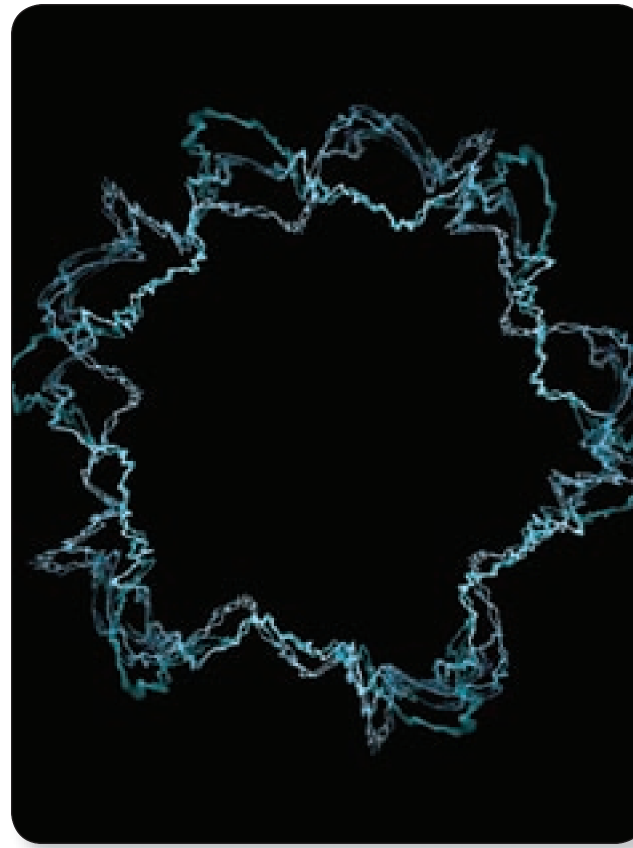


Figure 18: Isolation of signal return from the conductive path

Inductance: The Misconceptions, Myths, and Truth

(Size Matters)

BY BRUCE ARCHAMBEAULT, SAM CONNOR AND MARK STEFFKA



Inductance is one of the most misunderstood and misused concepts in electrical engineering. While in school, we learn about *inductors*, small components we can hold in our hands and lumped elements we can put in a SPICE circuit, but we seldom learn about *inductance*.

We also learned that "inductors" have a property that causes their impedance to increase as frequency increases (Equation 1) and that, when combined with capacitors, they produce resonant circuits. While inductors certainly have inductance (when used in a circuit*)*, we do not need a physical inductor to have inductance!

$$X_L = 2\pi f L \qquad (1)$$

Where:

X_L is the inductive impedance

f is the frequency

L is the inductance

WHY IS THIS IMPORTANT?

We are constantly exposed to products and components which claim to have low inductance. *This is one of the main causes of the misunderstandings surrounding inductance.*

The fundamental fact is that the only time we have inductance is when there is a loop of current. Without the current loop, we cannot have inductance. Of course, as soon as there is current, the current must return to its source, so there will always be a current loop whenever there is current. This is a fundamental fact of physics. The goal of this article is to try to dispel some of the misconceptions surrounding inductance and to encourage engineers to think more clearly about these physics.

DEFINITION OF INDUCTANCE

The definition of inductance comes from Faraday's Law (Equation 2). If we dissect this equation, and relate it to Figure 1, we see that both sides of the equation require a loop. The left hand side is the integral (or simply the summation) around a closed loop of the electric field multiplied by the length (which is simply the voltage). The voltage around the loop is the same as the voltage across a small gap, as shown in Figure 1. The point being that a loop is required creating the loop inductance.

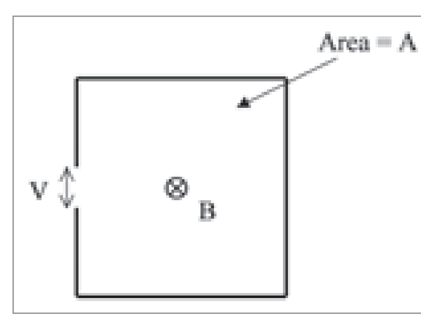


Figure 1: Simplified geometry for Faraday's Law

$$\oint E \cdot dl = -\iint \frac{\partial B}{\partial t} \cdot dS \qquad (2)$$

Engineering that will find a product's problem before that problem finds a customer.

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When we look carefully at the right-hand side of Faraday's Law, we see that there is a double integral (area of a surface) where the amount of time-varying magnetic flux density within the surface area is summed. Since there is a surface, there must be a defined perimeter, again forming a loop.

The standard unit of inductance is the henry. It is a derived unit that relates the amount of negative voltage created by a time varying current. If the rate of change of the current is 1 ampere/second, then one henry will induce a voltage across the gap (with a magnitude of negative one volt) to resist the change in current.

If the time-varying magnetic field within the surface area is not changing with position (an electrically small loop, for example), then Faraday's Law reduces to Equation 3.

$$V = -A\frac{\partial B}{\partial t} \qquad (3)$$

If we now induce a time-varying current in this loop, there will be a time-varying magnetic flux within the loop. Equation 3 shows us that there will be a *negative* voltage induced in the loop, effectively impeding the initial flow of current. Clearly, as the size of the loop area becomes larger, the amount of negative voltage (inductive impedance) will increase. The loop area is the primary physical effect that controls the amount of inductance a current will experience.

It is common for someone to expect the inductance of a circuit will be reduced by increasing the conductor size. This will be examined a little later, but it is worth the time to look at a simple formula for finding the inductance of a

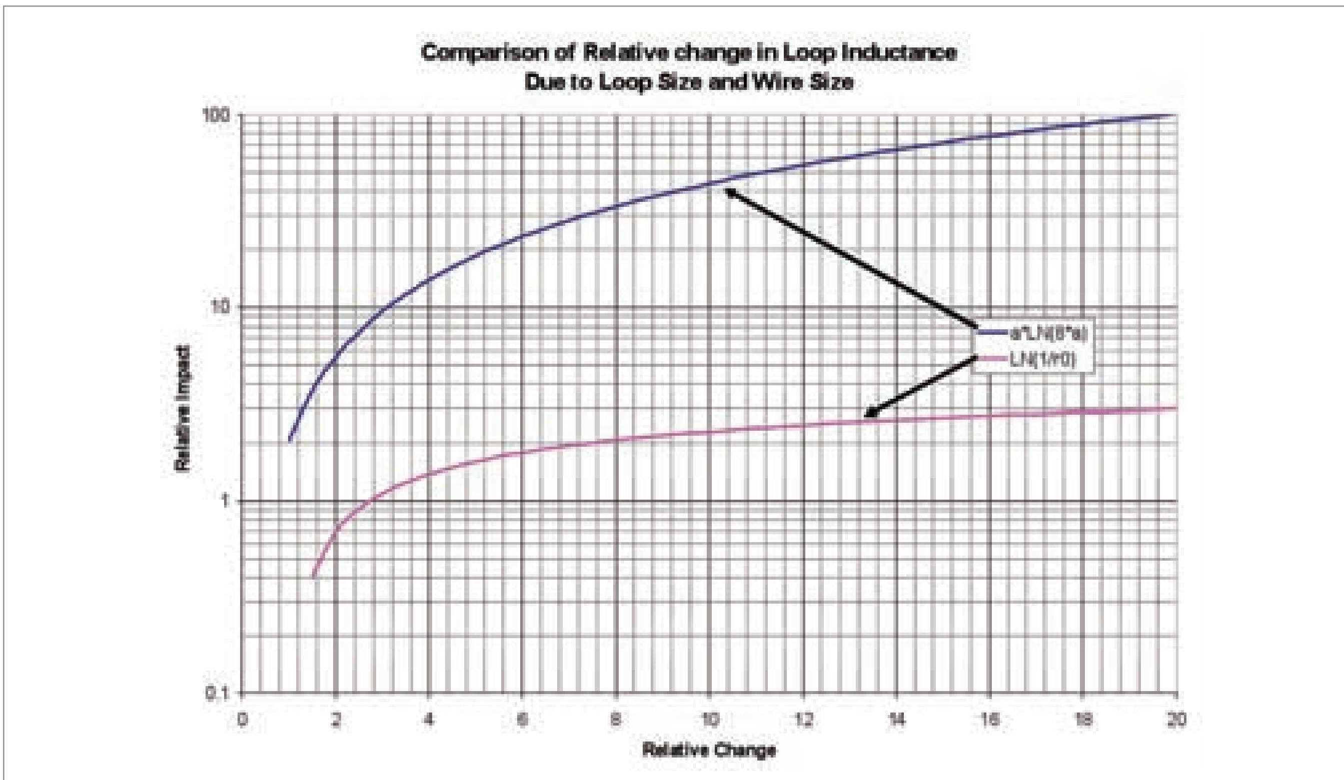

Figure 2: Relative impact on loop inductance from Equation 3

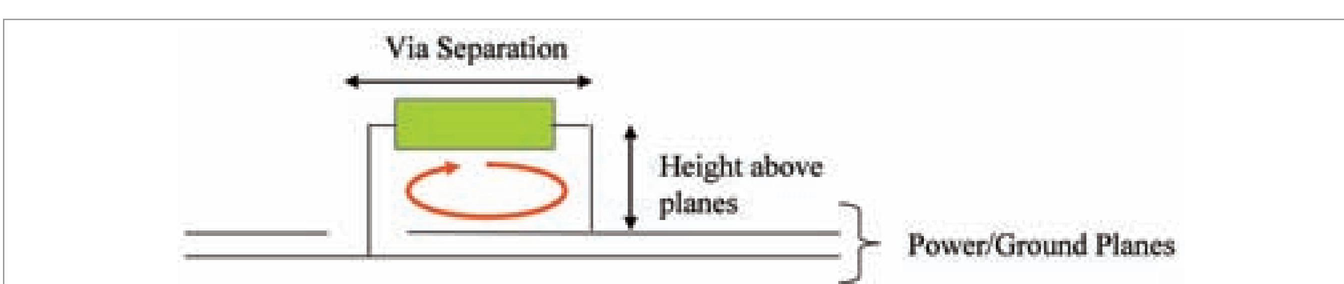

Figure 3: Typical surface-mounted decoupling capacitor loop inductance

simple isolated loop. Equation 4 allows us to calculate the inductance of a wire loop [1].

$$L = \mu_0 a \ln\left(\frac{8a}{r_0} - 2\right) \quad (4)$$

Where:

L = loop inductance

a = loop radius

r_0 = wire radius

The size of the loop is determined by a, the radius of the loop. This radius is both outside the natural log function and inside the function. The radius of the wire, r_0, is only within the log function, and so the inductance varies much more slowly with the radius of the wire. Figure 2 shows the relative change in total loop inductance as either the loop radius or the wire radius changes. It is clear that the loop area has a much more significant impact on loop inductance.[1]

The bottom line is that a loop must be defined before the term 'inductance' has any meaning. A simple, straight wire, a braided ground strap, and a surface-mounted capacitor do NOT have inductance by themselves! We could discuss the partial inductance[2] of those items, but until the loop is defined, the inductance is not defined.

When a vendor discusses the inductance of a braided ground strap, how the inductance is determined should be understood so that the user can determine if the braided strap will or will not perform in a similar fashion in his or her application. Similarly, a surface-mounted capacitor often has a specification for an equivalent series inductance (ESL). How is this possible without defining the loop where the current will flow? Again, we need to understand the measurement process. The vendor simply places the capacitor over a very thin insulator with a ground plane beneath it. A voltage is applied between the capacitor's port #1 and ground-reference, the current flows through the capacitor and returns directly below in the ground plane, forming as small a loop as possible. Of course, when the capacitor is used in a real-world printed circuit board and connects to internal PCB layers, the amount of actual inductance is much greater than in the ideal ESL.

DECOUPLING CAPACITOR CONNECTION INDUCTANCE

As mentioned in the above section, the actual inductance of a decoupling capacitor mounted on a PCB is much higher than the vendor's reported ESL. The connection inductance depends on the distance between the vias and the distance from the top (or bottom) mounting location to the planes that are to be decoupled[3]. Figure 3 shows a side view of a typical decoupling capacitor mounting on a PCB.

It is obvious that if the vias are placed close together and the planes to be decoupled are near the top of the PCB (when the capacitor is mounted on the top of the PCB), the connection inductance, represented by the loop, will be minimized. However, there are limits to how close the vias can be placed due to manufacturing issues. There are also limits to how close to the top surface the power/ground-reference planes can be located. So it is important to understand how the mounting will affect the performance of the capacitor and the connection inductance [2].

Connection inductance alone does not tell the complete story. The inductance associated with the spacing between the power/ground-plane pair, as well as any inductance associated with the distance between the IC and the decoupling capacitor, is not included in the connection inductance calculations.

1. The relative impact of the wire size was so small compared to the loop area that a log scale was required to see the effect of wire radius change!

2. Partial inductance will be briefly explained in a later section.

3. Connection inductance is considered to be 'above the planes' only and does not consider the separation between the power and ground planes, nor the distance from the capacitor to the observation point.

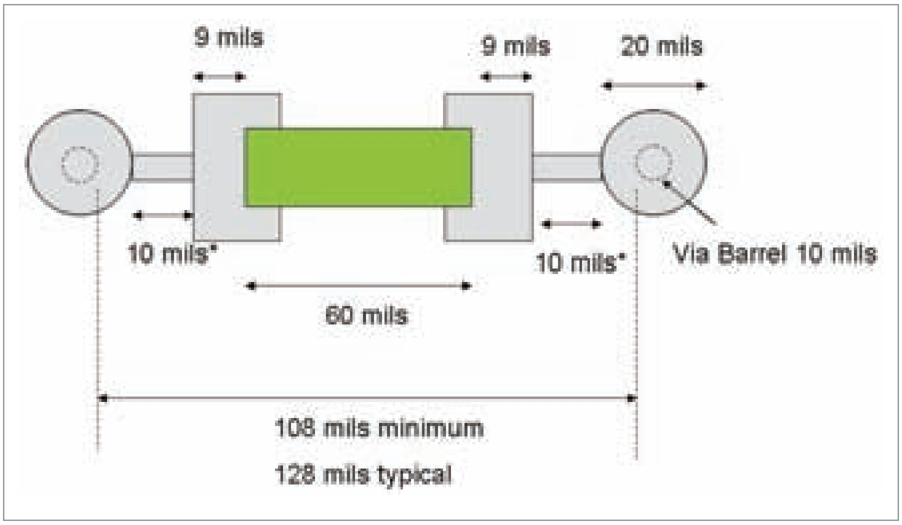

Figure 4: Typical minimum 0603 capacitor mounting dimensions

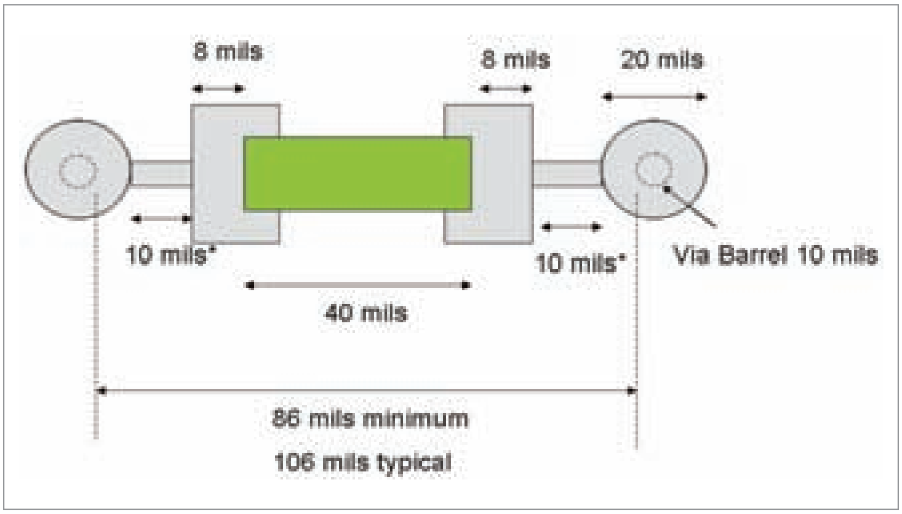

Figure 5: Typical minimum 0402 capacitor mounting dimensions

Figures 4 and 5 show common mounting configurations for capacitors of size 0603 and 0402, respectively, for typical manufacturing limits. Table 1 shows some calculated[4] connection inductances (without ESL) for 0805, 0603, and 0402 size SMT capacitors for different depths to the power/ground-reference plane pairs [3-4].

These values are calculated with the example of 7-8 mils from capacitor-to-mounting-pad-edge, 20 mils from capacitor-mounting-pad-edge-to-via-pad, via pad diameter of 20 mils, via barrel size of 10 mils, and trace width equal to 20 mils. The absolute minimum distance from via pad to capacitor mounting pad edge is reported to be 10 mils, but typically 20 mils is used to be safe.

The distance between the via pad and the capacitor mounting pad was kept to a small value in the above calculations. If this distance is increased slightly to 50 mils, the connection inductance increases to the values in Table 2.

The connection inductance plays a much greater role in the performance of decoupling capacitors than the typical ESL of these components. Connection inductance values of 1 to 3

4. See references for details on the formula used for this calculation.

Distance from board to planes (mils)	0805 typical/minimum (148 mils between via barrels)	0603 typical/minimum (128 mils between via barrels)	0402 typical/minimum (106 mils between via barrels)
10	1.2 nH	1.1 nH	0.9 nH
20	1.8 nH	1.6 nH	1.3 nH
30	2.2 nH	1.9 nH	1.6 nH
40	2.5 nH	2.2 nH	1.9 nH
50	2.8 nH	2.5 nH	2.1 nH
60	3.1 nH	2.7 nH	2.3 nH
70	3.4 nH	3.0 nH	2.6 nH
80	3.6 nH	3.2 nH	2.8 nH
90	3.9 nH	3.5 nH	3.0 nH
100	4.2 nH	3.7 nH	3.2 nH

Table 1: Connection inductance for typical capacitor configurations

Distance from board to planes (mils)	0805 (208 mils between via barrels)	0603 (188 mils between via barrels)	0402 (166 mils between via barrels)
10	1.7 nH	1.6 nH	1.4 nH
20	2.5 nH	2.3 nH	2.0 nH
30	3.0 nH	2.8 nH	2.5 nH
40	3.5 nH	3.2 nH	2.8 nH
50	3.9 nH	3.5 nH	3.1 nH
60	4.2 nH	3.9 nH	3.5 nH
70	4.5 nH	4.2 nH	3.7 nH
80	4.9 nH	4.5 nH	4.0 nH
90	5.2 nH	4.7 nH	4.3 nH
100	5.5 nH	5.0 nH	4.6 nH

Table 2: Connection inductance for typical capacitor configurations with 50 mils from capacitor pad to via pad

nanohenries are typical with the most common surface-mount capacitor sizes and manufacturing technologies. Using the tables, engineers can decide if a decoupling capacitor is better placed on the top or bottom surface of the PCB in order to provide charge to the power/ground-reference plane pairs.

MUTUAL INDUCTANCE

Mutual inductance is a measure of the current induced in a second loop, due to the flux from the first loop (Figure 6). As described above, a time-varying current in the first loop will create time-varying magnetic flux. If a second loop is close to the first loop, a significant portion of this magnetic field flux will penetrate the second loop, inducing a time-varying current in the second loop.

Figure 6 shows the two loops in a co-planar orientation. If they are oriented perpendicularly to each other, then the lines of flux from Loop 1 will not penetrate Loop 2, and there will be no mutual inductance[5]. If one of the loops is made much smaller, then the amount of flux is reduced, again reducing the mutual inductance. And finally, as the loops are moved further apart, the magnetic flux penetrating the second loop decreases rapidly, which also reduces mutual inductance.

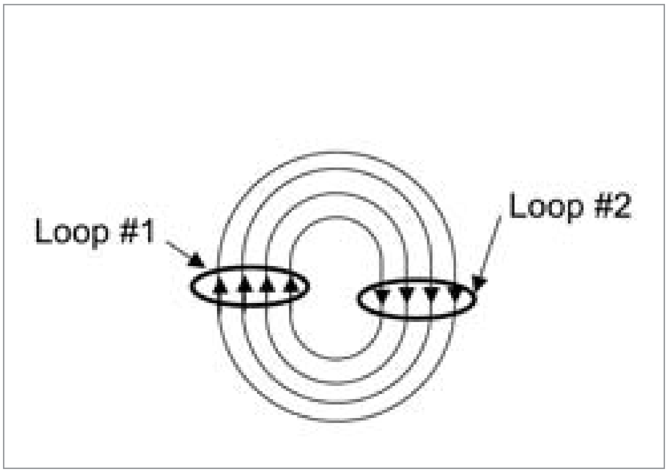

Figure 6: Mutual inductance from current in one loop creating flux in second loop

5. This is approximate. There would be a small amount of flux lines within the conductors, creating a small amount of mutual inductance.

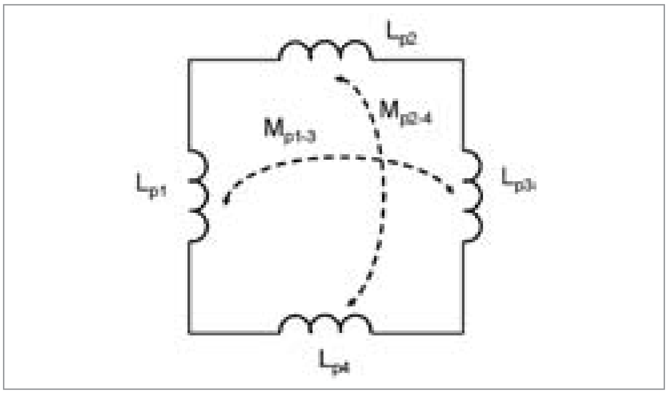

Figure 7: Partial inductance components of simple rectangular loop

PARTIAL INDUCTANCE

The definition of inductance requires a current flowing in a loop. *Without a complete loop, there cannot be inductance*. Practical considerations, however, lead us to discuss the inductance of a part of the overall current loop, such as the inductance of a capacitor. This idea of discussing the inductance of only a portion of the overall loop is called partial inductance [4]. Partial inductances can be combined to find the overall inductance. For the simple case of a rectangular loop of wire where sides 1 and 3 are parallel to each other and so are sides 2 and 4 (see Figure 7), Equation 5 can be used to calculate the total inductance from the partial inductances.

$$L_{total} = L_{p1} + L_{p2} + L_{p3} + L_{p4} - M_{p13} - M_{p24} \quad (5)$$

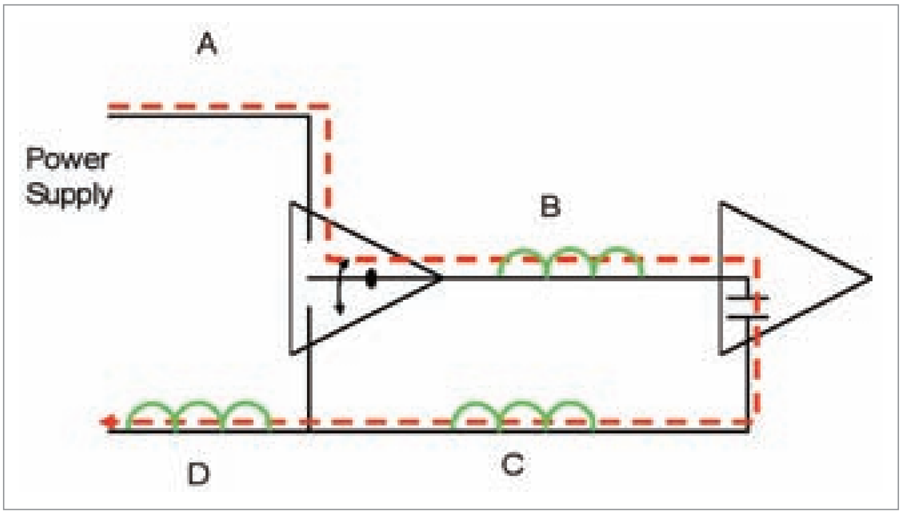

Figure 8: Current path for data through IC gates

Figure 7 shows this distributed inductance concept and relates back to Equation 5. In each portion of the loop we assign a partial inductance value as well as partial mutual inductance between all parts of the loop.[6] Though the conductors may have different sizes, it is not a problem to calculate the partial inductance values. Naturally, if the current follows a more complex path, additional partial inductances and partial mutual inductances will be needed.

The concept of partial inductance is especially useful when the physical geometry is complex and it is difficult to assign the loop inductance to any one location around the loop. For example, Figure 8 shows current flow from the power plane in a PCB through the output driver of an IC, through a trace to the IC load, and finally through the ground-reference plane back to the power supply source. Since there is a closed loop of current, there is an inductance associated with that current path … but where could we place the loop inductance in this circuit? First of all, since the various conductors have different sizes, it would be impossible to find a formula to find the loop inductance. However, since we know this inductance exists (even if we cannot calculate it easily),

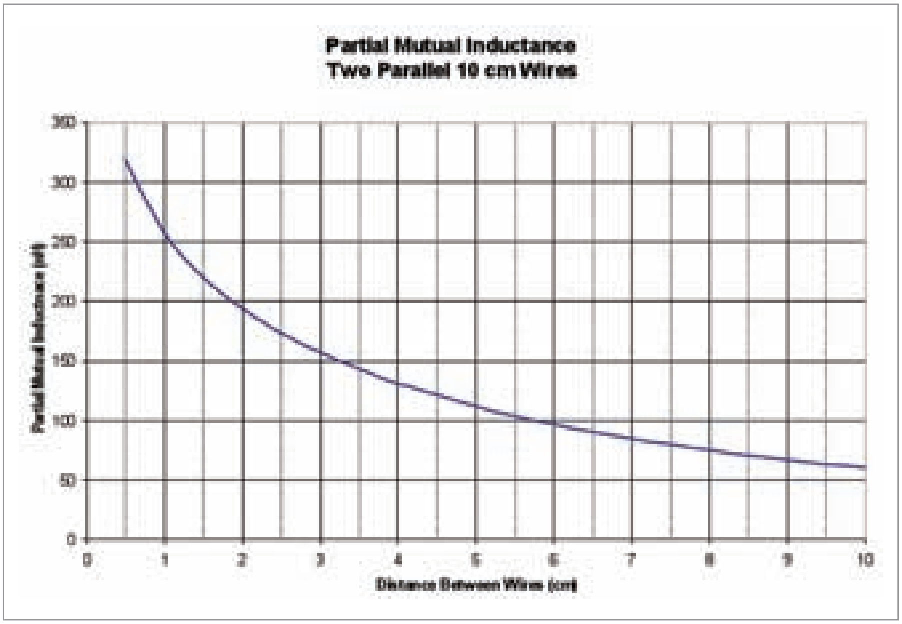

Figure 9: Example of partial mutual inductance of a pair of parallel wires

6. In this case, we only show the partial mutual inductance of the parallel sections, since perfectly perpendicular conductors will not have any mutual inductance.

where would we place the inductance? If we choose location 'A', then we ignore any voltage drop in the other conductors due to inductive impedance. The same is true for the other locations (B, C, and D). The inductance is actually a distributed quantity and must be considered to be throughout the loop. The concept of partial inductance allows us to do this.

The partial inductance for a length of wire is given by (6), and the partial mutual inductance between a pair of parallel wires is given in (7).

$$L_p = \frac{\mu_0}{2\pi} l \left[\log\left(\frac{l}{r} + \sqrt{\left(\frac{l}{r}\right)^2 + 1} \right) + \frac{r}{l} - \sqrt{\left(\frac{r}{l}\right)^2 + 1} \right] \tag{6}$$

$$M_p = \frac{\mu_0}{2\pi} l \left[\log\left(\frac{l}{d} + \sqrt{\left(\frac{l}{d}\right)^2 + 1} \right) + \frac{d}{l} - \sqrt{\left(\frac{d}{l}\right)^2 + 1} \right] \tag{7}$$

Where:

l = length of wire

r = radius of wire

d = distance between parallel wires

Figure 9 shows the partial mutual inductance for two parallel 10 cm long wires. Note that when the wires are close together, the partial mutual inductance is very high. Referring back to (5), we see that when the partial mutual inductance is high, the total inductance is low (because it is subtracted). When the wires are close, the loop area would be smaller, resulting in a lower inductance, as expected. Calculations for more complex geometries can be found in [5].

SUMMARY

The basic principle that inductance requires current to flow in a loop is an important concept to understand. This is not unreasonable since current *must* flow in a loop. The size of the current loop determines the amount of inductance.

Inductance is a basic building block in electronic circuits. That is, as soon as metal conductors are used and current flows through them, inductance exists. This inductance becomes the limiting factor in all high-frequency circuits. When capacitors are used as filter elements, the natural inductance associated with the current flowing though the capacitor limits the frequency range where the capacitor is an effective filter component.

Partial inductance is a useful concept, since with partial inductances one can discuss the contribution of a single part of the loop to the total inductance. An example is the via connecting between different layers on the PC board, the metal stand-off post between the PC board and the chassis, and traces on the PC board connecting filter components. Each of these metal structures can be analyzed to find their partial inductances, and the results can then be combined to find the total inductance.

This has been a very brief introduction to inductance. A much more complete study of this subject is available in the references.

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Low-level, Audio Frequency Conducted Emission Measurements

Motivation and Method

BY KEN JAVOR

Control of low audio frequency magnetic fields from cables, as required by some spacecraft EMI control standards, is best implemented as a conducted emission measurement, but these may require exceptionally efficient transducers and techniques, which are discussed herein.

Common-mode conducted emission (CMCE) limits and measurements are often specified within spacecraft EMI standards, such as the Space & Missile Command's *SMC-S-008, EMC Requirements for Space Equipment and Systems* [1], and the NASA Goddard Space Flight Center's *General Environmental Verification Standard (GEVS)* [2].

Above audio frequencies, the rationale for such control is generally either the control of cable-to-cable crosstalk, and/or indirect control of radiated emissions. Such control and measurement is much more accurate and repeatable than radiated measurements when the cable is electrically short.

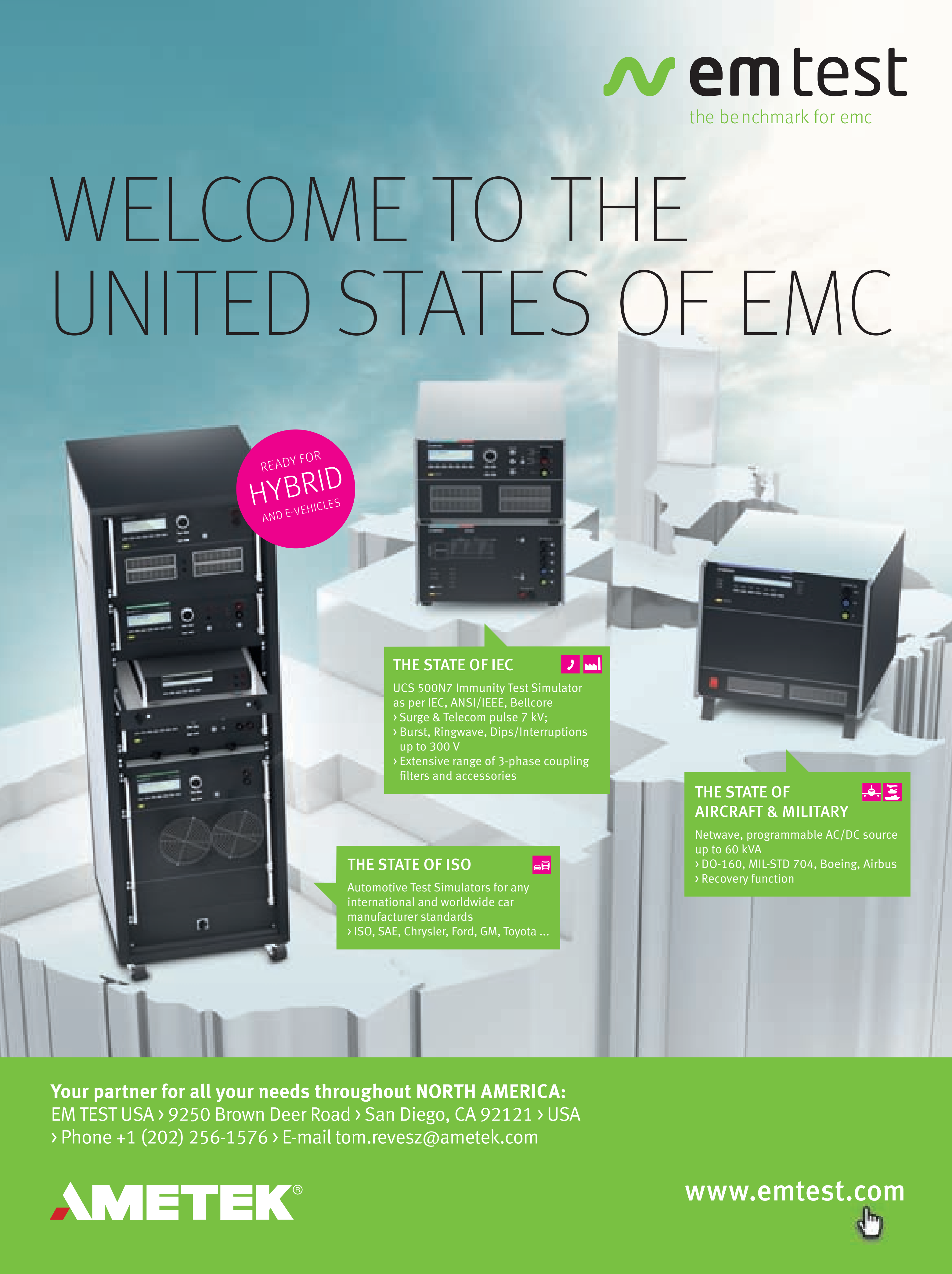
At audio frequencies, effective cable design usually precludes interference from crosstalk. There is no need to control CMCE at audio frequencies unless an unusually low-level signal is carried by a cable, and/or there are restrictions on the quality of shielding available, or the ability to twist a signal with its return.

But there is a special case where the control of CMCE at frequencies down to the very low end of the audio spectrum is desirable, and that is when a platform has a magnetic cleanliness requirement. Such platforms carry sensitive magnetometers. A sample derivation of such a limit is presented.

BACKGROUND

Consider the variable-mu magnetometer pictured in Figure 1. While this is earthbound test equipment, it will be shown that its sensitivity corresponds well with existing CMCE requirements in references [1] and [2].

Figure 1: Electro-Mechanics Company EMCO 6640 variable-mu magnetometer (circa 1964).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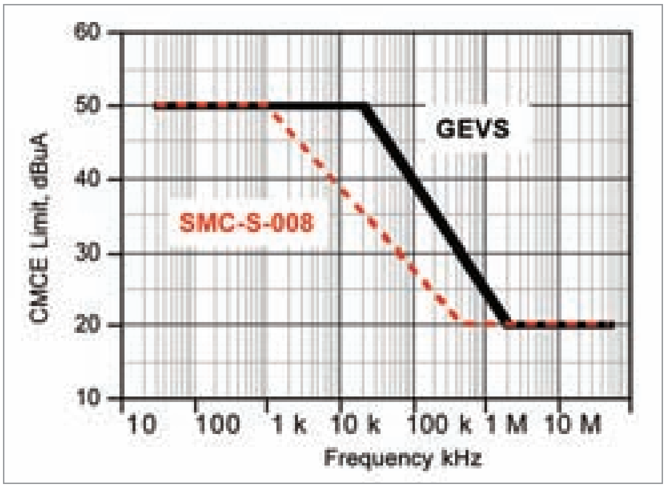

Figure 2: Existing spacecraft CMCE limits.

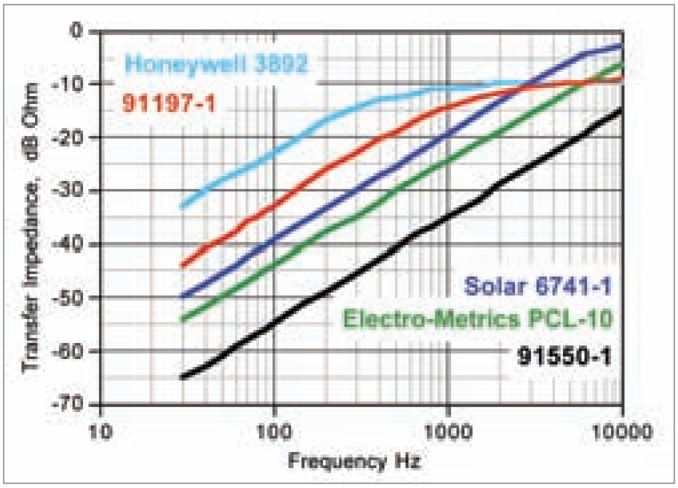

Figure 3: Transfer impedances of typical EMI current probes employed in the CE01/101 frequency range.

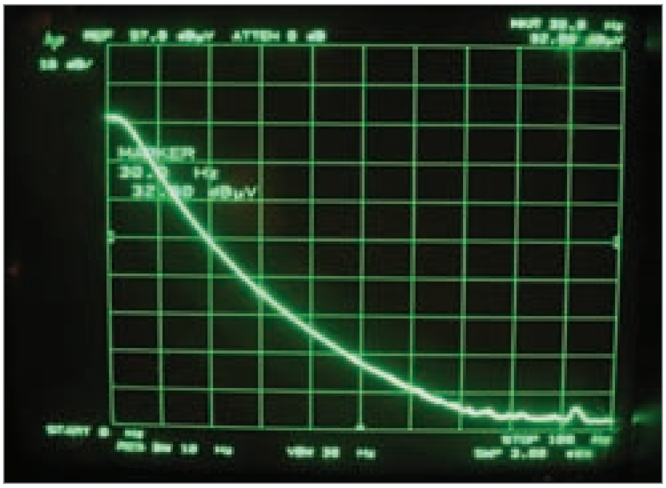

Figure 4: Degraded noise floor of HP 8566B spectrum analyzer below 100 Hz: about 33 dBuV at 30 Hz.

The EMCO 6640 has 50 kHz bandwidth and 60 dep't wideband sensitivity. An EMI receiver connected to its analog output can tune in narrowband signals down to 13 dBpT (13 dBpT + 10 * log (50 kHz) = 60 dBpT).

An EMCO 6640 or similar device can measure the field from a test sample and its interconnecting cables by specifying a distance and configuration of the test set-up and sensor. In fact, this has been done in the 1967 vintage RE04 MIL-STD-461 requirement and MIL-STD-462 test method.

Such a control may be valuable for an equipment housing, but since such fields fall off with the cube of distance (at distances where the equipment dimensions are small relative to the separation distance), it is most likely cables will be the culprits. Also, an optimally designed platform will separate magnetic sensors from localized magnetic hotspots, but it may be more difficult to separate sensors from any and all cables. Finally, magnetic emissions from cables fall off directly with distance (or in the case of cables above a conductive ground plane, as the square of distance) so that cable CMCE, although nowhere near as "hot" as a motor or transformer, may appear so at a distance.

In order to derive a CMCE limit from a magnetic flux density limit such as 13 dBpT, it is helpful to convert from units of flux density to magnetic field, assuming free space permeability.

The basic relation $B = \mu H$ converts to dBpT = dBuA/m + 2 dB uH/m in log-space. Hence, 13 dBpT is 11 dBuA/m.

If a cable far from ground carries a current "I" causing a circulating magnetic field "H", that relationship is the familiar $H = I/2\pi r$.

Assuming a separation of one meter between cable and sensor and converting to log-space, an H-field of 11 dBuA/m implies a common mode current on the cable of 27 dBuA. However, the more common situation is that the cable is near a conductive ground plane, and if the height above ground "s" is small relative to the observation distance "r", then the relationship between the common mode current and resultant circulating magnetic field is $H = I\,(2s)/2\pi r^2$

For a typical case where "s" is 5 cm and "r" is 1 meter, the above equation introduces a 20 dB relaxation in the allowable cm current, which is then 47 dBuA rather than 27 dBuA.

The ground plane is our friend! Compare this computed value of 47 dBuA with the Figure 2 CMCE low frequency plateau limit in the two standards cited in the Introduction.

The previous derivation does not prove that the low frequency CMCE limits shown in Figure 2 are derived from magnetic cleanliness requirements; the actual origin of the GEVS limit is shrouded in the mists of time. The derivation only goes to show that such a CMCE limit can be very useful in controlling magnetic cleanliness. The SMC limit is a GEVS derivative: it has no separate lineage. It differs from the GEVS limit in that it applies to the total CMCE from a unit, as opposed to just the power interface or individual cables. The SMC limit is measured by lifting the unit off ground, reattaching it via a wire, and measuring the CMCE through that wire, or alternatively by clamping a current probe around all the cables emanating from the unit.

As this is written (late 2011), the existing GEVS CMCE requirement applies only to power lines. However, a revision currently in process will extend applicability to all cables. The new revision will also relegate the requirement below 150 kHz to those platforms with a specific need for magnetic cleanliness, with the generally applicable limit above 150 kHz being based on crosstalk control. The 30 Hz to 50 MHz SMC limit applies to all platforms and all cables, with possible extensions to both lower and higher frequencies on a platform-dependent basis.

Finally, before moving on to CMCE test methods, it should be noted that another common form of such control is through design requirements mandating balanced above-ground circuits, or single-ended circuits, with dc isolation between signal returns and ground. This is practical at audio frequencies where uncontrolled parasitics will not perturb basic circuit functions.

TEST EQUIPMENT – CURRENT PROBES

A preferred technique for making audio frequency CMCE measurements is the legacy current probe-based CE02 measurement of MIL-STD-462 (1967). However, current probes available in most EMI test facilities (Figure 3) are not efficient enough to measure accurately at a level 6 dB below 50 dBuA (the Honeywell 3892 being a possible candidate, but are long obsolescent and only available if the test facility already owns one). To assess how efficient a transducer must be, the noise floor of the EMI receiver or spectrum analyzer must be known. Published specifications for the Rohde & Schwarz EMI receivers and spectrum analyzers show a noise floor at 30 Hz above 20 dBuV. Obsolescent machines such as the HP8566, designed to be used above 100 Hz but often "pushed" down to 30 Hz with resultant degraded noise floor, show even higher noise levels at 30 Hz (Figure 4). If the goal is to accurately measure a 30 Hz signal at 50 dBuA with a noise floor at 20 dBuV, the current probe transfer impedance cannot be less than -24 dB Ohm. None of the current probe transfer impedances in Figure 3 are adequate for that task.

Traditional EMI test current probes are based on ferrite cores. Cores constructed of other available materials, similar to laminated transformer cores, have better low frequency response. Transfer impedances of three such commercially available low frequency probes are shown in Figure 5.

Comparison of Figures 3 and 5 reveals that the *least efficient* Pearson probe is about 20 dB more efficient than any of the Figure 4 probes except the obsolescent and very scarce Honeywell probe. Additionally, all the Pearson probes are more efficient than the Honeywell model below 60 Hz.

A current probe inserts impedance into the line around which it is clamped. Generally, the inserted impedance is the transfer impedance divided by the turns ratio. For the special case when a resistor shunts the probe output, the inserted impedance is the shunt resistance divided by the square of the turns ratio. For the three Pearson probes discussed herein, the inserted impedances are negligible:

Model	Z_T, Ω	Inserted Impedance*, mΩ
3525	0.1	0.2
4688	1	20
5101	0.5	5

* Source: Pearson Electronics

EMC

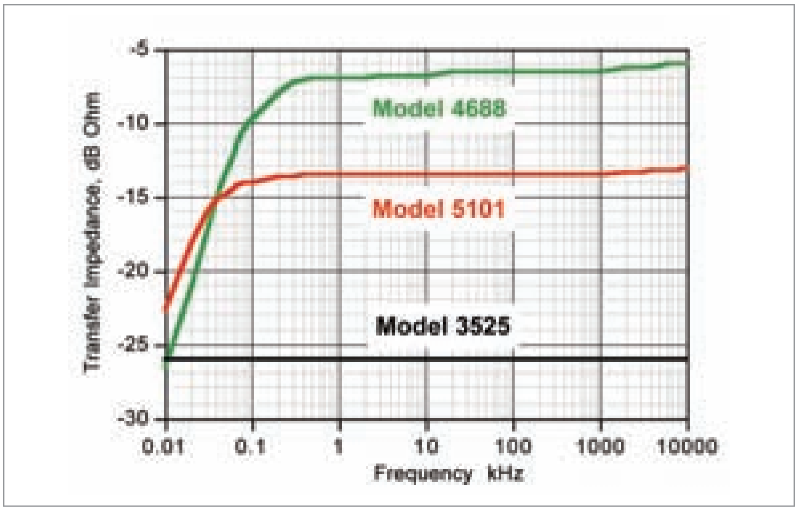

Figure 5: Transfer impedances of three Pearson Electronics wideband current probes. (Note: These probes are designed with 50 Ohm output impedances, and the plotted curves were made with a 50 Ohm network analyzer. If driving a 1 Megohm oscilloscope input, the plateau is 6 dB higher than shown. Thus, the Model 4688 is time domain spec'd as a 1 V/A probe with a lower 3 dB frequency of 600 Hz, the Model 5101 is spec'd as a 0.5 V/A probe with a lower 3 dB point at 150 Hz, and the Model 3525 is spec'd at 0.1 V/A, with a lower 3 dB point of 6 Hz. Source: the Pearson Electronics web site at http://pearsonelectronics.com.

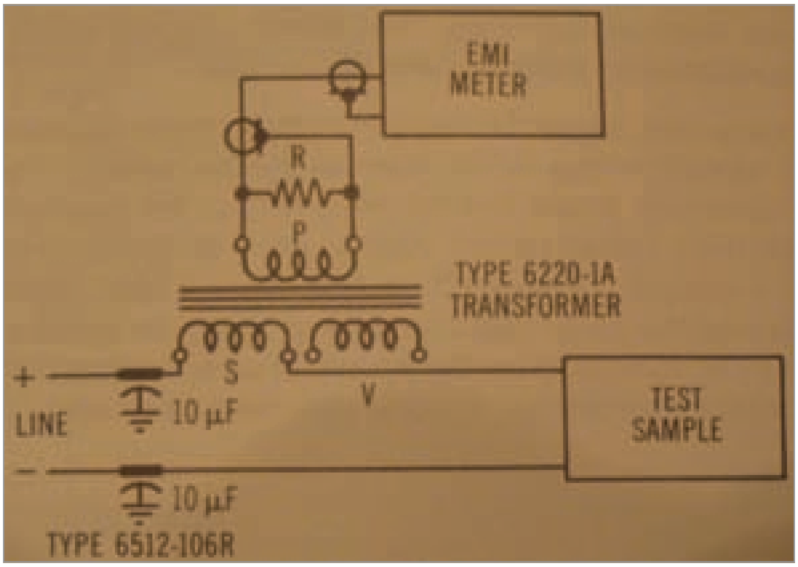

Figure 6: The Solar 6220-1 audio frequency coupling transformer used as a current probe (Source: Solar Electronics catalog application note).

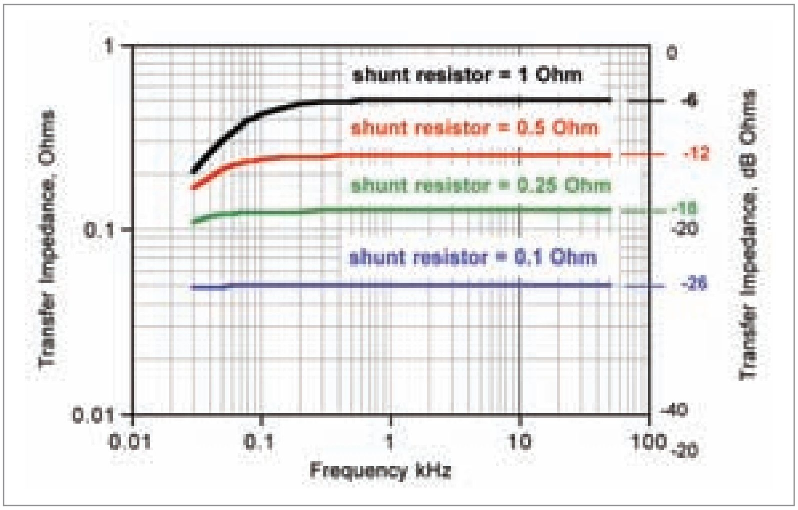

Figure 7: Solar 6220-1 transfer impedance using various shunt resistors on the primary side.

TEST EQUIPMENT – CURRENT PROBE ALTERNATIVE

For measurements on power lines or between a unit case and ground, the transformer method pioneered by the Solar Electronics Company can be adapted to provide even more efficient low-level, low frequency measurements. If measurements on individual cable bundles are necessary, an efficient current probe such as those discussed previously, is necessary. Regardless, the transformer method may still be helpful under certain conditions.

The transformer method is based on Solar Application Note AN62201, which has been around long enough that it was adopted by the United States Army and included in the 1971 Notice 3 to MIL-STD-462 (the "pink notice"). The application note, found in any edition of the Solar Electronics Catalog relies on the fact that a current probe is a type of transformer; therefore, a different kind of transformer may be substituted. The connection into the circuit, shown in Figure 6, is the same as for MIL-STD-461 CS01 or CS101. But instead of driving the Model 6220-1 coupling transformer with a power amplifier, the transformer's primary side is connected to an EMI receiver or spectrum analyzer. A loading resistor shunts the primary side to reflect a resistance into the secondary. The resulting transfer impedance has a flat asymptotic plateau at frequencies where the transformer's reactance is higher than the shunt resistance.

The principle of operation is that the secondary, unloaded on the primary side, has about 1.2 mH inductance. The reactance of that inductance, shunted by different resistors, yields a family of curves as shown in Figure 7. Because of the Model 6220-1 turns ratio of 2:1 primary to secondary, the transfer impedance plateaus in Figure 7 are equal to one-half the shunt resistor value in the circuit of Figure 6. [3] Given the 1.2 milliohm secondary inductance, the highest transfer impedance available at 30 Hz is about -13 dB Ohm. That value is obtained with no load, which is inadvisable since that would insert the entire 1.2 mH inductance into the power-line impedance. That is known to cause switched mode power supply instability. [4] The problem can be avoided using a 1 Ohm shunt, reflecting 0.25 Ohm into the power-line. Transfer impedance degrades 1 dB to -14 dB Ohm, which is the maximum practical transfer impedance available with this technique. This is 8 - 12 dB better than the various Pearson probes achieve.

If even better low frequency sensitivity is needed, say if the custodians of SMC-S-008 extend their CMCE limit below 30 Hz, an ordinary 50 or 60 Hz power transformer can be of assistance. A 60 Hz 120 V transformer primary stepping down to 25.2 volts and 2 amp load current yielded the transfer impedance shown in Figure 8, when the primary was loaded by 10 Ohms and the secondary was used to carry the current. A large increase in sensitivity is attained, acquired at the cost of inserting almost 0.5 Ohms in series with the circuit-under-test. Of course, the possibilities here are only limited by access to the power transformer of choice. It should be noted that somewhere between 1 to 10 kHz the power transformer performance deteriorated, and at 1 Hz the measured current waveform was distorted. A 50 Hz transformer could be expected to work to a slightly lower frequency, and the upper limit issue is not a problem because the 6220-1 or a current probe with adequate sensitivity is available at and above 1 kHz.

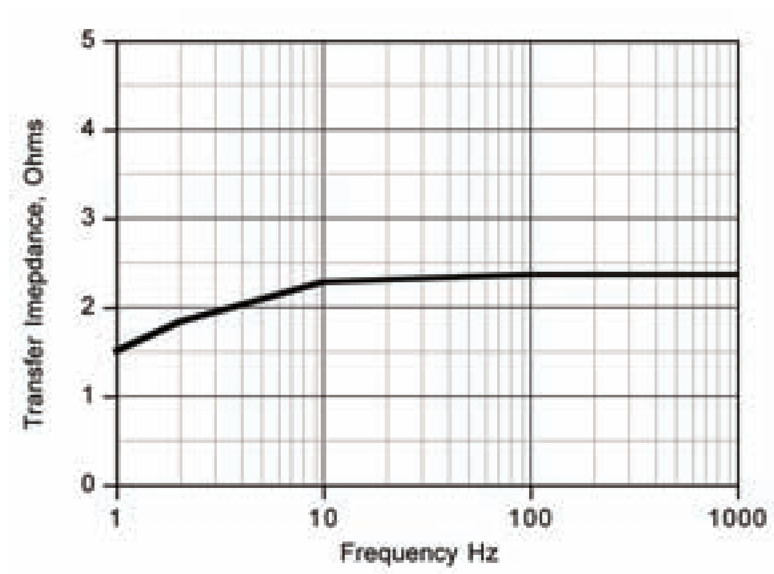

Figure 8: Transfer impedance of a step-down 60 Hz power transformer with primary shunted by 10 Ohms

COMMON MODE MEASUREMENTS

In addition to efficient transducer factors, a key property of a current probe to be used for making pure differential or pure common mode measurements (measurements that involve multiple conductors passing through its window) is adequate rejection of the undesired mode. The Pearson probes all provide at least 80 dB of differential mode rejection when used to measure common mode current up to 10 kHz. Brand new models 4688 and 5101 measured upwards of 90 dB rejection, but EMC Compliance's well-used Model 3525 measured just over 80 dB. The cases are identical in construction, so hard use accounts for the difference. Figure 9 is a plot of traditional CE01 limits superimposed on the CMCE limit of Figure 2. The dm rejection of the cm test method must exceed the difference between the CE01 limits and the CECM limits. The 80+ dB rejection of the Pearson probes more than suffices, except for the most relaxed GEVS CE01 limit. In the new GEVS, that limit is replaced by MIL-STD-461F CE101, with a low frequency plateau of 100 dBuA. For such a standard, the cited probes are a solution to making these sensitive cm measurements.

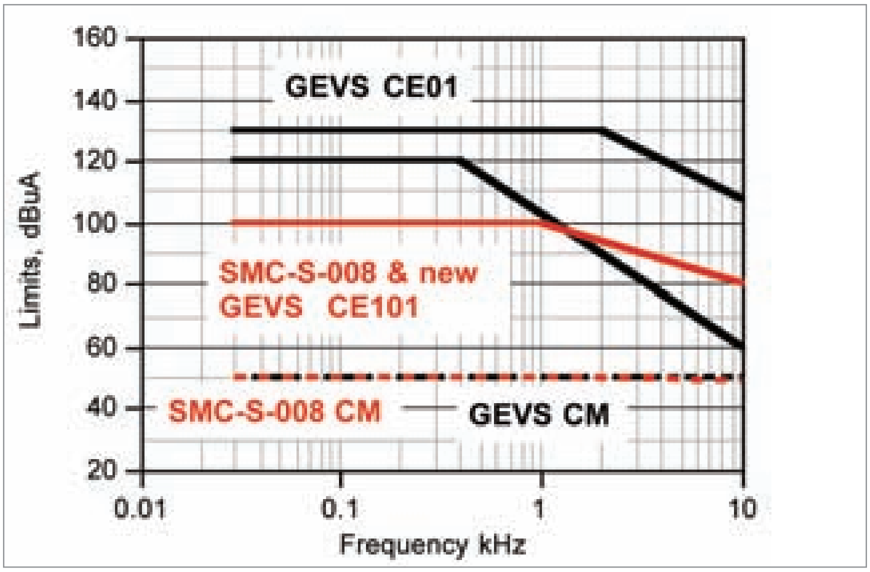

Figure 9: CE01 and CECM limits for GEVS and SMC-S-008

Figure 10: CM measurement on left; dm measurement on right.

To achieve maximum rejection of the undesired mode with multiple wires penetrating the window, it is necessary that the wires be tightly coupled to each other and centered in the window, so that capacitive coupling between either wire and the grounded current probe case is nearly equal. This is normally achieved with a split nonconductive dowel drilled down the center to take the two wires. It must be long enough so that wires clearing it drape away from the current probe body, and its diameter is just less than the probe window.

Using a pair of Solar 6220-1s to implement the transformer method in lieu of current probes, Figure 10 transforms into Figures 11 through 13 (pages 89 and 90). An important difference between hinged current probes and transformers is that a current probe may be opened and closed and wires rearranged within it without disturbing the flow of current to the test sample. The same is not true for a transformer. However, because the primary side is isolated from the current carrying secondary, the sense in which the primaries are connected to each other can be changed without disturbing the flow of current to the test sample, which is a blessing for any device which has to "boot" and requires significant time to reach proper operation subsequent to power cycling. The only difference between Figures 12 (cm measurement) and 13 (dm measurement) is how the bnc-to-banana adapters interconnect. Connections to the secondaries, shown in Figure 10, don't change.

For optimal rejection of the undesired mode, it is critical that the two transformers have *exactly* identical transfer impedances. Of course, this criterion is unachievable in practice, and although this technique produces more efficiency than the use of a current probe, the use of a single current probe to reject the undesired mode will always be superior. Undesired mode rejection is enhanced by using shunt resistors of lower resistance than the reactance of the transformers at the desired frequency. In this investigation, each transformer was shunted by 0.47 Ohms, for a net shunt resistance of about 0.235 Ohms. That compares favorably with the reactance of 1.2 mH at 30 Hz being 0.22 Ohms. Nevertheless, the maximum undesired mode rejection was about 40 dB.

Inspection of Figure 9 reveals that 40 dB differential mode rejection is insufficient to yield accurate cm measurements, because the dm limit is much more than 40 dB above the cm limit. However, the vast majority of electronic loads do not

Figure 11: CM/DM measurements made using a pair of Solar 6220-1 coupling transformers. The connection of the primaries (expanded on in Figures 12 and 13) determines which mode is measured and which rejected.

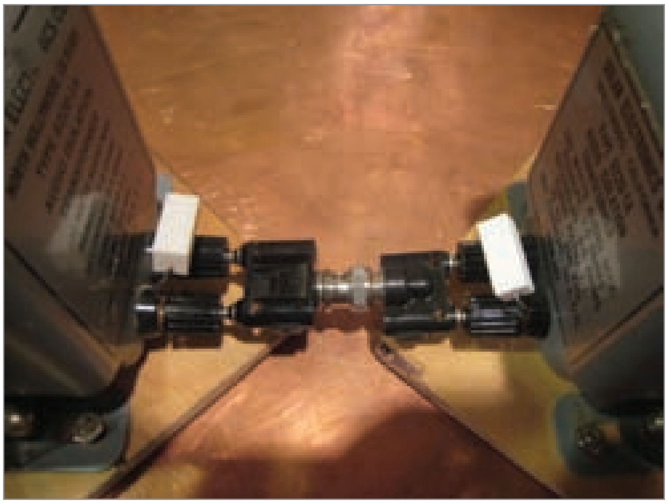

Figure 12: CM measurement connection close-up. The EMI receiver connection shown in Figure 10 has been removed for clarity.

Figure 13: DM measurement connection close-up. The EMI receiver connection shown in Figure 10 is there, but the connecting coaxial cable has been removed for clarity.

generate noise below the dc-dc converter frequency, and in that case the 40 dB value will be perfectly adequate. Low audio frequency conducted emissions are usually generated by rotating machinery of one kind or another, so if the test sample performs that sort of function, a current probe is a must.

There is a way around a low dm rejection ratio. This involves a modification to the cm measurement as per SMC-S-008, which requires measurement of total cm current, measured between test sample case and ground by raising the test sample case above ground and connecting it to ground with a wire, as shown in Figure 14.

The modification is to replace the current probe with the 6220-1 as per Figure 6, but instead of inserting a power wire, its secondary is inserted in series with the ground wire, effectively making the coupling transformer secondary as shunted by the primary, a series element in the ground connection (in Figure 15).

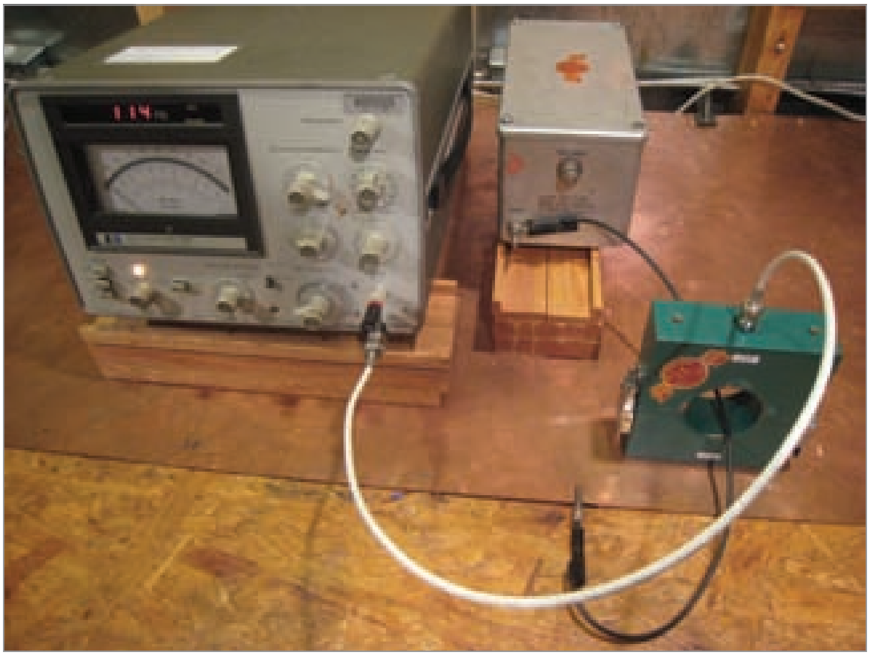

Figure 14: Total CMCE measurement per SMC-S-2008. The LISN represents a test sample whose metal case is raised above ground and then connected to ground via a wire.

This technique measures only the common mode current driven into ground, and thus there is no need to reject the undesired mode. It is ideal for working to SMC-S-008, but it is overkill if working to GEVS or any similar requirement that controls CMCE on a per-cable basis. Nevertheless, in the case of the unit that doesn't generate frequencies below that of its electronic switching power supply, there won't be any significant CMCE. A total summation of nothing is still nothing.

CONCLUSION

For the test facility that finds itself rarely working to one of these spacecraft EMI requirements, if the requirement is to only test the power interface, or if an SMC-like total CMCE measurement is made and the test sample generates no noise at audio frequencies, the CS01 coupling transformer technique is a handy way to measure with existing assets and adequate sensitivity. If a test facility is going to be making such measurements routinely, or if the test sample has cable connections beyond power that require individual sampling and generates significant audio frequencies, then the Pearson probes or probes with similar performance are preferable.

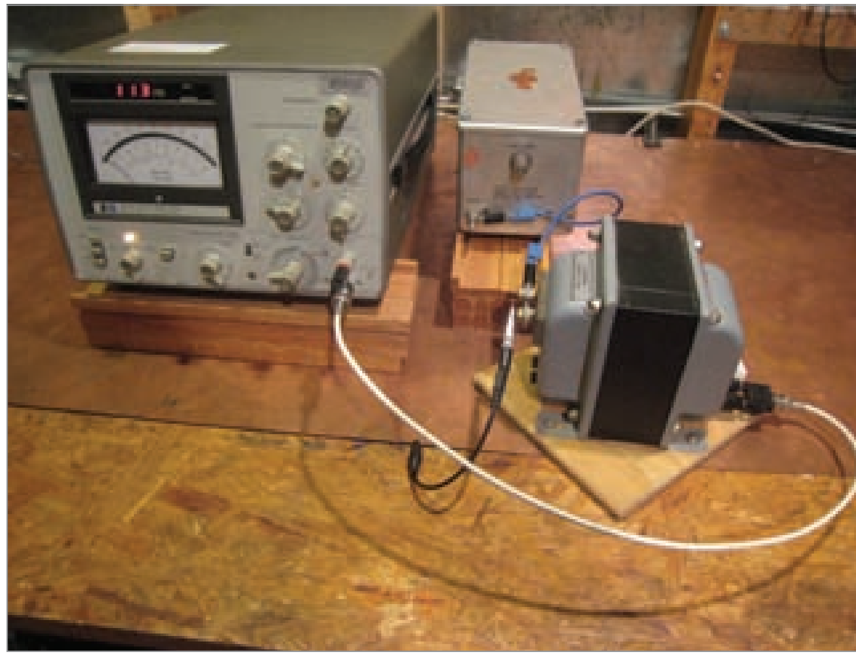

Figure 15: Total CMCE measurement per SMC-S-2008, but using the CS01 coupling transformer in lieu of a current probe.

ACKNOWLEDGMENT

Mark Nave's detailed review of the work contributed greatly to the overall effort and is deeply appreciated. The author would like to thank Pearson Electronics for the loan of Models 4688 and 5101 current probes in developing this article.

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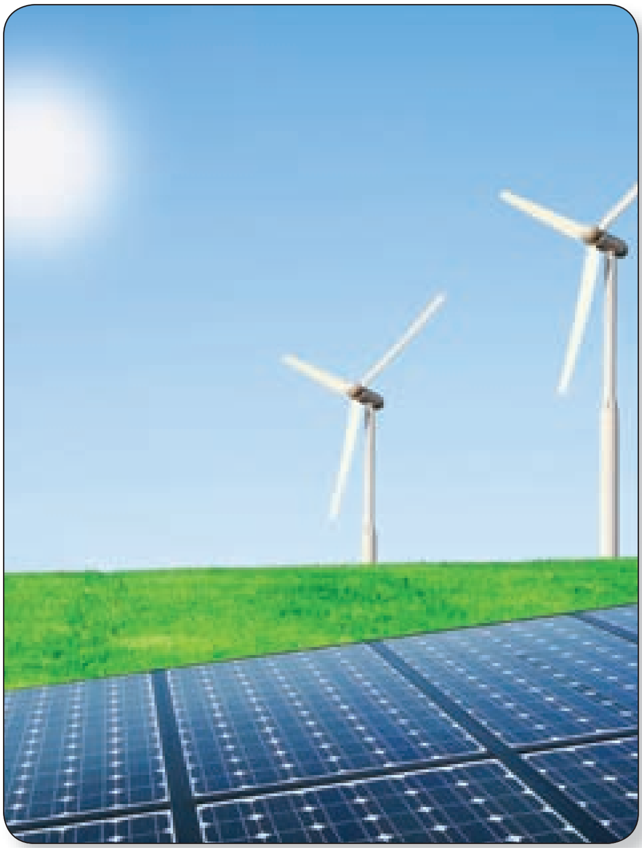
Low Frequency EMC and Power Quality

Development of Standards Towards Convergence

BY DR. MAGNUS OLOFSSON



FIGHTING CLIMATE CHANGE MEANS MORE ELECTRONICS

Electrification clearly facilitates our progress toward a resource-efficient and climate-friendly energy system. The share of electricity in total energy demand is projected to increase drastically in all the decarbonasation scenarios of the recent European Union (EU) Energy Road Map 2050[1] (Figure 1).

Wind and solar power are examples of expanding technologies for renewable power. Germany now has 25 gigawatts of installed solar power[2]. Electric vehicles, light emitting diode lamps and heat pumps are energy efficient electrical technologies of importance when fighting climate change. In virtually all such technologies, electrical energy is passing power electronics.
In addition to power electronics, there is also an increased use of electronics for supervision and control.

Smart Grid is More than Networks

The smart grid is a very topical issue. The term is widely used by many, especially politicians. Now the International Electrotechnical Commission (IEC) has defined the concept of smart grid[3]. The definition states that the smart grid is an electrical energy system that uses information technology. The smart grid is thus not only related to electrical networks, but to entire the power system. With smart grid technologies as well as power technologies for renewables and improved energy efficiency, there is an increased use of electronics. We see growth in the use of power electronics, as well as electronics for information technologies.

One example of smart grid application is the possibility of charging electric car batteries during hours with a surplus of low cost renewable energy. When electricity price is high, electric cars may feed energy back to the electrical network. This can be achieved using a continuous transfer of electricity price information with automatic control of the power flow to and from the electric cars. The term smart grid is thus enabling a ”smart” electrical system where the entire power system, with networks as well as connected equipment, is converting between electrical energy and other forms of useful energy.

Smart Grid and the Concept of EMC

The physical characteristic of smart grid technologies, with an increased incorporation of potentially sensitive electronics, naturally has implications with respect to electromagnetic compatibility (EMC). The satisfactory function of electrical and electronic equipment with respect to electromagnetic disturbances is the aim of EMC. The IEC defines[4] electromagnetic compatibility as ”the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment”. In the European Union EMC Directive the ”equipment or system” of IEC corresponds to the EU term “equipment”, where equipment in turn is subdivided into apparatus and fixed installation.

Electromagnetic disturbances may be radiated or conducted and electrical/electronic equipment is potentially sensitive to any or to both of these types of disturbances. Disturbances are in turn subdivided into a number of low and high frequency phenomena, where IEC defines low frequency up to and including 9 kilohertz.

Field Experiences with Smart Grid Technology

Examples of lack of EMC in relation to evolving smart grid technologies have been reported in Sweden. Kilowatt-hour meters in households sending data signals through power lines have caused interference with, for example, dimmer controlled lamps and electrical appliances. There are also cases reported where electrical apparatuses in households have interfered with electronic kilowatt-hour meters with adverse errors in registration of energy. Power electronics in wind power plants have emitted disturbances interfering with transfer of kilowatt-hour meter readings as signals on power lines.

Power electronic-based photovoltaic solar and wind energy equipment may emit disturbances causing variations such as voltage fluctuations and unbalance[5]. However, with a proper design such equipment may well improve voltage quality, for instance by reducing depth of voltage dips[6].

VOLTAGE QUALITY AND EMC

Both IEC and EU define EMC to cover electromagnetic phenomena from zero hertz. Furthermore, the IEC defines the following principal electromagnetic conducted phenomena[7]:

Conducted low-frequency phenomena:

- harmonics, interharmonics
- signals superimposed on power lines
- voltage fluctuations
- voltage dips and interruptions

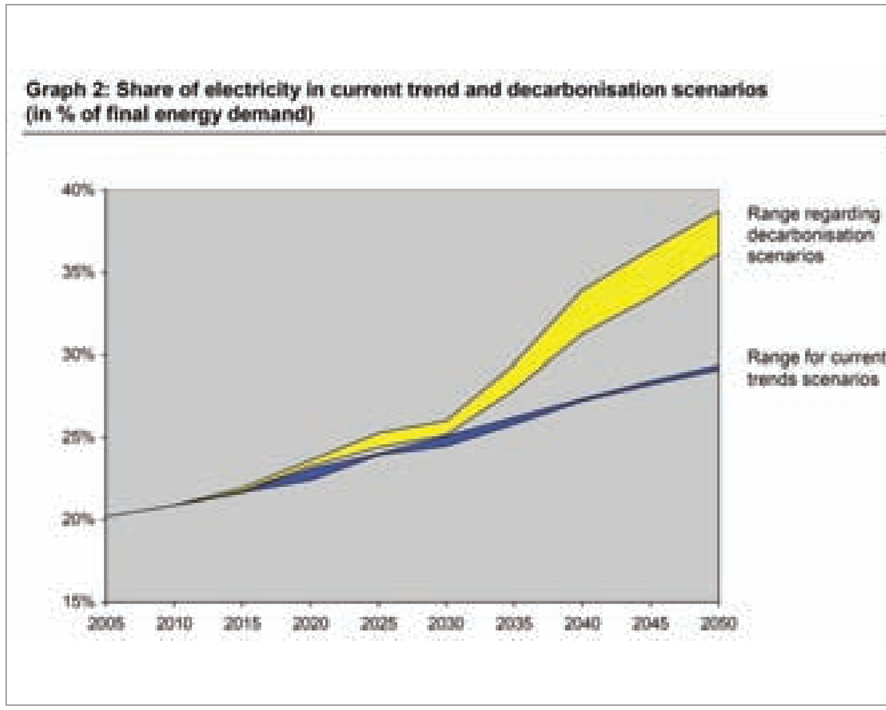


Figure 1: Share of electricity in final energy demand, according to the EU Energy Road Map 2050

- voltage unbalance
- power frequency variations
- induced low-frequency voltages
- DC component in AC networks

Conducted high-frequency phenomena:

- induced voltages or currents
- unidirectional transients
- oscillatory transients

Voltage quality can be seen as an umbrella name for deviations from ideal voltage conditions at a site in a network[8]. This is equivalent to electromagnetic disturbances of the voltage at the site. With no disturbances the voltage quality is perfect, otherwise it is not. electromagnetic disturbances are defined as electromagnetic phenomena that may degrade the performance of equipment[9]. Adequate voltage quality contributes to the satisfactory function of electrical and electronic equipment in terms of electromagnetic compatibility. Electromagnetic disturbances as imperfect voltage quality at a site in a network can be regarded as electromagnetic emission from the network[10]. According to the EMC Directive, a network is equipment. This is in line with the original name of the IEC Technical Committee (TC) 77, which was *EMC Between Electrical Equipment Including Networks* and is now simply EMC[11].

The technical function of an electrical network is electromagnetic energy transfer with adequate voltage quality at its sites(connection points). Similarly, immunity of an electrical network can be seen as the ability to absorb disturbing emissions (such as distorted current) with adequate voltage quality while transferring energy or, in other words, with satisfactory function. For example, for low order harmonics and voltage fluctuations, network strength is relevant for network immunity[12, 13].

Geomagnetically-induced current caused by space weather is another example of the relevance of electromagnetic immunity for keeping an electric grid[14] functioning satisfactorily.

The importance of voltage quality to achieve EMC is clearly stated in a report from the Council of European Energy Regulators (CEER)[15]: "Due to the nature of electricity, voltage quality is affected by all the parties connected to the power system. When voltage quality is too poor, a

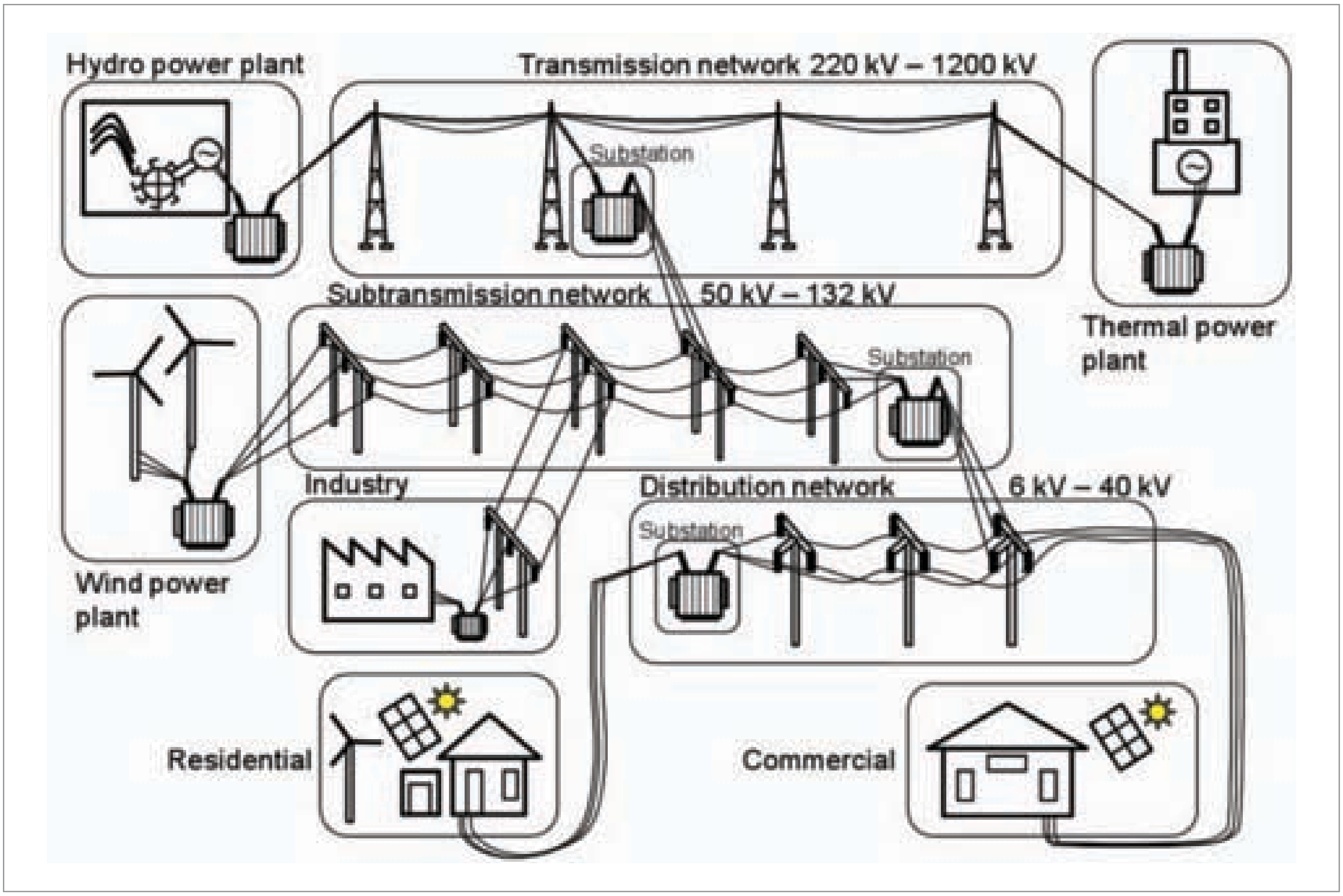


Figure 2: Power system made-up of equipment

key question is whether the disturbance (e.g. a harmonic disturbance) from a customer's installation into the power system is too big or whether the power system (the short circuit power) at the point of connection is too weak. The aim should be to have an electromagnetic environment where electrical equipment and systems function satisfactorily without introducing intolerable electromagnetic disturbances to other equipment. This situation is referred to as electromagnetic compatibility (EMC)."

EQUIPMENT-BASED POWER SYSTEM MODEL

Power systems consist of electrical equipment. Beyond safety, the usefulness of electricity in power systems relies on the function of such equipment. Electromagnetic compatibility is about the satisfactory function of equipment with respect to electromagnetic disturbances.

According to the EMC Directive, equipment are either apparatus or a fixed installation. Apparatuses are part of the EU system for CE marking, while fixed installations are not. However, protection requirements on emission and immunity are enforced on all equipment.

Examples of fixed installations are[16]: power plants, power supply networks, wind turbine stations, industrial plants and railway infrastructures. According to the EMC Guide, the classification of fixed installations is wide and the "definition covers all installations from the smallest residential electrical installation through to national electrical and telephone networks, including all commercial and industrial installations".

Applying the concept of fixed installations to power systems may suggest a schematic illustration like Figure 2. As indicated in the picture, various types of equipment are connected to other types of equipment. Equipment for energy conversion is normally connected to only one other type of equipment, creating a network. Equipment for conveying energy, such as networks, are normally connected to several other types of equipment including networks.

COMPATIBILITY MARGINS AND PROTECTION REQUIREMENTS

The objective of protection requirements for equipment, including fixed installations such as electrical networks and connected equipment, is the achievement of EMC.

When aiming for EMC in electrical power systems, it is reasonable to apply the same reference for voltage quality (emission) in electrical networks as for limits on immunity of connected equipment. This is schematically indicated in Figure 3, where a common compatibility level is applied

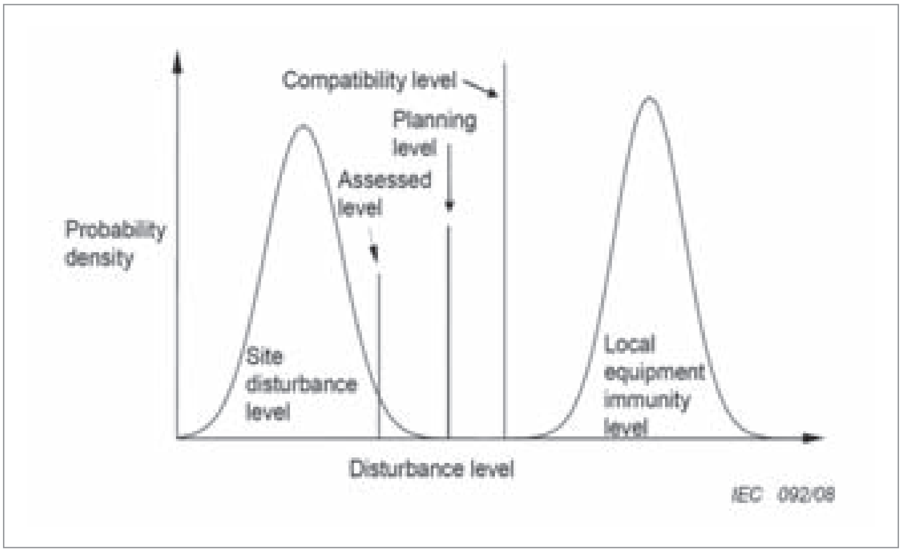


Figure 3: Voltage Quality concepts with time statistics for a site within a network[17]

> The first thing to do when faced with an out-of-tolerance unit is to read through the calibration certificate and data to get a firm understanding of what specifically failed calibration.

for voltage quality as well as for immunity of connected equipment. Electromagnetic compatibility levels are defined in the IEC 61000-2 series (IEC 61000-2/4/12 for use as references for emission and immunity of equipment). For very slow voltage variations, limits are given in the standard IEC 60038. Network emission levels, which are essentially voltage quality planning levels, are defined with a margin in relation to compatibility levels, as indicated in Figure 3.

PROTECTION REQUIREMENTS FOR EQUIPMENT IN POWER SYSTEMS

In the following example, application of protection requirements on emission and immunity are illustrated for selected principal electromagnetic phenomena.

HARMONICS AND INTERHARMONICS

Origins of low order harmonics are, for example, classical line commutated diode and/or thyristors based rectifiers. Examples of equipment emitting high order harmonics are voltage source converters, such as transistors which are switched at high frequency.

Emission of low order harmonics can often be modeled as current sources, while high order harmonics normally appear as voltage sources. In between these two simplified models there is naturally a more complex reality. Resonances may increase the complexity further.

When harmonic current of low order is injected into a network, the voltage is distorted which reduces voltage quality. The level of voltage distortion is dependent on the network strength. Similarly, high frequency current harmonics may cause voltage harmonics in the network. Network strength in terms of short-circuit power or fundamental frequency short-circuit impedance is less essential for voltage quality at higher frequencies. The geographical spread of higher frequency distortion is normally relatively small.

Current harmonics may cause overheating of e.g. neutral conductors and capacitors in three-phase systems. Voltage harmonics may upset electronics, e.g. due to multiple zero crossings. Loading capability of induction machines may be reduced.

Some sources of interharmonics are frequency converters and transformers saturated during energizing.

Suggested responsibilities for equipment's accountable parties are given in Table 1. Compatibility margins are found in IEC 61000-2/4/12. A basis for apportionment of harmonic disturbances in networks is available in IEC 61000-3-6.

Voltage Fluctuations

Voltage fluctuations may range from very slow voltage variations to rapid voltage fluctuations. Very slow voltage variations are equivalent to variations within voltage ranges, i.e. voltage deviations from nominal values. If the nominal voltage is 230 volt and the actual voltage is 240 volt, there is a voltage variation of 10 volts, which is an electromagnetic disturbance. However, a very slow variation causing an offset

Responsible	Emission	Immunity
Network operator	Voltage quality planning levels	Apportioning of distortion limits (except at public low voltage), network strength at lower frequencies
Equipment connected to network (may be another network)	Fulfillment of emission standards (e.g. within CE marking system), as well as as well as fulfillment of network operator apportioning levels	Fulfilling of immunity standards (e.g. within CE marking system), as well as consideration for EMC in own equipment

Table 1: Responsibility for protection requirements – harmonics and interharmonics

> Regardless of the phenomena, it is clear that a appropriate division of responsibilities for networks and connected equipment is paramount.

of only 10 volts is, in practice, not expected to cause any interference. Limits for very slow voltage variations are given in IEC 60038 at supply terminals, i.e. the connection point between the network and connected equipment.

Suggested responsibilities for controlling voltage fluctuations within the network system are given in Table 2. Slow voltage variations in a network are depending on a number of technical issues ranging from design, maintenance and operation.

Rapid voltage fluctuations may cause flickering of lights. Source of disturbance may be electric arc furnaces that cause rapid current fluctuations.

Suggested responsibilities for equipment's accountable parties are given in Table 2. A framework for apportioning of distortion limits is given in IEC 61000-3-7.

CONVERGENCE OF STANDARDS

A smart grid enables more renewables and more efficient use of electricity. The smart grid also is expected to boost use of electronically based equipment in the electrical power system.

To realize the smart grid, the following issues are important to consider:

1. EMC is essential for a robust smart grid, both with respect to radiated and to conducted disturbances.
2. Power quality is a means to achieve EMC between the smart grid and connected equipment.
3. Electrical networks, including smart grids, are equipment.
4. Protection requirements, such as those for emission and immunity, also are valid for electrical networks.
5. Protection requirements for networks and connected equipment should be economically and fairly balanced.
6. A complete set of standards for EMC in power systems, including power quality, is needed from the standardization community.
7. Seeing EMC as a technical issue, where cost optimization is to a large extent governed by the standardisation community, regulatory frameworks should be designed without links to market mechanisms, i.e. similar to the handling of electrical safety.

CHANGING FOCUS IN LOW FREQUENCY EMC OVER TIME

Over the years, focus has shifted between various electromagnetic phenomena. During 1980s, low-order harmonics were high on the agenda due to the introduction of thyristor and diode based current stiff line commutated power electronics. Similarly, voltage fluctuations causing flickering lights were of great concern where arc furnaces were the main source of disturbances. In the 1990s, the use of variable speed drives for induction motors was introduced

Responsible	Emission	Immunity
Network operator	Voltage quality planning levels	Network strength, apportioning of distortion limits (except at public low voltage)
Equipment connected to network (may be another network)	Fast changes in active and reactive power demand, generation kept within limits stated by network operator	Fulfilling of immunity standards (e.g. within CE-marking system), as well as consideration for EMC in own equipment

Table 2: Responsible for Protection Requirements – Rapid Voltage Fluctuations

on a large scale. Voltage dips were causing interruptions in industrial processes due to inadequate immunity for those drive systems.

Presently, there is an increased awareness of electromagnetic disturbances in the frequency range 2 to 150 kilohertz. This is due to switched converter technologies used over time in an increasing number of apparatuses, from energy efficient luminaries to charging units for electrical vehicles. Due to connection of wind and solar power at the end of weak feeders, the occurrence of temporary overvoltages is a disturbance of increased concern. Regardless of the phenomena, it is clear that a appropriate division of responsibilities for networks and connected equipment is paramount.

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Technology Advancements in Board Level Shields for EMI Mitigation

Not Your Daddy's Metal Can

BY GARY FENICAL AND PAUL CROTTY

PC BOARD EMI

If properly done, PC board (PCB) design control techniques can be the most cost effective means of resolving EMI issues. The techniques involve:

- partitioning
- board stack-up
- use of isolating lines
- routing
- board level shields

Other techniques involving additional component costs include high frequency grounding of the board and filtering techniques. It is important to mention that if these techniques are designed in at the initial stage, there will be minimal impact to schedule and cost. Correct techniques begin with component placement. Critical circuits (i.e. clock circuits, clock driver, etc.) and functions should be grouped together, providing the shortest trace lengths between components. Engineers should consider the use of multi-layer boards, having many ground planes, designing high-speed traces (such as transmission lines), and employing proper and adequate filtering and decoupling components. In addition, designers should add placements for filtering components, but place jumpers or "zero-ohm resistors" to hold them in place and only add the real components if required to by the test. Early board prototype testing can produce useful insight into potential problem areas. Board areas with high radiation and the measuring of interconnect cable noise currents are indicators of potential system radiation sources.

Both radiated noise and conducted noise can be a problem in these systems. For conducted noise issues, the use of ferrite chokes and proper signal line layout can prevent a host of issues when considered in the design phase rather than later on.

It is a well-known fact in the EMC community that the closer you are to the source of an EMI problem, the more efficient and less expensive it is to fix. One cannot get any closer than by using a board level shield (BLS). Having stated that, it is important to mention that there is no substitute for proper circuit design and layout.

Looking at a basic formula for RF emissions:

$E = 1.316\, AIF^2/(DS)$

where:

E = microvolts / meter

A = radiating loop area in cm^2

I = current in amps

F = frequency in MHz

D = measurement distance in meters

S = shielding effectiveness ratio

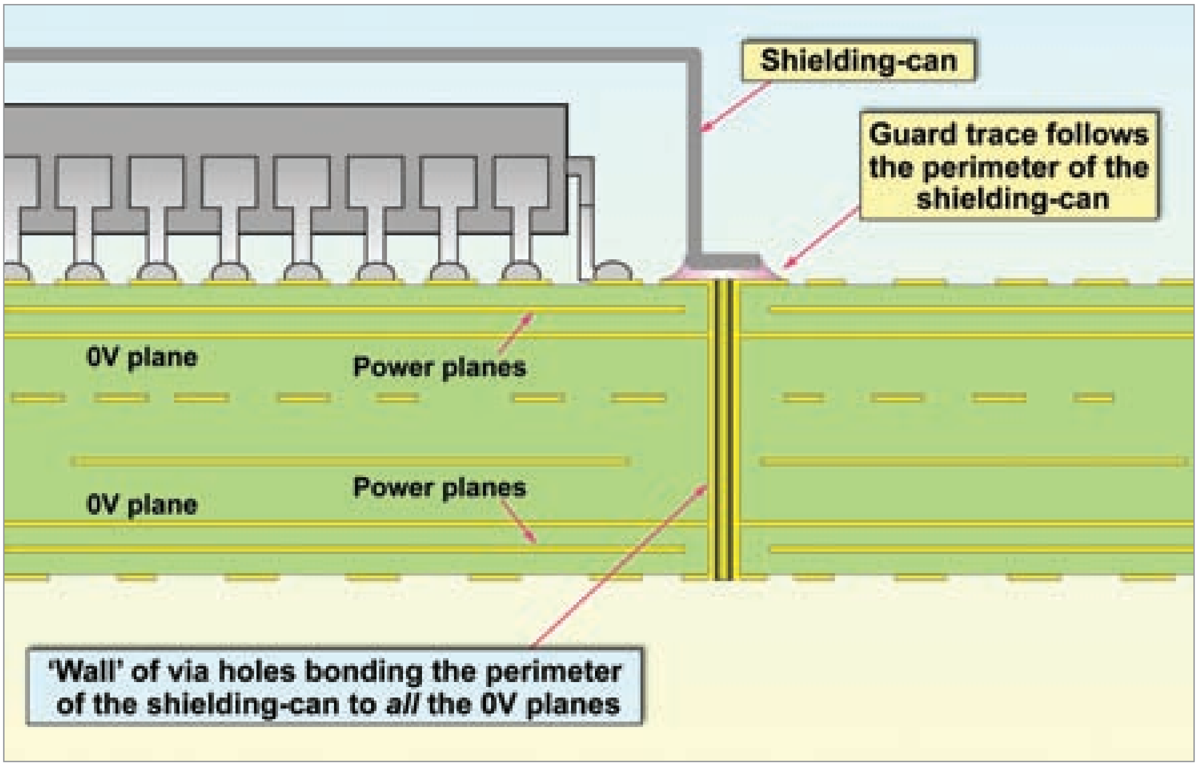


Figure 1: Section through one of the perimeter via holes (Courtesy of Eur Ing Keith Armstrong C.Eng MIEE MIEEE, Cherry Clough Consultants)

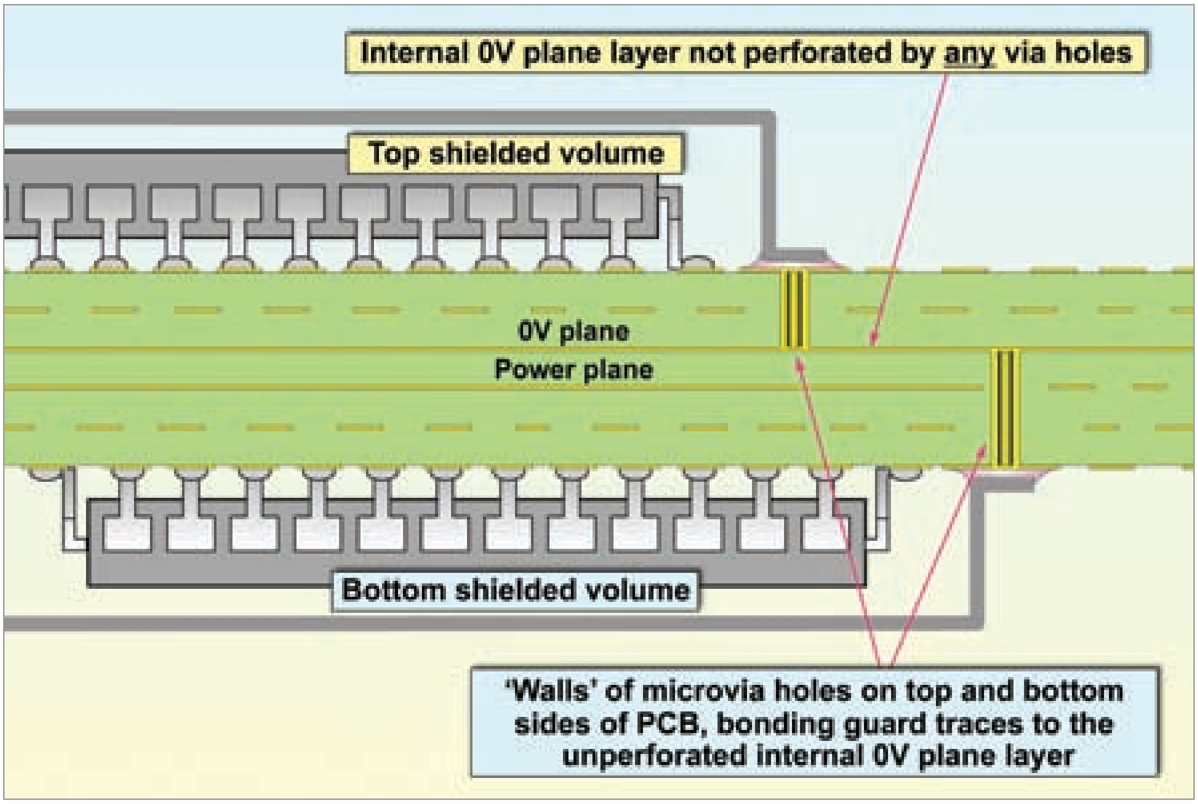


Figure 2: Courtesy of Eur Ing Keith Armstrong C.Eng MIEE MIEEE, Cherry Clough Consultants

Figure 3: Rigid corner technology (US Pat 7,488,902 B2)

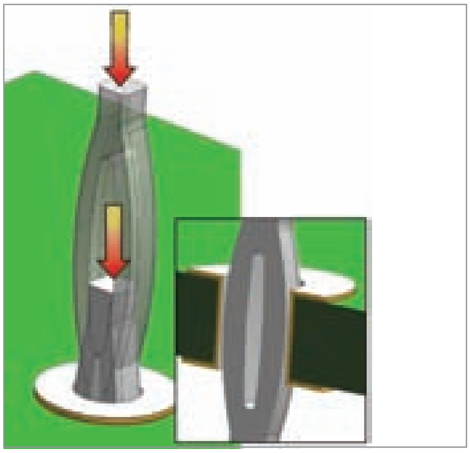


Figure 4: Eye-of-needle/compliant pin

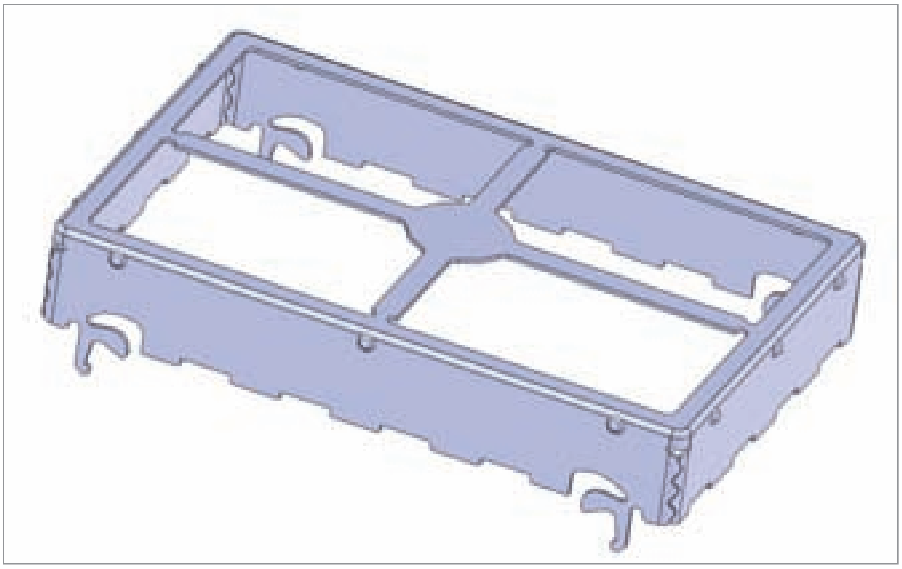


Figure 5: Through-hole lock pin

Let's examine the formula and break it down to better understand it. First we will eliminate 1.316 as it is a constant. D is the measurement distance specified by the standard to which you are testing. D can also represent the distance from the device to an object with which it may interfere. In any case, these are factors beyond the control of the device designer. If we further examine this formula, we see that emissions (E) increase linearly with current and loop area but increases exponentially with frequency. We see that it is extremely important to keep loop area as small as possible, especially for high current and/or high frequency circuits. We have seen over many decades that the most common cause of failure is caused by excessive loop area. Whether the excessive loop areas are caused by poor layout or by the offensive signal coupling into other circuits with large loop areas, the result is the same; failure to meet your mandatory emissions requirements. PCB layout software that does not include EMC software will generally not consider loop area. Therefore, the designer must take control and lay out high current and high frequency circuits manually to be sure to minimize loop area. Of course, if you cover the entire loop area with a shield, there is no loop area exposed and that value goes to zero. Again, keeping the loop area as small as possible allows for the smallest possible shield.

Going back to the formula we see that one term has not been addressed, S. S is for shielding. Once the designer has chosen the circuit components, which will determine the frequency and current, and has reduced the loop area to the smallest possible geometry, if the device does not meet its requirements, there is only one thing left to do. Shielding! Looking tot the opening statement of the article, the closer this shielding design is to the problem, the better. Allowing for proper BLS mounting must be done at the PCB design stage. It is essentially impossible to properly mount a BLS after the board has been laid out.

Consider this; the BLS supplier only provides 5 sides of the required 6-sided Faraday cage you are attempting to build. It is up to the PCB designer to build into the PCB the sixth side, usually an imbedded ground plane. The designer must also provide properly spaced mounting pads, as well as determine if through-hole or surface mounted methods will be used. Although BLS parts are needed to manage EMI requirements for both immunity (for product performance) and regulatory needs (FCC, EU etc.), the board shield design is usually not the only factor in EMI performance. As mentioned, the sixth side of the Faraday cage is the PCB ground plane, and the PCB design itself has much influence on overall EMI performance.

Remember that these same basic design principles hold true for susceptibility. Therefore, BLS works equally well for emissions and/or susceptibility.

Board level shields are generally categorized into four basic types:

1. one-piece
2. two-piece
3. drawn
4. one-piece with removable sections

A one-piece BLS is typically a stamped and formed sheet metal can, often produced on high-speed presses. These are usually the least expensive for high-volume production. A two-piece BLS is also stamped, with individual fences and covers. The two-piece BLS can be provided assembled, or as individual components. These are often used where access to PCB components is necessary for inspection, testing or rework. One-piece with removable sections is a one-piece BLS with removable areas that are scored for easy removal and access to components for adjustment or repair. A separate replacement cover is required. A drawn BLS is a one-piece BLS that uses drawn stamping technology to produce a BLS with no slits or apertures at the corners.

BLS FLATNESS

As more fine pitch components are utilized on a PCB, thinner solder paste thicknesses are required to prevent shorts or bridges. This has translated into better flatness requirements for SMT board level shields. Current flatness requirements are typically 0.10mm to 0.05mm. Drawn shields and rigid corner technology (US Patent 7,488,902 B2 Figure 3) can improve flatness capabilities by acting as a stiffener for the whole shield. Additionally, where acceptable, through hole features can be utilized to ensure a good mate exists between the BLS and PCB during assembly and reflow. Existing products and solutions are eye-of-needle pins and other compliant pins (Figure 4).

A newly available product is the through-hole lock pin (Figure 5), which allows for precise and repeatable fixturing of the BLS (frame or single piece) to the PCB for the subsequent reflow operation (conformal to the PCB).

POST REFLOW INSPECTION/ TESTING

In the PCB manufacturing process, there are often post reflow inspection or testing requirements that need as much open access to the PCB components as possible. For SMT BLS frames, the pickup bridge can be in the way of this inspection or testing requirement and must be removed. Post installation/reflow access to PCB components under the BLS pickup bridge is a common requirement. Manual removal of the pickup bridge by cutting or bending has been a necessary, labor-intensive step. A new product feature is the ReMovl pickup bridge (Figure 6). It is a pre-cut bridge for easy toolless removal or automated removal (Figure 7).

PRODUCT REWORK

For some applications, it is important to have the capability to rework areas on the PCB covered by the BLS. This may be part of the initial manufacturing process or later work in the field. Single piece BLS with simple rework capability is required. One solution is the EZ Peel BLS with scored lid (Figure 8, page 104). However, separate replacement covers are required, and this can lead to inconsistent performance on removal and replacement of the scored section.

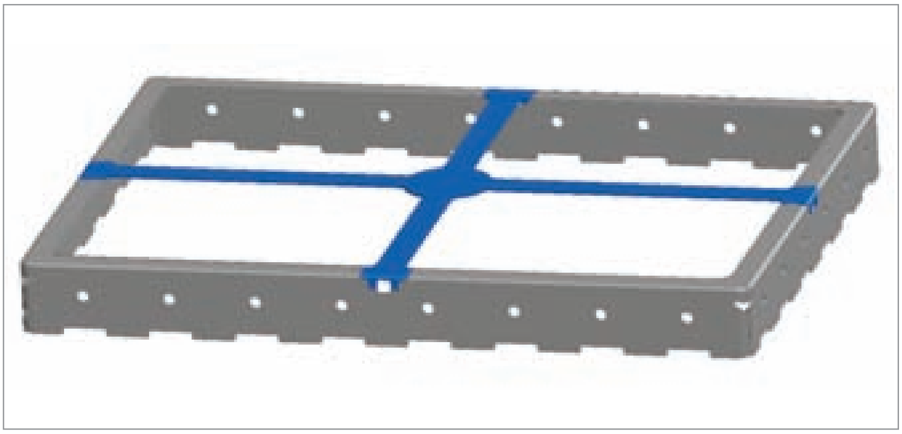


Figure 6: ReMovl pickup bridge BLS frame

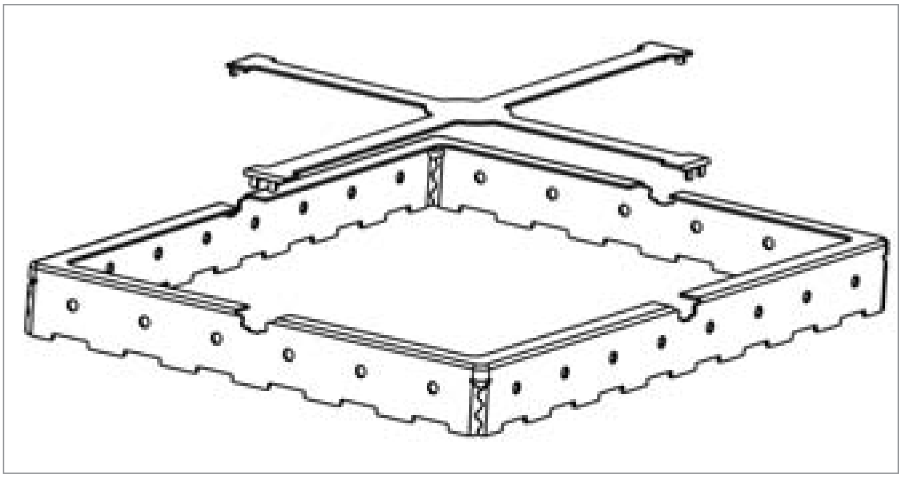
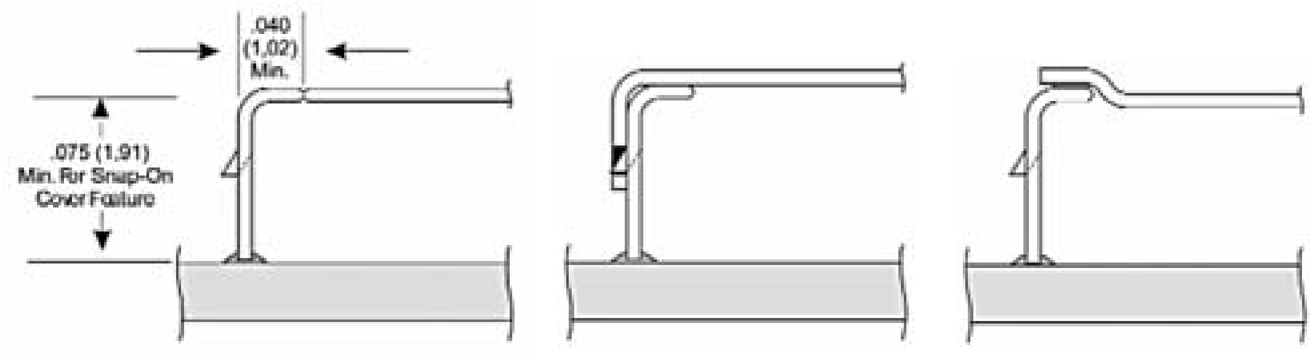


Figure 7: Bridge removed



Original EZ Peel Can

After removal of scored section and application of snap-in lid

After removal of scored section and application of dish lid

Figure 8: EZ Peel BLS

An alternative to this solution is the ReCovr BLS, a good alternative to the EZ Peel solution since it can reuse the original cover (Figures 9 and 10). It has the advantages of a two-piece BLS at a cost comparable to a one-piece BLS. Recent enhancements to the latching features of this design improve the cover retention force both as delivered, and after removal and replacement. This feature allows for applications where shock and vibration may be encountered.

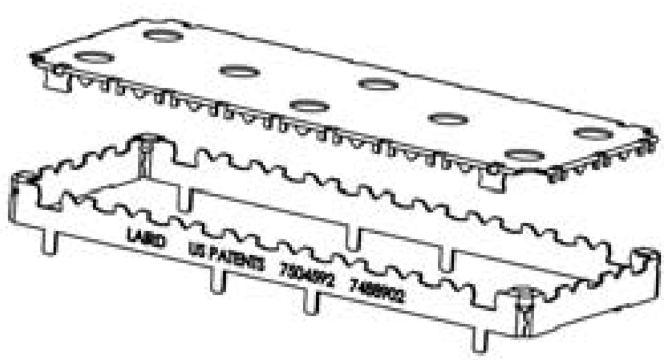


Figure 9: ReCovr with lid removed

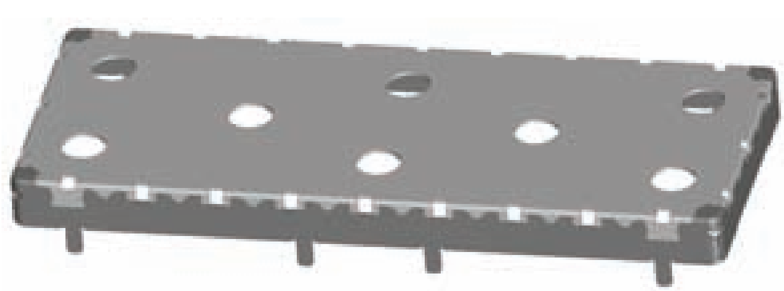


Figure 10: ReCovr with lid in place

LONG-TERM PERFORMANCE AND RELIABILITY

While many BLS applications have short product lifecycles, there are also many longer-term applications in automotive, industrial automation and military programs which require sustained performance over many years. In these cases, both corrosion concerns and tin whiskering must be considered in the base material and plating choices.

MULTI-FUNCTIONAL BLS

As relative PCB space continues to shrink and power/heat generation per unit area grows, more multi-functional BLS and thermal products will be needed. One potential solution exists with BLS and integrated thermal pads. If the frame assembly to PCB includes a pickup bridge for automated placement, this bridge needs to be removed to allow for contact of thermal interface material to the PCB component. The Removl pickup bridge is an ideal option for this application. The ReMovl pickup bridge facilitates the manufacturing process by simplifying the removal of the pickup bridge.

CUSTOMER REQUIREMENTS/ INDUSTRY DRIVERS

Today, based on current customer application needs for BLS products, there are even more choices and product features available. These technology innovations were driven by the application needs across multiple industries. These additional design choices are summarized in Figure 11.

CONCLUSION

As you now see, board level shields are not just five-sided metal boxes anymore. Today's advanced BLS designs provide solutions for many manufacturing, performance and rework requirements. Understanding all the options and utilizing the BLS design selection guide can help lead you to the most efficient and cost effective solution. In addition to the guide, remember that a trained field application engineer may still be the best choice for proper BLS design and feature selection.

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***Paul Crotty**, Director of Engineering and Product Development for EMI Metals, has been with Laird Technologies for 15 years. He holds a B.S. in Mechanical Engineering from Rennselaer Polytechnic Institute and has previously served as an officer in the U.S Navy. Within Laird Technologies, he has held various roles in tooling, engineering, and product design and has been instrumental in establishing the global resources for Laird Technologies EMI Metals capabilities. He holds several patents related to board level shield products with additional patents pending.*

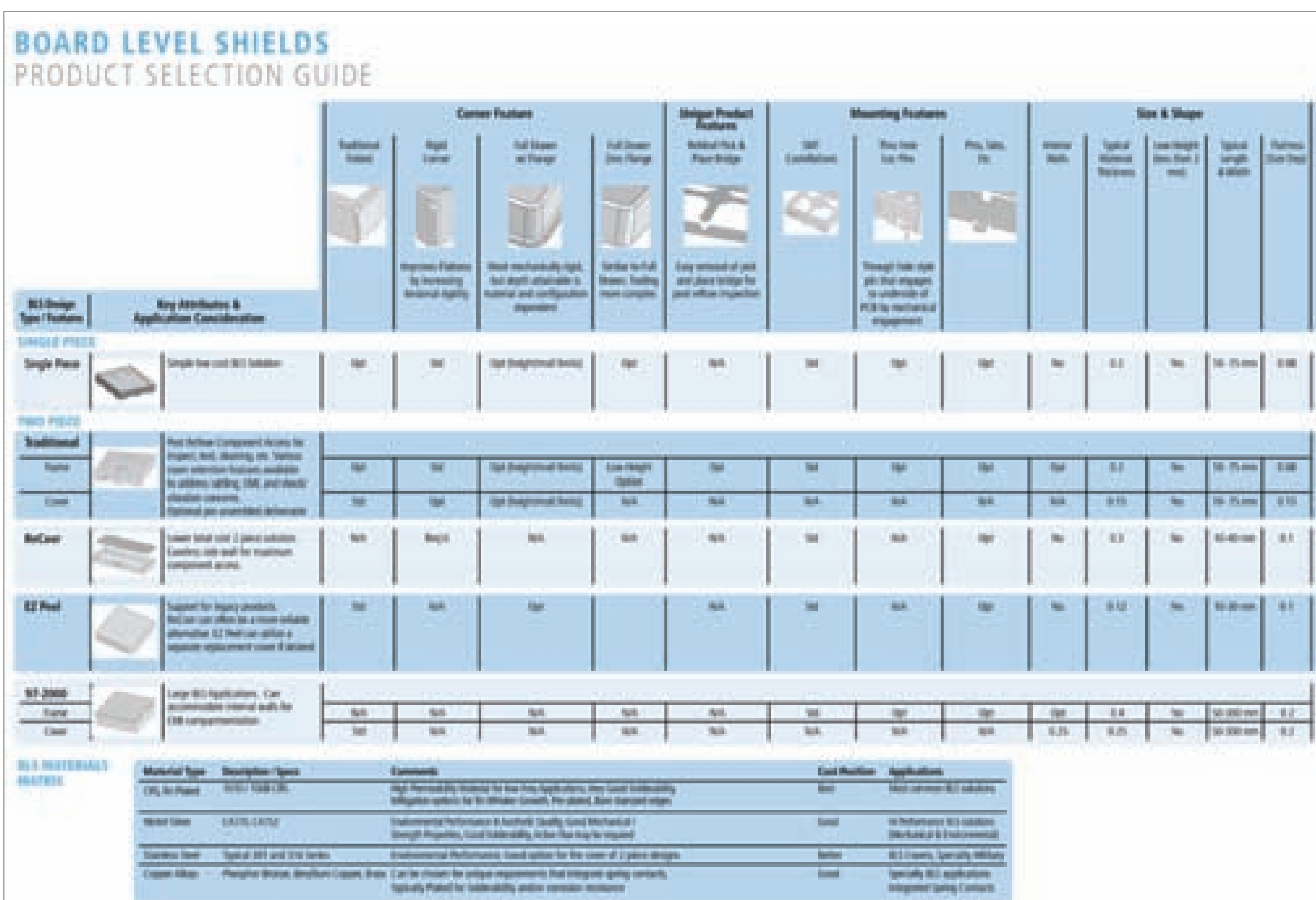

Figure 11

EMC

The Evolution of EMC Testing for Electrified Powertrains in Automotive Vehicles

A Brief History of Automotive EMC Testing and Standards Development

BY ROB KADO, JIM MUCCIOLI, DALE SANDERS AND TERRY NORTH

From the time when automotive vehicles were essentially mechanical with spark ignition the only electrical system, through the many decades that brought the development of electrical, electronic and computer controlled automotive systems, the need for and methods of automotive testing have evolved along with the vehicles. At one time, electrical testing was sufficient. But with the dawn of the digital computer era, compatibility became a major issue. Those pesky clocked systems are inherently noise producers and are also subject to immunity issues. During the 70's, industry experience included the development of advanced fuel management systems, then in progress to meet new exhaust emission standards, but the technology at the time was limited to analog controls. By the 80's, however, the digital revolution was well underway, bringing digitally controlled fuel injection systems and many other applications that pushed the envelope of EMC concerns. The automotive official equipment manufactures (OEM) recognized this challenge and began to develop EMC testing and evaluation capability. Initially, there were no applicable standards tailored for vehicle EMC, so the OEMs developed internal procedures that eventually became published as EMC requirements for both vehicle and component validation. Vehicles present a particularly challenging EMC immunity profile as they are numerous and versatile, being able to reach radio frequency (RF) exposure locations not accessible to most other products. Where most consumer electronics may be exposed to RF fields of a few volts per meter, vehicles face much greater threats and must be validated accordingly.

Over the years, automotive OEMs have made extensive use of road trips to RF transmitter and other high RF field sites to map the vehicle EMC environment, and have adapted their requirements and test methods to effectively protect vehicle electronics from these environmental threats.

One key example to illustrate this point is the introduction of vehicle passive restraint systems in the 80's. At that time, not all automotive OEMs had full vehicle EMC test facilities, however, they were aware of the potential immunity risks that electro-explosive systems presented and were fully committed to an exhaustive evaluation for EMC at both the component and vehicle levels. In past experience, in order to adequately validate this new technology, the standard component test methodologies were implemented and several new ones were developed in order to provide a greater diagnostic capability to predict system performance before the system was fully integrated. To evaluate the vehicle immunity profile, use was made of the military facilities at White Sands Missile Range, NM, which had the capability of generating high-level RF fields over the electromagnetic spectrum from long wave to microwave. On the test vehicles, the electro-explosive devices that trigger the passive restraint system deployment were instrumented with state-of-the-art monitoring capability so the amount of coupled RF current at each test frequency could be monitored. Due to this exhaustive evaluation and the experience gained, it was possible to establish good correlation between vehicle test validation methods and corresponding component validation procedures. This thorough analysis and evaluation led to a successful launch of this new technology without the adverse reactions that might have otherwise occurred. The EMC test methodologies that were put in place by vehicle OEMs became the basis for future EMC standards. Over the years, the automotive OEMs have worked with SAE, ISO, CISPR and IEC to develop workable EMC standards that reflect the real world EMC environment and the need to provide vehicles that can operate reliably in this environment. These cooperative efforts are ongoing.

VEHICLE EMC TESTING

An important element in the design and development of today's complex vehicles is assuring the compatibility of the electrical system and its numerous subsystems with itself and the environment in which it is used. To assure electrical system compatibility, we must understand and control the (RF) emission and immunity characteristics of all components and systems in the vehicle. This also includes fully characterizing these systems with regard to their immunity to electrostatic discharge (ESD) and other transient voltages. Furthermore, inductive components, such as motors and solenoids, must be evaluated to determine their potential to generate transient voltages within the vehicle's electrical system.

Vehicle EMC testing can be broken down to three major categories: immunity, emissions, and ESD/transients. In the following sections, we will describe in more detail how each is tested and the types of facilities required.

RF Immunity

In the presence of high electromagnetic fields created by radio transmitters (whether portable, mounted on the vehicle or roadside installations), the electronic subsystems on the vehicle could malfunction, cease to function temporarily, or experience a catastrophic failure. Furthermore, as electronics in general increase in complexity and the threat of interference increases, today we have much more spectral content generated with respect to cell phone use, radio/television broadcast, aftermarket electronics and the standard electrical content of vehicles. Testing for RF immunity not only covers external sources or devices, but also the actual in-vehicle electronics interfering with each other.

The general frequency range covered for immunity is 10 kHz – 4 GHz, with the capability of testing to 18 GHz when known threats exist. Along with this, the capability exists to generate the various types of modulation to simulate modulation used by standard real-world devices.

For the lower frequency range of 10 kHz – 30 MHz, a transverse electromagnetic mode (TEM) cell (Figure 1) or transmission line system (TLS) is typically used. In both cases, the field is created from an overhead structure and kept uniform/homogenous around the vehicle while various functions are monitored using shielded video cameras, wheel speed sensors and fiber optics for vehicle bus traffic and diagnostics. Both test methodologies are similar in that power is created using an RF amplifier (usually 10kW power) through a transmission line acting as an antenna radiating an RF field up to 200 V/m, depending on the specification. For the vehicle in the TEM cell shown in Figure 1, the metal plate above the vehicle is the septum or radiating antenna. A RF absorber is placed in specific locations in the TEM cell to help mitigate high voltage standing wave ratio (VSWR) situations.

For the mid to upper frequency range of 30 MHz – 800 MHz, an anechoic chamber is used. The vehicle and, in some cases, the antennae are on turntables as multiple sides of the vehicle must be tested based on harness routing and module location.

Figure 1: A vehicle positioned in a vehicle TEM cell

As with all immunity testing, monitoring such as cameras and fiber optics are used that are not affected by the RF being applied. Figure 2 shows a typical anechoic chamber with a vehicle on the turntable; note also that various antennae can be used to apply the fields. For these frequency ranges, depending on the equipment used, 1kW to 10kW is required to generate fields up to 200 V/m.

For the high frequency range of 800 MHz – 18 GHz, an anechoic or reverberation chamber is used. The advantage of a reverb chamber is that a single sweep is performed and testing is done; often with an anechoic chamber the testing takes much longer as the high frequency causes a very narrow beam width. The narrow beam width requires multiple positions of testing to cover the entire vehicle and ensure all areas are exposed to the RF field. In a reverb chamber, the field is generated and stirred with paddles to provide full exposure to the field surrounding the entire vehicle in a single sweep. Figures 3 and 4 show a typical reverb chamber with a vehicle and a closer shot of the paddles used for stirring the field. Another advantage of a reverb chamber is that much less power is required to create high field strengths of 200 V/m.

Another type of vehicle RF immunity testing is the testing of on-board transmitters. This test simulates the effect of radios being installed and used in a vehicle such as CBs, ham radios and more common devices such as cell phones or walkie-talkies. The testing consists of outfitting a vehicle with the various antennae both internal and external to the vehicle (e.g. roof top or bumper installation) and broadcasting at the various frequency and power levels while monitoring for disruption of normal vehicle operation. Figure 5 shows an example of antennae placement for on-board transmitter testing in a vehicle.

RF Emissions

The second major part of EMC testing is emissions; measuring the amount of noise a component and its wiring/apparatus puts out while in normal operation. This testing reveals potential interference, not only with other on-board electronics, but also with adjacent vehicles and other electronics/installations in the real world.

To protect for on-board receivers and other electronics, testing is performed per CISPR 25. The vehicle is tested in an anechoic chamber and the on-board antennae of the vehicle are used to measure their applicable fields; for other frequency bands, magnetic mount antennae are placed in the standard installation locations and used for measurement. Figure 6 shows an example of a vehicle in such an anechoic chamber.

To protect for off-board receivers and installations, testing is performed per CISPR 12; the main difference is the antennae used are set at a 3 or 10m distance from the vehicle. This testing is also performed either in an anechoic chamber or open area test site (OATS).

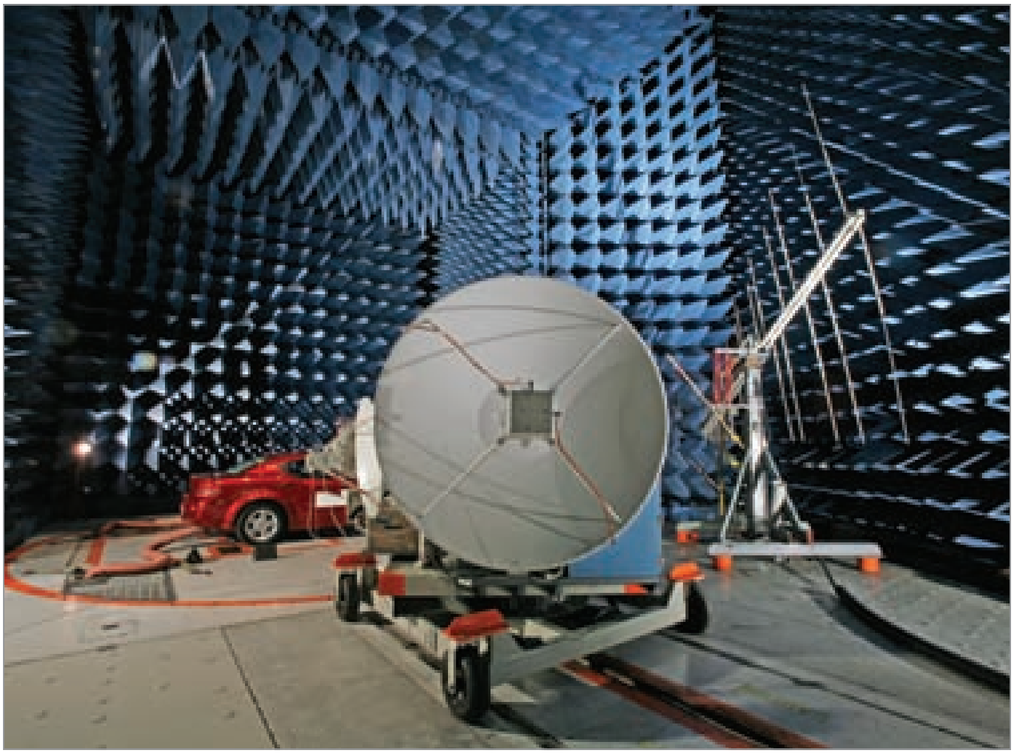

Figure 2: Vehicle in an anechoic chamber

To further validate these results; especially for AM/FM radio bands, radio noise evaluation testing is performed. During this testing, levels of injected power at the various frequencies are broadcast while the different subsystems are operated to evaluate reception.

In addition to RF emissions and as a result of new electrified powertrain vehicles, magnetic field emissions testing is also required. This testing is performed using special magnetic field probes and tested per International Commission on Non-ionizing Radiation Protection (ICNIRP) to limit human exposure to

Figure 3: Typical paddle/stirrer (left) in a reverb chamber and two radiating antennae (right)

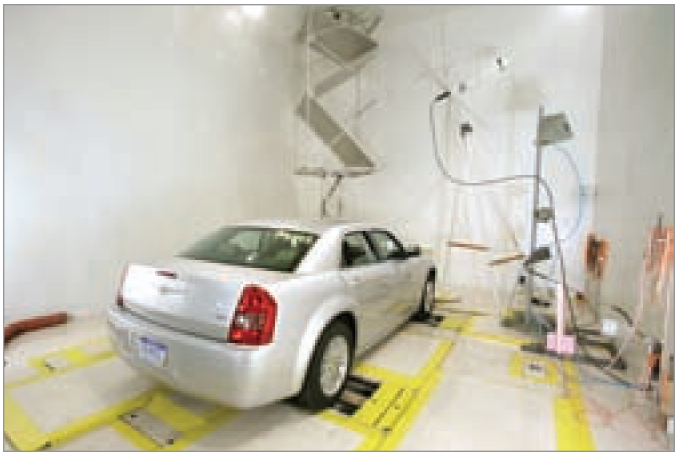

Figure 4: Example of a vehicle in a reverb chamber

such fields. The testing is performed in various locations, mainly throughout the interior of the vehicle where a human being would be. Figure 7 shows an example of a probe measuring magnetic fields in the engine compartment of a vehicle.

Other Types of Vehicle EMC Testing

There are other various types of EMC testing that occur on a vehicle such as (ESD), conducted transient emissions (CTE) and electrical tests. ESD is the simulation of discharge that occurs normally between a human and some part of the vehicle; this can be from entry, exit, or simply attempting to push a button or reach for the door handle. CTE is a measurement of the voltage transient that occurs when an inductive load such as a motor, solenoid or actuator is switched. Finally, various electrical tests are performed, such as load dump and reverse battery, to simulate these potential events.

Figure 5: Example of on-board transmitter testing

As can be seen, vehicle EMC testing is very in-depth and costly. The photos provided here are from the Chrysler EMC Facility which is valued at over 30 Million USD. With electrified powertrain emerging as a new technology in vehicles, the challenges for EMC increase. With such vehicles, new considerations such as testing while the vehicle is plugged into its charger, regenerative braking and, finally, operation cycles on a charged battery versus test time (some test runs can take in excess of five hours) are part of the validation process. The specifications are evolving as well;

Figure 6: Vehicle in an anechoic chamber for RF emissions testing

Figure 7: Example of magnetic field probe measurement

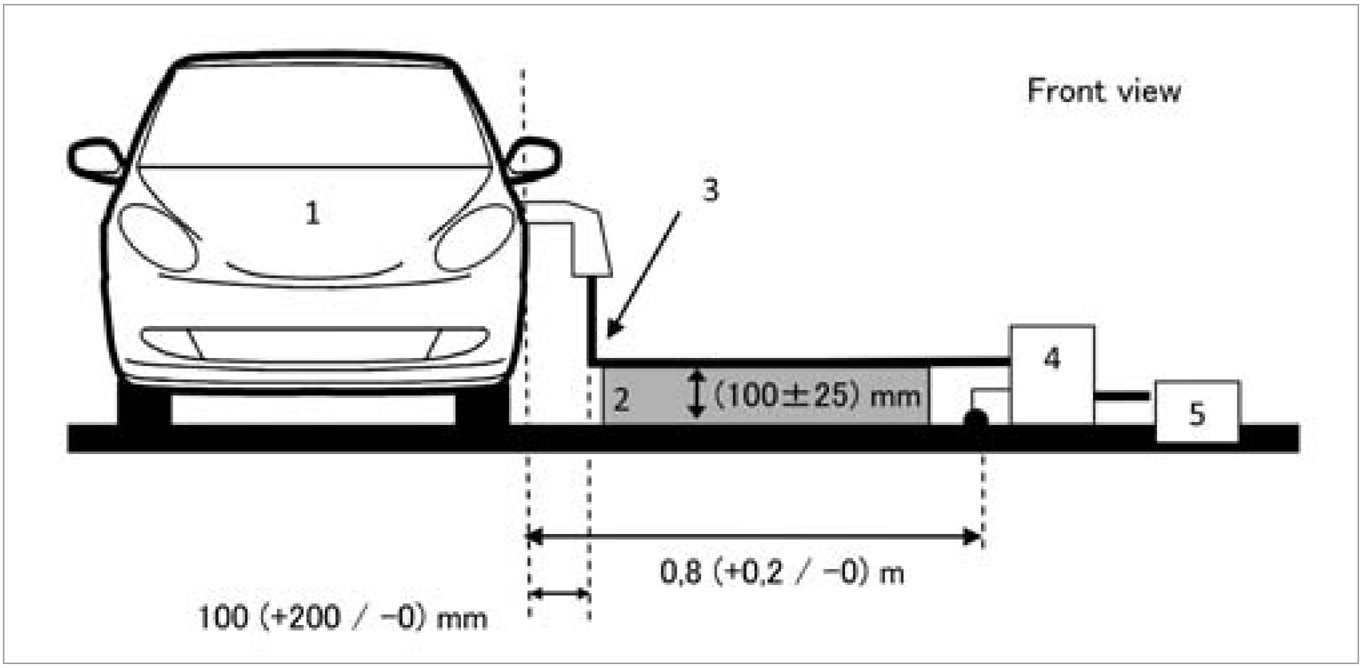

Figure 8: Example of a vehicle set-up while plugged in for charging

Figure 8 shows a set-up diagram for an electric vehicle to be tested while charging. As the specifications continue to be established and evolve to meet changing product requirements, the industry will adapt and evolve as well, as it always has in the past.

AUTOMOTIVE COMPONENT/MODULE TESTING

Similar to vehicle EMC testing, automotive component testing is categorically broken down into threetypes: emissions, immunity and ESD/transients. EMC requirements and test set-ups for automotive components are established by International Standards and OEM specifications that have been derived directly from vehicle testing and real-world experiences/measurements. Components that undergo EMC testing to established OEM component requirements provide a high confidence level of EMC (emissions, immunity and ESD/transients) performance when integrated into a vehicle or into a vehicle system. This is a significant distinction from other industries for several reasons:

1. All electronic products sold in the United States are required by law to be compliant to FCC Part 15. However, FCC Part 15 only addresses RF emission levels of an electronic product. Automotive OEMs at both the vehicle and component level require immunity and ESD/transient testing, as well as emissions. It should also be noted that automotive OEM emissions levels are much more severe than FCC requirements.

2. Vehicle operating environments, thus their requirements, are generally much harsher for automotive components than other electronic products sold in other industries. For example, vehicles are expected to operate safely in a wide range of operating temperatures and different weather conditions, as well as under exposure to varying sources of electromagnetic fields (natural and manmade), all of which impact electric components and design.

3. Automotive component EMC tests, conditions, set-ups and facilities have been developed specifically for correlation to vehicle environments. Compliance to automotive OEM component EMC requirements is considered as a pre-qualification. Components must also comply with vehicle EMC requirements when installed in a vehicle. As such, automotive components are given a functional and operational impact assignment as part of the pass/fail test criteria. This assessment is similar to what other safety critical industries are starting to adopt using International Standards such as ISO 26262. See Reference 1.

THE AUTOMOTIVE EMC DESIGN, REQUIREMENTS, VERIFICATION, AND VALIDATION PROCESS

The history and emphasis the automotive industry places on EMC (emissions, immunity, ESD/transients), from vehicle to individual components, requires a comprehensive process which comprises a collaboration of OEM and tier suppliers, as well as multiple engineering disciplines. To manage the EMC design, requirements, verification and validation process, a system engineering approach is typically used.

THE SYSTEMS ENGINEERING PROCESS AS APPLIED TO AUTOMOTIVE EMC

See References 2, 3, 4, 5 and 6.

The EMC systems engineering methodology integrates all requirements and objectives; additionally it facilitates the identification and specification of unknown or hidden requirements leaving behind a traceable, repeatable, documented path of engineering effort and decisions. Below is a high-level description of this approach that is used in the automotive industry.

The EMC system engineering process starts with OEMs and tier suppliers defining the following concepts for components, system architecture and vehicle integration:

- ***System*** – a set of components acting together to achieve a set of common objectives via the accomplishment of a set of tasks.
- ***System behavior*** – a sequence of functions or tasks, with inputs and outputs, which must be performed to achieve a specific objective.
- ***Requirements*** – mandates that something must be accomplished, transformed, produced or provided. The attributes of a good requirement are that it is unambiguous, understandable, traceable, correct, concise, unique and verifiable.
- ***Traceability*** – in reference to requirements; a requirement is said to be traceable if one can identify its source. The source may be a higher-level requirement or a source document defining its existence. An example would be if a component-level requirement (weight, reliability) is traceable back to a vehicle-level requirement
- ***Operational concept*** – an operational concept is a shared vision from the perspective of the users and development participants of how the system will be developed, produced, deployed, trained, operated, maintained, refined and retired to meet the operational needs and objectives.

It is recommended that a background study based on the following questions should be considered in preparation for the systems engineering process:

System requirements

- Has the need for the system or product been established and justified?
- Has the overall system technical design approach been justified through a feasibility analysis?
- Has the mission for the system been defined through scenarios or profiles?
- Have all basis system performance parameters been defined (technical performance measures)?
- Has the system or product lifecycle been defined (design, development, test and evaluation, production and/or construction, distribution, operational use, sustaining support, retirement and disposal)?
- Has the planned operational deployment and distribution been defined (customer requirements, quantity, distribution schedule)?
- Has the operational environment been defined in terms of temperature extremes, humidity, vibration and shock, storage, transportation, and handling? A dynamic scenario is desired.

System trade-off studies

- Have trade-off evaluations and analyses been accomplished to support major design decisions?
- Have all feasible alternatives been considered in trade-off studies?
- Have such analyses been accomplished with lifecycle considerations in mind (decisions based on lifecycle impacts)?
- Have system trade-off studies been adequately documented?
-

Once the above concepts have been defined and the background study performed, the six-step design process is applied as illustrated in Figures 9, 10, 11 and 12.

Step 1 - Bound the system for EMC

- Identify all external items.
- Establish interactions.
- Create system context diagram.

Step 2 - Identify the source of requirements

- Collect requirements.
- Sort requirements by classification.

Step 3 - Discover and understand requirements

- Discover system-, subsystem- and component-level requirements.
- Brainstorm scenarios.
- Benchmark competition.
- Use behavior models to:
  - o discover “hidden” interface requirements.
  - o resolve conflicts between models and scenarios.

Step 4 - Create alternatives

- List performance and operational objectives.
- Prioritize requirements with weighting factors.

- Synthesize physical architecture to support each alternative.
- Perform trade-off between candidate architectural solutions that satisfy the requirements.
- Collect the results in a derived set of requirements based on the chosen solution.

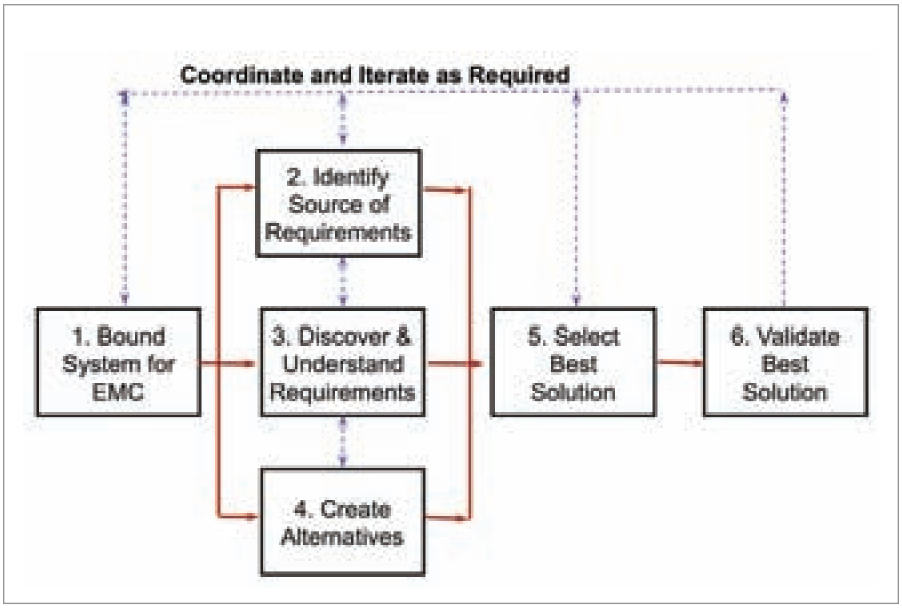

Figure 9: Six step system engineering process for EMC

- Compare the various alternatives, rank them and select the best approach.
- Evaluate candidate architectures using measures of effectiveness.

Step 5 - Select the best solution

- Compare proposed systems implementation.
- Select the *best* solution.

Step 6 - Validate best solution

- Define validation plan
- Link to design requirements at each level (vehicle, system, component)
- Verify all requirements. (mandatory)
- Plan for verification starting early and continuosly at the system level.
- Requirements Trace requirements forward to verification and link verification back to the requirements at all levels.
- <u>*Verification methods*</u> are:
  - inspection

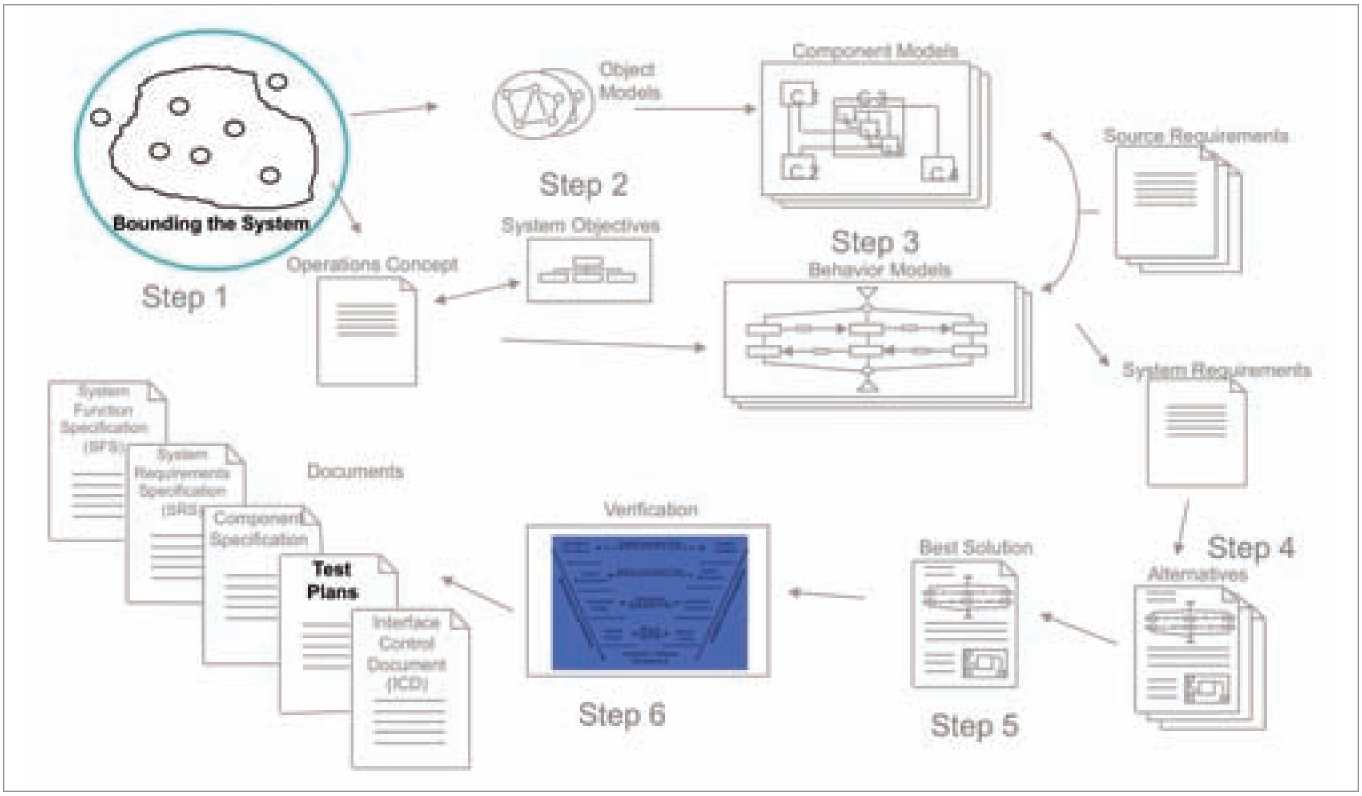

Figure 10: Data is generated and linked throughout the process

- test
- demonstration
- analysis, which may include simulation

System engineering process summary

- The EMC systems engineering process methodology integrates all requirements and objectives, and facilitates the identification and specification of unknown or hidden requirements.
- The systems engineering process leaves behind a traceable, repeatable, documented path of engineering effort and decisions.

THE IMPORTANCE OF EMC TEST PLANS AS GOVERNING DOCUMENTATION

See References 2, 3, 4, 5 and 6.

As automotive engineers work through the six-step design process, many documents are generated. For EMC, the most important document is the EMC test plan. Most OEM in North America provide a template to follow when generating this document. When properly completed, the EMC test plan provides a traceable link of not just the EMC tests performed and test parameters, but also documentation of the operating modes/states, justification of performance criteria, component uses in vehicles and systems, a component's mechanical and electrical interfaces, as well as any deviations and assumptions required for individual test circumstances.

Elements of a good EMC test plan to consider for any device-under-test (DUT) (component or vehicle) should describe or answer the following information:

1. DUT part number and revision
2. DUT subassemblies such as PCB, hardware and software revision

Figure 11

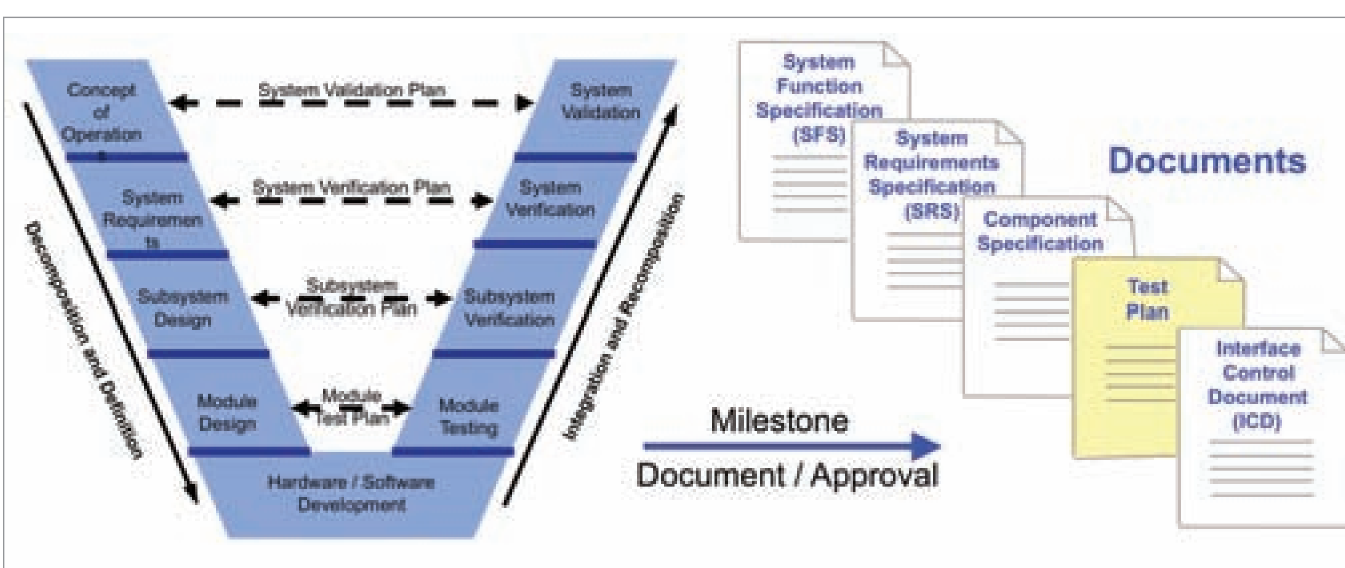

Figure 12: The "Big V" - validation and verification

3. DUT manufacturing/assembly location and suppliers
4. DUT customer and production release date
5. DUT releasing/program engineer
6. DUT EMC test plan revision history
7. Applicable EMC test standards (OEM or international)
8. EMC test facility, location, contact and accreditations
9. Type of EMC test report requested: engineering development, sign-off design validation or sign-off production verification

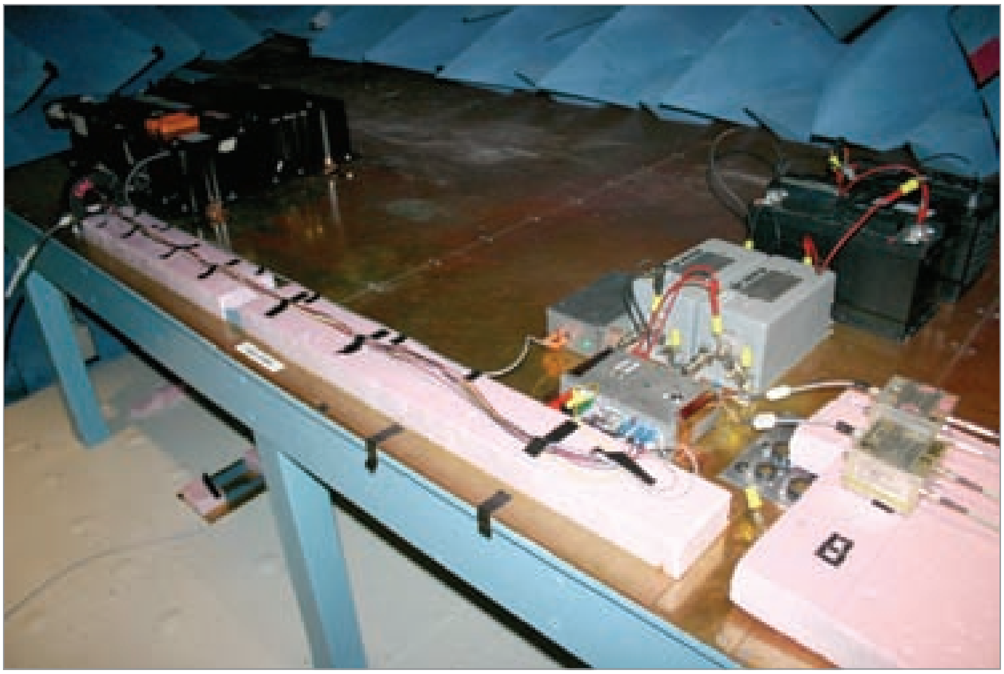

Figure 13: ESS bench setup for CISPR25 Radiated Emissions/ISO 11452-2 radiated immunity

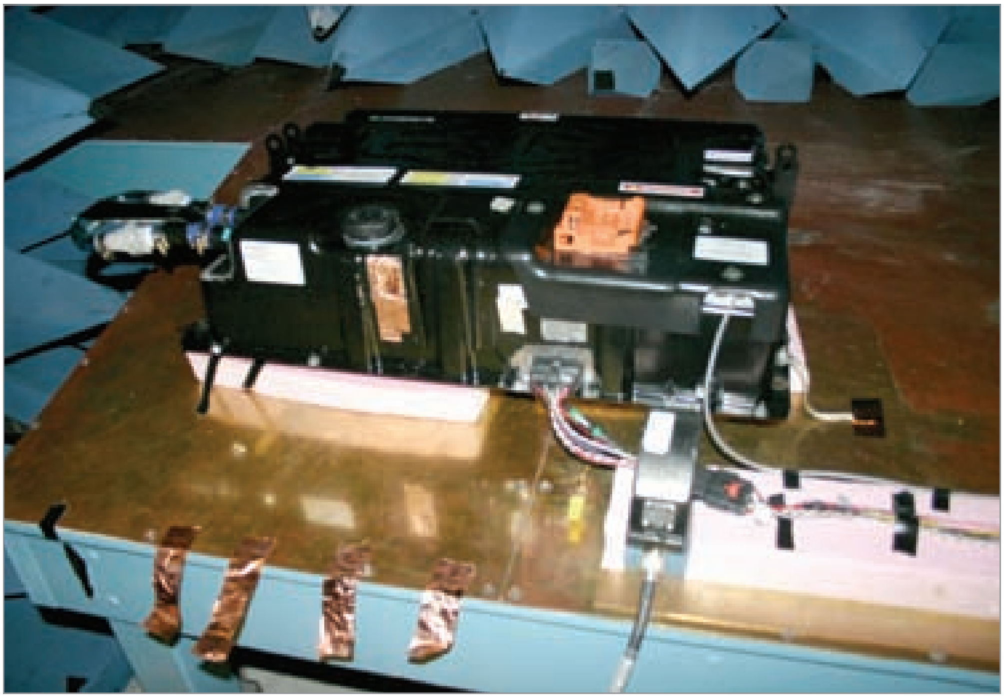

Figure 14: ESS (close-up) on a copper ground plane for CISPR25 radiated emissions/ISO 11452-2 radiated immunity testing

10. OEM/customer sign-off (if applicable)
11. DUT description and intended use
    a. DUT and DUT family introduction and functional description
    b. DUT description and sample selection
    c. DUT electrical and mechanical schematics, layout and diagrams
    d. DUT software functional description of operation
    e. DUT bill-of-materials (BOM)
    f. DUT operating modes
    g. DUT electrical and mechanical inputs, outputs, power requirements, loads and monitoring requirements
    h. DUT calibration procedures
12. Required loads, harness and support equipment needed to operate DUT
13. For each individual EMC test, the following should be noted or referenced:
    a. test modes
    b. environmental conditions
    c. grounding schemes and requirements
    d. harness requirements
    e. applicable loads and monitoring equipment
    f. power supply and signals

g. functional and operational requirements
h. test deviations
i. pass/fail criteria
j. instructions if an anomaly is observed
k. any DUT safety precautions or procedures

THE EMC TEST PLAN AND ELECTRIFIED POWER-TRAIN TECHNOLOGY

See References 2, 3, 4, 5 and 6.

As test standards evolve and adapt to new technologies in the automotive industry, the overall vehicle requirement remains essentially the same. For example, the emerging electrified powertrain technology has not had a substantial impact for vehicle EMC emissions, immunity and transient requirements; however, it has increased the importance of the EMC test plan for systems such as the energy storage system (ESS) which is a large part of the electrified powertrain architecture. ESSs have come to encompass several competing electric vehicle (EV) and hybrid electric vehicle (HEV) architectures. In turn, the ESS contains multiple sub-systems in addition to just battery cells.

The ESS and its sub-systems include design variables such as high-voltage DC-to-DC power converters, battery cell charging/discharging schemes, varying numbers of battery cells, shapes and technology, cooling schemes (liquid and/or air), diagnostic sensors (thermal, voltage, current, etc.), overall ESS physical shapes, sizes and weight, as well as on-board vehicle orientations.

When writing an EMC test plan for ESS, collaboration with the EMC test facility is a good idea. The size and weight of the ESS alone can cause an issue when testing. For example, an ESS can range from 8 cubic feet to more than 64 cubic feet in size and weigh 700 to 2500 or more pounds. EMC test facility chambers and ground planes need to be able to handle the weight as well as be able to safely move the ESS in and out of the chamber. Also, thought should be given to the orientations of the ESS needed for emissions and immunity testing, with consideration given to maintaining minimum clearances per the international or OEM standards used for testing. Some examples are shown in Figures 13, 14 and 15.

Another aspect the EMC test plan should clearly specify is the monitoring requirements of the ESS. It is not uncommon that input/output requirements to monitor an ESS are double or triple that of a normal automotive component and may require special software that interfaces to software running the EMC test, so when/if an observed anomaly occurs during a test cycle, the test parameters are known.

Finally, with regards to the ESS, the EMC test plan should note the high-voltage (HV) power requirements, charging procedure and safety operation procedure for working with the HV. The goal of the EMC test plan is to provide for safe operation, reduced test down-time and a traceable document for future testing and product development.

SUMMARY

The authors have presented a brief history of the development of methodologies by automotive OEM to effectively validate new technologies and the cooperative role OEM have played in the generation of new EMC standards, including an overview of vehicle and component EMC testing. The advantage of the system engineering process in providing an organized and traceable method to meet the challenges

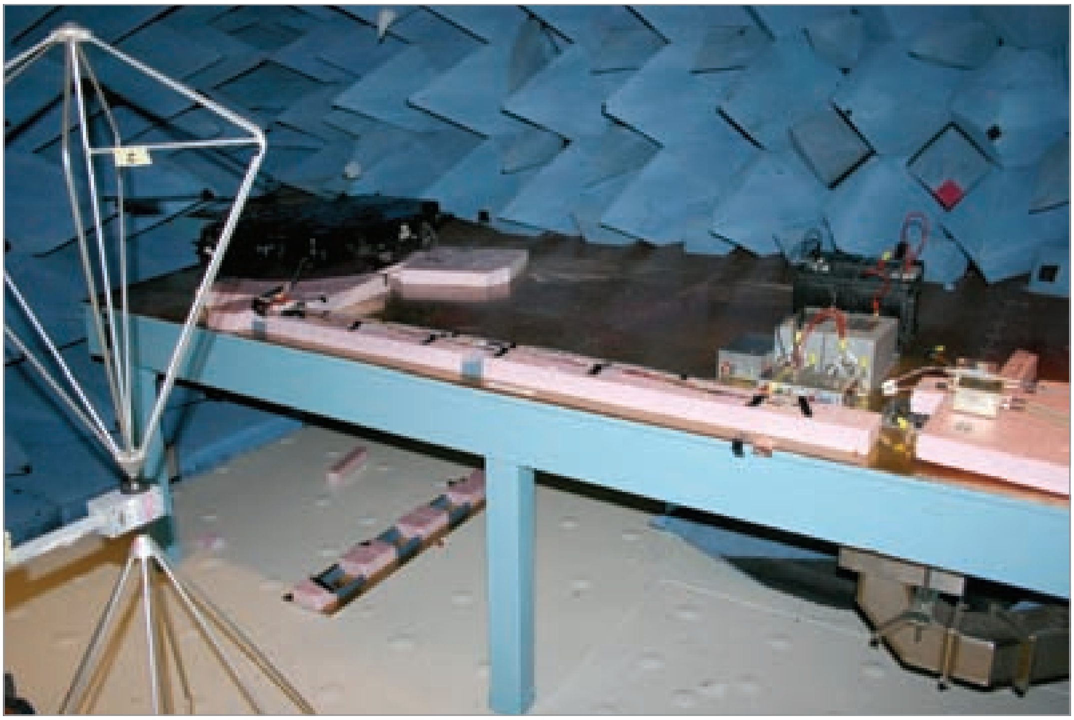

Figure 15: ESS CISPR25 radiated emissions/ISO 11452-2 radiated immunity bench setup with bi-conical antenna

of validating new technologies was presented, along with a practical approach to apply this method to a particular product. The importance of EMC test plans, particularly for complicated systems and new technologies, was stressed along with some useful guidelines for developing an effective test plan. Finally, the need for an EMC test plan to meet the particular challenges of validating electrified powertrain technology was described.

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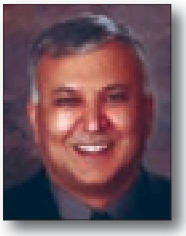

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Terry M. North *is an independent EMC consultant for Jastech EMC Consulting, LLC. His early experience includes service with the U. S. Army in RF communications and with Ford Motor Company in advanced fuel systems design. Over the more than 20 years that he was with Chrysler, he contributed to the development of a world-class, in-house automotive EMC capability and assisted in the overall advancement of the automotive industry in EMC. Mr. North was also involved in the EMC development and qualification of passive restraints systems. He was a major contributor in the development of Chrysler corporate EMC standards and served as a consultant on EMC and E/E systems issues. Mr. North is a senior member of the IEEE.*

EMC

As-Found: Out-of-Tolerance

What to do next?

BY PHIL MISTRETTA

When calibrated test equipment is found in an out-of-tolerance condition, there is additional risk to all products on which it was used. It is important to understand the magnitude of the potential risk because it can lead to dangerous consumer situations and additional business costs.

Typically quality systems have a procedure for handling non-conforming material, however, this is non-conforming instrumentation used in a process, not material produced by a process. There is little guidance available describing how to evaluate out-of-tolerance conditions leaving engineering and quality personnel to develop their own process. When faced with an As-Found: Out-Of-Tolerance (OOT) condition, a systematic approach to identify what the out-of-tolerance values were, when, where and how the OOT unit was used, will help concentrate your efforts to identify those areas that will need further analysis.

NON-COMPLIANCE

What does out-of-tolerance mean? Calibration is a comparison of a metrology laboratory's standard, with a known value and uncertainty, to the unknown behavior of a unit submitted for calibration. When the unit under test (UUT) does not meet the expected test limits, it is considered to be Out-of-Tolerance. The type of measurement data and calibration information provided can vary widely, depending on the type of metrology laboratory performing the calibration. For instance, at the National Metrology Institutes (NMI), such as NIST, the metrology laboratory may provide the comparison data only and not utilize any test limits and not make any statement of compliance. It is up to the instruments' owner to perform any analysis and determine the compliance status of each individual piece of calibrated equipment. For the typical NMI customer, this process is relatively easy to handle because they are staffed with highly knowledgeable metrology professionals who are responsible for a limited quantity of lab standards. However, if this is the only information received by a manufacturing environment customer, who has significant quantities of test and measurement equipment, monitoring the behavior of each individual piece of equipment is impractical at best! Fortunately, the manufacturers of test equipment have done most of the analysis work. This is accomplished through the manufacturers' published specifications which describe what type of behavior can be expected for the *majority* of the units manufactured, following a *typical* calibration interval. It is from the Original Equipment Manufacturers' (OEM) published specifications that purchasing decisions are made. It is also from these published specifications that a commercial calibration provider will *most likely* determine the allowable tolerances, or test limits for the calibration process. Many commercial calibration providers offer a default service that uses the OEM's published specifications; however, it is the responsibility of both the customer and the calibration lab (internal or external), to agree upon the specifications which will be used in the calibration process. A customer can request their equipment to be calibrated against any specification they provide. Once the calibration specifications have been agreed upon, the laboratory can calculate the test limits against which the laboratory results can be compared and a statement of compliance can be determined.

> The first thing to do when faced with an out-of-tolerance unit is to read through the calibration certificate and data to get a firm understanding of what specifically failed calibration.

STATEMENT OF COMPLIANCE

Most commercial calibration customers are looking for the calibration laboratory to make a statement of compliance for the As-Found condition of the Unit Under Test (UUT). On the surface, making this determination appears rather straight forward and simple, however, upon closer examination, it becomes more complex; there are no perfect instruments and no perfect measurements. All measurements have some degree of uncertainty and how to deal with these uncertainties with respect to making a statement of compliance differs greatly. There are several different approaches which could be used when making compliance statements. Some labs will not make a statement at all; some labs will mark the data that does not meet the limits with an asterisk or some other means, but not make a compliance statement; still other labs will make a compliance statement, quantify the results with an uncertainty value and provide additional consumer risk information**.** In any case, it is critical for the customer to understand the decision rules used by the laboratory in making any compliance statements.

The statement As-Found: In-tolerance is generally assumed to mean that the entire instrument, all functions, parameters, ranges and test points - are within the calibration specifications at the time of calibration, for the stated conditions at the location where the calibration took place. An As-found: in-tolerance condition is a good indication the UUT was performing within expectations since the last calibration was completed. For the commercial calibration customer who has hundreds or thousands of calibrated items, the statement of compliance may be the single most important piece of information on a calibration certificate. In essence the metrology laboratory, staffed with measurement experts, has completed an initial data evaluation and concluded the unit to be performing within the agreed upon specifications so the customer does not have to spend very much additional time reviewing the calibration. Likewise an As-Found: Out-Of-Tolerance (OOT) condition indicates that at least one data point in the data report drifted or shifted beyond the allowable tolerance limits and the measurements it was providing may not have been accurate at some point since the previous calibration. Again, the laboratory measurement experts have indicated that this unit had a problem and needs further analysis *by the customer*. The As-Found: Out-Of-Tolerance statement of compliance is the flag or trigger for many quality or manufacturing engineering departments to start an investigation, evaluation or analysis.

THE PROCESS

The object of the OOT evaluation process is to identify the at risk products the Out-of-Tolerance units touched. The following approach is not very difficult and follows a logical thought process; however there are a few pitfalls to be aware of and to avoid. This is an investigation; I caution against having the end result already in mind. It is tempting to want the conclusion to show that there were no at risk products because of the work involved. The answers to the questions in the process will lead you to the appropriate conclusion. The approach here is to eliminate products without risk and to narrow down the pool of at risk products.

WHAT IS OUT-OF-TOLERANCE?

The first thing to do when faced with an out-of-tolerance unit is to read through the calibration certificate and data to get a firm understanding of *what* specifically failed calibration. A *complete* set of As-Found and As-Left calibration measurement data is essential for a proper out-of-tolerance evaluation. A Calibration Certificate without data is never a good idea, but when faced with an out-of-tolerance unit, the lack of measurement data will significantly impact the ability to conduct an analysis and quantify any potential risk. If the metrology laboratory provides an out-of-tolerance report that only shows the out-of-tolerance data you have something on which to conduct an evaluation, but even this limited information does not provide a complete picture. A review of all the calibration data should be done to identify what functions, parameters, ranges and test points were found out-of-tolerance. For example, let's say a voltmeter has a full scale range of 1000 V, a resolution of 1 V, and an accuracy of ± 5 V, and the unit was found to read 1006 V at full scale (out-of-tolerance) and in-tolerance at all the other readings which were taken every 200 V. This means that during the use of the voltmeter, over its most recent calibration cycle, any measurements between 800 V and the full scale 1000 V were likely giving erroneous values to the user of the meter for the measurements taken. Again, a full set of data will be very helpful at this point in answering questions like: how many points within a range were out-of-tolerance; was the entire range out of tolerance; were all the ranges even checked; was there a linearity issue; was only the zero out-of-tolerance;

The quality of the calibration and quantity of data available can have a tremendous impact on narrowing the scope of the evaluation at this point.

or only the full scale reading out of tolerance; were other relevant test points close to or at their limits? The quality of the calibration and quantity of data available can have a tremendous impact on narrowing the scope of the evaluation at this point.

WHEN DID IT HAPPEN?

The next step should be to identify the *time frame* during which questionable measurements may have been taken. This objective is to identify a specific time when the instrument was last known to be taking correct measurements. Often, this is going to be the previous calibration date; the historical calibration certificate will have this date. Basically, the unit was known to be measuring correctly when it left the metrology lab through its As-Left measurement data on the most recent calibration certificate. This will provide a starting point to work from, and most likely the longest period to examine. If you are fortunate to have a well developed measurement assurance program, you might have collected additional data during the period in question which can reduce the evaluation time frame. Most metrology laboratories follow good metrology practices (GMetP) and conduct mid-cycle checks, tests, and inter-comparisons, also called cross-checks, to determine the "health" of their measurement processes and provide confidence in the quality of the measurement process. If these checks are documented and have measurement data, you may be able to reduce the period of questionable measurements. For example, let's say the voltmeter in a production cell was found out-of-tolerance during its annual calibration, but you have a process where a precision voltage source is used to verify the performance of the voltmeter every quarter. A review of this data may allow you to conclude the voltmeter was performing accurately 3 months ago, so the questionable period is only going to be the last 3 months instead of 12 months which significantly reduces the pool of potential at risk products. A schedule of cross-checks and inter-comparisons is often developed for critical measurements or high volume processes in order to reduce risk, liability, and evaluation time.

WHERE IS IT USED?

The objective at this point is to identify *where* this instrument has been used during the questionable period. This is where the really big challenges can start. Typically, this is where the last link in the chain of traceability is often broken, linking the actual calibrated instrument to the processes, products and services provided. The ease of identifying potential impacted product depends upon the design of the end users processes and systems. In a large facility test equipment can move around without tracking its location. This is especially true of handheld instruments and bench level instruments. A robustly designed system with strict instrument control procedures will be able to identify exactly where any given instrument was located for any given time frame. Nearly all companies have a system that assigns an identification number to each instrument, and some even track its assigned department or location, but few systems track the movement of equipment within the facility and even fewer log the date and use of instrumentation. The maintenance of such an instrument movement log must be strictly followed, any hole or missing location data will bring any evaluation to a halt. Imagine a facility with 50 identical instruments that move around different production cells without any control. It would be impossible to identify what measurements or products it touched and what errors went undetected. With a robust tracking system that indicates if and when this instrument moved, you should be able to identify where this instrument was at any given time.

HOW IS IT USED?

The last step in the out-of-tolerance information gathering process is to identify how the out-of-tolerance instrument was being used. Determine exactly what measurements were being made at a given location, during the time frame in question. This information will likely be found in the end users procedures, or the operator's work instructions, or an engineering specification. The objective at this step is to determine whether the out-of-tolerance instrument *could* have affected any of the products manufactured or services provided by this instrument, in this time frame, in this location, for these measurements. This can be accomplished by reviewing the process documentation, and all revisions that were in effect during the time frame in question, for the out-of-tolerance measurements that were identified in the first step. Were any of the out-of-tolerance functions, parameters, ranges and test points used to make the measurements listed in the process documentation? If the answer is no, congratulations, your evaluation has ruled out the potential risk to product. Now you just have to completely document the steps you have taken, your conclusion and justification, as

> Due to the wide variety of applications and situations possible, a few sample cases will be used to illustrate the analysis process for common situations likely to occur.

any auditor will tell you, if it isn't written, it didn't happen, you must produce objective evidence.

ANALYZING THE IMPACT

If the process documentation indicates that measurements *were* taken using any of the out-of-tolerance functions or ranges, then you have to go further and quantify the severity of the impacted products or services. Now comes the most difficult part of the process, quantifying the impact on products and services. In order to effectively complete this analysis, a thorough understanding of the affected process is necessary and a working understanding of tolerances and the application of uncertainties is extremely helpful. Due to the wide variety of applications and situations possible, a few sample cases will be used to illustrate the analysis process for common situations likely to occur.

Case 1: No Impact

Let's say the process documentation states that the voltmeter is used to measure a 600 V on a product with a process tolerance of ± 10 V. Since our process measurement was *not* in the out-of-tolerance portion of the meter (800 V to 1000 V), we can conclude with reasonable confidence that no product was affected.

Case 2: Impact Evaluation Using Ratios

In Case 2 we will use accuracy ratios in our analysis. An analysis by ratios can help quantify the potential impact by a rough order of magnitude, but may not be sufficient. For instance, a ratio change from 100:1 to 80:1 may be fairly insignificant, but a ratio change from 4:1 to 2:1 could have quite the impact on the end products. A ratio analysis may be a quick way to rule out potential recalls if the ratios involved are sufficiently high. However, if the ratios are low, then additional evaluation becomes necessary. This method may also be the only option available if there isn't any historical process measurement data to review. For example in this case, the process documentation states that the voltmeter is used to measure a 1000 V on a product with a process tolerance of ± 50 V. Since our process measurement *was* in the out-of-tolerance portion of the meter (800 V to 1000 V), product *might* have been negatively impacted. We need to go a step further and compare our process tolerance to the magnitude of the out-of-tolerance data. The process tolerance in this case was ± 50 V, so our process limits are 9950 V to 1050 V. The accuracy of the meter was ± 5 V which means the meter is 10 times more accurate than our process tolerance giving us a Process Accuracy Ratio (50 V / 5 V) of 10:1. Now the calibration report stated the meter was reading 1008 V when the calibration lab injected a precision 1000 V into the meter, which basically means the meter behaved as if it had an accuracy of ± 8 V which drops our Process Accuracy Ratio (50 V/ 8 V) to 6.25:1. Is the risk due to a reduced process ratio acceptable? That comes down to a business decision.

Case 3: Impact Evaluation Using As-Found Calibration Data

In this case, the process documentation states that the voltmeter is used to measure a 1000 V on a product with a process tolerance of ± 50 V. Since our process measurement *was* in the out-of-tolerance portion of the meter (800 V to 1000 V), product *might* have been negatively impacted. We need to go a step further and compare our process tolerance to the magnitude of the out-of-tolerance data. The process tolerance in this case was ± 50 V, so our process limits are 9950 V to 1050 V. The out-of-tolerance data indicated that the meter was reading 1008 V, or out of specification, beyond the upper tolerance limit of 1005 V, by +3 V. This additional 3 Volt error is well below our ± 50 V process tolerance, so there wasn't a problem…. or was there? You might want to jump to that conclusion, and you would be correct as long as your process stayed centered on 1000 V, but what if your process moved around and didn't stay centered? Isn't that why process tolerances are created to begin with! To figure out what is going on here, go back to the fact that the meter was reading high by +8V; the meter has a total +8 V bias or offset. The meter was actually delivering process limits of 9958 V to 1058 V. Which means any measurements greater than 1042 V during the time frame in question actually exceeded the upper process limit. With this information, you should review any historical process measurement data you have and identify any products that had measurements greater than 1042 V. You have now identified the specific units that might have been impacted by the out-of-tolerance unit and may have to be recalled. But wait, there's more! Remember, no measurement is perfect, so what about the metrology labs measurement data, doesn't that have some error in it too? Why yes, yes it does….

All this evaluation and analysis is a tremendous amount of work. However, it does not have to be difficult. A well thought out electronic system linking instrumentation to processes and product traceability as part of a measurement assurance program can ease the burden.

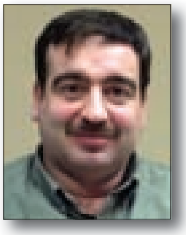
Case 4: Impact Evaluation Using As-Found Calibration Data and the Lab's Uncertainty

Continuing with Case 3 information, let's say the metrology lab reported their uncertainty for the measurement: 1008 V ± 7.1 mV. That means the value they report lies somewhere between 1007.9929 V and 1008.0071 V. This additional uncertainty will carry on down to the process tolerance calculation. So in the worst case the meter was actually delivering process limits of 9957.9929 V to 1058.0071 V, which in our case is insignificant because the resolution of the meter is not sensitive enough to see this small difference in voltage. It is interesting to note that in this situation the metrology lab had an uncertainty of ±7.1 mV for the calibration against the unit's tolerance of ± 5 V which provides a calibration Test Uncertainty Ratio of 704:1 (5 V / 7.1 mV) meaning the calibration lab standards were over 704 times more accurate than the meter being calibrated. Here is where the value of that pesky Test Uncertainty Ratio those metrology guys are always talking about comes into play. Had the metrology laboratory's uncertainty been ± 1.25 V, their reported measurement would have been 1008 V ± 1.25 V, and the TUR would have been 4:1 (5 V/ 1.25 V) meaning the meter would have actually been delivering process limits of 9957.675 V to 1059.25 V, which when rounded by the resolutions of the meter become 9958 V to 1059 V. Now this additional count might not seem like a big deal, but it does increase the size of the potential recall and increase the potential risk and cost.

Again, here is where a complete calibration report with As-Found and As-Left data becomes very helpful. This is also the point where the Test Uncertainty Ratio (TUR) and the Uncertainty of the Calibration Laboratory come into play and why all calibrations should include uncertainties for every measurement. The laboratory's uncertainty information on the measurements they provide will give you the information to further refine your evaluation and subsequent analysis. Every bit of measurement information at your disposal allows you to make additional distinctions, observations, calculations and improves the quality and confidence in your conclusions and recommendations for further actions. The cost of a single product recall will far exceed the additional cost associated with a complete calibration which includes As-Found and As-Left data with uncertainties.

As cases 2, 3, and 4 illustrate, an out-of-tolerance instrument that could affect the end product or service can lead to a tremendous amount of work because the analysis will need to be completed for each product or service identified. This could lead to hundreds or thousands of calculations! As you can imagine, any effort spent in the four steps (what, when, where, and how) in the evaluation process which eliminates additional products to be analyzed is well worth the time. When faced with an As-Found: Out-Of-Tolerance (OOT) condition, a systematic approach to identify what the out-of-tolerance values were, when, where and how the OOT unit was used, will help concentrate your efforts to identify those areas that will need further analysis. The objective is to filter out as many possible items that do not need closer analysis so you can get to the ones where detailed analysis is required in order to quantify the impact to the products or services provided.

All this evaluation and analysis is a tremendous amount of work. However, it does not have to be difficult. A well thought out electronic system linking instrumentation to processes and product traceability as part of a measurement assurance program can ease the burden of out-of-tolerance evaluations and analysis. A measurement assurance program is more than a calibration program; it is a thought process to link and relate measurements through the entire produce life cycle, from concept to end product. Hopefully this approach and general guidelines will ease the burden to solving one of the most dreaded situations in the measurement world: the evaluation of an out-of-tolerance instrument and its potential impact.



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EMC

EMC in Military Equipment

BY DARYL GERKE, PE, AND BILL KIMMEL, PE

Military EMC design can be particularly vexing. Multiple environments combined with multiple threats lead to multiple requirements. The threat levels, and the resulting requirements, are usually more stringent than found in the commercial world.

As a result, commercial design techniques are often woefully inadequate for military applications. This can lead to frustration for those moving into military EMC from other areas. It can also lead to frustration to those wishing to use COTS (commercial off the shelf) equipment in military environments.

In this article, we'll explore some of the unique EMC challenges presented by military electronics, and how they differ from those of the commercial world.

MULTIPLE ENVIRONMENTS WITH MULTIPLE THREATS

Unlike commercial equipment, military systems may need to work in a wide range of environments. These can range from the arctic to the desert, and from the bottom of the ocean to outer space. Fortunately, most systems only need to operate in selected environments, rather than in every potential situation. This leads to subsets of requirements, and even tailoring in select cases.

Furthermore, military systems are often subjected to multiple threats. These threats are typically more severe than in commercial environments. Here are some examples of five general environments and their associated threats, and how they contrast with nonmilitary environments.

Fixed Land Based - This environment includes residential and office buildings. For commercial electronics, these are considered relatively benign in terms of EMC. As an aside, this is the primary EMC environment for most commercial electronics.

The emissions concerns are moderate, and are aimed at protecting nearby television receivers. The susceptibility concerns are a bit more challenging, and include threats such as RF (radio frequency) energy from nearby hand held radio transmitters, human ESD (electrostatic discharge), and power disturbances such as lightning or EFT (electrical fast transients.)

These same buildings on a military base, however, may pose much more severe conditions, particularly for radiated emissions and susceptibility. Both field levels and frequency ranges can be much higher than commercial environments. Due to radar systems, those frequencies can extend to 40 GHz or more, well above the typical 1 - 5 GHz upper limits for commercial equipment. Also, many military systems are designed to include protection against EMP (electromagnetic pulse) effects from nuclear weapons, which adds another level of complexity.

As such, commercial emissions requirements may not be adequate to protect nearby military communications receivers, which can be much more sensitive that a television receiver. Commercial susceptibility requirements may also be inadequate, due to radio and radar transmitters with higher radiated field levels, and EMP. The little bit of good news is that commercial levels for ESD and power disturbances are often still adequate.

Mobile Land Based - These environments include cars, trucks, buses, etc. Even for commercial vehicular electronics, these can be quite harsh. The emissions concerns are severe, and usually aimed at protecting entertainment radios (AM/FM), with secondary concerns for protecting land mobile VHF/UHF radios. The susceptibility concerns are also severe, and include RF, ESD, and a range of power transients and other power disturbances unique to vehicles.

Military vehicles share these same concerns, but as with fixed systems, the frequencies and amplitudes may be well above commercial levels. Nevertheless, commercial vehicular electronics can be expected to do fairly well in military environments, but may need some additional protection for radar and EMP.

Due to their experience working with harsh environments, we've found that commercial vehicular EMC engineers often have a relatively easy time making the transition to military electronics.

Marine Based - These environments include large surface ships, submarines, and even smaller water craft. Ships with metal hulls have vastly different EMC concerns depending on whether the equipment is located above deck (outside) or below deck (inside).

For both the military and commercial environment, emissions concerns are severe and are aimed at protecting communications and navigation receivers, including radar. Susceptibility concerns are also severe, and include RF and power disturbances. Since most military ships have multiple communications and radar transmitters, the levels and frequencies can be much higher than for commercial ships.

A classic tale of military EMC at sea was the sinking of the HMS Sheffield in the Falkland Islands War in 1982. It turns out there was a compatibility problem between the satellite communications and a defensive radar system. The "solution" was to disable the radar when communicating via satellite. Unfortunately, the launch of an enemy missile went undetected during one of these radar blackouts, and the ship was lost due to an EMC problem.

One bit of good news is that ESD is usually not a big concern for marine applications, due to high humidity conditions. A notable exception is helicopter ESD, which has resulted in special requirements for both helicopters and electronics equipment (and ordnance) that might be located near a helicopter landing pad. Lightning and EMP, of course, are major concerns for all military naval vessels.

Air based - These environments include all aircraft, and include small aircraft, helicopters, fighters, bombers, and more. Like ships, EMC concerns vary depending on whether the electronics are located inside or outside the aircraft. An emerging concern is the use of composite material rather than aluminum, which can affect overall shielding performance.

The commercial and military EMC environments are actually quite similar. In fact, the predominant commercial avionics requirements (RTCA DO-160) are derived from the military requirements (MIL-STD-461). The commercial requirements are even a bit more comprehensive, and include very specific lightning and power quality requirements.

Additional military concerns include HIRF (high intensity RF) and EMP. The former can come from radar exposure which may be quite high in a tactical situation, or as a weapons effect. ESD is also a big concern, particularly for helicopters transporting materials or munitions.

Magnetic field emissions are a unique concern for antisubmarine warfare (ASW) aircraft. One way of locating submarines is to look for low level magnetic field perturbations. The sub hunters need to maintain clean electronic environments so they can detect the perturbations.

Space - This is probably the most unique and varied of military environments. There has been very little commercial space electronics, although this may be starting to change. Nevertheless, we expect to see the commercial space designers closely follow military design practices.

Due to the expense of launching hardware into space, the EMC requirements are often highly tailored. Extensive engineering efforts are made to optimize (and not over design) for EMC. Extensive testing is performed to assure EMC is achieved. After all, if something doesn't work, it is almost impossible to fix (the Hubble telescope being one very expensive exception.)

Space electronics are subjected to several environments that must be considered. For example, during *pre-launch*, precau-

Another unique space requirement is "magnetic cleanliness." This is often a requirement for satellites that employ magnetometers for navigation. Even small magnetic fields, from either permanent magnetization or from power electronics, can interfere with the on orbit navigation.

tions must be taken to prevent damage due to human ESD. During *launch*, precautions must be taken to prevent damage due to triboelectric charging and also due to high RF levels from tracking radar, etc. In a tactical situation, the RF may also include antimissile efforts. Once *on-orbit*, space electronics are subjected to "space charging," and also cumulative degradation from ionizing radiation present in space.

Another unique space requirement is "magnetic cleanliness." This is often a requirement for satellites that employ magnetometers for navigation. Even small magnetic fields, from either permanent magnetization or from power electronics, can interfere with the on orbit navigation. Of course, nuclear weapons effects (such as EMP and ionizing radiation) are a also a major concern for military space electronics.

MILITARY EMC REQUIREMENTS

These various environments and threats have resulted in specific EMC requirements. Although these have evolved over the years, we now have two major military EMC requirements, MIL-STD-461 and MIL-STD-464.

TABLE IV. Emission and susceptibility requirements.

Requirement	Description
CE101	Conducted Emissions, Power Leads, 30 Hz to 10 kHz
CE102	Conducted Emissions, Power Leads, 10 kHz to 10 MHz
CE106	Conducted Emissions, Antenna Terminal, 10 kHz to 40 GHz
CS101	Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz
CS103	Conducted Susceptibility, Antenna Port, Intermodulation, 15 kHz to 10 GHz
CS104	Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals, 30 Hz to 20 GHz
CS105	Conducted Susceptibility, Antenna Port, Cross-Modulation, 30 Hz to 20 GHz
CS106	Conducted Susceptibility, Transients, Power Leads
CS109	Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz
CS114	Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz
RE101	Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz
RE102	Radiated Emissions, Electric Field, 10 kHz to 18 GHz
RE103	Radiated Emissions, Antenna Spurious and Harmonic Outputs, 10 kHz to 40 GHz
RS101	Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz
RS103	Radiated Susceptibility, Electric Field, 2 MHz to 40 GHz
RS105	Radiated Susceptibility, Transient Electromagnetic Field

Source: MIL-STD-461F

Most commercial designs focus on circuit board design, and then apply shielding as needed. Military systems, however, take the opposite approach, emphasizing shielding (and other systems design issues) over the circuit boards.

MIL-STD-461 is applied at the module (box) level. The current revision level is MIL-STD-461F, and should be applied to new procurements. Existing equipment may use earlier versions, so it is important to be sure you are using the correct version when dealing with updates or legacy systems. MIL-STD-461F provides both recommended test levels and the test procedures for a number of different tests. These are divided into four broad categories:

CE - Conducted Emissions
CS - Conducted Susceptibility
RE - Radiated Emissions
RS - Radiated Susceptibility

These are further subdivided into specific tests, with a three number designator, such as RE101. As an aside, older versions of MIL-STD-461 (A,B, and C) used the same nomenclature but with two number designators, such as CS06. This distinction is important, as legacy systems may still be using the older versions of MIL-STD-461 for qualification purposes. For more details, see MIL-STD-461F, Table IV.

Note that not all tests are required for all equipment. Rather, different tests and different levels are recommended for various situations. These recommendations are based on anticipated environments and threats. For more details, see MIL-STD-461F, Table V (page 126).

Note that requirements may vary among the different services for similar equipment. For example, the electric field radiated emissions (RE102) differ for Army, Air Force, and some Navy aircraft. Since Air Force and most Navy aircraft rarely use radios below the 2 MHz, they have no recommended requirements at the lower frequencies, while the Army goes down to 10 kHz.

Special cases may deserve special attention. For example, Navy aircraft used for antisubmarine warfare extend their electric field emissions (RE102) down to 10 kHz. They also include magnetic field emission requirements (RE101) that are not recommended for other Navy aircraft. The reason is that hunting for submarines often means detecting low level magnetic fields at low frequencies. In order to detect these fields, the local environment must be clean at those low frequencies.

There are two important philosophical differences between MIL-STD-461 and commercial requirements. First, MIL-STD-461 can be tailored as needed. Second, test failures can be waived. Of course, both require the customer to agree. We feel both of these options should be considered as needed, as they often yield good EMC systems engineering solutions. One caveat on MIL-STD-461. It is not a guarantee of ultimate EMC, but rather it increases the overall probability of success. You still need to plug everything together and see if it works.

MIL-STD-464, the second common EMC requirement, is applied at the systems or platform level. This document supersedes a number of older documents, and addresses grounding, bonding, lightning, EMP, HIRF, and more. Since this requirement applies to the platform level, it is often of secondary concern to the box/module designer.

Unlike MIL-STD-461, the actual test methods are not well defined in MIL-STD-464. This makes sense, as these are platform requirements, and platforms can vary widely. But as a result, these requirements can be difficult if not impossible to validate at the box level.

In spite of the system emphasis, we have seen increasing attempts by the platform designers to “flow down” their system requirements to the box designer. Since systems level testing is not appropriate at the box level, the result is often a request for engineering analysis. This is certainly prudent early in the design, but should not be a substitute for testing later at the full system/platform level.

DESIGN SOLUTIONS – SYSTEMS ENGINEERING OVER CIRCUIT BOARDS

This is an area where commercial and military systems differ in their EMC approaches. Most commercial designs focus on circuit board design, and then apply shielding as needed. Military systems, however, take the opposite approach, emphasizing shielding (and other systems design issues) over the circuit boards.

We've seen this subtle difference cause frustration for designers moving from commercial to military electronics. We recall one young EMC engineer who was questioning why his new company even hired him. As he said, "All they worry about here is grounding, shielding, and cables. They aren't even using my circuit board experience." He felt much better after we assured him that his EMC experience was indeed very valuable – only the focus was different.

Most military systems are already in metal enclosures. Thus, shielding becomes a key EMC design approach. Furthermore, many military systems use embedded controllers, and don't need the latest and greatest speeds and raw performance. As a result, there is more emphasis on systems design, and less on circuit board design. (We still recommend good EMC circuit board design practices for military electronics.)

The systems design solutions often revolve around interfaces. These include the following:

Power - This is an *energy interface*. Design protection of this interface typically combines passive circuits (filters and transient protection) with active power supply circuits. The goal is to provide clean regulated output power under varying input conditions. Since the bandwidth for power is low, the input power wiring is often unshielded.

Signal - This is an *information interface*. Design protection of this interface typically includes a combination of passive circuits (filters and transient protection) with active I/O circuit design. Due to bandwidth requirements, filtering is often traded off with external cable shielding or even fiber optics. Thus, cables and connectors also become an important part of this interface, along with the specific I/O circuits.

Grounding - This is primarily a *safety interface*, but it also affects the power and signal interfaces. The primary strategy here is topology control. Single point grounds are preferred for low frequency circuits, such as analog sensors and input power. Multi-point grounds are preferred for high frequency circuits, such as digital and RF circuits. Hybrid grounding approaches (using capacitors and inductors to make grounding paths and connections frequency dependent) are often used when both types of circuits or threats are present.

TABLE V. Requirement matrix.

Equipment and Subsystems Installed In, On, or Launched From the Following Platforms or Installations	Requirement Applicability																	
	CE101	CE102	CE106	CS101	CS103	CS104	CS105	CS106	CS109	CS114	CS115	CS116	RE101	RE102	RE103	RS101	RS103	RS105
Surface Ships	A	A	L	A	S	S	S	A	L	A	S	A	A	A	L	A	A	L
Submarines	A	A	L	A	S	S	S	A	L	A	S	L	A	A	L	L	A	L
Aircraft, Army, Including Flight Line	A	A	L	A	S	S	S			A	A	A	A	A	L	A	A	L
Aircraft, Navy	L	A	L	A	S	S	S			A	A	A	L	A	L	L	A	L
Aircraft, Air Force		A	L	A	S	S	S			A	A	A		A	L		A	
Space Systems, Including Launch Vehicles		A	L	A	S	S	S			A	A	A		A	L		A	
Ground, Army		A	L	A	S	S	S			A	A	A		A	L	L	A	
Ground, Navy		A	L	A	S	S	S			A	A	A		A	L	A	A	L
Ground, Air Force		A	L	A	S	S	S			A	A	A		A	L		A	

Source: MIL-STD-461F

Legend:

A: Applicable
L: Limited as specified in the individual sections of this standard
S: Procuring activity must specify in procurement documentation

Shielding - This is an *electromagnetic field interface*. This is usually bi-directional, and designed to contain internal electromagnetic fields (emissions) while providing protection against external electromagnetic fields (susceptibility.) Design strategies include metallic enclosures, and then sealing any penetrations or discontinuities with gasket, screening, and filters.

In addition to interfaces, risk management is an important aspect for EMC systems design. This is accomplished several ways:
Design reviews - Most military programs follow a detailed design procedure that includes formal design reviews at critical junctures. Additional design checkpoints may also be employed. We often recommend dedicated EMC reviews. These can be brief, yet can be helpful in uncovering potential EMC problems early in the design process.

Engineering tests and analysis - Many military programs depend on test and analysis throughout the design process to validate design approaches. We certainly encourage this.

Documentation - Most military programs have mandatory documentation requirements. These typically include an EMC Control Plan, and EMC Test Plan, and an EMC Test Report. All three are used to document the process, and as communications tools between the contractor and customers. Yes, we know that most engineers don't like documentation, but this is a very important part of the EMC systems design process.

MISSION SUCCESS TRUMPS COST

All this design effort, analysis, test, and documentation costs money, which can lead to complaints about $100 hammers or $400 toilet seats. In spite of carping by politicians, the extra costs are usually justified. Furthermore, since most military systems have relatively low volumes, there are fewer units over which to amortize the extra engineering and test costs.

Military equipment must operate as designed and when needed. Reliability is crucial. For example, you can't power down or push the reset button on a missile or torpedo after it has been launched. Furthermore, you don't want them turning around and coming back home.

The true bottom line is not cost, but mission success. Remember, lives are often at stake. Our servicemen and women who go in harm's way deserve the absolute best engineering we can deliver – EMC and otherwise!

CONCLUSIONS

1. Military EMC is different from commercial EMC. There are multiple environments to consider, with multiple threats. Those are usually much more severe than commercial threats.
2. Complex military systems require systems engineering approach. The focus is often on interfaces, rather than on circuit boards. Design reviews and documentation are critical to keep everyone in the loop and on schedule.
3. Mission success trumps costs, and reliability is key.

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Daryl and Bill are both degreed Electrical Engineers, registered Professional Engineers, and NARTE Certified EMC Engineers. Between them, they share over 80 years of industry experience. For more information and resources, visit their web site at www.emiguru.com.

Product Design

How to Get the Design Right the First Time

BY CHERIE FORBES

You spend months, or even years, designing a product. After it's all ready to be shipped to your customer, you find out that you need a safety certification mark. So in a panic, you send the product off to a test lab for evaluation. The shipment is sitting in your loading bay waiting for the final certification to arrive and then the bad news arrives. Your test lab tells you that it fails! This is not only heartbreaking, but time, effort and money are wasted in redesign. Not to mention the delay in shipping your product to the customer! Everyone is looking at you and wondering why it wasn't initially designed correctly. If only you had a manual entitled "Things I need to know to design my product to ensure that it will pass safety testing"! Oh wait…you do! It's called a safety standard. It may have been published by the IEC, UL or CSA, but it contains everything you need to know, right there, in black and white.

If designers have access to safety standards, why is it that most products submitted for certification have a flaw of some sort that causes the product to fail the safety evaluation? Sometimes these flaws are minor in nature (e.g. missing label, wrong wire color used) which don't take much time to fix. But sometimes the flaws require a complete redesign (e.g. replace the power supply, redesign circuit boards, redesign the enclosure). Why don't designers pay more attention to the requirements? A variety of reasons come to mind: lack of time to research the requirements, lack of knowledge that the safety standard exists, miscommunication within the design team, etc. Even if the designer doeslook at the standards, it is often difficult to understand the requirements (if you can find them). Anyone who has read a safety standard will agree that they are not easy to understand, and tend to bring on lengthy discussions when it comes to interpretation of the requirements.

What is a designer to do? There are a variety of steps that the designer can take to help insure against costly redesigns.

DETERMINE THE MARKET WHERE THE PRODUCT WILL BE SOLD

The first thing to find out is exactly where your company will want to sell this product. Your marketing department may have already determined this (but may not have shared this with the design team). North American manufacturers will often focus on sales in North America, only later to be surprised when they find out the extent of the redesign required to comply with European requirements. Knowing the target market may affect many aspects of the design: voltage ratings, component selection, wiring methods, etc. For example, selecting an auto-ranging power supply (100-240V) will allow your product to be used in Europe (220-240V), Japan (100V) and North America (120V). If you've designed for the North American market only, you may have neglected the other voltage options, resulting in a costly redesign.

Now that you know what countries you will be targeting, determine what safety related marks are required. The United States and Canada have a variety of options available; many certifiers (e.g. CSA, UL, TUV Rheinland, etc.) are accredited by both the Standards Council of Canada (SCC) and the Occupational Safety and Health Administration (OSHA) as a Nationally Recognized Test Lab (NRTL). Knowing that you can talk to a single certifier to gain simultaneous marks for both countries will make things much easier.

Europe uses a self-evaluation method called the CE Mark. The CE Mark declares compliance to all the directives applicable to the product (e.g. Low Voltage Directive, EMC Directive, and Machinery Directive). Because it is a self-evaluation mark, manufacturers can evaluate the product themselves (with a high level of risk to the manufacturer), or use an agency to evaluate the product on their behalf (low level of risk). Europe has some extra requirements to consider, namely the RoHS and WEEE directives, which have specific restrictions on toxins (mercury, lead commonly used in solder, etc.) and requirements for disposal methods. Many component manufacturers have lead-free alternates to be selected for European markets.

Some countries, such as Japan, have a list of products that need to be certified. Any product not on this list does not need to be evaluated for safety. It's important to look into this beforehand so you can learn the requirements (if any) before designing your product.

DETERMINE THE CORRECT SAFETY STANDARD FOR THE PRODUCT

Now that you know where your product will be sold and the certification marks required for each market, you can determine the safety standard(s) that apply to your product. If you are designing Information Technology Equipment (ITE), you are fortunate because many countries have adopted the same safety standard (IEC 60950-1) [1] and only tweaked it slightly to meet with their National Electrical Codes. Often meeting the requirements for one country will meet the requirement of other countries sharing the same standard.

Some products are not so lucky and have different standards in each country. For example, Industrial Control Equipment has a standard in the United States (UL 508) [2], a very different standard in Canada (CSA C22.2 No. 14) [3], and a completely different standard in Europe (EN 61010-1) [4]. In circumstances such as this, you may need to design with three different standards in mind!

Knowing what the applicable standards are will allow you to purchase them, review their requirements, and use your new knowledge in the design of your product.

SELECT COMPONENTS THAT ARE SUITABLE FOR THE STANDARD

Most safety standards contain a list of component standards that are acceptable for compliance. Use these when selecting components! The safety standards generally allow for two choices: (1) evaluate the component to the applicable component standard (as listed in the standard), or (2) evaluate the component to the product's safety standard. If the component is already certified to the applicable component standard, you can be assured that the component is suitable and will not require additional testing. An uncertified component (including CE marking because it is self-declared) will require additional testing. In general, this testing is at an additional cost and will extend the amount of time allotted for certification.

Keep in mind that each standard may have different requirements for components. For example, the ITE standard for the United States will list many UL standards that need to be met. Since UL standards are used in the United States only, these certifications alone will not be suitable for the European market.

OBTAIN COMPONENT LICENSES

Many component datasheets and catalogues state the safety certification marks and safety standards that the components have been evaluated to. Don't believe them. The marketing teams that produce these datasheets and catalogues make mistakes, incorrect assumptions, or use outdated information. You need to collect proof that each component is certified according to their claims.

Some agencies, such as UL, CSA and TUV Rheinland, have powerful databases on their webpage that allow you to search for licenses. Use these online tools for all your components!

Now that you are sure that the certifications are valid, you need to ensure that you are using the component according to its ratings. Often these ratings are listed on the agency websites and are easy to check. However, for some components, finding the listing on the agency website is not enough. Sometimes the certification record is vague, doesn't list the exact standard, doesn't include things like current and voltage ratings, etc. The only practical way to be sure that the component will be acceptable is to get the licenses from the manufacturer. Component licenses will sometimes include an important section entitled "Conditions of Acceptability", because the component evaluation is not a complete product evaluation. The Conditions of Acceptability include conditions that will need to be met in the end-use product (e.g. enclosure requirements, wiring details) and assumptions that were made during certification (e.g. required airflow, fusing). UL provides this for every component certification in their UL Recognition Program. Other certifiers may provide the conditions, but not always. It is crucial to obtain the Conditions of Acceptability for key components such as power supplies, dc-dc converters and transformers.

Read the Conditions of Acceptability and license and ask yourself "Am I using this component according to its rating?" If you will be using a power supply in a 60°C environment, but the license states a rating of 40°C, then you are using that supply outside its ratings. Never mind that the manufacturer may have provided a derating curve in their datasheet. If it hasn't been evaluated by a certifying agency, consider it to be unproven and therefore unreliable. Using a component outside of its ratings will void the certification of the component and result in retesting of the component in your specific equipment. This is an extra cost and hassle that should be avoided if possible. One simple way of correct this is to source a more suitable component with the correct ratings or adjust your equipment ratings.

Also ask yourself if you are meeting all the conditions stated in the Conditions of Acceptability. If the Conditions of Acceptability state that there must be airflow over the power supply, make sure you are providing that same airflow. If the Conditions of Acceptability state that a terminal block is not for field wiring, you cannot use that terminal for field wiring! You must evaluate these Conditions of Acceptability as they apply to your product with a critical eye!

One more thing to consider is to make sure the licenses you receive from the manufacturer are current! Manufacturers are eager to send you agency licenses that show compliance to old standards or cancelled certificates. Always double check that the component is still certified (confirm on the agency website), and ensure that the standard (and the edition of the standard) used for compliance is listed in your product's safety standard.

Remember, even if the component is certified, if it's not certified to the correct component standard, used outside of its ratings, or certified to an older version of the standard, consider it to be uncertified. If you include that component into your design, you will have increased certification costs to cover the extra evaluation and testing.

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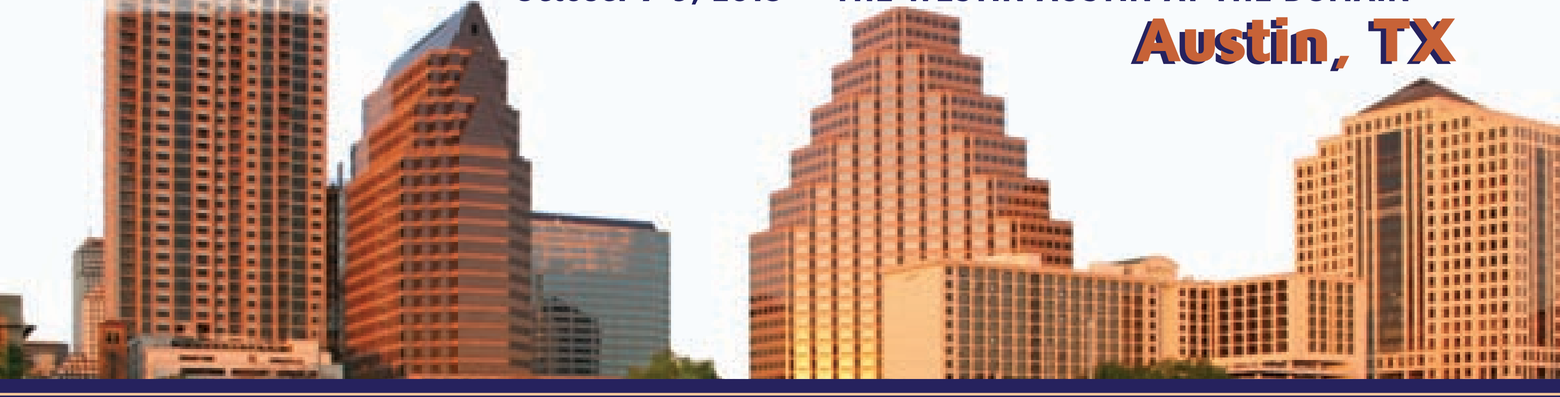

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Joe Bhatia
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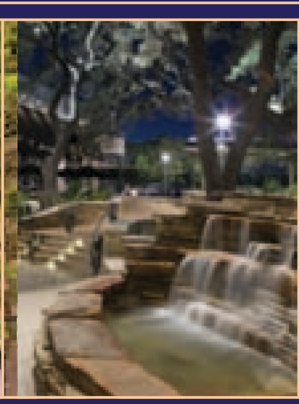
(American National Standards Institute)



DESIGN A SUITABLE ENCLOSURE

There are many things to look for when designing an enclosure for your product. Not only does it have to match the "look" that your marketing department desires, but it has to be functional and pass the tests of the appropriate safety standard. There are a variety of things to look at, including material selection, material thickness, openings (including ventilation) and sturdiness necessary to pass the tests of the standard.

Material Selection

Are you considering a plastic enclosure or metal enclosure? Plastic enclosures have some additional requirements to consider, such as flammability ratings of the plastic. These details are described in the safety standard. Consider the plastic to be a component and look it up on the agency website (UL has an excellent online database for plastics). Make sure the specific plastic you are using is listed there, with the appropriate flammability rating and in the correct color. If your plastic is not listed on this website, not only will you be required to have flammability testing conducted, but annual confirmation tests will also be required (at additional cost to you).

Material Thickness

Plastics that are certified will have been tested at a specific thickness. Often the flammability rating will differ depending on the thickness of the plastic. Making sure that the minimum thickness in your enclosure is greater than that listed on the agency certification is critical.

Openings

Openings in the enclosure, generally for ventilation purposes, create a few challenges: (1) if they are too big the user may be able to touch the circuit inside, creating a shock hazard, (2) if the enclosure is providing a fire enclosure the openings may allow flaming particles to exit or enter the enclosure, thereby defeating the purpose of the fire enclosure, and (3) large openings that house a fan or moving part could introduce pinch hazards without suitable shielding. Ensure that all your openings comply with the requirements of the standard.

Tests

Enclosure tests are commonly conducted in safety evaluations. The enclosure must be sturdy enough that it won't allow a hazard to occur after falling, being leaned on, stood on, impacted, heated, cooled, exposed to UV radiation, or any other foreseeable situation that may affect the safety of the product. You need to consider all the possible tests that will be conducted, as described in the safety standard, and design accordingly.

DETERMINE THE REQUIRED SPACINGS

Knowing what spacings are required between different types of circuits, or between a circuit and an accessible part (i.e. the enclosure) is critical. Planning and designing your wiring boards when you know what is required will save you much time and effort, and will avoid that costly redesign.

Identification of Circuits

The first step is to identify different circuits and accessible parts (i.e. mains circuit, unearthed secondary circuit, earthed enclosure, floating enclosure, etc.).

Create a Block Diagram

Each of these circuits and parts can be considered (and drawn as) a block. Include components that bridge these different blocks (i.e. a transformer, capacitor, relay, etc.). Litter your block diagram with arrows between blocks to indicate where insulation is required. See Figure 1 for a sample block diagram.

Determine the Level of Insulation Required

Referencing the safety standard, determine the type of insulation required between each of the blocks identified with an arrow. Examples of insulation include: basic insulation, reinforced insulation, and supplementary insulation.

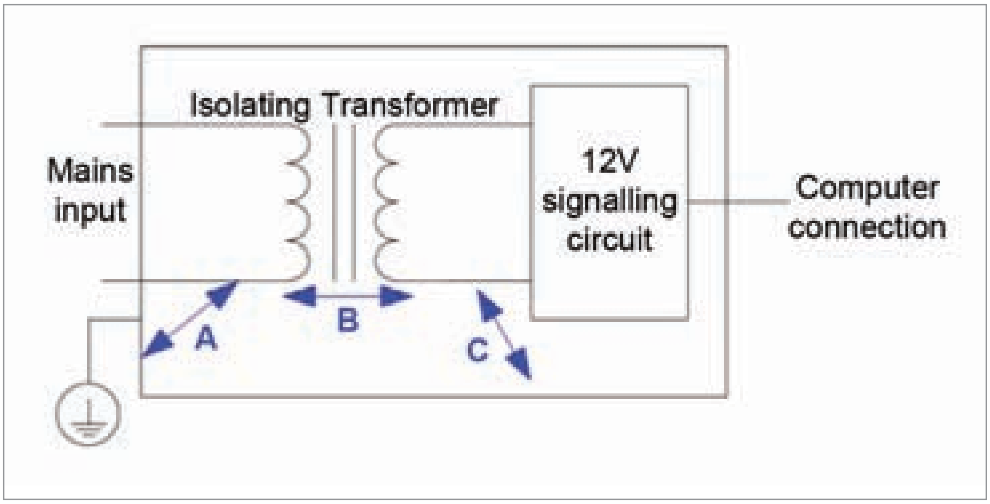


Figure 1: Sample block diagram

Using Tables in the Standard

Determine the creepage distances and clearances required for each of the locations indicated with an arrow. These requirements are found in the safety standard, generally in tables. The required distances will differ depending on the working voltage and the type of circuit.

After determining the required spacings, ensure you are applying these when laying out printed wiring boards. Also consider clearances between boards and enclosures or between adjacent boards.

SINGLE FAULT EXAMINATION

Knowing what single fault tests will be conducted on your product will help immensely during your design. You need to design your product so it can withstand the fault applied and remain safe. A fire or a shock hazard is unacceptable. Single fault tests include shorting and overloading transformer windings, short circuiting or open circuiting components (i.e. capacitors, legs of optocouplers, transistors, resistors, etc.), blocking air ventilation openings and stalling fans. Anticipating these faults and designing protection devices (such as fuses) into your design will be extremely beneficial.

OTHER STANDARD REQUIREMENTS

Every safety standard is different. You, as the designer, need to thoroughly go through the standard to make sure all requirements are met. There will be clauses about earthing methods and bonding tests, requirements for the sizes of wire used, disconnect devices, fusing requirements, touch current requirements, electric strength testing requirements, etc. Knowledge of these requirements will improve your design.

USING CONSULTANTS WHO UNDERSTAND THE REQUIREMENTS OF YOUR SAFETY STANDARDS

Consultants familiar with your safety standard can be a genuine asset for your design team. They have experience with the safety standard and agencies. They know what requirements you need to consider and can identify common pitfalls. They can advise you on the suitability of the components selected and assist with the design of your product (i.e. enclosure design, circuit board layout, etc.). Relying on a consultant will allow you to focus on other aspects of the design, feeling confident that the design will not result in failures during safety certification and evaluation.

SUMMARY

It's critical to know the market your product will be shipped to before the product design is started. Once you know this, you can use the appropriate safety standards when designing your product. Using consultants to assist with understanding the safety standard is another option to be considered.

If you are unfamiliar with the appropriate safety standards that will be used to evaluate your product during safety certification testing, your design will most likely fail. Your components may not be suitable, your enclosure may be inadequate, your circuits may need to be redesigned, etc. When your product fails during safety certification, you will be charged more for extra evaluation. Furthermore, certification failure significantly delays your time to market while you spend time and effort to fix the problems.

Designing to meet the safety standard is the smartest thing you can do!

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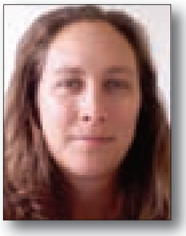

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Product Safety

Occupational Hazards of the Safety Engineer

OSHA Meets UL

BY TED ECKERT

The job of the product safety engineer is to reduce the risks associated with a product to an acceptably low level. The product safety engineer is interested in protecting the life and health of the customer who will use the product. However, the testing involved in safety engineering can entail some risks of its own. The environment for safety testing itself needs to be designed to provide an adequate level of safety for the person performing the test. This requires appropriate test equipment, properly designed environment, well documented procedures, personal protective equipment, training and monitoring of personnel who have access to the test lab.

There are numerous potential risks in the safety test lab, and these typically are similar to the potential risks we test for in our products. There are electrical hazards including shock and arc blast. There are thermal hazards including burns and the risk of flame. Mechanical hazards include risks from hazardous moving parts or from heavy objects crushing body parts. High energy lasers can be exposed in testing, and electrical arcs will generate significant amounts of UV light creating a risk of cataract formation in the eye. Medical products may generate ionizing radiation. There are even chemical exposure hazards for some testing. All of these potential risks need to be properly addressed and mitigated.

INJURY STATISTICS

It is difficult to find statistics for injuries in the product safety testing profession. As a profession, the number of practitioners is small and it doesn't warrant its own category by the U.S. Bureau of Labor Statistics (BLS). However, the BLS does record injuries as a rate per 100 workers, and it is reasonable to put product safety engineering in the same category as electrical manufacturing. For the most part, the types of hazards are similar. While the time spent at a desk will lessen the product safety engineer's total exposure time to hazards, it also reduces their experience and practice. An analogous situation would be comparing a professional carpenter versus a weekend woodworker. The professional may be exposed to the risk of injury for 40 hours a week, but this gives them the practice and experience to do the work right. The weekend woodworker may spend only 4 hours a week with a table saw, but their lack of experience significantly raises the risk of injury.

The BLS keeps records of reportable injuries, which are injuries severe enough to require medical treatment. The most recent BLS statistics are for 2009 where there were 3.5 reportable injuries per 100 workers in the electrical equipment, appliance and component manufacturing industry [1]. This is the most appropriate recorded category to extrapolate for product safety engineering and it shows a real risk of injury. Product safety testing is too small of an industry to be broken out separately by BLS, and it is likely that many injuries sustained during safety testing are not reported as worker compensation claims.

The rate of fatalities is a harder to extrapolate as the total number is lower and doesn't allow the BLS to categorize fatalities by narrow industry sectors. The total for 2009 in the United States was 4,551 out of approximately 130 million workers [2]. The fatality rate for the manufacturing sector was only about two thirds the overall rate for private industry, and this represents about one fatality per 1500 injuries in the electrical manufacturing sector. I do not have sufficiently specific data and I will not extrapolate to the product safety testing industry.

APPLICABLE REGULATIONS

Product safety testing laboratories must comply with the applicable occupational health and safety regulations of the jurisdiction in which they are located. The general principles of regulations are generally similar between North America and Europe. The application of these principles and the level of enforcement may be more variable in other jurisdictions, but I will address The United States and Canada specifically and Europe in general.

The governing authority in the United States is the Occupational Safety and Health Administration (OSHA) under the Department of Labor [3]. The OSHA rules apply to almost all employees in the private sector. Although there is a common belief that small employers are exempt from OSHA rules, this is a misunderstanding. The enforcement procedures may differ depending on the employer's size, and although OSHA will rarely audit a company with ten or fewer workers, these companies are still subject to the regulations. The OSHA regulations cover general work practices and some specific work situations. However, the requirements are NFPA and ANSI standards which are incorporated into OSHA regulations by reference [4]. The OSHA directly covers requirements for training, monitoring and reporting of injuries along with safety practices common among different work environments.

While OSHA is reviewing and adoption NFPA 70E for electrical safety, it is currently a reference document not carrying mandatory requirements. Following NFPA 70E will demonstrate due diligence should an OSHA inspector arrive at a facility. NFPA 70E is not to be confused with NFPA 70. Whereas NFPA 70 covers the rules for the installation of electrical equipment, NFPA 70E covers the rules for safe work practices around exposed hazardous voltages. Additional applicable standards referenced by OSHA are numerous and include, but are not limited to, ANSI standards such as ANSI Z87.1-89 for eye protection, ANSI Z87.2 for respiratory protection and ANSI A14.2-56 for metal ladder use. Additional regulations will apply for specific risks such as laser and X-ray testing.

The regulations for Canada are similar in their technical requirements. The regulations are governed by Health Canada under the Canada Occupational Health and Safety Regulations [5][6]. Many specific requirements are covered by referenced standards including the Food and Drugs Act, Hazardous Products Act, Nuclear Safety and Control Act, Radiation Emitting Devices Act and Controlled Products Regulations [7-11]. The Controlled Products Regulation for example specifically covers the marking and warning requirements for chemicals and hazardous materials. The specific requirements are very similar to those called out by OSHA in the United States.

European requirements will vary from country to country. The European Union does set some standards since the EU is intended to allow the movement of workers across borders without problems. The body setting policy at the European Union level is the European Agency for Safety at Work [12]. As with product safety regulations, there are EU Directives regarding occupational safety that member bodies are required to incorporate into national law. The framework is established in Directive 89/391 with additional Directives written to cover physical hazards, noise, radiation exposure, personal protective equipment, hazardous material handling and marking and many more potential hazards [13][14]. These Directives in turn may have specific applicable standards. For example, EN 50191 covers the installation and use of electrical test equipment and EN 60825-4 covers guarding and protection when there is exposure to Class 3 or Class 4 lasers. Each country must adopt these regulations as a minimum standard, but individual countries may choose to enact stricter regulations. The policy regarding the enforcement of regulations is handled at the national level and is not determined by the European Commission.

BASIC PRINCIPLES

Many product safety engineers will groan when they think about OSHA looking at their lab, but the general approach espoused by Environmental Health and Safety (EH&S) professionals can be implemented with minimal hassle and significant benefits. A six step approach can be used; eliminate the risk, provide adequate guarding and protection, use proper personal protective equipment (PPE), provide proper hazard marking and warning, train the affected employees and use continuous improvement. Although the final item isn't always included in some safety programs, it is important. Proper analysis is required whenever there is an injury or even a "near miss". Continuous improvement allows you to better focus a general safety program to the narrow field of hazards and issues found in safety certification testing. These issues are determined by systematic causal analysis of incidents that have occurred.

ELIMINATING RISK

Product safety testing involves abusing products to make sure that they fail in a safe manner. This may mean that the product safety engineer will be exposed to hazards, but the exposure can be controlled through the use of safe work practices. For example, measurements of hazardous voltages can be made without exposing personnel to those voltages by applying test probes using clip-on leads while the equipment under test (EUT) is disconnected from power. The test engineer should use enough test leads and meters to simultaneously record necessary voltages at once. Power can then be applied after all test leads are secured. This eliminates the risk of electrical shock by placing the hands close to hazardous voltages, and it reduces the risk of an arc flash from a test probe accidentally shorting out terminals as it is inserted into live equipment. Another example of risk reduction is the addition of outriggers during the stability testing of large, heavy equipment. The outriggers will stop the fall of equipment if it should start to tip over when subjected to the test force. Alternately, a large test jig can be used that will arrest the fall of equipment when it reaches a tilt of 12º, allowing a 10º tip test without the risk of equipment falling over onto personnel. Consider requiring more than one person be present in the laboratory when any potentially hazardous testing is performed. The second person should be clear of the area where the test is being performed so that they will not be put at risk should something go wrong with the test.

PHYSICAL LABORATORY DESIGN

The test laboratory should be designed with the assumption that problems may occur and will need to be addressed. Safety test laboratories should have two means of egress where possible, with the two doorways placed at opposite ends of the room. Security and other design concerns will typically result in doors that swing into the laboratory. If possible have one door that opens out and that has panic hardware that allows the door to be opened without the use of hands, such as a push-bar across the door. Each test area should have an egress route at least 1.25 meters wide. Practice good housekeeping to keep these aisles clear of test equipment and storage boxes. The laboratory should have adequate lighting, exit signage and emergency lighting. Make sure the lab has adequate cooling to handle the heat load that will be generated by the EUT. I once tested a 12 kW load in a room with 4 kW of cooling, and the room temperature finally stabilized at 46° C. This would have been an unacceptable environment had somebody been required to work in the room constantly during the testing. Eyewash stations and showers may be required depending on the chemicals that are used in the laboratory.

GUARDING AND PROTECTION

The next step is to provide adequate guarding and protection. Flammability testing should be done in a fume hood that will safely extract the combustion gasses from the room. The same fume hood can be used for other tests where volatile chemicals may be used or testing where there may be toxic gasses released into the air. The room itself should have a sprinkler system to protect in the event that a fire does start and get out of control. Hand-held fire suppression equipment should be available should materials ignite during fault testing. Sand or fire blankets can be used for small fires allowing for an easier cleanup. Special fire suppression equipment may be needed depending on the materials being tested, particularly with alkali metals such as lithium.

Some fault testing can result in flying debris, such as testing fuses at high fault currents. Current limiting devices can fail catastrophically when exposed to currents beyond their interrupt ratings. Plexiglas guards can be used to provide a barrier between equipment and personnel during fault testing if there is a risk of debris flying.

Flammable chemicals should be stored in an approved flammable storage cabinet. Chemicals should be stored in their original containers. If smaller volumes of chemicals are moved to another container, that container must be properly marked with the appropriate chemical properties.

Figure 1: Rolling platform ladder

If the EUT generates radiation, shields against that radiation need to be provided for the test engineer. This applies for both ionizing radiation and nonionizing radiation such as a laser. Wearable monitors may be required depending on the type of radiation.

Additional equipment may depend on the type of testing being performed. If your laboratory staff must work with tall equipment, consider providing personnel with a rolling platform ladder (Figure 1). This will provide a large and stable work surface for working above ground level and is preferable to a step ladder. Provide lifting equipment and hoists if personnel must handle heavy equipment or components. The personnel who use this equipment must be trained in its use. (See section entitled "Training".)

ELECTRICAL DESIGN

The safety laboratory needs to be designed with the proper electrical connections for the type of equipment to be tested. This may mean providing a variety of outlets of different ratings. One technique is to provide a higher current multi-phase outlet, and then to use adapter boxes that provide specific outlets, each with the proper overcurrent protection. Consider installing an Emergency Power Off (EPO) button that shuts off selected power in the room. The EUT gets connected to a protected outlet, and if there is a problem of such severity that the test engineer cannot easily disconnect power, the EPO can be used to shut off power to the EUT. The EPO can also be used to disable the door lock via an electronic strike plate, allowing entry by emergency responders should there be a situation in the lab requiring fire or medical personnel. In such cases, an indicator light should be placed outside the door to the laboratory to indicate that the EPO has been activated. Please note that the EPO should not turn off lights in the laboratory.

Ground Fault Circuit Interrupters (GFCIs) are required for outlets in close proximity to sources of water. However, GFCI should not be used in other locations for supplementary protection. GFCIs are susceptible to nuisance tripping due to the leakage current of ITE, and they can be impractical in the laboratory environment. Safe work practices are required to reduce the risk of exposing personnel to fault current. AFCIs are susceptible to tripping during abnormal condition testing and could terminate testing prematurely. Arc Fault Circuit Interrupters (AFCIs) also should not be used in a safety laboratory to provide supplementary protection. AFCI's intended purpose is to shut off power when arcing can go undetected in a residential environment where there are lots of flammable materials. AFCIs are not used in commercial environments in general and would provide few benefits in the safety laboratory.

If you perform fault testing that will result in tripping a branch circuit breaker, you need to take additional precautions. Circuit breakers are not designed for repeated tripping. Their detents and internal components will weaken slightly with each trip. Ground faults are especially hard on circuit breakers and significantly shorten their operating lives. Instead of depending on the branch circuit breaker to terminate a test, insert overcurrent protection between the EUT and the branch circuit breaker. This supplementary overcurrent protection must be of a type and rating such that it will open before the branch breaker, and it should be installed in such a way that it can be easily and safely replaced. The supplementary protector can be replaced as it degrades preventing the need to replace circuit breakers in an electrical panel. This protection can be installed in the previously mentioned adapter boxes. The box can then be unplugged and safely disassembled to replace the supplementary protector.

Figure 2: Electrical gloves

PERSONAL PROTECTIVE EQUIPMENT

All personnel who use the lab need to be issued the proper personal protective equipment (PPE) for the type of work that they do. The type of PPE should be based on the testing performed and the risks to which the personnel will be exposed. It is also important to note that "personal" is part of PPE. Each employee who works in the laboratory should be issued their own PPE. It is not to be shared among employees. PPE needs to be chosen in the correct size and type for the employee and they need to be trained in its proper use. Employees need to understand that if they don't have the proper PPE, they should forego the test until it can be done safely.

Safety glasses should be worn in almost any safety test laboratory as they will be recommended for many types of tests. Physical tests, ranging from drop tests to impact tests, may result in flying debris. Abnormal condition tests can have unpredictable results that can also result in flying debris. In the United States, NFPA 70E requires safety glasses be worn whenever working around exposed hazardous voltages. Electrical arcs generate intense ultraviolet light which can contribute to cataract growth in the eyes, so the glasses should provide UV protection in additional to impact protection.

PPE will be needed as physical protection for a number of risks possible in the test laboratory. Hearing protection may be required if testing will involve loud equipment. Safety shoes should be worn when working with heavy equipment to protect feet from crush injuries. These shoes should also have electrically insulating soles to reduce the shock hazard. Protective gloves may be required for some types of tests (Figure 2). Different gloves may be needed for protection against thermal burns, sharp edges or chemical hazards. Chemical exposure may also dictate the use of respirators. If so, the respirators need to be fitted properly, the filters need to be selected based on the hazard and the employee needs to be medically evaluated and well trained in the use of the respirator.

NFPA 70E imposes fairly strict requirements for PPE for working

Product Safety

with exposed hazardous voltages, so it is best to eliminate the need for the test engineer to place their hands in the equipment while it is live. If this must be done, NFPA 70E will require differing levels of protection depending on the voltages present. This protection includes electrical gloves with leather protectors, safety glasses, face shields and flame resistant clothing. The PPE required for testing a 120 V hand mixer may be simple, but much more would be required for testing a 250 kW, 480 V uninterruptible power supply. Do not rely on the practice of keeping one hand in your pocket. This may reduce the risk of hazardous current running through your heart, but you still run the risk of creating an accidental short circuit. This could still allow hazardous current to run through your hand resulting in significant burns. In higher power equipment, it can result in an arc flash or arc blast that can do even more damage.

Make it easy for employees to keep their PPE in or adjacent to the laboratory. Even if the employee's office isn't far away, there can be the temptation to just run a quick test even if they forgot to bring their PPE. Lockers or cubbies allow easy storage of safety glasses, lab coats, safety shoes, ear protection and other PPE. Provide additional PPE if you have regular visitors to the laboratory. Safety glasses and ear plug dispensers can easily be placed immediately outside the laboratory area allowing the quick outfitting of visitors when needed.

MARKING AND WARNING

Marking and warning should be used where hazards cannot be eliminated, guarded or controlled below safe levels. Chemicals should be properly marked where they must be used and the Material Safety Data Sheets (MSDS) must be available to personnel to provide them with the proper warnings, PPE requirements and information (Figure 3). Mark areas where there will be exposed hazardous voltages. The test engineer may be aware of the exposed voltages, but there may also be a possibility of others entering the lab without such knowledge. These people need to be able to see the proper warning signs to know the hazard is present. Similar marking should be used for hot surfaces or exposed hazardous moving parts. The National Electrical Code prohibits placing any object in front of an electrical panel, so mark the proper exclusion area around the panel. Use floor marking for areas used for storage of large items to clearly delineate storage areas from aisles.

Figure 3: MSDS station

Certain hazards will require additional marking. There will need to be marking on the door into the laboratory if there are radiation hazards, whether they are ionizing or nonionizing. Specific information about lasers in the laboratory will need to be marked including the laser class and the wavelength. Signs on the door should indicate the required PPE if there is ongoing testing dictating specific PPE be used at all times.

TRAINING

All affected employees need the proper training to reduce their risk of injuries. Affected employees include not only those performing the testing, but those with access to the laboratory area while testing is being performed. Personnel unfamiliar with specific testing may enter the lab and these people need the training to be able to assess and handle the risks present. It is important to document which employees have been trained and what hazards they have been trained to handle. An employee not trained to handle a specific hazard should not be permitted to perform testing where that hazard may be present. Training needs to be repeated periodically both as a refresher and to ensure new standards and requirements are well communicated.

The various regulating agencies, such as OSHA, mandate the training. Employees must be trained in the use of PPE before they can perform the tasks that require the PPE. If special equipment is required to perform a task, the affected employees must be trained to use the equipment. Employees must be trained in proper ergonomics, lifting techniques and use of hoists if their job requires them to lift heavy loads.

Training on its own has a limited benefit if there isn't enforcement of the rules. Enforcement need not be draconian, but it does need to provide an incentive to follow safe work practices. Laboratory safety needs to be part of the corporate culture, and the laboratory manager is responsible for the safety of the employees in the lab. It is important that the managers cultivate a culture of safety so that they can act as guides, not policemen.

CONTINUOUS IMPROVEMENT

Any laboratories safety program should include continuous improvement. Work practices may need to be tailored to the specific testing performed. If there is an incident, update the workplace practices for the laboratory to address appropriate corrective actions for the issue. Look for near misses and use them as an opportunity for improving work practices. Work with your employer's Environmental Health and Safety group to help minimize risks in the laboratory.

Continuous improvement should not be just a top-down program. All of the laboratory personnel should be involved. Suggestions that come from the workers in the lab are more likely to be easy to implement than programs dictated from management alone. Track incidents to determine if changes are having the intended effect.

CONCLUSION

The risk of injury in the safety test laboratory may seem low, but there are real hazards that do result in injuries and even a risk of death. The proper design of the laboratory along with good training and the proper use of protective equipment can significantly reduce the risk of injuries. The implementation of proper safety can be done cost effectively if designed into a laboratory program. These costs can pay for themselves by eliminating possible higher expenses ranging from noncompliance fines from the Occupational Safety and Health authority, withdrawal of an occupancy permit for unsafe condition, lost time from injured workers and increased workers compensation costs.

ACKNOWLEDGMENT

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Safety Considerations

for Smart Grid Technology Equipment

BY DON GIES

One of the biggest frontiers in electrical engineering in this early part of the 21st century is the development and implementation of smart grid technology.

Development of greener technologies and alternative fuels has become a global economic priority, so smart grid technology has the potential to be one of the next great technological waves. It can jump-start stagnated economies, and can fundamentally change the way power is delivered to consumers of electricity worldwide. The environmental benefits that smart grid technology can deliver are collectively demanded by most of Earth's inhabitants at this time, and the decrease in dependence on fossil fuels and other nonrenewable power sources is also sought through this new technology.

Smart grid technology can be viewed as a merging of power systems, information technology, telecommunications, switchgear, and local power generation, along with other fields that were once electrical technologies of separated industries. As these separate technologies become merged, much of the safety considerations will have to be merged and reconciled as well, particularly at interfaces. In some cases, new insight may have to be given to safety that was not necessary in the past.

This article provides a brief overview of smart-grid technology, and then explores the safety considerations that should be addressed in the design of smart grid technology equipment, particularly in low-voltage AC power applications operating below 1000 V AC. It recognizes smart-grid technology as the merger of power generation, distribution, metering and switching equipment with communication, information technology, and with new user applications. Then, it suggests a modular approach of evaluating the safety of smart-grid technology based on the safety requirements of the individual merged technologies. In addition, examples of some likely smart-grid applications and the safety considerations that would need to be addressed are discussed. It also points out known safety issues with localized electric power generation systems that will be more enabled by smart grid technology.

WHAT IS A SMART GRID?

A smart grid combines the existing electrical infrastructure with digital technologies and advanced applications to provide a much more efficient, reliable and cost effective way to distribute energy. The main function of a smart grid is to manage power consumption in optimal ways, providing the network with more flexibility in case of emergencies. Within the context of smart grids, there are different kinds of supporting technologies, such as smart meters that can help monitor energy consumption and promote more effective distribution. [1]

SMART GRID: WHAT TO EXPECT

Power industry experts look to the smart grid in much the same manner as computer and telecommunications experts looked at the advent of the internet, or "information superhighway" less than a generation ago. It is viewed as the necessary next step in order to modernize the power distribution grids, but there is no single view on what shape or format the smart grid will take.

Without a doubt, the expectation from the power generation and transmission industry is realization of efficiencies. Better sampling of usage and understanding demand patterns should allow the electric utilities to lower the use of power-generation plants, possibly saving millions of dollars by not having to build new plants to meet increases in power demand. Many of these plants burn coal and other fossil fuels that are non-renewable and greenhouse-gas producing sources of energy, and they are increasingly becoming more scarce and expensive.

ALEXANDER GRAHAM BELL VS. THOMAS EDISON

A popular comparison that points out the magnitude of change in the telecommunication industry as opposed to that of the power industry is to hypothetically transport Alexander Graham Bell and Thomas Edison to the 21st century, and allow them to observe the modern forms of the telecommunications and power industries that they helped create. It is said that Alexander Graham Bell would not recognize the components of modern telephony – fiber optics, cell phones, texting, cell towers, PDA's, the internet, etc. – while Thomas Edison would be totally familiar with the modern electrical grid [2]. Thus, with smart grid, there is the potential to modernize and advance the architecture of the power systems technology in the 21st century, as the newer technology has already advanced the telecommunications technology.

Still, Mr. Edison would be just as astonished as Mr. Graham Bell with the present power grid technology as it is today. The century-old power grid is the largest interconnected machine on earth. In the USA, it consists of more than 9,200 electric generating units with more than 1 million megawatts of generating capacity connected to more than 300,000 miles of transmission lines.[2] Mr. Edison would not be familiar with nuclear power plants or photovoltaic cells, as these technologies were developed after his death in 1931.

To celebrate the beginning of the 21st century, the National Academy of Engineering set out to identify the single most important engineering achievement of the 20th century. The Academy compiled a list of twenty accomplishments that have affected virtually everyone in the world. The internet took thirteenth place on this list, "highways" were ranked eleventh, but sitting at the top of the list as the most important engineering achievement of the 20th century was the development of the present electric power grid.

A MODULAR APPROACH TO SMART-GRID SAFETY

Since smart grids will involve the merger of new and familiar technologies, it would make sense to take a modular approach to safety. The best way to approach this new, merged technology is to break it down into its component technologies, then use existing or new standards to evaluate safety issues involving the component technologies. That is, rather than develop a single standard for, say, a new electrical service equipment with intelligence, for a smart meter, it would make sense to continue to use the base product safety standard for meters, but plug-in the additional telecommunications and information technology safety modules. Likewise, other product applicable safety modules, such as requirements for outdoor equipment, can serve as supplements or overlays to the base meter standard in this case.

Hazard-Base Safety Engineering Standard IEC 62368-1

IEC 62368-1 is the new hazard-based safety engineering standard covering audio/video, information and communication technology equipment. This state-of-the-art safety standard classifies energy sources, prescribes safeguards against those energy sources, and provides guidance on the application of, and requirements for those safeguards. It uses the "three-block" model for pain and injury from the energy source to the person, with the middle block covering the safeguarding necessary to prevent or limit the harmful energy to a person. [3]

If we agree to take a modular approach to evaluating the safety of the smart-grid technology equipment, then IEC 62368-1 will be well-suited for providing the plug-in modules for evaluating the safety of the information technology and communication circuitry portion of the smart grid equipment.

For example, if we have a smart meter with integral information technology and telecommunication interfaces, you could use the international or locally-adopted safety standard for power meters, then use IEC 62368-1 to evaluate the type of personnel that would require access to the smart meter ("skilled," "instructed," or "ordinary"), [3] and then determine the level of safeguarding necessary in such areas as isolation from the power equipment, isolation from the telecommunication equipment, construction of the enclosure as a safeguard against accessibility to shock and containment of fire, and so forth.

IEC 60950-1 Continued Use

For the near term, we would expect to use IEC 60950-1 to evaluate smart grid equipment with communication and information technology circuitry for safety, as well as the required protection and separation from other circuits that they require. [4] This would be until IEC 62368-1 becomes adopted by national standards committees.

IEC 60950-22 for Outdoor Information Technology and Communication Circuits

As both IEC 60950-1 and IEC 62368-1 standards reference IEC 60950-22 as a supplemental standard for equipment installed outdoors. We should expect this standard to be used extensively for smart-grid equipment. This standard provides requirements and considerations for enclosure construction, overvoltage category consideration, and pollution degrees (environmental exposure) associated with information technology and communications equipment installed outdoors.[5]

SAFETY OF UTILITY-OWNED SMART-GRID EQUIPMENT

As is the case today, we would expect safety of utility-owned smart-grid equipment located within the power generation or transmission circuits, up to and including the service conductors to the customers' buildings to continue to be evaluated for safety in accordance with basic utility-safety standards or Codes. These standards include IEEE C2, "National Electrical Safety Code," and CSA C22.3, "Canadian Electrical Code, Part III."

EXAMPLES OF SMART-GRID TECHNOLOGY

Automatic Metering Infrastructure (AMI)

Automatic Metering Infrastructure (AMI) is an approach to integrating electrical consumers based upon the development of open standards. It provides utilities with the ability to detect problems on their systems and operate them more efficiently.

AMI enables consumer-friendly efficiency concepts like "Prices to Devices." With this, assuming that energy is priced on what it costs in near real-time, price signals are relayed to "smart" home controllers or end-consumer devices like thermostats, washer/dryers, or refrigerators, typically the major consumers of electricity in the home. The devices, in turn, process the information based on consumers' learned wishes and power accordingly. [2]

Safety Concerns of AMI-Enabled Equipment

We could reasonably expect to see some form of communication interfaces and information technology in some appliances that traditionally would never have had such interfaces (washer/dryers, refrigerators, etc.). With this, we should expect a modular approach in evaluating the safety of these appliances, whereby we evaluate the communication subsystems as we would for communication equipment and information technology equipment (ITE), while the bulk of the appliance is evaluated in accordance with the basic safety standard that normally applies to such appliances. This would mean that either IEC 60950-1 or IEC 62368-1 are used to evaluate the communications and information technology subsystems, and communication links would be classified TNV, limited-power circuits, or the like if metallic, and other non-metallic communication technologies such as optical or wireless would be evaluated accordingly.

EXAMPLE: ELECTRIC VEHICLE POWERING

Email was arguably the "killer app" that most enabled the propagation of high-speed internet. It is not yet known what the smart-grid "killer app" is going to be, but like pre-season predictions of who is going to win the Super Bowl or the World Cup, some think that it is going to be plug-in hybrid electric vehicles (PHEVs) and possibly full electric vehicles (EVs).

As plug-in electric vehicles replace gasoline-only burning vehicles on the market, parking lots will need to be equipped with outdoor charging stations. We would not expect any commercial or government establishments to give away free electricity, so we should expect to see the rise of pay-for-use charging stations, integrating technologies such as electrical metering, switching, information technology, telecommunications, and currency-handling technology.

A pay-for-use charging station might involve the following technologies:

A. An AC-power outlet receptacle to plug in the vehicle for charging;

B. Electric power metering to measure electricity use;

C. Switchgear to switch charging circuits on or off, once enabled by information technology, and provide overcurrent protection or active shutdown in the event of a short-circuit fault in the vehicle's or the charging circuit's circuitry;

D. Information technology equipment to process the sale, timing, and user interface to purchase electrical charge, and to enable/disable the charging switchgear;

E. Telecommunications to communicate the sale and power use back to the electrical power retailer. We might expect to have campus-type communications from the charging station to a central control station, and then have a trunk telecommunication connection to the network;

F. Currency handling technology, which might involve direct input of paper or coin currency, credit-card transactions, smartcard or wireless interface, or, quite possibly, cell-phone enabled transactions; and

G. The equipment would be located outdoors and be installed in a weatherproof housing.

Higher Overvoltage Category for Information Technology in Charging Station

The meter safety standard and switchgear standards may assume that these components are installed in Overvoltage Category IV or III environments, but the information technology equipment standard expect equipment to be installed nominally in Overvoltage Category II environments.

According to IEC 62368-1, Annex I (also IEC 60950-1, Annex Z), electricity meters and communications ITE for remote electricity metering are considered to be examples of Overvoltage Category IV equipment, or equipment that will be connected to the point where the mains supply enters the building. "Power-monitoring equipment" is listed as examples of Category III equipment, or equipment that will be an integral part of the building wiring. In these higher overvoltage categories (IV and III), the value of the mains transient voltages is higher than it would be expected for general indoor-use Category II AC-mains connected appliances. This translates into a need for much greater creepage and clearance isolation distances, as well as much higher electric-strength withstand voltages.

Information technology equipment, on the other hand, is generally utilized in Overvoltage Category II environments, or connected to outlets on branch circuits a safe distance away from the service equipment. Also, as the amount of off-theshelf, commercially-available ITE sub-components increases in the charging station, it becomes more infeasible to simply increase the spacings or the quality of insulation. It may be necessary to use surge protection devices, either integral to the equipment, or externally connected to limit transient voltages from Overvoltage Category III and IV to Overvoltage Category II.

Protection of Communications Circuits

Metallic connections to a telecommunication network would need to be evaluated in accordance with IEC 62368-1 or IEC 60950-1.

Additionally, intra-campus communication conductors, such as those used for intra-system communications or status alarms, will also need to be protected like telecommunication conductors in accordance with the local electrical code or practices. This may mean putting telecommunication protectors—primary (voltage) or secondary (power-cross)-- at each end of a campus-run communication conductor where there exist an exposure to lightning or to accidental contact with electric power conductors.

User Accessibility

Additionally, the charging station terminal where the user pays for and plugs in his electric vehicle needs to be made safe so that unskilled persons may use the station. This would require the highest levels of guarding against intentional access to hazardous voltages.

ENERGY STORAGE SAFETY

Locally-generated electrical energy, such as that from photovoltaic systems, needs to be stored during accumulation cycles for use during peak demand cycles. In most cases, this will be achieved by use of DC storage batteries that invert the electrical energy to AC for local use or for sale back to the electric company. Battery technologies such as lithium ion or valve-regulated lead acid batteries are the most likely present technologies to be used, though advanced batteries such as sodium batteries may be considered.

The size and capacity of these battery storage systems would historically have been found in commercial or industrial installations where only service personnel would have access. Now as part of smart grid and green-power initiatives, you can expect to see such systems in residential locations where anyone might have access.

Safety issues to be considered include:

1. Prevention of access to live parts at high electrical energy levels;
2. Prevention of access to live parts at shock potentials;
3. Ventilation of batteries that outgas explosive gases, such as hydrogen from lead-acid batteries.
4. Containment of batteries capable of producing excessive heat during breakdown or thermal runaway.
5. For outdoor applications, suitably housing the batteries in an outdoor enclosure that, if equipped with lead-acid batteries, is well ventilated in accordance with IEC 60950-22 to prevent the accumulation of explosive gases.

OTHER SAFETY CONCERNS – LOCAL POWER GENERATION

Local power generation systems, such as photovoltaic systems, generators, fuel-cell systems, and the like, for which the smart grid will permit the sale of power back to the utility, involve the following safety concerns:

Synchronization

The frequency of the locally-generated power has to be synchronized with that of the main grid.

Islanding

Islanding is a condition in which a portion of an electric power grid, containing both load and generation, is isolated from the remainder of the electric power grid. When an island is created purposely by the controlling utility—to isolate large sections of the utility grid, for example—it is called an intentional island. Conversely, an unintentional island can be created when a segment of the utility grid containing only customer-owned generation and load is isolated from the utility control.

Normally, the customer-owned generation is required to sense the absence of utility-controlled generation and cease energizing the grid. However, if islanding prevention fails, energized lines within the island present a shock hazard to unsuspecting utility line workers who think the lines are dead.[6]

CONCLUSION

The smart grid promises to bring on a new age of distributing electricity in more efficient and greener ways, while enabling the developing of new ways to efficiently utilize and control power.

In many ways, it will take the form of a merger of power generation, distribution, switching, and metering technology with communications and information technology, along with other applications of electrical energy. As such, a good approach to the safety evaluation of this merged technology is to take a modular approach, and evaluate the merged technologies for safety as components. Furthermore, IEC 62368-1, the new international hazard-based safety engineering standard for audio/video, information and communication technology is well-suited for use in this modular-safety approach.

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Thermal Testing

A Primer

BY HOMI AHMADI

Thermal testing, also known as heat testing, is one of the most critical tests required by the majority of regulatory safety standards in determining the safety of a product. Excessive heat is the number one enemy in any electrical or electronic circuit. Designers are perpetually trying to improve the way to reduce heat or partially cool their products because they are being asked to design products with higher power density into smaller sizes, while operating temperatures of components or devices have not changed greatly over the past few decades. This means that component temperatures must be well controlled to avoid any failure and to increase the reliability of the product.

This article will cover basic fundamentals for thermal measurement and provide some of the methodology used to arrive at accurate measurements.

CHOOSING A THERMOCOUPLE

Accurate temperature measurement of components can be challenging. An important tool used in thermal measurement is the thermocouple, one of the most accurate and repeatable.

Although there are many devices or methods used for measuring temperature, thermocouples are one of the simplest and most commonly used sensors. Having said that, using an infrared camera can quickly help identify any hot spot.

Thermocouples consist of two wires of dissimilar metals, joined near the measurement point or junction (Figure 1). The output is a small DC voltage measured between the two wires. This differential voltage is then converted to a temperature using specially designed equipment such as a chart recorder or data logger.

There are over a dozen different types of thermocouples commonly used in various industries. Most of these have been given internationally recognized letter designator types, such as B, C, D, E, G, J, K, L, M, N, P, R, S, T, and U.

Types J, K, and T are among the most commonly used thermocouple types in the electronic industry due to their ease of use, low cost, and availability. Each thermocouple has its own temperature range and accuracy. For example, the range for type J thermocouples is –210°C to +750ºC, while for type T the range is –100°C to +350ºC; for this reason, they are used for different applications. These temperature ranges are approximate because manufacturers state slightly different

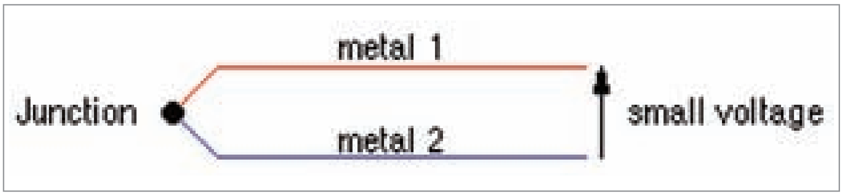

Figure 1: Thermocouple composition

numbers. They also have different color codes. For example, in North America a type J is white and red, but in the rest of the world a type J is typically black and white.

The following is a list of recommendation that must be considered before taking any thermal measurements:

- Choose the thermocouple based on your application — expected temperature, environment, abrasion, oil, etc. For example, if you are measuring temperature of a component in a furnace, it is best to use a type C thermocouple.
- Ensure that the chart recorder or data logger is compatible with the thermocouple wiring. If you are using type K, ensure that the data logger is also set to type K. An incorrect setting will result in measurement errors.
- Visually and physically check the outer jacket for any obvious damage by running the thermocouple wires through your hand and feeling for any possible damage.
- Visually check the tip. The smaller the weld tip, the more accurate the results will be. Figure 2 illustrates two different weld tips.
- A good weld has a small tip with a very small amount of wire stripped, whereas a poor weld shows the opposite.
- Check each thermocouple for its functionality. Valuable time can be wasted if the thermocouple is damaged or is not functioning correctly after it is affixed to a component. One of the easiest methods is to hold each thermocouple between your thumb and index finger for a few seconds. The thermocouple should read your body temperature (37ºC).
- Take care when using thermocouples in a noisy environment or when attaching them to windings of a transformer. Thermocouples typically have no shielding and can be susceptible to EMI noise. Measuring magnetic temperature can be tricky, in particular when measuring switching transformers. The closer the thermocouple tip is to the windings, the more accurate the results are. However, it is best if the thermocouple tip is not touching the magnet wires directly since some of the windings carry high voltages and this may damage the data logger if it comes in contact with the thermocouple. The safest approach is placing the thermocouple tip on insulation tape, which covers the winding. One of the best ways to overcome an electrical noise problem is to use a thermocouple with shielded leads and connectors or to rout it away from noisy circuits.
- Ensure that a thermocouple is calibrated.
- When repairing and welding a thermocouple, it is critical that the weld tip is carefully checked to ensure the weld is secure and that the thermocouple is recalibrated prior to use.
- Avoid using a thermocouple with long lead length. High resistance in the wire may lead to errors. Use an appropriate extension wire and adapter, if longer length is needed.
- Avoid performing thermal testing in an uncontrolled environment, high traffic area, or areas exposed to any air-conditioning. Excessive air movement will impact the final results.

MEASURING TECHNIQUES

The following factors may affect the final results:

- Position of the thermocouple: Critical when measuring temperature on the winding of a choke or transformer. The results are more accurate the closer the thermocouple is placed to the windings.
- Use of excessive glue or cement: Extra volume and mass can assist heat transfer, in particular when temperatures are close to their limits. Use an exact dose of adhesive. When using adhesive, ensure that the adhesive possesses a high thermal conductivity.
- Obstruction of the airstream around the thermocouple wires.
- Equipment voltage: Temperature results usually vary as the input voltage to the equipment changes. For example, some units run hotter at 90 V_{ac}, while others may run hotter at 264 V_{ac}. It is recommended that the input voltage source is as stable as practical. Any small variations in input voltage will result in variations in temperature. Ensure voltage tolerances are taken into consideration, as each safety standard uses different tolerance percentages.
- Equipment load: Equipment load plays a crucial role in the final thermal results. In the majority of the cases, the higher the load, the higher the temperature on individual

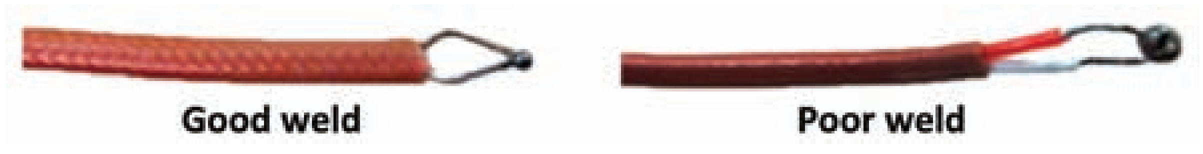

Figure 2: Good weld vs. poor weld

components. Most product safety standards require the equipment under test (EUT) to be loaded to its maximum normal operating load during the heating test.

- Local ambient conditions: As mentioned before, it is important that the thermal test is performed in a controlled environment. If there is excessive air movement, then the final results cannot be considered as accurate. One of the simplest solutions is to conduct tests in a corner of the lab where there is less traffic and there is no air-conditioning blowing cold air directly on the EUT.
- Stabilization or thermal equilibrium: In certain instances, engineers record the final data after a certain time, such as after one or two hours of operation. Since different products behave differently and reach their maximum temperature at different times, it is important to record the final data ONLY after the EUT has reached thermal equilibrium.

It would be helpful to explain what thermal stability is. A temperature is determined to be constant or stabilized when the graph on a chart recorder or data logger is shown to be flat without any temperature rise and shows three successive readings are within 1°C of each other when taken at 30-minute intervals. Unfortunately, there is no harmonized standard that defines thermal stability and each standard has its own definition. The most important point to bear in mind is that temperature rise is always an exponential curve. Therefore the easiest method is to use a chart recorder or data logger simply because the curve as temperature becomes stable is readily visible.

Figures 3 and 4 illustrate respectively measurements where thermal equilibrium has been achieved and where complete thermal stability has not been achieved.

DOCUMENTING THE RESULTS

Before publishing the final results, take the following steps:

- Review the raw data to ensure that nothing unusual stands out. Use engineering judgment. For example if the body temperature of an metallic oxide varistor (MOV) is lower than that of the printed circuit board (PCB) on which it is mounted, the data should be checked again.

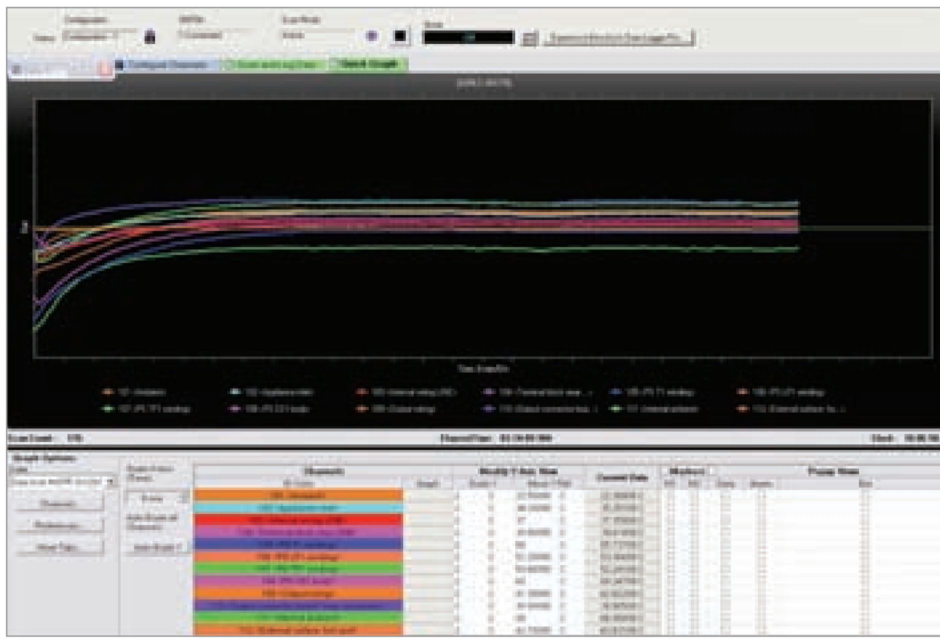

Figure 3: Example showing thermally stable measurements

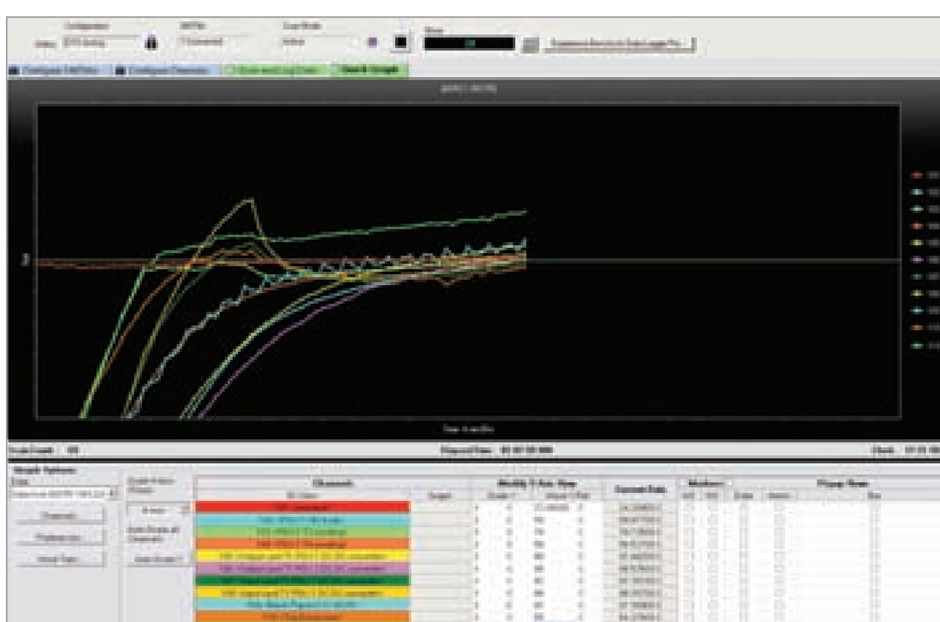

Figure 4: Example showing unstable temperatures

- Compare the test data to previous test data that has been done on the same product to find out if they all follow similar patterns.
- For almost each measurement of data, there is a limit to which the data is compared. These limits can be derived from verifiable sources such as product safety standards, component manufacturer data sheets, internal procedures, etc.

Tables 1 and 2, from IEC 60950-1, show the limits for some components.

- Prepare the final report by tabulating the data, correcting it to the corresponding T_{mra} (manufacturer recommended ambient), and include the limits for each component where possible.
- Prepare a complete report and ensure that all details (such as input voltage, load condition, amount and direction of any forced airflow, duration of test, and any other parameters that may be beneficial to the reader) are clearly documented.

COMPUTING TEMPERATURES

Typically manufacturers market their products much higher than 25ºC. Based on the manufacturer's recommended ambient temperature, also known as T_{mra}, either the limits or the measured temperatures must be corrected accordingly.

The formula below shows how to make the adjustment:

$T < T_{max} + T_{amb} - T_{ma}$

Part	Maximum temperature (T_{max}) °C
Insulation, including winding insulation: – of Class 105 material (A) – of Class 120 material (E) – of Class 130 material (B) – of Class 155 material (F) – of Class 180 material (H) – of Class 200 material – of Class 220 material – of Class 250 material	 100 [a b c] 115 [a b c] 120 [a b c] 140 [a b c] 165 [a b c] 180 [a b] 200 [a b] 225 [a b]
Rubber or PVC insulation of internal and external wiring, including power supply cords: – without temperature marking – with temperature marking	75 [d] Temperature marking
Other thermoplastic insulation	See e
Terminals, including earthing terminals for external earthing conductors of STATIONARY EQUIPMENT, unless provided with a NON-DETACHABLE POWER SUPPLY CORD	85
Parts in contact with a flammable liquid	See 4.3.12
Components	See 1.5.1

a If the temperature of a winding is determined by thermocouples, these values are reduced by 10 °C, except in the case of
– a motor, or
– a winding with embedded thermocouples.
b For each material, account shall be taken of the data for that material to determine the appropriate maximum temperature.
c The designations A to H, formerly assigned in IEC 60085 to thermal classes 105 to 180, are given in parentheses.
d If there is no marking on the wire, the marking on the wire spool or the temperature rating assigned by the wire manufacturer is considered acceptable.
e It is not possible to specify maximum permitted temperatures for thermoplastic materials, due to their wide variety. These shall pass the tests specified in 4.5.5.

Table 1: Temperature, limits, materials, and components

Where:

T = measured temperature

T_{max} = maximum limit allowed

T_{amb} = local ambient

T_{ma} = maximum ambient temp permitted by the manufacturer.

Example

An electrolytic capacitor is measured to be 63°C at a room ambient of 23°C. The capacitor is rated for 105°C and the manufacturer needs to qualify this product to 50°C operation. Does this component meet the required limits?

Using the above formula:

63 < 105+23-50

63 < 78

The component meets its permitted limit.

If the T_{mra} is higher than 25ºC, then the manufacturer has the choice of:

- Testing it on the bench in the lab and then mathematically correcting the temperatures as shown using the formula above
- Testing the product in an elevated environment, such as a heating oven

An oven is used when there is a specific request or the lab environment is unstable. When testing in an oven, accurately document the oven air temperature, level of oven air circulation, oven humidity, and sample placement. Additionally, an oven is used when the product is temperature controlled as stated in Clause 1.4.12.2 of IEC 60950-1, 2nd Ed. Most test agencies and standards allow both methods.

If the T_{mra} is 50°C or less, it is recommended that the testing is done on the bench. If the T_{mra} is higher than 50°C, then it is recommended that the testing is done in an oven.

Parts in OPERATOR ACCESS ARE AS	Maximum temperature (T_{max}) °C		
	Metal	Glass, porcelain and vitreous material	Plastic and rubber [b]
Handles, knobs, grips, etc., held or touched for short periods only	60	70	85
Handles, knobs, grips, etc., continuously held in normal use	55	65	75x
External surfaces of equipment that may be touched [a]	70	80	95
Parts inside the equipment that may be touched [c]	70	80	95

a Temperatures up to 100 °C are permitted on the following parts:
- areas on the external surface of equipment that have no dimension exceeding 50mm, and that are not likely to be touched in normal use; and
- a part of equipment requiring heat for the intended function (for example, a document laminator), provided that this condition is obvious to the USER. A warning shall be marked on the equipment in a prominent position adjacent to the hot part.

The warning shall be either
- the symbol (IEC 60417-5041 (DB:2002-10)):
- or the following or similar wording

WARNING
HOT SURFACE DO NOT TOUCH

b For each material, account shall be taken of the data for that material to determine the appropriate maximum temperature.

c Temperatures exceeding the limits are permitted provided that the following conditions are met:
- unintentional contact with such a part is unlikely; and
- the part has a marking indicating that this part is hot. It is permitted to use the following symbol (IEC 60417-5041 (DB:2002-10)) to provide this information.

Table 2: Touch temperature limits

Testing in an oven is typically exponential, where testing on the bench is typically linear when mathematically corrected.

Table 3 shows the temperature results of an information technology equipment (ITE) product that was tested both on a bench as well as in an oven.

Looking at Table 3, it is clear that testing on the bench and then mathematically correcting the values to the manufacturer's stated T_{mra} is much harsher than when it is tested in a heating oven that was set to T_{mra}.

TC Locations	Bench °C	Bench Adjusted to 50°C	Oven at 50°C
T3 windings	78.48	105.61	92.57
L24 winding	99.16	126.29	112.1
PCB next to Q9	91.36	118.73	104.56
CR32	63.84	90.97	77.73
PCB next to U19	50.02	77.15	65.59
Q40 body	77.40	104.53	91.19
Ambient	22.87		48.98

Table 3: Bench vs. Oven testing

DETERMINING LINEAR FEET PER MINUTE

Another issue that designers sometimes face relating to thermal testing is the terminology used in some of power supply specifications. Some power supply manufacturers use the term cubic feet per minute (CFM), while others may use linear feet per minute (LFM) when a supply requires forced air cooling. CFM is a measurement of volume while LFM is a measurement of velocity. Most fan manufacturers use CFM, while board designers prefer to use LFM as this makes calculating thermal derating curve or power dissipation much easier.

LFM is equivalent to CFM divided by the cross-sectional area of interest.

The larger the cross-sectional area, the smaller the LFM for a given CFM, as shown in the formula below:

LFM = CFM/area (ft^2)
Where:

area is the cross-sectional area of the opening which typically happens to be the fan box size in square feet.

if the fan is square, then the cross-sectional area is L x W.

if the fan is circular, then the cross-sectional area is πr^2.

Example:

A fan measures 40 x 40 mm and has a CFM of 5.2, then the LFM is calculated as:

1 mm = 0.00328 ft.

40 mm = 0.1312 ft.

40 mm^2 = 0.0172 ft^2

LFM = 5.2/0.0172

LFM = 302

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Applied Safety Science and Engineering Techniques (ASSET™)

Taking HBSE to the Next Level

BY THOMAS LANZISERO

Hazard Based Safety Engineering (HBSE) principles have been used to better understand product safety and to help guide the design and evaluation of appropriate safegards through analysis of sources, causes and mechanisms of harm. UL Applied Safety Science and Engineering Techniques (ASSET™) takes HBSE to the next level. ASSET leverages the strength of HBSE principles by expanding and integrating them with other established safety science and engineering techniques, including elements of risk management, systems and reliability engineering, functional safety and human factors. This paper outlines the expansion and integration of these principles and techniques, and demonstrates the potential of taking HBSE to the next level.

ASSET addresses diverse forms of harm, hazardous sources and objects of harm (persons, property, environment, critical operations), across a broad range of products, systems, services and applications, based on safety science. An asset in any organization is an item of value, a resource that provides advantage, such as a product realization design process that achieves safety by design. The design and evaluation of safety requires a systematic, methodical process. The effective use of a complete set of suitable, consistent design and evaluation techniques can help demonstrate that reasonable care and due diligence was exercised in the safety of a design.

The HBSE concepts initially conceived by engineers at HP/Agilent targeted typical types of hazards and forms of injury involving electronics products, such as information technology and office equipment. The HBSE concepts and tools have been further developed and applied with the support of research engineers at Underwriters Laboratories. UL University has been serving as the principal instructional organization for HBSE workshops. UL uses HBSE and applied safety science and engineering techniques in many facets of its work, such as research, development and interpretation of standards, and risk assessment with hazard and failure analysis of new and emerging products, applications and technologies. Applied safety science and engineering techniques will be briefly introduced in the context of safety and risk, and outlined in the context of other technical and managerial processes.

SAFETY

Safety and protection address the risk of harm. Safety has many meanings, applications, levels and contexts. Generally speaking, we can consider safety as freedom from unacceptable risk of harm. (IEC/ISO Guide 51). But let's consider the qualifiers in this statement.

Safety and protection address the risk of harm. Harm can include unwanted effects or consequences, including injury or damage to health of persons (or animals including livestock and pets), damage to property or the environment, or interruption in essential commercial operations.

Harm can include unwanted effects or consequences, including injury or damage to health of persons (or animals including livestock and pets), damage to property or the environment, or interruption in essential commercial operations. This harm may be the result of a variety of factors, independently or in combination or sequence, involving hazardous situations and circumstances. Risk of harm is based on probability and severity, that is, the likelihood of harm occurring and the severity of its consequences if it occurs.

Unacceptable risk of harm is a level that is not tolerated. The degree of tolerance varies in accordance with many factors, including specific applications, situations and circumstances of product use, misuse and exposure. Risk attitudes and appetites vary among individuals, companies, industries, cultures, etc. Levels of unacceptable risk may be defined, for example, by regulatory bodies, authorities having jurisdiction, standards development bodies, etc., with input from others involved or affected.

Freedom from unacceptable risk of harm is a beneficial condition. But like many other freedoms that we enjoy, this freedom also comes at a cost. To achieve safety is no small task. It requires comprehensive, systematic review of all potential harm from hazards, and the prioritization of mitigating safeguards throughout the entire product lifecycle, considering all manners of exposure. Safety is relative, posing a challenge in product realization to balance with other design requirements, factors and constraints. This balance may be addressed, for example, by risk-benefit analysis, cost-benefit analysis or other techniques.

Safety is not without any risk, but with risk reduced to an acceptable level – by design, analysis and validation, including evaluation and testing for certification. It is said that safety is no accident. It is the practical manifestation of suitable design concepts, applied consciously and conscientiously.

Risk Management

There are a variety of means to assess, reduce and manage risk of harm. Risk analysis involves hazard identification and risk estimation in terms of likelihood of the occurrence of harm and the severity of its consequences should it occur. Risk evaluation involves judgment of acceptability of risk. This leads to analysis of options to accept or reduce this risk, and then maintain or control it at an acceptable level. In some cases, this risk level may be considered to be As Low As Reasonably Practicable (ALARP), typically used in risk-benefit analysis for medical devices having health benefits to balance the risk of harm

But risk is not necessarily a simple or straightforward combination of probability and severity rankings. Weighting factors may be applied to rankings, and scales may be nonlinear or contain discontinuities. Other factors may also need consideration, such as frequency, exposure, vulnerability, etc. In estimating and evaluating risk, it is important to consider that when the severity of consequences is very high (serious harm, death), then the likelihood must be demonstrated or known to be reliably low. This approach would be more conservative (safe) than an initial assumption of very low probabilities, resulting in trivializing (even unintentionally) the importance of potentially severe consequences.

Risk Management Publications

Many publications address various aspects and applications of risk management, including international guides, standards and series published by organizations such as the IEC (International Electrotechnical Commission) and ISO (International Standardization Organization), ranging from general-use to industry-, product-, hazard-, harm- and safeguard-specific categories. Basic references, some with very recent publications, include ISO IEC Guide 51 (Safety aspects), ISO 31000 (Risk management — Principles and guidelines), IEC/ISO 31010 (Risk management – Risk assessment techniques), IEC Guide 116, Guidelines for safety related risk assessment and risk reduction for low voltage equipment, IEC 60300-3-9 (Dependability management), and Risk Assessment Guidelines for Consumer Products (in Official Journal of the European Union, referencing GPSD, General Product Safety Directive and RAPEX, Community Rapid Information System).

Additional IEC and/or ISO Guides cover more specialized aspects such as terminology (73), vulnerability (50, 71), applications (37, 63, 78, 110, 112), environment (64, 106, 114), and procedural matters (2, 75, 104, 108).

Many publications address various aspects and applications of risk management, including international guides, standards and series published by organizations such as the IEC (International Electrotechnical Commission) and ISO (International Standardization Organization).

Certain industries, such as medical devices and machinery have developed a tiered structure of risk publications. Publications covering medical devices range from guides on safety aspects (ISO Guide 51) and drafting of safety standards (ISO/IEC Guide 63) to risk management for medical devices (EN ISO 14971), quality management systems for regulatory purposes (ISO 13485), to more specific standards on basic safety and essential performance (IEC 60601-1), followed by a series of collateral standards (IEC 60601-1-1 to IEC 60601-112), particular standards (IEC 60601-2-1 to IEC 60601-2-54) and essential performance requirements (IEC 60601-3 (-1)). Likewise, publications covering machinery range from guides on safety aspects (ISO Guide 51) and drafting of safety standards (ISO Guide 78) to general standards on risk assessment principles (EN/ISO 14121-1), practical guidance and examples (-2), to more specific standards on design concepts with terminology, methodology (EN/ISO 12100-1) and technical principles (-2), and electrical equipment of machines (EN 60204-1).

ASSET and Risk Management

ASSET integrates the current IEC/ISO body of knowledge on risk management, and addresses specific aspects including appropriate risk and hazard identification, risk reduction and risk control. For example, guidelines are provided for a suitable assessment of the scope of the analysis, including general characteristics, intended use and users, environment, installation, operation, maintenance, repair, shipping, storage, and reasonably foreseeable unintended use and misuse conditions. Then for hazard identification, additional steps help identify sources and possible conditions for harm. Risk estimation is supplemented with guidance to estimate and express risk. Risk evaluation is aided by steps to define and apply tolerable risk criteria for decisions. Risk reduction is guided by steps to analyze protective measures that reduce and/or control risk via safeguard attributes. Reassessment of residual risk is supplemented by steps to monitor and apply field data.

Strategies are presented to identify, prioritize and validate appropriate safeguards that are suited to any product, including usage scenarios and exposure conditions. Such strategies help identify essential safeguard characteristics: those safety-critical functions relied upon under all conditions, including duress, throughout the product life. Relevant analysis techniques include Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA), which address failures and other conditions that may lead to system faults, as well as the need for, and the effects of, suitable protective mechanisms.

Safety Engineering Management Processes

Technical processes include the expansion and adaptation of HBSE, hazard analysis and risk assessment concepts, as well as application of techniques such as FTA and FMEA. Managerial processes include risk management, but the more overarching common element is "management" itself. Safety engineering management not only involves risk management, but also asset-, enterprise-, quality systems- (incl. quality assurance and continuous improvement), process- (design, mfg), document-, decision-, systems engineering- and system safety-, product safety-, project- and project risk-, design-, concurrent engineering-, design review-, configuration-, change control-, supply chain-, dependability-, life cycle model-, data(records), information security-, knowledge-, learning-, incident/recall- and disaster/emergency- management. As for risk management, these additional safety engineering management aspects are also addressed in many IEC, ISO and other publications. Document references are available upon request.

Safety Strategy

The strategy to meet safety objectives begins with applied safety science and engineering techniques. This helps to identify and prioritize research, and apply these findings to develop safety requirements and test methodologies that are appropriate, proactive, focused and consistent. This can then lead to safety attributes that are properly identified, validated and controlled for all scenarios, conditions, and lifecycle stages, both up and down the supply chain. The result is a demonstrated degree of safety and improvement.

Hazard Based Requirements

Hazard-based safety standards can offer clear safety objectives and various means to meet them. A hazard-based approach serves to reduce risk of harm by addressing each hazard. This approach would determine which undesirable effects are to be avoided, the susceptibility to them, their conditions and causes, and appropriate protection against them. A hazard-based standard would identify the objectives of protecting against each specific undesirable effect, and directly relate them to appropriate protection requirements and limits. HBSE principles have also formed the foundation of hazard-based requirements in product standards such as IEC 62368-1, Audio/video, information and communication technology equipment – Part 1: Safety requirements.

ASSET EXPANSION OF HBSE CONCEPTS AND TOOLS

ASSET expands the basic HBSE concepts and analysis tools in ways that include the following, as shown in Figure 1.

HBSE Premise

The HBSE Premise for Injury is a 3-block model based on energy transfer, which outlines the 1) hazardous source and 2) transfer mechanism to 3) a body/part that is subject to injury. Injury can occur when the magnitude and duration of energy transfer exceeds the body/part susceptibility, or its inability to withstand it.

Examples include mechanical forms of energy that may cause various types of physical injury; thermal energy (heat) that may cause skin burn injury; electrical energy that may cause "electric shock" or unwanted physiological (including lethal) effects; and electrically caused fire that may cause injury and property damage. This model can forewarn of injury if its elements can be quantified, in terms of the characteristics of the energy source and rate and degree of transfer (delivered and received), and the inability of a body/part to withstand it (susceptibility).

However, this simple model can be expanded in a variety of ways, adapted to address other types of hazards, transfers and harm. For example, the hazardous source (1) can involve other forms of energy, including acoustic noise, pressure (sonic/ultrasonic/fluid/gas), explosion/implosion, arc flash/blast, radiation (visible, UV, IR, ionizing (gamma)/non-ionizing (laser)), vibration, fields (electric/magnetic/electromagnetic), unintended motion or activation, as well as potential energy (suspended masses, support failures) or stored energy (springs, capacitors) that may be converted to other forms.

In addition, the hazardous source (1) can also be in the form of matter. This could include an object (person contributes to transfer), involving a sharp edge (laceration) or small part (choking) or long part (strangulation), where other factors of the harm mechanism need also be considered. This could also include a harmful substance, such as chemical (toxic/carcinogenic) or biological (bacteria) material. Recall the RoHS (Restriction of Hazardous Substances) directive that curtails the use of materials such as lead, mercury, cadmium, hexavalent chromium, PBB and PBDE to infinitesimal levels (parts per million).

The transfer mechanism (2) can cause harm in a direction to the body (e.g., applied force), as well as away from it (e.g., extracted heat), or even involve a reduction or restriction of transfer (energy or substance) that is needed to maintain health (e.g., air restriction due to small-part choking hazard).

And in addition to injury to persons (3), other forms and objects of harm can be addressed. Such harm may also involve damage to health or welfare of persons, injury to animals (livestock, pets), and damage to property, the environment or essential commercial operations.

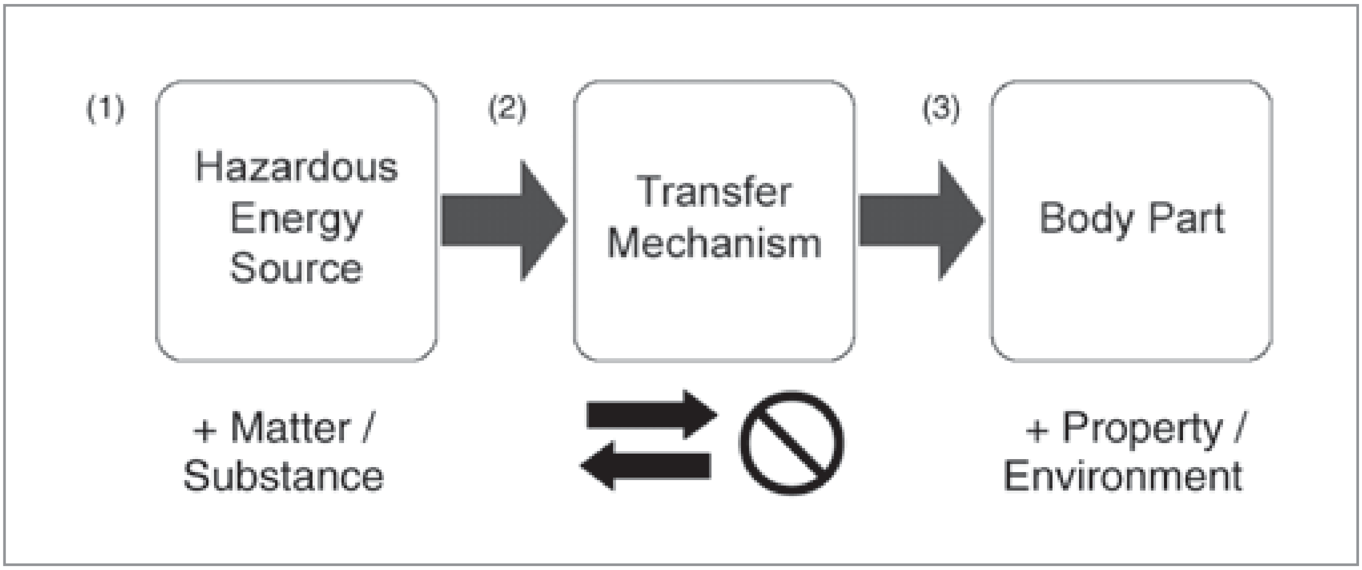

Figure 1: HBSE Premise, 3-block energy transfer model for injury, expanded

Other factors must also be considered. For example regarding environmental harm, lifecycle issues of electrical and electronic products raise additional safety concerns. With concern for PBTs (Persistent Bioaccumulative Toxins), is the hazard persistent, taking a relatively long time to break down in the environment? Is it bioaccumulative, whereby substances collect in living organisms and ultimately end up in the food chain and persons? Is it toxic, with known potential for harm, whether acute (immediate) or chronic (longer-term)? By what means is it transferred, and in what amounts and durations, and to what degree?

Other functional aspects such as incorrect outputs can also lead to harm, involving energy or substance, due to hardware, software or human interface factors, resulting from incorrect control, timing, duration, sequence, etc. These aspects are more closely associated with functional safety, addressed separately.

HBSE Process

The HBSE Process is a flow diagram that considers all sources (hazardous energy) associated with a product, how they may cause harm by transfer, and how this transfer can be reduced to protect against injury. It helps us to analyze specific protective mechanisms (safeguards) having features and properties that are needed to protect against specific harm mechanisms.

This simple model can also be expanded in a variety of ways. For the first HBSE Process step (1), "Identify Energy Source", consideration is needed for all sources (energy/ substance) that are supplied to, contained within, converted by, used by or associated with the product.

For the next step (2), "Is Source Hazardous", consideration is needed for whether the source is capable of causing harm. These steps need to conducted for each type of source, transfer means/mechanism, potential for harm and entity subject to harm. Is the source hazardous with respect to the product function, application, environment, uses, users and others involved, exposed, having access, or otherwise affected?

Is this an unacceptable risk of harm? How is an acceptable level of risk determined? What factors may this depend on (use, users, environment, values, etc.)? What conditions make the source hazardous or its transfer harmful? Can this occur in normal operation and intended, normal use? Or does it require an abnormal or unintended condition? Must other unwanted or fault conditions have occurred in the past or exist in the present?

Are these conditions of omission (inaction) or commission (action/ reaction)? Do they involve hardware, software and external influences (environment, human interaction and error, etc.)? Are these conditions reasonably foreseeable? It's been said that all conditions are foreseeable (which may not necessarily require action), but following an incident a jury may decide what is reasonable (what actions should have been taken).

The product may have been evaluated to perform all design functions as intended (do what intended). But have all reasonably foreseeable conditions been anticipated? Has the product been evaluated to suitably and safely respond to all these conditions, combinations and sequences and at least fail-safe (NOT do what NOT intended)? Has this performance been validated by test? Have the safeguards, and their specific properties, relied on for this performance been evaluated and controlled?

For the next step (3), "Identify Means by which Energy can be Transferred to a Body Part", consideration is also needed for direction and/or restriction of transfer, whether to, from, or blocked (if needed) from the person (body part) or other object of harm (property, environment, etc.).

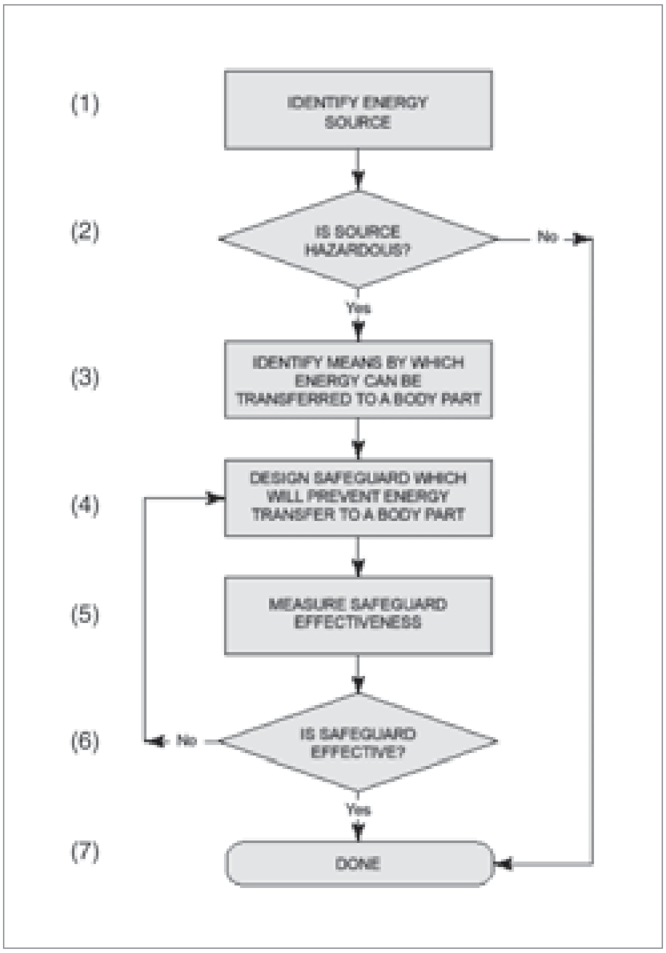

Figure 2: HBSE Process with expansion notes

For the next step (4), "Design Safeguard Which Will Prevent Energy Transfer to a Body Part", consideration is also needed for preventive safeguards that reduce, control or eliminate the source (total amount), as well as mitigating safeguards that reduce, control or eliminate the transfer (transferred rate, duration and amount). The hierarchy of protection should be to first eliminate the hazard (design it out), then guard against the hazard (reduce the source and then the transfer), then warn about the hazard (relying on personal responsibility and other factors for avoidance). In some cases it may also be possible to reduce susceptibility to a hazard by increasing the resistance to the source, such as through material properties including resistance to ignition.

For the next steps (5), "Measure Safeguard Effectiveness" and (6) "Is Safeguard Effective", much additional consideration is needed to properly understand and apply this "effectiveness" measure, which involves safeguard attributes. Which specific properties of safeguards are relied upon for each protective function? Under what conditions must they function effectively? What conditions may tend to degrade this performance or render it ineffective? How well do these attributes hold up under each of these conditions, including combinations and sequences? Just as in evaluating risk, when the severity of consequences is high (i.e., safeguard failure), the likelihood must be demonstrated or known to be reliably low.

Safeguards attributes are properties of protective features and mechanisms, which need to be specifically identified, evaluated and validation tested under all reasonably anticipated conditions, and controlled in design and manufacturing. These attributes can be summarized in the descriptive term DURESS (Durability, Usability, Reliability, Efficacy, Suitability, Scalability), which helps describe the needed characteristics:

Durability – protective characteristics should be able to withstand, and not be adversely affected by conditions, circumstances and scenarios of use (reasonably foreseeable use, unintended use, misuse or abuse)

Usability – protection should function as needed, without interfering with normal, intended product functions (so as not to invite defeating of safeguards)

Reliability – protection should maintain its essential performance throughout its entire design life, in all conditions and stages of the product lifecycle (cradle-to-grave)

Efficacy – protection should be able to effectively perform the needed safety function, without introducing or increasing other hazards (fix one problem but create another)

Suitability – protection should be provided to a degree appropriate for the application, based on the level of risk with a suitable safety factor that demonstrates the degree to which tested performance limits exceed minimum thresholds of harm

Scalability – protection should perform as needed in the intended scale of use, properly interacting with other materials, components, systems and environments (small-scale properties appropriate for large-scale applications and conditions)

HBSE Fault Tree for Injury

Fault Tree Analysis (FTA), a deductive, graphical, top-down analytical method in which the top event is a fault, such as harm or other undesirable event. It outlines the necessary and sufficient conditions and logical relationships for this harm to occur, in order to determine the most likely contributors (root causes on critical paths) and the most effective safeguard strategies.

The HBSE fault tree for injury outlines conditions leading to the injury top event, with initial necessary and sufficient conditions of hazardous energy and exposure of (for transfer to) a susceptible body part. This fault tree model can be expanded to include other types of hazards and harm. It can also depict the order of priority for safeguards, to eliminate, guard or warn about the hazard. Such FTA models have been successfully used in analysis of fire scenarios, including those caused by lithium ion batteries.

FTA AND FMEA/FMECA

To complement the deductive, top-down FTA, one can use an inductive, bottom-up analysis method such as Failure Modes and Effects Analysis (FMEA) or Failure Modes and Effects Criticality Analysis (FMECA), which more directly considers the effect of severity and risk rankings. This method begins at the "bottom", with individual items (components, materials) and their functions (in each operating mode). Failure modes, effects, severities, likelihoods and other factors are determined, and then potential causes, recommended actions, and resulting effects are analyzed methodically. Integrated FTA/FMECA techniques have also been successfully applied to fire risk involving lithium ion batteries, as we presented at the latest NASA Aerospace Battery Workshop (2009).

SYSTEMS ENGINEERING

Elements of the systems engineering approach address scope and context, from concept through all product lifecycle stages (cradle-to-grave), from design through prototyping, manufacturing, assembly, packaging, transport, storage, installation, commissioning, operation, maintenance, repair, decommissioning, reuse to disposal.

Specific properties of materials and components, including hardware, software and human elements, need to be compatible with the needs, influences and interfaces of subsystems and the overall system, including external systems and the environment (micro and macro). Functions, characteristics and properties need to be considered for materials, components, devices, circuits, subsystems, systems and processes, as contributing to harm or to protection.

RELIABILITY ENGINEERING

Reliability engineering elements address the criticality of safety-critical functions and features, and the conditions under which they must continue to perform effectively. Reliability approaches such as probability of failure, circuit redundancy and fail-safe modes are also used in techniques such as FTA and FMEA, and addressed by a number of related disciplines, including system safety and dependability management.

FUNCTIONAL SAFETY

Functional safety is a special field that specifically addresses electrical, electronic and programmable systems. Similar to other types of safeguards, reliance is placed on specific functions or characteristics of a product, requiring certain attributes. But a safeguard in functional safety is considered to be the essential performance of hardware and software controls that manage safety-critical functions. Some functional safety aspects may be directly protective by design (life safety). Functional safety aspects in other applications address functions for which failure may lead to increased risk of harm (immediate or imminent), loss of a required level of protection, or other reduced ability to protect against harm. In "single-fault" analysis, the conditions that rely upon protective mechanisms to operate should be considered as given conditions, and any failure or inadequacy of this protection would be considered as the fault condition.

HUMAN FACTORS

Elements of human factors address many aspects, including anthropometry, physiological responses and susceptibility to energy and substance transfer, behavior (product use, misuse, abuse or hazard avoidance), human error, interaction, and other human characteristics including performance, limitations, etc. related to aspects of a product or system, such as design, manufacturing, operation, maintenance, etc.

SUMMARY

ASSET integrates these elements to leverage the strengths of HBSE, risk management, and other techniques, to optimize the value of our resources and assets: our individual and

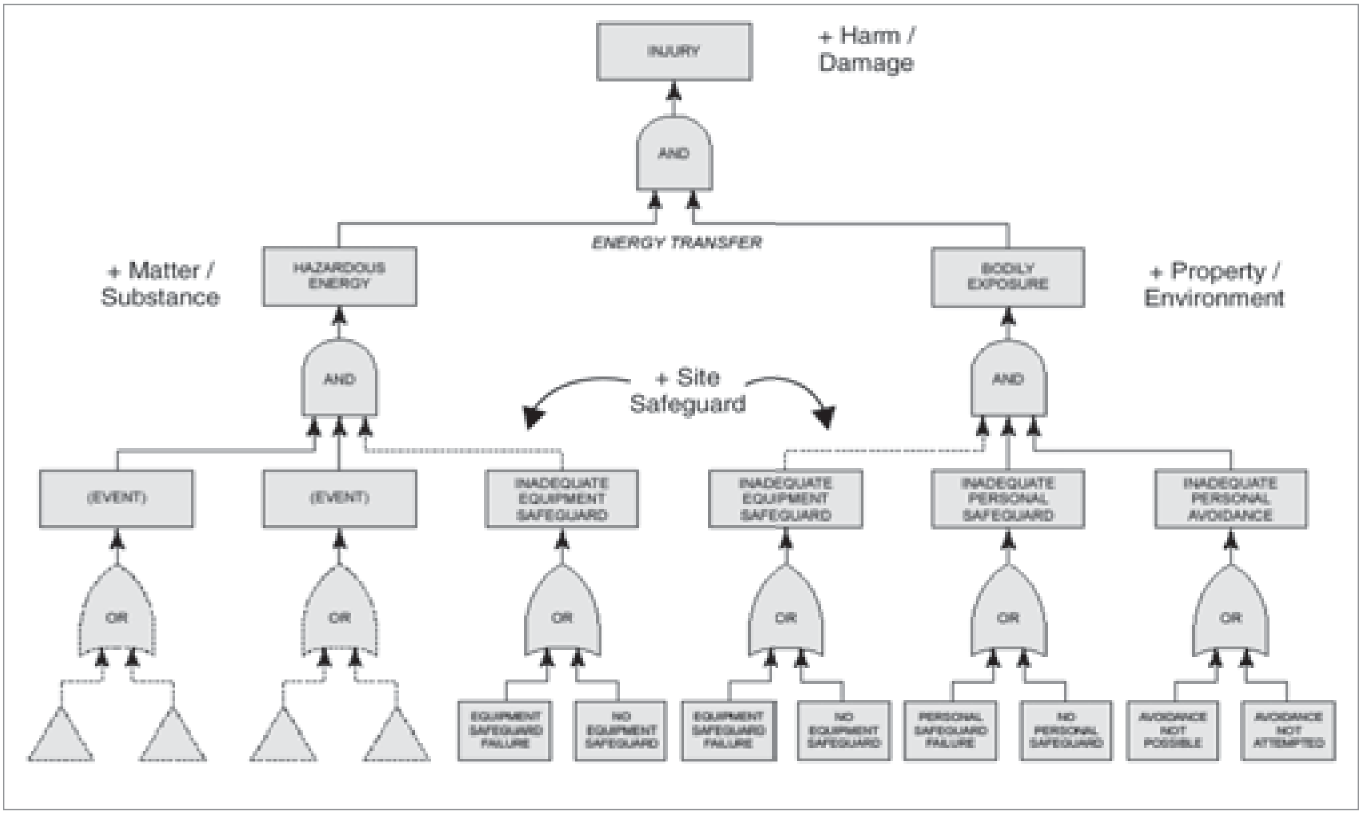

Figure 3: HBSE Fault Tree for Injury, expanded

collective safety knowledge, experience and expertise. The application of safety science and engineering techniques to any hazard is based on examining the types and mechanisms of harm in order to consider appropriate mechanisms for protection. This analysis includes the conditions and circumstances that must be present, first for harm to occur, and then for protection against it. It's a basic but robust approach, in which simple tools can be applied, with appropriate subject matter expertise, to simple or complex scenarios in a consistent, repeatable manner, an asset to any organization.

"The great liability of the engineer compared to men of other professions is that his works are out in the open where all can see them. His acts, step by step, are in hard substance. He cannot bury his mistakes in the grave like the doctors. He cannot argue them into thin air or blame the judge like the lawyers. He cannot, like the architects, cover his failures with trees and vines. He cannot, like the politicians, screen his shortcomings by blaming his opponents and hope the people will forget. The engineer simply cannot deny he did it. If his works do not work, he is damned." - Herbert Hoover (1874 - 1964).

ACKNOWLEDGMENT

The author wishes to acknowledge the HP/Agilent authors of the initial HBSE concepts, including R. Nute, R. Corson, J. Barrick and D. Adams, as well as UL Research, Engineering and UL University staff including R. Davidson and D. Bejnarowicz for their valuable technical contributions toward this material.

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***Thomas Lanzisero** is a Sr. Research Engineer and Distinguished Member of Technical Staff at UL LLC (Underwriters Laboratories, Melville, NY) with nearly 30 years of applied practice in safety engineering. He is a registered Professional Engineer (P.E.) and principal instructor and practitioner of Hazard Based Safety Engineering (HBSE). He has led development of Applied Safety Science and Engineering Techniques (ASSET™), including the ASSET Safety Management Process for informed decisions to achieve, maintain and continuously improve safety as a design objective. This work has recently been recognized with a 2011 IEEE Region 1 Award for Technological Innovation.*

This and related hazard analysis and risk assessment work has been extensively published and presented, including keynote presentation on the safety of consumer electronics into the future at the 2012 International Conference on Consumer Electronics (ICCE) by the IEEE CES, 2012 Advanced Product Safety Management course at St. Louis University, 2010 and 2011 International Symposium on Product Compliance Engineering by the IEEE Product Safety Engineering Society, 2011 IEEE Chicago Argonne National Laboratories Technical Conference, International Consumer Product Health and Safety Organization (ICPHSO 2011), Association of Southeast Asian Nations (ASEAN), Asia Pacific Economic Cooperation - Joint Regulatory Advisory Council (APEC JRAC Risk Assessment Workshop), American Society of Safety Engineers (ASSE) and NASA (2009 NASA Aerospace Battery Workshop).

An IEEE Senior Member, Tom is Founding Chair of the Long Island, NY Chapter of the IEEE Product Safety Engineering Society (PSES) and Vice Chair of the IEEE Risk Assessment Technical Committee (RATC). He serves as technical expert in committees for electric shock protection and risk management, including US National Committee Technical Advisory Groups (USNC TAGs), the International Electrotechnical Commission (IEC TC64 MT4) and the International Organization for Standardization (ISO 31000 / ANSI Z690). He can be contacted at +1.631.546.2464 or thomas.p.lanzisero@us.ul.com.

ASSET is trademark of UL LLC

ASSET and HBSE workshops are available through UL.

Product Safety

Applied Safety Science and Engineering Techniques (ASSET™)

The Evolution of Hazard Based Safety Engineering into the Framework of a Safety Management Process

BY THOMAS LANZISERO

Applied Safety Science and Engineering Techniques (ASSET) merge hazard based safety engineering and safety science principles in an overall framework of a safety management process to achieve, maintain and continuously improve safety. The ASSET process has been synthesized from current, industry-standard risk assessment and risk management guidelines, including recent ISO, IEC and ANSI publications.

Basic relationships are explored among hazards, exposure and harm to persons, property and the environment. Various potential approaches to protect against harm are then explored in the framework of safety management, systems engineering, quality management systems, concurrent engineering, human factors and other relevant principles.

This ASSET Safety Management process has potential application in virtually any industry and product segment to support informed decisions on solutions to difficult safety issues, using sound safety science and engineering experience and judgment. This article for the 2011 IEEE PSES symposium covers the ASSET safety management process, its guiding principles and objectives.

ASSET OBJECTIVE

The objective of the ASSET Process of Safety Management is to utilize Applied Safety Science and Engineering Techniques (ASSET™), together with existing standards, codes and regulations, to achieve, maintain and continuously improve the safety of products, processes and services for safer living and working environments. ASSET™ (Applied Safety Science and Engineering Techniques) is a trademark of Underwriters Laboratories Inc.

BACKGROUND

This article follows the introductory article *Applied Safety Science and Engineering Techniques (ASSET™): Taking HBSE to the Next Level* (*In Compliance,* Novmber 2012) which was presented at the 2010 ISPCE of the IEEE Product Safety Engineering Society, and had established the case and set the stage for ASSET.

A similar article was published by the American Society of Safety Engineers in their SH&E (Safety Health and Environment) Standards Digest, a publication of their Engineering Practice Specialty. ASSET also reflects concepts of the ANSI/ASSE Z690 series, the US national adoption of ISO 31000, ISO/IEC 31010 and ISO Guide 73, initiating membership on the ISO TAG on Risk Management.

Certain ASSET principles have been applied and presented in recent conferences including the 2009 NASA Aerospace Battery Workshop ("*FTA {Fault Tree Analysis}/FMEA {Failure Modes and Effects Analysis} Safety Analysis*

Model for Lithium-ion Batteries"), ASEAN/ ACCSQ 2010 ("*ASEANUS Enhanced Partnership Workshop on Hazard-Based Engineering Principles for the Electrical and Electronic Equipment: A Risk-Based Approach Applied to Li-Ion Battery (LIB) Hazards*"), as well as ICPHSO 2011 (International Consumer Product Health and Safety Organization, "*Hazard Analysis: Hazard Based Safety Engineering & Fault Tree Analysis*"). The ASSET Safety Management process will also be presented for the IEEE and Argonne National Lab, 2011 Today's Engineering Challenges – Tomorrow's Solutions Technical Conference and Exhibition, November in Chicago.

With essential technical input and development of Bob Davidson and strategic leadership of Dan Bejnarowicz, ASSET was developed in the safety management process framework. Notification has just been made that this ASSET work has earned a 2011 IEEE Region 1 Award (Northeastern US) in the category of "*Technological Innovation (Industry or Government): For significant Patents, for discovery of new devices, development of applications or exemplary contributions to industry or government.*"

ASSET is now the subject of a 2-day workshop to put your skills to the test by applying ASSET analysis to example products and prepare to address difficult safety issues using a multi-disciplined, team-oriented approach, supported by science as well as your own experience and judgment.

ASSET APPLICATION

The ASSET process has application in areas including the development of safety standards, codes, and regulations, and the design, evaluation, compliance, certification and safety management of products, processes and services. As such, ASSET applies to functions and responsibilities including safety designers, regulatory compliance, product safety certifiers, standards/codes developers and product and program safety managers. ASSET can also help to integrate and address the needs of various stakeholders including regulators, AHJs, standards developers, trade and professional organizations, consumer groups, government agencies and the public.

For example, relevant safety requirements are generally determined by first establishing the scope of the product, process, or service in question. This scope is then compared to the scope of identified standards, codes and/or regulations that may potentially apply. The scope and context of the assessment itself is also established, including boundaries, and scope alignment on all three counts is sought. In this early stage and throughout the process, potential gaps need to be identified and bridged. A gap may exist for example, if a product, process or service – in the context of its application – does not fall completely within the scope of existing safety standards. Another gap may exist whereby a product, process or service falls within the scope of a safety standard, but involves features, functions, technologies or applications that may (a) introduce a safety hazard, and (b) not be anticipated or addressed by the requirements in the standard.

ASSET AND STANDARDS

ASSET provides a process and methodology for (a) complementing existing standards in evaluating the safety of products, processes or services, (b) assisting in the evaluation of products, processes or services not within the scope of existing standards, (c) evaluating product features (materials, constructions), functions, technologies or applications not anticipated or covered by existing standards. In these situations, ASSET can be applied to (1) help identify hazards not anticipated or covered by existing standards and the need for additional requirements to meet the safety objective (intent) of the standards, and (2) help identify alternative protective measures not anticipated by the standard but which can achieve an equivalent level of safety to the protective measures specified in the standard, thereby meeting the safety objective (intent) of the standard.

In fact, the ASSET process stages include repeated "spec-checks", whereby the initially identified requirements are assessed at each stage.

ASSET SAFETY MANAGEMENT PROCESS

The ASSET process of safety management was developed as the evolution of hazard-based safety engineering principles and safety science into an overall framework of a safety management process. Hazard Based Safety Engineering (HBSE) was originally conceived by HP/ Agilent, and targeted typical types of hazards and forms of injury involving electronics products, such as information technology and office equipment.

The ASSET process is based on a number of acknowledged risk management/risk assessment principles and processes, for example those found in publications including but not limited to ISO/IEC Guide 51, IEC Guide 116, ISO 31000, ISO/IEC 31010, ISO 14121, ISO 14971, IEC 60300-3-9 and ANSI/ASSE Z690.

This process involves stages to (a) formulate the right types of questions to identify the scope of the product, system or service to be evaluated for potential harm, (b) identify and analyze hazards (potential sources of harm), (c) identify, analyze and evaluate protective measures to reduce the risk of harm (e.g., risk of injury from products), (d) assist in the determination of whether or not an acceptable level of safety is achieved, (e) understand and apply methods to maintain and continuously improve safety. This can help explain, apply and enhance existing requirements, and help address emerging technologies, products and applications.

This ASSET process was developed to address a broad spectrum of applications, and each stage has different needs and significance for the assessment of different products, processes, services in different applications. The following provides a brief look at each ASSET process stage and its objectives.

Determine Scope/Context

The goals of this stage are to determine and attempt to align the scope and context of the following: the product, process or service to be assessed, the assessment itself and the initially identified requirements. Relevant topics include (a) the subject of the assessment, including systems aspects of materials, components, subsystems, environment and boundaries with interfaces and interactions, (b) intended implementation, operation, use, users and others affected (c) conditions and requirements for installation, (d) recommended procedures for maintenance and repair, (e) potential effects of packing, shipping and storage, (f) reasonably foreseeable misuse (using a sub-process developed to determine degrees of reasonable foreseeable misuse and associated guidance) , (g) other conditions or factors of potential impact, and (h) applicable standards, codes and/or regulations.

Identify/Analyze Hazards

The goals of the stage are to (a) identify potential types and sources of harm (hazards), (b) determine how harm can occur (hazardous situations, hazardous and harmful events) and the severity of the harm, (c) sort consequences by the level of severity (initial consequence evaluation akin to worst case scenario, with guidance on severity factors, and consideration of extent and exposure of harm), and (d) determine if the applicable standards, codes and/or regulations address the identified hazards, or if there are gaps that need to be addressed.

Specify/Identify/Design Protective Measures

In this stage, protective measures are specified, identified or designed, depending on the given function and responsibility being fulfilled. For example, a protective measure may be specified by developers of standards, codes and regulations, designed by a manufacturer or identified by an evaluator. This stage has goals to (a) establish the safety objective(s), (b) determine the need for protective measures, (c) identify the potential protective measure strategies, categories and mechanisms, (d) analyze and prioritize protective measures, and (e) specify, design and implement the protective measures.

Evaluate Protective Measures

The goal of this stage is to determine whether protective measures are adequate and effective by (a) evaluating whether and how protective measures meet specific safety objectives, (b) identifying safety attributes that are being relied upon and need to be controlled, and (c) evaluating those safety attributes. In order to determine if the goal of this stage is achieved, key questions are asked which include the following:

- Have all the hazards been identified?
- Have the safety (risk reduction) objectives been determined?
- Have the protective measures intended to address the hazards and achieve the safety objectives been identified and designed?
- Have tests and evaluations been conducted to demonstrate that the protective measures are capable of achieving the safety objectives with acceptable results?
- Have the constructions, components and materials that are relied upon for the protective measure to meet the safety objectives been identified?

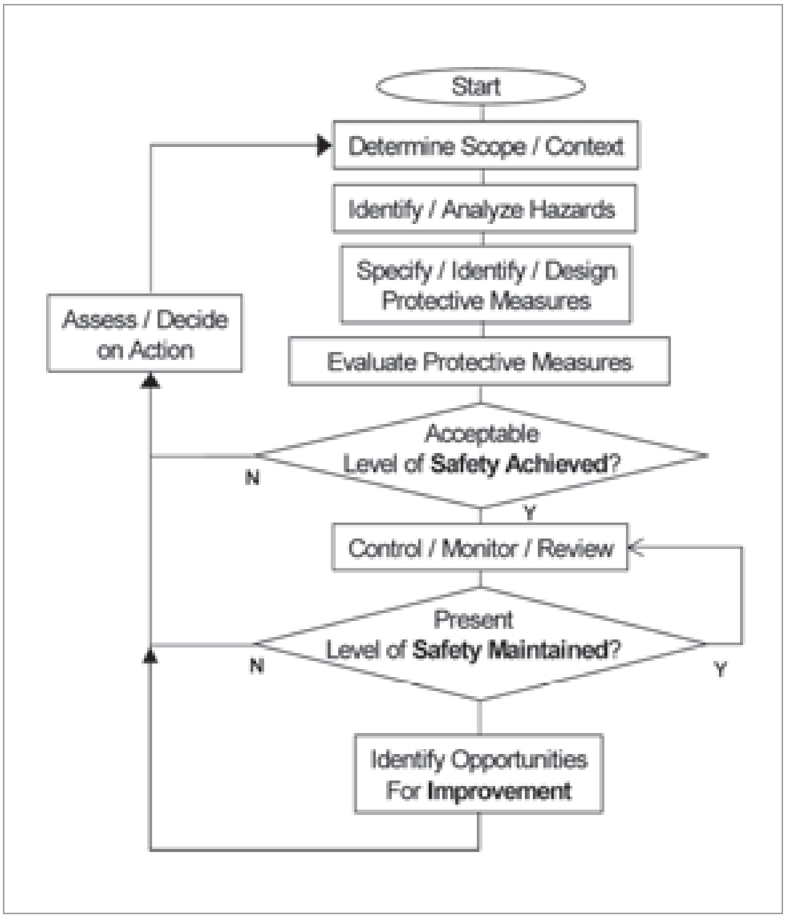

Figure 1: ASSET Process of Safety Management

Product Safety

- Have their safety-related characteristics (safety attributes), factors which may degrade those characteristics, and the tests and evaluations needed to determine their adequacy been identified?
- Have the necessary evaluations/tests been performed with acceptable results?

Through this point in the ASSET process, these stages generally involve activities such as hazard based safety engineering, safety research, safety design, conformity assessment and new standards development. It is also noted that the evaluation of certain protective measures, including life safety devices, may effectively begin at this stage.

Decision Gate: Acceptable Level of Safety Achieved?

There are two basic outcomes of this safety decision. If it is determined that an acceptable level of safety has been achieved, then there is a need to control, monitor and review to maintain safety. However, if an acceptable level of safety has not been achieved, there is a different need to assess and decide on action. This may involve revisiting earlier process stages or discontinuing.

This point of the ASSET process generally involves conformance and compliance activities.

Control/Monitor/Review to Maintain Safety

At this stage, if determined that an acceptable level of safety has been achieved, the goal is to ensure that safety is then maintained by (a) establishing controls throughout the life cycle, up the supply chain, to ensure that safety is maintained, (b) monitoring field performance down the supply chain and factors that may impact safety by means of surveillance and follow up, and (c) periodically reviewing and assessing results and deciding on appropriate actions.

Decision Gate: Present Level of Safety Maintained?

Similar to the prior decision gate, there are also two basic outcomes of this safety decision. If determined that the present level of safety is being maintained, then there is a need to continue to control, monitor, and review. However, if the present level of safety is not being maintained, there is a different need to assess and decide on action. Again, this may involve revisiting earlier process stages or discontinuing.

This point of the ASSET process generally involves activities including certification, market and conformity surveillance, follow-up for certification mark integrity, updates in regulations, standards and codes, and assessment of new/emerging technologies that may either benefit or threaten safety.

Identify Opportunities for Improvement

The goal of this stage is to monitor and identify the opportunity, or the need, for improvement in (a) safety and safety standards and (b) the processes, methods and tools used to determine whether and how safety is achieved and maintained. These opportunities are then assessed to decide on action, which may involve revisiting earlier process stages.

Activities involved in this stage of the ASSET process include improvements in regulations, standards and codes, as well as improvements in safety assessment processes, methods and tools.

MEETING THE OBJECTIVE

The stated objective of the ASSET Process of Safety Management is to utilize Applied Safety Science and Engineering Techniques (ASSET™), together with existing standards, codes and regulations, to achieve, maintain and continuously improve the safety of products, processes and services for safer living and working environments.

By this we mean to a) achieve an acceptable level of safety (once determined, based on specific safety objectives), b) maintain that present level of safety (throughout the entire lifecycle of the product, process or service, under all anticipated conditions, considering upstream (suppliers) and downstream (users and all affected) the supply chain), and c) continually seek and assess opportunities for improvement (based on the availability, need or demand for improvements).

ASSET stresses the importance of assessing the sources, causes and conditions of harm (as did HBSE before it), as well as the risk of harm (severity, likelihood, extent, exposure). ASSET also addresses different forms of potential harm to various entities, including persons (injury or health risk), property, the environment and even continuity of critical operations and functions. Sources are categorized in terms of energy or matter/substance that may be harmful, from different sources in various forms, conversions or conditions. The standard HBSE tools (3-block energy transfer model for injury, HBSE process to evaluate a safeguard and standard injury fault tree) are adapted and expanded.

Then the most effective protective measure strategies can be determined, with appropriate identification, evaluation and control of safety attributes -the very properties and characteristics of protective measures relied upon to achieve, maintain and improve this level of safety.

The ASSET process supports informed decisions using the best available information, data and other resources, based on the best available knowledge and experience, at progressive stages of development. This can help identify the degree of confidence in the decision and the relative need and value of additional inputs or analysis. ASSET can also serve as a tool for effective communication and interaction to share information, as needed by various stakeholders.

ACKNOWLEDGMENT

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This and related hazard analysis and risk assessment work has been extensively published and presented, including keynote presentation on the safety of consumer electronics into the future at the 2012 International Conference on Consumer Electronics (ICCE) by the IEEE CES, 2012 Advanced Product Safety Management course at St. Louis University, 2010 and 2011 International Symposium on Product Compliance Engineering by the IEEE Product Safety Engineering Society, 2011 IEEE Chicago Argonne National Laboratories Technical Conference, International Consumer Product Health and Safety Organization (ICPHSO 2011), Association of Southeast Asian Nations (ASEAN), Asia Pacific Economic Cooperation - Joint Regulatory Advisory Council (APEC JRAC Risk Assessment Workshop), American Society of Safety Engineers (ASSE) and NASA (2009 NASA Aerospace Battery Workshop).

An IEEE Senior Member, Tom is Founding Chair of the Long Island, NY Chapter of the IEEE Product Safety Engineering Society (PSES) and Vice Chair of the IEEE Risk Assessment Technical Committee (RATC). He serves as technical expert in committees for electric shock protection and risk management, including US National Committee Technical Advisory Groups (USNC TAGs), the International Electrotechnical Commission (IEC TC64 MT4) and the International Organization for Standardization (ISO 31000/ ANSI Z690). He can be contacted at +1.631.546.2464 or thomas.p.lanzisero@us.ul.com.

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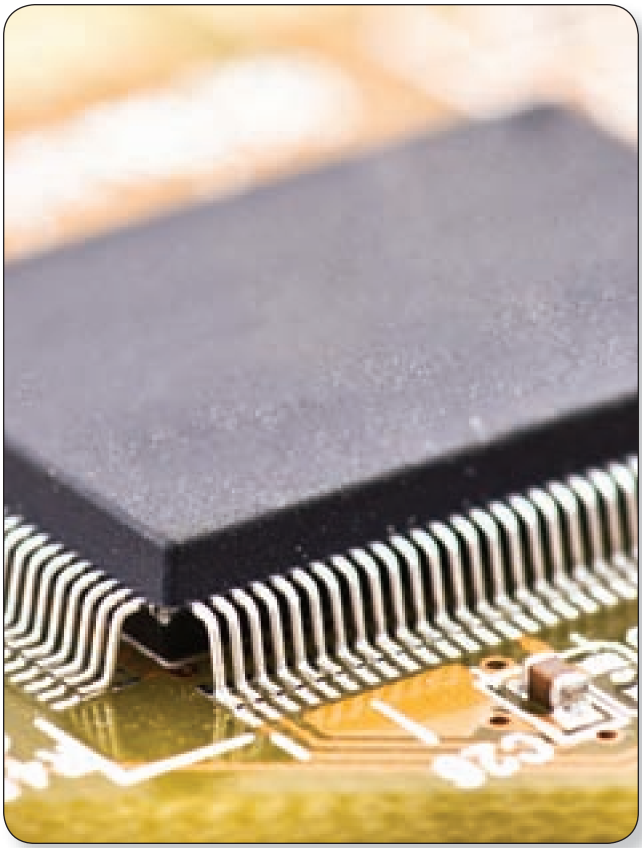
ESD Electronic Design Automation Checks

Part 1: Outlining the essential requirements of the ESD verification flow

BY MICHAEL G. KHAZHINSKY



ESD

The verification of electrostatic discharge (ESD) protection in a complex integrated circuit (IC) design is extremely challenging. Leading-edge designs have many supply domains and voltage levels for different functional parts like radio frequency (RF), digital and high voltage blocks, making ESD checking a complex and error prone task. Relying on manual verification alone poses a significant risk of missing design flaws, which can be very costly during manufacturing and in the field. Consequently, automated ESD checking is highly desired in today's design flow. This article outlines the essential requirements of the ESD verification flow as defined by the ESD Association (ESDA) Electronic Design Automation (EDA) Tool Working Group [1].

Figure 1 illustrates the timeline and main stages for an example design flow. The IC product design flow (top row) needs to be synchronized with an ESD development and implementation flow (middle row). The latter needs to be supported by an ESD check flow (bottom row).

The following sections describe the main IC development phases and give examples of different ESD checks relevant for these phases.

PRODUCT DEFINITION PHASE

The ESD performance specifications usually follow commonly accepted standards. However, depending on the field of application, they can be modified by marketing teams and IC customers. Product design specifications and required ESD performance dictate specifications of ESD components and ESD cells. Based on these functional requirements, suitable ESD cells are defined per each pin application node (signal, power, and ground). Typically the ESD cells are made accessible to the designer in a dedicated ESD library.

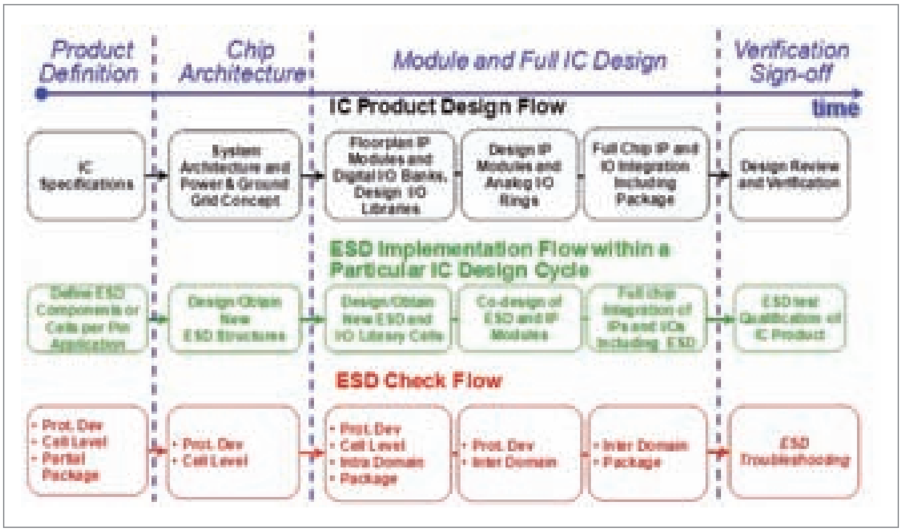


Figure 1: A simple ESD verification flow mapped to sample IC design flow.

In a situation when a mature semiconductor technology is used with already developed ESD libraries, only placement and product specific modifications of the existing ESD components and ESD cells need to be verified. For a new IC product that uses a new semiconductor process, an ESD library may not be available and no specific cell level ESD checks can be executed. However, performance specifications of the needed ESD library could still be defined, together with the IC customer, based on the available ESD technology development data and ESD EDA data from other products/ technologies.

Based on the available design data in this design phase, the following ESD checks can be performed:

- Protected device checks to verify that the available ESD library cells can provide the required safe operating conditions for the protected components at each pin, for the given design functional requirements.
- Cell-level checks on the existing ESD cells.
- Package-level checks to determine, for example, expected peak charged device model (CDM) currents, as well as package and die specifications to meet CDM performance specifications.

Due to the nature of these data, a simple check of the ESD compliance can be done based on the ESD characteristics of the ESD cells in a design database. The following is an ESD EDA check example performed during product definition.

An early analysis of the integrity of I/O cell, bus placement and the overall ESD robustness is one of the essential factors of a successful chip design. An ESD floorplanning checker for the chip could enforce the ESD design rules to be verified while planning I/O cell and power bus placement. In particular, the checker could verify the existence of an ESD cell/device between pads, estimate parasitic resistance between pad and ESD cell/ device, and give a rough estimate of the chip ESD robustness by predicting pad voltage (Figure 2).

CHIP ARCHITECTURE PHASE

At this design stage, the functional/behavioral level of chip architecture is defined and the required ESD components and library cells are identified. No circuit or layout level IC description is available in this phase. Similar to the previous section, cell level checks and protected device checks can be performed. The available design data are similar to those described in the previous section.

MODULE AND FULL IC DESIGN PHASE CHECKS

This is the main design activity phase, involving complex interaction between all product teams. It can be divided into three sub-stages.

The first stage is the floorplanning of the chip architecture modules and the standard digital I/O and power banks. The ESD checks that could be done at this design stage are limited to top-level verification of the ESD network within the digital I/O banks and ESD connectivity between the different modules, the related I/O banks in the different power domains and the package level ESD connections. These checks include:

- Protected device checks for the digital modules.
- Cell-level checks for the new ESD library cells.
- Intra-power domain checks for the digital intellectual property (IP).
- Floor plan/top-level ESD checks for the power and ground domain bus crossing.
- Basic packagelevel checks.

The second stage is the design of IP modules and analog I/O pad rings. At this design stage, the analog (and RF) modules and the related I/O banks are physically designed. In many cases, the analog IP module team is different from the I/O and power/ground cell design team, which is often responsible for integrating the ESD library cells. The module team may not have detailed information about the ESD components used at cell level and special attention is needed when checking the overall ESD implementation. A certain level of co-design between the analog modules and the dedicated ESD protection cells may be needed as well. Based on the available design data, the following ESD checks could be performed:

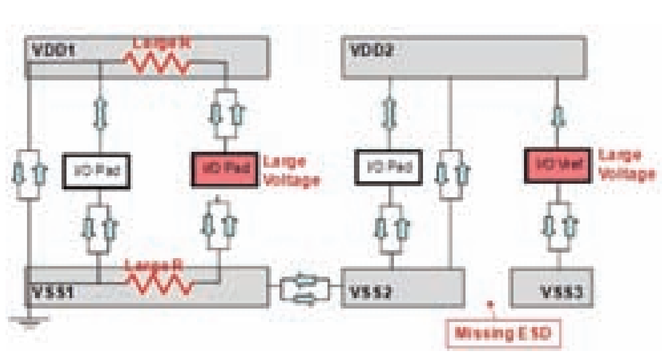


Figure 2: A sample I/O assembly checked with an ESD floor plan checker. Tool output flags missing ESD protection devices and large resistances in the ESD current path.

ESD

- Cell-level checks for the analog pin ESD library cells (can be newly developed, e.g. for custom analog form factors or in-module/off- pad ring placement).
- Intra-power domain checks for analog pad rings.
- Intra-power domain checks for each analog module.
- Inter-power domain checks (if there are several power domains in one analog module).
- Protected device checks for the individual modules.
- Special ESD rule checks on specific analog/RF blocks/IP's – e.g., differing ESD target levels.

Specific tool functionality is needed for the cases where the ESD protection cells are placed in the analog pad ring, which is not available to the team performing the ESD checks at module level. Such tool functionality can be extended to allow verification of module ESD robustness against cross-power domain or cross-IP stress events. This is especially useful when the counter pins are not available physically but some information about the involved ESD network (ESD cells, connectivity) is present in the design database. This can be considered a "virtual chip integration" where only a particular module design is physically available to the team running the check. This situation also applies to the verification of a given module involving evaluation of ESD performance of third party IP ("black box").

The third stage is full-chip IP and I/O integration, including package. This is the final level of ESD checks applied to the whole IC. The main purpose is to verify the integration of the individual IP ESD circuits at top IC level, to check for the new cross-IP integration ESD violations and parasitic devices, and to verify that the protected components at each individual IP module are still operating in their ESD safe operating area (SOA) for stress combinations including other IP.

Based on the available desicgn data, the following ESD checks could be executed:

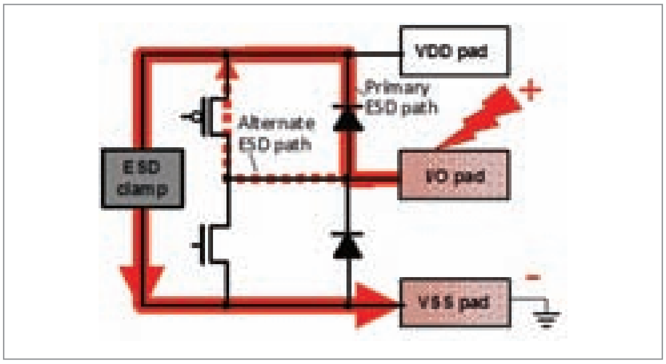


Figure 3: Check of an ESD path in an I/O ring. An appropriate check of these two current paths would involve high-speed static and dynamic simulations on the large netlist of interconnect and ESD relevant components.

- Inter-power domain checks.
- Package-level checks.
- Protected device checks for the full IC.

For certain classes of designs (e.g., some digital designs), it might be possible to implement certain hierarchy of checks so that at the full chip level the individual design blocks are considered as "black boxes" and only the integration of the blocks is verified.

The following is an example of ESD checks of the module and full IC design phase aimed at identifying potential ESD weaknesses of I/O assemblies (rings or arrays). An I/O assembly could be checked at this stage with an ESD verification tool covering both the layout checks and the electrical checks. The layout checks could ensure that the predefined ESD rules are strictly followed. In particular, the checker could flag input buffer gates and output buffer drains without adequate ESD protection, parasitic bipolars, violations of minimum ESD metal width, etc. The electrical checks of I/O assembly at this stage can vary in complexity: they can use simplified I/O netlists only or include detailed models of ESD protection elements and parasitics. The verification of primary ESD current path existence and checking of alternative current paths for each pin-to-pin combination is the main objective of the check at this stage [2]. The checker could flag the situation where no ESD current path exists or where an unintended parallel path with weak devices becomes preferred during an ESD event. Basic checks can be done using an extracted netlist from the schematic for all pin-to-pin combinations. This can then be followed by a more detailed analysis for selected pins using the netlist extracted from the layout. Figure 3 shows part of an I/O ring with primary and alternate current paths for a given pin stress combination. An appropriate check of these two current paths would involve high speed static and dynamic simulations on the large netlist of interconnect and ESD relevant components.

DESIGN QUALIFICATION PHASE

In this phase, final design audits and ESD performance assessments are executed using the verification results from the previous phases. This is often done based on a custom, company-defined standard practice methodology, summarized in an "ESD check list" or other document. The goal is to confirm that all required ESD verification activities have been performed.

EDA tool functionality at this design stage is mostly related to reporting and documenting the results of the checks executed earlier and storing the results in a suitable database for further analysis. Such analysis is usually needed for product ESD troubleshooting during IC qualification.

In practical design cases involving complex IC products and ESD solutions, there could be situations in which some ESD violations may still be reported when an IC is sent for manufacturing due to limitations of the ESD verification tools or due to non-ESD-related product development priorities. However, under all circumstances, the result of the formal ESD EDA check runs could allow for easy product ESD troubleshooting. The ESD EDA checker output could help with relating possible ESD test failures with identified ESD design marginalities.

The ESD checks of the final IC verification phase are most extensive. They are similar to the checks which have been performed during earlier design phases. However, ESD EDA tools could be capable of operating on much larger netlists, including full chip resistance, capacitance, and package information. The following are a few ESD EDA check examples performed during this phase.

A final ESD IC check could include verification of all designated ESD current paths using an EDA tool. To achieve better accuracy for a given pad stress combination, more than one ESD path could be found and analyzed since ESD current flow may not be limited to the shortest path identified earlier. A report from such a tool will include calculated node voltages and currents and can be used for the ESD signoff before the tape-out. Figure 4 shows an example of the final chip-level checker output, where three distinctive ESD paths for a chosen pair of pads (IO_D2 and IO_ANA) were found. Voltages and currents along ESD paths have been found by running DC simulations where an HBM 1.33A current has been forced between the two pads. Simulated voltage potentials and currents at each path node are shown in Figure 4. Bus parasitics have been included in simulations. For example, the voltage difference between nodes V2 (7.76V) and V3 (5.35V) is coming from both the diode D1 voltage drop (2.39V) and VSSIO bus resistance voltage drop (0.01V). Voltage stresses across most sensitive devices are being monitored to ensure that while the total voltage drop between stressed pads may be high (16.48V), devices are not being stressed in excess of their failure limits. In particular, voltage between VDD and VSS in this example does not exceed the 0.68V, and the IC core can be considered ESD robust.

After completion of the initial IC integration, critical cross-domain boundaries between different supply voltage networks on a chip could be identified. The high voltage drop across these boundaries during an ESD stress makes them more prone to ESD damage than the devices placed within the same power domain. The increasing number of different supply voltage domains in today's generation of chips necessitates an automated check to find devices that would be impacted during an ESD event. Depending on the acceptable voltage stress level for the specific devices at the domain interface, ESD design weaknesses could be identified by an EDA tool after checking thousands of possible interface connections. In addition, protection measures already implemented at power domain boundaries (diodes connected to an interface gate oxide, etc.) have to be taken into account as well when analyzing ESD robustness of devices at power domain boundaries. Figure 5 (page 168) gives an example of a cross-domain level shifter, where a gate connected to node 1 could be overstressed during an ESD event.

CONCLUSIONS

In this article the, essential requirements of an effective ESD EDA verification flow were described. These requirements are aligned within the IC design community ESD verification needs. The proposed verification flow offers a systematic approach to check ESD robustness across all IC blocks at

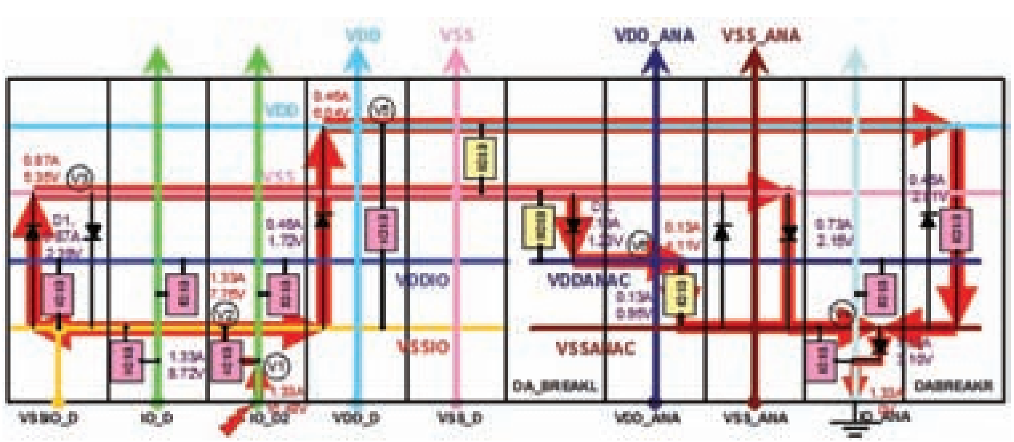


Figure 4: Example of the final chip-level checker output. Simulated voltage potentials and currents at each path node are shown. Bus parasitics are included in simulations.

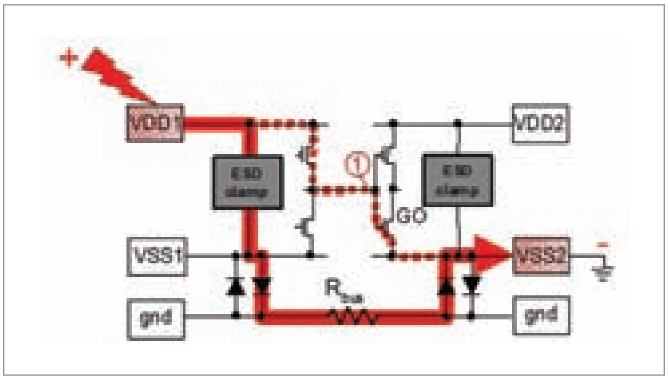


Figure 5: Power domain boundary-crossing check. Due to increased Rbus, the primary ESD current path (thick line) becomes less attractive, resulting in stressed gates at node 1.

different phases of design flow. This approach allows for the avoidance of many ESD design flaws, reducing the overall design cycle time. The ESD EDA tools would improve the ESD predictive capabilities by generating extended netlists (including ESD device, resistance, capacitance and package) and retiring an approach of crude "back of the envelope" extractions, manual/visual checks and resource-intensive SPICE simulations. Another important benefit of these tools is the possibility to use them for systematic ESD design optimization. The ESD EDA check requirements outlined in this article could be the basis for additional effort by the EDA vendors to adapt their tools and to make a comprehensive ESD verification flow feasible.

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More details on the proposed ESD EDA verification flow can be found in the ESDA Technical Report ESD TR18.0-01-11 [1], which is available for as a free download at http://www.esda.org/standards.html. At the time of the writing, the ESDA EDA Working Group consisted of the following members: Michael Khazhinsky (Silicon Labs), Fabrice Blanc (ARM), Gianluca Boselli (Texas Instruments), Shuqing (Victor) Cao (Global Foundries), Norman Chang (Ansys), Dan Clement (On Semiconductor), Rosario Consiglio (Impulse Semiconductor), Maxim Ershov (Silicon Frontline), Melanie Etherton (Freescale Semiconductor), Eleonora Gevinti (ST), Harald Gossner (Intel), Matthew Hogan (Mentor Graphics), Larry Horwitz (Synopsys), Kelvin Hsueh (ESD Consultant), Mujahid Muhammad (IBM), Louis Thiam (Cadence), Nitesh Trivedi (Infineon), and Vesselin Vassilev (Novorell).

Founded in 1982, the ESD Association is a professional voluntary association dedicated to advancing the theory and practice of electrostatic discharge (ESD) avoidance. From fewer than 100 members, the Association has grown to more than 2,000 members throughout the world. From an initial emphasis on the effects of ESD on electronic components, the Association has broadened its horizons to include areas such as textiles, plastics, web processing, cleanrooms and graphic arts. To meet the needs of a continually changing environment, the Association is chartered to expand ESD awareness through standards development, educational programs, local chapters, publications, tutorials, certification and symposia.

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ESD Electronic Design Automation Checks

Part 2: Implementing ESD EDA Checks in Commercial Tools

BY MATTHEW HOGAN

ESD

Electrostatic discharge (ESD) design rules verification has grown in volume and complexity as integrated circuit (IC) designs have become more complex and added significantly more power domains. With each additional power domain, verification of the signals that cross these domains becomes more difficult (particularly in the identification of inadvertent paths), as well as the check of interactions between circuit blocks that may result in many potential ESD discharge current paths [1]. While not strictly related to ESD, designs that incorporate multiple power domain checks are particularly susceptible to subtle design errors that are difficult to identify in the simulation space or with traditional PV techniques. Often, these subtle reliability errors don't result in immediate part failure, but in performance degradation over time. Effects such as negative bias temperature instability (NBTI) can lead to the threshold voltage of the PMOS transistors increasing over time, resulting in reduced switching speeds for logic gates [2-4]. At the same time, hot carrier injection (HCI), which alters the threshold voltage of NMOS devices over time [5], and soft breakdown (SBD) [5] also contribute as time-dependent failure mechanisms, adding to the degradation effects of gate oxide breakdown.

ESD rules for ICs with multiple power domains, IP reuse, and system integration require greater complexity to avoid device damage. Design hierarchy also comes into play where some rules are applied on a top cell and/or top pads, but others are applied between internal blocks that cross multiple power domains. Tracking the rules and the nets to which they apply is by no means a trivial task when performed manually. Automation is necessary to effectively and efficiently cope with these requirements.

As a result, multiple methods have been developed using modeling or simulation to perform chip-level ESD verification [6-8]. However, while simulation-based ESD verification methods, to verify compliance to human body model (HBM) and charged device model (CDM) requirements, are effective, they do not necessarily check all elements in the design for ESD violations. In particular, internal interfaces between different supply domains are not explicitly checked. Additionally, getting device models for simulation at these extreme conditions is often problematic.

Part 1 of this series, "Outlining the Essential requirements of the ESD Verification Flow", provided an overview of the essential requirements of an effective ESD EDA verification flow [14]. This article (Part 2) discusses a well-established topological methodology for checking ESD design rules. The ESDA Technical Report 18, "ESD Electronic Design Automation Checks" (TR18) [13], provides an overview of recommended ESD checks that should be performed to validate appropriate ESD protection structures within a design. We will focus our effort on TR18 rule 5.1.3, which applies to internal interfaces between power or ground domains, a requirement that has been recently highlighted [9-11]. Rather than modeling or simulating, the methodology uses the device netlist topology to check all domain crossing interfaces and associated ESD devices in the entire design, and is realized using the Calibre® PERC™ tool from Mentor Graphics. Although internal interfaces may span many levels in the design hierarchy, checking is done hierarchically by utilizing a novel technique for topology-aware verification. In addition to performing topology checking, at times there is the need to include both topology and physical information to create a more comprehensive checking environment. Such an environment is required to perform ESD layout verification checks [12].

The following sections cover the targeted ESD rules, the new hierarchical algorithm, ESD rule variations. and verification results.

THE ESD RULE

Transistors' gates can be exposed to direct ESD events. This is particularly common in input receivers, although many other topologies can expose a gate oxide to an ESD discharge path. Since gate oxides (by virtue of their small capacitance) cannot shunt any significant amount of current, they have to be considered voltage pulse driven as far as their failure mechanism is concerned. It is irrelevant whether the gate oxide is connected to signal, ground, or supply. The failure criteria will depend on the actual combination exercised and whether a soft vs. hard oxide breakdown sets the failure limit (application-dependent) [13].

ESDA TR18, check 5.1.3 [13] is intended to verify presence of protections on signals that cross a power domain boundary. As shown in Figure 1, when the pad VDD1 is struck with respect to VSS2, a high voltage could be developed across the gate-source oxide of the NMOS in the VDD2 power domain.

To define our rule, we begin by identifying the ESD protection strategy; to protect this component we need to ensure that the voltage across it does not exceed the set failure level. A simplified overview of the check that needs to be performed to ensure the gate oxide is adequately protected is as follows:

For each net in design,
IF net connects *driver* and *receiver* **THEN**
check *power domains* of driver and receiver
IF different power domains
THEN
check for anti-parallel *diodes*
IF anti-parallel *diodes* do not exist **THEN**
ESD error

Drivers and receivers are determined by net connectivity, as are the different power domains. Because this is an interface, the pieces of the circuit that must be checked are usually distributed between different levels of the design hierarchy, so it is not obvious how to check the rule independently on a cell-by-cell basis. However, using a flat approach does not provide sufficient capacity to run larger chips. For scalability reasons, it becomes necessary to develop a hierarchical topological approach to efficiently solve this issue. We present here such a method that performs hierarchical verification.

HIERARCHICAL VERIFICATION

Overview

The first requirement is a SPICE netlist, which can be either a schematic netlist or a netlist extracted from the layout. In the latter case, the LVS-like runset used for extraction must ensure that all ESD protection devices are extracted (Note: parasitics are not extracted, just intentional devices). While the netlist must contain the proper text names for device pins (so that power and ground domains can be established), in general, texting in the netlist is not used extensively for verification (see Figure 2).

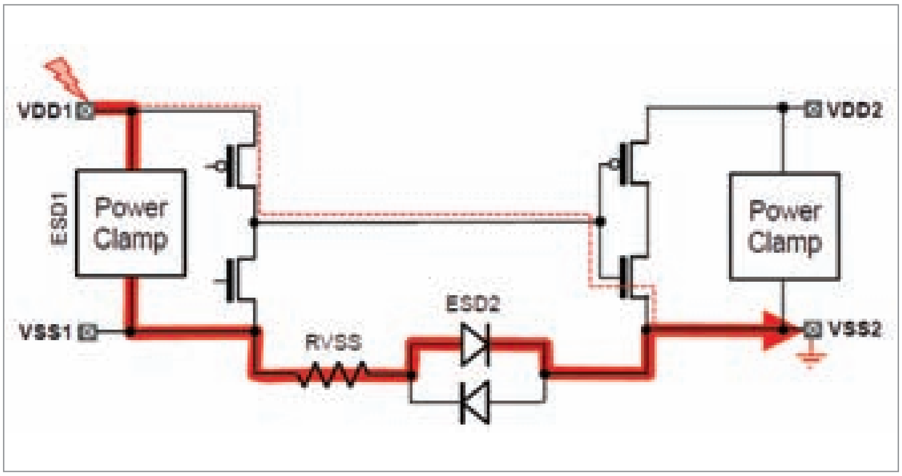

Figure 1: Typical signal cross-domain ESD issue (source: EDA Tool Working Group (2011), from ESD Electronic Design Automation Checks (ESD TR18.0-01-11) [13]

The second input is an ESD rule deck. It specifies the ESD design rules to be checked, and the list of power and ground domain names. Power and ground names are not generated automatically; they must be specified in the rule deck per the design specification. This rule deck is essential for making the verification method generic. For ease of discussion, however, we will describe the method in the context of the ESD design rule formulated above.

Conceptually, the hierarchical algorithm runs in two steps:
1) initialization, and 2) rule-checking.

In the initialization step, the algorithm gathers ESD-related topology information from each cell and propagates it throughout the design. In the second step, the algorithm checks ESD design rules independently, cell by cell, as each cell now has access to the entire ESD protection scheme propagated from all other cells.

ESD Rule-Checking

Once net connectivity is defined, we can check the ESD design rule cell by cell. Since a net's path through devices is, in general, instance-dependent, we cannot just check each cell once. Instead, we find a list of representative instances with unique net connectivity for each cell. Depending on the amount of regularity in the design, the list of instance representatives can be orders of magnitude smaller than the list of all instances for a cell. This greatly improves the speed of the tool compared to checking a flat netlist and is done while preserving any instance specific configurations.

Rule Deck Coding Considerations

Given the diversity in ESD rules, it is important to develop a robust rule deck that will not miss real violations. Within the framework of our method, there are two basic approaches: one is to code a new rule for each variation, and the other is to code a single general purpose rule that covers all variations. The tradeoff is speed vs. rule complexity. The first approach is simpler but slower, as each net will be checked multiple times (once for each rule). The second approach is faster but obviously more complex.

The rules should include checking of properties of the ESD protection devices, such as ESD components widths. Also, the rules should handle different protection types. For example, the ESD protection circuit in Figure 1 could be a dynamic or static clamp or diodes.

Similarly, the drivers and receivers in real circuits are not necessarily simple inverters. They can be NANDs, NORs, etc. However, this does not need special attention from the rule-writing point of view. The tool automatically handles different types of logic gates.

Moreover, the tool can recognize multiple drivers/receivers on an interface net—for instance, a driver with a fan-out to three inverters (in the same domain or in different domains). The rules should take advantage of this ability and report all drivers/receivers associated with a violation.

At the global level, a robust rule deck should also include other ESD checks. For example, the parameters used in the domain crossing interface check can be dependent on properties of the supply protections. As an example, in the case shown in Figure 1 where the driver and receiver have separate VDDs and VSSs, we are able to make a determination of the checks to be performed and determine the need for the specific protection circuit specified (in this case, anti-parallel diodes).

RESULTS

ESD rule decks have been written using this technique and have been verified in production design flows for both large blocks and complete chips. We will review the results in terms of functionality (How well did it identify real problems?) and reporting (How easy is it for users to manage and correct errors?).

Functionality

In practice, designs with multiple power and ground domains often involve hundreds or thousands of crossings that need to be verified. In addition to determining what signals require ESD clamps for protection, the crossing audit is also needed to determine which ground domains need interface protections.

In one example, for noise isolation purposes, a PLL was designed with separate ground domains for the core and 1.8V circuits. Traditionally, crossings between domains were checked manually to see if ESD clamps were present. However, crossings can be very difficult to find, since the connections may need to be traced through multiple schematics and there can be hundreds, if not thousands, of crossings. Using the PLL example, the hierarchical ESD audit identified all 133 crossings in just a few seconds. The crossing audit also successfully caught missed instances of clamps in the preliminary design.

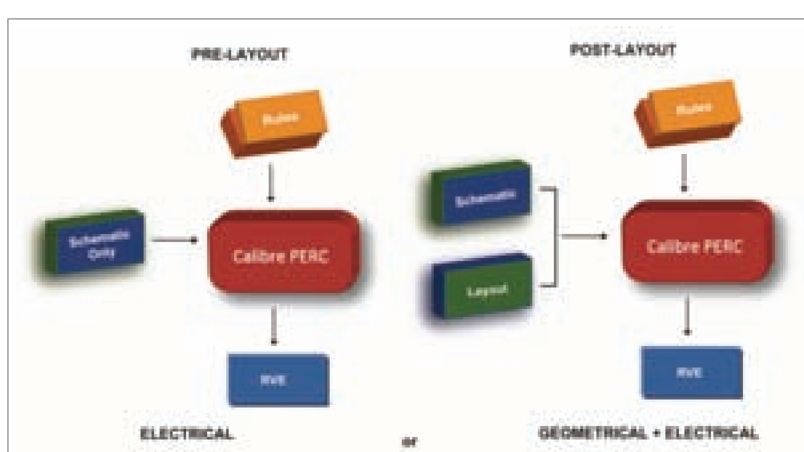

Figure 2: Hierarchical verification flow

ESD

Reporting

The output from the rule deck lists all the crossing nets and is organized by hierarchy (Figure 3). For each net, the MOSFETs on both sides of the interface, together with the associated grounds, are shown. This output can be customized as desired, and Calibre PERC provides a results viewing environment (Calibre RVE) to highlight devices in the schematic and/or layout when they are selected in the report. All 133 results are displayed in the graphical tree view shown in Figure 3. Analysis of these results will identify the specific details for each failure.

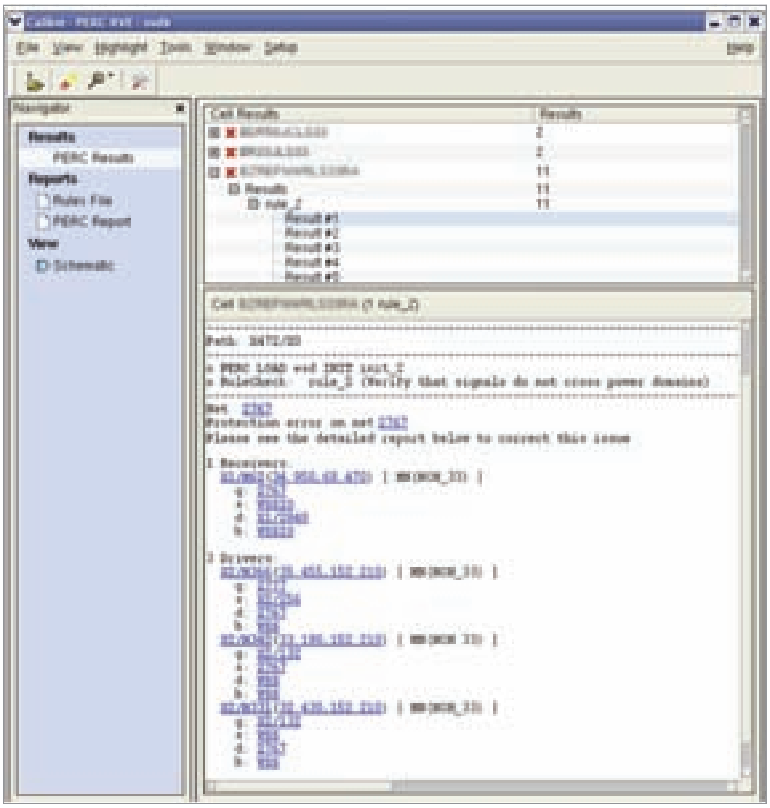

Figure 3: Results for an entire design showing an ESD protection error on net 2767, involving one receiver and three drivers

The schematic representation in the results viewer can provide a different perspective of an error (Figure 4) This often provides a holistic view of the connectivity, enabling much easier debugging than the original schematic. Of course, as these results are displayed in Calibre RVE, highlighting back to the original schematic is also supported.

Because you can specify nets, devices, pins, etc., and create "groupings" for testing conditions, the tool can use these conditions to determine how to evaluate a design.

CONCLUSION

In this paper, we presented a well-established, topologically-driven hierarchical verification methodology that has been developed to automate ESD rule-checking. It can handle large ICs and check ESD protection rules on the original design without netlist reduction. The hierarchical algorithm uses a novel topology-aware concept, allowing for verification of chip-level ESD design rules. The presented method has been extensively verified and is being used in production to significantly improve ESD quality.

Until now, there has been a clear gap in EDA solutions to address the demands of circuit and electrical verification. The ability to use both netlist and layout (GDS) information simultaneously to perform electrical checks enables designers to address both reliability concerns arising from crossing multiple power domains and catastrophic failures from ESD that can have large effects on yield and reliability. In addition, this method can employ topological constraints to verify that the correct structures are in place wherever circuit design rules require them.

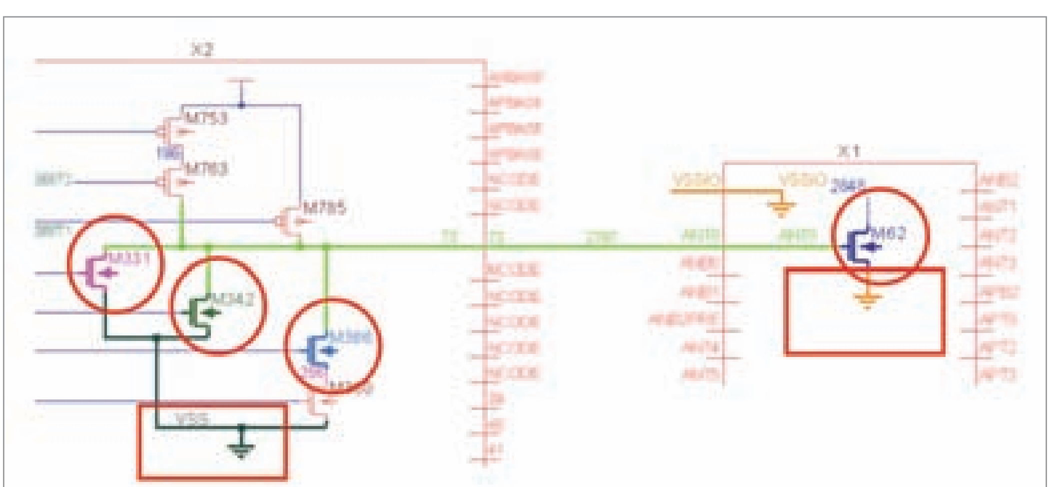

Figure 4: Schematic image from results viewing, identifying all the circuitry elements affected by the error: Net 2767, Receiver: X1/M62, Drivers: X2/M331, X2/M341, X2/M366, Ground nets VSS and VSSIO

An automated solution that verifies circuits at both the schematic and layout phase can reduce cost and time to market, while improving yield and device reliability.

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At the time of writing, the ESDA EDA Working Group consisted of the following members: Michael Khazhinsky (Silicon Labs), Fabrice Blanc (ARM), Gianluca Boselli (Texas Instruments), Shuqing (Victor) Cao (Global Foundries), Norman Chang (Ansys), Dan Clement (On Semiconductor), Rosario Consiglio (Impulse Semiconductor), Maxim Ershov (Silicon Frontline), Melanie Etherton (Freescale Semiconductor), Eleonora Gevinti (ST), Harald Gossner (Intel), Matthew Hogan (Mentor Graphics), Larry Horwitz (Synopsys), Kelvin Hsueh (ESD Consultant), Mujahid Muhammad (IBM), Louis Thiam (Cadence), Nitesh Trivedi (Infineon), Vesselin Vassilev (Novorell).

Founded in 1982, the ESD Association is a professional voluntary association dedicated to advancing the theory and practice of electrostatic discharge (ESD) avoidance. From fewer than 100 members, the Association has grown to more than 2,000 members throughout the world. From an initial emphasis on the effects of ESD on electronic components, the Association has broadened its horizons to include areas such as textiles, plastics, web processing, cleanrooms and graphic arts. To meet the needs of a continually changing environment, the Association is chartered to expand ESD awareness through standards development, educational programs, local chapters, publications, tutorials, certification and symposia.

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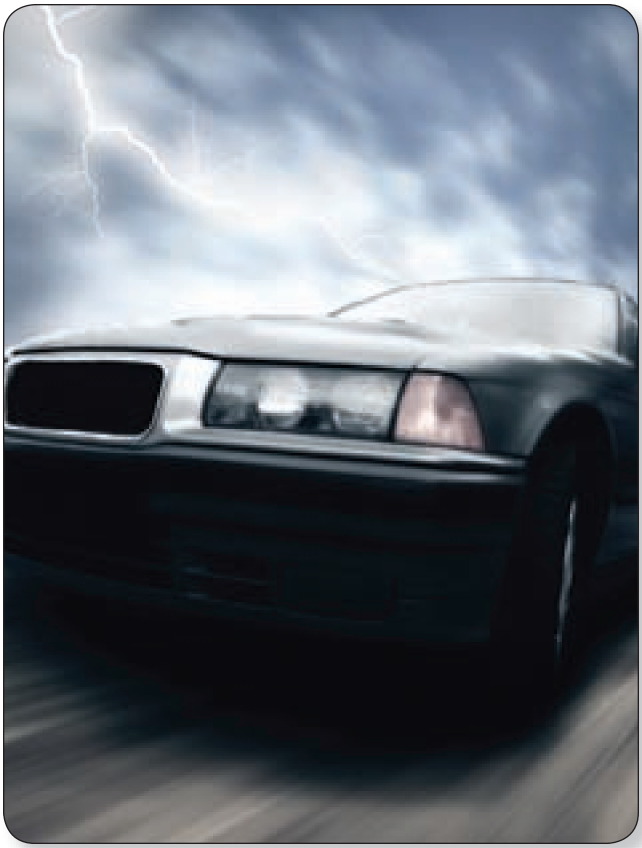

Discontinuing Use of the Machine Model

for Device ESD Qualification

BY CHARVAKA DUVVURY, ROBERT ASHTON,
ALAN RIGHTER, DAVID EPPES,
HARALD GOSSNER, TERRY WELSHER,
AND MASAKI TANAKA

ESD

The machine model (MM) test, as a requirement for component electrostatic discharge (ESD) qualification, is being rapidly discontinued across the industry. This article is intended to illustrate why MM evaluation is not necessary for qualification. The following major conclusions can be made about MM in general:

- MM is redundant to the human body model (HBM) at the device level since it produces the same failure mechanisms, and the two models generally track each other in robustness and in failure modes produced.
- MM testing has more variability than HBM due to MM's greater sensitivity to parasitic effects in the tester circuitry.
- There have not been any significant engineering studies (with verified data) which could be used to establish required passing level.
- The test method was incorrectly given the name "machine model", though no firm unique connection between the model and actual machine-induced device failures was ever established. In fact, the model was developed as a "low-voltage HBM".
- The charged device model (CDM) does a better job of screening for fast metal-to-metal contact events than MM.
- The vast majority (>99%) of electrical failures in manufacturing correlate to CDM and electrical overstress (EOS), and not to MM.
- MM testing has not shown any additional failures not explained by CDM, HBM or EOS.
- MM testing consumes resources and creates time-to-market delays while only providing failure modes or protection strategies that HBM and CDM already cover.

It is important to understand the scope of this article. It summarizes what has been learned about the test method *only*. The information summarized here in no way diminishes the importance of adequately grounding any metal which may come in contact with ESD-sensitive devices nor the importance of avoiding hard metal-metal discharges.

BACKGROUND TO THE ISSUE

As will be explained below, the machine model is a widely misunderstood component ESD qualification test method. It continues to generate confusion for both original equipment manufacturing (OEM) customers and their integrated circuit (IC) suppliers during ESD qualification. Many companies and design organizations continue to use MM, mostly as a legacy "required" practice, despite the fact that it has been downgraded by three standards bodies and is no longer recommended for qualification testing in accordance with JEDEC JESD47. The automotive industry, a longtime user of this method, no longer requires it in their AEC-Q100 list of qualification tests. The scopes of the JEDEC (JESD22-A115) and ESDA (ANSI/ESD STM5.2) test method documents have also been changed to reflect this status. There are a number of reasons for these changes, as outlined below. The continued use of MM for qualification based solely on legacy requirements has no technical merit given the information that has been gathered over the last few years. Those companies who continue to use MM take on an unnecessary and burdensome business approach. The reasons against use of the MM are given below.

1. Historically speaking, the 200pF, "0 ohm" model, which later became known as the machine model, originated with several Japanese semiconductor corporations as a worst-case representation of the human body model. The model was later presumed by some, because of the lower discharge impedance, to simulate abrupt discharge events caused by contact with equipment and empty sockets (functional testing, burn-ins, reliability testing, pick and place operations, etc.). This happened at a time when the very fast rise time of metal-metal discharges was not well-understood. Since that time, the charged device model has been proven to quite adequately cover these events.

2. Recently, M. Tanaka-san (Renesas Electronics) at the September 2011 JEITA meetings [3] presented rationale and data supporting the elimination of the MM test. According to his historical account, the so-called "machine model" originated at Hitachi (now Renesas Electronics) about 45 years ago and was introduced to Japanese semiconductor customers as a test case to represent the HBM test in their IC product test report. This test method spread widely to the Japanese customer base and was later established as an ESD test standard by the EIAJ in 1981. Around 1985, some people began mistakenly to refer to the test as the machine model. Then, starting in 1991, ESDA, JEDEC and IEC adopted the model and its name as a new test standard. As use of the model increased, it was realized that the machine model name caused a lot of misunderstanding that needed to be clarified.

3. In the early days of ESD device testing, there was also a desire to avoid the high pre-charging voltages of the HBM test (2kV and higher). The 200pF and low impedance of MM was thought to be an equivalent but safe lower voltage test to address the same failure mechanisms as HBM. However, establishment of a single translation from MM voltage to HBM voltage has been difficult to achieve. Protection design has traditionally been focused on meeting the HBM requirement, but MM testers are susceptible to parasitic circuit elements; these parasitics from relay switching networks in the simulators cause more variation in the MM waveform than waveforms from HBM testers. In spite of this and without any supporting data, 200V MM became established as a *de facto* requirement. It was thought to be the safe level for handling, and that this level had to be simultaneously met along with the *de facto* 2kV HBM standard. In reality a device with a 2kV HBM withstand voltage might have an MM withstand voltage anywhere from 100 to 300V, depending on the device characteristics and the MM tester parasitics. This led to much of the confusion associated with specifying both HBM and MM specification levels.

4. The next important reason for discontinuing MM is that fast discharges to or from a metal surface are not correctly represented by the MM. The characteristics of the MM rising pulse were not established based on comparison to measurements on machine pulses, but rather were determined by characteristics of the already developed HBM simulators. The fast rising leading edge of metal-to-metal discharges are actually more effectively simulated using the current standard CDM test methods. This is known today because of the development of high speed oscilloscopes. However, during the 1980s there was a misunderstanding that MM was a good representation for CDM. This misunderstanding actually delayed the eventual development and acceptance of the CDM standards used today. Later in the 1990s, with much improved and accurate test for CDM and wider recognition that the fast discharges are covered by CDM alone, the test for MM frequently became replaced with CDM.

MM VS. HBM AND CDM

The waveforms for HBM, MM and CDM are compared in Figure 1 (page 176). The HBM and MM have similar ranges of rise time (2-10ns). Therefore any thermal heating in silicon taking place in this time period leads to the same failure mechanisms for both models. This holds true for all technologies, including advanced technology nodes. This early part of the waveform determines where protection circuits must be deployed in design. With similar rise time characteristics, HBM and MM encourage the same protection designs. For CDM, on the other hand, the rise time is much faster (0.1 – 0.5 ns) and often leads to a unique failure mechanism like oxide breakdown. Even more important, the observed ESD field failures are dominated by oxide breakdown when the CDM level is not adequate. Thus, a different set of protection strategies are generally needed for CDM. This makes it even more critical to focus on CDM qualification, instead of duplicating the HBM test information by using the MM. In Figure 1, we also show the observed failure modes for the same I/O pin after stressing with HBM, MM and CDM. It is clear that with HBM and MM the damage sites were the same in the protection diode, but with CDM stress the damage site corresponds to oxide breakdown in the output transistor. This also illustrates the fact that meeting high levels of MM does not improve CDM performance until the right effective design techniques are employed.

Commercial MM testers have inductors built into the MM stimulus circuit. These inductors must be present to produce the oscillatory waveform required in the MM test method. The inductors, however, actually slow down the MM waveform (Figure 1), and therefore MM cannot represent

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very fast metal-to-metal contact discharge as CDM does. On the other hand, the CDM test is directly represented by elevating the package potential and directly grounding the pin to produce the fast discharge. MM cannot be relied on to accurately model fast metal to metal contact discharges, which are known to occur in the field.

METAL DISCHARGE VERSUS CDM DISCHARGE

The analysis of M. Tanaka [2] is shown here to demonstrate that a metal discharge from a small metallic object to a device is similar to the commonly used CDM test. Tanaka considers small objects because large machines (typically >10 pF) are almost always grounded for reasons beyond ESD and thus pose little practical threat for these events. On the other hand, tools and small machines are difficult to ground and may lead to charging effects where the capacitance of the metal object is related to surface area and distance. These values can range from <1pF to nearly 10 pF. For example, this value could be as much as 1pF for a small metal object of 10 cm^2 at a distance of 0.5 cm. Both the small metal discharge and the CDM discharge can be represented by the same set of equations for I(t), and thus both can be expected to generate the same discharge event if the values of the parameters are similar. Figure 2 illustrates the case for a small object of 10 pF for both metal discharge and CDM discharge.

The above analysis is confirmed by measurements as shown in Figure 3, [2] where the discharge in (A) from a charged tweezer to IC pin is the same as the direct discharge from metal as shown in (B), and both are similar to the generated CDM discharge in (C). The time scale for both metal discharge and CDM discharge are indeed the same, clearly indicating that CDM is a good representation of the metal discharge in the Electrostatic Protected Area (EPA).

- *Metal discharge events are well represented by the CDM test.*
- *Most of the field failure returns for ESD have been replicated by the CDM test, but none with MM testing that are not also produced by HBM.*

The Industry Council on ESD Target Levels has studied HBM and MM results on a wide variety of designs in many technologies and concluded that MM is intrinsically related to HBM, with a correlation factor range that is dependent on the HBM design level [3]. This data is represented in Figure 4 (page 178). However, the most important conclusion of the

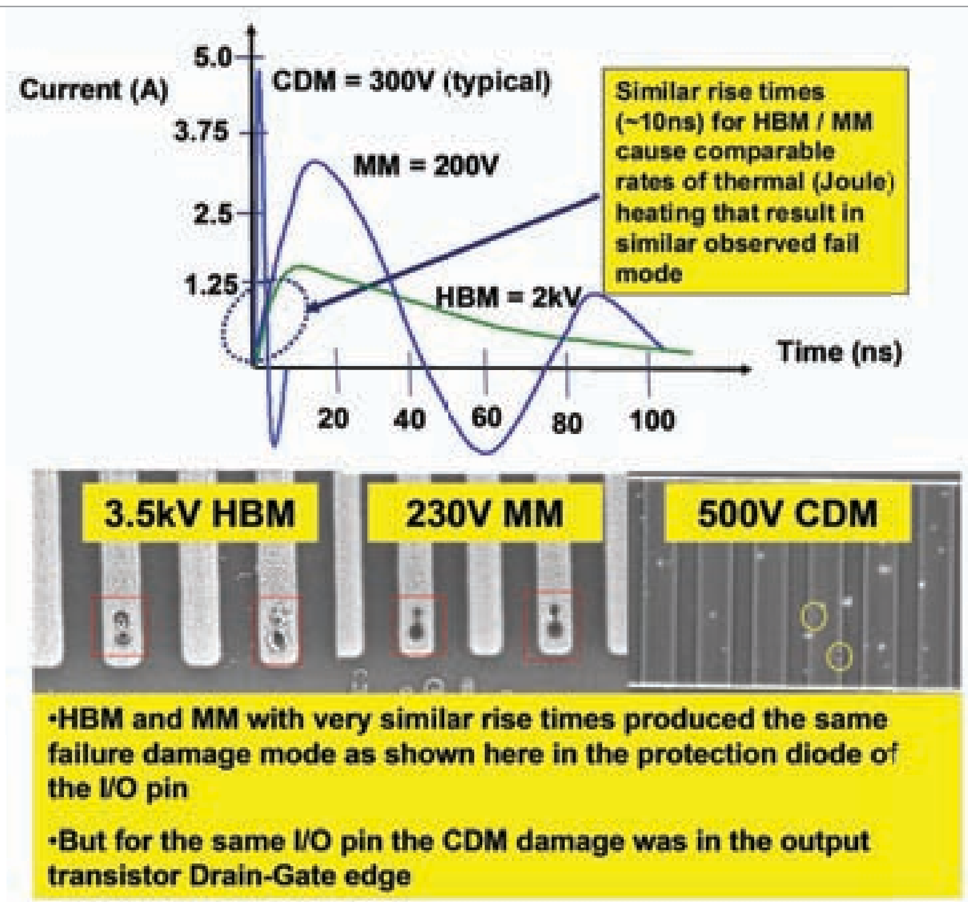

Figure 1: Comparison of HBM, MM and CDM waveforms

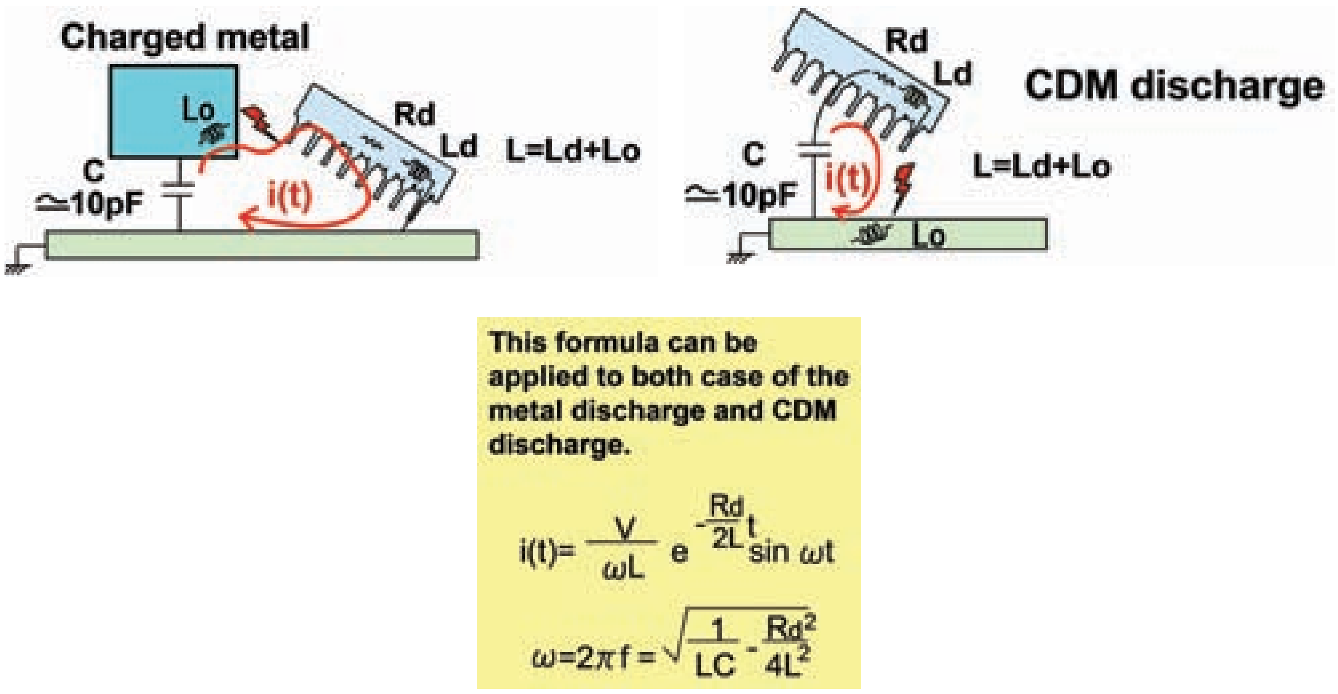

Figure 2: Discharge current equation for metal discharge or CDM discharge [1]

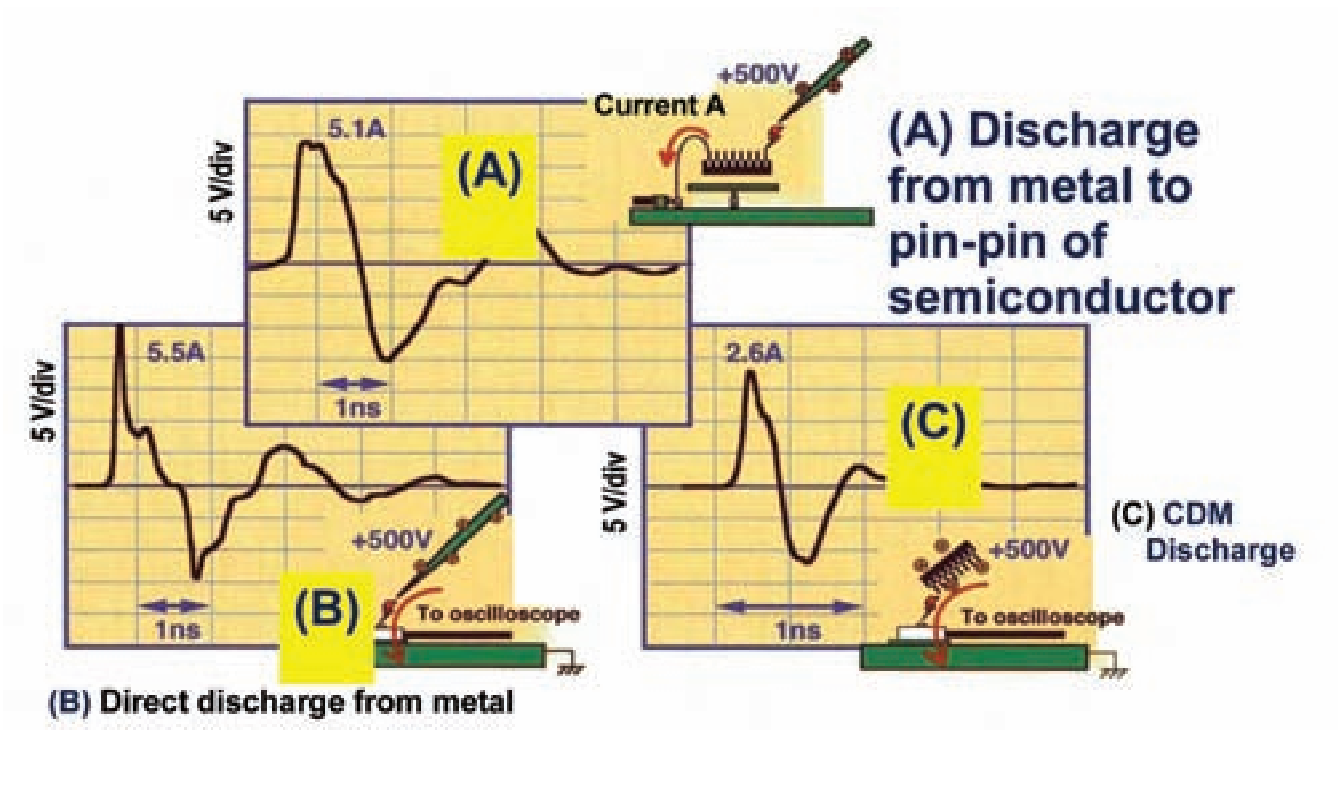

Figure 3: Comparison of measured waveforms for metal discharge and CDM discharge events [2]: (A) discharge from a charged tweezer on pin, (B) direct discharge from metal and (C) CDM test discharge

ESD

study was that MM is a redundant test and a sufficient level of MM robustness is automatically included in an adequate HBM design. This also includes the bipolar nature of the MM stress. Any oscillatory waveform which might be measured during discharges in the field is sufficiently covered if the part is proven to have an adequate HBM design.

This minimum design value, as measured by a MM tester, is well above any voltage remaining on all properly grounded machines in an ESD protected manufacturing environment. In essence, meeting a safe value for HBM (and CDM) is sufficient for production of ICs without needing to evaluate MM as an additional qualification.

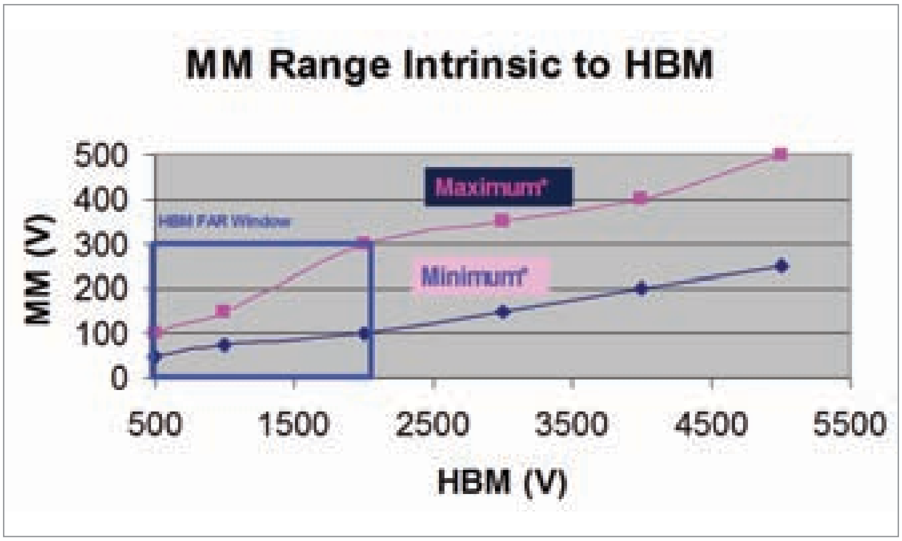

Figure 4: Correlation between HBM and MM measured on the same devices

- *The machine model test method specification to qualify ICs does not model or advance the real world ESD protection of IC products.*
- *IC evaluation with MM does not give any additional information as to how to address machine ESD control.*
- *While MM is an unnecessary qualification test, it is important to emphasize that control of voltage on machine parts that might contact device pins in accordance with ESD programs specifications such as S20.20 programs is still important.*

FIELD DATA ANALYSIS

The work from the Industry Council has shown that most of the overstress field returns exhibit failure signatures of higher energy EOS, and that the level of HBM ESD from 500V to 2000V (shown as the HBM Failure Analysis Return (FAR) window in Figure 2) on 21 billion shipped units did not show a correlation to the customer field return rates. Similarly, these very same shipped units (500V to 2kV HBM) also had MM levels in a range between 50-300V, as also seen from Figure 2. Therefore it can be concluded that the EOS field returns are indeed not related to this range of intrinsic MM levels. That is, it does not matter if a shipped device has a measured MM value of 50V or 300V.

- *Devices with various measured MM levels have shown no correlation to real world EOS failure returns.*

STANDARDS BODIES AND POSITIONS ON MM

During the last two decades, the electronics industry's standards bodies have changed their viewpoint with regard to MM and its requirement for IC qualification. At present, JEITA in Japan does not recommend MM. The Automotive Electronics Council's AEC Q100 standard gives a choice between HBM and MM, but does require CDM. In recent years, JEDEC has strongly recommended discontinuing use of the MM for ESD qualification because of its test variability and non-correlation to real-world failure modes. In general, standards bodies have come to recognize that:

- IC Qualification to HBM and CDM provides all the necessary ESD test requirements.
- MM testing of ICs is redundant to HBM and does not reflect unique real-world component ESD failure modes.
- Billions of IC components have been shipped worldwide and qualified using HBM and CDM testing only. No field failures have been found that would have been prevented by additional MM qualification.

The following statements are from the JEDEC web site:

- "JESD22-A115B is a reference document; it is not a requirement per JESD47G (Stress Test Driven Qualification of Integrated Circuits)."
- "Machine Model as described in JESD22-A115B should not be used as a requirement for IC ESD Qualification."
- "Only human body model (HBM) and charged device model (CDM) are the necessary ESD Qualification test methods as specified in JESD47G."

The ESD Association has downgraded the MM document from a Standard (S5.2) to a Standard Test Method (STM5.2) [4] and has adopted the following position:

- The ESD Association does not recommend using MM ESD as described in STM5.2 for IC qualification. IC Qualification should be done using the current standard HBM and CDM methods.

CONCLUSIONS

The information in this document supports the discontinuation of MM as part of IC qualification. The most important point to note is that a wide range of products, having only HBM and CDM testing performed, are being shipped today at volume levels in the billions with no field returns due to ESD. These products, passing at or above the recommended minimum HBM and CDM levels, are being routinely shipped by major suppliers and are accepted by major OEMs. No increase in field return rates has been observed with MM removed from qualification for these products.

The confusion generated by MM has persisted in the industry for over two decades. The presumed need for this test is causing additional qualification delay due to an extraordinary consumption of design/test resources, added delays in time-to-market and, in some cases, an impact on IC speed and performance. Maintaining safe HBM and CDM levels is sufficient to meet all IC manufacturing, handling and assembly needs.

EPILOGUE

Different customer sectors may feel that they need enhanced ESD requirements for specific reasons. For example, some automotive customers have more consistently required MM model testing; the impression being that an independent and redundant test provides enhanced safety, improved quality and reduced defectivity. However, industry experience has shown that passing a redundant (to HBM) MM qualification test does not help automotive manufacturers achieve these goals. Meeting current industry standard HBM/CDM will insure that a product can be safely handled with sufficient margin to prevent ESD damage and maintain the quality/reliability of the product as shipped from the component manufacturer. Since many suspected ESD failures turn out to be higher energy EOS in nature, methods to prevent electrical overstress during manufacturing will also help maintain product reliability.

COMMON GOALS

We have presented evidence and arguments that the MM test of ICs is redundant and there is no proof that devices have failed in the field because MM evaluation was not done. We strongly recommend that this test be discontinued for ESD qualification. This will save the semiconductor industry a tremendous and an unnecessary burden by greatly reducing the routine characterization that is done to support the qualification process. The ESD robustness designed into integrated circuits to survive HBM and CDM testing will provide protection against any MM-like stress. Eliminating MM testing of ICs has no deleterious effects and will free up resources for more important engineering challenges.

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Founded in 1982, the ESD Association is a professional voluntary association dedicated to advancing the theory and practice of electrostatic discharge (ESD) avoidance. From fewer than 100 members, the Association has grown to more than 2,000 members throughout the world. From an initial emphasis on the effects of ESD on electronic components, the Association has broadened its horizons to include areas such as textiles, plastics, web processing, cleanrooms and graphic arts. To meet the needs of a continually changing environment, the Association is chartered to expand ESD awareness through standards development, educational programs, local chapters, publications, tutorials, certification and symposia.

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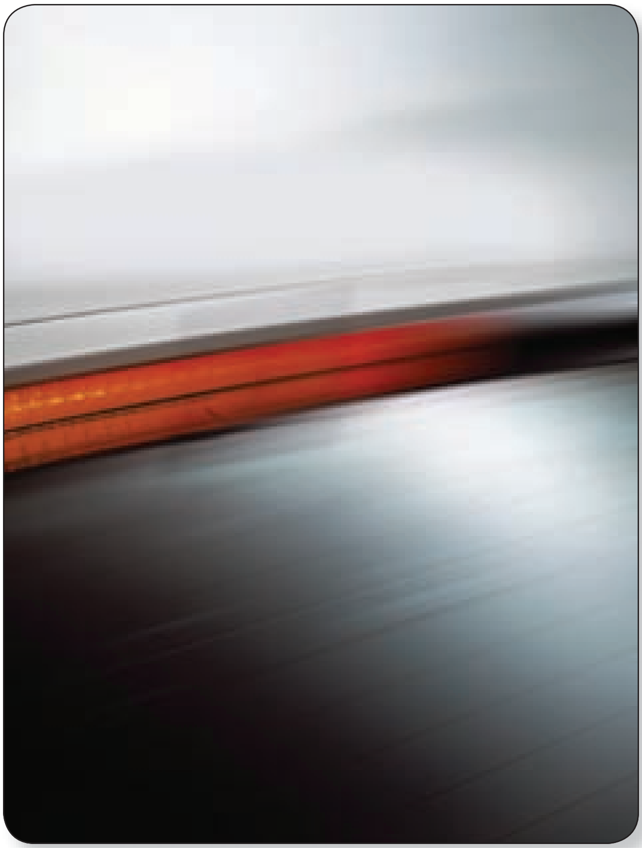
He is a recipient of the Outstanding Contributions Award from the EOS/ESD Symposium (1990), Outstanding Mentor Award from the SRC (1994), numerous Best Paper and Best Presentation awards from the EOS/ESD Symposium. He has served as the General Chairman both in 1994 and in 2005. He is a contributing Editor for the IEEE Transactions on Device and Materials Reliability (TDMR). Charvaka has been a member of the ESD Association Board of Directors since 1997, promoting university education and research in ESD. He is a co-chair of the Industry Council on ESD Target Levels. Charvaka is also a Fellow of the IEEE.

ESD



Effectiveness of Multilayer Ceramic Capacitors

for Electrostatic Discharge Protection

BY CYROUS ROSTAMZADEH, FLAVIO CANAVERO, FERAYDUNE KASHEFI AND MEHDI DARBANDI

A simple technique to deal with ESD can be achieved by mounting multilayer ceramic capacitors (MLCC) at the PCB I/O connector pins that is the ESD entry point. EMC engineers recommend using 0603 MLCC's placed at close proximity to each connector pin, mandating low-inductance mounting strategy associated with the PCB traces and vias. When selecting surface-mount techonology (SMT) MLCC for ESD protection of I/O pins, engineers specify the ESD capacitor value, its DC voltage rating, and a choice of technology (X7R or C0G). MLCC, as an ESD bypass or shunt device, is used to divert the ESD current to ground. ESD protection devices should perform ESD mitigation and should not exhibit degradation, while maintaining ESD robustness throughout the life span of a product. Nevertheless, post-ESD examination of small foot-print 0603 MLCC's reveals serious structural damage, manifesting itself electrically in a dramatic change in the impedance characteristics. This is a major departure from a pre-ESD capacitor, thus resulting in excessive low frequency leakage and functional misbehavior.

BACKGROUND

Electrostatic discharge (ESD) is one of the most important reliability problems in the electronic circuit industry. Typically in the integrated circuit (IC) industry, one-third to one-half of all field failures (customer returns) are due to ESD. As ESD damage has become more prevalent in newer technologies due to the higher susceptibility of smaller circuit components, there has been a corresponding increase in efforts to understand ESD failures through modeling and analysis. Manufacturers of integrated circuits provide ESD test information. However, the ESD data on IC level standards (human body model (HBM), charged device model (CDM), machine model (MM) and latch-up-to-the-system testing) is often confusing.

Design of robust ESD circuits remains challenging because ESD failure mechanisms become more acute as critical circuit dimensions continue to shrink. Circuit board designers are further constrained by the ability to design highly congested PCB's and meet ESD requirements. HBM provides much insight into device behavior during an ESD event [1,2].

An ESD event is the transfer of energy between two bodies at different electrostatic potentials, either through contact or via an ionized ambient discharge (a spark). This transfer has been modeled in various standard circuit models for testing the compliance of device targets. The models typically use a capacitor charged to a given voltage and then some form of current-limiting resistor (or ambient air condition) to transfer the energy pulse to the target.

In order to meet the module level ESD tests, various methods and techniques on printed circuit boards have been implemented and investigated. One effective technique is to add discrete noise-decoupling components or filters into complex CMOS based IC products to decouple, bypass, or absorb the electrical transient voltage (energy) under the system-level ESD test [3]. Various types of noise filter networks can be employed to improve system-level ESD stress tests, including capacitor filters, ferrite bead, transient voltage suppressor (TVS), metal oxide varistor (MOV), and 2nd order LC filter or 3rd order π-section filters.

Multilayer ceramic capacitors (MLCC) are employed as an ESD bypass mechanism at the connector pins of electronic control modules. An automotive control module may require the use of a single high-density connector with pin density in excess of 200. In a typical application, a connector may present the designer with a matrix of 4 x 50 (4 rows of 50 pins at each row) in a tightly congested PCB real estate. To accommodate the ESD protection for each and every I/O pin at the connector of highly congested PCB real estate, design engineers recommend the use of 0603 style MLC capacitors. In most applications, MLC capacitors used for ESD protection are rated for 100 V stress level. However, post-ESD characteristics of MLCC's are often ignored or misunderstood. In reality, MLCC's exposed to ESD stress exhibit a dramatic shift in characteristic impedance behavior. Careful examination of MLCC's reveals permanent structural damage resulting in excessive low frequency leakage. Post-ESD behavior of MLCC's results in a functional deviation for the control module, and it is fundamentally unsafe to use the product for its intended application. It is suggested that low profile 0603 capacitors should not be used for ESD protection, as reported in this paper. Alternative solutions can be met by the use of low profile transient voltage suppressors (TVS) or fast metal oxide varistors (MOV). However, 0805 style MLCCs with high value capacitance (> 47 nF) provide a good solution and are safe to be used as an ESD bypass element.

MLCCs used as a protective device or mechanism should consider the voltage, peak power and energy as the key components of an ESD threat. It is thus necessary to fully characterize the amplitude and timing of ESD components. Therefore, protection structure should reduce the voltage, peak power and energy threats by shunting the stress currents away from fragile portions of the microcontrollers and other ICs [4].

To solve ESD problems, MLC capacitors employed as ESD bypass or filter component on printed circuit boards (PCB), must shunt the ESD transient current safely to ground. It is important that MLC capacitors, employed as bypass components, absorb the ESD voltage and current safely and protect the device under test with no degradation. In addition, the MLC capacitor must remain within its parametric tolerance for it to be considered a reliable protection mechanism.

MLC CAPACITOR AS AN ESD PROTECTION DEVICE

Multilayer ceramic capacitors are designed for use where a small physical size with comparatively large electrical capacitance and high insulation resistance is required. The general purpose 0603 (1.6 mm x 0.5 mm) class II, type X7R (-55°C to +125 °C) is a popular choice for automotive electronic control module design. Therefore, it is a common practice to apply X7R MLCC's as an ESD protection component at all I/O pins.

Figure 1 illustrates a horizontal grind of the 0603 MLCC (magnification X 100) with plates spaced at 21 μm apart for a 10 nF, X7R type II capacitor. A higher value capacitor is designed with an increased number of plates. This will result in a narrow dielectric thickness, a possible drawback for high voltage transients. At the present time (May 2012), capacitor values for a type II X7R 0603 (100 V) range from 180 pF to a maximum value of 39 nF. However, the capacitor value range for the same technology but with larger physical size (0805) varies from 220 pF to a maximum value of 120 nF. This can be an important factor if ESD protection capacitor value is determined to exceed the maximum value of 39 nF available in 0603 package.

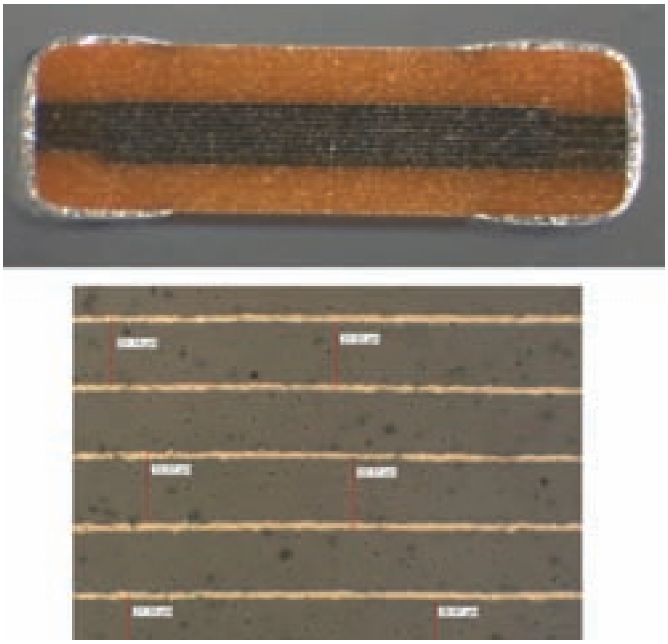


Figure 1: Standard 0603 MLCC (magnification x100)

Figure 2 illustrates two different styles of MLCC technology with respect to the design of conductive plates. Capacitor manufacturers recognize the over-voltage stress concern and have provided an ESD-enhanced MLCC product. Close examination of Figure 2 demonstrates the style B MLCC is an ESD-enhanced design.

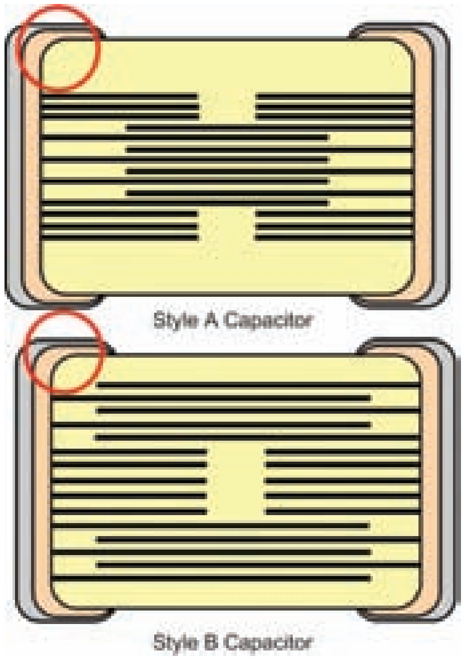


Figure 2: 'Standard' vs. 'ESD-enhanced' 0603 MLCC

Figure 3 illustrates a horizontal grind of an ESD-enhanced MLCC at x100 magnification. Comparison with Figure 1 demonstrates the differences in plate geometry design.

Printed circuit board designers with fundamental EMC training are required to ascertain the optimum mounting strategy for ESD capacitors. EMC engineers verify a "Y-connection" topology for all of ESD capacitors at every I/O pin of the connector. MLCC must be placed in close proximity to the I/O pin (< 1cm) with a short trace (< 1cm) to the PCB return plane. In this manner, added PCB parasitic trace inductance and its degradation effect on the effectiveness of the ESD bypass capacitor is minimized. The general concern is to limit the added inductance due to PCB mounting inductance, and thus provide a low-impedance path for ESD current flow to return plane.

Another limitation would be to use the lowest value capacitor available, where it is most effective at higher frequencies. ESD would result in an RF current with a bandwidth in excess of 330 MHz. The choice between a 1 nF and 680 pF would easily be reduced to the latter one. However, ESD HBM consists of a 150 pF capacitance, thus a higher value MLC capacitor is preferred. A voltage divider network is established by the combination of HBM capacitor and MLCC. The voltage developed across a larger value MLCC, would lower the voltage developed across an integrated circuit, as indicated in Equation 1.

$$V_{MLCC} = \frac{C_{HBM}}{C_{HBM} + C_{MLCC}} V_{ESD} \quad \text{Eq. 1}$$

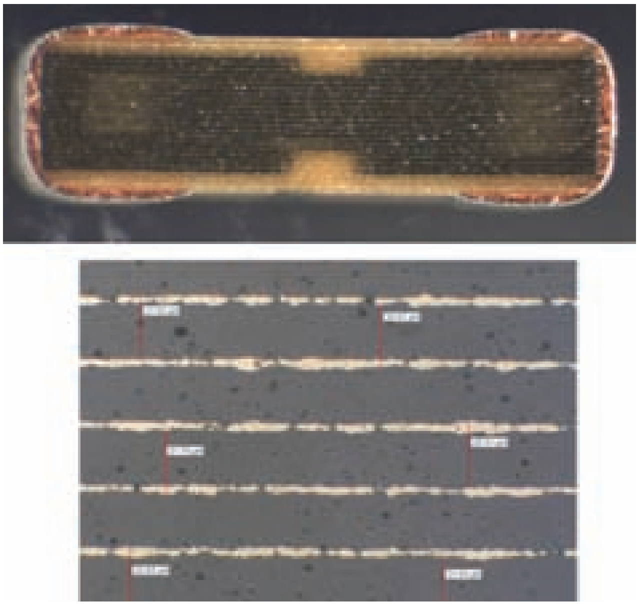


Figure 3: ESD-enhanced 0603 MLCC

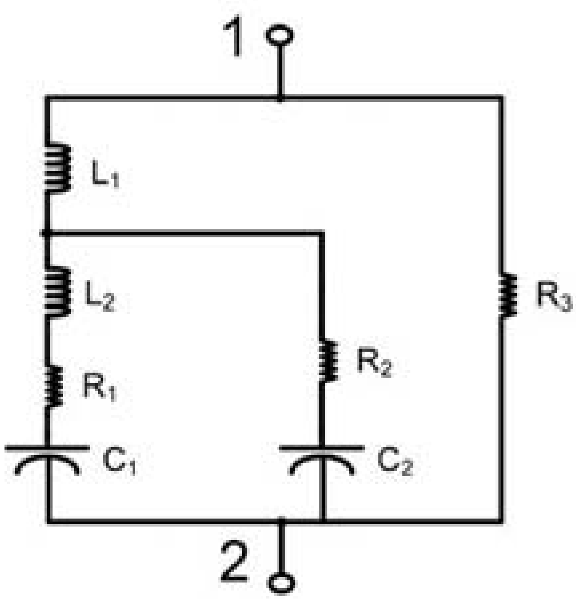


Figure 4: Improved electrical model of MLC capacitors

Therefore, where $V_{MLCC} << V_{ESD}$, it is required that $C_{MLCC} >> C_{HBM}$.

MLC CAPACITOR ELECTRICAL MODEL

Several electrical models of capacitors are available in textbooks and RF publications used by the EMC/RF community to describe the electrical behavior of MLC capacitors. A simple series RLC network is commonly used to provide accurate behavior for most applications. However, simple RLC model fails to provide the additional technical insight required for analysis of MLCC's exposed to ESD pulse. The modified model presented in Figure 1 has additional elements to describe the behavior of MLC capacitors exposed to ESD stress. In fact, the model described here is an accurate electrical description, necessary to account for the various physical attributes found within a capacitor.

1. L_1 is the series parasitic inductance associated with plate connections.
2. L_2 is the equivalent series inductance. It is also known as L_{ESL}.
3. R_1 is the equivalent series resistance (also known as R_{ESR}) and represents the actual ohmic resistance of the plates. This value is typically very low. It causes a power loss of I^2R_1. Its contribution to the total dissipation factor is $D_1 = 1/(\omega R_1 C_1)$.
4. C_1 is the nominal capacitance.
5. R_2, the dielectric loss, is a parallel resistance arising from two phenomena; molecular polarization and interfacial polarization (dielectric absorption). Dielectric loss is a complex phenomenon that can change with frequency in most any manner that is not abrupt. Its contribution to the total dissipation factor can be approximated by $D_3 \sim 1/(\omega R_2 C_2)$.
6. C_2 is the parallel dielectric absorption capacitor.
7. R_3, the leakage resistance or insulation resistance, is a parallel resistance due to leakage current in the capacitor. This value is typically very high. It causes a power loss of V^2/R_3. Its contribution to the total dissipation factor is $D_2 = 1/(\omega R_3 C_1)$.

The impedance characteristics of type II (0603, X7R MLC) capacitors for a 680 pF and 10 nF is illustrated in Figure 5.

ESD is a high frequency pulse with a rise time of less than one nano second, resulting in spectral content in excess of 330 MHz. Hence, the choice of ESD capacitor is reduced to a smaller value MLCC, as seen in Figure 2. Closer examination of Figure 2 reveals a lower impedance for a 680 pF (1.71 Ω at f = 330 MHz) compared with a 10 nF (3.97 Ω at f = 330 MHz). Another consideration may be the result of capacitive loading of certain I/O signals, i.e., CAN bus, where a limited capacitance can be added to the communication bus.

The requirements of a lower value ESD capacitor, as in the previous paragraph, may suggest the use of the lowest value MLCC available to the industry. In addition, there is a third factor that is outlined in Table 1; R3 (insulation resistance) that may add additional incentive for the use of the lowest

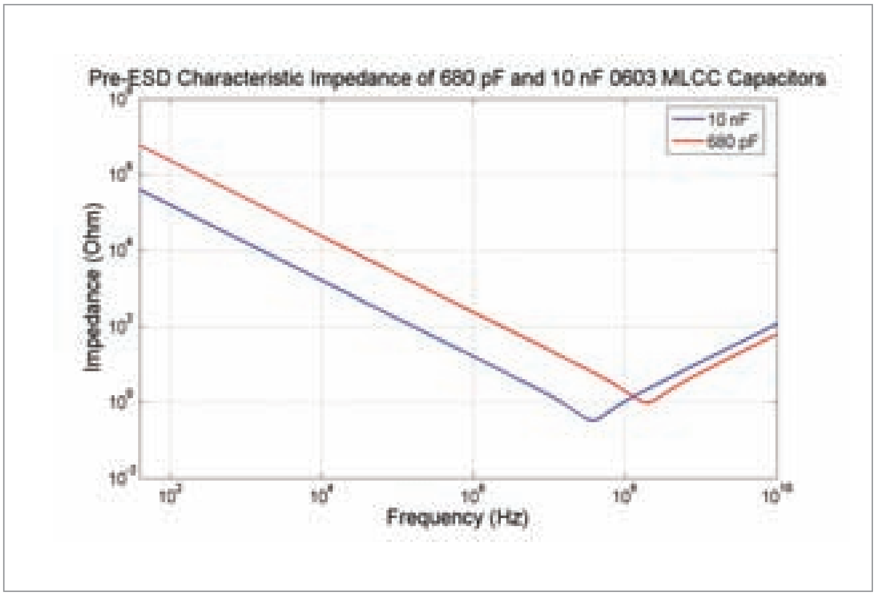


Figure 5: Pre-ESD impedance characteristics

Nominal Value @ 1 kHz	680 pF	10 nF
L1	49 pH	91 pH
L2	931 pH	1.730 nH
C1	680 pF	10 nF
C2	4.10 pF	4.10 pF
R1	5.15 kΩ	0.329 kΩ
R2	753.73 Ω	34.57 Ω
R3	$1.471 \times 10^{12}\Omega$	$.01 \times 10^{12}\Omega$

Table 1: MLCC 0603 capacitor model components

ESD

Figure 6: ESD air-discharge to 0603 MLCC

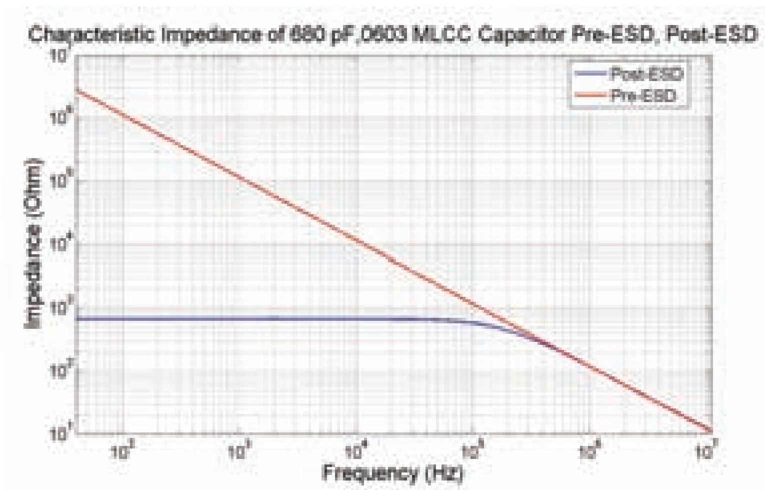


Figure 7: Measured pre-ESD and post-ESD (MLCC 680 pF)

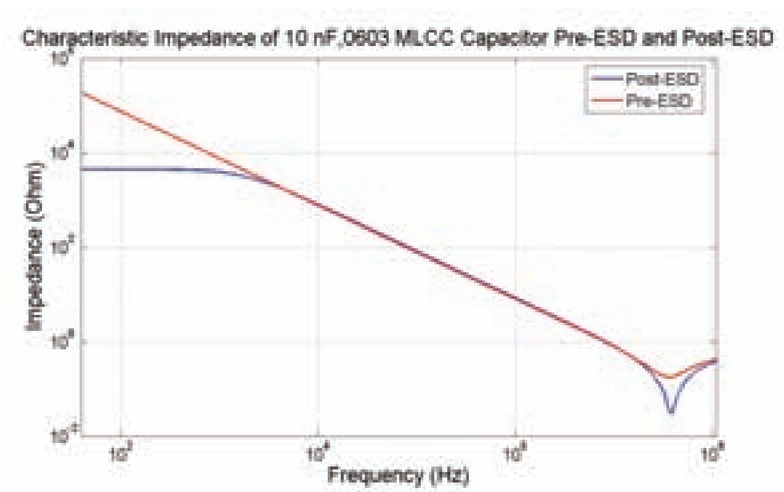


Figure 8: Measured pre-ESD and post-ESD (MLCC 10 nF)

value MLCC. However, further insight is required to distinguish the apparent easy choice.

In Table 1, all nominal and parasitic elements for both capacitors are listed as per MLCC supplier A.

It is important to note that the insulation resistor R3 is an order of magnitude higher in value for smaller value capacitor (Table 1). As more plates are stacked up to accommodate higher value capacitance in the same physical volume of the 0603-style package, the dielectric thickness is reduced by a factor of 14.7. Therefore, as a consequence of thinner dielectric material between the capacitor plates, the insulation resistor for higher value capacitor is reduced by the same ratio (capacitor ratio: 10 nF/680 pF = 14.7, insulation resistor ratio: $0.1 \times 10^{12}\ \Omega / 14.7 \times 10^{12}\ \Omega = 1/147$. It is clear that a higher value capacitor will sustain a dielectric breakdown in lower ESD voltages. It was suggested by this argument, for ESD applications, only necessary to consider lower-value capacitors with higher insulation resistance in order to protect for dielectric breakdown, i.e., 680 pF vs. 10 nF. Further investigation was required to address the accuracy of aforementioned statement.
If a smaller capacitor presents a higher insulation resistance as shown above, it is important to examine the behavior of the insulation resistance after ESD tests. For further insight, it is important to evaluate the impact of ESD stress on 680 pF and 10 nF capacitors by characteristic impedance of post-ESD capacitors.

HUMAN BODY ESD TEST

ESD tests for automotive applications are derived and based on a human body model specified by original equipment manufacturers (OEM) [5,6,7,8,9].

A typical HBM discharge network consists of a 150 pF capacitor with a 2 kΩ resistor. The HBM capacitor can be charged up to 25 kV for an air-discharge test. The static charge accumulated on the 150 pF discharge network capacitor (charged to 25 kV) would amount to 3.75 μC. ESD is a high-frequency, high-voltage and high current event that can deposit 46.875 mJ of energy in the protection device in a relatively short time duration.

HBM provides much insight into device behavior during an ESD event. Although the HBM stress is characterized by a certain charging voltage, V_{HBM}, the 2 kΩ series resistor of the circuit is usually much larger than the impedance of the device under test, so we think of the HBM tester as current sources, with the peak HBM current equal to 12.5 A. (V_{HBM} = 25 kV, air-discharge).

PRE-ESD AND POST-ESD MEASUREMENTS

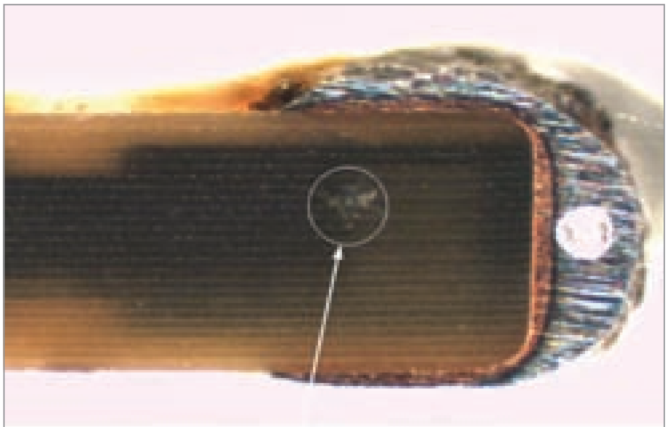
In order to evaluate the impact of ESD stress on 0603 MLCCs, two different types of tests were performed. Since a populated electronic control module is the intention of a realistic test, it is important to evaluate the impact of ESD stress per OEM ESD test techniques. In another method, a 0603 MLCC network was prepared, as shown in Figure 6, with two short wires (< 1 cm) at each end. Terminal 1 was connected to a ground plane where an ESD gun return wire would normally be connected. The ESD discharge tip was slowly approached to the floating terminal until an air discharge was achieved.

Pre-ESD and post-ESD characteristics of the 0603 capacitor were recorded using an Agilent 4294A impedance analyzer (40 Hz – 110 MHz) with the help of an Agilent 16034G test fixture.
Capacitors were removed from test PCB or ESD network wires, and mounted inside the 16034G test fixture for impedance characterization.

It was decided to apply an ESD pulse to a fully populated automotive electronic control module as designed with rigorous EMC guidelines. As OEM ESD requirements provides guidelines [7,8,9] for remote I/O access ESD stress tests. An HBM model with discharge network as outlined in section IV was calibrated and ESD voltage levels from +/- 4 kV up to +/- 25 kV were applied in successive order. After each discharge, the MLCC was removed and analyzed on an impedance analyzer as per the previous method.

Figure 7 illustrates the impact of the ESD pulse at +/-15kV level for the 680 pF capacitor. Figure 8 illustrates the impact of the ESD pulse at +/-15kV level for a 10 nF capacitor.

Post-ESD capacitor dielectric damage is illustrated in Figures 9 through 11 (horizontal grind) on a magnification scale of 100. The physical damage to X7R and C0G technologies are shown.

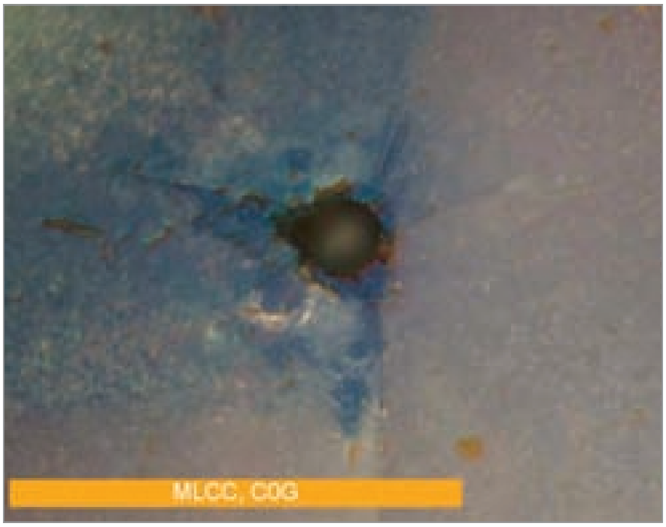


ESD Damage to ESD Capacitor SMD 0603 package
(magnification X 100)
"Horizontal Grind"

Figure 9: Dielectric damage for post-ESD MLCC

MLCC, X7R

Figure 10: Dielectric damage for post-ESD X7R MLCC



MLCC, C0G

Figure 11: Dielectric damage for post-ESD C0G MLCC

ESD

In Figure 12, a modified electrical model represented as per Figure 4, was used to illustrate post-ESD effects on both capacitors. In the electrical model per Table 1, R3 was replaced with a 500 Ω resistor to represent the nominal pre-ESD value provided by MLCC manufactures in Table 1 (14.7×10^{12} Ω).

It is important to note that the 10 nF capacitor developed severe leakage from 40 Hz up to 20 kHz, and for 680 pF the upper frequency is approximately 200 kHz. The impedance of both capacitors registers a 500 Ω resistive value in the aforementioned frequency range. It is thus concluded that ESD has caused non-recoverable, permanent damage to the MLCCs. Post-ESD behavior suggests physical damage to dielectric material due to metallization of capacitor plates. In reference to Figure 4, it is clear that R3 has shifted from its pre-ESD nominal value as per Table 1 (for 680 pF, R3 = 1.471×10^{12}Ω, or for a 10 nF, R3 = 0.1×10^{12}Ω to an extremely low value of 500 Ω).

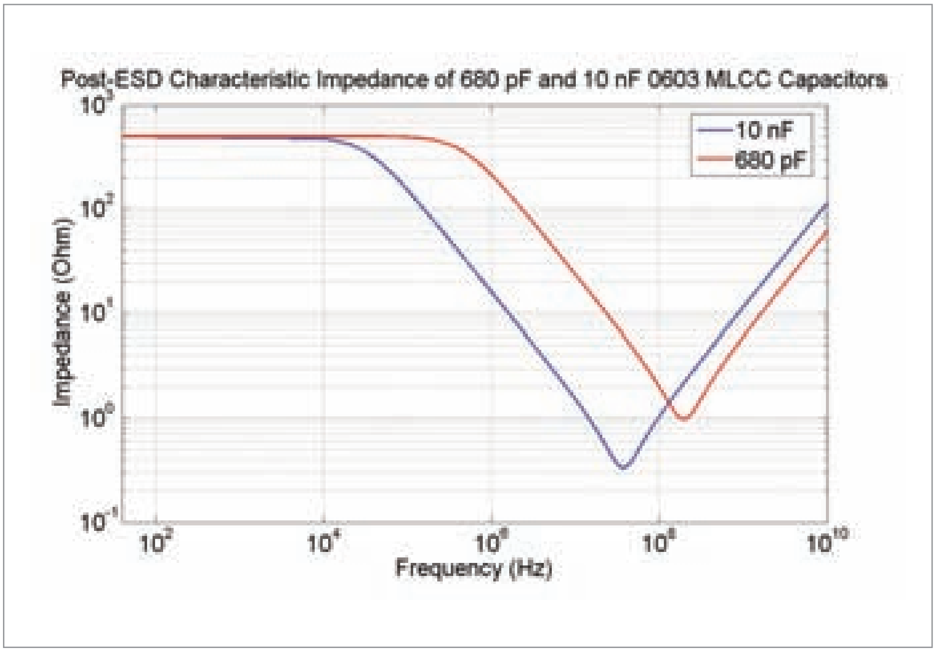


Figure 12: Simulated post-ESD impedance characteristics, R3 = 500 Ω

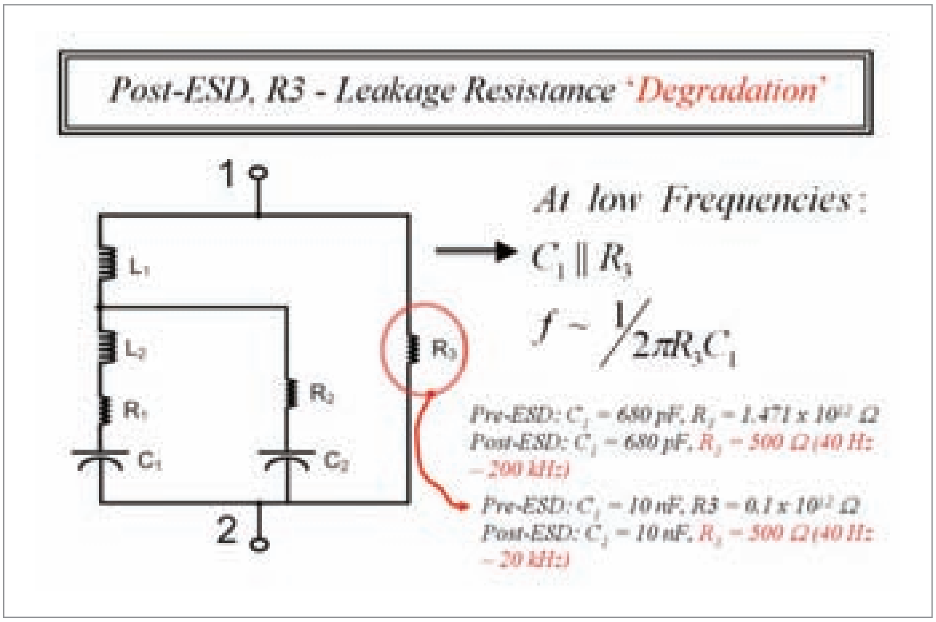


Figure 13: Post-ESD impedance behavior

The issue of why the 680 pF MLCC has a 500 Ω leakage up to 200 kHz, whereas 10 nF shows the ill-effect only up to 20 kHz, can be explained as follows: the circuit of Figure 4 simplifies to the parallel of C1 and R3 at low frequencies, and the knee of the impedance curve appears for $f \sim 1/2\pi R_3 C_1$. For post-ESD, the 680 pF MLCC is dominated by R3 from DC to ~ 300 kHz, whereas R3 contributes only up to 20 kHz for the 10 nF capacitor. Figure 13 illustrates the post-ESD leakage resistance degradation.

It is clear that smaller size MLCC will suffer extreme leakage to a much higher frequency range. Use of higher value MLCCs is recommended, in contradiction to previous recommendations.

As an extension to exposure of 0603 MLC capacitors to ESD stress, additional ESD tests were performed on modules populated with larger 0805 MLC capacitors. Figure 14 illustrates the impact of +/- 25 kV HBM ESD stress on a 4.7 nF capacitor. It is clear that a 4.7nF 0805 capacitor would fail the ESD requirements. However, extending the capacitor size (value) in an 0805 package to 10 nF results in ESD compliance.

CONCLUSION

This study is an examination of the physical damage to the 0603 MLC capacitors exposed to ESD transients. It shows that permanent damage to dielectric material resulted for ESD voltages in excess of 15 kV. The use of 0603 MLC capacitors for I/O connector pins, as an ESD bypass mechanism, is not recommended and should be avoided. However, in larger footprints, 0805 MLCCs will meet the ESD stress for 25 kV requirements, provided the capacitor size exceeds 10 nF, and is rated for 100 V applications. A preferred ESD bypass solution would use a low capacitance transient voltage suppressor (TVS, C_{TVS} < 100 pF) or a fast metal oxide varistor (MOV).

However, I/O pin ESD capacitors in the range of 1 nF to 100 nF are often utilized as an input RF filter at the connector pins. The ESD capacitors provide a bypass element for the induced RF currents on the module harness due to impinging electromagnetic fields. Low value TVS capacitance is insufficient to provide the required filter across the 1 MHz – 200 MHz frequency bandwidth. Use of a TVS in parallel with a 0603 capacitor (10 nF – 100 nF) is recommended, where permissible.

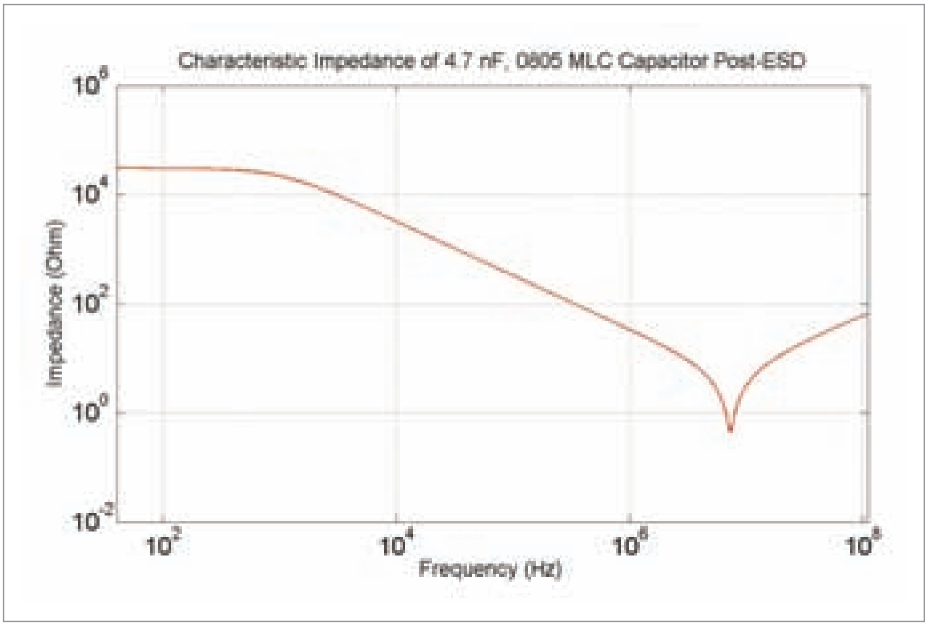


Figure 14: Measured post-ESD for a 4.7 nF 0805 capacitor

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ESD

International Wireless Registrations

Overview for Medical Manufacturers

BY MICHAEL CASSIDY

Telecom/Wireless

As medical devices go wireless, medical manufacturers face a new set of regulatory requirements and restraints. In addition to medical registration, wireless medical devices must receive radio spectrum approval. While the devices vary greatly, the wireless aspects are relatively uniform. That is to say, there are seemingly unlimited healthcare applications but only finite methods of sending data and, of course, limited RF spectrum. Thus, the wireless aspects of even a cutting edge medical device generally fall into familiar categories for international communications and radio spectrum authorities.

In my experience, international wireless compliance is often new territory for medical device manufacturers. Most countries, however, have had regulatory regimes in place for years and have well-established wireless regulations. Certain rules or restrictions may change, but the international process as a whole maintains fundamental characteristics and common pitfalls. Here are a few things to keep in mind before going global with a wireless medical (or any wireless) device.

CHECK OPERATING FREQUENCY AND APPLICATION EARLY AND OFTEN

A manufacturer should never assume commonalties between radio spectrum allocations across countries. Yes, commonalities exist, such as for certain ISM bands. However, one should always verify this and should also note the allowable output power. Many regulatory agencies publish frequency allocations on their website. Further, in some countries, certain RF technologies, such as ultra-wide band, may not be allowed at all.

MINIMIZE WORK AND COSTS

Medical manufacturers often purchase wireless components, from WLAN modules to GPRS modems, from an external vendor. So a radio module may already be approved in a given country. This 'modular' approval might be sufficient for the entire medical device, or it could reduce the cost, in-country testing, or paperwork needed for the regulating communications agency. Many countries require a local representative or license holder for a wireless certification. Manufacturers who have gone through medical registration and distribution with local partners should try to use their existing in-country network to fulfill any local representative requirements.

DON'T FORGET THE EXTRAS

In addition to the RF modules used in the device, medical products or systems may have supplemental components. Items such as power supplies, access points, or notebooks will likely need in-country certification. Medical manufacturers should speak with their vendors early and present them with a list of documents they will need. If, for example, a medical device works with a wireless access point, the AP vendor may need to provide block diagrams,

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authorizations forms, and even schematics. Presenting the vendor with this type of list at the last minute may cause delays, and it is best to know if the vendor is unwilling or unable to provide any necessary materials as early as possible.

KNOW THE TIMELINE

Those who have dealt with medical registrations may already intuit the often bureaucratic process of product registrations. While it is important to have the good connections on the ground and an understanding of a country's process, the lead-time for applicants is often fixed. Some countries, for example, require local testing at an approved lab before the application goes into review with the communications authority. Given this restraint, the applicant faces a minimum lead-time of several weeks. This is due to the time it takes to review documents, test the product, write the test report, and have the regulator review everything. Failing tests or having samples stuck in customs will, of course, cause unnecessary delays to the project. Knowing the common pitfalls and causes for delays in a given country will reduces the risk of falling behind schedule.

While the applicant should not be overly optimistic on the lead-time for approval, he should also be wary of lead-times that are too long. If the manufacturer is using a third party agent, that agent may want to 'under-promise and over-deliver'. The agent may state the lead-time for RF registration is twelve weeks, knowing that it usually takes only nine weeks. A medical manufacturer, new to international wireless approvals, may then think the agent has come in ahead of schedule. In fact, such sandbagging doesn't help the applicant plan his or her schedule. Therefore, one should err on the side of caution, as lead-times can vary depending on the regulators queue and other factors such as political unrest, natural disasters, etc. But, of course, the principal goal is having a realistic timeline for completion, as the whole team needs to know when they can enter a market. And medical manufacturers have the dual burden of dealing with two time lines for approval.

CONCLUSIONS

International wireless approvals add a new and independent dimension to the compliance picture for medical manufacturers. In the United States, for example, the FDA and FCC have issued a joint press release and the FDA has published recommendations relating to compliance. This suggests some overlap between the organizations on this issue. As *In Compliance Magazine* reported, the FCC has recently authorized the use of medical body area networks (MBANs) in the 23600-2400 MHz range. Medical manufacturers, however, will find that the communications authority ultimately dictates the parameters for use of a country's RF spectrum. Indeed, the FDA has officially 'suggested' that medical devices using RF adhere to all FCC regulations. In a 2007 publication, the FDA recommended RF medical devices undergo safety, EMC, and wireless testing. This is for the purpose of better anticipating how the device will function in a medical environment and ensuring crucial data transmissions do not fail. While these are valid points, the FDA recommendations are requirements for the FCC. Internationally, one generally sees communications agencies function autonomously. Exemptions to a RF-related regulation on the grounds that a device is medical are rare. Thus the manufacturer enters another jurisdiction.

Employees of medical manufacturers who have dealt with the FDA and its international counterparts may not end up handling the international wireless approval projects for the same devices. This task could go to an EMC, safety, or RF engineer. As mentioned, existing in-country networks, formed from distributors or medical compliance partners, can benefit the wireless process. Yet, since the regulatory agencies function separately, the employee managing international wireless submittals may not need an understanding of the medical registration process as it exists in each country (assuming someone has that covered). As the use of wireless medical technology accelerates, we may see the regulatory landscape evolve throughout the world. For now, medical manufacturers will join the IT, telecommunications, and many other industries in facing the world of international wireless compliance.

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Recent Changes to GR-63-CORE

BY CLAYTON FORBES

Telcordia recently released GR-63-CORE Issue 4 "Physical Protection Requirements for Network Telecommunications Equipment", with a total of 27 new requirements (Rs) and objectives (Os). It has been six years since the document was updated and, as in previous releases, the specification has numerous technical changes.

The first change you will notice is the reactivation of Section 3. Going back to the Issue 2 version of the specification in 2002, Section 3 was a look forward to generic framework requirements. In the Issue 3 release of 2006, this section was deleted from the document and was left dormant. For the Issue 4 release, the section is activated and renamed as "Equipment Spatial Design Requirements for Frames and Chassis". Activating this section allows for segregation between the office space planning requirements (Rs) and objectives (Os) and equipment spatial Rs and Os. In Section 4, some of the technical changes that will be reviewed include a new operational high temperature requirement based on the airflow of the equipment under test (EUT), new energy efficiency requirements, and an optional operational random vibration test, to name a few. Some tests remain unchanged and will be skipped in this recap. These include surface temperature, mix flowing gas, hygroscopic dust, and acoustics.

SECTION 2 - FACILITY AND SPACE PLANNING REQUIREMENTS

In previous issues of the document, space planning requirements and objectives were intertwined with test requirements throughout Section 4. In the latest version, the Section 4 Rs and Os dealing with building layouts, such as Central Office Lighting Requirement R4-98 and Objective O4-99, are moved to Section 2 and relabeled as R2-31 and O2-32. Other requirements and objectives that are moved around in the document can be tracked between the versions by using their absolute number, which is the bracketed number in the Rs or Os. By doing this, Sections 3 and 4 have become much cleaner and easier to follow for both manufacturers and laboratories.

SECTION 3 - EQUIPMENT SPATIAL DESIGN REQUIREMENTS FOR FRAMES AND CHASSIS

Section 3 now defines the spatial requirements for frames and chassis. The section includes most of the original Rs and Os from Section 2 and thirteen new Rs and Os. The thirteen new Rs and Os include R3-4 and R3-5 say that access to anchoring bolts is needed when shelves are installed in a frame. R3-7 is that a frame must have the ability to join to an adjacent frame at the top. R3-8 states that a dimensional drawing of the equipment must be supplied and enclosed in the test report. R3-29 demands that the mounting holes for a chassis be a closed slot.

TEMPERATURE TESTING

For the three storage temperature tests (low-temperature exposure and thermal shock, high relative humidity exposure, and high-temperature exposure and thermal shock) there is no change to the testing. The specification does clarify that testing the units in an unpackaged state is an acceptable test method. It also allows for slower ramp rates during the high humidity exposure test. The slower ramp rates allow the test to remain non-condensing for larger systems.

The operating temperature test has undergone significant changes. An ongoing issue with equipment being supplied to end-users is the airflow cooling pattern they use. Equipment with airflow patterns that deviate from the required preferential pattern of R4-34 or O4-35 will now be tested to a higher operational temperature. The high operational temperature test is performed at either 50ºC or 55ºC depending on whether the equipment under test (EUT) is frame level equipment or shelf (chassis) level. Now if the equipment has a non-preferential air intake, i.e. not in the front of the EUT, the maximum operating temperature rises to 60ºC or 65ºC depending whether it is a rack or a shelf. These new high temperature requirements are from Table 5-1 and 5-2 of the specification (Figure 1). Equipment with the non-preferential air intake can still be tested to the lower temperature levels if it is supplied and tested with an air deflector or air baffle that changes its air intake to the front of the equipment as stated in O4-36. Another change to the operating temperature profile was done to align the test with the requirements of ETSI EN 300 019-2-3 Class 3.2. During the 96 hour humidity dwell, the temperature and humidity are raised from 28ºC, 90% RH to 30ºC, 93% RH.

ALTITUDE, TEMPERATURE MARGIN, FAN COOLED EQUIPMENT

Altitude testing remains essentially the same with two exceptions. The temperatures for the test are raised to align with the changes in the operational temperature and humidity test. These temperature changes are also shown in Table 5-1 and 5-2 (Figure 1). The second change is to the alternate altitude test method using temperature compensation. In Issue 3, if the equipment met the configuration criteria to apply the temperature compensation method, it could be used. This entailed adding 1ºC/1000 feet to the operational temperature. For a shelf level product, the test temperature was 61ºC, 55ºC for the operational requirement, and 6ºC to simulate the 6000 feet from Objective 04-11. Objective 04-12 from Issue 3 is met by default since its required temperature for a shelf product is 58ºC. In Issue 4, the altitude of the test site can be considered and subtracted from the temperature compensation. If the test site is 3000 feet above sea level, the test will be performed at 58ºC, 55ºC from Objective 04-10 and 3ºC for the altitude compensation ([6,000 feet- 3000 feet

Table 5.1 Variable Test Temperatures for Frame-level Products

Operating Tests				
Effective Air Inlet Location	Operating Temperature and Humidity	Operating Altitude	Operation with Fan Failure	Temperature Margin Determination
Front aisle or none	T_{OH}=50ºC	T_{AL}=30ºC T_{AM}=40ºC T_{AH}=50ºC	T_{FH}=40ºC	T_{ML}=50ºC
All others	T_{OH}=60ºC	T_{AL}=40ºC T_{AM}=50ºC T_{AH}=60ºC	T_{FH}=50ºC	T_{ML}=60ºC

Table 5.2 Variable Test Temperatures for Shelf-level Products

Operating Tests				
Effective Air Inlet Location	Operating Temperature and Humidity	Operating Altitude	Operation with Fan Failure	Temperature Margin Determination
Front aisle or none	T_{OH}=55ºC	T_{AL}=35ºC T_{AM}=44ºC T_{AH}=55ºC	T_{FH}=40ºC	T_{ML}=55ºC
All others	T_{OH}=65ºC	T_{AL}=45ºC T_{AM}=55ºC T_{AH}=65ºC	T_{FH}=50ºC	T_{ML}=65ºC

Figure 1: Tables 5.1 and 5.2 from the GR-63-CORE

(lab ambient)]/1000 feet/1ºC). Objective O4-11 will still be met as well.

Temperature margin testing remains unchanged for equipment with front air intakes or equipment with air diverters as previously described. For equipment with air intakes other than the front face, the starting temperature is increased to 60ºC or 65ºC as listed in Table 5-1 or Table 5-2.

The fan-cooled equipment criteria changes involve removing the humidity requirement from R4-14. Testing is now performed at either 40ºC or 50ºC, depending on airflow, with un-monitored humidity. The other change in the section moves the fan filters requirements from paragraph 4.5.4 in Issue 3 to 4.1.5.2 in Issue 4.

HEAT DISSIPATION, AIRFLOW AND ENERGY EFFICIENCY

Heat dissipation remains as it was in Issue 3. Some guidance on how to perform the calculations is added by stepping through an example in paragraph 5.1.6. This provides consistency between manufacturers on how to report the value. Along with the standard heat dissipation calculation, there is a new requirement R4-31 for energy efficiency. The requirement directs you to use the Alliance for Telecommunication Industry Solutions ATIS-0600015. The document listed is a general requirement document and one of seven documents presently in that ATIS family. Based on the type of equipment being tested, you default to one of those documents (listed at the end of the article). If your equipment does not fit in one of those categories, you default to a telecommunications carrier document such as Verizon's VZ.TPR.9205 and then to an industry standard document.

The next section in the document with changes is equipment airflow. A large part of the telecommunication service providers (TSP) cost is energy usage for environmental control of their equipment space. One of the major contributors to the high cost is a mixture of equipment with contrasting airflow patterns; hot air exhausting into the cool air aisle. To standardize equipment airflow in the equipment space, the objectives in this section are turned into requirements. As mentioned above, if the EUT deviates from the acceptable airflow pattern, operating temperature testing is performed 10ºC higher than the previous standard. If an air baffle is used during the qualification to redirect the air to the proper pattern, then the test can be performed at the lower high temperature levels.

FIRE RESISTANCE

After the major changes that fire resistance went through for the Issue 3 update, including scaling of the line burner, the changes in Issue 4 are relatively small but still significant. The first change in the section deals with high velocity fans internal to the EUT. It's not uncommon during full scale fire resistance testing for the line burner to consistently self-extinguish due to the high velocity airflow. Once the protocol of ATIS-0600319.2008 has been completed and the EUT has complied due to the line burner self-extinguishing, one additional burn for that location will need to be performed. That burn will be done with the fans in a non-operating mode in accordance with two new objectives 04-44 for frames or O4-50 for shelves. The second change deals with printed circuit boards (PCBs) having a distance to each other equal to or greater than 25 mm. Under Issue 3, varying distances between the adjacent cards caused no change in the burn profile. The new Issue 4 protocol for adjacent PCBs greater than 25mm away, is to leave the PCB in place and insert the line burner through the faceplate on the component side of the card. The line burner peak flow rate is then calculated in the same way as other burns, using the vertical height of the card and adjusted to 50% of the calculated flow rate.

MECHANICAL TESTING

The Category "A" packaged drop test is updated to change the required (1) edge and (2) corners the packaged product is dropped on. The change was performed to align with shipping industry standards .The number of drops remained at a total of 13.

The unpackaged drop is the key change in this section for equipment weighing less than 25 kg. The traditional free fall flat drops onto a non-yielding surface (concrete) from 3.9 inches or 3 inches, depending on its weight, remains, but the number of flat drops was increased to all possible rest surfaces. The two corner drops and two edge drops were changed to pivot drops. These pivot drops, known in the industry as a bench handling, were adopted from MIL-STD-810G Procedure VI of Method 516. The new test procedure is to place the unpackaged, unpowered equipment onto a wooden bench surface or non-yielding surface on its normal rest face. While using one edge as a pivot point, the opposite edge is lifted 4 inches or 45º, whichever is less. The elevated edge is then allowed to free fall onto the bench top. This procedure is then repeated for the pivot edge and the two adjacent edges along the bottom. The drop sequence is then repeated for any other surface the unit could be rested on normally. If your item is able to be rested on a bench top on any of the surfaces, the number of drops would increase from the five required in Issue 3 to 30 in Issue 4. The 30 drops would include six free fall drops, one of each face, and 24 pivot drops, four on each face's edge.

Seismic testing has a clarification on which bolt the load cell should be placed on during the test if concrete anchors are omitted from the testing. The load cell is placed on the bolt at the innermost position, if the framework allows for a variety of anchor locations. In the test cases that were analyzed, this position was found to have the highest loads relative to the other mounting bolts locations. The second clarification is for testing of multiple shelves in a single frame. In accordance with the specification, units weighing less than 23 kg have to be placed at the top of the rack. In order to allow multiple units to undergo seismic testing in a single frame, direction is given that the smallest unit is to be placed at the top of the rack at the highest location. However. the lowest unit still has to be within the top 20% of the frame.

Office vibration has an additional test option to use a random vibration profile in lieu of the traditional 0.1 g sine sweep. The random vibration curve was adopted from the Class 4M5 requirements of EN ETSI 019-2-4 to align testing with European requirements. The issue with this alignment, done to reduce testing, will be the fixture requirements from each of the documents. GR-63-CORE has the requirement that shelf level products are placed at a specified height in a telecom frame depending on their weight. ETSI EN 300 019-2-4 requires that the test article be placed in a rigid fixture per IEC 60068-2-47, which telecom two-post frames do not comply to. However since European requirements for weather-protected equipment is performed to Class 3.2 of EN ETSI 019-2-3, the Issue 4 test curve is +3 dB higher as shown below (Figure 2). Based on this difference, a response accelerometer can be placed at the mounting location of the EUT in the telecom frame to verify it envelopes the Class 3.2 requirements. If it does not, separate tests will need to be performed for each of the documents.

The final change in the document in the acoustic section is the removal of the acceptance criteria for unattended locations.

REFERENCES

ETSI EN 300 019-2-3 v2.2.2 (2003-04) – *Environmental Conditions and environmental tests for telecommunications equipment; Part 2-3: Specification of environmental tests; Stationary use at weatherprotected locations.*

ETSI EN 300 019-2-4 v2.2.2 (2003-04) – *Environmental Conditions and environmental tests for telecommunications equipment; Part 2-4: Specification of environmental tests; Stationary use at non-weatherprotected locations.*

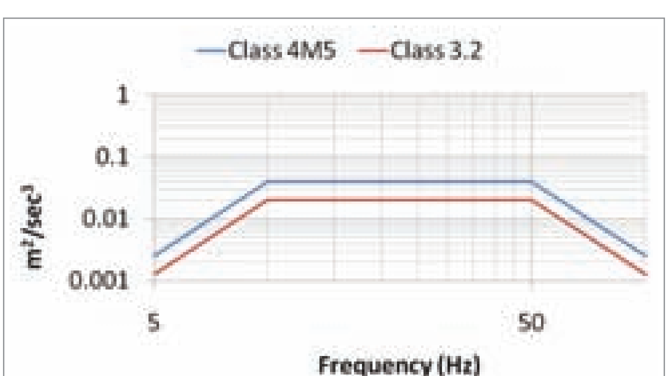

Figure 2

ATIS-0600015.2009- *Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting – General Requirements.*

ATIS-0600015.01.2009-*Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting -- Server Requirements.*

ATIS-0600015.02.2009-*Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting – Transport Requirements.*

ATIS-0600015.03.2009-*Energy Efficiency for Telecommunications Equipment: Methodology for Measurement and Reporting for Router and Ethernet Switch Products*.

ATIS-0600015.04.2010-*Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting DC Power Plant – Rectifier Requirements*.

ATIS-0600015.05.2010- *Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting Facility Energy Efficiency.*

ATIS-0600015.06.2011-*Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting of Radio Base Station Metrics*.

ATIS-0600319.2008- *Equipment Assemblies—Fire Propagation Risk Assessment Criteria*.

MIL-STD-810G October 31, 2008- *Department of Defense Test Method Standard Environmental Engineering Considerations and Laboratory Tests*.

VZ.TPR.9305 Issue 4, May 2011- *Verizon NEBS™ Compliance: NEBS Compliance Requirements for Telecommunications Equipment*.

VZ.TPR.9205 Issue 5, October 2011- *Verizon NEBS™ Compliance: Energy Efficiency Clarification Document*.

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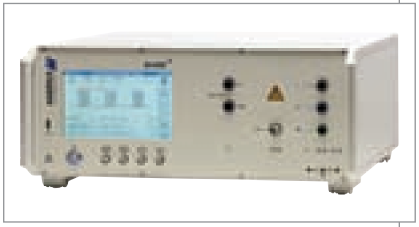

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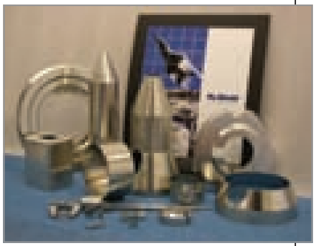

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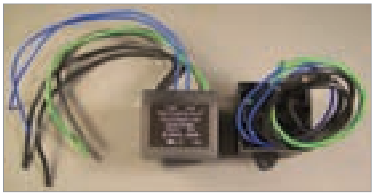

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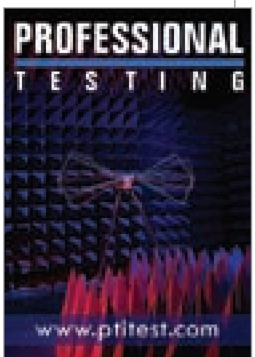

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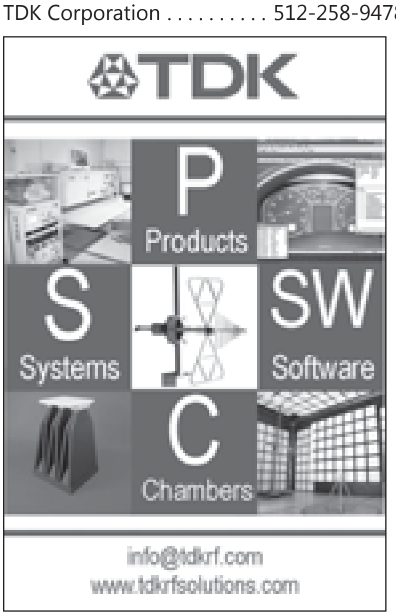

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Cuming-Lehman Chambers, Inc. 717-263-4101
Fil-Coil 631-467-5328
Microwave Vision Group . . . 678-797-9172
Panashield, Inc. 203-866-5888
Raymond EMC Enclosures Ltd. 800-362-1495

Shielded Rooms/Chambers

ARC Technical Resources, Inc. 408-263-6486
Audivo GmbH. 49 9435 5419 0
Braden Shielding Systems . . 918-624-2888
Cuming-Lehman Chambers, Inc. 717-263-4101
DJM Electronics 866-DJM-ELEC
Electronic Instrument Associates 630-924-1600
EMC Technologists 732-919-1100
ETS-Lindgren 512-531-6400
Magnetic Shield Corporation 888-766-7800
MI Technologies 678-475-8345
Microwave Vision Group . . . 678-797-9172
NTS Rockford 800-270-2516
NTS Tinton Falls 732-936-0800
Panashield, Inc. 203-866-5888
Raymond EMC Enclosures Ltd. 800-362-1495
Select Fabricators, Inc. 888-599-6113
TDK Corporation 972-409-4519
Universal Shielding 800-645-5578

Turntables

Braden Shielding Systems . . 918-624-2888
ETS-Lindgren 512-531-6400
Innco Systems GmbH . . . 49 9435 301659 0
Mag Daddy. 847-719-5600
NTS Newark 877-245-7800
Sunol Sciences Corporation . 925-833-9936

Consulting & Services

Calibration & Repair Services

Aum Electro Technology Pvt Ltd 00912512871365
Dynamic Sciences International 800-966-3713
Ergonomics, Inc.. 800-862-0102
ESDEMC Technology LLC . . . 877-864-8479
eti Conformity Services. 877-468-6384
ETS-Lindgren 512-531-6400
HCT Co., Ltd.. 82-31-645-6454
Liberty Labs, Inc. 712-773-2199
Noise Laboratory Co (NoiseKen) 81 (0) 42 712 2051
Prostat Corporation. 630-238-8883
Reliant EMC LLC. 408-600-1472
Restor Metrology. 877-220-5554
SE Laboratories 800-939-CALS
Teseq Inc.. 732-417-0501
Thermo Fisher Scientific 978-275-0800 x2302
World Cal, Inc. 712-764-2197

Conductive Painting Services

Protective Industrial Polymers 866-361-3331
Staticworx Flooring 888-STATICWORX

Consultants

Consultants, Cleanroom/Static Control

BestESD Technical Services . 831-824-4052
Stephen Halperin & Associates 630-238-8883

Consultants, EMC

Advanced ESD Services +. . . 607-759-8133
Alion Science and Technology 610-825-1960
American Certification Body, Inc. 703-847-4700
André Consulting, Inc. 206-406-8371
ARC Technical Resources, Inc. 408-263-6486
Atlas Compliance & Engineering 866-573-9742
BestESD Technical Services . 831-824-4052
Braden Shielding Systems . . 918-624-2888
CKC Laboratories, Inc.. 800-500-4362
Compatible Electronics, Inc. 650-417-EMC1 (3621)
Compliance & More, Inc . . . 303-663-3396
Compliance Management Group 508-281-5985
D. C. Smith Consultants 800-323-3956
D.L.S. Electronic Systems, Inc. 847-537-6400
Dayton T. Brown, Inc. 800-TEST-456
Design Chain Associates, LLC 866-322-7676 x2
DNB Engineering, Inc.. 714-870-7781
Don HEIRMAN Consultants 732-741-7723
Electronics Test Centre. . . . 613-599-6800
Elite Electronic Engineering . . 800-ELITE-11
EMC Compliance 256-650-5261
EMC Testing Laboratories, Inc. 770-475-8819
EMCC DR. RASEK. 49-9194-9016
EMCplus LLC. 303-663-3396
EMI Solutions 949-206-9960
ESDEMC Technology LLC . . . 877-864-8479
F2 Labs. 877-405-1580
G&M Compliance, Inc. 714-628-1020
Garwood Laboratories 888-427-4111
Go Global Compliance Inc. 408-416-3772
H.B. Compliance Solutions . . 480-684-2969
Henry Ott Consultants 973-992-1793
Hoolihan EMC Consulting. 651-213-0966
International Certification Services, Inc. 888-286-6888
IQS, a Division of CMG 508-460-1400
Jastech EMC Consulting LLC 248-876-4810
JDM LABS LLC 847-630-2769
Kimmel Gerke Associates, Ltd. 888-EMI-GURU
LCR Electronics, Inc. 800-527-4362
Lewis Bass International 408-942-8000
LS Research. 262-375-4400
Montrose Compliance Services 408-247-5715
NCEE Labs. 888-567-6860
Nemko Canada 613-737-9680
NexTek, Inc. 978-486-0582
NTS - Corporate HQ 800-270-2516
NTS Newark 877-245-7800
NTS Northeast 800-723-2687
NTS Rockford 800-270-2516
NTS Tinton Falls. 732-936-0800
Oxford University Technology . . . . . 44 (0)1865 286958
Phoenix Technical Group . . . 919-535-3662
Pulver Laboratories Inc. 800-635-3050
Raymond EMC Enclosures Ltd. 800-362-1495
RTF Compliance. 949-813-6095
SIEMIC 408-526-1188
SILENT Solutions LLC . . 603-578-1842 x203
Spectrum EMC Consulting, LLC 651-688-0634
Telcron LLC
Test Site Services Inc. 508-962-1662
TestingPartners.com 862-243-2329
Van Doren Company. 573-341-4097
Versus Global Certifications Pty Ltd. 27 83 5140709
WEMS Electronics 310-962-4410
Wyatt Technical Services LLC 877-443-9275

Consultants, EU

Alberi EcoTech 702-677-6923
Atlas Compliance & Engineering 866-573-9742
Compliance & More, Inc . . . 303-663-3396
Compliance Management Group 508-281-5985
CQC Co LTD 48 509959591
CSIA, LLC. 503-489-8006
D.L.S. Electronic Systems, Inc. 847-537-6400
Design Chain Associates, LLC 866-322-7676 x2
EMC Testing Laboratories, Inc. 770-475-8819
EMCplus LLC. 303-663-3396
Ergonomics, Inc.. 800-862-0102
H.B. Compliance Solutions . . 480-684-2969
International Certification Services, Inc. 888-286-6888
IQS, a Division of CMG 508-460-1400
LS Research. 262-375-4400
Montrose Compliance Services 408-247-5715
NCEE Labs. 888-567-6860
NTS Rockford 800-270-2516
O'Brien Compliance Management 978-970-0525
Phoenix Technical Group . . . 919-535-3662
Pulver Laboratories Inc. 800-635-3050
SIEMIC 408-526-1188
Spectrum EMC Consulting, LLC 651-688-0634
Technology Forecasters Inc.
TestingPartners.com 862-243-2329
Versus Global Certifications Pty Ltd. 27 83 5140709
Wyatt Technical Services LLC 877-443-9275

Consultants, GOST

American Certification Body, Inc. 703-847-4700
CQC Co LTD 48 509959591
CSIA, LLC. 503-489-8006
G&M Compliance, Inc. 714-628-1020
Go Global Compliance Inc. 408-416-3772
MC Global Access 760-696-3700
Nemko Canada 613-737-9680
TestingPartners.com 862-243-2329
Versus Global Certifications Pty Ltd. 27 83 5140709

Consultants, Lightning Protection

American Certification Body, Inc. 703-847-4700
André Consulting, Inc. 206-406-8371
D. C. Smith Consultants 800-323-3956
Dayton T. Brown, Inc. 800-TEST-456
DNB Engineering, Inc.. 714-870-7781
Elite Electronic Engineering . . 800-ELITE-11
EMI Solutions 949-206-9960
Garwood Laboratories 888-427-4111
NTS Northeast 800-723-2687
NTS Pittsfield 800-270-2516
Spectrum EMC Consulting, LLC 651-688-0634
WEMS Electronics 310-962-4410

Consultants, Medical Device

Alberi EcoTech 702-677-6923
American Certification Body, Inc. 703-847-4700
CertifiGroup Inc 800-422-1651
CKC Laboratories, Inc.. 800-500-4362
Compliance Management Group 508-281-5985
D.L.S. Electronic Systems, Inc. 847-537-6400
Design Chain Associates, LLC 866-322-7676 x2
DNB Engineering, Inc.. 714-870-7781
Eisner Safety Consultants . . . 503-244-6151

Elite Electronic Engineering . . 800-ELITE-11
EMC Testing Laboratories, Inc. 770-475-8819
F2 Labs. 877-405-1580
G&M Compliance, Inc. 714-628-1020
Garwood Laboratories 888-427-4111
Go Global Compliance Inc. 408-416-3772
International Certification Services, Inc. 888-286-6888
Kimmel Gerke Associates, Ltd. 888-EMI-GURU
Montrose Compliance Services 408-247-5715
The MuShield Company Inc. 888-669-3539
NCEE Labs. 888-567-6860
Nemko Canada 613-737-9680
NTS Newark 877-245-7800
NTS Northeast 800-723-2687
O'Brien Compliance Management 978-970-0525
Product Safety Consulting . . 877-804-3066
Pulver Laboratories Inc. 800-635-3050
SILENT Solutions LLC . . 603-578-1842 x203
Test Site Services Inc. 508-962-1662
Trace Laboratories, Inc.. 410-584-9099
Versus Global Certifications Pty Ltd. .27 83 5140709

Consultants, Product Safety

Abstraction Engineering Inc . 408-258-3282

Alberi EcoTech 702-677-6923
American Certification Body, Inc. 703-847-4700
CASE Forensics. 877-736-1106
CertifiGroup Inc 800-422-1651
Compliance & More, Inc . . . 303-663-3396
Compliance Management Group 508-281-5985
CSIA, LLC. 503-489-8006
D.L.S. Electronic Systems, Inc. 847-537-6400
Dayton T. Brown, Inc. 800-TEST-456
Design Chain Associates, LLC 866-322-7676 x2
DNB Engineering, Inc.. 714-870-7781
Eisner Safety Consultants . . . 503-244-6151
EMC Testing Laboratories, Inc. 770-475-8819
EMCplus LLC. 303-663-3396
Ergonomics, Inc.. 800-862-0102
F2 Labs. 877-405-1580
G&M Compliance, Inc. 714-628-1020
Garwood Laboratories 888-427-4111
Go Global Compliance Inc. 408-416-3772
IQS, a Division of CMG 508-460-1400
Lewis Bass International 408-942-8000
Montrose Compliance Services 408-247-5715
NCEE Labs. 888-567-6860
Nemko Canada 613-737-9680
NTS Newark 877-245-7800
NTS Northeast 800-723-2687
O'Brien Compliance Management 978-970-0525
Phoenix Technical Group . . . 919-535-3662
Product Safety Consulting . . 877-804-3066
Pulver Laboratories Inc. 800-635-3050
RTF Compliance 949-813-6095
SIEMIC 408-526-1188
Telcron LLC
Test Site Services Inc. 508-962-1662
TestingPartners.com 862-243-2329
Trace Laboratories, Inc.. 410-584-9099
Versus Global Certifications Pty Ltd. .27 83 5140709

Consultants, Quality

Alberi EcoTech 702-677-6923
American Certification Body, Inc. 703-847-4700
CASE Forensics. 877-736-1106
Design Chain Associates, LLC 866-322-7676 x2
Eisner Safety Consultants . . . 503-244-6151
Ergonomics, Inc.. 800-862-0102
NTS Newark 877-245-7800
O'Brien Compliance Management 978-970-0525
Pulver Laboratories Inc. 800-635-3050
Trace Laboratories, Inc.. 410-584-9099
Unitek, A Division of NQA . . 800-998-9395

Consultants, Telecom

CSIA, LLC. 503-489-8006
CV DIMULTI 6212132608337
D. C. Smith Consultants 800-323-3956
D.L.S. Electronic Systems, Inc. 847-537-6400
Elite Electronic Engineering . . 800-ELITE-11
EMC Testing Laboratories, Inc. 770-475-8819
Garwood Laboratories 888-427-4111
Go Global Compliance Inc. 408-416-3772
MC Global Access 760-696-3700
Nemko Canada 613-737-9680
NTS - Corporate HQ 800-270-2516
NTS Newark 877-245-7800
SIEMIC 408-526-1188
Test Site Services Inc. 508-962-1662
Versus Global Certifications Pty Ltd. .27 83 5140709

Consultants, Tempest

American Certification Body, Inc. 703-847-4700
André Consulting, Inc. 206-406-8371
Braden Shielding Systems . . 918-624-2888
Dayton T. Brown, Inc. 800-TEST-456
General Dynamics C4 Systems 480-441-5321
NexTek, Inc. 978-486-0582
Raymond EMC Enclosures Ltd. 800-362-1495

Consultants, Transients

American Certification Body, Inc. 703-847-4700
BestESD Technical Services . 831-824-4052
D. C. Smith Consultants 800-323-3956
D.L.S. Electronic Systems, Inc. 847-537-6400
DNB Engineering, Inc.. 714-870-7781
Kimmel Gerke Associates, Ltd. 888-EMI-GURU
NexTek, Inc. 978-486-0582
Pulver Laboratories Inc. 800-635-3050
SILENT Solutions LLC . . 603-578-1842 x203
Spectrum EMC Consulting, LLC 651-688-0634
WEMS Electronics 310-962-4410

Consultants, VCCI

American Certification Body, Inc. 703-847-4700
Atlas Compliance & Engineering 866-573-9742
Compliance & More, Inc . . . 303-663-3396
Compliance Management Group 508-281-5985
CSIA, LLC. 503-489-8006
D.L.S. Electronic Systems, Inc. 847-537-6400
EMCplus LLC. 303-663-3396
Go Global Compliance Inc. 408-416-3772
H.B. Compliance Solutions. . 480-684-2969
Nemko Canada 613-737-9680

Design Services

American Certification Body, Inc. 703-847-4700
BestESD Technical Services . 831-824-4052
Bittele Electronics 416-800-7540
CKC Laboratories, Inc.. 800-500-4362
D.L.S. Electronic Systems, Inc. 847-537-6400
DDB Unlimited, Inc 800-753-8459
DNB Engineering, Inc.. 714-870-7781
EMC Compliance 256-650-5261
F2 Labs. 877-405-1580
High Voltage Maintenance . 866-486-8326
IQS, a Division of CMG 508-460-1400
Jastech EMC Consulting LLC 248-876-4810
K-Form, Inc.. 703-450-4401
Keystone Compliance 724-657-9940
LCR Electronics, Inc. 800-527-4362
LS Research. 262-375-4400
MAJR Products, Inc.. 877-625-7776
Montrose Compliance Services 408-247-5715
NCEE Labs 888-567-6860
Nexlogic Technologies, Inc. . 866-845-1197
NexTek, Inc. 978-486-0582
NTS Albuquerque 505-821-4740
NTS Northeast 800-723-2687
Pulver Laboratories Inc. 800-635-3050
SILENT Solutions LLC . . 603-578-1842 x203
TestingPartners.com 862-243-2329
Vermillion, Inc. 305-968-5981
VEROCH 954-990-7544
WEMS Electronics 310-962-4410

Equipment Rental & Leasing

Dynamic Sciences International 800-966-3713
EMCC DR. RASEK. 49-9194-9016
Ergonomics, Inc.. 800-862-0102
Thermo Fisher Scientific 978-275-0800 x2302

Manufacturers' Representatives

Comply Tek, Inc.. 858-674-6155

Shielded Enclosure Design, Relocation Services

André Consulting, Inc. 206-406-8371
ARC Technical Resources, Inc. 408-263-6486
DDB Unlimited, Inc 800-753-8459
K-Form, Inc.. 703-450-4401
Magnetic Shield Corporation 888-766-7800
MAJR Products, Inc.. 877-625-7776
Microwave Vision Group . . . 678-797-9172
The MuShield Company Inc. 888-669-3539
Raymond EMC Enclosures Ltd. 800-362-1495
Universal Shielding 800-645-5578

Site Attenuation Testing Services

Alion Science and Technology 610-825-1960
ETS-Lindgren 512-531-6400
Raymond EMC Enclosures Ltd. 800-362-1495
Retlif Testing Laboratories 631-737-1500 x111
TestingPartners.com 862-243-2329
Universal Shielding 800-645-5578

Site Survey Services

Alion Science and Technology 610-825-1960
ARC Technical Resources, Inc. 408-263-6486
D. C. Smith Consultants 800-323-3956
Dayton T. Brown, Inc. 800-TEST-456
DNB Engineering, Inc.. 714-870-7781
eti Conformity Services. 877-468-6384
F2 Labs. 877-405-1580
Garwood Laboratories 888-427-4111
High Voltage Maintenance . 866-486-8326
Magnetic Shield Corporation 888-766-7800
Raymond EMC Enclosures Ltd. 800-362-1495
Retlif Testing Laboratories 631-737-1500 x111
RMV Technology Group, LLC 650-964-4792
Stephen Halperin & Associates 630-238-8883
TestingPartners.com 862-243-2329

Electrical & Electronic Components

Adapters

Admired Services Components 727-346-5157
Americor Electronics Ltd. . . . 800-830-5337
Conec Corporation 919-460-8800
Global Test Equipment 866-409-0400
Instruments For Industry, Inc. 631-467-8400
Murata Electronics. 800-554-4070
Power Dynamics, Inc 973-560-0019
Sabritec 949-250-1244

Air Filters

EMI Air Filters

Alco Technologies, Inc.. 310-328-4770
JEMIC Shielding Technology 717-232-1030
MAJR Products, Inc.. 877-625-7776

Shielded Air Filters

Alco Technologies, Inc.. 310-328-4770

JEMIC Shielding Technology 717-232-1030
MAJR Products, Inc.. 877-625-7776

Arrestors

CITEL, Inc. 800-248-3548
Okaya Electric America, Inc.. 800-852-0122
TDK-EPC Corporation 800-888-7728
Texas Spectrum Electronics . 972-296-3699

Attenuators

BMI Surplus 781-871-8868
Global Test Equipment 866-409-0400
Instruments For Industry, Inc. 631-467-8400

Backplanes

Schurter Inc. 800-848-2600

Backshells

Admired Services Components 727-346-5157
Conec Corporation 919-460-8800
Power Dynamics, Inc 973-560-0019
Sabritec 949-250-1244

Bluetooth Modules

Laird Technologies 636-898-6215
LS Research. 262-375-4400
Mag Daddy. 847-719-5600
Murata Electronics. 800-554-4070

Breakers

Clarion Safety Systems 800-748-0241
eti Conformity Services. 877-468-6384
Mag Daddy. 847-719-5600

Cabinets/Enclosures

Clarion Safety Systems 800-748-0241
DDB Unlimited, Inc 800-753-8459
K-Form, Inc.. 703-450-4401

Cable Assemblies

Americor Electronics Ltd. . . . 800-830-5337
Bittele Electronics 416-800-7540
CMD Ltd 441709829511
Global Test Equipment 866-409-0400
Lionheart Northwest 425-882-2587
Mag Daddy. 847-719-5600
Michigan Scientific Corporation 248-685-3939 x111
Vermillion, Inc. 305-968-5981

Circuit Breakers

Bittele Electronics 416-800-7540
eti Conformity Services. 877-468-6384
Interpower Corporation . . 800-662-2290
Schurter Inc. 800-848-2600
Texas Spectrum Electronics . 972-296-3699

Connectors

Admired Services Components 727-346-5157
Amphenol Canada Corp. . . . 416-754-5688
API Technologies Corp. 855-294-3800
ARC Technologies, Inc. . . . 978-388-2993
Conec Corporation 919-460-8800
EMI Solutions 949-206-9960
eti Conformity Services. 877-468-6384
Global Test Equipment 866-409-0400
Interpower Corporation . . 800-662-2290
LCR Electronics, Inc. 800-527-4362
Mag Daddy. 847-719-5600
Power Dynamics, Inc 973-560-0019
Sabritec 949-250-1244
Schurter Inc. 800-848-2600
Wurth Electronics Midcom. . 800-643 2661

Couplers

AR RF/Microwave Instrumentation 888-933-8181
BMI Surplus 781-871-8868
Conec Corporation 919-460-8800
EM TEST USA 858-450-0085
Instruments For Industry, Inc. 631-467-8400
Murata Electronics. 800-554-4070
Reliant EMC LLC. 408-600-1472
TDK Corporation 512-258-9478
Teseq Inc.. 732-417-0501

Diodes

Admired Services Components 727-346-5157
André Consulting, Inc. 206-406-8371
Mag Daddy. 847-719-5600
Sabritec 949-250-1244

Electronic Cooling Fans

Americor Electronics Ltd. . . . 800-830-5337
Mag Daddy. 847-719-5600

Fuses

Admired Services Components 727-346-5157
eti Conformity Services. 877-468-6384
Interpower Corporation . . 800-662-2290
Schurter Inc. 800-848-2600

Grounding Rods

Mag Daddy. 847-719-5600

Impedance Matching Networks

AR RF/Microwave Instrumentation 888-933-8181

Inductors

EMI/RFI Inductors

Americor Electronics Ltd. . . . 800-830-5337
André Consulting, Inc. 206-406-8371
API Technologies Corp. 855-294-3800
Fair-Rite Products Corp. . . 888-324-7748
LCR Electronics, Inc. 800-527-4362
TDK-EPC Corporation 800-888-7728
WEMS Electronics 310-962-4410
Wurth Electronics Midcom. . 800-643 2661

Surface Mount Inductors

Fair-Rite Products Corp. . . 888-324-7748
TDK-EPC Corporation 800-888-7728
Wurth Electronics Midcom. . 800-643 2661

Swtichmode Inductors

TDK-EPC Corporation 800-888-7728
Wurth Electronics Midcom. . 800-643 2661

Integrated Circuits

Admired Services Components 727-346-5157
BMI Surplus 781-871-8868
Global Test Equipment 866-409-0400
Nexlogic Technologies, Inc. . 866-845-1197

LEDs and Displays

Admired Services Components 727-346-5157
Audivo GmbH. 49 9435 5419 0
Mag Daddy. 847-719-5600
Okaya Electric America, Inc.. 800-852-0122

Liquid Crystal Display (LCD) Modules

Mag Daddy. 847-719-5600

Military (MIL-SPEC) Connectors

Admired Services Components 727-346-5157
André Consulting, Inc. 206-406-8371
API Technologies Corp. 855-294-3800
BMI Surplus 781-871-8868
EMC Technologists 732-919-1100
LCR Electronics, Inc. 800-527-4362
Mag Daddy. 847-719-5600

Oscillators

API Technologies Corp. 855-294-3800
Applied EM Technology 410-326-6728
Giga-tronics Incorporated . . 800-277-9764

Potentiometers

API Technologies Corp. 855-294-3800
Global Test Equipment 866-409-0400
Murata Electronics. 800-554-4070

Resonators

Admired Services Components 727-346-5157
TDK-EPC Corporation 800-888-7728

RF Frequency Converters

API Technologies Corp. 855-294-3800
Global Test Equipment 866-409-0400
Oak-Mitsui Technologies . 518-686-4961
Test Equipment Connection . 800-615-8378

Solid State Relays

Americor Electronics Ltd. . . . 800-830-5337
Global Test Equipment 866-409-0400

Surge Suppressors

CITEL, Inc. 800-248-3548
Fil-Coil 631-467-5328
Fischer Custom Communications 310-303-3300
Murata Electronics. 800-554-4070
Okaya Electric America, Inc.. 800-852-0122

Surge Suppressors *continued*

TDK-EPC Corporation 800-888-7728
Texas Spectrum Electronics . 972-296-3699
WEMS Electronics 310-962-4410

Switches

Admired Services Components
. . . . 727-346-5157
eti Conformity Services. 877-468-6384
Interpower Corporation . . 800-662-2290
The MuShield Company Inc.
. . . . 888-669-3539
Schurter Inc. 800-848-2600
Wurth Electronics Midcom. . 800-643 2661

Terminal Blocks

Americor Electronics Ltd. . . . 800-830-5337
Curtis Industries. 800-657-0853
eti Conformity Services. 877-468-6384
Global Test Equipment 866-409-0400
Interpower Corporation . . 800-662-2290
Mag Daddy. 847-719-5600
Texas Spectrum Electronics . 972-296-3699
Wurth Electronics Midcom. . 800-643 2661

Thyristors

Admired Services Components
. . . . 727-346-5157

Transformers

Transformers, Power Line Isolation

Clarion Safety Systems 800-748-0241
Elna Magnetics. 800-553-2870
Wurth Electronics Midcom. . 800-643 2661

Transformers, Signal Line Isolation

Elna Magnetics. 800-553-2870
Wurth Electronics Midcom. . 800-643 2661

Transformers, Telecommunications

Wurth Electronics Midcom. . 800-643 2661

Transformers, Third-Party Approved, EU

Americor Electronics Ltd. . . . 800-830-5337
Clarion Safety Systems 800-748-0241

Transformers, Third-Party Approved, US/Canada

Americor Electronics Ltd. . . . 800-830-5337
Clarion Safety Systems 800-748-0241
eti Conformity Services. 877-468-6384

Transformers, Toroidal

The MuShield Company Inc.
. . . . 888-669-3539

Pearson Electronics, Inc . . . 650-494-6444
Wurth Electronics Midcom. . 800-643 2661

Varistors

BMI Surplus 781-871-8868
TDK-EPC Corporation 800-888-7728
Wurth Electronics Midcom. . 800-643 2661

EMC/EMI Control

Air Cooling Systems

3Gmetalworx Inc.. 888-965-3634
DDB Unlimited, Inc 800-753-8459
HM Cragg 800-672-7244
Parker Hannifin, Chomerics Div
. . . . 781-935-4850

Architectural Shielding Products

3Gmetalworx Inc.. 888-965-3634
Fil-Coil 631-467-5328

Arrestors, Lightning and Surge

NTS Pittsfield 800-270-2516
Okaya Electric America, Inc.. 800-852-0122
Texas Spectrum Electronics . 972-296-3699

Braid, Bonding, and Grounding Accessories

DDB Unlimited, Inc 800-753-8459

Capacitors

Capacitors, Ceramic

André Consulting, Inc. 206-406-8371
API Technologies Corp. 855-294-3800
LCR Electronics, Inc. 800-527-4362

Capacitors, Decoupling

Captor Corporation. 937-667-8484
Oak-Mitsui Technologies . 518-686-4961
Quell Corporation 505-243-1423
TDK Corporation 512-258-9478
TechDream, Inc. 408-800-7362

Capacitors, Electrolytic

3Gmetalworx Inc.. 888-965-3634
LCR Electronics, Inc. 800-527-4362

Capacitors, Filter

3Gmetalworx Inc.. 888-965-3634
Americor Electronics Ltd. . . . 800-830-5337
André Consulting, Inc. 206-406-8371
API Technologies Corp. 855-294-3800
LCR Electronics, Inc. 800-527-4362
Solar Electronics Company . 800-952-5302
WEMS Electronics 310-962-4410

Capacitors, Mains (X and Y)

3Gmetalworx Inc.. 888-965-3634
Americor Electronics Ltd. . . . 800-830-5337
Captor Corporation. 937-667-8484
LCR Electronics, Inc. 800-527-4362
Okaya Electric America, Inc.. 800-852-0122
WEMS Electronics 310-962-4410

Capacitors, Planar Array

3Gmetalworx Inc.. 888-965-3634
Amphenol Canada Corp. . . . 416-754-5688
Oak-Mitsui Technologies . 518-686-4961

Capacitors, Tantalum

3Gmetalworx Inc.. 888-965-3634

Chokes

3Gmetalworx Inc.. 888-965-3634
Adams Magnetic Products. . 800-275-6312
André Consulting, Inc. 206-406-8371
Captor Corporation. 937-667-8484
Corcom/Tyco Electronics . . . 847-573-6504
Elna Magnetics. 800-553-2870
Fair-Rite Products Corp. . . 888-324-7748
LCR Electronics, Inc. 800-527-4362
Murata Electronics. 800-554-4070
Schaffner EMC Inc.
Schurter Inc. 800-848-2600
TechDream, Inc. 408-800-7362
WEMS Electronics 310-962-4410
Wurth Electronics Midcom. . 800-643 2661

Conductive Materials

Conductive Additives

Parker Hannifin, Chomerics Div
. . . . 781-935-4850

Conductive Adhesive

Parker Hannifin, Chomerics Div
. . . . 781-935-4850

Conductive Epoxy

3Gmetalworx Inc.. 888-965-3634
Parker Hannifin, Chomerics Div
. . . . 781-935-4850
Protective Industrial Polymers
. . . . 866-361-3331
VTI Vacuum Technologies, Inc.
. . . . 800-482-1941

Conductive Foam

3Gmetalworx Inc.. 888-965-3634
JEMIC Shielding Technology
. . . . 717-232-1030
Leader Tech . . . . 866-TECH EMI
Orbel Corporation. 610-829-5000
Parker Hannifin, Chomerics Div
. . . . 781-935-4850
Tech-Etch 508-747-0300

Conductive Laminates

JEMIC Shielding Technology . . . 717-232-1030

Conductive Lubricants

Parker Hannifin, Chomerics Div . . . 781-935-4850

Conductive Plastics

Parker Hannifin, Chomerics Div . . . 781-935-4850

Connector Fingers

Alco Technologies, Inc. . . . 310-328-4770
East Coast Shielding . . . 908-852-9160
Fotofab . . . 773-463-6211
Ja-Bar Silicone Corp . . . 973-786-5000
Leader Tech . . . 866-TECH EMI
Orbel Corporation . . . 610-829-5000
Tech-Etch . . . 508-747-0300
Wurth Electronics Midcom. . . 800-643 2661

Cord Sets, EMI

3Gmetalworx Inc. . . . 888-965-3634
Americor Electronics Ltd. . . . 800-830-5337
Captor Corporation . . . 937-667-8484
EMC Technologists . . . 732-919-1100
LCR Electronics, Inc. . . . 800-527-4362
Power Dynamics, Inc . . . 973-560-0019
Schurter Inc. . . . 800-848-2600

Ferrite Beads, Rods and Forms

Adams Magnetic Products. . . 800-275-6312
André Consulting, Inc. . . . 206-406-8371
Dexter Magnetic Technologies . . . 800 317 2537
Elna Magnetics . . . 800-553-2870
Fair-Rite Products Corp. . . . 888-324-7748

FerriShield . . . 866-TECH-EMI
Intermark USA, Inc. . . . 408-971-2055
Laird Technologies . . . 636-898-6215
Leader Tech . . . 866-TECH EMI
MAJR Products, Inc. . . . 877-625-7776
Murata Electronics . . . 800-554-4070
TechDream, Inc. . . . 408-800-7362
Wurth Electronics Midcom. . . 800-643 2661

Filter Coils

Captor Corporation . . . 937-667-8484
Fil-Coil . . . 631-467-5328
LCR Electronics, Inc. . . . 800-527-4362
Texas Spectrum Electronics . 972-296-3699
WEMS Electronics . . . 310-962-4410

Filter Pins

EMI Solutions . . . 949-206-9960
Quell Corporation . . . 505-243-1423

Filtered Connectors

EMI Solutions . . . 949-206-9960
Quell Corporation . . . 505-243-1423

Filters

Filters, Absorptive

Captor Corporation . . . 937-667-8484

Filters, Antenna

Captor Corporation . . . 937-667-8484
Murata Electronics . . . 800-554-4070
Oak-Mitsui Technologies . 518-686-4961
WEMS Electronics . . . 310-962-4410

Filters, EMC and RFI

André Consulting, Inc. . . . 206-406-8371
API Technologies Corp. . . . 855-294-3800
Curtis Industries . . . 800-657-0853
DJM Electronics . . . 866-DJM-ELEC
EMI Solutions . . . 949-206-9960
ETS-Lindgren . . . 512-531-6400
Filconn Inc. . . . 480 222 3565
Genisco Filter Corp . . . 858-565-7405
Jastech EMC Consulting LLC . . . 248-876-4810
LCR Electronics, Inc. . . . 800-527-4362
NexTek, Inc. . . . 978-486-0582
Oak-Mitsui Technologies . 518-686-4961
Parker Hannifin, Chomerics Div . . . 781-935-4850
Schaffner EMC Inc.
Schurter Inc. . . . 800-848-2600
Solar Electronics Company . 800-952-5302
Spira Manufacturing Corporation . . . 888-98-SPIRA
Tri-Mag, Inc. . . . 559-651-2222
WEMS Electronics . . . 310-962-4410

Filters, EMC Test Chamber

Captor Corporation . . . 937-667-8484
Corcom/Tyco Electronics . . . 847-573-6504
DJM Electronics . . . 866-DJM-ELEC
Panashield, Inc. . . . 203-866-5888
Spira Manufacturing Corporation . . . 888-98-SPIRA
TDK Corporation . . . 512-258-9478

Filters, Power Line

Captor Corporation . . . 937-667-8484
Corcom/Tyco Electronics . . . 847-573-6504
Curtis Industries . . . 800-657-0853
DNB Engineering, Inc. . . . 714-870-7781
ETS-Lindgren . . . 512-531-6400
Genisco Filter Corp . . . 858-565-7405
LCR Electronics, Inc. . . . 800-527-4362
Murata Electronics . . . 800-554-4070
NexTek, Inc. . . . 978-486-0582
Okaya Electric America, Inc. . 800-852-0122
OnFILTER, Inc. . . . 831-824-4052
Panashield, Inc. . . . 203-866-5888
Reliant EMC LLC . . . 408-600-1472
Schaffner EMC Inc.
Schurter Inc. . . . 800-848-2600
Texas Spectrum Electronics . 972-296-3699
Tri-Mag, Inc. . . . 559-651-2222
WEMS Electronics . . . 310-962-4410

Filters, RF and Microwave

API Technologies Corp. . . . 855-294-3800
ESDEMC Technology LLC . . . 877-864-8479
Filconn Inc. . . . 480 222 3565
Lionheart Northwest . . . 425-882-2587
Oak-Mitsui Technologies . 518-686-4961

Filters, Shielded Air

Alco Technologies, Inc. 310-328-4770
Parker Hannifin, Chomerics Div 781-935-4850
Spira Manufacturing Corporation 888-98-SPIRA
Tech-Etch 508-747-0300

Filters, Shielded Room

Alco Technologies, Inc. 310-328-4770
Captor Corporation 937-667-8484
DJM Electronics 866-DJM-ELEC
ETS-Lindgren 512-531-6400
Genisco Filter Corp 858-565-7405
NexTek, Inc. 978-486-0582
WEMS Electronics 310-962-4410

Filters, Signal Line

Amphenol Canada Corp. 416-754-5688
Captor Corporation 937-667-8484
Corcom/Tyco Electronics . . . 847-573-6504
DJM Electronics 866-DJM-ELEC
DNB Engineering, Inc. 714-870-7781
EMI Solutions 949-206-9960
Genisco Filter Corp 858-565-7405
LCR Electronics, Inc. 800-527-4362
Oak-Mitsui Technologies . 518-686-4961
Quell Corporation 505-243-1423
Reliant EMC LLC 408-600-1472
Solar Electronics Company . 800-952-5302
TDK Corporation 512-258-9478
Texas Spectrum Electronics . 972-296-3699
WEMS Electronics 310-962-4410

Filters, Third-Party Approved, EU

LCR Electronics, Inc. 800-527-4362

Filters, Third-Party Approved, US/Canada

LCR Electronics, Inc. 800-527-4362

Finger Stock

Laird Technologies 636-898-6215
Leader Tech . . . . . 866-TECH EMI
Orbel Corporation 610-829-5000
P & P Technology Ltd . . 44 (0)1376 550525

Foils, Shield Tape

Ad-Vance Magnetics 574-223-3158
André Consulting, Inc. 206-406-8371
East Coast Shielding 908-852-9160
JEMIC Shielding Technology 717-232-1030
The MuShield Company Inc. 888-669-3539
Orbel Corporation 610-829-5000
P & P Technology Ltd . . 44 (0)1376 550525
Parker Hannifin, Chomerics Div 781-935-4850
PRISMIER 630-592-4515
TechDream, Inc. 408-800-7362

Gaskets

3Gmetalworx Inc. 888-965-3634
Alco Technologies, Inc. 310-328-4770
East Coast Shielding 908-852-9160
Fotofab 773-463-6211
Intermark USA, Inc. 408-971-2055
Ja-Bar Silicone Corp 973-786-5000
JEMIC Shielding Technology 717-232-1030
Laird Technologies 636-898-6215
Leader Tech . . . . . 866-TECH EMI
MAJR Products, Inc. 877-625-7776
Metal Textiles Corporation . 732-287-0800
Omega Shielding Products, Inc. 800-828-5784
Orbel Corporation 610-829-5000
P & P Technology Ltd . . 44 (0)1376 550525
Parker Hannifin, Chomerics Div 781-935-4850
PRISMIER 630-592-4515
SAS Industries, Inc. . . . 631-727-1441 x302
Schlegel Electronic Materials, Inc. 800-204-0863
Spira Manufacturing Corporation 888-98-SPIRA
Tech-Etch 508-747-0300
TechDream, Inc. 408-800-7362
Vanguard Products Corporation 203-744-7265
VTI Vacuum Technologies, Inc. 800-482-1941
W. L. Gore & Associates, Inc.
Wurth Electronics Midcom. . 800-643 2661

Resistors

Americor Electronics Ltd. . . . 800-830-5337

Shielded Cable Assemblies and Harnesses

Alco Technologies, Inc. 310-328-4770
Bittele Electronics 416-800-7540
Electri-Flex Company 800-323-6174
Vermillion, Inc. 305-968-5981

Shielded Conduit

Americor Electronics Ltd. . . . 800-830-5337
Electri-Flex Company 800-323-6174
Magnetic Shield Corporation 888-766-7800
The MuShield Company Inc. 888-669-3539
Zero Ground LLC 866-937-6463

Shielded Connectors

3Gmetalworx Inc. 888-965-3634
Ad-Vance Magnetics 574-223-3158
Alco Technologies, Inc. 310-328-4770
API Technologies Corp. 855-294-3800
East Coast Shielding 908-852-9160
Ja-Bar Silicone Corp 973-786-5000
PRISMIER 630-592-4515
Schurter Inc. 800-848-2600
Spira Manufacturing Corporation 888-98-SPIRA
Wurth Electronics Midcom. . 800-643 2661
Zero Ground LLC 866-937-6463

Shielded Enclosures

3Gmetalworx Inc. 888-965-3634
Ad-Vance Magnetics 574-223-3158
André Consulting, Inc. 206-406-8371
API Technologies Corp. 855-294-3800
Cuming-Lehman Chambers, Inc. 717-263-4101
DDB Unlimited, Inc 800-753-8459
Fil-Coil 631-467-5328
Fotofab 773-463-6211
K-Form, Inc. 703-450-4401
Magnetic Shield Corporation 888-766-7800
The MuShield Company Inc. 888-669-3539
Panashield, Inc. 203-866-5888
Parker Hannifin, Chomerics Div 781-935-4850
Raymond EMC Enclosures Ltd. 800-362-1495
Select Fabricators, Inc. 888-599-6113
VTI Vacuum Technologies, Inc. 800-482-1941

Shielded Modules

Ad-Vance Magnetics 574-223-3158
The MuShield Company Inc. 888-669-3539

Shielded Tubing

Ad-Vance Magnetics 574-223-3158
Electri-Flex Company 800-323-6174
The MuShield Company Inc. 888-669-3539

Shielded Wire and Cable

Alco Technologies, Inc. 310-328-4770
Electri-Flex Company 800-323-6174
EMC Technologists 732-919-1100
Magnetic Shield Corporation
. . . . 888-766-7800

The MuShield Company Inc.
. . . . 888-669-3539
Vermillion, Inc. 305-968-5981
W. L. Gore & Associates, Inc.
Zero Ground LLC 866-937-6463

Shielding Coatings

Magnetic Shield Corporation
. . . . 888-766-7800
Parker Hannifin, Chomerics Div
. . . . 781-935-4850
VTI Vacuum Technologies, Inc.
. . . . 800-482-1941

Shielding Compounds

3Gmetalworx Inc. 888-965-3634
Parker Hannifin, Chomerics Div
. . . . 781-935-4850

Shielding Material

Shielding Material, EMI/RFI

3Gmetalworx Inc. 888-965-3634
Ad-Vance Magnetics. 574-223-3158
Alco Technologies, Inc. 310-328-4770
André Consulting, Inc. 206-406-8371
DDB Unlimited, Inc 800-753-8459
Dexmet Corporation 203-294-7867
East Coast Shielding 908-852-9160
Electri-Flex Company 800-323-6174
FerriShield. 866-TECH-EMI
Fotofab 773-463-6211
Intermark USA, Inc. 408-971-2055
Ja-Bar Silicone Corp 973-786-5000
JEMIC Shielding Technology
. . . . 717-232-1030
Leader Tech . . . . .866-TECH EMI
Magnetic Shield Corporation
. . . . 888-766-7800
MAJR Products, Inc. 877-625-7776
Microwave Vision Group . . . 678-797-9172
The MuShield Company Inc.
. . . . 888-669-3539
Omega Shielding Products, Inc.
. . . . 800-828-5784
Orbel Corporation 610-829-5000
P & P Technology Ltd . . 44 (0)1376 550525
Panashield, Inc. 203-866-5888
PRISMIER. 630-592-4515
Pulver Laboratories Inc. 800-635-3050
Raymond EMC Enclosures Ltd.
. . . . 800-362-1495
SAS Industries, Inc. . . . 631-727-1441 x302
Schlegel Electronic Materials, Inc.
. . . . 800-204-0863
Spira Manufacturing Corporation
. . . . 888-98-SPIRA
Tech-Etch 508-747-0300
TechDream, Inc. 408-800-7362
Vermillion, Inc. 305-968-5981
VTI Vacuum Technologies, Inc.
. . . . 800-482-1941
W. L. Gore & Associates, Inc.
Wurth Electronics Midcom. . 800-643 2661
Zero Ground LLC 866-937-6463

Shielding Material, Magnetic Field

3Gmetalworx Inc. 888-965-3634
Ad-Vance Magnetics. 574-223-3158
André Consulting, Inc. 206-406-8371
Dexmet Corporation 203-294-7867
FerriShield. 866-TECH-EMI
Fotofab 773-463-6211
Magnetic Shield Corporation
. . . . 888-766-7800
MAJR Products, Inc. 877-625-7776
Microwave Vision Group . . . 678-797-9172
The MuShield Company Inc.
. . . . 888-669-3539
Orbel Corporation 610-829-5000
Panashield, Inc. 203-866-5888
Vermillion, Inc. 305-968-5981
VTI Vacuum Technologies, Inc.
. . . . 800-482-1941

Shielding, Board-Level

3Gmetalworx Inc. 888-965-3634
Leader Tech . . . . .866-TECH EMI
Orbel Corporation 610-829-5000
PRISMIER. 630-592-4515

Suppressors

Suppressors, Transient

Captor Corporation. 937-667-8484
NexTek, Inc. 978-486-0582
Okaya Electric America, Inc. . 800-852-0122
Texas Spectrum Electronics . 972-296-3699
WEMS Electronics 310-962-4410

ESD Equipment & Products

Air Ionizers

3M Electronic Solutions 512-984-6747
MKS ION Systems 800-367-2452
TREK, INC. 800-FOR-TREK

ESD Tape

Mag Daddy. 847-719-5600
Polyonics. 603-352-1415

Meters

Meters, Static Charge

ESDEMC Technology LLC . . . 877-864-8479
Megalin Source International
. . . . 886-2-8698-4181
MKS ION Systems 800-367-2452
Monroe Electronics, Inc. . . 585-765-2254
Prostat Corporation. 630-238-8883
Staticworx Flooring 888-STATICWORX
TREK, INC. 800-FOR-TREK

Simulators

Simulators, EMP

EM TEST USA 858-450-0085
Teseq Inc. 732-417-0501

Simulators, ESD

Advanced Test Equipment Rentals
. . . . 858-558-6500
ARC Technical Resources, Inc.
. . . . 408-263-6486
Barth Electronics, Inc. 702-293-1576
EM TEST USA 858-450-0085
ESDEMC Technology LLC . . . 877-864-8479
Grund Technical Solutions, LLC
. . . . 510-453-2617
Haefely EMC Technology
. . . . 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . 703-365-2330
Noise Laboratory Co (NoiseKen)
. . . . 81 (0) 42 712 2051
Teseq Inc. 732-417-0501
Thermo Fisher Scientific
. . . . 978-275-0800 x2302

Simulators, Lightning

Advanced Test Equipment Rentals 858-558-6500
EM TEST USA 858-450-0085
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . 703-365-2330
Mag Daddy.............. 847-719-5600
Noise Laboratory Co (NoiseKen) 81 (0) 42 712 2051
NTS Pittsfield 800-270-2516
Teseq Inc................. 732-417-0501
Thermo Fisher Scientific 978-275-0800 x2302

Static Control

Static Control Containers

3M Electronic Solutions 512-984-6747

Static Control Flooring

3M Electronic Solutions 512-984-6747
Protective Industrial Polymers 866-361-3331

Staticworx Flooring 888-STATICWORX

Static Control Footwear

Staticworx Flooring 888-STATICWORX

Static Control Garments

3M Electronic Solutions 512-984-6747

Static Control Mats

3M Electronic Solutions 512-984-6747
ESDEMC Technology LLC . . . 877-864-8479
Prostat Corporation........ 630-238-8883

Static Control Monitoring Equipment

3M Electronic Solutions 512-984-6747
MKS ION Systems 800-367-2452
TREK, INC.................800-FOR-TREK

Static Control Packaging

3M Electronic Solutions 512-984-6747

Static Control Workstations

3M Electronic Solutions 512-984-6747

Static Control Wrist Straps

3M Electronic Solutions 512-984-6747
ESDEMC Technology LLC . . . 877-864-8479
Prostat Corporation........ 630-238-8883

Transient Detectors and Suppressors

D. C. Smith Consultants 800-323-3956
EMI Solutions............. 949-206-9960
ESDEMC Technology LLC . . . 877-864-8479
MKS ION Systems 800-367-2452
Quell Corporation 505-243-1423
Texas Spectrum Electronics . 972-296-3699
WEMS Electronics 310-962-4410

Materials, Adhesives & Coatings

Absorbing Materials

Dexmet Corporation....... 203-294-7867
DMAS .... 0031-(0)715012526
Intermark USA, Inc........ 408-971-2055
Laird Technologies 636-898-6215
Leader Tech ....866-TECH EMI
NTS Albuquerque 505-821-4740
Oak-Mitsui Technologies . 518-686-4961
Orbel Corporation......... 610-829-5000
Panashield, Inc. 203-866-5888

Adhesives

Ja-Bar Silicone Corp 973-786-5000
Master Bond.............. 201-343-8983
Polyonics................. 603-352-1415
Staticworx Flooring 888-STATICWORX

Alloys

Ad-Vance Magnetics....... 574-223-3158
Dexmet Corporation....... 203-294-7867
Lubrizol Conductive Polymers 866-680-1555
Magnetic Shield Corporation 888-766-7800
The MuShield Company Inc. 888-669-3539
NTS Albuquerque 505-821-4740

Coatings

Master Bond.............. 201-343-8983
Krefine Co.Ltd............. 520-838-0548
Polyonics................. 603-352-1415
Protective Industrial Polymers 866-361-3331
Staticworx Flooring 888-STATICWORX
TestingPartners.com 862-243-2329
VTI Vacuum Technologies, Inc. 800-482-1941

Foams and Foam Materials

Krefine Co.Ltd............. 520-838-0548
Laird Technologies 636-898-6215
TechDream, Inc............ 408-800-7362
W. L. Gore & Associates, Inc.

Insulation

Polyonics................. 603-352-1415

Powders

Lubrizol Conductive Polymers 866-680-1555

Resins and Compounds

Krefine Co.Ltd............. 520-838-0548
Lubrizol Conductive Polymers 866-680-1555
RTP Company............. 800-433-4787

Sealants

Master Bond.............. 201-343-8983
W. L. Gore & Associates, Inc.

Silicone Conductive Sponge

Ja-Bar Silicone Corp 973-786-5000
JEMIC Shielding Technology 717-232-1030
P & P Technology Ltd . . 44 (0)1376 550525

Thermally Conductive Silicone Materials

Ja-Bar Silicone Corp 973-786-5000
Laird Technologies 636-898-6215
TechDream, Inc............ 408-800-7362

Thermoplastic Components

Lubrizol Conductive Polymers 866-680-1555

Thermoplastics and Thermoplastic Materials

Dexmet Corporation....... 203-294-7867
Krefine Co.Ltd............. 520-838-0548

Lubrizol Conductive Polymers
. . . . 866-680-1555
Oak-Mitsui Technologies . 518-686-4961
RTP Company. 800-433-4787

Power & Power Management

Constant Voltage Regulators

OPHIR RF. 310-306-5556

Converters

Murata Electronics. 800-554-4070
OPHIR RF. 310-306-5556

Cord Sets

CSA Group 866-463-1785
HM Cragg 800-672-7244
Mag Daddy. 847-719-5600
Power Dynamics, Inc 973-560-0019
Schurter Inc. 800-848-2600

Electronic Loads

Chroma Systems Solutions, Inc.
. . . . 949-600-6400

Interrupters, AC Power

OPHIR RF. 310-306-5556

Isolators, Power/Signal Line

OPHIR RF. 310-306-5556

Line Cords

Americor Electronics Ltd. . . . 800-830-5337
Mag Daddy. 847-719-5600
OPHIR RF. 310-306-5556
Power Dynamics, Inc 973-560-0019

Motors

BMI Surplus 781-871-8868
CSA Group 866-463-1785
The MuShield Company Inc.
. . . . 888-669-3539

Multiple Outlet Strips

DDB Unlimited, Inc 800-753-8459
HM Cragg 800-672-7244
Interpower Corporation . . 800-662-2290
Mag Daddy. 847-719-5600

Overcurrent Protection

CITEL, Inc. 800-248-3548
Okaya Electric America, Inc. . 800-852-0122
Schurter Inc. 800-848-2600

Overvoltage Protection

CITEL, Inc. 800-248-3548
NexTek, Inc. 978-486-0582
Okaya Electric America, Inc. . 800-852-0122

Power Amplifier

AE Techron, Inc. 574-295-9495

Com-Power Corporation . . . 714-528-8800
Mag Daddy. 847-719-5600
OPHIR RF. 310-306-5556
TechDream, Inc. 408-800-7362
TREK, INC. 800-FOR-TREK

Power Converters

Associated Power Technologies
. . . . 877-322-7693
Chroma Systems Solutions, Inc.
. . . . 949-600-6400

Power Cords

Americor Electronics Ltd. . . . 800-830-5337
CSA Group 866-463-1785
HM Cragg 800-672-7244
Interpower Corporation . . 800-662-2290
Schurter Inc. 800-848-2600

Power Distribution Systems

API Technologies Corp. 855-294-3800
Captor Corporation. 937-667-8484
CMD Ltd 441709829511
HM Cragg 800-672-7244
IQS, a Division of CMG 508-460-1400
Oak-Mitsui Technologies . 518-686-4961
Schurter Inc. 800-848-2600

Power Entry Modules

Americor Electronics Ltd. . . . 800-830-5337
Corcom/Tyco Electronics . . . 847-573-6504
Interpower Corporation . . 800-662-2290
Oak-Mitsui Technologies . 518-686-4961
OPHIR RF. 310-306-5556
Power Dynamics, Inc 973-560-0019
Schurter Inc. 800-848-2600

Power Generators

Clarion Safety Systems 800-748-0241
Laird Technologies 636-898-6215

Power Line Conditioning Equipment

Mag Daddy. 847-719-5600
NexTek, Inc. 978-486-0582
Okaya Electric America, Inc. . 800-852-0122

WEMS Electronics 310-962-4410

Power Rectifier

DDB Unlimited, Inc 800-753-8459
HM Cragg 800-672-7244

Power Supplies

AE Techron, Inc. 574-295-9495
Americor Electronics Ltd. . . . 800-830-5337
API Technologies Corp. 855-294-3800
Associated Power Technologies
. . . . 877-322-7693
Chroma Systems Solutions, Inc.
. . . . 949-600-6400
CSA Group 866-463-1785
HM Cragg 800-672-7244
Murata Electronics. 800-554-4070
Test Equipment Connection . 800-615-8378
TREK, INC. 800-FOR-TREK
Tri-Mag, Inc. 559-651-2222

Switch Mode Power Supply

AE Techron, Inc. 574-295-9495
Associated Power Technologies 877-322-7693
Chroma Systems Solutions, Inc. 949-600-6400
Tri-Mag, Inc. 559-651-2222

Switching Power Supplies

Americor Electronics Ltd. . . . 800-830-5337
Associated Power Technologies 877-322-7693
Chroma Systems Solutions, Inc. 949-600-6400
Interpower Corporation . . 800-662-2290
Tri-Mag, Inc. 559-651-2222

Safety and Protective Equipment

Safety and Warning Labels

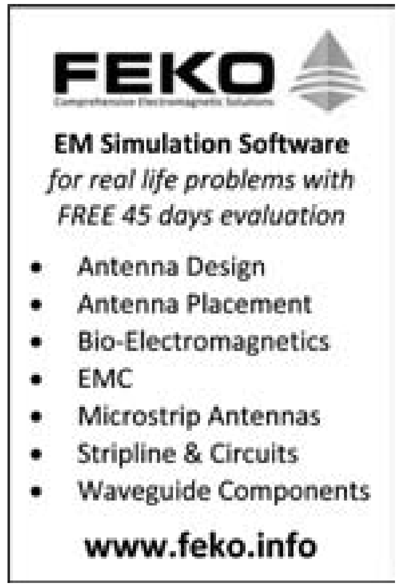
Clarion Safety Systems 800-748-0241
Lewis Bass International 408-942-8000
NTS Newark 877-245-7800

Software Suppliers

3D Simulation Software

CST of America. 508-665-4400

Delcross Technologies, LLC . 217-363-3396
EM Software & Systems (USA) Inc . . . . .800-419-5566 (FEKO)



EM Software & Systems-S.A. 27 21 831 1500
EMSS Consulting 27 2188 01880

Anechoic Chamber Software

EM Software & Systems (USA) Inc . . . . .800-419-5566 (FEKO)

EMC Simulation Software

ANDRO Computational Solutions 315-334-1163
CST of America. 508-665-4400
Delcross Technologies, LLC . 217-363-3396
EM Software & Systems (USA) Inc . . . . .800-419-5566 (FEKO)
EM Software & Systems-S.A. 27 21 831 1500

EMC/EMI Software

AR RF/Microwave Instrumentation 888-933-8181
ARC Technical Resources, Inc. 408-263-6486
CST of America. 508-665-4400
Delcross Technologies, LLC . 217-363-3396
EM Software & Systems (USA) Inc . . . . .800-419-5566 (FEKO)
MossBay EDA 206-779-5345
NEC Corporation
Reliant EMC LLC. 408-600-1472
TechDream, Inc. 408-800-7362

ESD, Static Control Software

CST of America. 508-665-4400
MKS ION Systems 800-367-2452

Product Safety Software

Aum Electro Technology Pvt Ltd 00912512871365
EMSS Consulting 27 2188 01880
Finero USA L.L.C. 239-898-8487

Signal Integrity and EMC Analysis Software

Aum Electro Technology Pvt Ltd 00912512871365
CST of America. 508-665-4400
MossBay EDA 206-779-5345
TechDream, Inc. 408-800-7362

Wireless Propagation Software

Aum Electro Technology Pvt Ltd 00912512871365
Delcross Technologies, LLC . 217-363-3396
EM Software & Systems (USA) Inc . . . . .800-419-5566 (FEKO)
EMSS Consulting 27 2188 01880
MetaGeek 208-639-3140

Standards Suppliers

Clarion Safety Systems 800-748-0241
EMC Compliance 256-650-5261
ESD Association 315-339-6937
Hoolihan EMC Consulting. 651-213-0966
Trace Laboratories, Inc.. 410-584-9099

Test & Measurement Equipment

Amplifiers

Amplifiers, Low Noise

A.H. Systems, Inc. 818-998-0223
Advanced Test Equipment Rentals 858-558-6500
AE Techron, Inc. 574-295-9495
Agilent Technologies 800-829-4444
API Technologies Corp. 855-294-3800
AR RF/Microwave Instrumentation 888-933-8181
Avalon Equipment Corporation 888-542-8256
Com-Power Corporation . . . 714-528-8800
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
Giga-tronics Incorporated . . 800-277-9764
Instruments For Industry, Inc. 631-467-8400
OPHIR RF. 310-306-5556
Teseq Inc.. 732-417-0501

Amplifiers, Power

Advanced Test Equipment Rentals 858-558-6500
AE Techron, Inc. 574-295-9495
Agilent Technologies 800-829-4444
AR RF/Microwave Instrumentation 888-933-8181
Avalon Equipment Corporation 888-542-8256
Com-Power Corporation . . . 714-528-8800
CPI, Inc. 905-877-0161
Electro Rent Corporation . . . 800-688-1111
Electronic Instrument Associates 630-924-1600
Giga-tronics Incorporated . . 800-277-9764
HV TECHNOLOGIES, Inc. . . 703-365-2330
Instruments For Industry, Inc. 631-467-8400
Lionheart Northwest 425-882-2587
MILMEGA Ltd 44 (0) 1983-618004
OPHIR RF. 310-306-5556
Rohde & Schwarz, Inc. 888-TEST-RSA
Solar Electronics Company . 800-952-5302
Vectawave Technology, Ltd. 44 1983 821818

Amplifiers, RF

Advanced Test Equipment Rentals 858-558-6500
Agilent Technologies 800-829-4444
API Technologies Corp. 855-294-3800
AR RF/Microwave Instrumentation 888-933-8181
ARC Technical Resources, Inc. 408-263-6486
Avalon Equipment Corporation 888-542-8256
BMI Surplus 781-871-8868
Com-Power Corporation . . . 714-528-8800
CPI, Inc. 905-877-0161
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
HV TECHNOLOGIES, Inc. . . 703-365-2330
Instruments For Industry, Inc. 631-467-8400
Lionheart Northwest 425-882-2587
MetaGeek 208-639-3140
MILMEGA Ltd 44 (0) 1983-618004
OPHIR RF. 310-306-5556
Reliant EMC LLC. 408-600-1472
Rohde & Schwarz, Inc. 888-TEST-RSA
Test Equipment Connection . 800-615-8378
Vectawave Technology, Ltd. 44 1983 821818

Analyzers

Analyzers, EMI/EMC Spectrum

Advanced Test Equipment Rentals 858-558-6500
Aeroflex. 800-835-2352
Agilent Technologies 800-829-4444
ARC Technical Resources, Inc. 408-263-6486
Avalon Equipment Corporation 888-542-8256
Com-Power Corporation . . . 714-528-8800
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
Electronic Instrument Associates 630-924-1600
GAUSS INSTRUMENTS . . 49-89-5404699-0
MetaGeek 208-639-3140
Reliant EMC LLC. 408-600-1472
Rigol Technologies 877-474-4651
Rohde & Schwarz, Inc. 888-TEST-RSA
Tektronix, Inc. 800-833-9200
Teseq Inc. 732-417-0501
Test Equipment Connection . 407-804-1299

Analyzers, Flicker

Advanced Test Equipment Rentals 858-558-6500
ARC Technical Resources, Inc. 408-263-6486
Avalon Equipment Corporation 888-542-8256
EM TEST USA 858-450-0085
Lionheart Northwest 425-882-2587
Reliant EMC LLC. 408-600-1472

Analyzers, Harmonics

ARC Technical Resources, Inc. 408-263-6486
Avalon Equipment Corporation 888-542-8256
Electro Rent Corporation . . . 800-688-1111
EM TEST USA 858-450-0085
Lionheart Northwest 425-882-2587
Reliant EMC LLC. 408-600-1472

Analyzers, Network

Advanced Test Equipment Rentals 858-558-6500
Aeroflex. 800-835-2352
Agilent Technologies 800-829-4444
Avalon Equipment Corporation 888-542-8256
BMI Surplus 781-871-8868
Electro Rent Corporation . . . 800-688-1111
Giga-tronics Incorporated . . 800-277-9764
Global Test Equipment 866-409-0400
Rohde & Schwarz, Inc. 888-TEST-RSA
Test Equipment Connection . 800-615-8378

Analyzers, Power Quality

Advanced Test Equipment Rentals 858-558-6500
Avalon Equipment Corporation 888-542-8256
Electro Rent Corporation . . . 800-688-1111
Lionheart Northwest 425-882-2587
Test Equipment Connection . 800-615-8378

Analyzers, Telecom

Advanced Test Equipment Rentals 858-558-6500
Aeroflex. 800-835-2352
Avalon Equipment Corporation 888-542-8256
Hermon Laboratories TI . . . 972-4-6268401
MetaGeek 208-639-3140

Automatic Test Sets

Aeroflex. 800-835-2352
Amber Precision Instruments, Inc. 408-752-0199 x102
ARC Technical Resources, Inc. 408-263-6486
Aum Electro Technology Pvt Ltd 00912512871365
Chroma Systems Solutions, Inc. 949-600-6400
Hermon Laboratories TI . . . 972-4-6268401
Innco Systems GmbH .0049 9435 301659 0
Reliant EMC LLC. 408-600-1472

Teseq Inc. 732-417-0501
Thermo Fisher Scientific 978-275-0800 x2302
VEROCH 954-990-7544

Avionics Test Equipment

AE Techron, Inc. . . . 574-295-9495
Aeroflex . . . 800-835-2352
Avalon Equipment Corporation . . . 888-542-8256
Dayton T. Brown, Inc. . . . 800-TEST-456
EM TEST USA . . . 858-450-0085
HV TECHNOLOGIES, Inc. . . . 703-365-2330
MI Technologies . . . 678-475-8345
Narda Safety Test Solutions . . . 631-231-1700
Thermo Fisher Scientific . . . 978-275-0800 x2302

Buildings, EMC Testing

Audivo GmbH. . . . 49 9435 5419 0
Cuming-Lehman Chambers, Inc. . . . 717-263-4101
Narda Safety Test Solutions . . . 631-231-1700

Burn-in Test Equipment

VEROCH . . . 954-990-7544

Calibration & Repair Services

Aeroflex . . . 800-835-2352
Agilent Technologies . . . 800-829-4444
Avalon Equipment Corporation . . . 888-542-8256
EM TEST USA . . . 858-450-0085
ESDEMC Technology LLC . . . 877-864-8479
eti Conformity Services . . . 877-468-6384
Fischer Custom Communications . . . 310-303-3300
GAUSS INSTRUMENTS . . . 49-89-5404699-0
Global Test Equipment . . . 866-409-0400
Liberty Labs, Inc. . . . 712-773-2199
MI Technologies . . . 678-475-8345
Prostat Corporation . . . 630-238-8883
Restor Metrology . . . 877-220-5554
VEROCH . . . 954-990-7544
World Cal, Inc. . . . 712-764-2197

Current Leakage Testers

Advanced Test Equipment Rentals . . . 858-558-6500
Associated Research, Inc . . . 800-858-8378
Chroma Systems Solutions, Inc. . . . 949-600-6400
ED&D Inc. . . . 800-806-6236
Ergonomics, Inc. . . . 800-862-0102
ESDEMC Technology LLC . . . 877-864-8479
Finero USA L.L.C. . . . 239-898-8487
NTS Santa Clarita . . . 800-270-2516
Slaughter Company, Inc. . . . 800-504-0055
VEROCH . . . 954-990-7544
Vitrek Corporation . . . 858-689-2755

Data Acquisition Monitoring Systems

3M Electronic Solutions . . . 512-984-6747
Advanced Test Equipment Rentals . . . 858-558-6500
Avalon Equipment Corporation . . . 888-542-8256
Global Test Equipment . . . 866-409-0400
MKS ION Systems . . . 800-367-2452
NTS Albuquerque . . . 505-821-4740

Dielectric Strength Testers

Advanced Test Equipment Rentals . . . 858-558-6500
Associated Research, Inc . . . 800-858-8378
Chroma Systems Solutions, Inc. . . . 949-600-6400
ED&D Inc. . . . 800-806-6236
Ergonomics, Inc. . . . 800-862-0102
Slaughter Company, Inc. . . . 800-504-0055
Vitrek Corporation . . . 858-689-2755

Electrical Safety Testers

Advanced Test Equipment Rentals . . . 858-558-6500
AE Techron, Inc. . . . 574-295-9495
Associated Research, Inc . . . 800-858-8378
Avalon Equipment Corporation . . . 888-542-8256
Chroma Systems Solutions, Inc. . . . 949-600-6400
ED&D Inc. . . . 800-806-6236
Ergonomics, Inc. . . . 800-862-0102
Finero USA L.L.C. . . . 239-898-8487
Prostat Corporation . . . 630-238-8883
Slaughter Company, Inc. . . . 800-504-0055
VEROCH . . . 954-990-7544
Vitrek Corporation . . . 858-689-2755

EMC Testers

Advanced Test Equipment Rentals . . . 858-558-6500
AE Techron, Inc. . . . 574-295-9495
Aeroflex . . . 800-835-2352
Amber Precision Instruments, Inc. . . . 408-752-0199 x102
Avalon Equipment Corporation . . . 888-542-8256
D. C. Smith Consultants . . . 800-323-3956
Electronic Instrument Associates . . . 630-924-1600
EM TEST USA . . . 858-450-0085

EMC Test Design, LLC . . . 508-292-1833
EMSCAN . . . 877-367-2261
GAUSS INSTRUMENTS . . . 49-89-5404699-0
Haefely EMC Technology . . . 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Noise Laboratory Co (NoiseKen) . . . 81 (0) 42 712 2051
Reliant EMC LLC. . . . 408-600-1472
Rohde & Schwarz, Inc. . . . 888-TEST-RSA
TechDream, Inc. . . . 408-800-7362
Teseq Inc. . . . 732-417-0501
Test Equipment Connection . . . 800-615-8378
Thermo Fisher Scientific . . . 978-275-0800 x2302
TÜV SÜD America Inc. . . . 800-888-0123

EMP Simulators

Dayton T. Brown, Inc. . . . 800-TEST-456
EM TEST USA . . . 858-450-0085
Fischer Custom Communications . . . 310-303-3300
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Teseq Inc. . . . 732-417-0501

Environmental Chambers

Advanced Test Equipment Rentals . . . 858-558-6500
ED&D Inc. . . . 800-806-6236
NTS Newark . . . 877-245-7800
NTS Rockford . . . 800-270-2516
Thermotron Industries . . . 616-393-4580
TÜV SÜD America Inc. . . . 800-888-0123
VEROCH . . . 954-990-7544

ESD Test Equipment

3M Electronic Solutions 512-984-6747
Amber Precision Instruments, Inc. 408-752-0199 x102
Avalon Equipment Corporation 888-542-8256
Barth Electronics, Inc. 702-293-1576
Electro Rent Corporation . . . 800-688-1111
Electronic Instrument Associates 630-924-1600
ESDEMC Technology LLC . . . 877-864-8479
Grund Technical Solutions, LLC 510-453-2617
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Monroe Electronics, Inc. . . . 585-765-2254
Noise Laboratory Co (NoiseKen) 81 (0) 42 712 2051
NTS Newark 877-245-7800
TechDream, Inc. 408-800-7362
Thermo Fisher Scientific 978-275-0800 x2302
TREK, INC. 800-FOR-TREK

Fiber-Optic Systems

Audivo GmbH. 49 9435 5419 0
Global Test Equipment 866-409-0400
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Michigan Scientific Corporation 248-685-3939 x111

Flow Meters

VEROCH 954-990-7544

Gaussmeters

BMI Surplus 781-871-8868
Ergonomics, Inc.. 800-862-0102
Magnetic Shield Corporation 888-766-7800
Narda Safety Test Solutions . 631-231-1700

Generators

Generators, Arbitrary Wave Form

Aeroflex. 800-835-2352
Electro Rent Corporation . . . 800-688-1111
Rigol Technologies 877-474-4651
Tektronix, Inc.. 800-833-9200
Test Equipment Connection . 800-615-8378

Generators, ESD

EM TEST USA 858-450-0085
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Teseq Inc.. 732-417-0501
Thermo Fisher Scientific 978-275-0800 x2302

Generators, Fast/Transient Burst

Advanced Test Equipment Rentals 858-558-6500
Electro Rent Corporation . . . 800-688-1111
EM TEST USA 858-450-0085
Fischer Custom Communications 310-303-3300
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Noise Laboratory Co (NoiseKen) 81 (0) 42 712 2051
Thermo Fisher Scientific 978-275-0800 x2302

Generators, Impulse

Applied EM Technology 410-326-6728
Electro Rent Corporation . . . 800-688-1111
EM TEST USA 858-450-0085
Haefely EMC Technology 845-279-3644 x240
Noise Laboratory Co (NoiseKen) 81 (0) 42 712 2051
Thermo Fisher Scientific 978-275-0800 x2302

Generators, Interference

Electro Rent Corporation . . . 800-688-1111
Noise Laboratory Co (NoiseKen) 81 (0) 42 712 2051

Generators, Lightning

EM TEST USA 858-450-0085
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Solar Electronics Company . 800-952-5302
Thermo Fisher Scientific 978-275-0800 x2302

Generators, Signal

Aeroflex. 800-835-2352
Agilent Technologies 800-829-4444
AR RF/Microwave Instrumentation 888-933-8181
Electro Rent Corporation . . . 800-688-1111
Giga-tronics Incorporated . . 800-277-9764
Global Test Equipment 866-409-0400
Reliant EMC LLC. 408-600-1472
Rigol Technologies 877-474-4651
Rohde & Schwarz, Inc. 888-TEST-RSA
Tektronix, Inc.. 800-833-9200
Test Equipment Connection . 800-615-8378

Generators, Surge Transient

Advanced Test Equipment Rentals 858-558-6500
Electro Rent Corporation . . . 800-688-1111
EM TEST USA 858-450-0085
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Lionheart Northwest 425-882-2587
Noise Laboratory Co (NoiseKen) 81 (0) 42 712 2051
Solar Electronics Company . 800-952-5302
Thermo Fisher Scientific 978-275-0800 x2302

Ground Bond Testers

Associated Research, Inc . . . 800-858-8378
Chroma Systems Solutions, Inc. 949-600-6400
ED&D Inc. 800-806-6236
Finero USA L.L.C. 239-898-8487
Slaughter Company, Inc. . . . 800-504-0055
Staticworx Flooring 888-STATICWORX
Vitrek Corporation. 858-689-2755

Ground Resistance Testers

Associated Research, Inc . . . 800-858-8378
Chroma Systems Solutions, Inc. 949-600-6400
Ergonomics, Inc.. 800-862-0102
Finero USA L.L.C. 239-898-8487
Prostat Corporation. 630-238-8883
Slaughter Company, Inc. . . . 800-504-0055
Staticworx Flooring 888-STATICWORX

Hipot Testers

Associated Research, Inc . . . 800-858-8378
Avalon Equipment Corporation 888-542-8256
Chroma Systems Solutions, Inc. 949-600-6400
ED&D Inc. 800-806-6236
Electro Rent Corporation . . . 800-688-1111
Ergonomics, Inc.. 800-862-0102
Finero USA L.L.C. 239-898-8487
Slaughter Company, Inc. . . . 800-504-0055
Test Equipment Connection . 800-615-8378
VEROCH 954-990-7544
Vitrek Corporation. 858-689-2755

Meters

Megohmmeters

Chroma Systems Solutions, Inc. 949-600-6400
Finero USA L.L.C. 239-898-8487
Monroe Electronics, Inc. .. 585-765-2254
Staticworx Flooring 888-STATICWORX
Vitrek Corporation......... 858-689-2755

Meters, Field Strength

AR RF/Microwave Instrumentation 888-933-8181
EMC Test Design, LLC...... 508-292-1833
Ergonomics, Inc............ 800-862-0102
ETS-Lindgren 512-531-6400
Magnetic Shield Corporation 888-766-7800
Narda Safety Test Solutions .631-231-1700
TREK, INC.................800-FOR-TREK

Meters, Magnetic Field

EMC Test Design, LLC...... 508-292-1833
Ergonomics, Inc............ 800-862-0102
Magnetic Shield Corporation 888-766-7800
Narda Safety Test Solutions .631-231-1700

Meters, Radiation Hazard

EMC Test Design, LLC...... 508-292-1833
ETS-Lindgren 512-531-6400
Narda Safety Test Solutions .631-231-1700

Meters, RF Power

Aeroflex.................. 800-835-2352
Agilent Technologies 800-829-4444
AR RF/Microwave Instrumentation 888-933-8181
BMI Surplus 781-871-8868
Electro Rent Corporation ... 800-688-1111
EMC Test Design, LLC...... 508-292-1833
Giga-tronics Incorporated .. 800-277-9764
Global Test Equipment..... 866-409-0400
MetaGeek................ 208-639-3140

Meters, Static Charge

Monroe Electronics, Inc. .. 585-765-2254
Prostat Corporation........ 630-238-8883
Staticworx Flooring 888-STATICWORX
TREK, INC.................800-FOR-TREK

Meters, Static Decay

Monroe Electronics, Inc. .. 585-765-2254
Prostat Corporation........ 630-238-8883
Staticworx Flooring 888-STATICWORX

Monitors

Monitors, Current

3M Electronic Solutions 512-984-6747
Pearson Electronics, Inc... 650-494-6444

Monitors, EMI Test

3M Electronic Solutions 512-984-6747
EMC Test Design, LLC...... 508-292-1833
MKS ION Systems 800-367-2452
Test Equipment Connection . 800-615-8378

Monitors, ESD

3M Electronic Solutions 512-984-6747
MKS ION Systems 800-367-2452
Noise Laboratory Co (NoiseKen) 81 (0) 42 712 2051
TREK, INC.................800-FOR-TREK

Monitors, Ionizer Balance

MKS ION Systems 800-367-2452

Monitors, Static Voltage

MKS ION Systems 800-367-2452
TREK, INC.................800-FOR-TREK

Oscilloscopes and Transient Recorders

Aeroflex.................. 800-835-2352
Agilent Technologies 800-829-4444
Aum Electro Technology Pvt Ltd 00912512871365
Avalon Equipment Corporation 888-542-8256
BMI Surplus 781-871-8868
D. C. Smith Consultants 800-323-3956
Electro Rent Corporation ... 800-688-1111
GAUSS INSTRUMENTS .. 49-89-5404699-0
Global Test Equipment..... 866-409-0400
Lionheart Northwest....... 425-882-2587
MetaGeek................ 208-639-3140
Rigol Technologies 877-474-4651
Tektronix, Inc.............. 800-833-9200
Test Equipment Connection . 800-615-8378

Probes

Probes, Current/Magnetic Field

A.H. Systems, Inc. 818-998-0223
Agilent Technologies 800-829-4444
Amber Precision Instruments, Inc. 408-752-0199 x102
AR RF/Microwave Instrumentation 888-933-8181
Com-Power Corporation ... 714-528-8800
D. C. Smith Consultants 800-323-3956
EM TEST USA 858-450-0085
EMC Test Design, LLC...... 508-292-1833
Ergonomics, Inc............ 800-862-0102
ESDEMC Technology LLC... 877-864-8479
ETS-Lindgren 512-531-6400
Fischer Custom Communications 310-303-3300
MI Technologies 678-475-8345
Solar Electronics Company . 800-952-5302
Tektronix, Inc.............. 800-833-9200
Teseq Inc................. 732-417-0501
Test Equipment Connection . 800-615-8378
Van Doren Company....... 573-341-4097

Probes, Electric Field

Agilent Technologies 800-829-4444
Amber Precision Instruments, Inc. 408-752-0199 x102
AR RF/Microwave Instrumentation 888-933-8181
Com-Power Corporation ... 714-528-8800
D. C. Smith Consultants 800-323-3956
Electronic Instrument Associates 630-924-1600
EMC Technologists 732-919-1100
EMC Test Design, LLC...... 508-292-1833
ESDEMC Technology LLC... 877-864-8479
ETS-Lindgren 512-531-6400
Test Equipment Connection . 800-615-8378
Van Doren Company....... 573-341-4097

Probes, Voltage

Agilent Technologies 800-829-4444
ARC Technical Resources, Inc. 408-263-6486
Barth Electronics, Inc. 702-293-1576
BMI Surplus 781-871-8868
D. C. Smith Consultants 800-323-3956
Fischer Custom Communications 310-303-3300
Global Test Equipment..... 866-409-0400
Reliant EMC LLC........... 408-600-1472
Tektronix, Inc.............. 800-833-9200
Test Equipment Connection . 800-615-8378
VEROCH 954-990-7544

Receivers

Receivers, EMI/EMC

Advanced Test Equipment Rentals 858-558-6500
Agilent Technologies 800-829-4444
API Technologies Corp. 855-294-3800
AR RF/Microwave Instrumentation 888-933-8181
Com-Power Corporation ... 714-528-8800
Dynamic Sciences International 800-966-3713
Electro Rent Corporation ... 800-688-1111
EMI Instrumentation....... 805-835-8547
GAUSS INSTRUMENTS .. 49-89-5404699-0
Reliant EMC LLC........... 408-600-1472
Rohde & Schwarz, Inc..... 888-TEST-RSA
TechDream, Inc............ 408-800-7362

Receivers, RF

Agilent Technologies 800-829-4444
API Technologies Corp. 855-294-3800
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
GAUSS INSTRUMENTS . . 49-89-5404699-0
Global Test Equipment 866-409-0400
MI Technologies 678-475-8345

Receivers, Tempest

API Technologies Corp. 855-294-3800
Dynamic Sciences International 800-966-3713
GAUSS INSTRUMENTS . . 49-89-5404699-0

RF Leak Detectors

AR RF/Microwave Instrumentation 888-933-8181
ETS-Lindgren 512-531-6400
MetaGeek 208-639-3140
Narda Safety Test Solutions . 631-231-1700
Test Equipment Connection . 800-615-8378

Safety Test Equipment

Associated Research, Inc . . . 800-858-8378
Avalon Equipment Corporation 888-542-8256
Chroma Systems Solutions, Inc. 949-600-6400
Com-Power Corporation . . . 714-528-8800
ED&D Inc. 800-806-6236
EMC Technologists 732-919-1100
Ergonomics, Inc.. 800-862-0102
Finero USA L.L.C. 239-898-8487
Narda Safety Test Solutions . 631-231-1700
Slaughter Company, Inc. . . . 800-504-0055
VEROCH 954-990-7544

Shock & Vibration Testing Shakers

Aum Electro Technology Pvt Ltd 00912512871365
Dayton T. Brown, Inc. 800-TEST-456
NTS Newark 877-245-7800
NTS Santa Clarita 800-270-2516
Thermotron Industries 616-393-4580
TÜV SÜD America Inc. 800-888-0123

Susceptiblity Test Instruments

AE Techron, Inc. 574-295-9495
Amber Precision Instruments, Inc. 408-752-0199 x102
AR RF/Microwave Instrumentation 888-933-8181
ARC Technical Resources, Inc. 408-263-6486
Com-Power Corporation . . . 714-528-8800
Electronic Instrument Associates 630-924-1600
EM TEST USA 858-450-0085
EMC Test Design, LLC 508-292-1833
Narda Safety Test Solutions . 631-231-1700
NexTek, Inc. 978-486-0582
Solar Electronics Company . 800-952-5302
Thermo Fisher Scientific 978-275-0800 x2302

Telecom Test Equipment

AE Techron, Inc. 574-295-9495
Aeroflex 800-835-2352
ED&D Inc. 800-806-6236
Electro Rent Corporation . . . 800-688-1111
Electronic Instrument Associates 630-924-1600
EM TEST USA 858-450-0085
Global Test Equipment 866-409-0400
Haefely EMC Technology 845-279-3644 x240
Hermon Laboratories TI . . . 972-4-6268401
HV TECHNOLOGIES, Inc. . . 703-365-2330
MetaGeek 208-639-3140
NTS Newark 877-245-7800
NTS Tinton Falls 732-936-0800
Test Equipment Connection . 800-615-8378
Thermo Fisher Scientific 978-275-0800 x2302

Temperature Cycling Systems

ED&D Inc. 800-806-6236

Used & Refurbished Test Equipment

A.H. Systems, Inc. 818-998-0223
AR RF/Microwave Instrumentation 888-933-8181
Avalon Equipment Corporation 888-542-8256
BMI Surplus 781-871-8868
Giga-tronics Incorporated . . 800-277-9764
Global Test Equipment 866-409-0400
Test Equipment Connection . 800-615-8378
TÜV SÜD America Inc. 800-888-0123
VEROCH 954-990-7544

Testing Services

Accredited Registrar

CKC Laboratories, Inc.. 800-500-4362
CSA Group 866-463-1785
Curtis-Straus (Bureau Veritas) 877-277-8880
Electro Magnetic Test, Inc. . . 650-965-4000
Nemko Canada 613-737-9680
Nemko USA - SouthEast . . . 813-662-4606
NQA Canada 514-242-2655
NQA Indiana 800-398-8282
NQA West Coast 888-734-4476
NQA, USA 800-649-5289
Parker Hannifin, Chomerics Div 781-935-4850
TÜV Rheinland of North America 1-TUV-RHEINLAND
TÜV SÜD America Inc. 800-888-0123

CE Competent Body

Abstraction Engineering Inc . 408-258-3282
American Certification Body, Inc. 703-847-4700
CKC Laboratories, Inc.. 800-500-4362
Compatible Electronics, Inc. 650-417-EMC1 (3621)
Compliance Management Group 508-281-5985
CSA Group 866-463-1785
Curtis-Straus (Bureau Veritas) 877-277-8880
D.L.S. Electronic Systems, Inc. 847-537-6400
Electro Magnetic Test, Inc. . . 650-965-4000
Elite Electronic Engineering . . 800-ELITE-11
EMCC DR. RASEK 49-9194-9016
G&M Compliance, Inc. 714-628-1020
LS Research. 262-375-4400
Nemko Canada 613-737-9680
Nemko USA - SouthEast . . . 813-662-4606
Parker Hannifin, Chomerics Div 781-935-4850
SIEMIC 408-526-1188
Test Site Services Inc. 508-962-1662
TÜV Rheinland of North America 1-TUV-RHEINLAND
TÜV SÜD America Inc. 800-888-0123
UL LLC

CE Notified Body

American Certification Body, Inc. 703-847-4700
CKC Laboratories, Inc.. 800-500-4362
Compatible Electronics, Inc. 650-417-EMC1 (3621)
CSA Group 866-463-1785
Curtis-Straus (Bureau Veritas) 877-277-8880
D.L.S. Electronic Systems, Inc. 847-537-6400
Electro Magnetic Test, Inc. . . 650-965-4000
EMCC DR. RASEK 49-9194-9016
G&M Compliance, Inc. 714-628-1020
Intertek 800-WORLDLAB
LS Research. 262-375-4400
Nemko Canada 613-737-9680
Northwest EMC Inc. - Washington 888-364-2378
Northwest EMC, Inc. - Oregon 888-364-2378

CE Notified Body *continued*

NTS Newark . . . 877-245-7800
SGS Consumer Testing Services . . . 800-777-TEST (8378)
SIEMIC . . . 408-526-1188
Test Site Services Inc. . . . 508-962-1662
TÜV Rheinland of North America . . . 1-TUV-RHEINLAND
TÜV SÜD America Inc. . . . 800-888-0123
UL LLC

Environmental Testing and Analysis Services

ACS - Boca Raton, FL . . . 561-961-5585
Alberi EcoTech . . . 702-677-6923
Cascade TEK - Oregon . . . 888-835-9250
Cascade TEK - Colorado . . . 888-835-9250
CertifiGroup Inc . . . 800-422-1651
Core Compliance Testing . . . 603 889-5545
CSA Group . . . 866-463-1785
CSZ Testing Services . . . 513-793-7774
D.L.S. Electronic Systems, Inc. . . . 847-537-6400
EMC Testing Laboratories, Inc. . . . 770-475-8819
G&M Compliance, Inc. . . . 714-628-1020
Garwood Laboratories . . . 888-427-4111
Garwood Laboratories Inc. SC . . . 888-427-4111
Green Mtn. Electromagnetics . . . 802-388-3390
Keystone Compliance . . . 724-657-9940
LabTest Certification Inc. . . . 604-247-0444
NTS Santa Clarita . . . 800-270-2516
Staticworx Flooring . . . 888-STATICWORX
Test Site Services Inc. . . . 508-962-1662
TestingPartners.com . . . 862-243-2329
Thermotron Industries . . . 616-393-4580
VEROCH . . . 954-990-7544

Homologation Services

ACS - Atlanta, GA. . . . 770-831-8048
ACS - Boca Raton, FL . . . 561-961-5585
ACS - Melbourne, FL . . . 321-951-1710
American Certification Body, Inc. . . . 703-847-4700
CertifiGroup Inc . . . 800-422-1651
CSIA, LLC . . . 503-489-8006
Curtis-Straus (Bureau Veritas) . . . 877-277-8880
Dayton T. Brown, Inc. . . . 800-TEST-456
Electro Magnetic Test, Inc. . . . 650-965-4000
H.B. Compliance Solutions . . . 480-684-2969
IQS, a Division of CMG . . . 508-460-1400
Jacobs Technology . . . 248-676-1101
Lewis Bass International . . . 408-942-8000
Nemko Canada . . . 613-737-9680
Nemko USA - SouthEast . . . 813-662-4606
O'Brien Compliance Management . . . 978-970-0525
SGS Consumer Testing Services . . . 800-777-TEST (8378)
SIEMIC . . . 408-526-1188
Telcron LLC
Test Site Services Inc. . . . 508-962-1662
TestingPartners.com . . . 862-243-2329
Versus Global Certifications Pty Ltd. . . . 27 83 5140709

Pre-Assessments

Abstraction Engineering Inc . . . 408-258-3282
ACS - Atlanta, GA. . . . 770-831-8048
ACS - Boca Raton, FL . . . 561-961-5585
ACS - Melbourne, FL . . . 321-951-1710
Advanced ESD Services + . . . 607-759-8133
Alberi EcoTech . . . 702-677-6923
American Certification Body, Inc. . . . 703-847-4700
CASE Forensics . . . 877-736-1106
CertifiGroup Inc . . . 800-422-1651
Compatible Electronics, Inc. . . . 650-417-EMC1 (3621)
Corcom/Tyco Electronics . . . 847-573-6504
CSA Group . . . 866-463-1785
Curtis-Straus (Bureau Veritas) . . . 877-277-8880
Electro Magnetic Test, Inc. . . . 650-965-4000
EMI Solutions . . . 949-206-9960
G&M Compliance, Inc. . . . 714-628-1020
Garwood Laboratories Inc. SC . . . 888-427-4111
H.B. Compliance Solutions . . . 480-684-2969
IQS, a Division of CMG . . . 508-460-1400
Jastech EMC Consulting LLC . . . 248-876-4810
Lewis Bass International . . . 408-942-8000
MI Technologies . . . 678-475-8345
Montrose Compliance Services . . . 408-247-5715
NCEE Labs . . . 888-567-6860
O'Brien Compliance Management . . . 978-970-0525
Product Safety Consulting . . . 877-804-3066
Pulver Laboratories Inc. . . . 800-635-3050
RF Exposure Lab . . . 760-471-2100
RMV Technology Group, LLC . . . 650-964-4792
SIEMIC . . . 408-526-1188
SILENT Solutions LLC . . . 603-578-1842 x203
Spectrum EMC Consulting, LLC . . . 651-688-0634
Stephen Halperin & Associates . . . 630-238-8883
Telcron LLC
Test Site Services Inc. . . . 508-962-1662
TestingPartners.com . . . 862-243-2329
TÜV Rheinland of North America . . . 1-TUV-RHEINLAND

Product and Component Testing Services

Abstraction Engineering Inc . . . 408-258-3282
ACS - Atlanta, GA. . . . 770-831-8048
ACS - Boca Raton, FL . . . 561-961-5585
ACS - Melbourne, FL . . . 321-951-1710
Cascade TEK - Oregon . . . 888-835-9250
Cascade TEK - Colorado . . . 888-835-9250
CertifiGroup Inc . . . 800-422-1651
Compatible Electronics, Inc. . . . 650-417-EMC1 (3621)
CSA Group . . . 866-463-1785
CSIA, LLC . . . 503-489-8006
Electronics Test Centre - Airdrie . . . 403-912-0037
EMC Testing Laboratories, Inc. . . . 770-475-8819
EMI Solutions . . . 949-206-9960
Ergonomics, Inc. . . . 800-862-0102
Garwood Laboratories . . . 888-427-4111
Garwood Laboratories Inc. SC . . . 888-427-4111
Jastech EMC Consulting LLC . . . 248-876-4810
Keystone Compliance . . . 724-657-9940
L-3 Communications Cincinnati . . . 800-543-8220
LabTest Certification Inc. . . . 604-247-0444
Lambda Calibration Ltd
LCR Electronics, Inc. . . . 800-527-4362
MI Technologies . . . 678-475-8345
Nexlogic Technologies, Inc. . . . 866-845-1197
Product Safety Consulting . . . 877-804-3066
Raymond EMC Enclosures Ltd. . . . 800-362-1495
RF Exposure Lab. . . . 760-471-2100
SGS Consumer Testing Services . . . 800-777-TEST (8378)
SIEMIC . . . 408-526-1188

Telcron LLC
Test Site Services Inc. 508-962-1662
TestingPartners.com 862-243-2329
TÜV Rheinland of North America
. . . . 1-TUV-RHEINLAND
UL LLC

UL Verification Services . . .86 20 28667188

Testing Laboratories

Accelerated Stress Testing

Cascade TEK - Oregon 888-835-9250
Cascade TEK - Colorado. . . . 888-835-9250
Compliance Management Group
. . . . 508-281-5985
Core Compliance Testing . . . 603 889-5545
CSZ Testing Services 513-793-7774
Dayton T. Brown, Inc. 800-TEST-456
DNB Engineering, Inc.. 714-870-7781
Elite Electronic Engineering . . 800-ELITE-11
EMC Testing Laboratories, Inc.
. . . . 770-475-8819
Flextronics. 613-895-2053
Garwood Laboratories Inc. SC
. . . . 888-427-4111
Global EMC Inc. 888-441-7337
IQS, a Division of CMG 508-460-1400
Keystone Compliance 724-657-9940
MET Laboratories. 410-354-3300
NTS - Corporate HQ 800-270-2516
NTS Fullerton 800-677-2687
NTS LAX. 800-559-3202
NTS Northeast 800-723-2687
NTS Plano 877-717-2687
NTS Santa Clarita 800-270-2516
NTS Tempe 480-966-5517
NTS Tinton Falls 732-936-0800
Professional Testing 800-695-1077
Retlif Testing Laboratories
. . . . 631-737-1500 x111
Test Site Services Inc. 508-962-1662
Trace Laboratories, Inc.. 410-584-9099
TÜV SÜD America Inc. 800-888-0123

Acoustical Testing

Compliance Worldwide, Inc.
. . . . 603-887-3903
Core Compliance Testing . . . 603 889-5545
Dayton T. Brown, Inc. 800-TEST-456
DNB Engineering, Inc.. 714-870-7781
Ergonomics, Inc.. 800-862-0102
ETS-Lindgren 512-531-6400
Flextronics. 613-895-2053
Garwood Laboratories Inc. SC
. . . . 888-427-4111
IQS, a Division of CMG 508-460-1400
MET Laboratories. 410-354-3300
NCEE Labs 888-567-6860
NTS Fullerton 800-677-2687
NTS LAX. 800-559-3202
NTS Northeast 800-723-2687
NTS Plano 877-717-2687
NTS Santa Clarita 800-270-2516
NTS Tempe 480-966-5517
NTS Tinton Falls 732-936-0800
Professional Testing 800-695-1077
Pulver Laboratories Inc. 800-635-3050
Retlif Testing Laboratories
. . . . 631-737-1500 x111

BSMI Compliant Certification Testing

ACS - Atlanta, GA. 770-831-8048
ACS - Boca Raton, FL 561-961-5585
ACS - Melbourne, FL. 321-951-1710
Atlas Compliance & Engineering
. . . . 866-573-9742
Compliance & More, Inc . . . 303-663-3396
Compliance Management Group
. . . . 508-281-5985
Compliance Worldwide, Inc.
. . . . 603-887-3903
Core Compliance Testing . . . 603 889-5545
D.L.S. Electronic Systems, Inc.
. . . . 847-537-6400
DNB Engineering, Inc.. 714-870-7781
Electro Magnetic Test, Inc. . . 650-965-4000
EMC Integrity Inc. 888-423-6275
EMCplus LLC. 303-663-3396
G&M Compliance, Inc. 714-628-1020
Nemko USA - SouthEast . . . 813-662-4606
Northwest EMC Inc. - Minnesota
. . . . 888-364-2378
Northwest EMC Inc.- California
. . . . 888-364-2378
Northwest EMC Inc. - Washington
. . . . 888-364-2378
Northwest EMC, Inc. - Oregon
. . . . 888-364-2378
NTS Fremont 877-245-7800
SGS Consumer Testing Services
. . . . 800-777-TEST (8378)
SIEMIC 408-526-1188
Test Site Services Inc. 508-962-1662
TÜV Rheinland of North America
. . . . 1-TUV-RHEINLAND

CB Test Report

ACS - Atlanta, GA. 770-831-8048
ACS - Boca Raton, FL 561-961-5585
ACS - Melbourne, FL. 321-951-1710
Compliance & More, Inc . . . 303-663-3396
CSA Group 866-463-1785
CSIA, LLC 503-489-8006
Curtis-Straus (Bureau Veritas)
. . . . 877-277-8880
DNB Engineering, Inc.. 714-870-7781
Electro Magnetic Test, Inc. . . 650-965-4000
EMCplus LLC. 303-663-3396
G&M Compliance, Inc. 714-628-1020
MET Laboratories. 410-354-3300
Nemko USA - SouthEast . . . 813-662-4606
NTS Fremont 877-245-7800
NTS Newark 877-245-7800
O'Brien Compliance Management
. . . . 978-970-0525
Professional Testing 800-695-1077
SGS Consumer Testing Services
. . . . 800-777-TEST (8378)
SIEMIC 408-526-1188
Test Site Services Inc. 508-962-1662
TÜV Rheinland of North America
. . . . 1-TUV-RHEINLAND
UL LLC

CE Marking

ACS - Atlanta, GA. 770-831-8048
ACS - Boca Raton, FL 561-961-5585
ACS - Melbourne, FL. 321-951-1710
American Certification Body, Inc.
. . . . 703-847-4700
Atlas Compliance & Engineering
. . . . 866-573-9742
CertifiGroup Inc 800-422-1651
CKC Laboratories, Inc.. 800-500-4362
Compatible Electronics, Inc.
. . . . 650-417-EMC1 (3621)
Compliance & More, Inc . . . 303-663-3396
Compliance Management Group
. . . . 508-281-5985
Compliance Worldwide, Inc.
. . . . 603-887-3903
Core Compliance Testing . . . 603 889-5545
CSA Group 866-463-1785
CSIA, LLC 503-489-8006
Curtis-Straus (Bureau Veritas)
. . . . 877-277-8880
D.L.S. Electronic Systems, Inc.
. . . . 847-537-6400
DNB Engineering, Inc.. 714-870-7781
Electro Magnetic Test, Inc. . . 650-965-4000
Electronics Test Centre. . . . 613-599-6800

CE Marking *continued*

Electronics Test Centre - Airdrie 403-912-0037
Elite Electronic Engineering . . 800-ELITE-11
EMC Integrity Inc. 888-423-6275
EMC Testing Laboratories, Inc. 770-475-8819
EMCC DR. RASEK.......... 49-9194-9016
EMCplus LLC............. 303-663-3396
Ergonomics, Inc........... 800-862-0102
F2 Labs.................. 877-405-1580
G&M Compliance, Inc. 714-628-1020
Garwood Laboratories 888-427-4111
Garwood Laboratories Inc. SC 888-427-4111
Global EMC Inc........... 888-441-7337
Green Mtn. Electromagnetics 802-388-3390
H.B. Compliance Solutions. . 480-684-2969
HCT Co., Ltd............ 82-31-645-6454
International Certification Services, Inc. 888-286-6888
Intertek 800-WORLDLAB
Keystone Compliance...... 724-657-9940
LabTest Certification Inc. ... 604-247-0444
Lewis Bass International 408-942-8000
LS Research.............. 262-375-4400
MET Laboratories.......... 410-354-3300
Montrose Compliance Services 408-247-5715
NCEE Labs............... 888-567-6860
Nemko Canada 613-737-9680
Nemko USA - SouthEast ... 813-662-4606
Northwest EMC Inc. - Minnesota 888-364-2378
Northwest EMC Inc.- California 888-364-2378
Northwest EMC Inc. - Washington 888-364-2378
Northwest EMC, Inc. - Oregon 888-364-2378
NTS Fremont 877-245-7800
NTS Fullerton 800-677-2687
NTS Newark 877-245-7800
NTS Northeast 800-723-2687
NTS Rockford 800-270-2516
O'Brien Compliance Management 978-970-0525
Product Safety Consulting . . 877-804-3066
Professional Testing 800-695-1077
Pulver Laboratories Inc. 800-635-3050
Radiometrics Midwest Corp. 815-293-0772
Retlif Testing Laboratories 631-737-1500 x111
SGS Consumer Testing Services 800-777-TEST (8378)
SIEMIC.................. 408-526-1188
Test Site Services Inc....... 508-962-1662
Thermo Fisher Scientific 978-275-0800 x2302
TÜV Rheinland of North America 1-TUV-RHEINLAND
TÜV SÜD America Inc. 800-888-0123
UL LLC

China Compulsory Certification (CCC)

American Certification Body, Inc. 703-847-4700
Compliance & More, Inc ... 303-663-3396
CSA Group 866-463-1785
CSIA, LLC................ 503-489-8006
D.L.S. Electronic Systems, Inc. 847-537-6400
Electro Magnetic Test, Inc. . . 650-965-4000
EMC Integrity Inc. 888-423-6275
EMCplus LLC............. 303-663-3396
G&M Compliance, Inc. 714-628-1020

Garwood Laboratories 888-427-4111
Garwood Laboratories Inc. SC 888-427-4111
Go Global Compliance Inc. 408-416-3772
HCT Co., Ltd............ 82-31-645-6454
Nemko Canada 613-737-9680
Nemko USA - SouthEast ... 813-662-4606
RTF Compliance.......... 949-813-6095
SGS Consumer Testing Services 800-777-TEST (8378)
SIEMIC.................. 408-526-1188
TÜV Rheinland of North America 1-TUV-RHEINLAND
TÜV SÜD America Inc. 800-888-0123
UL LLC

Electrical Safety Testing

ACS - Atlanta, GA.......... 770-831-8048
ACS - Boca Raton, FL 561-961-5585
ACS - Melbourne, FL....... 321-951-1710
American Certification Body, Inc. 703-847-4700
CASE Forensics............ 877-736-1106
CertifiGroup Inc 800-422-1651
Compliance Management Group 508-281-5985
Core Compliance Testing . . . 603 889-5545
CSA Group 866-463-1785
Curtis-Straus (Bureau Veritas) 877-277-8880
D.L.S. Electronic Systems, Inc. 847-537-6400
DNB Engineering, Inc....... 714-870-7781
Electro Magnetic Test, Inc. . . 650-965-4000
Elite Electronic Engineering . . 800-ELITE-11
EMCC DR. RASEK.......... 49-9194-9016
eti Conformity Services..... 877-468-6384
F2 Labs.................. 877-405-1580
G&M Compliance, Inc. 714-628-1020
Global EMC Inc........... 888-441-7337
Green Mtn. Electromagnetics 802-388-3390
HCT Co., Ltd............ 82-31-645-6454
High Voltage Maintenance . 866-486-8326
Intertek 800-WORLDLAB
LabTest Certification Inc. ... 604-247-0444
Lewis Bass International 408-942-8000
MET Laboratories.......... 410-354-3300
NCEE Labs............... 888-567-6860
Nemko Canada 613-737-9680
Nemko USA - SouthEast ... 813-662-4606
NTS Fremont 877-245-7800
NTS Fullerton 800-677-2687
NTS Tinton Falls........... 732-936-0800
Product Safety Consulting . . 877-804-3066
Professional Testing 800-695-1077
Pulver Laboratories Inc. 800-635-3050
Retlif Testing Laboratories 631-737-1500 x111
SGS Consumer Testing Services 800-777-TEST (8378)
Test Site Services Inc....... 508-962-1662
TestingPartners.com 862-243-2329
Trace Laboratories, Inc...... 410-584-9099
TÜV Rheinland of North America 1-TUV-RHEINLAND
TÜV SÜD America Inc. 800-888-0123
UL LLC
Ultratech EMC Lab......... 905-829-1570

EMC Testing

ACS - Atlanta, GA.......... 770-831-8048
ACS - Boca Raton, FL 561-961-5585
ACS - Melbourne, FL....... 321-951-1710
Alion Science and Technology 610-825-1960
Amber Precision Instruments, Inc. 408-752-0199 x102
American Certification Body, Inc. 703-847-4700
Americor Electronics Ltd. ... 800-830-5337

Atlas Compliance & Engineering . . . 866-573-9742
CKC Laboratories, Inc. . . . 800-500-4362
Compatible Electronics, Inc. . . . 650-417-EMC1 (3621)
Compliance & More, Inc . . . 303-663-3396
Compliance Management Group . . . 508-281-5985
Compliance Worldwide, Inc. . . . 603-887-3903
Core Compliance Testing . . . 603 889-5545
CSIA, LLC . . . 503-489-8006
Curtis-Straus (Bureau Veritas) . . . 877-277-8880
D.L.S. Electronic Systems, Inc. . . . 847-537-6400

Dayton T. Brown, Inc. . . . 800-TEST-456
Electro Magnetic Test, Inc. . . . 650-965-4000
Electronics Test Centre . . . 613-599-6800
Electronics Test Centre - Airdrie . . . 403-912-0037
Elite Electronic Engineering . . . 800-ELITE-11
EMC Compliance . . . 256-650-5261
EMC Integrity Inc. . . . 888-423-6275
EMC Testing Laboratories, Inc. . . . 770-475-8819
EMCC DR. RASEK . . . 49-9194-9016
EMCplus LLC . . . 303-663-3396
eti Conformity Services . . . 877-468-6384
F2 Labs . . . 877-405-1580
Flextronics . . . 613-895-2053
G&M Compliance, Inc. . . . 714-628-1020
Garwood Laboratories . . . 888-427-4111
Garwood Laboratories Inc. SC . . . 888-427-4111
General Dynamics C4 Systems . . . 480-441-5321
Global EMC Inc. . . . 888-441-7337
Green Mtn. Electromagnetics . . . 802-388-3390
H.B. Compliance Solutions . . . 480-684-2969
HCT Co., Ltd. . . . 82-31-645-6454
International Certification Services, Inc. . . . 888-286-6888
Intertek . . . 800-WORLDLAB
Jacobs Technology . . . 248-676-1101
Keystone Compliance . . . 724-657-9940
L-3 Communications Cincinnati . . . 800-543-8220
LabTest Certification Inc. . . . 604-247-0444
LCR Electronics, Inc. . . . 800-527-4362
Lewis Bass International . . . 408-942-8000
LS Research . . . 262-375-4400
MET Laboratories . . . 410-354-3300
Microwave Vision Group . . . 678-797-9172
Montrose Compliance Services . . . 408-247-5715
NCEE Labs . . . 888-567-6860
Nemko Canada . . . 613-737-9680
Nemko USA - SouthEast . . . 813-662-4606
NexTek, Inc. . . . 978-486-0582
Northwest EMC Inc. - Minnesota . . . 888-364-2378
Northwest EMC Inc.- California . . . 888-364-2378
Northwest EMC Inc. - Washington . . . 888-364-2378
Northwest EMC, Inc. - Oregon . . . 888-364-2378

NTS - Corporate HQ . . . 800-270-2516
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Keystone Compliance 724-657-9940
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