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THE 2023 ANNUAL REFERENCE GUIDE

A Compliance Handbook for Electrical and Electronics Engineers


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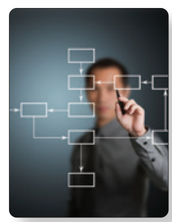

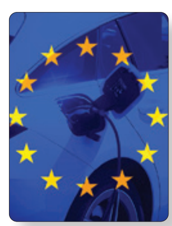

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IN COMPLIANCE

editor/publisher Lorie Nichols
lorie.nichols@incompliancemag.com
(978) 873-7777

business development director Sharon Smith
sharon.smith@incompliancemag.com
(978) 873-7722

production director Erin C. Feeney
erin.feeney@incompliancemag.com
(978) 873-7756

marketing director Ashleigh O'Connor
ashleigh.oconnor@incompliancemag.com
(978) 873-7788

circulation director Alexis Evangelous
alexis.evangelous@incompliancemag.com
(978) 486-4684

features editor William von Achen
bill.vonachen@incompliancemag.com
(978) 486-4684

senior contributors

Bruce Archambeault
bruce@brucearch.com

Keith Armstrong
keith.armstrong@cherryclough.com

Leonard Eisner
Leo@EisnerSafety.com

Daryl Gerke
dgerke@emiguru.com

Ken Javor
ken.javor@emcompliance.com

Ken Ross
kenrossesq@gmail.com

Werner Schaefer
wernerschaefer@comcast.net

columns contributors

EMC Concepts Explained
Bogdan Adamczyk
adamczyb@gvsu.edu

Hot Topics in ESD
EOS/ESD Association, Inc
info@esda.org

advertising For information about advertising contact Sharon Smith at sharon.smith@incompliancemag.com.

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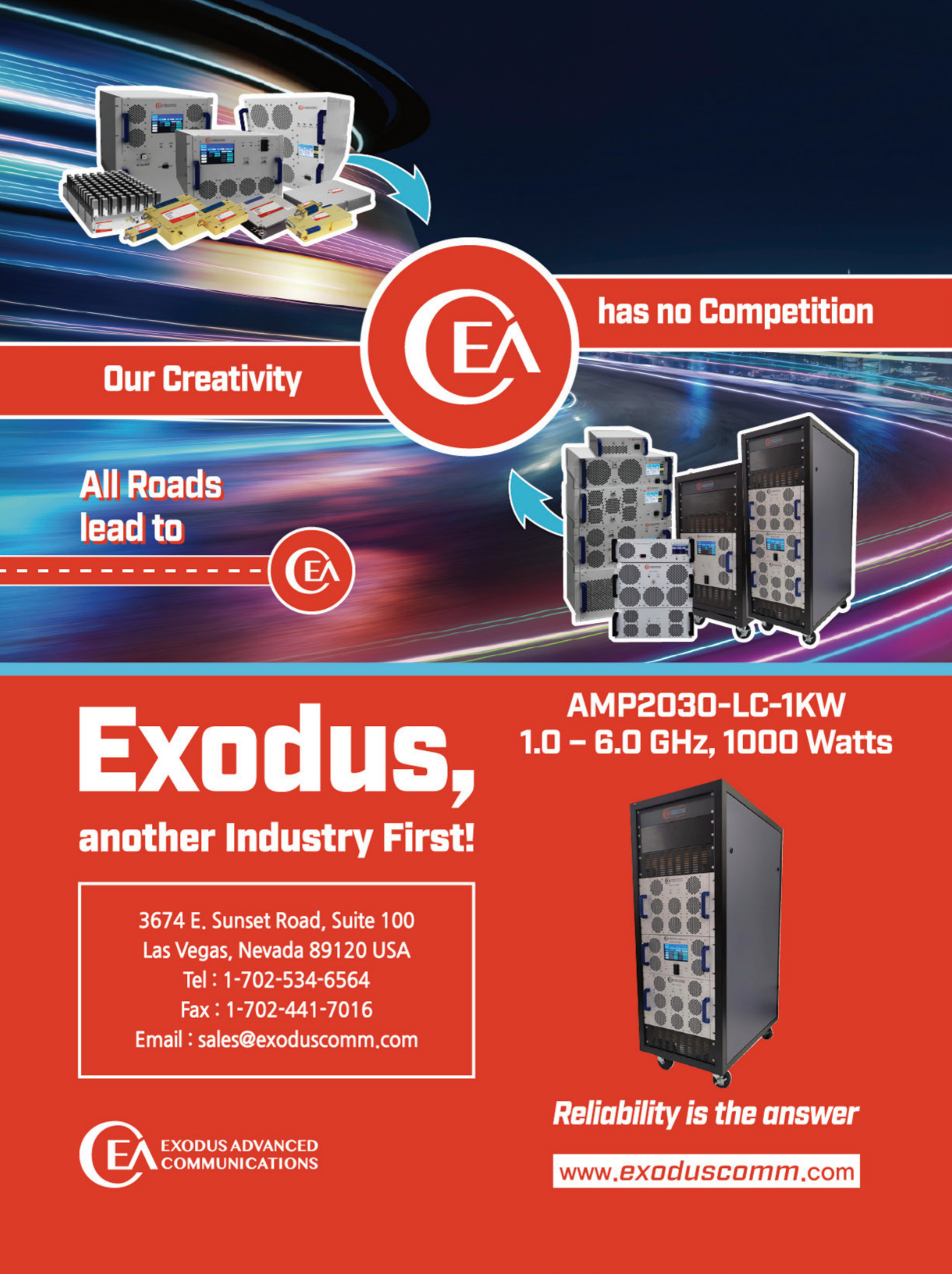
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LETTER From the Editor

Welcome to 2023 and this year's edition of *In Compliance Magazine's* Annual Reference Guide!

"Just when you thought it was safe to go back in the water…" This oft-quoted line was an essential part of the marketing campaign for the 1978 movie *Jaws* 2. That movie was the sequel to the 1975 blockbuster *Jaws* which ends with police chief Martin Brody (Roy Scheider) killing the monster shark that has threatened the tiny New England beach town of Amity Island. In *Jaws* 2, a new shark threat emerges, endangering the community and forcing Brody to step up once again to save his family and the town.

For a world slowly emerging from the horrors of the Covid-19 pandemic over the previous two years, 2022 seemingly offered little space to "go back in the water." Russia's invasion of Ukraine in February has so far resulted in the loss of tens of thousands of lives and the displacement of millions of people. Closer to home, shootings in May at a supermarket in Buffalo, New York and at an elementary school in Uvalde, Texas resulted in the violent deaths of more than 30 people. And the world mourned the loss of former Japanese prime minister Shinzo Abe, who was assassinated in July, and the passing in September of Britain's Queen Elizabeth, England's longest-ruling monarch.

Yet, despite these tragedies, we still chalked up some major successes in science and technology that are worth celebrating. For example, the renowned James Webb Space Telescope entered earth orbit in January, providing astronomers and scientists with spectacular images of deep space and previously undiscovered galaxies. Biotech and pharmaceutical firms are building on the success of the rapid development and deployment of Covid vaccines and are on the verge of introducing new vaccines for respiratory syncytial virus (RSV), malaria, and other medical conditions. And tech companies are rapidly leveraging advances in artificial intelligence (AI) and machine learning (ML) to improve both their products and their business models.

In their seminal book *Switch: How to Change Things When Change is Hard*, authors (and brothers!) Chip Heath and Dan Heath talk about the importance of focusing on what they call "the bright spots," when seeking to implement change. Instead of looking for things that need to be fixed, they recommend looking instead at what's working and find ways to build on those successes. To me, there are fewer lessons that are more relevant or meaningful in our efforts to make progress in our constantly changing environment.

For all of us here at *In Compliance Magazine*, finding the bright spots is an essential part of what we do, that is, delivering accurate and comprehensive information about the ever-changing regulatory compliance landscape, and providing our readers with the information they need to successfully navigate their design challenges. This year's edition of our Annual Reference Guide features 15 of the articles we published in 2022 that were most frequently read and referenced by our readers. By reprinting them here, we hope to share these "bright spots" with those who may have missed them and with others who are new to this challenging but exciting field.

In the meantime, our never-ending thanks to our readers, our editorial contributors, and our advertisers for your continued commitment to our publication. Knowing that we have your support gives us the best reason to keep moving forward!

Sincerely,

Bill von Achen

Features Editor
In Compliance Magazine


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ETS-Lindgren is an international manufacturer of systems and components that measure, shield, and control electromagnetic and acoustic energies. Our products are used for electromagnetic compatibility (EMC), microwave and wireless testing, electromagnetic field (EMF) measurement, radio frequency (RF) personal safety monitoring, magnetic resonance imaging (MRI), and control of acoustic environments.

Having the technical depth expected of an industry leader with more than 50,000 RF shielded installations worldwide, ETS-Lindgren guides our customers to optimal Test and Measurement Solutions for their specific product applications. Customers appreciate knowing our vertically integrated capabilities ensure quality and schedule control since some 90% of the products on any given project are manufactured by ETS-Lindgren. And our team of 750+ employees in six manufacturing sites worldwide provide continual customer support.

ETS-Lindgren's leading-edge technology is evident in the many markets we serve, resulting in numerous patents and "Industry Firsts." For example, ETS-Lindgren is the first and only manufacturer to have its complete EMP protection system performance acceptance-tested to the requirements of MIL-STD-188-125 by an independent lab: Little Mountain Test Facility operated by Boeing at Hill Air Force Base, in Ogden, Utah.

Other examples include: The world's first CTIA-Authorized Test Lab (CATL) for mobile station over-the-air (OTA) performance testing; first to provide in-house certified Building Information Modeling (BIM) services; first to design, manufacture, and install the world's largest RF shielded anechoic chamber; first to design and manufacture a pneumatic RF shielded sliding door; first to manufacture RF shielded panels and components on a global level; and first to use an in-house NVLAP-accredited acoustic test lab (NVLAP Code 100286-0) to develop and produce acoustic chamber solutions.

ETS-Lindgren's proven expertise in the diverse markets we serve fosters innovative solutions that can be individually tailored to meet a customer's specific performance requirements and budget parameters. Today, this crossover expertise is most notable in the rapidly evolving technology seen in the automotive market. With our expertise in EMC and wireless antenna pattern measurement testing, ETS-Lindgren is uniquely positioned to leverage our experience in the developing autonomous vehicle test arena.

ETS-Lindgren's Vehicle Antenna Measurement Arch (VAMA)

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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.

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- 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

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Defence Electronics

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Component Testing

Energy & Utility
Equipment

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We have offices in major markets worldwide and participate in international standard committees to continuously develop our areas of expertise. Partner with Nemko for a less complicated process that gets your product to market faster and more efficiently, adding value to your brand by demonstrating indisputable conformity from a third-party laboratory.

The EMI Protection Leader




Spectrum Control, formerly APITech, has been an innovator and leading provider of EMI filter solutions since 1968. Today we offer the industry's most comprehensive product line including an expanded offering of filtered D-sub and circular filtered connectors.

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Are you looking to filter EMI at the power source, the I/O connection, the barrier wall, or on the PCB? We have the solution. Our line includes glass- and resin-sealed filters, solder-in filters, filter plates and arrays, filtered connectors, and custom designs for power, with most meeting RoHS standards. Filtered circular connectors can be designed to meet AC- or lightning-caused transient voltages (for RTCA/ DO160 section 22.

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Design & testing support

Our in-house, fully equipped EMC laboratory offers you a flexible resource to assist in product development by identifying and correcting EMI susceptibility and emission problems. We can also evaluate, and fine-tune installed filter performance to find a solution for your unique requirements.

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We offer more than 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 standard product or an engineered solution.

Spectrum Control is a leading provider of technologies, components, subsystems, and custom solutions to manage and control the electromagnetic spectrum. Innovators around the world turn to our engineering and design teams and build with our proven solutions. Our customers are the prime movers in aerospace & defense and commercial applications.

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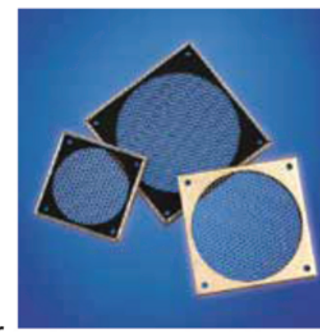
FEATURED PRODUCTS: Spira's newest and most popular products are featured.

EMI Shielded Honeycomb Fan Filters and Air-Vent Filters



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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SINUSOIDAL STEADY STATE ANALYSIS OF TRANSMISSION LINES

Part III: Voltage, Current, and Input Impedance Calculations – Circuit Model 2

By Bogdan Adamczyk

This is the third of the three tutorial articles devoted to the frequency-domain analysis of a lossless transmission line. In the previous article, [1], several methods of calculating the voltage, current and input impedance along the lossless transmission line were presented, using Circuit Model 1, shown in Figure 1.

In this model, the source is located at *z = 0*, and the load is located at *z = d*. The voltage, current, and input impedance were derived as a function *z*, when moving from the source towards the load.

In this article, we will present the results for the voltage, current, and input impedance derived from the transmission line circuit shown in Figure 2, referred to as Circuit Model 2.

In this model, the load is located at *d = 0*, and the source is located at *d = L*. The voltage, current, and input impedance now are a function of *d*, when moving from the load towards the source. Note that the input impedance to the line at any location *d*, $\hat{Z}_{in}(d)$, is always calculated looking towards the load, regardless whether we use Model 1 or Model 2.

1. VOLTAGE AND CURRENT AT ANY LOCATION D AWAY FROM THE LOAD

The two distance variables are related by

$$d = L - z \quad \Rightarrow \quad z = L - d \tag{1.1}$$

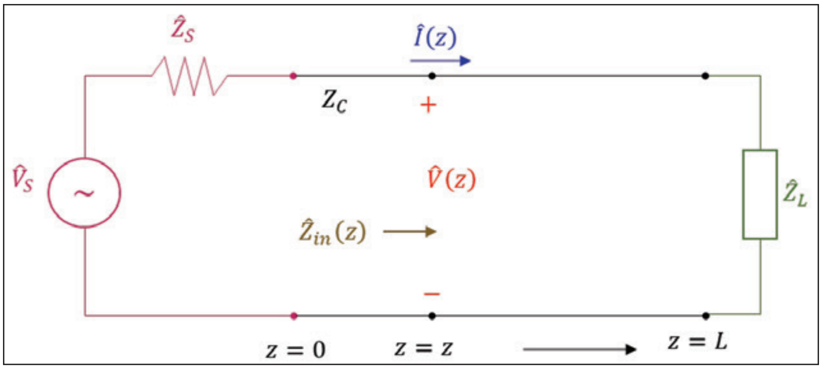


Figure 1: Model 1 - the source located at *z = 0* and the load at *z = L*

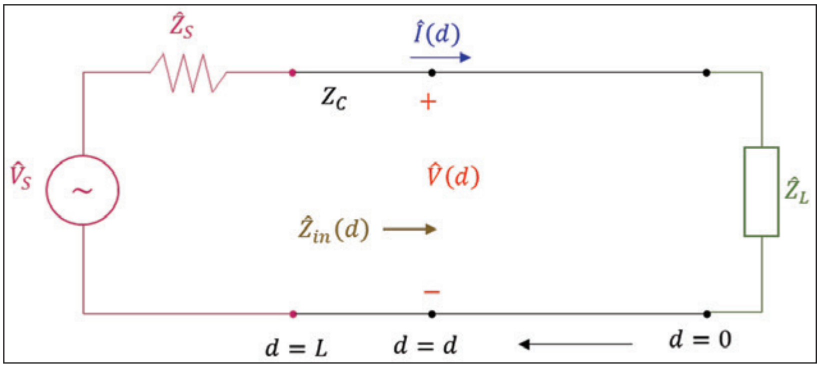


Figure 2: Model 2 - the load located at *d = 0* and the source at *d = L*

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 2023). He can be reached at adamczyb@gvsu.edu.

In [1] the voltage and current *at any location* z away from the source were derived as

$$\hat{V}(z) = \hat{V}_z^+ e^{-j\beta z} + \hat{V}_z^- e^{j\beta z} \tag{1.2a}$$

$$\hat{I}(z) = \frac{\hat{V}_z^+}{Z_C} e^{-j\beta z} - \frac{\hat{V}_z^-}{Z_C} e^{j\beta z} \tag{1.2b}$$

Using the relations (1.1), the voltage and current *at any location d* away from the load are

$$\hat{V}(d) = \hat{V}_z^+ e^{-j\beta(L-d)} + \hat{V}_z^- e^{j\beta(L-d)} \tag{1.3a}$$

$$\hat{I}(d) = \frac{\hat{V}_z^+}{Z_C} e^{-j\beta(L-d)} - \frac{\hat{V}_z^-}{Z_C} e^{j\beta(L-d)} \tag{1.3b}$$

or

$$\hat{V}(d) = \hat{V}_z^+ e^{-j\beta L} e^{j\beta d} + \hat{V}_z^- e^{j\beta L} e^{-j\beta d} \tag{1.4a}$$

$$\hat{I}(d) = \frac{\hat{V}_z^+}{Z_C} e^{-j\beta L} e^{j\beta d} - \frac{\hat{V}_z^-}{Z_C} e^{j\beta L} e^{-j\beta d} \tag{1.4b}$$

leading to

$$\hat{V}(d) = \hat{V}_d^+ e^{j\beta d} + \hat{V}_d^- e^{-j\beta d} \tag{1.5a}$$

$$\hat{I}(d) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d} - \frac{\hat{V}_d^-}{Z_C} e^{-j\beta d} \tag{1.5b}$$

where

$$\hat{V}_d^+ = \hat{V}_z^+ e^{-j\beta L} \tag{1.6a}$$

$$\hat{V}_d^- = \hat{V}_z^- e^{j\beta L} \tag{1.6b}$$

The solutions in Eqns. (1.5) consist of the forward- and backward-traveling waves. The forward-traveling voltage wave is described by

$$\hat{V}_f(d) = \hat{V}_d^+ e^{j\beta d} \tag{1.7a}$$

while the backward-traveling voltage wave is given by

$$\hat{V}_b(d) = \hat{V}_d^- e^{-j\beta d} \tag{1.7b}$$

Using these two waves, we define the voltage reflection coefficient *at any location d*, as the ratio of the backward-propagating wave to the forward-propagating wave

$$\hat{\Gamma}(d) = \frac{\hat{V}_b(d)}{\hat{V}_f(d)} = \frac{\hat{V}_d^- e^{-j\beta d}}{\hat{V}_d^+ e^{j\beta d}} = \frac{\hat{V}_d^-}{\hat{V}_d^+} e^{-j2\beta d} \tag{1.8a}$$

Thus,

$$\hat{\Gamma}(d) = \frac{\hat{V}_d^-}{\hat{V}_d^+} e^{-j2\beta d} \tag{1.8b}$$

From Eq. (1.8b) we obtain

$$\hat{V}_d^- = \hat{\Gamma}(d)\hat{V}_d^+ e^{j2\beta d} \tag{1.9}$$

Utilizing Eq. (1.9) in Eq. (1.5a) gives

$$\hat{V}(d) = \hat{V}_d^+ e^{j\beta d} + \hat{\Gamma}(d)\hat{V}_d^+ e^{j2\beta d} e^{-j\beta d} \tag{1.10a}$$

or

$$\hat{V}(d) = \hat{V}_d^+ e^{j\beta d}\left[1 + \hat{\Gamma}(d)\right] \tag{1.10b}$$

Utilizing Eq. (1.9) in Eq. (1.5b) gives

$$\hat{I}(d) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d} - \frac{\hat{\Gamma}(d)\hat{V}_d^+ e^{j2\beta d}}{Z_C} e^{-j\beta d} \tag{1.11a}$$

or

$$\hat{I}(d) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d}\left[1 - \hat{\Gamma}(d)\right] \tag{1.11b}$$

Equations (1.10b) and (1.11b) express voltage and current at any location *d*, away from the load, in terms of the unknown constant $\hat{V}_d^+$ and the voltage reflection coefficient $\hat{\Gamma}(d)$, at any location *d* away from the source.

Let us return to this reflection coefficient, given by Eq. (1.8b). Letting $d = 0$, we obtain the voltage reflection coefficient at *the load*

$$\hat{\Gamma}(0) = \hat{\Gamma}_L = \frac{\hat{V}_d^-}{\hat{V}_d^+} \tag{1.12a}$$

Note that the load reflection coefficient can always be obtained directly from the knowledge of the load and the characteristic impedance of the line as

$$\hat{\Gamma}_L = \frac{\hat{Z}_L - Z_C}{\hat{Z}_L + Z_C} \tag{1.12b}$$

Utilizing Eq. (1.12a) in Eq. (1.8b) we get

$$\hat{\Gamma}(d) = \hat{\Gamma}_L e^{-j2\beta d} \tag{1.13}$$

Which expresses the voltage reflection coefficient *at any location d*, away from the load, in terms of the load reflection coefficient.

Equation (1.8b) can be used to determine the voltage reflection coefficient *at the input to the line*, i.e., at $d = L$, (we will need it shortly),

$$\hat{\Gamma}(L) = \hat{\Gamma}_L e^{-j2\beta L} \tag{1.14}$$

Utilizing Eq. (1.13) in Eqns. (1.10b) and (1.11b) gives

$$\hat{V}(d) = \hat{V}_d^+ e^{j\beta d}\left[1 + \hat{\Gamma}_L e^{-j2\beta d}\right] \tag{1.15a}$$

$$\hat{I}(d) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d}\left[1 - \hat{\Gamma}_L e^{-j2\beta d}\right] \tag{1.15b}$$

Equations (1.15) express voltage and current at any location d, away from the load, in terms of the unknown constant $\hat{V}_d^+$, and the load reflection coefficient.

In summary, the voltage and current at any location d, away from the load, can be obtained from

$$\hat{V}(d) = \hat{V}_d^+ e^{j\beta d} + \hat{V}_d^- e^{-j\beta d} \tag{1.16a}$$

$$\hat{I}(d) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d} - \frac{\hat{V}_d^-}{Z_C} e^{-j\beta d} \tag{1.16b}$$

or

$$\hat{V}(d) = \hat{V}_d^+ e^{j\beta d}\left[1 + \hat{\Gamma}(d)\right] \tag{1.16c}$$

$$\hat{I}(d) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d}\left[1 - \hat{\Gamma}(d)\right] \tag{1.16d}$$

or

$$\hat{V}(d) = \hat{V}_d^+ e^{j\beta d}\left[1 + \hat{\Gamma}_L e^{-j2\beta d}\right] \tag{1.16e}$$

$$\hat{I}(d) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d}\left[1 - \hat{\Gamma}_L e^{-j2\beta d}\right] \tag{1.16f}$$

The last set of equations is perhaps the most convenient since the load reflection coefficient, $\hat{\Gamma}_L$, can be obtained directly from Eq. (1.12b) and the only unknown in this set is the constant $\hat{V}_d^+$.

Figure 3 compares the results for Model 2 to those of Model 1.

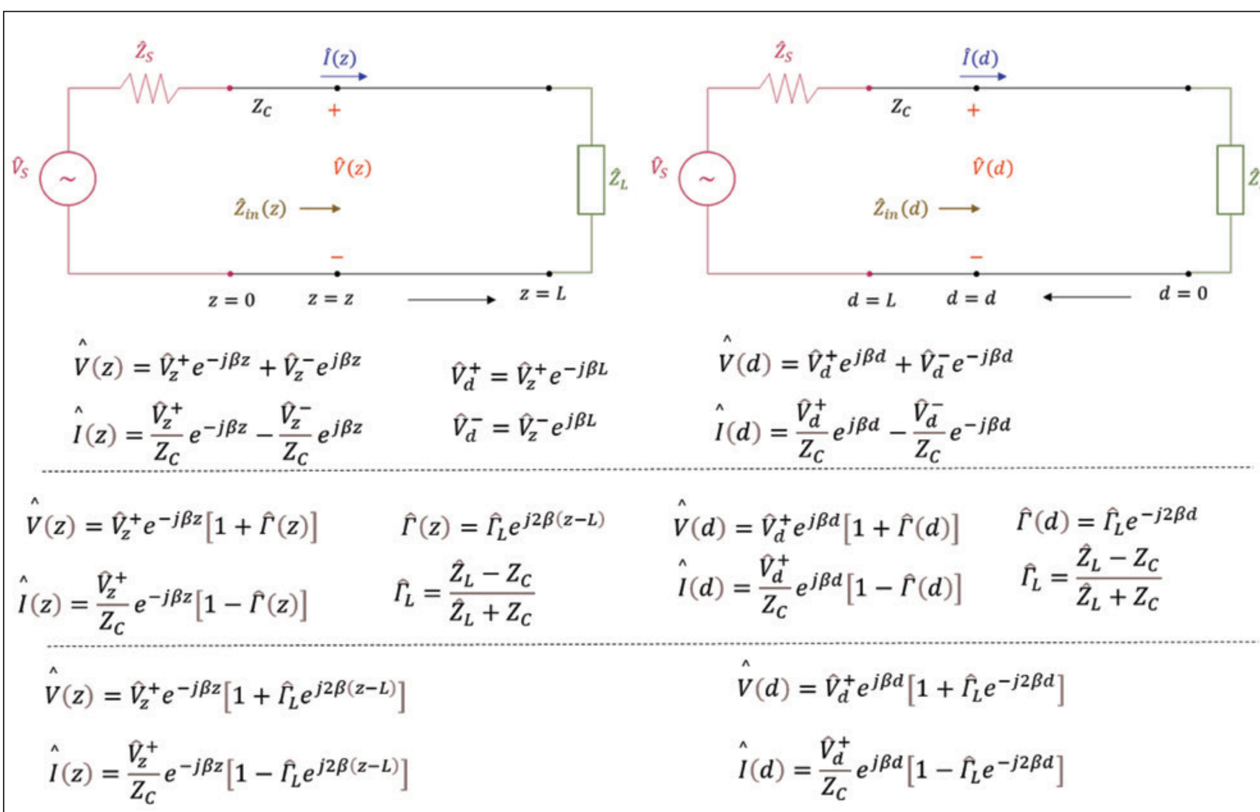


Figure 3: Model 1 vs. Model 2 - voltage and current along the line

The three sets of equations (1.16) can be used to determine the voltage and current at the load and at the input to the line.

Letting $d = 0$, in Eqns. (1.16a) and (1.16b) we obtain the *voltage and current at the load* as

$$\hat{V}(0) = \hat{V}_d^+ + \hat{V}_d^- \tag{1.17a}$$

$$\hat{I}(0) = \frac{\hat{V}_d^+}{Z_C} - \frac{\hat{V}_d^-}{Z_C} \tag{1.17b}$$

or

$$\hat{V}(0) = \hat{V}_d^+[1 + \hat{\Gamma}_L] \tag{1.17c}$$

$$\hat{I}(0) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d}[1 - \hat{\Gamma}_L] \tag{1.17d}$$

Letting $d = L$, in Eqns. (1.11) we obtain the *voltage and current at the input to the line* as

$$\hat{V}(L) = \hat{V}_d^+ e^{j\beta L} + \hat{V}_d^- e^{-j\beta L} \tag{1.18a}$$

$$\hat{I}(L) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta L} - \frac{\hat{V}_d^-}{Z_C} e^{-j\beta L} \tag{1.18b}$$

or

$$\hat{V}(L) = \hat{V}_d^+ e^{j\beta L}[1 + \hat{\Gamma}(L)] \tag{1.18c}$$

$$\hat{I}(L) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta d}[1 - \hat{\Gamma}(L)] \tag{1.18d}$$

or

$$\hat{V}(L) = \hat{V}_d^+ e^{j\beta L}[1 + \hat{\Gamma}_L e^{-j2\beta L}] \tag{1.18e}$$

$$\hat{I}(L) = \frac{\hat{V}_d^+}{Z_C} e^{j\beta L}[1 - \hat{\Gamma}_L e^{-j2\beta L}] \tag{1.18f}$$

Next, let us turn our attention to the undetermined constants $\hat{V}_d^+$ and $\hat{V}_d^-$. These constants can be determined from the knowledge of the voltage and current *at the load*.

Eqns. (1.17a) and (1.17b) can be rewritten as

$$\hat{V}(0) = \hat{V}_d^+ + \hat{V}_d^- \tag{1.19a}$$

$$Z_C\hat{I}(0) = \hat{V}_d^+ - \hat{V}_d^- \tag{1.19b}$$

Adding Eqns. (1.19a) and (1.19b) gives

$$\hat{V}(0) + Z_C\hat{I}(0) = 2\hat{V}_d^+ \tag{1.20}$$

and thus

$$\hat{V}_d^+ = \frac{\hat{V}(0) + Z_C\hat{I}(0)}{2} \tag{1.21}$$

Subtracting Eq. (1.19b) from Eq. (1.19a) gives

$$\hat{V}(0) - Z_C\hat{I}(0) = 2\hat{V}_d^- \tag{1.22}$$

and thus

$$\hat{V}_d^- = \frac{\hat{V}(0) - Z_C\hat{I}(0)}{2} \tag{1.23}$$

These two undetermined constants $\hat{V}_d^+$ and $\hat{V}_d^-$ can alternatively be obtained from the knowledge of the voltage and current *at the input to the line*.

Eqns. (1.18a) and (1.18b) can be rewritten as

$$\hat{V}(L) = \hat{V}_d^+ e^{j\beta L} + \hat{V}_d^- e^{-j\beta L} \tag{1.24a}$$

$$Z_C\hat{I}(L) = \hat{V}_d^+ e^{j\beta L} - \hat{V}_d^- e^{-j\beta L} \tag{1.24b}$$

Adding Eqns. (1.24a) and (1.24b) gives

$$\hat{V}(L) + Z_C\hat{I}(L) = 2\hat{V}_d^+ e^{j\beta L} \tag{1.25}$$

and thus

$$\hat{V}_d^+ = \frac{\hat{V}(L) + Z_C\hat{I}(L)}{2} e^{-j\beta L} \tag{1.26}$$

Subtracting Eq. (1.24b) from Eq. (1.24a) gives

$$\hat{V}(L) - Z_C\hat{I}(L) = 2\hat{V}_d^- e^{-j\beta L} \tag{1.27}$$

and thus

$$\hat{V}_d^- = \frac{\hat{V}(L) - Z_C\hat{I}(L)}{2} e^{j\beta L} \tag{1.28}$$

Observation: To obtain the voltage or current at any location d, away from the load, we need the knowledge of the undetermined constants $\hat{V}_d^+$ and $\hat{V}_d^-$ (or at least $\hat{V}_d^+$). To obtain the undetermined constants $\hat{V}_d^+$ and $\hat{V}_d^-$, we need the knowledge of the voltage and current at the input to the line, or at the load. We resolve this stalemate in a similar way we did in [1], by introducing the concept of the input impedance to the line.

2. INPUT IMPEDANCE TO THE LINE AT ANY LOCATION D AWAY FROM THE LOAD

At any location *d*, away from the source, the input impedance to the line, $\hat{Z}_{in}$, shown in Figure 2, is defined as the ratio of the total voltage to the total current at that point.

$$\hat{Z}_{in}(d) = \frac{\hat{V}(d)}{\hat{I}(d)} \quad (2.1)$$

Since the total voltage and current at any location *d* away from the load can be obtained from the three different sets of Eqns. (1.16), it follows that the input impedance to the line, *at any location d away from the load* can be obtained from

$$\hat{Z}_{in}(d) = Z_C \frac{\hat{V}_d^+ e^{j\beta d} + \hat{V}_d^- e^{-j\beta d}}{\hat{V}_d^+ e^{j\beta d} - \hat{V}_d^- e^{-j\beta d}} \quad (2.2a)$$

or

$$\hat{Z}_{in}(d) = Z_C \frac{1+\hat{\Gamma}(d)}{1-\hat{\Gamma}(d)} \quad (2.2b)$$

or

$$\hat{Z}_{in}(d) = Z_C \frac{1+\hat{\Gamma}_L e^{-j2\beta d}}{1-\hat{\Gamma}_L e^{-j2\beta d}} \quad (2.2c)$$

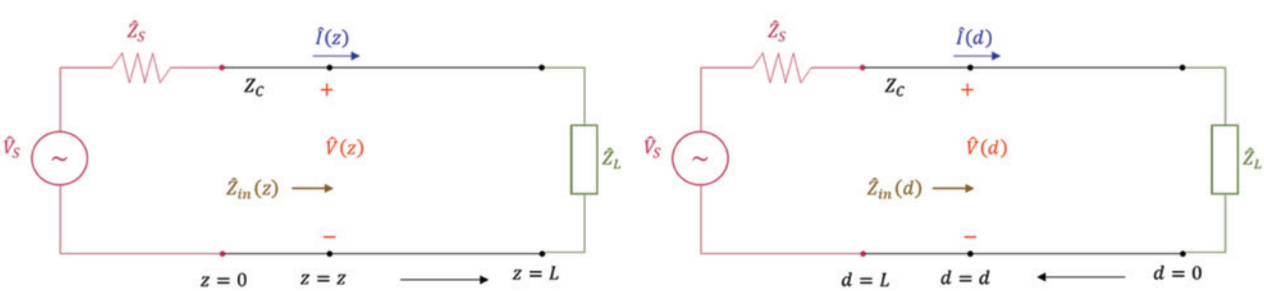
Figure 4 compares the results for Model 2 to those of Model 1.

Letting $d = L$, in Eqns. (2.2) we obtain the *input impedance to the line at the input to the line* as

$$\hat{Z}_{in}(L) = Z_C \frac{\hat{V}_d^+ e^{j\beta L} + \hat{V}_d^- e^{-j\beta L}}{\hat{V}_d^+ e^{j\beta L} - \hat{V}_d^- e^{-j\beta L}} \quad (2.3a)$$

or

$$\hat{Z}_{in}(L) = Z_C \frac{1+\hat{\Gamma}(L)}{1-\hat{\Gamma}(L)} \quad (2.3b)$$



$$\hat{Z}_{in}(z) = Z_C \frac{\hat{V}_z^+ e^{-j\beta z} + \hat{V}_z^- e^{j\beta z}}{\hat{V}_z^+ e^{-j\beta z} - \hat{V}_z^- e^{j\beta z}} \qquad \hat{V}_d^+ = \hat{V}_z^+ e^{-j\beta L} \quad \hat{V}_d^- = \hat{V}_z^- e^{j\beta L} \qquad \hat{Z}_{in}(d) = Z_C \frac{\hat{V}_d^+ e^{j\beta d} + \hat{V}_d^- e^{-j\beta d}}{\hat{V}_d^+ e^{j\beta d} - \hat{V}_d^- e^{-j\beta d}}$$

$$\hat{Z}_{in}(z) = Z_C \frac{1+\hat{\Gamma}(z)}{1-\hat{\Gamma}(z)} \qquad \hat{\Gamma}(z) = \hat{\Gamma}_L e^{j2\beta(z-L)} \quad \hat{\Gamma}_L = \frac{\hat{Z}_L - Z_C}{\hat{Z}_L + Z_C} \qquad \hat{Z}_{in}(d) = Z_C \frac{1+\hat{\Gamma}(d)}{1-\hat{\Gamma}(d)} \qquad \hat{\Gamma}(d) = \hat{\Gamma}_L e^{-j2\beta d} \quad \hat{\Gamma}_L = \frac{\hat{Z}_L - Z_C}{\hat{Z}_L + Z_C}$$

$$\hat{Z}_{in}(z) = Z_C \frac{1+\hat{\Gamma}_L e^{j2\beta(z-L)}}{1-\hat{\Gamma}_L e^{j2\beta(z-L)}} \qquad \hat{Z}_{in}(d) = Z_C \frac{1+\hat{\Gamma}_L e^{-j2\beta d}}{1-\hat{\Gamma}_L e^{-j2\beta d}}$$

Figure 4: Model 1 vs. Model 2: input impedance to the line

or

$$\hat{Z}_{in}(L) = Z_C \frac{1+\hat{\Gamma}_L e^{-j2\beta L}}{1-\hat{\Gamma}_L e^{-j2\beta L}} \quad (2.3c)$$

Since the constants $\hat{V}_d^+$ and $\hat{V}_d^-$ are still unknown, in the calculations of the input impedance to the line at the input to the line, we are left with the remaining two equations, (2.3b) and (2.3c).

Since,

$$\hat{\Gamma}(L) = \hat{\Gamma}_L e^{-j2\beta L} \quad (2.4)$$

at this point, we effectively have just one equation (2.3c) to determine the input impedance to the line at the input to the line. Towards this end, we first determine the load reflection coefficient from

$$\hat{\Gamma}_L = \frac{\hat{Z}_L - Z_C}{\hat{Z}_L + Z_C} \quad (2.5)$$

and then use Eq. (2.3c) or Eq. (2.7b), shown next, to calculate the input impedance to the line *at the input to the line*.

There is one more useful set of formulas for obtaining the input impedance to the line at the input to the line. Using Eq. (2.5) in Eq. (2.3c) we get

$$\hat{Z}_{in}(L) = \hat{Z}_C \frac{1+\frac{\hat{Z}_L - Z_C}{\hat{Z}_L + Z_{C_L}} e^{-j2\beta L}}{1-\frac{\hat{Z}_L - Z_C}{\hat{Z}_L + Z_C} e^{-j2\beta L}} \quad (2.6)$$

The right-hand-side of Eq. (2.6) is equivalent to, [2],

$$\hat{Z}_{in}(L) = Z_C \frac{\hat{Z}_L \cos\beta L + jZ_C \sin\beta L}{Z_C \cos\beta L + j\hat{Z}_L \sin\beta L} \quad (2.7a)$$

or equivalently,

$$\hat{Z}_{in}(L) = Z_C \frac{\hat{Z}_L + jZ_C \tan\beta L}{Z_C + jZ_L \tan\beta L} \quad (2.7b)$$

3. VOLTAGE, CURRENT, AND INPUT IMPEDANCE TO THE LINE AT ANY LOCATION D AWAY FROM THE LOAD

At the input to the line, we have a situation depicted in Figure 5.

It is apparent the voltage and current *at the input to the line* can be now obtained from

$$\hat{V}(L) = \frac{\hat{Z}_{in}(L)}{\hat{Z}_S + \hat{Z}_{in}(L)} \hat{V}_S \quad (3.1a)$$

$$\hat{I}(L) = \frac{\hat{V}(L)}{\hat{Z}_{in}(L)} \quad (3.1b)$$

Now, from the knowledge of $\hat{V}(L)$ and $\hat{I}(L)$ we can determine the constants $\hat{V}_d^+$ and $\hat{V}_d^-$ from

$$\hat{V}_d^+ = \frac{\hat{V}(0) + Z_C \hat{I}(0)}{2} \quad (3.2a)$$

$$\hat{V}_d^- = \frac{\hat{V}(0) - Z_C \hat{I}(0)}{2} \quad (3.2b)$$

or

$$\hat{V}_d^+ = \frac{\hat{V}(L) + Z_C \hat{I}(L)}{2} e^{-j\beta L} \quad (3.2c)$$

$$\hat{V}_d^- = \frac{\hat{V}(L) - Z_C \hat{I}(L)}{2} e^{j\beta L} \quad (3.2d)$$

At this point we can obtain the voltage, current, or impedance at any location *d* away from the load using the previously derived equations.

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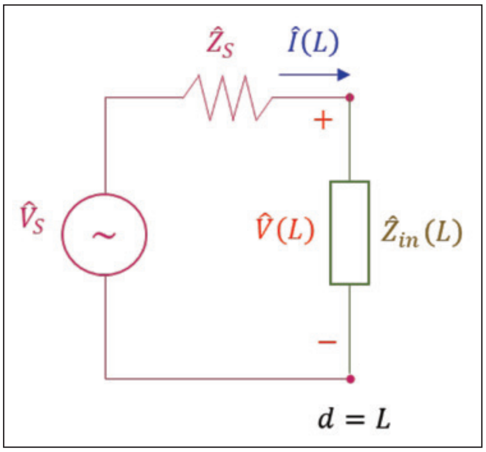

Figure 5: Equivalent circuit at the location $d = L$

ESD CHALLENGES IN 2.5D/3D INTEGRATION

By Mirko Scholz and Marko Simicic for EOS/ESD Association, Inc.

INTRODUCTION

2.5D/3D integration is an Integrated Circuit (IC) packaging technique that allows the combination of dies of the same or different technologies in the same IC package. Back in the 1990s IC dies were placed next to each other and connected through wire bonding. Later in the 2000s this was also applied to three-dimensional die stacking. Since the 2010s the industry has been working on IC packaging where vertical stacked dies are connected through embedded Through-Silicon-Via (TSV) and micro-bumps or hybrid bonding. In 2.5D ICs the dies are placed next to each other and connected through an interposer. In 3D ICs the dies are vertically stacked and TSVs and die-to-die interfaces are used to connect the single dies.

ESD CHALLENGES IN 2D/3D ICS

Electro-Static Discharges (ESD) can occur during die or wafer stacking. Die pick-up, die transfer and die or wafer bonding (Figure 1) are process steps with an increased risk for ESD. Like for conventional IC packaging ESD control and ESD protection design are available to prevent ESD related damages. ESD

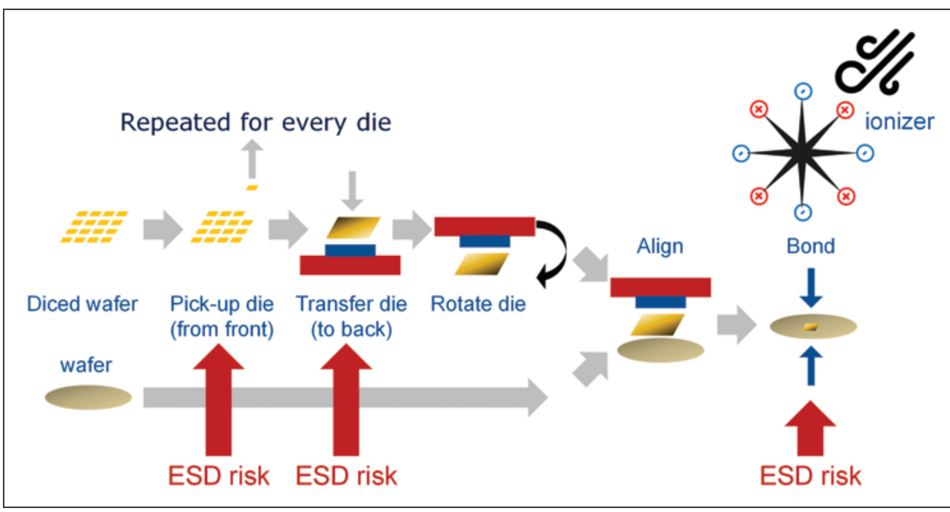

Figure 1: ESD risks in a die-to-wafer bonding process [1]

Dr. Mirko Scholz, Infineon Technologies AG, received his Ph.D. in Electrical Engineering from the Vrije Universiteit in Brussels (VUB). He has authored/co-authored more than 100 publications, tutorials, and patents in the field of ESD design and testing. He is a regular reviewer for several IEEE journals and a current member of the IRPS sub-committee on ESD and Latchup.

Marko Simicic joined the ESD team at imec in Belgium in 2017 with the focus on researching ESD solutions for devices and circuits. He has authored or co-authored more than 35 papers in international journals and conference proceedings and is an active member of the JS-002 ANSI/ESDA/JEDEC joint standard for CDM ESD device sensitivity testing.

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.

control techniques minimize the charging and discharging during the stacking and bonding process. Protection design increases the ESD robustness of die-to-die interfaces.

The manufacturing of commercial 2.5D and 3D ICs has specific ESD related challenges that need to be solved. Typically, there are a very large number of die-to-die interfaces and small bump pitches. It is expected that the number of die-to-die interfaces in 3D ICs will increase further. Figure 2 shows a roadmap for the coming years.

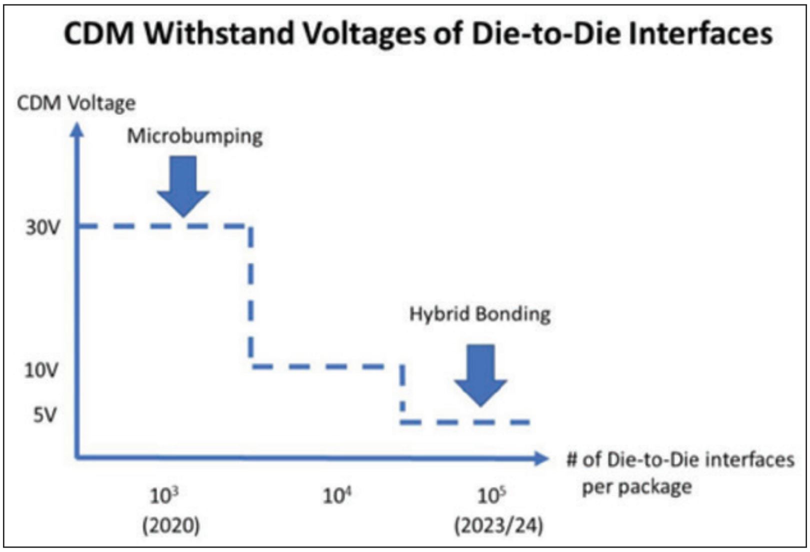

Figure 2: Industry council roadmap for number of die-to-die interfaces per 3D IC package and expected CDM withstand voltages [1]

The large number of interfaces leaves no or only little area for an ESD protection design of every die-to-die IO. Instead, very often a self-protecting approach must be used together with sufficient ESD control measures. Two scenarios can be assumed. If the stacking and bonding is done in-house the 3D IC manufacturer has control over all process steps. A very good ESD control and a self-protecting only approach for the die-to-die IOs is possible. If the stacking and bonding is done by an external supplier, the ESD control may follow only the requirements of S20.20. Some ESD protection design for the die-to-die IOs might be necessary.

Both approaches require extracting the intrinsic ESD robustness of the die-to-die IOs. ESD testing methods are needed that can test reliable with low stress level, low variability. Also, they must be capable of applying the stress to bare dies. Contact CDM testing methods like Charge-Coupled TLP (cc-TLP, [2]) and Low-impedance Contact Charge Device Model (LICCDM, [3]) are examples for suitable ESD testing methods.

ESD verification of a 3D IC products designs provide another challenge because of the large number of die-to-die interfaces and possible metal routing across different dies. To enable a reliable ESD verification for these types of products it is required to use advanced Electronics Design Automation (EDA) tools, new verification approaches and to deal with high computing power requirements.

OUTLOOK

There is a lot of on-going research and development work to further improve the ESD control and to better understand the electrostatic effects during the bonding process. To support the industry in this effort the Industry Council will soon publish a white paper that provides guidance on ESD target levels, on ESD testing of die-to-die interfaces and for IP development in 2.5D and 3D ICs.

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Banana Skins

417 Mains harmonic distortion from electronic equipment upsets energy providers

The increasing use of electronic equipment is causing 'harmonic distortion' on the UK supply network. This is caused by non-linear loads on the electricity supply system, such as PCs, lighting systems, switch mode power supplies and variable speed drives.

Regulation ER G5/4-1, published by the energy networks association (ENA) is the UK's instrument to control this distortion and to assist compliance with the harmonised network standards such as EN 50160. ER G5/4-1, which was first published in 2001 and subsequently updated in November 2005, is the UK's attempt to control harmonic distortion back onto the supply network and is the updated version of the earlier G5/3 which was published in 1976. Ironically, many of those affected by power quality issues remain unaware of the original regulation, let alone the updated version.

I have personal experience of a number of installations where compliance issues have been tackled badly and the remedial measures have more costly than early preventative considerations. A £50k investment in preventative measures, for example, for example, could have saved a small food and beverage company in the North of England around £1m which they subsequently had to spend on mandatory remedial issues.

One example, in the food and beverage industry, concerns a soft drinks company which was inadvertently creating power quality issues onto the local 1kV supply network and causing domestic lighting in the area to flicker uncontrollably. The first the company knew of this problem was a visit from its electricity supplier threatening to cut them off!

(Extracted from "The Hidden Cost", *Steve Barker, IET Computing and Control Engineering, February/March 2007, pp10-11, https://www.theiet.org. Other very similar articles by Steve Barker on the same subject (compliance with G5/4-1) and containing the same examples include:* "The Hidden Cost of Power Quality Problems", *Electrical Engineering, February 2007, pp 36-37, http://www.connectingindustry.com, and* "Industry Vulnerable to Hidden Power Costs", *Electrical Review, Vol. 240 No. 3, pp 10-12, https://www.electricalreview.co.uk.)*

418 Crocs slippers can cause ESD interference to hospital equipment

A hospital in Sweden has banned workers from wearing 'Crocs' slippers after learning the popular footwear can build up static electricity.

After officials at the Blekinge Hospital in Karlkrona determined the comfortable shoes built up so much static electricity they interfered with medical equipment they decided to ban the offending footwear, The Local reported Wednesday.

The fashion statement-turned-medical problem began in February when a two pieces of respiratory equipment for premature babies shut off for no discernable reason.

Eventually the machines' mysterious power outage was linked to the plastic slippers that many staff members wore on duty and the ban was suggested.

"Everybody generates static electricity. But it usually loses its charge, either by disappearing through one's shoes or elsewhere," said Bjorn Lofqvist, a spokesman for the hospital.

The Local said the slippers were found to be capable of becoming charged with a maximum electrical charge of 25,000 volts.

(Copied entirely from "Insulating slippers have shocked hospital", *NewsTrack – Quirks, United Press International, UPI, April 19, 2007 12:28 AM http://www.upi.com, sent in by Paul Bertalan of Sensis Corporation on 19th April 2007.)*

419 Portable transmitters could interfere with control of nuclear power plants

Although the power output from handheld RF devices is generally limited to a maximum of 7 watts because of RADHAZ safety constraints, their portability makes them particularly troublesome. As illustrated in Table 2, the higher power hand held devices can easily create electric field levels over 20 V/m. Tests performed by Oak Ridge National Laboratories (ORNL) summarized in Figure 3 indicated that approximately 50% of electronic devices are susceptible to EF levels in the amplitude range from 20 to 50 V/m. Devices tested were predominantly non-RF solid state analogue control systems used in Nuclear Power Plants.

Although operational controls exist for these handheld type emitters, the number of people who carry these devices is great so relying completely on operational constraints in the handheld frequency range is a risk.

(Extracted from "Modern Spacecraft – Antique Specifications", *Ron Brewer, Launch Service Program, Analex Corporation, IEEE International*

Symposium on EMC, Portland, OR, USA, August 14-18 2006, ISBN: 1-4244-0294-8/06.)

420 Powerful solar bursts interfered with GPS in December 2006

The National Oceanic and Atmospheric Administration (NOAA) reports that a solar eruption last December affected global positioning systems (GPS) and other technologies using radio waves. That conclusion, based on findings by researchers at Cornell University, were announced on April 4, 2007 at the first Space Weather Enterprise Forum in Washington, DC. This group of academic, governmental, and private sector scientists are examining Earth's ever-increasing vulnerability to space weather impacts.

Forecasters from the NOAA Space Environment Center in Boulder, CO observed two powerful solar flares on December 5 and 6, 2006. These violent eruptions originated from a large sunspot cluster. On December 6, a solar flare created an unprecedented intense solar radio burst causing large numbers of receivers to stop tracking the GPS signal.

"The solar radio burst occurred during the solar minimum, yet produced as much as 10 times more radio noise than the previous record," according to Dale Gary, Ph.D. of the physics department at the New Jersey Institute of Technology. "Measurements with NJIT's solar radio telescope confirmed that, at its peak, the burst produced 20,000 times more radio emission than the rest of the sun. This was enough to swamp GPS receivers over the entire sunlit side of the Earth."

(Copied entire from: "Powerful Solar Bursts Affected GPS Systems in December", *Interference Technology News, April 20 2007. Also see Banana Skin No. 388, which predicted this problem. Why are so many organisations planning to rely on GPS for safety-critical systems? A quick search through 'Banana Skins' should show them what an unreliable system it is.)*

421 Spacecraft interference experiences from Mark Simpson

- Programs that cut corners usually cut too many and run into serious trouble with interference
- Checklists are very helpful in preventing missing following one or more good EMC design rules
- Most interference problems that have occurred could have been caught by using highly skilled and experienced engineers
- Many engineers have experience limited to a handful of programs, and most problems occur when an engineer works on a program with more stringent and complex requirements than they are familiar with
- Most programs use requirements and units from last program: 'Built to boilerplate', hope it works, test and patch when it inevitably doesn't work
- Heritage (legacy) claims of 'no problems' are almost always wrong – only a small percentage of problems make it back to current program people (*This approach is sometimes called 'proven in use – Editor*)
- Some failures have been serious, e.g. transmitters jamming sensors; jammed command receivers; premature deployment; failure to deploy
- Over the past 12 years, 7 programs have each taken more than a year to fix their interference problems
- Most programs have operational problems caused by interference
- ESD from spacecraft charging continues to plague programs – sometimes only discovered after several vehicles have been launched
- One program had to be cancelled due to EMI
- A payload had to be turned off because it caused massive interference
- I have personally saved several programs from complete mission loss due to interference problems
- Independent EMC oversight saves programs
- Using my 'lessons learned' will help you save your program

(From "Speaking the Unspeakable: The Role of Independent Oversight", *Mark Simpson, presented at the Workshop session on* "Aerospace EMC at the Centennial of Flight", *IEEE 2004 International EMC Symposium, Santa Clara, CA, August 2004,ISBN (CD-ROM) 0-7803-8444-X, IEEE reference: 04CH37559C .)*

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.

The 6G Future:
How 6G Will Transform Our Lives

Increased Bandwidth and Accelerating Speed Will Deepen Our Connection with the Digital World

BY PURVA RAJKOTIA

With the global deployment of 5G networks still underway and many areas of the world still using older and less advanced communications networks, researchers and industry leaders are already looking ahead to 6G and its potential benefits. Following the 10-year development timelines of previous cellular technologies, we could expect 6G trials and deployments as early as 2030. But much work is ahead of us in these coming eight years to develop relevant standards that address the needs that are evident today and those that will reveal themselves in the coming years. To this end, the IEEE Standards Association (IEEE SA) is at the forefront of efforts to define 6G technology.

The high-level vision for 6G is to deepen the connection and integration between the digital, physical, and human worlds. While it's too early to know what final form 6G will take before it is standardized, we can speculate on the characteristics the next generation network will have, including the technologies that will be included and why they are important.

THE 6G NETWORK

As the name suggests, 6G is the successor to 5G communications technologies. Beyond supporting mobile, 6G will support technology like automated cars and smart-home networks, helping create seamless connectivity between the internet and everyday life.

Currently, 5G promises download speeds many times faster than 4G LTE networks and with significantly less latency. Naturally, we can expect 6G networks to use higher frequencies than 5G networks and provide substantially higher capacity and much lower latency. Current projections call for 6G to hit a maximum speed of one terabit per second (Tbps), which is 100-times faster than 5G. In terms of frequency, 6G looks to elevate from 5G's frequency of 60 kilobits and reach 95 kilobits. 6G will use more advanced radio equipment and a greater volume and diversity of airwaves than 5G, including an extremely high frequency (EHF) spectrum that delivers ultra-high speeds and huge capacity over short distances. All 6G networks will have integrated mobile edge computing

Purva Rajkotia is the Director of Global Business Strategy & Intelligence (GBSI) and the Connectivity and Telecom Practice Lead at IEEE SA. Prior to IEEE, Purva held leadership positions with Qualcomm, Samsung, and Disney, as well as with various standards in various standards organizations including ITU, 3GPP, 3GPP2, and CENELEC. He has authored more than 100 patents granted by the U.S. Patent Office and other worldwide patent organizations. Purva obtained his MSEE degree from the Georgia Institute of Technology and his MBA from Colorado State University. He can be reached at p.rajkotia@ieee.org.

technology, not an add-on like current 5G, providing benefits such as improved access to AI capabilities and support for sophisticated mobile devices and systems.

Beyond amplifying applications for better connectivity and performance, tomorrow's 6G network design should use AI and machine learning (to improve assistance and efficiencies), support greater sustainability outcomes, increase security (to foster trust and reliability), and expand and improve connectivity with remote areas of the world.

The 6G network must be more efficient than 5G and consume less power. Energy efficiency achieved through digitization is critical for a more sustainable mobile industry because of the anticipated growth in data generation. The 6G network can power the applications needed to make this happen.

The network must be more than just secure. It must also be reliable. While privacy is an important component of security, consistent, reliable, and rapid, end-to-end data delivery, such as that needed to support the safe and efficient operation of driverless vehicles without concerns about potentially dangerous latency glitches, is essential.

The COVID-19 pandemic helped clarify the importance that future networks will need to emphasize societal and economic needs by focusing on expanded global access instead of just performance. Many areas worldwide, particularly rural and underprivileged areas, are without broadband access. Future networks will need to serve an ever-increasing number of users and their anticipated network use cost-effectively to achieve the goal of universal wireless communications access. 6G satellite technology, combined with intelligent surfaces capable of reflecting electromagnetic signals, can deliver low latency and multi-gigabit connectivity. This potential could be especially transformative in parts of the world where providing access to conventional mobile networks is too difficult, too expensive, or both. The advances provided by the open radio access network (Open RAN) should also help drive down network costs.

6G AND THE TRANSFORMATION OF SOCIETY

Like the evolution of all technologies, including faster networks and mobile, 6G will further transform how we do business, manage and operate our community infrastructures, and live. Key to the promise of 6G, sensing is the basis for all interaction with and emulation of the physical environment, and its potential extends to autonomous vehicles, smart factories, precision healthcare, and much more.

If 6G were available today, developers would most certainly be eager to leverage its anticipated attributes. 6G's exceptional data rates, low latency, secure reliability, agility, and dynamic insights will expand the scope of capabilities to support new and innovative applications in wireless connectivity, cognition, sensing, and imaging.

We can already feel the demand pull for 6G by examining the applications being deployed today. For example, technology trends seen with 5G, such as virtualized networks, are setting the stage for 6G by enabling things like specialized deployments. Operators have densified radio networks with more antennas. It is now easier to get a signal, especially indoors. Users now have close access to data storage and processing through cloud technologies and edge computing. Even at scale, latency is much lower.

The 5G platform already harnesses AI for optimization, dynamic resource allocation, and data processing. But extremely low latency of less than one millisecond and distributed architecture mean that 6G will be able to deliver global, integrated intelligence. 6G will propel the fourth industrial revolution, enabled largely by the industrial Internet of Things (IoT) services integrated with AI and machine learning.

6G wireless sensing solutions will impact government and industry approaches to public safety and critical asset protection, such as threat detection, health monitoring, and air quality measurements. We can anticipate greater decision-making capabilities using real-time information, improving the responsiveness of law enforcement officials and first responders.

Autonomous driving is one of the main use cases in which 6G is expected to play a critical role by enabling greater accuracy and reliability. The recently released IEEE 2846, a new standard for autonomous vehicle (AV) safety, provides an important step in advancing the mass testing of AVs in the U.S. Looking further ahead, 6G and future networks will be needed to drive an AV society. For example, it's easy to understand that data speed with complete coverage will be required to enable thousands of AVs to navigate traffic in a geographical area. But it will also be needed for connection with a network of sensors that can direct the AV to an open parking spot close to the desired end of the route.

An essential part of AV navigation systems will be sophisticated maps, successors to GIS on the ground. The future includes the advent of real-time 4D maps, which everyone, including government organizations, will use to monitor, manage, and operate infrastructure, including traffic largely comprised of autonomous vehicles. A vast sensor network, aggregating data from ground and air inputs, will be used to map everything from traffic to weather conditions. With 4D mapping, we may see how we manage all space, including the air space above us.

6G will also enable immersive communication experiences through location and context-aware digital services, sensory experiences, such as truly immersive extended reality (XR), and high-fidelity holograms. Look for virtual reality, which usually requires a cumbersome headset, to be replaced with augmented reality. Holographic technology will be integrated into many applications, including communication, telemedicine, architecture, interior design, and gaming. Instead of today's video conferences, it will be possible to speak to people in real-time in virtual reality (VR), using wearable sensors allowing users to have the physical sensation of being in the same room together.

Because 6G is more power-efficient than 5G, it may even be possible for low-power IoT devices to be charged over the network. This efficiency would transform the economics of mass deployments and aid sustainability. But beyond the network, 6G will also drive the technologies that can make our world more sustainable through global sensors measuring inputs from vast ecosystems, including forests, oceans, cities, and homes. At the most granular level, a smart home could pull intelligence from sensors inside and outside the home to learn from and adapt to your behaviors, such as when to turn on HVAC systems and when to put them on pause or shut them down.

We also can look forward to advances in precision healthcare, in which data science, analytics, and biomedicine are combined to create a learning system that conducts research in the context of clinical care while also optimizing tools and information to provide better outcomes for patients. Precision healthcare can include the use of tiny nodes that measure body functions tied to devices that can medicate and assist patients.

Leveraging satellite and other technologies, the 6G network has the potential to empower tremendous intelligence and limitless connectivity and connect all aspects of our physical and digital worlds – holistically, what some call the metaverse. The launch of 6G could fuel a massive increase in IoT adoption, allowing the transmission of data to update its digital representation, such as climate sensors in a factory or scattered throughout a city, in real time. With 6G, applications will be developed to observe and analyze events, provide more reliable predictions about likely outcomes, and automatically program response actions.

In a personal and relatable example for most everyone, 6G will provide terabit speeds that will inevitably make streaming more enjoyable and video calls less painful.

HOW IEEE SA SUPPORTS THE DEVELOPMENT AND LAUNCH OF 6G

Through our Connectivity & Telecom Practice, IEEE SA is building an ecosystem of interested stakeholders from across the globe to address the need for robust, responsible, and affordable wired/wireless platforms focused on providing improved and reliable connectivity to meet the ever-increasing data needs. The technologies and societal issues envisioned for 6G technology that are part of the focus of our efforts include virtualized RAN (Open RAN), universal connectivity, energy savings, cybersecurity, IoT, augmented reality, and a sustainable future. We welcome the involvement of participants from academia, government, and industry. For more information or to join the standards activity, please visit the Connectivity & Telecom Practice webpage[1].

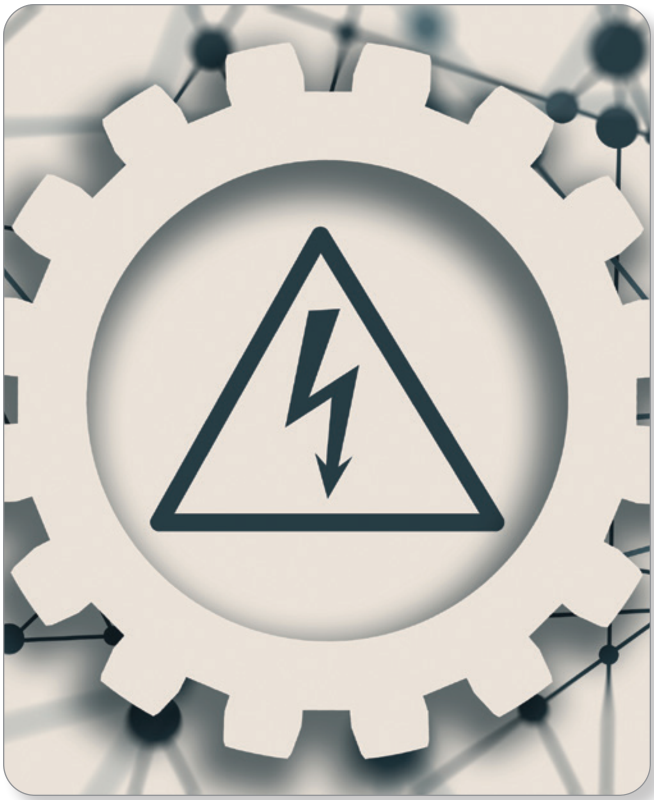
ENDNOTE

1. https://standards.ieee.org/practices/connectivity-telecom

Users Guide to Hipot Testing

Production Safety Testing Ensures Compliance with Global Safety Standards

BY CHAD CLARK



Because virtually all electronic devices and electrical apparatus require safety certification, manufacturers must submit samples of their products to compliance agencies and regulatory authorities to ensure they meet global standards.

This article gives an overview of the many safety standards required for certification and how advanced hipot testers have evolved to speed and simplify the compliance process. It also discusses the critical pre-testing setup and safety procedures required to ensure user safety. Finally, it describes the four types of essential hipot tests, dialectic withstand, insulation resistance, ground continuity, and ground bond testing, conducted during final production as well as the test results to look for.

UNDERSTANDING GLOBAL SAFETY STANDARDS

During the production phase of product development, products destined for sale in the U.S. market are typically sent to Nationally Recognized Testing Laboratories (NRTLs) for compliance testing. NRTLs provide services to certify compliance with the relevant standard(s) and regularly inspect the testing equipment and facilities.

The compliance evaluation conducted by an NRTL typically investigates two key areas of a product, as follows:

1. Construction—Mechanical construction, spacing, clearances, etc.; and
2. Safety—To assure safe operation, even under high-stress conditions.

The details of what constitutes an NRTL-certified product depend on the specific standard (or standards) applicable to that product. For products that will be sold and used in jurisdictions outside the U.S., the requirements of different standards may be applicable, potentially complicating the process of achieving global access.

In an effort to address this challenge, efforts are ongoing to harmonize standards internationally. An example is IEC 61800-5-1, a standard developed by the International Electrotechnical Commission (IEC) that addresses the safety aspects related to electrical, thermal, and energy in adjustable speed electrical power drive systems. In the U.S., the requirements of IEC 61800-5-1 have effectively replaced those of UL 508C, which has been withdrawn and superseded by UL 61800-5-1.

Chad Clark has been with Vitrek LLC since 2008. Over the years, Chad has had the opportunity to work directly with end-users to develop safe methods and procedures, enabling countless products to be NRTL safety listed. Chad holds a BE in Economics from California State University, Long Beach and can be reached at chad@vitrek.com.

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THE EVOLUTION OF HIPOT TESTING

Hipot testing has long been a standard procedure for various types of equipment. Hipot testers get their name from the "high potential" (high voltage) that they produce in order to perform dielectric withstand and insulation resistance tests. Many hipot testers also provide accurate, low-resistance measurements and low-resistance/high-current outputs to test ground resistance and ground bond integrity.

The early commercial hipot tester was not much more than a step-up transformer used to adjust an applied voltage in stepped increases over prescribed time segments to test for leakage or component breakdown. However, this legacy method could easily lead to incorrect results when leakage current causes the voltage output from a high-impedance transformer source to drop.

In contrast, today's most advanced hipot testers utilize electronic source technology to assure compliance with IEC-61010, which explicitly requires that "the voltage test equipment shall be able to maintain the required voltage for the specified period of time."

Figure 1: Modern hipot testers are designed to perform a range of electrical safety testing procedures.

HIPOT TESTING SETUP AND SAFETY PROCEDURES

By its very nature, electrical safety testing involves the use of high voltages and requires test operators to follow strict adherence to safety procedures. Operators should understand that high voltages are dangerous and that care must be taken to avoid contact with energized circuits. The importance of having trained personnel as the first step in ensuring a safe testing environment can't be overstated.

Station Setup

The next step is determining where the test station will be located. The test area should be isolated from the factory assembly area and located away from routine foot traffic to help ensure the safety of those who occasionally come near the test station. In addition, operator distractions should be kept to a minimum and the area should be conspicuously marked with internationally approved signage, such as "DANGER - HIGH VOLTAGE."

During testing, the hipot tester itself should have indicator lights to denote when high voltage is present. There should be ample and reliable power supplied to the test station. Verify that the power wiring meets electrical code requirements for polarization and grounding. Always use an outlet that has a properly connected protection ground and make sure this ground has been tested to ensure a low impedance path to the panel ground and earth bonded ground.

Figure 2a/2b illustrates two alternative approaches to the setup of a benchtop hipot test. In Figure 2a, the operator is wearing safety glasses, and the device under test (DUT) is placed on the test bench equipped with a combination of palm switches and a footswitch to prevent the operator from making direct contact with the DUT while testing is underway. As a practical matter, the use of palm switches is typically restricted to short-duration tests done on a repetitive basis with a series of DUTs. If this test setup is

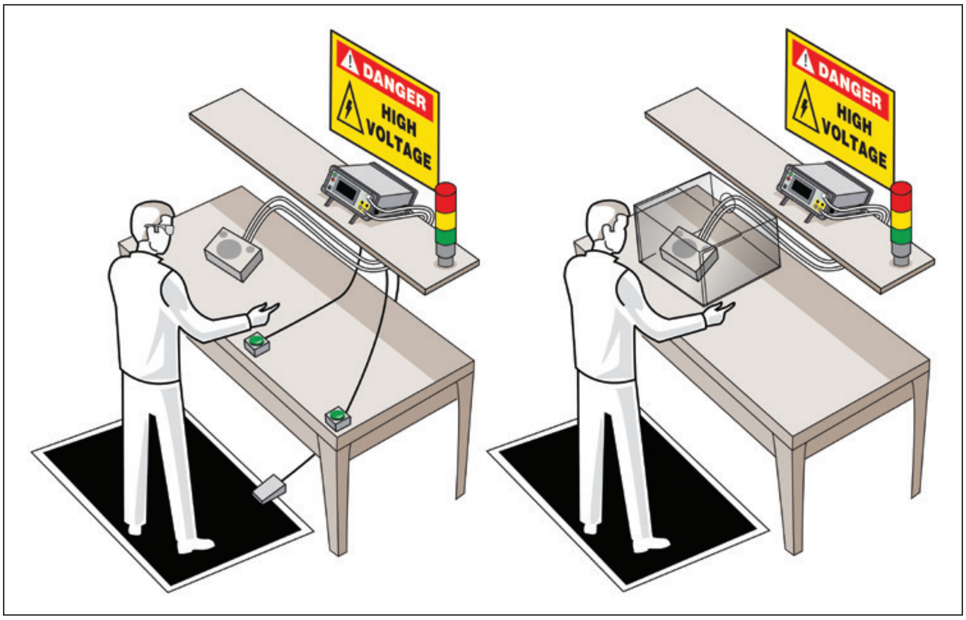


Figure 2a/2b: Two alternatives for benchtop hipot testing setup. 2a (left) employs palm and footswitches. In 2b, the DUT is placed under a protective cover.

used for longer tests, operators often find a way to bypass the palm switches, thereby defeating their intended purpose of protecting the operator.

Figure 2b shows the DUT placed under a protective cover with an interlock to isolate the operator during the test. The use of an enclosure is a more reliable means of assuring operator safety, particularly when testing requires longer time periods. More elaborate test stations can include a hipot tester interlock as well.

One safety method that utilizes the interlock is a light curtain, which is an infrared light beam that opens the interlock if anyone interrupts any part of the beam. The output of the light curtain is connected to the interlock terminal on the hipot tester. If the interlock is open, high voltage is immediately terminated. The light curtain is placed in between the hipot tester or the DUT and the operator. For the operator to touch the high voltage, they would have to pass through the light curtain, triggering the opening of the interlock and terminating the high voltage.

If the hipot is placed behind a light curtain, a method must be available to initiate the test, and a footswitch is an easy solution. But keep in mind that the test space must be designed to prevent anyone from reaching the high voltage by going around the light curtain.

Operator injury may result if the hipot tester is not properly connected to an earth ground. The work area and bench surface should consist of non-metallic materials, which means that metalwork surfaces should be avoided, and metal objects should not be placed between the operator and the DUT. All other metal objects should either be grounded or placed outside of the test area altogether. An ESD mat is not a recommended platform for a test station, as it may cause erroneous readings for leakage and is unnecessary in this application.

The test equipment should also provide for immediate and safe removal of the output voltage using internal discharge circuity, either at the conclusion of the test or if the test is interrupted. Never remove power for the hipot tester. If there is a power interruption, use extreme care in any

Periodic inspection and calibration of test equipment is a standard requirement to maintain NRTL certification for the product being produced. This inspection will include a check of hipot instrument calibration certification.

contact with the DUT. The safest approach is to leave the DUT connected to the hipot tester until power is restored and the tester can conduct its discharge function.

The test station should have sufficient space for the tester and the DUT without the operator having to reach over the DUT to access the tester. The tester should be at least three inches away from the wall to provide proper airflow for the unit. Ideally, the DUT should be isolated from the operator and the tester. For larger DUTs, which are wheeled to the test station, the cart should be non-conductive and have locking wheels. (This also applies if the tester needs to be wheeled to the DUT.) Keep the area clean and neat, and arrange the equipment so that it is easy and safe for the operator to use.

There are many safety features that can be added to the test station to prevent the operator from encountering high voltage, such as guards or enclosures. When placed around a DUT, guards or enclosures should be non-conducting and be equipped with safety interlocks that interrupt all high voltages when open. Interlocks should be arranged so that operators are never exposed to high voltages under any conditions.

In addition, it is easy to implement circuit palm switches that prevent the operator from encountering high voltage during testing. The basic operation of a palm switch requires the operator to use both hands to initiate a test with, potentially, a footswitch to activate the test. If one or both hands are removed from the switches while testing, the test is immediately stopped. The switches are placed directly in front of the operator and spaced shoulder-width apart. Spacing the switches in this way prevents an operator from trying to press both buttons down with one hand or object.

No high voltage can be applied to the output terminals and DUT until both switches are pressed simultaneously. The operator cannot touch the DUT or test leads if both hands are on the palm switches. The palm switches are connected to the digital I/O on the hipot tester. Only when the switches are in the down position is the start function enabled. Once one switch goes up, the safety interlock is enabled, terminating the output voltage of the hipot test. This method is safe, quick, and effective.

On a regular basis, typically at the start of every shift, the tester itself should be checked by connecting the tester to both PASS and FAIL samples. These samples should be designed to confirm the proper operation of the tester based on the type(s) of tests to be conducted (hipot, insulation resistance, ground resistance, or ground bond). Once all of the connections are made, and the prescribed test procedure is selected, the operator should confirm that all test parameters specified in the testing documentation are displayed on the tester screen. Operation of the test can then be conducted, keeping in mind the safety considerations described previously.

HIPOT TESTING DURING PRODUCTION

Hipot testing during production is performed to:

- Assure compliance with safety agency labeling requirements;
- Detect defective components or assembly flaws; and
- Reduce the incidence of latent field failures and the attendant warranty costs.

Once in production, products must be 100% tested to confirm compliance with the related agency certifications and safety standards. Production tests are less stringent than initial certification testing but will generally include basic dielectric withstand and shock hazard (leakage) tests.

Plug-connected devices will also be subjected to ground resistance and ground bond tests if required by the applicable standard. Electrical motors, transformers, and other such devices will likely include insulation resistance tests.

Periodic inspection and calibration of test equipment is a standard requirement to maintain NRTL certification for the product being produced. This inspection will include a check of hipot instrument calibration certification. This "cal cert" is typically required to be renewed on an annual basis. (NRTLs require compliance certification with ISO 17025.) Another common requirement prescribed by most NRTLs is a daily functional test of the hipot equipment.

Test 1: Dielectric Withstand

The basic hipot test applies a high voltage from the conductors to the chassis of the DUT. This test is often

In many instances, insulation resistance needs to be measured between several conductors. Examples include cable/connector assemblies, multiconductor cables, and relays.

referred to as dielectric test or voltage withstand test. Its purpose is to confirm that the insulation and isolation of the non-conducting surfaces from the operating voltage are sufficient to avoid a shock hazard. The typical specification for this test is 1000V + 2x normal operating voltage.

Both AC and DC hipot tests are possible and, in general, the test should use the same type of voltage as would be used during normal operation. However, if a DC hipot test is used on an AC circuit, the hipot voltage should be two times the peak, that is (2 x 1.4 x RMS) + 1000V (see Figure 3).

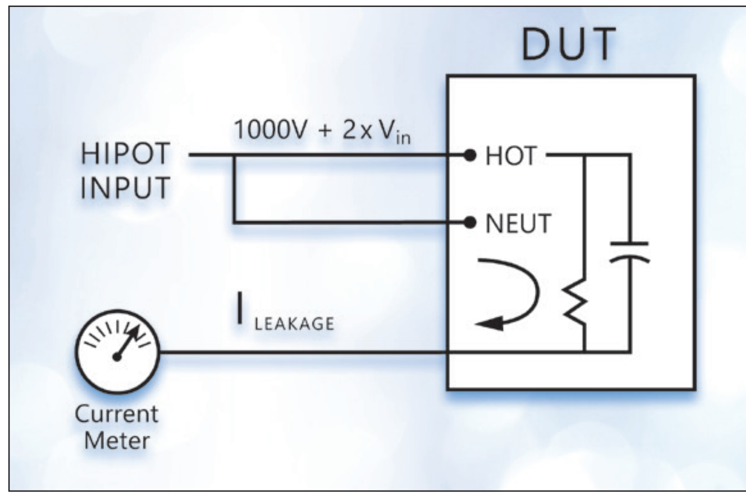


Figure 3: Hipot is applied to both conductors and leakage is measured in the return circuit through the ground connection.

Depending on the applicable standard, units will pass this test if either:

- The leakage current measured is less than the maximum allowable current; or
- No breakdown occurs, i.e., there is no sudden and uncontrolled flow of current.

In the case of double-insulated products, higher voltages are often specified in the test standard. In addition, this class of device typically requires special fixturing to connect the non-conductive outer shell to a conductive element.

Defects that are often detected with the hipot test include contamination (e.g., dirt, debris, etc.) and lack of proper spacing (creepage and clearance) of components. Creepage is measured across surfaces, while clearance is the air gap between components. Contamination would likely cause an unacceptable level of leakage current. Clearance problems can result in a breakdown.

Desirable hipot tester features for dielectric withstand testing include:

- Adjustable maximum output voltage:
    - 5KV is adequate for many applications
    - Higher voltages (up to 30KV) may be required
    - AC and DC outputs
    - Excellent regulation – both line and load
    - Controllable ramp rates, dwell times, and discharge features
    - Phase angle measurement of leakage current – capacitive coupling detection
    - Some standards allow for in-phase and quadrature currents to be measured separately. Leakage current due to capacitive coupling may not be a safety concern
- Min/max pass/fail current limits:
    - Separate limits during ramp
- Programmable multichannel testing

Test 2: Insulation Resistance

Insulation resistance testing is likely to be required in motor winding, transformer winding, and other applications involving cabling or insulated wire. Insulation resistance testing typically involves confirming that the resistance exceeds a defined high resistance value.

In many instances, insulation resistance needs to be measured between several conductors. Examples include cable/connector assemblies, multiconductor cables, and relays. To make this measurement, all the conductors except one are shorted together, and the test voltage is applied from the remaining conductor across the bundled

Hipot testing is an important final step in the production process for most electrical and electronic equipment. With programmable features and advanced functionality, today's hipot testers simplify electrical safety testing.

ones. Each wire is then tested in this fashion (see Figure 4.)

Desirable hipot tester features for insulation resistance testing include:

- Wide range of selectable test voltages
- Accurate/repeatable high-resistance measurement
- Programmable high voltage switching accessory
- Multichannel programmable testing
- Pass on steady and increasing voltage

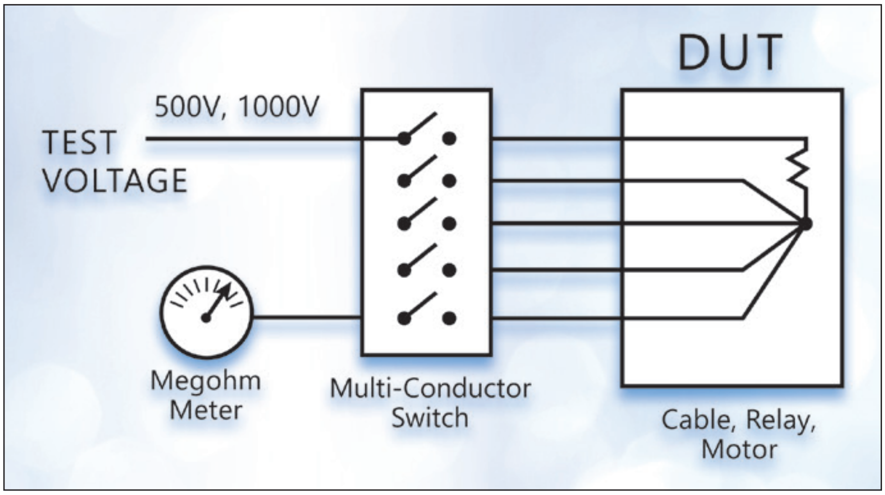


Figure 4: Voltage is applied to one conductor at a time while adjacent conductors are bundled. Resistance is calculated based on leakage current.

Test 3: Ground Continuity

Ground continuity testing is performed to confirm that the conductive chassis of a device is safely connected to the earth ground pin on the power plug. This assures protection against shock hazards even if the equipment suffers an internal short to the chassis. The current would be shunted via the ground wire and would likely trip the breaker or blow the fuse.

Ground continuity is performed by applying a low current (e.g., 50 mA) and calculating the resistance from the ground pin on the power plug to selected locations on the exposed surfaces of the DUT.

Desirable hipot tester features for ground continuity testing include:

- Accurate, repeatable low resistance meter
- Plug adaptor accessory to speed testing

Test 4: Ground Bond

Whereas ground continuity measures the resistance of the safety ground connection, the ground bond test assures the integrity of the connection. Using the same test setup, a high current is passed through the circuit. If the ground bond is solid, the current passes without a change in resistance.

Desirable hipot tester features for ground bond testing include:

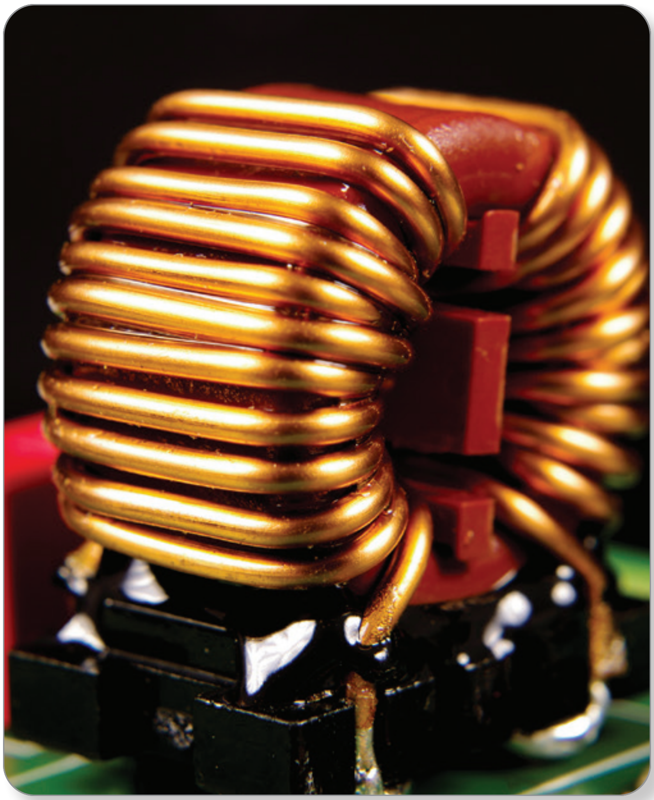
- Accurate high-current source
- Programmable test currents and test times
- Plug adaptor accessory to speed testing
- 4-wire milliohm meter - providing a Kelvin connection for highly accurate low resistance measurement

CONCLUSION

Hipot testing is an important final step in the production process for most electrical and electronic equipment. With programmable features and advanced functionality, today's hipot testers simplify electrical safety testing. But before commencing testing, manufacturers should be aware of the many updated safety certification standards and their requirements. And test operators must ensure upfront that they have set up a safe testing environment and fully understand the applicable testing protocols.

Common Mode Filter Design Guide

BY LEONARD CRANE



The selection of component values for common mode filters need not be a difficult and confusing process. The use of standard filter alignments can be utilized to achieve a relatively simple and straightforward design process, though such alignments may readily be modified to utilize pre-defined component values.

GENERAL

Line filters prevent excessive noise from being conducted between electronic equipment and the AC line. Generally, the emphasis is on protecting the AC line. Figure 1 shows the use of a common mode filter between the AC line (via impedance matching circuitry) and a (noisy) power converter. The direction of common mode noise (noise on both lines occurring simultaneously referred to as earth ground) is from the load and into the filter, where the noise common to both lines becomes sufficiently attenuated. The resulting common mode output of the filter onto the AC line (via impedance matching circuitry) is then negligible.

Leonard Crane has published numerous papers and is a popular speaker on the subject of inductors and magnetic components. Crane has many years of experience in the design and application of magnetics and is an expert on the optimal selection and use of RF and power inductors, transformers, and EMI chokes. For more information, email tech.support@coilcraft.com.

The design of a common mode filter is essentially the design of two identical differential filters, one for each of the two polarity lines with the inductors of each side coupled by a single core (see Figure 2).

For a differential input current ((A) to (B) through L1 and to (A) through L2), the net magnetic flux which is coupled between the two inductors is zero.

Any inductance encountered by the differential signal is then the result of imperfect coupling of the two chokes. They perform as independent components with their leakage inductances responding to the differential signal, and the leakage inductances attenuate the differential signal.

When inductors L1 and L2 encounter an identical signal of the same polarity referred to ground (common mode signal), they each contribute a net, non-zero flux in the shared core. The inductors thus perform as independent components with their mutual inductance responding to the common signal: the mutual inductance then attenuates this common signal.

THE FIRST ORDER FILTER

The simplest and least expensive filter to design is a first order filter. This type of filter uses a single reactive component to store certain bands of spectral energy without passing this energy to the load. In the case of a low pass common mode filter, a common mode choke is the reactive element employed.

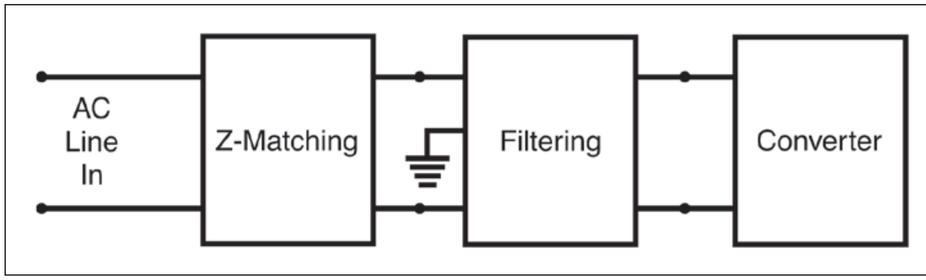


Figure 1: Generalized line filtering

The value of inductance required of the choke is simply the load in Ohms divided by the radian frequency at and above which the signal is to be attenuated. For example, attenuation at and above 4000 Hz into a 50Ω load would require a 1.99 mH ($50/(2\pi \times 4000)$) inductor. The resulting common mode filter configuration is shown in Figure 3 on page 54.

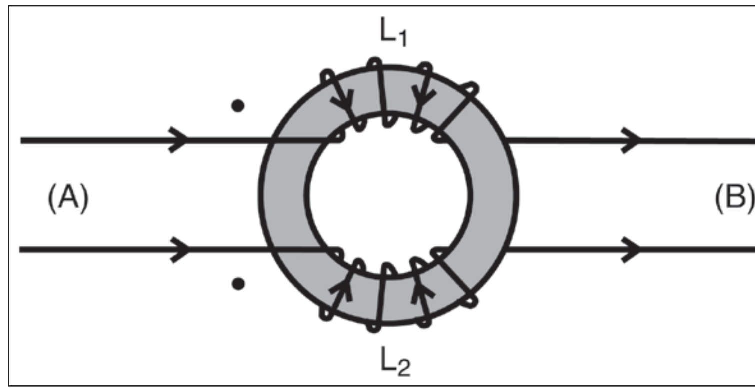


Figure 2: The common mode inductor

The attenuation at 4000 Hz would be 3 dB, increasing at 6 dB per octave. Because of the predominant inductor dependence of a first order filter, the variations of actual choke inductance must be considered. For example, a ± 20% variation of rated inductance means that the nominal 3 dB frequency of 4000 Hz could be anywhere from 3332 Hz to 4999 Hz.

It is typical for the inductance value of a common mode choke to be specified as a minimum requirement, thus ensuring that the crossover frequency not be shifted too high.

It is typical for the inductance value of a common mode choke to be specified as a minimum requirement, thus ensuring that the crossover frequency not be shifted too high. However, some care should be observed in choosing a choke for a first order low pass filter because an inductance with a much higher than typical or minimum value may limit the choke's useful band of attenuation.

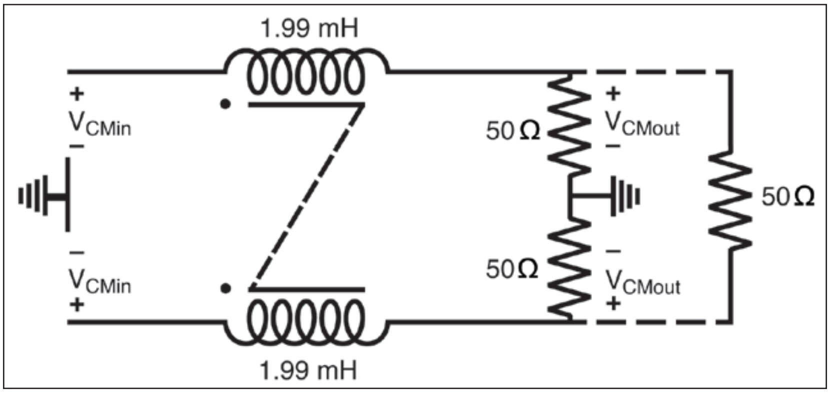


Figure 3: A first order (single pole) common mode filter

SECOND ORDER FILTERS

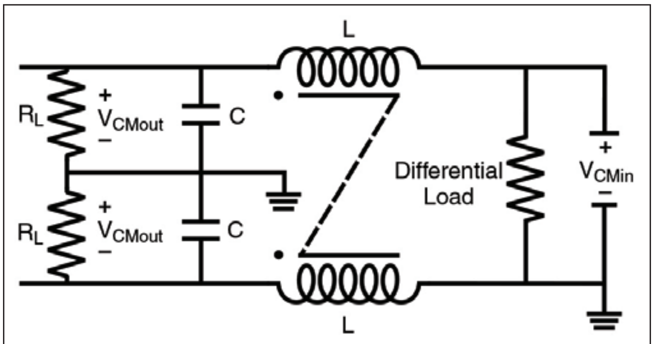
A second order filter uses two reactive components and has two advantages over the first order filter. Ideally, a second order filter: 1) provides 12 dB per octave attenuation (four times that of a first order filter) after the cutoff point; and 2) provides greater attenuation at frequencies above inductor self-resonance (see Figure 4).

The design of a second order filter requires more care and analysis than a first order filter to obtain a suitable response near the cutoff point, but there is less concern needed at higher frequencies, as previously mentioned.

One of the critical factors involved in the operation of higher order filters is the attenuating character at the corner frequency. Assuming tight coupling of the filter components and reasonable coupling of the choke itself (conditions we would expect to achieve), the gain near the cutoff point may be very large (several dB). Moreover, the time response would be slow and oscillatory. On the other hand, the gain at the crossover point may also be less than the presumed -3 dB (3 dB attenuation), providing a good transient response, but frequency response near and below the corner frequency could be less than optimally flat.

In the design of a second order filter, the damping factor (usually signified by the Greek letter zeta (ζ)) describes both the gain at the corner frequency and the time response of the filter. Figure 5 shows normalized plots of the gain versus frequency for various values of zeta.

As the damping factor becomes smaller, the gain at the corner frequency becomes larger, and the ideal limit for zero damping would be infinite gain. The inherent



$$\frac{V_{CMout}(s)}{V_{CMin}(s)} = \frac{1}{1+\frac{L}{R_L}s + LCs^2}$$

$$= \frac{1}{1 - LC\omega^2 + j\omega\left(\frac{L}{R_L}\right)}$$

$$= \frac{1}{1 + j2\zeta\frac{\omega}{\omega_n} - \left(\frac{\omega}{\omega_n}\right)^2}$$

$\omega \equiv$ radian frequency

$R_L \equiv$ the noise load resistance

$$\omega_n \equiv \frac{1}{\sqrt{LC}}$$

$$\zeta \equiv \frac{L}{2R_L\sqrt{LC}}$$

Figure 4: Analysis of a second order (two pole) common mode low pass filter

parasitics of real components reduce the gain expected from ideal components but tailoring the frequency response within the few octaves of critical cutoff point is still effectively a function of ideal filter parameters (i.e., frequency, capacitance, inductance, resistance).

For some types of filters, the design and damping characteristics may need to be maintained to meet specific performance requirements. However, for many actual line filters, a damping factor of approximately 1 or greater and a cutoff frequency within about an octave of the calculated ideal should provide suitable filtering.

The following is an example of a second order low pass filter design:

1. *Identify the required cutoff frequency*—For this example, suppose we have a switching power supply (for use in equipment covered by UL 478) that is 24 dB noisier at 60 kHz than permissible for the intended application. For a second order filter (12 dB/octave roll-off), the desired corner frequency would be 15 kHz.
2. *Identify the load resistance at the cutoff frequency*—Assume R_L = 50 Ω
3. *Choose the desired damping factor*—Choose a minimum of 0.707, which will provide 3 dB attenuation at the corner frequency while providing favorable control over filter ringing.

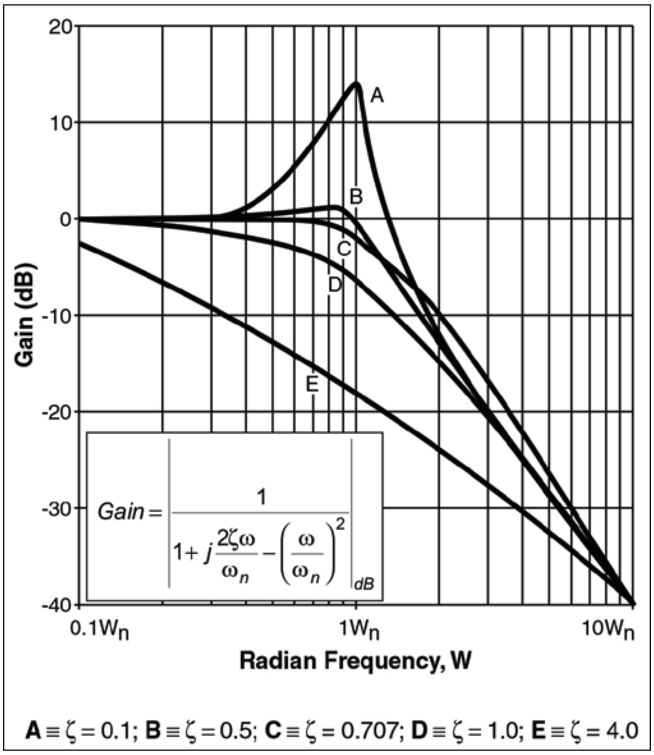


Figure 5: Second order frequency response for various damping factors (ζ)

4. Calculate required component values using the following equations:

$$\omega_n = 2\pi f_n = 94248 \text{ rad / sec}$$

$$C = \frac{1}{L\omega_n^2}$$

$$\zeta = 0.707 = \frac{L\omega_n}{2R_L}$$

$$L = 750\mu\text{H}$$

5. Choose available components as follows:

   C = 0.05 µF (Largest standard capacitor value that will meet leakage current requirements for UL 478/ CSA C22.2 No. 1: a 300% decrease from design)

   L = 2.1 mH (Approximately 300% larger than design to compensate for reduction or capacitance)

6. Calculate actual frequency, damping factor, and attenuation for components chosen using the following equations:

$$\frac{1}{2\pi\sqrt{LC}} = 15532 \text{ Hz (very nearly 15 KHz)}$$

   ζ = 2.05 (a damping factor of about 1 or more is acceptable

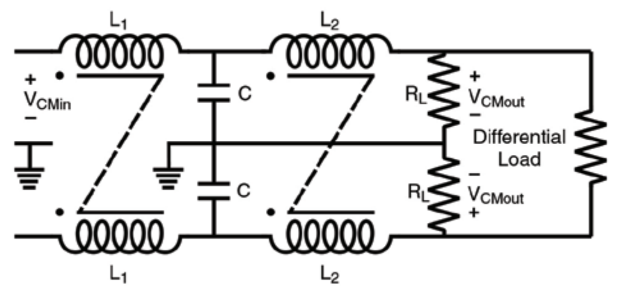
   Attenuation = (12 dB/octave) x 2 octaves = 24 dB

7. The resulting filter is that of Figure 4 with: L = 2.1 mH; C = 0.05 µF; R_L = 50 Ω

Note: Damping factors much greater than 1 may cause unacceptably high attenuation of lower frequencies, whereas a damping factor much less than 0.707 may cause undesired ringing and the filter may itself produce noise.

THIRD ORDER FILTERS

A third order filter ideally yields an attenuation of 18 dB per octave above the cutoff point (or cutoff points if the three corner frequencies are not simultaneous). This is



$$\frac{VCMout(s)}{VCMin(s)} = \left(\frac{R_L}{R_L + L_2 s}\right)\left(\frac{\frac{(R_L + L_2 s)}{sC}}{\frac{(R_L + L_2 s)}{sC} + R_L L_1 s + L_2 L_1 s^2 + \frac{L_1 s}{sC}}\right)$$

$$= \frac{1}{1 + \frac{L_1 + L_2}{R_L}s + L_1 C s^2 + \frac{L_1 L_2 C}{R_L}s^3}$$

$$\text{Butterworth} \rightarrow \frac{1}{1 + \frac{2s}{\omega_{n1}} + \frac{2s^2}{\omega_{n2}} + \frac{s^3}{\omega_{n3}}}$$

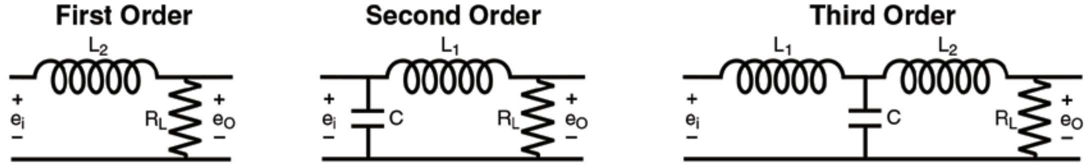
$$\frac{(L_1 + L_2)}{R_L} = \frac{2}{\omega_{n1}} \; ; \; \omega_{n1} = \frac{2R_L}{(L_1 + L_2)}$$

$$L_1 C = \frac{2}{\omega_{n2}^2} \; ; \; \omega_{n2} = \frac{1.414}{\sqrt{(L_1 C)}}$$

$$\frac{L_1 L_2 C}{R_L} = \frac{1}{\omega_{n3}^3} \; ; \; \omega_{n3} = \omega_{n2}^2 \frac{R_L}{2L_2} = \omega_{n2}^2 \omega_{n4}$$

$$\omega_{n4} = \frac{R_L}{2L_2}$$

Figure 6: Analysis of a third order (three pole) low pass filter where ω_1, ω_2, and ω_4 occur at the same -3dB frequency of ω_0



	First Order	Second Order	Third Order
Filter Schematic	(see figure above)	(see figure above)	(see figure above)
Filter Transfer Function	$\frac{e_o}{e_i} = \frac{1}{\frac{Ls}{R_L} + 1}$	$\frac{e_o}{e_i} = \frac{1}{LCs^2 + \frac{Ls}{R_L} + 1}$	$\frac{e_o}{e_i} = \frac{1}{\frac{L_1 L_2}{R_L}s^3 + L_1 C s^2 + \frac{(L_1 + L_2)s}{R_L} + 1}$
Butterworth Alignment	$\frac{e_o}{e_i} = \frac{1}{\frac{s}{\omega_n} + 1}$	$\frac{e_o}{e_i} = \frac{1}{LCs^2 + \frac{Ls}{R_L} + 1}$	$\frac{e_o}{e_i} = \frac{1}{\frac{s^3}{\omega_{n3}} + \frac{2s^2}{\omega_{n2}} + \frac{2s}{\omega_{n1}} + 1}$

Figure 7: The first three order low pass filters and their Butterworth alignments

the prominently positive aspect of this higher order filter. The primary disadvantage is cost since three reactive components are now required. Higher than third order filters are generally cost-prohibitive.

The design of a generic filter is readily accomplished by using standard alignments such as a maximally flat alignment (also known as a Butterworth alignment). Figure 6 shows the general analysis and component relationships to the Butterworth alignments for a third order low pass filter. Butterworth alignments provide an inherent z of 0.707 and a -3 dB point at the crossover frequency. The Butterworth alignments for the first three orders of low pass filters are shown in Figure 7.

The design of a line filter need not obey the Butterworth alignments precisely (although such alignments provide a good basis for design). Moreover, because of leakage current limits placed upon electronic equipment (thus limiting the amount of filter capacitance to ground), adjustments to the alignments are usually required, but they can be executed very simply as follows:

1. First design a second order low pass with $\zeta \geq 0.5$;
2. Add a third pole (which has the desired corner frequency) by cascading a second inductor between the second order filter and the noise load so that:

   $L = R/(2 \pi f_c)$

   Where f_c is the desired corner frequency.

DESIGN PROCEDURE

The following example determines the required component values for a third order filter (for the same requirements as the previous second order design example):

1. List the desired crossover frequency, load resistance:

   Choose $f_c = 15000$ Hz

   Choose $R_L = 50\ \Omega$

2. Design a second order filter with $\zeta = 0.5$ (see second order example above)
3. Design the third pole:

   $R_L/(2\pi f_c) = L_2$

   $50/(2\pi 15000) = 0.531$ mH

4. Choose available components and check the resulting cutoff frequency and attenuation:

   L2 = 0.508 mH

   $f_n = R/(2\pi L_1) = 15665$ Hz

   Attenuation at 60 kHz: 24 dB (second order filter) + 2.9 octave × 6 = 41.4 dB

5. The resulting filter configuration is that of Figure 6 with:

   $L_1 = 2.1$ mH

   $L_2 = 0.508$ mH

   RL = 50 Ω

CONCLUSIONS

Specific filter alignments may be calculated by manipulating the transfer function coefficients (component values) of a filter to achieve a specific damping factor.

A step-by-step design procedure may utilize standard filter alignments, eliminating the need to calculate the damping factor directly for critical filtering. Line filters, with their unique requirements, yet non-critical characteristics, are easily designed using a minimum allowable damping factor.

Standard filter alignments assume ideal filter components, but this does not necessarily hold true, especially at higher frequencies.

Everything You Need to Know About EV Battery and BMS Testing in Validation and Production Scenarios

An Overview of Battery Pack Design and Testing Considerations

BY BRENT HOERMAN AND JESSE BATSCHE

Electric vehicles are clearly a rapidly growing part of the automotive scene. They promise low or no emissions, conceivably low cost of energy from the power grid, yet they will continue to deliver us safely from here to there. However, electric vehicle design and manufacturing is clearly a paradigm shift for the automotive industry – new drive systems, technologies, and test plans.

Electric vehicles are bringing new test and validation challenges as the electronic and software content of the vehicles grow. In this article, we will discuss the basics of electric vehicle battery pack designs and some of the tests that should be performed on them in a manufacturing environment. We'll also discuss a conceptual solution to this complex testing challenge.

THE MOTIVATION FOR EV BATTERY TESTING

The battery packs used as the rechargeable electrical storage system (RESS) in electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs) are large and complex. Controlled release of the battery's energy provides useful electrical power in the form of current and voltage. Uncontrolled release of this energy can result in dangerous situations such as release of toxic materials (i.e. smoke), fire, high pressure events (i.e. explosions), or any combination thereof.

Uncontrolled energy releases can be caused by severe physical abuse, such as crushing, puncturing, or burning, which can be mitigated by mechanical safety systems and proper physical design. However, they can also be caused by shorted cells, an abnormally high discharge rate, excessive heat buildup, overcharging, or constant recharging, which can weaken the battery. These causes are best prevented by a properly designed and validated electronic safety and monitoring system, better known as a battery management system (BMS).

One of the major validation and safety challenges to be tackled in modern EVs, HEVs, and PHEVs concerns the effective testing of the Battery Pack itself and the Battery

Brent Hoerman is a Project Manager at DMC and can be reached at brent.hoerman@dmcinfo.com.

Jesse Batsche is a Project Director at DMC and can be reached at jesse.batsche@dmcinfo.com.

Management Systems (BMS) – the complex electronic system that manages the performance and safety of the battery pack and the high levels of electrical energy stored within. In the sections below, we will describe both the battery pack and the BMS in greater detail.

INSIDE AN EV BATTERY PACK

Battery pack designs for EVs are complex and vary widely by manufacturer and specific application. However, they all incorporate combinations of several simple mechanical and electrical component systems that perform the pack's basic required functions.

Cells and Modules

Battery cells can have different chemistries, physical shapes, and sizes as preferred by various pack manufacturers. However, the battery pack will always incorporate many discrete cells connected in series and parallel to achieve the pack's total voltage and current requirements. In fact, battery packs for all electric drive EVs can contain several hundred individual cells.

The large stack of cells is typically grouped into smaller stacks called modules to assist in manufacturing and assembly. Several of these modules will be placed into a single battery pack. The cells are welded together within each module to complete the electrical path for current flow. Modules can also incorporate cooling mechanisms, temperature monitors, and other devices. In most cases, modules also allow for monitoring the voltage produced by each battery cell in the stack by the BMS.

Safety Components and Contractors

Somewhere in the middle, or at the ends, of the battery cell stack is a main fuse that limits the pack's current under a short circuit condition. There is also commonly a service plug or service disconnect located somewhere within the battery stack's electrical path, which can be removed to split the battery stack into two electrically isolated halves. With the service plug removed, the exposed main terminals of the battery present reduced electrical danger to service technicians. A high voltage interlock circuit will often run throughout key elements and connection points of the pack to establish hard-wired safety functions.

The battery pack also contains relays, or contactors, which control the battery pack's electrical power distribution to the output terminals. In most cases, there will be a minimum of two main relays that connect the battery cell stack to the pack's main positive and negative output terminals, those supplying high current to the electrical drive motor. Some pack designs will include alternate current paths for pre-charging the drive system through a pre-charge resistor or for powering auxiliary busses with their associated control contactors. For obvious safety reasons these contactors are all normally open.

Temperature, Voltage, and Current Sensors

The battery pack also contains a variety of temperature, voltage, and current sensors. At least one main current sensor will measure the current being supplied by, or sourced to, the pack. The current from this sensor can be integrated to track the actual state of charge (SoC) of the battery pack. The state of charge is the pack capacity expressed as a percentage and can be thought of as the pack's fuel gauge indicator. The battery pack will also have a main voltage sensor, for monitoring the voltage of the entire stack and a series of temperature sensors, such as thermistors, located at key measurement points inside the pack.

Collection of data from the pack sensors and activation of the pack relays are accomplished by the pack's battery management system (BMS). The BMS is also responsible for communications with the world outside the battery pack and performing other key functions, as described in the following section.

INSIDE AN EV BATTERY MANAGEMENT SYSTEM (BMS)

The BMS controls almost all electronic functions of the EV battery pack, including battery pack voltage and current monitoring, individual cell voltage measurements, cell balancing routines, pack state of charge calculations, cell temperature and health monitoring, ensuring overall pack safety and optimal performance, and communicating with the vehicle engine control unit (ECU).

In a nutshell, the BMS system must read voltages and temperatures from the cell stack and inputs from associated temperature, current, and voltage sensors. From there, the BMS must process the inputs, make logical decisions to control pack performance and safely, and report input status and operating state through a variety of analog, digital, and communication outputs.

BMS TOPOLOGY

Modern BMS systems for EV applications are typically distributed electronic systems. In a standard distributed topology, routing of wires to individual cells is minimized by breaking the BMS functions up into at least two categories. The monitoring of the temperature and voltage of individual cells is done by a BMS sub-module board, which is mounted directly on each battery module stack. Higher level functions such as computing state of charge, activating contactors, etc. along with aggregating the data from the sub modules and communicating with the ECU are done by the BMS main module.

The sub-modules and main module communicate on an internal data bus such as controller area network (CAN). Power for the BMS can be supplied by the battery stack itself or from an external primary battery such as a standard 12V lead acid battery. In some cases, the main module is powered externally, while the sub modules are powered parasitically from the battery modules to which they are attached.

BMS STATE OF CHARGE CALCULATION

The BMS is responsible for tracking a battery pack's exact state of charge (SoC). This may simply be for providing the driver with an indication of the capacity left in the battery (fuel gauging), or it could be used for more advanced control features.

For example, SoC information is critical to estimating and maintaining the pack's usable lifetime. Usable battery life can be dramatically reduced by simply charging the pack too much or discharging it too deeply. The BMS must maintain the cells within safe operating limits. The SoC indication is also used to determine the end of the charging and discharging cycles.

To measure SoC the BMS must include a very accurate charge estimator. Since you can't directly measure a battery's charge, the SoC must be calculated from measured characteristics like voltage, temperature, current, and other proprietary (depending on the manufacturer) parameters. The BMS is the system responsible for these measurements and calculations.

BMS CELL BALANCING FUNCTIONS

The BMS must compensate for any underperforming cells in a module, or stack, by actively monitoring and balancing each cell's SoC. In multi-cell battery chains, small differences between cells (as a result of production tolerances, uneven temperature distribution, intrinsic impedance, and/or aging characteristics) tend to be magnified with each charge and discharge cycle. In EV applications the number of cycles can be very high due to the use of regenerative braking mechanisms.

When degraded cells with a diminished capacity exist within the battery stack, the performance of the pack as a whole is degraded. During the charging cycle, there is a danger that degraded cells would be subject to overcharging before the rest of the cells in the chain reach their full charge. As a result, temperature and pressure may build up and possibly damage that cell. The weakest cell will have the greatest depth of discharge during discharging and will tend to fail before the others. The voltage on the weaker cells could even become reversed as they become fully discharged before the rest of the cells resulting in the early failure of the cell.

Cell balancing is an active way of compensating for weaker cells by equalizing the charge on all the cells in the chain and thus extending the battery pack's usable life. During cell balancing, circuits are enabled which can transfer charge selectively from neighboring cells, or the entire pack, to any undercharged cells detected in the stack.

To determine when active cell balancing should be triggered and which target cells, the BMS must be able to measure the voltage of each individual cell. Moreover, each cell must be equipped with an active balancing circuit.

STATE OF HEALTH AND DIAGNOSTICS

The state of health (SoH) is a measure of a battery's capability to safely deliver its specified output. This metric is vital for assessing the readiness of the automobile and as an indicator of required maintenance.

SoH metrics can be as simple as monitoring and storing the battery's history using parameters such as number of cycles, maximum and minimum voltages and temperatures, and maximum charging and discharging currents, which can be used for subsequent evaluation. This recorded history can be used to determine whether it has been subject to abuse, which can be an important tool in assessing warranty claims.

More advanced measures of battery SoH can include features such as automated measurement of the pack's isolation resistance. In this case, specialized circuits inside the battery pack can measure the electrical isolation of the high current path from the battery pack ground planes. Such a safety system could preemptively alert the operator or maintenance technicians to potential exposure to high voltage.

BMS COMMUNICATIONS

Most BMS systems incorporate some form of communication with the world outside the battery pack, including the ECU, the charger controller, and/or your test equipment. Communications interfaces are also used to modify the BMS control parameters and for diagnostic information retrieval.

CAN (controller area network) is the most common communications bus in automotive applications, although automotive ethernet, RS232 / RS485 serial, SPI, TCP/IP, or other networks could be used. CAN networks come in various implementations and can include a range of higher level "application layer" protocols like unified diagnostic services, OBD II, J1939, etc.

Aside from a digital bus, separate analog and/or digital inputs and outputs should be considered as supplemental parts of the BMS interface and communication. Discrete inputs and outputs can be used for redundancy and for operations requiring a separate interface such as activating an external contactor, fan, or dashboard lamp.

TESTING AN EV BATTERY PACK

Developing a test strategy for an assembly as large, complex, and powerful as an EV battery pack can be a daunting task. Like most complex problems, breaking the process down into manageable pieces is the key to finding a solution. Accordingly, testing only at carefully selected points in the development and manufacturing process will

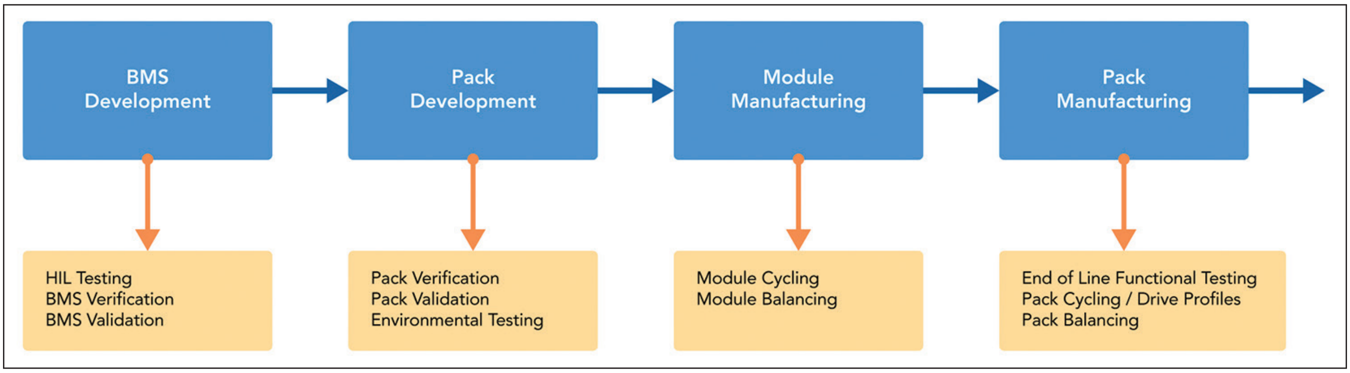


Figure 1: EV battery pack test sequencing

reduce the effort required. These key points for many pack manufacturers include BMS development, pack development, module production, and pack production. What tests are performed at each step is a different matter altogether and depends on the specifics of the process and the device.

BMS Development Testing

During BMS Development, engineers need a way to reliably test the BMS under real-world conditions to complete their verification and validation plans. Test strategies such as hardware-in-the-loop (HIL) testing are often performed at this stage. HIL testing involves simulating physical inputs and external connections to the pack while monitoring its outputs and behavior relative to design requirements.

Accurately simulating all the conditions to which a BMS may be subjected during real world operation is not easy. However, one must consider the long-term cost of skipping testing over a full range of conditions, remembering that any given condition could lead to a critical failure in the field. In the end, simulating nearly every combination of cell voltages, temperatures, and currents you expect your BMS to encounter is really the only way to verify that your BMS reacts as you intended in order to keep your pack safe and reliable.

Pack Development Testing

At the pack development stage, engineers are typically concerned about testing the entire assembly through various types of environmental stress testing as part of design validation or product validation plans. Environmental stress could include exposure to temperature extremes, thermal shock cycling, vibration, humidity, on-off cycling, charge discharge cycling, or any combination of these. The testing requirements here typically include performing a full batch of performance tests on a pack both before and after application of the stress. Live monitoring of the pack throughout the environmental stress period may also be required.

Since every battery pack design has unique elements, and since testing requirements vary accordingly based on agreements between the manufacturer and end user, in reality, there is no one-size-fits-all solution for everyone's battery pack testing needs.

Module Production Testing

Requirements for module level testing vary widely depending on the actual design of the system. The main testing to be done at this point involves simple charge/discharge testing to ensure that connections between cells are robust and can handle the intended current loads without failing or shedding excessive heat. Further testing could involve ensuring the cell voltages are reported correctly, that the cells are balanced, and/or that the cooling and temperature monitoring sensors are working properly.

Pack Production Testing

Pack level testing is done after the pack has completed, or is at least very close to, the point of final assembly, or end of line (EOL). At this stage, the pack must complete a full batch of tests to ensure proper functioning of every major pack subsystem (functional testing). These tests include simple pinout and continuity checks, confirming proper relay operation, testing functionality of safety devices such as high voltage interlocks, carefully measuring the isolation resistance under high potential (hi-pot testing), and testing proper communications and operation of the BMS.

After EOL functional testing is completed, packs may also be subjected to charge/discharge cycling and drive profile cycling, which will simulate the typical conditions the pack will see when integrated into the EV drivetrain. Packs can also be run through active cell balancing routines to set each cell's initial charge state to a nominal condition or set the Pack SoC to a level appropriate for shipping and storage.

EV BATTERY PACK TESTING SOLUTIONS

Once you have decided where you are testing and what you are testing, you need to determine how you will be testing. Since every battery pack design has unique elements, and since testing requirements vary accordingly based on agreements between the manufacturer and end user, in reality, there is no one-size-fits-all solution for everyone's battery pack testing needs.

Off-the-Shelf Testing Solutions

That being said, some portions of the testing, such as charge/discharge/drive cycle evaluation, are standardized. As such, pre-packaged, off-the-shelf hardware and software solutions exist for these particular test steps. These systems typically use only the positive and negative output terminals, as these are the only elements common to every battery pack. These turn-key systems may even allow you to add in options required to test components and functions specific to your battery pack, such as CAN communications, external relay activation, etc.

When considering off-the-shelf systems for use in your test plan, make sure to ask yourself these three basic questions:

1. Are you getting everything you need just the way you want it, or are you settling for what the other person needs?
2. Are you using everything you will pay for, or are you paying for things you won't use?
3. Is it flexible enough to accommodate your future needs but not so flexible that it becomes cumbersome to use?

Arguments for a Customized, Modular Test System Approach

Building a functional test system tailored to your battery pack and your specific testing needs often sounds like a more costly and time-consuming approach, and it can be. However, the route you take to achieve that end goal makes a world of difference in the outcome and in long-term ROI.

Choosing a modular hardware and software testing platform tailored to meet your requirements can be used to jump start this approach, making it a very viable option. This is especially true if the platform you choose leverages proven commercial technologies and open industry standards.

In the end, this modular platform-based testing approach can have several benefits:

1. It can dramatically lower the cost of the test system, both in initial capital expenditure and overall cost of ownership, through the use of commercial technologies and standards.
2. It can increase your test throughput with fast measurement hardware and software capable of managing multiple test routines in parallel.
3. The time required to adapt such test systems for new products will decrease through the use of flexible, modular software and hardware.

4. You can get exactly what you need, the way you want it. You can get everything you paid for and your test station will be flexible, without being cumbersome to use.
5. The system is tailored to your product and workflows, resulting in a simplified user experience, shorter learning curve, and corresponding personnel time savings.

A PLATFORM APPROACH

The preceding sections describe the challenging problem statement of thoroughly testing a complex, high power system like an EV battery packs and BMS.

It is highly desirable to achieve standardization, cohesion, and efficiency of testing throughout the EV component product cycle and during inevitable future product evolution. It is best to take a platform-based approach to address this testing challenge to achieve this. This means establishing a unified suite of test equipment built on common reusable building blocks (both hardware and software) and utilizing various configurations of this platform to cover testing of battery cells, modules, packs across various testing regimes (R&D, validation, HIL, production, and lifecycle tests).

This requires incorporating reliable software and hardware architectures and flexible and reliable subsystem components, which can be customized to specific use cases and changing requirements. Utilizing high-quality COTS (commercial off-the-shelf) hardware assembled from best-in-class instrumentation vendors typically improves system performance, reliability, and maintainability while significantly reducing the engineering effort involved in deploying the system.

CONCLUSION

Battery packs used in today's EVs are complex systems designed to provide safe and efficient electrical power. As such, a comprehensive testing strategy to evaluate possible safety and performance considerations is essential to the battery pack manufacturing process. However, testing requirements often vary from manufacturer to manufacturer and from one battery design to another, further complicating the testing process. Using a customized modular test system can be an efficient, cost-effective approach to conducting necessary battery pack testing in a manufacturing environment.

NASA Space Shuttle's Return to Flight:

The Untold Electromagnetic Backstory

How Applied Electromagnetics Guided the 22 Post-*Columbia* Shuttle Missions

BY BRIAN M. KENT

DEDICATION

With deepest respect, this article is dedicated to the extended families and friends of the astronauts lost on Columbia's *final Shuttle mission.*

On February 1, 2003, NASA's Space Shuttle Orbiter *Columbia* broke apart upon re-entry into the earth's atmosphere, tragically ending the lives of seven highly-trained and experienced astronauts. This accident not only personally affected the extended families of the astronauts, it permanently changed the trajectory of the U.S. manned space program. After a lengthy accident investigation and root cause analysis, the Shuttle successfully flew again on July 26, 2005. The Shuttle's subsequent 22 missions made possible the completion of the assembly of the International Space Station (ISS) and provided a final service call for the Hubble Space Telescope, before the Shuttle fleet was retired in 2011.

While much has been written about the Shuttle program, this specific article will focus on a very little-known element of the Shuttle's return-to-flight (RTF) story. Beginning with the *Columbia* investigation and ending with the creation and deployment of the NASA Ascent Debris Radar (NDR) System, this article will cover the "Electromagnetics (EM) Backstory" that was instrumental in allowing the Shuttle to safely fly again.

THE COLUMBIA ACCIDENT INVESTIGATION AND THE FLIGHT DAY 2 OBJECT: A BRIEF RECAP

On February 1, 2003, the nation witnessed in real time the disintegration of the Shuttle Orbiter *Columbia* as it attempted to re-enter the atmosphere after its 15-day mission. Within hours, the formal *Columbia* Accident Investigation Board (CAIB) began its work. Over the next several months, the CAIB gathered evidence to determine root cause of the accident, which included recovering and analyzing fallen debris articles from every state overflown by *Columbia's* final de-orbit trajectory.

Summarizing the CAIB's final [1] report, we quickly home in on the root cause sequence. During *Columbia's* ascent on

Dr. Brian M. Kent is an independent aerospace consultant with 43 years' experience in electromagnetic analysis and radar signature measurement technology. During his 37-year career as a US Air Force Career Civilian, Kent co-served the Technical Staff of the Columbia Accident Investigation Board (CAIB) from 2003 - 2009, and later served as a technical radar consultant for the Space Shuttle Requirements Change Board (PRCB). He is a Life Fellow of the IEEE and is the recipient of the Presidential Rank Award from the Secretary of the Air Force in 2009. Kent can be reached at brian.kent.phd@gmail.com.

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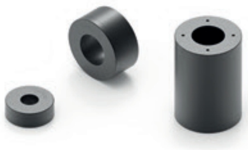

January 16, 2003, the left main tank bi-pod ramp insulation foam broke off the external tank about 81.9 seconds into the flight and struck *Columbia's* left wing (an image from a NASA launch camera is shown in Figure 1). Unbeknownst to NASA Mission Control or the astronauts on board, the strike damaged and left a hole in the reinforced carbon-carbon (RCC) leading edge around panel 8 of the left wing. The RCC is considered "hot structure" and the RCC protects the interior aluminum wing structure from the frictional heat of re-entry.

Note that Figure 1 is a highly enhanced image produced *after the accident*, and was *not available* during the actual mission. In addition, due to the positions of ground cameras and those available on orbit, there was not a clear line of sight to the damaged wing area. NASA material engineers estimating the physics of the kinetic impact suggested a possibility of RCC edge damage. Sadly, there was a lack of program-wide consensus that the wing RCC edge was compromised until the fatal re-entry day.

Through an exhaustive process, the CAIB was able to determine the RCC edge failure as the root cause through three independent investigative paths. First, Columbia's equivalent of a flight data recorder was recovered in the fallen debris. An analysis of the combined 600 plus temperature, pressure, and vibration sensors verified that the 2000° F re-entry plume entered the left wing at panel 8 and slowly melted the interior structure of the left wing. The wing eventually collapsed and the vehicle disintegrated. Second, the CAIB conducted a series of "air cannon impact tests" in June and July of 2003, wherein pieces of insulation foam were repeatedly fired at various angles and velocities to prove that the foam likely punched a hole in the RCC edge from the Figure 1 wing strike. [2,3]

The third and most circuitous path was the EM investigation into the mysterious so-called "flight day two" (FD2) object. During its second day in orbit, when the *Columbia* was flying in an upside down and backward direction relative to its orbital velocity vector, *Columbia* performed a slight yaw maneuver to calibrate an on-board navigation sensor, then re-maneuvered to return to its base orbit. Right after this maneuver, low frequency USAF space monitoring radars automatically detected the departure of a small debris piece from *Columbia*, as shown in the tracking radar data in Figure 2.

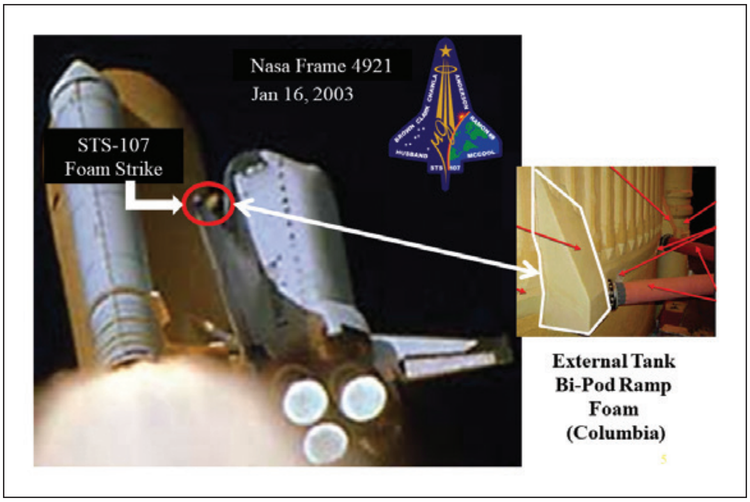

Figure 1: Bipod ramp foam striking *Columbia's* left wing during launch ascent on January 16, 2003

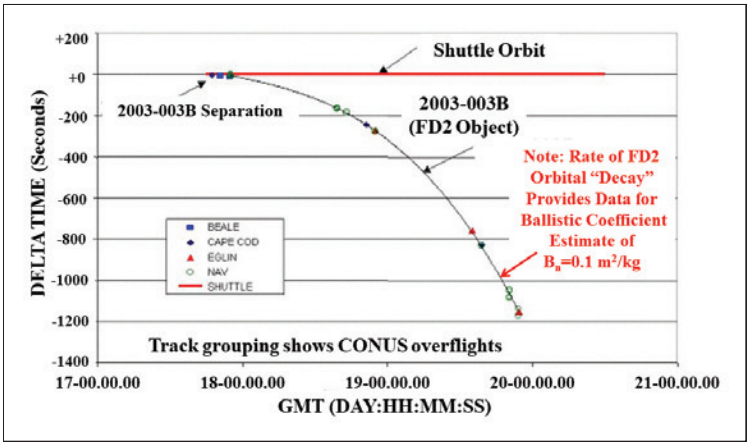

Figure 2: FD2 Radar track separating from *Columbia's* orbital path versus time [4]

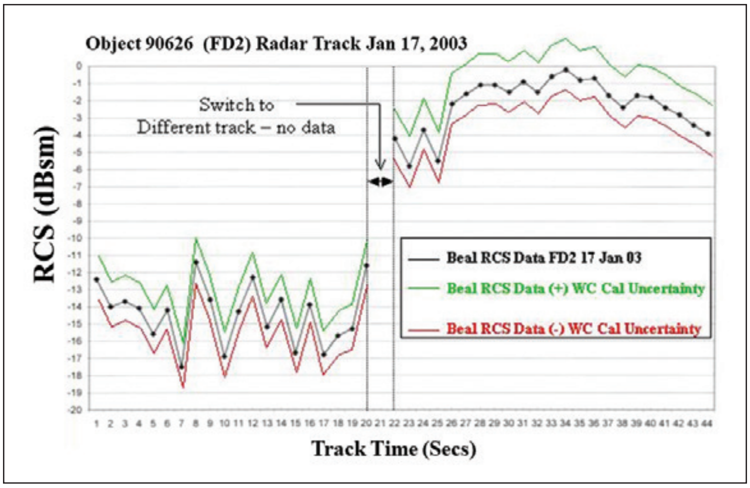

Figure 3: Maximum on-orbit measured RCS of FD2 object on 17 Jan 2003 tracked by Beal UHF Radar [3]

This object was tracked for three days, after which it disintegrated in the atmosphere due to aerodynamic drag. The object was reacquired on multiple days, and the radar data automatically recorded by the source radars. Unfortunately, this data was not known to NASA nor the Air Force until weeks after the accident. In fact, such data was not "knowable" in real time due to the automated nature of the space radar recorders.

As a radar signature expert, I must explain that every radar target has a property called "radar cross section" (RCS) that is a measure of how an object scatters radar energy in all directions. Generally RCS is denoted by the symbol σ, with SI units of m^2 or dB_{sm}. RCS generally varies with the frequency of the radar and 32the orientation of the target with respect to the radar. Since the FD2 object tumbled in space, ground radar sensors saw a varying RCS versus time.

After the CAIB investigation began, U.S. Air Force Space Command (AFSPC) analysts determined the aeronautical ballistic coefficient (B_n) from the shape of the ballistic re-entry profile in Figure 2. This meant NASA now had two pieces of technical information about the FD2 object: 1) the RCS at 433 MHz of the object varied between -1 and -20 dB_{sm} +/- 1.33 dB; and 2) its average ballistic coefficient, B_n = 0.1 m^2/kilogram +/- 15%. What we *didn't know* was FD2's *absolute* size as we did not have access to the actual FD2 object itself.

Nonetheless, Air Force Research Laboratory (AFRL) was contacted and I was assigned to investigate whether it was possible to narrow down the potential material candidate of the FD2 object to determine if the FD2 object was relevant to the CAIB investigation.

By February 12th, 2003, I was paired up with Steve Rickman of NASA-JSC, then Chief of the Thermal Design Branch. Rickman's organization was home to subject matter expertise and had responsibility for the Space Shuttle Orbiter Thermal Protection Subsystem (TPS), and the RCC Leading Edge Structural Subsystem (LESS). His team also was familiar with the Thermal Control System (TCS) materials present on the inside of the payload bay.

Rickman's team worked with our AFRL team to analyze 24 different potential Shuttle material candidates and provided AFRL with representative samples of all 24 materials. AFRL conducted subsequent RCS measurements in a laboratory called the Advanced Compact Range (ACR) which precisely measured the RCS of these material targets at 433 MHz (see Figure 4). The AFRL team quickly built up a database of possible material RCS characteristics, while NASA independently calculated the area to mass or B_n ratio values for these same materials. Our hope was to reduce the possible number of potential Shuttle material candidates.

To our team's collective astonishment, the *initial* RCS and B_n data analysis definitively eliminated 21 of the original 24 materials, leaving only *3* remaining Shuttle materials candidates.

During this on-going FD2 RCS analysis, NASA mission specialists mentioned that, in previous Shuttle flights, maintenance tools inadvertently left in the payload bay had floated away. To include the possibility that a lost maintenance tool could have floated out of the payload bay, the CAIB audited the tool record logs for *Columbia's* three previous pre-flight maintenance cycles. The CAIB found that only three tools (a screwdriver, a snap crimping tool, and a specialized fastener tool) were unaccounted for. This didn't mean the tools were necessarily on-board *Columbia*, but only that they were not accounted for in the ground maintenance logs. Nevertheless, AFRL obtained copies of these three tools, and performed RCS tests that definitively eliminated these tools from consideration as the FD2 object.

After compiling our test results, the AFRL-NASA FD2 team briefed the CAIB in private testimony on April 13, 2003, then publicly on May 6, 2003. This was weeks before the definitive July 7, 2003 Southwest Research Air Cannon test. [3] The remaining three material candidates included: 1) a fractured "acreage" piece (Figure 5) of the RCC edge segment of at least 90-140 in² originating from RCC panels 8, 9, or 10, panels which are thicker than the other 19 RCC edge sections and whose acreage pieces would be too light to meet the B_n test criteria; 2) an "RCC "tee seal" that fills the joints between wing edge segments had some initial test ambiguities and wasn't immediately eliminated; and 3) a large piece of Incoflex "ear muff" spanner beam insulator composed of a cerachrome alloy that was present between the RCC edge and the aluminum spar of the leading edge.

Within weeks of the May 6, 2003 CAIB briefing, AFRL executed a complex computational electro-magnetics (CEM) RCS analysis of all 26 Orbiter tee seal geometries (in whole or in fragments) and definitively showed through this analysis that the tee seal *could not be the FD2 object* (see Figure 6). Finally, subsequent forensic analysis of

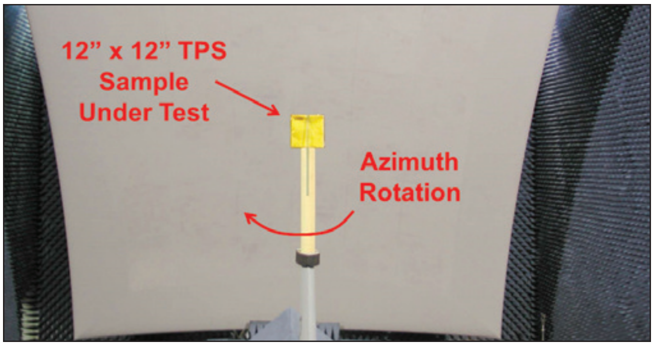

Figure 4: AFRL ACR facility for measuring RCS with 12" x 12" TPS sample shown mounted [3]

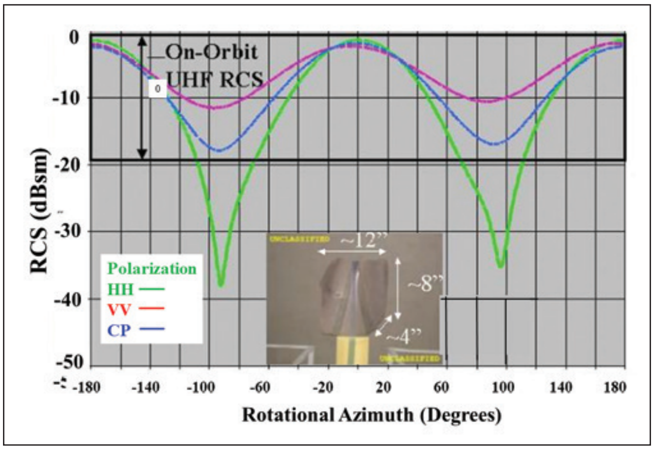

Figure 5: RCS of ~96 in² fractured panel 8 RCC edge acreage piece at 433 MHz vs Azimuth [3]

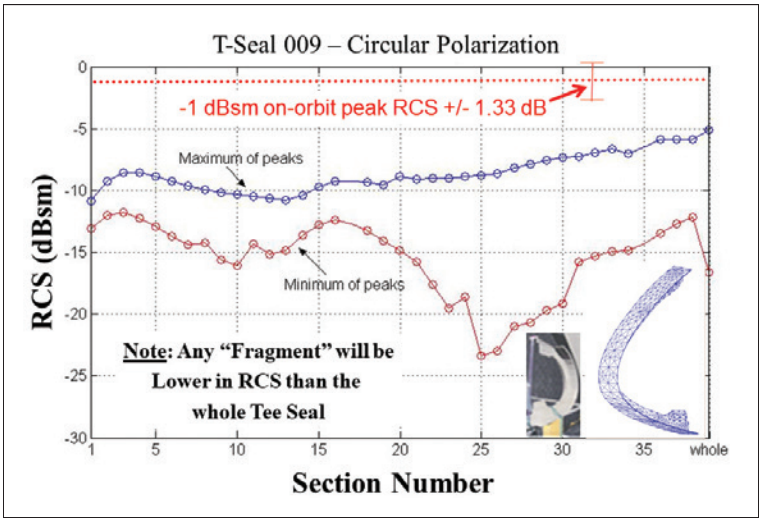

Figure 6: CEM analysis *eliminates* RCC tee seal as FD2 object as RCS *is too low* [5]


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fractured left wing edge debris pieces recovered from the multi-state debris field showed significant cerachrome alloy melted onto surrounding recovered edge fragments, so therefore the spanner-beam insulator was present during re-entry. This meant the *only material* that could meet all the criteria of the FD2 object was *a fractured piece of RCC edge originating from panel 8, 9, or 10 on the left wing of at least 90 in²* in area. *None* of the other 23 materials fit the combined exclusionary criteria of having the correct RCS, B_n, and also be forensically supported by other evidence. Hence, through careful EM analysis and high-quality RCS testing, AFRL provided critical EM data supporting the *Columbia* accident root cause, both of which were cited in the CAIB main report and technical Annexes. [1]

SHUTTLE RETURN-TO-FLIGHT – THE "WAR" ON ASCENT DEBRIS

Within a week of the CAIB report's publication, I was re-engaged through a phone call from NASA-JSC's Anthony D. Griffith. A long-time NASA space operations specialist, Griffith had been assigned the problem of detecting any undesired liberated debris from the Shuttle stack during the critical ascent stage. Griffith was a member of a much larger engineering team chartered by John Muratore, then Shuttle Chief Engineer, who had declared a "war" on future unintentional Shuttle ascent debris releases.

Muratore had three areas of emphasis; 1) study all previous historical Shuttle launches prior to *Columbia* to assess any and all previous debris releases and their potential sources, 2) re-examine the Shuttle stack design elements (Orbiter plus two booster rockets plus the entire external tank) from first principles with an emphasis to change designs that reduced debris events; and 3) put together a safety net of optical and radar sensors that closely monitored the Shuttle during the launch and ascent phases to definitively detect/capture debris releases. This information would promptly be provided to the Mission Control flight director on *any* perceived safety hazards due to liberated debris striking the Shuttle stack.

I assisted with the historical study of radar debris tracks and also provided technical assistance on the new debris radar sensors. By September of 2003, Griffith and I recruited a diverse team of EMI/EMC, radar and weather experts from NASA-JSC, the U.S. Navy (USN), MIT Lincoln Laboratory, Mission Research Corporation, and the Air Force. The radar team had two primary duties. We first worked to support Muratore's thrust of pouring over archived tracking radar from previous Shuttle flights prior to *Columbia*. In the process, we discovered both optical and radar records of debris separation events especially near, during, or shortly after solid rocket booster separation. Figure 7 shows legacy radar debris data from a low-resolution tracking radar at NASA-KSC. Since the radar resolution was ~+/-150 meters, this tracking radar didn't give insight into the debris environment, especially debris considered "normal."

However, the tracking radars consistently demonstrate that, during the solid rocket booster (SRB) separation period, the entire RCS of the Shuttle increased dramatically. The radar team was asked to figure out the physics of this RCS bloom phenomena. After studying the propulsive design, we speculated that the burned $AlCl_3O_{12}$ (aluminum perchlorate) solid rocket propellant present in the main boosters *and* the 16 small, quick-firing booster separation motors (BSM) were the cause. The

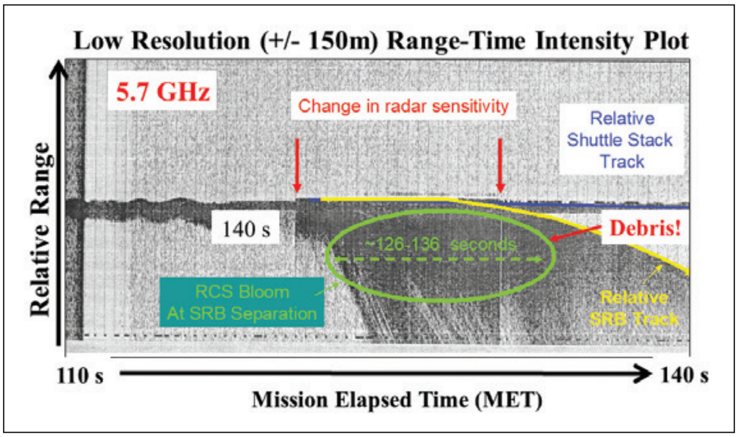

Figure 7: Low resolution USAF tracking radar ascent debris as recorded during a pre-Columbia mission

Figure 8: Shuttle ascent surrounded by Al_2O_3 smoke during BSM firing preceding booster separation

16 BSM boosters (four at both the top and the bottom of each booster), each kicked out 20,000 pounds of thrust for 0.8 seconds, which pushed the expended main boosters away from the Shuttle stack after the booster net propulsive force turned to net drag. The burned propellant residual was Al_2O_3, a highly reflective smoke residual, as shown in Figure 8. In addition, the Shuttle's two main booster rocket engines generated literally tons of both gaseous and liquid Al_2O_3 "slag" which left a wake in the airstream behind the whole Shuttle stack. But how could we prove this theory?

Working with the USN, NASA and AFRL devised a plume RCS test by firing a series of six individual BSM motors on a captive engine stand at China Lake while measuring the plume and debris signatures. Figure 9 shows the test set-up and Figure 10 shows a sample of dynamic plume data. Indeed, the smoke cloud filled with particulate Al_2O_3 acted like a giant radar chaff cloud for a few seconds. It also explained why it was going to be nearly impossible to transmit any radar energy directly up to and

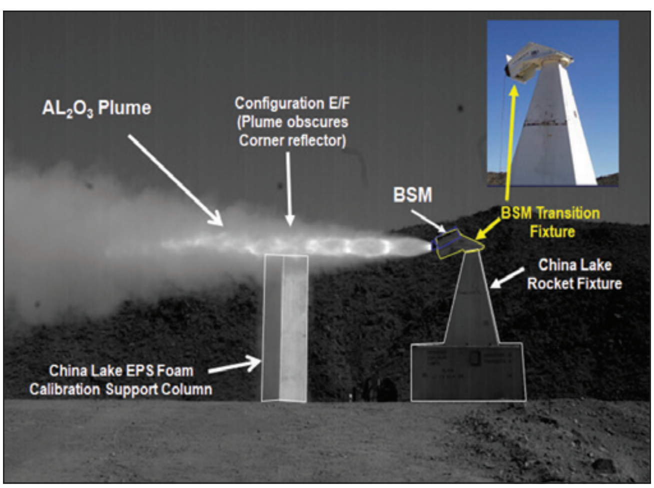

Figure 9: China Lake BSM plume RCS test 2004 [6]

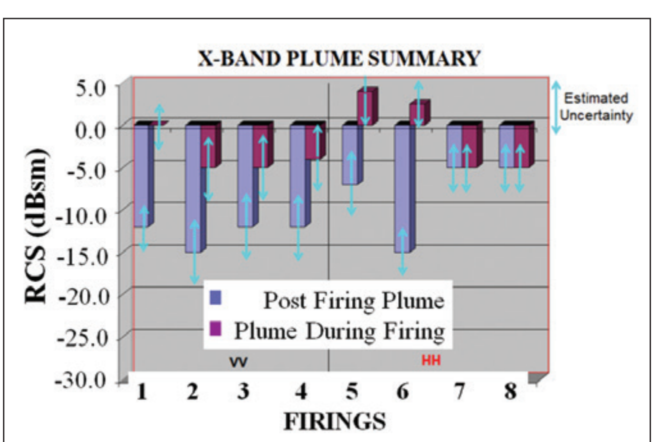

Figure 10: RCS peak for 1 BSM plume (5.4 GHz) [6]

through the rear end of the Shuttle Al_2O_3 plume during ascent to "detect" unwanted ascent debris events within the Shuttle stack.

Any potential NASA debris radar (NDR) sensor had to be sited to get a lateral side view of the ascending Shuttle, which ultimately eliminated all possible radar sites southwest of the Shuttle launch pads 39A and 39B, where all current USAF tracking radars were located. The NDR team needed a site to the northwest of the cape, potentially on the grounds of a U.S. Park Service National Wildlife Refuge. How was *that* going to happen?

SELECTING AND SITING THE NASA DEBRIS RADAR (NDR) SYSTEM

After obtaining the critical plume RCS data, the NDR team briefed NASA on April 4th, 2004. The team recommended that NASA acquire and employ a combination of a DoD C-band (5.45-5.95 GHz) high resolution imaging radar combined with upgraded commercial versions of an X-band (10 GHz) high resolution Doppler radar. Although NASA concurrently planned significant visual camera enhancements, radar sensors were absolutely necessary because the remaining Shuttle launch manifest included several night launches where the cameras would have highly degraded performance.

The technology recommended by the radar team was already deployed on USN ship platforms for monitoring western pacific test launches of mobile ICBMs. Furthermore, the USN had recently decided to relocate a $50 million C-band radar from Puerto Rico and were looking for a replacement site in Bermuda or Florida. The USN also supplied technical contacts in Denmark for a Weibel high resolution Doppler radar that worked in the velocity range needed during Shuttle ascent.

The USN's Charlie McSorley, Mike Hardman, and Marty Stuble jointly spearheaded efforts between the Navy and NASA to get the C-band radar moved. Ultimately, NASA executed a joint agreement with the USN to relocate the C-band radar near Kennedy Space Center. Recall that our plume RCS results required us to site the USN C-band radar for a lateral launch view. Since all big projects need at least some luck, the NDR team finally got a break. We found a small fenced-off 0.5-acre plot on Merritt Island sited to the NNW of Pad 39A. This plot formerly sited a thunderstorm research radar for the National Center for Atmospheric Research (NCAR). The NCAR radar was long gone, but the perimeter fenced land

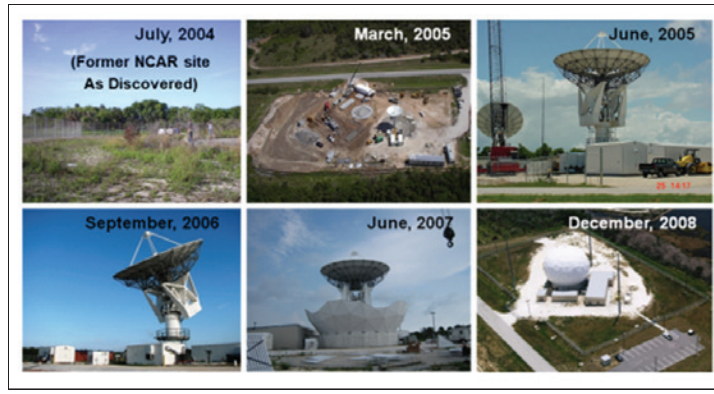

Figure 11: NDR site July 2004-December 2008

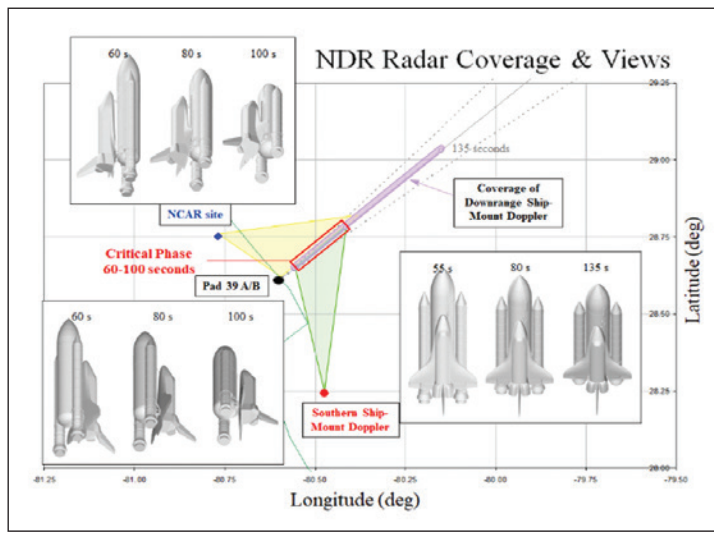

Figure 12: Combined NDR radar coverage from NCAR radar site plus 2 ships with Doppler sensors

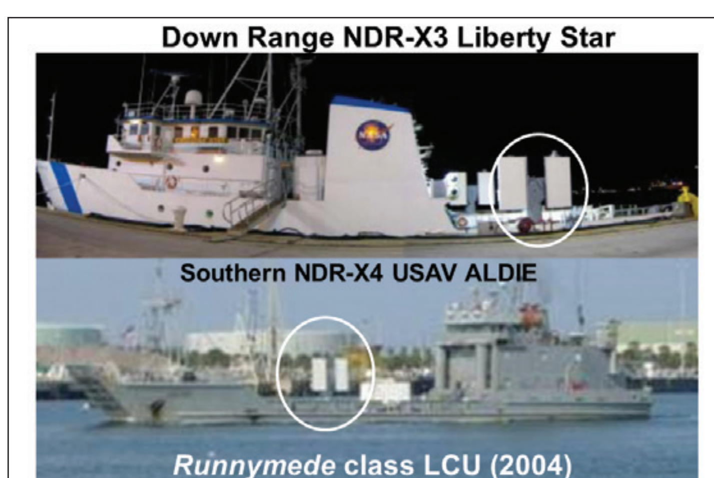

Figure 13: Sea-based NDR Weibel Doppler radars

Figure 14: Debris samples under ACR RCS testing

still belonged to NCAR even though it was now on a National Wildlife Reserve. NASA and NCAR quietly and efficiently transferred the property to NASA on permanent loan, and NDR had its radar site!

The photo sequence in Figure 11 shows the original 2004 NCAR site and its transformation to its present form. Figure 12 shows the combined "field of view" of the ascending Shuttle as seen from the fixed C-band NCAR site plus the two, ship-deployed X-band Doppler radar sites. Figure 13 shows the two Dutch-made Weibel Doppler radars deployed downrange on the NASA SRB recovery vessel *Liberty Star* and on a U.S. Marine Runnymede class LCU.

CHARACTERIZING TYPICAL ASCENT DEBRIS RCS AND BALLISTIC PROPERTIES

With the type and locations of the NDR radars fixed, AFRL, NASA and the USN now collaborated to create a massive theoretical and empirical database of typical Shuttle debris pieces based again on RCS and B_n coefficients. NASA's debris team had identified hundreds of legacy debris sources from previous Shuttle flights. These debris materials could have originated anywhere on the Shuttle stack or from the Shuttle solid rocket propulsion subsystems. A lengthy list of items was created, and NASA decided to return to AFRL's compact range to conduct RCS measurements at C and X band for every debris candidate.

Meanwhile, NASA-JSC created a database of matching ballistic coefficient, B_n, for each candidate. This involved hundreds of RCS measurements of everything from various pieces of tank foam, cork insulation, space-qualified RTV sealant and so forth.

Each sample was measured from 2-18 GHz, 360° in azimuth, and for three X-Y-Z orientations. The observable signatures were medianized over observable tumbling angles (like liberated debris in free stream air) and their corresponding B_n numbers included. Figure 14 shows a small sample of materials whose RCS was characterized in the ACR.

After compiling data on hundreds of sample combinations, yet another "realism" test was executed. The US Navy loaded up about one-third of the heavier samples, and ejected them from a C-130 Hercules at 10,000-foot altitude. The debris pieces were tracked and RCS characterized with Doppler instrumentation radars out of Patuxent River, MD. Figure 15 on page 76 shows 4 samples whose dynamic tumbling signatures were measured. This also help correlate the B_n analysis for each sample.

At the conclusion of these RCS tests, we had a very good feel for the combined RCS and B_n for nearly every Shuttle material. What we didn't know was whether the NDR system radars, which operated at fairly high powers, would interfere with the operational Shuttle systems during launch and ascent. It was a safety concern that NASA demanded be addressed before return to flight.

THE *DISCOVERY* EMI/EMC SAFETY OF FLIGHT TEST

Historically, basic NASA range tracking radars operated on every Shuttle launch. Conventional USAF range safety radars have been in existence for over 35 years and typically operate in C-band at two specific frequencies, 5.69 GHz and 5.8 GHz. NASA needed to better understand the behavior of the radar signatures from debris shedding off the Shuttle during the ascent phase in order to monitor potentially dangerous debris shedding events.

After the acquisition of the NDR system was approved, Shuttle EMI engineers realized these three new monitoring radars would emit frequencies to which the Shuttle had not been exposed during previous launch and ascent operations. The new "debris" radars were to operate in two specific frequency bands, with the C-band radar emitting an FM sweep continuously from 5.45 GHz to 5.95 GHz, and the new X-band "Weibel" Doppler radars tunable to any fixed frequency between 10.0 GHz to 10.55 GHz. Clearly, it became imperative to verify that the new C-band and X-band debris radars would not interfere with any existing Shuttle system during the ascent phase. Since the aft bay of the Shuttle houses the critical Space Shuttle Main Engine (SSME) controllers, NASA was particularly concerned about RF exposure of sensitive equipment inside the aft bay to exterior radar RF levels from outside the aft bay. Fundamental knowledge of the RF shielding characteristics was required before *Discovery* could be certified for safe flight.

The purpose of the EMI test was to provide NASA an accurate estimate of the RF attenuation at specific radar frequencies of the Orbiter Aft engine bay, including an estimate of measurement uncertainty. The measurements had to be performed while the Shuttle was contained in a hangar-like facility called the orbiter processing facility (OPF). The relative geometry of the Shuttle and the OPF high-bay (HB) 3-door area along with the test receiver is shown in Figure 16. (Note the Shuttle *Discovery* was located *inside* OPF 3, and the hanger doors were opened so that the RF attenuation measurements could be made *outside*.)

During the test, the target was static with all normal work stands in place. The translator platforms behind the

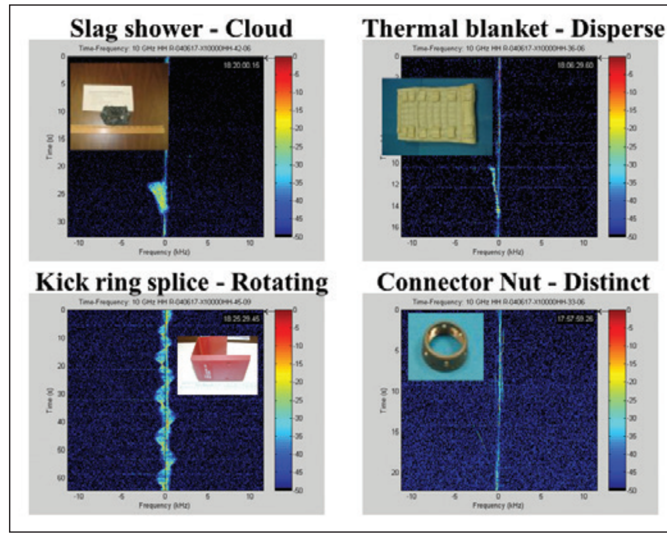

Figure 15: USN C-130 dynamic debris data samples

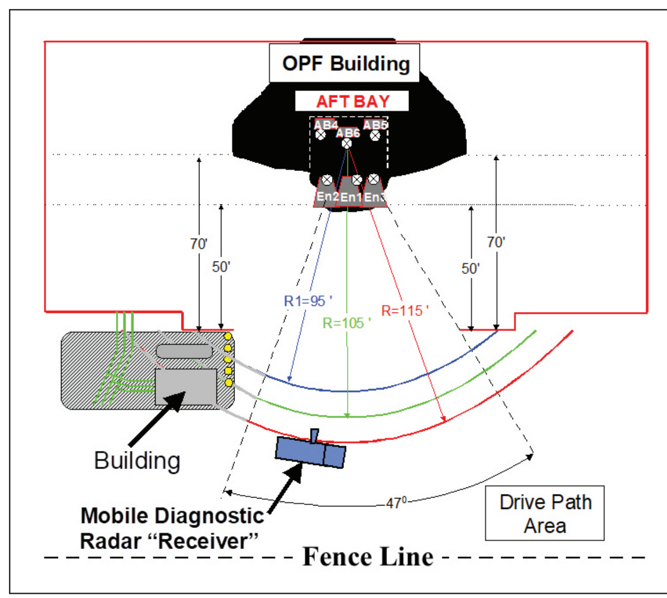

Figure 16: Orbiter *Discovery* RF attenuation measurement diagram.

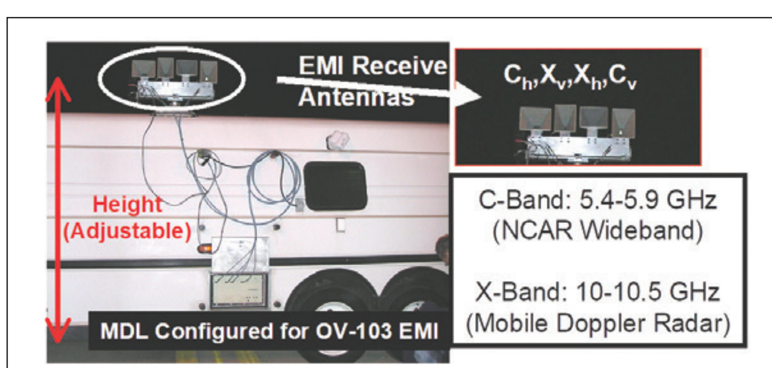

Figure 17: Side of MDL showing receive EMI antennas with a pneumatic mast height adjustment

aft section of the Shuttle were moved completely to the side to avoid line-of-site blockage between the aft bay and the receiver. In order to achieve the test objectives, the Orbiter was placed in as near-flight condition as possible to simulate ascent attenuation characteristics. Three semicircular drive paths represent a constant mean range between the Orbiter aft bay centroid and the receive antennas during the RF attenuation tests. Attenuation data was obtained for three separate ranges (95, 105, 115 ft) and multiple receive antenna heights (10, 15, 20 and 25 ft). The Cross-X's in Figure 16 represent six Vivaldi broadband antennas inserted inside the aft bay, three by the rear avionics bay wall and one next to each of the Shuttle's main engine computers.

The orbiter *Discovery* was in preparation to launch around mid-July 2005. To assure this RF attenuation measurement data was flight representative, AFRL needed the Orbiter in the closest possible state to flight. It was essential that the AFRL MDL EMI/EMC test did not impact *Discovery's* flight schedule. For this reason, we came up with a reasonable test configuration that minimally impacted the Orbiter schedule. Since EM reciprocity allows one to interchange source and receive antennas in a one-way RF measurement, we decided to place the RF radiators *inside* the Aft engine bay, then measure the RF leakage with a passive receiver positioned *outside* the vehicle. Since the aft engine bay is physically large, the test team decided to place six, dual-polarized radiating antenna elements inside the aft bay, all connected together with a commercial off-the-shelf (COTS) RF feed network.

To receive the energy, AFRL positioned their mobile diagnostic laboratory (MDL) [7,8] in a receive-only mode as indicated earlier. To help reduce unintentional local electromagnetic interference (EMI) during the RF attenuation measurements, we used the existing MDL radar as the exciter, running a long, fixed cable between the transmitter and the aft bay emitters. During a typical RF attenuation measurement, the MDL was driven along a fixed radius circle relative to a point in the center of the aft bay. The receiver was triggered at regular intervals along the radius, and measurements were performed for all radar bands and polarizations, three ranges and four antenna heights. C-band data was acquired from 5.45-5.95 GHz, while X-band Data was acquired from 10.0-10.5 GHz. Figure 17 shows the MDL receive antennas on the side of the MDL.

The MDL drove along the three drive paths for each antenna height. Figure 19 shows the network used, while Figure 20 shows one of the six interior dual-polarized exciters used. AFRL performed pre-test and post-test network analyzer measurements with MDL pointed at the *Discovery* during one of its drive paths. AFRL performed pre-test and post-test network analyzer measurements

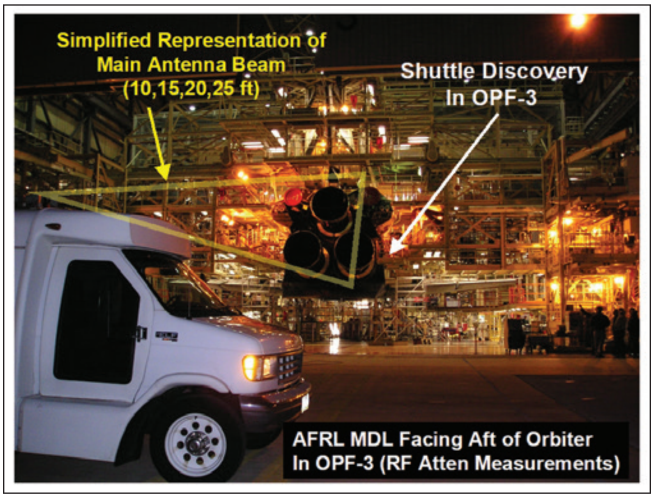

Figure 18: MDL at *Discovery's* EMI test Jan 17 2005

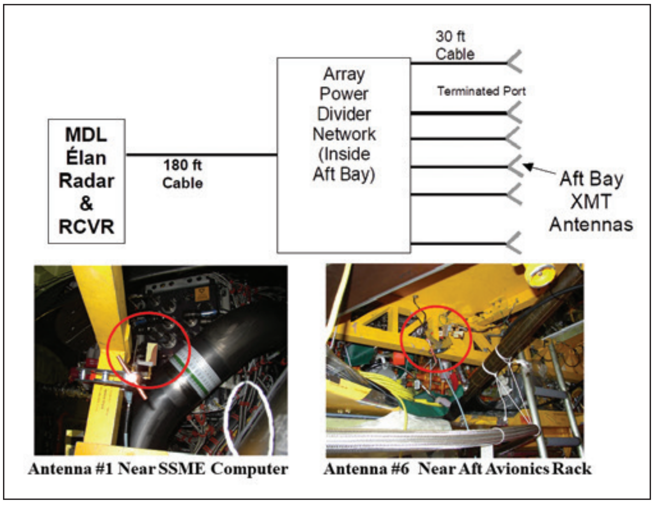

Figure 19: RF network used in *Discovery* EMI test

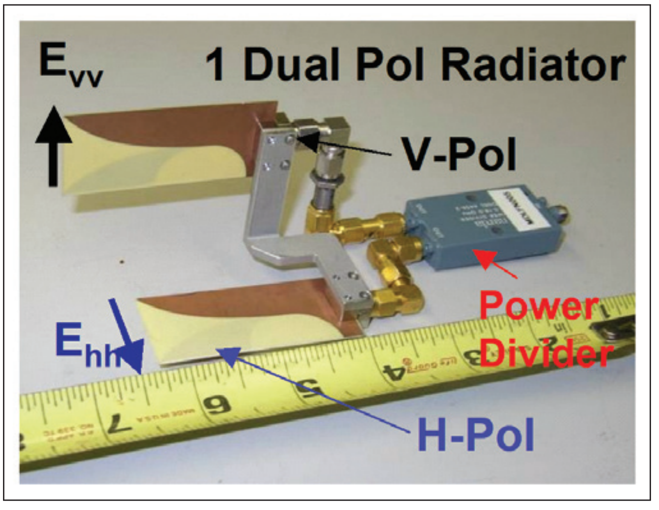

Figure 20: EMI dual-polarization exciter antennas

to assure the RF network didn't change during the test. We also characterized every one of the six distinct RF pathways through the network.

The entire data acquisition was completed in 4.5 hours, and the overall aft bay modification/de-modification for this test was completed in one 16-hour shift. NASA's Robert Scully co-analyzed the EMI/EMC test data and ultimately certified the results to the Shuttle PRCB, which adopted his recommendations.

In the end, the aft bay EMI attenuation experiment was successful, and the corresponding C-band attenuation data is shown in Figure 21. This attenuation data was combined with a NASA susceptibility analysis. NASA determined that neither the NDR C-band or X-band radar waveforms would create any EMI/EMC disruption of critical Shuttle systems during ascent.

EM SIMULATION BEFORE *DISCOVERY* RETURN-TO-FLIGHT

With the overall NDR system under construction and sited, it was clear the large 50 ft diameter C-band mid-course radar (MCR) would not be ready by *Discovery's* first flight in July 2005. Fortunately, the USN had a similar ship-based radar system called the Navy missile imaging system (NMIS) which operated over the same frequency band but at slightly lower radiated power. The USN had the NMIS system temporarily installed at the NCAR site side-by-side with the larger MCR under construction, providing an operational NDR system from the very first return to flight mission.

However, in order to train the radar operators, NASA needed a true C-band radar simulation of the Shuttle fly-out. This meant calculating the scattered field and RCS of the entire Shuttle stack, properly oriented in space and time relative to the NCAR site. The model had to include the period before SRB staging, SRB staging, and after SRB staging.

AFRL was again called to help, and through the technical leadership of Drs. Kueichien Hill and Tri Van, a viable solution was found. First, Hill and Van created an extremely detailed geometric grid of the entire Shuttle stack. NASA then provided three precise Shuttle-to-ISS fly-out launch trajectories over the five-minute launch window. The geometric grid was then coded into a physical optics-ray tracing RCS code called "X-Patch" and run on the U.S. Army's best (2005 era) supercomputer.

The Shuttle geometry had over 1.2 million facets. The RCS was calculated at 2048 frequencies, from 5.45-5.95 GHz, for every 1/3rd of a second, and for 302 seconds of mission elapsed time (MET). Given the three trajectories, the overall run-time was over two months of CPU time! The representation of the geometry is shown in Figure 22, and the constructed range-time intensity (RTI) data provided from X-patch is shown in Figure 23.

If NASA understood what basic scattering structure *should be* in the Shuttle radar returns, undesired departing debris

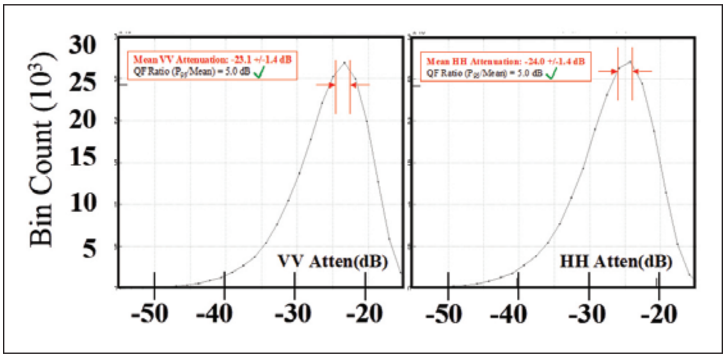

Figure 21: C-band VV/HH aft bay attenuation

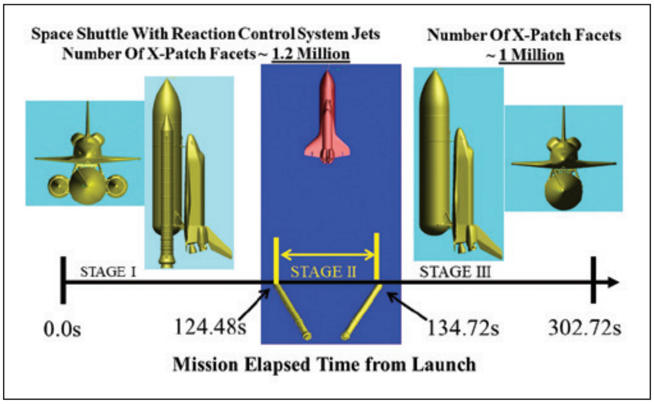

Figure 22: X-Patch geometry used for predicting C-band NDR radar fly-out range-time-intensity (RTI)

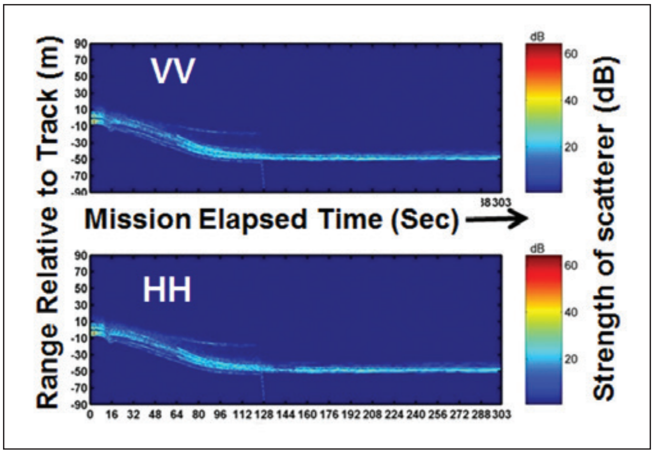

Figure 23: Supercomputer RTI calculations for one of *Discovery's* possible launch trajectories.

separating from the *real* RTI plots generated by the radar would be very visible. Although the RCS simulations were calculated every 1/3rd of a second, the real NDR created RTIs at a rate of 160 times a second, making ascent debris much easier to spot as it departed the Shuttle stack. Figure 23's predicted RTI data nearly overlaid measured RTI data from the Shuttle stack structural scattering. For validation purposes, Figure 24 shows a later comparison at MET = 165 seconds (post staging of SRB's) of the AFRL predicted (far left and far right) and actual RTI data from two Shuttle flights. (Note the vehicle is nearly 300 nautical miles downrange at this point!) While the plume was not modelled, these calculations provided crucial insight into the Shuttle stack scattering under the orbiter, well ahead of the plume.

PRACTICE MAKES PERFECT

With the NDR infrastructure constructed and staffed, and Discovery's July 2005 mission approaching, NASA wanted the NDR to simulate and practice their mission operations. Fortunately, there were several unmanned space launches out of the Kennedy Complex, and the NDR team "shadowed" several launches to learn real-time and post launch debris identification and reporting processes.

The most notable mission was the August 3, 2004 launch of a Delta-2 rocket carrying the NASA Mercury *Messenger* deep space probe. The Delta 2 was a great target to watch because it had nine strap-on solid rocket motor (SRM) boosters that used the same aluminum perchlorate propellant as the Shuttle SRBs. In addition, six of these boosters lit at lift off, burned for 60 seconds and were then ejected. The remaining three boosters then lit off, burned for another 60 seconds and were also ejected. In short, Delta-2 rockets generate lots of "normal debris" during a typical successful launch.

Figure 25 shows visual images of a daytime (not-Messenger) Delta 2 launch from an onboard and off-board camera, showing the moment of 3 air-ignited SRM's separating from the Delta 2 at MET = ~120 seconds. The *Messenger* launch was at 2:00 am, so we had no such visual camera support, making the *Messenger* mission a perfect night launch dress rehearsal. The mission was successfully conducted, and the combined RTI and Doppler data processed overnight with clear and stunning results. During the period of six ground-lit SRM's separating from MET 88-98 seconds, we saw very dim and low-level debris events, including particulate Al_2O_3 "slag" ejecting from the tumbling but spent SRM booster rockets. [10]

This mission was so crucial to RTF that the NDR team got an unexpected visit from the seven astronauts of the STS-114 crew the following afternoon after the Delta-2 mission. Based on this success and several other unmanned launches prior to July 2005, the NDR was approved for use on the very first RTF mission, STS-114 *Discovery*.

STS-114 RETURN TO FLIGHT AND NASA'S FINAL TRIAD OF DEBRIS DETECTION

As the NDR awaited the first Shuttle launch, NASA was exercising for the first time a completely new 3-tiered debris safety protocol for STS-114 and all Shuttle launches to follow. First, during the launch and ascent phase, the NDR radar system and upgraded ground camera systems would monitor the Shuttle stack for launch debris. The most critical periods of the launch were near 62 seconds

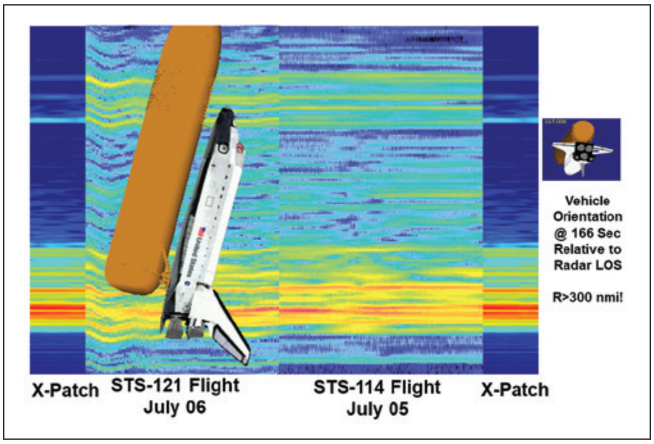

Figure 24: Comparing AFRL Xpatch and actual flight RTI data at 165 seconds mission elapse time

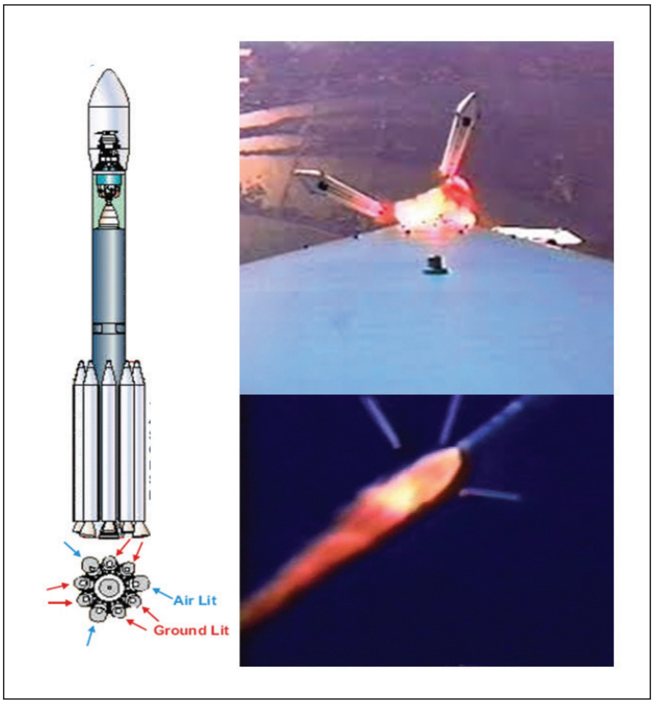

Figure 25: Air-lit SRM Separation from a typical Delta-2 Mission (Courtesy Space.com) [11]

The Shuttle ultimately completed the International Space Station (ISS) and was retired in 2011. As long as the ISS remains in operational service, NASA can proudly point to its completion in the Shuttle's storied legacy.

when the vehicle breaks the speed of sound, and at about 120 seconds when the two SRB boosters are separated. After 300 seconds, the vehicle is largely out of the atmosphere, so debris releases were of much lesser concern.

The powered flight mission lasts about 8.6 minutes, after which the NDR ground radar teams and photo teams go to work, pouring over all data to detect ascent debris events. NASA's debris teams were especially concerned about any liberated debris that had a secondary collision with the orbiter itself. Radar could see such "ricochet" events as debris tracks that suddenly changed trajectory. In addition, we had installed trajectory overlay software that allowed a 3-dimensional Shuttle to be overlaid with range-time-intensity radar plots, as shown previously in Figure 24. The radar and photo teams had precisely 24 hours to report their findings to Mission Control in Houston.

In the meantime, once in orbit, the Shuttle deployed a second-tier inspection tool on the end of the payload bay boom to self-inspect its entire thermal protection system. Any inspection results would be correlated with the debris events recorded by the combined radar and optical debris teams. Lastly, as the Space Shuttle approached the ISS, the third tier required the Orbiter to perform a full pirouette tumble maneuver before docking, allowing ISS astronauts to photograph the entire Shuttle surface area at close range. This photographic data was also downloaded to a dedicated damage assessment team comprised of subject matter experts who assessed the health of the TPS to determine its adequacy for safe Shuttle re-entry.

At the conclusion of mission, and normally after undocking with the ISS, the Shuttle would again deploy their tier 2 inspection tool in orbit to assure themselves that the TPS system had not be struck by *orbital debris* during its time on orbit. If all systems showed no damage, the Shuttle would reenter the atmosphere and land. Of course, in the event anything was damaged beyond the ability to repair on orbit, The Shuttle would simply re-dock with the ISS and await a second Shuttle for the ride back to earth.

July 26, 2005 dawned warm and clear at the NCAR sight of the NDR radar system. Nearly a dozen radar technicians and data processing experts were awaiting the launch of *Discovery* at 10:49 EDT. The launch window was a very narrow 5 minutes long. The launch occurred right on time, and the NDR acquired the Shuttle shortly after it cleared the launch tower. We had excellent tracks for both the C and X band NDR radars, and data was acquired without a hitch.

Then the bedlam of data analysis started. To speed things up, we parsed the mission radar data with parallel teams working 20 second segments of the flight from launch to 450 seconds. The optical teams, working independently at first, were doing the same with nearly 50+ optical HD movie cameras. Our debris event report was due to Mission Control leadership within 24 hours of launch, and the clock was running!

Almost immediately, we got our first challenging debris release. The external tank for the STS-114 return to flight system had been modified to remove much of the foam pieces that had a history of liberation in previous flights. But the first completely new tank design would not be delivered to NASA for three more flights, so everyone expected some foam debris events. One foam release was detected by the on-board external tank camera (inset of Figure 26) which raised immediate concerns. It was

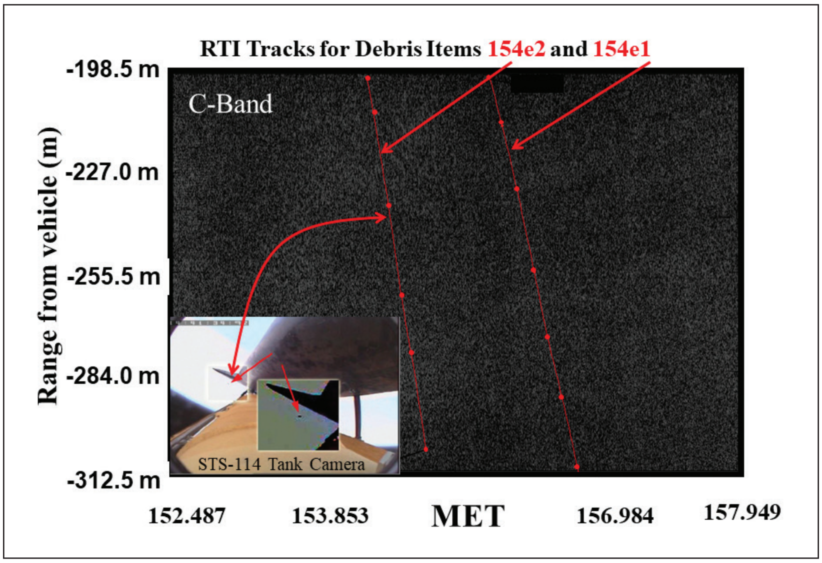

Figure 26: Radar and optical tracks of STS-114 PAL ramp foam debris liberation at MET=154 s

a very small piece of foam debris, a tiny fraction of the size of *Columbia's* bipod ramp foam release. The camera clearly saw it depart and fly between the orbiter and tank, striking nothing. Despite its small size and very small corresponding RCS, the NDR not only detected this piece, but another smaller foam release the camera could not see. On its very first operational mission, the NDR proved that it could accomplish the debris detection and identification of material based on a combination of RCS, the location of the release, and its ballistic properties, B_n. So the ID strategy that effectively worked in the *Columbia* FD2 object investigation worked for Return to Flight ascent debris.

EPILOGUE – THE NDR'S 22 SHUTTLE MISSIONS

As I worked on the NDR console for the first four RTF missions, NDR evolved operationally. The downrange and in-range ship based Doppler radars, combined with the NCAR C-band site, now gave NASA a nearly 360° view of the Shuttle during launches. STS-117 (the fifth RTF mission) flew the first redesigned external tank. AFRL's Christopher Thomas and USN's Hardman and Stuble led mission debris analysis efforts and ultimately created automated software (later patented) which catalogued even harmless and miniscule debris events. Over time, NDR sensors revealed Shuttle's "war on ascent debris" had been won. The number and size of liberated particles went down dramatically during the critical first 300 seconds of powered flight. Fewer and fewer external tiles required repair after missions. NASA never wavered from their new safety protocol, and the 3-tiered ascent debris inspection protocol was used for the rest of the remaining Shuttle flights.

The Shuttle ultimately completed the ISS and was retired in 2011. As long as the ISS remains in operational service, NASA can proudly point to its completion in the Shuttle's storied legacy. In the end, NASA recognized those responsible for the myriad of EM analysis, EMI/EMC, and RCS measurements whose backstory played a huge but unseen role in Shuttle's return to flight.

ACKNOWLEDGEMENTS

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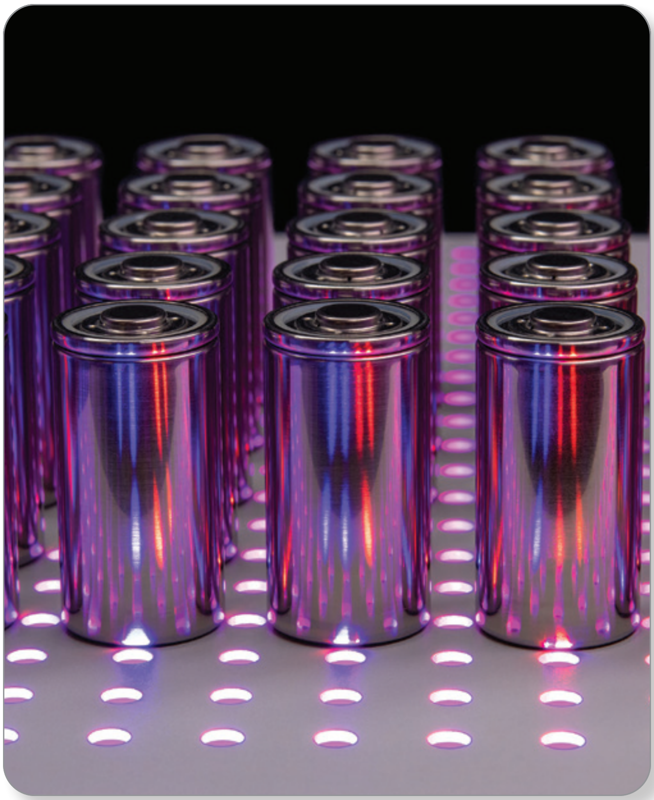
Energy Release Quantification for Li-Ion Battery Failures



Evaluation and Testing Can Reduce Battery-Related Safety Risks

BY FRANCESCO COLELLA, SERGIO MENDOZA, MICHAEL BARRY, ARTYOM KOSSOLAPOV, RYAN SPRAY, AND TIMOTHY MYERS

This article presents an experimental framework to characterize the energy released during thermal runaway events involving Li-ion cells and battery packs used in applications ranging from electric vehicles to consumer electronics and medical devices to aerospace applications. A brief introduction to lithium-ion batteries and battery thermal runaway is provided. The article then describes various methods for obtaining energy release in cells undergoing thermal runaway.

The first method involves testing a cell inside a sealed pressure vessel, which allows for the estimation of the volume of gas produced as a result of thermal runaway and a quantitative assessment of the vent gas composition. This technique is generally used to assess the flammability hazards associated with thermal runaway. The second method described is oxygen consumption calorimetry. This technique provides an estimation of the heat released by a cell undergoing thermal runaway via chemical analysis (i.e., how much oxygen has been consumed and the associated heat release).

The third and fourth methods include two techniques designed to estimate the energy yielded during a battery thermal runaway event: the accelerating rate calorimetry (ARC) and a novel methodology designed to estimate the sensible energy released during a battery thermal runaway failure using a fractional thermal runaway calorimeter (FTRC) apparatus.

THE GROWING RISK OF LI-ION BATTERY FAILURES

Over the last ten years, lithium-ion (Li-ion) batteries have become the energy storage technology of choice for different industries, including automotive, consumer electronics, and aerospace applications. As Li-ion battery chemistries improve, battery energy and power densities have increased. Increasing energy densities, including implementation of lithium-metal-containing cells, result in higher potential risks and/or severity of battery failure events. The increased risk stems from both the presence of higher amounts of energy and thinner, tighter tolerances of internal components.

Francesco Colella is a Senior Managing Engineer in Exponent's Thermal Sciences practice and can be reached at fcolella@exponent.com.

Sergio Mendoza specializes in battery model-based control, estimation, information theory, and experiment design.

Michael Barry specializes in assessing mechanical and thermal failures in a wide range of products and systems.

Artyom Kossolapov has expertise in heat transfer, fluid mechanics, multiphase flow, and thermal hydraulics of nuclear reactors.

Ryan Spray is a Principal Scientist in Exponent's Polymer Science & Materials Chemistry practice.

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One catastrophic failure mechanism that can lead to battery fires is a thermal runaway event. In large, multi-cell packs such as those commonly used in electric vehicles or stationary energy storage systems, the heat generated by one failed cell can heat up neighboring cells which may lead to a thermal cascade throughout the battery pack. It is generally expected that there will occasionally be single cell failures within a population of lithium-ion battery packs. This potential for propagation of failures presents an increased risk to property and safety.

Underwriters Laboratories (UL) recently created a new test method (UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems) that specifically seeks to assess the propensity of energy storage systems to exhibit propagating failures. One reason for the concern over the propagation of failures is that thermal runaway events can result in the venting of flammable gases, and these gases can generate a fire or an overpressure event if ignited in a confined area. Multiple failures occurring due to propagation will subsequently release a larger volume of flammable gases.

An accurate evaluation of the energy yielded during a battery thermal runaway failure is of critical importance for the design of any battery-powered product from both safety and performance standpoints. Accurate energy yield estimates are valuable for a large variety of tasks, including but not limited to:

- Comparisons of failure characteristics of batteries from different formats and vendors;
- Evaluation of the ultimate fate of the energy released (i.e., is the heat released contained within the vented gases or in the cell body);
- Design of safer battery packs that minimize the likelihood of cascading failure events involving neighboring cells; and
- Create reliable inputs for mechanical or thermal models of devices or battery packs.

The energy released during a battery thermal runaway failure can roughly be assessed by evaluating the sensible energy and chemical energy components that evolved during the event. The sensible energy components can be evaluated by estimating the amount of energy required to increase the temperature of the cell body, gases, and ejecta to the levels experienced during a thermal runaway failure (prior to any combustion event occurring). The chemical energy component can be assessed by estimating the energy released by the combustion of the vent gases following their release from the cell body during the thermal runaway event. The characterization of the combustion energy requires a characterization of the composition and amounts of vent gases released during the failure event.

The following sections provide an overview of a battery thermal runaway failure as well as a number of techniques that can be used to characterize the energy yielded during a battery failure and its components.

BATTERY THERMAL RUNAWAY

Thermal runaway occurs when the internal temperature of a cell increases in an uncontrolled manner, leading to its failure. In the first phase of thermal runaway, the solid electrode interface (SEI) layer decomposes in an exothermic reaction. This is followed by an exothermic reaction between the intercalated Li ions and the electrolyte. As the positive electrode materials react with the electrolyte, oxygen is evolved inside the cell, the electrolyte decomposes, and the cell disintegrates. During the thermal degradation of the Li-ion cell, the temperature increase generates gases, which are released through pressure relief vents when the pressure inside the cell rises above a design relief pressure or if the cell's enclosure fails. For Li-ion cells, these gases are hot and combustible, which can become a hazard if a pack was not designed to control the causes and consequences of thermal runaway.

All thermal runaway events are a result of a rise in cell temperature. This temperature rise can be due to multiple causes, including but not limited to:

- External heating from a high ambient temperature, thermal abuse, or external fire;
- A defect inside the cell that results in an internal short circuit, which causes the cell to heat up at the location of the defect;
- A surge in the charging or discharging current. When cells are charged or discharged, heat is generated. The higher the current, the higher the heat generation;
- An improper electrical connection at the tab of a battery. This causes an increased electrical resistance which generates heat at the electrical contacts;
- Mechanical damage to the cell or battery that can also lead to internal shorts and result in heat generation.

During a thermal runaway event, the cell produces gases that build up within the cell. Some cell designs (e.g., cylindrical cells) include one or more designed vents that open to release the gases. In some cases, these vents can become obstructed or may not be able to adequately vent gases, which may result in rupture of the cell enclosure. Other cell form factors, such as pouch cells, often do not include a specific vent and the gases will release at weak points in the external pouch, typically near the tabs of the cell or along the pouch seams in unconstrained cells.

SEALED VESSEL TESTING

Vent gas composition, flammability characteristics, and potential combustion energy released in the event of ignition can be evaluated by forcing a cell failure in a sealed vessel testing apparatus. The sealed vessel is designed to contain the battery vent gases and to quantify the vent gas volume by tracking the temperature and pressure increase in the vessel. The sealed vessel testing apparatus includes a sampling port through which the vented gases can be collected in a sample canister and analyzed for composition using techniques such as gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS). Note that depending on the cell capacity, different sealed vessel sizes need to be used depending on the expected vented gas volume. Figure 1 shows a photograph of a 60-liter sealed vessel connected to a 20-liter combustion chamber used for battery vent gas explosion testing.

We previously produced a paper outlining the methodology for this type of testing [3]. The results presented were relative to small format Li-ion pouch cells (7.7 Wh nominal, 2.1 Ah, 3.7 V) even though both the testing and analytical methods presented could be

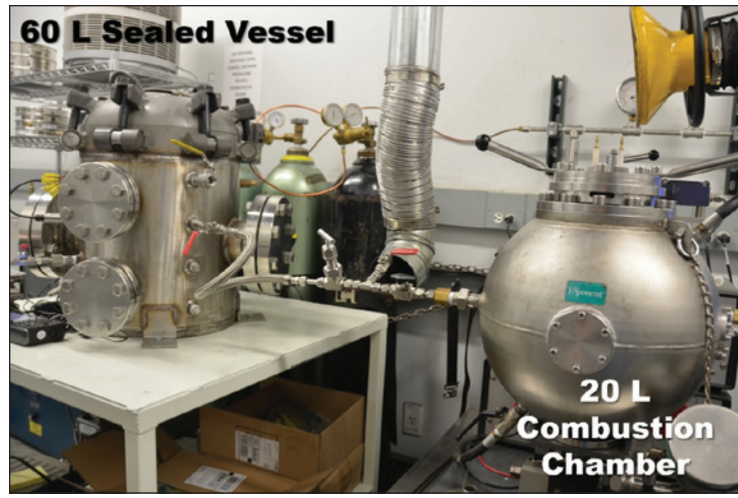

Figure 1: Photograph of a 60-liter sealed vessel connected to a 20-liter combustion chamber for battery vent gas explosion testing

similarly applied to larger format cells. The cells consisted of a negative electrode with graphite active material and a positive electrode with $LiCoO_2$ active material. Note that cell chemistry, cell geometry, ambient atmosphere, as well as the way the thermal runaway process is initiated all influence the quantitative behavior of the failure.

Table 1 summarizes the amount of gas vented during a thermal runaway event for pouch cells at three different states of charge (a more detailed description can be found in [1]). For comparison, the volume reported is referenced to standard pressure and temperature. It should be noted that for large battery packs, the amount of gas that is released can be substantial.

Table 1 and Table 2 show (1) the vent gas volume as a function of the cell SOC, and (2) the gas composition for different SOCs, respectively. With the exception of carbon dioxide, all the substances reported in Table 2 are flammable. In addition, carbon monoxide and some of the hydrocarbons are not only flammable but can also pose significant health hazards.

Note that Table 2 summarizes the species volume fraction of the vent gases. The absolute volume of each species depends on the total volume of gas vented, which increases as the SOC increases. Therefore, the total volume of hydrogen released from a 150% SOC cell is significantly higher than from a 50% SOC cell, despite having similar hydrogen volume fractions.

The combustion characteristics of the vented gases are summarized in Table 3 and compared with those of common gases. The combustion properties of the vented gases are similar to typical hydrocarbons despite the large presence of carbon dioxide. Another point to note is that the gases vented from Li-ion cell failures have a broader combustion range than typical hydrocarbons increasing the potential for ignition (likely due to the presence of hydrogen). More information on the testing methodology to evaluate the explosibility characteristics of battery vent gas is available in [1,2].

OXYGEN CONSUMPTION CALORIMETRY

Oxygen consumption calorimetry has been used for many years used to estimate the heat released during the combustion of fabrics or other typical organic materials. The established technique has found new relevance with respect to battery heat release assessments. In an oxygen consumption calorimeter, a sample usually reaches ignition and burns after being subjected to external heating. The energy released during combustion and the volume of combustion products are determined by collecting and analyzing the oxygen, carbon dioxide, and carbon monoxide contents of the exhaust gases.

State of Charge	Vented Gas Volume	Volume per Wh
50%	0.8 L / 0.2 Gal	0.10 L/Wh
100%	2.5 L / 0.7 Gal	0.33 L/Wh
150%	6.0 L / 1.6 Gal	0.78 L/Wh

Table 1: Venting gas volumes for a 7.7 Wh pouch cell at standard pressure and temperature. As a comparison, the cell has a volume of 0.014 L.

Gas		50% SOC (%vol)	100% SOC (%vol)	150% SOC (%vol)
Carbon Dioxide		32.3	30.0	20.9
Carbon Monoxide		3.61	22.9	24.5
Hydrogen		31.0	27.7	29.7
Hydrocarbons	Methane	5.78	6.39	8.21
	Ethylene	5.57	2.19	10.8
	Ethane	2.75	1.16	1.32
	Propylene	8.16	4.52	0.013
	Propane	0.68	0.26	2.54
	Isobutane	0.41	0.20	0.13
	n-Butane	0.67	0.56	0.39
	Butenes	2.55	1.58	0.60
	Isopentane	0.45	0.07	0.036
	n-Pentane	1.94	0.73	0.30
	Hexanes +	4.94	2.32	8.21
	Benzene	0.14	0.11	0.33
	Toluene	0.061	0.018	0.052
	Ethyl-benzene	0.009	0.002	0.003

Table 2: Vented gas composition for a 7.7 Wh pouch cell [3]

Gas	LFL	UFL	P_{max} (barg)	K_g (m-bar/s)
Li-Ion Vent Gas (100% SOC)	6%	~38%	7.1	65
Li-Ion Vent Gas (150% SOC)	6%	40%	7.7	90
Methane	5%	15%	6.7	46
Propane	2%	10%	7.2	76
Ethane	3%	12%	8.0	171
Hydrogen	4%	75%	6.5	250

Table 3: Combustion characteristics of vented gases released during a thermal failure of 7.7 Wh cells, and of common gases [4]

The standard method by which the cone calorimeter results are processed is sometimes modified to account for the complex composition of a Li-ion cell. A detailed description of the challenges associated with performing calorimetry of Li-ion cells is discussed in [5]. Often, the combustion event does not only involve the combustion of the vented gases, but solid components of the cell itself also burn and release energy.

To quantify the amount of energy that can be released by a cell involved in a fire, small format Li-ion pouch cells (7.7 Wh nominal, 2.1 Ah, 3.7 V) were tested in a cone calorimeter. Evolutions of gases released, oxygen consumed, and mass loss from the combustion reaction of the Li-ion cell charged at 50% SOC are presented in Figure 2. Figure 2a. shows an initial increase in production rates of CO_2 and CO concurrent with an initial mass loss of cell material (Figure 2c.) for about 15 seconds, starting at approximately 50 seconds. This phase corresponds to the ignition of the vented gases. The release of combustion gases is combined with an initial increase in oxygen consumption as shown in Figure 2b. During this period, the bulk material within the Li-ion cell is not involved in the combustion reaction. Electrolyte vapors are most likely the major contributor to the combustion during this 1^{st} phase.

After the 1^{st} phase, a transition to faster reaction kinetics is observed at approximately 65 seconds. Increases in the CO_2 and CO production rates combined with a rise in oxygen consumption areshown on Figure 2a., 2b., and 2c. This large increase is confirmed by changes in the slope of the production, consumption, and mass loss rate curves. At this stage, the bulk material within the cell is involved in the combustion process. This 2^{nd} phase lasts for approximately 35 seconds before extinction occurs. The peaks of CO_2 and CO are respectively 1.3 and 0.02 g/s. The total mass loss at the end of the test is about 8.4 g. This mass loss compares to the total mass of organic compounds present in the Li-ion cell and is evaluated to be approximately 9.0 g.

Although the cone calorimeter can be used to determine several parameters (e.g., critical heat flux for ignition, ignition time, etc.), one of the most important parameters measured is the heat release rate (HRR). The HRR is the amount of energy produced by the combustion process per unit of time (expressed typically in kW). It is the single most important parameter for determining the fire hazards associated with a given material or product and for designing fire protection systems.

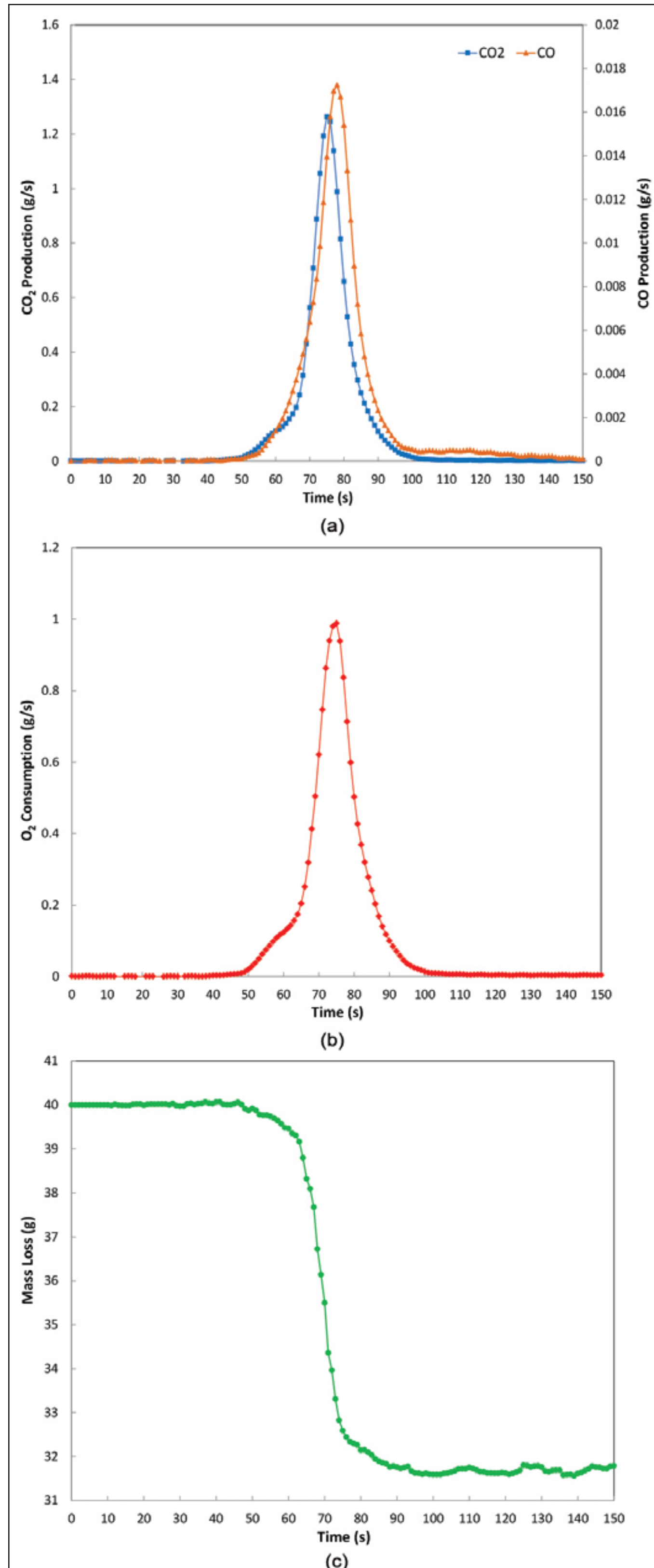

Figure 2: (a) CO_2 and CO production rates, (b) O_2 consumption rate, and (c) mass loss from the combustion of Li-ion cell charged at 50% SOC

Figure 3 shows the evolution of the heat release rate as a function of time for a 7.7 Wh Li-ion cell at 0%, 50%, and 100% SOC. At the peak of the combustion event, the fire releases approximately 22 kW, 13 kW, and 2 kW of power for cell SOCs equal to 100%, 50%, and 0%, respectively. Once again, the heat release rate is very dependent on the state of charge of the cell.

ACCELERATING RATE CALORIMETRY (ARC)

An accelerating rate calorimeter (ARC) is an instrument designed to characterize the self-heating behavior of materials and reaction kinetics that in recent years, has become highly utilized to understand the thermal runaway processes of batteries.

In ARC testing of batteries, the protocol typically follows a heat-wait-search (HWS) algorithm that minimizes heat losses from the sample to the surroundings. More specifically, the ARC system and sample are first heated to a set temperature point and are independently monitored for temperature. Both are then allowed to wait to equilibrate temperatures for a set amount of time, before actively searching for temperature rise from the sample. If no sample self-heating is detected, the system moves to the next temperature step, typically 5 ˚C or 10 ˚C, and begins the H-W-S process again.

Once the system detects self-heating of the sample during a search step, the system increases its temperature to match the sample temperature, thus creating an adiabatic environment. This temperature tracking continues until the cell thermally fails or a designated temperature set point is reached. Evaluating the self-heating as a function of temperature, cell voltage, and sometimes the evolved gas/pressure for ARC tests in a sealed vessel allows for analysis of various chemical reactions and events that occur during thermal failure of a cell. These include solid electrolyte interface (SEI) decomposition, electrolyte venting from cell enclosures, separator failure and/or shut-down, positive electrode oxidation, and more (see Figure 4).

ARC can be used to study the variety of variables that affect the thermal decomposition and runaway characteristics, including cell size/shape/capacity, cell format,

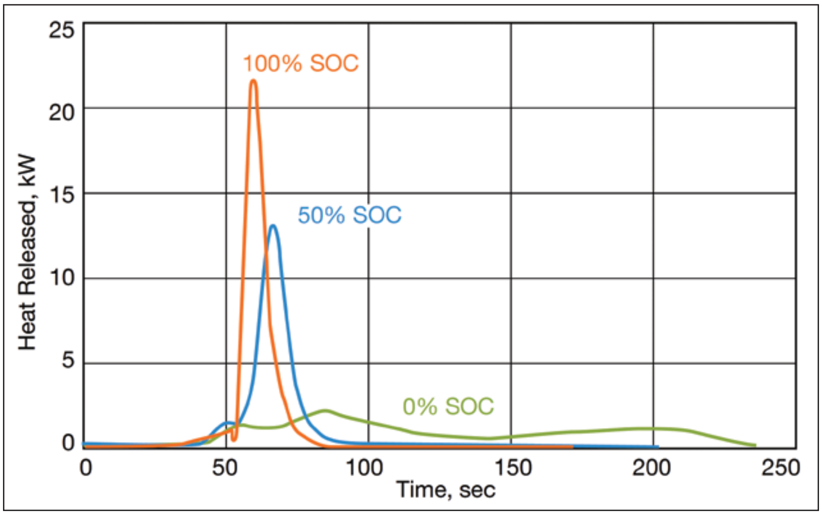

Figure 3: Heat release rate (HRR) during the combustion of a 7.7 Wh Li-ion cell at 0%, 50%, and 100% SOC

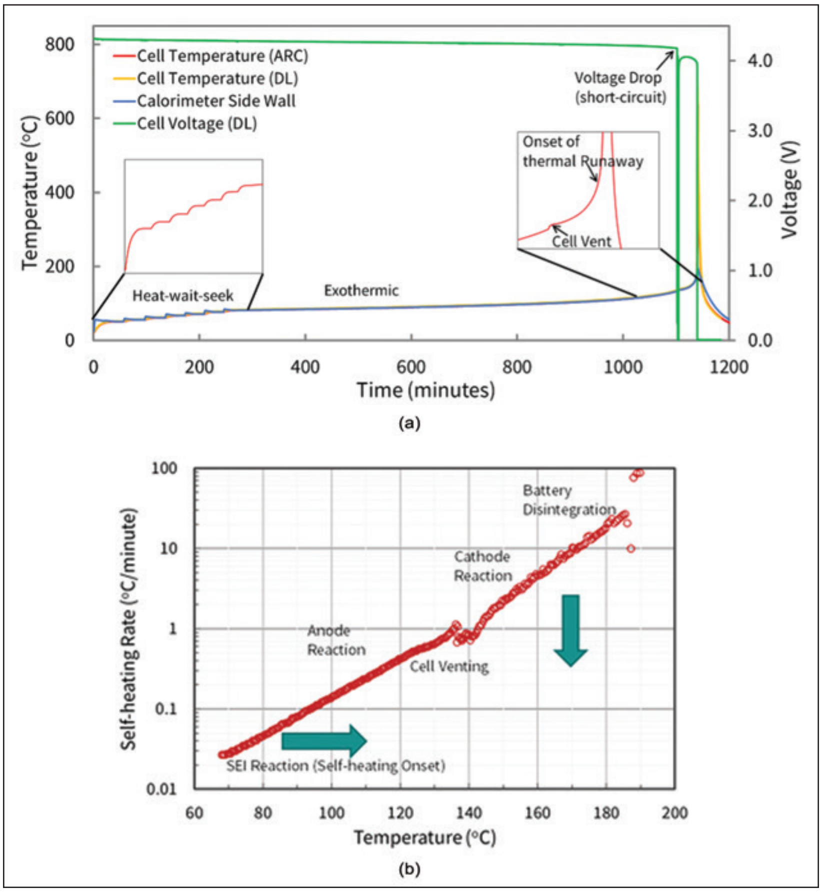

Figure 4: Accelerating rate calorimetry data showing (left) heat-wait-search program testing of a charged lithium-ion battery and (right) a self-heating rate vs. temperature plot identifying characteristic features in the battery failure

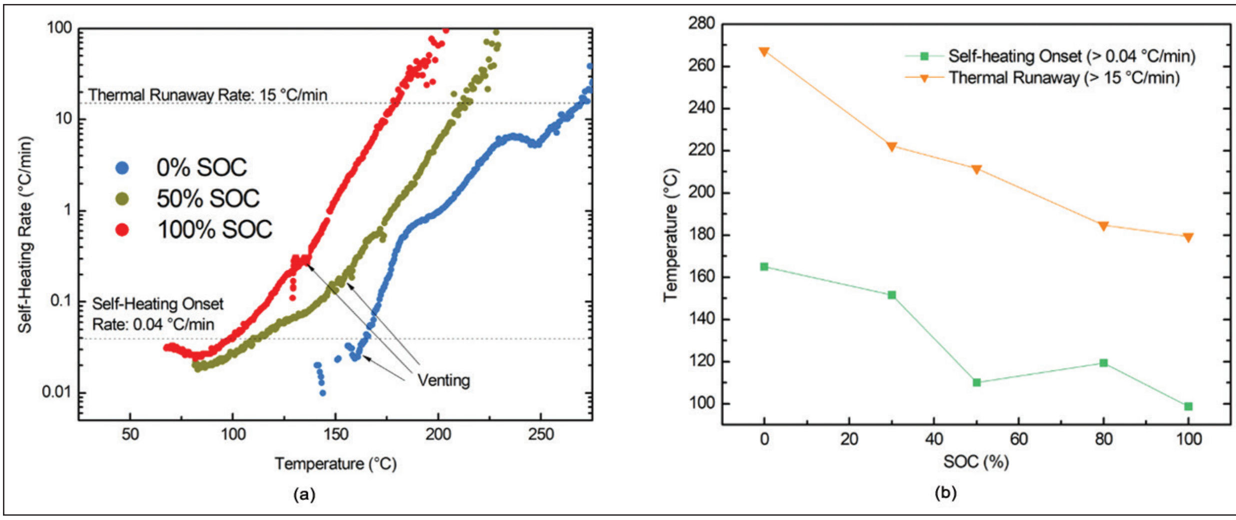

Figure 5: ARC analysis of 18650-format lithium-ion cells at various SOC showing a decrease in the self-heating onset and thermal runaway temperatures with an increase in SOC

SOC (see Figure 5), chemistry and morphology of the electrodes, electrolyte composition, state-of-health (or life), presence of plated lithium metal, etc. If ARC testing is performed with the battery sample in a sealed vessel (e.g., inside of the larger ARC chamber), the overall energy release from the thermal runaway event can be estimated using the heat capacity of the sample in conjunction with the temperature rise experienced on the sample, the temperature rise of the ARC vessel, and the known heat input into the system via recorded heater power.

FRACTIONAL THERMAL RUNAWAY CALORIMETER

A fractional thermal runaway calorimeter (FTRC) is a battery testing apparatus specifically designed by the National Aeronautics and Space Administration (NASA) to measure the energy output and mass ejections associated with a battery thermal runaway event [6]. The FTRC is equipped with interchangeable cell chambers that can accommodate cells with various form factors and capacity (i.e., 18650 cells, 21700 cells, D cells) as well as different cell triggering mechanisms ranging from external heating to nail penetration and internal short circuit devices. The cell chamber is centrally located and is interfaced on either side with (1) ejecta mating assemblies, (2) ejecta bore assemblies, and (3) rod-and-baffle assemblies.

An FTRC apparatus equipped with a standard 18650 cell chamber is fundamentally a symmetric device that can evaluate energy released associated with cell failures encompassing top venting, bottom venting, or both. The operation of the FTRC rests on simple physical principles. The various assemblies of the FTRC are all composed of known materials with known masses. The temperatures of these components are recorded throughout a test run. Since the material composition of the assemblies is well known, it is known how much energy must be added to the assemblies to cause a given rise in temperature. Thus, by measuring the component temperatures, it is simple to compute how much energy was transferred to those components (i.e, how much energy the cell released).

The cell chamber is connected to the ejecta mating assemblies via ceramic bushings that provide a certain degree of thermal isolation between the sub-assemblies while guaranteeing the continuity of the flow path for the vent gases ejected during the battery failure event. The ejecta mating assemblies are designed to capture large debris and ejecta released during cell failure. The ejecta bore assemblies and rod-and-baffles assemblies

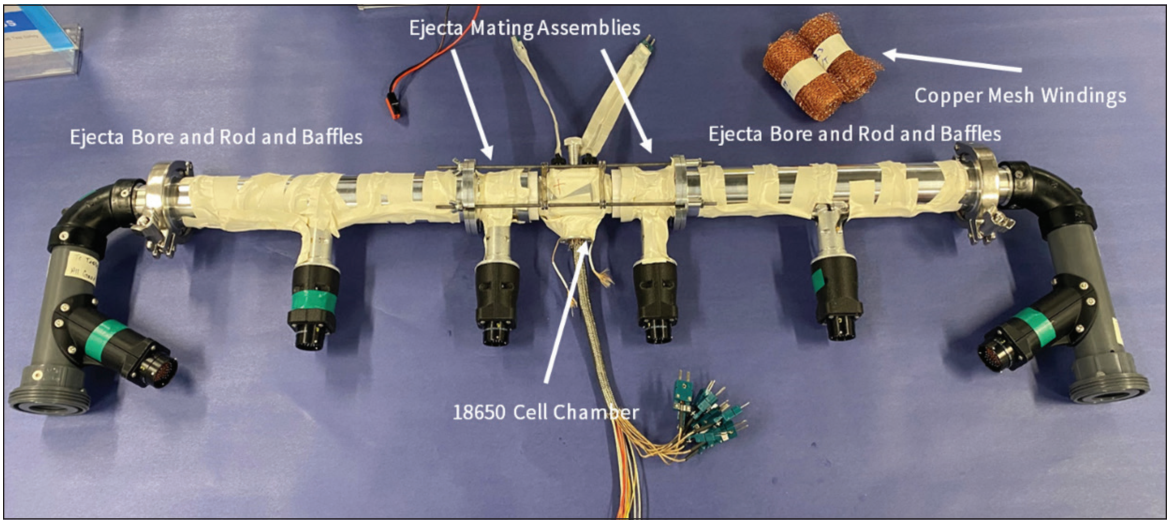

Figure 6: Photograph of an FTRC apparatus equipped with a 18650 cell chamber in the center of the device

are located downstream of the ejecta mating and are designed to extract sensible energy from the vent gases by creating a tortuous flow path encompassing (1) a series of aluminum baffles and (2) copper mesh windings. Figure 6 shows a photograph of an FTRC equipped with a 18650 cell chamber. Note the two copper mesh windings prior to installation in the FTRC.

The energy evolved during the battery failure can be evaluated in terms of total energy yield, fractional energy yields associated with the battery body, and positive/negative vent gas and ejecta. The cell energy yield is obtained by solving an energy balance equation for all the sub-components of the calorimeter based on the mass, specific heat, and temperature increase experienced by each sub-assembly. More specifically, the sub-assembly temperature increase is measured by over 100 type-K thermocouples attached to the hardware of the calorimeter in multiple locations.

Examples of energy yield estimations associated with battery thermal runaway events is presented in Figures 7, 8, and 9. We performed triplicate FTRC tests on 18650 cells with a capacity of 2.6 Ah and a state-of-charge of 100%. Figure 7 shows a bar plot depicting the total energy yield that evolved during a thermal runaway event of the three subject cells. The testing results show a total energy yield ranging between approximately 48 kJ and 52 kJ. The yield fractions associated with the cell body range between 26 kJ and 31 kJ and those associated with the positive vent gas and eject range between 19 kJ and 26 kJ. Figure 8 shows the time-dependent evolution of energy yielded by the cell failure as measured by the calorimeter apparatus. Figure 9 shows the fractional mass distribution measured during the tests.

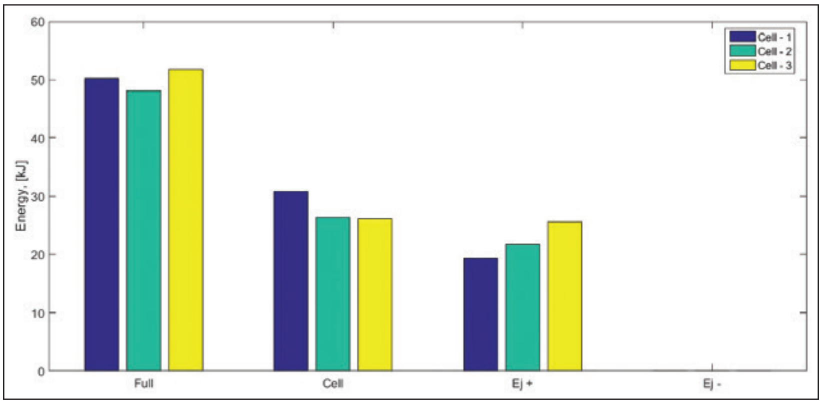

Figure 7: Bar plot showing the total energy yield during the thermal runway event for the three subject 18650 cells

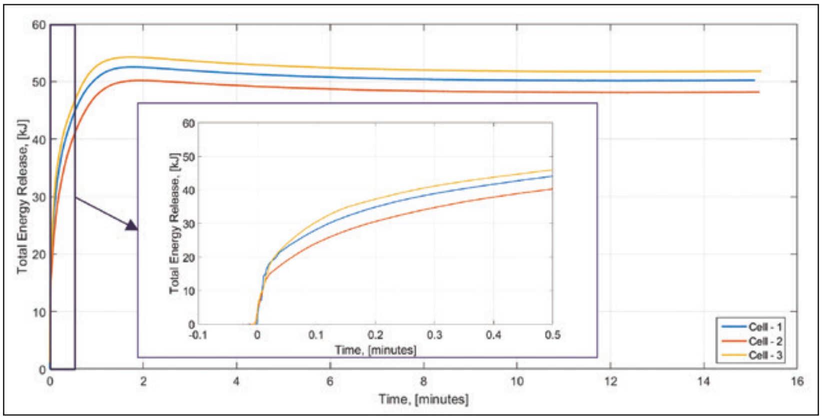

Figure 8: Time-dependent evolution of the energy evolved during the thermal runway event for the three subject 18650 cells

The results show that the vast majority of the mass remains within the cell body following the thermal runaway event. Smaller mass fractions were associated with the ejecta that were accumulated along the positive side of the calorimeter (i.e., in the positive ejecta mating, copper mesh, rod-and-baffles, and bore). Virtually no mass (or energy) was released towards the negative portion of the calorimeter that interfaces with the bottom of the cell.

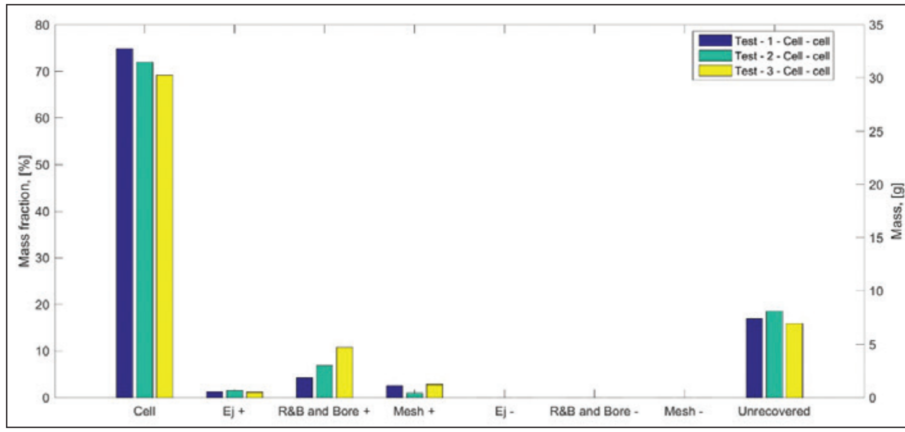

Figure 9: Fractional mass distribution associated with the thermal runaway event for the three subject 18650 cells

Figure 9 also shows the amount of unrecovered mass during the experiment. Unrecovered mass is associated with the amounts of vent gases and small ejecta that can leave the apparatus during the test. It should be noted that the energy fraction associated with the unrecovered mass is generally small. This is due to the fact that the temperature of vent gases and ejecta leaving the calorimeter is relatively close to ambient since the calorimeter is designed to extract all their sensible energy along the tortuous path leading from the cell chamber (where vent gases and eject are generated) through the rod-and-baffles assemblies and the copper mesh.

CONCLUSION

This article presents a chemistry-agnostic, experimental framework to characterize the energy released during a thermal runaway event of a lithium-ion cell. The characterization of the energy yielded during a failure is a critical parameter that can inform the design of battery-powered products from safety and performance standpoints. The framework relies on multiple experimental methodologies such as (1) sealed vessel testing, (2) oxygen consumption calorimetry testing, (3) ARC, and (4) FTRC testing. Combined, these techniques offer quite a complete picture of the energy and materials released during the thermal runaway of a lithium-ion battery.

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Low-Frequency Magnetic Fields in Electric Vehicles

Challenges, Shielding, and Design Considerations

BY DR. MIN ZHANG

***Editor's Note:** Readers may also be interested in Zhang's other* In Compliance Magazine *articles addressing EMC issues with electric vehicles, "EMC Design Techniques for Electric Vehicle Powertrain Modules" (February 2021), and "EMC Design Techniques for Electric Vehicle DC-DC Converters" (December 2021).*

Most electromagnetic interferences (EMIs) in the field are conducted emissions/immunities, radiated emissions/immunities, electric fast transients (EFT), and electrostatic discharge (ESD). There are, however, other types of EM-related disturbances, including low-frequency magnetic fields, the subject of this article.

The power-frequency (50-60 Hz) magnetic field is a direct result of currents flowing in power networks. When low-frequency currents flow in the entire power network, depending on the size of the current-circulating loop, the impact on equipment/products in the environment can be significant. A typical case is an equipment with a cathode ray tube (CRT) screen. The display on a CRT screen would appear to wobble due to the presence of a nearby low-frequency field[1]. Professional audio equipment such as electric guitars, tape recorders, and loudspeakers are also sensitive to external magnetic fields. EN 61000-4-8 defines the test method for basic power-frequency magnetic fields[2].

In recent years, many low-frequency magnetic field issues have been identified in new product applications, such as products using electron-beam technology and electric vehicles (EVs). Products such as additive manufacturing equipment using electron-beam technology are also sensitive to power-frequency magnetic fields and poor immunity could lead to inaccuracy in the manufacturing process. In the case of EVs, traction motors generate fluctuating currents up to 2 – 3 kHz, and wireless power transfer (WPT) systems for battery charging are operated at about 85 kHz[3].

The issue with low-frequency magnetic fields in this case is often related to health and safety. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines 2020[4] describes the potential health and safety impacts of human exposure to electromagnetic fields. According to the Guidelines, the main physiological effects of electromagnetic field exposure include the electro-stimulation of the nervous system, resulting from electric fields being induced

Dr. Min Zhang is the founder and principal EMC consultant of Mach One Design Ltd, a UK-based engineering firm that specializes in EMC consulting, troubleshooting, and training. His in-depth knowledge in power electronics, digital electronics, electric machines, and product design has benefitted companies worldwide. Zhang can be reached at info@mach1design.co.uk.

in biological tissues under exposure to time-varying magnetic fields with frequencies up to 10 MHz.

Not only can low-frequency magnetic fields pose health hazards to human beings, but they can also affect some electric control units (ECUs) in a vehicle. An ECU that consists of Hall-effect sensors located near the battery pack or powertrain modules could be affected by the low-frequency magnetic field if no sufficient shielding is provided.

In this article, the discussion of low-frequency magnetic fields is based on applications where the frequency range is below 500kHz. The low-frequency magnetic field challenges in EV applications are discussed. Low-frequency electric fields and plane waves are outside the scope of this article, as are low-frequency magnetic fields produced during the EV charging process.

First, some basic theory about low-frequency magnetic fields is in order.

THE PHYSICAL LIMITATION OF LOW-FREQUENCY MAGNETIC FIELD SHIELDING

Shielding techniques, which are widely used for radiated emissions, are effective because they work in the far-field. Since the wavelength is physically small, the attenuation of a shielding material combines both absorption loss and reflection loss[5].

As shown in Figure 1, the laws of physics dictate that the wavelength is large when the frequency is low (900 kHz), hence the same distance becomes near field for lower frequency noise. In this case, the shield cannot provide sufficient reflection loss. The absorption loss is also reduced and is at a low-frequency. As a result, low-frequency magnetic field shielding can only be achieved by the following techniques:

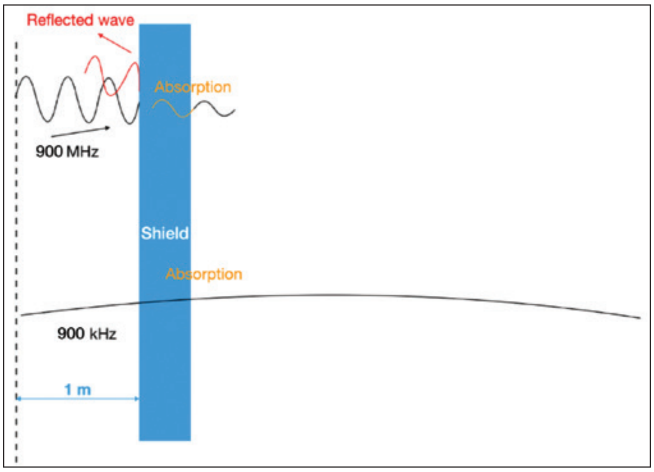

Figure 1: In near field, low-frequency noise can only be absorbed but the absorption loss is also reduced.

1. Using thick conductive metal material such as steel, which often works well, but the drawback is the weight. Aluminium or magnesium are much lighter than steel, but they have insufficient low-frequency shielding properties and, therefore, cannot be used in this application.
2. Using a magnetic material such as mu-metal to increase the absorption loss. However, this technique doesn't work for low-frequency electric fields or plane waves (see Endnote #5). Another drawback of magnetic materials is that their permeability decreases with frequency.
3. Active shielding techniques to cancel out the low-frequency field[6], which works in applications where the product suffered from power-frequency (50-60 Hz) magnetic fields and is not constrained by size.

LOW-FREQUENCY MAGNETIC FIELDS IN EV APPLICATIONS

Low-frequency magnetic fields are often generated by the four primary high-voltage modules in an EV, namely, the powertrain module, the on-board charger (OBC), the battery pack, and the DC-DC module.

A simplified system diagram is shown in Figure 2. Often there is a high-voltage (HV) junction box between the HV battery pack and other HV loads. For demonstration purposes, the junction box and other HV loads are not shown.

When the traction motor is in motoring mode (that is, when the motor is in cruising mode), currents are drawn from the battery pack. The currents can reach a much higher level when the vehicle accelerates as the motor demands more power. When an EV is in braking mode, the motor starts regeneration and large amounts of currents are fed back to the battery pack. In this case, the HV wiring and harnessing determine the current-circulating loop area. Hence, the low-frequency magnetic field depends on the motor speed, the motor drive switching frequency, its operating mode, and the impedance of the cables.

The HV bus bar currents consist of many frequency contents. Here is the frequency contents breakdown:

1. From 1 Hz to a few kHz, static magnetic field noise is often generated by the battery pack and DC bus bar current flow.
2. In the frequency range of a few kHz, noise is generated by the electric frequency of a rotor, which depends on the mechanical speed and the number of poles of the rotor.
3. From tens of kHz to a few hundred kHz, noise is generated by the switching frequency of the motor drive.
4. The sharp rise time of the motor drive generates noise in the high-frequency range between a few MHz and a few hundred MHz.

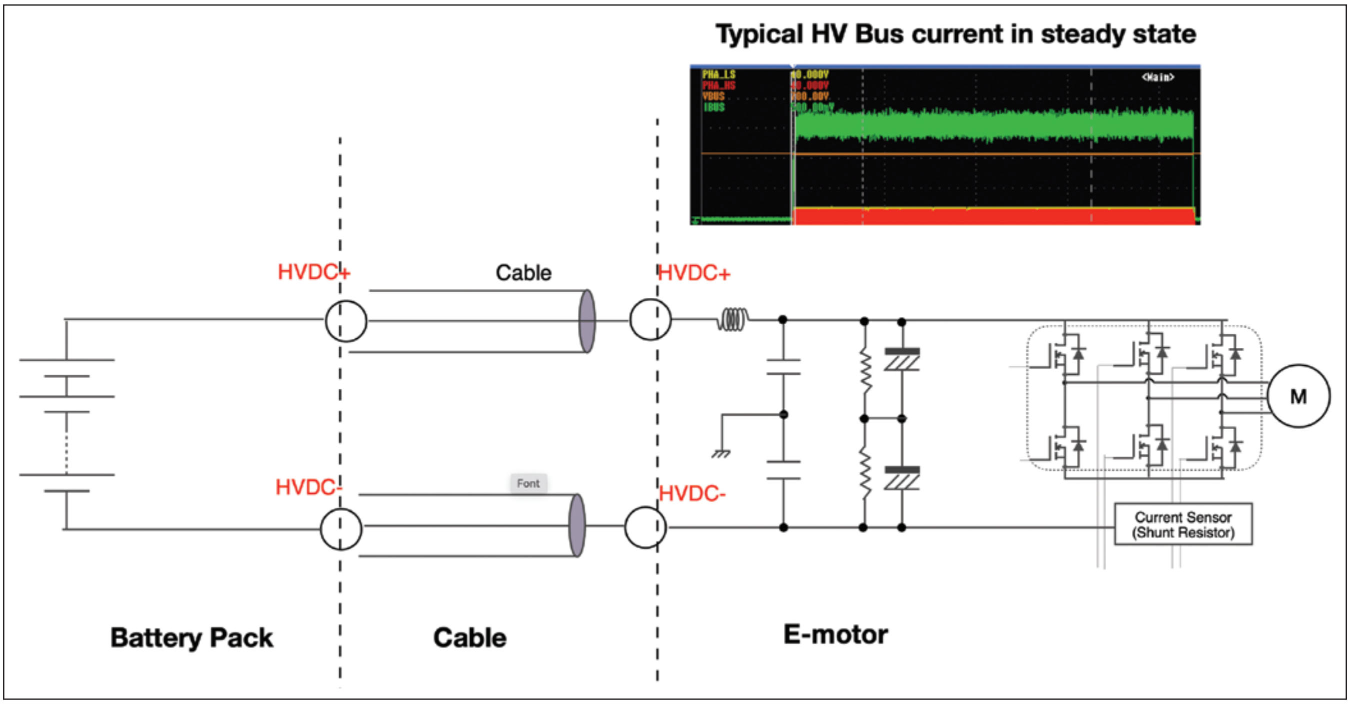

Figure 2: A simplified system diagram of a battery pack supplying power to a traction motor

5. Partial discharge of HV cables and bearing currents of the traction motor generate noise beyond hundreds of MHz.
6. The battery pack, HV cable, and the traction motor forms a C-L-C circuit; resonances could occur depending on the geometry of the structure.

Generally speaking, it is in a design engineer's interest to shorten the cable length between the battery pack and the motor drive unit. Any extra length of an HV cable connection means an increase in loss (i^2R) and is, therefore, not desired. But the vehicle design often decides the layout of HV subsystems. When it comes to overall vehicle design, it is safe to say that trade-offs need to be made between vehicle design and safety, efficiency, and thermal effects.

As stated previously, the time-varying, operation modes-dependent traction currents lead to rapidly changing magnetic fields that can potentially disrupt Hall-effect sensors and pose electro-stimulation hazards to human tissues.

Test standards are being developed to test against low-frequency magnetic fields. The aim of these tests is to place a limit on the magnitude of the electromagnetic fields generated by a unit to ensure that compliance to the human exposure reference limits detailed in ICNIRP Guidelines can be achieved during vehicle level testing. Unless specified in the approved test plan, testing is often performed in the frequency range from 1Hz to 500 kHz using a 100 cm^2 three-axis sensor, though there can be proximity errors in the test set-up[7].

DESIGN TECHNIQUES FOR LOW-FREQUENCY MAGNETIC FIELDS

Because automotive applications are a volume manufacturing business, cost is often at the top of the list during the design stage. High-tensile steel is used to shield the 100s of kHz noise generated by the traction motor in the example shown in Figure 3 on page 96. Considered as a cost-effective solution, this approach also has the benefit of being mechanically strong, which is great from the battery pack safety point of view. It does, however, have the disadvantage of being heavy, which could be a big drawback for an EV application. One of the pain points of modern EVs is their limited mileage, which could be extended significantly when the weight of the vehicle is reduced.

A similar application is electric aircrafts where weight is even more important. Currently, the solution there is to use aluminium material for the battery pack. But even aluminium material is considered heavy, so carbon fibre composite material is preferred. Layers of copper sheeting need to be added for shielding and to protect against lightning strikes.

There is a strong demand for better low-frequency magnetic shielding materials that have higher shielding properties, that are lightweight, and can potentially be moulded through additive manufacturing processes. As shown in Figure 3, some new materials have shown great potential in this regard. It should be pointed out here that the reference is a 115 µm copper foil, rather than high-tensile steel. Generally, below 100 kHz, steel achieves much greater attenuation than copper. From 100 kHz up to 10 MHz, copper becomes a better shield than steel. Therefore, it can be expected that this material would work well for shielding motor drives and DC-DC converters. In terms of the lower frequency performance (1 Hz to 100 kHz), such as the traction currents discussed previously, there is still a question mark. On top of that, cost is also an important factor to consider.

Because of the limited options to shield low-frequency magnetic fields effectively, a better approach is to control the magnetic fields at their source, and avoid or minimize generating them[8].

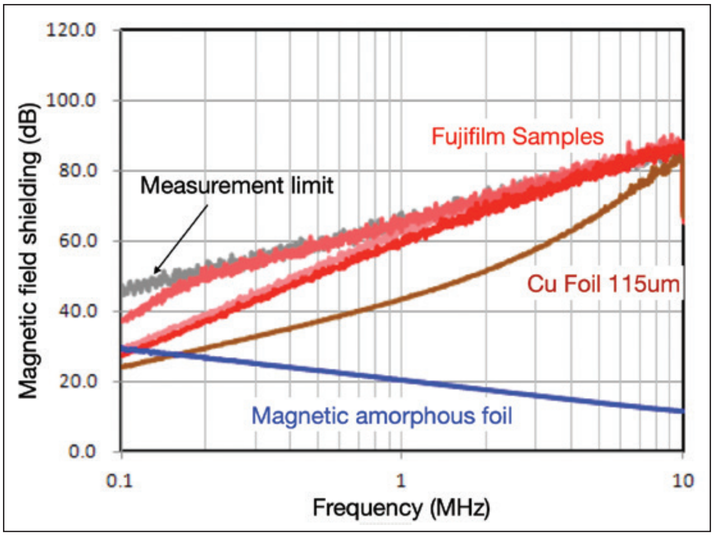

Figure 3: The low-frequency magnetic field shields developed by Fujifilm showed great shielding properties between 100 kHz and 10 MHz. (Graph courtesy of Fujifilm)

Magnetic fields depend on the loop size and the current level. Since the current level cannot be reduced, efforts should be made to reduce the loop size. Reducing loop size for low-frequency magnetic fields mainly involves:

1. Planning battery housing, which includes battery cells module layout, battery management system (BMS) wiring layout, and battery bus bar layout. The good news here is that safety, thermal, and system efficiency requirements all require an optimized wiring structure.
2. HV junction boxes also need to adopt smaller/improved conductor rail designs. This is often an area that can be overlooked by design engineers. A typical case is that bus bar/wiring can be separated by the larger contactors. In Figure 4, two examples are shown to demonstrate the point.

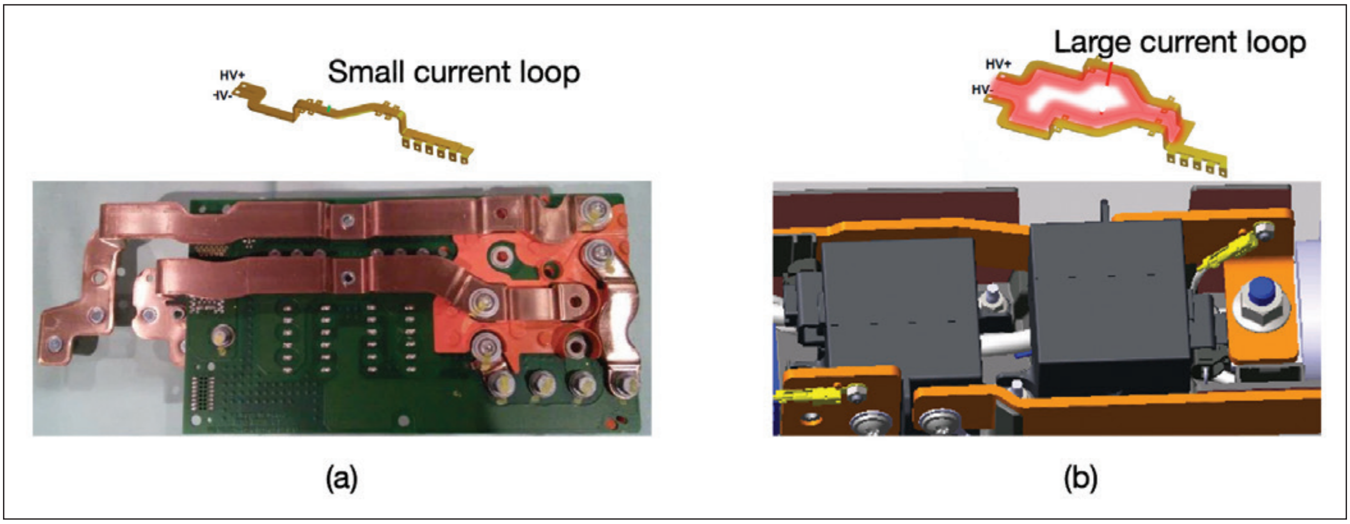

Figure 4: An HV junction box developed by Tesla (shown in Figure 4a) demonstrates the small current loop (Figure 4b). Another HV junction box has a larger current loop because of the HV contractor's layout.

3. Optimizing the wiring and harnessing in the HV power network. An optimized system is often achieved by integrating multiple modules.

SUMMARY

In this article, low-frequency magnetic fields below 500 kHz in EV applications were discussed. The shielding capability of low-frequency magnetic fields is limited by the laws of physics. As a result, design engineers are left with limited options.

Reducing the magnetic field loop size and using advanced materials should be considered in the vehicle design stage. Due to its superior attenuation at very low frequencies (<10 kHz), steel might still be a preferred choice for vehicle manufacturers. Integration of power modules should also reduce the risk of emitting low-frequency magnetic fields. Active shielding may be used for such applications but require further study.

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Product Regulatory Compliance:

Definition, Scope, Importance, and Impact

A Rigorous Process to Achieve Core and Global Market Access

BY THOMAS KILLAM AND CYRIL MECWAN

According to the U.S. Consumer Product Safety Commission (CPSC), at least 41 Americans were killed and about 133,000 injured between 2017 and 2019 in incidents tied to e-scooters, e-bikes, and hoverboards.[1] Ten companies were forced to recall approximately 500,000 hoverboards after the CPSC received about 100 reports of the lithium-ion battery packs that power hoverboards overheating, sparking, smoking, catching fire, or exploding.[2]

While these examples may represent a small segment of concern, their occurrence highlights the importance of product regulatory compliance and the consequences of failing to integrate compliance considerations into the design, development, production, and distribution of a wide range of products.

BACKGROUND AND DEFINITIONS

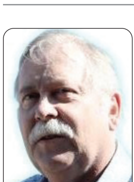
The world is full of regulations. Local, state, national, and international jurisdictions have in place a variety of regulations and regulatory compliance requirements addressing user safety and health, energy use, environmental issues, and other product-related considerations.

The product regulatory compliance process encompasses all of these aspects in the regulation of end products, components, materials, systems, and processes. It chiefly consists of testing an end product to assess its compliance with applicable requirements and receiving certification from a regulatory agency or a self-declaration by the manufacturer that the end product meets these requirements.

Typically, these requirements apply to products that utilize modern electronic technologies. However, many product regulatory requirements address various health, environmental, and safety issues specific to other types of products, including foods and grains, drugs, oils, chemicals, fabrics, cosmetics, etc.

An original equipment manufacturer (OEM) is obligated to test its products to determine their conformity with the applicable standards mandated by the regulatory authority of the country in which the products will be sold or marketed. In many cases, OEMs are also required to obtain independent verification of conformity and receive certification or other form of approval prior to shipping the product to that market. A copy of the certification or other evidence of product approval is generally required to accompany the product when shipped.

Product regulatory compliance is achieved at the product or stock-keeping unit (SKU) level, and marking verifying that



Thomas Killam is the Compliance Officer at OnRule, a world-leading company offering SaaS platform to manage product regulatory compliance. He has over 40 years of product regulatory experience working for large, global companies.

Cyril Mecwan is the CEO of OnRule, with over 30 years of experience in the fields of new product introduction (NPI), supply chain management, and product regulatory compliance. The authors can be reached at authors@onrule.com.

compliance is generally required to be visible on the product. In some cases, product regulatory compliance requirements are also applicable to critical components within the product or spare parts that accompany the product when sold. Generally speaking, achieving compliance with component level regulations is the responsibility of the component supplier, and test data verifying component compliance is included in documentation submitted in compliance declarations covering the actual end product.

Relevant regulatory requirements can vary based on a country or jurisdiction, the industry, or the technology used. For electrical and electronic systems, devices, and components, requirements may include, but are not limited to, issues related to safety, electromagnetic compatibility (EMC), radio, telecommunications, energy efficiency, environmental, quality, performance, etc. Further complicating the compliance picture, individual technical requirements can vary from country to country, contributing to the challenges of achieving global regulatory compliance.

Rapid advances in technology are bringing many benefits to humankind, but they are also accompanied by threats and vulnerabilities. As businesses are rapidly digitizing records and processes through the use of SaaS products, and as new devices increasingly rely on the use of radio for internet connectivity, the field of cybersecurity is quickly advancing to protect businesses and people from digital attacks. Product regulatory compliance globally is making a foray into cybersecurity as a next frontier that must be tackled and is aggressively advancing to include cybersecurity as one of the critical disciplines of conformance.

In addition to compliance certifications and approvals issued by regulatory authorities, several industry special interest groups (SIGs), consortiums, and alliances, such as the Wi-Fi Alliance, the Zigbee Alliance, and the LoRA Alliance, offer product or technology-specific approvals that allow the use of their logo or other identification on products that have been reviewed and verified for compliance with their technology-specific requirements.

Medical devices and instruments used for important functions are also held to rigid performance standards. A few examples of devices and instruments that must meet performance-related standards include pulmonary and respiratory systems, ventilators, blood pressure measurement devices, intravenous instruments, pediatric tracheostomy tubes, feeding systems, culture media used in microbiology laboratories, certain materials used in the practice of dentistry, patient transfer chairs, and sterile containers, etc.

Many government agencies, including those overseeing aviation and military systems and applications, may also require conformity with specialized performance and quality standards that may not fall within the typical definition of product regulatory compliance but which must be addressed nonetheless. For example, "The U.S. Internal Revenue Service released Notice 2015-4 which specifies the performance and quality standards that small wind turbines must meet in order to qualify for the 30% investment tax credit, and which requires that small wind turbine models be certified …"[3]

Consumer and enterprise products requiring access to telecommunications networks operated by mobile phone carriers may have to comply with the requirements developed by Telcordia, a telecommunications standards body. In addition to the Telcordia requirements, carrier-specific requirements are often imposed by network providers like Verizon, AT&T, T-Mobile, Vodafone, Orange, Telstra, etc. Typically, collaborating with the network providers to conduct tests and satisfy such requirements also becomes the responsibility of compliance engineers.

Finally, large e-commerce retailers and distributors may have their own requirements applicable to the products that they procure for sale or distribution that might be more stringent than those imposed by local, regional, or national regulatory authorities.

SCOPE

Product regulatory compliance touches on every aspect of the product lifecycle (from concept to retirement) and for the entire value chain (from critical components suppliers to the end customers) and is an important and omnipresent function impacting all other functions and stages (see Figure 1).

Concept to Launch

In the NPI phase, a product design is validated for product regulatory compliance through the testing process. Design-related issues, weaknesses, and defects identified during the testing of early prototypes are then incorporated into the next iteration of the product design to make the product more robust and compliant. Testing of the final product is then conducted to produce the test reports that are submitted to the relevant authority to obtain regulatory approval. Once approval has been received, the product is ready for general availability and for release in those core market(s) where approvals have been granted.

This process usually follows the following trajectory:

- *Core Market Access (CMA):* Companies generally first launch new products into their core or primary markets. Meeting the relevant compliance and testing requirements applicable in the EU and/or U.S. and Canada helps to validate the integrity of the product while also establishing a generally accepted baseline conformance to compliance.
- *Global Market Access (GMA):* Following a successful launch and acceptance of its new product into its core markets, companies then launch their product globally into other countries in succession. Some countries, such as China and India, typically require in-country testing, which requires shipping product samples to a local testing lab for the purpose of testing. Even in those countries where in-country testing is not required and in which regulatory authorities accept test results and approvals obtained in the EU or the U.S., companies may still be required to go through a time-consuming regulatory process, submitting applications and other forms to the relevant government agencies.

Launch to Retirement

Once a product has been released into production, it enters the sustaining mode. To support the growth of sales in new markets, fulfillment of testing and certification requirements applicable in additional countries is required. Global market access (GMA) is achieved through the fulfillment of the testing and certification needs of additional countries. In this phase, certification management of a company's current product portfolio becomes critically important, and several

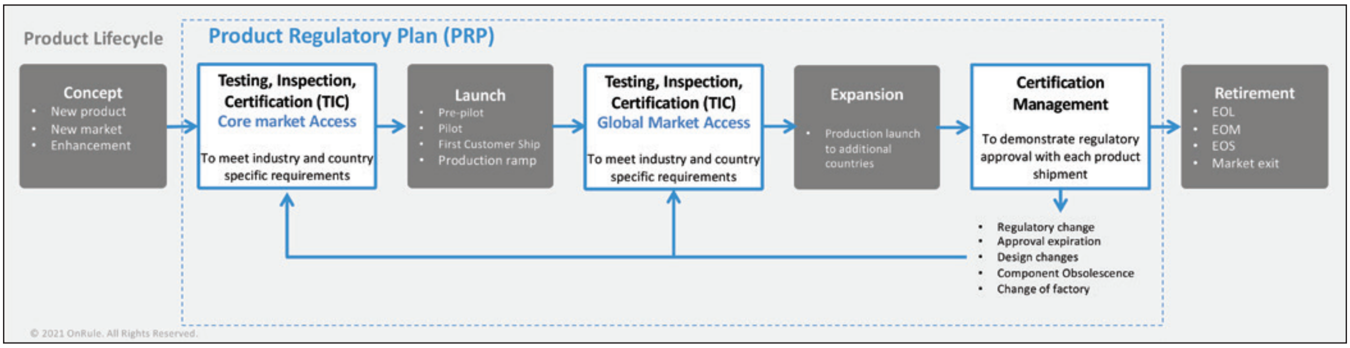


Figure 1: Product regulatory plan

events can occur that require a company to review existing product certifications for continued compliance. These events can include:

- Changes in an underlying standard (or standards) in a given country or jurisdiction may require retesting of the product to the new or revised requirements to either retain approval or receive a new approval.
- In cases in which a country or jurisdiction does not grant lifetime approval for a given product, renewal of an existing certification may be required. Typically, the frequency of such renewals can be anywhere from one to five years from the original approval date.
- A significant change in an existing product design can trigger the need to retest and/or recertify the product.
- A change in a critical component such as a power supply may also require a company to retest and/or recertify the end product.
- In cases in which regulatory authorities require follow-up inspections of the factory (or factories) where a product is produced, the use of a new or different factory may require a review of current product certifications and retesting.

As mentioned earlier, product regulatory compliance is evaluated at the product or SKU level. However, an OEM is required to disclose the list of critical components used in the final product. As part of the overall evaluation of the end product, some regulatory authorities may require evidence of safety testing and certification of those critical components. If a critical component is sourced from more than one supplier, (typically is the case for the purpose of managing the supply chain risk), evidence of safety testing and certification from all suppliers may be required.

IMPORTANCE

If a product's compliance with applicable regulatory requirements cannot be demonstrated, a company may be legally prohibited from shipping that product to their customers and may risk seizure of their product by customs officials at border crossings. This is not an uncommon occurrence, and many regulatory compliance engineers experience this situation multiple times during their careers.

Product regulatory compliance requirements play a significant role in your ability to ship your company's products to foreign and domestic customers. Having sufficient evidence demonstrating your product's compliance with applicable regulations to support a factory audit or to accompany your product when shipped requires verifying the validity, quality, and availability of your regulatory compliance documentation. Organizing that documentation and designating a secure location for it is also an obvious and commonplace practice that is essential to support the uninterrupted shipment of goods.

Figure 2: The importance of product regulatory compliance

Engineering, NPI, and Product Management

During the new product development process, the product regulatory function must provide guidance to the design engineers as to the particular technical requirements that will apply to that product. The individuals or team responsible for product regulatory compliance should develop a test plan and testing methodologies to assess the new product. Doing so will help sharpen everyone's focus on the particular regulatory requirements that will apply to the product when formal regulatory testing is conducted. It can also help the compliance team understand the potential compliance issues that might arise during the design and testing phase. Providing this guidance at an early stage in the product development process can reduce or prevent time-consuming iterations of the product design itself in order to comply with regulatory requirements. This early involvement in the design can also help the product to be designed so that the technical boundaries affecting the performance and safety around many critical parameters are taken into account.

In many cases, early testing on product prototypes against the limits set forth in applicable technical standards will pinpoint issues that may lead to non-conformity. Waiting until the product design has been completed to conduct testing almost always results in the need to redesign the product and to conduct regression testing on the updated design to verify its compliance. This inevitably leads to delays in bringing your product to market and increases the overall development cost for the product.

Product Management and Marketing

Obtaining product regulatory approvals is typically the last step before a product launch and represents a critical milestone in the NPI schedule. By this point, your product management and marketing teams should have a clear plan for the markets in which they want to launch the product, including a country-by-country sequence for market deployment. It is extremely difficult to launch a product in all targeted global markets in the same time period due to variations in the approval process among individual regulatory authorities in different markets and the amount of time required in individual jurisdictions. This is why a global product rollout is generally broken into different market segments to provide staggered availability dates for the product.

The best approach involves the development of marketing waves, that is, segmenting individual countries into groups to be given priority in the initial product rollouts to customers. The success of this wave approach ultimately requires the product regulatory group to develop a clear plan that accurately accounts for the time required for the testing and approval phases in individual jurisdictions so that product approvals coincide with the planned market availability. This regulatory compliance plan should be fully transparent to the entire product development team and the marketing team so that the necessary distribution channels can be established or verified as operational.

Sales

The ability to sell any new product depends on obtaining the required regulatory approvals to ensure the product's legal availability to customers. The order management process in place in most companies typically will not authorize acceptance or shipment of an order for a new product until the required regulatory approval has been secured. Further, selling a new product in a new country or a region will first depend on the company's ability to secure regulatory approval for the product in that country.

Distributors and System Integrators

Conforming with regulatory compliance requirements and obtaining independent verification of compliance is the responsibility of the OEM. Third-party distributors and system integrators who have a presence in a local market or country are often required to serve as an importer of the product into that country. As a result, most third-party distributors typically require documented proof of compliance before assuming responsibility for making a company's product available to their end customers through their distribution channels.

Operations, Logistics, and Quality

The product regulatory compliance process is often part of the quality metrics that are presented during the product readiness review that takes place before the launch of a new product. At the same time, at the point of shipment, operations and logistics personnel need the required compliance documentation (approval certificates, manuals, packaging labels, etc.) in hand to avoid having products held up or denied at customs checkpoints or delayed at shipping docks and failing to reach the end customer as promised.

Customer Support

Existing end customers, channel partners, and field sales personnel will often contact customer support teams for compliance documentation that verifies that the requirements of the product regulatory approval process have been met. In some cases, this request can be for the approval documentation required for spare parts and critical components scheduled for shipment by the service department to existing customers.

Legal

Lastly, in several companies, the legal department gives the final nod to the product launch upon reviewing the completion of all regulatory milestones. Evidence that the product regulatory compliance process has been completed and that regulatory approval has been received is one of the important metrics reviewed and signed off by the legal team. In some companies, the product regulatory compliance team reports to the legal department.

THE IMPACT OF NON-CONFORMANCE

The failure to ensure product conformity with regulatory compliance considerations may have important impacts on several fronts, including on communities and on the business. Here are just some examples:

- *Safety and well-being:* A lack of conformity may result put the safety and well-being of people at risk. According to the CPSC, in 2019, there were an estimated 22,500 treadmill-related injuries treated at U.S. emergency departments among all ages (of which around 2,000 were children under eight years of age).[4]
- *Revenue impact:* It is all too common for companies to miss quarterly or annual revenue targets because they could not ship orders on hand from available inventory due to a lack of compliance documentation availability. We know of incidents in which a distributor could not bring inventory into a target market because the products were being delayed at customs due to a lack of compliance approval documentation. As a result, the OEM could not register the necessary revenue recognition during a fiscal quarter, falling short of both the company's and investors' expectations.
- *Customer satisfaction:* Missing an order commitment date due to lack of regulatory approval directly impacts customer satisfaction, a critical metric to business success. Note that an OEM customer may be a reseller, distributor, system integrator, or end customer.
- *Brand impact:* Recalls from the market due to poor quality and performance may adversely impact the OEM brand. The bad press from an incident can be devastating to a company's reputation, from which it may never recover. In the infamous hoverboard issue cited previously in this article, more than ten companies were forced to recall 100,000 hoverboards after the CPSC received about 100 reports of the lithium-ion battery packs that power hoverboards overheating, sparking, smoking, catching fire, or exploding.
- *Legal impact:* Typically, good business practices dictate that a company secures product liability insurance prior to placing the product on the market. Generally speaking, product liability insurance premiums for a product that meets all of the applicable regulatory requirements will be significantly less than that paid for a non-compliant product or a product that has no proof of compliance. If a non-compliant product is introduced into a market and an event occurs that brings a safety issue to light, there can be many ramifications that directly affect the company, including fines and possible jail time for those responsible.

CONCLUSION

The emergence and importance of product regulatory compliance as a formal discipline in governing and ensuring the release of safe, environmentally sustainable, and energy-efficient products in the global markets have now been established and recognized. CE, FCC, UL, etc. marks are understood and regarded by consumers and businesses at large. But the scope and impact of product regulatory compliance in safeguarding our universe, planet, and human beings through the introduction of compliant products are much broader and deeper. Products, whether used underwater, on earth, or in space, are all subjected to and benefit from this ubiquitous discipline. As technologies evolve and as mankind races to explore far space, it is imperative that this discipline be further promoted, developed, and implemented.

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The Rise of Time-Sensitive Networking (TSN) in Automobiles, Industrial Automation, and Aviation

IEEE Standards Association advances new TSN application profiles as adoption increases across industry sectors

BY GLENN PARSONS

Ethernet is one of the most widely adopted technologies for the transmission of data between devices and is used in many industries because of its speed, affordable cost, and versatility. Over the years, Ethernet standards have evolved to meet increasing needs to transmit more data faster. However, in addition to speed, a key performance factor – determinism – is influencing the increasing need for time-sensitive networking (TSN).

A deterministic system is a system in which no randomness is introduced in future states of the system, thus allowing a deterministic network to exchange packet data in a precise manner with a defined latency. Because data exchange in Ethernet networks lacks determinism with its packet buffering and varying queuing delays, deterministic data exchange in Ethernet has, until recently, only been possible with proprietary solutions.

TSN, a relatively new technology, is making Ethernet bridged networks deterministic by design – guaranteed data transport with bounded low latency, low delay variation, and extremely low loss. Today, TSN is notably leveraged in industries where deterministic communication is important, such as automotive, manufacturing, aerospace, transportation, and utilities applications.

TSN STANDARDS

TSN is the focus of a series of standards from the IEEE Standards Association (IEEE SA) under development by the IEEE 802.1™ Working Group's Time-Sensitive Networking Task Group. The standards define mechanisms for the time-sensitive transmission of data over deterministic Ethernet networks. TSN is not addressed in a single standard. Rather, its collection of capabilities are governed and managed by several separate IEEE standards. TSN uses a profiles approach, which defines the specific set of features, options, configurations, and protocols appropriate for a particular set of TSN applications. Some profiles are well defined, while others are still works in progress.

TSN IN THE AUTOMOTIVE INDUSTRY

Functionality advancements and driver features in today's automotive systems require high-bandwidth and low-latency

Glenn Parsons is the chair of the IEEE 802.1 Working Group and a principal standards advisor for Ericsson. Parsons is an internationally known expert in networking, including mobile transport and Ethernet, and is currently involved in 5G transport standardization efforts with the IEEE SA and ITU-T. Parsons was also the founding Editor-in-Chief of IEEE Communications Standards Magazine. He can be reached at glenn.parsons@ericsson.com.

in-vehicle communications. Innovation in automotive technology is focused on both hardware and software for an increasing number of applications, including but not limited to adaptive cruise control with stop-and-go, lane departure warning, blind-spot warning, traffic sign recognition, night vision, active headlight system, parking automation, efficient dynamics, hybrid engines, internet access, telematics, online services, Bluetooth integration, local hazard warning, personalization, SW update, and smartphone apps.

This list goes on and continues to grow with the pace of new, innovative features and, of course, the advent of autonomous vehicles.

Embedded software is a key enabler for advanced functionality and features in automotive systems, which is becoming more complex and requiring increasing amounts of source code. And software complexities lead to more challenges such as requirements for timing predictability and the distribution of software over electronic control units (ECUs), just to name two.

In the automobile sector, Ethernet is the answer for several reasons, including:

- Data needs such as raw camera data, data logging, map data, backbone aggregation, high-resolution displays, and in-vehicle Wi-Fi hotspot (carrier link aggregation) wired backhaul;
- Latency requirements, with the minimum need determined by hardware and the maximum determined by software;
- Services, including precise time awareness, redundancy/fail-over, and security;
- More challenging standards for fuel economy, oftentimes by pioneering and using lighter weight materials; and
- Reduced costs for vehicle manufacture, an underlying reason that cannot be ignored.

To leverage Ethernet, the TSN protocol can precisely guarantee the time certainty of the key signals of automotive Ethernet. Accurate timing and guaranteed data delivery are critical in the automotive environment. IEEE 802.1AS™ provides timing accuracy in the sub-microsecond range, which is required as Ethernet usage grows within the vehicle. In addition, other IEEE and TSN standards provide secure, ultra-reliable, bounded low-latency communications throughout the vehicle at multiple data rates.

Cabling is the third highest cost component in a car, with the engine being first followed by the chassis.

Wire harnesses are constructed one at a time, with half of the cost coming from labor. And the wire harness also is the third heaviest component in a car. We can clearly see that reducing the cable weight in a vehicle will directly impact its fuel economy. Thus, because the in-vehicle wiring plant is a tremendous challenge with regards to weight and space coupled with higher throughput requirements for automotive sensors, various PHYs targeting automotive are available today, including 2-wire 10 Mb/s (IEEE 802.3cg™), 100 Mb/s (IEEE 802.3bw™), 1 Gb/s (IEEE 802.3bp™) and 2.5/5/10 Gb/s (IEEE 802.3ch™).

Previously known as the audio video bridging (AVB) series of standards, which are successfully used in automotive infotainment systems today, AVB has evolved into time-sensitive networking in order to reflect the expanded scope of work toward autonomous driving.

In the automotive sector, TSN is leveraged to achieve:

- *Time synchronization*—IEEE 802.1AS maintains synchronized time (+/- 500 nsec worst case) and supports scheduling-bounded low-latency traffic through the network where required while also allowing asynchronous traffic.
- *Very low jitter*—IEEE 802.1AS reduces jitter associated with audio/video, command, sensor, and control packet delivery to upper layers.
- *Bounded low latency*—Time scheduled traffic (IEEE 802.1Qbv™) and preemption (IEEE 802.1Qbu™) are combined with no need to compress video and other advanced driver assistance systems (ADAS) data (since speeds up to 10 Gbit/s allow multiple channels of high-definition video). As a result, the use of TSN avoids the latency and processing power penalties associated with compressions and decompression.
- *Ultra-reliability*—TSN provides reliability in the network (IEEE 802.1CB™ - frame replication and elimination), protection from errant devices (ingress policing), and backup for network timing master (standby GM).
- *Security*—Authentication of installed devices (IEEE 802.1AR™ - secure device identity), segregation of traffic types and flows between authorized devices, message integrity, and authenticity are possible.
- *Fast startup*—Preconfigured values for timing and bandwidth reservation allows quick startup followed by an optional transition to negotiated values for dynamic adjustments.
- *Faster updates*—Firmware updates are quicker with Ethernet's higher speed.
- *Information sharing*—A homogeneous Ethernet network allows instant sharing of information between allowed devices without the delays and security risks associated with interconnecting different bus types through gateways.

TSN IN MANUFACTURING

A prevalent need for deterministic Ethernet can be found in industrial automation in the ongoing quest to achieve fast, deterministic, and robust communication. While there are several proprietary solutions available, TSN can help standardize real-time Ethernet across the industry.

IEEE 802.1 TSN is an enabler of Industry 4.0, such as the smart factory of cyber-physical systems. TSN is the foundation that provides connectivity and real-time quality of service to time and mission-critical industrial applications on converged networks of operations technology and information technology and converging multiple independent applications in one network, enabling real-time communication on the same infrastructure (cables, bridges). TSN meets these requirements by providing interoperability via open standards. TSN provides synchronization and supports real-time communication, for example, closed loop control over a single standard Ethernet network.

IEEE SA and the International Electrotechnical Commission (IEC) have established a joint project, the IEC/IEEE 60802™ Time-Sensitive Networking Profile for Industrial Automation, so that the right mix of experts is involved in defining the use of TSN for industrial automation. By selecting TSN features and describing their use including configurations and defaults, the IEC/IEEE 60802 standard aims to benefit vendors offering and/or developing TSN products as well as the users of industrial automation technologies.

In smart factories, TSN provides guaranteed data transport with bounded low latency, low jitter, and extremely low data loss. In the manufacturing sector, TSN is leveraged to achieve:

- *Time synchronization*—IEEE 802.1AS maintains synchronized time (+/- 500 nsec worst case) end-to-end, i.e., including the devices running the control applications. Time synchronization is the basis of multiple TSN quality of service (QoS) solutions, e.g., time-based scheduling.
- *Bounded low latency*—TSN includes multiple solutions to provide bounded low latency, e.g., time-scheduling, preemption, and traffic shaping mechanisms. Time

As TSN continues to gain interest and use across multiple industries, so too does the demand for an increasing number of profiles – the selection and use of TSN tools for specific applications.

synchronization and TSN QoS solutions can reduce packet delay variation (jitter).

- *Resource management*—Standard protocols, data models, and interfaces to dedicate resources for time and mission-critical traffic.
- *Zero congestion loss*—TSN provides zero congestion loss via the bounded low latency and the resource management solutions.
- *High availability/ultra-reliability*—TSN provides ultra-reliability and high availability in the network up to seamless communication over redundant paths (frame replication and elimination), protection from errant devices (ingress policing), and backup for network timing master (standby grandmaster).
- *Security*—Authentication of installed devices, segregation of traffic types and flows between authorized devices, message integrity, and authenticity are possible.
- *Converged network*—TSN supports multiple traffic classes that may have very different requirements. Thus, control data traffic in real-time and multiple independent applications using the same network can be carried together with best-effort traffic in the same network infrastructure, increasing the economic feasibility of the network.
- *Interoperability*—TSN leverages the benefits of existing IEEE 802.3 Ethernet, e.g., diagnostics; thus, TSN is applicable in brownfield deployments. A common information model for the network resources enables common TSN engineering and diagnostics. The harmonized interfaces and the protocols for stream set-up support interoperability. Variants should be limited by a harmonized TSN profile for industrial automation, i.e., IEC/IEEE 60802, to enable multi-vendor networking to interconnect different bus types used in end stations.

TSN IN THE AVIATION INDUSTRY

In the aviation sector, high-bandwidth and low-latency communications are required for technology-rich modern aircraft for avionics, sensors, communications, and entertainment systems, all of which rely on on-board networks. For many years, Ethernet has been the network infrastructure protocol of choice. More recent innovations, notably on commercial aircraft, include advanced avionics systems, onboard Wi-Fi, in-flight entertainment, and connectivity (IFEC) systems, global position system (GPS) data, and more.

IEEE P802.1DP™ / SAE AS6675 is a joint project of IEEE 802 and SAE Avionics Networks AS-1 A2 to define TSN profiles for aerospace. This work will provide a jointly developed standard that serves as both an SAE and an IEEE standard. This standard specifies profiles of IEEE 802.1 TSN and IEEE 802.1 security standards for aerospace onboard bridged IEEE 802.3 Ethernet networks. The profiles select features, options, configurations, defaults, protocols, and procedures of bridges, end stations, and local area networks facilitate the design of deterministic networks for aerospace onboard communications.

Additionally, this standard specifies profiles for designers, implementers, integrators, and certification agencies of deterministic IEEE 802.3 Ethernet networks that support a broad range of aerospace onboard applications, including those requiring security, high availability and reliability, maintainability, and bounded latency.

CONCLUSION

As TSN continues to gain interest and use across multiple industries, so too does the demand for an increasing number of profiles – the selection and use of TSN tools for specific applications.

Join us in this initiative! The IEEE 802.1 Working Group welcomes participants from academia, government, and industry. We invite those interested in the noted application spaces or in new ones. For more information or to join the standards activity, please visit the TSN webpage at https://1.ieee802.org/tsn. To learn more, follow the latest news about our work at https://1.ieee802.org/category/latest-news.

SCIF and Radio Frequency Secured Facility Design, Part 2

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

BY JOEL KELLOGG

In recent years, we've noticed a growing confusion in the industry over design and performance requirements for sensitive compartmented information facilities (SCIF). Part 2 of this article is intended to highlight the significant difference in the performance of radiofrequency (RF) shielding between facilities designed per ICS/ICD-705[1] and those intended to meet NSA 94-106[2] performance requirements. We will also highlight some of the design and construction methodologies that lead to significant differences in performance.

INTRODUCTION TO SCIF SPECIFICATIONS

As noted in Part 1[3] of this article, there is a common misconception that a SCIF design utilizing ICS/ICD-705 construction recommendations will achieve the performance requirement set forth in NSA 94-106, the NSA standard for RF shielding performance and testing. Part 1 reviewed the typical construction recommendations identified in ICS/ICD-705, recommended materials, and typical installation methodologies used. The article further identified differences in typical construction between SCIF designs and facilities designed to meet the performance requirements identified in NSA 94-106 and provided explanations as to how those differences impact RF shielding effectiveness.

Part 2 of this article will highlight some of the methods utilized in ICS/ICD-705 that limit RF shielding performance and some alternate methods that could increase the RF shielding performance. Further, we will discuss other common deviations that often increase project costs without providing any enhanced RF performance. Finally, Part 2 will document the significant differences in potential RF performance utilizing measurement data collected from a facility built per ICS/ICD-705 construction methods and a facility designed to meet NSA 94-106 requirements.

SCIF OVERVIEW

Ranging from physical barriers to facilities constructed using RF shielding with construction methods to reduce acoustic noise, SCIF requirements and construction specifications for a given project are based on a host of factors, including the purpose of the facility, surveillance risk, physical location, etc. The risk and vulnerability of the SCIF should be evaluated by the Accrediting Officer (AO) and Site Security Manager (SSM). That evaluation will help inform the selection of the technical measures required for each SCIF application. The project's Certified

Joel Kellogg is the Director of Business Development for Healthcare, Industry, and Government at ETS-Lindgren, and has more than 20 years of design, production, and management experience in healthcare, government, and industrial projects. He can be reached at joel.kellogg@ets-lindgren.com.

TEMPEST Technical Authority (CTTA) will assess the requirements for TEMPEST,[4] providing direction on RF shielding requirements and design.

Despite a clear process for design direction and general construction recommendations established in ICS/ICD-705, many project documents deviate from the typical ICS/ICD-705 direction. Those deviations can range from specifying alternate shielding materials to utilizing alternate construction methods to establishing RF performance requirements not supported by the project's design. These deviations often have a variety of adverse effects from increased project costs to designs that do not support the shielding requirements. This puts all involved, including the facility owners, facility designers, and general contractors, in the challenging position of having to work through the disconnects between design and specified performance, often during the construction phase of a project.

NSA 94-106 VERSUS ICD/ICS-705 PERFORMANCE

In Part 1 of this article, we noted that it is not uncommon for NSA 94-106 RF shielding performance requirements to be specified as part of a project's requirements for a SCIF using ICS/ICD-705 wall types and construction methods. Further, many projects will reference what appears to be an arbitrary performance requirement. For example, a project's specifications may require 60 dB of performance from 1 GHz to 10 GHz, despite the fact that ICS/ICD-705 does not specify an RF shielding performance. Further, the general construction methods outlined in ICS/ICD-705 are not intended to achieve a specific RF shielding performance utilizing industry-standard methods for quantifying RF shielding performance as defined in test specifications such as IEEE 299[5] and NSA 94-106.

Previously, we noted several reasons why design recommendations in ICS/ICD-705 will not achieve NSA performance requirements. Some of these reasons include the manufacturer's data for the shielding foil material typically specified for SCIF applications clearly demonstrating that the material will not achieve NSA 94-106 shielding performance requirements. We also identified that the recommended construction for walls in ICS/ICD-705 results in substantial perforation of the shielding material, which will degrade performance. Other factors include the typical ICS/ICD-705 design recommendations that do not require shielding on the ceiling or floor and do not call for use of other elements critical to achieving high levels of RF shielding performance, including filters, waveguides for mechanicals, and RF shielded doors.

Based on their assessment, the CTTA may provide recommendations or require the shielding of floors and ceilings and request the inclusion of filters, treated penetrations, and RF doors. But this does not mean the design will meet NSA 94-106 performance without substantial changes to the general design recommendations provided in ICS/ICD-705.

To highlight this discrepancy, data is provided from two different SCIF facilities. The first facility, with performance data provided in Figure 1, was designed and constructed in strict accordance with NSA 94-106. Therefore, this facility was designed and constructed using shielding materials that meet all the magnetic field, electric field, plane wave, and microwave performance requirements identified in NSA 94-106, which include 100 dB of attenuation at 10 GHz. This requires a six-sided RF shielded enclosure with properly treated penetrations, electrical filters, and a high-performance shielded door.

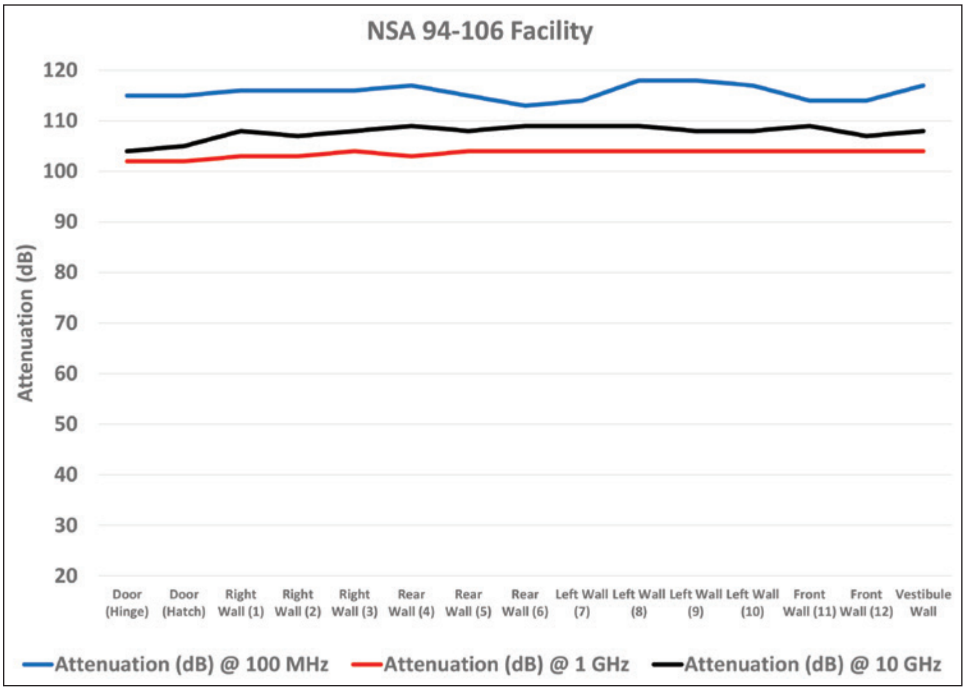

Figure 1: Facility design to meet NSA 94-106 requirements. Attenuation measured utilizing IEEE 299 test procedure.

The second facility design utilized the ICS/ICD-705 Wall A construction for interior walls and along exterior building perimeters. The facility design provided shielding enhancements beyond those identified in ICS/ICD-705, including RF doors, electrical filters for power and building management systems, HVAC RF waveguides, and RF waveguides for plumbing, which enhanced performance over the typical recommendations provided in ICS/ICD-705. Finally, the facility also included windows, which are typically discouraged under ICS/ICD-705 but are occasionally included in a SCIF design. This facility's project requirement identified custom RF shielding performance at 90 MHz, 900 MHz, and 6 GHz with attenuation requirements of 10 dB to 30 dB.

Since the SCIF facility performance requirements identified frequencies that did not coincide with NSA 94-106 test frequencies, only the 100 MHz, 1 GHz, and 10 GHz test frequencies of the facility designed to meet NSA 94-106 were provided to achieve as relevant a comparison as possible. There is clearly a significant difference in the performance, with average differences of 55 dB or more and peak differences of up to 80 dB. The ICS/ICD-705 Wall A calls for the shielding layer to be sandwiched between two layers of drywall, but the finish layer of drywall had not been installed at the time that these measurements were recorded and the shielding performance would likely decrease further once the drywall is added.

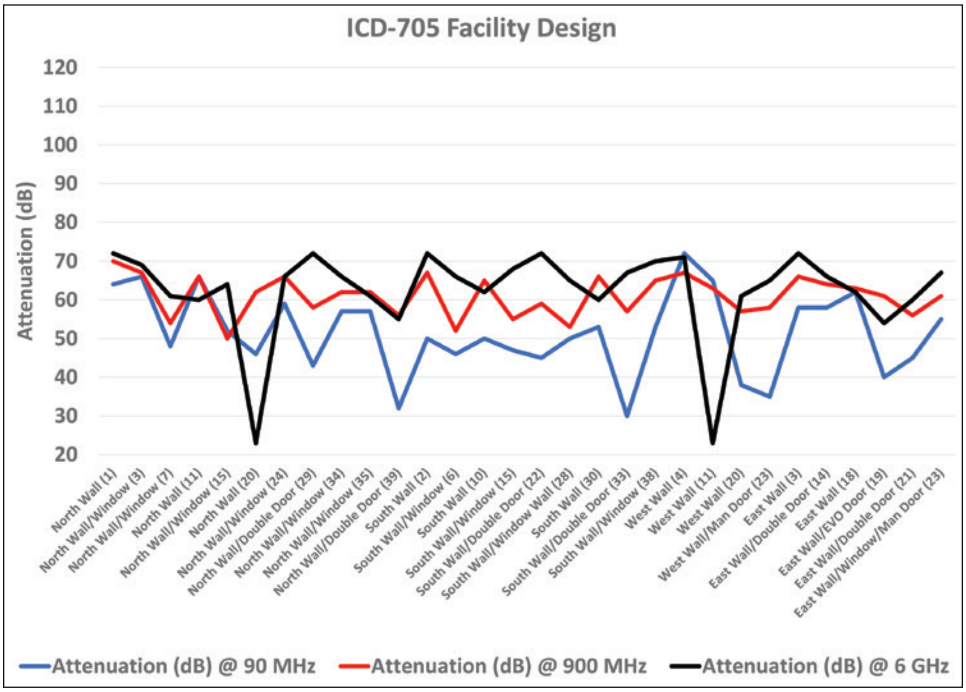

Figure 2: Facility design using ICD-705 Wall A with the addition of floor and ceilings, RF doors, filters, and treated penetrations. Attenuation measured utilizing IEEE 299 test procedure.

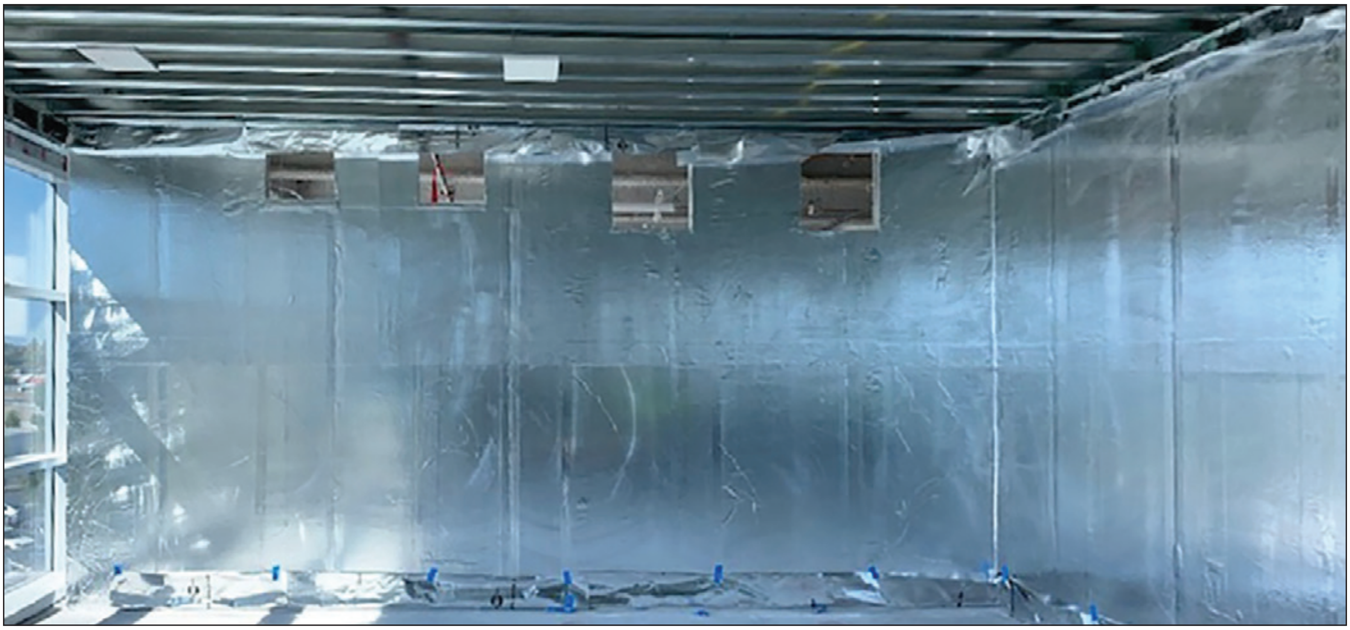

Figure 3: Example of ICS/ICD-705 RF shielding barrier installation

There are multiple examples of a facility filtering all power sources but choosing not to filter all data lines because the data is entering through the floor, which is slab on grade. However, it does not matter the location from where that cable or wire is entering.

DESIGN AND PRODUCT SELECTION CONTRIBUTORS TO LIMITED RF SHIELDING PERFORMANCE

RF performance will be significantly limited in cases where the SCIF design only calls for the ICS/ICD-705 wall construction without shielding on the ceiling and floor, and without RF doors, no treated penetrations, or filtered power. However, it is apparent from the data presented in Figure 2, the case in which many of these factors were eliminated, that there are still additional factors that limit performance.

In this specific application, the windows are one factor that limited performance. There are a few different types of protection for windows, including RF film, RF glass, and RF shielded windows, which incorporate an RF shielded screen. These technologies are typically limited to between 40 dB and 80 dB at 10 GHz, depending on the performance of a specific product, and vary in performance from 1 kHz to 10 GHz.

Another factor limiting the RF shielding performance is the primary recommended shielding material. An example of the material often used in SCIF designs is shown in Figure 3. The most frequently recommended shielding material does meet the RF shielding attenuation requirements of NSA 94-106, according to the manufacturer's data. But the manufacturer's data is based on a small sample under ideal test conditions, tested on an RF shielded enclosure, and performs optimally at greater than 100 dB from 100 MHz to approximately 1.5 GHz. Above 1.5 GHz, the performance rolls off according to the manufacturer's data. The performance below 100 MHz appears to roll off as well, and the attenuation will certainly decrease substantially for magnetic (H-field) fields as the frequency decreases.

To overcome the limited performance in some frequency ranges, some designs will specify thicker copper foil or aluminum sheets. But the specified materials may still not meet NSA 94-106 if identified as a performance requirement. Further, in the next section of this article, we will identify some construction challenges that will degrade RF shielding performance and limit the benefit of specifying a different material

It is also common to see many issues overlooked in designs that are critical to RF performance, resulting in incremental degradation of RF shielding performance. Common issues include not identifying all items that require filtering. Whether it is used for power, communication, data, or building management systems, a component than includes or uses conductive cables or wires needs to be filtered to maximize the RF performance of a shielding system.

There are multiple examples of a facility filtering all power sources but choosing not to filter all data lines because the data is entering through the floor, which is slab on grade. However, it does not matter the location from where that cable or wire is entering. If it is conductive, it has the ability to carry signals and radiate similar to an antenna. Similarly, critical or protected signals are at risk of coupling to those cables or wires and leaving the secured space. In some cases, this lack of protection may be a concern over costs associated with data filters or communication filters. However, a cost-effective solution may be to use fiber-optics in the secure space that can penetrate the shielding through an inexpensive RF waveguide or series of RF waveguides.

Other common design issues include allowing untreated mechanicals and plumbing not specific to the SCIF to penetrate and pass through the SCIF RF shielding. This simply creates additional points where RF signals can leak into or out of the SCIF. Again, if the purpose is to maximize RF shielding performance, then any penetration into or out of the shielded space must be properly treated. To avoid potential RF performance issues, it is recommended that only items being utilized in the RF shielded space of a SCIF pass through the RF barrier and that any other items supplying other areas of the facility be routed outside the shielded space. Of course, there are exceptions, but those should be evaluated individually based on an assortment of factors including the cost and the impact on RF performance.

CONSTRUCTION CHALLENGES CONTRIBUTORS TO LIMITED RF SHIELDING PERFORMANCE

The recommended wall detailed in ICS/ICD-705 shows the RF shielding material sandwiched between two layers

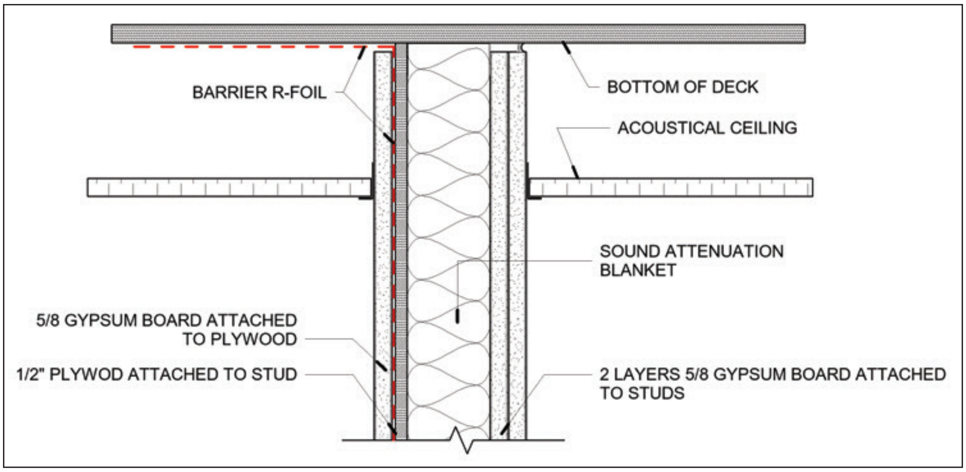

Figure 4: ICS/ICD-705 Wall C depicting an RF barrier between plywood substrate and finish drywall

of drywall or drywall and a substrate such as plywood (see Figure 4). The second layer of drywall must be secured to the wall, and this is typically achieved by mechanically fastening the drywall with screws. But this method penetrates the RF shielding, thus creating the potential for RF shielding leakage.

As mentioned in the previous sections, some designs will identify the use of an alternative shielding material. But this method of construction results in potential RF shielding leakage regardless of shielding material specified. Therefore, the installation of alternative shielding materials may not necessarily enhance RF shielding performance and result in additional project costs with no benefit to the RF shielding performance.

Other common construction challenges when building a SCIF include shielding at the ceiling, RF-shielded doors, and treatment of penetrations when specific RF performance requirements have been identified as part of the design requirements. Many SCIF designs may require that the wall foil turns onto and overlaps the ceiling around the perimeter of the SCIF when the ceiling is a metal pan deck. However, RF performance will be limited by the existing penetrations through the metal deck.

Additionally, projects may identify that a shielding material must be applied to a ceiling. In most cases, the ceiling is also used to support electrical and mechanical systems and components such as plumbing and HVAC. This is often accomplished using threaded rods or angles that are attached through the ceiling. An example is shown in Figure 5.

Figure 5: HVAC, electrical, and plumbing support angles with threaded rod penetrating copper fabric shielding material at the ceiling

Unfortunately, this technique may result in hundreds, if not thousands, of penetrations through the ceiling, creating the potential for RF leakage. RF shielding companies know how to treat these connections to maximize the RF shielding performance, but an HVAC contractor or plumber with no RF shielding experience is not likely to know how to manage the penetrations. Regardless, these additional penetrations of the shielding can have a negative impact on the overall RF shielding performance.

There may also be untreated penetrations through the walls. If the penetrations are made of a conductive material, such as with conduit, plumbing, and HVAC ducts, it may be recommended that the shielding be bonded to the penetration in an effort to maximize the shielding performance. However, this recommendation does not represent a best practice for RF shielding and will likely reduce the overall shielding performance. Further, these penetrations may have construction debris or paint and may limit electrical conductivity if not cleaned properly. Lastly, the penetration may not be conductive, made of either PVC or some other nonconductive material. These penetrations represent additional areas that could significantly reduce the RF shielding performance. An example is shown in Figure 6.

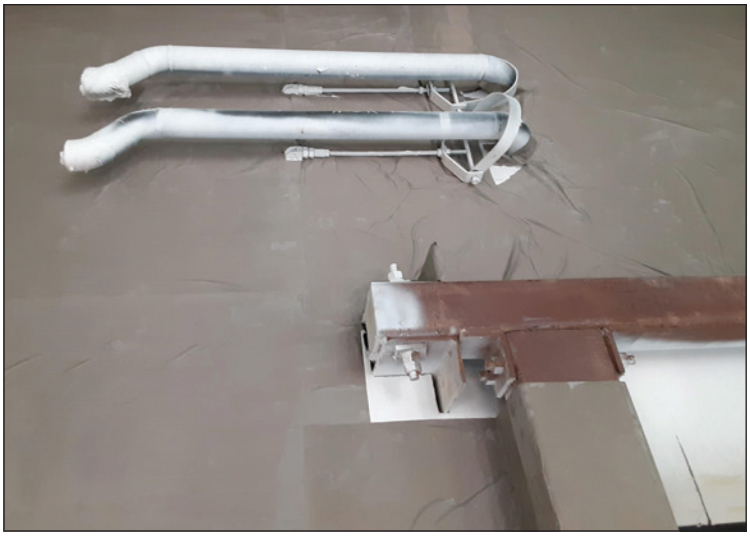

Figure 6: Untreated penetrations passing through shielding material representing a point where shielding performance may be significantly degraded

ADDRESSING SECURITY REQUIREMENTS FOR RF SHIELDED DOORS

There is also a significant impact to doors when referencing NSA 94-106 or some other level of higher RF performance criteria for a SCIF application. Currently, there is no RF door available on the market that meets the typical acoustic requirements for a SCIF and the high levels of RF performance required under NSA 94-106. Additionally, specific high-security locks, including X10 locks, are required to meet security requirements. In order to maintain RF attenuation levels of 100 dB, locks typically need to be taken apart and modified to be integrated into an RF door. But this step voids the security rating of the lock.

Under NSA 94-106, these issues are addressed by either creating a vestibule or an enlarged door jamb to accommodate an acoustic door with the required security locks and a separate RF door to meet the RF performance requirements. Most SCIF designs do not include this type of design for doors, creating a significant and expensive construction issue when SCIF project documents identify NSA 94-106 or some other elevated level RF performance (>60 dB at 10 GHz).

CONCLUSION

As discussed in Part 1 of this article, referencing both ICD/ICS-705 and NSA 94-106 as part of a project can create much confusion in terms of project requirements. Part 2 of this article highlights the performance differences between the construction recommendations presented in ICD/ICS-705 and the requirements identified in NSA 94-106. Further, we highlighted that project-specific performance requirements may be difficult to achieve utilizing the construction recommendations provided in ICD/ICS-705. Placing specific RF attenuation requirements on a project utilizing ICD/ICS-705 can put a project at risk if the project's design is not carefully reviewed to ensure that RF performance requirements are met.

Finally, it is not uncommon to discover that a project's design will not meet the RF performance requirements. This puts the project team in the precarious position of having to determine where to compromise between design and project performance requirements while absorbing unexpected and potentially substantial additional costs.

To mitigate these issues, we recommend that SCIF design teams review the actual requirements with the CTTA before a project specification or request for quotation is finalized. It's also a good idea to include an RF shielding consultant on the design team to assist in coordinating the RF shielding design and to ensure that the finished structure meets the performance requirements.

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2. NSA 94-106 (not available for public reference).
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5. IEEE 299, "IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures."

Latest EU Ecodesign and Energy Labeling Developments

The Proposed Sustainable Products Regulation and the 2022-2024 Working Plan

BY ALEX MARTIN

When it comes to energy-related products,[1] sustainable product policy in the European Union (EU) is largely implemented through the ecodesign and energy labeling legislative frameworks. Product-specific laws have been adopted under each framework. For example, various household appliances are the subject of individual EU Regulations concerning ecodesign[2] and energy labeling. In all, about 30 product groups are regulated through some 50 measures.

While the legislative frameworks have been in place for many years, they have also been subject to periodic review and updating. For instance, the 2017 adoption of the EU Energy Labelling Framework Regulation came with the repeal of the 2010 Energy Labelling Framework Directive and the introduction of obligations associated with a product database – later known as the European Product Database for Energy Labelling (EPREL).

This article discusses the intention to update EU ecodesign legislation through the recent tabling of a proposal for a Sustainable Products Regulation. It is anticipated that this proposed EU Regulation will be adopted within the next two years. Meanwhile, a plan has been published for advancing existing EU policy concerning the sustainability of energy-related products between now and 2024. This is the European Commission's 2022-2024 Ecodesign & Energy Labelling Working Plan – something that this article also comments upon.

Dr. Alex Martin is Principal Regulatory Consultant at RINA. He provides advice and compliance support on various regulations affecting electro-technical products, from EMCD, LVD, and RED through to environmental laws like RoHS, REACH, and WEEE. Martin can be reached at alex.martin@rina.org

THE PROPOSED SUSTAINABLE PRODUCTS REGULATION

On 30 March 2022, the European Commission tabled a proposal for an EU Regulation establishing a framework for setting ecodesign requirements for sustainable products. The intent of this proposed Regulation is to replace the current Ecodesign Framework Directive (2009/125/EC). If adopted, the proposed Regulation would overhaul the existing EU ecodesign legislative framework.

In particular, the proposed Regulation would broaden the legislative scope such that any physical good placed on the EU market could be targeted (at present, the scope is confined to energy-related products), while more focus would be given to regulating product aspects other than energy performance (e.g., durability, reliability, reusability, upgradability, repairability, information requirements). Other things in contention include digital product passports, new obligations for fulfillment service providers, online marketplaces, and online search engines, and preventing the destruction of unsold consumer products.

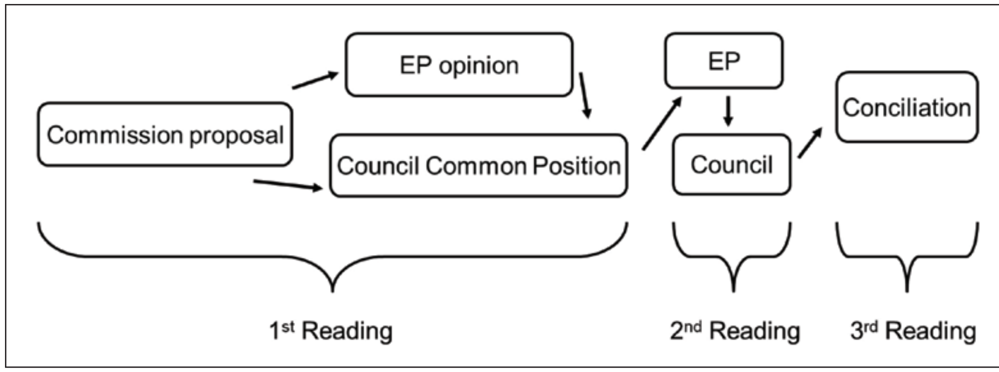

Figure 1: The ordinary legislative procedure

Requirements for specific products or product groups would be set via delegated acts. It appears that the European Commission will soon consult on which products or product groups should be prioritized for regulation in the years ahead.

In the meantime, the proposed Regulation is subject to the EU's ordinary legislative procedure, meaning that the proposal will be scrutinized by the European Parliament (EP) and the Council of the EU in the coming months with tripartite meetings between Parliament, the Council, and the Commission also taking place. The ordinary legislative procedure is illustrated in Figure 1.

It will be interesting to see whether the proposed Regulation is adopted during a first reading or if it takes a second or third reading for the proposal to make its way into law. Come what may, the adoption of a new law is at least 18 months away, while it will still take longer for product-specific delegated acts to be drafted and adopted.

For the moment, those involved in the manufacture and supply of electrical and electronic equipment (and other products) should take heed of the proposal while noting that it is likely to be two years or more before anything substantive emerges in the form of new EU sustainable products legislation. In the meantime, all existing EU ecodesign legislation continues to apply, as do scheduled legislative reviews, completion of outstanding ecodesign preparatory studies, and so on.

For readers interested in the detail, Table 1 on pages 116 and 117 summarizes the main changes the proposed Regulation would bring into effect. The text in this table is reproduced from a European Parliamentary Research Service briefing paper on the proposed Regulation.[3]

THE 2022-2024 ECODESIGN & ENERGY LABELLING WORKING PLAN

Coinciding with its proposed Sustainable Products Regulation, the European Commission published its new Ecodesign Working Plan. Specific to the next two years, the Plan also outlines what is in the cards for energy labeling.[4]

Ecodesign Working Plans consider the potential for setting and/or furthering ecodesign requirements for different products. To date, the Commission has published three working plans, and it published its fourth in April of this year – although its scope has been broadened to also consider the potential for energy labeling this time round.

According to the Commission, the 2022-2024 Ecodesign & Energy Labelling Working Plan "strengthens the focus on the circularity aspects of ecodesign, following the example set in the previous Working Plan and in line with the Circular Economy Action Plan 2020." To this end, "new product-specific requirements on material efficiency aspects can and will be explored. This should result in further improved circularity and overall reduction of environmental and climate footprints of energy-related products, as well as stronger EU resilience."

Review Priorities

The Commission intends to prioritize the review of the following product groups:

- *Heating and cooling appliances*—This is based on the Council of the EU's request that the Commission "accelerate the ongoing work on heating and cooling appliances by rescaling energy labels as soon as possible." Meanwhile, the Commission affirms that the work will "be a critical contribution to the decarbonization of buildings and the Zero Pollution action plan as part of the overall Green Deal objectives, and these products are those with the highest energy consumption of all regulated products."
- *Other product groups with energy labels up for rescaling*—The EU energy label was subject to rescaling in 2020 and, in 2021, the provision and display of rescaled energy labels became a legal requirement in the case

Scope	The scope would be extended beyond energy-related products, so the new Regulation would apply to any physical good placed on the market, with a few exceptions, such as food, feed, medicinal, and veterinary products (Article 1(2)).
Ecodesign requirements	Products on the internal market would have to comply with ecodesign requirements, which would be set out later, in delegated acts, for each group of products separately (Article 3). Ecodesign requirements would aim to improve product durability, reliability, reusability, upgradability, reparability, possibility of maintenance and refurbishment, presence of substances of concern, energy use and energy efficiency, resource use or resource efficiency, recycled content, possibility of remanufacturing and recycling, possibility of recovery of materials, environmental impacts and expected generation of waste materials. Product groups would be prioritized based on their potential contribution to EU climate, environmental and energy efficiency goals, and their potential for improvement without disproportionate costs (Article 16). The ecodesign requirements would continue to be prepared by an expert group comprising Member State representatives and other interested parties, such as industry, small and medium-sized enterprises, trade unions, traders, retailers, and consumer and environmental organizations. The group would be renamed the Ecodesign Forum (Article 17).
Performance and information requirements	The Regulation distinguishes between performance requirements, such as durability and ease of repair (Article 6 and Annex I), and information requirements (Article 7). Information requirements should include at least requirements related to the product passport and to substances of concern. They could also include information on the performance of the product (with the Commission being required to determine classes of performance to enable consumers to compare products); information for consumers on installation, use, maintenance, and repair; and information on treatment facilities for disassembly, recycling, or disposal, etc. The required information would have to be provided on the product, on the product packaging, the product passport, a label, in a user manual, or on a website or application.
Misleading labels	The Commission would be empowered to adopt rules on labels indicating the performance of a particular group of products. For those products where no rules on labels are adopted by the Commission, using labels that mimic such labels and that could mislead or confuse consumers would be banned (Article 15).
Product passport	Delegated acts for specific product groups would require a product passport to be available for each product. The product passport could include information on performance and information requirements; information related to traceability of the product; the declaration of conformity; technical documentation; user manuals; and information about the manufacturer, importer, or authorized representative. The delegated acts would determine which information would be included and who would have access to what (e.g., consumers could have access to different information than manufacturers, importers, repairers, recyclers, or national authorities) and who would be allowed to update which information (Article 8). The information would be stored in a registry set up by the Commission (Article 12) and would be accessible via a data carrier (such as a barcode) on the product, its packaging or documentation (Article 9).
Self-regulation measures	Two or more economic operators would be able to submit a self-regulating measure establishing ecodesign requirements as an alternative to the adoption of a delegated act, provided that their market share in terms of volume is at least 80% of the units placed on the market (Article 18).

Table 1: Key changes envisaged within the proposed Sustainable Products Regulation

of household washing machines and washer-dryers, household dishwashers, electronic displays, refrigerating appliances, and light sources. The Commission is now keen to pursue the "timely rescaling and updating [of] the remaining 'old' energy labels… tak[ing] full advantage of the new features offered by EPREL." Among the other product groups likely to be targeted when it comes to the rescaling of existing energy labels are air conditioners, domestic ovens and cooker hoods, household tumble dryers, space heaters, residential ventilation units, solid fuel boilers, and more.

- *Other product groups with the potential for significant additional energy savings*—This includes product groups that represent significant additional savings potential in terms of energy or material savings, that are long overdue, or where particular circumstances imply a clear or urgent need for revision. For example, the Commission names water pumps, fans, and external power supplies.

Products Targeted for Future Ecodesign Preparatory Studies

The Working Plan explains that the Commission has identified 31 product groups that could be targeted for ecodesign and energy labeling. It advises that, together, these product groups present "new potential use phase savings in 2030 in the order of 1 000 PJ, or 278 TWh, i.e., circa 2% of EU primary energy use in 2020."

Destruction of unsold goods	Companies that discard unsold consumer products would be subject to transparency requirements and would have to publish, for instance, the number of discarded products, the reasons for discarding them, and how many of the discarded products were prepared for reuse, remanufacturing, recycling, energy recovery, and disposal. Companies would need to disclose the information on a publicly accessible website. The Commission would be empowered to ban the destruction of particular groups of products that have significant environmental impacts. In principle, these rules would not apply to SMEs, but a delegated act for a particular group of products could still specify otherwise (Article 20).
Incentives for sustainable products	Member States would be allowed to provide incentives for consumers to make sustainable choices, in particular when more sustainable products are not sufficiently affordable, by, for instance, introducing eco-vouchers and green taxation. The incentives would have to be targeted at products in the two highest classes of sustainability performance (Article 57).
Green public procurement	The Commission would be empowered to adopt delegated acts establishing ecodesign requirements applicable to public contracts, including mandatory technical specifications, selection criteria, award criteria, and contract performance clauses or targets (Article 58).
Obligations for online marketplaces	The Regulation would specify the obligations of online marketplaces concerning market surveillance. They would be required to cooperate with the market surveillance authorities to ensure effective market surveillance measures; inform the market surveillance authorities of any action taken in cases of non-compliant products; establish a regular exchange of information on offers that have been removed; and allow online tools operated by market surveillance authorities to access their interfaces in order to identify non-compliant products. Online marketplaces would be required to design and organize their online interfaces in a way that would enable dealers to comply with the requirements of the Digital Services Act regarding pre-contractual information and product safety information. Member States would be required to empower their market surveillance authorities to order an online marketplace to remove products that do not comply with the ecodesign requirements (Article 29).
Prevention of circumvention	Products that can detect if they are being tested in order to alter their performance and achieve a more favorable result would be banned (Article 33).
Market surveillance plans	Every two years, Member States would be required to draw up an action plan for market surveillance activities in relation to ecodesign and communicate these plans to the Commission and other Member States (Article 59). The Commission would be empowered to adopt delegated acts laying down the minimum number of checks by market surveillance authorities on specific products or specific requirements (Article 60).
Evaluation	The Commission would be required to carry out an evaluation of the Regulation eight years after its adoption (Article 69).
Entry into force	The Regulation would enter into force 20 days after its adoption and would be applicable immediately. However, since this would be a Framework Regulation, new ecodesign requirements would be applicable to specific groups of products only after the adoption of product-specific delegated acts.

Table 1: Key changes envisaged within the proposed Sustainable Products Regulation *continued*

However, given that the Commission must work within time and budgetary constraints, it has shortlisted five of the 31 product groups for which it "envisages initiating exploratory studies." These are identified in Table 2, which is a reproduction of what is found in the European Commission Communication that accompanied the publication of the Working Plan.[5]

Of further note is the Commission's stated wish to "further assess the possibility and appropriateness of establishing more product-specific requirements" when it comes to:

- Recycled content;
- Durability, firmware. and software; and
- Reducing or eliminating uses of scarce, environmentally relevant, and critical raw materials in energy-related products.

Here, the Commission states that "the requirements are theoretically applicable to all energy-related products; dedicated preparatory studies will be needed to help identifying the product categories that are most relevant for potential regulatory approaches."

The EPREL

The Commission states that "there are important functionalities that need to be addressed in 2022," all with a view to "operationalis[ing] several EU policies, including in relation to public incentives, sustainable private sector investments, green public procurement, and reduced VAT rates for certain energy-labeled products." The envisaged functionalities include:

- Introducing a dedicated web portal that will be the single access point, providing targeted information for citizens, national authorities, suppliers, dealers, and policymakers;
- Improving the user interface and tools available to market surveillance authorities to better streamline their activities;
- Transforming the structure of the technical documentation to streamline registration activity by suppliers and facilitate analysis thereof by compliance authorities; and
- Starting the implementation of revised regulations for some product groups and possibly adding new ones (e.g., smartphones and tablets).

In addition, the Commission asserts that "it will be necessary to consider the conditions for, and modalities of, granting access to EPREL or some of its features to operators and possibly authorities from specific third countries, notably those that are part of the customs union or the Energy Community."

Market surveillance

Over the next two years, the Commission intends to step up its support to Member States "to contribute to a more effective and uniform application of market surveillance in the field of ecodesign and energy labeling." This effort is likely to include:

- Continuous improvement of IT tools such as the Information and Communication System for Market Surveillance (ICSMS) and EPREL;
- Giving technical and logistical support to Administrative Cooperation Groups (AdCos);
- Financing joint or concerted actions and campaigns;

Product Group	Energy Saving Potential 2030 (related to use phase or material efficiency)	Considerations
Low temperature emitters (radiators, convectors, etc.)	170 petajoule (PJ) (use phase)	Highest energy saving potential, important for Renovation Wave[7]/building decarbonization.
Professional laundry appliances	33 PJ (use phase)	Studied in the past and now considered more mature in view of progress in technical standardization.
Professional dishwashers	20 PJ (use phase)	
Universal External Power Supplies (EPS)	12-27 PJ (embedded)	Link to Common Charger initiative[8], will be done as part of the review of the existing EU External Power Supplies Ecodesign Regulation.
Electric vehicle chargers	11 PJ (use phase)	After 2030 the potential savings increase, to in 2050 almost 76 PJ annually. Hence, it is reasonable to consider setting requirements before large volumes of potentially inefficient chargers are installed.

Table 2: Product groups shortlisted for ecodesign preparatory studies

While the European Commission's proposed Sustainable Products Regulation will be subject to scrutiny and amendment by both the European Parliament and the Council of the EU in the months ahead, it will almost certainly be adopted.

- Engaging with the Member States on ways to improve market surveillance, including what resources they make available; and
- Proposing new legal provisions that will improve market surveillance.

The Commission will also continue to support economic operators' (e.g., product manufacturers) efforts to comply. Some examples of this effort cited by the Commission include the operation of functional mailboxes where questions can be addressed, and the publication of specific guidance documents, FAQs, and other information on the Commission website. It will also consider providing EU funding to set up an "industry-driven compliance support facility." Seemingly, the idea here is to increase outreach and provide more timely and targeted assistance to help suppliers and retailers more easily understand and meet their obligations.

The new Working Plan is an ambitious one, especially when one considers that it succeeds the Third Ecodesign Working Plan that was originally set to run until 2019 and, in the Commission's own words, "about 40% [of this Working Plan] is still ongoing and will be rolled over to the current planning period." So, there is much to do.

CONCLUSION

The EU's longstanding ecodesign legislative framework is on the cusp of change.

While the European Commission's proposed Sustainable Products Regulation will be subject to scrutiny and amendment by both the European Parliament and the Council of the EU in the months ahead, it will almost certainly be adopted. It is also highly likely that it will lead to the implementation of new measures relating to product durability, reliability, reusability, upgradability, and repairability. To this end, interested readers may find developments in European material efficiency standardization[6] something worth following.

Concerning the 2022-2024 Ecodesign & Energy Labelling Working Plan, it will be interesting to see what progress is made. If anything, the Commission's delivery fell short of its stated ambitions when it came to previous Working Plans. However, the Commission appears to have set itself both realistic and achievable goals for the next two years. We will have to wait and see what happens.

ENDNOTES

1. These are any goods or systems "with an impact on energy consumption during use which is placed on the market or put into service, including parts with an impact on energy consumption during use which are placed on the market or put into service for customers and that are intended to be incorporated into products."
2. Under the legislation, this is a term that refers to "the integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle."
3. Šajn, N. (2022) *Ecodesign for Sustainable Products*, Brussels: EPRS. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)733524
4. To obtain a copy of the Working Plan, please visit https://energy.ec.europa.eu/ecodesign-and-energy-labelling-working-plan-2022-2024_en
5. Accessible from https://energy.ec.europa.eu/ecodesign-and-energy-labelling-working-plan-2022-2024_en
6. A European Commission strategy that is intent upon renovating building stock to improve energy efficiency while driving a clean energy transition. It envisages the overhaul of 220 million buildings standing today by 2050. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en
7. See https://ec.europa.eu/commission/presscorner/detail/en/IP_21_4613
8. CEN and CENELEC were mandated by the European Commission to develop general, wide-ranging standards on material efficiency aspects for ecodesign. CEN-CENELEC Joint Technical Committee 10 handled this, and it has developed and published various generic standards in the EN 4555X series. For example, EN 45552:2020 *General method for the assessment of the durability of energy-related products*.

A Bias Tee for Broadband Measurement of Power Electronic Components

BY MICHAEL FUCHS, CHRISTOPH MAIER, AND DAVID POMMERENKE

***Editor's Note:** The paper on which this article is based was originally presented at the 2021 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMC, SI & PI), where it received recognition as the Best Symposium Paper. It is reprinted here with the gracious permission of the IEEE. Copyright 2022 IEEE.*

INTRODUCTION

In many EMC applications, passive components need to be characterized to provide simulation models and physical insight into the dominant processes within these components. Passive filters consist of inductors and capacitors, some of which are 3- or 4-terminal devices, such as common-mode chokes. For small signals, these components can be considered linear with respect to voltage and current. However, in many applications, non-linear effects must be considered and characterized. This can be achieved with a time-domain large-signal approach or by linearization around certain bias points. Linearized characterization of potentially non-linear devices such as filter inductors or capacitors requires simultaneous excitation of the small-signal evaluation signal and the large-signal bias, which is current for inductors and voltage for capacitors. The most commonly used method relies on a vector network analyzer (VNA) and a bias network to apply the large signal bias.

For higher current or voltage levels, external bias tees must be used for VNA measurements. In particular, when these span a wide frequency range, here from 9 kHz to 500 mHz, they present the following challenges:

- The calibration plane is moved away from the VNA to a position after the bias tee. The basic assumption of the VNA calibration is time invariance. Any changes in the path from the VNA to the calibration plane that occur after the time of calibration are not corrected. Thermal expansion, such as in inductors, and saturation due to current or capacitance changes caused by the bias voltage can change the RF characteristics of the bias tee. Therefore, a thermally well-designed, highly linear bias tee is required.
- The bias tee will influence the RF path. It connects inductors for the DC feed to the RF path and it interrupts the RF path to block the DC voltage from reaching the VNA. In principle, the VNA calibration compensates for these effects. Even if these effects were completely time invariant, they would reduce the dynamic range of the test system if the calibration had to correct for large changes in the RF path through the bias tee. Thus, the RF path through the capacitor and the decoupling through the inductors requires a design that minimizes the effects on the RF path and thus does not require strong compensation by the calibration.
- The energy stored in mH inductors at 10 A current can endanger the VNA if the current path to the DUT is suddenly interrupted. Simply adding transient voltage suppression (TVS) diodes to the VNA is difficult

because large diodes are required to handle the energy, but they have larger capacitances that will negatively impact the RF path. A distributed protection solution is therefore required.

This paper shows design details of a linear bias tee for a frequency range of 9 kHz - 500 mHz which can handle 10 A continuously, or 30 A for 10 minutes and can be biased up to 500 V. Although there are countless publications on bias tees for high frequency applications, there are relatively few in the low frequency range and even fewer suited for high DC currents and voltages. In [1] it is stated that *"The proposed Bias-T was designed for the target values* I_{DCmax} = 1 A *and* U_{DCmax} = 150 V *at the lower frequency* f_{min} = 2 mHz *and at the current minimum bandwidth of* B_{min} *of* 100 mHz" while in [2] the targeted frequency range reaches from 300 kHz to 100 mHz with a maximum DC current of 3A. Both publications do not present any considerations regarding the protection concept and also target lower bandwidth and smaller DC currents and voltages. In [2], coils with iron core are used, which probably results in the need to make several calibrations for different DC current values to account for the influence of saturation effects. However, no information was given in this respect.

For very low frequencies there are also interesting active solutions for bias tees [3], which again cannot be used for higher frequencies. However, the bias tee published in this paper is intended to be used primarily for the measurement of conducted electromagnetic emissions, for which a lower frequency limit of 9 kHz is quite adequate. A passive solution is therefore preferred.

Although some of the concepts described regarding the construction of the individual components are already known in the literature, to the best of the authors' knowledge, there are no publications yet on such a composition for the construction of a bias tee. The particular advantage of this special form of bias tee is the possible use for small-signal characterization of power electronic components while maintaining high large-signal bias currents and voltages. By measuring the S-parameters of various power electronic components and measuring the

The capacitor in a bias tee acts as a DC block, allowing RF currents to pass in the frequency range of interest. Lower minimum frequencies require larger capacitance values to avoid influencing the RF path.

changes due to bias over a large frequency range, valuable data can be easily obtained for modeling the behavior of these components under large signal bias. Measurements of this configuration show good results regarding important properties of the tee, like insertion loss, return loss and temperature behavior.

DESIGN OF THE BIAS TEE

Figure 1 shows four common bias tee consisting of a DC block capacitor and an RF decoupling inductor. The general topology of a bis tee is maintained in this design. The core challenge is the design of the components for the needed inductance, capacitance, voltage and current values and their physical arrangement in a bias tee such that four of those bias tees can be arranged to form a 4-port measurement system, like depicted. The schematic of the proposed bias tee is shown in Figure 2 and discussed in detail in the following sections.

Capacitors

The capacitor in a bias tee acts as a DC block, allowing RF currents to pass in the frequency range of interest. Lower minimum frequencies require larger capacitance values to avoid influencing the RF path. If 2 Ω is set as upper impedance limit for the capacitor a value of 8.8 μF is needed at 9 kHz. Linearity requirements up to 500 V exclude the usage of high K ceramics or electrolytic capacitors. This constraint increases the size of the capacitors such that the upper frequency limit becomes a challenge. The parasitic inductances and parasitic capacitances of the capacitor arrangement needs to be utilized to obtain low RF losses in the RF path. This is realized by a distributed arrangement of the capacitors seen in Figure 3.

To obtain a constant characteristic impedance of 50 Ω along the capacitor arrangement the structure must maintain a cross section that provides 50 Ω including the parasitic effects of the capacitors. To obtain the needed capacitance of about 8.8 μF a total of 13 capacitors of size 0.68 μF have been placed in parallel [4]. The capacitor has a width of 6 mm.

On a 1.6 mm FR-4 board a 3 mm wide trace leads to a 50 Ω characteristic impedance. To distribute the

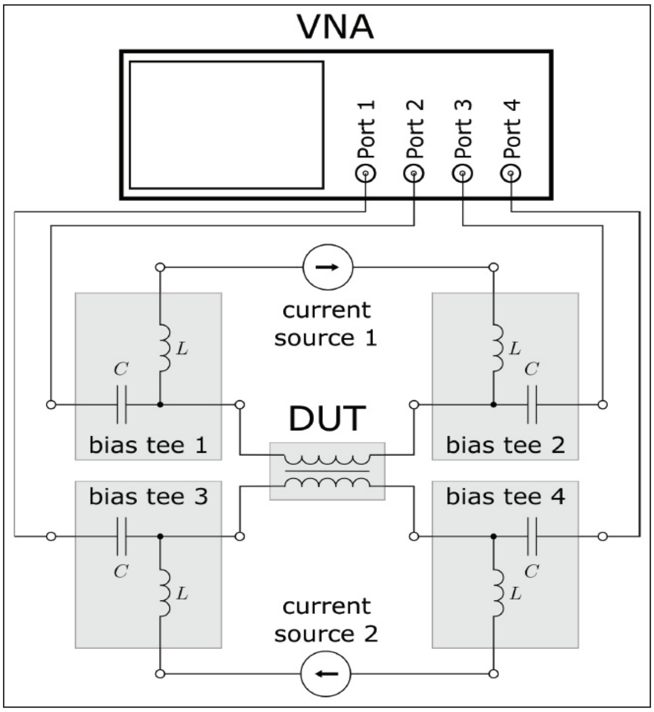

Figure 1: Possible test setup for measuring a common mode choke

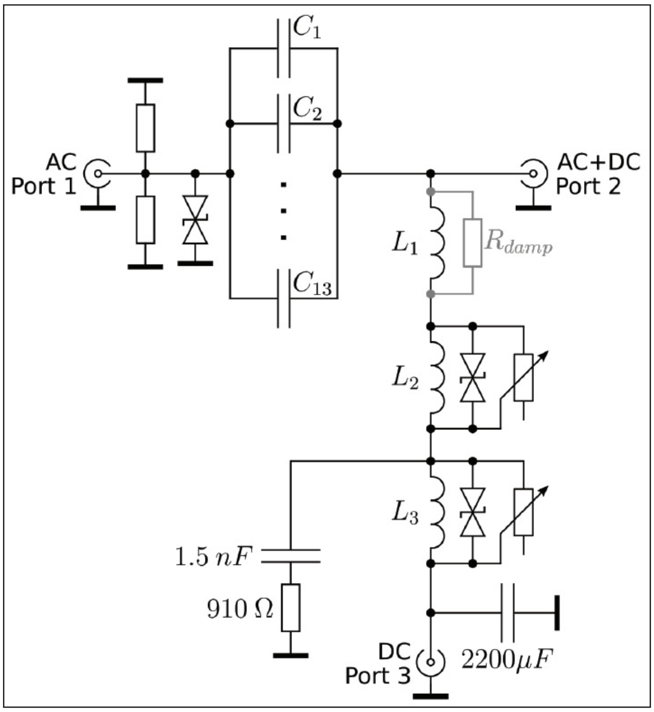

Figure 2: Schematic of the proposed bias tee

capacitances along the transmission line, thus to allow for a undisturbed TEM wave the capacitors are placed vertically, like it is shown in Figure 3. To match the trace width to the width of the capacitors two layers of 1.6 mm FR-4 are used creating a 6 mm wide microstrip line which allows placement of the capacitors without interrupting the RF path. Two carefully designed transitions guide the RF signal from the 3 mm wide trace to the 6 mm wide trace. Figure 4 shows the results of the designed microstrip line using a TDR measurement with a bandwidth of 14 GHz. It can be seen that the capacitive coupling of the TVS diodes used to protect the VNA, as discussed in the section "Protection Concept," have an influence on the line. This influence can be counteracted by changing the diameter of the microstrip line at the point where the diodes are connected.

Although the capacitors are voltage-dependent due to their dielectric (X7R), this only has a negative effect on the behavior of the bias tee in the lowest frequency range, where large capacitance plays a decisive role. Class 2 X7R capacitors promise a maximum capacitance change of 15 % at nominal voltage.

Inductors

For the calculation of the necessary inductance values, a minimum impedance of 43 dBΩ (referred to 1 Ω) was aimed at. At the minimum frequency of 9 kHz this results in a necessary minimum inductance of about 2.5 mH. The needed bandwidth and current carrying capability poses several problems for the inductor design. High currents require thick wires which adds parasitics at high frequencies; not being able to use cores because of saturation effects increases the inductor size, which again is detrimental to the RF performance and the use of large value inductors increases the difficulty of over-voltage protection of the VNA in case the DUT current is suddenly interrupted. In addition, large coils have greater DC resistance and thus higher power dissipation, which leads to increased temperatures in the package (see the section "Temperature Behavior").

In order to optimize the behavior at high frequencies, a conical coil (L_1), shown in Figure 5, was used. Following the design in [5] the conical inductor was connected to the 50 Ω microstrip line that holds the DC block. The

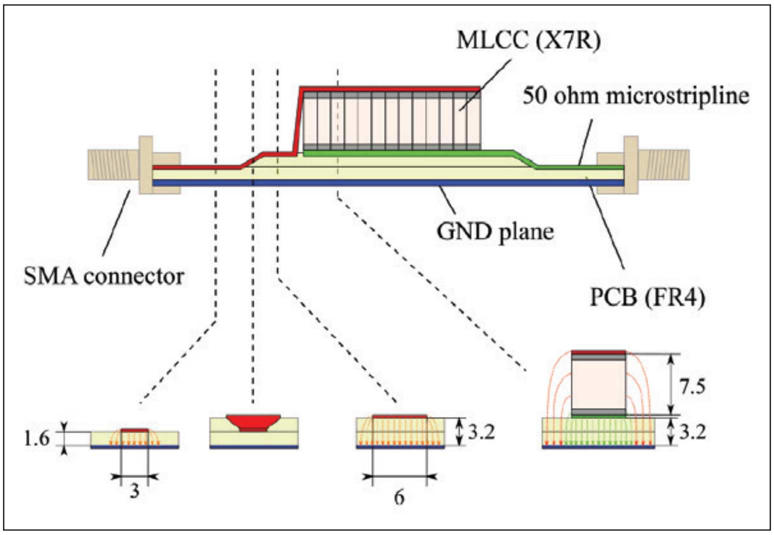

Figure 3: Design of the DC block capacitor with 50 Ω characteristic impedance. Copper layer thickness is not to scale. All dimensions are in mm.

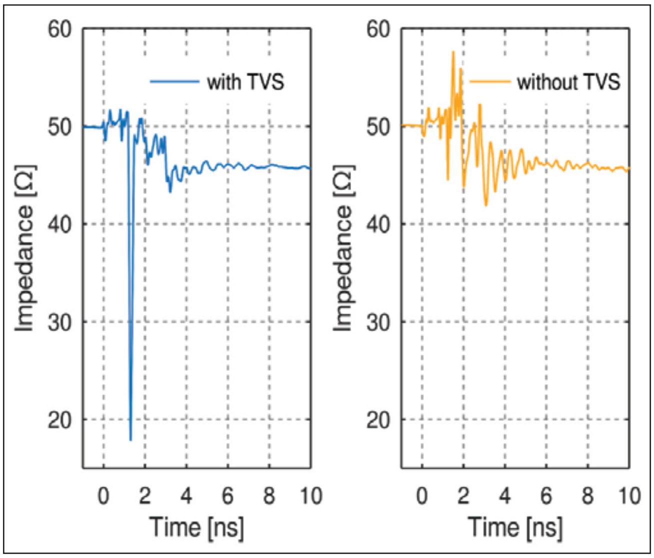

Figure 4: TDR measurement of the designed capacitor with and without TVS diodes as protection device

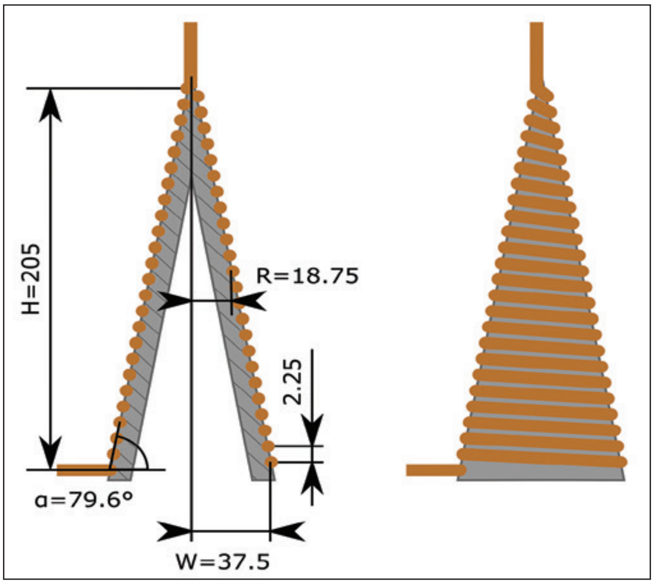

Figure 5: Design of the conical inductor with dimensions in millimeters

advantages of a conical design over a cylindrical inductor can be seen in Figure 6. The conical shape improves the RF performance however, it offers less inductance compared to a cylindrical inductor having the same number of turns and length. Both inductors in the plot have the same inductance and do not use a magnetic core. Up to the resonance, no differences are visible. However, after the first resonance, the conical inductor shows a series of resonances maintaining in average higher impedance relative to its cylindrical partner. The distribution of these additional resonances depends on details of the winding, the wire diameter and the distance between the wires. The higher the frequency, the more important is the design of the tip of the conical inductor and its connection to the 50 Ω trace. According to [6] the inductance of the conical inductor can be derived from the inductances of related cylindrical and spiral inductors. The inductance of a spiral inductor in µH is given by Equation 1 where R is the mean radius of the inductor in mm, W is the radius difference on both cone ends in mm and N is the number of windings.

$$L_S = \frac{1}{25.4} \cdot \frac{(N \cdot R)^2}{8R + 11W} \tag{1}$$

The inductance of a cylindrical (helical) inductor is given by Equation 2, where H is the coil height in mm and again R and N are the mean radius and the number of windings respectively.

$$L_H = \frac{1}{25.4} \cdot \frac{(N \cdot R)^2}{9R + 10H} \tag{2}$$

Using L_S and L_H the inductance of a conical inductor can be obtained by Equation 3 where α is the angle of the conical inductor, being 0° for a totally flat inductor.

$$L = \sqrt{(L_H \cdot sin(\alpha))^2 + (L_S \cdot cos(\alpha))^2} \tag{3}$$

For this coil an inductance of about 63 µH is calculated with the geometrical values given in Figure 5. For achieving an inductance value of 2.5 mH the conical inductor would need to be more than three times as long, which is why two further coils of higher inductance (L_2 = 0.27 mH and L_3 = 2.2 mH) had to be connected in series behind it to reach the desired inductance value. The coils have a total DC resistance of 300 mΩ and thus dissipate 30 W at 10 A DC current.

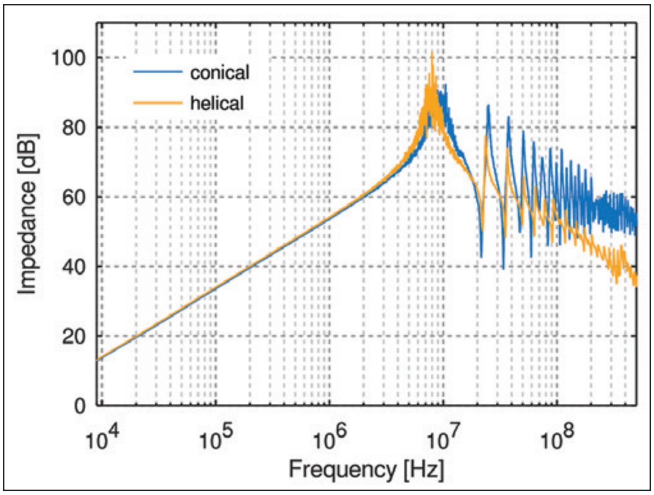

Figure 6: Comparison of the frequency characteristic of a conical and a helical inductor

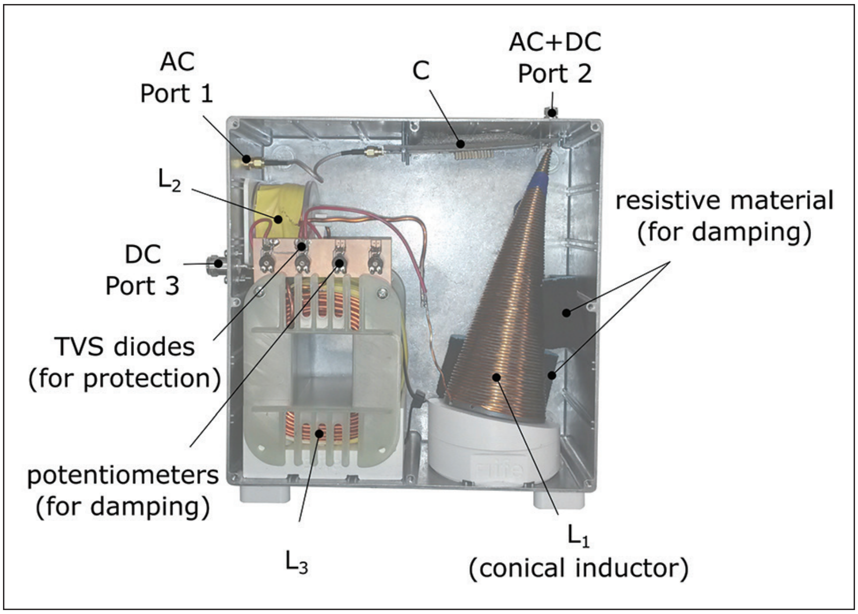

Figure 7: Picture of the bias tee in aluminum housing

Dampening

The coil assembly forms a complex system of the nominal coils and parasitic capacitances between the windings, to the enclosure and between the coils. This leads to a multitude of resonances, which was already shown in Figure 6 for the conical inductor itself. These resonances have a threefold negative effect on the system performance:

- The anti-resonances may reach low impedance values. Those are placed in parallel to the 50 Ω trace, thus, at those frequencies the S12 of the RF path is diminished. This requires stronger correction during calibration.

- Even if they could be compensated by calibration, they must remain time invariant. Small geometrical changes, e.g., thermally induced may move the resonances. The higher the Q-factor is, the stronger small changes will impact the impedance.
- The inductors will warm up to 60 °C at 10 A current. This increases the wire resistance which increase damping. If the calibration would be based on high Q resonance even this small change may lead to an inaccurate correction during measurements by the stored calibration values.

Thus, it is advisable to introduce losses that dampen the resonances. This will reduce the impedance at resonances and increase the impedance at anti-resonances. Of the several available damping methods, electrically lossy material placed near the conical inductor was used for the first stage inductor, represented by R_{damp} in Figure 2. Magnetically lossy material would pose the risk of introducing non-linear behavior due to the large DC current. Placing a resistor across the conical inductor would add parasitic capacitance to the connection point at the DC block on the RF path. The disadvantage of the electrically lossy material is its blocking effect on the cooling of the coil.

For the other inductors adjustable resistors have been placed in parallel to allow for a smooth impedance behavior which leads to a smooth loss characteristic show in Figure 8.

Protection Concept

A maximum permissible direct current of 10 A will store about 126.5 mJ of energy in the inductors. This energy is divided among the three inductors (E_{L1} = 3 mJ, E_{L2} = 13.5 mJ, E_{L3} = 110 mJ).

Without protection, a sudden interruption of current flow through the DUT, e.g., a solder joint breaks, will dissipate the stored energy into the VNA (RIP). Protective devices such as transient voltage suppressor (TVS) diodes are well suited to protect the VNA. If they are placed directly in the RF path, their capacitance needs to be kept small to avoid further disturbances on the RF path. However, those diodes cannot handle the energy. The problem is resolved by distributing diodes across the inductors. The high value inductors store most of the energy, but their electrical function is limited to lower frequencies, thus TVS having larger capacitance of about 100 pF can be used [7]. No TVS is placed across the conical inductor, instead 2.5 pF TVS are placed on the RF path [8].

A second protection problem arises from the 1.1 J stored in the DC block capacitors. If the DUT is suddenly shorted to GND the 8.8 µF charged at 500 V would be discharged into the VNA (RIP). The low capacitance diodes placed to protect against the energy in the conical inductor cannot handle the energy. A second level protection is needed. This is realized by placing polymer based snap back devices from the RF path to GND [9]. These devices offer very low capacitance < 0.05 pF, a fast turn on of 0.1 ns. After internal breakdown within the component, they clamp at about 25 V DC. The amount of energy in the DC block capacitor can destroy them and the TVS devices, but they protect the VNA in case of a short circuit.

Internal DC Block of the VNA

An additional problem for this circuit is the internal DC block of the VNA. Since it has a small capacitance compared to the DC block of the bias tee, a capacitive voltage divider is created, which means that at high DC voltages, a voltage would always be present at the input of the VNA and could destroy it. Therefore, two parallel 10 kΩ resistors are connected between internal and external DC block against ground. These dissipate a slowly changing DC current until the large capacitor of the external DC block is full and the internal DC block can no longer be charged.

The Complete Bias Tee

After initial measurements, discussed in the following section, an additional capacitor with 1.5 nF and resistor with 910 Ω was inserted between L_1 and L_2, as shown in Figure 2, to further flatten the insertion loss curve. Furthermore, an additional capacitor of 2200 µF was added to the DC port to ensure a well-defined impedance to ground which is independent of the impedance of the DC source. Figure 7 shows the complete bias tee with all components. These were installed in a die- cast aluminum housing, which on the one hand reduces the susceptibility to interference and on the other hand ensures temperature stability.

MEASUREMENTS AND VERIFICATION

The verification covers linear frequency response, temperature behavior and linearity check at high currents and voltages.

Frequency Response

To verify the linear behavior the S-parameters of two identically built bias tees have been measured. Because of the well-defined impedance due to the large capacitor at the DC port, port 3 can be left open during calibration. In Figure 8 on page 126 an insertion loss measurement of the two bias tees is depicted, which shows very satisfying results from 9 kHz up to a frequency of about

500 mHz with an insertion loss of less than 1 dB and an insertion flatness of about 0.5 dB. Above 500 mHz, the insertion loss increases to 2 dB at 1 GHz, largely due to the high frequency characteristics of the conical inductor. Measurements using conical coils with thinner wire showed better properties here but cannot pass the DC current. It can also be seen from the return loss measurement in Figure 9, that even though the two shown bias tees are built identically, their return loss differs quite significantly. This is the effect of slightly different coils and potentiometer settings. In general, one could create an S-parameter set for each bias tee and use this for de-embedding. Even though this procedure would result in better measurement performance, one would need the de-embedding profiles for each individual tee and must never interchange the bias tees for each measurement. Instead, a self-made calibration kit with previously measured de-embedding parameters was used. Two bias tees and the self-made calibration kit (TOSM) was used for calibration, which works regardless of the arrangement of the bias tees. For the final measurement, shown in Figure 1 a four-port calibration has to be done. In general, all calibration methods can run into the same limitations, which are small remaining non-linearities or mechanical changes due to heat or mechanical instability.

Temperature Behavior

The DC resistance of the coils (R_{L1} = 0.1 Ω, R_{L2} = 0.04 Ω, R_{L3} = 0.16 Ω) leads to internal heating at high currents. A stress test of the bias tee was carried out in the course of an initial test. The bias tee was loaded with 10 A DC current for 30 minutes causing the temperature at the tip

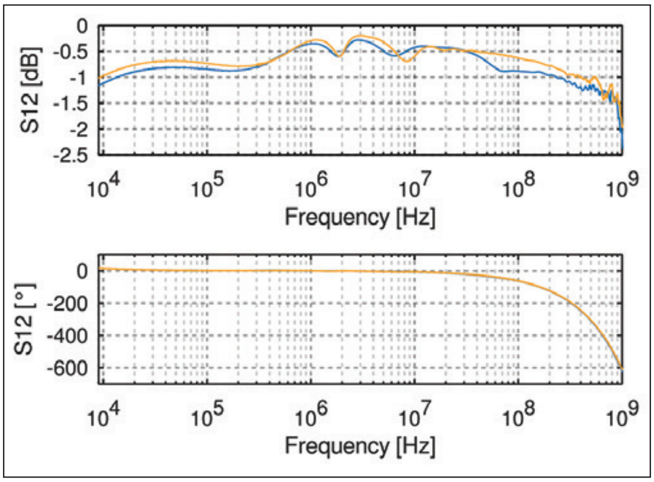

Figure 8: Insertion loss of two identically built bias tees

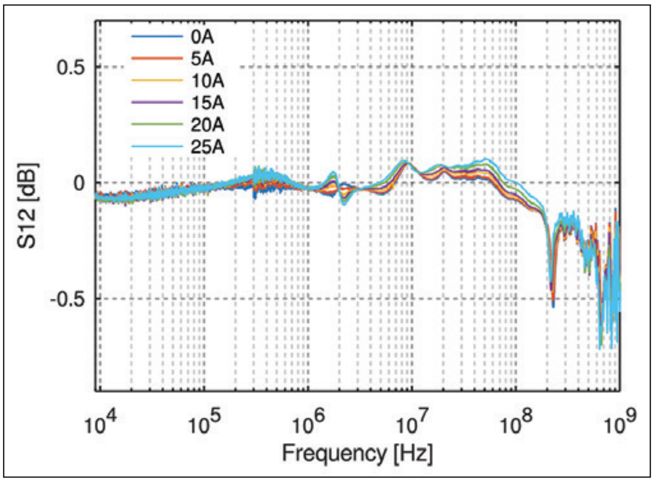

Figure 10: Insertion loss of two bias tees in series

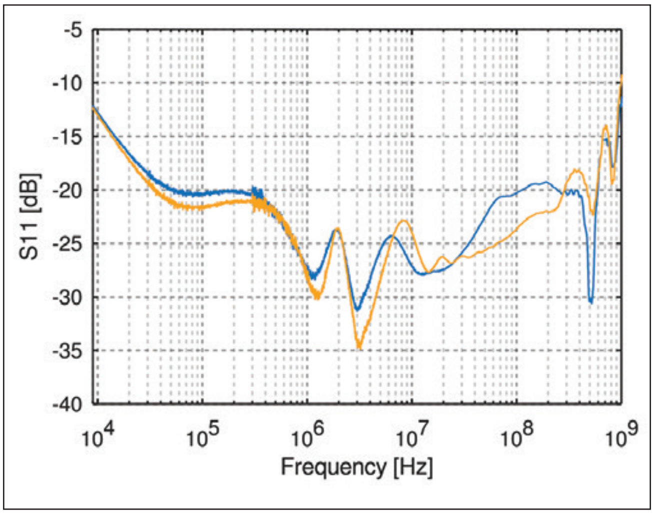

Figure 9: Return loss of two identically built bias tees

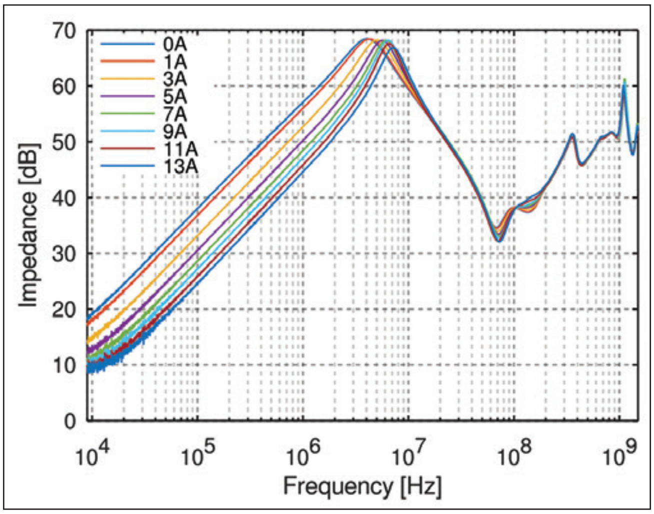

Figure 11: Measurement of an inductor with different DC bias currents.

of the conical inductor to increase to 60 °C. No forced cooling was applied. No significant heating was detected elsewhere in the enclosure.

Protection Circuit Response

The maximum voltage at the input of the VNA in the event of a fault is specified by the manufacturer as 30 V. The protection circuit, described in Sec. II-D was tested by connecting two bias tees in series and a fuse with 10 A rated current which should simulate a sudden interrupt of current flow. A DC current of 25 A was applied to the test setup with a 50 Ω dummy load and a small capacitor as DC block instead of the VNA. The resulting voltage at the dummy VNA did not exceed the maximum allowed voltage of 30 V and the resulting energy of about 125 µJ does not pose any danger to the input of the VNA.

Linearity Check

Figure 10 shows an S12 measurement of two bias tees connected in series at different DC bias currents. It can be seen that the DC bias current causes practically no difference in the behavior of the tees up to 25A.

Measurement of an Inductor

Figure 11 shows a test measurement of an inductor [10] at different DC bias currents between 0 A and 13 A. Saturation effects due to the DC bias current can be observed in the lower frequency range by a shift towards the right. At higher frequencies not much changes due to the bias current, since the permeability of the material has reduced to a level at which the flux cannot reach saturation levels.

CONCLUSION

This paper shows a way to build a bias tee for power electronics applications. Especially if saturation effects of coils or larger filter elements in a low frequency range are to be investigated, this bias tee offers a possibility to tackle this problem with the help of vector network analysis. This allows to measure a device under test in magnitude and phase to gain detailed conclusions about its frequency behavior. The data can then be used to optimize filter circuits in real application situations, or to generate load-dependent models of these filters. The presented bias tee shows good frequency response over a wide frequency range and can be loaded with high DC currents and voltages. Measurements show that the behavior of the bias tee is not influenced by DC bias currents. When these bias currents are abruptly interrupted, the presented protection circuit serves to protect the measurement equipment.

ACKNOWLEDGEMENT

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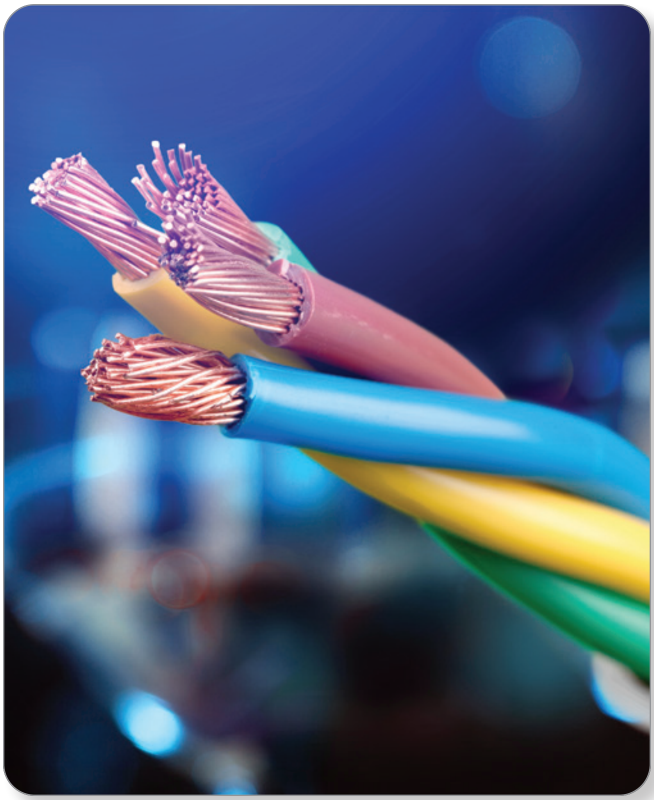
Getting the Best EMC from Shielded Cables Up to 2.8 GHz

How to Terminate Multiple Shields in a Cable Bundle

BY KEITH ARMSTRONG



A couple of years ago, I needed to know the shielding effectiveness (SE) of screened[1] cables up to at least 18GHz, but – apart from coaxial cables intended for use in EMC[2] test laboratories – I could only find information up to 100MHz, such as Figure 1.

Accordingly, I set out to make my own measurements with the resources and time made available to me.

In these measurements, I used many different constructions of cable to try to answer the perennial debate about how best to terminate the individual shields of multiple-shielded cables, including single or double overall braids (overbraids), and individual shielded cables contained within an overbraid.

These measurements covered a great deal more than I have described in this brief article, but I am unable to report the other results for confidentiality and/or security reasons.

But before I can describe the cables and results I am permitted to share with you (see Part 2 of this article), I first need to establish the basic rules for terminating cable shields, so that you understand why I did what I did.

UNFORTUNATELY, PEOPLE OFTEN DEVIATE FROM GOOD SHIELDING PRACTICES

Except for conductors designed specifically for use as antennas, all conductors are often called accidental antennas [2]. For this reason, achieving a project's EMC requirements quickly and cost-effectively often requires shielded (sometimes called screened) cables.

1. In the context of this article, the words: screened; screen, or screening may be replaced by shielded; shield, or shielding respectively, and vice-versa, without any changes in meanings.
2. EMC = Electromagnetic Compatibility, the engineering discipline of ensuring that: a) electromagnetic emissions are low enough for radio/telecommunications and other electronic equipment to function as intended without suffering from unacceptable electromagnetic interference (EMI); and that, b) the electromagnetic immunity of equipment is sufficient for it to function as intended in the electromagnetic environment expected to be present where it is used.

Keith Armstrong is a senior contributor to In Compliance Magazine and the founder and principal of Cherry Clough Consultants Ltd, a UK-based engineering firm that utilizes field-tested EMC engineering principles and practices to help companies achieve compliance for their products and reduce their potential risk. He is a Fellow of the IET and a Senior Member of the IEEE and holds an Honors Degree in Electrical Engineering from the Imperial College, London (UK). Armstrong can be reached at keith.armstrong@cherryclough.com.

For these cable's shields to provide the EMC benefits needed, they must be correctly terminated at their ends. Correct termination techniques for RF have been well-proven for decades (see References [1] and [3] through [14], which span the period 1976 to 2019).

Unfortunately, despite all this publicly available knowledge on well-proven shield termination methods, they are still neither well-known nor widely used.

WELL-PROVEN GOOD EMC PRACTICE: ALWAYS TERMINATE SHIELDS 360°, AT BOTH ENDS

People are always quoting Henry Ott's excellent book [12] to me, claiming that it proves that low-frequency analog signals (such as those used in audio and certain kinds of sensors) must only ever terminate shields at one end. Similar guidelines for low-frequency signals and power also exist in [1], [3] through [11], [13] and [14].

These guidelines were usually acceptable in most ordinary consumer, commercial, and light industrial applications up until the 1990s because their electromagnetic environments were quite benign. But they were never sufficient for applications with very tough electromagnetic environments, as covered by [1] and [3] through [8].

However, when personal/portable computers and digital cellphones became widespread during the 1990s, their large electromagnetic emissions at frequencies up to almost 1GHz meant that IEC and similar EMC test standards for immunity started to test with at least 3 Volts/meter up to at least 1GHz, which is roughly equivalent to a cellphone operating at full power 2 meters away. Such standards were then adopted as part of claiming compliance to the European Union's EMC Directive.

Even electronic circuits that use low-frequency signals (say, below 20kHz) can be expected to demodulate and intermodulate RF noises (say, above 150kHz), as almost every designer of such products who took the trouble to perform these immunity tests discovered. [3] warned about this issue in the mid-1990s.

Now, in the 2020s, we can look back on thirty years of ever-worsening electromagnetic environments, and the EMC test standards for ordinary consumer, commercial, and light industrial applications now have to test immunity up to 6GHz or more. 28GHz will soon be necessary when 5G is extended into that frequency range as planned, see [15] and [16].

These days, the plain fact of the matter is that all analog and digital signals, and all power, are now heavily polluted with conducted RF noises up to at least 6GHz. These are common mode (CM) noises that are both picked up from the noisy electromagnetic environment, and created by the electronics themselves, even being emitted from analog inputs! (See [17].)

The result is that all guidelines for shielding low-frequency signals and power are now insufficient for EMC compliance, and techniques for shielding against high-frequency RF noises are always required, including instances when using RF filtering [18]. Reference [12] and all the other references in this article describe such techniques, and they all require terminating cable shields in 360˚, and at both ends.

Based on my own experience and that of the many EMC experts I know worldwide, the good news is that doing this not only results in good EMC, but also the quickest and most cost-effective project designs, and the quickest and most cost-effective installations (see [19]).

There is also some persuasive real-world evidence for improvements in functional performance where legacy equipment and its installations have been redesigned to use shielded cables terminated in 360˚ at both ends (see the two examples in [20]).

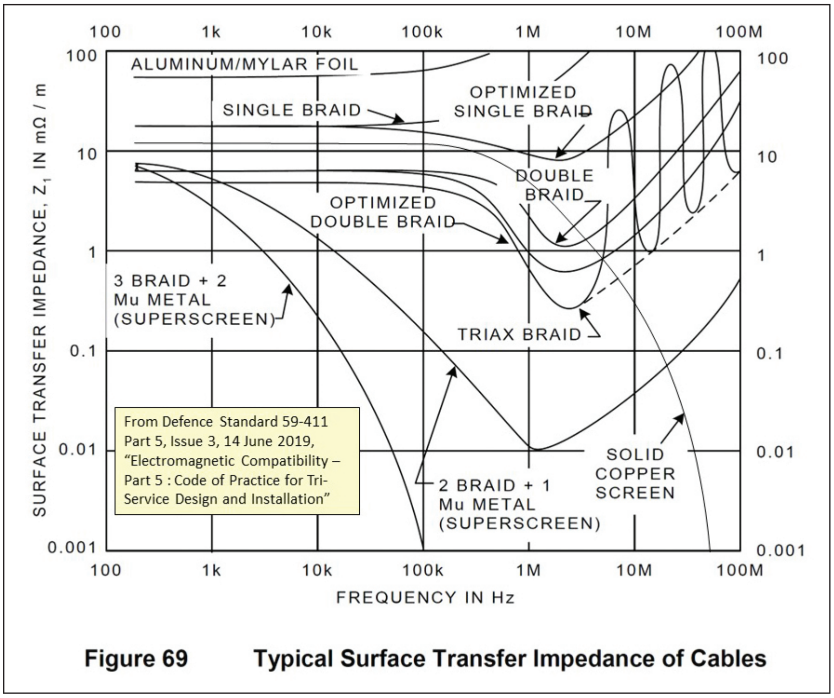


Figure 1: Typical surface transfer impedance of shielded cables

WHAT IS 360° SHIELD TERMINATION?

This is EMC-industry jargon, meaning: direct metal-to-metal connection all the way around. It is sometimes also referred to as all-around, circumferential, or peripheral termination.

And shield termination is sometimes called shield bonding, shield grounding, or shield earthing. However, I strongly advise against using terms that use the words ground or earth for anything other than electrical safety purposes (see [21]).

As for worries about so-called ground loops, hum loops, earth loops, etc., when bonding cable shields at both ends, see my blog [22] and remember that bonding cable shields at both ends has been a requirement for military electronics since 1976 (see [3] through [11]).

We can always deal with such noisy loops by circuit design, which I learned how to do in the 1980s. Without such circuit design, the only generic alternative for poor EMC caused by badly shielded cables is to use shielded panel-mounted filters and/or better cable shielding. Of the two, better cable shielding is quicker and more cost-effective unless we are stuck with legacy cable systems that can't be replaced.

Note that fiber-optic converters and their cables may seem costly but can be more cost-effective overall, taking everything into account. I expect them to become more economically favorable year-on-year, going forward.

WHY *NOT* USE PIGTAILS?

All the references at the end of this article warn against using pigtails, sometimes simply called tails.

Figure 2 shows that even a 5mm pigtail makes shielding worse than 360° termination by between 10 and 20dB over the range 1MHz to 1GHz. Note that manual pigtailing is very difficult indeed if shorter than 20mm, which Figure 2 shows is up to 30dB worse.

However, the shielding degradation caused by using pigtails instead of 360° terminations depends very much on the test method used. For example, a 1991 study [23] found that using a pigtail in a subminiature 25-way D-type made shielding 20dB worse at 1kHz (only 1kHz!) and 75dB worse at 100MHz (see Figure 3).

I have seen test results showing that pigtails can cause shielded cables to emit more RF noise between 50MHz and 500MHz than an unshielded cable would have. So Figure 3's 75dB degradation at 100MHz could well mean that the cable shield was *amplifying* the RF coupling through its shield, instead of attenuating it as expected.

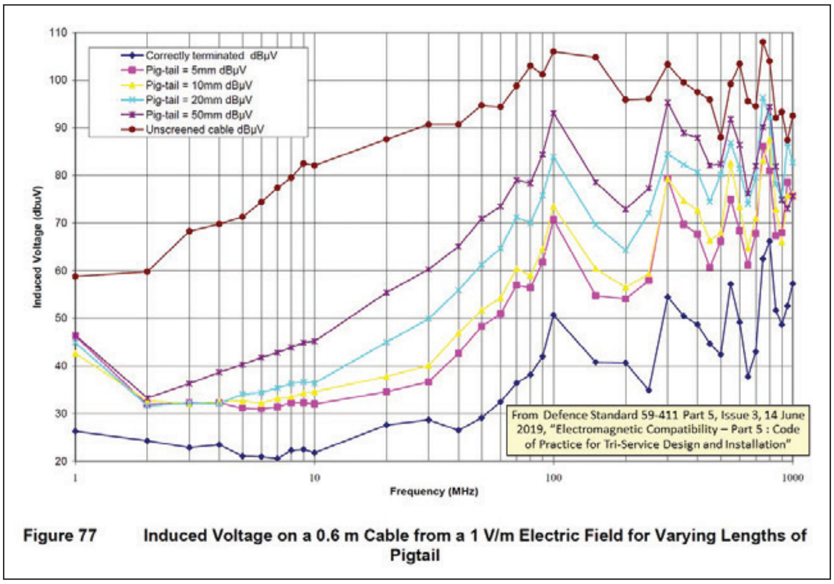


Figure 2: Effect of varying the length of a shield pigtail termination, from [1]

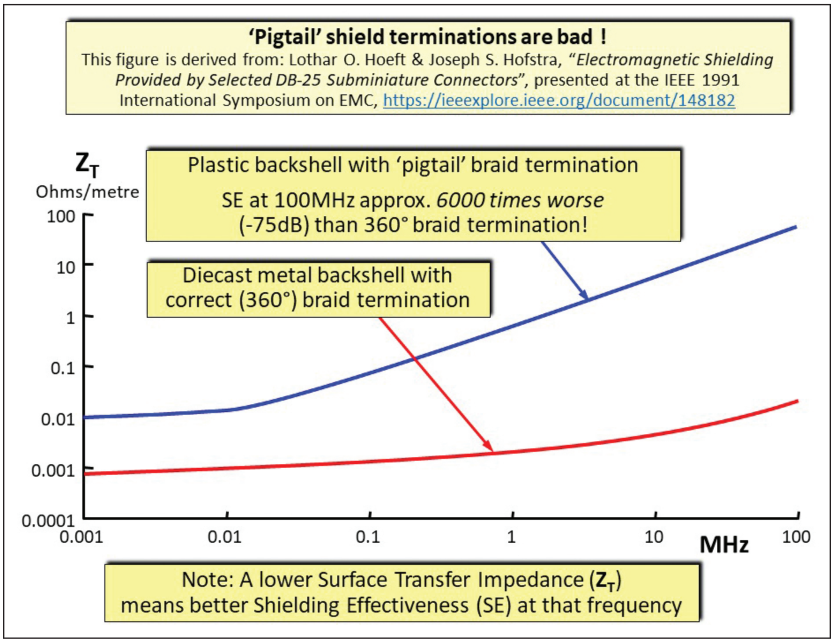


Figure 3: Effect of replacing a 360° shield termination with a pigtail, see [23]

If, in ten years' time, you remember only two points about this article they should be:

1. Never use pigtails for terminating cable shields; and,
2. Always terminate shields at both ends (dealing with the inevitable ground loops, hum loops, etc., by circuit design, see [22]),

By remembering these two key points, you will almost certainly have saved yourself a great deal of work, cost, and project delays by reducing the number of design iterations required to pass EMC tests. (It is usually practical to design to quickly and cost-effectively design to pass EMC tests the first time, see [19] and [20].)

For a simple method for predicting a cable's SE from measurements of Z_T (surface transfer impedance, as used in Figure 3), see [24].

WHY TEST MULTIPLE SHIELD TERMINATIONS FROM 100MHZ TO 2.8GHZ?

A couple of years ago, I did some work for two suppliers of high-spec military equipment, involving projects that used a great deal of electronics that had to be interconnected with many bulky copper cables or cable bundles carrying analog and/or digital signals and/or power.

As their EMC specifications were required by their customers to be the toughest of all the UK's Defense Standards, these cables or cable bundles were all shielded with two layers of overbraid, directly in contact with each other along their lengths, as recommended by [1].

Many of the cables or cable bundles contained internal braid-shielded twisted-pair (TP) or multicore cables, with their individual braids insulated from the whole cables' or cable bundles' overbraids by their individual plastic jackets.

The customers for these equipment designs had made several of their own proprietary specifications for EMC design, assembly, and installation part of the contract for supply. Unfortunately, their own specifications did not always agree with each other, or with [1] when it came to issues of how to deal with the individual shields and overbraids of the cables or cable bundles.

Each designer of the suppliers' equipment cables or cable bundles seemed to have been differently confused by their customers' inconsistent shielding requirements, with the result that different cable assembly drawings often differed from each other in their use of shield termination methods. Some cable assembly drawings even contained an eclectic mix of shield-terminating methods because they had been worked on by different designers at different times.

Enquiring as to why this was the case, I discovered that no designers at either supplier even knew about the existence of the official UK guidance on terminating shields in [1], despite compliance with [1] also being part of their contract requirements. This was even the situation with one supplier whose designers I had trained in good EMC design/assembly techniques three years beforehand. They relied almost entirely on subcontract designers, and in the intervening three years, these had all been replaced by new subcontractors who had not attended my course!

As well as the usual issues of which ends of the shields, or both, to terminate, whether pigtails could be used, and whether to connect internal cable shields to the overbraids or not, there was also the issue of whether to insert a thin insulating tube in between two overbraids.

Many of the cable bundles were 2 inches or more in diameter and, when assembled with two overbraids in direct contact with each other along their lengths, very stiff, making them difficult to install in military vehicles. Adding an insulating tube between their overbraids made them usefully more flexible, but I knew (from [3], [4], [1], and other reference materials) that this should reduce their shielding effectiveness (SE).

Some customers' specifications required thin insulating layers between double overbraids without commenting on the likely impact on EMC. This might have been because they wanted the mechanical flexibility and didn't realize that SE could be compromised. But it could also have been because they had seen some of the few references listed below (but not [1], [3], [4], [9], or [10]) that claim (incorrectly, in my view) that placing an insulating film between two overbraids along their length gives a 10 to 30dB improvement in SE, compared with two overbraids in direct contact along their length.

Other issues were that all the measurements I have seen published on cable shielding methods only covered up to 100MHz, and only for coaxial or triaxial cables. However, these projects had to pass the toughest EMC emissions and immunity tests up to 18GHz and were very far indeed from being simple coaxial or triaxial types. The guidance in [1], especially that shown in Figure 1, implies that, at and above 1GHz, few shielded cables could be expected to provide any useful shielding at all!

So, I wanted to discover for myself, and for the benefit of other designers on these projects, how best to design and assemble the shields in their cables or cable bundles, and above what frequency we might need to have to use filtering or galvanic isolation techniques (such as fiber-optics) because flexible metal shielding layers would be no use anymore.

THE MEASURED CABLES

Note: all these cables' overbraids, whether single or double layers, used the same type of braid clamped to the backshells in the same way at both ends.

Cable 1: the "Null" cable for noise floor verification (see Figure 4)

A single overbraid on its own, to check that the noise floor of the test is low enough.

Cable 2: the "Reference" unshielded TP cable (see Figure 4)

An unshielded twisted-pair (TP) cable on its own (actually, the single-braid-shielded TP cable used to assemble cables 3 to 6, with its outer plastic jacket and shield removed).

The measured results on this cable were used as the reference that was subtracted from the measured results of each of the other cable tests (i.e., cables 3 to 12) to determine their relative SE versus frequency.

Careful control of the entire test set-up tried to ensure that the RF coupling from the antenna to the cable and the room resonance effects were identical on every test so that they canceled out. The results showed that we were reasonably successful in this.

Cables 3, 4, and 5: single-braid-shielded TP cables with single overbraids (i.e., two shield layers in total) (See Figures 4, 10, and 11)

- Cable 3: Insulated single braid TP cable pigtailed to the backshells at both ends; plus a single overbraid 360° clamped to the backshells at both ends.
- Cable 4: Same as Cable 3, but with the internal TP cable's braid now 360° soldered to the overbraid at the backshell at the CM measured end, but still pigtailed at the 120Ω end (see Figure 7).
- Cable 5: Same as Cable 3, but with the internal TP cable's braid now 360° soldered to the overbraid at the backshells at both ends (i.e., no pigtails at all).

Note: these cables, and Cables 6, 10, 11, and 12 below, all used the same type of single-shielded TP cable.

Cables 6, 10, 11, and 12: single-braid-shielded TP cables with double overbraids (i.e., three shield layers in total) (see Figures 5, 12, and 13)

- Cable 6: Same as Cable 3 (internal TP cable with an insulated single braid shield pigtailed to backshells at both ends), but now with double overbraids in direct electrical contact with each other along the entire cable length, and both overbraids 360° clamped together to the backshells at both ends.
- Cable 10: Same as Cable 6, but with the internal TP cable's braid 360° soldered to both overbraids at the backshell at the CM measured end while still pigtailed at the 120Ω end (see Figure 7).

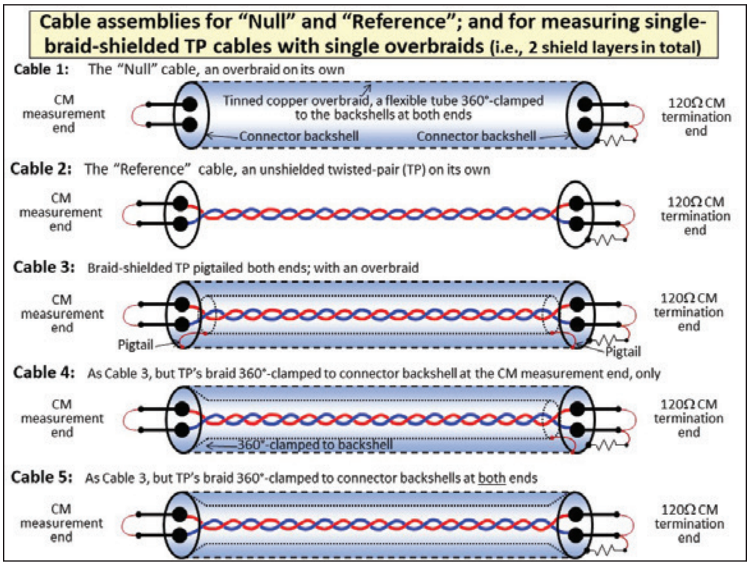


Figure 4: The cable assemblies for the reference measurements, and for the single-braid-shielded TP cables with single overbraids (i.e., two braid shield layers in total)

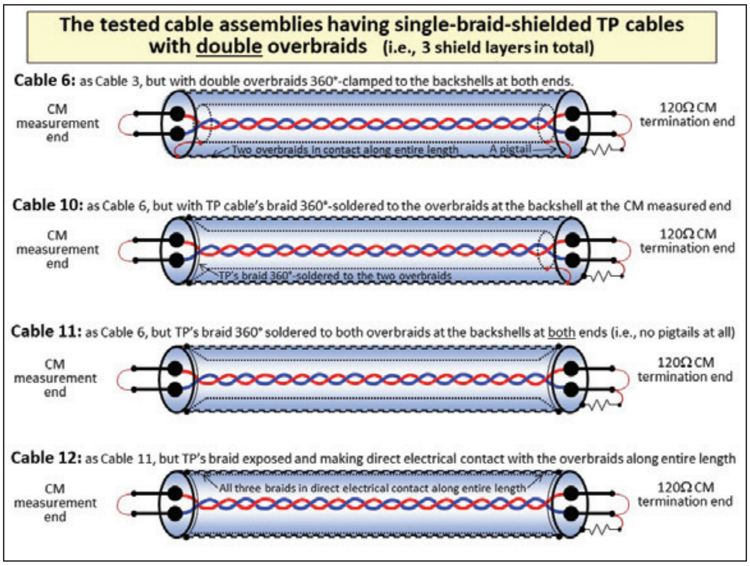


Figure 5: The cable assemblies having single-braid-shielded TP cables with double overbraids (i.e., three braided shield layers in total)

There are many ways of testing the SE of cable assemblies (i.e., cables plus their connectors), and each should be expected to give different results even with identical cable assemblies.

- Cable 11: Same as Cable 6 but with the internal TP cable's braid 360° soldered to both overbraids at the backshells at both ends (i.e., no pigtails at all).
- Cable 12: Same as Cable 11, but internal TP cable's braid exposed and making direct electrical contact with the overbraids along the entire length of the cable. That is, all three braided shields are in direct electrical contact with each other along the entire length of the cable, and all are clamped together in 360° to the backshells at both ends. This cable was very stiff!

Note: these four cables, and Cables 3, 4, and 5 above, all used the same type of single-shielded TP cable.

Cables 7, 8, and 9: double-braid-shielded TP cables with double overbraids (i.e., four shield layers in total) (See Figures 6, 14, and 15)

- Cable 7: Same as Cable 6, but with the internal TP cable having double braid shielding in direct electrical contact with each other along its whole length, plus an overall layer of insulation, and pigtailed to the backshells at both ends. Cable 7 also has double overbraids in direct electrical contact with each other along the entire cable, and 360° clamped together to the backshells at both ends.
- Cable 8: Same as Cable 7 but with thin mylar film inserted between the two overbraids (except where they are clamped together to the backshells at both ends).

Note: these two cables both used the same type of double-braid-shielded TP cable.

THE MEASUREMENT METHOD

There are many ways of testing the SE of cable assemblies (i.e., cables plus their connectors), and each should be expected to give different results even with identical cable assemblies. So, I chose a test method that best represented the situation I was most interested in and that was also the easiest and quickest to do with the facilities and resources I had available at the time (see Figures 7, 8, and 9).

The worst of the imperfections in this method were canceled out by careful control of consistency and repeatability, and by subtracting the measured results for each cable assembly from the measurements of the Reference unshielded TP cable, Cable 2 (see above, and Figure 4).

The test chamber had once been a large TEMPEST chamber for secure communications, but for a long time had been used as a storeroom.

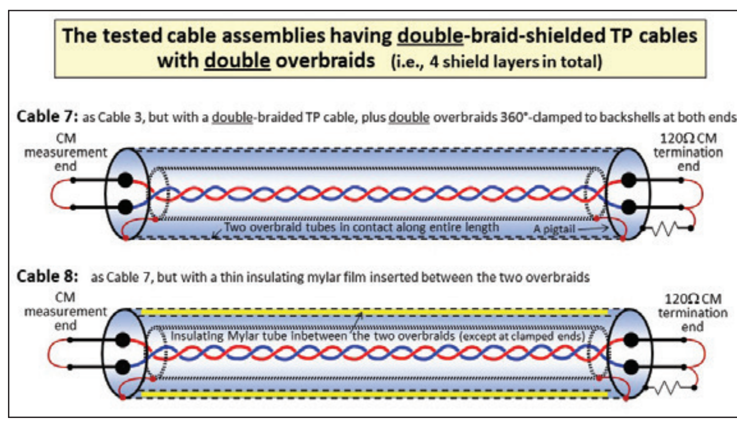


Figure 6: The cable assemblies having double-braid-shielded TP cables with double overbraids (i.e., four braided shield layers in all)

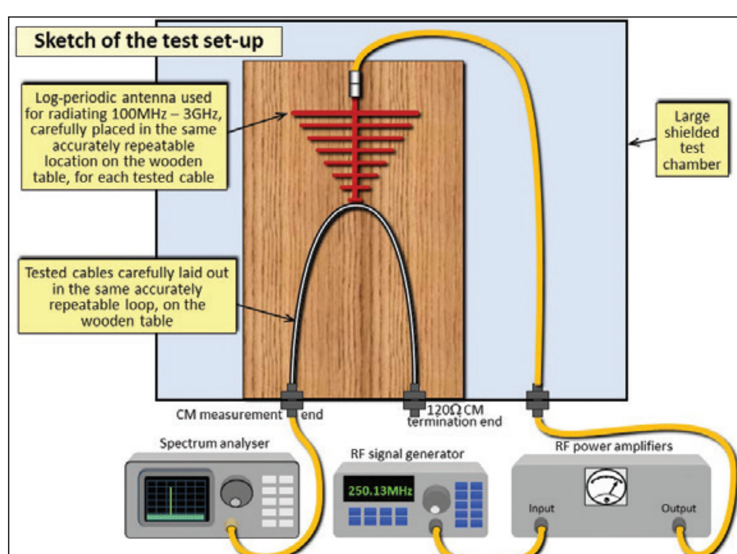


Figure 7: Sketch of the test set-up

With a spectrum analyzer, near-field RF probe effective up to 6GHz, and a Tek box TBCG1 radiating comb generator, 100MHz - 6GHz, it did not take long to identify the RF leakages and fix them (corroded spring fingers around the door, and a telephone wire that had been brought in without RF suppression). A connector panel (visible in Figure 8) was designed, fabricated, and affixed to a hole cut in the chamber wall and also checked for RF leaks up to 6GHz.

I would have preferred either an anechoic chamber or a mode-stirred chamber, but at least the metal racking and the stored equipment in the room broke up most of its major resonant modes! And a few scraps of left-over ferrite tiles from an anechoic EMC test chamber were enough to deal with the worst remaining standing waves.

I was not interested in absolute values of SE, only in which cable design/assembly methods were the best for SE. In other words, their relative SE performances. I hoped to extract some general guidance rules for overbraid-shielded cables or cable bundles containing at least one individually shielded TP cable.

To help achieve this, with the imperfect test set-up briefly described above, a null cable (Cable 1, see Figure 4) was first measured. Being just an empty overbraid, the measurement identified any leakages from the antenna to the CM measurement pins of the bulkhead-mounted shielded connector, which included all chamber and panel leakages, and also the leakages inherent in the overbraid and its shield-bonding to the cable connectors, and from the cable connector to the bulkhead-mounted shielded connectors. This measurement showed that leakages were at or below the measurement noise floor for both frequency ranges.

Next, the Reference cable, Cable 2, was measured. This was an unshielded twisted-pair (TP) cable on its own, as shown in Figure 4, and previously described in detail.

Two different RF power amplifiers, one operating at 100MHz – 1GHz and a second at 800MHz – 2.8GHz, were used to cover the two frequency ranges reported in this article, with the above null and reference tests repeated for each amplifier.

To help achieve consistency between the different RF power amplifiers, a triaxial field probe with a fiber-optic cable passed through a waveguide-below-cutoff in the bulkhead connector panel was used to measure the field strengths around the antenna and the measured cables.

External low-noise preamplifiers with good, flat frequency responses over the measured frequency ranges were used before the spectrum analyzer's input in cases where they would help reduce the noise floor.

All the other measured cables covered by this article consisted of the same null cable assembly used for Cable 1. Additional internal conductors and cables were made by the same very skilled cable assembler, in the same ways, with the same materials, and within a limited time span (a few days) so that we could assume consistency between them.

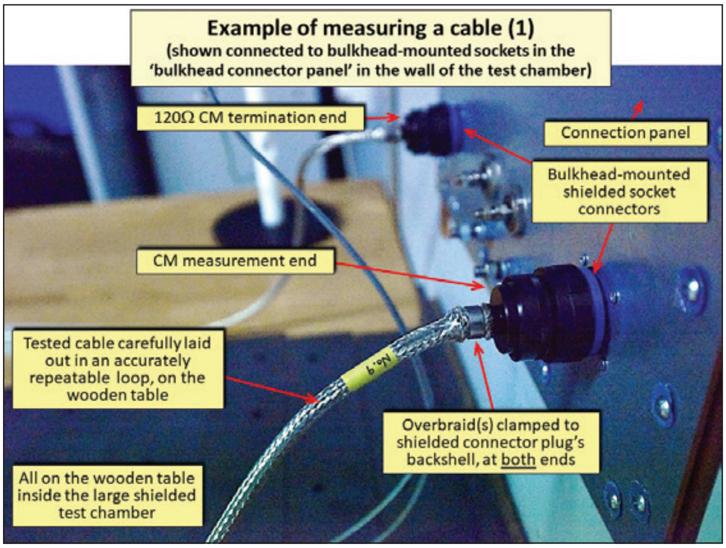


Figure 8: Example of measuring a cable, showing the connections to bulkhead-mounted connectors on the bulkhead connector panel in the wall of the test chamber

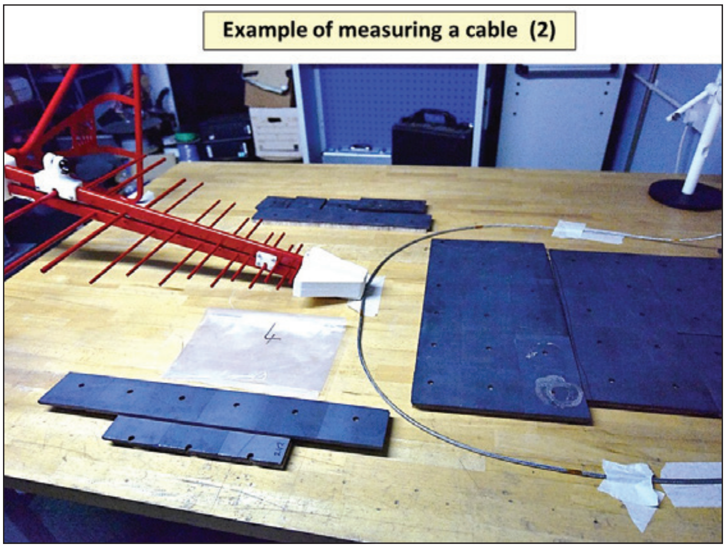


Figure 9: Example of measuring a cable, showing injecting RF into a cable

Given all the above and with the results from each amplifier, subtracting each cable's results from the reference result should have substantially reduced the effects of:

1. Frequency-related variations in the RF power output from each RF amplifier (see Figure 7);
2. Frequency-related variations in the antenna's response to the RF power from the power amplifiers;
3. Frequency-related variations in the coupling between the antenna and the measured cables (see Figure 9);
4. Frequency-related variations in the reflections from the shielded room (and the items stored in it);
5. Frequency-related variations due to RF impedance mismatches in the shielded connectors, and the resulting resonances caused by the length of the cable between them; and
6. There are many other possible causes of frequency-related variations in the measurements of the amplitudes of the CM noises picked up by the cables that are also reduced by the subtraction method described above, but they are all much smaller than the five listed above, so are not listed here.

This subtraction/cancellation approach was successful enough to draw conclusions on how best to terminate the shields of multiple shielded cables in an overall cable or bundle with overbraids, up to 2.8GHz. However, there were still some small errors that were deemed insignificant (see if you can spot them in the following figures!).

Results for Single-Braid-Shielded TP Cables with a Single Overbraid – Cables 3, 4, and 5

These are shown in Figure 10 for 100MHz – 1GHz, and Figure 11 for 800MHz – 2.8GHz.

Conclusions for Single-Braid-Shielded TP cables with a Single Overbraid – Cables 3, 4, and 5

A. Above 100MHz, the SE of these cables does not generally appear to continually degrade at the rate of 20dB/decade implied in Figure 1. Instead, they generally degrade more gradually and become more consistent as frequency increases. I don't know why this was the case and will not speculate here.

B. Fluctuations (frequency ripple) of up to ±12dB are seen on Cable 5, as predicted by the TRIAX BRAID curve in Figure 1, and I was pleased to have replicated it here.

Apart from the UK defense standards referenced later, most of the other documents do not mention this effect at all. In my experience, this effect is much less widely known in real-world engineering than whether shields should be terminated at one end, the other end, or both ends.

Ripples up to ±20dB are seen on Cables 4 and 3, which have pigtails at one or both ends, respectively.

C. It is important to 360°-terminate any/all internal cable shields to the overbraids and/or backshells at both ends – and *never use any pigtails*.

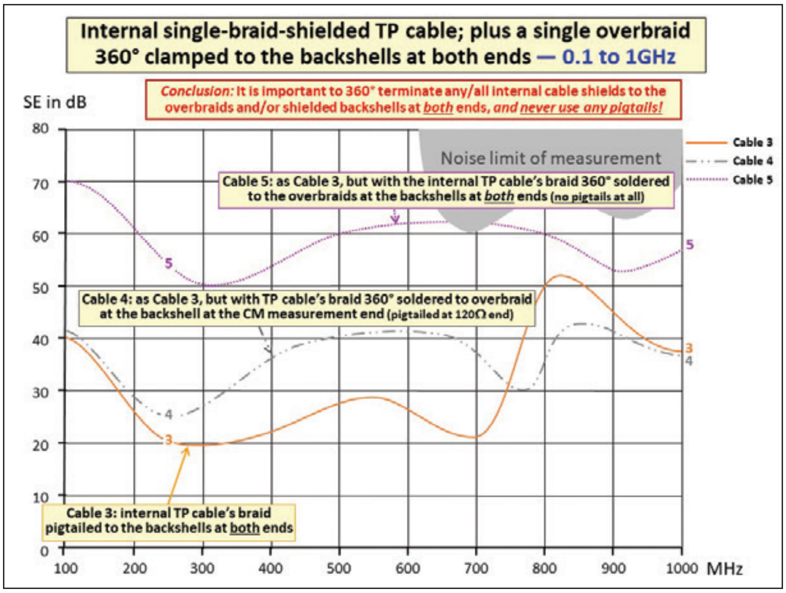


Figure 10: Results for internal single-braid-shielded TP cable, plus a single overbraid 360° clamped to the backshells at both ends — 0.1 to 1GHz

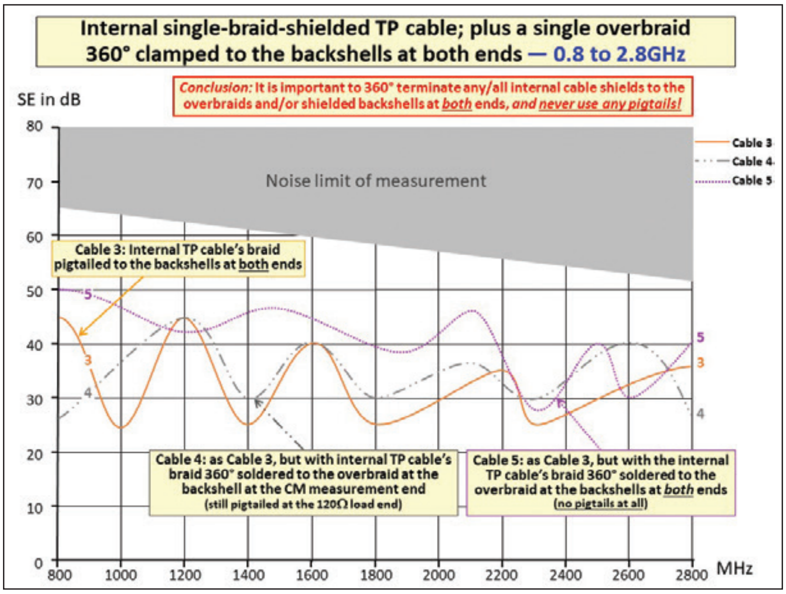


Figure 11: Results for internal single-braid-shielded TP cable, plus a single overbraid 360° clamped to the backshells at both ends — 0.8 to 2.8GHz

Results for Single-Braid-Shielded TP cables with Double Overbraids – Cables 6, 10, 11, and 12

These are shown in Figure 12 for 100MHz – 1GHz, and Figure 13 for 800MHz – 2.8GHz.

Conclusions for Single-Braid-Shielded TP Cables with Double Overbraids – Cables 6, 10, 11, and 12

D. Above 100MHz, the SE of these cables does not generally appear to continually degrade at the rate of 20dB/decade implied by Figure 1. The SE of Cables 10 and 6, which have pigtails at one or both ends, respectively, degrade more gradually than this as the frequency increases.

However, Cables 11 and 12 (which have no pigtails) maintain a consistent SE up to 1GHz.

Between 1GHz and 2.8GHz, Cable 11's SE degrades gradually as the frequency increases, but Cable 12's SE remained so good that it was in the noise floor and we could not measure it with this test set-up in this frequency range.

E. Fluctuations (frequency ripple) of up to ±6dB are seen on Cable 11, a little worse than this for Cable 12.

Ripples up to ±20dB are seen on Cables 10 and 6, which have pigtails at one or both ends, respectively.

F. It is important to 360°-terminate any/all internal cable shields to the overbraids and/or backshells at both ends – and *never use any pigtails*.

Results for Double-Braid-Shielded TP Cables with Double Overbraids – Cables 7 and 8

These are shown in Figure 14 for 100MHz – 1GHz, and Figure 15 for 800MHz – 2.8GHz.

Conclusions for Double-Braid-Shielded TP Cables with Double Overbraids – Cables 7 and 8

Note: both of these cables use an internal TP cable with a double shield that is pigtailed at both ends.

G. Above 100MHz, the SE of these cables does not appear to continually degrade as fast as the rate of 20dB/decade implied by Figure 1.

H. Fluctuations (frequency ripples) of up to ±20dB are seen, which is fairly typical of all the cables that use pigtails, at one or both ends, in all these measurements.

I. Adding an insulating film between two overbraids makes SE *worse* (not up to 30dB better, as claimed in some of the later references).

It is much better for SE (although not for mechanical flexibility) for multiple overbraids to be in direct contact along their entire length.

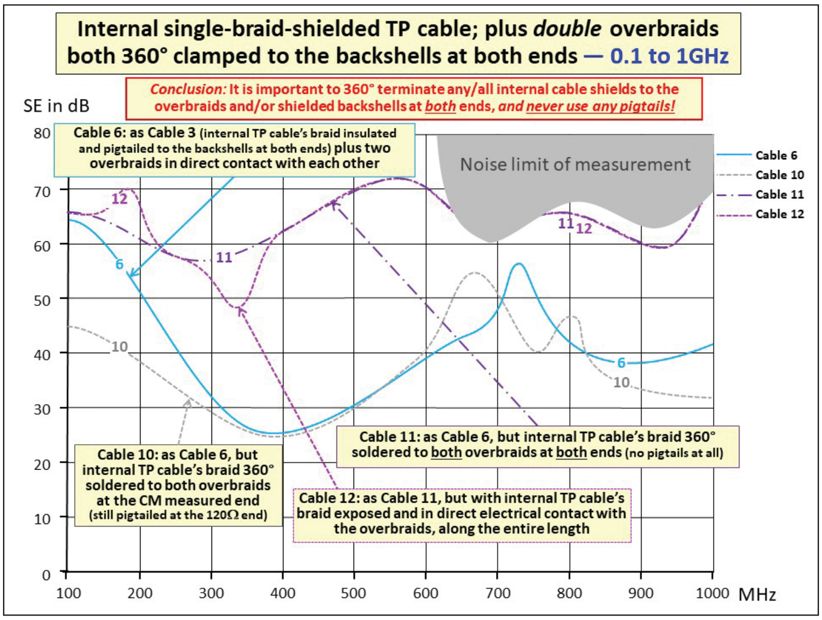


Figure 12: Results for internal single-braid-shielded TP cable, plus *double* overbraids both 360° clamped to the backshells at both ends — 0.1 to 1GHz

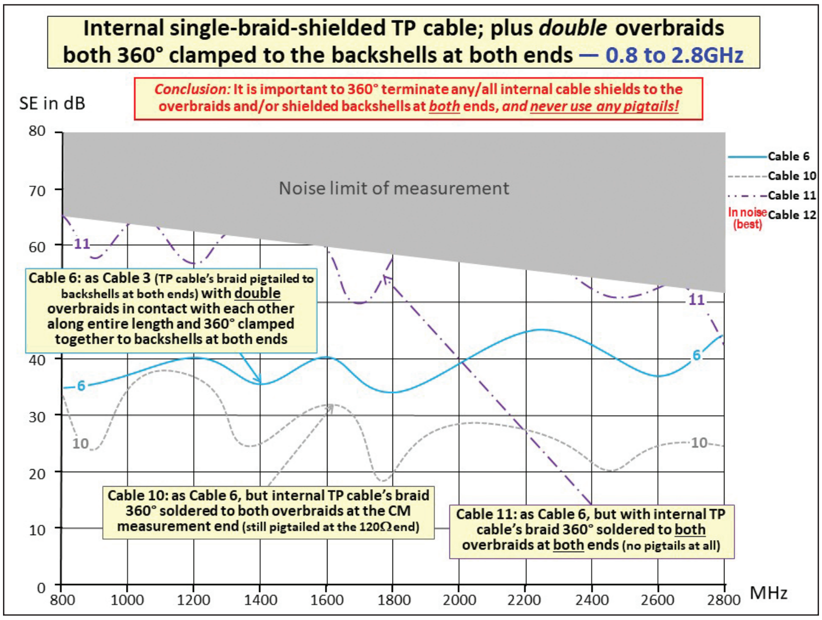


Figure 13: Results for internal single-braid-shielded TP cable, plus *double* overbraids both 360° clamped to the backshells at both ends — 0.8 to 2.8GHz

Few publications in the public domain address how to terminate the shields of individually shielded cables within overbraided cables or cable bundles (ignoring those recommending pigtailing through connector pins!).

J. Comparing the measurements of Cables 7 and 8 with those of the other cables discussed in this article, we see that their rate of fall in SE as frequency increases and their frequency ripples affirm the need to 360°-terminate any/all internal cable shields to the overbraids and/or backshells at both ends – and *never use any pigtails*.

FINAL COMMENT

I would expect double-braid-shielded TP cables in an overall cable or bundle with double overbraids, with all shield layers 360° terminated to the overbraids and/or backshells at both ends *(and no pigtails at all)*, to give better results than any of the cables measured above. But we did not assemble or measure such a design.

BUT HOW TO TERMINATE THE SHIELDS OF INTERNAL CABLES WITHOUT USING PIGTAILS?

Few publications in the public domain (including mine) address how to terminate the shields of individually shielded cables within overbraided cables or cable bundles (ignoring those recommending pigtailing through connector pins!).

This is perhaps because it tends to be an issue for high-spec military or aerospace companies, whose internal design/assembly guides often seem to me to be specifying outdated or non-cost-effective practices, such as pigtailing via connector pins, or requiring a great deal of (costly!) manual assembly by skilled personnel (e.g., 360° soldering an internal braid to an overbraid).

How to cost-effectively terminate cable shields could, on its own, easily fill a whole article, but rather than extend this article by a few thousand words I've added Figures 16 to 18 on pages 138 and 139, taken from my training course on cable EMC [25], and hope they are sufficiently self-explanatory.

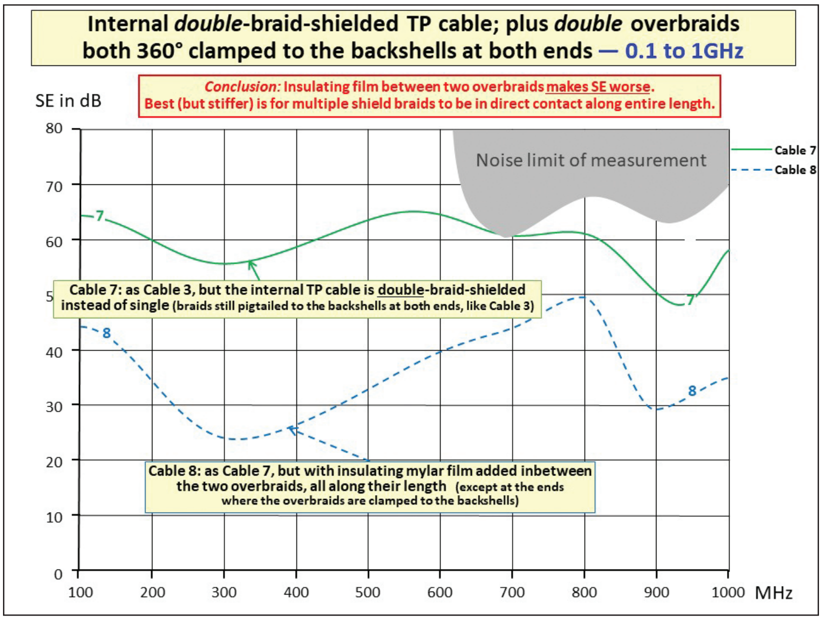


Figure 14: Results for internal *double*-braid-shielded TP cable, plus *double* overbraids both 360° clamped to the backshells at both ends — 0.1 to 1GHz

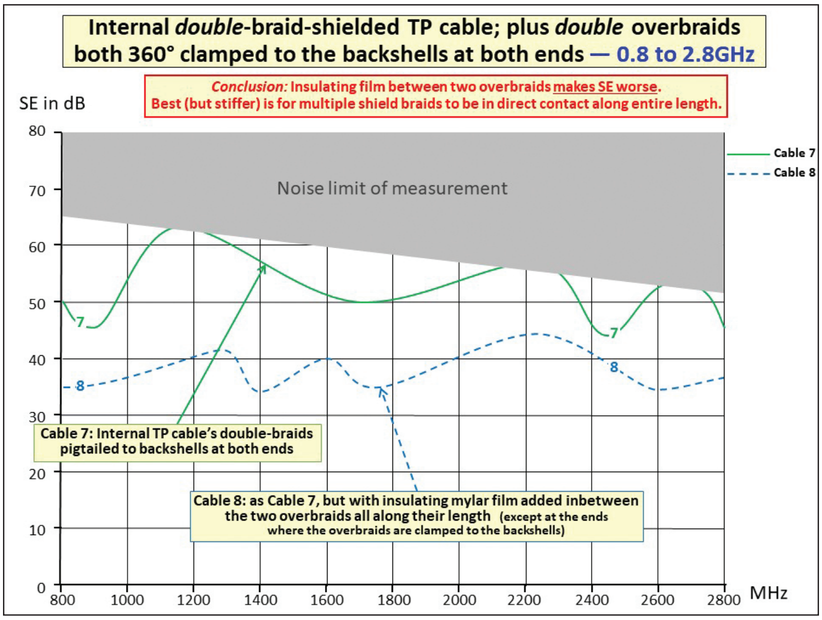


Figure 15: Results for internal *double*-braid-shielded TP cable, plus *double* overbraids both 360° clamped to the backshells at both ends — 0.8 to 2.8GHz

ACKNOWLEDGMENTS

I would like to thank Lockheed Martin (UK) Ltd, near Ampthill, for the use of their facilities and for providing the test equipment used.

I would also like to thank the many people at LM(UK) who helped with these tests, particularly the following:

- Paul Moore (who made the resources available);
- Richard Clark (for helping convert his storeroom back into a shielded room);
- Chris Angove for his assistance with the shielded room and the measurements (including performing most of them and processing their data); and,
- Sean Tunn for his awesome knowledge and expertise in making shielded military cable assemblies.

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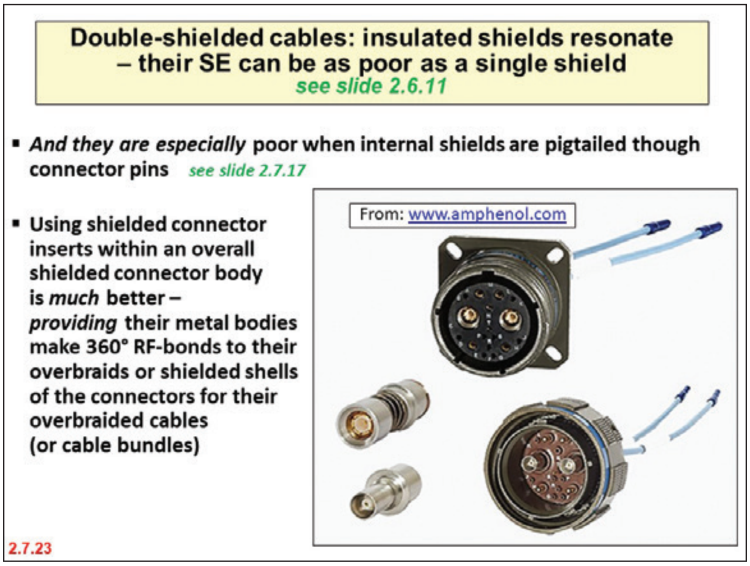

Figure 16: Slide 2.7.23 from [25]

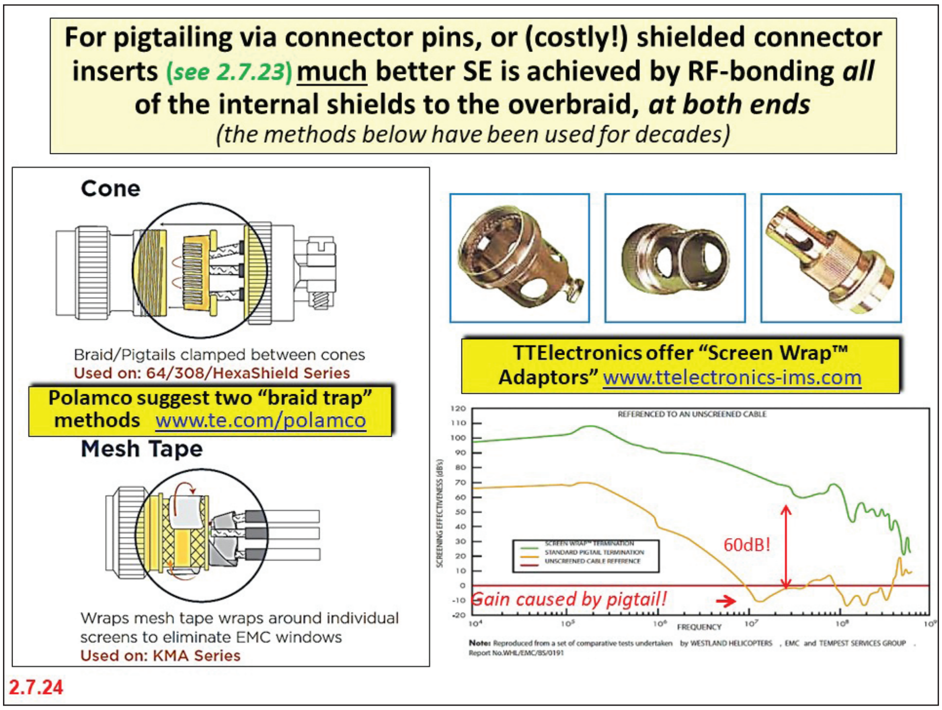

Figure 17: Slide 2.7.24 from [25]

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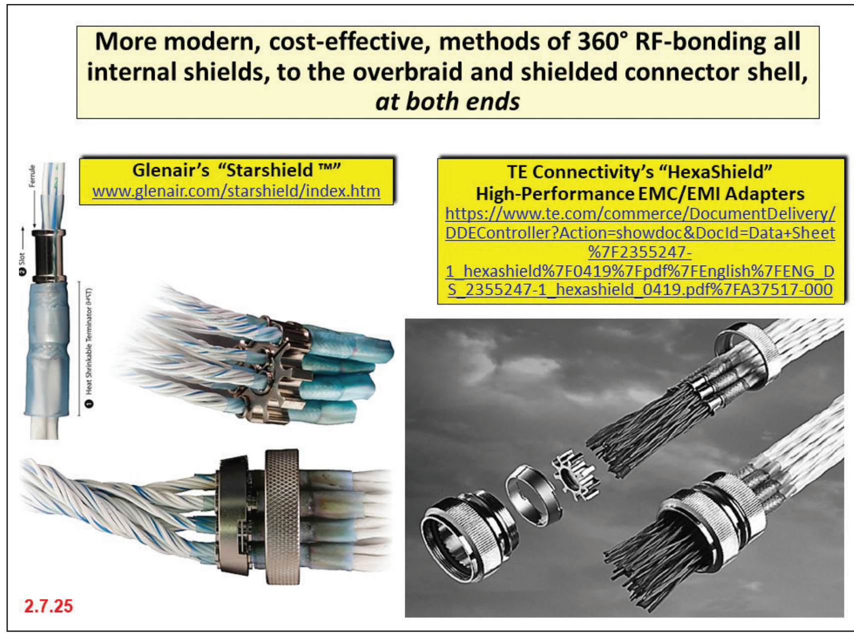

Figure 18: Slide 2.7.25 from [25]

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ESD Compliance in a Server Room

How To Select ESD Flooring for a Space with No Set Industry Standards

BY DAVID LONG

Static-control flooring provides protection against electrostatic discharge (ESD) in multiple industries servicing disparate applications that range from eliminating annoying shocks to protecting aircraft flight-tower operations from equipment malfunctions. Often referred to by the term ESD flooring, this category of flooring can protect static-sensitive electronic devices and equipment from harmful (but, due to its invisibility, seemingly inconsequential) levels of static discharge, far below the threshold of human sensitivity. In other instances, ESD flooring is installed to prevent static sparks from causing ignition of flammable chemicals, munitions, explosives, and energetic materials.

In their article "Are Data Centers Drying Up,"[1] authors Beaty and Quirk discuss alternatives to humidification, like ESD flooring, for preventing real-life ESD problems in data centers, such as:

- Self-correcting errors (such as a lost package in LAN traffic);
- An upset that may need user intervention; or
- Actual physical damage to IT equipment

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.

Specified and used properly, ESD flooring prevents the generation of static electricity and provides a path to ground for charged objects, including people, materials, machines, and transport equipment. ESD flooring also grounds any object with intrinsic conductivity that makes contact with the floor. For data centers, multiple ASHRAE-funded studies strongly suggest the use of at least moderately conductive flooring systems in controlled areas to reduce the overall level of electrostatic charge accumulation, regardless of environmental moisture or the type of footwear used in the space.

STANDARDS VARY BY INDUSTRY

Depending on the industry and application, different static-control requirements and test methods take precedent. For example, static-control requirements for handling explosives usually fall under the jurisdiction of either the Department of Defense (DoD) contractor manual, DOD 4145.26, or Department of Energy (DoE) Standard, DOE 1212-2019. In contrast, organizations handling static-sensitive electronic devices follow the guidelines of ESD Association standard ANSI/ESD S20.20.

It's critical to match the right standard and static mitigation strategy to your specific application. When comparing the value, jurisdiction, and viability of any organization and standards, it's worth noting the possibility of legal complications should the wrong floor be installed. In a January 2012 article published by *In Compliance Magazine*, nationally recognized liability attorney Kenneth Ross says that in a lawsuit:

> *"…Industry standards and even certifications like UL are considered minimum…the standard establishes a reasonable alternative design, and the manufacturer has to justify why it didn't comply."*[2]

Although this advice applies specifically to safety risks, it presents a second problem on a much wider scale. What about product performance? Static discharge is a very real problem, but it is mostly an invisible problem. How does the end user know they actually installed a compliant solution? Does the end-user organization rely on supplier literature and specifications, or does the organization do its own testing? What are the metrics for establishing product compliance, and does their space resemble the conditions under which the product was designed to operate? ESD footwear, for example, greatly enhances the performance of ESD flooring but may be impractical for spaces such as call centers and server rooms.

Given that standards vary, how do you determine which standards and test methods should be referenced for which environment? To understand why this is important, consider the different requirements for resistance testing between UL 779, DoE/DoD, and the ANSI/ESD test requirements. DoE and DoD resistance testing of conductive flooring is usually performed with an ohm meter set at 500 volts. The ANSI/ESD and ASTM requirement for the same resistance test specifies applying either 10 volts or 100 volts, depending on the resistive properties of the material under test.

Flooring manufacturers do not typically provide product specifications based on 500-volt resistance testing, and most flooring specifiers don't ask for results obtained at different voltages. Why would using different voltages in a resistance test present a problem? In the case of the DoD, the government set a minimum flooring resistance of 40,000 ohms tested at 500 volts to assess "safety" from electrocution. According to Ohm's Law, increasing applied voltage lowers resistance. A floor that measures 40,000 ohms using test method ANSI/ESD STM 7.1 at 10 volts will measure well below the 40,000-ohm requirement when subject to 500 V applied voltage.

Figure 1: Deteriorating floor in cable company server room

ASTM and ANSI both evaluate the resistance of conductive floors at 10 and 100 volts. If a specifier chooses a conductive floor based on test results obtained using ASTM F150 or ANSI/ESD STM 7.1 test methods, the floor may not meet DoD (500 volts) requirements.

What happens if resistance testing isn't performed until after the floor has been installed? This occurred at a U.S. Air Force base earlier this year. The facility handles explosives, and the floor, tested post-installation, was not in compliance with government requirements. The supplier has spent over $100,000 in labor and materials to remove their ESD floor and install a new floor that complies with the government standard. Either floor would have eliminated static satisfactorily, but the Department of Defense doesn't provide waivers for non-compliant materials used in explosives applications.

A CASE HISTORY

A large cable television provider enlisted a local flooring contractor to provide costs for a complex project involving the removal of old flooring in a large operational data center/server room and replacement with a static-control solution—the project presented many challenges.

The bond between the old floor tiles and the concrete (see Figure 1) had deteriorated due to age and adhesive breakdown. Flooring directly under racks could not be removed because the facility operates 24/7. Removing the floor surrounding the racks was risky due to potential problems with dust containment. These obstacles and preexisting conditions steered the cable company towards solutions that could be installed directly over the existing floor.

Several different ESD flooring materials were evaluated. The primary objective was to find a material that could be installed without adhesives. This limited the options to interlocking tiles or a floating solution such as rubber, vinyl, or ESD carpet tile. The carpet option was dismissed due to the need to move heavy equipment without adding rolling resistance. This led directly to the decision to install a hard-surface interlocking floor.

The next question: did they want dissipative or conductive flooring? To ESD program managers in electronics manufacturing facilities, this may seem like a simple choice, but this application required grounding people who were handling and changing circuit boards in an operational environment. The client wanted to know how high the resistance could be before it was too high to effectively decay charges and what resistance might be considered too low or unnecessarily conductive, thus posing a potential safety risk. The floor also needed to inhibit charge generation on a person wearing regular footwear in an environment with varying humidity.

Per ANSI/ESD STM 7.1, conductive flooring is defined as any flooring with a resistance to a groundable point of less than one million (< 1.0×10^6) ohms. A dissipative floor measures from one million ohms to less than one billion ohms (< 1.0×10^9). This test's ANSI/ESD S20.20 qualification phase is typically performed in a lab at low relative humidity (RH). An ohm meter is used to measure the aggregate resistance of all the components required to install the floor. With glue-down floor tiles, this entails installing tiles to a test substrate with the proper adhesive and then measuring the resistance from the tile's surface to a ground connection buried into or under the adhesive. The measurements obtained from this simple lab test determine whether a floor is categorized as conductive or dissipative.

To attain a compliant resistance, floors with conductive surfaces are sometimes installed with dissipative adhesive. As long as the adhesive assures a path to ground above 1.0×10^6 and less than 1.0×10^9, this type of flooring system would be characterized as a static-dissipative flooring system. Lab testing cannot predict whether or not this may be problematic in the field because labs don't present variables found in the intended installation environment. For example, a dissipative flooring system that relies on dissipative adhesive to control its resistance to ground could be rendered conductive if installation conditions introduce concrete moisture vapor transmission or if grounded equipment placed on the flooring surface creates an unintended ground path.

Depending on the construction of the flooring system, certain types of floors could also measure differently in the field than in the qualification test. A composite floor such as carpet tile or a floating vinyl floor, for example, might be manufactured with a more conductive surface layer than the layers below the surface. Performing tests on a mock-up installation can catch such possible pitfalls ahead of time, preventing surprises after the floor has been installed.

FOLLOWING A STANDARD

In the case of data centers and server rooms, there are no official standards for choosing the right electrical resistance for ESD flooring. But we can look for static-control guidance from manufacturers who build this equipment. Most use some type of ESD flooring. Since their ESD-prevention programs are designed to meet ANSI/ESD S20.20, they install flooring with a resistance measurement below 1.0×10^9 ohms to ground and charge generation (per test method ANSI/ESD STM 97.2 lower than 100 volts on personnel wearing ESD footwear.

Given that S20.20, IEC 61340-5-1 (the international equivalent of S20.20), and FAA standards all set an upper limit of < 1.0×10^9, the point at which the performance of static-control flooring is significantly diminished, it's logical that this would be a universally accepted upper threshold.

HOW CONDUCTIVE IS TOO CONDUCTIVE?

For decades, NFPA publications set a minimum electrical resistance of 25,000 ohms for floors installed in operating rooms. This resistance value was determined using an ohm meter set at 500 volts. UL 779 requires an average minimum resistance of 25,000 ohms. DoD 4145.26 sets 40,000 ohms as the minimum in areas with 110-volt service and 75,000 ohms near 220-volt service. (For DoD, a ground fault interrupter meets the same requirement.) A post on an IBM data center website, updated in May 2022, says:

> *"For safety, the floor covering and flooring system should provide a resistance of no less than 150 kilohms when measured between any two points on the floor space 1 m (3 ft) apart."*[3]

FAA 019f, Motorola R56, and ATIS 0600321 all require ESD flooring to measure above 1.0×10^6. Like the company in the case study that needed to protect grounded personnel, people employed by facilities covered by these standards work near electrified equipment. These industries created their standards with the intention of protecting workers from the risk of electrocution. While we don't know of a case where someone was electrocuted by an ESD floor, it's a theoretical possibility that has been upheld in laboratory testing.

SPECIFYING HIGHER ELECTRICAL RESISTANCE IS NOT A SAFETY MEASURE

It's paramount to keep in mind that resistance measurements made with an ohm meter should never be relied upon to determine how much current will pass through a static-control floor. One study in particular, by Fowler Associates in Simpsonville, SC, demonstrated a significant variance in the actual measured electrical current on ESD flooring materials versus the predicted electrical current based on resistance measurements obtained using an ohm meter.[4] The only flooring products marketed to protect workers from electrical current are highly insulative and serve no static-control purpose. ESD flooring is not designed to prevent the flow of electricity. It is exactly the opposite. ESD flooring facilitates the flow of charges to ground.

Table 1: Summary data in probability for voltages greater than a threshold value (based on fitted lines).						
Type of Data Center	500 volt discharge probability		4,000 volt discharge probability		8,000 volt discharge probability	
	15% RH & 59° F	50% RH & 80° F	15% RH & 59° F	50% RH & 80° F	15% RH & 59° F	50% RH & 80° F
No Static Control	18%	0.2%	0.5%	3.7×10^{-6}%	0.1%	3.2×10^{-8}%
Dissipative Floors, Dissipative Footwear	16%	19%	0.016%	1.0×10^{-4}%	5.5×10^{-5}%	2.2×10^{-7}%
Dissipative Floors, Uncontrolled Footwear	34%	44%	0.9%	0.001%	0.09%	2.3×10^{-5}%
Conductive Floors, Dissipative Footwear	0.003%	1.6×10^{-7}%	1.8×10^{-7}%	1.8×10^{-11}%	7.4×10^{-9}%	8.9×10^{-13}%
Conductive Floors, Uncontrolled Footwear	8%	0.1%	0.004%	4.7×10^{-10}%	4.1×10^{-5}%	7.5×10^{-13}%
Conductive Rubber Floors, Dissipative Footwear	0.003%	1.6×10^{-7}%	1.8×10^{-7}%	1.8×10^{-11}%	7.4×10^{-9}%	8.9×10^{-13}%
Conductive Rubber Floors, Uncontrolled Footwear	0.1%	9.6×10^{-13}%	8.6×10^{-7}%	1.4×10^{-20}%	1.6×10^{-8}%	3.5×10^{-23}%

Source: Determination of the Effect of Humidity on the Probability of ESD Failure or Upset in Data Centers, Moradian et al, 2014

* Using ESD-mitigating flooring and footwear, the risk of ESD upset and damage can be reduced to an insignificant level, even if the humidity is allowed to drop to low values, such as 8%. Unfortunately, controlling the footwear in most data centers is very impractical.

This leaves us with requisite policies such as following national and local electrical codes, limiting electrical work to only qualified personnel and organizations along with developing, implementing, and enforcing an electrical safety program. This isn't to say that we shouldn't consider a minimum resistance. It just means that we shouldn't rely on electrical resistance as a safety measure. But whether resistance is a reliable predictor of leakage current or not, flooring manufacturers should take Ken Ross's advice into consideration, i.e., a standard (UL, NFPA, DOD, FAA) establishes a reasonable alternative design, and in the case of an accident, the "manufacturer would have to justify why it didn't comply."

REMEMBER FOOTWEAR

Server rooms differ from electronics manufacturing spaces, and the criteria for selection differ as well. One significant question when selecting an ESD floor for a server room as opposed to a manufacturing environment is whether or not the floor can mitigate static charges without ESD footwear. In electronics facilities, all personnel on the floor are required to wear some type of ESD footwear. The use of ESD footwear would be impractical in a server room. This limitation creates a strong need for installing a floor that generates minimal charges regardless of footwear or low relative humidity.

According to a major ASHRAE-funded study:

> *"While it may prove impossible to control with certainty the footwear worn by personnel who enter or work in data centers, facility owners and managers should be aware that footwear can lead to issues in the daily operation of the data center. Just about any conventional polymer-based sole material may lead to high charge levels, some more than others – regardless of humidity. A conductive floor will help mitigate electrostatic charging even on shoes with the highest potential for generating static."*[5]

The type of static-control flooring material also plays a part in charge generation. Among the most compelling documented statistics is the probability of generating a charge over 500 volts while walking on a static-control floor wearing ordinary shoes (see Table 1). The probability of 500 volts occurring on a static dissipative vinyl floor was calculated at 35%; for a conductive vinyl floor, the probability dropped to 8%. The probability of a conductive rubber floor allowing a charge over 500 volts was only .1%.

ESD FLOORING: A PRACTICAL, MONEY-SAVING CHOICE

Historically data centers have relied upon humidification to control static. The ESD Association removed humidification as a requirement in the 2007 version of ANSI/ESD 2020. We can and should draw from other standards to address the specific needs of these spaces.

ASHRAE research project RP-1499 shows that the installation of static control flooring in data centers and server rooms can control, reduce and prevent problematic levels of static generation and, as a result, enable a significant reduction of long-standing humidification and energy requirements in these spaces.

Combatting these problems with a one-and-done infrastructure solution like ESD flooring makes sense, particularly compared with wasting energy to cool a highly humidified space. In "The Effect of Humidity on Static Electricity Induced Reliability Issues of ICT Equipment in Data Centers" (Endnote #5), authors Wan, Swenson, Hillstrom, Pomerenke, and Stayer strongly suggest the use of:

> *"at least moderately conductive flooring systems in controlled areas to reduce the overall level of electrostatic charge accumulation, regardless of footwear or environmental moisture. Flooring has to be installed anyway, and the cost associated with a conductive rather than insulative floor is minor compared to continuing operational costs to sustain proper moisture levels (low humidity)."*

When evaluating an ESD floor, multiple performance factors should be investigated, including maximum and minimum electrical resistance, electrical codes and industry standards, charge generation at the lowest operational relative humidity, and performance with and without ESD footwear. Whether the data center is under construction or already in operation will impact and possibly limit ESD flooring options.

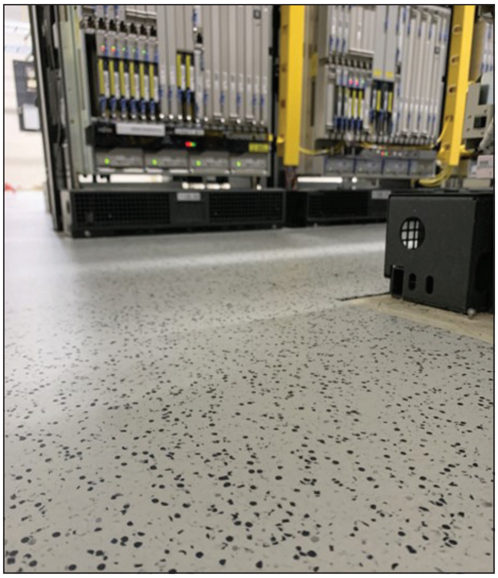

Figure 2: Server room covered with interlocking conductive floor. Note the floor edges are trimmed to avoid contact with the racks

Some organizations prefer that conductive flooring not make electrical contact with racks (see Figure 2) due to the potential impact on system analysis due to a ground path from the rack to the floor. Another consideration is whether contact with grounded racks might alter a floor's surface-to-ground resistance properties. Experimental installations can expose these possibilities prior to specifiers making a final selection.

Combined with static-control chairs and grounding straps, static-control flooring can provide a highly effective, single-expense solution for all types of ICT spaces.

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EMC Management in Charging Applications

Managing the EMC Process So You Can Pass the First Time

BY DR. MIN ZHANG

INTERPRETING EMC STANDARDS

Picture yourself as part of a team of engineers who are specialized in designing chargers. A new project comes along. How do you ensure the final design will pass the standard EMC tests the first time?

A typical first step is to interpret the relevant EMC standards that are applicable to the specific application. (Quality, safety, and environmental standards are equally if not more important, but they are not in the scope of this discussion.) One must look at the commercial EMC standards if the product is a fast charger for mobile phones and laptops. The automotive EMC standards should be applied if the product is an on-board charger (OBC) used in an electric vehicle. If it is a product based on wireless power transfer (WPT), one should refer to relevant standards and stay alert to changes as the standards are still being developed.

Dr. Min Zhang is the founder and principal EMC consultant of Mach One Design Ltd, a UK-based engineering firm that specializes in EMC consulting, troubleshooting, and training. His in-depth knowledge in power electronics, digital electronics, electric machines, and product design has benefitted companies worldwide. Zhang can be reached at info@mach1design.co.uk.

As an example, Table 1 lists the typical EMC test requirements that are applicable to an OBC.

AN OVERVIEW OF THE EMC DESIGN PROCESS

Once the requirements have been agreed upon by the design company and their customer, the design process

Test Items	Standard
Radiated emission – Broadband sources	ECE R10.6 Chapter 7.10 & Annex 7
Radiofrequency disturbance voltages on AC or DC power lines	ECE R10.6 Chapter 7.13 & Annex 19, average and quasi-peak detector IEC 61000-6-3
Radiated immunity	ECE R10.6 Chapter 7.18 & Annex 9
Transient disturbances conducted along 12V/24V supply lines	ECE R10.6 Chapter 7.19 & Annex 10
Fast transients – burst conducted along AC and DC power lines	ECE R10.6 Chapter 7.15 & Annex 21
Surge conducted along AC and DC power lines	ECE R10.6 Chapter 7.16 & Annex 22
Immunity to low frequency conducted disturbances – voltage dips and interruptions on AC supply lines	IEC 61000-4-11 <16A per phase IEC 61000-4-34 >16A per phase
Immunity to electrostatic discharger	ISO 10605

Table 1: Standards and regulations applicable to on-board charging systems

At the concept stage, engineers evaluate and select the topology of a charging converter based on the product requirements. It is essential to review the design with EMC in mind.

follows. This design process typically follows a staged approach, as shown in Figure 1. It is highly recommended that the EMC design reviews should be performed at each stage of a product's design and preliminary tests should be arranged as soon as the prototype of the PCB is ready. It is perhaps the only way to ensure strict EMC control to avoid major design changes at a later design stage.

In this article, we discuss how to implement EMC management during the design and development stage using practical demonstrations.

THE CONCEPT STAGE

At the concept stage, engineers evaluate and select the topology of a charging converter based on the product requirements. It is essential to review the design with EMC in mind. A popular power converter topology for charging applications is a power factor correction (PFC) stage followed by a resonant circuit. Common PFC circuits include interleaved boost converters, bridgeless totem-pole converters, and interleaved totem-pole converters. Popular resonant circuits are an LLC, a phase-shifted full-bridge converter with current doubler rectifier, and so on. Figure 2 illustrates the converter topology of a 12 kW OBC (for demonstration purposes, only rail 1 of the converter is shown).

It is essential to have a PFC stage to improve the power factor of the grid and to achieve lower total harmonics distortion (THD) during the charging state. Without the PFC, charging, especially fast charging, draws a high peak current at the voltage peak and almost no current over the remaining mains cycle. This results in excessive high current flow in the mains conductors, the power transmission lines, and the power transformers.

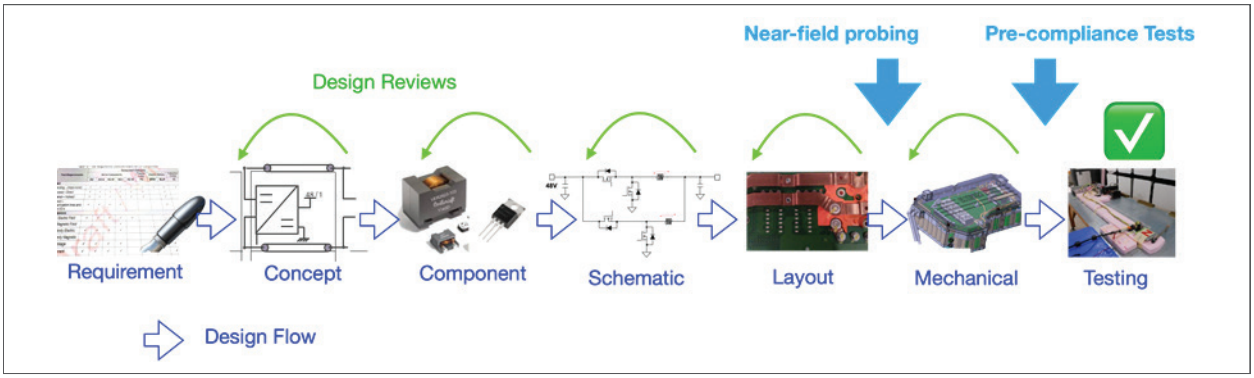

Figure 1: A typical design process showing design stages

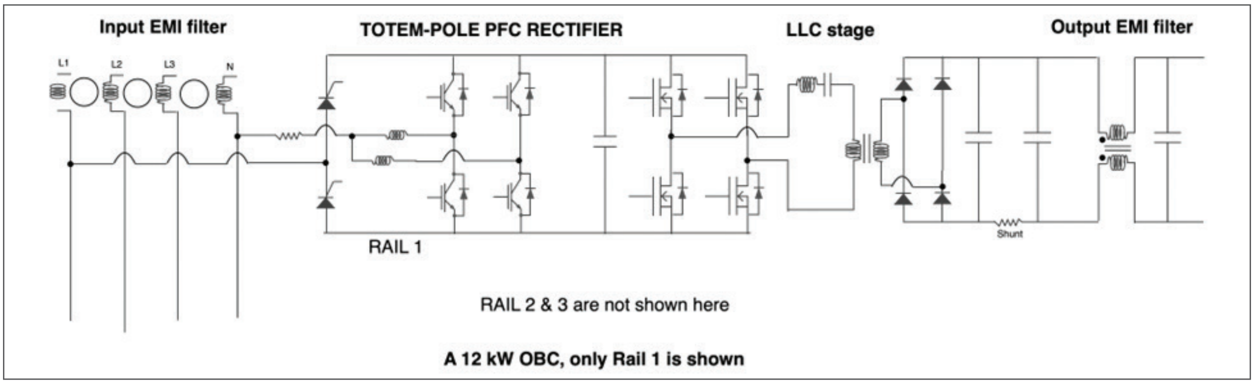

Figure 2: Schematics of a 12 kW on board charger (rails 2 and 3 are not shown in this diagram)

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In the example shown in Figure 3, an interleaved boost totem-pole PFC is selected because the two interleaved rails topology achieves halved current rating per half bridge. This results in ripple current cancellation on both the input and output of the PFC stage. As a result, this reduces the size of the bulk capacitor and lowers the EMC impact of the PFC. But this approach increases the number of switching devices and the complexity of the control. (Reference 1 offers a detailed comparison study between different PFC topologies but does not focus on the EMC performance analysis.)

It is the design engineer's job to select the PFC topology based on the intended application. The decision needs to be based on the trade-offs between efficiency, ease of manufacturing, cost, weight, thermal considerations, and EMC. The topology also depends on the power rating of the applications. For instance, if it is a fast-charging device for a laptop or mobile phone, the PFC topology will be a simple boost PFC without interleaving. A number of trade-offs can also be seen when it comes to selecting the resonant converter stage. It should be noted that the zero-voltage switching (ZVS) has been widely used for resonant converters. When designed properly, ZVS provides significant circuit improvements in zero voltage switching and other areas, such as reducing common mode currents.

THE COMPONENT SELECTION STAGE

Reference 2 discusses the importance of selecting the right types of power electronics devices. For charging applications, choosing the right devices is essential to achieve a compact design and comply with EMC requirements. Among the devices of choice, wide bandgap devices such as gallium nitride (GaN) devices are widely seen in commercial applications such as fast chargers for laptops and phones, while silicon carbide (SiC) devices are dominant in the high voltage high power applications such as OBCs used in electric vehicles.

As shown in Figure 4, most GaN devices are surface-mounted with integrated driver circuits, while most SiCs are through-hole discrete devices because of the high-power level. Though D2PAK SiC devices are available, they are not a design engineer's favorite choice, mainly because of the different thermal characteristics associated with the package.

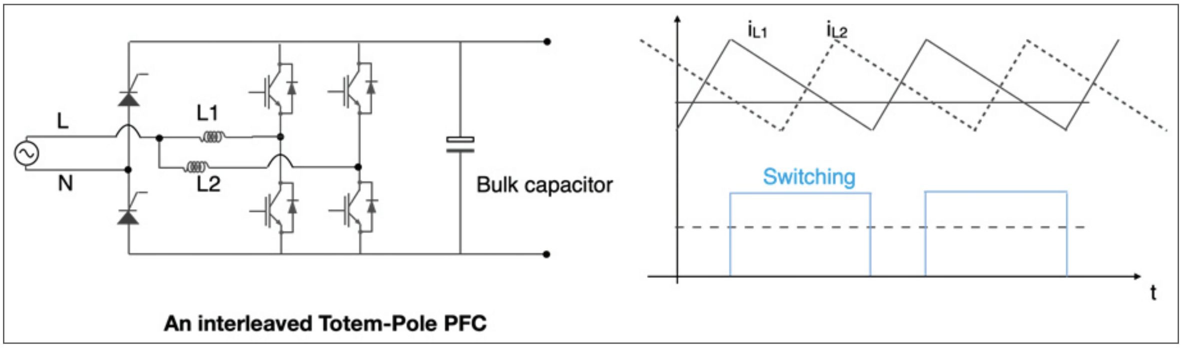

Figure 3: One of the benefits of using an interleaved totem-pole topology is ripple current cancellation

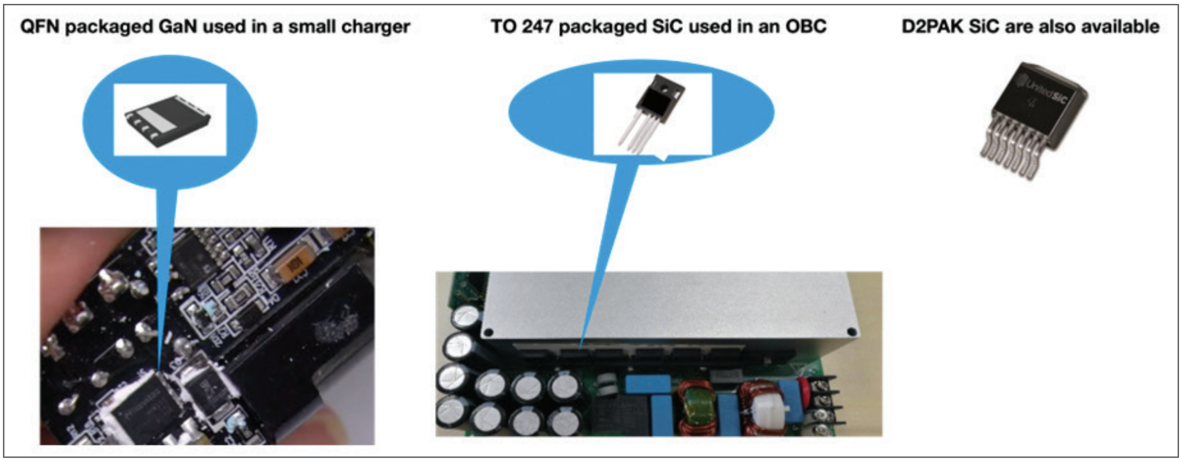

Figure 4: Wide band gap devices such as GaN and SiC FETs are widely seen in charging applications

Through-hole devices are robust, low cost, and enjoy better thermal characteristics, and are therefore widely used in high voltage, high power applications. But, for EMC, they are not as good as the surface-mounted devices because the extra-long leads of the package introduce larger inductance.[2] Being physically tall, they also radiate more efficiently compared with surface-mounted devices. The thermal design around these devices is crucial as heatsinks are often much larger than the devices themselves. If the heatsink is not grounded well, it can radiate much more at a lower frequency range (30-300MHz).[3]

Apart from switching devices, magnetics components such as the transformer used in the resonant converter stage also need to be designed with EMC considerations in mind. System efficiency is always the most important design factor. Therefore, a transformer's losses (including core losses, copper losses, skin effect, and proximity effect) are often given significant consideration during the design stage. The ZVS scheme also requires a saturable core of the transformer and prefers higher leakage inductance. This means that the EMC design of a transformer is often overlooked.

A simple electrostatic shield can often help reduce the common mode current when added to the transformer.[4] The shield needs to be connected to 0V on the primary side and should be kept as thin as possible to minimize eddy current loss due to the proximity effect. A second shield on the secondary side improves the EMC performance further, but at extra manufacturing cost.

Other techniques in the transformer design include common mode current cancellation or the so-called common mode current balance based on a unique winding structure design.[5] It should be noted that transformer design is also the key to optimizing the ZVS of the converter.

During the design review, pros and cons of each component selection should be assessed. Efficiency, size, and cost are often the key factors in selecting components. But the comparison should also account for EMC considerations as well. For example, engineers often select components so that the best form factor and minimum cost are achieved, only to find out that a heavy, bulky, and expensive filter needs to be added on at a later stage because the selected switches/transformer create too many EMI issues. If the issue had been highlighted early during the component selection stage, total time and cost could have been reduced.

THE SCHEMATIC AND LAYOUT REVIEW STAGE

During the schematic review, attention should be paid to the following areas:

1. The gate driver design should be reviewed, switching speed (rise time and fall time) of the switching devices should be analyzed based on the gate resistors, and risk analysis should be performed. The review should also extend to the bootstrap circuit for non-isolated gate drivers and snubber circuit design.
2. Input and output filters are key to the EMC performance of a charger. The insertion loss of each filter stage should be calculated/simulated. The filters should be most effective in the frequency range between a few kHz to 100s of MHz.
3. Decoupling capacitors are essential for all switched mode power supply designs. Design engineers should check if sufficient decoupling capacitors are placed in the key areas of interest. These key areas are power lines (primary and secondary sides), transformers (between primary and secondary), and connections to the chassis.

When it comes to the layout review, the devil is in the details. A layout review can easily cost a few days' time with design engineers from multiple disciplines involved. Decoupling capacitors, filter locations, connectors, traces, vias, and more all need scrutiny in the review stage.

One example is shown in Figure 5. In order to dissipate the heat generated by the GaN devices, a large copper area and thermal vias are often used. This is a design

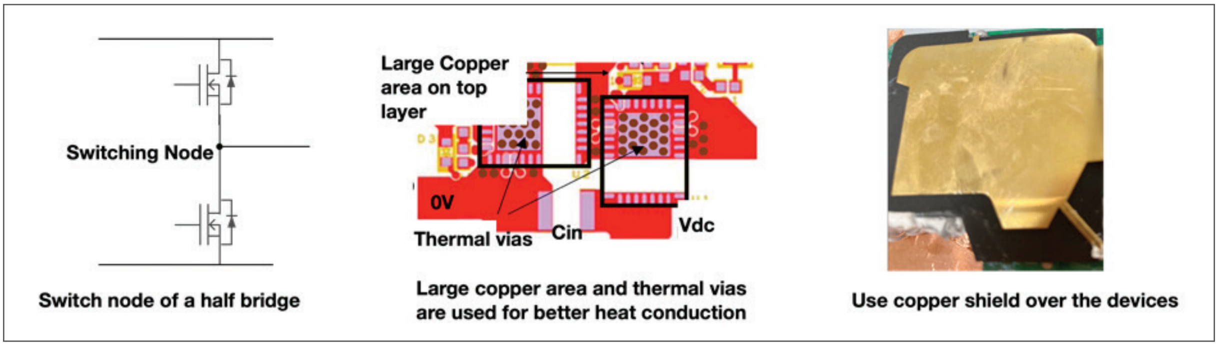

Figure 5: Using a large copper area under the switch node could lead to worse EMI, a shield over the devices is beneficial for both thermal and EMC

feature generally favored by both electronic engineers and thermal engineers as large copper areas dissipate heat more efficiently, thereby achieving a higher efficiency conversion. The switching node of a half bridge connects the source node of one device and the drain node of the other. But having a large copper area effectively increases the size of the switching node, making the emission worse and hard to contain. This EMC-related risk should be highlighted in the layout design stage and a mitigation plan should be designed. In this case, a possible mitigation plan would be to use an aluminum/copper sheet over the devices. This sheet helps dissipate the heat while also providing shielding over the switching node. This contingency plan can then be implemented and tested in the packaging and mechanical stage.

TESTING AT AN EARLY STAGE

A preliminary test should be performed as soon as the first prototype PCB is ready. It is true that a product's EMC performance is dependent on the layout and packaging, and the noise profile of a final product will be different from that of a single PCB. However, an early-stage, near-field probing exercise can often indicate red flags and will reap benefits at the tail end of the design process.

On the PCB level, two simple benchtop tests can be performed. Near field probing, such as using a magnetic field loop over the PCB area, can locate the noise source (see Figure 6). The noise profile is generally a good indication of both conducted and radiated emissions.[6] As shown in Figure 7, measuring the common mode current on the cables using an RF current monitoring probe is another efficient way of predicting conducted and radiated emissions of the PCB under investigation.[7]

PACKAGING AND MECHANICAL ASSEMBLY STAGE

The packaging of the final product is often considered to be a mechanical job. At this stage, the final product is assembled, and the thermal design is applied. PCB assemblies could involve stacking up PCBs, stacking PCBs on stand-offs to chassis, wire-connecting PCBs, PCB connections to chassis connectors, etc. On the thermal design, for small power applications, this means applying thermal paste/glue, and thermal pads. For large power applications, this means implementing heatsinks and liquid cooling pipes.

The key challenges at this stage are to minimize connection impedance. For instance, the height of the stand-offs determines the inductance between PCBs to chassis. Therefore, multiple shorter stand-offs are preferable from the EMC point of view, a preference typically endorsed by mechanical engineers as well[2]. However, with stacked-up PCBs, cavity resonances could occur, and ways of de-risking resonance structures can be found in References 8 and 9.

Heatsinks need to be bonded to either 0V or power rails to prevent them from radiating emissions. Shields such as the aluminum/copper shield introduced previously also need to be bonded to the 0V plane to make them work for EMC.[3] (For thermal design, they don't need to be bonded to any point.)

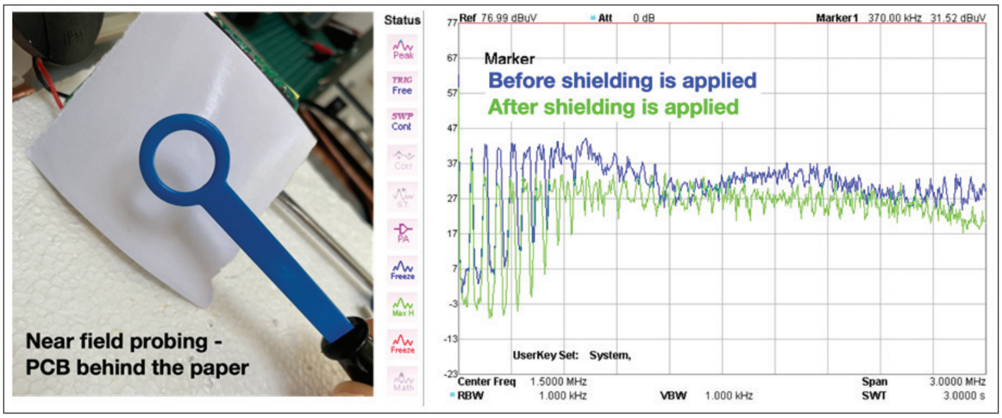

Figure 6: Using near field magnetic probe serves as a quick way of testing the EMC performance of the PCB

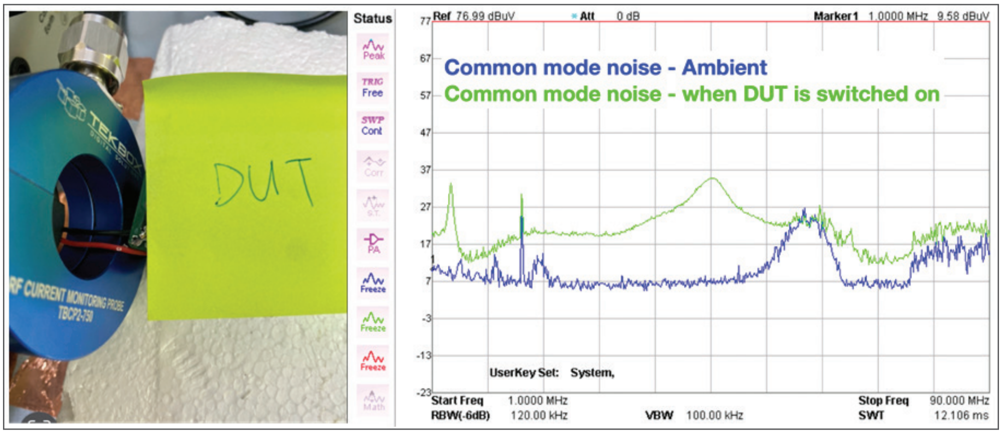

Figure 7: Using an RF current monitoring probe to measure the common mode current on the cables of the PCB

PRE-COMPLIANCE EMC TESTING

The two most important EMC tests for charging applications are for conducted and radiated emissions. It is always a good practice to test the products in a pre-compliance EMC test set-up before sending the unit for formal compliance testing. The good news is that both conducted and radiated emission pre-compliance tests can be performed on a benchtop at a relatively low cost.

CONDUCTED EMISSION

Depending on the power rating of the DUT, suitable power rated LISNs can be used for conducted emission testing. Because it is a high voltage application, high voltage safety should take priority when setting up a pre-compliance test set-up. Using an isolation transformer and grounding the test ground plane to safety earth are absolutely necessary to secure the safe operation of conducted emission test. Figure 8 shows a benchtop pre-compliance conducted emission set-up for a product in development using GaN switches.

Figure 8: A fast charger is being tested against conducted emission in a pre-compliance test set-up

RADIATED EMISSIONS

An open transverse electromagnetic (TEM) cell is often used to determine radiated patterns of a DUT. It should be noted that a TEM cell set-up will not deliver exactly the same quantitative results as a measurement using far-field antennas. Due to space constraints, longer wires are often wound within the TEM cell space, which also affects the radiated emission profile. Nonetheless, using a TEM cell has proved to be an effective way of predicting the radiated emissions of a DUT.

As shown in Figure 9, an OBC is placed inside the TEM cell. To draw a complete emission profile of the DUT, three main orthogonal orientations of the DUT need to be placed.[10] But this also illustrates the limitations of using a TEM cell for testing large power-rated products such as on OBC due to the spectrum height of a TEM cell (in this case, this TEM cell has 15 cm spectrum height). Therefore, in this case, only one orientation of the DUT is tested. However, for home appliance charging applications, a DUT is small enough to be tested with the three main orthogonal orientations.

Hopefully, at this stage, the pre-compliance results provide a high level of confidence that the

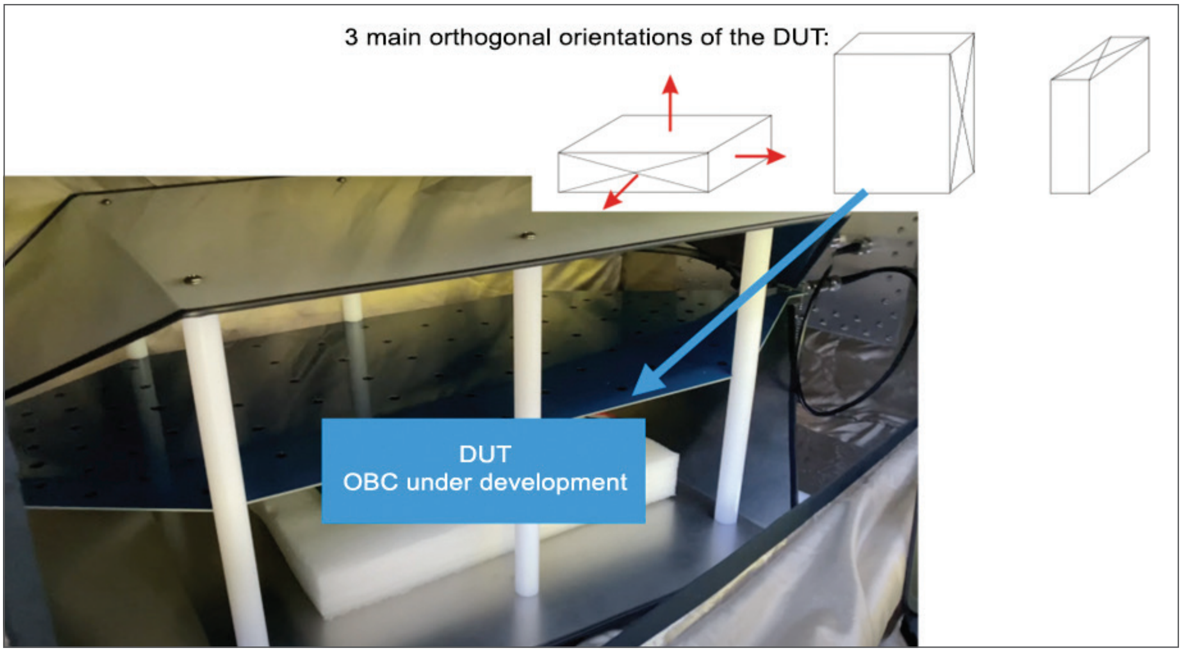

Figure 9: An OBC for automotive application is being tested against radiated emission in a TEM cell

device will pass the emission tests. However, if red flags are highlighted, engineers can walk back to the previous stage to work out a troubleshooting plan that will eventually address the highlighted issues.

SENDING THE PRODUCT FOR FORMAL EMC TESTING

There is always some degree of uncertainty when it comes to final EMC testing. But, by following the EMC management process described in this article, there should not be any big surprises. The process helps to ensure that all foreseeable EMC aspects have been considered and addressed during the design process. The meeting notes of each design review should be well-documented in an EMC risk assessment. The EMC risk assessment serves as convincing evidence that the company has at least attempted to address EMC issues.

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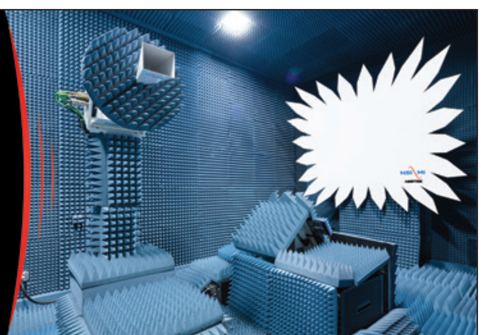

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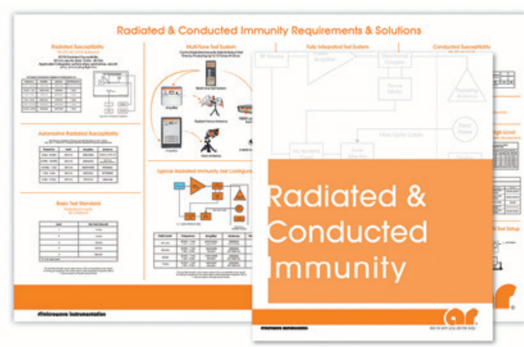

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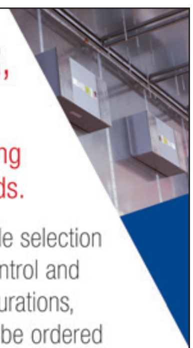

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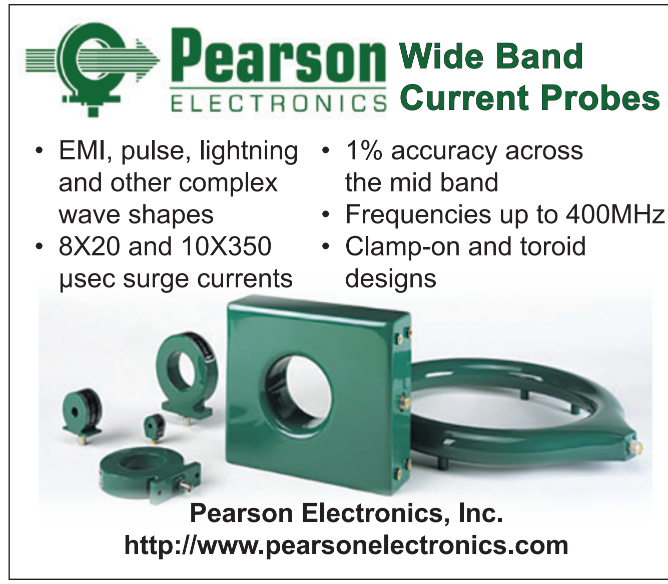

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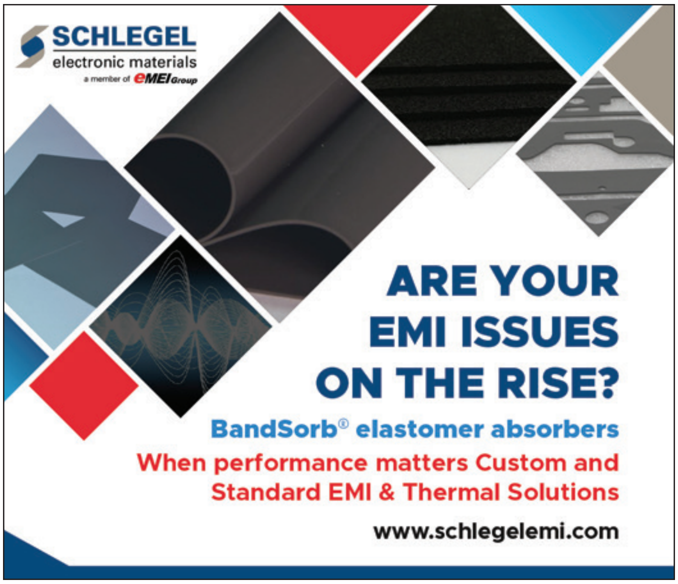
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Omni Controls
Tampa, FL USA https://www.omnicontrols.com

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Southampton, Hampshire United Kingdom https://www.pce-instruments.com

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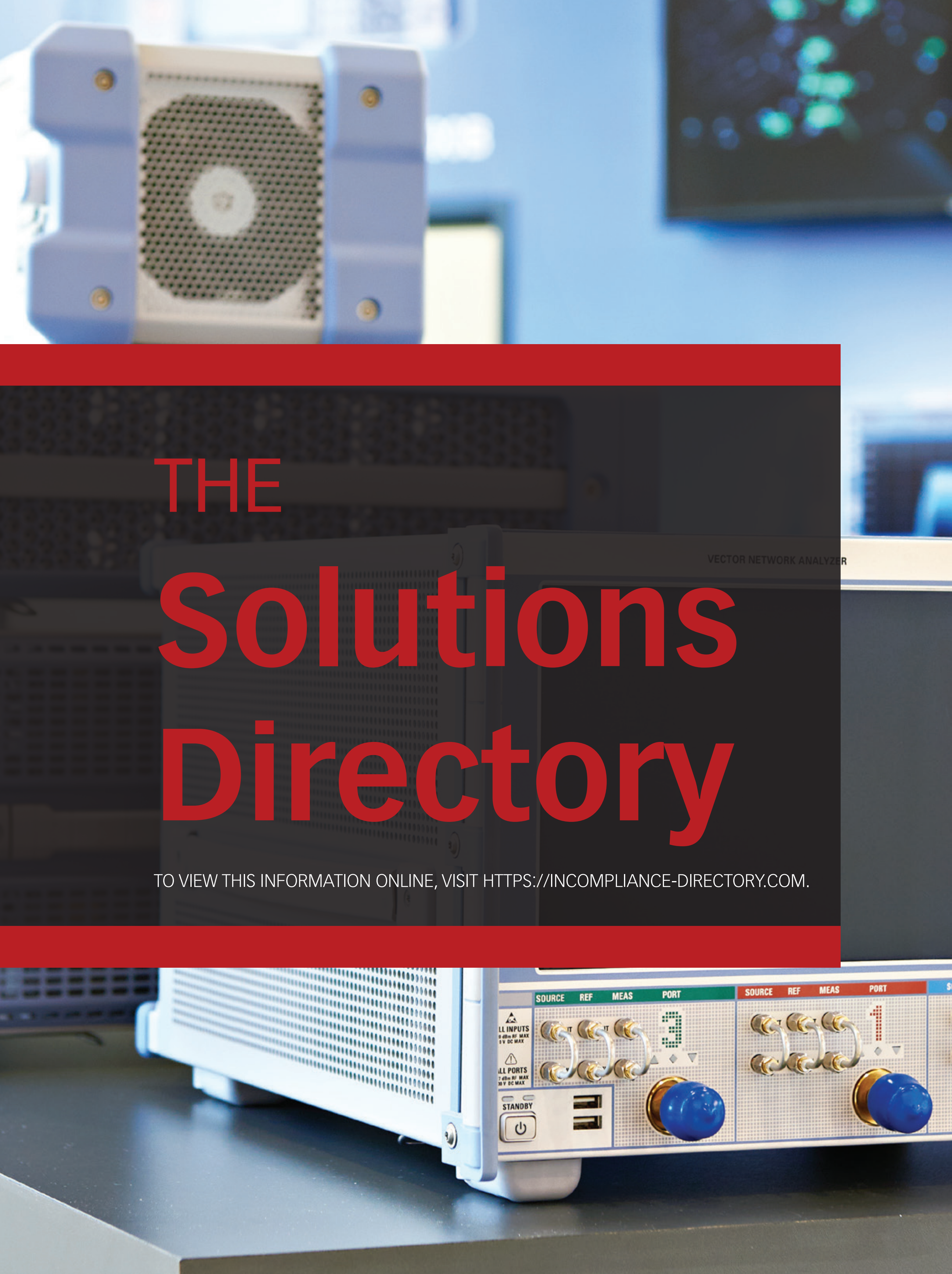

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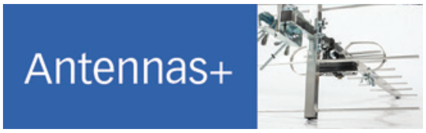

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SCHURTER, Inc.
Solar Electronics Co.
Spectrum Control
Spira Manufacturing Corporation
TDK Electronics
TDK RF Solutions
Tech-Etch
TTE Filters
WEMS Electronics
Würth Elektronik

Filter Coils

Coilcraft Critical Products & Services
Curtis Industries/Tri-Mag, LLC
TTE Filters

Filter Pins

EMI Solutions, Inc.

Frequency Converters

TTE Filters
VEROCH - Testing Equipment USA

Oscillators

Gemini Electronic Components, Inc.

Passive & Discrete

Capacitors

Ceramic Capacitors

Dexter Magnetic Technologies, Inc.
ES Components
Knowles (UK) Ltd
KOA Speer Electronics
KYOCERA AVX Components Corporation
RCD Components
TDK Electronics
Würth Elektronik

Decoupling Capacitors

Oak-Mitsui Technologies

EMC Feedthrough Capacitors

Captor Corporation
NexTek, Inc.
RCD Components
Schaffner EMC Inc.
WEMS Electronics

EMC Suppression Capacitors

Americor Electronics Ltd.
Captor Corporation
Oak-Mitsui Technologies
RCD Components
Würth Elektronik

Filter Capacitors

Captor Corporation
CONEC Corporation
EMI Solutions, Inc.
NexTek, Inc.
Oak-Mitsui Technologies
Okaya Electric America, Inc.
RCD Components
Würth Elektronik

Planar Array Capacitors

CONEC Corporation
EMI Solutions, Inc.
Oak-Mitsui Technologies

Tantalum Capacitors

KYOCERA AVX Components Corporation
RCD Components

Ferrite Beads, Rods & Forms

Fair-Rite Products Corp.
Faraday Defense Corp.
Gowanda Electronics
iNRCORE, LLC
KOA Speer Electronics
Leader Tech Inc.
MAJR Products
MH&W International Corporation
TDK Electronics
Vanguard Electronics

Inductors/Chokes

Data & Signal Line Chokes

iNRCORE, LLC
NRD LLC
SCHURTER, Inc.
TDK Electronics
WEMS Electronics

EMI/RFI Inductors

Captor Corporation
Coilcraft Critical Products & Services

Coilcraft, Inc.
iNRCORE, LLC
KYOCERA AVX Components Corporation
NRD LLC
WEMS Electronics

Power Line Chokes

Coilcraft Critical Products & Services
Gowanda Electronics
iNRCORE, LLC
MH&W International Corporation
SCHURTER, Inc.
Vanguard Electronics
WEMS Electronics

Reactors for Frequency Converters

Coilcraft Critical Products & Services
NRD LLC
OnFILTER

RF Chokes

Coilcraft Critical Products & Services
Gowanda Electronics
iNRCORE, LLC
MH&W International Corporation
NRD LLC
Schaffner EMC Inc.
Vanguard Electronics

Surface Mount Inductors

Coilcraft Critical Products & Services
Gowanda Electronics
iNRCORE, LLC
KYOCERA AVX Components Corporation
Vanguard Electronics

Switchmode Inductors

Coilcraft Critical Products & Services
Gowanda Electronics
iNRCORE, LLC
Vanguard Electronics

VHF Chokes

Coilcraft Critical Products & Services
NRD LLC

Mains (X & Y)

Okaya Electric America, Inc.

Resistors & Potentiometers

Electronic Loads

ES Components
Gemini Electronic Components, Inc.

Potentiometers

Betatronix
Bourns, Inc.

Power Line Isolation

iNRCORE, LLC
RCD Components

Signal Line Isolation

iNRCORE, LLC
RCD Components

Transformers

Americor Electronics Ltd.
Coilcraft, Inc.
ELSCO Transformers
Gowanda Electronics
iNRCORE, LLC
Pearson Electronics, Inc.
RCD Components
Vanguard Electronics

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.
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

Power Supply & Conditioning

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
Oak-Mitsui Technologies
Polyonics
SCHURTER, Inc.

Resonators

ES Components

Semiconductors

ES Components
Gemini Electronic Components, Inc.
Nexperia Semiconductor

Surge Suppressors

Captor Corporation
CITEL, Inc.
Curtis Industries/Tri-Mag, LLC
EMI Solutions, Inc.
ES Components
Faraday Defense Corp.
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

Marktek Inc.

Adhesives

Alpha Assembly Solutions
ARC Technologies, a Hexcel Company
DELO Adhesives
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

Faraday Defense Corp.
Globe Composite Solutions
Kemtron Ltd., now part of TE Connectivity
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
Bolting Specialist, a division of Resistant Metal Alloys LLP
Eastern Steel Manufacturing Co.,Ltd
Ferrotec-Nord
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
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
Globe Composite Solutions
Lubrizol Engineered Polymers
MFG Tray Company (Molded Fiber Glass Tray Co.)
Parker Chomerics

Resources

Associations

A2LA
EOS/ESD Association Services, LLC
Saf-T-Gard International, Inc.

Education

Seminars

André Consulting, Inc.
Archambeault EMI/EMC Enterprises
BestESD Technical Services
Cherry Clough Consultants Ltd
D. C. Smith Consultants
Eisner Safety Consultants
Equipment Reliability Institute (ERI)
ESD Association
Go Global Compliance Inc.
Hoolihan EMC Consulting
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
WorkHub
Wyatt Technical Services LLC

Training Courses

A2LA
André Consulting, Inc.
ARC Technical Resources
Cherry Clough Consultants Ltd
D. C. Smith Consultants
DEKRA
DG Technologies
Eisner Safety Consultants
Electronic Instrument Associates
EMC Center at Grand Valley State University
EMC FastPass
EOS/ESD Association Services, LLC
Equipment Reliability Institute (ERI)
Eurofins York
Hoolihan EMC Consulting
iNARTE
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
University of Oxford Continuing Professional Development - Technology Programme
Washington Laboratories
WorkHub
Wyatt Technical Services LLC

University

EMC Center at Grand Valley State 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
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
EOS/ESD Association Services, LLC
ESD Association
LearnEMC
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
WorkHub
Wyatt Technical Services LLC

Publications

Books

EMI/EMC Books

André 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
PAVONE Technologies
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., a Transcat Company
Fischer Custom Communications, Inc.
Haefely AG
Keysight Technologies Inc.
Lightning EMC
M Precision Laboratories, Inc.
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.

Consulting

Cleanroom/Static Control

Advanced ESD Services +
BestESD Technical Services
Bystat International Inc.
Estion Technologies GmbH
OnFILTER
Protective Industrial Polymers

EMC Consulting

André Consulting, Inc.
Atlas Compliance & Engineering
BestESD Technical Services
Cherry Clough Consultants Ltd
CKC Laboratories, 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.
Hoolihan EMC Consulting
International Certification Services, Inc.
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
EOS/ESD Association Services, LLC
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
André Consulting, Inc.
Atlas Compliance & Engineering
CKC Laboratories, 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

André 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

André Consulting, Inc.
D. C. Smith Consultants
D.L.S. - Military
Electro Magnetic Applications, Inc. (EMA)
NexTek, Inc.

Medical Device

André 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
G&M Compliance, Inc.
GreenSoft Technology
Kimmel Gerke Associates Ltd.
Laird Connectivity
MedicalRegs.com
Orbis Compliance LLC

Consulting

Medical Device *(continued)*

Pacific EMC
The Photonics Group
Product Safety Consulting
Pulver Laboratories
Test Site Services Inc.
TJS Technical Services Inc.

Product Safety Consulting

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.
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

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
PAVONE Technologies

Tempest

Dayton T. Brown, Inc.

Transient

André 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

Transient

PAVONE Technologies

Design

André 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
Globe Composite Solutions
JBRC Consulting LLC
Machinery Safety & Compliance Services
Orbel Corporation
The Photonics Group
SILENT Solutions LLC
V Technical Textiles, Inc.
VEROCH - Testing Equipment USA
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.
Slayson
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
EOS/ESD Association Services, LLC
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

Shielding

Architectural Shielding Products

ETS-Lindgren
Faraday Defense Corp.
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

Kemtron Ltd., now part of TE Connectivity
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
Diamond Microwave Chambers Ltd
Elma Electronic Inc.
Emcor Enclosures
ETS-Lindgren
Faraday Defense Corp.
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.
Slayson
Universal Shielding Corp.
V Technical Textiles, Inc.
VTI Vacuum Technologies, Inc.

Shielded Tubing

Electri-Flex Company
Kemtron Ltd., now part of TE Connectivity
Leader Tech Inc.
Magnetic Shield Corporation
Marktek Inc.

Shielded Wire & Cable

Cinch Connectivity Solutions
CONEC Corporation
Isodyne Inc.
Leader Tech Inc.
Metal Textiles Corporation
SF Cable

Shielding Gaskets

3Gmetalworx Inc.
Kemtron Ltd., now part of TE Connectivity
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.
Kemtron Ltd., now part of TE Connectivity
KITAGAWA INDUSTRIES America, Inc.
Leader Tech Inc.
MAJR Products
Metal Textiles Corporation
MH&W International Corporation
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.
Kemtron Ltd., now part of TE Connectivity
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
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
TESEO SpA
TOYO Corporation

Product Safety Software

OnRule
The Photonics Group

Signal Integrity & EMC Analysis Software

AFJ INSTRUMENTS Srl
Altair Engineering Inc.
Remcom
TDK RF Solutions
TOYO Corporation

Wireless Propagation Software

Altair Engineering Inc.
Remcom

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
StaticWorx, Inc.

Floor Coatings

ACL Staticide Inc.

Correct Products, Inc.
Estatec
Ground Zero
Julie Industries, Inc.
Protective Industrial Polymers
Static Solutions, Inc.
StaticStop
StaticWorx, Inc.
United Static Control Products Inc.

Mats

Bystat International Inc.
Correct Products, Inc.
Elimstat.com
Estatec
Static Solutions, Inc.
StaticStop

Flooring

Tiles

Bystat International Inc.
Ground Zero
Julie Industries, Inc.
StaticStop

StaticWorx, Inc.

Furniture

BIMOS

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.
montena technology sa

ESD Simulators

Electro-Tech Systems
ESDEMC Technology LLC
Hilo-Test
Kikusui America Inc.
montena technology sa

Transient Detectors & Suppressors

CITEL, Inc.
EMI Solutions, Inc.
Fischer Custom Communications, Inc.
NexTek, Inc.

Workstations

ACL Staticide Inc.
BIMOS
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

Low Power Amplifiers

A.H. Systems, Inc.
AR RF/Microwave Instrumentation
ETS-Lindgren
Exodus Advanced Communications
Siglent Technologies North America

Microwave Amplifiers

AMETEK CTS
Applied Systems Engineering, Inc.
AR RF/Microwave Instrumentation
Axiom Test Equipment Rentals
CPI TMD Technologies
Empower RF Systems, Inc.
ETS-Lindgren
Exodus Advanced Communications
HV TECHNOLOGIES, Inc.
Lionheart Northwest
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
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
Lionheart Northwest
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

Traveling Wave Tube Amplifiers

AMETEK CTS
AR RF/Microwave Instrumentation
Avalon Test Equipment
CPI TMD Technologies
CPI, Inc.
Empower RF Systems, Inc.
Hilo-Test
OPHIR RF/Ophir EMC

Analyzers

EMI/EMC, Spectrum Analyzers

Aaronia USA
Absolute EMC Llc.
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
Excalibur Engineering Inc., a Transcat Company
GAUSS INSTRUMENTS
Keysight Technologies Inc.
Laplace Instruments Ltd
MPB Measuring Instruments
Rohde & Schwarz
Siglent Technologies North America
Signal Hound
TOYO Corporation
VIAVI Solutions

Flicker Analyzers

Eurofins York
HV TECHNOLOGIES, Inc.
Kikusui America Inc.
Lionheart Northwest

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., a Transcat Company
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., a Transcat Company

Telecom Analyzers

MPB Measuring Instruments

Audio & Video

Audio Systems

Audivo GmbH

CCTV

Audivo GmbH
TDK RF Solutions
TESEO SpA

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

AE Techron, Inc.
Alltest Instruments
Cincinnati Sub Zero, LLC
CPI TMD Technologies
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
RIGOL Technologies USA, Inc.

Fiber-Optic Systems

Absolute EMC Llc.
DG Technologies
Essco Calibration Laboratory
Excalibur Engineering Inc., a Transcat Company
Ferrotec-Nord
HV TECHNOLOGIES, Inc.
Michigan Scientific Corp.
montena technology sa
Ross Engineering Corp.
TESEO SpA

Flow Meters

Essco Calibration Laboratory
Omni Controls
PCE Instruments
VEROCH - Testing Equipment USA

Generators

Arbitrary Waveform Generators

Absolute EMC Llc.
AMETEK CTS
Applied Physical Electronics, L.C. (APELC)
Eurofins York
Giga-tronics Incorporated
Hilo-Test
Keysight Technologies Inc.
Siglent Technologies North America
Suzhou 3ctest Electronic Co., Ltd.

EMP Generator

HV TECHNOLOGIES, Inc.
montena technology sa
Suzhou 3ctest Electronic Co., Ltd.

ESD Generators

Absolute EMC Llc.
Advanced Test Equipment Rentals
AMETEK CTS
ARC Technical Resources
The EMC Shop
Grund Technical Solutions, Inc.
Haefely AG
HV TECHNOLOGIES, Inc.
Lightning EMC
M Precision Laboratories, Inc.
montena technology sa
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
M Precision Laboratories, Inc.
Suzhou 3ctest Electronic Co., Ltd.

Impulse Generators

Absolute EMC Llc.
AFJ INSTRUMENTS Srl
AMETEK CTS
Applied Physical Electronics, L.C. (APELC)
Grund Technical Solutions, Inc.
Haefely AG
Hilo-Test
HV TECHNOLOGIES, Inc.
Lightning EMC
M Precision Laboratories, Inc.
montena technology sa
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.

Interference Generators

Absolute EMC Llc.
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
M Precision Laboratories, Inc.
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.

Signal Generators

Aaronia USA
AFJ INSTRUMENTS Srl
Alltest Instruments
Electro Rent Corporation
Eurofins York
Excalibur Engineering Inc., a Transcat Company
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
M Precision Laboratories, Inc.
Solar Electronics Co.
Suzhou 3ctest Electronic Co., Ltd.
Techmaster Electronics
Thermo Fisher Scientific

Meters

Field Strength Meters

Absolute EMC Llc.
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

Absolute EMC Llc.
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.

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 USA, Inc.
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
montena technology sa
MPB Measuring Instruments
Pearson Electronics, Inc.
Prana
Siglent Technologies North America
Solar Electronics Co.
Techmaster Electronics

Electric Field Probes

Absolute EMC Llc.
AR RF/Microwave Instrumentation
The EMC Shop
EMC Test Design, LLC
Enerdoor
ETS-Lindgren
Langer EMV-Technik GmbH
montena technology sa
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

Absolute EMC Llc.
AFJ INSTRUMENTS Srl
AR RF/Microwave Instrumentation
EMZER
Excalibur Engineering Inc., a Transcat Company
GAUSS INSTRUMENTS
HV TECHNOLOGIES, Inc.
Laplace Instruments Ltd
Lionheart Northwest
Reliant EMC LLC
Rohde & Schwarz
Schwarzbeck Mess-Elektronik OHG

RF Receivers

AFJ INSTRUMENTS Srl
AMETEK NSI-MI Technologies
Giga-tronics Incorporated
Narda STS, USA
Rohde & Schwarz

TEMPEST Receivers

Rohde & Schwarz

RF Leak Detectors

AR RF/Microwave Instrumentation
MPB Measuring Instruments
NRD LLC

Safety Test Equipment

Absolute EMC Llc.
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
Lionheart Northwest

Shock & Vibration Testing Shakers

Cincinnati Sub Zero, LLC
Globe Composite Solutions
Micom Laboratories Inc.
Sanwood Environmental Chambers Co., Ltd
Thermotron
Wewontech

Susceptibility Test Instruments

ARC Technical Resources
DG Technologies
EMC Test Design, LLC
ESDEMC Technology LLC
Grund Technical Solutions, Inc.
Laplace Instruments Ltd
Lionheart Northwest
montena technology sa
Pendulum Instruments
TDK RF Solutions

Telecom Test Equipment

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
RIGOL Technologies USA, Inc.
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, a Transcat Company
Grund Technical Solutions, Inc.
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
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

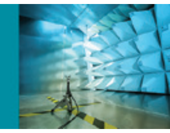
Used & Refurbished Test Equipment

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, a Transcat Company
Globe Composite Solutions
Micom Laboratories Inc.
Thermotron

Testing



Accredited Registrar

ANAB ANSI-ASQ National Accreditation Board
DEKRA
Element Materials Technology - Brooklyn Park, MN
Element Materials Technology - Dallas Plano, TX
Element Materials Technology - Portland Hillsboro, OR
Excalibur Engineering, a Transcat Company
Green Mountain Electromagnetics, Inc.
MiCOM Labs
QAI Laboratories

Calibration Testing

Agile Calibration
Bharat Test House Group
Essco Calibration Laboratory
Haefely AG
ITC India
M Precision Laboratories, Inc.

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
QAI Laboratories

CE Notified Body

American Certification Body
Bureau Veritas Consumer Products Services Inc.
CKC Laboratories, Inc.
Clark Testing
Compatible Electronics, Inc.
DEKRA

CE Notified Body *(continued)*

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.

Eurofins York

MiCOM Labs

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

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

Dayton T. Brown, Inc.

DNB Engineering, Inc.

Elite Electronic Engineering Inc.

ITC India

Micom Laboratories Inc.

NTS

Quanta Laboratories

Retlif Testing Laboratories

Sanwood Environmental Chambers Co., Ltd

Test Site Services Inc.

Washington Laboratories

Homologation Services

American Certification Body

Bharat Test House Group

Bureau Veritas Consumer Products Services Inc.

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

EOS/ESD Association Services, LLC

F2 Labs - Damascus, MD

F2 Labs - Middlefield, OH

International Certification Services, Inc.

Lewis Bass International Engineering Services

Product Safety Consulting

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

EOS/ESD Association Services, 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.

PAVONE Technologies

The Photonics Group
Product Safety Consulting
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
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
NTS
Product Safety Consulting
Quanta Laboratories
Radiometrics Midwest Corporation

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 Asia
Nemko Canada
Nemko Europe
Nemko USA
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 Asia
Nemko Canada
Nemko Europe
Nemko USA

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 Asia
Nemko Canada
Nemko Europe
Nemko USA
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 Asia
Nemko Canada
Nemko Europe
Nemko USA
NTS
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 Asia
Nemko Canada
Nemko Europe
Nemko USA

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 Asia
Nemko Canada
Nemko Europe
Nemko USA
Orbis Compliance LLC
TÜV Rheinland of North America

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
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
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
Laird Connectivity
MiCOM Labs
Montrose Compliance Services, Inc.
National Institute for Aviation Research
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA
NTS
Parker Chomerics
Pulver Laboratories
QAI Laboratories
R&B Laboratory

Solutions Directory

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.

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 Asia

Nemko Canada

Nemko Europe

Nemko USA

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 Asia

Nemko Canada

Nemko Europe

Nemko USA

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

EOS/ESD Association Services, LLC

ESDEMC Technology LLC

Estion Technologies GmbH

F2 Labs - Middlefield, OH

H.B. Compliance Solutions

Laird Connectivity

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

Pulver Laboratories

VPI Laboratories, Inc.

GOST R Certification

G&M Compliance, Inc.

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

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.

Nemko Europe

Nemko USA

R&B Laboratory

Retlif Testing Laboratories

Testing Laboratories

National Recognized Testing Laboratory (NRTL)

Applied Research Laboratories
Bureau Veritas Consumer Products Services Inc.
CertifiGroup Inc.
CSA Group
Eurofins MET Labs
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA
Product Safety Consulting
TÜV Rheinland of North America

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 Asia
Nemko Canada
Nemko Europe
Nemko USA
Product Safety Consulting
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
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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 Asia
Nemko Canada
Nemko Europe
Nemko USA
NTS
Product Safety Consulting
Pulver Laboratories
TÜV Rheinland of North America
TÜV SÜD America Inc.
Washington Laboratories

Radio Performance & Functionality Testing

American Certification Body
Applied Physical Electronics, L.C. (APELC)
CVG Strategy
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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
Nemko Asia
Nemko Europe
Nemko USA
Orbis Compliance LLC
Radiometrics Midwest Corporation
Test Site Services Inc.
Washington Laboratories

RoHS Directive Compliance

CertifiGroup Inc.
D.L.S. - Product Safety
F2 Labs - Middlefield, OH
ITC India
Nemko Asia
Nemko Canada
Nemko Europe
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
NTS
Quanta Laboratories
Retlif Testing Laboratories
Sanwood Environmental Chambers Co., Ltd
WEMS Electronics

Standards Council of Canada Certification Body

CSA Group

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 Asia
Nemko Canada
Nemko Europe
Nemko USA
NetSPI
NTS
Orbis Compliance LLC
Retlif Testing Laboratories
Southwest Research Institute

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 Asia
Nemko Canada
Nemko Europe
NTS
Orbis Compliance LLC
Test Site Services Inc.
TÜV Rheinland of North America
TÜV SÜD America Inc.
VPI Laboratories, Inc.

Solutions Directory

Events

February 28 - March 2

Fundamentals of Random Vibration and Shock Testing Training

March 20 - 24

EMC Designing for Compliance

March 23 - 31

17th European Conference on Antennas and Propogation (EUCAP)

March 26 - 30

2023 International Applied Computational Electromagnetics Society (ACES) Symposium

March 27 - 30

Military Standards 810 (MIL-STD 810) Test Training

March 27 - 31

EMC Designing for Compliance

March 28 - 30

EMV 2023

April 5

Smart Grid EMC Standards

April 6-7

Principles of EMC

April 11-12

AMTA and Seattle IEEE EMC Chapter Regional Event

April 11-14

Applying Practical EMI Design & Troubleshooting Techniques

Advanced Printed Circuit Board Design for EMC + SI

Mechanical Design for EMC

Always check the event website for current information.

https://incompliancemag.com/events

April 16-19

A2LA Annual Conference

May 1 -3

2023 IEEE International Symposium on Product Compliance Engineering (ISPCE)

May 16-19

Applying Practical EMI Design & Troubleshooting Techniques

Advanced Printed Circuit Board Design for EMC + SI

Mechanical Design for EMC

May 16-17

EMC and Compliance Internationa Exhibition and Training

May 22-25

2023 Joint Asia-Pacific Symposium on EMC (APEMC) and International Conference on EMI & C (INCEMIC)

May 22-25

2023 International Instrumentation and Measurement Technology Conference (I2MTC)

May 23

Annual Chicago IEEE EMC MiniSymposium

May 25

EMC Fest 2023

June 11-16

IEEE International Microwave Symposium (IMS)

June 20-22

Sensors Expo & Conference

July 10-13

Military Standards 810 (MIL-STD 810) Test Training

July 23-28

IEEE International Symposium on Antennas and Propogation and USNC-URSI Radio Science Meeting

July 31-August 4

2023 IEEE International Symposium on EMC and SIPI (EMC+SIPI 2023)

September 4-8

EMC Europe

September 12-14

The Batter Show (USA)

September 17-22

European Microwave Week

September 21

2023 Minnesota EMC Event

October 4-6

The Battery Show (India)

October 8-13

45th Annual Meeting and Symposium of the Antenna Measurement Techniques Association (AMTA)

November 7-9

Fundamentals of Random Vibration and Shock Testing Training

December 4-7

Military Standards 810 (MIL-STD 810) Test Training

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Advertiser Index

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Mail emcsales@hvtechnologies.com
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