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THE 2022

ANNUAL REFERENCE GUIDE

A Compliance Handbook for Electrical and Electronics Engineers


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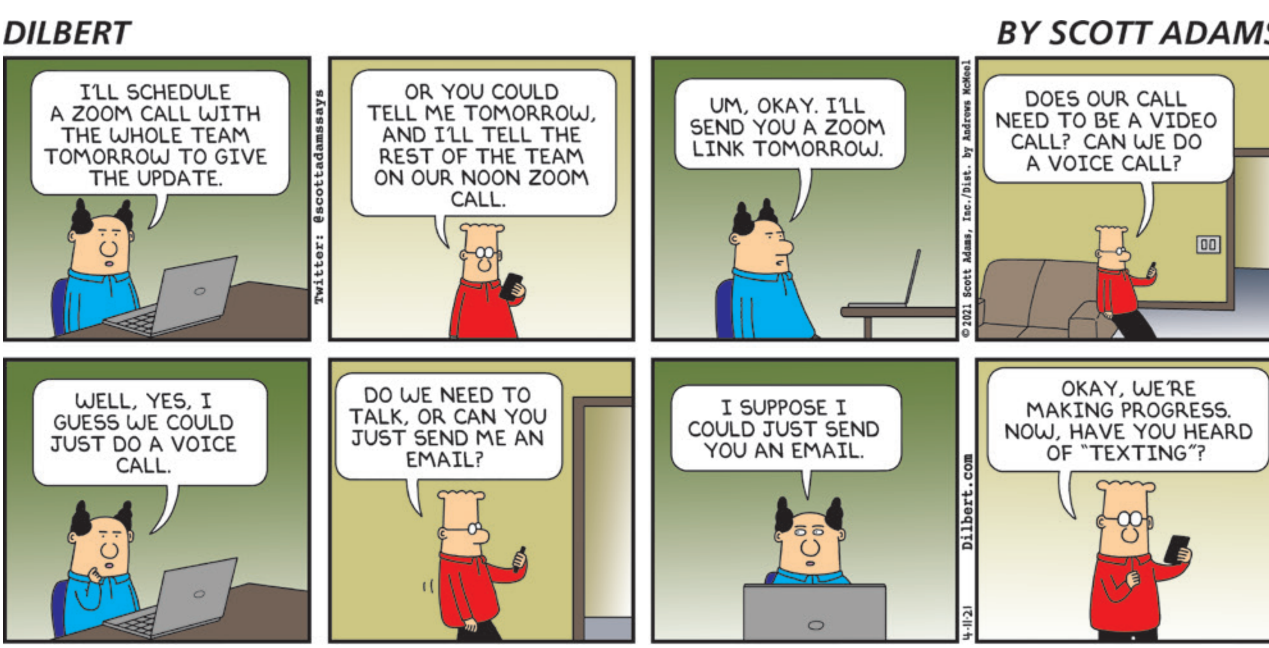
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IN COMPLIANCE
2022 Annual Reference Guide

LETTER From the Editor

Welcome to 2022 and this year's edition of *In Compliance Magazine's* Annual Reference Guide!

For the past several years, I've typically spent the month of January connecting with friends and colleagues and discussing with them the lessons that each of us has learned about ourselves during the past year, as well as the changes that we've made to help integrate those insights into our daily lives.

Prior to the onset of the COVID-19 pandemic two years ago, these conversations generally took the approach that most of us follow when it comes to formulating our resolutions for the new year. That is, we'd focus on the things we didn't do or the mistakes that we made and did not want to repeat in the year ahead and resolve to do better by taking specific actions.

But the world changed for all of us in early 2020. We struggled to deal with the spread and severity of COVID and the accompanying economic uncertainty and upheaval that came with it. And even the lucky ones among us who managed to avoid getting sick and had the economic resources to weather the storm had to adjust to an ever-changing dynamic at home and at work.

In our own individual ways, each of us has been forced to find the strengths within us and to step up when and where we can for ourselves, our family, and others that we care about. And, in this context, it seems wrong somehow to focus on our weaknesses. Instead, we should reflect on what we've been able to accomplish under these unprecedented conditions, acknowledge the importance of our strengths above all else, and explore how we can better leverage those strengths in the future for the benefit of ourselves and others.

For all of us here at *In Compliance Magazine*, the past two years have given us an opportunity both as a team and individually to reconnect with our primary mission, that is, to deliver the most accurate and comprehensive picture of the ever-changing regulatory compliance landscape, and to provide engineers with the information they need to successfully navigate their design challenges. We've gained new insight into what we do well and what we can build on to provide even more value to our readers. And we'll be working hard in the year to come to deliver on that promise.

In the meantime, our never-ending thanks to our readers, our editorial contributors, and our advertisers for your unswerving commitment to our publication. Your support in helping us fulfill our mission is what keeps us going every day!

Sincerely,

Bill von Achen

Features Editor
In Compliance Magazine

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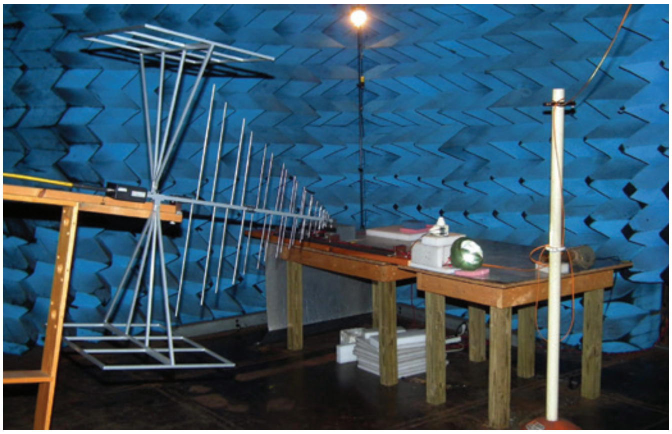

MIL Qualified Products

APITech offers over 800 standard QPL products and DSCC part numbers. Look to us for the largest number of MIL-PRF-15733, MIL-PRF-28861, DSCC 84084, MIL-PRF-49470, MIL-C-11015, and HEMP requirement MIL-STD-188-125 filters. We are the ideal source for your design, whether a COTS buy or an engineered solution.

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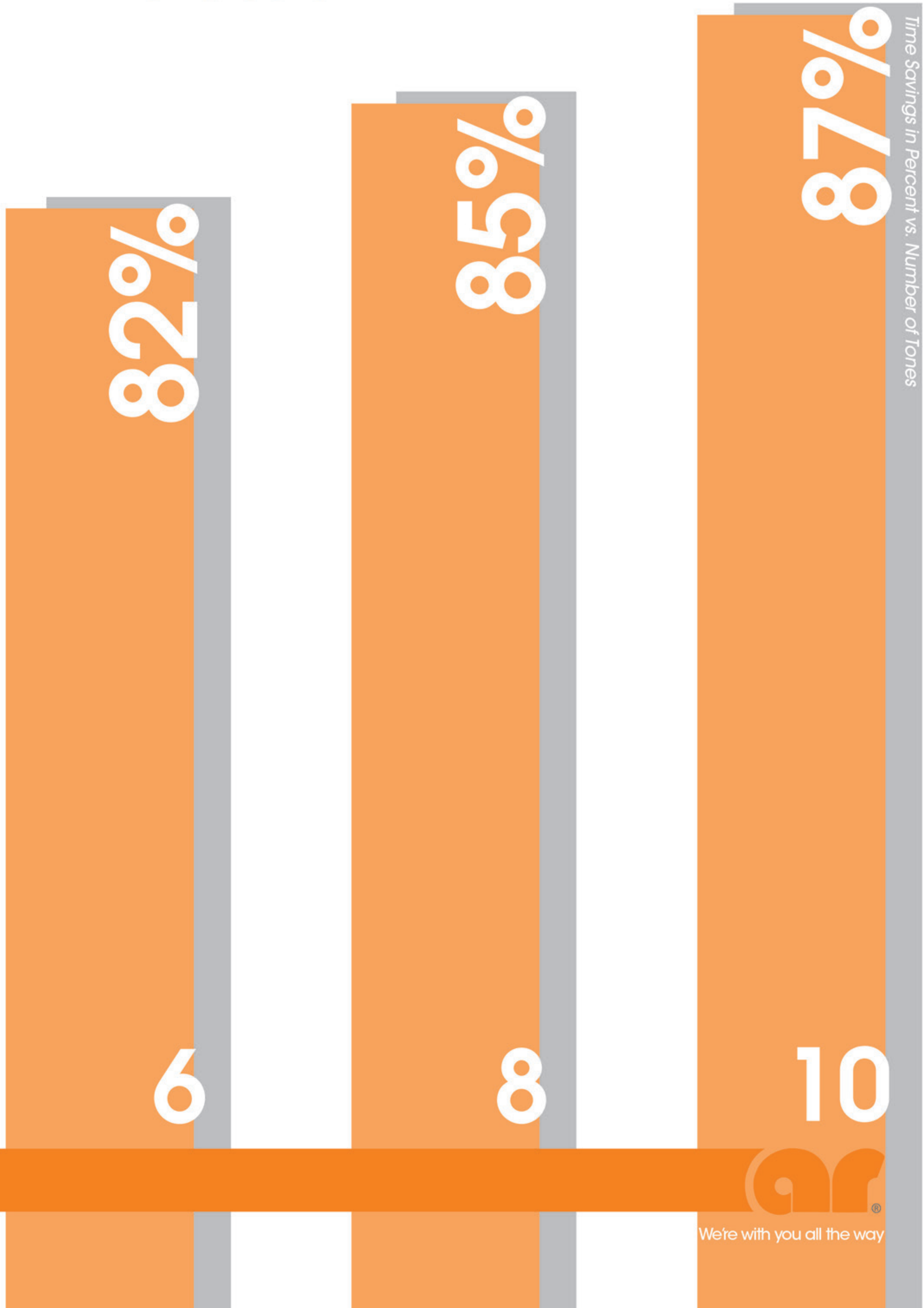

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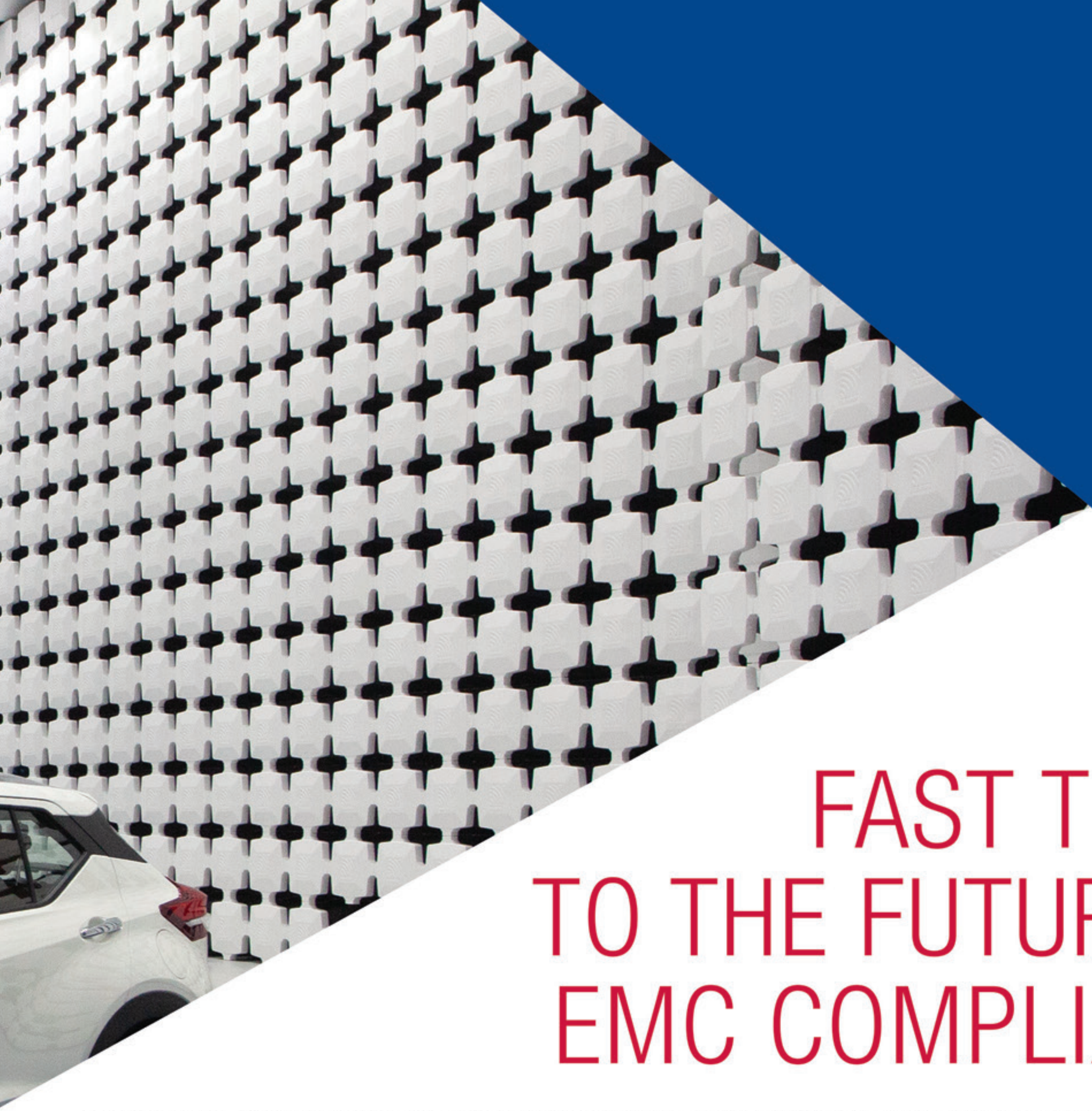


Providing Customers More Than 100 Years of Technical Product and Management Experience

The Company's Products

Exodus Advanced Communications, "Exodus" is a "Best-in-Class" SSPA manufacturer delivering products from 10KHz - 51GHz. The company's extremely ruggedized product line consists of LDMOS, GaN (HEMT) and GaAs devices where we customize significant quantities of our own devices. The company uses clean rooms for manufacturing and the latest advancements in technology designing and fabricating low, medium and high-power amplifiers with chip and wire technology. The company has a very wide range of stand-alone modules, integrated amplifier chassis configurations, and full turn-key systems as needed to satisfy customers specific applications.

Products

- LNA's
- Low, Medium, & High-Power Amplifiers 10KHz-51GHz, Modules & Systems
- HF, VHF, UHF, Power, Microwave, Millimeter
- Ultra-Broadband models
- Octave & narrow band models
- Power levels from Milliwatts to Kilowatts
- Continuous wave (CW)
- Pulse and Dual types available
- Synthesizers
- Block-up converters

About the Company

Exodus is a multinational RF communication equipment and engineering company serving commercial and government entities and their affiliates worldwide. Headquartered in Las Vegas, Nevada, the company utilizes its global network of sales and service partners to effectively support extensive wide ranges of customer applications and requirements.

Markets

- Aerospace & Defense
- Commercial
- EMC, EMP, EMI, HIRF
- Communications
- Educational
- Medical
- Military
- Radar
- 5G

Technical/Market Experience

Exodus is providing customers more than 100 Years of technical product, market and management experience with the broad knowledge of our management team.

Added Value

- Excellent Technical Support
- Excellent Warranty
- Excellent Delivery
- Global Sales & Service Network

Exodus Advanced Communications has amplifiers for virtually every application. Our product offering ranges from 10KHz to 51GHz with levels exceeding 1KW for modules and 50KW for systems.

01 RF Amplifier Modules & Systems from 10KHz to 75GHz

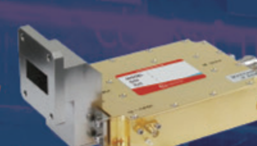
02 Power Levels exceeding 1KW for modules and 50KW for systems

03 LDMOS, GaN and GaAsFET discrete devices and hybrid Chip & Wire Technology

04 Linear, Broadband & Pulsed High Power Amplifier Modules

05 High Power RF & Microwave Modules and Systems

06 High Power RF Communication Equipment and Accessories



- Suitable for all modulation standards
- Instantaneous wide bandwidth
- High reliability and ruggedness
- Built-in protection circuits
- Class A & AB Linear LDMOS, GaAs and GaN design

PARTNER

Common noun

UK: [ˈpɑːtnə]   US: [ˈpart·nər]

- *A person / organization joining another person / organization in a business activity*
- *A person / organization that you or your organization are closely involved with*
- *When partnering, the work is carried out together by partners*

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TECH INFO: Spira was built on engineering excellence. Our library of technical papers assists design engineers in solving their EMI design challenges, and learning the latest breakthroughs in EMI shielding theory.

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FEATURED PRODUCTS: Spira's newest and most popular products are featured.

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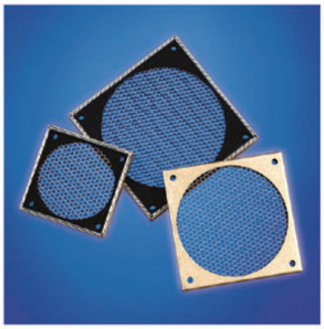

Spira's Shielded Fan Filters provide a high and reliable level of shielding at a great price. They include our patented spiral gasket and patented honeycomb "blending" process of the aluminum panels that provides up to 80dB of shielding at 1GHz. The filters are compatible with 40, 60, 80, 92 and 120mm fans or custom sizes with no additional design fees. Available in 1/8" cell by 1/4" or 1/2" thick honeycomb panels. Excellent EMI Shielded Air-Vent Filters also available in custom configurations.

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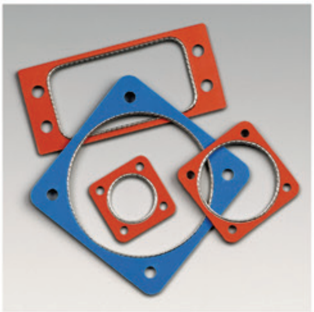

Spira's Connector-Seal gaskets, in standard and front-mount configurations, provide the best EMI and environmental protection on the market! Our unique design includes a rigid layer between either silicone or fluorosilicone elastomeric sealing, and includes our patented spiral gasket for excellent EMI shielding. This gasket is extremely durable and provides reliable one atmosphere environmental sealing for flange-mounted connectors.

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Precisely Right.

EVALUATION OF EMC EMISSIONS AND GROUND TECHNIQUES ON 1- AND 2-LAYER PCBS WITH POWER CONVERTERS

Part 10: Complete System – Conducted and Radiated Emissions Results

By Bogdan Adamczyk, Scott Mee, and Nick Koeller

This is the 10th and the final article in a series of articles devoted to the design, test, and EMC emissions evaluation of 1- and 2-layer PCBs that contain AC/DC and/or DC/DC converters and employ different ground techniques [1-9]. The goal of this study was to evaluate the impact of different grounding strategies and the tradeoff with other design constraints that designers often face. In this article, we present the conducted and radiated emissions results performed according to the CFR Title 47, Part 15, Subpart B, Class B.

1. COMPLETE SYSTEM AND BOARD TOPOLOGIES

Figure 1 shows the top side complete system PCB assembly and its top-level schematic with the functional blocks.

The board is capable of accepting either an AC or DC input. The AC to DC conversion takes part in Partition A of the board (not drawn to scale). The DC to DC converter in Partition B accepts 24V DC input either from the AC/DC converter in Partition A or from an external source [1]. The AC to DC converter is controlled by a Maxim MAX5022 IC, the DC to DC converter is controlled by MAX17783CATB+.

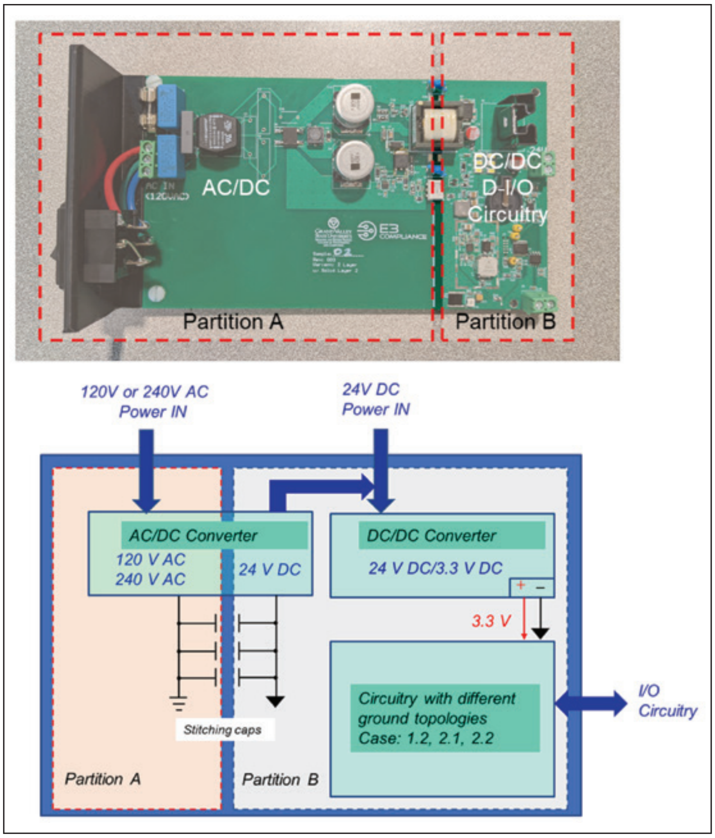

Figure 1: Complete PCB assembly and its block diagram

Dr. Bogdan Adamczyk is professor and director of the EMC Center at Grand Valley State University (http://www.gvsu.edu/emccenter) where he regularly teaches EMC certificate courses for industry. He is an iNARTE certified EMC Master Design Engineer. Prof. Adamczyk is the author of the textbook "Foundations of Electromagnetic Compatibility with Practical Applications" (Wiley, 2017) and the upcoming textbook "Principles of Electromagnetic Compatibility with Laboratory Exercises" (Wiley 2022). He can be reached at adamczyb@gvsu.edu.

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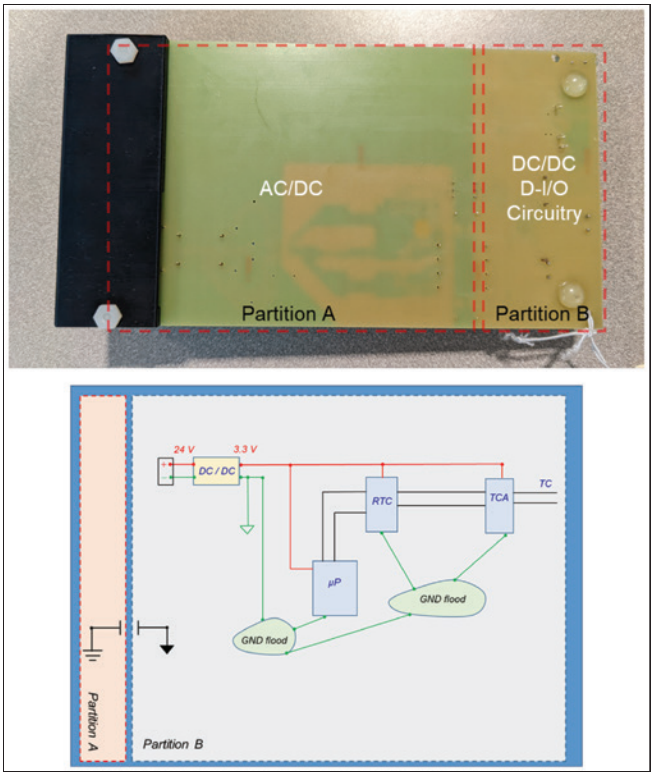

Figure 2: One-layer board – bottom side view (no ground reference return on bottom side)

These two circuits provide power to the embedded system section of the board, which consists of a ST Microelectronics STM32G030F6P6 microcontroller, a Microchip MCP7940NT-I/MS real time clock, and a Maxim Integrated MAX31855JASA+ cold-junction compensated thermocouple to digital converter.

These circuits contained several EMC countermeasures the effectiveness of which are assessed in the previous articles in this series. The AC/DC converter contains an AC input filter, a DC input filter, a slew resistor on the gate of the primary side switching MOSFET, and a snubber on the primary side switching MOSFET. The DC/DC converter contains an input pi filter, a Vishay IHLE electric field shielded switching inductor, and a high frequency output filtering capacitor. The STM32G030F6P6 microcontroller, and MCP7940NT-I/MS real time clock had high frequency decoupling capacitors placed close to the power input pins of the device. The Maxim Integrated MAX31855JASA+ had high frequency decoupling capacitors placed near the power input pins, and a high frequency filtering capacitor across the two pin screw terminal connection for the J-type thermocouple.

Three different PCB topologies were evaluated.

A one-layer board with ground traces and ground floods located only on the top side. The back side of this board is shown in Figure 2.

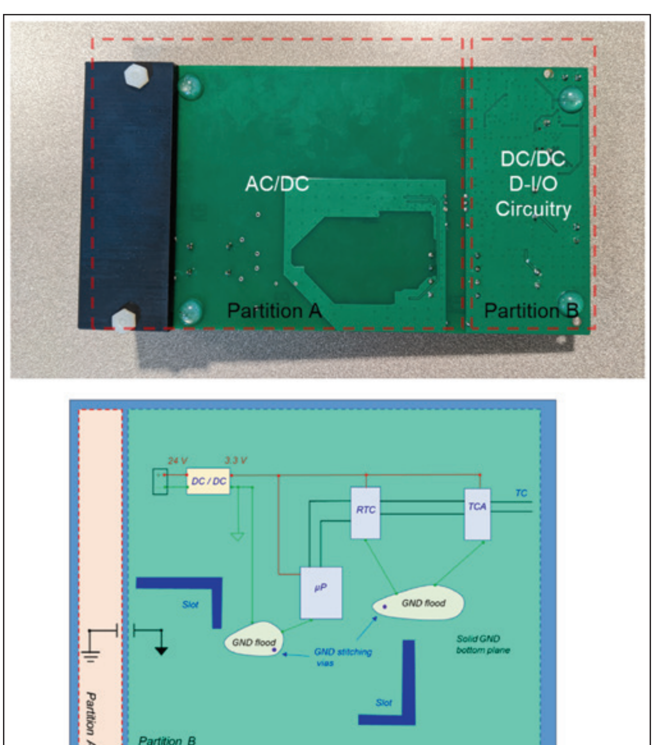

Figure 3: Two-layer board – bottom side view (slots in ground reference return)

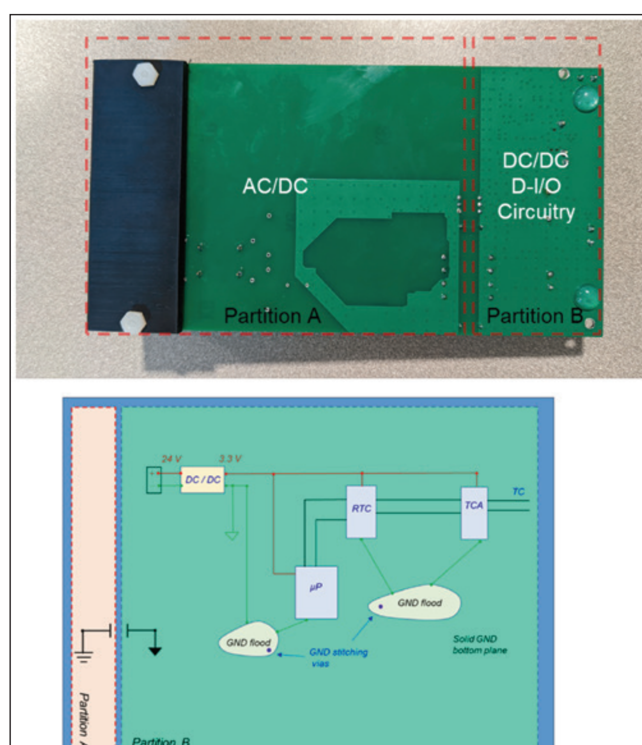

Figure 4: Two-layer board – bottom side view (full ground reference return)

Next, we evaluated a two-layer board where the bottom layer is a mostly solid ground reference plane with some slots accounting for the need to route signals on the bottom layer. The bottom layer of this board is shown in Figure 3.

And finally, a two-layer board where the bottom layer is a complete ground flood with via stitching to the top-layer ground reference return areas. This is shown in Figure 4.

2. CONDUCTED EMISSIONS RESULTS

Conducted emissions were measured in the frequency range of 150 kHz – 30 MHz. Figure 5 shows a reference legend for these measurements.

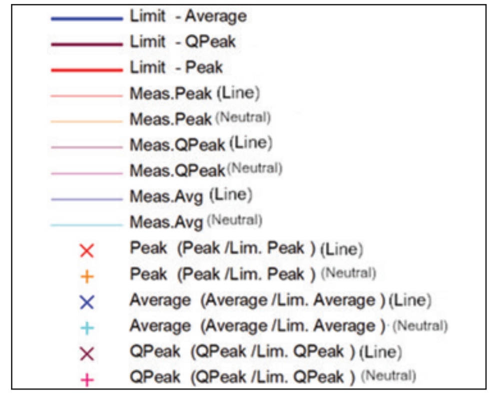

Figure 5: Reference legend for conducted emission results

Figure 6 shows the conducted emissions results for a one-layer board.

The conducted emissions results show multiple failures over a wide frequency range.

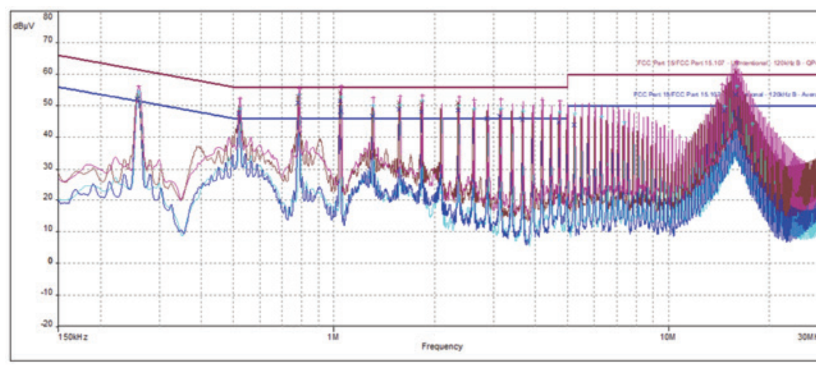

Figure 6: Conducted Emissions Results: one-layer board

Figure 7 shows the conducted emissions results for the two-layer board with slots in the ground reference return.

Figure 7 shows at least 8dB of improvement across most of the 150kHz-30MHz frequency range. We can conclude that introducing a ground reference return (even with slots in it) on the bottom layer significantly improves the conducted emissions performance and results in passing the test.

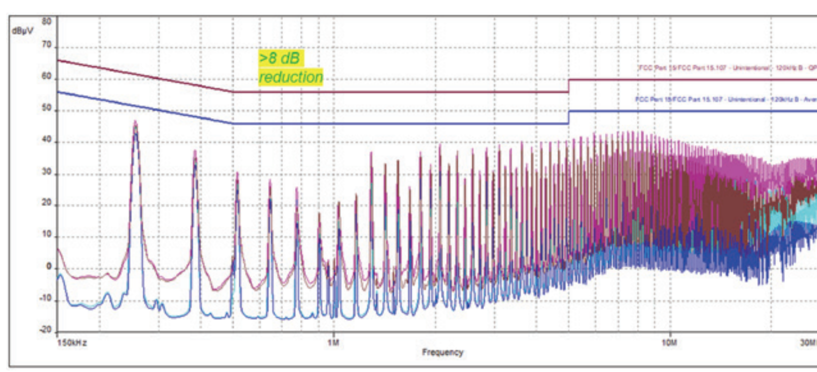

Figure 7: Conducted Emissions Results: Two-layer board with slots in ground reference return

Figure 8 shows the conducted emissions results for a two-layer board with a solid ground reference return on the bottom layer.

Comparing the ground reference return with slots on the bottom layer to the case with a solid ground reference return on the bottom layer shows little change in conducted emissions. Approximately 1-3dB of variation in emissions levels occurred between 500kHz–2MHz. However, comparing the solid ground reference return to the case with a one-layer PCB (no ground reference return on bottom layer) there are substantial improvements across the entire frequency range for the conducted emissions test.

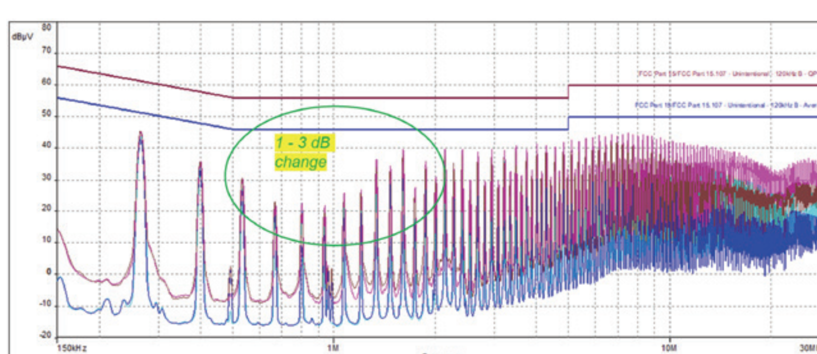

Figure 8: Conducted Emissions Results: Two-layer board with solid ground

3. RADIATED EMISSIONS RESULTS

Radiated emissions were measured in the frequency range of 30-300 MHz. Figure 9 shows a reference legend for these measurements.

Figure 10 shows the radiated emissions results for a one-layer board.

The single-layer radiated emissions results show multiple broadband failures over the wide frequency range.

Figure 11 shows the radiated emissions results for the two-layer board with slots in the ground reference return.

Figure 11 shows that the introduction of a ground reference return, even with slots in it, provides us with a 6-8dB improvement from 30-45MHz, and an improvement of greater than 10dB from 45MHz-240MHz.

Figure 12 shows the radiated emissions results for a two-layer board with solid ground reference return.

As shown in Figure 12, using the solid ground reference return causes a 1-2dB increase from 30-33MHz, and a ~5dB increase from 40-48MHz compared to the two-layer board with slots in the ground reference return. Additionally, there is general improvement in emissions between 100MHz and 300MHz. Specifically, a 3dB decrease in emissions around 160-170MHz, and a 3dB decrease in emissions at 214MHz can be observed. The differences in the lower frequencies 30-45MHz are most likely attributed to differences in operating conditions between the two AC/DC converter circuits. Differences in operating conditions may be related to different fundamental switching frequencies, transformer tolerances, and other component tolerances. The improvement in emissions between 120MHz–300MHz is likely to be from the improvement in the ground reference return.

4. CONCLUSION

In conclusion, the single-layer board had failures in both conducted and radiated emissions. As one would expect, adding a ground reference return layer either with or without slots caused significant improvements in both conducted and radiated emissions. When comparing the two-layer designs with and without slots in the ground reference return plane, there were subtle differences in conducted emissions and a net improvement in radiated emissions. This study has identified and confirmed a number of best practices in EMC design such as:

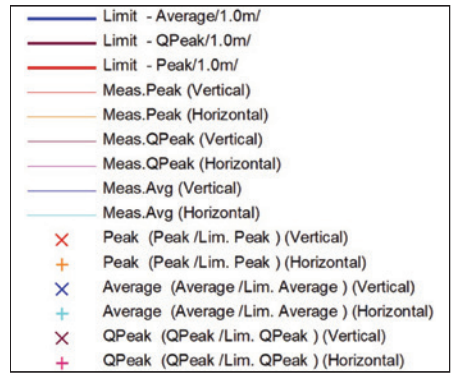

Figure 9: Reference legend for radiated emission results

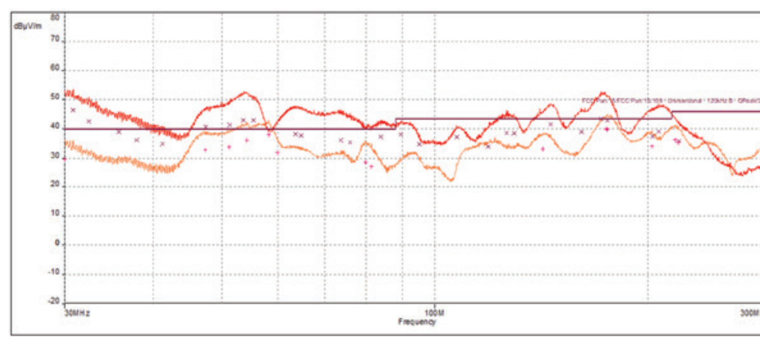

Figure 10: RE results: one-layer board

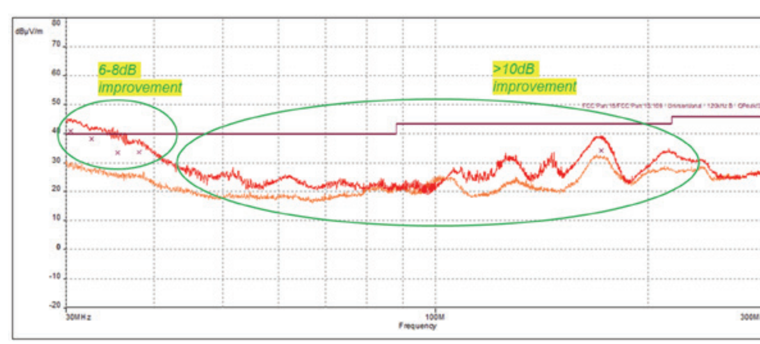

Figure 11: RE results: Two-layer board with slots in ground reference return

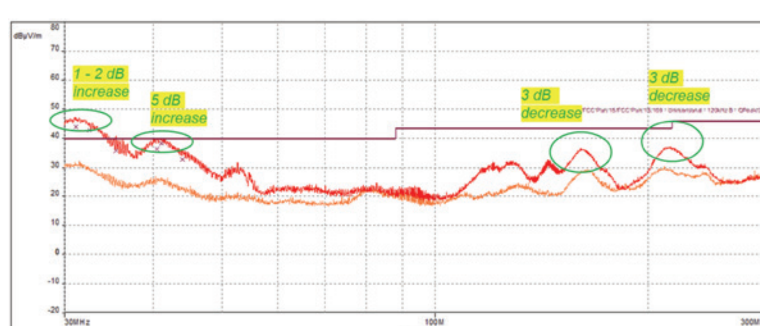

Figure 12: RE results: Two-layer board with solid ground reference return

1. PCB layout can have a dramatic effect on RF emissions performance
2. The ground reference return in the power converter designs used should be:
    a. Filled on adjacent layers to the extent possible to provide a good reference return
    b. Connected as direct and low impedance as possible between input filtering reference to output filter reference
    c. Stitched between layers to improve the reference return path
3. It is recommended to fill with ground reference beneath switching magnetics when possible (eg. Isolation issues, efficiency issues allow it)
4. Lower frequency emissions failures in conducted and radiated emissions can be addressed by ensuring good input and output filtering
5. Mid to high frequency emissions failures in conducted and radiated emissions can be improved through the use of snubber circuits, gate drive slewing, good decoupling, and PCB or inductor shielding
6. In isolated switching supplies, stitching capacitance is important to evaluate and tune to optimize emissions performance without violating any isolation requirements

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CHARACTERIZATION FOR ESD DESIGN, THE TLP ZOO: PART 2

By Robert Ashton for EOS/ESD Association, Inc.

INTRODUCTION

This is the second of a two-part series on transmission line pulse (TLP) testing. The first article in the series [1] discussed the motivation for performing TLP testing, introduced the basics of TLP and presented the most popular form of TLP testing, time domain reflection TLP. If you are new to TLP testing, that article would be an excellent introduction. This article will present alternative TLP configurations which can improve the quality of TLP data or capture additional information. Also covered will be two extensions to TLP testing for performing charged device model (CDM) testing. Traditional field inducted CDM testing suffers from poor reproducibility at low voltage due to variable air discharge spark resistance, which is eliminated in the proposed methods. The article will conclude with some additional resources for TLP testing provided by the Electrostatic Discharge Association (ESDA).

KELVIN TLP

Variable contact resistance in time domain reflection TLP, especially in wafer-level measurements, can introduce significant noise into voltage data. This is compounded in vf-TLP when two large voltages need to be subtracted to get the device under test (DUT) voltage. These issues can be reduced significantly using Kelvin TLP. In Kelvin TLP, the voltage is measured with voltage taps right at the DUT. For waferlevel measurements, this requires a separate set of RF probes with appropriate sense resistors. Kelvin measurements can be used for either 100 ns or vf-TLP. For 100 ns TLP a current probe is needed to determine the pulse current. For vf-TLP, a separate voltage pickoff Tee is often used to measure the separated incident and reflected voltage to calculate the stress current. In addition to reducing voltage noise, Kelvin TLP gives a direct measurement of the voltage versus time characteristics of the DUT without the uncertainty introduced by time-shifting the incident and reflected voltage pulses.

An example of the time dependence of a 28 A vf-TLP pulse is shown in Figure 2 for a low capacitance transient voltage suppressor (TVS). The 5 ns long current pulse is well-formed with a rise time of a small fraction of a ns. The TVS device clamps the voltage to below 5 V within 1 ns. There is, however, a voltage overshoot of about 20 V. Measurements like this give considerable insight into the properties of devices in the ESD time and current regime.

TIME DOMAIN REFLECTION AND TRANSMISSION TLP

The time domain reflection and transmission (TDRT) TLP system, shown in Figure 3, provides a direct measurement of the current. In this system, the DUT is inserted in line between the pulse source and the oscilloscope 50-ohm input, rather than between the pulse source and ground. The device current and voltage are calculated with the following formulas where V_I is the voltage measured on the current measuring channel of the oscilloscope, and V_{Tee} is the voltage measured on the voltage pickoff Tee. In vf-TLP, it will likely be

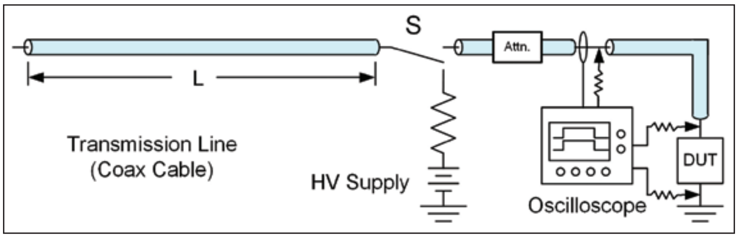

Figure 1: Kelvin TLP. The arrows are voltage taps with 500 to 5000-ohm voltage taps.

Robert Ashton is the Chief Scientist at Minotaur Labs. Robert is an active member of ESDA working groups for device testing standards and the JEDEC latch-up working group. He has been a regular member of the EOS/ESD Symposium technical program committee. Robert served on the ESDA board of directors from 2011 to 2013. He is currently serving as co-chair of the human metal model (HMM) working group.

Founded in 1982, EOS/ESD Association, Inc. is a not for profit, professional organization, dedicated to education and furthering the technology Electrostatic Discharge (ESD) control and prevention. EOS/ESD Association, Inc. sponsors educational programs, develops ESD control and measurement standards, holds international technical symposiums, workshops, tutorials, and foster the exchange of technical information among its members and others.

necessary to do time shifting between the V_{Tee} and V_I measurements. Depending on cable lengths, it may be necessary to time shirt V_{Tee} or V_I before calculating V_{DUT}.

$$I_{DUT} = \frac{V_I}{50\ ohms} \qquad V_{DUT} = V_{Tee} - V_I$$

The TDRT system is especially useful in situations where there is a desire to directly measure the time dependence of the current through the device. It is important to note that the TDRT system has a characteristic impedance of 100 ohms, which is the sum of the 50-ohm characteristic impedance of the coaxial cable delivering the pulse and the 50-ohm impedance of the oscilloscope input. The importance of a system's characteristic impedance will be discussed in the next section.

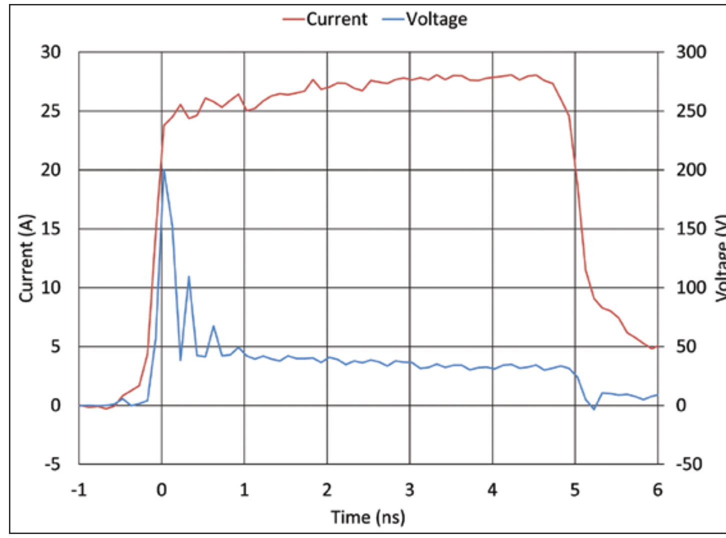

Figure 2: Example of a 28 A vf-TLP pulse through a low capacitance transient voltage suppressor

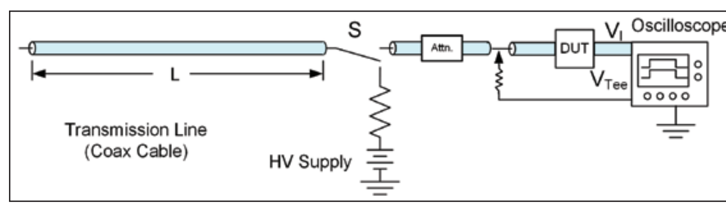

Figure 3: Time Domain Reflection and Transmission TLP. The arrow is a voltage pickoff Tee.

CURRENT SOURCE TLP

Another member of the TLP Zoo is the current source TLP, which is one of the original configurations introduced by Tim Maloney in 1985[2]. This method removes the reflection problem without an attenuator, as in our other examples, by incorporating a matching network just before the DUT. The importance of this method goes far beyond the method of removing reflections since it introduces a TLP system with a characteristic impedance much higher than 50 ohms. This difference can be significant for devices with deep snapback. Deep snapback is common for higher voltage protection devices.

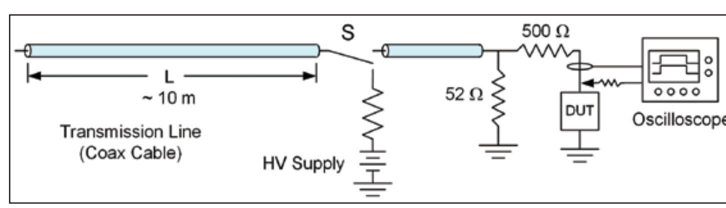

Figure 4: Current source TLP with sample matching network values

A schematic of a current source TLP is shown in Figure 4. At the end of the cable leading to the DUT is a termination resistor and a 500 ohm or more resistor in series with the DUT. The value of the termination resistor is a compromise to give good reflection control over a range of DUT impedances.

While the matching network limits the peak current for the current source TLP system, this arrangement provides a TLP system with a high source impedance. The source impedance sets the load line for a system, which is the straight line connecting the open circuit voltage with the short circuit current. The slope of this curve is one over the source impedance. For a particular TLP charging voltage, all possible current-voltage pairs must be on this line. The significance of this for TLP measurements on a snapback device is shown in Figure 5. Consider the data point which is about to trigger the device into snapback. Up to this point measurements with a 50-ohm TDR TLP or a 500-ohm current source TLP will give the same results. In Figure 5, the load lines for a 50-ohm and a

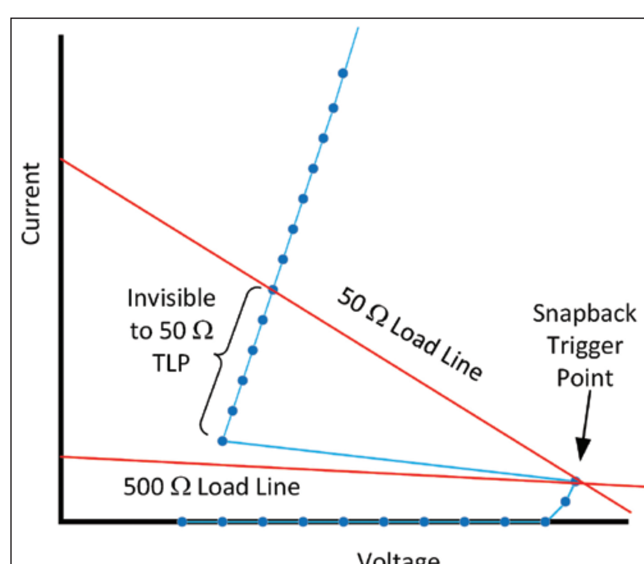

Figure 5: Example of the importance of Load Line

500-ohm TLP system are drawn for the snapback trigger point. The next TLP pulse will trigger the device into snapback. The load line requires that the next data point be on the load line for the TLP system being used. For the device in question, the next possible current voltage pair for the 50-ohm TLP is well up in the device's snapback region. For the 500-ohm system, with its shallow load line, additional measurement points can be captured in the low current snapback region. As demonstrated in Figure 5, a significant portion of the snapback region is invisible to the 50-ohm TLP. For some devices, the entire snapback region may be invisible and the first data point after the snapback trigger can cause device damage. In the case of devices that fail soon after snapback, the invisible points give valuable information on the true failure threshold level.

TLP IDEAS FOR CDM TESTING

Field-induced CDM testing relies on an air discharge, which becomes less reproducible at low voltages. Unfortunately for the fastest interconnects and other sensitive pins accurate, and repeatable CDM testing at low voltages is becoming more important. Vf-TLP has inspired two test methods, capacitively coupled TLP (CC-TLP) [3] and low impedance contact CDM (LICCDM)[4][5], which could supplement or even replace field-induced CDM testing at low voltages.

Figure 6 illustrates a capacitively coupled TLP system. The DUT is placed on a wafer chuck in either package or wafer form. A vf-TLP system provides the pulse for a specialized wafer probe. The end of the wafer probe has a ground plane tied to the shield of the pulse cable. The ground plane is placed parallel to the DUT and a small distance above the DUT. The coax cable's center conductor is connected to a wafer probe needle which extends through a hole in the ground plane and contacts the pin under test. The capacitance between the DUT and the ground plane completes the current path between the cable center conductor and the cable shield. A voltage pickoff Tee is used to measure the incident and reflected pulses. The incident and reflected pulses are used to calculate the stress delivered to the DUT.

LICCDM similarly starts with a vf-TLP system as a pulse source, although this is modified with a capacitor and 50-ohm resistor at the far end of the charging cable. The 50-ohm resistor eliminates reflections, and the capacitor provides a slow decay to the trailing edge of the pulse. A rise time filter is used to adjust pulse properties to better match CDM waveform properties. The pulse is delivered through a hole in the ground plane with a pogo pin to contact the DUT. In addition to the delivery cable connected to the pogo pin, a second 50-ohm cable connects to an oscilloscope input as well as a 50-ohm resistor to ground. The two 50-ohm cables and 50-ohm resistor in parallel with each other creates a 16.7-ohm termination, 50 ohms divided by 3. Conveniently, 16.7 ohms is similar to the source impedance of an air discharge field-induced CDM tester. The current through the DUT is calculated by measuring the pulse current while in contact with the DUT and not in contact with the DUT combined with the known 50-ohm impedance of the two cables and the 50-ohm resistor to ground.

Both CC-TLP and LICCDM produce stress currents with stress currents similar to field-induced CDM but without the reproducibility issues of air discharge. Several studies show that the failure currents and failure modes produced by CC-TLP and LICCDM are similar to failures in CDM testing. For either of these systems to become an alternative to traditional CDM will require the development of correlation methods between CDM voltage levels and the stress levels of CC-TLP and LICCDM. This work is currently underway in the joint JEDEC/ESDA CDM working group.

ADDITIONAL TLP RESOURCES

Electrostatic Discharge Association (ESDA) working group WG5.5 is dedicated to TLP. Their primary document is a Standard Test Method, ANSI/ESD STM5.5 [6] detailing procedures necessary for the accurate measurement of quasi-static IV curves in both standard TLP and vf-TLP. The working group has also recently published two especially useful Technical Reports. ESD TR5.5-04-18 [7] is a TLP User Guide giving a range of tips on how to get the most out of TLP measurements as well as examples of use of TLP. ESD TR5.5-05-20 [8] gives guidance on how to perform transient measurements, primarily using vf-TLP.

SUMMARY

TLP has become one of the most important tools available to the ESD protection design engineer. TLP can be used to characterize both the protection circuit as well as devices needing protection. As this article has shown, there are a variety of members of the TLP Zoo, each with its own strengths and weaknesses. Today most TLP users employ commercially built TLP systems. Some systems are designed to be used in a single configuration, simplifying their operation but limiting flexibility. Other systems can be configured in multiple ways, and choosing the best configuration for each measurement is key to getting the most from the system. This article has reviewed some of the important members of the TLP Zoo and should be helpful in getting the most out of whatever system is used as well as understanding some of the limitations.

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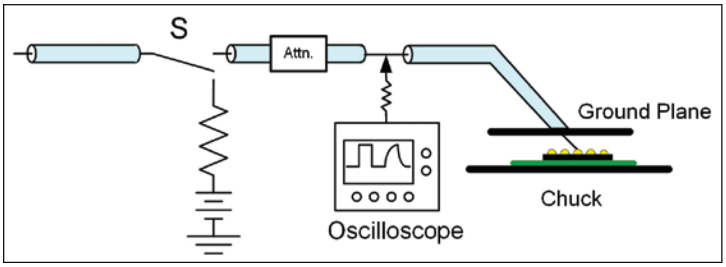

Figure 6: Capacitively Coupled TLP

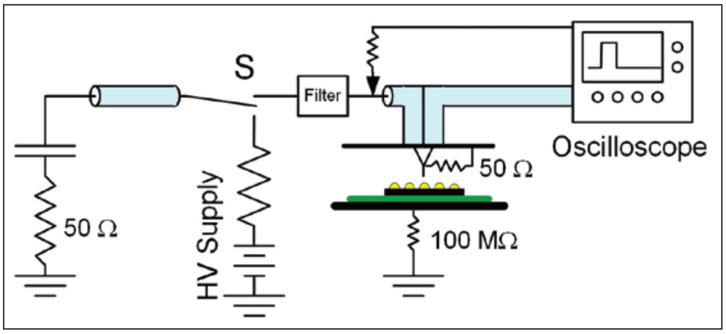

Figure 7: Low Impedance Contact CDM

Banana Skins

365 Can interference from passenger electronic devices make aircraft unsafe? – Part 3

Is it safe to use cellphones on airplanes? The real question should be: "Is it safe for passengers to use any electronic equipment on airplanes?" My older notebook computer interferes with VHF Channel 11 on my TV. My newer notebook doesn't, but my older one didn't when it was new, either. And when I'm in my home office with the FM radio on, I always hear a buzz on the radio just before my cellphone rings. Granted, aircraft may not be using the VHF and FM bands, but if these devices cause interference on these bands, how can we be sure that they're not causing interference on other bands?

(Letter from Michael L Nelson responding to the article mentioned in Banana Skin No. 363 above, in "Forum" in the IEEE Spectrum, May 2006, page 4.)

366 Airbags triggered by ESD

Holden Commodore, Statesman, Monaro and Crewman models fitted with side airbags are being recalled after some cars were found to have earthing problems which may inadvertently deploy a side airbag. Holden says the deployment can occur when the car is stationary and is caused by a static discharge as an occupant exits the car. Owners can call their Holden dealer for a simple fix, which involves fitting two small earthing springs and takes just a few minutes.

(From the "Drive" section of 'The Press," Christchurch, New Zealand, Wednesday March 15 2006, page E8.)

367 Co-location of wireless services causes interference

This veritable cocktail of spectrum and services is leading to a more challenging interference scenario – and not just in the US. As services operating in neighboring frequency bands are co-located, significant – and initially unforeseen – interference issues can arise.

This has already been observed extensively in China and Brazil, where a "cross-pollination" of 900-MHz Global System for Mobile communications (GSM) and 800-MHz code-division-multiple-access (CDMA) services exists. In such cases, GSM services have suffered significant interference – and hence quality problems – as the direct result of co-location with CDMA.

Similar issues are also being experienced by US carriers with other combinations of services – and such problems will only increase with increasing demands for wireless bandwidth and services.

(Taken from: "Filtering Compromises from Co-Located Systems," Ganesh Krishnan and Andre Doll, Microwaves & RF, March 2006, pp 57-64)

368 Optical microphone has no emissions and is unaffected by interference

The Security Optical Microphone (SOM) from Winkelmann UK Kingfisher is used by many law enforcement agencies. Unlike traditional microphones, which can be detected using a conventional detector during a counter surveillance sweep, the SOM uses fibre optic technology and an extremely small 6mm diameter head which, when installed, is invisible to all but the most rigorous searches, and it is unaffected by interference (a major source of induced noise in conventional equipment).

(Taken from: "Breakthroughs in Defence," Nick Morris, Electro-Optics, April/May 2006, pp 17-18).

369 Anti-jamming system for satellite operator

UK Defence specialist QinetiQ is to supply Space Communications Corporation of Japan with a geolocation system that will allow the Tokyo-based company to identify and accurately locate the source of any interference to its satellites. The US Department of Defense bought three such systems last year. Nigel Smith, QinetiQ's satID commercial director in the USA, commented: "Satellite interference is a growing problem for both military and commercial operators and satID provides a rapid and effective solution to that problem."

(From "Japanese Satellite operator turns to UK for anti-jamming system," IET Communications Engineer, April/May 2006, page 4.)

370 AC motor and contactor interferes with satellite receiver around 4GHz

I have a 3 phase 480V 50A contactor and motor causing interference to a C-band satellite receiver in the 3700-4200MHz range, what are some options to prevent this?

(Question posted by JD Moats on Conformity magazine's "Ask the Experts," 21 March 06.)

371 FCC fines manufacturer US$75,000 for using emergency radio bands

The Federal Communications Commission (FCC) levied a proposed forfeiture of US$75,000 against San Jose Navigation, Inc. for marketing four models of the company's GPS signal re-radiator kits that operated on restricted frequency bands allocated for safety-of-life operations.

In this instance, the Commission acted on complaints from the National

Telecommunications & Information Administration, the Department of Transportation and other federal agencies which had expressed concern that the GPS re-radiator equipment could potentially interfere with government GPS operations.

(From "FCC Continues to Crack Down on Marketing of Unauthorized Equipment," in the News Breaks section of Conformity magazine, June 2006, page 10.)

372 FCC levies US$1 million fine on audio equipment manufacturer for non-compliance

As we've previously reported (see *Conformity* May 2006, page 8) the Federal Communications Commission (FCC) recently proposed a US$1 million forfeiture against Behringer USA, Inc. for illegally marketing over a five year period as many as 66 different models of mixers, amplifiers and digital effects processors, none of which had been verified for compliance with FCC requirements.

(From: "FCC Continues to Crack Down on Marketing of Unauthorized Equipment," in the News Breaks section of Conformity magazine, June 2006, page 10, The complete text of the FCC's Notice of Apparent Liability against Behringer can be found at http://www.fcc.gov/eb/Orders/2006/FCC-06-13A1.html, also available in Word and PDF versions.)

373 Vehicle engine management systems suffer interference

Q: My 45,000 mile four-year-old Hyundai Accent 1.3i sometimes cuts out, although it restarts almost immediately. I took the car to my local mechanic, but after three hours (and £140) he was unable to isolate the problem. He thinks the ECU might have failed.

A: This is happening to quite a lot of cars at present. It seems that powerful electric fields emitted by power lines and government establishments upset vehicle electronics – it's a particular problem when cars have CAN-bus multiplex wiring systems.

(From the "Honest John" column in the Daily Telegraph's Motoring section, Saturday May 27 2006, page 9.)

374 Light fittings can interfere with fire detectors

Fire detectors close to a light fitting may pick up electrical interference, resulting in false alarms or, even worse, the masking of a real alarm. Detectors affected must be moved.

(From "Top 10 fiery errors," Electrical Products and Applications magazine, May 2006, page 17.)

Read Banana Skin No. 375 online

https://incompliancemag.com/banana-skins

376 Windshield washer interferes with ABS

In the development cycle of a certain automobile, it was found that the pump motor for the windshield washer was creating interference and causing an ABS warning light to activate. This vehicle's brake lines were coated with a new material which had a much higher conductivity than on older models. It was later determined that the pump motor was generating a transient that was directly coupled to the ABS module by the new conductive coating on the brake lines. This transient was interfering with the ABS module and activating the ABS warning light.

A capacitor was placed inside the pump motor housing and the housing material was changed from plastic to aluminium to fix the problem.

(From: "The Back Page…Examples of EMC Related Problems" in the EMC Society of Australia Newsletter, June 2006, Issue No. 33.)

377 Mobile phones can interfere with medical equipment

Patients are at risk if medical apparatus malfunctions due to EMC interference from mobile phones. There are several types of equipment which can be subject to interference. Infusion pumps can cause equipment malfunctions on dialysis wards, by racing or fluctuating in speed. This results in patients receiving the wrong dosage. The temperature level of incubators has been affected. Reports have been received that the temperature of incubators has been set at the maximum level. Ventilators have malfunctioned. On one occasion, an electrically-driven wheelchair was caused to move unintentionally by the communication radio in a taxi. The handicapped person involved asked the taxi driver to use his radio again to confirm that it was actually causing the wheelchair to move and it was.

(Taken from "Application Areas for MobilePhoneGuard™.")

The regular "Banana Skins" column was published in the EMC Journal, starting in January 1998. Alan E. Hutley, a prominent member of the electronics community, distinguished publisher of the EMC Journal, founder of the EMCIA EMC Industry Association and the EMCUK Exhibition & Conference, has graciously given his permission for In Compliance to republish this reader-favorite column. The Banana Skin columns were compiled by Keith Armstrong, of Cherry Clough Consultants Ltd, from items he found in various publications, and anecdotes and links sent in by the many fans of the column. All of the EMC Journal columns are available at: https://www.emcstandards.co.uk/emi-stories, indexed both by application and type of EM disturbance, and new ones have recently begun being added. Keith has also given his permission for these stories to be shared through In Compliance as a service to the worldwide EMC community. We are proud to carry on the tradition of sharing Banana Skins for the purpose of promoting education for EMI/EMC engineers.

EMC Design Techniques for Electric Vehicle Powertrain Modules

State-of-the-Art EMC Designs to Consider Before Your Next Module Project

BY DR. MIN ZHANG

When helping clients in the electric vehicle (EV) industry with their module design, I often find that engineers tend to follow an out-of-date list of do's and don'ts in the form of EMC design rules without understanding the basics. These kinds of design rules are often borrowed from other industries, and they are not up to date with the latest technology involved in the fast-paced EV industry.

In this article, using a powertrain module as an example, I will first introduce the high voltage EMC regulations with which a powertrain module needs to comply. I will then highlight the risks and challenges when designing such modules. The main part of this article will share design techniques that engineers can apply on various parts of a powertrain module, including ground, front-end filter, inverter design, and so on. Examples are given to demonstrate some of the key design techniques.

It should be noted that the introduced design techniques in this article share the same principles as any other EMC engineering. Therefore, engineers from other industries can also benefit from these techniques.

Dr. Min Zhang is the founder and principal EMC consultant of Mach One Design Ltd. His in-depth knowledge of power electronics, digital electronics, electric machines, and product design has been benefitting companies worldwide. Zhang can be reached at info@mach1desgin.co.uk.

BACKGROUND

The past decade has witnessed the fast-paced adoption of electrification in the automotive industry, with an increasing number of hybrid and full electric vehicles coming to the market. A recent study has shown that going half-way (as plug-in hybrid vehicles do) might not be sufficient to bring carbon emissions in line with new regulations, which will require more full EVs on the road [1].

Powertrain modules are one of the key differentiators in the EV industry. Both vehicle manufacturers and Tier-1 suppliers have been spending considerable resources researching and developing state-of-the-art technologies for EVs. The current trend is to achieve a more compact module design with higher power density and system efficiency. For instance, the Nissan LEAF has achieved a very compact e-powertrain module design by integrating an on-board charger (OBC), a DC-DC converter, and a junction box with the electric drive unit (EDU) [2].

This article presents the EMC design of a powertrain module, which consists of an electric motor, an inverter, and a mechanical gearbox. The electric system diagram of an EV powertrain module is illustrated in Figure 1 on page 40.

The importance of design engineers taking a system-level overview of an EV powertrain module was presented in my previous work, "Demystifying EMC in an Electric Vehicle's Drive Unit" [3]. It is critical to factor in EMC design considerations at an early stage so as to achieve the overall system design goal. The high voltage (HV)

EMC regulations and requirements present a daunting task for not only new entrants but also for well-established companies in the automotive industry. Therefore, we'll first review in this article the HV standards and regulations that apply to electric powertrain modules. Then, we'll highlight EMC challenges in the powertrain module design and demonstrate design techniques to address potential EMC issues. Engineers will then have a better understanding of how to design a module that will pass the EMC requirements in the EMC test chamber.

HV EMC STANDARDS AND REGULATIONS FOR EV POWERTRAIN MODULES

CISPR 25:2016 [4] serves as a general EMC guideline for automotive developers, although vehicle manufacturers often have their own proprietary EMC specifications [5]. Annex I of CISPR 25 defines test methods for shielded power supply systems for high voltages in electric and hybrid vehicles. CISPR 36:2020 [6] was released recently, and it defines the test methods for electromagnetic field emission on a vehicle level. A component-level electromagnetic field emission test to reflect this standard is expected to be available soon from vehicle manufacturers.

(Note that OBCs require a different set of test methods that are related to charging and are not covered in this article. Also not included here is a discussion of low voltage (LV)-associated EMC tests, electrical tests, or electrostatic discharge (ESD) tests.)

HV Component Emission, Immunity, and Transients

Annex I of CISPR 25 defines both conducted and radiated emission limits for shielded HV systems, and unshielded systems shall comply with the same limits as shielded systems. Annex I of CISPR 25 also introduces the HV/LV coupling attenuation test. This test is performed while the equipment under test (EUT) is unpowered. Essentially the test result is the $-S_{21}$ plot of the EUT by an impedance analyzer. For good system decoupling behavior, the Class A1 or A2 in requirements for minimum coupling attenuation given in [4] need to be achieved.

For RF-immunity, the ISO 11452 series is relevant for vehicle component tests. The newest revisions of subparts under ISO 11452, such as ISO 11452-4:2020, include HV component test setups and high voltage artificial networks (HV-ANs). Other subparts are expected to adopt these HV component requirements accordingly.

ISO/TS 7637-4:2020 deals with transient emissions and transient immunity on HV lines.

Electric and Magnetic Field Strength

The standards SAE J551-5 [7] and GB/T 18387-2017 [8] define limits and test methods in the U.S. and China, respectively, for the magnetic and electric field emissions from electric vehicles. CISPR 36:2020 [6] deals with electromagnetic field emissions. A recent comparison study between GB/T 18387-2017 and CISPR 36:2020 on the magnetic field radiated disturbance test requirements has found that GB/T 18387-2017 is more stringent [9].

Magnetic field exposure will be the most critical aspect for electrical vehicles because of the high currents associated with their electric drives. To cover this aspect also on the component level, test methods have to be defined.

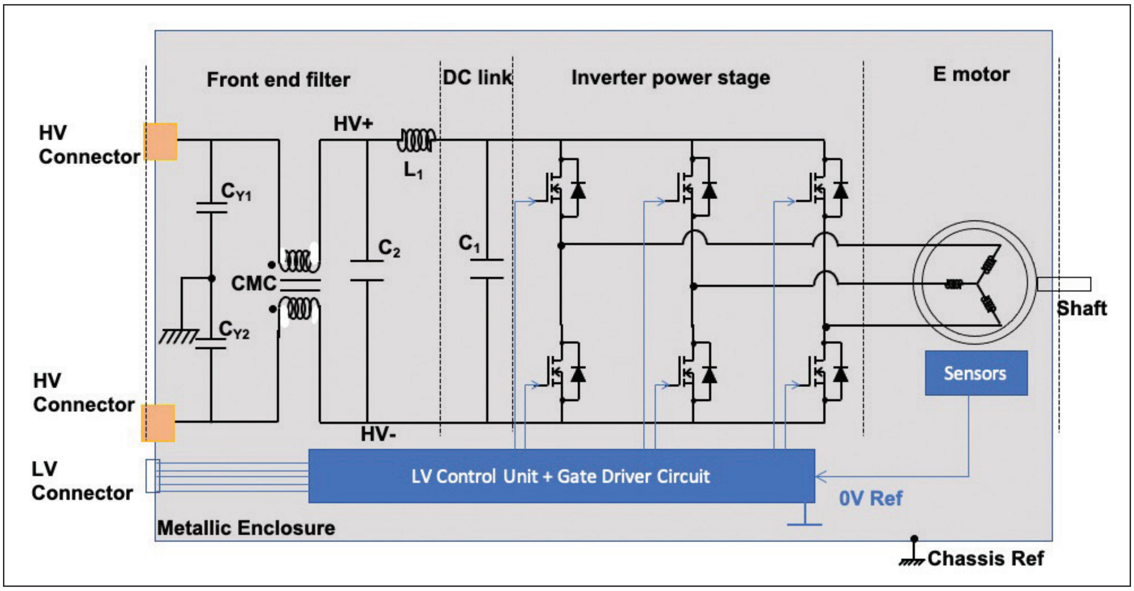

Figure 1: System diagram of an EV electric powertrain module

Human exposure to magnetic fields is tested in accordance with a Guideline issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). IEC TS 62764-1 defines the measurement procedures for magnetic field levels generated by electronic and electrical equipment in the automotive environment with respect to human exposure.

A summary of the HV EMC test is listed in Table 1.

EMC CHALLENGES

A more compact, larger power rating, and higher efficiency powertrain module generally means more EMC challenges.

High Voltage

Currently, the most common HV rating adopted by modern automotive manufacturers is 400V (Audi e-tron, Tesla, Nissan Leaf, etc.). The Porsche Taycan is the first EV in the market to have adopted an 800V power system [10]. For the same power rating, increasing the voltage reduces the current in the system, resulting in reduced copper loss (I^2R loss). Therefore, higher voltages correlate with an increased system efficiency. However, the HV rating of a powertrain module is limited by factors such as the voltage ratings of commercially available power electronics devices, the insulation breakdown of HV cables, worse EMC performance, and so on.

The roadmap for the next generation of power electronics devices for powertrain modules has indicated a breakdown voltage level beyond 1000V. It won't be long before most of the automotive design houses move to 800V (and above) systems for the benefit of achieving higher efficiency. This predictable trend also poses great challenges for EMC design. As voltage level doubles (from 400V to 800V, for instance), and assuming the same parasitic characteristics of a design, noise levels associated with electric field will increase because of the high d*V*/dt characteristics.

Another great challenge associated with high voltage systems is safety. EMC and safety cannot be discussed separately in an HV system. Global Technical Regulation on Electrical Vehicle Safety (EVS) [11] defines the maximum capacitor energy that may be stored in the Y-capacitors to be 0.2J. This hard limit has a profound impact of front-end input filter design of all HV modules because Y-capacitors are very effective filters for broad band noise attenuation, particularly in the lower frequency range (starting from 300kHz).

This means that when voltage level doubles, the available Y-capacitance value drops by 75% according to Equation 1:

$$E = 0.5 \cdot C_Y V^2 \qquad \text{Eq. 1}$$

where E is the total energy stored in the Y-capacitor, C_Y is the available Y-class capacitance, and V is the upper band of HV system nominal voltage.

The relationship between noise level (as represented by common-mode current) and available Y-capacitance is illustrated in Figure 2.

HV EMC Test	Reference
RF Conducted & Radiated Emission	Annex I, CISPR 25:2016 Edition 4
Electric and Magnetic Field Strength	Component test plan shall reflect vehicle test requirements GB/T 18387/2017 or CISPR 36:2020
HV Transient Emission and Immunity	ISO/TS 7637-4:2020
Human exposure to Magnetic Field	ICNIRP Guideline
RF Conducted & Radiated Immunity	ISO 11452 Series
HV LV coupling	Annex I, CISPR 25:2016 Edition 4

List only consists of HV EMC tests, LV, electrical and ESD tests are not included

Table 1: List of HV EMC tests for powertrain module [1]

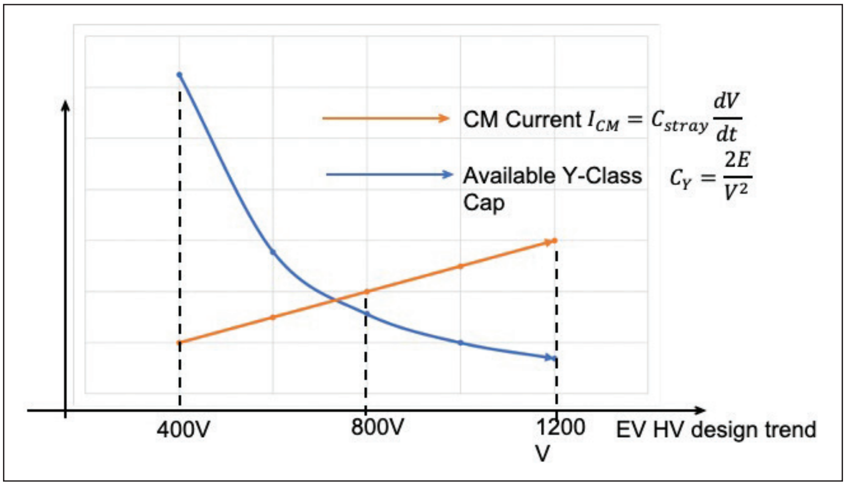

Figure 2: As voltage level increases, common-mode noise increases proportionally while the available Y capacitance reduces in an inverse square trend


CW & Pulse
Watts-to-KW
10kHz-51GHz
is your
Key to Success
AMP2121-LC, 80-1000 MHz, 2000 Watts
An Unprecedented Compact size!
... we are redefining
Ingenuity!
EXODUS
a world apart!
EXODUS ADVANCED COMMUNICATIONS
3674 E. Sunset Road, Suite 100
Las Vegas, Nevada 89120
Tel: 702-534-6564
Web: www.exoduscomm.com
Email: sales@exoduscomm.com

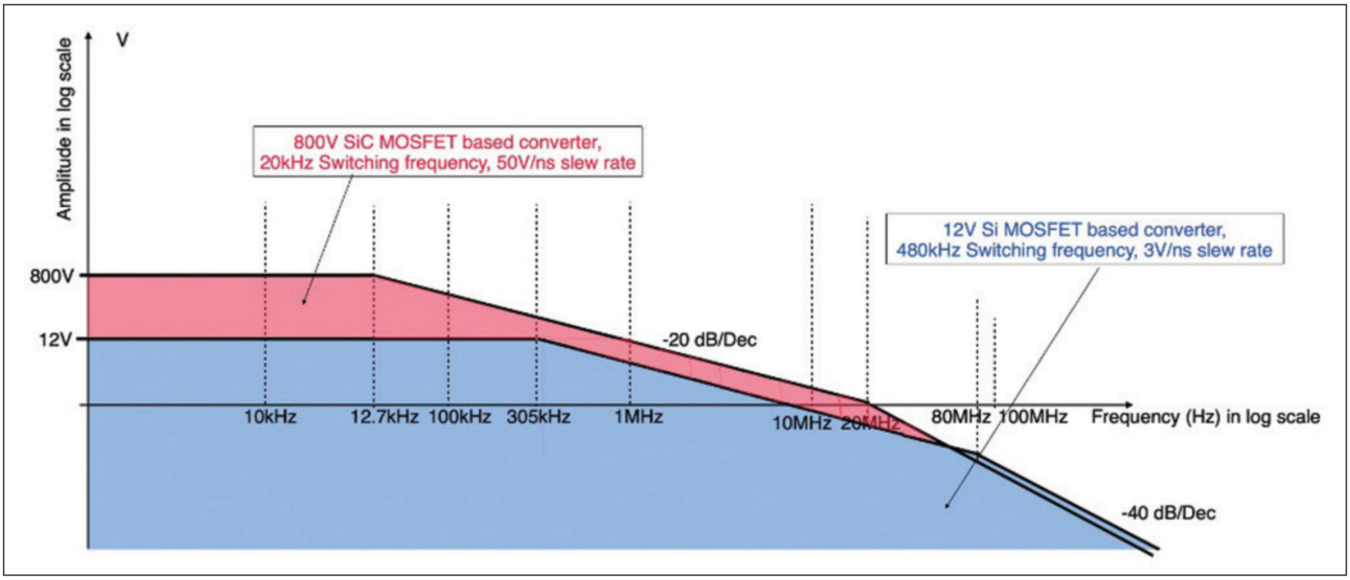

Figure 3: Switching device noise profile comparison

High Power/Current

Since the powertrain module is the performance unit of a vehicle, its power rating directly determines the acceleration rate, the horsepower, and the torque of a vehicle. Given a defined voltage rating of a powertrain module, higher power means higher current. As current is directly related to the magnetic field, higher power also means an increased magnetic field for a vehicle.

As the electric motor and inductors in the inverter are both inductive, higher current also means higher transient behavior caused by sudden state change. The back electromotive force (EMF) or kickback voltage caused by L·d*i*/dt can stress or destroy components if not contained and send huge voltage spikes propagating on the HV bus line.

Fast Switching Power Electronics Devices

Insulated-gate bipolar transistors (IGBTs) were adopted in the early days of powertrain modules (such as the one in an earlier version of the Tesla Model S). The switching frequency of an IGBT-based power system is theoretically limited to 20kHz. The thermal concern of an IGBT often limits its switching frequency below its theoretical value. Wide-band-gap devices such as SiC MOSFETs have recently started replacing IGBTs as the device of choice thanks to their fast switching speeds (hence low switching losses) and better thermal characteristics. Switching frequencies of 20 kHz and above could be comfortably achieved with SiC MOSFET-based powertrain module.

The downside of adopting wide-band-gap devices is the increase in electromagnetic interference (EMI)-related issues caused by their faster switching events. The rise time of a SiC MOSFET can be as small as a few nanoseconds, leading to a slew rate of 50-200V/ns [12]. To enable such fast speed characteristics, gate drivers are equipped with short high peak pulse current features, which could also pose EMI issues.

More SMPS and ICs

To provide power to microprocessors, gate drivers, and analog and digital integrated circuits (ICs), multiple power

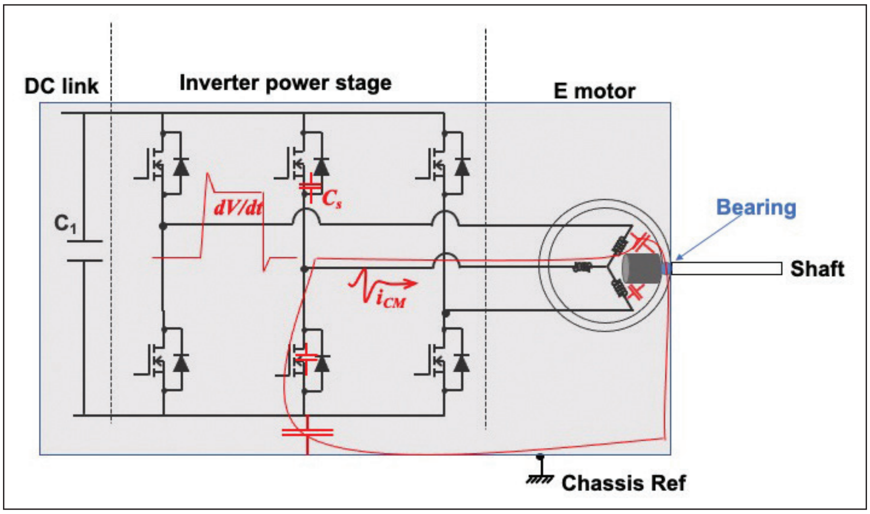

Figure 4: Bearing current caused by fast switching circulates through parasitic capacitance

suppliers are often integrated into the design of the control unit board, with switched-mode power supply (SMPS) units the most common.

SMPS units such as buck and boost converters in the automotive application often have a switching frequency range between 150kHz and 500 kHz. The rise and fall time of the switches can be as short as a few nanoseconds. The noise spectrum shows less energy compared with power switching devices but covers a much wider frequency range. Figure 3 demonstrates the switching noise profile between an LV buck converter and an HV inverter.

Bearing Current

Bearing currents are mainly caused by electrostatic discharges, magnetic asymmetries (caused by unbalanced three-phase windings), and common-mode voltages paired with high switching rates [13].

Bearings in an electric motor have moving metal balls or rollers in fixed metal shells. Very thin layers of lubricant sit between the two parts which therefore have a high capacitance and can carry high displacement currents. Because the lubricant is so thin, and because the bearings are not perfect, there can be an occasional electrical breakdown and even direct touching of the two metal parts. Therefore, the bearing current is partly capacitive, which gives a pulse of current during every switching transition and partly random high current spike [3]. This random breakdown can cause very high random peak currents that can give high quasi-peak noise in the EMI scan.

Bearing current can cause an electric motor's bearings to deteriorate, hence reducing the lifetime of the powertrain. Bearing currents that circulate in the powertrain also cause conducted and radiated emissions, as shown in Figure 4.

EMC DESIGN TECHNIQUES IN ELECTRIC POWERTRAIN MODULE

Grounding Design

It is not uncommon to see many ground symbols in one module design, even though the point of clarifying the use of the term ground has been stressed by many EMC experts [14] [15]. One recent project that I've reviewed had more than five ground symbols in one schematic. It is very confusing to see all these symbols in the first place, not to mention how the grounds are connected.

In Figure 1, the term reference is used rather than the term ground. It should be noted that circuit grounds are not necessarily the same as EMC grounds. To keep it simple and clear, there can only be one EMC ground, which is the metal chassis of the unit, or what we call the

RF reference. The metal enclosure of a module has contact points to the vehicle chassis (either through direct bonding or mechanical fixtures); therefore, we treat the metal enclosure as a chassis reference.

The HV-line is the HV design reference, and it should be isolated from the vehicle chassis reference (either by dielectrics or by Y-capacitors). LV designs should have 0V as the reference points, and that should be the only design reference point. The idea of splitting analog and digital ground points is based on misconceptions and is not a good design approach [16].

The connection between the 0V reference (either on a PCB or a connector pin) and the chassis reference will introduce inductance [16]. The RF currents will inevitably flow in those inductances, leading to noise voltages that will help drive emissions. This is shown in Figure 5. As a result, efforts to minimize the inductance of the connection should be made in the module design. Among the schemes that reduce inductances between two reference points, the most effective way is to increase direct contact areas between the 0V Ref and Chassis Ref. This is demonstrated in Figure 6. Most of the time, multiple contact points along the edges and around corners of a PCB create a quasi-360-degree contact.

Connector Design

HV cables of a powertrain module are usually shielded, and shielding terminations have closely-spaced contacts (360 degrees) to the module enclosure [17]. The reason for having a low impedance bond is the same as what we explained in the previous section. However, the mechanical quality of the contactor design needs to be considered very carefully because high temperatures, aging, vibration, and chemical ingress can damage the bonding configuration over time. An example of a failed shielding connector is shown in Figure 7.

Front-end Filter Design

The front-end filter design is crucial for electric powertrain modules as it helps to block the noise from the inverter power switches. It also suppresses the noise traveling from outside of the module enclosure via the HV DC wirings.

There are many types of front-end filters, including the two-stage filter shown in Figure 1. In Figure 1, the L_1 and C_2 configuration forms the first-stage low-pass filter. The second-stage filter consists of a CMC and Y-capacitors. Notice that, together with the DC link capacitor C_1, the first-stage filter effectively acts as a p (C-L-C) filter.

Nanocrystalline Core

Due to its high voltage and high current characteristics, the saturation of the magnetic core needs to be accounted for when designing HV inductive components. Nanocrystalline materials enjoy a very high saturation magnetization. Because windings that carry such high currents will inevitably increase the size and the weight of a module, toroid or oval shape nanocrystalline cores are typically used in common-mode suppression chokes in automotive applications. They are effective in the frequency region between 150kHz and 120MHz.

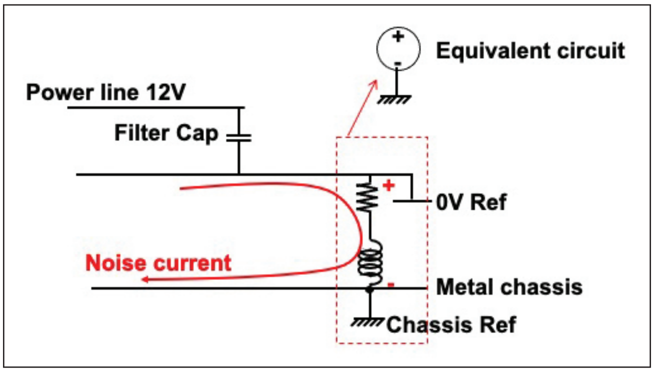

Figure 5: Connection between 0V Ref and Chassis Ref creates impedance for RF noise currents

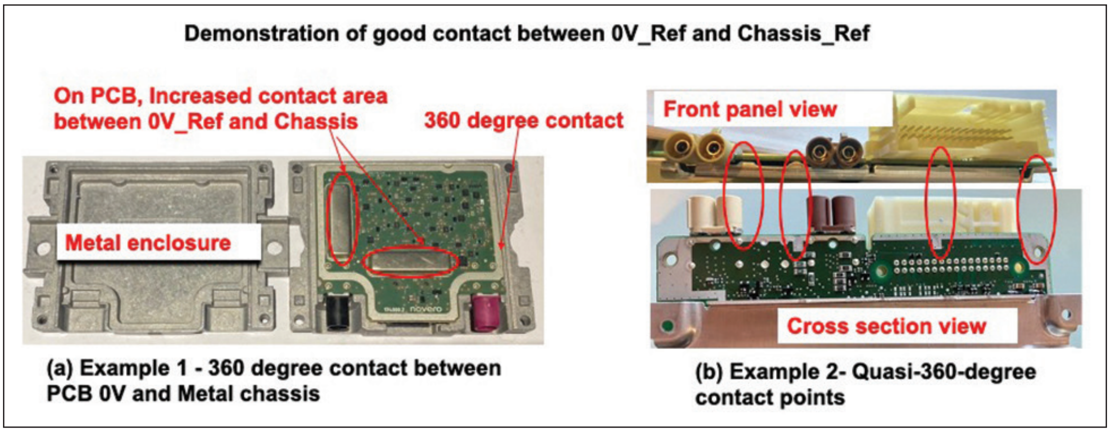

Figure 6: Demonstration of good contact between PCB 0V ref and chassis reference to reduce inductance

For powertrain applications, cores can be either used on a single power line (HV+) as an inductor or on both power lines as a CMC. It should be noted here that the designers might find CMCs such as nanocrystalline cores are not needed due to other good EMC practices in place. However, it is best to allow for Murphy's law and to design properly from the start so that the cores can be added later if necessary [18].

Y-capacitors

Compared with the use of CMCs, the benefits of using Y-capacitors include great high-frequency conducted emission attenuation (generally effective starting from 5 MHz), smaller sizes, lighter weight, and no saturation concerns. The connection of Y-capacitors to the chassis reference should also be designed to achieve very low impedances. The internal equivalent series resistance (ESR) and equivalent series inductance (ESL) are the main factors that affect the effectiveness of Y-capacitors. The imbalance of the impedance of two Y-capacitors also affects the common-mode filtering performance. These drawbacks can be compensated by layout or by using alternative parts such as X2Y capacitors.

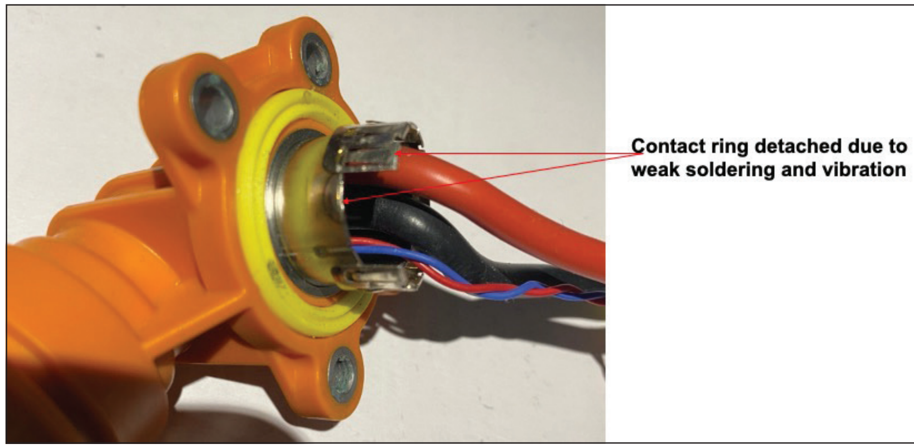

Figure 7: An example of weak contact of shielding connector

X2Y capacitors

X2Y capacitors(see Figure 8) [19] provide great EMI filtering and can be used to replace CMCs (Figure 8(a)) in applications where size, weight, and cost are design constraints. Two capacitors are balanced shunt so as to create a cancellation of the mutual inductance. The X2Y capacitors also provide a shielding effect. Alternatively, as Figure 8 (b) shows, the X2Y capacitors can be configured as decoupling capacitors with ultra-low inductance. Currently, 500V X2Y parts are not automotive qualified, but it is worth paying attention to this component as manufacturers will probably upgrade the high voltage parts so they are AEC-Q200 qualified.

DC Link Design

The DC link includes the HV DC bus bars and DC link capacitors. The DC bus bars should be designed as short as possible and in close proximity to each other to reduce the loop area between them. DC link capacitors should be designed to cope with high voltage, high-frequency switching ripples, and high temperatures.

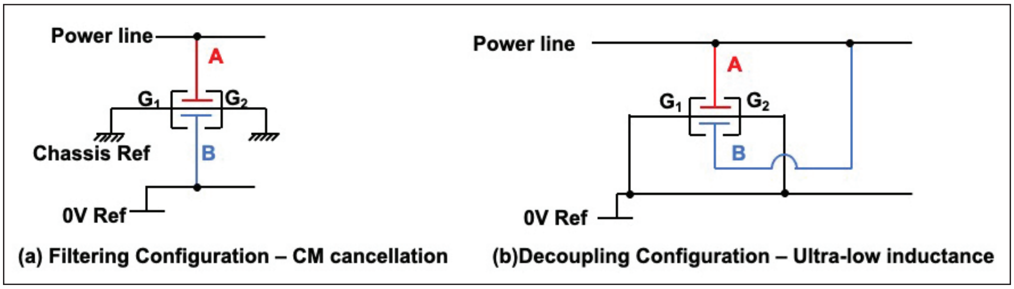

Figure 8: X2Y capacitor connections in an electric system, (a) filtering configuration; (b) decoupling configuration [19

The capacitance value should be large enough for the full power operation of a powertrain module. Low ESR and ESL film capacitors and electrolytic capacitors are often used in powertrain modules.

Film Capacitors

Film capacitors are widely seen in powertrain module design due to their high performance and reliability. The brick size of film capacitors limits the design freedom; therefore, it is important for design engineers to engage film capacitor suppliers early in the design stage. Parameters such as ESL and ESR are crucial for EMC, as self-inductance of the capacitor is caused by geometry of the component (such as capacitor wrapping, upper conductor rail, and lower conductor rail).

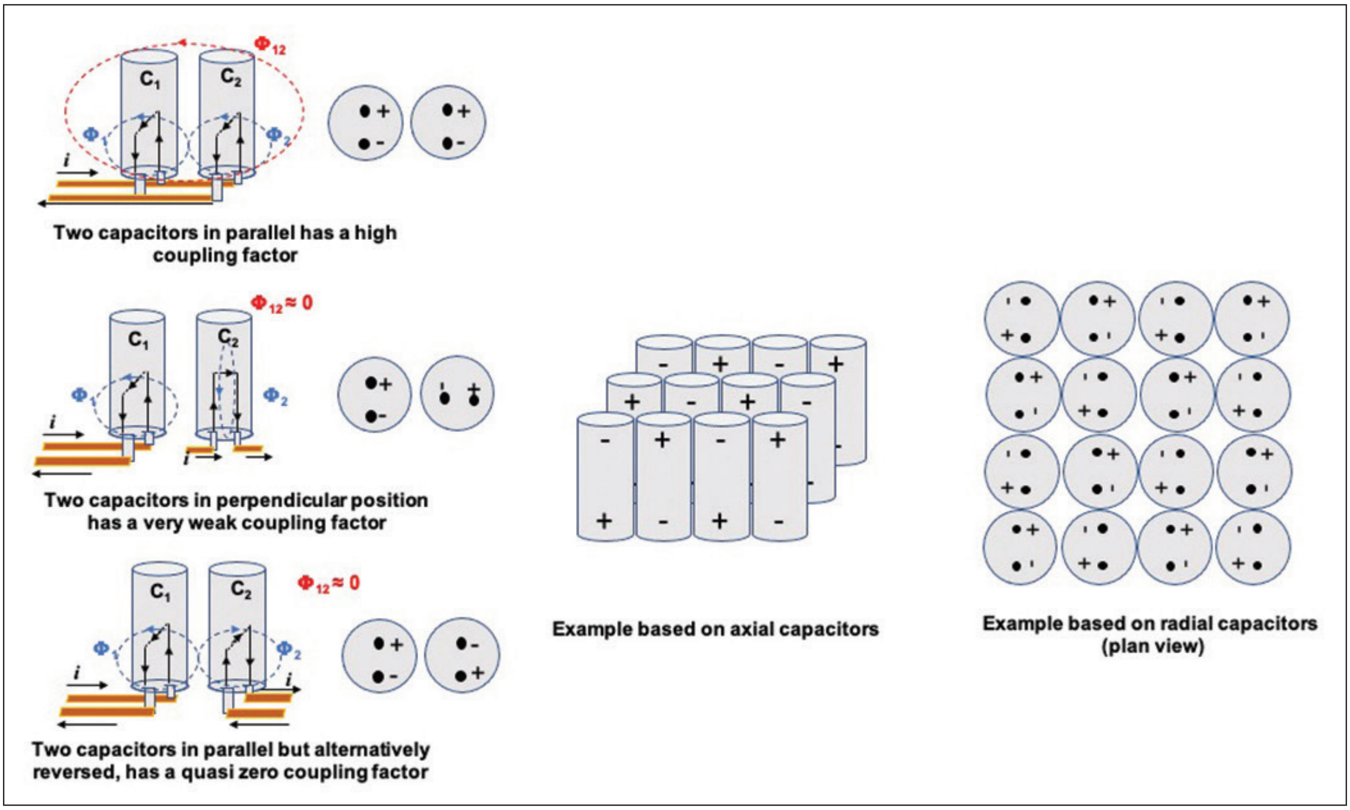

Figure 9: Layout rules for a number of electrolytic capacitors

Electrolytic Capacitors

In some cases, manufacturers use a high-performance electrolytic capacitor bank as the DC link. The current flowing in the self-inductance of a capacitor creates a magnetic field. The smaller the self-inductance, the smaller the magnetic field for a given current, and vice-versa. Connecting a number of capacitors in parallel connects their self-inductances in parallel. But, if they are too close together, their magnetic fields will interact since the overall inductance is not reduced when the magnetic fields are all in the same direction. As a result, the overall inductance is not reduced to 1/N (as we might expect from circuit theory or SPICE simulations).

But if we arrange N-paralleled capacitors closely together, and so that they are alternately reversed or so that the self-inductance of the capacitors are in perpendicular position to each other, their magnetic fields will tend to oppose each other, canceling them out to some extent (as now mutual inductance is kept at a minimum). Since weaker fields mean lower inductances, we may be able to achieve greater than a 1/N reduction in overall self-inductance [20].

Figure 9 demonstrates the magnetic field coupling due to mutual inductance between capacitors. Examples are given to show how layouts of arrays of capacitors can achieve lower overall inductances by their magnetic fields and cancel each other out, to some extent.

Inverter Power Electronics Devices Design

The EMC design consideration of using wide-band-gap devices such as SiC MOSFETs was introduced in [3]. The subject itself could easily inspire a few dedicated articles. Therefore, we only summarize here some of the best design practices.

Because the common-mode current I_{CM} can be calculated by Equation 2:

$$I_{CM} = C_{stray} \cdot dV/dt \qquad \text{Eq. 2}$$

where dV/dt is the slew rate of the switching device, C_{stray} is the stray (parasitic) capacitance and can be calculated by Equation 3:

$$C_{stray} = C_{FET} + C_D + C_L \qquad \text{Eq. 3}$$

where C_{FET} is the SiC MOSFET parasitic capacitance (predominantly drain to source capacitance C_{DS}), C_D is the free-wheeling diode capacitance, and C_L is the parasitic capacitance caused by layout (for instance, the capacitance between the device and a heatsink).

Reducing the slew rate helps to mitigate spikes or ringing, but at the cost of increased switching loss.

Reducing C_{stray} can be achieved by selecting optimized packaging and applying good layout practice. The ringing of the switching is caused by the L-C circuit resonance, and good layout practice to achieve lower stray inductance (e.g., device connections to the bus bar) helps reduce the ringing.

To share the large current, N SiC MOSFETs are placed in parallel. This configuration results in 1/N $R_{DS(ON)}$, allowing very low conduction loss. The total ESL of the devices might not be as low as 1/N for the same reason we explained when we talked about multi capacitors in parallel. However, ways of shortening the connections, such as connections between the devices and bus bars and the connections between the devices and motor windings, can minimize the inductance.

Figure 10 on page 50 demonstrates the SiC MOSFETs layout in the powertrain module of a Tesla Model 3. Four MOSFETs are put in parallel to form one switching block. Altogether, there are 24 switching devices in a very tight package space, with short connections to minimize the parasitic inductance. Direct sintering of the SiC MOSFET to the bottom of the heat sink helps remove the heat efficiently.

Techniques such as using SiC Schottky diodes in parallel to SiC MOSFETs to eliminate the reverse recovery charge effect were presented in [3]. But more manufacturers are integrating very fast and robust intrinsic body diode into the device package; hence separate antiparallel diodes are not required. Generally, locating decoupling capacitor arrays close to the switching devices is also crucial to reduce the ringing effect of the switching events.

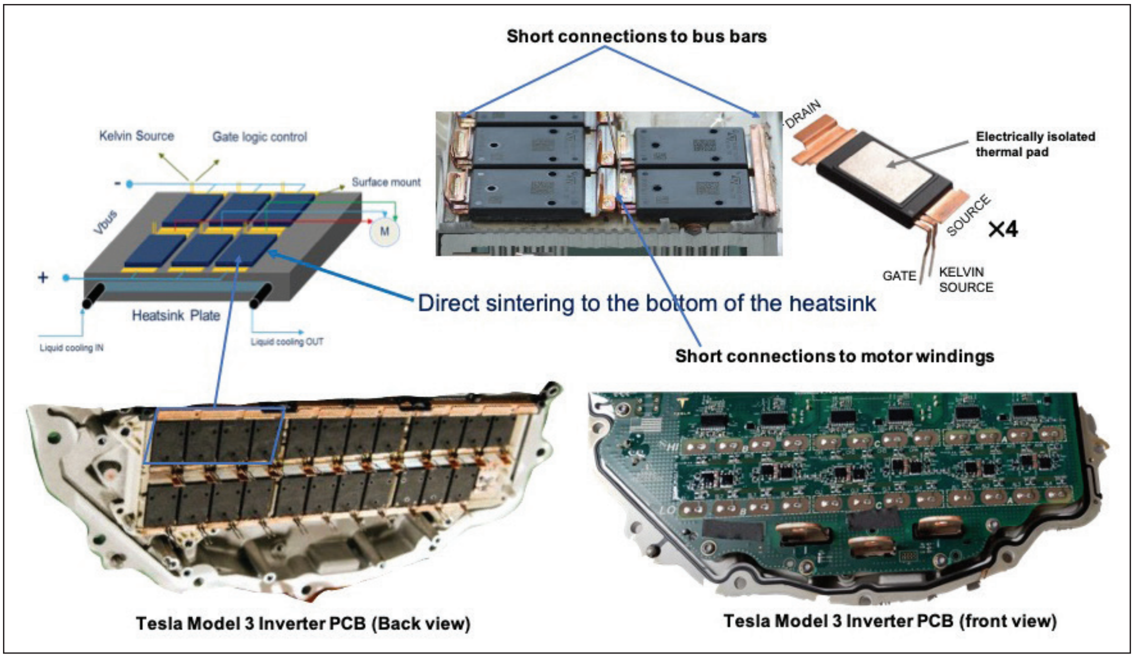

Figure 10: SiC MOSFETs layout in Tesla Model 3 powertrain inverter

Inverter Control Unit Design

Compared with the power stage, the low voltage control unit often has various high-frequency noise sources. The noise spectrum of a control unit covers a much wider range, as listed in Table 2.

LV Electronics	Frequency Range
Switched Mode Power Supply (SMPS)	150 kHz – 2 MHz
Communication Lines (LIN, CAN, FlexRay, etc)	10 kHz – 2.5 MHz
Microcontroller/DSP	200 MHz – 600 MHz
Digital Isolator	200 kHz – 10s of MHz

Table 2: List of LV electronics frequency range in powertrain module

The EMC design follows guidelines similar to those we previously discussed, which is to apply good layout practice, design front-end and output filters on both power and signal lines, and apply sufficient global and local decoupling capacitors.

CMCs are often seen in the LV power system design, and the X2Y balanced capacitor was introduced previously in this article. Although the HV (above 400V) X2Y part is not automotive qualified, there are plenty of AEC-Q200 qualified parts [19] that can be used in the control unit of a powertrain module. [21] introduced X2Y capacitor in an SMPS design.

Bearing Current Mitigation

At the design stage, there are two approaches one can apply to mitigate the bearing current, as described in the following paragraphs.

Hardware Mitigation Schemes

Ceramic bearings or hybrid bearings (a combination of steel rings matched with ceramic) are good candidates for an electric motor because of their mechanical characteristics. Because ceramic is an electric insulator, it can reduce the bearing currents and mitigate the electrical arcing [22]. Alternatively, the rotor of an electric motor can be directly grounded with a small thrust bearing that can easily be changed [13] [23]. This grounding also helps prevent the motor shaft from radiating due to the stray RF currents induced into it.

Other methods of mitigating the common-mode noise, which contributes to the shaft voltage and bearing current, are to add the common-mode filter along the motor windings. Shielded cables also help [13]. But for a compact module design, these methods are generally not considered.

Software Mitigation Schemes

Apart from using the hardware approach, certain switching schemes can be adopted to reduce the common-mode voltage of an electric motor, therefore reducing the bearing current. The method proposed in [24] proved to achieve both high performance and low common-mode voltage and current but unfortunately does not include a spectrum analyzer evaluation of the results as compared with normal PWM schemes. The implementation of the proposed method also requires an in-depth understanding of the motor drive system.

CONCLUSION

In this article, we reviewed the HV-related EMC regulations for powertrain modules in EV applications. We then discussed the design challenges they present and demonstrated the EMC design techniques that can be implemented at the design stage.

Most of the techniques introduced in this article follow EMC design principles, such as reducing parasitic parameters, 360-degree shielding, and bonding. New passive components (such as nanocrystalline core and X2Y capacitors) can also be considered, as well as software schemes to mitigate the common-mode noise. By adopting these design techniques, engineers can be more confident that the powertrain module they design will pass the EMC tests, potentially even the first time around!

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Expected Service Life of Medical Electrical Equipment

Clarifying Confusion Around Life Definitions

BY STELI LOZNEN

The main purpose of mandatory regulations is to obtain marketing authorization to enter global markets. Consequently, a manufacturer must demonstrate that all safety-related aspects, including compliance with relevant standards for basic safety, essential performance, risk management, usability, etc., have been reviewed, that all applicable requirements have been met, and that a quality system mechanism has been implemented.

With regard to medical devices included within the field of the medical electrical equipment (MEE), it is striking to observe how the clauses describing these specific concepts vary among applicable EU Directives, guidelines, regulations, IEC, ISO standards, and other requirements applicable to design, regulatory compliance, marketing, and health professionals.

Moreover, the concept of expected service life (ESL) for MEE comes on top of the already existing standards. Thus, due to an incomplete definition of ESL, there is a long chain of misunderstandings regarding the analysis and assessment required to determine compliance with MEE requirements.

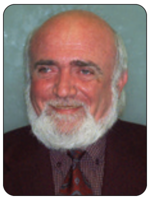
In this article, we'll attempt to clarify this confusion through a discussion of the standard definition of ESL found in IEC 60601-1 and the requirements applicable to MEE at the end of their ESL.

WHAT DOES EXPECTED SERVICE LIFE MEAN?

With reference to the ESL of medical devices, applicable regulatory documents specify many life-related terms, including service life, shelf life, useful life (or practical life), lifetime (or life span), and life cycle. (Don't confuse the use of these terms in the context of a device's safety or performance with warranty-related issues, which is a commercial consideration.)

An explanation of the meaning of the following life terms should help to provide a better understanding of the issues we seek to address in this article:

a. The term service life includes the time of use that a device is intended to remain functional after it has been manufactured, put into service, and maintained as specified.



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b. Shelf life is the term or period during which a device or accessory remains suitable for the intended use, whether it is stored or used. The termination of shelf life is represented by the expiration date, after which the device may no longer function as intended.[1]

The EU Guidance document in the medical devices vigilance system MEDDEV 2.12/1[2] requires that the service life and the shelf life must be specified by the device manufacturer and included in the master record (technical file) and, where appropriate, in the instructions for use (IFU) or labeling, respectively.

For life-sustaining equipment, the failure rate should approach zero within the labeled shelf life.

To determine if a particular piece of equipment requires a shelf life and be assigned an expiration date, several parameters must be considered, including susceptibility to degradation that would lead to functional failure (e.g., implantable devices) and the level of risk that the failure would present.

If parts or accessories with a specified shelf life are used in a device, their shelf life must be carefully considered in relation to the shelf life of the whole device.

Examples

1. The patient could not be defibrillated due to insufficient contact of the defibrillator pads with the patient's chest because the labeled shelf life of the pads was exceeded.
2. The patient is given a blood glucose test, receives a faulty diagnosis, and is given an incorrect insulin dosage because the test strip used for the blood glucose test was beyond the expiration date specified by the manufacturer.

c. In general, the useful life is defined as an estimation of the average number of years an asset is considered usable before its value is fully depreciated. Specifically, for an electrical device, IEC 60050 defines useful life as the time interval beginning at the start of use (a given moment in time) and ending when the failure intensity becomes unacceptable or when the item is considered to be unrepairable as a result of a fault.[3]

Another similar definition is the time interval from first use until user requirements are no longer met due to economics of operation and maintenance or obsolescence.

(Note: In this context, first use excludes testing activities prior to hand-over of the item to the end-user. For the useful life of a medical device, the accepted definition is the duration of actual use, or the number and duration of repeat uses before some change results in the device's inability to achieve its intended function.)

d. The lifetime (life span) of a medical device refers to the time interval from design and development of the device to the decommissioning (proper disposal) of the MEE. The lifetime of the device could be how long the MEE is expected to be functional (i.e., fulfill its intended use) and remain safe (i.e., free from unacceptable risk) per IEC 60601-1 requirements.

e. The life cycle represents all phases in the life of a medical device, from the initial conception to final decommissioning and disposal.[4]

f. The expected service life is defined in the third edition of IEC 60601-1:2005 as the maximum period of useful life as defined by the manufacturer, but fails to provide an explanation or reference about the meaning of useful life (!).

The needed clarification was achieved in IEC 60601-1, Amendment 1:2012 which clarifies the ESL definition as being the:

> *"…time period specified by the manufacturer during which the ME equipment or ME system is expected to remain safe for use (e.g., maintain basic safety and essential performance); (Note: Maintenance may be necessary during the Expected Service Life.)"*

Fortunately, Rationale Annex A4 provides a further explanation of the meaning of safe for use, as follows:

> *"The ESL is the time period during which the ME equipment or ME system is expected to remain suitable for its intended use, and all risk control measures remain effective ensuring that risks remain acceptable. The ESL needs to be determined by the manufacturer, as part of the risk management process, as a precondition for assessing compliance with many requirements of this standard, such as 4.5, 4.7, 7.1.3, 8.6.3, 9.8.2, and 11.6.6".*[5]

The expected service life is the anticipated and planned safe for use in-service life of the device. Safe for use means that the state of the device maintains both basic safety and essential performance. Therefore, it is critical to establish the ESL of a device regardless of the method chosen to verify it.

In reading these definitions, we find clear differences among various standards and specifications. Although all refer to the life of medical devices, the term means different things. Indeed, it seems that the terms lifetime and life cycle cover the most extended period of the life of a medical device.

But these varying terminologies and definitions are the source of many misunderstandings and much confusion, especially now when the term ESL represents a compliance requirement within IEC 60601-1. However, the ESL requirement must be regarded as a safeguard equal to those addressing intended use (function), ratings, environmental conditions of installation and use, etc.

ESL AND IEC 60601-1

The inclusion of the ESL in the 3rd edition of IEC 60601-1 should be seen as a positive step since it is the manufacturer who has the responsibility and obligation to specify the time segment of the lifetime or of the life cycle for a medical device in which the basic safety and essential performance are maintained.

We are reaching a very sensitive point of our analysis: unequivocally, clause 7.9.2.15 of IEC 60601-1 ed.3.1 specifies:

> *"The instructions for use shall provide advice on the proper disposal of waste products, residues, etc. and of the MEE and accessories at the end of their expected service life."*

In other words, IEC 60601-1 specifies that the MEE shall be decommissioned as a waste product at the end of its ESL. According to the standard, the end of ESL represents the end of all other lives.

However, in the real world, the situation may be different. For example, a medical device can finish its specified ESL (e.g., seven years) and, through sufficient refurbishing or re-manufacturing, start a new ESL period (e.g., three years), during which time its basic safety and essential performance requirements continue to be met. In theory, this cycle could continue until such time that a device can no longer be refurbished or re-manufactured. This is the real moment of the end of lifetime, life cycle, or useful life (or however you want to designate the whole life of the device!).

In using terms like refurbished or re-manufactured, it is important to remember that there is no universal standard applicable to refurbished goods. Thus, the terms refurbished, re-manufactured, renovated, and reconditioned are considered to be synonymous. All can be defined as the processes of restoring a used device to an as-new condition for performance and safety so that the device can again be safely placed on the market.

Maybe due to the misunderstanding of terms or misinterpretation of them, IEC 63077[6] defines the refurbishment as a:

> *"…process or combination of processes applied during the expected service life to restore used medical imaging equipment to a condition of safety and performance according to the specification of the manufacturer."*

But in the same standard, used equipment refers to equipment that has been put into service. Mysteriously, it seems to indicate that if a problem arises with a device after just a week of use, the device must be refurbished. Perhaps the standard's contributors considered the maintenance or repair processes, which are different from refurbishment. During the ESL, safety and performance need to be maintained (as IEC 60601-1 requires), and there is no need to perform a refurbishment. This kind of confusion can lead to difficult situations for a manufacturer and for a device user, since the necessity to replace one component or another doesn't mean a refurbishment.

Of course, if at some point during the life of the device, the majority of components need to be replaced to keep the device functioning or to fulfill the ESL specified by the manufacturer, this should be considered the end of the original ESL of an MEE while leaving open the potential for a refurbishment.

Estimated typical equipment lifetimes for healthcare technology can be found in published literature.[7,8,9] In general, the expected lifetime is estimated at a minimum of seven years. A few exceptions exist, such as cardiac laser units (three years), alarms oxygen depletion units (five years), ECG leads (two years), cell counters (five years), cuffs (two years), duodenoscopes (five years, aneroid sphygmomanometers (five years) and infrared thermometers (five years).

HOW DOES A DEVICE MANUFACTURER DETERMINE EXPECTED SERVICE LIFE?

Decisions related to device ESL can be made, in part, by controlling identified residual risks that can increase to unacceptable levels as the period of use of an MEE is extended. The ESL is just one of the inputs of the risk management file that can affect the probability of occurrence of harm. Medical device ESL may be based on technical, legal, commercial, or other considerations.

The manufacturer, who needs to specify the ESL in their risk management file, needs tools to accurately determine this time period. The best way to determine the ESL of the equipment is through reliability analysis and tests. Using reliability engineering techniques such as accelerated life testing (HASS and HALT) analysis can help with estimating the potential for initial failures or projecting the average expected functional life (with random failures) or the point of expiration (wear-out failures), etc.

However, one needs to be careful with the use of such reliability information because safety and reliability are different product characteristics that are sometimes in conflict with each other. Reliable products are not necessarily safe, and safe products are not inherently reliable. In general, safety has a broader scope than failures, and failures may not compromise safety in all situations.

The Practical Guide for the implementation of ISO 13485 standard (formerly ISO 14969) does list a few things that may need to be considered when defining device lives. The basis of the defined lifetime of the medical device should be documented. To assist in determining the lifetime of the medical device, the rationale for the determination should be recorded and may involve consideration of the following:

- Shelf life of the medical device
- Expiration date for medical devices or components which are subject to degradation over time
- Number of cycles or periods of use (frequency of use) of the medical device, based on life testing of the medical device
- Environmental conditions of use that can result in material degradation
- Stability of packaging material
- For implantable devices, the residual risk that results from the entire period of residence of the device inside the patient's body
- For sterile medical devices, the ability to maintain sterility
- An organization's ability/willingness or contractual or regulatory obligation to support service
- Spare parts cost and availability
- Legal considerations including liability

In addition, the following factors may also be considered:

- Intended use
- Experience and knowledge of the user
- Care and attention paid to use and operator maintenance
- Existence, capability, and cost of maintenance support
- Management of scheduled and unscheduled maintenance
- Availability and cost of replacement devices
- Business, safety risks, strategic, and political risks associated with continued or discontinued use
- Compliance with current codes and standards
- Technological or clinical redundancy
- Funding availability

Based on the above factors, a device manufacturer should have sufficient information to determine the ESL, which will be included in the risk management file and the accompanying documents. Additionally, Rationale Annex A4 of ed. 3.1 of IEC 60601-1 recommends:

> *"The accompanying documents should provide information to allow the responsible organization (e.g., hospital) to assess when the equipment is approaching the end of its expected service life. This could be given in terms of years of service or number of uses, or tests as part of preventative maintenance to allow the responsible organization to make an appropriate determination of ESL".*

To summarize, once the ESL is determined, it is expected that the device remains safe for use during ESL basic safety and essential performance is maintained, and the user is informed about the signs of ESL end proximity. We will see in the next section the fate of the device after the period when ESL ends.

IS IT NECESSARY TO SUPPLY DECOMMISSION INFORMATION?

During the ESL period as declared by the manufacturer to be (e.g., seven years), an MEE which has undergone the recommended periodic maintenance as specified in the accompanying documents can be considered compliant with the basic safety and essential performance as required in IEC 60601-1. However, at the end of its ESL, is a device that is still compliant with the standard's requirements be decommissioned? The answer is a categorical no.

As we have previously discussed, the life cycle of an MEE ends when the user is forced to decommission it when it can no longer be used safely and or fails to meet its performance specifications. This point in time can occur either before or after the endpoint of the ESL.

For example, a device may have completed its intended service and can no longer be serviced or maintained due to obsolete procedures, a lack of spare parts, or the cost of servicing. So, instead of lasting seven years (for example), the device needs to be removed from service and decommissioned as a waste product. In other cases, a device can reach the specified end of its ESL in good condition and is able to continue to be used beyond its ESL if it is serviced or repaired as needed.

In such situations, based on the actual IEC 60601-1 requirements, a manufacturer can claim that they are no longer responsible for the product after the end of ESL and are not required to take steps to ensure that use of the device is discontinued. However, questions of product liability now come into sharper focus. It would be most helpful if the working group responsible for developing and updating IEC 60601-1 provided some clarification on this situation (for example, by issuing an Interpretation Sheet) or by including clarification in a 4th edition of the standard.

For device manufacturers, another ESL-related challenge is presented by the scope of basic safety and essential performance requirements found in IEC 60601-1. Specifically, only certain clauses in the standard refer to ESL, including 4.7 – Single Fault Condition; 7.1.3 - Durability of Markings; 7.9.2.15 - Environmental Protection; 8.6.3 - Protective Earth of Moving Part; 8.8.4.1 - Mechanical Strength and Resistance to Heat; 9.8.2 - Tensile Safety Factor; 11.6.6 - Cleaning and Disinfection of ME Equipment and ME Systems; and 15.3.7 - Environmental Influences. Shouldn't all other clauses in the standard be applicable during a device's defined ESL? Yes would be the logical answer, but the standard is unclear on that point.

WHAT EVIDENCE SHOULD A DEVICE MANUFACTURER PROVIDE TO A NOTIFIED BODY REGARDING EXPECTED SERVICE LIFE

Lifetime is mentioned twice in Annex I of the MDR:

- Paragraph 6: *"The characteristics and performance of a device shall not be adversely affected to such a degree that the health or safety of the patient or the user and, where applicable, of other persons are compromised during the lifetime of the device, as indicated by the manufacturer, when the device is subjected to the stresses which can occur during normal conditions of use and has been properly maintained in accordance with the manufacturer's instructions".*
- Paragraph 23.4: *"The instructions for use shall contain all of the following particulars:*

  … "(k) the information needed to verify whether the device is properly installed and is ready to perform safely and as intended by the manufacturer, together with, where relevant:

  - *"Details of the nature, and frequency, of preventive and regular maintenance, and of any preparatory cleaning or disinfection,*
  - *"Identification of any consumable components and how to replace them,*
  - *"Information on any necessary calibration to ensure that the device operates properly and safely during its intended lifetime, and*
  - *"Methods for eliminating the risks encountered by persons involved in installing, calibrating or servicing devices."*

Compliance with the above requirements should be demonstrated with objective evidence and documented in the device Technical File. These documents, together with the information used to determine the ESL, will then serve as the basis for a thorough and objective assessment of the basic safety and essential performance of an MEE during the ESL.

WHAT IS THE BEST WAY TO DEFINE THE EXPECTED SERVICE LIFE OF A DEVICE?

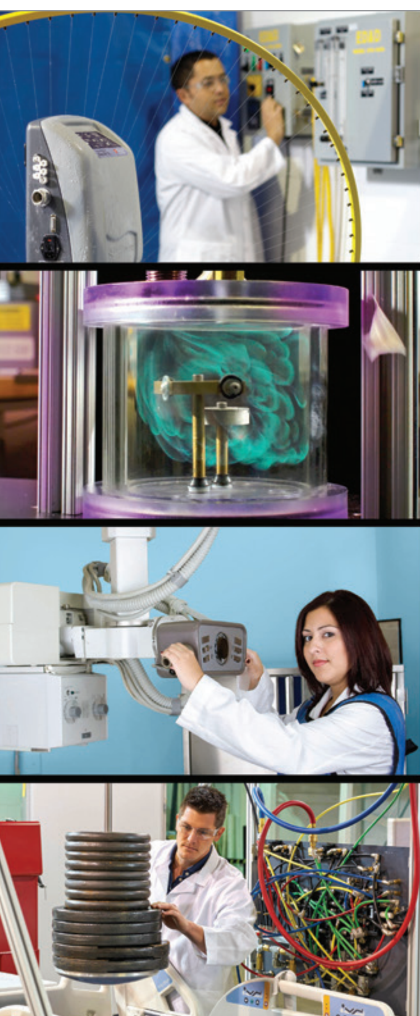
We believe that a small addition to the actual ESL definition found in Amendment 1 of IEC 60601-1 would provide the necessary clarification and help to eliminate future confusion. As such, the updated definition of expected service life would read as follows:

> *"Time period* of the life cycle*, specified by the Manufacturer during which the ME Equipment or ME System is expected to remain safe for use (e.g., maintain Basic Safety and Essential Performance)."*

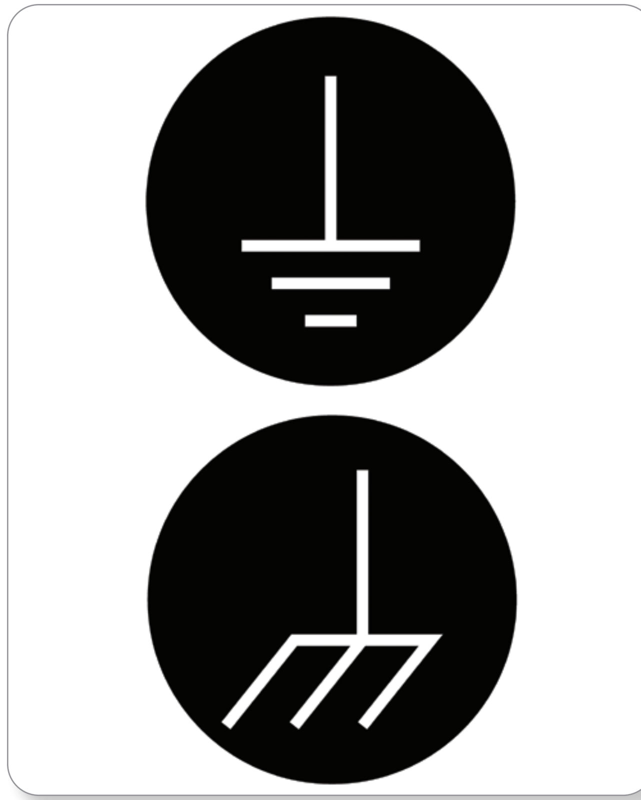
By adding *of the life cycle* to the ESL definition, it becomes clear that ESL is a time part of the life cycle of an MEE in which the expectation to be safe for use is present. This time part can be extended by refurbishing or remanufacturing until the MEE becomes obsolete from a performance point of view or cannot be put back into operation due to outdated technology, lack of parts, or economic reasons. This is the point at which the MEE is decommissioned from service and recycled, destroyed, or discarded as appropriate.

ENDNOTES

1. FDA, "Shelf Life of Medical Devices," 1991.
2. MEDDEV 2.12/1 rev.8, *Guidelines on a Medical Devices Vigilance System*, 2013.
3. IEC 60050:2012, *International Electrotechnical Vocabulary*, Chapter 191: Dependability and Quality of Service, Definition IEV 191-19-06.
4. ISO/IEC Guide 63:2019, *Guide to the development and inclusion of aspects of safety in International Standards for medical devices*, Definition 3.5.
5. IEC 60601-1: 2012, Ed.3.1, *Medical electrical equipment – Part 1: General requirements for basic safety and essential performance*.
6. IEC 63077: 2019, *Good refurbishment practices for medical imaging equipment*.
7. "Life span of Biomedical Devices," Biomedical Engineering Advisory Group SA, Australia, 2004.
8. "Estimated Useful Lives of Depreciable Hospital Assets," American Hospital Association, 1998.
9. "Personal Property Manual," State of Nevada, Department of Taxation, 2009.



System-Level Grounding



Is Your System Well Grounded? Consider These Points in Effective Grounding

BY VLADIMIR KRAZ

Grounding is the most fundamental property of all types of electrical equipment. There are plenty of quality articles on specific subjects in *In Compliance Magazine* and in other publications, largely on grounding on a printed circuit board (PCB) level. This article focuses on a path less traveled, grounding on a system level, that is grounding of the equipment in actual use at the factories.

There are several key aspects of grounding, including safety, electrostatic discharge (ESD), electromagnetic interference (EMI), and signal integrity. While this and other magazines have published detailed articles on one or more of these subjects, this article combines them all to assist equipment users and tool makers in understanding what is important and how to achieve optimal ground performance. This article does not cover PCB grounding (there are plenty of excellent articles on this subject) and portable tools with double insulation that do not have grounding.

SAFETY

Safety is always first. Too many specialists in ESD and EMI are not professionally trained in electrical safety.

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This article is far from a comprehensive safety guide, and it doesn't cover every important safety point. The whole purpose of this section is to bring electrical safety to the attention of ESD and EMI specialists at factories and tool designers who otherwise may not be aware that grounding is a safety item. I strongly recommend that those who deal with such subjects take an electrical safety course, make friends with factory's licensed electricians, or join a factory safety committee. In this article, we will just scratch the surface and touch on the basics.

So why is grounding a safety element? As an example, let us consider a typical piece of industrial equipment, such as an integrated circuit (IC) handler, or surface mounted technology (SMT) pick-and-place machine (or any other tool that you are familiar with). Each of these tools takes its power from AC mains, meaning that typically anywhere from 100VAC to 440VAC enters the equipment. If a live wire inside such a machine or tool gets loose for whatever reason, it can touch and energize (that is, supply voltage to) a metal part to which an operator has access. Now this metal part, such as the enclosure, is under high voltage. The operator can easily be electrocuted simply by touching such a part.

Here is where grounding comes to the rescue. If all operator-accessible metal parts are properly grounded, an energized loose wire that touches such a part effectively short-circuits any live voltages to ground, and the resulting

excessive current triggers the circuit breaker to cut power to the tool. For all this to work, these conditions must be met:

- All operator-accessible conductors must be grounded;[1] and
- The ground path must have a low enough impedance to allow a high current sufficient to trigger the circuit breaker.

How conductive should a ground path be in order to trigger the circuit breaker? There are several varying standards and guidelines on this subject, but the essential answer is that the ground path should be at least as conductive as either the live or neutral paths. If your power cable utilizes AWG12 (or 2mm diameter) power wires, you cannot have ground wires that are thinner than that. A ubiquitous AWG18 green wire just won't do.

Must all grounding wires inside the tool be as thick as the power wires that enter it? Not necessarily. In places where grounding is done for purposes other than safety (for example, ESD/EMI) and where there are no voltage-carrying conductors, grounding wires can be selected based on other criteria (see further on in this article).

Ground and Neutral Reversal

More often than desired, ground and neutral wires are reversed in either facility wiring or in the internal wiring of the equipment itself. This leads to return current flowing through ground rather than through the neutral wire, resulting in a multitude of functional problems in addition to being a safety issue. A ubiquitous three-LED outlet checker cannot detect that. The easiest way to check for it is to measure AC current on the ground wire entering the equipment using a simple AC current clamp (make sure to properly identify ground wire). If the equipment ground current exceeds 0.1 A during operation, an investigation is in order. This does not account for excessive leakage current in equipment even if the wiring is correct.

ESD

After safety, the second most common use of grounding in equipment is to address ESD considerations, more specifically, to provide a discharge path to ground for conductors and static-dissipative materials. If accumulated static charges on electrically floating conductors and dissipative materials are not discharged to ground potential, they may carry unwanted voltage and cause problems for ESD-sensitive devices.

How do we effectively ground such objects? Standards such as ANSI/ESD S6.1[1] and an omnibus standard ANSI/ESD S20.20 [2] provide good recommendations. Here we will add some helpful narrative.

It is curious to me that engineers and technicians dealing with grounding issues don't ask the most important and logical question about ground, that is, what is the voltage on ground? Not the resistance since resistance is just the means of reducing the voltage on grounded parts. The whole purpose of grounding for ESD purposes is to create an equipotential environment.

There are currently no coherent standards, standard practices, or technical reports issued by either the ESD Association or the IEC that touch this subject with any specifics on validation. Yet, this is the most important question for the safety of the devices in the process. The only document addressing it is SEMI Standard SEMI E.176 [3] which I'll cover later in this article.

How do we assure that what needs to be grounded actually is? There are implicit and explicit ways of providing grounding connections. Implicit ways include mechanical fastening of conductive parts of the tool to the grounded frame so that there are no obvious grounding wires, but the electrical connection via mechanical fastening is still present and is adequate. The problem with such implicit connections is that they are uncontrolled. Depending on the construction of the tool, any component in the electrical connection chain can be altered in the next revision of the tool or during repair or service and modified to the degree where the electrical connection is no longer assured. During any revision, maintenance, or repair, a metal washer can be replaced by a nylon one, or an originally bare metal part may become anodized, and so on.

There are two ways to prevent such problems. One way is to add requirements for adequate ground connection to the tool's specification and to the maintenance procedure and verification documentation (and to meticulously follow it). Another way is to use an explicit, separate grounding method. Either of these methods is viable, and the choice is up to the user of the equipment since its manufacturer may not appreciate the importance of proper grounding for ESD.

1. Due to its construction, some equipment may have electrically floating metal parts, i.e., not electrically connected to anything. These parts are generally small. Special care must be exercised to assure that such floating pieces of metal physically cannot have electrical contact with live voltage.

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An example of explicit grounding is shown in Figure 1. I'll come back to this figure later in this article.

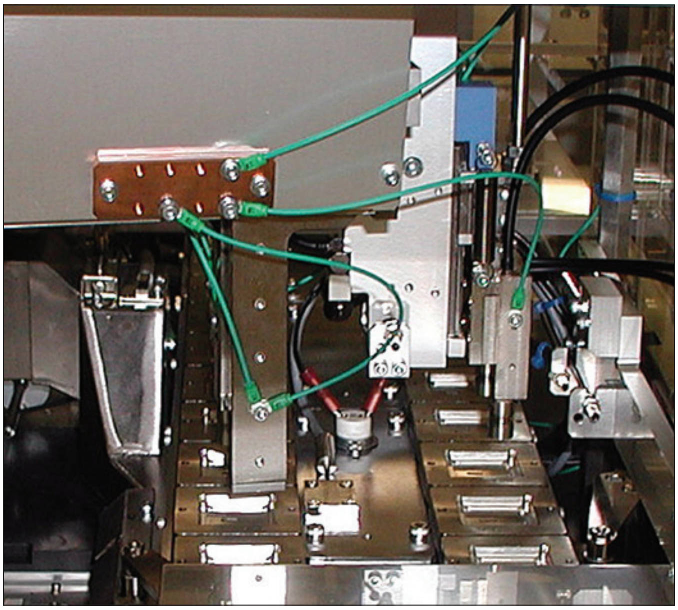

Figure 1: Explicit grounding in the IC handler

ESD GROUND: HOW GOOD IS GOOD?

Various ESD-related standards such as ANSI 6.1, ANSI/ESD S20.20, ESD S10.1 [4], IEC 61340 [5], and some other documents, plus proprietary factory-wide documents, provide guidance on grounding. This section simply attempts to provide clarification on some of the details.

Metal Ground

For explicit grounding and for the grounding of floating metal parts, these documents specify (or recommend) a resistance path to ground of less than 1 Ohm. While this goal is reasonably easy to achieve with stationary equipment, it can be quite elusive and not feasible for some of the moving parts.

If the part moves just a little (even just a few centimeters, as is common in many tools) grounding is often done using flexible steel cable (quite similar to a bicycle brake cable, see Figure 2). Careful selection of material, flex radius, and the number of bend cycles of such cables is required to avoid breakage of the cable in use. Obviously, steel is not as good a conductor as copper, but it is much more durable. And, with very short cable runs, resistivity isn't really an issue.

Longer movements require much longer runs of ultra-flexible cables protected by flex conduits, as shown in Figure 3. The internal construction of such flex cables does not support a sufficiently thick gauge of wire. Therefore, many ultra-flexible cables include an additional layer of Teflon or similar material around each wire that facilitates a low friction coefficient, allowing wires to slide against each other while bending.

This would be the case with any ultra-flex cables, with or without an external harness, as shown in Figure 2. The result is higher resistivity of such wires, making a 1 Ohm requirement of the entire connection almost unachievable, considering all the interconnects along the chain. Requirements to the total resistance of flex ground connections typically vary between 2 and 10 Ohms, depending on the factory, although I've seen 20 Ohms requirements as well. Would such an increase over 1 Ohm noticeably alter the ESD environment in the process? Actually, that's very unlikely, but what would cause the problem is a loss of ground connection.

The problem with the reliability of explicit grounding using dedicated conductors is that the failure of a ground connection may not be obvious right away. After all, such grounding or the absence of it does not alter the basic

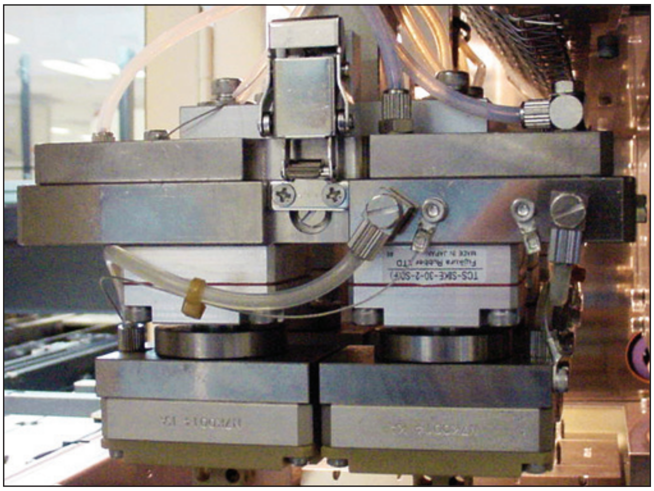

Figure 2: Grounding of moving parts using flexible steel cable

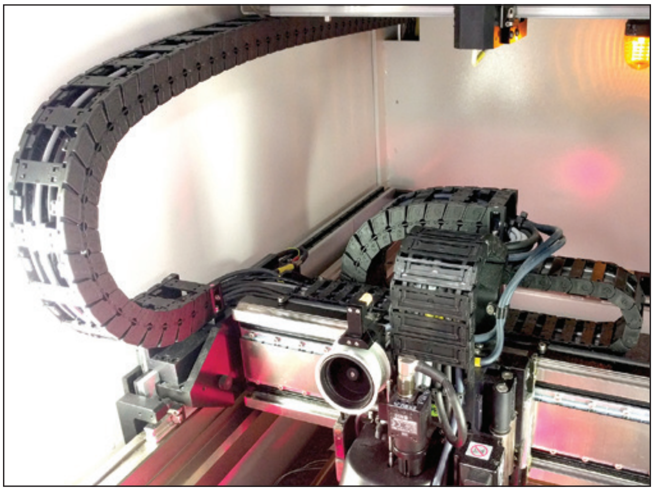

Figure 3: Flex cables on a robotic arm

functionality of the tool and can go unnoticed for some time. I've witnessed an unfortunately large number of situations where explicit ground wires were disconnected for tool's maintenance but, instead of being reconnected, the wires were either completely removed or their ends were left hanging, making the tool look a bit like a hedgehog. And these issues typically emerge when there's a need to resolve a sudden ESD or EMI problem.

One of the solutions to a lost ground problem is ground monitoring, and there are plenty of ground monitors on the market. Such monitors independently connect to the grounded point and to the reference ground and sound an alarm whenever a ground connection fails.

The 1 MOhm Question

Wriststraps and/or wriststrap cords contain a 1 MOhm resistor in line with ground for a simple reason, that is, to prevent electrocution of personnel. Should an operator wearing a wriststrap accidentally touch a grounded conductor, the current through the operator should not exceed 0.5mA (ANSI/ESD S1.1 ANNEX B [7]), a limit that is consistent with several broader safety standards. At 250V RMS, which is the highest RMS AC voltage among common electrical outlets, the minimum resistance should be no less than 500 kOhms (not accounting for the electrical resistance of the operator's body). A 1M resistor would satisfy this requirement, including dual wriststraps that would have two resistors, electrically parallel to each other, between the operator's body and ground. Try to avoid low-cost wrist straps and cords unless their resistance is verified.

Should the same 1 MOhm resistor be used to ground other items, such as metal objects or dissipative materials? The often-stated reason for use of a 1 MOhm resistor in such applications is to slow down the discharge. Would it truly slow down the discharge?

Let us consider an electrically floating metal object that needs to be grounded. This object would have an electrical capacitance dependent on its size (among other things). Assuming that this object is at ground potential, would it make a big difference in discharge properties whether the object is grounded via sub-Ohm resistance, via 1 M resistance, or left electrically floating?

Figure 4 shows a highly simplified equivalent electrical schematic of such a connection (parasitic inductances and capacitances have been omitted for clarity). A device (IC) has a certain capacitance, C1, and is charged, to voltage V1, likely as a result of being lifted from the tray. An IC handler's arm is about to place this device onto a shuttle (a metal tray for moving ICs in the handler). When the IC comes in contact with the shuttle, the voltage is almost instantly equalized.

For exercise purposes, we will assume that the shuttle is implicitly grounded via resistor Rg and not by mechanical means. In the end, whatever charges were left on the shuttle will dissipate to ground via Rg. But the issue we are trying to resolve is the role that the Rg plays in the properties of the discharge itself.

Resistance Rc of contact between the IC and the shuttle is negligible, perhaps just a few milliohms. If we set Rg to 1 MOhm, most of the action will happen between the IC and the shuttle, since Rg is too large to participate in voltage equalization during a short nanosecond-long discharge. If we bring this situation to an extreme, assuming that Rg has infinite resistance, would this slow down the discharge? Of course not, since the waveform of the discharge is defined only by the capacitances of metal parts and contact resistance Rc. ESD practitioners know well that touching a floating plate of CPM easily produces discharge, just like touching a completely insulated metal doorknob would produce the same. The only function of Rg is to eventually dissipate whatever little charge the IC shared with the shuttle to ground and to bring shuttle voltage to ground potential.

The same holds true for static-dissipative mats. Inserting a 1 MOhm resistor into the ground connection will not change the rise time or amplitude of the discharge. Instead, it will only slow down the dissipation of charge to ground which, in the case of static-dissipative materials, may leave these materials under voltage in fast-paced processes. While existing practices allow a 1 MOhm resistor to be used in a ground circuit with dissipative materials, it is counterproductive in reality.

EMI

We are finally coming to the most interesting part of grounding, that is, high-frequency voltages on ground, or EMI. The term in this context may not satisfy a purist but, since it is widely used in the industry, this is what we will be using as well.

Every electrical equipment generates some sort of parasitic, for example, unplanned or unwanted signals. Automated equipment contains plenty of sources of high-frequency voltage and current signals [8], with the strongest generated by pulse-driven motors (servo, steppers, and

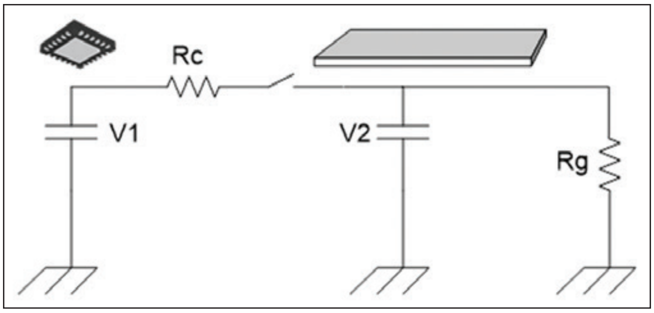

Figure 4: Discharge equivalent schematic

VFD – variable frequency drives) [9], and switched-mode power supplies, including those in LED lighting as well. These high-frequency signals leak to ground via parasitic capacitance, resulting in highly undesirable voltages between different grounded parts of equipment. This is never good news, but it's especially bad news for sensitive devices and for testing and measurement.

Why are we focusing on high-frequency voltages and not any other voltages? Simply, conventional grounding methods deal with DC and low-frequency AC voltages reasonably well. They sink to ground any leakage AC and static DC voltages that happen to be on metal and static dissipative parts of equipment, given their low ground path resistance (see the previous discussion). That leaves only high-frequency voltage signals, due to the parasitic inductance and capacitance of conductors and the mutual influence between them. While resistance path to ground can be very low for DC and for low frequencies, this is not the case for high-frequency signals, which we'll analyze it in detail.

A Wire is an Inductor

Simple, straight wire that would be great for ESD and safety grounding is, in fact, an inductor. Although calculating this inductance may be a bit involved, there are plenty of useful Java-based inductance calculators on the internet that are far more practical [10] than doing the calculation by hand.

As a point of reference, a 1mm diameter wire (AWG18) of 1 m length has an inductance of 1.5μH. At 1MHz this would present an impedance of 9.42 Ohms. This is for the straight wire only, and the typical service loops of ground wire only add to impedance. There are calculators for that too [11]. As an example, five turns of the same wire coiled in a 6" (15cm) diameter coil produces 6.1μH inductance with an impedance of 38 Ohms at 1MHz. The same wire would have a resistance of only 0.06 Ohms at DC.

Only Outer Layer of Wire is a Conductor at High Frequency

At high frequencies, the current is pushed out by the magnetic field resulting from the passing current, the so-called skin effect. The higher the frequency, the thinner the conductive layer. At 1 MHz, the outside conductive layer is only 66µm thick. Skin effect doesn't add as much resistance as pure inductance (1m of AWG18 wire constitutes 0.09 Ohms vs. 0.021 Ohms Ohms if there were no skin effect), but it all adds up. Multi-stranded wires help, since the bigger the wire surface the lower the resistance. But the wires typically found in manufacturing environments have too few strands to be effective.

Capacitive Coupling

Two wires running in the same conduit influence each other via capacitive and inductive coupling. In Figure 2, there are drive signals among the wires in the flex channel to servo motors on the robotic arm, along with a wire to ground the arm itself, all of which are in immediate proximity to each other. A typical robotic arm of automated equipment has three servo motors, one for each degree of freedom. This amounts to nine wires carrying pulsed voltage with typically 200V peak voltage (not counting ringing and other artifacts). The rise and fall times of such drive pulses are under 50 nS, creating signals with the spectrum extending up to 20 MHz.

In the example of Figure 2, the length of wires in the flexible harness is 3m. The capacitance between two adjacent wires would be approximately 63pF [12] which at 20MHz constitutes 125 Ohms impedance. The rough equivalent schematic would look like the one in Figure 5a.

Due to the properties of capacitive coupling, the higher the frequency, the higher the induced voltage. Correspondingly, the sharper the edges of the pulses, the higher the induced voltage.

Inductive Coupling

The long wires running in parallel form a distributed transformer. Without the core and the turns of windings, it works only at higher frequencies, and this is where the problem lies. Figure 5b shows how the current in one wire imposes corresponding currents on a nearby wire. Due to the properties of this parasitic transformer, only high-frequency signals are being passed from one wire to another, creating waveforms similar to those shown in Figure 5a.

Field Data

One can get easily absorbed in simulations and calculations of induced voltages and currents. In our case, however, this is not likely to produce realistic results due to the number of variables not accounted for in the equivalent schematic, and the variability of parameters between the

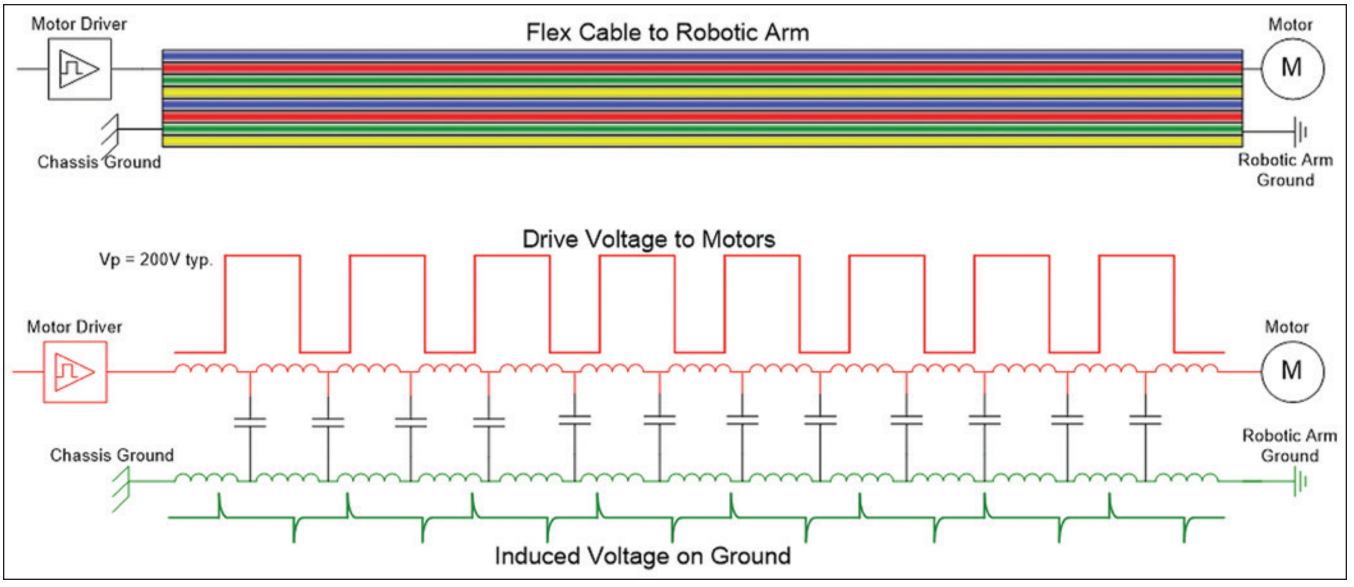

Figure 5a: Induction of high-frequency voltages into group wire in a flex conduit of Figure 2

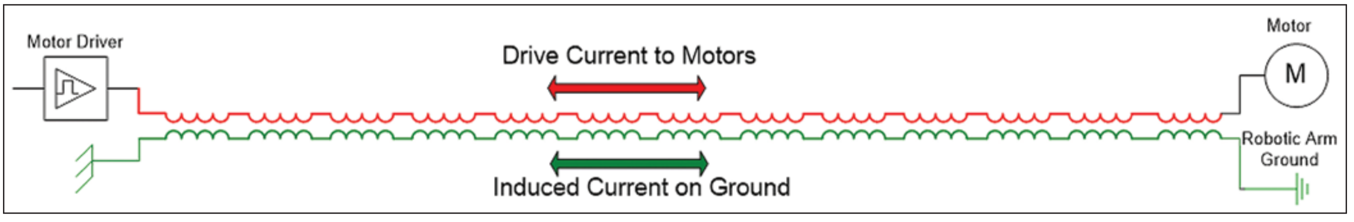

Figure 5b: Induced current on ground

tools. But measurements serve a much more practical purpose. Measurement methodology and techniques are described in detail in this article [13], previously published in *In Compliance*.

Figure 6 shows typical voltage between the nozzle of the robotic arm in the IC handler and the chassis. The spikes correspond to the rise and fall edges of the interfering signal.

Figure 7 depicts the current between the robotic arm and the chassis in a different tool. The current was measured using Tektronix's CT1 probe with 5mV/mA ratio, and the peak current is 76.8mA. Ringing is simply an artifact of imbalanced impedance match, and manufacturing equipment is a far cry from fully matched RF instruments.

What Harm Can Little Ground Voltage Do?

What could be wrong with a little voltage between different grounded parts? In many tools and processes, it's not a problem. If your devices are not sensitive to electrical overstress (EOS), and if you are not concerned with data integrity and measurement accuracy, there is not much to worry about. However, since you are reading this article, you must have some interest in keeping voltages and currents on ground as low as possible.

Electrical Overstress (EOS)/Electrically Induced Physical Damage (EIPD)

Grounded surfaces are supposed to provide a safe space for sensitive components without the possibility of any overvoltage exposure. But if we actually conduct measurements, the situation can be quite different and often unsafe.

Consider, for example, the common handling of ICs in an IC handler or SMT pick-and-place machine (Figure 8). An actuator/nozzle at the end of the robotic arm has plenty of high-frequency voltage vs. the chassis that we described above. A silicon die of the IC is capacitively coupled to the nozzle in its immediate proximity. At high frequencies, this capacitive coupling presents a very low impedance. When this IC is placed on either a test socket or on a shuttle (a metal holder for moving ICs in the horizontal plane), excessive current may flow through the device, weakening its structure and causing failures in the field, or even resulting in an outright failure.

This is just one example. Any metal contact with the device, such as soldering [14], wire bonding [15], or others can expose the devices to unwanted voltages and currents.

How Much Ground Voltage and Current Are Too Much?

There are plenty of documents about controlling the resistance/impedance of ground connections. But SEMI Standard E.176 "Guide to Assess and Minimize Electromagnetic Interference (EMI) in a Semiconductor

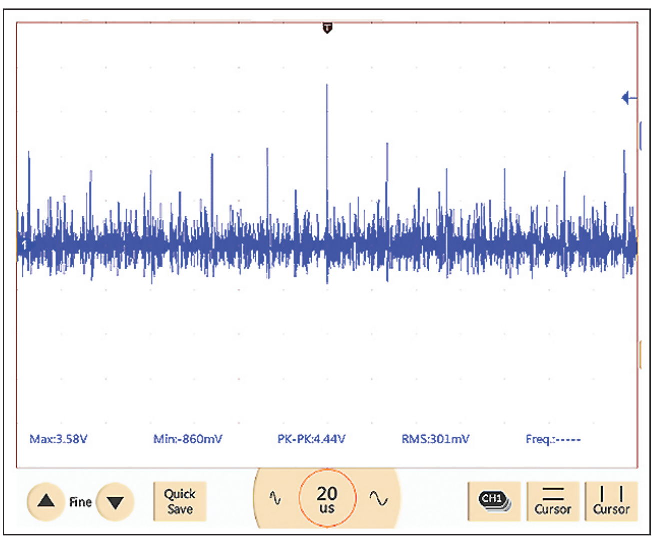

Figure 6: Voltage between the nozzle of the robotic arm in IC handler and the chassis

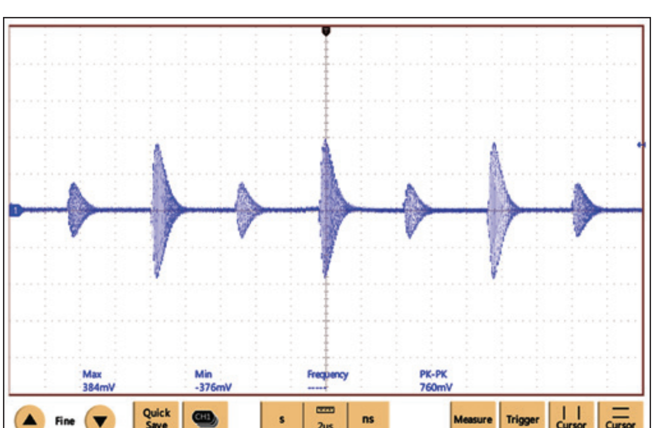

Figure 7: Current between the robotic arm and the chassis

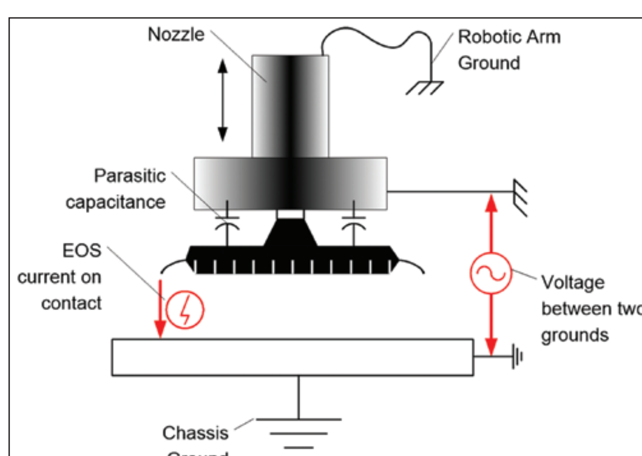

Figure 8: Mechanism of EOS in automated handling of ICs

Manufacturing Environment is the only relevant industry document that actually specifies the maximum allowed EMI voltages and currents on ground based on the properties of devices used in the process.

While written largely for semiconductor manufacturing, SEMI E.176 has a direct bearing on all applications of semiconductors, which includes most of today's equipment. After all, the sensitivity of semiconductor devices doesn't change once it has been shipped to a PCB assembly plant. I've written several articles published in previous issues of *In Compliance* [16] [17] that discuss SEMI E.176 in detail.

As one point of reference, today's common IC with 10nm geometry in its unpowered state (i.e., in IC manufacturing and handling, such as PCB and product assembly) should typically not be subject to voltages higher than 0.1V across it, and the peak ground currents for this geometry should not exceed 10mA (Level 3 in SEMI E.176).

Unless you can measure and quantify ground voltages and current, you cannot control it. Another of my articles previously published in *In Compliance* [13] provides detailed guidance on the methodology, instrumentation, and techniques for such measurements, and I encourage you to read it before performing any measurements.

EMI: EFFECT ON DATA

High-frequency signals can interfere with data and measurements in several ways. Induced EMI voltage can present itself as a valid signal since it can be close in amplitude and in waveform to the real signal. This leads to data corruption [18] and measurement errors [19],[6]

Ground Bounce on a System Level

Electrical engineers are familiar with ground bounce effect in semiconductors (see, for example, [20]). Ground bounce is mostly thought of as happening on the IC level, but the physics of ground bounce work on a system level as well. Figures 9 and 10 show an example of how it happens.

Figure 9 shows how current spikes from sources such as motor operation travel to the facility ground and thus create a voltage drop on the tool's ground wiring. The resulting voltage on the tool's ground is no longer the same as the facility ground, and not the same as the ground of another tool with which the tool is trying to communicate (in this example, the USB). In such conditions, logic levels are no longer valid as shown in Figure 10, and the very next logic gate can easily mistake 1 for 0 and vice versa, depending on the timing and the amplitude of such interference. The worst part of it is that there is no record in the system of such occurrence, and reproducing it is often impossible.

I HAVE EMI ON GROUND - NOW WHAT?

Simply understanding the problem is only the first step in resolving it. There are several methodologies to mitigate EMI issues on ground. All revolve around the same three basic principles:

- Reduce EMI at the source;
- Block propagation of EMI; and
- Reduce susceptibility of your circuit/devices to EMI

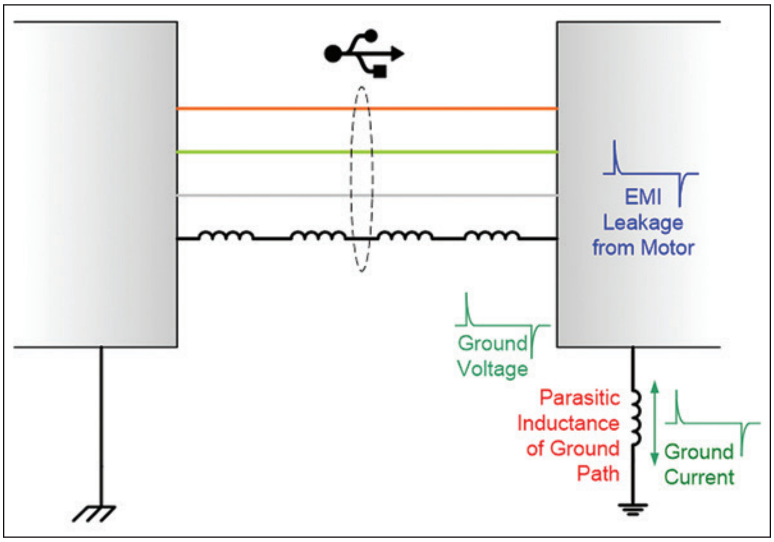

Figure 9: Ground bounce on a system level

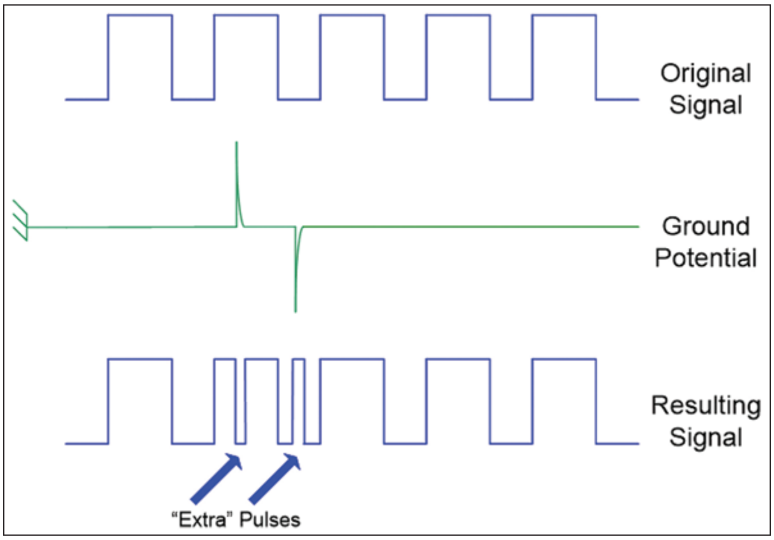

Figure 10: Ground bounce causes extra pulse

Depending on whether you are an equipment designer or an equipment user, your options may vary.

Reducing EMI at the Source

The two biggest sources of EMI in equipment are pulse width modulation (PWM) motors (e.g., servo, stepper, and VFD), and switched-mode power supplies (SMPS). If we manage to decrease dV/dt of the edges of their pulses (in other words, slow down the signal transitions), there will be less EMI to induce on ground. Designers of PWM drives and SMPS are trying to make these edges as sharp as possible so that the output transistor drivers do not heat up as much and the circuit is simpler. Typical rise/fall times of drive pulses in a servo motor are around 50nS, which translates into the spectrum of up to 20MHz.

It is now our job to make these drives and SMPS work for us in the way we want them to. The only practical way to increase the rise and fall times of pulse edges is filtering. For SMPS, the more filtering that is applied to their DC output the better. PWM drives require a more careful approach since trying to filter pulsed drive signals may easily make the motors perform poorly or not work at all.

Figure 11 shows the original rise edge of a servo motor drive pulse, and the modified edge after applying a servo motor filter. Figures 12a and 12b show the result of such edge modification, with a ground current drop of around 50 times.

For reducing EMI from switched-mode power supplies, DC filters such as the one shown in Figure 13 are often used since they remove high-frequency content from DC supply.

Blocking Propagation of EMI

Filtering of EMI is just like filtering polluted water in which you block contaminants and let clean water pass through. Our readers are likely already familiar with the concept of filtering EMI on wires and cables, even if they never considered a filter. The ubiquitous ferrite clamp (typically a black lump on a computer cable) is, in fact, an EMI filter for cables. From a technical perspective, a ferrite clamp is a current transformer with a shorted secondary that converts high-frequency signals in cables into heat (no, you won't be able to check it by touch – the energy is too low to be noticed this way). And ferrite clamps are inexpensive and easy to implement.

The problem is their limited performance. Most ferrite clamps become effective only at the higher end of the spectrum, above 50MHz or so (a lot of energy

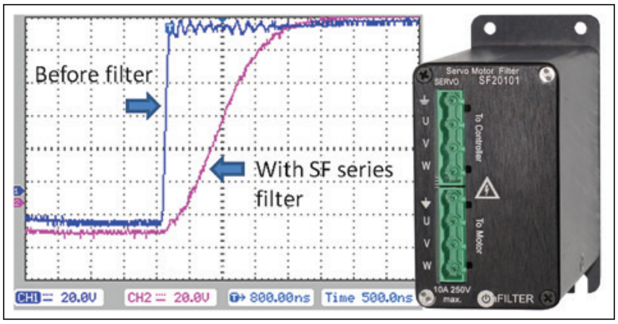

Figure 11: Modified rise time with SF20101 motor filter

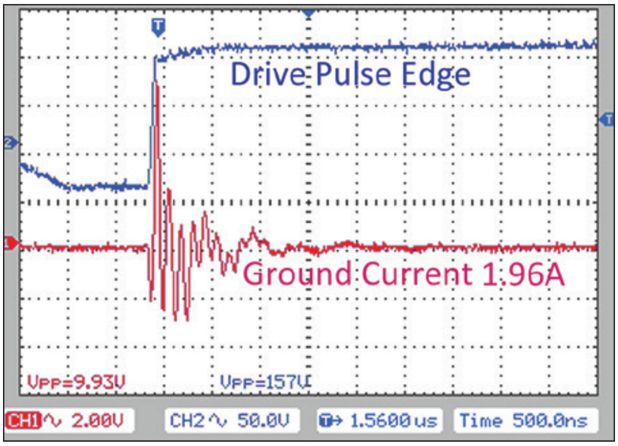

Figure 12a: Ground current without filter

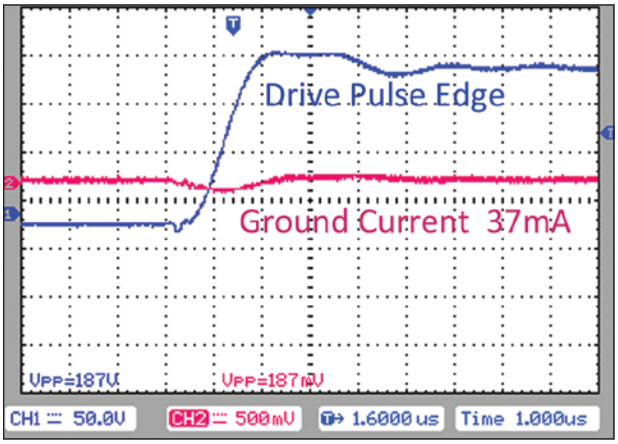

Figure 12b: Ground current with the filter

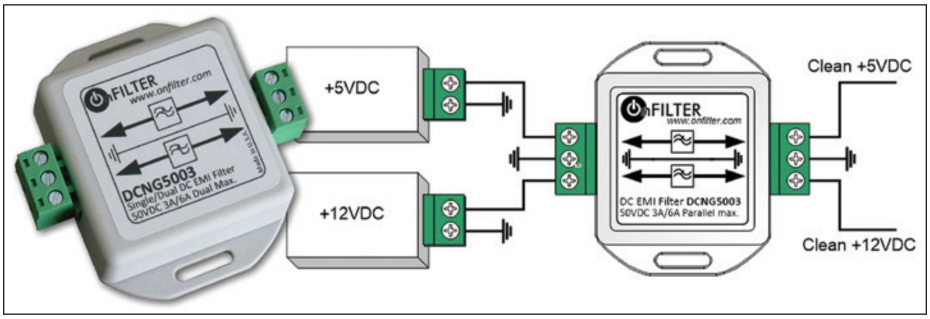

Figure 13: DC filter [23]

of EMI in manufacturing is below 1 MHz), and the attenuation they offer at these frequencies is largely limited to 10dB. A ferrite clamp is often the first way to bring EMI propagation in check. But using a ferrite clamp is not unlike using a band-aid. It will stop minor bleeding and cover a small scratch, but it just won't be sufficient in cases involving more serious injuries.

Ground EMI filters, such as the one shown in Figure 14, offer much better performance by providing substantial attenuation of broadband signals while also providing low impedance for the mains' frequencies (let's not forget that ground is a safety element). One of the applications of a ground filter is shown in Figure 15. It addresses the issue of EMI-caused EOS exposure, as shown in Figure 8. The modification is straightforward and involves an insulative

Figure 14: Ground EMI filter for equipment [25]

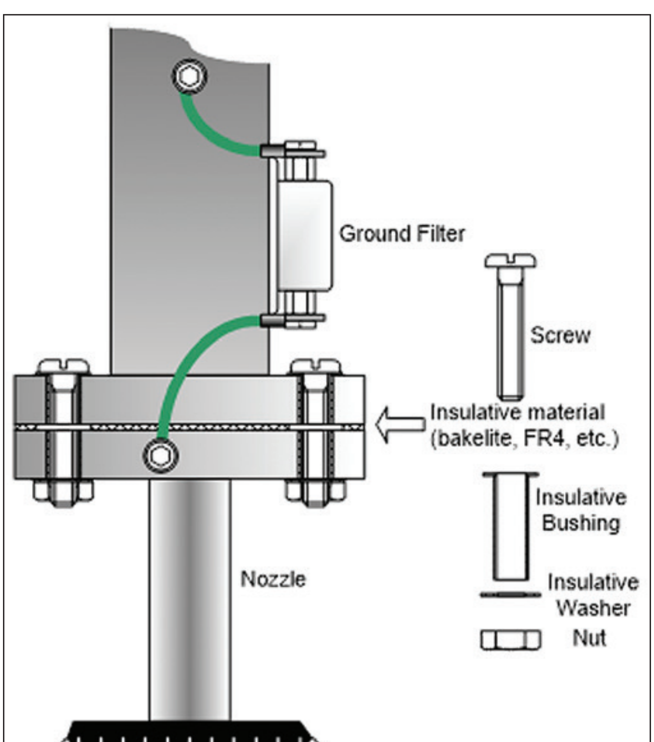

Figure 15: Ground filter on robotic arm blocks EMI on the nozzle

plate made of mechanically hard material, such as FR4, Bakelite, or equivalent, sandwiched between the parts of the robotic arm and the end piece is grounded via the filter of Figure 14. (See [24] for a detailed description of the implementation of such filtering in an IC handler in production).

Figures 16a and 16b show ground current between the robotic arm and the corresponding chassis without and with the filter. Such a ground filter inserted in wires for ESD grounding inside equipment will block the propagation of EMI throughout the tool while complying with all relevant ESD and safety standards. A similar approach with similar results can also be taken at a facility ground level, especially in facilities that employ separate grounding. In such cases, inserting a ground filter every few meters prevents EMI from propagating from noisy tools to the tools that require a low-noise environment.

The key takeaway about ground filters is remembering that grounding is a safety element and that use of ground filters should not influence compliance with relevant ESD standards and practices.

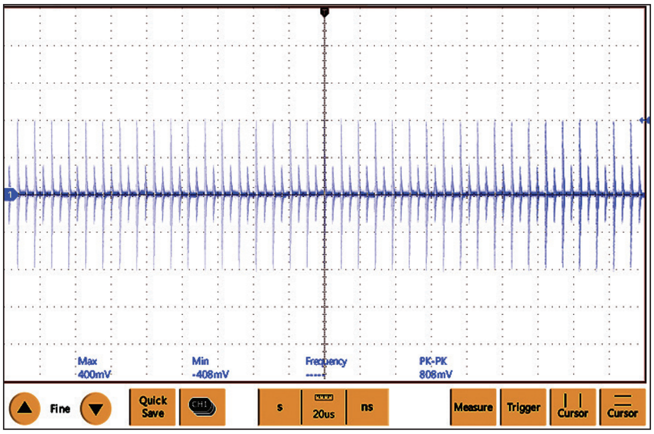

Figure 16a: Ground current without filter

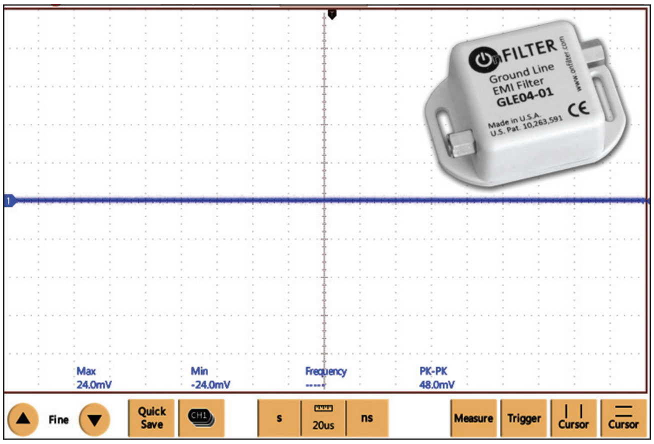

Figure 16b: Ground current with GLE04-01 installed

CONCLUSION

Proper grounding extends beyond just running a green wire. A good grounding can help ensure the uninterrupted operation of your equipment and the integrity of your data, while a bad ground can do just the opposite. Whether you are an electrician, an ESD practitioner, or an EMC engineer, you should consider and address not just the aspect of grounding that aligns with your specialty but all grounding considerations, including safety, ESD, EMI, and data integrity. In most cases, a single standard cannot sufficiently account for all needs in the process. Pay special attention to EMI on ground as it connects all equipment and is a conduit for EMI spread. Comprehensive, quality ground is a solid foundation to help ensure the smooth and efficient running of your processes and equipment.

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Assessing Advanced Driver Assistance Systems (ADAS) in Vehicles

Testing Can Help to Ensure Effectiveness and Safety

BY RALPH BUCKINGHAM

The National Highway Traffic Safety Administration (NHTSA) estimates that 94% of traffic accidents are caused by driver error and the leading cause of these is recognition mistakes.[1] Advanced driver-assistance systems (ADAS) can help decrease accidents, injuries, and fatalities by reducing these errors using electronic technologies. In fact, ADAS is one of the fastest-growing sectors in the automotive industry, with expectations that the ADAS market will see a compound annual growth rate (CAGR) of 11.6% by 2027.[2]

ADAS are designed to increase the safety of vehicles by assisting motorists with driving and parking functions. They use automated technology, such as sensors, cameras, software, lighting, and audio components to detect obstacles and errors, then respond accordingly. ADAS technologies can range from passive to active, alerting drivers to problems, implementing safeguards, and/or taking control of the vehicle.

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Passive systems simply give an alert but require the driver to act. Examples might be systems that make noises or vibrate when an object, such as another vehicle or pedestrian, is sensed in a blind spot or as the car drifts into another lane without a turn signal activated. With the warning, the driver needs to take corrective action. On the other hand, active ADAS not only sense the danger, but also automatically activate the required corrective action, such as emergency braking when an obstruction is sensed.

While the systems today are becoming more sophisticated and widely adopted, the general concept of ADAS is not new. The roots of ADAS go back nearly 70 years to anti-lock braking systems (ABS), and today include blind spot information systems, 360-degree cameras, adaptive cruise control, lane departure warnings, traction control, night vision, adaptive lights, collision warning, parking assistance and more. As technology quickly evolves and the industry increasingly moves toward autonomous vehicles, the possibilities for ADAS seem limitless.

ADAS TESTING IS ESSENTIAL TO OVERALL SAFETY

Yet, as ADAS technology is incorporated into vehicles at such an astonishing pace, it is essential to properly evaluate the systems through testing programs that can provide valuable information in developing the advanced technology.

Testing ADAS systems involves exposing a vehicle to situations that trigger the system to intervene, then measuring the outcome to assess system performance.

An example of this might be using a mannequin to simulate a pedestrian to test whether the ADAS triggers emergency braking or using simulated cars to determine if collision warning or parking assistance systems are functioning as intended. The testing is monitored, and variables are controlled to ensure the consistent, repeatable application of each test method. Additionally, factors such as weather, dirt, or less optimal road conditions (i.e., lane line deterioration or potholes) can be added to the testing to ensure that the ADAS system goes beyond requirements and provides more robust, usable results.

The methods used to assess and evaluate ADAS come from a variety of sources. For example, the Insurance Institute for Highway Safety (IIHS) includes guidance for automatic emergency braking (AEB) and for AEBs and pedestrians. The European New Car Assessment Programme (NCAP) offers guidance on car-to-car AEB, vulnerable road user AEB, lane support systems, and speed assistance systems. In the U.S., the NHTSA has several guidelines in development covering active parking assistance, blind-spot detection and intervention, intersection and opposing traffic safety assistance, pedestrian AEB, rear automatic braking, traffic jam assists, and heavy vehicle forward collisions warning (FCW). While the NHTSA guidelines have not been finalized, manufacturers and their testing partners can use the draft guidance for product development and assessment.

ADAS system testing provides valuable data that can be used for a variety of needs: validation to OEM standards and requirements, benchmarking to establish design baselines, R&D information, and data for ratings from organizations or programs like IIHS or NCAP. These insights can be quite significant for this increasingly used technology. For example, testing during the R&D and validation phase can help to reduce system redesigns and even the number of formal qualification tests required. Benchmark testing can assess the performance of systems being offered by many manufacturers to set performance requirements and goals. And for programs like NCAP or IIHS, preliminary testing can reduce formal testing and speed up compliance and time to market. The testing can vary from basic (monitoring velocity, direction, location, and response) to intermediate (basic with the addition of audio/video recording) to advanced (adds the capture of the vehicle bus messages for a complete understanding of vehicle behavior and intended response).

THE BENEFITS OF MULTIPLE TEST SETTINGS

ADAS testing requires facilities and equipment capable of exposing the vehicle to the scenarios that trigger the engagement of those systems. Assessments can be done in the lab, on the road, and/or on proving grounds. Each setting offers its own benefits and drawbacks, and often a combination of these test locations provides the best results.

Here are some of the benefits of each assessment approach:

- Laboratory testing allows for rigorous testing in a highly controlled environment. Engineers can evaluate products for safety, interoperability, functionality, connectivity, overall performance, and controlled environmental exposure to elements such as ultraviolet (UV) light, dust, water intrusion, and more.
- On-road testing uses real-world conditions (including unexpected and random situations) to subject systems to elements like weather, geography, light, infrastructure, obstacles, human activity, and more. Road tests can assess ADAS over an extended period, providing a realistic view of lifespan and functionality.
- Proving ground analysis evaluates products on the road, in a predictable, safe, controlled, and repeatable setting. This method ensures specific elements are included in the evaluation, such as direct sunlight, weather conditions, tunnels, on-ramps, and other potential obstacles. Testing can be configured to duplicate real-world environments and applications, depending on the design and capability of the proving ground.

A thorough test plan will integrate testing in multiple environments to provide robust, comprehensive data and actionable results. Some equipment and components will require lab assessments for items such as electrical safety, electromagnetic compatibility (EMC), performance, and other considerations. These same pieces of equipment and the overall system can then be sent to the proving ground for realistic, on-road assessments to see how they perform in action. Additional lab testing may then be required to help assess how the equipment has responded to those scenarios. For example, it may illustrate whether on-road usage impacts electrical safety or overall system functionality.

ADAS TESTING EQUIPMENT REQUIREMENTS

The equipment used to evaluate ADAS can vary both in type and number of testing systems and devices needed. For example, assessing how ADAS functions in a traffic jam will be more complex than assessing how it interacts with a pedestrian. More components will be needed to simulate the traffic jam, thus more equipment is used and more data collected. ADAS assessments will commonly include the use of several types of equipment, as follows:

- *Inertial measurement systems capable of real-time kinematics, or RTK:* These are used to assess things like speed, position, force, angular rate, and orientation. Because data needs to be pulled as the car is in motion and as systems are reacting, real-time kinematics are important for accuracy.
- *Guided soft targets:* Used to simulate other cars, guided soft targets are self-propelled platforms and aerodynamically stable. However, because they are soft targets, when they come into contact with a vehicle, they will break apart and not cause damage to the test car and on-board systems.
- *Other soft targets:* Used to simulate people (both adults and children) who are moving or static, as well as bicycles and other obstacles. They replicate the size, shape, and, when needed, the motion of the object to assist in evaluating the response to encountering these objects.
- *Driving robots:* Driving robots, such as steering robots, pedal robots, provide repeatable, accurate control of the vehicle and use RTK for speed and position corrections for accurate path following. The use of robots versus humans allows for multiple evaluations with less variability to factors like speed, control, path, angles, and impact.
- *Controller Area Network (CAN) decoding/recording equipment:* CAN equipment allows for communication, data gathering, and recording without a host computer. Commonly used for in-vehicle communications since the 1980s, it provides low-cost, lightweight networks for the communication of data and information.
- *Additional rear-vehicle targets:* Simulates items such as buildings, lighting, signs, and other obstacles a car may encounter in reverse.
- *Various road and intersection types:* Used to assess systems such as AEB, blind-spot detection, and testing for intersections and traffic jams. These include different surfaces and speeds to ensure more comprehensive data.
- *Different test environments:* Varying environments, such as parking lots, highways, traffic jams, cities, rural roads, and more, are important to assess various systems such as AEB, parking assistance, lane keep/centering, customized tests, and more.

A COMPREHENSIVE TEST PLAN IS ESSENTIAL

Given the variety of test settings and equipment that can be used, it is important to establish a comprehensive test plan before evaluations begin. Start the process with the end goal in mind: Why are you testing? What information do you need? Then proceed to identify the best way to get the information needed. This will determine where the testing needs to be done, when, what equipment and environmental conditions are required, what data is needed, and how the data will be collected and, ultimately, analyzed. Once a test plan is in place, the ADAS evaluation can begin.

ADAS testing begins with preliminary set up and practice days, which can be beneficial for reducing downtime and completing the tests in a time-efficient manner. At this stage, engineers can map test surfaces and create different routes to ensure that the necessary test environments, lane configurations, and test targets are accounted for.

This preliminary phase can also include other recommendations to ensure time-effective testing. This might include planning and scheduling remote software resources for immediate updates, pre-testing software subroutines, and ensuring maintenance tools and lifts are available to fix any mechanical issues. Validating test system set up, confirming test equipment like RTK systems function properly, and making sure proper technical support is on hand to troubleshoot any challenges is always a high priority to limit downtime once testing begins.

After this preliminary stage, testing can be completed. It may take a few days to gather all the necessary data, especially if the test plan includes a combination of lab evaluations and on-road/proving ground analysis. Test set up and completion could also take time, especially as simulations are conducted. As with any testing, it is important to be prepared for the reality that test runs, data collection, compilation, and analysis can be a lengthy process. In the end, though, the information provided is invaluable in ensuring the quality, performance, and safety of ADAS and the vehicles where they are present.

CONCLUSION

As the automotive industry seeks to find better ways to help ensure the safety of drivers, pedestrians, property, and vehicles, ADAS offers the technology and ability to reduce driver error and, as such, accidents. They also provide consumers with the benefits of convenience and safety. As the technology and use of these systems continue to advance at a high rate, ensuring their functionality and safety is critical. It is important to know the requirements in place for these systems, as well as the supplemental assessments that apply to ADAS.

Knowing what information is needed and how to find it, then partnering with experienced, knowledgeable engineers to prepare and execute a test plan, can help provide valuable information for R&D, benchmarking, marketing, regulatory purposes, and more. Safer ADAS can mean safer vehicles and safer transportation for everyone.

ENDNOTES

1. National Highway Traffic Safety Administration, Traffic Safety Facts, https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812115.
2. Globe Newswire, May 6, 2021, "Advanced Driver Assistance System (ADAS) Market Size Worth Around US$ 142 bn by 2027," https://www.globenewswire.com/en/news-release/2021/05/06/2225177/0/en/Advanced-Driver-Assistance-System-ADAS-Market-Size-Worth-Around-US-142-bn-by-2027.html.

MIL-STD-464D: A Review of Recent Changes

A Long-Awaited Update to an Essential Standard for Military Procurement

BY KEN JAVOR

MIL-STD-464D was released on December 24, 2020. This revision is in keeping with the routine five-year revision cycle applicable to many such standards, and MIL-STD-464 must keep in sync with MIL-HDBK-235, from which the electromagnetic field intensity tables are drawn. In this case, the routine five-year cycle took ten years to complete.

MIL-STD-464 is the U.S. Department of Defense (DoD) top-level E3 requirement set for the procurement of complete or modified systems. In this context, systems means an integrated platform of one type or another, such as a ground or air vehicle, a ship or submarine, a spacecraft, or launch vehicle. Note that some systems can be parts of other systems, such as an F-18 fighter aircraft that operates from an aircraft carrier.

The original release of MIL-STD-464 was in 1997. MIL-STD-464A (2002) and MIL-STD-464C (2010) provided minor, evolutionary changes to the original release.[1]

1. MIL-STD-464C is really MIL-STD-464B, but there was a release cycle error, and MIL-STD-464B was replaced after just a few months. The content didn't change.

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Compared to MIL-STD-464C, the changes in MIL-STD-464D are very minor. This article serves as a laundry list of the substantive changes, including the EME tables, and indications of what values changed in the EME tables, so that the reader may see at a glance where the changes are, rather than checking each table row-by-row and cell-by-cell.

The purpose of this article is to inform and save the reader the time the author spent combing through MIL-STD-464D vs. MIL-STD-464C (referenced as D and C throughout the rest of this article). Entertaining the reader was not a practical goal.

NEW DEFINITIONS

3.1 All-up-round (AUR)

"The completely assembled munition as intended for delivery to a target or configured to accomplish its intended mission. This term is identical to the term all-up-weapon."

3.2 Bare devices

"Bare electrically initiated devices (EIDs) such as electrical initiators, exploding foil initiators, detonators, etc., in an all-up round that have either one or both pins accessible on an external connector."

3.3 Below deck

Extended to include the pressure hull of a submarine.

3.7 Energetics

"A substance or mixture of substances that, through chemical reaction, is capable of rapidly releasing energy. A few examples of energetics are: liquid and solid propellants such as in rockets and air bags, gun propellants, polymer bonded explosives (PBX) for warheads, pyrotechnics for flares and ignition systems."

3.8 Flight deck

"The upper deck of an aircraft carrier that serves as a runway. The deck of an air-capable ship, amphibious aviation assault ship, or aviation ship used to launch and recover aircraft."

3.12 Helicopter-borne electrostatic discharge (HESD)

"The sudden flow of electric charge between a helicopter or rotary winged aircraft and an object of different electrical potential. A buildup of static electricity can be caused by triboelectric charging or electrostatic induction generated from operating rotary wings."

3.13 High power microwave (HPM)

Deletes the frequency range.

3.18 Maximum no-fire stimulus

MIL-STD-464D	MIL-STD-464C
"The greatest firing stimulus that will not cause initiation or degrade an EID of more than 0.1 % of all electric initiators of a given design at a confidence level of 95%. Stimulus refers to electrical parameters such as current, rate of change of current (di/dt), power, voltage, or energy, which are most critical in defining the no-fire performance of the EID."	*"The greatest firing stimulus which does not cause initiation within five minutes of more than 0.1% of all electric initiators of a given design at a confidence level of 95%. When determining maximum no-fire stimulus for electric initiators with a delay element or with a response time of more than five minutes, the firing stimulus will be applied for the time normally required for actuation."*

3.22 Ordnance (fewer words than C)

"Explosives, chemicals, pyrotechnics, and similar stores (e.g., bombs, guns, and ammunition, flares, smoke, or napalm)."

3.23 Personnel-borne electrostatic discharge (PESD)

"The sudden flow of electric charge between personnel and an object of different electrical potential. A buildup of static electricity can be caused by triboelectric charging or electrostatic induction generated by the movement of the person's body."

3.27 Spectrum-dependent systems

Adds this statement at the end:

"This includes transmitters, transceivers, and receive-only systems."

3.34 Vertical replenishment (VERTREP)

"The transfer of ordnance and cargo using rotary winged aircraft."

3.35 Weather deck

"The topside of the ship that is exposed to the weather. The weather deck does not include the flight deck, hangar, well deck, man-aloft areas, or the ship's mast."

MAIN BODY REQUIREMENTS

5.1 Margins (MIL-STD-464D)[2]

"Margins shall be established for safety and mission critical subsystems/equipment within the system. Margins shall be no less than 6 dB for safety critical subsystems/equipment, unless otherwise stated in the detailed requirements of this standard. Compliance shall be verified by test, analysis, or a combination thereof."

Compare this with the text in C, as follows:

"Margins shall be provided based on system operational performance requirements, tolerances in system hardware, and uncertainties involved in verification of system-level design requirements. Safety critical and mission critical system functions shall have a margin of at least 6 dB. EIDs shall have a margin of at least 16.5 dB of maximum no-fire stimulus (MNFS) for safety assurances and 6 dB of MNFS for other applications. Compliance shall be verified by test, analysis, or a combination thereof. Instrumentation installed in system components during testing for margins shall capture the maximum system response and shall not adversely affect the normal response characteristics of the component. When environment simulations below specified levels are used, instrumentation responses may be extrapolated to the full environment for components with linear responses (such as hot bridgewire EIDs).

When the response is below instrumentation sensitivity, the instrumentation sensitivity shall be used as the basis for extrapolation. For components with non-linear responses (such as semiconductor bridge EIDs), no extrapolation is permitted."

2. Author's note: The significant truncation is due to moving ordnance-related margins to their own separate section. The ordnance margins haven't changed – this just represents a reorganization of the standard.

5.2 Intra-system electromagnetic compatibility (EMC)

MIL-STD-464D	MIL-STD-464C
"The system shall be electromagnetically compatible within itself such that system operational performance requirements are met. Compliance shall be verified by system-level test, analysis, or a combination thereof. This includes permanent, temporary, and portable electronic equipment."	*"The system shall be electromagnetically compatible within itself such that system operational performance requirements are met. Compliance shall be verified by system-level test, analysis, or a combination thereof. For surface ships, MIL-STD-1605(SH) provides test methods used to verify compliance with the requirements of this standard for intra- and inter-system EMC, hull generated intermodulation interference, and electrical bonding."*

5.2.2 Shipboard internal electromagnetic environment (EME)

The very last sentence in C section 5.2.2.b after the listing of the individual device and total EIRP is not found in D. This sentence in C that is not in D reads:

> *"Additionally, no device shall be permanently installed within 1 meter of safety or mission critical electronic equipment."*

Also, whereas verification in C is by test in all cases, in D, for submarines an analysis consisting of a summation of all individual device EIRP into total radiated power (TRP) is allowed.

(See Tables I – VI, pages 80, 81, and 82)

5.5 Lightning

Has some expanded wording about near strikes and slightly different wording describing Figure 2 and Table VII.

5.7 Subsystems and equipment electromagnetic interference (EMI)

Now includes new wording (in non-italicized text in the excerpt that follows):

"Individual subsystems and equipment shall meet interference control requirements (such as the conducted emissions, radiated emissions, conducted susceptibility, and radiated susceptibility requirements of MIL-STD-461) so that the overall system complies with all applicable requirements of this standard. This includes permanent, temporary, and portable electronic equipment. *Compliance shall be verified by tests that are consistent with the individual requirement (such as testing in accordance with MIL-STD-461)."*

Frequency Range		Shipboard Flight Decks		Shipboard Weather Decks	
		Electric Field (V/m-rms)		Electric Field (V/m-rms)	
(MHz)	(MHz)	Peak	Avg	Peak	Avg
0.01	2	*	*	*	*
2	30	164	164	189/169	189/169
30	150	61	61	61	61
150	225	61	61	61	61
225	400	61	61	61	61
400	700	196	71	445	71
700	790	94	94	94	94
790	1000	491/246	100	744/1307	141/244
1000	2000	212	112	212/112	112
2000	2700	159	159	159	159
2700	3600	4700/2027	595/200	4700/897	595/200
3600	4000	1225/298	200	1859	200
4000	5400	200	200	200	200
5400	5900	361	213	711	235
5900	6000	213	213	235	235
6000	7900	213	213	235	235
7900	8000	200	200	200	200
8000	8400	200	200	200	200
8400	8500	200	200	200	200
8500	11000	913/200	200	913	200
11000	14000	745/744	200	833	200
14000	18000	745/744	200	833	200
18000	50000	200	200	267	200

TABLE I: Maximum external EME for deck operations on Navy ships vs. -464C Table 1. Maximum external EME for deck operations on Navy ships

Frequency Range (MHz)		Main Beam (distances vary with ship class and antenna configuration)	
		Electric Field (V/m –rms)	
		Peak	Avg
0.01	2	*	*
2	30	200	200
30	150	15/10	15/10
150	225	17/10	17/10
225	400	43	43
400	700	2036	268
700	790	20/10	20/10
790	1000	2615/2528	489/485
1000	2000	930	156
2000	2700	21/10	21/10
2700	3600	27460	7500/2620
3600	4000	8553	272
4000	5400	1357/139	198/139
5400	5900	3234	637/267
5900	6000	637/267	637/267
6000	7900	667/400	667/400
7900	8000	667/400	667/400
8000	8400	449/400	449/400
8400	8500	400	400
8500	11000	6900/4173	6900/907
11000	14000	3329	642
14000	18000	3329/3529	642/680
18000	50000	2862	576

‡ The EME levels in the table apply to shipboard operations in the main beam of systems in the 2700 to 3600 MHz frequency range on surface combatants. For all other operations, the unrestricted peak EME level is 12667 V/m and the unrestricted average level is 1533 V/m.

TABLE II: Maximum external EME for ship operations in the main beam of transmitters vs. -464C TABLE 2. External EME for shipboard operations in the main beam of transmitters

-464D values first, -464C values second, where different. Red fill means level has increased. Yellow fill means change is less than 3 dB, either higher or lower, and blue fill means -464D level is lower than for -464C. * means no emitters in that frequency range.

5.7.1 Portable electronic devices and carry-on equipment requirements

Newly added in D, as follows:

> *"Portable electronic devices and carry-on equipment containing electronics which are not permanently installed or integrated into platforms and require airworthiness certification shall meet, as a minimum, the following EMI interface control requirements:*
>
> - *Safety Critical: All platform emissions and susceptibility requirements (such as those defined in MIL-STD-461) that are defined for safety critical equipment.*
> - *Non-Safety Critical: All platform emissions requirements (such as those defined in MIL-STD-461).*
>
> *"If any part of the portable electronic device/carry-on equipment contains radio frequency transmission capability, then transmitter emissions characteristics shall be measured (such as in MIL-STD-461 Test Method CE106), in addition to the applicable requirements stated above. An aircraft EMC evaluation per 5.2 shall also be required to demonstrate platform compatibility of the portable electronic devices/carry-on equipment which have radio frequency transmitting capability.*
>
> *"If any part of the portable electronic device/carry-on equipment contains ordnance or is integrated into an ordnance system, then the HERO requirements stated within this standard shall also be met. Compliance shall be verified by test per the applicable requirements."*

Frequency Range (MHz)		Electric Field (V/m-rms)	
		Peak	Avg
0.01	2	1	1
2	30	73	73
30	150	17	17
150	225	4	1
225	400	*	*
400	700	47	6
700	790	1	1
790	1000	7	7
1000	2000	63	63
2000	2700	187	187
2700	3600	23	8
3600	4000	2	2
4000	5400	3	3
5400	5900	164	164
5900	6000	164	164
6000	7900	6	6
7900	8000	3	1
8000	8400	1	1
8400	8500	3	1
8500	11000	140	116
11000	14000	114	114
14000	18000	16	9
18000	50000	23	23

NOTE: *denotes no emitters in that frequency range.

TABLE III: Maximum external EME for space and launch vehicle systems vs. -464C TABLE 3. External EME for space and launch vehicle systems

Frequency Range (MHz)		Electric Field (V/m-rms)	
		Peak	Avg
0.01	2	54/73	54/73
2	30	103	103
30	150	74	74
150	225	41	41
225	400	92	92
400	700	98	98
700	790	58/267	58/267
790	1000	58/284	58/267
1000	2000	232/2452	94/155
2000	2700	638/489	42/155
2700	3600	1148/2450	219
3600	4000	320/489	25/49
4000	5400	645	173/183
5400	5900	5183/6146	129/155
5900	6000	40/549	40/55
6000	7900	3190/4081	292/119
7900	8000	2471/549	296/97
8000	8400	2471/1095	296/110
8400	8500	82/1095	82/110
8500	11000	810/1943	139
11000	14000	3454	102/110
14000	18000	7897/8671	243
18000	50000	2793	48/76

TABLE IV Maximum external EME for ground systems vs. -464c TABLE 4. External EME for ground systems

-464D values first, -464C values second, where different. Red fill means level has increased. Yellow fill means change is less than 3 dB, either higher or lower, and blue fill means -464D level is lower than for -464C. * means no emitters in that frequency range.

5.7.3 Shipboard DC magnetic field environment. (5.7.2 in C)

In the C revision, this requirement could only be verified by test. In the D revision, the ubiquitous phrase, "Compliance shall be verified by test, analysis, or a combination thereof," is used.

5.8.1 Vertical lift and in-flight refueling

Slightly reworded, but the same overall requirement with one significant deletion. The C applicability to "any man portable items that are carried internal to the aircraft" has been deleted.

5.8.3 Ordnance subsystems

Rewritten with two brand new sub-paragraphs that break out separately the pre-existing C requirement to withstand a 25 kV personnel ESD and adds a separate new requirement to withstand helicopter ESD (300 kV).

5.8.4 Electrical and electronic subsystems

Rewritten to refer to MIL-STD-461G (CS118) for test, whereas previously they had to point elsewhere.

Frequency Range (MHz)		Electric Field (V/m – rms)	
		Peak	Avg
0.01	2	200	200
2	30	200	200
30	150	200	200
150	225	200	200
225	400	200	200
400	700	1311	402
700	790	700	183/402
790	1000	700	215/402
1000	2000	6057	232
2000	2700	3351	200
2700	3600	4220	455
3600	4000	3351	657/200
4000	5400	9179	657
5400	5900	9179	657
5900	6000	9179	200
6000	7900	400	200
7900	8000	400	200
8000	8400	7430	266
8400	8500	7430	266
8500	11000	7430	266
11000	14000	7430	558
14000	18000	730	558
18000	50000	1008	200

TABLE V: Maximum external EME for rotary-wing aircraft, excluding shipboard operations vs. -464C Maximum external EME for rotary-wing aircraft, including UAVs, excluding shipboard operations

Frequency Range (MHz)		Electric Field (V/m-rms)	
		Peak	Avg
0.01	2	88	27
2	30	64	64
30	150	67	13
150	225	67	36
225	400	58	3
400	700	2143	159
700	790	554/80	81/80
790	1000	289	105
1000	2000	3363	420
2000	2700	957	209
2700	3600	4220	455
3600	4000	148	11
4000	5400	3551	657
5400	5900	3551	657
5900	6000	148	4
6000	7900	344	14
7900	8000	148	4
8000	8400	187	70
8400	8500	187	70
8500	11000	6299	238
11000	14000	2211	94
14000	18000	1796	655
18000	50000	533	38

TABLE VI: Maximum external EME for fixed-wing aircraft, excluding shipboard operations vs. -464C TABLE 6. External EME for fixed wing aircraft, including UAVs, excluding shipboard operations

-464D values first, -464C values second, where different. Red fill means level has increased. Yellow fill means change is less than 3 dB, either higher or lower, and blue fill means -464D level is lower than for -464C. * means no emitters in that frequency range.

5.9.3 Hazards of electromagnetic radiation to ordnance (HERO)

Rewritten to include ordnance safety margins that were struck from general margin paragraph 5.1.

5.14.2 Platform radiated emissions

Renamed from the same paragraph in C labeled *5.14.2 Inter-system EMC*. The requirement has both greater generality and is more specific about what parameters need to be controlled. New sub-paragraph in D.

6.2 Acquisition requirements

Acquisition documents should specify the following: a. Title, number, and date of this standard.

6.3 DIDs

Not updated.

6.5 Key Words

Adds two new terms, electrostatic and HESD.

6.6 International standardization agreement implementation.

Rewritten slightly in D from the previous similar section 6.5 in C.

6.7 Acronyms

Replaces EMRADHAZ with RADHAZ. Also, PESD and HESD are added.

6.8 Technical points of contact

Air Force and Army points-of-contact have been updated.

APPENDICES AND GUIDANCES

A.1.1 Scope

Includes extra language emphasizing that appendix is guidance only, not mandatory.

A.2.1.1 Specifications, standards, and handbooks

Slightly different wording. Also, the following additions, changes, and deletions:

- MIL-STD-1576, Electroexplosive Subsystem Safety Requirements and Test Methods for Space Systems—removed from applicable documents
- MIL-STD-3023 HEMP Protection for Military Aircraft—added
- MIL-STD-4023 HEMP Protection for Maritime Assets—added
- MIL-HDBK-83578 Criteria for Explosive Systems and Devices Used on Space Vehicles—deleted

Frequency Range		Field Intensity (V/m – rms)			
		Unrestricted*		Restricted **	
(MHz)	(MHz)	Peak	Avg	Peak	Avg
0.01	2	200	200	80	80
2	30	200	200	100	100
30	150	200	200	80	80
150	225	200	200	70	70
225	400	200	200	100	100
400	700	2200	410	450	100
700	790	700	190	270	270
790	1000	2600	490	1400	270
1000	2000	6100	420	2500	160
2000	2700	6000	500	490	160
2700	3600	27460	5350/2620	2500	220
3600	4000	8600	280	1900	200
4000	5400	9200	660	650	200
5400	5900	9200	660	6200	240
5900	6000	9200	640/270	550	240
6000	7900	3190/4100	670/400	3190/4100	240
7900	8000	2500/550	670/400	550	240/200
8000	8400	7500	450/400	1100	200
8400	8500	7500	400	1100	200
8500	11000	7500	3450/910	2000	300
11000	14000	7500	650/680	3500	220
14000	18000	7900/8700	650/680	7900/8700	250
18000	50000	2900	580	2800	200

NOTES:

*It must be noted that on certain naval platforms, there are radar systems (and unique modes of operation) that may produce fields in excess of those in Table IX, and MIL-HDBK-235 must be consulted to identify specific EME test requirements.

** In some of the frequency ranges for the "Restricted Average" column, limiting the exposure of personnel through time averaging will be required to meet the requirements of 5.9.1 for personnel safety.

TABLE IX: Maximum external EME levels for ordnance vs. -464C TABLE 9. Maximum external EME levels for ordnance.

-464D values first, -464C values second, where different. Red fill means level has increased. Yellow fill means change is less than 3 dB, either higher or lower, and blue fill means -464D level is lower than for -464C. * means no emitters in that frequency range.

A.2.1.2 Other Government documents, drawings, and publications

- Army, ATPD-2407 Electromagnetic Environmental Effects (E3) for U.S. Army Tank and Automotive Vehicle Systems Tailored from MIL-STD-464C—added
- TOP 01-2-511A US Army Test and Evaluation Command Test Operations Procedure—added

A.2.2 Non-Government Publications

- Institute of Electrical and Electronics (IEEE) Transactions on Electromagnetic Compatibility
- DOI:10.1109/TEMC.2016.2575842 Effect of Human Activities and Environmental Conditions on Electrostatic Charging—added
- Franklin Applied Physics
- F-C2560 RF Evaluation of the Single Bridgewire Apollo Standard Initiator—deleted

A.3 Acronyms

- AMITS air management information tracking system—deleted
- EMRADHAZ—deleted
- HESD helicopter-borne electrostatic discharge—added
- PESD personnel-borne electrostatic discharge—added
- RADHAZ Radiation hazards—added

A.4.1 Requirement Guidance

Adds Army ATPD-2407 and TOP 01-2-511A is EMC guidance and test procedures.

A.4.1.e Requirement Guidance

Includes additional guidance and a slightly different approach than C. Margin Requirement Guidance A.5.1 adds the non-italicized statement in the following excerpt:

> *"Margins need to be viewed from the proper perspective. The use of margins simply recognizes that there is variability in manufacturing and that requirement verification has uncertainties. The margin ensures that every produced system will meet requirements, not just the particular one undergoing a selected verification technique. Smaller margins are appropriate for situations where production processes are under tighter controls or more accurate and thorough verification techniques are used. Smaller margins are also appropriate if many production systems undergo the same verification process, since the production variability issue is being addressed. Margins are not an increase in the basic defined levels for the various electromagnetic environments. The most common technique is to verify that electromagnetic and electrical stresses induced internal to the system by external environments are below equipment strength by at least the margin.* This approach is similar to the test methodology described in A.4.1 (e). *While margins can sometimes be demonstrated by performing verification at a level in excess of the defined requirement, the intent of the margin is not to increase the requirement."*

This paragraph is deleted from this section in D (look for it in the EID section):

> *"MNFS values for EIDs are normally specified by manufacturers in terms such as DC currents or energy. Margins are often demonstrated by observing an effect during the application of an electromagnetic environment that is the same effect observed when applying a stimulus level in the form under which the MNFS is defined. For example, the temperature rise of a bridgewire can be monitored in the presence of an EME relative to the temperature rise produced by a DC current level that is 16.5 dB below MNFS. The space community has elected to use MNFS levels determined using RF rather than DC. This approach is based on Franklin Institute studies, such as report F-C2560. Outside of the space community, the use of DC levels has provided successful results."*

A.5.2 Intra-system EMC

Under *Requirements Rationale***,** the final sentence in C:

> *"To ensure EMC is achieved in Navy ships, a MIL-STD-1605(SH) survey should be performed."*

is replaced by a more descriptive version in D:

> *"For surface ships, MIL-STD-1605(SH) provides test methods used to verify compliance with the requirements of this standard for intra- and inter-system EMC, hull generated intermodulation interference, and electrical bonding."*

A.5.2 Verification Guidance

The following and final line item is modified in D to read:

> *"For portable electronic devices and carry-on equipment, EMI requirements are defined in 5.7.1."*

In C, line item h reads:

> *"TABLE A- 1 identifies what kind of EMI/EMC testing is required when new, modified, or carry-on equipment will be used on military aircraft."*

Table A-1 Type of EMI/EMC testing doesn't exist in D.

A.5.3 Requirement Guidance

These words added to the very end of this section:

> *"A platform design, while descriptively fitting the title of an external EME table (e.g., Fixed Wing or Rotary Wing), may not coincide with the platform's operational EME definition. Strict attention must be paid to the assumptions used in deriving the tables to ensure appropriate EMC compliance."*

A.5.4 Requirement Guidance (HPM)

Eliminates Tables A-4 – A-10 from C and also calculation of some example problems using these tables.

A.5.4 Requirement Rationale (HPM)

Eliminates some wording questioning the effectiveness of HPM.

A.5.4 Verification Guidance (HPM)

Eliminates reference to these deleted examples in D.

A.5.6 Requirement Guidance (EMP)

Contains some extra description of HEMP composite environment. It also adds descriptions of EMP-related military standards for dealing with EMP, including effects on spacecraft.

A.5.6 Requirement Lessons Learned

Has this sentence in common with C:

> *"Hardening against ground-burst nuclear radiation environments is often not cost effective because a burst near enough to produce a radiation and electromagnetic threat is also close enough for the blast to disable the facility."*

But D adds this last sentence not in C:

> *"Buried facilities such as ICBM launch sites are an exception."*

A.5.6 Verification Rationale (EMP)

D replaces this C paragraph:

> *"For many systems, the cost of EMP verification is a major driver. Therefore, the procuring activity should decide what level of verification is consistent with the risk that they are willing to take."*

with this paragraph:

> *"High-altitude EMP protection standards have been developed for fixed ground-based facilities, transportable ground-based systems, aircraft and ships. Each of these standards contains detailed verification testing protocols and pass/fail criteria. Use of these standards is mandatory for DoD military system procurements that have a HEMP requirement."*

Note the emphasis on the cost of EMP design has been replaced with wording more conducive to getting EMP designs installed.

In the same section, this new D wording:

> *"MIL-STD-3023 and MIL-STD-4023 for HEMP protection of military aircraft and ships, respectively provide a similar verification test approach except that these standards require illuminating the aircraft and ships with a simulated plane wave HEMP threat environment and measuring the induced stresses at each MCS equipment interface. Each MCS must be tested to MIL-STD-461 CS116 to establish its immunity before being installed into the platform. A user selectable margin is then applied to the measured current stress which is then pulse current injected (PCI) at the same interface used in the MIL-STD-461 CS116 testing. This enables direct stress to immunity comparisons at common interfaces for each mission critical equipment throughout the system. Monitoring for upset and damage is also performed at this time."*

has been appended to this existing C wording:

> *"MIL-STD-188-125-1 and MIL-STD-188-125-2 contain verification test methods for demonstrating that C^4I fixed ground-based facilities and transportable ground-based systems meet HEMP requirements. The test methods describe coupling of threat-relatable transients using pulse current injection to penetrating conductors at injection points outside of the facility shield."*

A.5.7 Requirement Guidance (Subsystem & Equipment EMI)

Eliminates wording about DO-160 section 22 now that CS117 is available.

A.5.7.1 Portable Electronic Devices and Carry-On Equipment Requirements

All new appendix material. Basically refers to A.5.2. Intra-system EMC.

A.5.8.1 Vertical lift and in-flight refueling

Slightly rewritten, no changes.

A.5.8.3 Ordnance Subsystems

Greatly expanded and also includes the following new sections:

- A.5.8.3.1 Personnel-borne ESD (PESD) for ordnance and ordnance systems

- A.5.8.3.2 Helicopter-borne ESD (HESD) for ordnance and ordnance systems

A.5.9.3 Requirement Rationale (Ordnance RADHAZ (HERO)).

This section is rewritten with substantive changes.

A.5.9.3 Requirement Guidance (Ordnance RADHAZ (HERO))

This section is rewritten with substantive changes. MIL-STD-464C was:

> *"OD 30393 provides design principles and practices for controlling electromagnetic hazards to ordnance. MIL-STD-1576 and MIL-HDBK-83578 (USAF) provide guidance on the use of ordnance devices in space and launch vehicles. For space applications using ordnance devices, an analysis of margins based on the RF threshold determination of the MNFS should be performed."*

The last sentence refers to measuring the rf TOS of bridgewires, and that has been completely debunked. This section now reads:

> *"NASA document TP2361 provides design guidelines for space and launch vehicle charging issues. Subsystems and equipment installed aboard space systems should be able to meet operational performance requirements during and/or after being subjected to representative discharges simulating those due to spacecraft charging."*

A.5.14.2 Requirement Rationale (Platform Radiated Emission)

Rewritten with added information.

A.5.15 Requirement Guidance (EM Spectrum Compatibility)

Completely rewritten.

A.5.15 Verification Rationale (EM Spectrum Compatibility)

Completely rewritten.

A.5.15 Verification Guidance (EM Spectrum Compatibility)

Added information.

Application of Thrifty Test Equipment for EMC Testing

Low-Cost Instruments and Procedures to Troubleshoot EMC Issues

BY ARNOLD NIELSEN

Issues related to electromagnetic compatibility (EMC) are often identified during qualification testing in an accredited EMC test lab which typically occurs late in the product design cycle. Obtaining a cost-effective solution to these EMC issues may be time-consuming, and many EMC labs can be fully booked or have limited availability, have long lead times, or involve significant costs. But inexpensive test equipment and procedures (let's call them thrifty methods) used for helping to solve these EMC issues outside an EMC lab are very desirable, especially if no in-house EMC facilities are readily available.

Figure 1: Vector network analyzer

There are several excellent resources for troubleshooting methods and building a low-cost EMC toolkit.[1] This article offers some other test equipment options that have different capabilities and which can

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be even less costly. Although the thrifty method is mainly used to compare results before and after implementing a fix (not meeting a specification limit), with some experience, it can also be used in the pre-qualification development stage early in the design cycle to identify potential issues before formal lab testing. Identifying issues early allows maximum flexibility to experiment and provides sufficient time to make cost-effective changes before a design is frozen and difficult to change.

THRIFTY TEST EQUIPMENT

Vector Network Analyzer

One of the low-cost instruments discussed in this article is a vector network analyzer (VNA). Figure 1 shows an example of such an instrument (the NanoVNA[2]). Even though this VNA typically costs less than $150, it is useful from 50 kHz to 3 GHz and comes with cables and calibration terminations. It can be used as a standalone unit via touchscreen, but it is best used with free software QT and Saver. Although this VNA has a lot of capability, I used it for input impedance (S11) and VSWR measurements in the testing on which this article is based.

Software Defined Radio

Figure 2 shows another low-cost instrument, a software defined radio (the SDRplay[3]). Also, typically less than $150, most SDRs also offer lots of capabilities. For the purposes of this article, we'll use the SDR as a spectrum analyzer with the addition of another free software program (Spectrum Analyzer 1.1). While this software may have limitations, such as only fixed frequency spans, it can still be very effective.

Figure 2: Software defined radio

RF Signal Amplifier

A radio frequency (RF) signal amplifier is required for radiated emissions measurements. Figure 3 shows one low-cost example. This particular unit uses a monolithic microwave integrated circuit (MMIC) amplifier and is useful from 50 kHz to at least 2 GHz, Gain = 20-30 dB, and only costs about $30. For a device under test (DUT) with very low emission limits, two amplifiers in series may be required.

RF Power Amplifier

For radiated immunity (e.g., in this article, bulk current injection, or BCI), an RF power amplifier is required. Figure 4 shows one example (NWDZ-RF-PA) that covers 2 - 700 MHz and is about $25. This particular unit uses a SBA5089Z amplifier IC and RD01MUS1 MOS FET. However, the MOS FET overheats which, can be corrected by changing the bias on its gate (R6 changed from 5k ohms to 3.3k ohms).

RF Signal Generator

Another tool in our thrifty set is an RF signal generator. The example shown in Figure 5 (TinySA[4]) has an amazing set of capabilities and only costs about $85. Although its main function is that of a spectrum analyzer, we'll use it in testing described in this article as an RF signal generator. The unit has two outputs. The high output is a square wave, which covers 240 - 960 MHz, and the low output is a sinewave and covers 0.1 - 350 MHz. This low output is the one to be used here and is easily configurable by the touchscreen for amplitude (up to -7 dBm, 1 or 10dB steps), frequency, CW, sweep, and modulation.

TEM Cell Variant

Radiated emissions are often the most common issue. In general, near-field probing correlation with EMC lab testing can be poor. Even if near-field probing indicates the potential source of the emissions and a fix is implemented, lab chamber radiated emissions testing may not show any improvement. This is due to the many coupling mechanisms involved from the noise source to the PCB, housing, and wiring harness.

To evaluate radiated emissions, I've used a variation of a TEM cell (see Figure 6a-c) for over a decade. Such an enclosure is required to keep out ambient radiation such as AM/FM radio. Although you cannot compare results on an absolute level as those obtainable in an EMC lab anechoic chamber, the use of a TEM cell shows similar trends. For

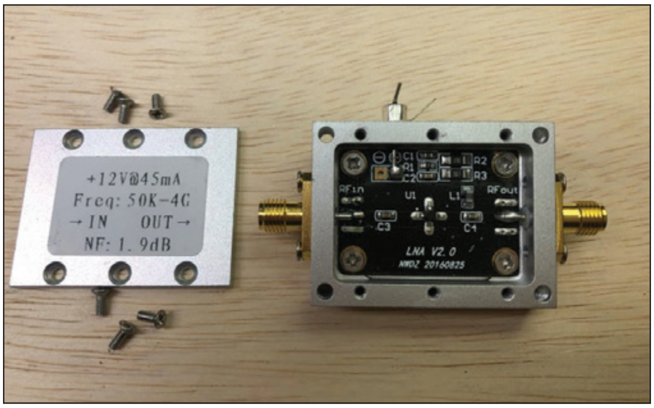

Figure 3: RF signal amplifier

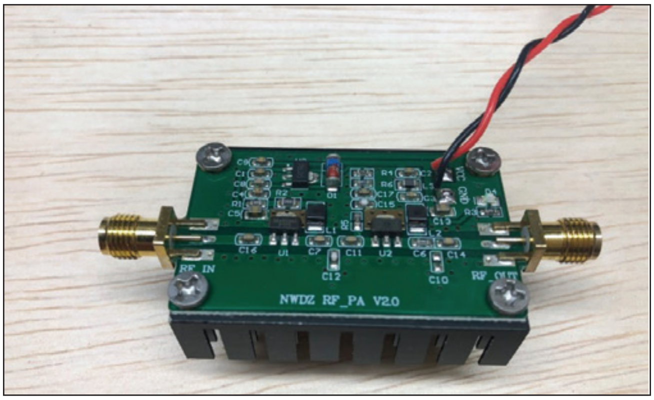

Figure 4: RF power amplifier

Figure 5: RF signal generator

Figure 6a: DIY TEM cell variant (front door removed)

example, if the improvement for a particular fix is x dB, there will be similar improvement in an EMC lab chamber.

This homemade cell is made from HVAC sheet metal ducting available at many home improvement stores. The dimensions are 16 x 16 x 37 inches, with a center plate (without end tapers) of 32 x 13.5 inches. The center plate height is adjustable to accommodate different DUT sizes (default is in center between top and bottom). Figure 6b shows a small opening in the door. This opening is to help isolate the source of the noise (DUT, harness, or both) by allowing placement of the harness outside the TEM cell.

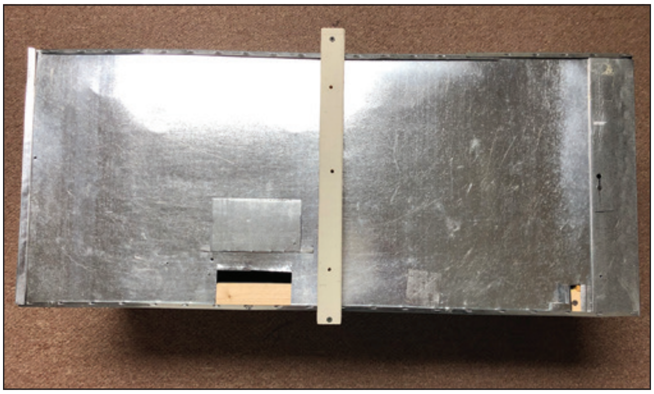

Figure 6b: DIY TEM cell variant (sliding door in place)

Figure 6c: TEM cell variant, end taper and BNC connection detail

In Figure 6d, looking at the S11 and voltage standing wave ratio (VSWR), it appears that this TEM cell is only useful for frequencies less than about 200 MHz. However, it has been used with success in finding fixes for frequencies greater than 1 GHz. Since we are only using the TEM cell to assess before and after results from any fixes, any discrepancies can usually be ignored as long as the DUT and harness locations are controlled (i.e., consistency in DUT positioning and orientation). In an anechoic chamber, the antenna is much farther from the DUT and harness than in this homemade chamber, and proximity coupling with DUT variation is less of an issue.

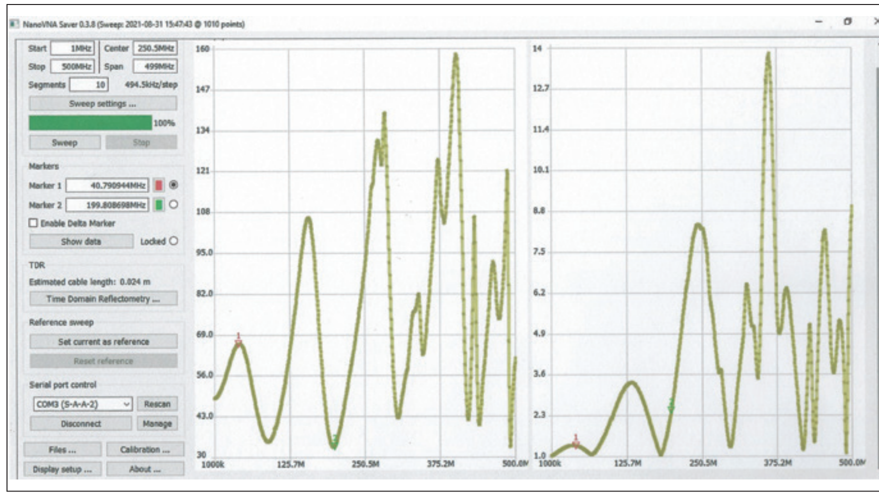

Figure 6d: VNA results for TEM cell (Saver software)

Bulk Current Injection (BCI) Probe

If issues have been identified in EMC lab testing for bulk current injection (BCI), a thrifty method of investigating and possibly solving these issues can be of great value. A low-cost version can be made from a ferrite current clamp as shown in Figure 7a.[5] Using the VNA mentioned previously in this article, I was able to determine that anything over one turn was detrimental. Figure 7b for one turn shows a reasonable impedance and VSWR, but Figure 7c illustrates how these values get much worse even after just two turns.

Figure 7a: DIY bulk current injection probe (single turn) for radiated immunity

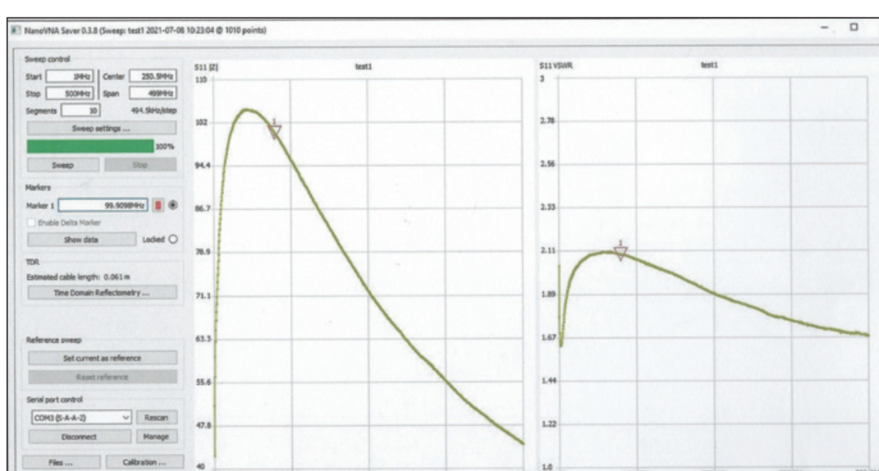

Figure 7b: BCI injection probe (single turn, Figure 7a) VNA measurements

Figure 7d shows a calibration setup using a signal generator feeding an RF power amp whose output feeds a 3 dB attenuator and the BCI probe. The induced current is measured with a cheap version of the BCI calibration jig. The voltage is measured across a 50-ohm, 10 dB attenuator leading to the spectrum analyzer. Induced current was measured at over 2 - 350 MHz, and the maximum is about 100 mA rms which is similar to what is required to meet most automotive EMC specifications.

ESD Simulator

A piezoelectric barbecue lighter like that shown in Figure 8a has been suggested as a low-cost ESD simulator. However, based on verification testing I conducted in a commercial EMC test lab, this lighter has much lower energy than a commercial ESD gun like that shown in Figure 8b, I compared both the piezoelectric simulator and an ESD gun with a calibration target (e.g., IEC 61000-4-2) and high frequency scope. The piezoelectric simulator has no control for magnitude and repeatability. The ESD example in the next section of this article shows that it is important to quantify ESD parameters. Unfortunately, there is no low-cost version of a commercial ESD gun in this case.

PRODUCT APPLICATION EXAMPLES

Figures 9a-c and Figures 10a-b on pages 94 and 95 illustrate thrifty TEM cell results before

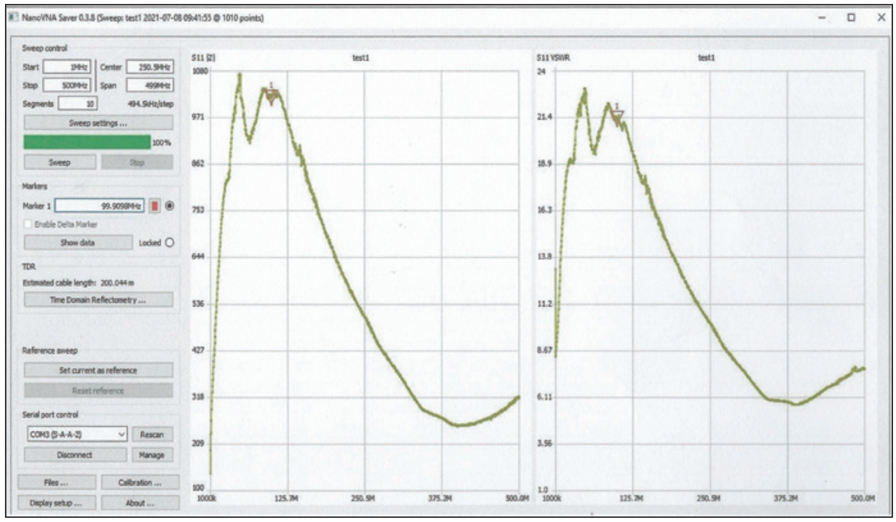

Figure 7c: BCI injection probe (two widely spaced turns) VNA measurements

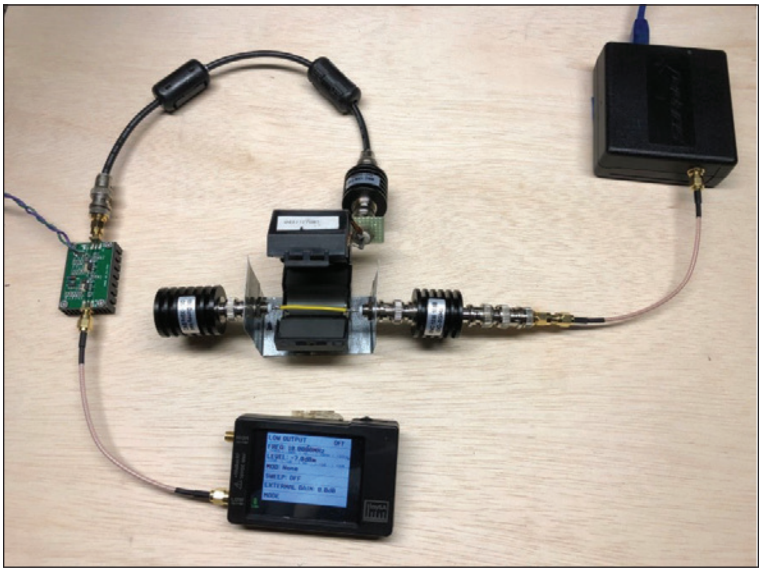

Figure 7d: BCI calibration setup

Figure 8a: ESD low-cost simulator

Figure 8b: ESD gun example

and after fixes were applied to two different automotive devices. These examples illustrate that the TEM cell setup is valid for a wide frequency range. Before the fixes, neither meet the auto manufacturers' EMC specification limits. But after, they both did as verified in an EMC lab. Figure 9a shows a typical setup with the DUT, wiring harness and battery within the TEM cell.

Automotive LED Taillight, ESD

This example is based on an actual case in the field. It was originally thought that power line voltage transients were the cause of the issue. We conducted testing using transients specified in SAE J2628.[6,7] These transients are very realistic and severe but could not precipitate the issue.

The next potential culprit was thought to be due to ESD. Testing as shown in Figure 11 (PCB over ground plane) showed that this was indeed the root cause problem. The ESD gun was applied directly to each pin of the suspect IC (air discharge not repeatable). The IC had one pin that had much lower immunity (< 2 kV, one discharge) than the other pins (> 6 kV, multiple discharges). To determine this immunity, many PCBs were sacrificed.

SUMMARY AND CONCLUSION

In this article, we've presented a number of effective low-cost (thrifty) test instruments that can be used for EMC testing for both pre-qualification and troubleshooting, along with application examples that validate their usefulness. These options can enable you to resolve design potential issues efficiently without the time and cost constraints of an EMC test laboratory.

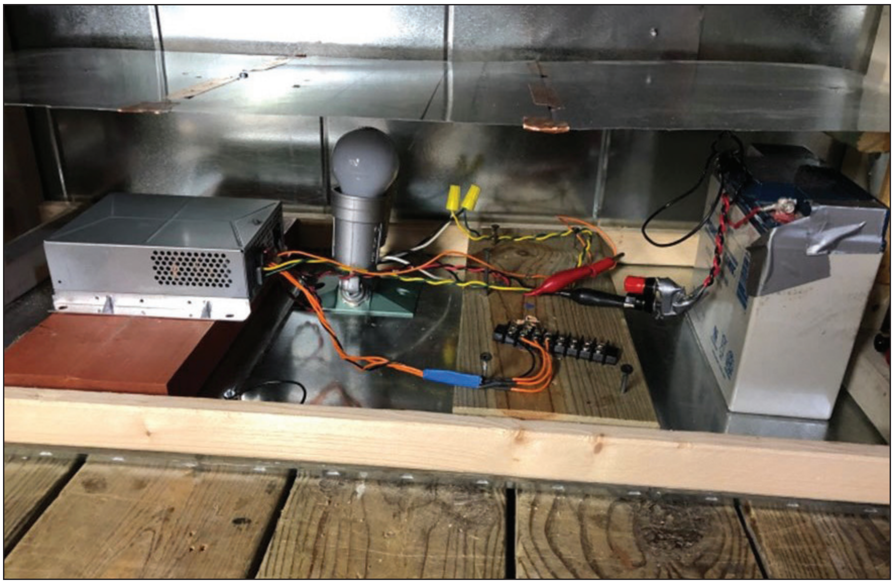

Figure 9a: Example 1—Module A, TEM cell setup

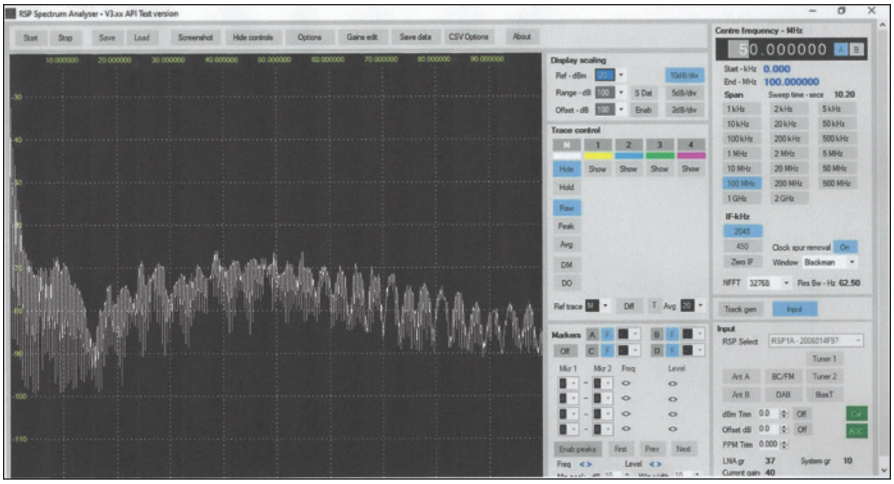

Figure 9b: Example 1—Module A, without fixes, 0 - 100 MHz (20 dB external amp)

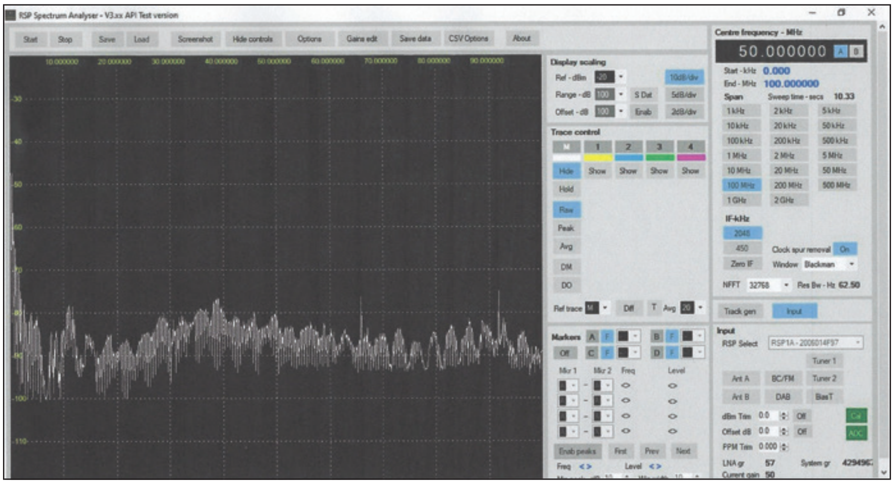

Figure 9c: Example 1—Module A, with EMC fixes

ENDNOTES

1. See, for example, *EMI Troubleshooting Cookbook for Product Designers* by Patrick G. Andre and Kenneth Wyatt.

2. Detailed information about the NanoVNA is available at https://nanorfe.com.

3. Detailed information about the SDRplay is available at https://www.sdrplay.com.

4. Detailed information about the TinySA is available at https://www.tinysa.org/wiki.

5. See “Injection Probe Modeling for Bulk Current Injection Test on Multi Conductor Transmission Lines” by Frédéric Lafon, Younes Benlakhouy, and François de Daran for a cut-away of the BCI probe shown in Figure 7a.

6. SAE J2628, *Characterization, Conducted Immunity.*

7. For a detailed comparison of these transients and ISO 7637-2, see “Comparison of ISO 7637 Transient Waveforms to Real World Automotive Transient Phenomena” by Keith Frazier and Sheran Alles, *2005 IEEE EMC Symposium*.

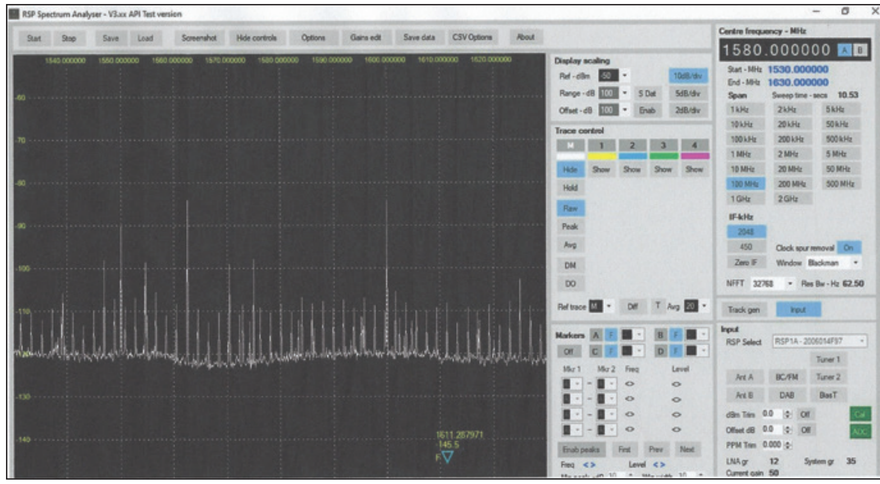

Figure 10a: Example 2—Module B, without fixes, 1530 - 1630 MHz (2 x 20 dB external amps)

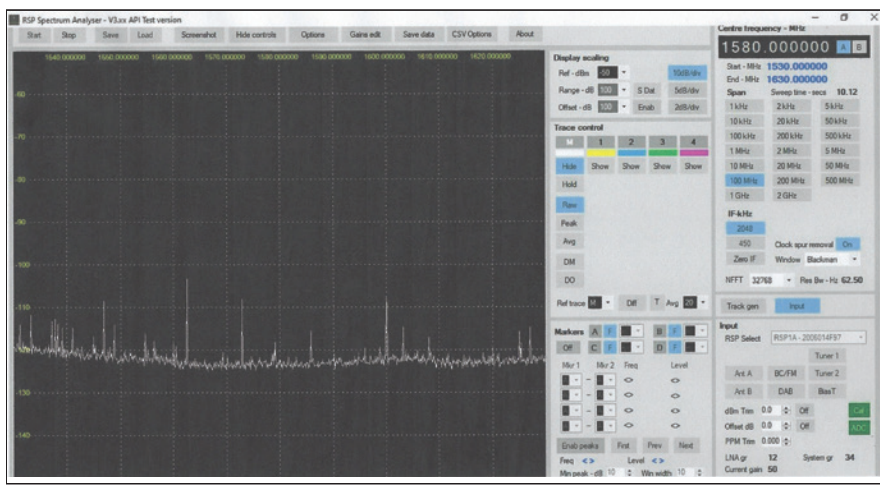

Figure 10b: Example 2—Module B, with EMC fixes

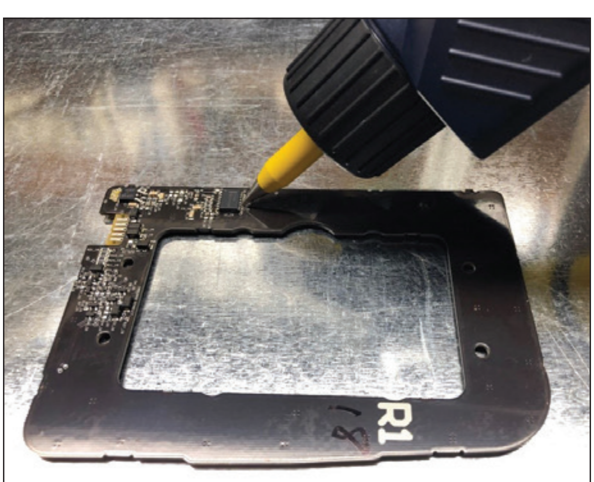

Figure 11: ESD gun applied to IC pins

SCIF and Radio Frequency Secured Facility Design

An RF Shielding Design Guide to Navigating ICS/ICD 705 and NSA 94-106 Requirements

BY JOEL KELLOGG

In recent years, we've noticed a growing confusion in the industry over sensitive compartmented information facilities (SCIF) design and performance requirements. Part 1 of this article is intended to bring some clarity to various documents and performance requirements from a radiofrequency (RF) shielding perspective to aid in the design and construction of these facilities.

INTRODUCTION TO SCIF SPECIFICATIONS

The two most referenced documents for SCIF design are ICD/ICS-705 Technical Specification for Construction and Management of Sensitive Compartmented Information Facilities.[1] and NSA 94-106 [2]. It has been our experience that these documents are often referenced interchangeably or in conjunction with each other.

In some cases, project documents will indicate that a facility has been designed to meet NSA 94-106 as identified in ICD/ICS-705. This is problematic as ICD/ICS-705 does not reference NSA 94-106, nor is ICD/ICS-705 intended to meet the requirements set forth in NSA 94-106. This article will analyze the purpose of ICD/ICS-705 and NSA 94-106 as it pertains to RF shielding and highlight some of the differences between the two standards.

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SCIF OVERVIEW

It is important to understand that a SCIF can come in many different forms. In some applications, a SCIF may be a physical barrier or a physically secured room, and other applications may require acoustic and RF shielding enhancements. An Accrediting Officer (AO) and Site Security Manager (SSM) will evaluate the risk and vulnerability of a SCIF to determine the physical and technical measures that must be deployed for each SCIF application. Further, the Certified TEMPEST[3] Technical Authority (CTTA) will evaluate for TEMPEST requirements and provide direction on RF shielding requirements based upon risk of RF interference to the SCIF.

SCIF CONSTRUCTION METHODS AND RF SHIELDING PERFORMANCE REQUIREMENTS

While it is not uncommon for NSA 94-106 to be referenced as part of a SCIF project, the ICD/ICS-705 construction recommendations will not achieve the RF performance required under NSA 94-106, which include attenuation levels as high as 100 dB at 10 GHz.

In order to achieve the performance requirements under NSA 94-106, a six-sided shielding system with higher performance RF doors, filters, and appropriately treated RF

penetrations is required. The details in ICD/ICS-705 show a more limited RF shielded partition using RF foil between layers of drywall with 6" to 8" returns at the floor and ceiling per Figures 1 and 2). This can become confusing if both standards are referenced as part of a project.

Beyond the limited shielded barrier presented in ICD/ICS-705, the technical specification identifies the use of 1800 Ultra Radiant Barrier for SCIFs manufactured by rFOIL® [4]. A review of the product data provided by the manufacturer demonstrates that the product can be used for ICD/ICS-705 but is not intended for use in NSA 94-106 applications.

The product data as depicted in Figure 3 indicate the shielding material is not capable of providing 100 dB at frequencies greater than 1.5 GHz. Additionally, it is unclear whether the material would meet the NSA 94-106 requirements below 100 MHz. Based on the trend in performance provided in the product data, it is unlikely that the material would meet the NSA RF performance requirements.

Lastly, the product data sheet appears to indicate that a smaller sample of material was tested on a steel RF shielded enclosure. This test would provide an indication of the material's performance under ideal circumstances but would not provide a clear indication of how performance would be impacted by various installation methods.

Beyond the product data, the construction methodology under ICD/ICS-705 should also be considered. ICD/ICS-705 identifies that the barrier be installed between two layers of drywall for the walls with the shielding material being turned at the floor and ceiling and extending several inches away from the wall. When the ceiling is comprised of a metal pan deck, it is often recommended that the shielding barrier be tied into the metal pan deck.

But the installation of the shielding barrier between two layers of drywall results in the shielding being perforated by the drywall screws utilized to install the second layer of drywall. Each perforation further degrades the overall shielding performance. This results in a less effective shielding system or Faraday cage and will not achieve the performance requirements of NSA 94-106.

IMPORTANCE OF RF SHIELDED COMPONENTS

ICD/ICS-705 only identifies an RF barrier when required and does not identify requirements for other RF shielded

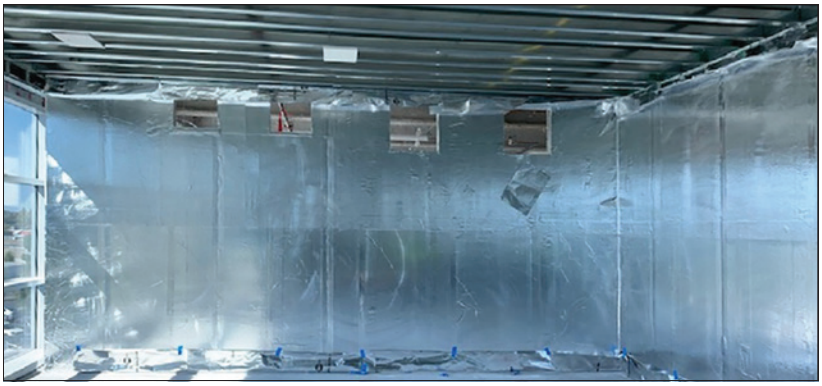

Figure 1: Example of ICD/ICS-705 RF shielding barrier installation

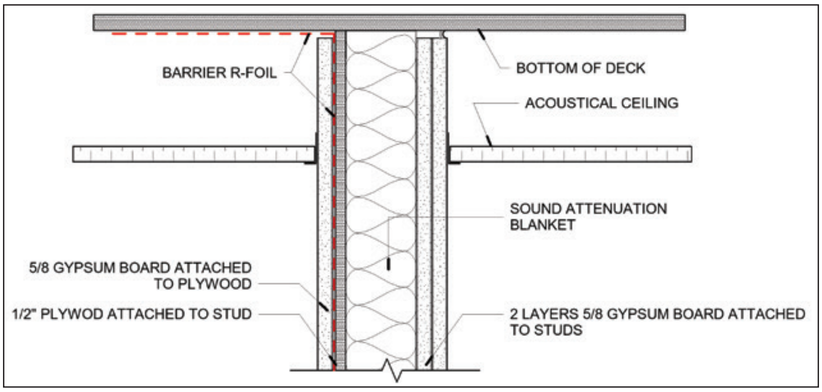

Figure 2: One of three wall sections presented in ICD/ICS-705 depicting an RF barrier

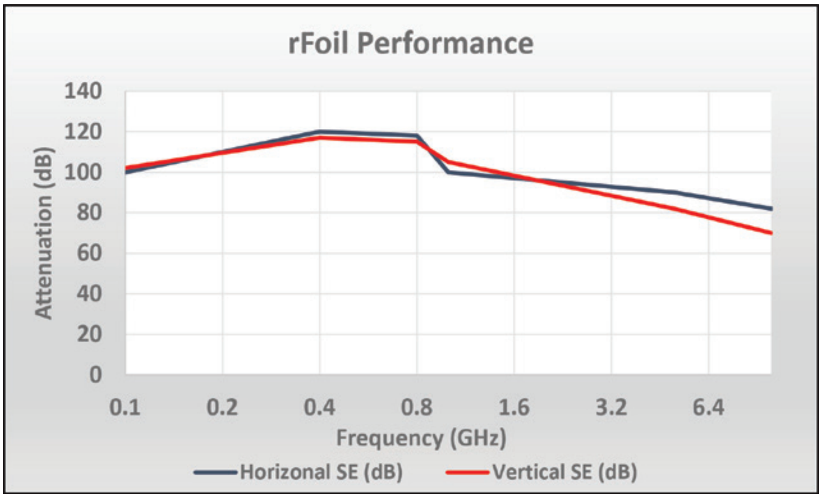

Figure 3: rFOIL RF shielding effectiveness product data[4]

components including doors, filters, and penetrations such as waveguide air vents. The structure of ICD/ICS-705 renders these components unnecessary as they provide limited value from an RF shielding effectiveness perspective without a six-sided shielding system. Despite this, many projects identify requirements for these RF components when utilizing ICD/ICS-705 construction methods while referencing the NSA 94-106 shielding effectiveness or some other (often arbitrary) level of RF shielding effectiveness. These components may provide some value but, in terms of improving the RF shielding effectiveness, that value is often limited. For example, RF filters could attenuate unwanted conducted emissions, but will provide little improvement in overall shielding attenuation.

SECURITY CONSIDERATIONS

ICD/ICS-705 is intended to provide a level of security and often takes advantage of distances from the SCIF to the perimeter of a facility. But, by itself, the facility is not RF secure. A facility or space designated to meet NSA 94-106 is RF secure as it requires a six-sided shielding system, RF doors, penetrations, and filters to achieve the performance objectives set forth in NSA 94-106.

As shown in Figure 4, these shielding systems are often comprised of modular construction capable of providing 100 dB of attenuation up to 10 GHz and meeting the low frequency electric and magnetic shielding performance at frequencies as low as 1 kHz.

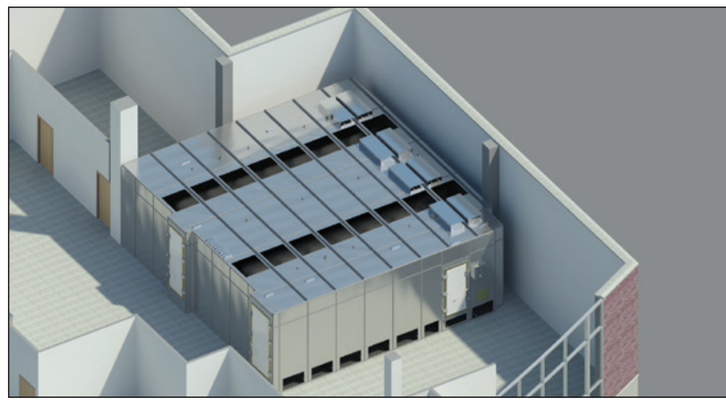

Figure 4: Example of a NSA 94-106 compliant RF shielding system integrated into a building

In addition to a six-sided RF shielded enclosure, other RF components will be required to achieve the RF shielding performance requirements as specified in NSA 94-106. These include RF shielded doors, RF shielded penetrations for HVAC, plumbing, and fiber, and RF filters for electrical, lighting, and building management systems. Examples of electrically filtered penetrations and RF treated sprinkler or plumbing penetrations are presented in Figures 5 and 6, respectively. Without proper product selection and treatment of all these components, the secure space will be at risk of not complying with the NSA 94-106 performance requirements.

For a shielding system to comply with NSA 94-106, all aspects of the shielding must be identified and coordinated with the design team, the general contractor, and mechanical, electrical, and plumbing (MEP) subcontractors to ensure that all building systems and penetrations are properly addressed.

ICD/ICS-705 does not specifically identify requirements for treating penetrations through the shielding with most utilities passing through the shielding system untreated.

KEY DIFFERENCES BETWEEN ICD/ICS-705 AND NSA 94-106

Many projects reference both ICD/ICS-705 and NSA 94-106. As previously discussed, the requirements for each specification are quite different and should not be used interchangeably or in conjunction with each other. ICD/ICS-705 does not identify specific performance requirements while NSA 94-106 specifies performance requirements from 1 kHz to 10 GHz.

ICD/ICS-705 primarily provides direction on the construction of a SCIF with instructions on how to incorporate an RF barrier, but not a shielding system intended to meet NSA 94-106 RF performance requirements. This is evident by the construction methodology and materials identified in ICD/ICS-705.

A six-sided shielding system (Faraday cage) is required to meet the performance requirements under NSA 94-106, but ICD/ICS-705 simply calls for an RF shielding barrier on the wall. Further, the material specified in ICD/ICS-705 is not capable of achieving the NSA 94-106 performance objectives as noted by the rFOIL product performance data. Additionally, ICD/ICS-705 does not require the same level of RF treatment of doors, electrical systems, and mechanical penetrations as would be required under NSA 94-106.

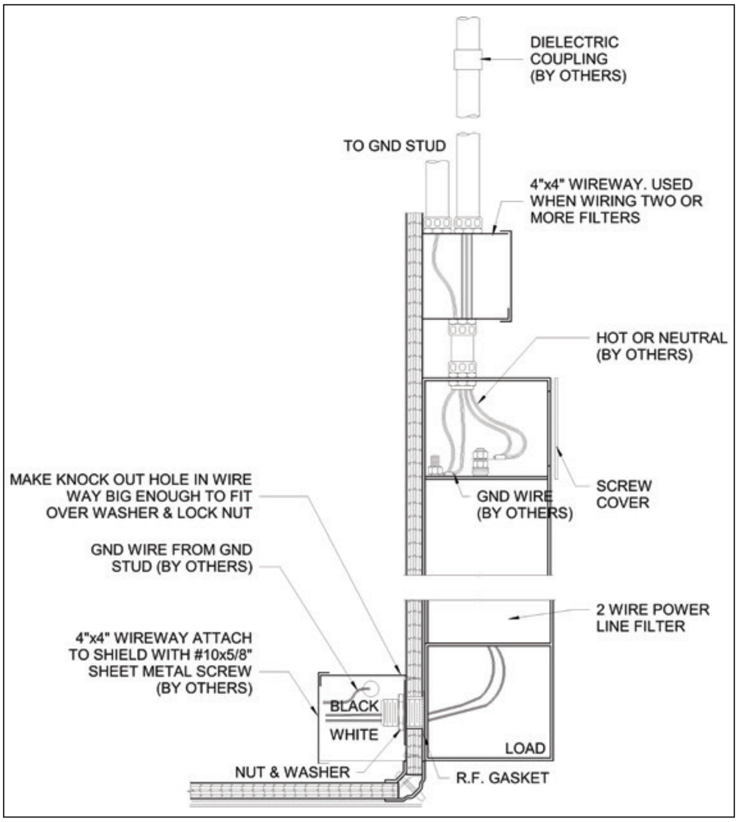

Figure 5: Example of a filter detail for electrical, lighting, and building management systems per NSA 94-106

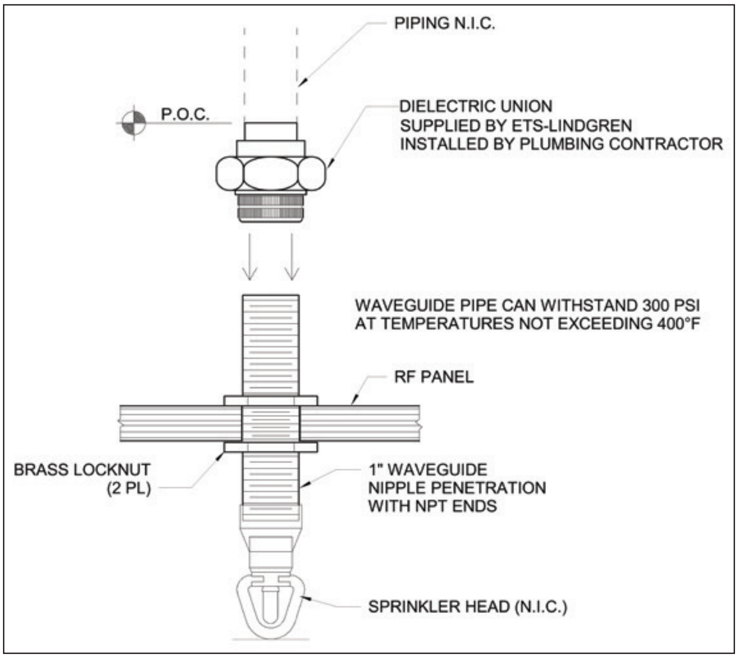

Figure 6: Example of a plumbing penetration for a sprinkler system per NSA 94-106

Table 1 summarizes these key differences between ICD/ICS-705 and NSA 94-106.

	ICD/ICS-705	NSA 94-106
Requires RF Shielding	Maybe*	Yes
Limited RF Shielding Barrier	Yes	No
Six-Sided Shielding Required	No	Yes
Requires RF Doors	No	Yes
Requires RF Filters	No	Yes
Requires RF Treated Penetrations	No	Yes
Includes Magnetic Field Performance Requirements	No	Yes
Includes Electric Field Performance Requirements	No	Yes
Includes Plane Wave Performance Requirements	No	Yes

Table 1: ICD/ICS-705 and NSA 94-106 Summary of Requirements

**The project CTTA will determine the SCIF requirement, which may or may not include an RF barrier.*

CONCLUSION

As discussed above, referencing both ICD/ICS-705 and NSA 94-106 as part of a project can create much confusion in terms of project requirements. This can have significant performance and cost implications. Most general contractors lack expertise in RF shielding. These discrepancies can go unidentified, placing a project at risk of not meeting project requirements and potentially incurring large cost overruns unless an experienced RF shielding company or consultant is involved. Therefore, it is critical to clearly identify the project requirements and ensure that the differences between ICD/ICS-705 and NSA 94-106 are well understood.

REFERENCES

1. ICD/ICS-705 – Technical Specification for Construction and Management of Sensitive Compartmented Information Facilities, https://www.dni.gov/files/Governance/IC-Tech-Specs-for-Const-and-Mgmt-of-SCIFs-v15.pdf.
2. NSA 94-106 – not available for public reference.
3. TEMPEST is a U.S. National Security Agency specification and a NATO certification used in reference to secure facilities.
4. rFOIL product data, https://rfoil.com.

Cellular Approvals and RCM Certification in Australia

BY SHAUN REID AND SHABBIR AHMED

In Australia, all electrical and electronics devices, including cellular modules, need to comply with the requirements of the Regulatory Compliance Mark (RCM). The RCM is of two parts jointly owned by the Australian Communications Media Authority (ACMA) and the Electrical Regulatory Authorities Council (ERAC). Cellular approvals are technically complex and involve all aspects of the ACMA regulations and the ERAC Electrical Equipment Safety System (EESS) RCM certification process.

ACMA RCM REQUIREMENTS

Most recently amended in 2018, the ACMA's standard *TLN: Telecommunications (Labelling Notice for Customer Equipment and Customer Cabling) Instrument 2015* mandates that cellular devices intended for connection to the public mobile telecommunications service (PMTS) must comply with *Telecommunications (Mobile Equipment Air Interface) Technical Standard 2018*, which in turn references AS/CA-S042.1, *Requirements for Connection to an Air Interface of a Telecommunications Network – Part 1: General*. All telecommunications devices, including those utilizing 3G, 4G, 5G, or satellite communications technologies, must comply with the requirements of the latest updated version of the standard issued in 2020. 3G and 4G devices must also comply with the requirements of AS/CA S042.4, *Requirements for Connection to an Air Interface of a Telecommunications Network—Part 4: IMT Customer Equipment*.

The Communications Alliance (the CA of AS/CA) Working Committee 94 (WC94) has been established and is currently discussing an update to the scopes of AS/CA S042.1 and AS/CA S042.4, and the introduction of a new Part 5 to the S042 series to address the requirements of 5G technologies. The new and updated standards are likely to be published in 2022.

Compliance requirements for the current AS/CA S042.1 (2020) and AS/CA S042.4 (2018) vary depending on device functionality and the technologies used. Devices such as remote dataloggers, where the cellular and/or satellite functionality are only used for data transfer,

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are the simplest devices to assess for conformity. But requirements for even these simple devices vary depending on technology (i.e., satellite, 3G, 4G, Cat M1, or NB-IoT) and the frequency bands used (e.g., Band 5 devices must comply with U.S. Federal Communications Commission (FCC) Part 22 requirements).

Complexity increases when voice functionality is introduced. The least complex assessment is for walkie-talkie type devices, where the device is restricted to a preconfigured call group and does not operate in a standard telephone service (STS) access mode. STS access mode allows devices to make cellular or satellite calls to other devices (cellular, satellite, or landlines).

Additional requirements apply to the devices operating in an STS access mode. Cellular and satellite devices must be assessed to confirm their emergency service access and their handling of emergency calls to the national emergency service numbers 000, 112, and 106. Test calls for satellite services are limited to 000 (the general emergency service number), whereas cellular devices additionally include 112 (the alternative emergency service number for digital mobile phones). Test calls are performed with the device in multiple configurations, such as various lock states, with and without SIM, and using manual and/or soft keys.

Devices capable of both satellite and cellular functionality are required to comply with the requirements of each service. Additionally, if a device is incapable of operating in STS access mode but can provide these services to another device through a local port and/or RF interface, the gateway device is subject to the requirements of each provided service.

AS/CA S042.1: 2020 introduced advanced mobile location (AML) testing. Test calls made to the emergency service numbers 000 and 112 by a device supporting AML and GPS functionality now require contacting the emergency call person (ECP) to confirm that the device information and location data was received correctly.

Devices used in close proximity to the ear for voice communications in a typical handset style or a headset are also required to comply with the maximum sound pressure level output requirements to confirm that the device will not cause acoustic shock to the user. Devices used in a speaker phone or walkie-talkie style where the device is not used near the ear in a typical handset style are not required to undergo this testing.

To reflect the importance of emergency service access and acoustic safety, AS/CA S042.1 for devices that are used to supply a standard telephone service (STS access mode) is treated as a high-risk standard, and the test report must be endorsed by an accredited facility.

The requirements of Part 4 do not vary as much as those in Part 1. Most devices coming to market are integrating pre-certified modules from well-known manufacturers. The test reports and declarations for these modules are usually available from the module manufacturer and passed on to testing laboratories for use in the telecommunications assessment. These reports are used to demonstrate the RF compatibility, network integrity, and interoperability with the STS of the module and host device.

A common misconception with host device manufacturers is that these module reports are enough to establish conformity for their device to AS/CA S042.4. However, the standard refers to the device undergoing assessment as customer equipment, not the cellular module itself.

It is understood that the ACMA's position is that device manufacturers integrating a pre-certified module (with suitable evidence of conformity for Australian requirements) are not expected to re-establish the RF compatibility, network integrity, and interoperability with the STS conformance of the module. However, the integrated host device must be assessed for radiated spurious emissions to determine that integration into the host device and antenna configuration used has not caused any unintentional emissions from the module that exceed the limits.

AS/CA S042 Part 1 and 4 assessments mainly requires gathering documentation, including the following information:

S042.1:2020 General

- Testing for emergency service access and AML (if applicable)
- Testing for audio acoustic safety (if applicable)
- Manufacturer's Declaration of Conformity (DoC) for mobile identity requirements
- Warning notice requirements

S042.4:2018 3G/4G Devices

- The cellular module test reports to FCC Part 22 Rules; or FCC/TCB Grant of Equipment Authorization based on FCC ID/Manufacturer's DoC.
- The cellular module test reports to ETSI EN 301 908, Parts 1, 2, and 13 (as applicable); or EU-type examination by a Notified Body (NB)/Manufacturer's DoC, based on conformity assessment procedures

described in the EU's Radio Equipment Directive (2014/53/EU, also referred to as the RED).

- Manufacturer's DoC stating compliance with mandatory requirements of the core protocol specifications as per applicable ETSI technical standards.
- Radiated spurious emissions test report on the final integrated/composite customer equipment.

A National Association of Testing Authorities (NATA)-accredited report is largely accepted as proof of compliance by the ACMA and the Australian telecommunications industry. NATA is a signatory to the ILAC Mutual Recognition Agreement (MRA). Therefore, a report accredited by an equivalent accreditation body is also acceptable. A Certification Body Statement (CBS) by an ACMA Certification Body is not mandatory but a NATA (or equivalent) endorsed report may be used to obtain one.

OTHER ACMA REQUIREMENTS

The ACMA requirements also include EMC, EMR/SAR, Radiocommunications, and Electrical Product Safety as follows:

EMC Compliance

For most telecommunication devices, the most common standard is CISPR 32, *Electromagnetic compatibility of multimedia equipment – Emissions requirements*. As the title suggests, this standard relates to multimedia equipment (IT, audio, video, broadcast receivers, entertainment lighting control equipment, or any combinations). EN/IEC 61326-1, *Electrical equipment for measurement, control and laboratory use – EMC requirements – Part 1: General requirements*, is another common standard as it relates to measurement, control, and laboratory equipment (e.g., dataloggers).

For equipment used in vehicles, UN ECE R10, *Electromagnetic Compatibility*, is usually applicable.

Where multiple standards are applicable, the ACMA advises selecting the standard that best matches the main purpose of the product.

EMR/SAR Compliance

The ACMA standard, *Radiocommunications (Electromagnetic Radiation – Human Exposure) Standard 2014*, is the applicable standard for electromagnetic radiation (EMR) and specific absorption rate (SAR) compliance. If the integral antenna of the device is greater than 20 cm from a human body, e.g., a wireless router, compliance with the ACMA EMR standard requires an assessment of the radio frequency (RF) exposure levels performed in accordance with AS/NZS 2772.2:2016, *Radiofrequency fields – Principles and methods of measurement and computation – 3 kHz to 300 GHz*.

International human exposure assessments (FCC Part 2.1091, RSS-102, EN 62311, etc.) provide useful information for the AS/NZS 2772.2 assessment, but only AS/NZS 2772.2 is accepted as evidence of conformity for the ACMA EMR standard.

For the ACMA standard, the human body includes only the torso, neck, and head, and not limbs such as arms and legs.

If the device has an integral antenna and is normally used within 20 cm of a human body, a NATA (or equivalent)-endorsed SAR test report is required. SAR must be measured in accordance with methods described in EN 62209-1 (at the ear) and EN 62209-2 (at the body). All bands and all radio transmitters must be assessed. If simultaneous operation via telecommunications (3G/4G), and/or radiocommunications (Wi-Fi/Bluetooth) is possible, SAR measurements must be conducted with the device in a simultaneous transmission mode.

The exposure levels are assessed against the reference limits for occupational and general public exposure (as applicable) as defined in the recently released ARPANSA RPS S-1 (February 2021).

European EN 62209 SAR reports must state compliance with the performance requirements of the ACMA EMR Standard 2014. FCC SAR reports are not acceptable for ACMA compliance purposes.

Radiocommunications Compliance

Bluetooth, Wi-Fi, and NFC transmitters must comply with ACMA Radiocommunications (Compliance Labelling – Devices) Notice 2014 as per the short-range devices (SRD) standard, AS/NZS 4268:2017, *Radio equipment and systems – Short range devices – Limits and methods of measurement*. EU RED reports showing compliance with EN 301 893 (5 GHz Wi-Fi), EN 300 328 (Bluetooth and 2.4 GHz Wi-Fi), EN 300 220 (25 MHz to 1 GHz), and EN 300 330 (9 kHz to 25 MHz) can be used to show compliance with AS/NZS 4268. In most instances, a CE RED radio report or an FCC radio report may be used to show compliance to the requirements of AS/NZS 4268.

Electrical Product Safety Requirements

The ACMA TLN requirements mandate that satellite/3G/4G devices must comply with the Telecommunications (Customer Equipment Safety) Technical Standard 2018 (AS/NZS 60950.1:2015, *Information technology equipment – Safety*, or AS/NZS 62368.1:2018, *Audio/video, information and communication technology equipment – Safety requirements*). The Customer Equipment Safety standard is classified as a high-risk standard, and test reports must be NATA or equivalent endorsed.

AS/NZS 60950.1 has been superseded by AS/NZS 62368.1 and the transition period ends on 15 February 2022. For those targeting CE marking compliance as well, AS/NZS 62368.1 with EN variation testing is the preferred option as EN 60950-1 is no longer accepted for CE marking.

For devices where the intended application is such that the ingress of water is possible, the electrical safety standards require an ingression protection (IP) test report to IEC 60529:2004, *Degrees of protection provided by enclosure (IP Code)*, to a declared IP rating.

Although the Telecommunications Customer Equipment Safety standard mandates AS/NZS 60950.1 or AS/NZS 62368.1, there may be additional relevant electrical safety product standards. The EESS defines products as being in-scope and not in-scope. Suppliers of electrical safety equipment that are not in-scope still have a responsibility to ensure their products are electrically safe. AS/NZS 3820, *Essential safety requirements for electrical equipment*, provides the essential safety criteria for electrical equipment and requires evidence of conformity to the relevant product standard to be held.

In-scope products are classified as risk level 1, 2, or 3. Risk levels 2 and 3 are defined in AS/NZS 4417.2, *Regulatory compliance mark for electrical and electronic equipment – Specific requirements for particular regulatory applications*. Products not defined in the standard are classified as Risk Level 1 and are low or unknown risk.

One point of note for international suppliers or manufacturers is that the ACMA requires a local Australian representative such as the supplier, importer, or an agent (someone in Australia who acts on behalf of a manufacturer or importer) for their RCM compliance declaration. However, agents cannot be registered as Responsible Suppliers under the ERAC/EESS.

ERAC EESS RCM REQUIREMENTS FOR CHARGER/POWER ADAPTERS

The applicable standard for electronic or ferromagnetic power supplies or chargers for use with IT, audio, and video equipment is AS/NZS 60950.1:2015 as per the in-scope electrical equipment definitions and risk levels for the Electrical Equipment Safety System (EESS) document published by the EESS. This document is a freely available alternative summary of the class 2 and 3 applicable standards available in AS/NZS 4417.2.

An accredited test report (NATA or equivalent) to the applicable Australian safety standards is required to obtain electrical authority approval and certification for chargers/power adapters. Assuming an Australian approved plug and cord set is provided, the local supplier or importer into Australia must prepare and submit for electrical authority approval, application, and certification, pay fees, obtain approval number, and register the charger/adapter on the ERAC national database.

It is recommended that an Australian-approved (ERAC registered) OEM charger be used (must be sourced in Australia) to eliminate testing, certification, and registration costs. An EMC report to AS/NZS CISPR 32 or EN 55032 is also required for the charger if sourced separately.

An external power supply used as a charger is required to meet the minimum energy performance standards (MEPS) and needs to be tested to AS/NZS 4665.1:2005, *Performance of external power supplies – Part 1: Test method and energy performance mark*, and registered in the Equipment Energy Efficiency (E3) database.

Existing report to AS/NZS 60950.1:2015 or AS/NZS 62368.1:2018 will be suitable if the report of the testing is NATA- (or equivalent-) accredited. CB reports or reports to IEC 60950 or IEC 62368 that include Australian variations are also acceptable.

CONCLUSION

The compliance requirements for cellular devices that connect to the mobile phone networks in Australia involve all aspects of the ACMA technical regulations including EMC, telecommunications, electrical safety, radiocommunications, electromagnetic radiation (EMR/SAR), and the ERAC regulations for chargers and power adapters. Most information on the technical requirements is readily available on the respective regulatory body websites.

Caster Contact: The Achilles Heel of ESD Floors

Standard ESD Resistance Tests Do Not Fully Evaluate a Floor's Suitability for Grounding Carts, Chairs, and Mobile Workstations

BY DAVID LONG

What's the purpose of installing an ESD floor? The most common answer to this question is "We need ESD flooring to prevent static charges on mobile personnel when they handle static sensitive parts and systems." In other words, we need the effectiveness of a wrist strap, but we don't want to deal with the restrictions of wires and cords.

While this answer highlights a key attribute of a properly functioning ESD floor, it sets the bar very low. It also short sells the many advantages an ESD floor actually offers. Like every other static mitigation component, ESD flooring is only one piece of a larger comprehensive system that keeps all parts, machines, tools, packaging, work surfaces, and personnel at the same potential.

When floors are evaluated, specifiers focus on two main performance parameters: 1) the flooring system's electrical resistance; and 2) how much charge a person can develop when walking on the floor wearing specific footwear. But what about the parts themselves? How do we protect them? When we move parts from one operation to another, we don't cradle them in the palm of our hands. We move parts and systems in zip lock bags, on wheeled carts with trays, and possibly with automatically guided vehicles. In agile manufacturing operations, the ESD floor might even be used as the primary ground for workbenches on wheels.

FLOORING BASICS

ESD floors are designed to prevent static discharge from harming electronic parts and assemblies in an ESD-protected area (EPA.) They are installed for multiple reasons. The ideal floor prevents static on:

- people
- parts and equipment
- shelves, mobile workstations, and ESD chairs

Some ESD floors satisfy all three tasks. Other inhibit static from developing on people but do little or nothing to protect equipment or ground mobile workstations, carts, and ESD chairs.

Dave Long is the CEO and founder of Staticworx, Inc., a leading provider of flooring solutions for static-free environments. He has 30-plus years of industry experience and combines his comprehensive technical knowledge of electrostatics and concrete substrate testing with a practical understanding of how materials perform in real-world environments. Long can be reached at dave@staticworx.com.

WHY DOES THIS MATTER?

To produce quality products, pass ISO certification, and satisfy customers, electronics facilities must meet ANSI/ESD S20.20. In an effort to meet ESD flooring requirements in ANSI 20.20, buyers and specifiers often focus all their attention on the electrical resistance of the flooring/adhesive system. But resistance is only one performance parameter.

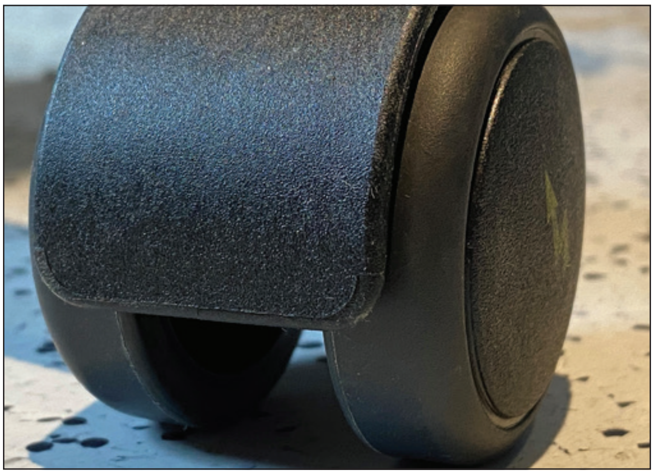

Figure 1: Conductive chair caster on an ESD Floor

Finding floors that meet S20.20 point-to-point (RTT) and point-to-ground (RTG) resistance requirements is an easy task. Adherence to all aspects of ANSI/ESD S20.20 requires the floor to perform multiple functions, and not just meet an electrical resistance parameter. It's equally important to determine the maximum voltage the floor will generate on a person in combination with specific footwear. Furniture, mobile workstations, and equipment must also be properly grounded through the floor, with resistance between the castors and ESD floor ground within the S20.20 acceptable range (< 1.0×10^9).

Following are some tests every end-user should perform when evaluating floors:

- STM 7.1 Acceptable system resistance < $1.0 \text{ X } 10^9$ (Tool used: Ohm meter and NFPA probes)
- STM 97.1 Acceptable person + footwear + flooring system resistance < $1.0 \text{ x } 10^9$ (Equipment used: Ohm meter and NFPA probes)

- STM97.2 Maximum voltage measured on a person wearing ESD footwear while walking on an ESD floor: less than 100 volts (Equipment used: Charge plate monitor/field meter)
- STM4.1 Verification (page 18, Section 12.3 TR53-01-18) Maximum resistance between mobile ESD workstation surface and ground while resting on a grounded ESD floor < 1.0 X 10^9 (Equipment used: Ohm meter and NFPA probes)

A CASE HISTORY

As part of an ESD tile evaluation by the facilities department at a medical instruments manufacturer, test floors were installed. Various properties were evaluated, including flatness, slip characteristics, flooring system resistance, body voltage generation, ease of rolling heavy equipment, maintenance, and difficulty of installation and repairs.

One of the flooring options met all criteria including the ability to install without adhesive using internal labor. However, prior to ordering the flooring, a manufacturing engineer placed several mobile carts on the test floor and measured resistance to ground from the cart surface through the conductive casters to the floor's groundable point.

9 x 10 E6	5 x 10 E6	6 x 10 E6	8 x 10 E6
1 x 10 E7	1 x 10 E6	2 x 10 E7	7 x 10 E6
5 x 10 E6	1 x 10 E6	1 x 10 E7	2 x 10 E2
2 x 10 E8	1 x 10 E12	1 x 10 E8	8 x 10 E6
5 x 10 E7	2 x 10 E7	1 x 10 E7	7 x 10 E6
2 x 10 E6	2 x 10 E6	1 x 10 E1	2 x 10 E6
2 x 10 E10	4 x 10 E9	1 x 10 E8	2 x 10 E10
5 x 10 E6	9 x 10 E7	1 x 10 E6	9 x 10 E6
2 x 10 E11	9 x 10 E8	9 x 10 E9	5 x 10 E7
8 x 10 E7	2 x 10 E9	9 x 10 E6	3 x 10 E9

Table 1: 40 resistance measurements from cart surface to groundable point through medium density ESD floor tiles. Cart locations were altered by as little as one inch between measurements. Test area measured over 100 square feet. Multiple areas were tested. Carts were equipped with four conductive casters.

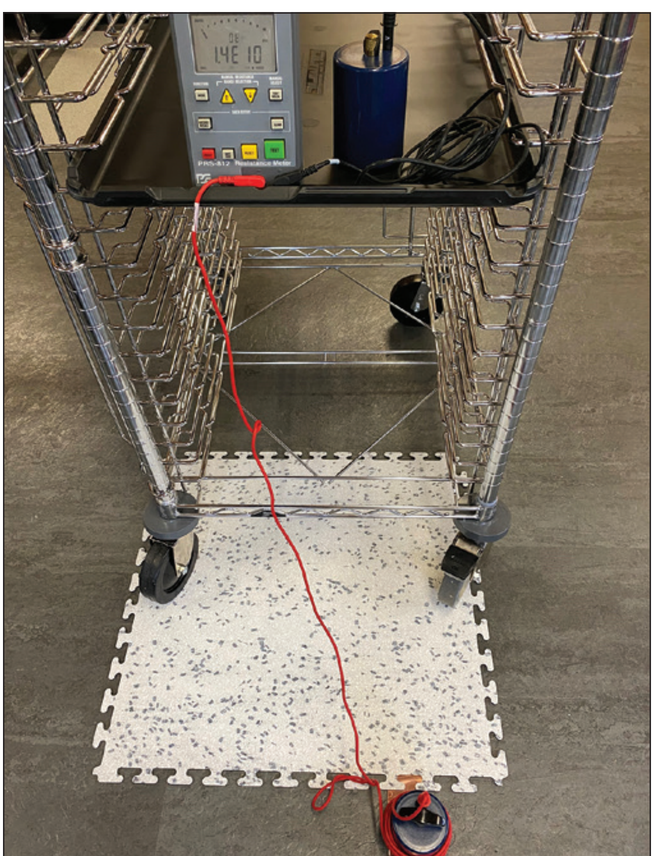

Figure 2

Figure 3

Despite the fact that the floor by itself had measured in the conductive range (< 1.0×10^6) per ANSI/ESD S7.1 tests, the flooring failed the mobile workstation test, with the resistance to ground measurements from the cart surface ranging from 1.0×10^6 to 1.0×10^{12}. Per ANSI/ESD S20.20, any measurement $\geq 1.0 \times 10^9$ constitutes a failure. Seven measurements out of the initial 40 test points exceeded the ANSI maximum (see Table 1).

This sampling was followed up with over 1000 measurements. The reject rate was approximately 16%. Was the cart the problem? When placed on a metal plate, the cart resistance to ground measured well below 1.0×10^7. To eliminate contamination as a variable, the flooring and casters were thoroughly cleaned and retested. This had little impact and measurements remained unacceptable. The resistance between the cart and the floor changed by four to six orders of magnitude simply by moving the cart as little as one inch. Given that the flooring resistance and the cart caster resistance exhibited consistency, the only remaining variable was the random placement of casters (caster and floor interface) on the floor tiles.

ANALYZING THE DATA

Figures 2 and 3 are photos of a tray cart commonly found in electronic manufacturing service (EMS) facilities. The cart is resting on a flooring system that utilizes conductive chips. This floor would be categorized as a low density (LD) conductive chip floor. This particular flooring system provides a conductive path from black surface chips through its thickness to a carbon loaded ground plane on the underside. A 24" copper strip was used as a groundable point. When tested with a five-pound (2.27 Kg) NFPA probe measuring 2.5" (6.35 cm) the flooring resistance measures well below 1.0×10^6.

In Figure 2, the cart to ground measurement exceeds the limits (< 1.0×10^9) of ANSI/ESD S20.20. In Figure 3, a compliant measurement is the result of a minor change in the position of the same cart on the same floor tile. Just like the results in Table 1, these resistance measurements confirm a high correlation between negligible changes in caster placement and significant changes in resistance.

Like the cart shown in Figures 2 and 3, the carts used by the medical equipment manufacturer were built with four conductive casters. The resistance to ground between the cart and groundable point met ANSI/ESD requirements 84% of the time. An 84% pass rate means that, for 16% of the time, not a single conductive caster made adequate contact with the conductive chip floor.

Another way to look at this would be to view the data from the perspective of the probability of four consecutive events having the same outcome. In this case, the events would be simultaneous. For example, what is the probability of flipping heads four times in a row in a coin toss experiment? The equation would be the odds of a single event occurring multiplied by itself four times, that is ½ x ½ x ½ x ½ = one in 16.

If we loosely apply this approach to our flooring problem (for simplification we are excluding particle density vs total area), we might say that after 100 tries we can randomly get all four casters to simultaneously not touch a conductive particle 16 times. So, what is the possibility of any single caster not touching a conductive particle? At a minimum, we are questioning the likelihood of four consecutive either/or events occurring. Our simple equation might look as follows. X times X times X times X = 16/100. So, if we solve for X, the fourth root of 16 equals two and the fourth root of 100 equals 3.1. Essentially the odds of any single caster not touching the conductive elements on the floor is 66%.

For starters, this presents a valid argument to install conductive casters on every cart post. But the real takeaway is to pull out that old statistics book and conduct a valid experiment before assuming any ESD floor will ground mobile workstations based on compliant ANSI/ESD 7.1 test results.

EFFECTIVE FLOORING IS THE SOLUTION

This problem can be easily avoided when new floors are purchased. When evaluating an ESD floor, it's imperative to evaluate the floor as part of the facility and the processes within the facility. Flooring should be tested for compatibility with all ESD mitigation components, including material handling processes. A fully functional floor can act as the anchor to all mobile grounding requirements.

A key attribute of many ESD floors is the ability to eliminate cumbersome and redundant tethering processes inside the EPA. ESD floors also eliminate the need for enclosing parts in covered tote boxes and shielding bags. But in order to eliminate the use of cumbersome packaging and tethering protocols, the floor must provide a compliant path to ground for mobile material handling fixtures on casters.

Figure 4

Some ESD floors cannot ground conductive casters effectively due to poor contact between casters or glides and a low density of conductive points or chips on the surface of the floor. In certain cases, this problem is exacerbated by a micro-thin factory application of low-maintenance polyurethane or ceramic coating on the floor's surface. These UV-cured coatings reduce maintenance at a cost. Most testing shows that micro-thin coatings increase the floor's electrical resistance and diminish the control of walking body voltage.

CHIPS vs. CONDUCTIVE VEINS

Some ESD vinyl tiles derive their conductivity from randomly located conductive chips similar to the tile shown in Figure 4. The black chips are the only conductive element on the tile surface. The rest of the surface is ordinary vinyl, that is, an insulative polymer that provides no connectivity to ground.

As illustrated in Figure 4, we can evaluate this liability by turning our NFPA probe on its edge and measuring a contact area between conductive chips and ground. The tile sample shown in the Figure measured less than 1.0 x 10^6 when the full 31 cm^2 probe surface was used in an ANSI/ESD S7.1 test. However, the polymer between the chips is nonconductive. When a caster contacts the non-conductive polymer in between chips instead of contacting a conductive chip, measurements change by over five orders of magnitude.

Figure 5: A space or void would show a contact area/patch between caster and tile.

Figure 6: The solid grey area between the quarter and the dime represents the contact area of the caster and tile.

For a portable workstation or chair to meet ANSI/ESD S20.20, resistance to ground must be below 1.0 x 10^9.

CONTACT AREA AND ITS IMPACT ON CONTINUITY

To understand the problem, we looked at the size of the conductive casters and tried to determine how much of their surface area actually touches the floor. First, we tucked four pieces of paper under the caster, sliding the paper from four different directions until it would not slide any further (see Figure 5).

When we lifted the paper, we expected to see a space where the four slips of paper did not meet. The space or void would show us approximately where the castor had been in contact with the floor. Before moving the caster, we taped the pieces of paper together so they would stay in place. Then we rolled the chair off the paper. Because we were able to tuck a fair amount of paper under the castor, we expected the contact area between the castor and floor tile to be small. We were surprised to see that it was barely larger than a sliver. In fact, the actual contact area was smaller than a dime (see Figure 5).

Figure 7: Contact area/patch of caster superimposed over conductive vein technology floor

Figure 8: Low-density chip floor (on left) and high-density chip floor (right)

Think of the open space in the paper as a viewing window. We slid the window around the tile. When we don't see a black chip inside the viewing window, we are looking at a section of tile that will not ground a caster. Even when it provides some degree of conductivity when most of the caster contact area rests on the void between chips, the resistance will likely measure above 1.0 x 10^9.

CASTER BASICS

A typical conductive caster measures approximately 10 cm in diameter but has a contact area of only one square cm. To put this in perspective, the NFPA probe used to measure the resistance from the surface of an ESD floor to ground has a contact area of 31 square centimeters. The distance between conductive particles used in a low-density chip technology (see Figure 9) ESD floor can measure from .5 cm up to 10 cm with an average of 2 to 5 cm. Therefore ANSI/ESD STM 7.1 resistance testing will not predict whether a particular floor will consistently provide electrical contact between casters and flooring.

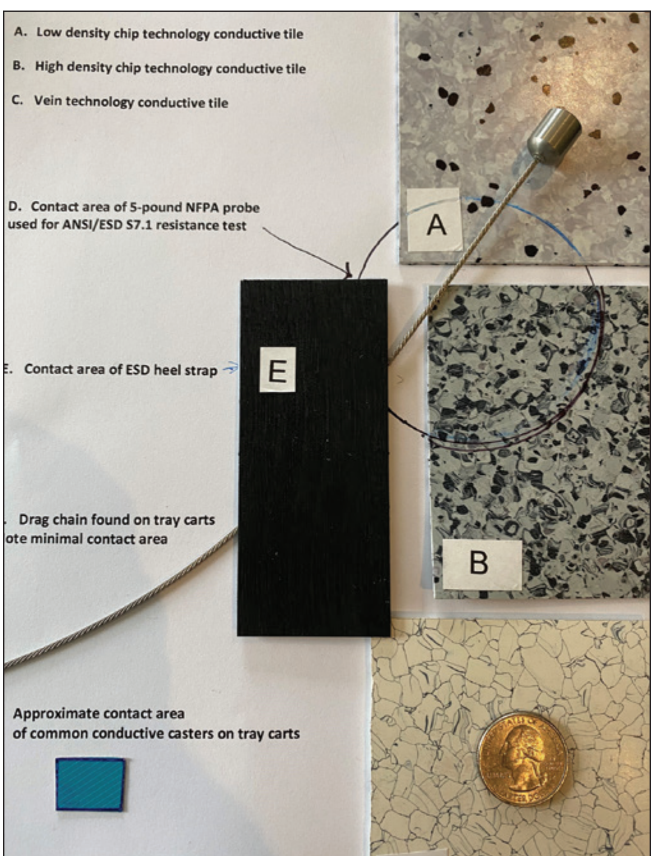

Figure 9: Note the large contact area of an NFPA probe in comparison to actual items intended for grounding through an ESD floor:

- D—NFPA probe contact area = approx. 31 cm^2
- E—Typical heel strap: > 13 cm^2
- G—Caster contact area = 1 cm^2
- F—Ground chain contact area = negligible

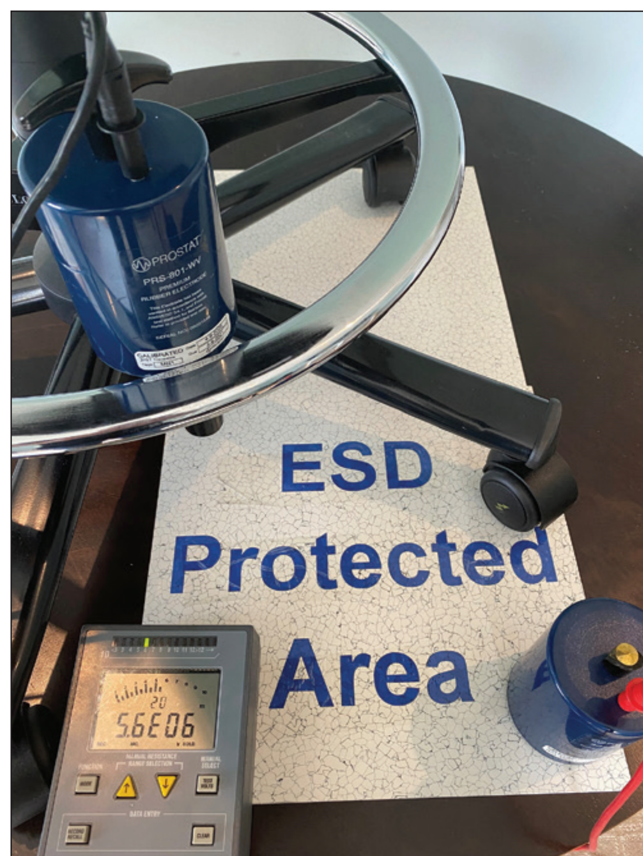

Figure 10: A conductive vein matrix ensures compliant grounding.

The only way to make an accurate determination is by conducting a statistically valid sampling of resistance measurements using the carts, casters, and flooring that will be purchased by the facility. This should be done before any flooring is ordered. Once a floor has been installed, it is too late to address the problem. Most flooring manufacturers do not provide data or warranties involving caster contact resistance.

ESD VINYL AND RUBBER WITH CONDUCTIVE VEIN TECHNOLOGY

If we place the same paper with the caster contact-sized viewing window on an ESD vinyl tile made with a tight matrix of conductive veins, we can move the window any place on the tile and still see veins. Due to the tight distance between veins in this conductive matrix, it's impossible to find an area of the floor that is not conductive. This tight matrix of conductive veins increases contact opportunities between tiny caster surfaces and the conductive elements in the tile. Any place we see veins, the conductivity in the tile will ground chairs and carts.

ESD vinyl tiles made with conductive vein technology contain approximately 150 linear feet of conductive veins per square foot. To put this in perspective, the veins on thirty-six tiles provide one linear mile of conductive contact points. With this many conductive contact points, even contact from a single caster yields an ANSI S20.20-compliant measurement 100% of the time. Can this issue be resolved with floors using conductive chip technology?

Figure 8 provides a visual comparison between a low density (LD) dispersion conductive chip floor with a high density (HD) dispersion conductive chip floor. The distance between chips on an LD floor can range between .5 to 5 centimeters within the same tile or sheet. Chip distances rarely exceed .5 cm on an HD chip floor. Chip technology floors can be produced in sheets or rolls for seamless installations. Vein technology floors cannot be made in rolls due to limitations in the manufacturing process. Vein floors are only available as tiles.

CONCLUSIONS AND TAKEAWAYS

ESD floors should be thoroughly evaluated for multiple functions, including compatibility with material handling equipment. There are two main technologies used for producing ESD tile and sheet flooring: conductive vein technology and conductive chip technology. The technology used to produce ESD flooring influences performance. Conductive vein floors outperform low and medium-density chip technology floors in instances where the floor must ground mobile workstations and carts. This is due to an inadequate number of conductive contact points in typical LD and medium-density conductive chip floors. New high-density chip technology solves this problem and offers the same level of performance as conductive vein technology floors.

To wrap up, here are a few key takeaways:

- Don't assume compliant ANSI/ESD S7.1 test results validate a flooring material's ability to ground mobile equipment on casters. STM 7.1 probes make 31 cm^2 of contact. A caster only makes 1 cm^2 of contact.
- Always perform a statistically valid sampling of ANSI/ESD STM 4.1 tests on shelving, carts, and mobile workstations using the ESD floor as ground surface.
- Always move casters and glides between tests. Slight variations in caster location contribute to extreme fluctuations in measurements. Perform tests in multiple areas. Tiles coated with urethane and ceramic exhibit variations from tile to tile.
- Test all potential cart/caster flooring combinations.
- Always use four conductive casters. Use conductive not dissipative casters.
- Never rely on drag chains for mobile workstation ground connections since the contact area is too small.
- Test before you buy. Install a test area of several tiles.
- As always, ESD floors must be tested for walking body voltage generation per ANSI/ESD 97.2.

Troubleshooting EMC Problems Like an MD

First-Hand Lessons From Three Medical Professionals

BY DARYL GERKE, PE

Ever ponder how a physician troubleshoots medical issues in their patients? Neither did I until a consulting client pointed out I was following a medical methodology known as *differential diagnosis*.

Intrigued by the comment, which led me to further investigate how doctors work to fix patients, just like we work to fix EMC problems.

But first, a little background…

Early in my EMC consulting career, a client asked me to explain each step as we worked to improve ESD immunity on an existing product. In addition to solving the problem, he wanted to better understand my thinking process. Fair enough, I thought.

At one point, I laid out a fault tree of possibilities, along with prescribing a short course of action. As it was getting complicated, I apologized for any confusion. The conversation went something like this:

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"Not a problem," my client said, "you are doing differential diagnosis."

"Stop," I said. "What did you just say? And where did you hear that?" Joking, I added, "I'm a consultant — we make our living with buzz words like that."

Laughing, he responded, "It is a medical term. My brother-in-law is a physician, and we often discuss troubleshooting methods."

This began my fascination with how doctors troubleshoot problems. In this article, I'll share three concepts — *differential diagnosis* (DD), *gross and microscopic diagnosis*, and *the 90 percent rule*. All were the results of conversations with medical doctors over the years, in reverse chronological order.

DIFFERENTIAL DIAGNOSIS

A few weeks after my initial introduction to this concept, I struck up a conversion with a seatmate on a cross-country flight. Upon learning he was a doctor with the Mayo Clinic, I asked about DD and was treated to a most interesting lecture. After all, he was a teaching doctor and I was a very willing student. Those of us who teach love these situations.

He began by explaining the father of DD was Arthur Conan Doyle (the creator of Sherlock Holmes). Doyle was an MD who also wrote short stories. He had an idea for a detective based on a favorite medical professor who taught clinical diagnosis. As we all know, the rest is history. It also explains the presence of Holmes's medical sidekick, Dr. Watson.

The objective is rule things in/rule things out by creating two lists - high probability and low probability. The goal is to quickly narrow down a large list of potential causes to a smaller list, maybe even one likely root cause.

For example, if a patient presents with a red rash, there may be a hundred or more possibilities. Maybe it is the measles, or maybe it is bubonic plague. The first step is looking at vitals (temperature, blood pressure, etc.), which helps quickly eliminate possibilities.

The next step is the physical examination, along with detailed questions. Sometimes an immediate diagnosis can be made — other times additional tests may be necessary.

At that point, the prescription can follow — but not before. As the Mayo doctor on my flight emphasized to me, "Prescription without diagnosis is malpractice." As an aside, how many of us have performed EMI tests or thrown solutions at the problem without thinking it through? Think like a doctor instead.

If there are multiple possibilities, address the likely simple ones first (Occam's razor.) The doctor shared another medical saying: "If you hear the sound of hoofbeats, don't assume zebras." It is probably a horse (unless you are in Africa). As technical people, we all like to sink our teeth into a juicy problem, but most problems are simple.

On rare occasions, however, it well may be a zebra. He pointed out the Mayo Clinic often deals with zebras. There may be 100 possibilities, of which 99 have been ruled out by previous doctors, making it simple to identify the zebra. This is why it is important to ask what has already been done to address the problem.

For many non-EMI engineers, all EMI problems seem like zebras, rarely seen but still common for those of us in the EMI trenches.

Start with the highest probability, as that has the best chance of success. If that does not work, move on to the next item on your list. Remember, "If at first you don't succeed, try again..." Solving EMI problems is often a process of elimination.

So what steps should we follow? Years ago, I learned a simple framework for attacking problems with the acronym ACT (aware, critique, try.) The last step in the framework is very important to avoid paralysis by analysis — eventually one must try something, but best to have a logical approach. Or at least a plausible hypothesis.

Aware—First, gather information.
Begin with four key questions:

1. What are the symptoms? (Equipment issues.) Focus inside the equipment. Think like a doctor, and ask where does it hurt? When did you first notice the pain? What else is wrong?
2. What are the likely causes? (Environmental issues.) Focus outside the equipment. Three likely suspects for upsets/failures are ESD (electrostatic discharge,) RFI (radio frequency interference), and power disturbances.
3. What are the constraints? (Systems issues.) Focus on the cost of failure not the cost of components. Once you find a solution, you can then optimize for cost. Determine constraints like no mods to circuit boards, etc. And watch out for wishful thinking.
4. How will you know when it is fixed? (Success issues.) Establish a goal and a method to validate it. For chronic problems, this might include no field failures for six months, etc. But do have a measurable objective.

Critique—Next, sort and prioritize the information

This is where you apply differential diagnosis. The goals are to rule out the least likely scenarios and determine the most likely. It is all about probabilities and priorities. Don't discard the low probabilities - you may need them later. Remember the zebras — occasionally you will find one. But don't chase them first, no matter how interesting.

Try—The last step

Start with the highest probability, as that has the best chance of success. If that does not work, move on to the next item on your list. Remember, "If at first you don't succeed, try again…" Solving EMI problems is often a process of elimination.

However, if something is very simple, go ahead and try that first. I learned this the hard way chasing a problem for several days, only to discover moving a simple ground connection solved it. A bit embarrassing but my client was still happy to have the problem solved.

A bonus to the above. Assuming a one percent probability of success, that still means that one time in a hundred you will succeed. When that happens, everyone will think you are a genius. So be sure to pick the low-hanging fruit first.

Two caveats as you try. First, start with an open mind — don't fight last year's battle. Second, don't be too scientific and try only one thing at a time. Rather, stack the fixes up. EMI problems are often like a leaky boat — if you have multiple holes in the boat and only patch one at a time, you will never succeed.

Finally, don't be afraid to change directions. I've solved more than one problem by just starting over, asking "What if up was down?" These are often the most interesting problems when solved, as one is left musing, "Who would have thought?" And those cases make for great EMI war stories to share later.

GROSS AND MICROSCOPIC DIAGNOSIS

I learned this troubleshooting technique from a pathologist years prior to EMC consulting. Moonlighting at the time, I was engaged to help automate a hospital pathology lab. It was one of the more interesting consulting projects in my career. Not for the squeamish, though — my pathologist had buckets of preserved human hearts on a bookshelf. And we think EMC engineers are weird?

Most of us assume pathologists spend their time in ghoulish activities like autopsies, but they also serve as quality controls on hospital procedures like surgery. For example, if a surgeon removes an appendix (or anything else), the tissue is not just thrown away. Rather, it is sent to the pathology lab for a two-step procedure. Even a small hospital may run several thousand samples per month. Thus, the need to automate the process.

The first step is the gross diagnosis, that is, a quick visual inspection. "Yes," the pathologist says, "this looks like a

First, go with the diagnosis/treatment that works 90% of the time. If that fails, go with the next 9%, and so on. Or as we say in the engineering world, first try Plan A, then Plan B, etc. Always good to have those alternate plans in reserve.

diseased appendix." But then it is tagged and may be preserved and sliced and diced for further investigation.

The second step is the microscopic diagnosis, occurring sometime later. Typically examined under a microscope, this may be done by the same pathologist or another — it doesn't matter. If the microscopic diagnosis does not match the gross diagnosis, no harm/no foul. It just means we now have more detailed information.

I find this useful when dealing with EMI problems, particularly when people are in a panic and want a quick answer. I'm often able to give the gross diagnosis, but I remind them that this may change upon additional information or test data.

Explaining this helps manage expectations, and also gives me permission to change my own mind. No, it is not flip/flopping — it just means we now have a better handle of the problem. If pressed, I often share the pathologist story to explain my change in EMI diagnosis.

THE 90 PERCENT RULE

I learned this troubleshooting technique as a young EMC engineer. We drank a lot of coffee in the EMC lab (too much really) and I ended up with an occasional irregular heartbeat. In my mid-20s, this was a bit scary and sent me to my doctor.

After a few quick questions, including my coffee consumption, I was advised to cut back on the caffeine. Pretty simple, right? Except it did not resolve the problem. So back to the doctor I went.

He next prescribed some kind of pill, and it worked and after a few months was no longer needed. But being the curious engineer, I asked why the initial diagnosis did not work, and also what the next step was if the pill did not work.

My doctor knew I was an engineer, so he asked with a grin, "Does everything you do work the first time?" Well, no.

He then shared his 90 percent rule. First, go with the diagnosis/treatment that works 90% of the time. If that fails, go with the next 9%, and so on. Or as we say in the engineering world, first try Plan A, then Plan B, etc. Always good to have those alternate plans in reserve.

So Plan B worked for me, but I asked about Plan C? My doctor replied, "Well we could get out the scalpel." At that time, I decided Plan C was not in my future.

FINAL THOUGHTS

One more medical story that goes back almost a century. A great uncle of mine was a doctor from around 1900 to 1950. I barely remember him, but his wife (also his nurse) once showed me the little black bag he used on house calls.

An engineering student at the time, I was intrigued with the simple tools of his trade — a stethoscope, a simple surgical kit, and some pretty basic drugs. Yet he was able to troubleshoot medical problems with these tools, along with using the gray matter between his ears. As EMC engineers we can do the same.

I hope these anecdotes and examples help clarify your thinking on troubleshooting, as they have for me. Troubleshoot like a doctor indeed!

Applying ISO 26262 to Power Management in Advanced Driver Assistance Systems

Understanding the Tools and Methods Used to Develop Functionally Safe Power Systems for ADAS Applications

BY CHRISTOPHER SEMANSON

Over the last decade, automotive original equipment manufacturers (OEMs) like Ford, GM, and Tesla have been at the forefront of mobility and advanced driver assistance systems (ADAS), jockeying for a leadership position in this hotly contested, quickly developing field. As these systems advance, with them comes an increase in the number of semiconductor components in the vehicle to support devices like cameras, radars, and modules used to make decisions based on their information.

This has provided an opportunity for semiconductor manufacturers to increase their market share, allowing them to pivot from their traditional base microcontroller (MCU) offerings to highly integrated system on chip (SoC) processors, memory, and power devices. However, as the industry evolves, the question remains for both consumers and OEMs alike, "How can we standardize the development and design of these components across the industry, such that we can satisfy the risk that comes along with these components, while confidently claiming the part functionally safe?"

Enter the first edition of ISO 26262, *Road vehicles—Functional Safety*, which was the industry's attempt at standardizing the development of the components of these large systems to minimize both:

- Systematic risk, errors generated in the design process through a missed requirement cascade or an incomplete analysis; and
- Random hardware faults specific to the malfunction of the device in question.

For roughly the last decade, automotive OEMs have been relying on part 5 of this standard to help them address hardware malfunction at the component level and to establish what the industry considers safe design practices. The result of this analysis has led the industry to focus mostly on the core of each electronic module, the microcontroller, in addition to adopting the failure mode effects and diagnostic analysis report, dependent failure analysis, and their peer reviews.

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And this is how engine, gateway, and body controllers coalesced around what is considered mostly common for functionally safe electronic control units (ECUs). They employ things like dual core lockstep processors, double stored variables, and other safety mechanisms that enhance their coverage metrics to achieve the all-important Automotive Safety Integration Level (ASIL) rating. Building upon part 5 of the standard, and the level of complexity to which automotive systems have ascended, ISO 26262 has expanded its coverage to include part 11, which focuses on semiconductor components, with the goal of simplifying the automotive system by both:

- Combining multiple functions into one large system on chip, thereby creating large SoC devices with multiple power domains, and
- Wanting to simplify wiring such that only one low voltage bus runs throughout the vehicle.

An example of this integration is shown in Figure 1.

This leads automotive system designers to adopt multi-rail, high power, power management devices (PMICs) that have traditionally been reserved for high-end server systems and other highly integrated consumer devices. These devices are capable of splitting one voltage rail into multiple lower voltage rails via integrated switching and linear regulators, in addition to being able to monitor each output. But semiconductor manufacturers who've normally prioritized speed in development to get into a next-generation server socket and are now tasked with applying part 11 to their products, with customers left to determine how to implement them.

To help automotive designers understand what to look for when shopping for PMICs and other power devices, we'll use an analysis containing a hypothetical situation that starts with a simple quality managed (QM) switching architecture for a basic DC/DC converter, then apply the tools ISO 26262 gives us to analyze the possible failures and, finally, present an architecture that attempts to address dependent and random hardware failures. It's important to note that many solutions to the "What makes this device safe?" question exist, so the analysis and mechanisms discussed here are common.

This article isn't meant to be conclusive, and a lot depends on what extra functions are required of the device by the system integrator. But this article will allow you, the automotive module designer or safety manager, to recognize what to look for when shopping for your next power device for your module.

ISO 26262 ANALYSIS TOOLS

In reading through ISO 26262, the standard suggests three widely accepted analysis tools that help the safety manager lead the design team to an understanding of how to create a functionally safe product. These tools are:

- The block diagram;
- The failure mode effects and diagnostic analysis (FMEDA); and
- The dependent failure analysis (DFA).

These tools are suggested for their ability to reduce complexity and allow the team performing the analysis to confidently arrive at a functionally safe design. In this article, we'll review each technique, give examples of how they're used, and then apply them in the safety analysis.

The Block Diagram

Reading through ISO 26262's specification, it's very clear that the authors valued one thing: *avoid needless complexity*

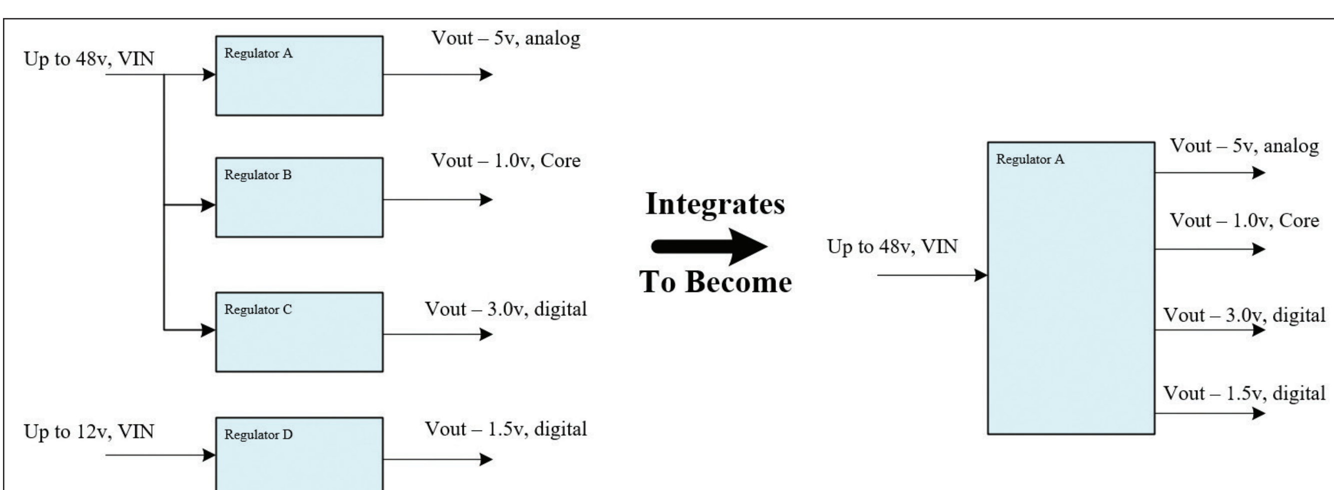

Figure 1: Integrating individual regulators into a PMIC

in the design process. And, if you notice, you'll see that the standard identifies a standard design practice of creating a block diagram to help:

- Abstract the design to ensure that each block has a dedicated function, eliminating the need for needless (and often confusing) mixing of functions, and forcing the designer to plan their design prior to implementing it; and
- Allow the conceptual safety analysis to easily understand information flow and determine where mechanisms need to be implemented, and the design decisions that need to be made in order to create a design free from dependency.

A simple example of such a diagram is shown in Figure 4.

When establishing a hierarchy, it's important to remember. *Abstraction*! Without it, the diagram loses context and becomes a burden to maintain and develop. A recommended rule of thumb is to create a hierarchy not more than three to four sublevels deep, with the goal being to be able to have enough detail such that the box being described becomes self-describing.

Failure Analysis

Before we start performing the analysis that will lead to a summary of commonly implemented safety mechanisms, we first need to review the tools that the specification expects us to employ in the analysis. These tools help the design team identify dependencies between safety mechanisms and the sections each safety mechanism protects, and how to apply commonly accepted failure modes in order to come up with a robust design.

- *The dependent failure analysis*: This analysis tool is designed to help identify dependent failures between safety mechanisms and components they're meant to protect, this is largely requirements driven and is dependent upon the system safety goals.

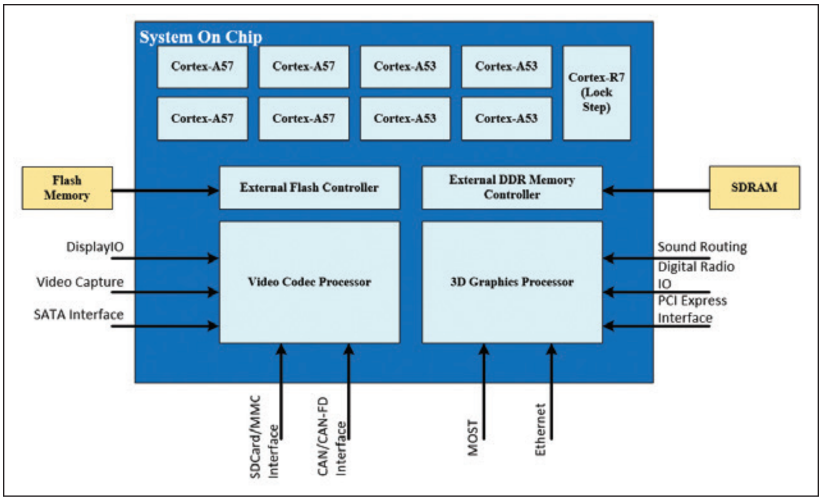

Figure 2: Integrating discrete HW components into a SoC

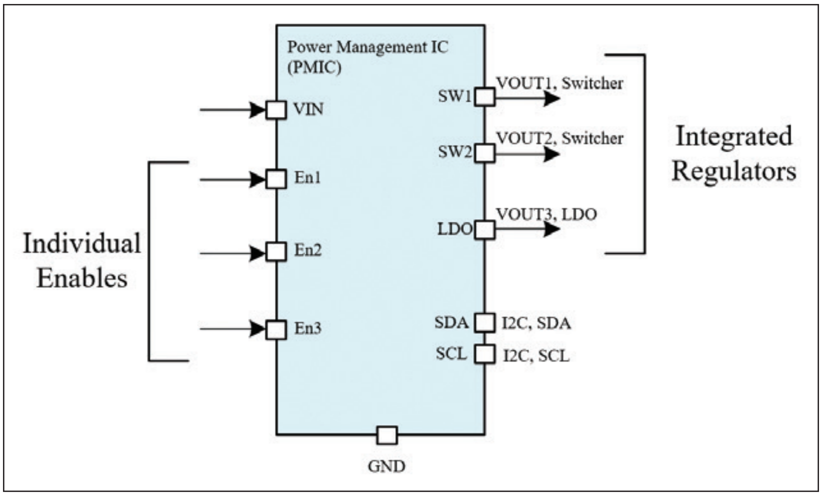

Figure 3: Basic PMIC with 3 outputs

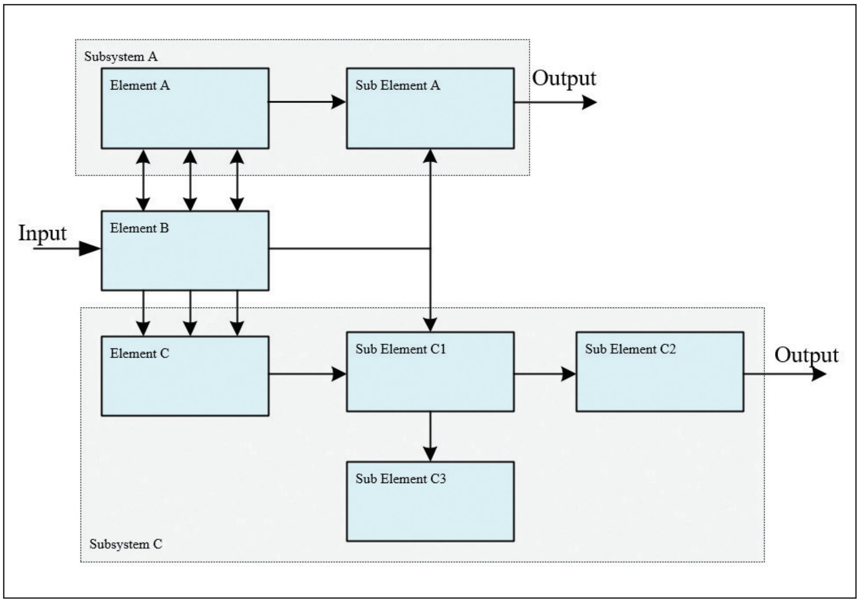

Figure 4: Example system diagram

- *The failure mode effects and diagnostic analysis:* This analysis tool takes into account commonly accepted failure modes such as broken resistor strings and component drift and determines the impact on function of the device. It is also used as a calculator, justifying your safety coverage for an ASIL rating.

These dependencies and failure modes are analyzed within the context of the stated safety goal of the device. The safety goal is the primary high-level safety related function that the device is designed to support. In most power management devices, at the PMIC component level this goal relates to output power monitoring which plays an important role in supporting the system safety concept; this is usually defined in context higher-level function such as providing a self-driving function.

In this article, our example safety goal is to monitor the output for any voltage irregularities and provide a means to notify the system when we're unable to provide this support properly such that they can suspend any safety-related decisions that might be impacted by an output failure.

For the safety manager evaluating devices for potential use in their module, they're mostly concerned with voltage drift, spikes, and oscillations of the output rail, while maintaining the ability to warn the system if any of these occur.

Dependent Failure Analysis

The DFA is an analysis tool that examines the relationship between a safety mechanism and the circuit it is assigned to protect. The analysis starts out by identifying failures that are commonly known to impact more than one system. These include:

- *VCC and ground circuits:* Where drifts, noise, or failures of circuits powering the safety mechanism and the device it powers could adversely impact both.
- *Temperature:* Where an increase or decrease in temperature could impact a mechanism's monitoring accuracy while at the same time decreasing its ability to control something.
- *Shared components:* Where the failure of components like memory buses and other shared devices could impact both a monitor and regulator function.

The DFA helps a design to become free from interference by obtaining dependence, as shown in Figure 5, by addressing cascading faults and common cause faults (CCF).

Companies that have implemented a culture of safety in their design process have defined initiators that that are meant to help guide the design and safety teams in their analysis.

Failure Mode Effects and (Diagnostic) Analysis

While the DFA is used to determine independence to help create a design that is free from CCF and cascading failures, the FMEDA is implemented as a straightforward approach meant to analyze the failures of each component in the design. The goal of the FMEDA is to systematically go through the hierarchy of the design and apply ISO 26262-recognized failure modes to each component to determine the output. Failures covered here were initially introduced in part 5 of ISO 26262 and then expanded in Part 11 in the Second Edition. They include, but are not limited to:

- Resistor failures and component drift
- Soft error rate in memory, and stuck at faults in digital logic circuits
- Data transmission failures, including loss of message, corrupted messages, and unintended message

In the conceptual phase, these faults are applied to the design, mechanisms are created to address the failure modes, and then a quantitative analysis is conducted to

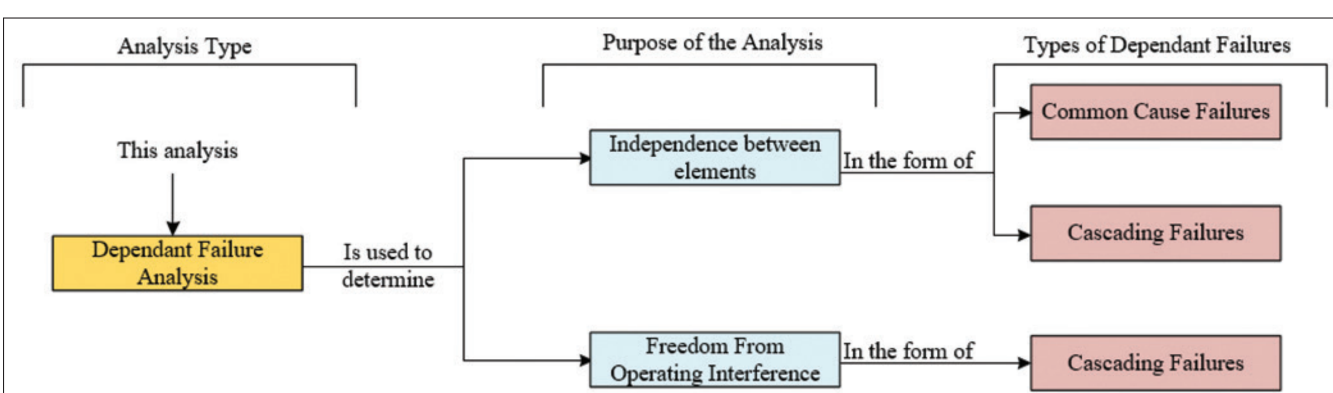

Figure 5: Types of dependent failures

determine exactly how well the mechanism addresses the failure mode. The DFA is conducted to ensure that the device addresses dependencies.

The FMEDA considers faults into multiple classes, two of which include:

- Single point failure mode (SPFM), where the failure of the circuit or device directly impacts the ability for the device to perform a task related to the stated safety goals. An example would be a feedback control loop opening leading to oscillatory behavior.
- Latent fault (LF) failure mode, where the failure of the circuit or device indirectly impacts the ability for the device to perform a task related to the stated safety goal. An example would be a monitor that only outputs no fault due to a short circuit failure; it requires a fault to be impactful to the system.

Latent faults are more nuanced, as their occurrence alone is not enough to impact the function of the system as it relates to the safety goal and requires as a single point fault for impact. Conversely, a single point fault's impact will directly impact the it [the safety goal]. A more complete fault classification is contained Table 1/Figure 6.

The challenges of a FEMDA stem from the fact that it's meant to be an exhaustive analysis. In devices that implement a large number of discrete components (e.g., millions of transistors) it can be a daunting task, which is why it's often paired with a DFA for an exhaustive analysis. The effectiveness of the DFA and FEMDA all depend on how well the design is understood at the time of analysis, which is even more reason for a disciplined design group to have a well thought out design.

Next, we'll use these three tools in analyzing, and creating a functionally safe power management device.

INTRODUCING THE BASIC DC/DC CONVERTER ARCHITECTURE

To design and analyze our conceptual DC/DC converter, we first create a block diagram to set an architecture and establish a hierarchy. By understanding how information flows between major blocks, it will help to dissect the design. A typical power management devices' circuit architecture includes:

- *Voltage reference generation:* This normally includes the bandgap, and a digital to analog converter that provides references to switching converter, monitors, and any other devices that need a bias current or voltage.
- *Internal rail generation:* The internal power domain that provides power to the internal components of the device and sets the voltage input/output (VIO) level.
- *The switches:* These devices span the range of implementation, but in general, this includes the pre-driver and driver circuitry that provide the switching from the input voltage.
- *The PWM control circuitry:* This comprises the entirety of the control loop, which is generally made up of an error amplifier, compensation, and the feedback (either internal or external)
- *Regulator enabling:* In general, these are things that enable or disable regulation such as a power on reset device, over current, over voltage, or over temperature setting, and an external enable.

Type of Fault	Description
SAFE FAULT	Not in safety relevant parts of the logic, or In safety relevant logic but unable to impact the design function
SINGLE POINT FAULT	Dangerous, failure can result in the violation of the safety goal of the device; no safety mechanism to detect this fault.
RESIDUAL FAULT	Dangerous, can violate the safety goal of the system. They are single point faults partially detected by a safety mechanism.
MULTIPOINT FAULT (LATENT)	Faults that do not directly violate the safety goal, but only do so if another fault occurs; for example, in a safety mechanism.
PERCEIVED MULTIPOINT FAULT (LATENT)	Multipoint faults detected by a safety mechanism.

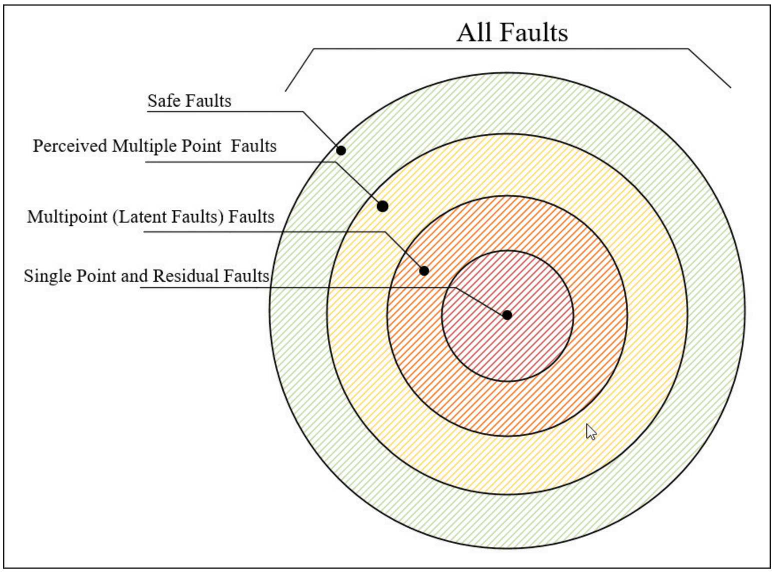

Table 1/Figure 6: Types of faults

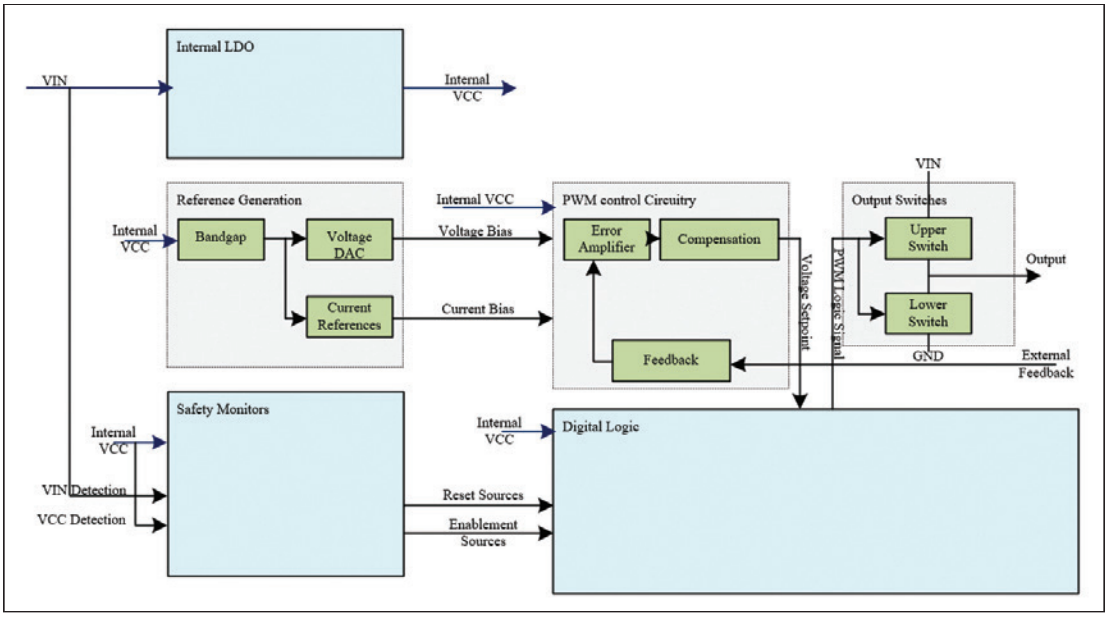

Figure 7: Basic regulation architecture

- *Digital core:* The glue that ties the above together, allowing the flexibility to the marketing manager to option the part out such that it can be programmed to fit multiple different applications.

Together, these systems work to form the basics of a power management device, which is shown in Figure 7.

The full design and implementation of each of these circuits depends upon a wide variety of factors specific to the application. In the following sections, we'll discuss some high-level circuits that make up these blocks, which will allow us to facilitate the completion of our conceptual analysis.

THE SAFETY ANALYSIS

Combining the dependent and failure mode analysis, we can conceptually analyze our architecture and come up with mechanisms and additional architecture enhancements to improve our robustness to hardware failures. While this analysis is not considered to be exhaustive, it will provide some context for a safety manager or product designer evaluating datasheets to compare capabilities.

INTERNAL RAIL AND BIAS GENERATION

In our hierarchy, we start by creating a powertrain used to help generate bias voltages, currents, and an internal rail to power all of our onboard devices. Part of this powertrain will be a voltage DAC that will provide tap voltages for various references around the device.

We define the fault models from the DFA, and come up with the following.

- *Common cause faults:* Where a singular fault leads to two faults in two separate elements (Figure 8).
- *Cascading faults*: Where a fault in one element, leads to the fault in another element (Figure 9).

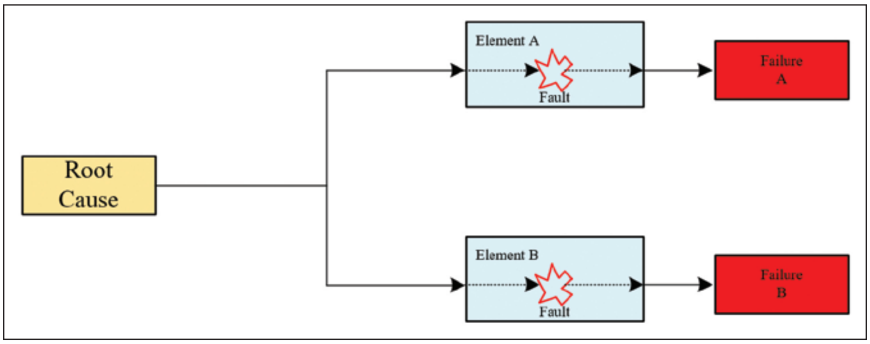

Figure 8: Common cause failure model

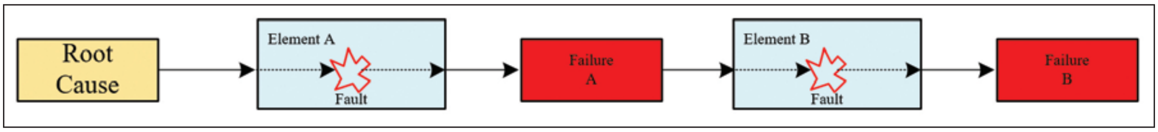

Figure 9: Cascading failure model

Taking these two fault models into context against Figure 7 (the basic regulation architecture), we see that there is only one source of bias and VCC for the entire chip, if that source were to experience a failure mode of either:

- Drift, due to either component failure or temperature; or
- Oscillation, due to loss of feedback in the voltage generation circuit.

Then that common cause fault would impact both the voltage monitor accuracy as well as regulation targets. To address this, the original architecture is modified to be more independent.

Figure 10 illustrates just one way to address this dependency, in which there are separate bias circuits (bandgaps) and voltage DACs to create separate bias points. This reduces the dependency between circuits and is often why datasheets feature a separate safety bandgap or a different voltage domain for their safety devices. Other examples include:

- Distinctly designed bandgaps to prevent both from experiencing the same failure.
- In addition to architectural changes, it is not uncommon to monitor each bandgap against one another, as well as to monitor the source of VCC against a reference over which it has no influence.

The more rigid the safety requirements, the more complex the solution becomes. Now that we've addressed dependencies and discussed the implementation of safety mechanisms in the internal bias and power generation section, we turn our attention to the voltage control loop and output switches.

PWM CONTROL CIRCUIT & OUTPUT SWITCHES AND DRIVERS

Arguably the most important part of a power management device, the feedback loop design is critical since the choice in architecture denotes what type of safety mechanisms are necessary as well as performance. There are a wide variety of control architectures, but in this conceptual design, we'll be employing:

- A voltage control outer loop that utilizes an error amplifier, compensation, reference, and feedback to control the output to a setpoint. In our conceptual architecture, we'll be utilizing external feedback.
- An inner current loop controller that acts as a quick modifier to the setpoint to compensate for load changes. In our conceptual architecture, we'll be sensing current through the (integrated) output switches in terms of high and low side current sensing.

The basic architecture is found in Figure 11.

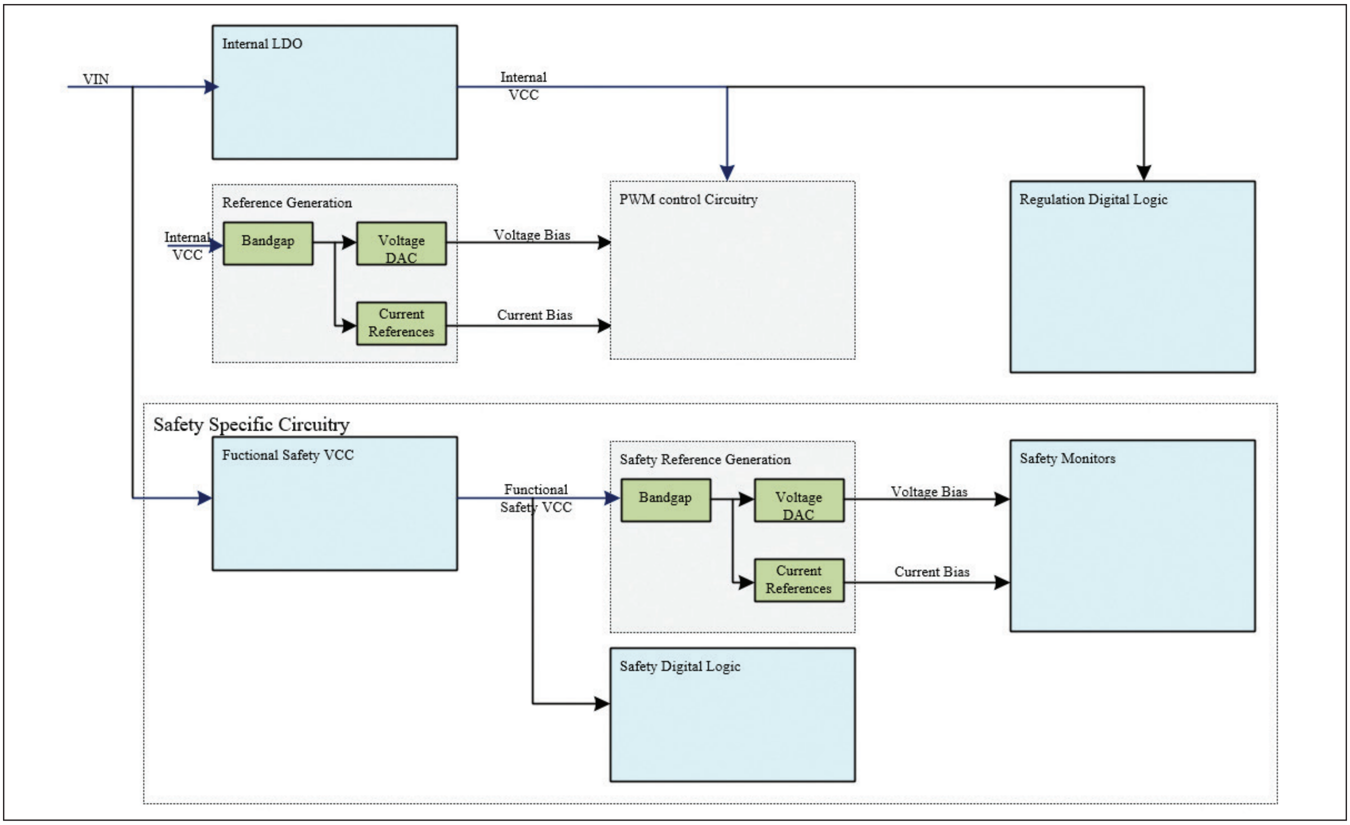

Figure 10: An improved biasing structure, with separate power delivery

While the fully exhaustive analysis would take quite some time, some pronounced examples include the compensation circuit, output switches, and references. The failure modes analyzed are shown below:

- *Failure of the output switches by being stuck high or low:* This would lead to an irregularity in switching and would cause either an output overvoltage, under voltage, over current, and/or over temperature event due to shoot through or directly connecting the output to either ground or VIN.
- *Compensation, which damps the response of the control loop to prevent excessive deviations from the setpoint during a load change, and oscillatory behavior:* A potential failure here would be an overvoltage event or oscillatory behavior if the bandwidth of the controller drastically changes.

First, taking these three failure modes into consideration, we can easily develop two different failure mode protection mechanisms:

- A window comparator which measures for over and under voltage on the output; or
- An over current monitor which senses the current through either the high side or low side switch.

For this reason, the hallmarks of most power management devices are output current and voltage monitoring, and are often done via comparators instead of an onboard analog to digital (A/D) converter. And, taking lessons from our previous section, these output monitors will be referenced with a uniquely powered and referenced bandgap.

Next, we continue with the DFA and automatically clue into the feedback node, which is shared between the regulation and output monitor. If we lose the resistor due to a failure in the resistor divider or if the pin shorts, the device's regulation will malfunction as the target becomes incorrect, and the monitor runs the risk of not catching it. A DFA leads to the following two criteria:

- The device needs to implement two independent sources of feedback to address the dependent failure of the feedback node shorting to another pin or another voltage on the board; and
- This independent source of feedback needs a redundant resistor divider to address the failure mode of any part of the resistor feedback network shorting.

Again, for this reason, it is not uncommon to see a feedback pin and another pin that is used for monitoring. If the feedback resistor is instead internal, then that is redundant and often through a different path. With these additions, we can expand our definition to include an example of what a safety manager or module engineer might see when shopping power parts.

For the last two sections, the design turns its focus to things that are often under the category as monitors instead of the control loop.

MONITORS AND CONTROLS

The monitors and enabling controls are arguably some of the most important circuits in the device. They are comprised of a series of comparators and measurement circuits that make up:

- Over current monitors.
- Power on reset detectors.

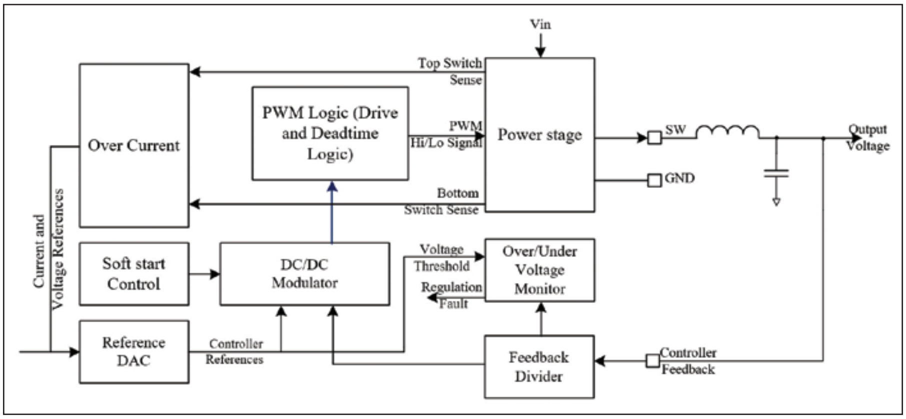

Figure 11: Basic DC/DC modulator, with dependencies in the monitor

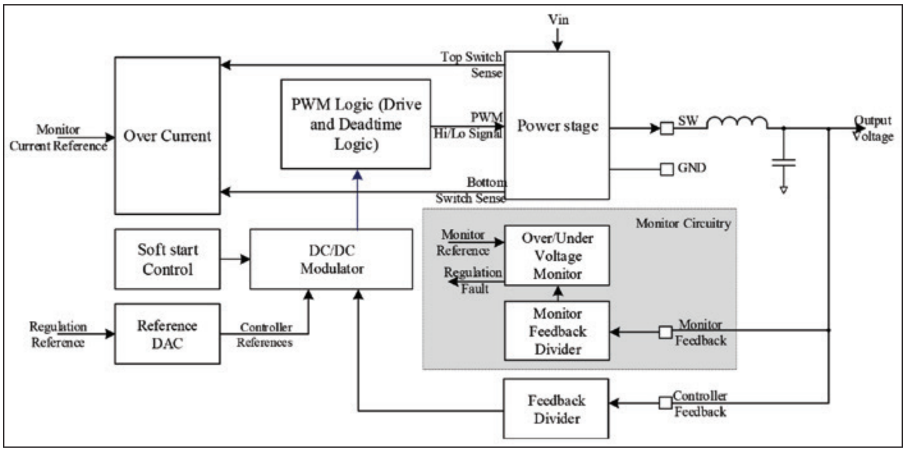

Figure 12: Basic DC/DC modulator, without dependencies in the monitor

- Output voltage (over and under voltage) monitoring.
- Internal clock monitoring

Each of these monitors often have the ability to reset/alert downstream components when an irregularity has occurred. Applying our DFA theory again, we notice that the same situation continues to come up, that is, dependencies in the feedback loop and in how we reference the thresholds for the monitors.

Next, conducting the FMEDA, we apply example failure modes found in ISO 26262 only to the comparator. The faults models here are comparator output stuck at faults (stuck high and low). Of these two faults, stuck low is the more impactful of the two when it comes to monitoring, as the fault occurrence would be missed. In order to increase the device's ability to detect these stuck low faults, which would cause the device to miss a fault in the event of one occurring, you will often see a term ABIST, an acronym for analog built-in self-test.

The process outlined in Figure 13 allows a brief moment in time for the digital part of the device to take control of the comparator input and force the input above or below the trigger voltage in order to see if the comparator circuit works.

After successful determination, the input control is given back, and it becomes a nominal sensing circuit again. This process takes a moment during startup and is why many datasheets mention some sort of ABIST in their feature section as it is a low impact way of checking for stuck faults.

Lastly, we'll examine the brains, the digital core of a mixed-signal regulator.

DIGITAL CORE

The digital core is most likely the closest thing power management devices have to flash memory in terms of implementing configurability. Power management devices often contain the following elements as part of the digital core:

- A wide variety of configurations held in fuses and registers;
- A main high-speed oscillator; and
- A serial communications interface- usually I2C or SPI.

The digital core sits next to the analog parts, as shown in Figure 14, and is often broken up between a section of digital logic that makes functionally safe decisions and a section responsible for startup and control of the regulator.

This architecture is often preferred to mitigate the possibility of dependencies found through a DFA analysis. In order to better understand the breakup of the digital core, see Figure 14, where the main functions consist of:

- Configuration, often in the terms of runtime configuration registers and one time programmable (OTP) fuses;
- Functional safety decision making, often realized as a state machine; and
- Communication, either implemented as a I2C or SPI controller.

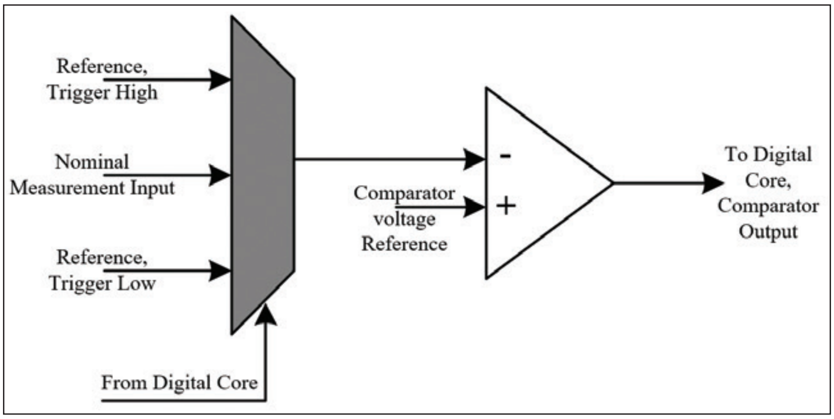

Figure 13: Comparator BIST architecture example

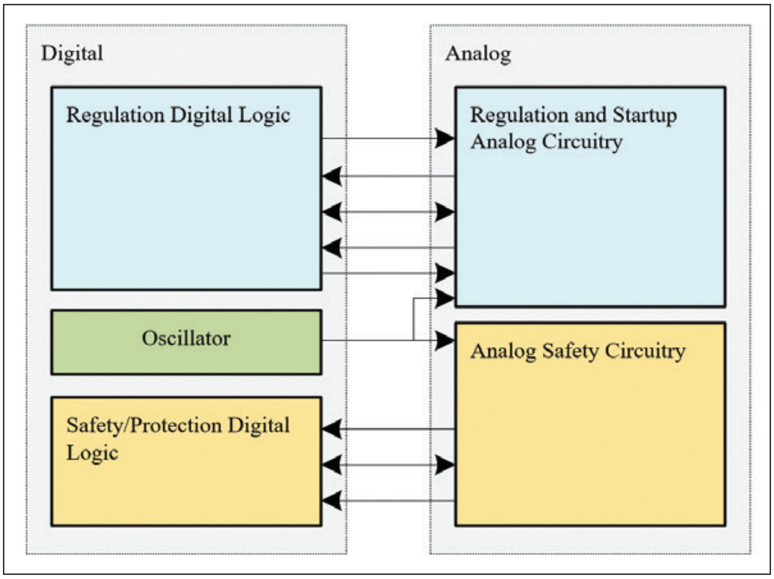

Figure 14: Analog and digital partitioning

Here, the fault modes suggested by ISO 26262 are more aligned to what you would see in a microcontroller setting. We first realize this by applying our FMEDA criteria in terms of bit corruption at the one-time programmable (OTP) fuse array and configuration registers. A failure here could misconfigure the chip, either at startup and during runtime. In order to protect against this issue, an n-bit cyclic redundancy calculation (CRC) is often executed both at startup and periodically on the configuration of the device to ensure integrity. This is also extended to the communication interface, where a CRC is performed on each communication transaction.

While the list of digital safety mechanisms and design options is vast, it is normal to see the following among the top listed as safety mechanisms in addition to the CRC:

- Redundant logic where necessary;
- Clock monitoring; and
- Logic BISTing (LBIST) which, like the ABIST, checks the digital logic for critical stuck faults.

After addressing each main function of our basic DC/DC buck converter and the random hardware failures associated with these sections, our focus turns on how to evaluate metrics and grade the effectiveness.

ASIL FAULT METRICS

The analysis done was qualitative. The process starts with a diagram of interconnections for our power converter and continues by applying industry standard failure modes to each block and reviewing their effects. It continues with the DFA that allows the design team to address dependencies in the architecture, and also allow the device to showcase various safety mechanisms and architectural enhancements that allow for a certain ASIL.

We define the coverage metric as a means for standardizing analysis in a quantitative way across the industry from part to part and manufacturer to manufacturer. This means that if the target for our power converter is an ASIL B system, that would require a specific level of coverage, as opposed to an ASIL D system which requires a higher single point, and latent fault detection coverage. The summary is shown below in Table 2.

And often, you will see comments in the datasheet like "supports applications up to," which often means that during the analysis, certain assumptions were made that, if followed, would allow for the system to make up for the lack of detection.

Before you begin reviewing your supplier datasheets or before you begin designing, I recommend that you review ISO 26262 as the specification provides an overview of common ways of dealing with faults and provides strategies for low, medium, and high coverage which the industry recognizes. An example is shown in Table 3, but as always, refer to your copy of ISO 26262 for a comprehensive list.

CONCLUSION

Functional safety is an evolving area of automotive and industrial design, and the right device can be difficult to find since each semiconductor manufacturer presents their product in the best possible way. With each new design comes a new set of safety mechanisms implemented by the design and safety teams, which the marketing team then uses as saleable features. But, without some basic background, this can lead to confusion.

The conceptual analysis presented in this article is meant to give you, the reader, some tools to understanding why ASIL-rated power management devices have the safety features listed in their hardware datasheet. And, in preparing for your next ADAS design, remember that ISO 26262 outlines the tools needed to address both random hardware and systematic design faults, not just high-level digital components but of standard mixed-signal analog/digital designs as well!

Metric	ASIL B	ASIL C	ASIL D
Single Point Fault Metric	≥ 90%	≥ 97%	≥ 99%
Latent Fault Metric	≥ 60%	≥ 80%	≥ 90%
Probabilistic Metric for Random Hardware Faults (in FIT)	100 FIT	100 FIT	10 FIT

Table 2: ASIL metrics

Safety Mechanism	What the safety mechanism protects	Typical Diagnostic Coverage Considered Achievable	Note
Ram Pattern Test	Volatile Memory	Medium	High Coverage for stuck
Voltage Monitoring	Power Supply	High	Depends upon the quality of monitor
Majority Voter	General System Measure	High	Depends upon the quality of voting
Comparators	General System Measure	High	Depends upon the quality of comparison

Table 3: Safety mechanism and coverage

Controlling Static Electricity: A 50-Year History

The Recognition and Control of Static Electricity Today Has Benefitted From a Continuously Evolving Approach

BY DAVID E. SWENSON, JOHN KINNEAR, AND THE ESDA

It is well understood that static electricity has been with us forever. Our awareness of problems associated with static electricity probably originated with the invention of gun powder when, no doubt, there were some mysterious ignitions that took place during chemical blending operations that could not be explained at the time.

The manifestation of static electricity problems in an industrial setting likely began with Gutenberg's invention of the automatic printing press in 1440.[1] Paper and velum (two different materials) sticking together had to be an issue. Somewhere along the line, it was likely observed that a fire burning in the vicinity of the printing press could magically make the paper less sticky. Flame treatment was used in industrial printing presses back then and in newspaper printing presses well into the 1950s, and perhaps even longer in some areas.

Static control has been practiced in munitions, modern pyrotechnics, petroleum processing, and other industries dealing with explosive and flammable materials for a long time. The grounding of process tools, equipment, and personnel has been practiced since Ben Franklin's time.

The industry we are primarily dealing with today, electronics, did not report any significant static electricity-related issues until the later stages of the 1960s. Changes in the resistance values of some shipments of carbon resistors appear to be the first reported issue associated with static electricity in any electrical or electronic-related products. The development of metal-oxide-semiconductor (MOS) devices caused many issues in the early days of modern electronics manufacturing. Early advances in disk drive technology and the manufacture of read-write heads were almost brought to a stand-still in companies due to the fallout from static damage.

David Swenson has been a member of the ESD Association since 1984 and has served in several key Association leadership positions over his long career. He has received numerous Association and industry awards for his work, most recently the EOS/ESD Symposium David F. Barber Sr. Memorial Award in 2018. Swenson is also the convener of Joint Working Group 13 between TC101 and TC40 (Capacitors and Resistors). He can be reached at static2@swbell.net.

John Kinnear is an IBM senior engineer specializing in process and system technology, and facility certification in accordance with ANSI/ESD S20.20. He has been a member of the ESDA for more than 30 years. Kinnear also serves as the appointed technical advisor to the U.S. National Committee/IEC technical committee 101, where he works to support the international adoption of ANSI/ESD S20.20. He can be reached at john.kinnearjr@gmail.com.

The EOS/ESD Association, Inc. (ESDA) was formed in 1982, following the success of the initial EOS/ESD Symposiums. The founding members of the ESDA naively believed that the Association and its annual Symposium would be needed for just a few years, after which it could be disbanded.

THE ORIGINS OF MODERN STATIC CONTROL EFFORTS

Our review of the history of modern static control begins in the late 1960s. The first materials used for static control then were carbon-filled conductive plastics and organically treated plastics that created low charging materials (known as antistatic materials at the time). These materials were distinctly different in performance and application requirements. When these material types were used in combination for packaging electronic parts for storage and shipment, they made a highly effective static control packaging product. But this happened infrequently due to the competition between the companies that made these materials.

Grounding systems for people were already available, with innovators coming up with new concepts in wrist straps and shoe grounding devices. Varieties of these systems and concepts had been used for a long time in munitions and chemical processing facilities, but they were somewhat cumbersome and uncomfortable to use in the typical electronics assembly operation. The new designs were lighter in weight and easier to use, so they became the first line of static control in the growing electronics industry.

Special worksurfaces and flooring materials began to enter the marketplace in the middle 1970s and helped to establish what we know today as the electrostatic protective area or EPA. At about the same time, standards for military and defense-related applications entered the market, which helped support the development of industry specifications for the workplace and packaging materials. Damage to electronic parts was becoming a significant reliability issue in the later part of the 1970s. In fact, the first EOS/ESD Symposium was convened in Denver in 1979 to discuss the issues of the time, predominantly those dealing with military electronics.

Packaging innovations eventually led to the invention of transparent static shielding films used to make protective static discharge shielding bags. By the early 1980s, these film materials became ubiquitous throughout the electronics industry, and the need for further electronics packaging standardization became more obvious.

In response, several industry groups emerged around that time. Leading the way was the Electronics Industry Association (EIA), which established the Packaging of Electronics for Shipment committee (PEPS). The EIA PEPS Committee ultimately drafted EIA-541–1988, *Packing Material Standards for ESD Sensitive Items*, the first commercial standard devoted to packaging materials used in the storage and shipment of ESD susceptible electronic devices.

THE ROLE OF THE ESDA IN STANDARDS DEVELOPMENT

The EOS/ESD Association, Inc. (ESDA) was formed in 1982, following the success of the initial EOS/ESD Symposiums. The founding members of the ESDA naively believed that the Association and its annual Symposium would be needed for just a few years, after which it could be disbanded. But this turned out not to be the case, and plans are now in the works for the 44th EOS/ESD Symposium, currently scheduled for September 2022.

The ESDA formed its own Standards Committee in 1982 and immediately started work on Standard #1, *Wrist Straps*, since that was viewed as the front line of protection at the time. That standard served as the foundation for the development of other standards, standard test methods, standard practices, and advisory documents over the ensuing 40 years that have helped establish specifications for most of the products used for static protection and mitigation. And the emergence of automated handling and assembly operations has required the development of new ESD control standards and test methods to manage static electricity developed within such equipment.

The period from the late 1980s to the late 1990s saw a massive amount of work in standardization. Just about all the static control products available today were the subject of some level of standards activity during that period. Over time, many of the ESDA's standards, test methods, standard practices, and technical reports have been reviewed and revised several times since their original release. Today, the standards development effort within the ESDA is still going strong, with the participation of 200 active members worldwide.

THE SHIFTING LANDSCAPE OF STATIC CONTROL EFFORTS

During the same period, the electronics industry shifted major portions of its manufacturing activities to locations around the world. Large factories employing thousands of people for manual assembly operations were established. But there was a steep learning curve in efforts to produce high reliability in device fabrication (wafer fabs), circuit board assembly, and equipment assembly. Large offshore factories with huge numbers of employees required extensive training, massive installation of electrostatic protection products and materials, and frequent travel by corporate-based management and technical staff to oversee product control and maintain quality.

The development of local expertise to manage static control issues became a priority in the late 1990s to the early 2000s, and many of the current members of the ESD Association represent companies and operations from outside of the U.S. Arguably, the most far-reaching static control standards activity occurred in 1995 when the U.S. Department of Defense (DoD) formally asked the ESD Association to take the lead in the development of a new, state of the art, ESD control program standard for commercial and military users. That effort ultimately led to the introduction of ANSI/ESD S20.20–1999, *Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)*, which was quickly adopted by the DoD and several branches of the military.

Around 2000, DNV, an ISO 9001 Certification Body, proposed that the ESDA adopt a facilities audit program in connection with ANSI/ESD S20.20, eventually leading to the ESD facility certification program. Today, there are several hundred certified facilities around the world. Other certification programs were developed subsequently to that initial effort, most notably the ESD Certified Professional Program Manager certification and the ESD TR53 Certified Technician certification.

THE EMERGENCE OF STATIC CONTROL MEASUREMENT TOOLS

As the electronics industry created standards and materials to control static electricity, measurement tools were needed to validate the materials and to evaluate the manufacturing processes. Original validation equipment typically consisted of a high resistance meter, called a megger, and an electrostatic field meter. The megger was designed for measuring the electrical system to ground (or insulation) resistance. The typical voltages first used for measurement were 500 to 1000 volts. As materials to control static electricity and the standards to measure them were further developed, resistance measurement voltages were revised to 10 and 100 volts to create more measurement sensitivity and to help ensure that the materials and products could perform their intended function in an EPA.

The evaluation of static control materials at low relative humidity also has become a requirement to make sure the product maintains its specifications and performance attributes at the lowest environmental moisture condition expected. Electrostatic voltmeters were developed along with a device called a charge plate monitor to measure ionization.

THE CHALLENGES OF AUTOMATED PRODUCTION

The emphasis today in comparison to the early days relates to automated electronics processing. It is well understood that personnel must be grounded all the time when handling unprotected susceptible items. The most significant change in the grounding of personnel has been the increased reliance on footwear and flooring. Wrist straps are still used by the millions every year since they are a requirement for seated operations in the ESD Control Program development standards ANSI/ESD S20.20 and IEC 61340-5-1, *Electrostatics-Part 5-1: Protection of Electronic Devices from Electrostatic Phenomena – General Requirements*.

Footwear and flooring test methods now have significant importance since mobile personnel are required to operate and maintain automated process equipment and assembly lines. The electrical resistance to ground and voltage of personnel while in motion are important considerations for the modern EPA. The instrumentation for measuring and recording voltage on people has become arguably the most essential tool in the ESD control practitioner's toolbox.

Testing device susceptibility to ESD events has been the subject of standardization for well over 50 years. For a long time, separate industry standards existed for the evaluation of the human body model (HBM). Today, the HBM requirements and specifications have been harmonized into a single harmonized HBM standard through a joint effort between the JEDEC Solid State Technology Organization and the ESDA.[2]

Similarly, the susceptibility of devices during automated handling have been harmonized in a joint charged device model (CDM) standard.[3] The ESD susceptibility test method known as machine model (MM) has been dropped as a device qualification standard since the damage mechanism is much the same as HBM, only at a lower threshold.

Over the last 5-8 years, there has been further development to connect device testing specifications and susceptibility levels to what happens in the factory during production. What is called process assessment has become one of the important activities of the ESDA standardization activity. The effort is providing test methods and techniques for the evaluation of electrostatic charging and ESD events within automated handling equipment. One technical report is now available,[4] and a standard practice[5] was released in 2021.

These documents, along with new measurement tools such as the high impedance contact voltmeter and event detector devices, will provide knowledgeable practitioners with valuable tools and insight for the evaluation of automated handling equipment capabilities. The question "What device sensitivity/susceptibility level can my process handle?" will be easier to answer using the new documents and new tools.

CONCLUSION

The physics of electrostatics has not changed over the decades, but the ability to measure and protect from the phenomenon certainly has. Materials science and innovation have led to vast improvements in products used to control static electricity in the workplace. ESD standards and test methods have brought a level of understanding into an area that was once considered black magic.

ENDNOTES

1. Childress, Diana, *Johannes Gutenberg and the Printing Press*, Minneapolis: Twenty-First Century Books, 2008
2. *ESDA/JEDEC Joint Standard – For Electrostatic Discharge Sensitivity Testing – Human Body Model (HBM) Device Leve*l, ESD Association, 7900 Turin Road, Bld. 3, Rome, NY 13440, 315-339-6937, http://www.esda.org
3. *ESDA/JEDEC Joint Standard – For Electrostatic Discharge Sensitivity Testing – Charged Device Model (CDM) Device Level*, ibid
4. *ESD TR17.0-01-14 ESD Association Technical Report – For Electrostatic Discharge Process Assessment Methodologies in Electronic Production Lines – Best Practices Used in Industry*
5. *ESD Association Standard Practice – For the Protection of Electrostatic Discharge Susceptible Items – Process Assessment Techniques*, ibid (not published at time of this writing but coming soon)

Protection of High Voltage Power Substation Control Electronics from HEMP and IEMI

An Approach Using EMC Standards

BY DR. WILLIAM A. RADASKY

This article describes an approach for hardening high-voltage power substation control electronics from high-altitude electromagnetic pulse (HEMP) that would occur if a nuclear weapon were detonated in space. While we hope that this type of electromagnetic event never occurs, it is a possibility, and the impact on unprotected electronics and the power grids that they control could be severe. In the case of HEMP, a single high-altitude nuclear burst could expose thousands of power substations to high-frequency transients within one power cycle, creating essentially a simultaneous distributed event for which the power grid was not designed.

While the emphasis for this article will be on the protection from early-time (E1) HEMP, it will also discuss the additional efforts that can be made to protect the electronics from intentional electromagnetic interference (IEMI) produced by electromagnetic weapons. By considering both the E1 HEMP and IEMI together, we cover the main high frequency transient high-power EM (HPEM) threats that have become important in recent years.

As described in the work in IEC SC 77C, while high power electromagnetic (HPEM) disturbances are low probability events, they can be protected against with existing protection technology and often at low cost. The field of electromagnetic compatibility (EMC) is well established, and methods for shielding against electromagnetic fields and attenuating conducted transients are widely known. The main issue is to determine the requirements for these protective elements as they relate to E1 HEMP and IEMI.

This article focuses on the fact that the electronics found in the control houses of electric power substations are already exposed to high levels of natural power system EM transients and are therefore required to have immunity against high levels of radiated and conducted transients. The major generic EMC standards for establishing immunity tests and test levels for electronics placed in control houses are set forth in IEC 61000-6-5 [1]. By considering the basic immunity of the electronics in the control houses for EMC and the external HEMP and IEMI radiated field waveforms and their coupling to

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external cables outside of the control house and internal cables (thereby creating conducted transient disturbances), protection methods can be established. The recently developed IEC 61000-5-10 [2] provides different strategies for protection for both new and retrofit applications, relying on several other published IEC SC 77C standards.

In this article, we'll first review the basic HEMP and IEMI electromagnetic waveforms as discussed in our previously published article in *In Compliance Magazine* [3]. Next, we'll describe the basic layout of high voltage substations and the electronics found in a substation control house. Then, we'll discuss the EMC immunity requirements for the control electronics and how these can be leveraged to determine the specialized HEMP/IEMI protection methods. Following this discussion, we'll share and describe the techniques for rapidly assessing the existing shielding and penetration protection of an existing control house. Finally, we'll discuss some of the protection options available.

HEMP/IEMI ENVIRONMENTS

As described in [3], high-altitude HEMP is defined as three separate waveforms as shown in Figure 1. The waveforms are described as early-time, intermediate-time, and late-time waveforms, and they are also described more briefly as E1, E2, and E3 HEMP. The IEC has standardized these waveforms, which can be found in IEC 61000-2-9 [5]. In this article, our focus will be on E1 HEMP, as the electronics in the control house are most impacted by this high-frequency waveform. There are possible effects on these electronics that could occur due to harmonics in the power supply system attributable to E3 HEMP, but this aspect is under evaluation in separate research projects.

Figure 2 describes in the frequency domain the relationship between early-time (E1) HEMP and IEMI environments that can be produced from electromagnetic weapons. It also indicates at lower frequencies the typical levels of lightning electromagnetic fields from very near cloud-to-ground strikes. It is important to understand that, while lightning currents and fields are very energetic, they do not extend significantly above 1 MHz in frequency content, as do both the E1 HEMP and IEMI. This means that most grounding and bonding methods used for lightning are not sufficient for the higher frequency content E1 HEMP and IEMI. This will be discussed later in this article.

LAYOUT OF HIGH VOLTAGE SUBSTATIONS AND CONTROL HOUSES

Power substations are built for transmission grids at high voltages above 100 kV and, in the United States, at extra high voltages (EHVs) above 345 kV. A majority of the power moved by transmission power lines in the U.S. is at a voltage of 500 kV. These higher voltages move high power levels over long distances from power plants to areas where power is needed by industry and homes (this is still true today, despite local renewable power sources). Inside the power substation fence, the high voltages are stepped down to lower high or medium voltages for distribution to customers.

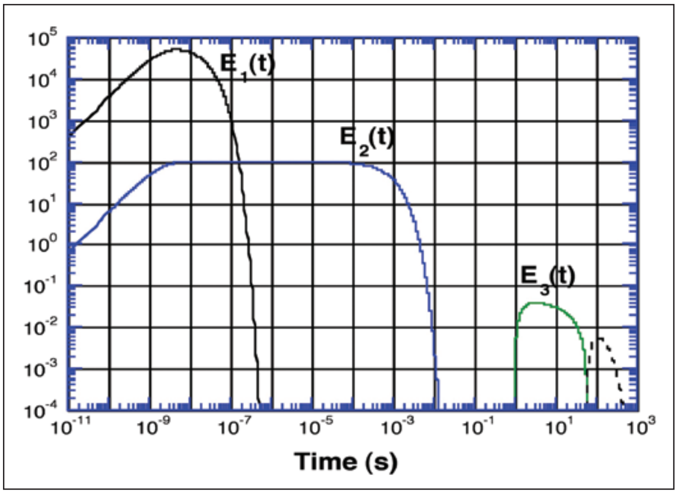

Figure 1: Graphical description of three analytic functions that describe the early-time (E1), intermediate-time (E2), and late-time (E3) HEMP as described in [4]

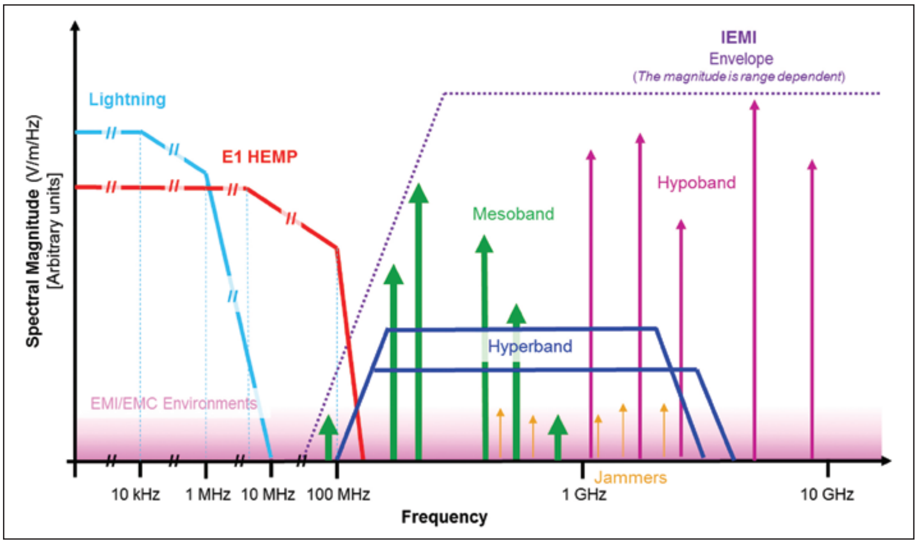

Figure 2: The relationship of IEMI electromagnetic fields in the frequency domain to the E1 HEMP and an example of nearby lightning EMP fields from a cloud to ground strike [6]

There are also distribution substations found within towns and cities, but the focus of this article is on the transmission substations due to the much higher amount of power passing through the substation. The loss of power flowing through a few transmission substations in a region can create a severe power supply/load imbalance that can result in a power blackout.

As long transmission lines arrive at a power substation, there are sensors on each line to monitor the current and voltage levels arriving at the substation (known as CTs and VTs). These sensors have low voltage cables attached that run (as shown in Figure 3) to a control building (often referred to as a control house), where these currents and voltages are monitored using mainly solid-state protective relays.

As a simple example, if the voltage on a line decreases rapidly and the current increases sharply, this could be an indication of a line being grounded to a tree, and the relay receiving this information will send a signal to a circuit breaker (along another cable) to disconnect the power line from the step-down transformer to avoid damage. These relays are programmed ahead of time to determine what levels will trigger such a response, and actions are taken automatically without human intervention. These protection relays are therefore critical to the operation of a power substation and the overall power grid.

Inside the control houses, most of the control cables used today are not shielded. However, there are often ground wires or cable meshes that are grounded to an internal grounding system inside the building (see Figure 4). From an E1 HEMP or IEMI point of view, grounding cables inside of a building is not the best approach as the induced currents from E1 HEMP and IEMI will flow on these cables inside the building and will create electromagnetic fields that can couple to the internal wiring and to the nearby electronics. In addition, the use of wires is not effective in grounding high frequency transients as the inductance of a grounding wire is more important than the wire resistance. As we'll discuss later, using shielded control cables and grounding them outside of a building will greatly reduce the conducted and radiated EM disturbances that can create failures to the operating solid-state equipment.

It is important to understand that for both E1 HEMP and IEMI the electromagnetic transients are created external to the building. There, they couple to external cables, external antennas, and interact with the walls of the control house to penetrate to the inside through apertures (for air flow and doors, for example) and through nonmetallic walls such as concrete.

Figure 3: A trenway (or trench) containing multiple cables running from the power line sensors to the control houses which contain the protective relays. Covers are sometimes metal, but often concrete, fiberglass, or wood, and the bottom and sides of the trenways are usually nonmetallic.

Figure 4: Typical cable grounding and junction box connections inside of a control house.

Figure 5 illustrates the types of aspects that should be considered for the penetration of external fields and voltages into a control house.

However, it is important to note that not all of the penetration features are equally important for E1 HEMP and for IEMI. For example, the coupling of E1 HEMP to buried cables is much stronger than for IEMI, as the IEMI fields at higher frequencies are significantly attenuated in the ground. On the other hand, wiring above the ground is well exposed to IEMI environments, and apertures in the walls of the building allow more penetration of the IEMI environments. GPS antennas are also at risk due to jamming by IEMI. Later in this article, we'll address in greater detail the protection options for these different types of radiated and conducted penetrations.

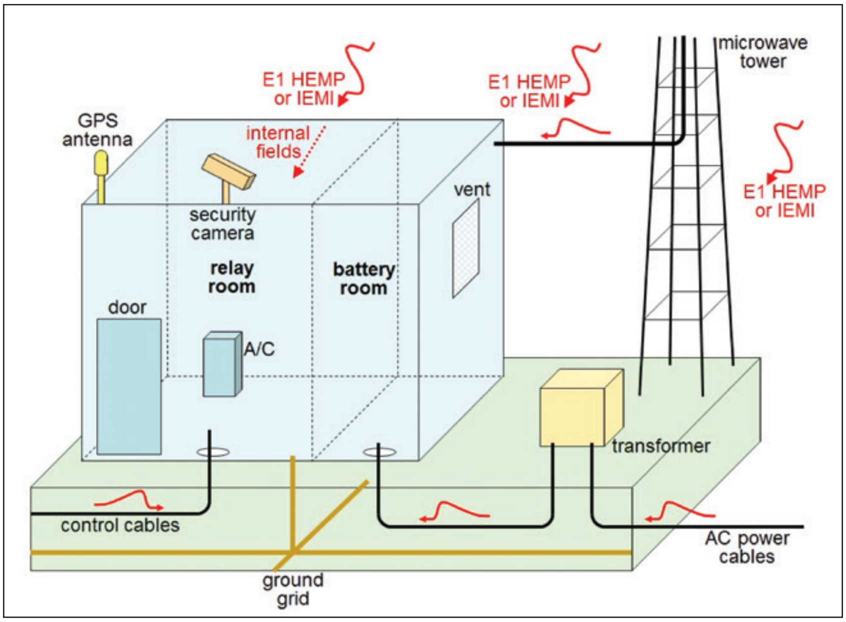

Figure 5: A general example of a typical control house showing the ways that E1 HEMP and IEMI environments could penetrate the building (AC enclosure is mounted on the external wall).

EMC IMMUNITY REQUIREMENTS FOR CONTROL HOUSE EQUIPMENT

It is well established that the normal electromagnetic environments are severe situations for electronics in power control houses due to the nearby presence of high voltage and current lines. While it might appear that the main EM disturbances are associated with 50 or 60 Hz, it turns out that connections and disconnections of high voltage circuits create a disturbance known as the electric fast transient (EFT) in low voltage control cables. The IEC test waveform for the EFT [7] is a 5/50 ns (10-90% rise time/ 50-50% pulse width) which is repeated at a frequency of up to 100,000 times per second. It is also noted that this same waveform is recommended for testing of conducted E1 HEMP transients (although only 1 or 2 pulses) [8], as it represents a typical conducted E1 HEMP waveform.

In addition, due to the presence of transmission lines and busbars within a substation, there is the possibility of nearby lightning strikes. Cloud-to-ground lightning strokes will create currents that will flow to the electronics through the control cables, and the IEC recommends a 1/50 microsecond voltage transient to test the low voltage electronics inside of a control house [9]. It is important to note that according to IEC 61000-6-5 [1] power substation equipment should be tested to the highest levels of these two tests due to their severe EM environment. IEC 61000-6-5 recommends many additional EMC immunity tests to be performed for power system electronics, but these two pulsed tests are the most important for their relationship to E1 HEMP and IEMI.

While it is important to reduce the external radiated and conducted environments associated with E1 HEMP and IEMI, we wish to make the important point that, due to the severe EMC tests required for the individual electronic boxes, the reductions required for the radiated and conducted transients from E1 HEMP and IEMI are not as large as would be required for commercial or industrial electronics.

ASSESSMENT METHODS TO EVALUATE EM STATUS OF CONTROL HOUSES

For existing buildings, it is important to evaluate the situation with respect to the attenuation of electromagnetic fields and conducted currents and voltages as they relate to the specific threats of E1 HEMP and IEMI. Two initial aspects need initial attention: 1) the determination of the shielding effectiveness of the control house itself; and 2) the physical examination of the cables as they enter the building. Fortunately, most power companies use specific methods to construct their control houses and specific types of control cables, including trenches between the high voltage power lines and the control houses. In addition, power companies tend to ground and bond their cables in similar fashions. Of course, there can be older control houses still operating within a power company's region, and there can also be newer building and cable designs that are being introduced to their system based on new communications protocols for Smart Grid applications.

Figure 6 presents the steps required to perform a complete assessment for a control house for both E1 HEMP and IEMI. The first step is to evaluate the shielding effectiveness of the control house from 1 to ~100 MHz for E1 HEMP and from ~100 MHz to ~5 GHz for IEMI. There is a relatively new method available [10] to assess the shielding effectiveness of operating facilities with shielding levels below 50 dB, known as the commercial radio signal assessment method. This method uses measurements of local AM, FM, digital TV, and cellular signals both inside and outside of the building to estimate the amount of attenuation present (see Figure 7 as an example of external signals which are well above the noise).

Through frequency domain to time domain translations, this process can convert any external time domain transient to an internal room time domain transient, as long as the frequency range information acquired is appropriate. This also does not require Federal Communications Commission (FCC) approval of special transmitters and allows a proper plane wave simulation of E1 HEMP conditions, as even at 1 MHz, the wavelength is 300 meters, which would require a transmitter standoff of much greater than this distance. Evaluations of this technique have been performed with good results and have been applied to over 100 control houses in the past ten years.

Once the shielding effectiveness has been evaluated over the frequency range of interest, one must then define the E1 HEMP and IEMI waveforms to be applied. IEC 61000-2-9 [5] provides a good example for E1 HEMP, and IEC 61000-2-13 provides several examples for IEMI threats [11]. In addition, since the IEMI EM weapon threat is a local threat, the closest approach to the control building needs to be evaluated. Satellite mapping tools can be used for this purpose.

Once the external EM threats are defined, the internal time field waveforms can be developed using the measured EM attenuation information. The next step is to evaluate the currents and voltages coupled to the internal wiring using coupling evaluations based on random orientations and polarizations performed for different cable lengths. Then, a probabilistic method can be used to select worst-case or average levels of coupling.

In addition to this coupling to wiring by fields penetrating the building, one must also consider the coupling to external control cables and other cables penetrating the building, such as conduits from security cameras and antennas. These levels can vary considerably based on the grounding and bonding of these cables as they enter. Also, for the control cables in trenches, IEC 61000-2-10 [12] provides information on the levels of E1 HEMP currents and voltages appropriate for above-ground and buried cables.

Once the coupled currents and voltages appearing inside the control house have been determined, these need to be compared to the immunity of the equipment. Fortunately,

- **Building shielding effectiveness**
  - **— Measure building EM attenuation**
- **External EM**
  - **— Select HEMP parameters**
  - **— IEMI: Select IEMI weapon parameters, determine closest stand-off distance, and calculate EM levels at the building**
- **Internal EM field levels**
  - **— Apply building attenuation to external EM levels**
- **Cable coupled voltages**
  - **— Identify cable lengths**
  - **— Apply statistical coupling approach, using EM levels and cable lengths**
  - **— Evaluate contribution of external cables entering building**
- **Equipment vulnerability voltages**
  - **— Determine dominant internal equipment and estimate typical upset and damage voltage levels**
- **Protection deficit**
  - **— Protection needed: compare induced voltages and vulnerability levels**
- **Protection measures**
  - **— Review options for lowering coupled voltage or strengthening equipment**

Figure 6: E1 HEMP and IEMI assessment procedure for establishing the amount of protection required for the electronics in a high voltage control house.

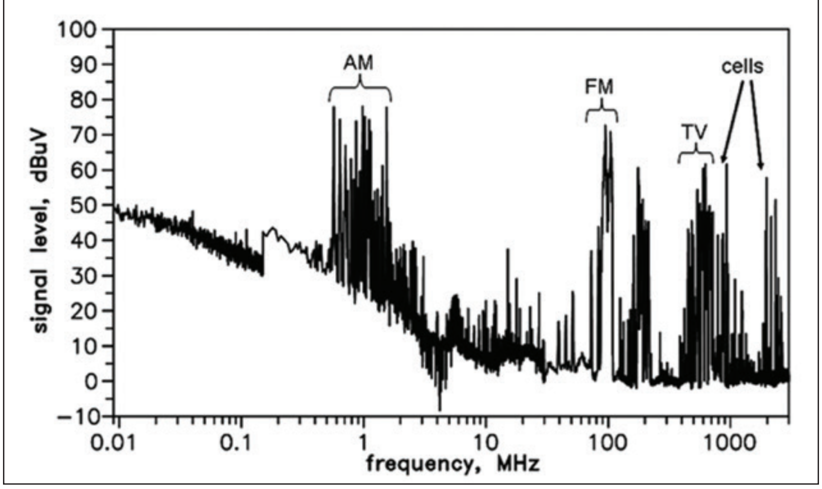

Figure 7: External measurements of radio signals outside of a control house for the E1 HEMP and IEMI frequency bands.

the standard IEC 61000-4-4 EFT waveform for EMC can be used as a proxy. It requires a fast ~4 kV pulse (5/50 ns) for power system equipment [7]. Recent testing has found that most protective relays satisfy this requirement, and some will be able to withstand higher levels, but it is difficult to establish specifically upset levels for all situations. Therefore, it is recommended that the immunity level for the internal electronics using the EFT waveform be used to determine whether any additional protection will be required for E1 HEMP or IEMI (last step of the assessment process in Figure 6).

PROTECTION OPTIONS FOR CONTROL EQUIPMENT

Once the assessment process is complete (and it must be done separately for both E1 HEMP and IEMI), there are a range of protection techniques that can then be deployed (see Figure 8). In particular, one needs to compare the levels of currents and voltages induced on cables inside of the building from the penetrating EM fields through the building walls to the current and voltage levels that are due to the external cable penetrations. If the external cables' currents and voltages are small due to good bonding and grounding techniques, then the focus must be on reducing the internal fields' coupling to the cables. If the reverse is true, then the focus needs to be on the external cables.

Since control houses are typically not very large and are often constructed of reinforced concrete, it is possible to add external metallic sheeting or internal shielded wallboard to increase the shielding effectiveness of the building. Also, if there is some extra-sensitive equipment inside the building, a shielded rack or room can be built inside. If there is a plan to upgrade the internal electronics to newer technologies, a last option would be to remove the existing building and rebuild it as a metal building, which tends to provide higher levels of protection. Note that this does not require a perfect 80-100 dB building, but rather a typical bolted metal building that can be built off-site and transported to an existing concrete pad.

Separately, since the resistive grounding for lighting transients is often not sufficient, all external cables should be evaluated to ensure that they are grounded properly for high frequency transients. For shielded control cables, one should ground them before entry into the building to metallic surfaces (using U clamps, not ground wires). If the building is of concrete construction, then a metal plate can be mounted on the side of the building and connected to the grounding grid. Ideally, the bonding should take place below the surface of the earth, so the cable itself is not exposed to the air after the bonding.

This procedure has been applied with good success for several existing control buildings. Of course, it is recommended that, if unshielded cables are used for the control cables, these should be converted to shielded cables or fiber optic cables (according to the new power substation communications standard IEC 61850-3 [13]). A recent design has used fiber optic control cables according to this new IEC standard, reducing its vulnerability to HEMP and IEMI [14].

Once the reductions of internal wire currents and voltages are completed, it is still possible that the reductions won't be sufficient with respect to the immunity of the equipment. In these cases, it may be possible to use internal wire metallic conduits, ferrites, and, in the worst case, surge arresters. The latter is not the best choice as there will be a need to test and replace surge arresters over time. Also, surge arresters designed for very fast transients are not easy to find and may be very expensive (most lightning surge arresters operate too slowly to be effective).

A final point to mention is that for the IEMI threat, distance between the attacker and the control house is very important, as the fields fall off rapidly from any EM weapon. All substations are fenced around the outside to keep the public away from hazardous electrical voltages, currents, and fields. In fact, many substations are now using solid fencing instead of chain link to reduce the potential threat related to attacks using firearms. A solid material will provide additional attenuation to an attacker at the fence position, and any effort to move further back to find an elevated position to illuminate a control house will extend the distance and reduce the field on target. As part of IEMI assessments, I have participated in

- **Improve the building/room shielding effectiveness**
  - **External metal sheeting**
  - **Internal metallic walls**
  - **Shield rooms or racks**
  - **New metallic building**
- **Improve shielding/grounding of internal cabling**
- **Apply cable ferrites on internal metallic cables**
- **Add filters and/or surge arresters at metallic cable connections (including antenna connections)**
- **Use fiber optic cables (w/o metal) inside**
- **Use high quality shielding and external grounding for external cables – Replace metallic cabling with fiber optic cables**
- **Improve security measures for IEMI (distance, monitoring, etc.)**

Figure 8: Examples of protection techniques to be applied after an assessment is complete.

evaluating the best locations for line-of-sight attacks on multiple control houses, and often the fields that would be directed on a control house can be reduced by factors of 2-10 based on extended ranges and opaque fencing.

SUMMARY

This article has described the basic threat information for both E1 HEMP and the EM weapon fields that can create IEMI. We have described the special problem of the high voltage control houses found within transmission substations and the importance of the reliable operations of the electronics inside.

Although the electronics inside the control houses are protected from natural high voltage transients, the frequency content and levels of the E1 HEMP and IEMI fields exceed the normal EMC protection methods found in these buildings today. This is mainly due to the fact that the EM shielding of the control houses is much higher for lightning fields than it is for E1 HEMP/IEMI, and the cable grounding techniques are only adequate for lightning.

This means that an assessment method is needed to evaluate the situation for existing control houses and their control cable system. In this article, we have detailed a method that has been applied to over 100 control house buildings. We have also presented several methods of improving the protection of these buildings from E1 HEMP and IEMI by examining different grounding methods, the use of shielded cables, the use of ferrites, etc., through laboratory and installation measurements.

Given that there are multiple methods available to reduce the susceptibility of the important equipment inside the control houses, it is possible to evaluate the effectiveness and the cost of these options. In addition, for those power companies who are upgrading the electronics and communications protocols in their substation control houses, it is possible to develop a specific protection approach that can be replicated over and over.

One last point I want to emphasize is that while E1 HEMP and IEMI are very unusual, and hopefully, low probability threats, the protection methods to be used are found within the EMC toolbox. Ultimately, it is a matter of defining the requirements for protection as opposed to developing new protection methods.

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The EU Conflict Minerals Regulation

Implications for the Electronics Sector

BY ALEX MARTIN

Over the last 10-15 years, supply chain management has increasingly entailed addressing environmental, social, and governance (ESG) issues alongside the likes of quality, cost, service, and delivery. This has been experienced in the electronics industry, but equally the likes of the textiles and apparel, jewelry, automotive, and aerospace and defense sectors. Corporate practices have changed in light of campaigning by political activists and non-governmental organizations, as has legislation and/or government-backed voluntary initiatives.

For those involved in the manufacture, distribution, and sale of electrical and electronic equipment, understanding conflict minerals – metals and minerals derived under duress and traded to keep armed groups funded – is likely best cast in terms of the wider identification, assessment, and management of ESG risks in supply chains (other risks might include, for example, child and forced labor, corruption and bribery, environmental pollution, etc.). While existing legislation may not apply to your business today, it might tomorrow.

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Moreover, customers may have their own expectations and pressures can come from other actors like campaign groups and investors. This is emphasized early on in this article, especially as the EU Conflict Minerals Regulation does not presently apply to electrical equipment manufacturers unless they also happen to import conflict minerals into the EU – and in quantities that exceed specified threshold values. Even so, such manufacturers are a target of an EU effort to encourage voluntary disclosure on conflict mineral uses (on which, more below).

BACKGROUND

Human history is littered with conflicts arising from natural resource access, so in one sense, the concept of a conflict resource or conflict mineral is nothing new. However, at any given time, some natural resources will likely prove more valuable than others. Over the last 30 years or so, demand for tin, tantalum, tungsten, and gold (the so-called 3TG and what are presently considered conflict minerals) has made controlling their extraction and processing lucrative. Table 1 on page 144 lists 3TG uses in a variety of products, electrical and electronic equipment included.

In turn, control of these resources and trade in them can become a political flashpoint and something fought over in civil wars. This was the case in the Democratic Republic of the Congo (D.R.C.) in the late 1990s and early 2000s, when the First and Second Congo Wars entailed both the

The last decade has been marked by governments, specifically in the developed world, increasingly recognizing and highlighting concerns to industry over the use of conflict minerals in the manufacture of products.

Congolese national army and rebel groups seeking control over 3TG mining, which encompasses many artisanal and small-scale mines.

Conditions in such mines are tough. Miners are known to work up to 48 hours at a time and risk life and limb in an environment of mudslides and tunnel collapses. As well as the human cost associated with this type of mining, the wars in the D.R.C. region have caused the deaths of more than five million people, many due to disease and starvation. Although progress has been made towards a lasting peace since the wars ended, armed groups retain control over some mines, and the trade in conflict minerals persists.

U.S. AND EU REGULATORY RESPONSES

The last decade has been marked by governments, specifically in the developed world, increasingly recognizing and highlighting concerns to industry over the use of conflict minerals in the manufacture of products. This has led to legislation, with the earliest adopter being the U.S. with the Dodd-Frank Act of 2010. Section 1502 of this particular law sets requirements for companies whose products incorporate 3TGs derived from the D.R.C. and neighboring countries.

Provisions of the Dodd-Frank Act were implemented through inclusion within the general rules and regulations of the Securities Exchange Act of 1934, specifically Section 240.13p-1. This requires issuers – major stock market-listed companies required to make regular Securities and Exchange Commission (SEC) filings – to report on efforts to eliminate conflict-implicated 3TGs from supply chains if they are used in their products. Companies covered by Section 240.13p-1 must take the following steps:

- Determine applicability;
- Conduct country of origin inquiry;
- Establish a due diligence process;
- Determine status; and
- File a report.

The Dodd-Frank Act does not prescribe a due diligence process, but the Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas,[1] published by the Organization for Economic Co-Operation and Development (OECD), is cited as a suitable reference. At the core of the OECD's Due Diligence Guidance is a five-step framework, as summarized in Table 2.

In 2017, the EU adopted its own law concerning conflict minerals, Regulation (EU) 2017/821.

Regulation (EU) 2017/821 applies to EU-based importers of 3T ores and concentrates as well as gold above certain defined thresholds, as detailed in the Regulation's Annex I.

Tin	• Used in alloys, tin plating, and solders for electronic circuits. • Used in car parts ranging from engine components through to gears, pumps, joints, and windshields. • Used as solder in buttons, zippers, and other fasteners as well as in jewelry. Composite material in rivets and eyes.
Tantalum	• Used mainly to produce tantalum capacitors, particularly for applications requiring high performance, small format and high reliability, such as hearing aids, pacemakers, global positioning systems (GPS), laptops, mobile phones, and games consoles.
Tungsten	• Used in metal wires, electrodes, contacts in lighting, and electronic, electrical and heating applications. Tools may incorporate tungsten, often when alloyed with steel.
Gold	• Present in some chemical compounds used in semiconductor and manufacturing processes. • Used as plating to produce the shine on zippers, fasteners, and other metal components. • Composite metal in or on jewelry and watches.

Table 1: 3TG uses

Electrical equipment manufacturers are not directly affected by the EU Regulation in the way that they otherwise might fall within the scope of the Dodd-Frank Act if publicly listed in the U.S.

For in-scope importers, obligations span establishing suitable management systems, assessing and managing relevant supply chain risks, conducting third-party audits, and information disclosure.

It is worth highlighting that the EU law is quite different from the Dodd-Frank Act, with the following summarizing specific points of difference:

- The EU Regulation does not impose any obligations upon downstream users of 3TGs, i.e., manufacturers of components or finished products, unless they also happen to be importing 3TGs into the EU. By comparison, U.S. legislation does apply in the downstream, with publicly listed companies that manufacture or contract to manufacture products that contain 3TG falling within the scope of the legislation.
- Unlike Dodd-Frank, the EU Regulation exempts small volume importers of 3TG by stipulating that the law "shall not apply to Union importers of minerals or metals where their annual import volume of each of the minerals or metals concerned is below the volume thresholds set out in Annex I."[2] No such exemption exists under the U.S. legislation.
- The EU Regulation is more specific in defining what 3TG ores, concentrates and metals come within its scope. The Regulation's Annex I gives a lot of detail, including Combined Nomenclature codes.
- Geographically, the EU Regulation is non-specific. Rather, the law concerns itself with 3TG sourced from conflict-affected and high-risk areas (CAHRAs) that might exist in the world. The U.S. legislation is specific though, applying only to conflict minerals sourced from the D.R.C. and its nine neighboring states.

As such, electrical equipment manufacturers are not directly affected by the EU Regulation in the way that they otherwise might fall within the scope of the Dodd-Frank Act if publicly listed in the U.S. (e.g., as the likes of many of the largest consumer electronics companies are). However, this is not to say that EU policy-makers had not given thought to the EU Regulation applying to downstream users of 3TGs, including businesses

	Step	Practice
1	Establish strong management systems	• Adopt and commit to a supply chain policy for conflict minerals. • Establish a system that allows the identification of the smelters in the company's mineral supply chain. • Maintain records (preferably electronic) for at least five years. • Incorporate policies and traceability into supplier agreements and contracts. • Establish mechanisms for grievances and whistle-blowers.
2	Identify and assess risks	• Identify smelters/refiners in supply chain. • Assess due diligence practice of smelters.
3	Respond to risks	• Report findings to senior management. • Exercise leverage over suppliers that can work most effectively to mitigate risks further back in the chain. • Monitor, track, adapt, and adjust risk mitigation efforts.
4	Audit	• Carry out an independent third-party audit of smelter's/refiner's due diligence program.
5	Publicly report	• Report – preferably in annual sustainability or corporate social responsibility reports – on the due diligence program, such as: the company policy, responsible management, steps taken to identify and assess smelters/refiners.

Table 2: The five-step framework of the OECD Due Diligence Guidance

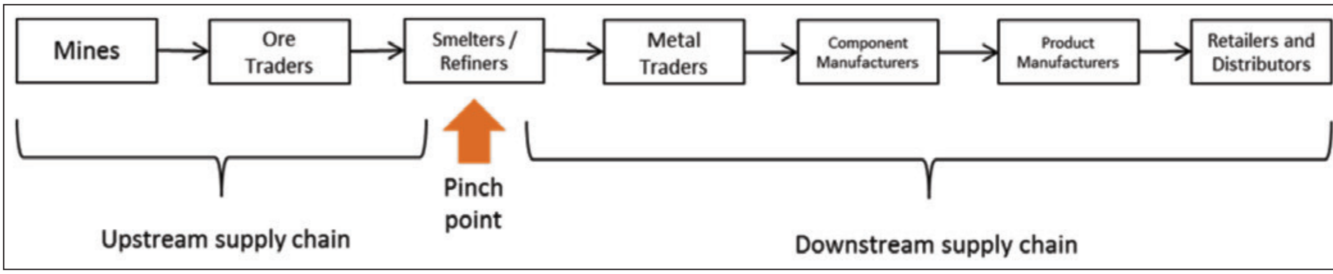

Figure 1: Actors in a minerals supply chain

in the electronics sector. They had, and for those interested in the discussions that took place and what compromise was reached before the Regulation was adopted, a partial record exists within minutes of the European Commission's "Member State Expert Group on responsible sourcing of tin, tantalum, tungsten, and gold" that are available online.[3]

Minutes from the 9 March 2018 meeting of this Group reveals that the compromise which saw Regulation (EU) 2017/821 "based on only importers of metals and minerals being covered by the legal requirements of the Regulation" entailed an expectation that "a series of measures also should be taken to retain the focus on and validity of efforts taken by downstream companies." What, then, of these measures?

THE EU'S "TRANSPARENCY PLATFORM FOR DOWNSTREAM COMPANIES"

At the time of writing, the measure of most prominence and greatest significance for manufacturers, importers and distributors of components and finished products (including but not limited to items of electrical and electronic equipment) is the proposed transparency platform. Detail related to this can be found within minutes of the above-mentioned Member State Expert Group, but the author was fortunate enough to get an insight from a European Commission policy officer first-hand when she presented on conflict minerals at the RINA Electrical and Electronic Equipment and the Environment Conference in November 2019. This presentation revealed that the platform is to take the name of ReMIS, the Responsible Minerals Information System.

REMIS: WHAT WE KNOW SO FAR

The European Commission describes[4] it as an "information system that aims to support downstream companies, in particular, to share and publish – on a voluntary basis – information regarding their due diligence practices and exchange best practices in this regard." The European Commission has also outlined how the system will likely work, with company-submitted registration information initially being reviewed and validated by the Competent Authority appointed under Regulation (EU) 2017/821 of the EU Member State in which the company is legally based.

To register, business information including name and address, supply chain position (upstream/downstream), industry sector(s) in which the business is active, metals and minerals handled, and a summary account of due diligence practice appears to be anticipated. It would then seem that any more detailed information a company wished to share for online publication on ReMIS would be reviewed by a designated European Commission service desk. What this review would entail is, however, currently unclear.

A prototype version of ReMIS has been tested, with at least some industry stakeholders involved in this testing. This is reported upon in the 5 June 2019 minutes of the responsible sourcing Member State Expert Group, which notes that "the Commission received positive feedback on the usability and functionalities of the system." However, it seems that safeguarding personal data is a concern, as is managing both European Commission and Member State Competent Authority compliance with requirements under the EU General Data Protection Regulation (GDPR). Concerning this, the Commission has prepared an initial draft of a GDPR-required "joint controllership agreement," but it is not known whether this has been accepted at the time of writing.

IMPLICATIONS FOR ELECTRICAL EQUIPMENT MANUFACTURERS

It is likely that, in the years ahead, the European Commission's ReMIS platform will result in various businesses that use 3TGs in their components and products publicly reporting upon this, as well as the efforts they are taking to assure themselves that 3TGs are responsibly sourced. Demand for information may come from the investment community, particularly to help the community become better informed – and so able to assess – ESG risks within business supply chains.

How, then, to prepare for this?

Many large, consumer-facing electronics companies whose products incorporate 3TGs have already taken significant strides in their management practices. Among them are Apple, Dell, HP Inc., and Intel. The way these companies have responded provides insight into how to manage and report upon conflict mineral uses in electronics supply chains.

There is overlap in practice, which includes policy- and goal-setting, surveying suppliers, determining smelters in use, comparing smelters with those on approved lists (e.g., as published by the U.S.-based Responsible Minerals Initiative, RMI[5]), arranging smelter audits, and running awareness-raising training events. It is worth explaining the emphasis placed upon smelters here, and this is simply because they are perceived to constitute the pinch point in minerals supply chains (see Figure 1[6]).

For practitioners, the following steps are advisable:

- Understand and scale the challenge facing your company. This is likely to include determining possible 3TG uses in products, then determining which suppliers you are going to engage with and how you are going to do this (e.g., by working up your own survey or making use of, say, the RMI Conflict Minerals Reporting Template[7]).
- Frame the company response, either with a new program of work or by expanding existing ones (e.g., programs for managing substance restrictions found in, for example, the EU RoHS Directive and/or EU REACH Regulation). Initially, this will be a top-level exercise anticipated to involve achieving senior management buy-in, securing a budget, documenting key policies and procedures, and determining roles and responsibilities for the likes of contacting suppliers and the collection, collation, and analysis of data. Cross-functional work is expected, so even if the program is owned and led by an Environmental or Corporate Responsibility Manager, the support of personnel from, for example, Procurement, Finance, and IT, should be considered, approved, and documented early on.
- Consider the optimal IT solution. This will depend on how many products and suppliers you are dealing with. If a large number, this will result in a lot of data, making a more automated (and sophisticated) solution desirable.
- Document as you go, including scoping decisions and other such judgements. This is good practice with regard to due diligence, constituting a record of key decision-making and reasoning deployed.
- Phase the program in, monitoring as you proceed. This provides scope for identifying problems and making corrections for better implementation overall.

Fostering a perspective that goes beyond compliance will be beneficial. To see conflict minerals as something to be complied with is to miss potential opportunities like reducing supply-side ESG risk and enhancing relationships with preferred suppliers and customers. It is something the investment world is also likely to use to assess company performance in the future, so getting ahead with respect to practice and disclosure may offer a competitive advantage.

ENDNOTES

1. http://www.oecd.org/corporate/mne/mining.htm
2. Note that, and as is explained in the Regulation's Article 1(3), volume thresholds are set at a level to ensure that the vast majority of each ore, concentrate or metal targeted are implicated – and "no less than 95% of the total volumes imported into the Union of each mineral and metal under the applicable Combined Nomenclature code."
3. Accessible through the "Meetings" tab on the webpage of https://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetail&groupID=3256
4. Information comes from the presentation "The EU Regulation on responsible sourcing of minerals ("Conflict Minerals"): progress on implementation" given by Zora Mincheva, DG TRADE Policy Officer, to the RINA EEE & the Environment Conference on 14 November 2019.
5. http://www.responsiblemineralsinitiative.org/smelters-refiners-lists
6. Adapted from ChainLink Research, "Turning conflict minerals law compliance into a competitive advantage," September 2013.
7. https://www.conflict-minerals.com/solution/cmrt-512

How Grounds Affect the Peak Voltage Due to Lightning

Why the Most Common Characterization of a Ground Rod May Not Work for Lightning

BY ALBERT R. MARTIN

In 1997, an experiment at the Camp Blanding center for lightning testing [1] challenged the predominant view that ground rods are essentially resistive. What that experiment found was that the waveshapes of lightning currents in a building grounding system and those entering the electrical circuits of the building were considerably different. That was at odds with IEC 61312-1:1995 [2] assertions that they should be the same. The conclusion was that, for lightning, the ground rod had an impedance with a reactive component in addition to the resistive one.

So how do we take into account the impedance effects for lightning? Well, it turns out not to be so simple. Professor Leonid Grcev, who with his students has conducted extensive studies of grounds, has found that a simple modeling of a ground rod as an R-L-C circuit doesn't give correct results, due to surge propagation effects which cause a deviation from the low frequency behavior during the fast-transient period. So the challenge is to determine what this deviation is.

Considering normal grounds (those not chemically treated or otherwise enhanced), Grcev has shown that they can be characterized in terms of effective length and impulse coefficient (IC) [3]. The IC is the ratio of peak voltage across an actual ground rod to the peak voltage across a purely resistive ground rod in response to a surge. It shows how the impedance of the ground rod affects the expected peak voltage due to a surge relative to what it would have been if the ground rod were purely resistive.

EFFECTIVE LENGTH

The first thing to consider is the ground rod effective length l_{eff}, which is the maximum length of the ground electrode for which the impulse coefficient is equal to one. l_{eff} will be used later in the discussion of the IC (which is what we really want).

To calculate l_{eff}, Grcev [3] has developed the relation:

$$l_{eff} = \frac{1-\beta}{\alpha} \tag{1}$$

where:

$$\alpha = 0.025 + exp[-0.82(\rho \cdot T_1)^{0.257}] \tag{2}$$

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$$\beta = 0.17 + exp[-0.22(\rho \cdot T_1)^{0.555}] \quad (3)$$

ρ = soil resistivity in *ohm-m* and T_1 is the zero-to-peak rise time of the lightning current pulse. MIL-HDBK-419 Table 2.3 [6] shows a range for average soil resistivity of 1 to 500 ohm-m. CIGRE TB549 Table 3.5 [7] shows a range of front durations of 1.1 µsec for the average subsequent stroke to 18 µsec for the maximum first stroke. Considering those values, the ρT_1 product could reasonably range from 1 to over 1000 ohm-m-µsec. We can use those values in Equations 2 and 3) to make a plot of l_{eff} vs. ρT_1, as shown in Figure 1. Both slower rise-time and higher soil resistivity lead to a longer effective ground-rod length.

IMPULSE COEFFICIENT

If the length s of the ground rod is less than l_{eff} (see Figure 1), the ground rod is primarily resistive, with some capacitive effect. If the length of the ground rod is greater than l_{eff}, the ground rod will have inductive effects. So which effect do we have, and what is the consequence of that effect? Well, that's what the IC determines. Grcev [3] has proposed the relation:

$$A = \alpha s + \beta \quad (4)$$

where A = Z/R is the impulse coefficient, Z is the effective impedance, R is the ground rod resistance, α is calculated from Equation 2, and β is calculated from Equation 3.

For A > 1, the ground rod has an effective series inductance in addition to its resistance. In this case, the peak voltage will be A times bigger than it would have been if the ground rod were purely resistive.

For A < 1, the ground rod has an effective parallel capacitance in addition to its resistance. In this case, the peak voltage will be A times lower than it would have been if the ground rod were purely resistive.

From Equation 4 the effect of the ground rod reactance can be calculated. As an illustration, take the four cases of ρT_1, = 100, 300, 1000, and 10,000, and use Equation 4 to plot the impulse coefficient A vs. length of the rod. Ground rods with a low ρT_1 product have a high impulse coefficient, whereas ground rods with a high ρT_1 product have a low impulse coefficient, as shown in Figure 2.

Figure 3 is a replot of Figure 2 for ground rods of a length normally used (≤ 10 m).

For ground rods ≤ 10 m, the low value of the impulse coefficient means that the peak voltage across the ground rod will be less than would be calculated for a purely

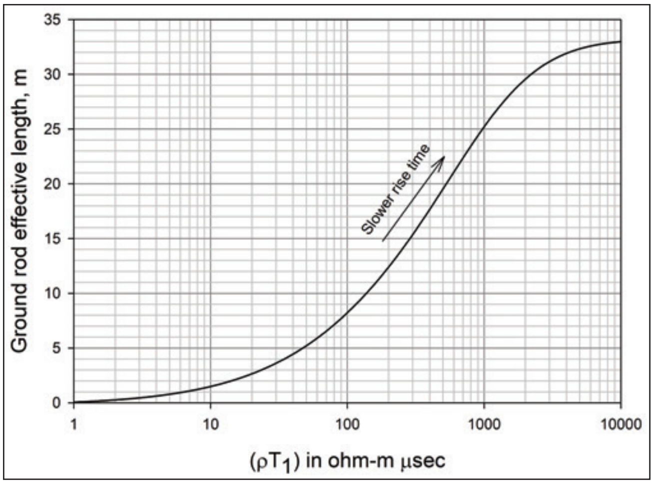

Figure 1: This figure shows the variation in the effective length of a ground rod with soil resistivity and the zero-to-peak time of the surge.

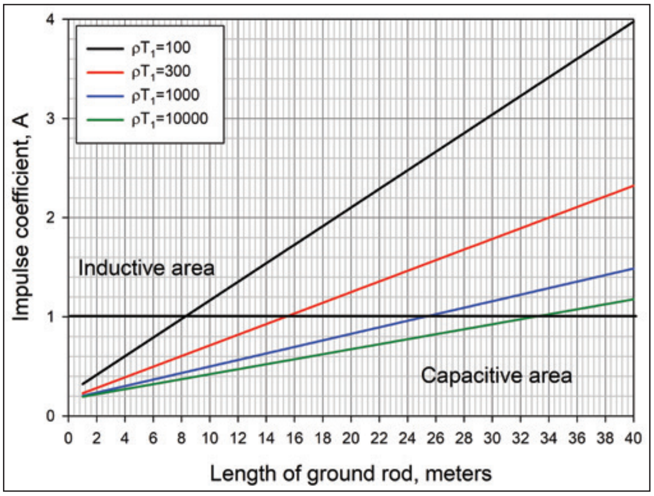

Figure 2: Impulse coefficient (ratio of peak voltage to the peak voltage across a purely resistive ground rod) versus length of ground rod

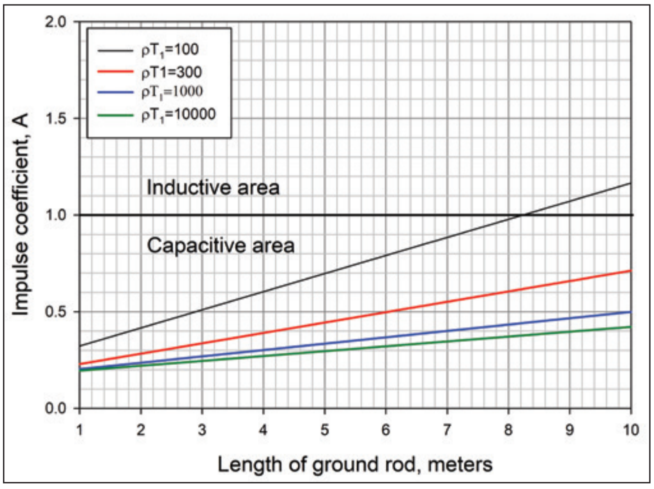

Figure 3: Impulse coefficient for ground rods ≤ 10 m long

resistive ground rod. For example, for a common 2 m rod, the ratio of peak voltage to the peak voltage across a purely resistive ground rod is in the range of 0.2 to 0.4, depending on the ρT_1 product. The voltage across the ground rod as a surge decays is determined primarily by the resistance of the ground rod. So as the surge decays, the effect of the ground rod reactance dies away (remember that the impulse coefficient is relevant only during the rise-time period).

CURRENT FLOWING IN THE GROUND ROD

The peak voltage developed across the ground rod is given by:

$$V_{peak} = ZI_{rod} \tag{5}$$

where I_{rod} is the peak current captured by the ground rod, and Z is the ground rod impedance.

To calculate I_{rod} we need to calculate the fraction of the lightning current I_{max} captured by the ground rod. IEEE Std 142 [5] shows that 99% of the current flowing in the ground rod is captured in a volume having a radius of twice a ground rod length, s. Figure 4 illustrates this situation, where d is the distance from the lightning strike

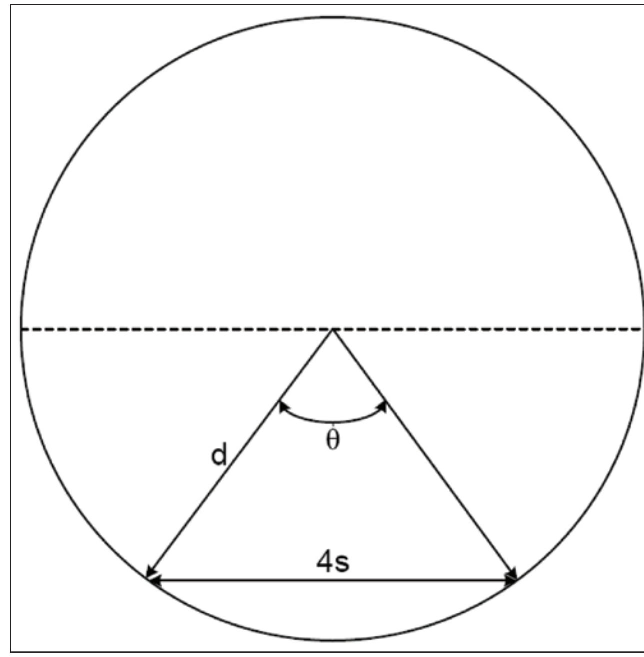

Figure 4: The effective capture area of the ground rod

point to the edge of a cylinder representing the ground rod outer effective extent.

The angle θ subtended by the ground rod is given by:

$$\theta = 2\arcsin\left(\frac{2s}{d}\right) \tag{6}$$

Note that the arcsin is not defined for arguments greater than 1, so there are two cases for Equation 6: Case 1 where d ranges from $2s$ to infinity, and case 2 where d ranges from $2s$ to 0.

For case 1, if the arcsin is in degrees, then the fraction f_1 of the lightning current I_{max} captured by the ground rod is:

$$f_1 = \frac{2\arcsin\left(\frac{2s}{d}\right)}{180} = \frac{\arcsin\left(\frac{2s}{d}\right)}{90} \tag{7}$$

For case 2, if the fraction f_2 of the lightning current I_{max} captured by the ground rod is:

$$f_2 = \frac{\arcsin\left(1-\frac{d}{2s}\right)}{90} \tag{8}$$

Combining Equations 7 and 8, $I_{rod} = I_{max}\,(f_1 + f_2)$, which is:

$$I_{rod} = I_{max}\left\{\left[\frac{\arcsin\left(\frac{2s}{d}\right)}{90}\right] + \left[\frac{\arcsin\left(1-\frac{d}{2s}\right)}{90}\right]\right\} \tag{9}$$

Remember that in calculating I_{rod}, the first term in Equation 9 is only valid for d greater than $2s$, and the second term is only valid for d less than $2s$.

PEAK VOLTAGE

The peak voltage is calculated from Equation 5. The effective impedance Z of the ground rod to be used in Equation 5 can be calculated from Dwight's [4] equation multiplied by A:

$$Z = \frac{A\rho}{2\pi s}\left[\ln\left(\frac{4s}{a}\right) - 1\right] \tag{10}$$

where a is the radius of the ground rod.

Substituting Equations 9 and 10 in Equation 5:

$$V_{peak} = I_{max}\left\{\left[\frac{\arcsin\left(\frac{2s}{d}\right)}{90}\right] + \left[\frac{\arcsin\left(1-\frac{d}{2s}\right)}{90}\right]\right\}\left\{\frac{A\rho}{2\pi s}\left[\ln\left(\frac{4s}{a}\right) - 1\right]\right\}$$

$$V_{peak} = \frac{A\rho I_{max}\left[\arcsin\left(\frac{2s}{d}\right) + \arcsin\left(1-\frac{d}{2s}\right)\right]}{180\pi s}\left[\ln\left(\frac{4s}{a}\right) - 1\right] \tag{11}$$

As an example of the calculation of V_{peak}, consider a 12 kA 4.5/77 subsequent surge from TB549 [7] impinging on a 10 m rod 5/8 inches in diameter in the soil of 50 ohm-cm, 200 ohm-cm 600 ohm-cm, and 3000 ohm-cm.

For these cases, Figure 5 shows how V_{peak} changes due to a decrease in ground-rod current capture with increasing distance.

APPLICABILITY OF THE PEAK VOLTAGE CALCULATION

Now a word about the applicability of the foregoing analysis. In the region near the lightning strike point, the ground resistivity ρ is highly variable. In particular, soil breakdown can happen when the electric field overcomes the soil ionization gradient [8]. Soil ionization occurs when the electric fields at the ground electrode surface become greater than the ionization threshold of approximately 300 kV/m [9]. In this case, in the region surrounding the current striking point, local transverse discharges start from the lightning strike point and stop at the points where the electric field drops below the critical breakdown strength. An illustration of this point is shown in Figure 6.

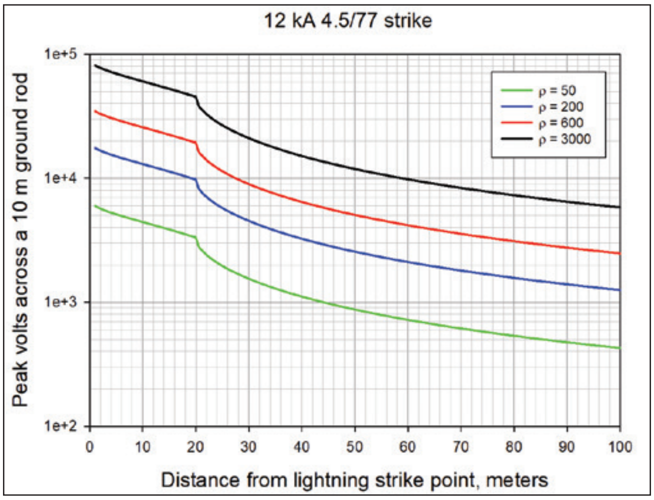

Figure 5: Example of the peak voltage across a 2 m ground rod due to a 12 kA 4.5/77 strike

Figure 6: Extent of ionization from a lightning strike to the flag marking the hole

The literature on lightning shows that the streaks in Figure 6 are places where the ground is ionized. A circle of radius r_0 can be put around this area. The size of r_0 is determined by both the magnitude of the lightning current and ρ. In Figure 6, r_0 appears to be about 6 m, but that may or may not be typical. In any case, to avoid the area where ρ is highly variable, *d* should generally exceed $2r_0$.

With the foregoing discussions in mind, different lightning waveforms, different ρ, and different ground rod lengths will result in different peak voltages from those shown in Figure 5.

SUMMARY

The usual assumption that ground rods are purely resistive is actually not what is observed in the case of lightning. Particularly for the relatively short ground rods commonly used, during the rise-time period the ground rods look like an impedance with a significant capacitive component. The result is that for these commonly used ground rods, the peak voltage due to a lightning strike is generally significantly lower than would be the case for a purely resistive ground rod. Whether the peak voltage is higher or lower than for a purely resistive ground rod depends on a number of variables, including the surge waveform, the ground resistivity, the length of the ground rod, and the distance the observer is from the lightning strike point. The peak voltage across the ground rod can be calculated, based on estimates of these variables.

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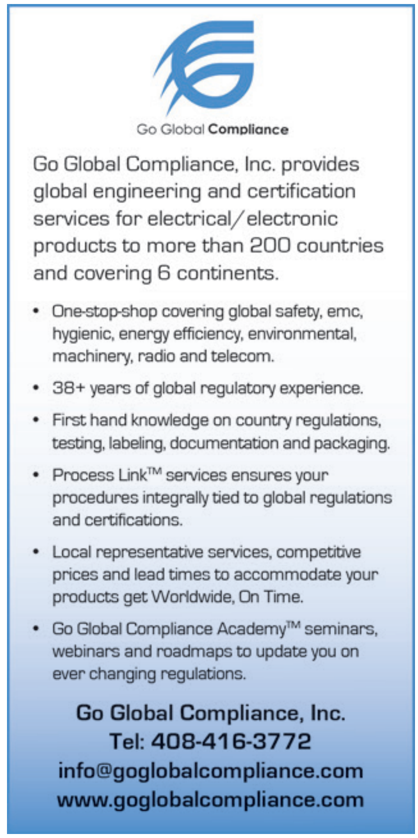

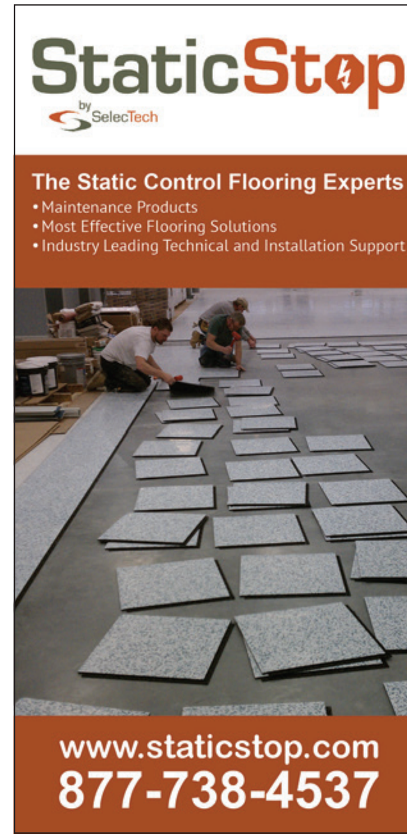

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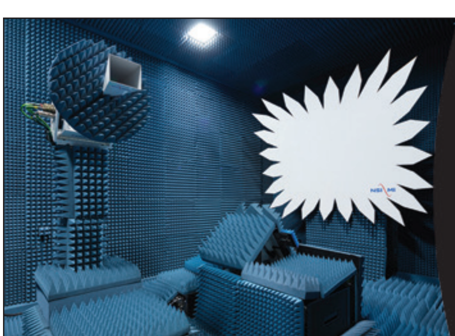

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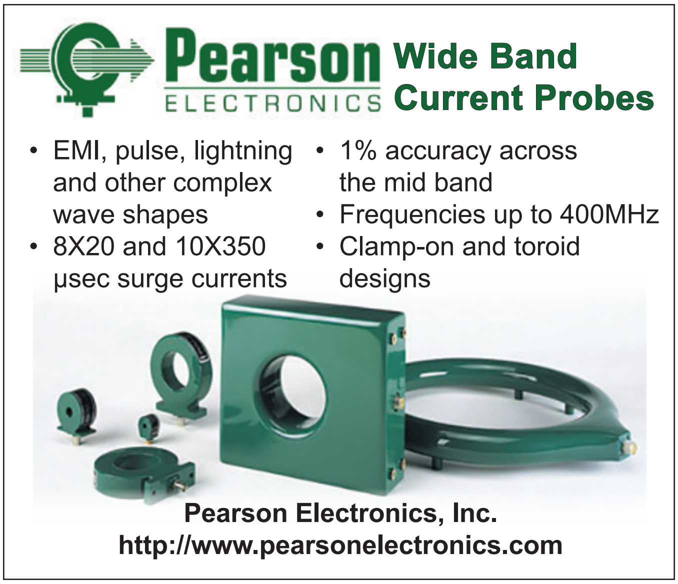

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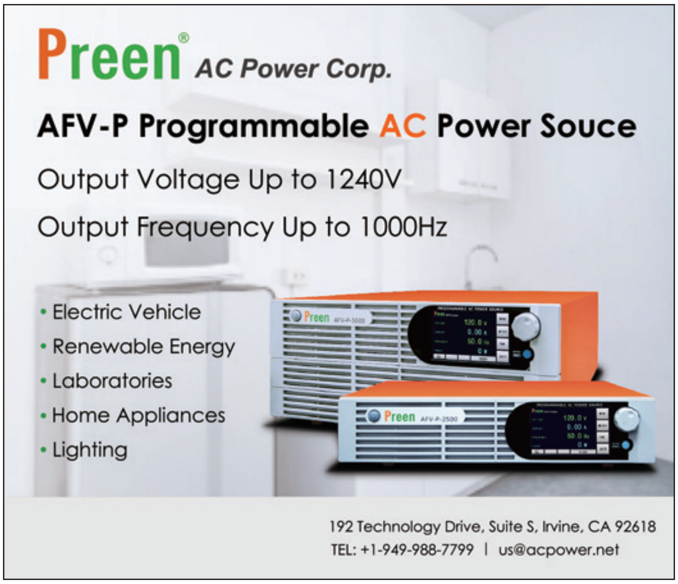

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Quanta Laboratories
Santa Clara, CA USA — http://www.quantalabs.com

Quell Corporation
Albuquerque, NM USA — http://www.eeseal.com/ic

R&B Laboratory
West Conshohocken, PA USA — http:///www.rblaboratory.com

Radiometrics Midwest Corporation
Romeoville, IL USA — http://www.radiomet.com

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tel: (800) 362-1495
http://www.raymondemc.ca

Raymond EMC specializes in the design, fabrication, installation and testing of custom radio frequency shielded enclosures, anechoic chambers and secure processing and secure discussion facilities for military, government, high tech, industrial, automotive, aviation and medical applications. With over 30 years of experience serving our industries, Raymond EMC prides itself on being a leader in product quality, performance and innovation while providing unmatched client care and product support through all processes. See how Raymond EMC can take your projects to the next level - learn more and request pricing at http://www.raymondemc.com.

Raymond RF Measurement Corporation

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Reality Consulting Yemen

Sana'a Yemen — http://www.reality-consulting.com

Reliant EMC LLC

Prescott Valley, AZ USA — http://www.reliantemc.com

Remcom

State College, PA USA — http://www.remcom.com

Retlif Testing Laboratories

Ronkonkoma, NY USA — http://www.retlif.com

RF Solutions, LLC.

Syracuse, NY USA — https://rfsolutionsllc.us

Rigol Technologies

Beaverton, OR USA — http://www.rigolna.com

RM Regulatory & Export Compliance, LLC

Port St. Lucie, FL USA — http://www.rmregcompliance.com

Rohde & Schwarz

Columbia, MD USA — https://www.rohde-schwarz.com

Ross Engineering Corp.

Campbell, CA USA — http://www.rossengineeringcorp.com

Roxburgh EMC

North Lincolnshire, Yorkshire
Great Britain — http://www.dem-uk.com/roxburgh

Saf-T-Gard International, Inc.

Northbrook, IL USA — http://www.saftgard.com

Safe Engineering Services & Technologies

Laval, QC Canada — http://www.sestech.com

Sanwood Environmental Chambers Co., Ltd

Dongguan City, Guangdong China — http://www.climatic-chambers.com.tw

SAS Industries, Inc.

Manorville, NY USA — http://www.sasindustries.com

The Schaffner Group

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Schlegel Electronic Materials

Rochester, NY USA — http://schlegelemi.com

SCHURTER, Inc.

Santa Rosa, CA USA — http://www.schurterinc.com

Schwarzbeck Mess-Elektronik OHG

Schönau, Baden-Württemberg
Germany — http://www.schwarzbeck.de

SCI

Lake Forest, IL USA — http://www.hipot.com

SCR ELEKTRONIKS

Dist. Thane, Maharashtra India — http://www.screlektroniks.com

Seal Science, Inc.

Irvine, CA USA — http://www.sealscience.com

Select Fabricators, Inc.

Canandaigua, NY USA — http://www.select-fabricators.com

Siglent Technologies North America

Solon, OH USA — http://www.siglentamerica.com

Signal Hound

La Center, WA USA http://www.signalhound.com

SILENT Solutions LLC

Amherst, NH USA http://www.silent-solutions.com

Simco-Ion

Alameda, CA USA http://www.simco-ion.com

Solar Electronics Co.

North Hollywood , CA USA http://www.solar-emc.com

Southwest Research Institute

San Antonio, TX USA http://www.swri.org

Spectrum EMC, LLC

Sierra Vista, AZ USA http://www.spectrumemc.com

Spes Development Co

Ann Arbor, MI USA http://www.spesdev.com

Spira Manufacturing Corporation

San Fernando, CA USA http://www.spira-emi.com

Sprinkler Innovations

Seabrook, NH USA http://www.sprinklerinnovations.com

Static Solutions, Inc.

Hudson, MA USA https://staticsolutions.com

StaticStop ESD Flooring

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Avon, MA 02322 USA
tel: (877) 738-4537
http://www.staticstop.com

StaticStop manufactures a full line of ESD/Static Control Flooring, including an adhesive-free interlocking flooring that can be used over bad subfloors and installed directly on top of existing floors without any disruption to operations. We offer the most comprehensive line of ESD flooring solutions available, including installation and maintenance options to provide the right product at the best price for any application.

StaticWorx, Inc.

Waterbury Center, VT USA http://www.staticworx.com

SteppIR Communication Systems

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Bellevue, WA 98040 USA
tel: (425) 453-1910
https://steppir.com

SteppIR Communications Systems is the manufacturer of the SY3-EMC antenna system, the solution for a 50-year-old problem with MIL-STD-461 RS103 radiated susceptibility in the frequency range of 30-200 MHz. Our system utilizes a mechanically adjustable Yagi antenna, which with the help of a sophisticated software algorithm, creates unique, fully optimized antennas at every frequency within its range, in both horizontal and vertical polarization.

SunAR RF Motion

Dublin, CA USA http://www.sunarrfmotion.com

Suzhou 3ctest Electronic Co. Ltd.

99 Emeishan Rd, SND, Suzhou
Jiangsu, 215153, China
tel: 86 512 6807 7192
http://www.3c-test.com

3CTEST, established in 2004 in Suzhou, China, is dedicated to scientific research and technological progress in the field of Electromagnetic Compatibility (EMC) and Complicated Electromagnetic Environment (CEE), and has been a leading enterprise integrating design, manufacture, sales and service of corresponding testing equipment. 3CTEST's R&D team is rich with experience, having participated in the drafting and reviewing of more than 40 national EMC standards in China, also published two EMC-related books. Having set up offices in Beijing, Shenzhen, Chengdu, Xi'an and partnered with overseas distributors in Asia, North America and Europe, 3CTEST is committed to supreme product quality and professional customer service.

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Union City, CA USA http://www.swsafety.com

Swift Textile Metalizing LLC

Bloomfield, CT USA http://www.swift-textile.com

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1101 Cypress Creek Road
Cedar Park, TX 78613 USA
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TDK RF Solutions is a world leader in the design, development & manufacture of technical solutions for the EMC testing and Antenna measurement industries. We offer a complete range of solutions including automated test systems, anechoic chambers, RF absorber, antennas, software, RF filters, and a wide range of test products & accessories. We call it Total System Technology®, and it means TDK RF Solutions is your best choice of partner for proven solutions & services. If you are in the market for a complete turnkey solution or looking to expand your test capabilities with a new antenna, contact us to see what TDK can do for you.

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Mesa, AZ USA
http://www.techwear.com

Tech-Etch

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http://www.tech-etch.com

Techmaster Electronics

Vista, CA USA
https://techmaster.us

Technical Safety Services

Berkeley, CA USA
http://techsafety.com

Teledyne LeCroy

Chestnut Ridge , NY USA
http://teledynelecroy.com

TESEO SpA

Druento, Terni Italy
http://www.teseo.net

Test Site Services Inc

Milford, MA USA
http://www.testsiteservices.com

Testing Partners

Boardman, OH USA
https://testingpartners.com

TestWorld Inc

Rocklin, CA USA
http://www.testworldinc.com

Thermo Fisher Scientific

Tewksbury, MA USA
http://www.thermoscientific.com

Thermotron

Holland, MI USA
http://www.thermotron.com

Thermtest

Fredericton, NB Canada
https://thermtest.com

Timco Engineering, Inc.

Newberry, FL USA
http://www.timcoengr.com

Times Microwave Systems

Wallingford, CT USA
https://www.timesmicrowave.com

TJS Technical Services Inc.

Airdrie, AB Canada
http://tjstechnical.com

Tomort Electronics Co., Ltd.

T'ao-yuan Taiwan
http://www.tomort.com.tw

TOYO Corporation

Fremont, CA USA
https://toyotechus.com

Transient Specialists, Inc.

Burr Ridge, IL USA
http://transientspecialists.com

Transtector

Hayden, ID USA
https://www.transtector.com

Trescal

Hartland, MI USA
http://www.trescal.com

TTE Filters, LLC

Los Angeles, CA USA
http://www.tte.com

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Wakefield, MA USA
https://www.tuv-sud-america.com/us-en

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Northbrook, IL USA
http://www.ul.com/knowledgesolutions

UL LLC

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http://www.ul.com

United Static Control Products Inc.

Bradenton, FL USA
http://ultrastatinc.com

Universal Shielding Corp.

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Deer Park, NY 11729 USA
tel: (631) 667-7900
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http://www.universalshielding.com

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University of Oxford Continuing Professional Development - Technology Programme

Oxford, Oxfordshire Great Britain — http://www.conted.ox.ac.uk/about/continuing-professional-development

USA Microwave Laboratories

Summerfield, NC USA — http://www.usmicrolabs.com

V Technical Textiles, Inc.

Palmyra, NY USA — https://www.vtechtextiles.com

VDE Americas

Burlington, MA USA — http://vdeamericas.com

Vectawave Technology Limited

Newport, Isle of Wight Great Britain — http://vectawave.co.uk

VEROCH - Testing Equipment USA

Sunrise, FL USA — http://www.veroch.com

Versus Technology (Versus Global LLC)

Wilmington, DE USA — http://www.versusglobal.com

VIAVI Solutions

Wichita, KS USA — https://www.viavisolutions.com

Videon Central, Inc.

State College, PA USA — http://videon-central.com

Vitrek Corporation

Poway, CA USA — http://www.vitrek.com

VPI Laboratories, Inc.

Draper, UT USA — http://www.vpilaboratories.com

VTI Vacuum Technologies, Inc.

Reedsburg, WI USA — http://www.vactecinc.com

W. L. Gore & Associates, Inc.

Landenberg, PA USA — http://www.gore.com

Washington Laboratories

Frederick, MD USA — http://www.wll.com

Wave Computation Technologies, Inc.

Durham, NC USA — http://www.wavenology.com

Wave Scientific Ltd

Henfield, West Sussex Great Britain — http://www.wave-scientific.com

Wavecontrol Inc.

Roseland, NJ USA — https://www.wavecontrol.com/rfsafety/en

WECO Electrical Connectors

Kirkland, QC Canada — http://www.wecoconnectors.com

WEMS Electronics

Hawthorne, CA USA — http://www.wems.com

Wewontech

Dongcheng, Hong Kong China — http://www.wewontech.com

Willrich Precision Instrument Company, Inc

Cresskill, NJ USA — http://willrich.com

WorkHub

Calgary, AB Canada — https://www.workhub.com

Wurth Elektronik

Waldenburg, Baden-Württemberg Germany — https://www.we-online.com

Wyatt Technical Services LLC

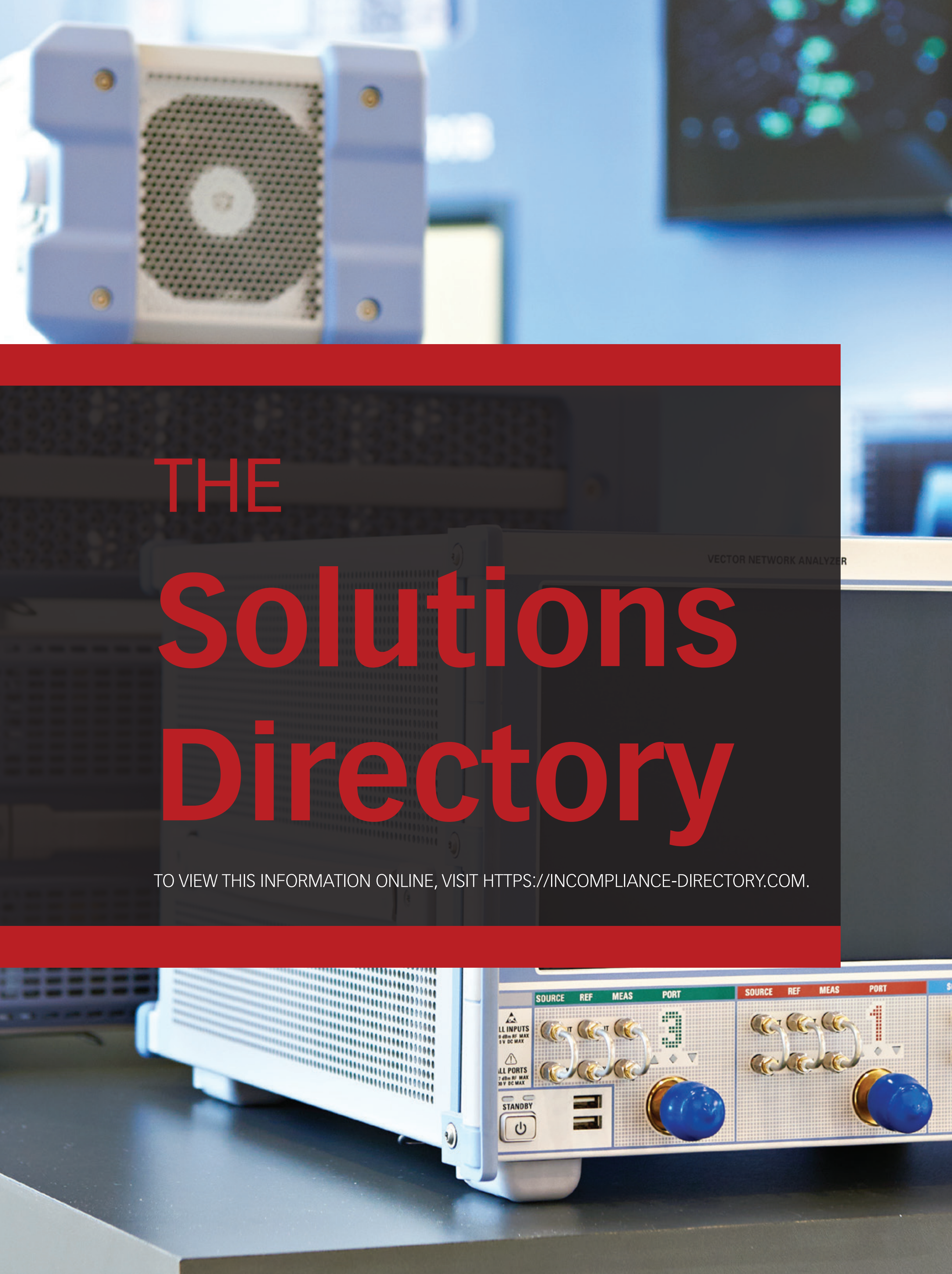
Woodland Park, CO USA — http://www.emc-seminars.com

XGR Technologies

Newark, DE USA — http://www.xgrtec.com

Yazaki Testing Laboratory

Canton, MI USA — http://www.yazakiemc.com



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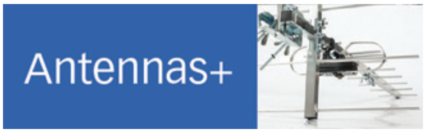

Antenna Couplers

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KYOCERA AVX Components Corporation
Mag Daddy, LLC

Antenna Masts

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AR RF/Microwave Instrumentation
C-Wave, Inc.
Com-Power
Electronic Instrument Associates
ETS-Lindgren
Frankonia GmbH
HV TECHNOLOGIES, Inc.
Innco Systems GmbH
Mag Daddy, LLC
Schwarzbeck Mess-Elektronik OHG
SunAR RF Motion
TDK RF Solutions

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Clark Testing
Com-Power
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Frankonia GmbH
Mag Daddy, LLC
Schwarzbeck Mess-Elektronik OHG
SteppIR Communication Systems
SunAR RF Motion
TDK RF Solutions
Techmaster Electronics

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Barth Electronics, Inc.
C-Wave, Inc.
Com-Power
EMC Test Design, LLC
ETS-Lindgren
Eurofins York
Frankonia GmbH
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Mag Daddy, LLC
Microwave Vision Group
Reality Consulting Yemen
Schwarzbeck Mess-Elektronik OHG
SteppIR Communication Systems
SunAR RF Motion
TDK RF Solutions

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Applied EM Technology
Applied Physical Electronics, L.C. (APELC)
AR RF/Microwave Instrumentation
Barth Electronics, Inc.
C-Wave, Inc.
Clark Testing
Com-Power
Electronic Instrument Associates
The EMC Shop
EMC Test Design, LLC
Enerdoor
ETS-Lindgren
Eurofins York
Frankonia GmbH
Lionheart Northwest
Mag Daddy, LLC
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Reliant EMC LLC
Rohde & Schwarz
Schwarzbeck Mess-Elektronik OHG
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TOYO Corporation

Horn Antennas

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Loop Antennas

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Tunable Dipole

A.H. Systems, Inc.
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Com-Power
ETS-Lindgren
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Whip Antennas

Com-Power

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Reliant EMC LLC
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Microwave Vision Group
PPG Aerospace Cuming-Lehman Chambers
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GTEM Cells

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ETS-Lindgren
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Cells

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ESDEMC Technology LLC
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TESEO SpA
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Universal Shielding Corp.

Wave Scientific Ltd

Environmental Chambers

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Alltest Instruments
Axiom Test Equipment Rentals
Cincinnati Sub Zero, LLC
Electro-Tech Systems
HEMCO Corporation
inTEST Thermal Solutions
Product Safety Consulting
QAI Laboratories
Sanwood Environmental Chambers Co., Ltd
Thermotron
VEROCH - Testing Equipment USA
Videon Central, Inc.

Fire Protection Chambers

MPB Measuring Instruments
QAI Laboratories
Sprinkler Innovations

Portable Structures

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QAI Laboratories
Sanwood Environmental Chambers Co., Ltd
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Universal Shielding Corp.
V Technical Textiles, Inc.

Reverberation Chambers

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ES Components
Pearson Electronics, Inc.
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Bluetooth Modules

TDK Electronics

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Cable Assemblies

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Magnetic Shield Corporation
MegaPhase, LLC
METZ CONNECT
Pickering Interfaces
Times Microwave Systems
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CONEC Corporation
Gemini Electronic Components, Inc.
Isodyne Inc.

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Amphenol Industrial Products Group
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Gemini Electronic Components, Inc.
Isodyne Inc.
MegaPhase, LLC
Nolato Jabar LLC
Quell Corporation
Tech-Etch

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APITech
Cinch Connectivity Solutions
CONEC Corporation
Curtis Industries/Tri-Mag, LLC
METZ CONNECT
SCHURTER, Inc.
WECO Electrical Connectors

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DELO Adhesives

Touch Screen Display

DELO Adhesives
Parker Chomerics
Videon Central, Inc.

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Megger

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SCHURTER, Inc.

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SCHURTER, Inc.
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Grounding Rods

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Lightning Protection Systems

Captor Corporation
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Jaro Thermal
Seal Science, Inc.

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Equipnet
Globe Composite Solutions
Omni Controls
Ross Engineering Corp.

Solid State Relays

Applied Physical Electronics, L.C. (APELC)

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C&K Components
EaglePicher Technologies
ES Components
Gemini Electronic Components, Inc.
Pickering Interfaces
Ross Engineering Corp.
SCHURTER, Inc.
Würth Elektronik

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Absorptive Filters

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Air Filters

HEMCO Corporation
Metal Textiles Corporation

Antenna Filters

Würth Elektronik

EMC & RFI Filters

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APITech
Astrodyne TDI
BLOCK USA, Inc.
Captor Corporation
Coilcraft Critical Products & Services
Coilcraft, Inc.
CONEC Corporation
Curtis Industries/Tri-Mag, LLC
Diamond Microwave Chambers Ltd
EMC Instrument & Solution
EMI Filter Company
EMI Solutions, Inc.
Enerdoor
Gemini Electronic Components, Inc.

Filters

EMC & RFI Filters *(continued)*

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MH&W International Corporation
NexTek, Inc.
Nolato Jabar LLC
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Premier Filters
Quell Corporation
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TDK Electronics
TDK RF Solutions
Tech-Etch
TTE Filters, LLC
WEMS Electronics
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Coilcraft Critical Products & Services
Curtis Industries/Tri-Mag, LLC

Filter Pins

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Frequency Converters

VEROCH - Testing Equipment USA

Oscillators

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Passive & Discrete

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Ceramic Capacitors

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Dexter Magnetic Technologies, Inc.
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Knowles (UK) Ltd
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KYOCERA AVX Components Corporation
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Oak-Mitsui Technologies

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Oak-Mitsui Technologies
Würth Elektronik

Filter Capacitors

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CONEC Corporation
EMI Solutions, Inc.
NexTek, Inc.
Oak-Mitsui Technologies
Okaya Electric America, Inc.
Würth Elektronik

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CONEC Corporation
EMI Solutions, Inc.
Oak-Mitsui Technologies

Tantalum Capacitors

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Ferrite Beads, Rods & Forms

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Gowanda Electronics
KOA Speer Electronics
Leader Tech Inc.
MAJR Products
MH&W International Corporation
TDK Electronics

Inductors/Chokes

Data & Signal Line Chokes

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NRD LLC
SCHURTER, Inc.
TDK Electronics
WEMS Electronics

EMI/RFI Inductors

Captor Corporation
Coilcraft Critical Products & Services

Coilcraft, Inc.
Gowanda Electronics
KYOCERA AVX Components Corporation
NRD LLC
WEMS Electronics

Power Line Chokes

Coilcraft Critical Products & Services
Gowanda Electronics
MH&W International Corporation
SCHURTER, Inc.
WEMS Electronics

Reactors for Frequency Converters

Coilcraft Critical Products & Services
Gowanda Electronics
NRD LLC
OnFILTER

RF Chokes

Coilcraft Critical Products & Services
Gowanda Electronics
MH&W International Corporation
NRD LLC
The Schaffner Group

Surface Mount Inductors

Coilcraft Critical Products & Services
Gowanda Electronics
KYOCERA AVX Components Corporation

Switchmode Inductors

Coilcraft Critical Products & Services
Gowanda Electronics

VHF Chokes

Coilcraft Critical Products & Services
Gowanda Electronics
NRD LLC

Mains (X & Y)

Okaya Electric America, Inc.

Resistors & Potentiometers

Electronic Loads

ES Components
Gemini Electronic Components, Inc.

Potentiometers

Betatronix
Bourns, Inc.

Transformers

Americor Electronics Ltd.
Coilcraft, Inc.
ELSCO Transformers
Pearson Electronics, Inc.

Varistors

KOA Speer Electronics
KYOCERA AVX Components Corporation

Power Supply & Conditioning

Adapters

Americor Electronics Ltd.
Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
Oak-Mitsui Technologies
Siglent Technologies North America

Converters

Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
Equipnet
Oak-Mitsui Technologies

Interruptions, AC Power

Astrodyne TDI
DANA Power Supplies
Hilo-Test

Isolators, Power/Signal Line

OnFILTER

Line Conditioning Equipment

DANA Power Supplies
Merus Power
MH&W International Corporation
Okaya Electric America, Inc.

Power Amplifiers

Astrodyne TDI

Power Cords

Americor Electronics Ltd.
DANA Power Supplies
SCHURTER, Inc.

Power Generators

DANA Power Supplies
Preen AC Power Corp.

Power Rectifier

Astrodyne TDI
DANA Power Supplies

Power Strips

DANA Power Supplies
SCHURTER, Inc.

Power Supplies

Americor Electronics Ltd.
AMETEK Programmable Power Supplies
Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
EaglePicher Technologies
Equipnet
Foster Transformer Company
Hilo-Test
Kikusui America Inc.
Langer EMV-Technik GmbH
MH&W International Corporation
Preen AC Power Corp.
Rigol Technologies
Siglent Technologies North America

Switching Power Supplies

Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
Kikusui America Inc.
MH&W International Corporation
Würth Elektronik

Voltage Regulators

Astrodyne TDI
DANA Power Supplies
Preen AC Power Corp.

Printed Circuit Boards

Americor Electronics Ltd.
Candor Industries Inc
Captor Corporation
Curtis Industries/Tri-Mag, LLC
Elma Electronic Inc.
KYOCERA AVX Components Corporation
MegaPhase, LLC
Polyonics
Oak-Mitsui Technologies
SCHURTER, Inc.

Resonators

ES Components

Semiconductors

Diodes

Gemini Electronic Components, Inc.

Transistors

ES Components

Surge Suppressors

Captor Corporation
CITEL, Inc.
Curtis Industries/Tri-Mag, LLC
EMI Solutions, Inc.
ES Components
Fischer Custom Communications, Inc.
Gemini Electronic Components, Inc.
NexTek, Inc.
Okaya Electric America, Inc.
OnFILTER
TDK Electronics
Transtector

Materials

Absorbing Materials

3Gmetalworx Inc.
AR RF/Microwave Instrumentation
ARC Technologies, a Hexcel Company
Diamond Microwave Chambers Ltd
Dutch Microwave Absorber Solutions
Frankonia GmbH
Globe Composite Solutions
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
Marktek Inc.
Microwave Vision Group
PPG Aerospace Cuming-Lehman Chambers
Raymond EMC Enclosures Ltd.
Seal Science, Inc.
TDK RF Solutions
V Technical Textiles, Inc.

Additives

Fonon Technologies
Marktek Inc.

Adhesives

Alpha Assembly Solutions
ARC Technologies, a Hexcel Company
DELO Adhesives
Fonon Technologies
Master Bond
Metal Textiles Corporation
Polyonics
Seal Science, Inc.

Coatings and Sealants

Eeonyx Corporation
Enviro Tech International
Oak-Mitsui Technologies
Seal Science, Inc.

Conductive Materials

Globe Composite Solutions
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
Marktek Inc.
MFG Tray Company (Molded Fiber Glass Tray Co.)
Nolato Jabar LLC
Parker Chomerics
Polyonics
Quell Corporation
Seal Science, Inc.
Tech-Etch
Thermtest

Foams & Insulation

Enertech UPS Pvt Ltd

Metals and Alloys

3Gmetalworx Inc.
Alpha Assembly Solutions
Ferrotec-Nord
Fonon Technologies
Globe Composite Solutions
Johnson Bros Metal Forming Co
Leader Tech Inc.
Magnetic Shield Corporation
The MuShield Company, Inc.
PPG Engineered Materials
Testing Partners

Plastics

Resins & Compounds

ARC Technologies, a Hexcel Company
Bicerano & Associates Consulting
DELO Adhesives
Fonon Technologies
Globe Composite Solutions
Jordi Labs
Lubrizol Engineered Polymers
Seal Science, Inc.

Thermoplastics & Thermoplastic Materials

ARC Technologies, a Hexcel Company
Bicerano & Associates Consulting
Conductive Containers Inc
Crystal Rubber Ltd
Fonon Technologies
Globe Composite Solutions
Lubrizol Engineered Polymers
MFG Tray Company (Molded Fiber Glass Tray Co.)
Parker Chomerics

Resources

Associations

A2LA
Saf-T-Gard International, Inc.

Education

Seminars

Andre Consulting, Inc.
Archambeault EMI/EMC Enterprises
BestESD Technical Services
Cherry Clough Consultants Ltd
Compliance inSight Consulting Inc.
D. C. Smith Consultants
Eisner Safety Consultants
Equipment Reliability Institute (ERI)
ESD Association
Go Global Compliance Inc.
Hoolihan EMC Consulting
In Compliance Magazine
Jastech EMC Consulting LLC
Keysight Technologies Inc.
Kimmel Gerke Associates Ltd.
LearnEMC
Lewis Bass International Engineering Services
Montrose Compliance Services, Inc.
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
SILENT Solutions LLC
UL Knowledge Solutions
WorkHub
Wyatt Technical Services LLC

Training Courses

A2LA
Andre Consulting, Inc.
ARC Technical Resources
Cherry Clough Consultants Ltd
D. C. Smith Consultants
DEKRA
DG Technologies
Eisner Safety Consultants
Electronic Instrument Associates
EMC FastPass
Equipment Reliability Institute (ERI)
Eurofins York
Hoolihan EMC Consulting
iNARTE
Jastech EMC Consulting LLC
Kimmel Gerke Associates Ltd.
LearnEMC
Lewis Bass International Engineering Services
Lion Technology, Inc.
Montrose Compliance Services, Inc.
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
SILENT Solutions LLC
UL Knowledge Solutions
University of Oxford Continuing Professional Development - Technology Programme
Washington Laboratories
WorkHub
Wyatt Technical Services LLC

University

Purdue Engineering Professional Education
WorkHub

Videos

ARC Technical Resources
ESD Association
Keysight Technologies Inc.
Purdue Engineering Professional Education
Washington Laboratories
WorkHub
Wyatt Technical Services LLC

Webinars

Cherry Clough Consultants Ltd
Compliance inSight Consulting Inc.
Eisner Safety Consultants
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
ESD Association
LearnEMC
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
WorkHub
Wyatt Technical Services LLC

Publications

Books

EMI/EMC Books

Andre Consulting, Inc.
Cherry Clough Consultants Ltd
D.L.S. - Military
Montrose Compliance Services, Inc.
Wyatt Technical Services LLC

Product Safety Books

Lewis Bass International Engineering Services

Magazines

In Compliance Magazine

Standards Resellers

ESD Association

Eyes, Face, and Head

HEMCO Corporation
Saf-T-Gard International, Inc.
WorkHub

Hand and Foot Protection

Saf-T-Gard International, Inc.
SW Safety Solutions
WorkHub

Safety & Warning Labels

Abstraction Engineering Inc
Clarion Safety Systems
Coast Label
Enerdoor
HM Cragg
InfoSight Corporation
Lewis Bass International Engineering Services
Polyonics
Saf-T-Gard International, Inc.
WorkHub

Safety Clothing

Saf-T-Gard International, Inc.
SW Safety Solutions
TECH WEAR, INC.
WorkHub

Calibration & Repair

A.com Electronic Measurement Technology
A.H. Systems, Inc.
Alltest Instruments
AMETEK NSI-MI Technologies
ARC Technical Resources
Avalon Test Equipment
Barth Electronics, Inc.
Electronic Instrument Associates
Enertech UPS Pvt Ltd
ETS-Lindgren
Excalibur Engineering Inc.
Fischer Custom Communications, Inc.
Haefely AG
Keysight Technologies Inc.
Lightning EMC
MPB Measuring Instruments
NRD LLC
Omni Controls
Pearson Electronics, Inc.
Ross Engineering Corp.
Sanwood Environmental Chambers Co., Ltd
Schwarzbeck Mess-Elektronik OHG
Solar Electronics Co.
TDK RF Solutions
Techmaster Electronics
Technical Safety Services
TESEO SpA
Trescal
VEROCH - Testing Equipment USA
Wave Scientific Ltd
Willrich Precision Instrument Company, Inc

Codes, Standards & Regulations

A2LA
American Certification Body
American National Standards Institute
Clarion Safety Systems
CSA Group
DEKRA
DG Technologies
Eisner Safety Consultants
Enerdoor
Enertech UPS Pvt Ltd
Go Global Compliance Inc.
GreenSoft Technology
Grund Technical Solutions, Inc.
H.B. Compliance Solutions
iNARTE
InfoSight Corporation
Micom Laboratories Inc
MiCOM Labs
Omni Controls
The Photonics Group
RM Regulatory & Export Compliance, LLC
TJS Technical Services Inc.
UL Knowledge Solutions

Consulting

Cleanroom/Static Control

Advanced ESD Services +
BestESD Technical Services
Bystat International Inc
Estion Technologies GmbH
OnFILTER
Protective Industrial Polymers

EMC Consulting

Andre Consulting, Inc.
Atlas Compliance & Engineering
BestESD Technical Services
Cherry Clough Consultants Ltd
CKC Laboratories, Inc.
Compliance inSight Consulting Inc.
D. C. Smith Consultants
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
D.L.S. - Wireless
Dayton T. Brown, Inc.
DG Technologies
DNB Engineering, Inc.
Electro Magnetic Applications, Inc (EMA)
EMC Instrument & Solution
Enerdoor
ESDEMC Technology LLC
ETS-Lindgren
Eurofins York
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Go Global Compliance Inc.
Grund Technical Solutions, Inc.
Heavyside Corporation
Hoolihan EMC Consulting
International Certification Services, Inc.
Jastech EMC Consulting LLC
JBRC Consulting LLC

JDM LABS LLC

Kimmel Gerke Associates Ltd.

Laird Connectivity

LearnEMC

Machinery Safety & Compliance Services

Montrose Compliance Services, Inc.

OnFILTER

Pulver Laboratories

R&B Laboratory

Remcom

RM Regulatory & Export Compliance, LLC

SILENT Solutions LLC

Southwest Research Institute

Spectrum EMC, LLC

Test Site Services Inc

TJS Technical Services Inc.

Wave Scientific Ltd

WEMS Electronics

Wyatt Technical Services LLC

ESD Consulting

BestESD Technical Services

Conductive Containers Inc

D. C. Smith Consultants

D.L.S. - EMC

D.L.S. - Military

Electro-Tech Systems

ESDEMC Technology LLC

Estion Technologies GmbH

F2 Labs - Damascus, MD

F2 Labs - Middlefield, OH

JBRC Consulting LLC

Laird Connectivity

Montrose Compliance Services, Inc.

OnFILTER

SILENT Solutions LLC

Wyatt Technical Services LLC

Government Regulations

BSMI Regulatory Consulting

Atlas Compliance & Engineering

D.L.S. - EMC

D.L.S. - Wireless

Go Global Compliance Inc.

RM Regulatory & Export Compliance, LLC

TJS Technical Services Inc.

EU (Europe) Regulatory Consulting

ACEMA

Andre Consulting, Inc.

Atlas Compliance & Engineering

CKC Laboratories, Inc.

Compliance inSight Consulting Inc.

The Compliance Map

Compliance Specialty International Associates

Compliance Worldwide, Inc.

D.L.S. - EMC

D.L.S. - Environmental

D.L.S. - Product Safety

D.L.S. - Wireless

Eisner Safety Consultants

Elite Electronic Engineering Inc.

F2 Labs - Damascus, MD

F2 Labs - Middlefield, OH

Go Global Compliance Inc.

GreenSoft Technology

International Certification Services, Inc.

JBRC Consulting LLC

Kimmel Gerke Associates Ltd.

Laird Connectivity

Montrose Compliance Services, Inc.

RM Regulatory & Export Compliance, LLC

TJS Technical Services Inc.

VPI Laboratories, Inc.

FCC (U.S) Regulatory Consulting

Andre Consulting, Inc.

Atlas Compliance & Engineering

CKC Laboratories, Inc.

Compliance Specialty International Associates

Compliance Worldwide, Inc.

D.L.S. - EMC

D.L.S. - Product Safety

D.L.S. - Wireless

Element Materials Technology - Brooklyn Park, MN

Element Materials Technology - Dallas Plano, TX

Element Materials Technology - Irvine, CA

Element Materials Technology - Portland Hillsboro, OR

Element Materials Technology - Washington, Columbia, Oakland Mills

Elite Electronic Engineering Inc.

F2 Labs - Damascus, MD

F2 Labs - Middlefield, OH

Go Global Compliance Inc.

International Certification Services, Inc.

JBRC Consulting LLC

Kimmel Gerke Associates Ltd.

Laird Connectivity

Montrose Compliance Services, Inc.

RM Regulatory & Export Compliance, LLC

TJS Technical Services Inc.

TÜV Rheinland of North America

VPI Laboratories, Inc.

GOST (Russia) Regulatory Consulting

Go Global Compliance Inc.

RM Regulatory & Export Compliance, LLC

TJS Technical Services Inc.

VCCI Consulting

Atlas Compliance & Engineering

CKC Laboratories, Inc.

D.L.S. - EMC

RM Regulatory & Export Compliance, LLC

TJS Technical Services Inc.

Lightning Protection

Andre Consulting, Inc.

D. C. Smith Consultants

D.L.S. - Military

Electro Magnetic Applications, Inc (EMA)

NexTek, Inc.

UL Knowledge Solutions

Medical Device

Andre Consulting, Inc.

CertifiGroup Inc.

D. C. Smith Consultants

D.L.S. - EMC

D.L.S. - Environmental

D.L.S. - Product Safety

D.L.S. - Wireless

Eisner Safety Consultants

F2 Labs - Damascus, MD

F2 Labs - Middlefield, OH

Consulting

Medical Device *(continued)*

G&M Compliance, Inc.
GreenSoft Technology
Kimmel Gerke Associates Ltd.
Laird Connectivity
MedicalRegs.com
Orbis Compliance LLC
Pacific EMC
The Photonics Group
Product Safety Consulting
Pulver Laboratories
Test Site Services Inc
TJS Technical Services Inc.
UL Knowledge Solutions

Product Safety

360 Compliance Partners
Applied Research Laboratories
CertifiGroup Inc.
Clarion Safety Systems
Compliance inSight Consulting Inc.
D.L.S. - Environmental
D.L.S. - Product Safety
Eisner Safety Consultants
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Go Global Compliance Inc.
InfoSight Corporation
Intertek
JBRC Consulting LLC
Lewis Bass International Engineering Services
M.C. Global Access LLC
Machinery Safety & Compliance Services
Orbis Compliance LLC
PC Squared Consultants
The Photonics Group
Product EHS Consulting LLC
Product Safety Consulting
RM Regulatory & Export Compliance, LLC
Test Site Services Inc
UL Knowledge Solutions
VDE Americas
VEROCH - Testing Equipment USA

Quality

DEKRA
Eisner Safety Consultants
Estion Technologies GmbH
Globe Composite Solutions
InfoSight Corporation
RM Regulatory & Export Compliance, LLC
Spectrum EMC, LLC
UL Knowledge Solutions

Telecom

Compliance Specialty International Associates
CV. DIMULTI
D. C. Smith Consultants
D.L.S. - Wireless
F2 Labs - Middlefield, OH
Go Global Compliance Inc.
Orbis Compliance LLC
UL Knowledge Solutions

Tempest

Dayton T. Brown, Inc.

Transient

Andre Consulting, Inc.
BestESD Technical Services
D. C. Smith Consultants
D.L.S. - EMC
F2 Labs - Middlefield, OH
Grund Technical Solutions, Inc.
JBRC Consulting LLC
NexTek, Inc.
SILENT Solutions LLC

Design

Andre Consulting, Inc.
BestESD Technical Services
Captor Corporation
Clarion Safety Systems
Conductive Containers Inc
DG Technologies
Empower RF Systems, Inc.
EMS-PLUS
Enertech UPS Pvt Ltd
Fonon Technologies
Globe Composite Solutions
Jastech EMC Consulting LLC
JBRC Consulting LLC
Machinery Safety & Compliance Services
Orbel Corporation
The Photonics Group
SILENT Solutions LLC
UL Knowledge Solutions
V Technical Textiles, Inc.
VEROCH - Testing Equipment USA
Videon Central, Inc.
WEMS Electronics

Other

Conductive Painting Services

VTI Vacuum Technologies, Inc.

Shielded Enclosure Design

3Gmetalworx Inc.
Conductive Containers Inc
Diamond Microwave Chambers Ltd
Elma Electronic Inc.
Leader Tech Inc.
VTI Vacuum Technologies, Inc.

Site Survey Services

Analysis and Measurement Services Corporation
BestESD Technical Services
Clarion Safety Systems
Dayton T. Brown, Inc.
Electronic Instrument Associates
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
NRD LLC
Spectrum EMC, LLC
Wave Scientific Ltd
WorkHub

Other Services

Jay Hoehl Inc.
Machinery Safety & Compliance Services
Technical Safety Services

Architectural Shielding Products

ETS-Lindgren
Leader Tech Inc.
MAJR Products
Marktek Inc.
Metal Textiles Corporation

Fingerstock

3Gmetalworx Inc.
Leader Tech Inc.
Metal Textiles Corporation
Orbel Corporation
Parker Chomerics
Raymond EMC Enclosures Ltd.
Schlegel Electronic Materials
Tech-Etch

Shielded Air Filters

Leader Tech Inc.
MAJR Products
Nolato Jabar LLC
P & P Technology Ltd
Parker Chomerics
Premier Filters
Spira Manufacturing Corporation
Tech-Etch
Universal Shielding Corp.

Shielded Cable Assemblies & Harnesses

CONEC Corporation
Leader Tech Inc.
MAJR Products

Shielded Coatings

A&A Coatings
ARC Technologies, a Hexcel Company
Leader Tech Inc.
Marktek Inc.
Parker Chomerics
VTI Vacuum Technologies, Inc.

Shielded Compounds

Leader Tech Inc.
Marktek Inc.
Parker Chomerics

Shielded Conduit

Electri-Flex Company
Leader Tech Inc.
Magnetic Shield Corporation

Shielded Connectors

American Swiss
Amphenol Industrial Products Group
Cinch Connectivity Solutions
CONEC Corporation
Gemini Electronic Components, Inc.
Isodyne Inc.
Leader Tech Inc.
Metal Textiles Corporation
Quell Corporation
Spira Manufacturing Corporation
Tech-Etch
Würth Elektronik

Shielded Enclosures

3Gmetalworx Inc.
AR RF/Microwave Instrumentation
Comtest Engineering BV
Diamond Microwave Chambers Ltd
Elma Electronic Inc.
Emcor Enclosures
ETS-Lindgren
Frankonia GmbH
Leader Tech Inc.
Lionheart Northwest
Magnetic Shield Corporation
Marktek Inc.
The MuShield Company, Inc.
PPG Aerospace Cuming-Lehman Chambers
Raymond EMC Enclosures Ltd.
Select Fabricators, Inc.
Universal Shielding Corp.
V Technical Textiles, Inc.
VTI Vacuum Technologies, Inc.

Shielded Tubing

Electri-Flex Company
Leader Tech Inc.
Magnetic Shield Corporation
Marktek Inc.

Shielded Wire & Cable

Cinch Connectivity Solutions
CONEC Corporation
Isodyne Inc.
Leader Tech Inc.
Metal Textiles Corporation

Shielding Gaskets

3Gmetalworx Inc.
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MAJR Products
Metal Textiles Corporation
Nolato Jabar LLC
Orbel Corporation
P & P Technology Ltd
Parker Chomerics
Quell Corporation
SAS Industries, Inc.
Schlegel Electronic Materials
Spira Manufacturing Corporation
Tech-Etch
VTI Vacuum Technologies, Inc.
W. L. Gore & Associates, Inc.
XGR Technologies

Shielding Materials

EMI/RFI Shielding Materials

A&A Coatings
Aaronia USA
AR RF/Microwave Instrumentation
Bal Seal Engineering
Diamond Microwave Chambers Ltd
Fabritech, Inc.
Fair-Rite Products Corp.
Isodyne Inc.
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MAJR Products
Metal Textiles Corporation
MH&W International Corporation

Shielding Materials

EMI/RFI Shielding Materials

(continued)

Nolato Jabar LLC
Orbel Corporation
P & P Technology Ltd
Polyonics
PPG Aerospace Cuming-Lehman Chambers
Schlegel Electronic Materials
Spira Manufacturing Corporation
Swift Textile Metalizing LLC
Universal Shielding Corp.
V Technical Textiles, Inc.
VTI Vacuum Technologies, Inc.
W. L. Gore & Associates, Inc.
Würth Elektronik
XGR Technologies

Magnetic Field Shielding Materials

3Gmetalworx Inc.
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
Magnetic Shield Corporation
MAJR Products
The MuShield Company, Inc.
PPG Aerospace Cuming-Lehman Chambers
V Technical Textiles, Inc.

Shielding, Board-Level

3Gmetalworx Inc.
Conductive Containers Inc
Elma Electronic Inc.
Faspro Technologies
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MAJR Products
Orbel Corporation
XGR Technologies

Software

Compliance Management Software

GreenSoft Technology
WorkHub

EMC Simulation Software

AE Techron, Inc.
Altair Engineering Inc.
ANSYS Inc.
Electro Magnetic Applications, Inc (EMA)
EMS-PLUS
Heavyside Corporation
Hilo-Test
Remcom
TESEO SpA
TOYO Corporation
Wave Computation Technologies, Inc.

ESD/Static Control Software

ACL Staticide Inc.
Antistat Inc
Desco Industries Inc.
Estion Technologies GmbH
Langer EMV-Technik GmbH

Lab Control Software

AR RF/Microwave Instrumentation
ETS-Lindgren
Lionheart Northwest
TESEO SpA
TOYO Corporation

Product Safety Software

Heavyside Corporation
OnRule
The Photonics Group

Signal Integrity & EMC Analysis Software

AFJ INSTRUMENTS Srl
Altair Engineering Inc.
EMZER Technological Solutions
Heavyside Corporation
Remcom
TDK RF Solutions
TOYO Corporation

Wireless Propagation Software

Altair Engineering Inc.
Heavyside Corporation
Remcom

Static Control

Air Ionizers

Bystat International Inc
Desco Industries Inc.
Elimstat.com
Estatec
NRD LLC
Simco-Ion

Clothing & Accessories

ESD Garments

Bystat International Inc
Correct Products, Inc.
Desco Industries Inc.
Elimstat.com
Estatec
TECH WEAR, INC.
United Static Control Products Inc.

Footwear

Amstat Industries, Inc.
Estatec
Lubrizol Engineered Polymers
Saf-T-Gard International, Inc.

Wrist Straps

Amstat Industries, Inc.
Bystat International Inc
Correct Products, Inc.
Desco Industries Inc.
Estatec
Lubrizol Engineered Polymers
Static Solutions, Inc.
United Static Control Products Inc.

Containers

Bystat International Inc

Conductive Containers Inc

Correct Products, Inc.

Desco Industries Inc.

Estatec

Lubrizol Engineered Polymers

MFG Tray Company (Molded Fiber Glass Tray Co.)

ESD Tape

Conductive Containers Inc

Correct Products, Inc.

Desco Industries Inc.

Elimstat.com

Leader Tech Inc.

Polyonics

United Static Control Products Inc.

Flooring

Carpet

Ground Zero

Julie Industries, Inc.

Protective Industrial Polymers

StaticStop ESD Flooring

StaticWorx, Inc.

Floor Coatings

ACL Staticide Inc.

Correct Products, Inc.

Estatec

Ground Zero

Julie Industries, Inc.

Protective Industrial Polymers

Static Solutions, Inc.

StaticStop ESD Flooring

StaticWorx, Inc.

United Static Control Products Inc.

Mats

Bystat International Inc

Correct Products, Inc.

Elimstat.com

Estatec

Static Solutions, Inc.

StaticStop ESD Flooring

Tiles

Bystat International Inc

Ground Zero

Julie Industries, Inc.

StaticStop ESD Flooring

StaticWorx, Inc.

Packaging

Bystat International Inc

Conductive Containers Inc

Correct Products, Inc.

Desco Industries Inc.

EaglePicher Technologies

Elimstat.com

Estatec

Lubrizol Engineered Polymers

MFG Tray Company (Molded Fiber Glass Tray Co.)

Simulators

EMP Simulators

Fischer Custom Communications, Inc.

Grund Technical Solutions, Inc.

ESD Simulators

Electro-Tech Systems

ESDEMC Technology LLC

Hilo-Test

Kikusui America Inc.

Solutions Directory

Transient Detectors & Suppressors

CITEL, Inc.
EMI Solutions, Inc.
EMZER Technological Solutions
Fischer Custom Communications, Inc.
NexTek, Inc.

Workstations

ACL Staticide Inc.
Bystat International Inc
Conductive Containers Inc
Correct Products, Inc.
HEMCO Corporation
Langer EMV-Technik GmbH
Lubrizol Engineered Polymers
MFG Tray Company (Molded Fiber Glass Tray Co.)
NRD LLC
United Static Control Products Inc.

Test and Measure

Accelerometers

Clark Testing
Essco Calibration Laboratory
PCE Instruments
Techmaster Electronics

Amplifiers

Amplifier Modules

AR RF/Microwave Instrumentation
Empower RF Systems, Inc.
Exodus Advanced Communications
OPHIR RF/Ophir EMC
Prana
Vectawave Technology Limited

Low Power Amplifiers

A.H. Systems, Inc.
AR RF/Microwave Instrumentation
ETS-Lindgren
Exodus Advanced Communications
Siglent Technologies North America
Vectawave Technology Limited

Microwave Amplifiers

AMETEK CTS
Applied Systems Engineering, Inc.
AR RF/Microwave Instrumentation
Axiom Test Equipment Rentals
CPI TMD Technologies Ltd.
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
OPHIR RF/Ophir EMC
Prana
Reliant EMC LLC
Wave Scientific Ltd

Power Amplifiers

Advanced Test Equipment Rentals
AE Techron, Inc.

AMETEK CTS
AR RF/Microwave Instrumentation
CPI TMD Technologies Ltd.
CPI, Inc.
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Lionheart Northwest
OPHIR RF/Ophir EMC
Prana
Reliant EMC LLC
Rohde & Schwarz
TESEO SpA
TOYO Corporation
Vectawave Technology Limited

RF Amplifiers

A.H. Systems, Inc.
Advanced Test Equipment Rentals
AMETEK CTS
AR RF/Microwave Instrumentation
Avalon Test Equipment
Axiom Test Equipment Rentals
CPI, Inc.
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
OPHIR RF/Ophir EMC
Prana
Rohde & Schwarz
US Microwave Laboratories
Wave Scientific Ltd

Solid State Amplifiers

AMETEK CTS
AR RF/Microwave Instrumentation
CPI, Inc.
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
OPHIR RF/Ophir EMC
Prana
Vectawave Technology Limited

Traveling Wave Tube Amplifiers

AMETEK CTS
AR RF/Microwave Instrumentation
Avalon Test Equipment
CPI TMD Technologies Ltd.
CPI, Inc.
Empower RF Systems, Inc.
Hilo-Test
OPHIR RF/Ophir EMC
Reliant EMC LLC

Analyzers

EMI/EMC, Spectrum Analyzers

Aaronia USA
Advanced Test Equipment Rentals
AFJ INSTRUMENTS Srl
Agile Calibration
Alltest Instruments
Anritsu Company
Axiom Test Equipment Rentals
Electro Rent Corporation
Electronic Instrument Associates
EMC Instrument & Solution
EMZER Technological Solutions
Excalibur Engineering Inc.
GAUSS INSTRUMENTS
Keysight Technologies Inc.
Laplace Instruments Ltd
MPB Measuring Instruments
Reliant EMC LLC
Rigol Technologies
Rohde & Schwarz
Siglent Technologies North America
Signal Hound
TOYO Corporation
VIAVI Solutions

Flicker Analyzers

Eurofins York
HV TECHNOLOGIES, Inc.
Kikusui America Inc.

Harmonics Analyzers

Eurofins York
HV TECHNOLOGIES, Inc.
Kikusui America Inc.
Laplace Instruments Ltd

Network Analyzers

AFJ INSTRUMENTS Srl
Agile Calibration
Copper Mountain Technologies
Electro Rent Corporation
Excalibur Engineering Inc.
Keysight Technologies Inc.
PCE Instruments
Rohde & Schwarz
Siglent Technologies North America
TOYO Corporation
VIAVI Solutions

Power Quality Analyzers

Advanced Test Equipment Rentals
Axiom Test Equipment Rentals
Electro Rent Corporation
Excalibur Engineering Inc.
Lionheart Northwest

Telecom Analyzers

MPB Measuring Instruments

Audio & Video

Audio Systems

Audivo GmbH
Videon Central, Inc.

CCTV

Audivo GmbH
TDK RF Solutions
TESEO SpA
Videon Central, Inc.

Automatic Test Sets

AFJ INSTRUMENTS Srl
ARC Technical Resources
Essco Calibration Laboratory
General Test Systems LLC
Omni Controls
Pendulum Instruments
Preen AC Power Corp.
TOYO Corporation
United Static Control Products Inc.

Avionics Test Equipment

Absolute EMC Llc.
AE Techron, Inc.
Alltest Instruments
Cincinnati Sub Zero, LLC
CPI TMD Technologies Ltd.
The EMC Shop
Essco Calibration Laboratory
HV TECHNOLOGIES, Inc.
Omni Controls
Pickering Interfaces
Preen AC Power Corp.
VIAVI Solutions
Vitrek Corporation

Burn-in Test Equipment

Essco Calibration Laboratory
General Test Systems LLC
inTEST Thermal Solutions
Mechanical Devices
OPHIR RF/Ophir EMC
Preen AC Power Corp.
Sanwood Environmental Chambers Co., Ltd

Data Acquisition Monitoring Systems

AMETEK NSI-MI Technologies
Analysis and Measurement Services Corporation
Degree Controls, Inc.
Desco Industries Inc.
DG Technologies
Essco Calibration Laboratory

Fiber-Optic Systems

Absolute EMC Llc.
DG Technologies
Essco Calibration Laboratory
Excalibur Engineering Inc.
Ferrotec-Nord
HV TECHNOLOGIES, Inc.
Michigan Scientific Corp.
Ross Engineering Corp.
TESEO SpA

Flow Meters

Essco Calibration Laboratory
Omni Controls
PCE Instruments
VEROCH - Testing Equipment USA

Generators

Arbitrary Waveform Generators

AMETEK CTS
Applied Physical Electronics, L.C. (APELC)
Eurofins York
GIGA-TRONICS INCORPORATED
Hilo-Test
Keysight Technologies Inc.
Rigol Technologies
Siglent Technologies North America
Suzhou 3ctest Electronic Co., Ltd.

Generators

EMP Generator

HV TECHNOLOGIES, Inc.
Suzhou 3ctest Electronic Co., Ltd.

ESD Generators

Advanced Test Equipment Rentals
AMETEK CTS
ARC Technical Resources
The EMC Shop
Grund Technical Solutions, Inc.
Haefely AG
HV TECHNOLOGIES, Inc.
Lightning EMC
Suzhou 3ctest Electronic Co., Ltd.

Fast/Transient Burst Generators

Absolute EMC Llc.
ARC Technical Resources
The EMC Shop
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
Lightning EMC
Suzhou 3ctest Electronic Co., Ltd.

Impulse Generators

Absolute EMC Llc.
AFJ INSTRUMENTS Srl
AMETEK CTS
Applied EM Technology
Applied Physical Electronics, L.C. (APELC)
Grund Technical Solutions, Inc.
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
Lightning EMC
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.

Interference Generators

Suzhou 3ctest Electronic Co., Ltd.

Lightning Generators

Absolute EMC Llc.
Advanced Test Equipment Rentals
ARC Technical Resources
Avalon Test Equipment
The EMC Shop
Haefely AG
HV TECHNOLOGIES, Inc.
Lightning EMC
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.

Signal Generators

Aaronia USA
Absolute EMC Llc.
AFJ INSTRUMENTS Srl
Alltest Instruments
Applied EM Technology
Electro Rent Corporation
Eurofins York
Excalibur Engineering Inc.
GIGA-TRONICS INCORPORATED
Keysight Technologies Inc.
Kikusui America Inc.
Laplace Instruments Ltd
Reliant EMC LLC
Rohde & Schwarz
Signal Hound
Suzhou 3ctest Electronic Co., Ltd.
Techmaster Electronics
TOYO Corporation
VIAVI Solutions

Surge Transient Generators

Absolute EMC Llc.
Advanced Test Equipment Rentals
AMETEK CTS
ARC Technical Resources
Avalon Test Equipment
The EMC Shop
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
Lightning EMC
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.
Techmaster Electronics
Thermo Fisher Scientific

Meters

Field Strength Meters

AR RF/Microwave Instrumentation
Desco Industries Inc.
Narda STS, USA
United Static Control Products Inc.
Wavecontrol Inc.

Gaussmeters

Omni Controls
PCE Instruments
Wavecontrol Inc.

Magnetic Field Meters

AR RF/Microwave Instrumentation
MPB Measuring Instruments
PCE Instruments
Wavecontrol Inc.

Megohmmeters

ACL Staticide Inc.
Amstat Industries, Inc.
Axiom Test Equipment Rentals
Chroma Systems Solutions, Inc
Megger
PCE Instruments
Ross Engineering Corp.
Static Solutions, Inc.
United Static Control Products Inc.

Radiation Hazard Meters

AR RF/Microwave Instrumentation
EMC Test Design, LLC
Wavecontrol Inc.

RF Power Meters

Alltest Instruments
Anritsu Company
AR RF/Microwave Instrumentation
Electro Rent Corporation
Keysight Technologies Inc.
OPHIR RF/Ophir EMC
VIAVI Solutions

Static Charge Meters

ACL Staticide Inc.
Electro-Tech Systems
Estion Technologies GmbH

Static Decay Meters

Electro-Tech Systems

Monitors

Current Monitors

Grund Technical Solutions, Inc.
PCE Instruments
Pearson Electronics, Inc.

EMI Test Monitors

DG Technologies
OnFILTER

ESD Monitors

Bystat International Inc
Elimstat.com
Estion Technologies GmbH
Static Solutions, Inc.

Ionizer Balance Monitors

Static Voltage Monitors

Desco Industries Inc.
Michigan Scientific Corp.

Oscilloscopes & Transient Recorders

Agile Calibration
Alltest Instruments
Avalon Test Equipment
Axiom Test Equipment Rentals
Electro Rent Corporation
Essco Calibration Laboratory
Keysight Technologies Inc.
PCE Instruments
Rigol Technologies
Rohde & Schwarz
Siglent Technologies North America
Techmaster Electronics
Teledyne LeCroy

Pressure Measurement

Gauges

Willrich Precision Instrument Company, Inc

Probes

Current/Magnetic Field Probes

A.H. Systems, Inc.
AEMC Instruments
Alltest Instruments
Fischer Custom Communications, Inc.
General Test Systems LLC
Langer EMV-Technik GmbH
MPB Measuring Instruments
Pearson Electronics, Inc.
Prana
Rigol Technologies
Siglent Technologies North America
Solar Electronics Co.
Techmaster Electronics

Electric Field Probes

AR RF/Microwave Instrumentation
The EMC Shop
EMC Test Design, LLC
Enerdoor
ETS-Lindgren
Langer EMV-Technik GmbH
MPB Measuring Instruments
Narda STS, USA
Siglent Technologies North America
Wavecontrol Inc.

Voltage Probes

Fischer Custom Communications, Inc.
Hilo-Test
Langer EMV-Technik GmbH
Laplace Instruments Ltd
OnFILTER
Ross Engineering Corp.
Solar Electronics Co.

Receivers

EMI/EMC Receivers

AFJ INSTRUMENTS Srl
AR RF/Microwave Instrumentation
EMZER Technological Solutions
Excalibur Engineering Inc.
GAUSS INSTRUMENTS
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Reliant EMC LLC
Rohde & Schwarz
Schwarzbeck Mess-Elektronik OHG

RF Receivers

AFJ INSTRUMENTS Srl
AMETEK NSI-MI Technologies
EMZER Technological Solutions
GIGA-TRONICS INCORPORATED
Narda STS, USA
Rigol Technologies
Rohde & Schwarz

TEMPEST Receivers

Rohde & Schwarz

RF Leak Detectors

AR RF/Microwave Instrumentation
MPB Measuring Instruments
NRD LLC

Safety Test Equipment

AE Techron, Inc.
AEMC Instruments
Chroma Systems Solutions, Inc
Cincinnati Sub Zero, LLC
ED&D
EMC Test Design, LLC
Kikusui America Inc.
Micom Laboratories Inc
MPB Measuring Instruments
Packaging Compliance Labs
Preen AC Power Corp.
Product Safety Consulting
Pulver Laboratories
Saf-T-Gard International, Inc.
Sanwood Environmental Chambers Co., Ltd
United Static Control Products Inc.
VEROCH - Testing Equipment USA
Vitrek Corporation

SAR Testing Equipment

ART-MAN
GIGA-TRONICS INCORPORATED

Shock & Vibration Testing Shakers

Cincinnati Sub Zero, LLC
Globe Composite Solutions
Micom Laboratories Inc
Sanwood Environmental Chambers Co., Ltd
Thermotron
Wewontech

Susceptibility Test Instruments

Absolute EMC Llc.
ARC Technical Resources
DG Technologies
EMC Test Design, LLC
ESDEMC Technology LLC
Grund Technical Solutions, Inc.
Laplace Instruments Ltd
Pendulum Instruments
TDK RF Solutions

Telecom Test Equipment

Absolute EMC Llc.
AE Techron, Inc.
Anritsu Company
Avalon Test Equipment
Axiom Test Equipment Rentals
Cincinnati Sub Zero, LLC
Electro Rent Corporation
Fischer Custom Communications, Inc.
Haefely AG
Megger
Pickering Interfaces
VIAVI Solutions

Test Equipment Rentals

Advanced Test Equipment Rentals
Alltest Instruments
AR RF/Microwave Instrumentation
Avalon Test Equipment
Axiom Test Equipment Rentals
Barth Electronics, Inc.
Electro Rent Corporation
Electro-Tech Systems
The EMC Shop
ESDEMC Technology LLC
Excalibur Engineering Inc.
Grund Technical Solutions, Inc.
Lionheart Northwest
Megger
Michigan Scientific Corp.
MPB Measuring Instruments
Techmaster Electronics
TestWorld Inc
Transient Specialists, Inc.
United Static Control Products Inc.
VEROCH - Testing Equipment USA

Testers

Common Mode Transient Immunity (CMTI)

Barth Electronics, Inc.

Current Leakage Testers

Associated Research, Inc.
Chroma Systems Solutions, Inc
ESDEMC Technology LLC
Kikusui America Inc.
Megger
Ross Engineering Corp.
SCI

Dielectric Strength Testers

Associated Research, Inc.
Chroma Systems Solutions, Inc
Megger
Ross Engineering Corp.
SCI

Electrical Safety Testers

Associated Power Technologies
Associated Research, Inc.
Chroma Systems Solutions, Inc
Kikusui America Inc.
Megger
Saf-T-Gard International, Inc.
SCI

EMC Testers

Absolute EMC Llc.

AMETEK CTS
DG Technologies
EMC PARTNER AG
EMC Technologies
EMC Test Design, LLC
EMZER Technological Solutions
ESDEMC Technology LLC
Grund Technical Solutions, Inc.
Langer EMV-Technik GmbH
OPHIR RF/Ophir EMC
Pendulum Instruments

ESD Testers

CDM (Charged Device Model)

Barth Electronics, Inc.
Electro-Tech Systems
Thermo Fisher Scientific

HBM (Human Body Model)

Electro-Tech Systems
Thermo Fisher Scientific

TLP (Transmission Line Pulser)

Barth Electronics, Inc.
Thermo Fisher Scientific

Ground Bond Testers

Associated Power Technologies

Ground Resistance Testers

AEMC Instruments
Associated Research, Inc.
Megger
SCI

Hipot Testers

Applied Physical Electronics, L.C. (APELC)
Associated Power Technologies
Associated Research, Inc.
Chroma Systems Solutions, Inc
Electro Rent Corporation
GW INSTEK
Kikusui America Inc.
Ross Engineering Corp.
SCI

Thermocouples

Applied Physical Electronics, L.C. (APELC)
Pickering Interfaces
VEROCH - Testing Equipment USA

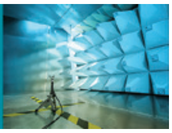
Used & Refurbished Test Equipment

Alltest Instruments
AR RF/Microwave Instrumentation
Avalon Test Equipment
Axiom Test Equipment Rentals
Electro Rent Corporation
Techmaster Electronics

Vibration Controllers

Cincinnati Sub Zero, LLC
Excalibur Engineering Inc.
Globe Composite Solutions
Micom Laboratories Inc
Thermotron

Testing



Accredited Registrar

ANAB ANSI-ASQ National Accreditation Board
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Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Portland Hillsboro, OR
Excalibur Engineering Inc.
Green Mountain Electromagnetics, Inc.
MiCOM Labs
QAI Laboratories

Calibration Testing

Agile Calibration
Bharat Test House Group
Essco Calibration Laboratory
Haefely AG
ITC India

CE Competent Body

Bureau Veritas Consumer Products Services Inc.
D.L.S. - Environmental
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
Professional Testing (EMI), Inc., a Nemko Company
QAI Laboratories
UL LLC

CE Notified Body

American Certification Body
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Element Materials Technology - Washington, Columbia, Oakland Mills
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Eurofins York
MiCOM Labs
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Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
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Pulver Laboratories
QAI Laboratories
TESEO SpA
Test Site Services Inc

Environmental Testing & Analysis Services

Bharat Test House Group
Bureau Veritas Consumer Products Services Inc.
CertifiGroup Inc.
The Compliance Management Group
D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Wireless
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Elite Electronic Engineering Inc.
ITC India
Micom Laboratories Inc
NTS
Quanta Laboratories
Retlif Testing Laboratories
Sanwood Environmental Chambers Co., Ltd
Test Site Services Inc
UL LLC
Washington Laboratories

Homologation Services

American Certification Body
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Compliance Specialty International Associates
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Portland Hillsboro, OR
Go Global Compliance Inc.
Lewis Bass International Engineering Services
MiCOM Labs
Orbis Compliance LLC
Versus Technology (Versus Global LLC)

Pre-Assessments

A2LA
American Certification Body
Analysis and Measurement Services Corporation
Applied Research Laboratories
Bharat Test House Group
Clark Testing
Compatible Electronics, Inc.
Curtis Industries/Tri-Mag, LLC
CVG Strategy
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
D.L.S. - Wireless
DEKRA
Eisner Safety Consultants
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
International Certification Services, Inc.
Jastech EMC Consulting LLC
Lewis Bass International Engineering Services
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
Product Safety Consulting
Professional Testing (EMI), Inc., a Nemko Company
Quanta Laboratories
SILENT Solutions LLC
Spectrum EMC, LLC
Testing Partners
VPI Laboratories, Inc.
Washington Laboratories

Product & Component Testing Services

Agile Calibration
Analysis and Measurement Services Corporation
ART-MAN
Bharat Test House Group
Bureau Veritas Consumer Products Services Inc.
CertifiGroup Inc.
The Compliance Management Group
Compliance Specialty International Associates
Compliance Testing, LLC
CVG Strategy
D.L.S. - EMC
D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
D.L.S. - Wireless
Dayton T. Brown, Inc.
DEKRA
DNB Engineering, Inc.
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Elite Electronic Engineering Inc.
Energy Assurance LLC
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
FEMA Corporation
Ferrotec-Nord
Green Mountain Electromagnetics, Inc.
International Certification Services, Inc.
ITC India
Micom Laboratories Inc
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
The Photonics Group
Product Safety Consulting
Professional Testing (EMI), Inc., a Nemko Company
Pulver Laboratories
R&B Laboratory
Retlif Testing Laboratories
RF Solutions, LLC.
RM Regulatory & Export Compliance, LLC
Sanwood Environmental Chambers Co., Ltd
Southwest Research Institute
Testing Partners
UL LLC
VPI Laboratories, Inc.
Washington Laboratories
Wyatt Technical Services LLC

Testing Laboratories

Accelerated Stress Testing

Core Compliance Testing Services
D.L.S. - Environmental
D.L.S. - Wireless
Dayton T. Brown, Inc.
Elite Electronic Engineering Inc.
Intertek
Nemko USA, Inc.
NTS
Product Safety Consulting
Professional Testing (EMI), Inc., a Nemko Company
Quanta Laboratories
Radiometrics Midwest Corporation
Videon Central, Inc.

Acoustical Testing

A2LA
Clark Testing
The Compliance Management Group
Core Compliance Testing Services
D.L.S. - Environmental
D.L.S. - Product Safety
Dayton T. Brown, Inc.
DNB Engineering, Inc.
Electronic Instrument Associates
ETS-Lindgren
Intertek
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Quanta Laboratories
Retlif Testing Laboratories

BSMI Compliant Certification Testing

Atlas Compliance & Engineering
Compliance Worldwide, Inc.
Core Compliance Testing Services
D.L.S. - EMC
D.L.S. - Wireless
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
Professional Testing (EMI), Inc., a Nemko Company

CB Test Report

CSA Group
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
Energy Assurance LLC
Eurofins MET Labs
Intertek
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
Professional Testing (EMI), Inc., a Nemko Company
TÜV Rheinland of North America

CE Marking

Abstraction Engineering Inc
Atlas Compliance & Engineering
CertifiGroup Inc.
CKC Laboratories, Inc.
Compatible Electronics, Inc.
The Compliance Management Group
Compliance Worldwide, Inc.
Core Compliance Testing Services
D.L.S. - EMC

D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
D.L.S. - Wireless
DNB Engineering, Inc.
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Elite Electronic Engineering Inc.
EMC Bayswater Pty Ltd
Energy Assurance LLC
Eurofins MET Labs
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Global Testing Laboratories
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
International Certification Services, Inc.
Intertek
Laird Connectivity
Lewis Bass International Engineering Services
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
NTS
Professional Testing (EMI), Inc., a Nemko Company
Pulver Laboratories
Retlif Testing Laboratories
TESEO SpA
Test Site Services Inc
TÜV Rheinland of North America
VPI Laboratories, Inc.

China Compulsory Certification

D.L.S. - EMC
D.L.S. - Product Safety
G&M Compliance, Inc.
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.

Testing Laboratories

Electrical Safety Testing

Abstraction Engineering Inc
Applied Research Laboratories
Bharat Test House Group
CertifiGroup Inc.
Coilcraft Critical Products & Services
CSA Group
CVG Strategy
D.L.S. - Product Safety
Dayton T. Brown, Inc.
DNB Engineering, Inc.
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Washington, Columbia, Oakland Mills
EMC Bayswater Pty Ltd
Energy Assurance LLC
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
Intertek
ITC India
MiCOM Labs
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
Orbis Compliance LLC
Professional Testing (EMI), Inc., a Nemko Company
TÜV Rheinland of North America
UL LLC

EMC Testing

A2LA
Abstraction Engineering Inc
AHD
APREL Inc.
ART-MAN
Atlas Compliance & Engineering
Bharat Test House Group
Bureau Veritas Consumer Products Services Inc.
CKC Laboratories, Inc.
Clark Testing
Compatible Electronics, Inc.
The Compliance Management Group
Compliance Worldwide, Inc.
Core Compliance Testing Services
CSA Group
CVG Strategy
D.L.S. - EMC

D.L.S. - Environmental
D.L.S. - Military
D.L.S. - Product Safety
D.L.S. - Wireless
Dayton T. Brown, Inc.
DNB Engineering, Inc.
Electronics Test Centre
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
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Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Elite Electronic Engineering Inc.
EMC Bayswater Pty Ltd
F2 Labs - Damascus, MD
F2 Labs - Middlefield, OH
G&M Compliance, Inc.
Global Testing Laboratories
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
International Certification Services, Inc.
Intertek
ITC India
Jastech EMC Consulting LLC
Laird Connectivity
MiCOM Labs
Montrose Compliance Services, Inc.
National Institute for Aviation Research
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
NTS
Parker Chomerics
Professional Testing (EMI), Inc., a Nemko Company
Pulver Laboratories
QAI Laboratories
R&B Laboratory
Radiometrics Midwest Corporation
Retlif Testing Laboratories
Southwest Research Institute
Spes Development Co
Test Site Services Inc
Timco Engineering, Inc.
TÜV Rheinland of North America
TÜV SÜD America Inc.
UL LLC
VPI Laboratories, Inc.
Washington Laboratories
Wave Scientific Ltd
WEMS Electronics
Yazaki Testing Laboratory

Energy Efficiency Testing

Applied Research Laboratories
Bharat Test House Group
Bureau Veritas Consumer Products Services Inc.
CSA Group
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
UL LLC

Environmental Simulation Testing

Coilcraft Critical Products & Services

The Compliance Management Group
Core Compliance Testing Services
CVG Strategy
D.L.S. - Environmental
D.L.S. - Military
DNB Engineering, Inc.
Energy Assurance LLC
FEMA Corporation
H.B. Compliance Solutions
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
Professional Testing (EMI), Inc., a Nemko Company
Quanta Laboratories
Retlif Testing Laboratories
Sanwood Environmental Chambers Co., Ltd

ESD Testing

Barth Electronics, Inc.
The Compliance Management Group
Compliance Worldwide, Inc.
CVG Strategy
D.L.S. - EMC
D.L.S. - Military
DNB Engineering, Inc.
Electro-Tech Systems
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
ESDEMC Technology LLC
Estion Technologies GmbH
F2 Labs - Middlefield, OH
H.B. Compliance Solutions
Laird Connectivity
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
Pulver Laboratories
VPI Laboratories, Inc.

GOST R Certification

G&M Compliance, Inc.
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.

GS Mark Certification

TÜV Rheinland of North America

Lithium-Ion Battery Testing

Bharat Test House Group
CSA Group
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Energy Assurance LLC
F2 Labs - Middlefield, OH
ITC India
NTS
Quanta Laboratories

Marine Electronics Testing

Core Compliance Testing Services
D.L.S. - Military
D.L.S. - Wireless
Green Mountain Electromagnetics, Inc.
Professional Testing (EMI), Inc., a Nemko Company
R&B Laboratory
Retlif Testing Laboratories

National Recognized Testing Laboratory (NRTL)

Applied Research Laboratories
Bureau Veritas Consumer Products Services Inc.
CertifiGroup Inc.
CSA Group
Eurofins MET Labs
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
Product Safety Consulting
Professional Testing (EMI), Inc., a Nemko Company
TÜV Rheinland of North America
UL LLC

Network Equipment Building System (NEBS) Testing

Eurofins MET Labs
International Certification Services, Inc.
NTS
Quanta Laboratories

Testing Laboratories

Product Pre-Compliance Testing

ART-MAN

Atlas Compliance & Engineering

Bicerano & Associates Consulting

CertifiGroup Inc.

Coilcraft Critical Products & Services

Compatible Electronics, Inc.

Compliance Worldwide, Inc.

Core Compliance Testing Services

CVG Strategy

D.L.S. - EMC

D.L.S. - Environmental

D.L.S. - Military

D.L.S. - Product Safety

D.L.S. - Wireless

Element Materials Technology - Brooklyn Park, MN

Element Materials Technology - Dallas Plano, TX

Element Materials Technology - Irvine, CA

Element Materials Technology - Portland Hillsboro, OR

Element Materials Technology - Washington, Columbia, Oakland Mills

Energy Assurance LLC

F2 Labs - Middlefield, OH

G&M Compliance, Inc.

Green Mountain Electromagnetics, Inc.

H.B. Compliance Solutions

International Certification Services, Inc.

ITC India

Laird Connectivity

Lewis Bass International Engineering Services

Nemko Canada Inc. - Montreal, QC

Nemko Canada Inc. - Ottawa, ON

Nemko Canada Inc. - Toronto, ON

Nemko USA, Inc.

Product Safety Consulting

Professional Testing (EMI), Inc., a Nemko Company

Quanta Laboratories

Test Site Services Inc

VPI Laboratories, Inc.

Washington Laboratories

Product Safety Testing

Abstraction Engineering Inc

Applied Research Laboratories

Bicerano & Associates Consulting

Bureau Veritas Consumer Products Services Inc.

CertifiGroup Inc.

Coilcraft Critical Products & Services

Compatible Electronics, Inc.

Core Compliance Testing Services

CSA Group

D.L.S. - Product Safety

Element Materials Technology - Brooklyn Park, MN

Element Materials Technology - Dallas Plano, TX

Element Materials Technology - Irvine, CA

Element Materials Technology - Portland Hillsboro, OR

Element Materials Technology - Washington, Columbia, Oakland Mills

Energy Assurance LLC

Ergonomics, Inc.

Eurofins MET Labs

F2 Labs - Damascus, MD

F2 Labs - Middlefield, OH

G&M Compliance, Inc.

Global Testing Laboratories

Green Mountain Electromagnetics, Inc.

Lewis Bass International Engineering Services

Nemko Canada Inc. - Montreal, QC

Nemko Canada Inc. - Ottawa, ON

Nemko Canada Inc. - Toronto, ON

Nemko USA, Inc.

NTS

Product Safety Consulting

Professional Testing (EMI), Inc., a Nemko Company

Pulver Laboratories

TÜV Rheinland of North America

TÜV SÜD America Inc.

UL LLC

Washington Laboratories

Radio Performance & Functionality Testing

American Certification Body

Applied Physical Electronics, L.C. (APELC)

CVG Strategy

D.L.S. - Wireless

Element Materials Technology - Brooklyn Park, MN

Element Materials Technology - Dallas Plano, TX

Element Materials Technology - Irvine, CA

Element Materials Technology - Portland Hillsboro, OR

Element Materials Technology - Washington, Columbia, Oakland Mills

EMC Bayswater Pty Ltd

Eurofins MET Labs

H.B. Compliance Solutions

Orbis Compliance LLC

Professional Testing (EMI), Inc., a Nemko Company

Radiometrics Midwest Corporation

Test Site Services Inc

UL LLC

Washington Laboratories

RoHS Directive Compliance

CertifiGroup Inc.

D.L.S. - Product Safety

F2 Labs - Middlefield, OH

ITC India

Pulver Laboratories

TÜV Rheinland of North America

Shock & Vibration

Clark Testing
Coilcraft Critical Products & Services
The Compliance Management Group
CVG Strategy
D.L.S. - Environmental
DNB Engineering, Inc.
Elite Electronic Engineering Inc.
Energy Assurance LLC
Eurofins MET Labs
FEMA Corporation
ITC India
Nemko USA, Inc.
NTS
Professional Testing (EMI), Inc., a Nemko Company
Quanta Laboratories
Retlif Testing Laboratories
Sanwood Environmental Chambers Co., Ltd
WEMS Electronics

Standards Council of Canada Certification Body

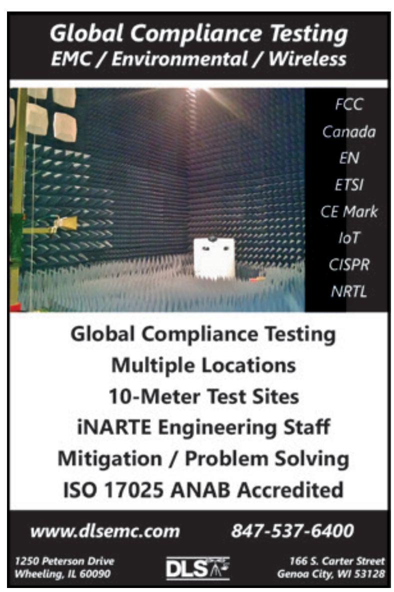
CSA Group
Professional Testing (EMI), Inc., a Nemko Company

Telecommunications Testing

A2LA
American Certification Body
CKC Laboratories, Inc.
Clark Testing
The Compliance Management Group
Compliance Worldwide, Inc.
D.L.S. - Wireless
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Eurofins MET Labs
F2 Labs - Damascus, MD
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
Megger
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
NetSPI
NTS
Orbis Compliance LLC
Professional Testing (EMI), Inc., a Nemko Company
Retlif Testing Laboratories
Southwest Research Institute
UL LLC

Wireless

American Certification Body
Bureau Veritas Consumer Products Services Inc.
CKC Laboratories, Inc.
Compliance Worldwide, Inc.
D.L.S. - EMC



D.L.S. - Product Safety
D.L.S. - Wireless
Electronic Instrument Associates
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Irvine, CA
Element Materials Technology - Portland Hillsboro, OR
Element Materials Technology - Washington, Columbia, Oakland Mills
Elite Electronic Engineering Inc.
EMC Bayswater Pty Ltd
ETS-Lindgren
Eurofins MET Labs
F2 Labs - Damascus, MD
International Certification Services, Inc.
Megger
MiCOM Labs
Nemko Canada Inc. - Montreal, QC
Nemko Canada Inc. - Ottawa, ON
Nemko Canada Inc. - Toronto, ON
Nemko USA, Inc.
NTS
Orbis Compliance LLC
Professional Testing (EMI), Inc., a Nemko Company
Test Site Services Inc
TÜV Rheinland of North America
TÜV SÜD America Inc.
VPI Laboratories, Inc.

Events

March 7-10

Power Electronics Design for Electromagnetic Compatibility

March 8-11

EMC Compo

March 27-April 1

The 16th European Conference on Antennas and Propagation (EuCAP 2022)

April 3-6

A2LA Tech Forum 2022

April 5-7

DesignCon 2022

April 18-22

EMC Week

April 19

EMC mini 2022

April 28-29

Fundamental Principles of Electromagnetic Compatibility and Signal Integrity

May 8-11

2022 Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC)

May 10-13

Applying Practical EMI Design and Troubleshooting Techniques

Advanced PCB Design for EMC & SI

Mechanical Design for EMC

May 10

Chicago IEEE EMC Mini Symposium

May 12

EMC Fest 2022

May 16-19

2022 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)

May 18-19

EMC & Compliance International Workshop

June 19-24

International Microwave Symposium

June 27-29

Sensors Expo & Conference

July 12-14

EMV 2022

August 1-5

2022 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity (IEEE EMC+SIPI 2022)

September 5-8

EMC Europe 2022

September 13-15

The Battery Show North America

September 13-16

Lab Techniques, Robust Design, and Troubleshooting

September 18-23

44th Annual Electrical Overstress/ Electrostatic Discharge Symposium (EOS/ESD Symposium)

September 20-22

2022 IEEE International Symposium on Product Compliance Engineering (ISPCE)

September 29

2022 Minnesota EMC Event

October 6-7

Fundamental Principles of Electromagnetic Compatibility and Signal Integrity

October 9-14

44th Annual Meeting and Symposium of the Antenna Measurement Techniques Association (AMTA 2022)

Due to COVID-19 concerns, event details may change. Please check the event website for current information.

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