IN COMPLIANCE™

THE COMPLIANCE INFORMATION RESOURCE FOR ELECTRICAL ENGINEERS

THE 2012 ANNUAL REFERENCE GUIDE

A Compliance Handbook for Electrical Engineers

LXI
RFI AC
CATV Accessories Software
Agricultural Test Audio Test
Antennas Amplifiers
Attenuators AXIe Buyer's Guides **Repair**
Balances Calibration
Chromatography Instruments EMC Test **Oscilloscopes**
Clamp Meters Data Acquisition
Distortion Analyzers Frequency Counters Bio-Medical Test
EMI Test DC Power Supplies
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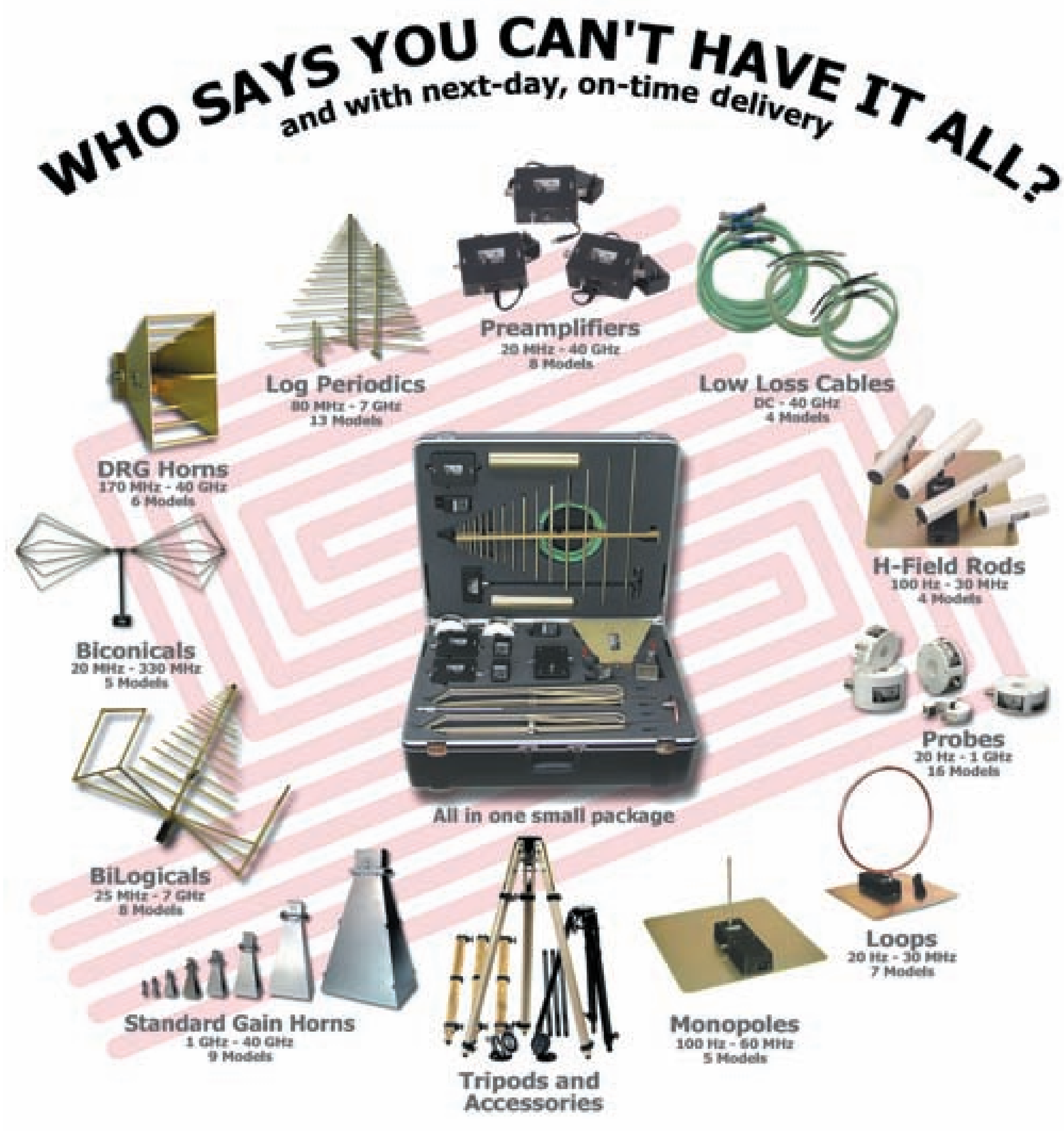
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2012 Annual Reference Guide

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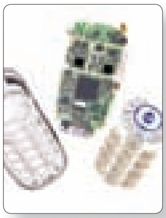
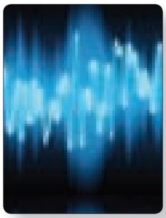
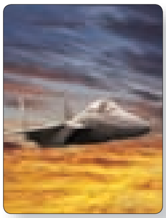
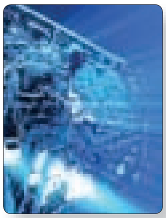
EMC









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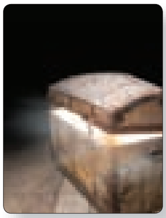

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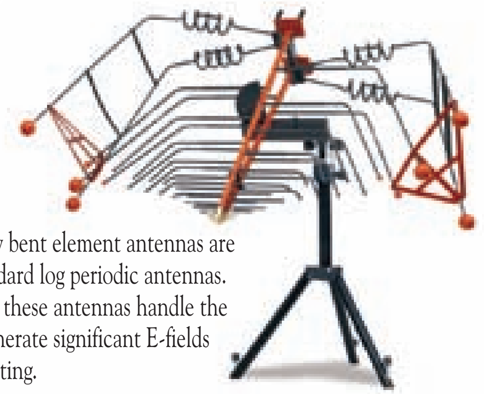
What Have You Done For Me Lately? Plenty!



16,000 Watts of Pure Power
Stand back! We've exceeded our old limits with the new 16000A225 amp. It covers 10 kHz to 225 MHz and delivers 16,000 watts of power.

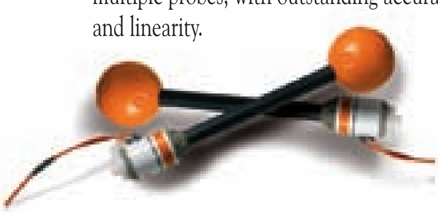
We've Bent The Rules
Our family of Radiant Arrow bent element antennas are up to 75% smaller than standard log periodic antennas. Covering 26 MHz to 6 GHz, these antennas handle the necessary power levels to generate significant E-fields for radiated susceptibility testing.

We've Pushed The Technology Envelope
We ripped that envelope wide open with our small, lightweight Solid State Hybrid Power Modules. They deliver high output power (up to 5 watts) across an ultra-wide instantaneous bandwidth (4 to 18 GHz).

Our New Dual Band Amplifiers Break Down Old Barriers
With two amplifiers in a single package, you can finally go all the way from 0.7 to 18 GHz with the reliability of solid state.

Our New EMI Receiver: Amazing Speed, Incredible Accuracy
The CISPR-compliant DER2018 covers 20 Hz to 18 GHz and beyond. It combines sensitivity, dynamic range and speed with a more intuitive interface.

Accuracy, Linearity & Bandwidth. Need We Say More?
Our two newest laser-powered E-Field probes, FL7040 – 2 MHz to 40 GHz and FL7060 – 2 MHz to 60 GHz; each do the work of multiple probes, with outstanding accuracy and linearity.



More Power To You
They're smaller and lighter. Yet our new "S" Series amps are available from 0.8 to 4.2 GHz, 20 to 1200 watts and everything in between.

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DILBERT
BY SCOTT ADAMS
CAN YOU SHOW ME HOW TO DOWN-LOAD APPS ON MY NEW PHONE?
I COULD...
BUT THAT WOULD TAKE TIME AWAY FROM MY PRIMARY JOB OF SHOWING YOU HOW TO DO FORMULAS IN EXCEL.
APPARENTLY THE EIGHT TIMES I ALREADY TAUGHT YOU WEREN'T ENOUGH.
I DON'T USE EXCEL OFTEN ENOUGH TO REMEMBER FROM ONE TIME TO THE NEXT.
HOW OFTEN DO YOU EXPECT TO DOWN-LOAD APPS?
IT'S HARD TO SAY. I JUST KNOW I WANT ALL OF THEM.
HOW MANY ARE THERE?
FOUR.

Letter from the editor

Innovation for a Better World

Dear Readers,

We'd like to welcome you to In Compliance Magazine's 2012 Annual Reference Guide, our third edition of this annual compliance engineering handbook.

As I write this letter, I've just begun reading Walter Isaacson's best-seller, *Steve Jobs*. Although only into the first few chapters, I am already mesmerized by the birth and development of this brilliant, creative, innovative man who literally changed the face of multiple industries throughout his lifetime. His pursuit of excellence was an unwavering, life-long quest – one which we have all greatly benefited from.

I sat with my granddaughter the other day, watching as her tiny hand swooshed through the apps on her mother's iPad until she found the one she wanted to open. I watched in total amazement as this little 22 month old child proceeded to build puzzles and play house on this incredible tool that was brought to us by the house that Steve built.

This moment was a reminder to me of the integral role the compliance community plays in the advancement of technological innovation. For without the work of this community, my granddaughter may not have the advantage of using this intuitive tool. The devices you develop, test, and produce using sound engineering principles give her the advantage of growing up with products that are compliant, and above all safe for her to hold in those tiny hands

It is in the spirit of the advancement of technology that we bring you the *2012 Annual Reference Guide*, a collection of essential articles and resources for today's working electronics engineer. The articles in this year's Guide are chosen specifically to refresh fundamental practices and also to provide comprehensive, useful content on designing and developing compliant devices.

Thank you, dear readers, for helping to make In Compliance your magazine of choice. We hope our efforts to keep you informed will continue to support you in the vital role you play in making our world a better place.

Until next time,

Lorie Nichols, Editor
editor@incompliancemag.com

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

Company Roots

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

Global Scope

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

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

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

Commitment, Growth and Investment

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

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

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

Environment and Safety

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

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

Our Work Ethic

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

Partners for EMC Test Equipment Solutions

Fully Compliant Transient Test Instruments

The staff of HV TECHNOLOGIES, Inc. (HVT), in partnership with EMC Partner AG and Montena Technology, is focused on providing our clients with top quality, full compliance transient test instruments at the most competitive prices. Our staff has been supporting the EMC testing community by designing, producing, and distributing the best in high voltage transient test instruments for over two decades. When using our products, customers experience the most reliable transient test instruments with the cleanest waveforms, most accurate phase angle synchronization, and repeatable wave shapes available. This has been possible through innovative product design and the deployment of unique leading-edge technologies.

HV TECHNOLOGIES, Inc.

We have the products, delivery, and support you need today and for years to come.

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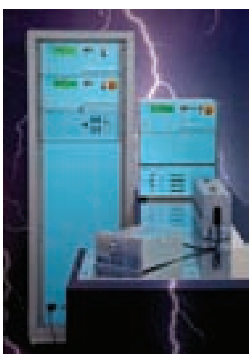


Together, with EMC Partner AG, we are the largest supplier of lighting test equipment in the world.

New composite materials in airplanes help lower fuel costs, but removes shielding previously provided directly exposing electronics to lightning events. Required lightning test levels continue to increase as a result. HV TECHNOLOGIES has all of the solutions available including the Airbus A350 requirements.

Our offering extends into MIL-STD transients and HEMP Test systems to meet all of your test pulse needs.

EMERGING TECHNOLOGIES

EMC Testers for Smart Grid, Solar Panels, Electric Vehicles/Hybrids

With the ever changing world, come new and innovative technologies that promise a better tomorrow. HV TECHNOLOGIES, Inc. is in the forefront working with the industry to meet the upcoming requirements today. Common mode module in the TRA3000 (smart meters), MIG1203 Solar (solar panels), 690V/200A CDNs (EV Charging stations)

NTS Reinvents Traditional Test Laboratory Model

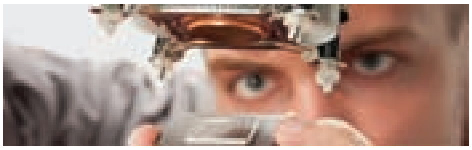
Engineering Services and Supply Chain Solutions Provide Complete Product Lifecycle Support

For more than 50 years NTS has been providing testing & certification services to customers in a wide range of industries and today we operate the largest network of commercial test laboratories in North America. But half a century worth of experience has taught us that most customers have needs that go beyond testing & certifications. That's why NTS has undergone a dramatic expansion in recent years to bring on the necessary resources and expertise required to provide true "cradle to grave" product lifecycle support solutions.

Today, NTS assists its customers with front-end design stage consultation, helping them build more durable and efficient products while maintaining key performance and functionality requirements. Naturally, once those products are ready for release, NTS also has the full range of testing & certification solutions necessary to bring them to market anywhere in the world. But our support doesn't end there. We understand that once a product is released there are many Supply Chain challenges that need to be carefully managed in order to ensure effective production and distribution going forward. Enter NTS Supply Chain services, a global network of trained professionals who stand ready to be your eyes and ears within the facilities of your key suppliers, wherever they might be located around the world. Together, these new services combine to form a complete product lifecycle management solution that traditional test labs simply cannot offer.

TESTING & CERTIFICATION

Here at NTS we offer a vast array of testing and certification services for product developers and manufacturers in numerous industries. This is the heritage of our company. It is what we have done for over 50 years and it is how we have built NTS from a single independent testing facility into the largest commercial test laboratory network in North America. Over the years our testing capabilities have expanded in many different directions to meet the ever-changing needs of our customer base, and the number of NTS test laboratories inside and outside of the USA continues to grow as well. Additionally, our LabInsight customer portal brings our lab right to your desktop, wherever you may be!



ENGINEERING SERVICES

Here at NTS, we know that testing & certification is just one piece of the puzzle. That's why we offer a wide range of Integrated Engineering Services for complete product lifecycle management. Whether you need design consultation, development support, or assistance with products already deployed in the field, NTS offers a wide range of solutions to meet your needs. We also offer Managed Services for companies and governmental agencies that need to outsource the staffing of their internal engineering resources. Whether the design is still "on the napkin" or the product is already deployed in the field, we have the engineering support services to ensure your success.

SUPPLY CHAIN MANAGEMENT

In addition to our Engineering Services and Testing & Certifications, NTS also offers a wide range of Supply Chain Management solutions. This exciting new aspect of our business truly enables us to provide end-to-end product lifecycle support for manufacturers in numerous industries. Not only do we support our clients by helping them design superior products that have been rigorously tested and properly certified, but now we can also help ensure that the supply chain that keeps those products moving into the marketplace is just as effective, efficient and reliable as the products themselves. Ensure your production schedule with NTS Supply Chain services.

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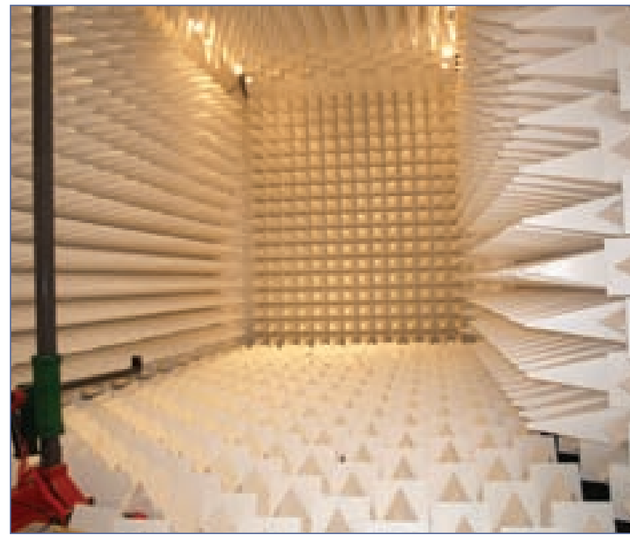
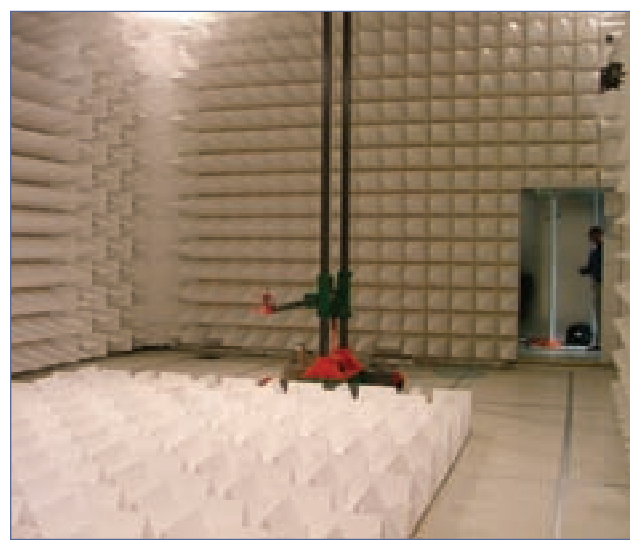
Put us to the test today and learn how NTS can help you!

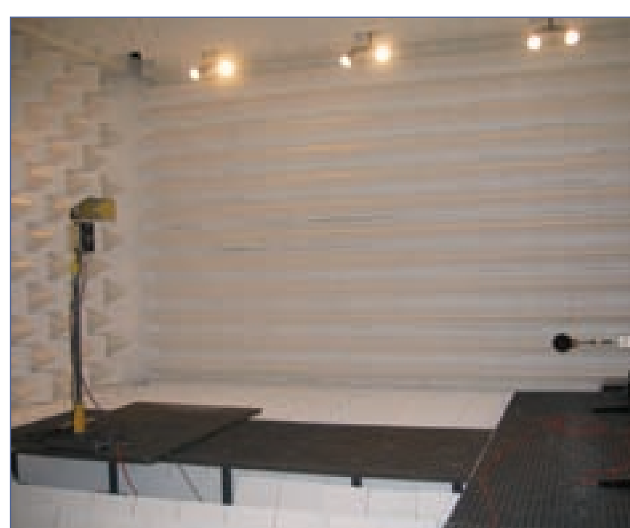
NTS
WE ENGINEER SUCCESS

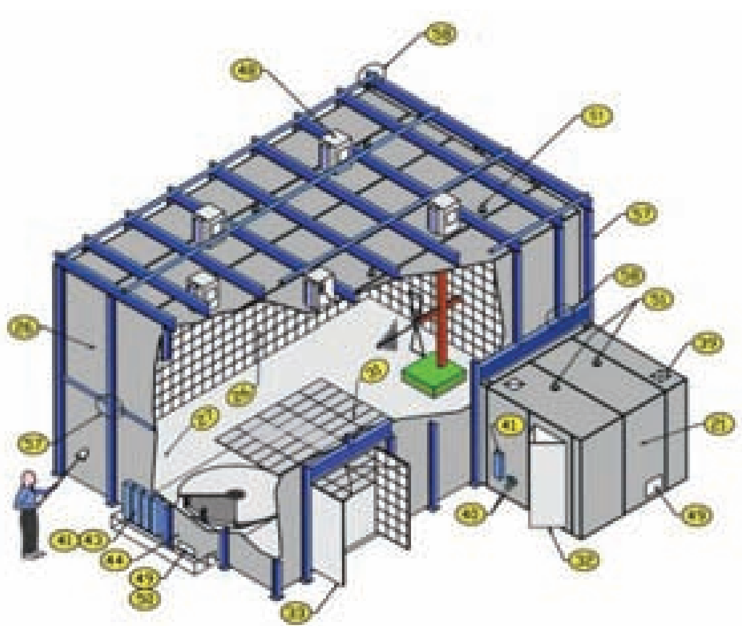
Facilities Designed with Compliance to Multiple International EMC Testing Standards are an EMC Engineer's Essential Asset

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









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

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TÜV Rheinland – The Worldwide Leader in Market Access

If country-specific regulatory compliance is slowing your time-to-market, you need better resources. One call to TÜV Rheinland can give you all of the resources you need.

2012 marks our 140th year of reliably delivering premier independent certification, testing and assessment services. With in-country experts in more than 200 countries around the world, TÜV Rheinland can ease your path to regulatory compliance with technical expertise, cost-effective pricing and quick turnaround times. Each locally based expert works on your behalf to assure your products meet all necessary local, national and international requirements, getting them to market on time. This is why many of the world's busiest and largest global companies depend on TÜV Rheinland.

While TÜV Rheinland offers a broad spectrum of testing and certification services, some of our most requested offerings include Product Safety, EMC and overall International Approval services.

International Approvals Education Series

TÜV Rheinland's complimentary roundtable series offer:

- An overview of global regulatory/International Approvals requirements with focus on Telecom/Radio, Wireless, Product Safety, EMC and Mutual Recognition Agreements
- Information on country-specific regulatory requirements in:
  - o BRICK countries (Brazil, Russia, India, China and Korea)
  - o Countries with regulatory changes (Russia, Korea, Taiwan and Ukraine)
  - o Additional challenging markets

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September 18 – Atlanta, GA

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http://education.tuv.com/IA-Roundtables

International Approvals

TÜV Rheinland offers seamless solutions for global market access with timely and accurate product certification management. The company's broad experience and extensive global network of 500 locations in more than 60 countries ensures its customers' products maintain access to global markets in today's constantly evolving regulatory landscape.

Product Safety Testing and Certification

TÜV Rheinland evaluates, tests and certifies the safety and quality of products in virtually all categories– from consumer toys to state-of-the-art computer equipment and heavy industrial machinery. With these services, you can:

- Ensure compliance with national and international regulatory requirements
- Gain a quick access to the global market with streamlined and timely solutions
- Competitively position yourself with TÜV Rheinland's independent third-party certification

EMC Testing

With five (5) state-of-the-art testing facilities in North America alone, TÜV Rheinland is uniquely qualified to help its clients get their products to market quickly. Customers can choose conveniently located EMC labs equipped with 5 and 10 meter chambers to handle large products such as industrial equipment and medical devices, as well as small- and medium-sized products. When requirements include large industrial equipment that is built in place, one of TÜVRheinland's dedicated mobile EMC labs can test at the customer's location – outdoors, indoors, or right on the factory floor. As an EMC Notified Body (CAB) and international service provider, we offer a flexible, competent service to help you meet the requirements of the EMC directive 2004/108/EC as well as all North American EMC requirements required by the FCC and Industry Canada. We also have a dedicated international approvals team to assist customers with EMC requirements anywhere in the world. For wireless radio compliance needs, TUV Rheinland is a TCB for the US and an FCB for Canada and can provide the wireless product certifications required. TUV Rheinland is a MRA CAB and is constantly expanding the global list of countries we can provide EMC testing services for. ***

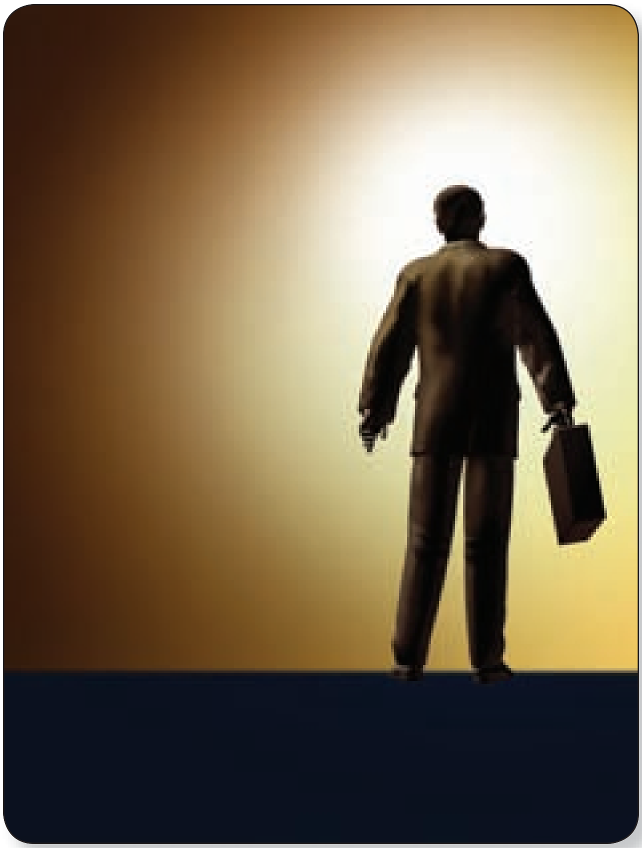
In addition, TÜV Rheinland offers CE Marking and other services to give companies a competitive advantage selling their products to global markets.

For more information, call 1-TUV-RHEINLAND or visit www.us.tuv.com.

***All TUV Rheinland's EMC labs are 17025:2005 accredited, FCC listed, VCCI registered, IC recognized and our Pleasanton CA lab carries both WiFi & Zigbee accreditations.

So You Are a New EMC Engineer... Now What?

BY DARYL GERKE, PE, AND BILL KIMMEL, PE



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

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

FIRST, FIND A MENTOR...

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

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

GET SOME EXPERIENCE - FAST...

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

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

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

START ON YOUR SELF-EDUCATION...

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

Books

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

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

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

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

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

Magazines

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

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

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

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

Courses

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

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

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

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

REGULATIONS

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

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

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

PARTICIPATE IN THE EMC COMMUNITY...

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

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

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

Join an EMC Chapter

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

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

Attend EMC Symposiums

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

Here are some suggestions for attending the symposium:

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

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

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

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

Use LinkedIn

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

MAKE A PLAN, AND THEN WORK IT...

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

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

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

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

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

A Regulatory Roadmap

That's just regulations... Right?

BY PETER S. MERGUERIAN
AND DENNIS W. BARTELT

Pressure to get product to market is stressful, as well as full of scenarios that most engineers and designers would like to forget about. Yet in the beehive of activity, the regulations that a product must comply with are critical to those design engineers, as well as other teams. So much, in fact, that a slight misstep early on or during the product life cycle can create devastating circumstances. Driven by market or other business issues some may succumb to the "limp factor" (LF): get it to work and ship at all costs for the first country or countries of use and worry about the others at a later time when the pressure is off. So, how can we prevent the LF from occurring?

Despite good intent, business operations may lack the understanding of what engineering and other teams need to determine the correct regulations, as well as how these same teams could be impacted by them in their daily jobs. Biz ops may believe word of mouth or an occasional e-mail is adequate. Information may dribble out from multiple sources, or it may be released in phases. All this non-value added activity is spoon feeding with potential for major issues down the road. Simply, a "Regulatory Roadmap" (RM) is needed. But what is it and what does it mean beyond a name that sounds good?

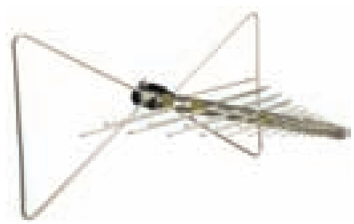
The RM is a global regulatory perspective for the product. But a slight twist exists; there is more than just the regulations. A robust RM should provide visibility across the organization, beyond that of engineering, and clearly link key product or customer criteria to the applicable regulatory requirement and the business team it touches. Groups such as distribution, quality, technical operations and sales and marketing can use the RM to see how they fit into the aggregate regulatory requirements and the impact on them. The effectiveness of the RM is only as good as the upfront effort placed into it along with the follow-up to maintain its accuracy over time. In preparing and developing the RM several key factors need consideration.

Business Discipline: This is required by all the business teams including sales and marketing, product planning, engineering, manufacturing, quality, distribution and supply chain to make the RM part of the jargon and working plan of the organization. It should be embedded as a deliverable to all organizations and made part of the program management scheme that monitors the product design, shipment and launch cycle. Practically speaking, the RM is active throughout the product lifecycle, from birth to end of life, and continued focus on it is required to maintain accuracy. Key staff, or champions, should be assigned to make this a real, live, breathing task as opposed to being a one time, one shot picture. One has to remove the organizational mindset that "it was complete when we first launched the product so that should be good enough."

Staff Support: The RM is rarely a static entity. The champions noted above should partner with the right players to collect key information regarding the product

Wide Variety of Products for Your EMC Testing Needs


Biconical Antenna

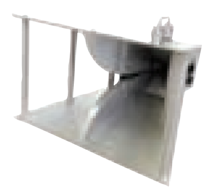

Combilog Antenna

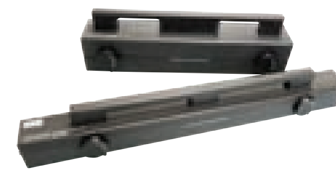

Log Periodic Antenna


Passive Horns up to 40 GHz

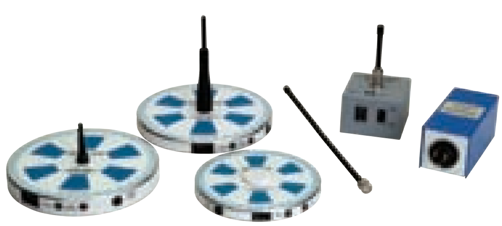

Monopole Antenna

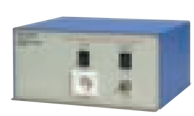

Loop Antenna


Active Horn Antenna


Absorbing Clamps


Preamplifiers


Comb Generators up to 34 GHz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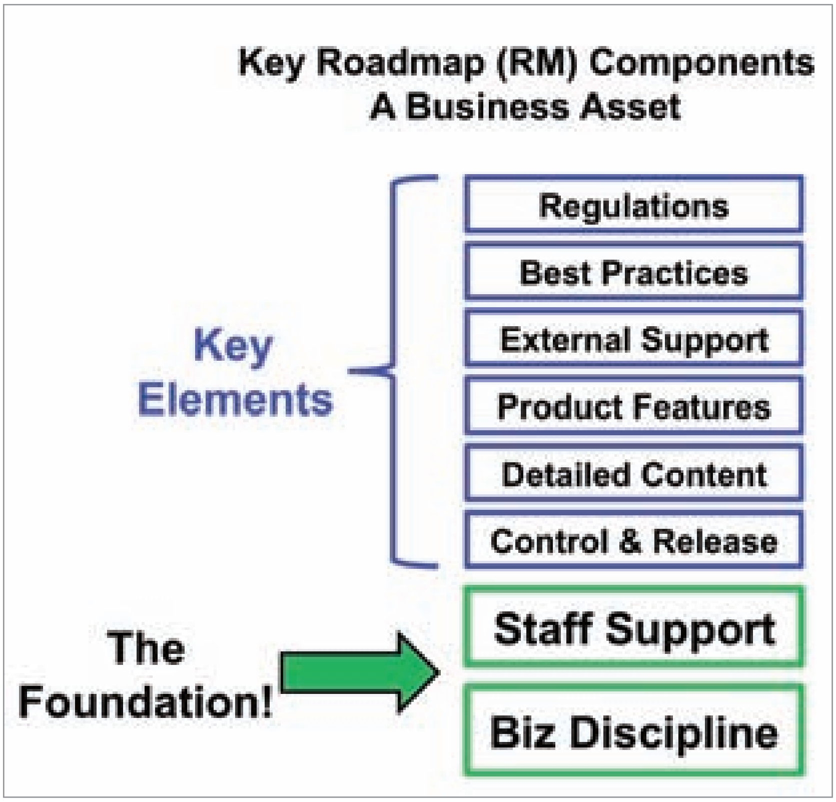
and finalize on a method to deploy the RM on a routine basis throughout the product lifecycle. These champions should be multi-disciplinary, having representatives from all functional teams. These players will determine who and what assignments are needed to complete the entire RM, as well as select a delivery method such as Excel or a database program. Unless one can guarantee they know other champions' job and role, it is dangerous to "not invite" all the representatives to the RM building process. They must work as a team to prepare and distribute the RM to all parties needing it.

Control and Release: The RM should be under documentation and version control, be integral to the quality system, and be in the teams' hands well ahead of critical milestones where this information would be needed to make product decisions. One example is the initial conceptual block diagram design of the product, where the product's architecture is fundamental to meeting many specifications on a broad level.

Detailed Content: The content of the RM should not be underestimated or simplified. This can be a dangerous situation leading to serious implications. The key point is to get all business functions involved in its development so that the contents inside the RM can include each business operations input. It should include the general terminology such as Americas, EMEA, Russia and CIS, or Asia Pacific, but in addition be specific by the product model or type, down to the country, customer, launch date, how it will be identified to the market place, key specification or feature requirement and pertinent information on the market segment such as commercial or consumer, or governmental. The specifics on the product's distribution plan such as direct import, dealers or distributors need to be identified for purposes of meeting import regulations that could be problematic if not accounted for.



Product Features: It is extremely important to consider product feature additions or upgrades and when and where they occur and in which product. Other factors must also be considered such as indoor/outdoor use, transmitter frequency bands, channels and power limits, interfaces to the network, etc. These can trigger added regulatory requirements and may complicate the filing and certification procedures. Also, certain products may have specific requirements that need to be captured on the RM, including items such as labeling, packaging or manuals with safety instructions that must be included with the product as part of maintaining regulatory approval.

External Help – Labs/Consultants: There are most certainly internal experts within a business that are responsible in one way or another for the regulatory compliance of a product. Some companies design products with a "take it one country at a time" attitude due to their internal capability, only to find out that the next country may have requirements quite different or more strict regulatory wise. Generally companies have individuals with a "basic" handle on the scope of the regulations. However, unless there is an ongoing process to keep up to speed on the latest regulatory requirements, it makes good business sense to identify competent business(es) whose job it is to be 100% current on the latest requirements. During the RM development processes identify competent firm(s) and share the RM under a non-disclosure agreement. They should be able to assist in pointing out the regulation requirements, as well as be the check and balance. In selecting the external firm(s) make sure in the initial discussions that they indeed have the scope to handle the RM. Summarize the RM into major discussion areas first such as RF, packaging, EMI, safety, energy efficiency, product environmental (RoHS, REACH), etc., and then go into detail, as well as provide a global indication of the countries. Surprisingly some firms do not have the internal expertise to know everything and as such they must bring in others to assist. This is not generally a bad business practice, but be aware of it. Probe on their internal processes and how they keep current, what the limitations of their company are and how gaps can be addressed. Do you detect they will be proactive or reactive to your needs?

Sharing Information Best Practices: One meeting rarely completes the RM analysis. Several will be needed before you finalize it. Remember, these firms are in business to help, but if you do not provide a clear discussion and spend the time working with them so they fully understand your product, the results you get may indeed be incomplete. Share with them the aggregate business picture, point out your concerns, communicate the unknowns or other concerns you have and, most importantly, represent equally each of your internal business functions and how they touch the product. Best case, there will be no regulation and some business functions may not be impacted at all. Worst case, a product could be shipped non-compliant, and no one is aware of it. The product may get stuck in customs due to a missing mandatory regulatory Mark; it may be tested by the competition and non-compliance reported to the regulator(s); it may need to be recalled due non-compliant critical components or materials supplied in the marketplace.

Capturing Regulations: Should you need their help, use your external business support described above to help complete the RM. In the context of the previous items, the appropriate regulation(s) need to be entered by name, reference number, version, date and key specification. More than likely one may find that a "lowest common denominator" regulation may indeed cover more than one product requirement. Challenge in all cases any RM item that does not have a regulation associated with it. Understand why or why not, and be cautious if there is an indication that the regulation is vague or non-descript. Vague items quickly spiral into being non-issues, i.e. the "limp factor," yet in reality the homework was not done to rule it out one way or the other. It may indeed be correct that none exists and if such is the case that item could be removed from the RM for simplicity sake. In addition, recognize that regulations are not static and in most cases will change over time. Your RM needs to take this into consideration and capture these changes and when they occur. When considering any regulation always have a forward looking view of at least 2+ years (can vary based on your product design and release cycle) to prevent surprises. No one wants to release a service or product only to find that a new regulation kicks in one month after initial release! By having a forward looking view, knowing when new regulations will be effective, and how they are going to impact shipping product, you can make design allowances and changes so that when the new regulations become effective your product lineup can be ready.

Cautions: Some may feel that regulations are centric to a specific organization or function, or wrongly assume the other team "has it under control." Efficiency wise, the RM provides a level playing field to all parties integral to the product. It documents the commitment to do it right the first time, ensures that all functional organizations have their vested interests included, and serves as a foundation upon which future products can be built upon. If done correctly the RM is an asset, but doing it for the first time can appear as overkill. However, the impact on the business for not knowing a regulation is non-forgiving, can easily degrade market share, drive customers toward competition, or potentially lead to the dreaded "r" word - recall.

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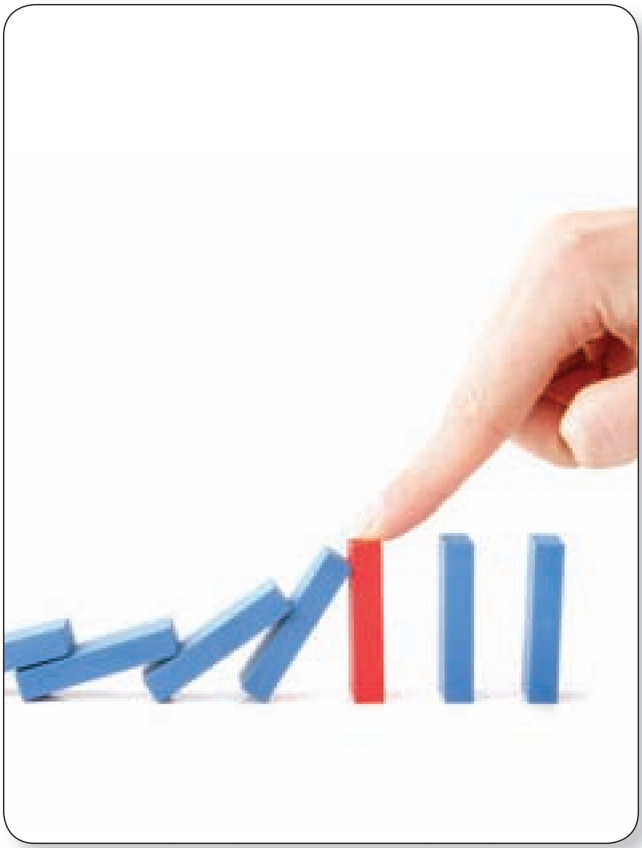
Dennis W. Bartelt *is President of Bartelt Consulting Corp. (BCC). He has 30+ years of past experience in telecommunications and consumer products with Motorola Mobility Inc.(formerly the cellular division of Motorola Inc.). His credentials include product design, software quality, service and repair, product safety, regulatory and environmental compliance, customer satisfaction and process enhancement. Under his leadership the teams he managed provided approvals for more than 100,000 unique products. Dennis has a Master's Degree in Electrical Engineering Technology from Northern Illinois University along with 30 hours pre-doctorate work. He is currently consulting with industry firms and specializes in process enhancement in the product regulatory and safety compliance areas. Dennis can be reached at barteltconsultingcorp@yahoo.com or dennis@goglobalcompliance.com.*

EMI Risk Analysis

BY KEITH ARMSTRONG



The reliability of electronic technologies (including the software and firmware that runs on them) can become critical when the consequences of errors, malfunctions, or other types of failure include significant financial loss, mission loss, or harm to people or property (i.e. functional safety).

Electromagnetic interference (EMI) can be a cause of unreliability in all electronic technologies [1], so must be taken into account when the risks caused by malfunctioning electronics are to be controlled.

Most EMC engineers believe that the normal EMC tests do a good job of ensuring reliable operation, and indeed they do make it possible to achieve normal availability (uptime) requirements. However, the levels of acceptable risk in safety-related applications are generally three or more orders of magnitude more demanding, and applications where (for example) mission or financial risks are critical can be as demanding as safety-related applications, sometimes more so.

Unfortunately, most functional safety engineers leave all considerations of EMI to EMC engineers, with the result that – at the time of writing – most major safety-related projects do little more to control EMI than insure that the items of equipment used pass when tested to the relevant immunity test standards. As a result, safety risks due to EMI are not yet being effectively controlled.

The challenge for engineers is to demonstrate adequate confidence in the reliability of their designs in the operational electromagnetic environment (EME).

The solution [2] is to use well-proven EMC design techniques plus risk assessment that shows the overall design achieves acceptable risk levels, all verified and validated by a variety of techniques (including EMC testing).

This article only addresses the issue of how to take EMI into account when performing a Risk Analysis.

THE NATURE OF THE PROBLEM

"High reliability", "mission-critical", "safety-critical", or security applications might need to have a meantime to failure (MTTF) of more than 100,000 years (corresponding to Safety Integrity Level 4 (SIL4) in IEC 61508 [3], see Figures 1 and 2 on page 38).

Mass-produced products (e.g. automobiles, domestic appliances, etc.) also require very low levels of safety risk because of the very large numbers of people using them on average at any one time.

It is usually very difficult to determine whether a given undesirable incident was caused by EMI, and the resulting lack of incidents officially attributed to EMI has led some people to feel that current EMI testing regimes must therefore be sufficient for any application. Indeed, it is commonplace to read words such as "….passes all contractual and regulatory EMC tests and is therefore totally immune to all EMI."

However, as Ron Brewer says in [4]: "*...there is no way by testing to duplicate all the possible combinations of*

frequencies, amplitudes, modulation waveforms, spatial distributions, and relative timing of the many simultaneous interfering signals that an operating system may encounter. As a result, it's going to fail."

Prof. Nancy Leveson of MIT says, in [5]: *"We no longer have the luxury of carefully testing systems and designs to understand all the potential behaviors and risks before commercial or scientific use."*

The IET [6] states: *"Computer systems lack continuous behavior so that, in general, a successful set of tests provides little or no information about how the system would behave in circumstances that differ, even slightly, from the test conditions."*

Finally, Boyer et al [7] say: *"Although electronic components must pass a set of EMC tests to (help) ensure safe operations, the evolution of EMC over time is not characterized and cannot be accurately forecast."* This is one of the many reasons why any EMC test plan that has an affordable cost and duration is unlikely to be able to demonstrate confidence in achieving better than 90% reliability. The reasons for this are given in [4], [8], [9], section 0.7 of [10], and [11].

Since the confidence levels that are needed for functional safety compliance (for example) are a *minimum* of 90% for SIL1 in [3], 99% for SIL2, 99.9% for SIL3 and 99.99% for SIL4, it is clear that more work needs to be done to be able to demonstrate compliance with [3] and similar functional safety standards (e.g. [12] [13] and others such as IEC 61511 and IEC 62061), as regards the effects of EMI on risks.

The best solution at the time of writing is to use well-proven EMC design techniques to reduce risks, and to verify and validate them using a number of different methods, including immunity testing. Risk assessment is a vital part of such an approach, as required by [3]. Unfortunately, neither the IEC's basic publication on Functional Safety [3], nor the basic IEC publication on "EMC for Functional Safety" [2], describe how to take EMI into account during risk assessment; although [10] – a practical guide based on [2] – does cover this.

This article is concerned with how to include EMI issues as part of a risk assessment (whether the risks are safety or other, e.g. financial), and is based on [10] and a paper I presented in 2010 [14]. I have also presented papers on assessing lifetime electromagnetic, physical and climatic environments [15], appropriate EMC design techniques [16], and verification and validation methods (including testing) [17].

As Prof. Shuichi Nitta says in [18]: *"The development of EMC Technology taking account of systems safety is demanded to make social life stable."* I hope this article makes a contribution to this essential work, but there is much more yet to be done!

RISK ASSESSMENT

Most readers of *In Compliance* will be very familiar with EMC, but perhaps not (yet) with Functional Safety, so a brief introduction to hazards and risks is probably a good idea.

What are "hazards" and "risks"?

A HAZARD is anything with potential to do HARM, and the hazard level is derived from the type of harm and its severity. For example, a bladed machine can cause harm by cutting skin, flesh, or even bone. We say it has a cutting hazard and define its severity as being either minor, serious, or deadly (other classifications are possible) depending on the maximum depth of cut and the respective parts of the anatomy.

IEC 61508's SILs for "on demand" safety functions...

Safety Integrity Level (SIL)	Average probability of a dangerous failure of the safety function, "on demand" or "in a year"	Equivalent mean time to dangerous failure, in years*	Equivalent confidence factor required for each demand on the safety function
4	$\geq 10^{-5}$ to $< 10^{-4}$	$> 10^{4}$ to $\leq 10^{5}$	99.99 to 99.999%
3	$\geq 10^{-4}$ to $< 10^{-3}$	$> 10^{3}$ to $\leq 10^{4}$	99.9 to 99.99%
2	$\geq 10^{-3}$ to $< 10^{-2}$	$> 10^{2}$ to $\leq 10^{3}$	99% to 99.9%
1	$\geq 10^{-2}$ to $< 10^{-1}$	> 10 to $\leq 10^{2}$	90 to 99%

* Approximating 1 year = 10,000 hrs of operation

"Failure" includes any error, malfunction or fault that causes a hazard

Figure 1: Safety systems that operate "upon demand"

IEC 61508's SILs for "continuous" safety functions...

Safety Integrity Level (SIL)	Average probability of a dangerous failure of the safety function per hour	Equivalent mean time to dangerous failure, in hours	Equivalent confidence factor required for every 10,000 hours of continuous operation
4	$\geq 10^{-9}$ to $< 10^{-8}$	$> 10^{8}$ to $\leq 10^{9}$	99.99 to 99.999%
3	$\geq 10^{-8}$ to $< 10^{-7}$	$> 10^{7}$ to $\leq 10^{8}$	99.9 to 99.99%
2	$\geq 10^{-7}$ to $< 10^{-6}$	$> 10^{6}$ to $\leq 10^{7}$	99% to 99.9%
1	$\geq 10^{-6}$ to $< 10^{-5}$	$> 10^{5}$ to $\leq 10^{6}$	90 to 99%

"Failure" includes any error, malfunction or fault that causes a hazard

Figure 2: Safety systems that operate continuously

A hazard has a probability of occurrence. The RISK is the product of the hazard level, its probability of occurrence, and a factor that takes into account the observation that, when they occur, not all hazards result in the same harm; for example if there is the possibility of avoidance or limitation. (Risk level = {Hazard level} × {Probability of the hazard occurring} × {Possibility of hazard avoidance or limitation}).

Other multiplying factors can also be applied, and often are. We may decide that a safety risk level should vary according to social factors, such as the type of person (for example, small children, pregnant women, healthy adults, etc.).

We could also consider a financial hazard to be the loss of a defined amount of money, and the financial risk to be the amount of the money multiplied by the probability of losing it.

EMI does not affect the hazards themselves but can affect their probability of occurrence, which is why EMI must be taken into account when trying to achieve acceptably low risk levels.

Nothing can ever be 100% reliable; there is always some risk. To insure that risks are not too high requires using hazard analysis and risk assessment, which takes the information on a system's environment, design, and application and – in the case of [3] – creates the Safety Requirements Specification (SRS) or its equivalent in other standards.

Using hazard analysis and risk assessment also helps avoid the usual project risks of over- or under-engineering the system.

The amount of effort and cost involved in the risk assessment should be proportional to the benefits required. These include: compliance with legal requirements, benefits to the users and third parties of lower risks (higher risk reductions), and benefits to the manufacturer of lower exposure to product liability claims and loss of market confidence.

Risk assessments are generally applied to simple systems

Modern control systems can be very complex and are increasingly often "systems of systems". If they fail to operate as intended, the resulting poor yields or downtimes can be very costly indeed. Risk assessment – done properly – is a complex exercise in which competent and experienced engineers apply at least three different types of assessment technique to the entire system under review.

To risk-assess a complex system is a large and costly undertaking, but not usually necessary because the usual approach (e.g. [3]) is to insure the safety of the overall control system by using a much simpler and separate "safety-related system" that can be risk-assessed quite easily. Safety-related systems often use "fail-safe" design techniques – when an unsafe situation is detected, the control system is overridden and the equipment under control brought to a condition that prevents or mitigates the harms that it could cause.

For many types of industrial machinery, the safe condition is one in which all mechanical movement is stopped and hazardous electrical supplies isolated. The safe condition might be triggered, for example, by an interlock with a guard that allows access to hazardous machinery.

Such a fail-safe approach is, of course, useless in many life-support applications or anywhere where continuing operation-as-usual is essential, such as "fly-by-wire" aircraft. However, even in situations where a guard interlock or similar fail-safe techniques cannot be used – and the control system is too complex for a practicable risk assessment – it is still generally possible to improve reliability by means of simple measures that can be cost-effectively risk-assessed.

A typical approach is to use multiple (redundant [19]) control systems with a voting system so that the majority vote is used to control the system. Alternatively, control might be switched from a failing control system to another that is not failing (e.g. the Space Shuttle uses a voting system based on five computers [20]).

Specifying the acceptable risk level

For each identified hazard, the level of risk that is specified should be at least broadly acceptable. UK Health and Safety publications [21] and [22] provide very useful guidance on this, and on what may be tolerable under some circumstances.

Figure 3: A systematic failure for Ariane V [29]

Acceptable risk levels are culturally defined and not amenable to mathematical calculation. They must be specified before the design process starts. The engineering principle of establishing an acceptable risk level and then designing to achieve it is enshrined in the functional safety standards ([3], [12], [13], and others) and helps:

- manufacturers maximize their return on investment over the short, medium, and long terms by reducing their exposure to lawsuits and having a valid defense in case of a lawsuit,
- engineers and organizations abide by the IEEE's ethical guidelines [23].

Acceptable risk levels for functional safety are generally provided by "Risk Charts" (or "Risk Graphs"), e.g. Annex D in Part 5 of [3], Annex D of [12], Section 7.4.5 of Part 3 of [13].

Reducing the risk from an identified hazard is performed by what [3] calls a "Safety Function". [3] applies a SIL specification to each safety function, chosen according to the rules in [3] to achieve the specified risk level for the particular hazard being risk-reduced. So, for example, a safety-related system might provide three safety functions at SIL 2 and two safety functions at SIL 3.

Developed from Tables 2 and 3 of Part 1 of [3], Figures 1 and 2 show the reliability ranges covered by SILs.

Examples of safety functions that operate on-demand include the braking system of an automobile and guard interlocks in industrial plant.
Examples of safety functions that operate continuously, include the speed and/or torque control of automobile and other types of engines, and the motors in some machines and robots.

There is no requirement for a safety function to employ electronic technologies. In many situations mechanical protection such as bursting discs, blast walls, mechanical stops, etc., and management (such as not allowing people nearby during operation), etc., and combinations of them, can help achieve a safety function's SIL.

A SIL 3 specified safety function requiring, say, 99.95% reliability, could be achieved by employing three independent protection methods, each one of which achieves just 99.65%. All three, two, just one, or none of these protection devices or systems could use electronic technology. (Note that 99.95% reliability is seven times tougher than 99.65%.)

The most powerful EMC design technique for achieving a SIL is not to use any electronic or electromechanical technologies in the safety-related system!

A philosophical point

Many EMC test professionals, when faced with the information on hazards and risks above, say that because there is no evidence that EMI has contributed to safety incidents, this means the EMC testing done at the moment must be sufficient for safety. However, anyone who uses this argument is either poorly educated in matters of risk and risk reduction, or is hoping the education of their audience is lacking in that area [24].

The assumption that because there is no evidence of a problem, there is no problem, was shown to be logically incorrect in the 19th Century [25]; its use by NASA led directly to the Columbia space shuttle disaster [26]. Redmill [27] affirms: *"Lack of proof, or evidence, of risk should not be taken to imply the absence of risk."*

EMI problems abound [28], but it is unlikely that incidents caused by EMI will be identified as being so caused, because:

- Errors and malfunctions caused by EMI often leave no trace of their occurrence after an incident.
- It is often impossible to recreate the EM disturbance(s) that caused the incident, because the EM environment is not continually measured and recorded.
- Software in modern technologies hides effects of EMI (e.g. EMI merely slows the data rate of Ethernet™ and blanks the picture on digital TV, whereas its effects are obvious in analogue telecommunications and TV broadcasting).
- Few first-responders or accident investigators know much about EMI, much less understand it, and as a result the investigations either overlook EMI possibilities or treat them too simplistically.
- Accident data is not recorded in a way that might indicate EMI as a possible cause.

If a thorough risk assessment shows EMI can cause financial, mission or safety hazards, then undesirable incidents due to EMI *will occur*. If the probability of the incidents caused by EMI is higher than acceptable risk levels, their rate should be reduced until they are at least acceptable (i.e. risk reduction).

Hazards can be caused by multiple independent failures

It is often incorrectly assumed that only single failures need to be considered (so-called: "single-fault safety"). However, the number of independent failures that must be considered as happening simultaneously depends upon the required level of safety risk (or degree of risk reduction) and the probabilities of each independent failure occurring.

Not all failures are random

Many errors, malfunctions, and other faults in hardware and software are reliably caused by certain EMI, physical or climatic events, or user actions (for example, corrosion that degrades a ground bond or a shielding gasket after a time, an over-voltage surge that sparks across traces on a printed circuit board, etc.).

These are "systematic" errors, malfunctions, or other types of faults. They are not random, but may be considered "built-in" and so <u>*guaranteed to occur*</u> whenever a particular situation arises. An example is shown in Figure 3.

UK Health and Safety [30] found that over 60% of major industrial accidents in the UK were systematic, i.e., were "designed-in" and so were bound to happen eventually.

Not all failures are permanent

Many errors, malfunctions, or other types of failure can be intermittent, for example:

- poor electrical connections (a very common problem that can create false signals)
- transient interference (conducted, induced, radiated)
- "sneak" conduction paths caused by condensation, conductive dust, etc.

The operation of error detection and correction techniques, microprocessor watchdogs, and even manual power cycling can cause what would otherwise have been permanent failures to be merely temporary ones.

"Common-Cause" errors, malfunctions and other failures

Two or more identical units may be exposed to the same conditions at the same time, for example:

- ambient under- or over-temperature
- power supply under- or over-voltage
- EM disturbances (conducted, induced, radiated, continuous, transient, etc.)
- condensation, etc.

This can cause the units to suffer the same systematic errors, malfunctions, etc., which are known as "common-cause" failures.

So, using multiple redundant units [19] – a very common method for improving reliability to random errors, malfunctions or other types of failures – will not reduce risks of systematic failures if identical units, hardware, or software are used to create the redundant system.

Risk assessments need multiple techniques and expertise

No one risk assessment technique can ever give sufficient "failure coverage", so at least three and probably more different types should be applied to any design:

- at least one "inductive" or "bottom-up" method, such as FMEA [31] or Event-Tree
- at least one "deductive" or "top-down" method, such as Fault Tree Analysis [32] or HAZOP
- at least one "brainstorming" method, such as DELPHI or SWIFT

No risk analysis methods have yet been developed to cover EMI issues, so it is necessary to choose the methods to use and adapt them to deal with EMI. Successful adaptation requires competency, skills, and expertise in both safety engineering and real-life EMI (not just EMC testing).

Devices can fail at two or more pins simultaneously

EMI can cause two or more pins on a semiconductor device, such as an integrated circuit (IC), to change state simultaneously. An extreme example is "latch-up" – when all output pins simultaneously assume uncontrolled fixed states. This is caused by high temperatures, ionizing radiation, and over-voltage or over-current on any pin of an IC. The presence of any one of the three causes increases an IC's susceptibility to latch-up due to the other two.

However, traditional risk analysis methods (e.g. FMEA) have often been applied very simplistically to electronics, for example I have seen (so-called) FMEA-based risk assessments on safety-critical electronics conducted by a major international manufacturer of automobiles that simply went through all of the ICs one pin at a time and assessed whether a safety problem would be caused if each pin was permanently stuck high or low. Also, this was the only failure mode identification method applied.

Reasonably foreseeable use/misuse

It should never be assumed that an operator will always follow the Operator's Manual, or would never do something that was just "too stupid."

Assessing reasonably foreseeable use or misuse requires the use of "brainstorming" techniques by experienced personnel, and can achieve better "failure coverage" by including operators, maintenance technicians, field service engineers, etc., in the exercise.

THE TWO STAGES OF RISK ASSESSMENT

When creating the SRS (or equivalent), the system has not yet been designed, so detailed risk analysis methods such as FMEA, FMECA, etc., cannot be applied. At this early stage, only an "Initial Risk Assessment" is possible, but there are many suitable methods that can be used and many of them are listed in 3.7 of [10].

During the design, development, realization, and verification phases of the project, detailed information becomes available on all of the mechanics, hardware and software. Appropriate risk analysis methods (such as FMEA) are applied to this design information – as it becomes available – to guide the project in real-time and to achieve the overall goals of the Initial Risk Assessment.

As the project progresses the Initial Risk Assessment accumulates more depth of analysis, eventually (at the end of the project) producing the "Final Risk Assessment" – a very important part of a project's safety documentation. But it can only be completed when the project has been fully completed, and its real *engineering* value lies in the process of developing it during the project to achieve acceptable risk levels (or risk reductions) while also saving cost and time (or at least not adding significantly to them).

INCORPORATING EMI ISSUES IN RISK ASSESSMENTS

The reasonably foreseeable lifetime EM environment is an important input to an EMI risk analysis process, as it affects the risk level directly. Because exposure to other environmental effects like shock, vibration, humidity, temperature, salt spray, etc., can degrade EM characteristics (and also faults, user actions, wear, and misuse), their reasonably foreseeable lifetime assessments are also important inputs.

Many foreseeable environmental effects can occur simultaneously, for example:

- Two or more strong radio-frequency (RF) fields (especially near two or more cellphones or walkie-talkies, or near a base-station or broadcast transmitter).
- One or more radiated RF fields plus distortion of the mains power supply waveform.
- One or more radiated RF fields plus an ESD event.
- A power supply over-voltage transient plus conductive condensation.
- One or more strong RF fields plus corrosion or wear that degrades enclosure shielding effectiveness.
- One or more strong RF fields plus a shielding panel left open by the user
- Conducted RF on the power supply plus a high-impedance ground connection on the supply filter due to loosening of the fasteners that provide the bonding connection to the ground plane due to vibration, corrosion, etc.
- Power supply RF or transients plus filter capacitors that have, over time, been open-circuited by over voltages, and/or storage or bulk decoupling capacitors that have lost much of their electrolyte due to time and temperature.

Hundreds more examples could easily be given, and all such reasonably foreseeable events and combinations of them must be considered by the risk assessment.

Intermittent contacts, open or short circuits, can cause spurious signals just like some kinds of EMI, and are significantly affected by the physical/climatic environment over a lifetime. One example of this kind of effect is contact resistance modulated by vibration. This effect is called "vibration-induced EMI" by some.

EMI and intermittent contacts can – through direct interference, demodulation and/or intermodulation [11] – cause "noise" to appear in any conductors that are inadequately protected against EMI (perhaps because of a dry joint in a filter capacitor). "Noise" can consist of degraded, distorted, delayed or false signals or data, and/or damaging voltage or current waveforms.

When a "top down" risk analysis method is used, it should take into account that significant levels of such noise can appear at any or all signal, control, data, power, or ground ports of any or all electronic units – unless the ports are adequately protected against foreseeable EMI for their entire lifetime, taking into account foreseeable faults, misuse, shock, vibration, wear, etc. (For radiated EMI, the unit's enclosure is considered a port.)

The noises appearing at different ports and/or different units can be identical or different, and can occur simultaneously or in some time-relationship to one another.

When a "bottom-up" risk analysis method is used, the same noise considerations as above apply, but in this they can appear at any or all pins of any or all electronic devices on any or all printed circuit boards (PCBs) in any or all electronic units – unless the units are adequately protected against all EMI over their entire lifetime taking into account foreseeable faults, misuse, etc., as before.

Similarly, the noises appearing at different pins or different devices, PCBs or units can be identical or different, and can occur simultaneously or in some time relationship.

It is often quite tricky to deal with all possibilities for EMI, physical, climatic, intermittency, use, misuse, etc., which is why competent "EMC-safety" expertise should always be engaged on risk assessments, to help insure all reasonably foreseeable possibilities have been thoroughly investigated.

If the above sounds an impossibly large task, the good news is that one does not have to wade through all of the possible combinations of EMI and environmental effects, faults, misuse, etc. There are design approaches that will deal with entire classes of EMI consequences and risk analysis techniques that determine if they are a) needed, and b) effective.

For example, at one design extreme there is the "EMI Shelter" approach: a shielded filtered enclosure with a dedicated uninterruptible power supply and fiber-optic datacommunications is designed and verified as protecting whatever electronic equipment is placed within it from the nasty outside environment for its entire life, up to and including a number of direct lightning strikes, earthquakes, flooding and nearby nuclear explosions if required. Several companies manufacture such shelters.

Door interlocks and periodic proof testing insure it maintains that protection for the required number of decades. Nothing special needs to be done to the safety system that is placed inside it. Of course, [3] (or whatever other functional safety standard applies) will have many requirements for the safety system, but EMI is taken care of by the EMI shelter. Validation of the finished assembly could merely consist of checking that the shelter manufacturer's installation rules have been followed.

If the EMI shelter solution does not seem appropriate for your project, then how about a different extreme: error detection and fail-safe. It is possible to design digital hardware to use data with embedded protocols that detect any possible interference, however caused. When such interference is detected, the error is either corrected or the fail-safe is triggered. Designing sensors, transducers and analogue hardware to detect any interference is not as immediately obvious as it is for data, but can be done.

Safety systems have been built that used this technique alone and ignored all immunity to EMI, but unfortunately they triggered their fail-safes so often that they could not be used. So, some immunity to EMI is necessary for adequate availability of whatever it is the safety system is protecting. Since passing the usual EMC immunity tests often seems to be sufficient for an acceptable percentage of uptime, this is probably all that needs to be done.

CONCLUSIONS

Any practicable EMC testing regime can only take us part of the way towards achieving the reliability levels required by the SILs in [3] or similar low levels of financial or mission risk.

Risk assessment is a vital technique for controlling and assessing EMC design engineering, but since no established risk analysis techniques have yet been written to take EMI into account, it is necessary for experienced and skilled engineers to adapt them for that purpose.

I hope that others will fully develop this new area of "EMI risk assessment" in the coming years.

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ITE Requirements Around the Globe

BY JOHN MAAS

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

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

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

REGULATORY FUNDAMENTALS

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

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

It should be noted that some regulations may not require explicit action on some of these elements. For example, certain regulations do not require a statement of compliance to be included in the documentation provided to the end user of the product.

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

Once the technical evaluation is completed, the results must be documented. The old adage of the work not being done until the paperwork is completed definitely applies in hardware compliance. Without adequate documentation of the evaluation,

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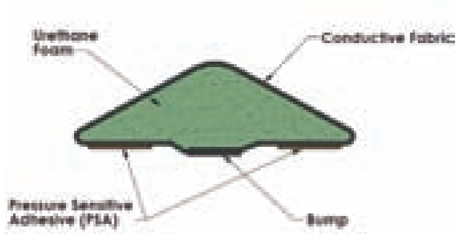

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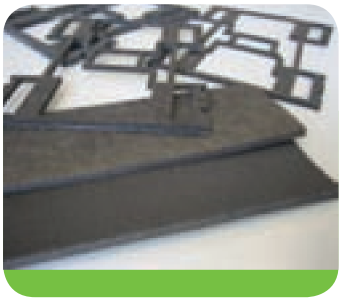

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one cannot truly demonstrate compliance with the requirements. What product was evaluated? How was the evaluation performed? Who did the work, and were they properly qualified to do it? The list of content that must be included in a test report can be quite extensive. Consider the following example.

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

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

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

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

These procedures can be placed into three basic categories:

- Certification
- Suppliers Declaration of Conformity
- Verification

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

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

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

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

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

Market surveillance includes any activates undertaken by the authorities to verify that products being sold do, in fact, comply with all applicable regulations. These activities include checking products at retail outlets to ensure proper labeling as well as testing samples acquired from manufacturers, importers or retail outlets. Compliance verification by Customs officials at the time of importation is another form of market surveillance and typically involves document inspection to see if all the paperwork accompanying a shipment is in order.

EMC

Let us now explore EMC regulations around the globe.

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

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

This referencing of common standards substantially reduces the testing burden, although changes and revisions to the reference standards are not always adopted on uniform schedules by the various regulations. A recent example of the variations that can happen in adoption is the roll out of the CISPR 22 limits on radiated emissions between 1 and 6 GHz. Compliance with these limits became mandatory in October 2010 for the Republic of China (Taiwan), in March 2011 for the Peoples Republic of China, and October 2011 in Australia, the European Union and Japan. Now that the new CISPR 32 standard for emissions from multimedia equipment has been published, it will be interesting to see how the various jurisdictions incorporate the standard into their requirements.

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

CONCLUSION

Many countries around the world have a variety of hardware regulations that must be met before ITE is marketed, sold or imported into those countries. These regulations exist for valid reasons and generally are intended to protect something: people, other equipment or the environment. For the most part, the technical details of hardware regulations can be met without placing excessive burden on the manufacturer, provided the requirements are understood at the start of a product's design cycle. The most challenging aspect of complying with the regulations is often the conformity assessment process – the administrative details that need to be completed after the technical analysis or testing is finished.

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

Table 2: Sampling of compliance details for EMC regulations

Assessing the EMC Performance
of PCB Shields by Electromagnetic Modeling

BY DAVID P. JOHNS, PHD
AND SCOTT MEE

PCB SHIELDING

In the past EMC Engineers have relied on metallic enclosures to contain electromagnetic fields and meet radiated emissions limits in military and consumer products. Modern commercial electronics products typically use molded plastic enclosures since they are considered to be aesthetically more pleasing than a metal enclosure, but also to save weight and cost.

With correct PCB layout, differential signaling and common mode filtering on cables, it is sometimes possible to meet commercial EMI requirements without employing any shielding in the enclosure. However with the increased complexity, component density and speed of logic, designers are frequently coating the plastic enclosure with a thin conductive layer to provide a level of shielding. In addition, metal shields may be placed directly over noisy and sensitive components on the PCB, to further reduce emissions and improve immunity.

A conductive coating in principle can be very effective. In practice, the seam between the two halves of a clam-shell type enclosure or between the enclosure and the PCB reference plane limits the shielding effectiveness. This is due to poor electrical contact at the interface, caused by inadequate pressure, low contact surface area and gaps due to unevenness in the formed parts or the coating.

In a high density compact electronics system, such as a cell phone, it may be necessary to place solid metal EMI enclosures over noisy components to reduce emissions, or over sensitive components to improve immunity. This can be particularly important when multiple radio communications systems are closely located and radio frequency interference (RFI) must be minimized. The shielding performance of metal enclosures also strongly depends on electrical contact to the PCB. The enclosure typically includes a number of tabs to connect to the PCB and there can be gaps between successive tabs. Furthermore, the enclosure may be perforated, typically on the top surface, to provide ventilation and this may compromise the shielding performance, especially at high frequencies.

The relative shielding effectiveness of various PCB shield strategies will be investigated in this article by applying 3D electromagnetic field simulation, based on the time-domain

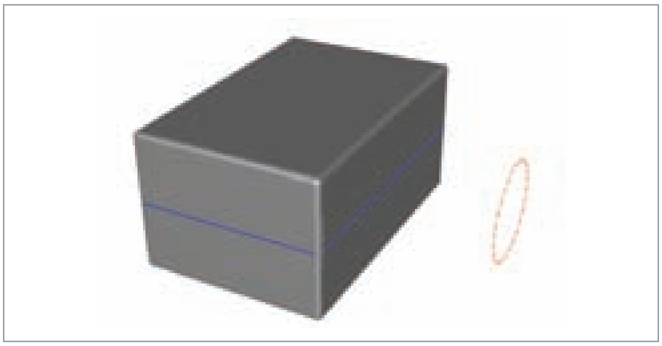
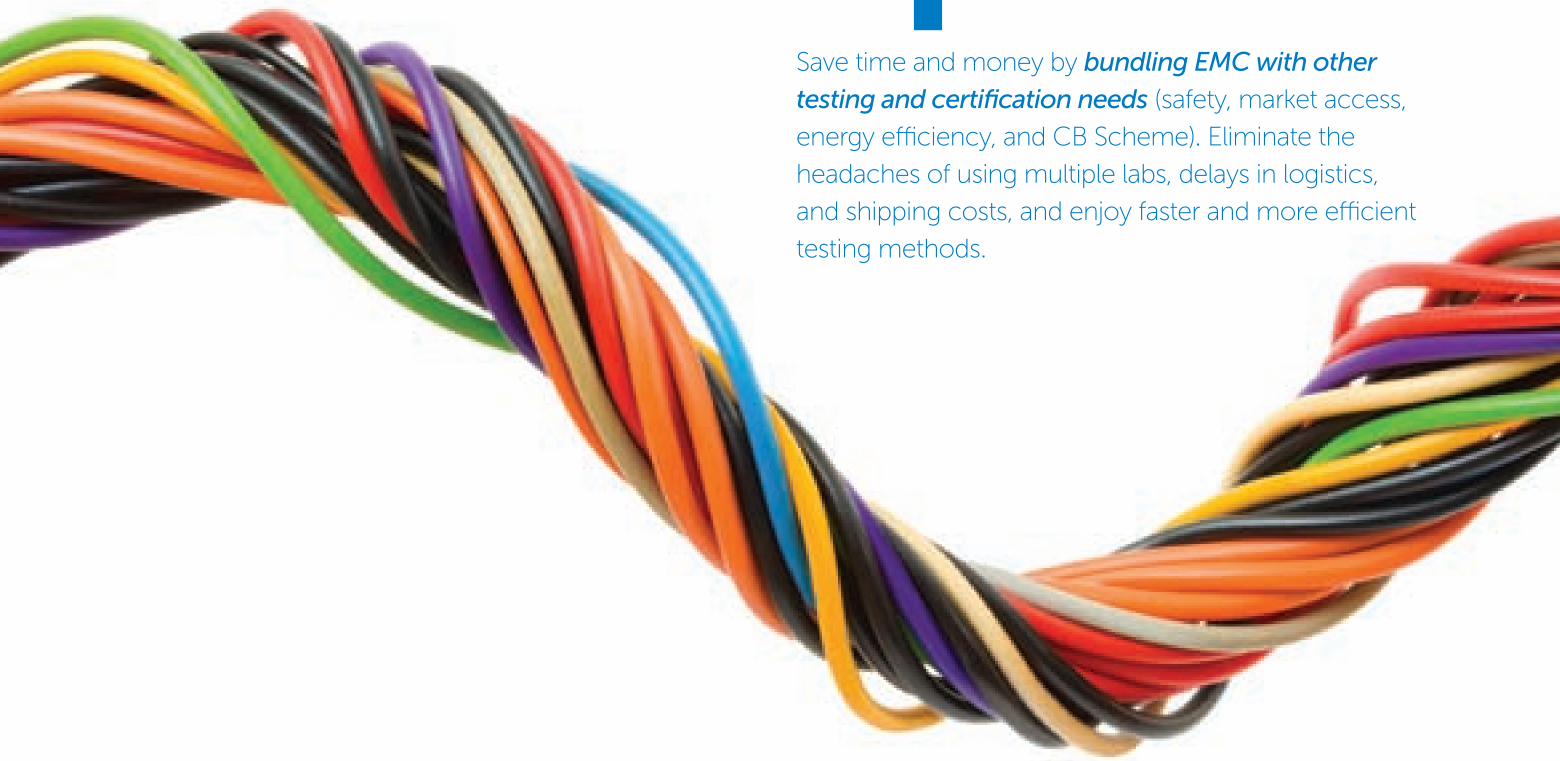


Figure 1: 3D TLM model of Conductive Coated Enclosure with Transmit Loop



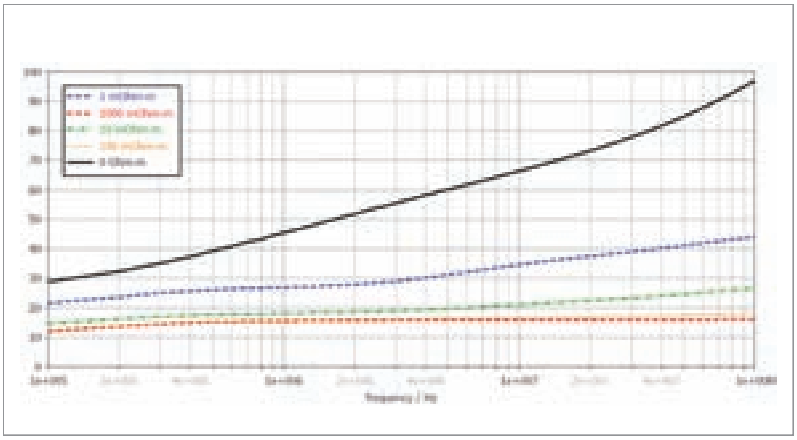


Figure 2: Magnetic Shielding Effectiveness Plotted Against Frequency

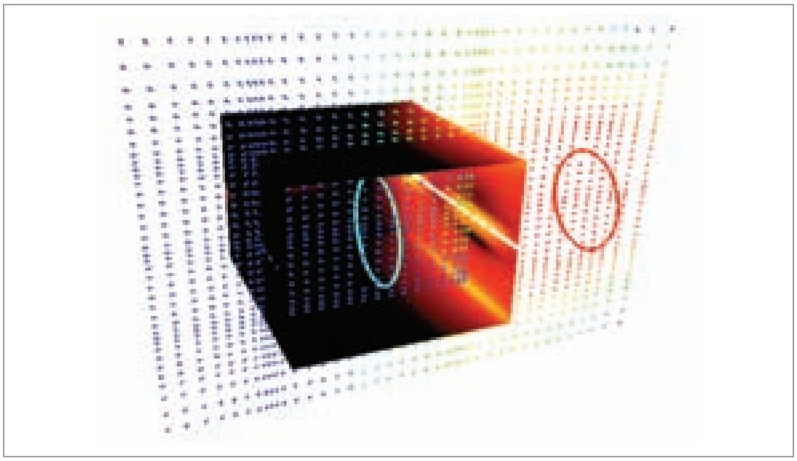


Figure 3: Magnetic Field at 1 MHz with 10 milli Ohm-m Seam Transfer Impedance

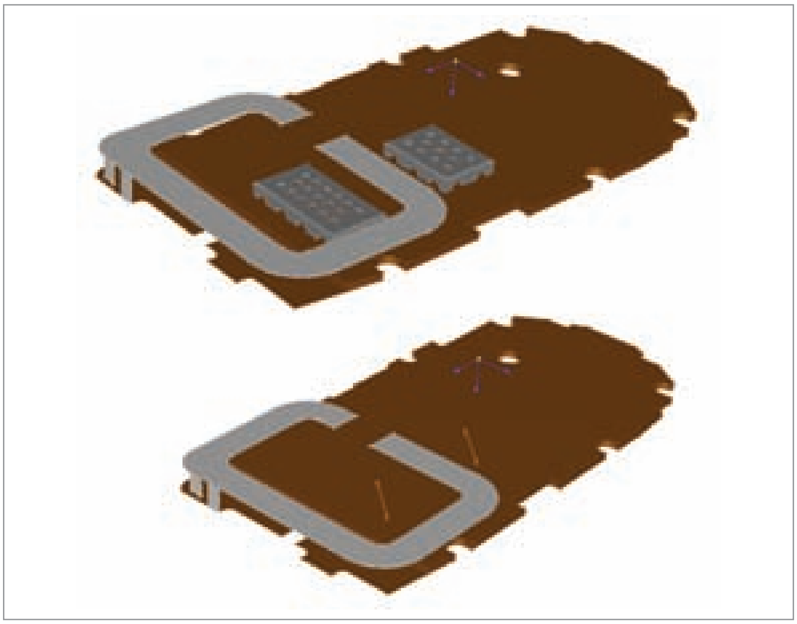


Figure 4: Cell Phone Model with Component Shields Present and Removed

3D Transmission-Line Matrix (TLM) solver. Solving the EM fields in the time-domain enables the system impulse response to be extracted from a single computation. Fourier transform can subsequently be applied to yield the broadband peak radiated field or emissions. Shielding effectiveness can be calculated by comparing the radiation with and without the shield present.

We will first calculate the shielding of a conductively coated plastic enclosure and explore the degradation in performance with increasing seam impedance. We will then investigate the use of component shielding in a GSM cell phone application to isolate two sensitive PCB components from the antenna fields. Finally we will model a graphics PCB used in an automotive display system, where a metal cover is placed on one side of the board to shield noisy digital circuits.

CONDUCTIVELY COATED CLAM SHELL ENCLOSURE

For this first application a plastic enclosure 8cm wide, 12cm long and 6cm high is coated with a conductive Nickel film of thickness 0.001 inch (0.0254 mm). For thin conductive coatings, it is important to assess the magnetic field shielding effectiveness, since it is possible that the skin depth of the surface current is larger than the conductive film thickness. The skin effect causes the effective resistance of the conductor to increase with the frequency of the current. At 1 MHz in Nickel, the skin depth is about 0.12 μm. The skin depth (δ) is inversely proportional to the square root of frequency (f) and conductivity (σ). Increasing frequency results in smaller skin depths.

$$\delta = 1 / \sqrt{\pi f \mu \sigma}$$

The frequency-dependent diffusion of current through the thin conductive coating is represented accurately in the TLM model by a special thin panel boundary condition. It is not necessary to use volume mesh cells to capture the film thickness so this speeds up the calculation and reduces the computer memory required to solve the problem.

In reality, the enclosure contains a groove to hold a conductive gasket which makes electrical contact between the two mating halves of the enclosure. This is modeled by an equivalent conductive seam model in the TLM electromagnetic simulation. The model allows for the transfer impedance of the joint to be varied and the impact on shielding performance assessed. The two halves are screwed together in all 4 corners with conductive screws and it is assumed that there is good electrical contact at these points.

Due to the thin conductive coating and skin depth effect, the magnetic field shielding effectiveness is the primary concern for this study. To assess the magnetic shielding, a 20cm radius transmitter loop is located 5cm away from one of the walls and a similar receiver loop placed at the geometric center of the enclosure. The transmitter loop is driven with a 1V source and series 1 Ohm load and the receiver loop is terminated in a 1 ohm load. The mutual inductive coupling between the loops with the enclosure removed is first solved to obtain a reference result. The enclosure is then inserted and the fields re-calculated. The magnetic shielding effectiveness is determined by normalizing the results, or subtracting dB.

Shielding (dB) = Reference Result (dB) – Shielded result (dB)

Results are provided for seam transfer impedance values of 0, 1, 10, 100, 1000 milli Ohm-m. The results show a progressive reduction in shielding performance with increasing seam transfer impedance. The voltage developed across the seam (V) is proportional to the surface current flowing over the seam (Js) and the transfer impedance (Zt).

$$V = Js \times Zt$$

If the seam impedance is zero, in other words perfect electrical contact between the two halves of the enclosure, the seam voltage will be zero and the shielding will be purely based on the inherent ability of the conductive film to attenuate the fields. From the curve in the graph plot, we can observe that the conductive film provides approximately 30dB shielding at 100 KHz. The shielding effectiveness improves with increasing frequency and this is due to the skin depth effect. At high frequencies the skin depth is smaller than the film thickness and the current is confined to the external surfaces of the enclosure.

The field plot in Figure 3 shows the magnetic field vectors at 1 MHz with a 10 milli Ohm-m seam transfer impedance. The magnetic field is mainly coupling through the seam and this is limiting the shielding performance of the enclosure.

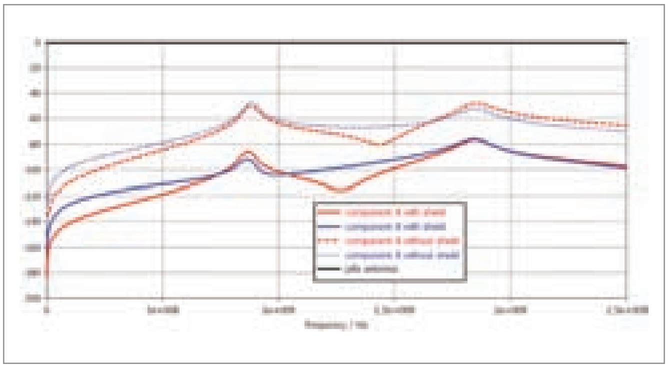


Figure 5: Coupling Between PIFA and Components With and Without Shields

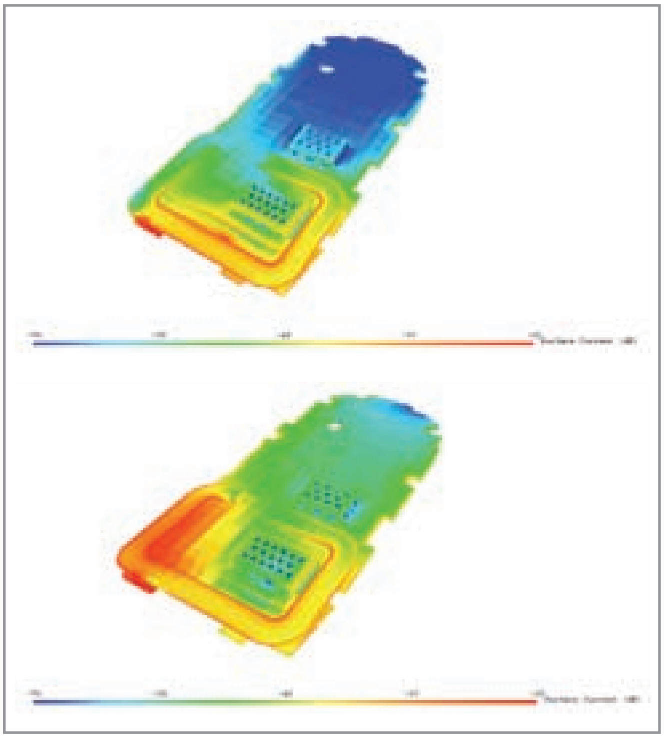


Figure 6: Surface Current and Field Distribution at 850 MHz (top), Surface Current and Field Distribution at 1900 MHz (bottom)

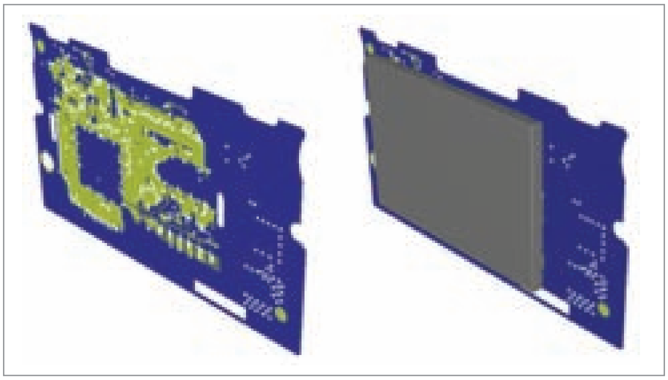


Figure 7: Automotive Display System Graphics PCB Model With and Without Shield

The TLM simulation requires approximately 10 minutes run time on a core 2 Duo T9600 based laptop. The model uses 10,500 mesh cells and requires only 13 MB of computer RAM.

RFI SHIELDING IN A GSM CELL PHONE APPLICATION

The next application is a cell phone with a dual-band Printed Inverted F Antenna (PIFA) antenna, tuned for the GSM frequencies 850 and 1900 MHz, typically used in North America. The model is used to investigate the isolation of two sensitive electronics components located nearby to the antenna element. Component A is located approximately 10mm away from the PIFA antenna element and component B is directly under the element. Wire traces are used to model nets at the component locations and the induced voltage and current monitored. The wires are arranged diagonally to ensure that different polarizations of the field are captured.

Simulation is used to predict the reduction in coupling when metal shields are placed over the components. The PIFA antenna is essentially a folded monopole, with an inductive stub used to compensate for the capacitance between the radiating element and PCB reference plane. The near field impedance is relatively high, so mutual capacitance between the antenna element and victim traces could be the coupling mechanism of concern. The metal covers serve as electric field shields and shunt the RF current to the reference plane.

The covers are not perfect shields, due to the use of 1mm diameter round perforations to provide ventilation for cooling of the internal electronics. There are also small gaps between the metal tabs used to make contact to the PCB reference plane. The results in Figure 5 plot the coupling to the two components when a constant 1 Amp (0dB) current is driven into the PIFA antenna.

With no shields present, the received current is approximately 48dB down at the antenna resonances of 850 and 1900 MHz. The metal enclosures provide around 38dB to 44dB shielding at 850 MHz, increasing the isolation to 86dB (component A) and 92dB (component B). The shielding effectiveness reduces to 28 dB at 1900 MHz, but this still improves the isolation to 76dB (both components). It is not surprising that the shielding is less for higher frequencies since the ventilation holes and spaces between contact tabs become electrically larger.

The surface current density is plotted in Figure 6 at the antenna resonant frequencies. Notice that the current prefers to flow along the sharp metal edges of the antenna element and corners of the metal cans, indicated by the orange-red coloring. This is a well known effect for high frequency currents. The electric field will be strong at the metal edge discontinuities, so it is possible that there is capacitive coupling from the edges of the antenna element to the edges of the metal enclosures.

The GSM cell phone simulation requires 15 minutes run time on a core 2 Duo T9600 based laptop and uses 25 MB RAM. This produces the shielding results of the entire spectrum from DC to 2.6 GHz.

PCB SHIELDING IN AN AUTOMOTIVE DISPLAY SYSTEM

The final example is concerned with the shielding of a graphics PCB used in an automotive display cluster. The PCB is approximately 10 x 6 cm and has multiple layers. For the electromagnetic analysis we focus our attention on the emissions generated by the DRAM clock net, which is routed on one of the outer layers. The net is essentially a microstrip conductor surrounded by a reference plane structure and this is intended to provide return paths for the high frequency currents and thereby reduce the emissions. Nevertheless, some field will inevitably "escape" and lead to radiation from the PCB. To contain the fields, a metal shield of size 7cm x 5cm is placed over the PCB. It is critical that the shield does not short out components and traces on the PCB, so contact can only be made to the reference plane at certain locations. For this design, contact is made at the 4 corners of the shield and also the middle points along the two longer edges. Therefore, we do not expect the shield to be perfect, but we would certainly hope for some level of shielding across the frequency band of interest.

In reality the DRAM clock signal has a certain frequency and rise/fall time which generates a spectrum of discrete frequencies including the fundamental and harmonics. We could drive the model with this transient signal, but it is often more useful to excite the net with a pseudo-impulse which contains all frequencies up to the limit of the model. This ensures that any narrowband peaks in radiated emissions are detected. The impulse response of the electric field observed at a point 1m above the PCB is shown in Figure 8. The response includes all the reflections and resonances associated with the PCB and shield structure.

The radiated field is monitored at a single point 2cm above the metal shield (near field probe) and at multiple points scattered around the PCB on a 1m radius (far-field probes). The field is also scanned continuously on a 1m radius to determine the peak radiated emissions.

The graph plot in Figure 9 shows the shielding effectiveness as observed by the probe 2cm above the metal shield. The metal enclosure provides good shielding at low frequencies, and this is due to the observation point being located in the "shadow" of the electromagnetic field. For other components placed in this location we can expect very good isolation. The shielding steadily reduces with increasing frequency and in fact negative shielding is seen at 2.1 GHz. Negative shielding can occur when one or more half wavelengths match one or more physical dimensions of the structure. Reflections back and forth between opposing boundaries generate standing waves, producing cavity resonances and build up of field strength.

The shielding derived from the 1m emissions scan is not as effective. This is due to radiation from the air gaps formed between the shield and PCB reference plane. The distant 1m observation points are in the path of the radiated field. The air gaps can essentially be considered to be slot antennas that will radiate very efficiently when the wavelength is comparable to the slot length.

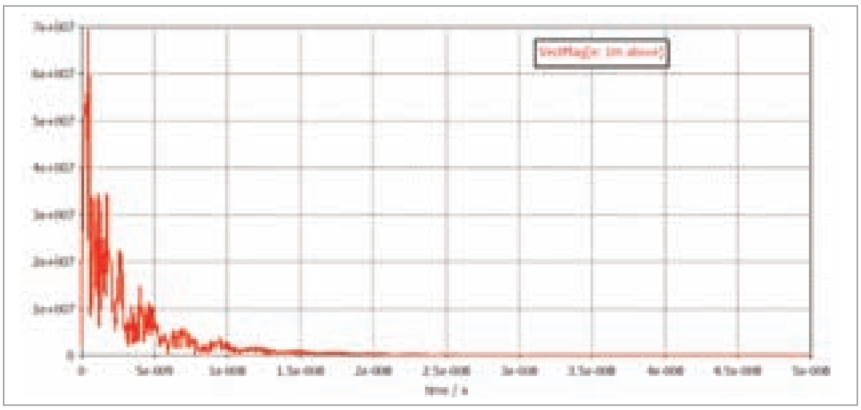


Figure 8: Typical Impulse Response from the Time-Domain TLM Analysis

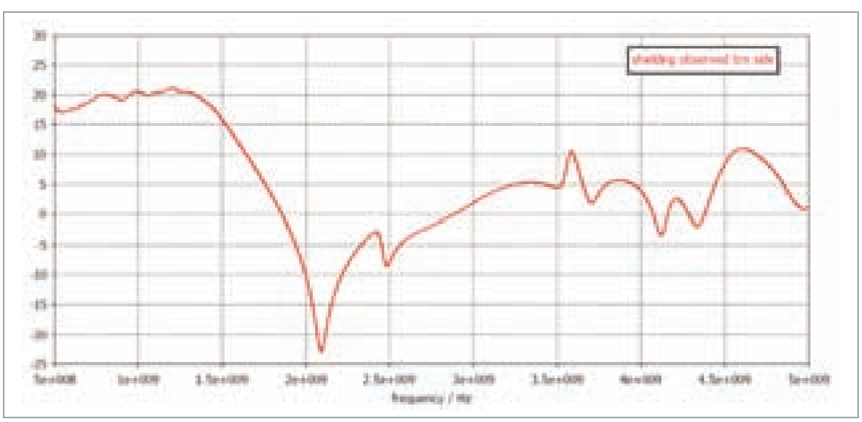


Figure 9: Shielding Effectiveness Observed 2cm above the PCB/Shield

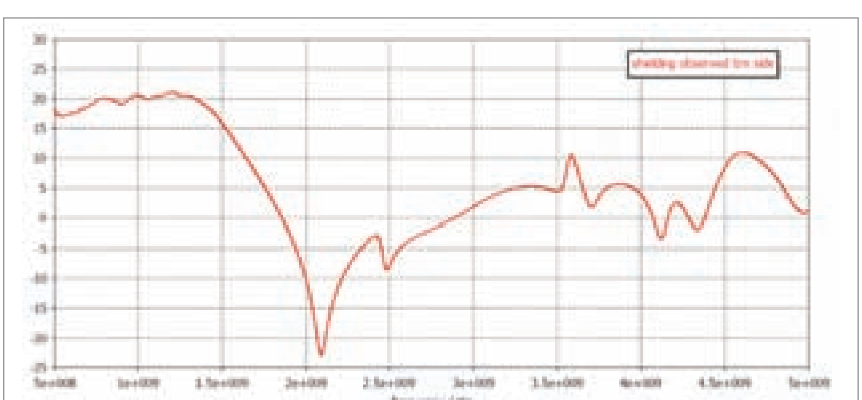


Figure 10: Shielding Effectiveness Observed 1m Away from the PCB/Shield

The surface current density and peak electric field distribution is plotted in Figure 11 at 867 MHz for the cases without and with the shield present. 867 MHz is chosen because the DRAM clock net exhibits a resonance around this frequency and shielding of the radiated fields is important. The field plot clearly shows very little field escaping beyond the shield. The scale is from -100dB to 0 dB. The deep blue regions are -100dB down on the peak electric field.

The peak electric field distribution is plotted in Figure 12 at 2.1 GHz for the cases with and without the shield present. At this frequency the air gaps between successive electrical contact points are just the right length to resonate and radiate electromagnetic waves. Comparing the two field plots it is clearly seen that the shield actually increases the emissions at this particular frequency (negative shielding effectiveness). Notice the high field strength in the PCB/shield gaps and propagation of the fields beyond the shield.

The PCB/shield simulation requires a 2 hour run time on a dual quad-core computer and uses 275 MB RAM. This produces the shielding results over the entire spectrum from DC to 5 GHz.

SUMMARY

We have shown through 3 application examples how electromagnetic modeling can be effectively used to assess the performance of PCB shields. In all cases, the simulation run times and computer memory requirements are quite reasonable and this enables multiple iterations to be solved quickly to determine trends in the results. The ability to display the surface currents and fields can provide greater insight and verification of the dominant coupling mechanisms. There is tremendous value in simulating EMC problems early in design and revealing potential issues before manufacturing and testing. In the applications considered here, it has been shown that a PCB shield can be effective over certain bands, but it can have the opposite effect and increase emissions for certain frequencies. It is important for EMC Engineers to understand the limitations of proposed solutions when making decisions in product design reviews.

Dr David P. Johns *is the VP of Engineering and Support for CST of America and is based in CST's Boston MA location. He received his PhD in Electromagnetic Analysis from Nottingham University (UK) in 1996 for developing a new 3D frequency-domain Transmission-Line Matrix (TLM) method for solving electromagnetic fields. He contributed to the development of CST's 3D time-domain TLM code MICROSTRIPES and in particular efficient techniques for modeling current diffusion, apertures and wires. David has over 20 years of electromagnetic simulation experience and specializes in the modeling of real world EMC/EMI problems. He is a regular speaker at IEEE EMC conferences and chapter meetings and recently the co-chair of the IEEE EMC Symposium Workshop "How to simplify real-world complex systems into realistic, solvable, accurate models."*

Scott Mee *received his BSEE in 1998 from Michigan Technological University (MTU) with focus areas in RF communications and electromagnetics. Since his graduation he has been working for Johnson Controls in EMC test development, A2LA/AEMCLRP accreditations, EMC design and simulation. Currently he is the Global Manager of the EMC expert team in the Automotive Electronics group at Johnson Controls. Scott is an IEEE EMC Society member and has been a contributing author to numerous technical papers and presentations on EMC. He served as a co-chair of the technical paper committee for the 2008 IEEE EMC symposium and an automotive EMC special session chair for the 2007 IEEE EMC Symposium. Scott is a NARTE certified EMC Engineer and his interests include EMC design, simulation, pre-compliance testing and product debugging.*

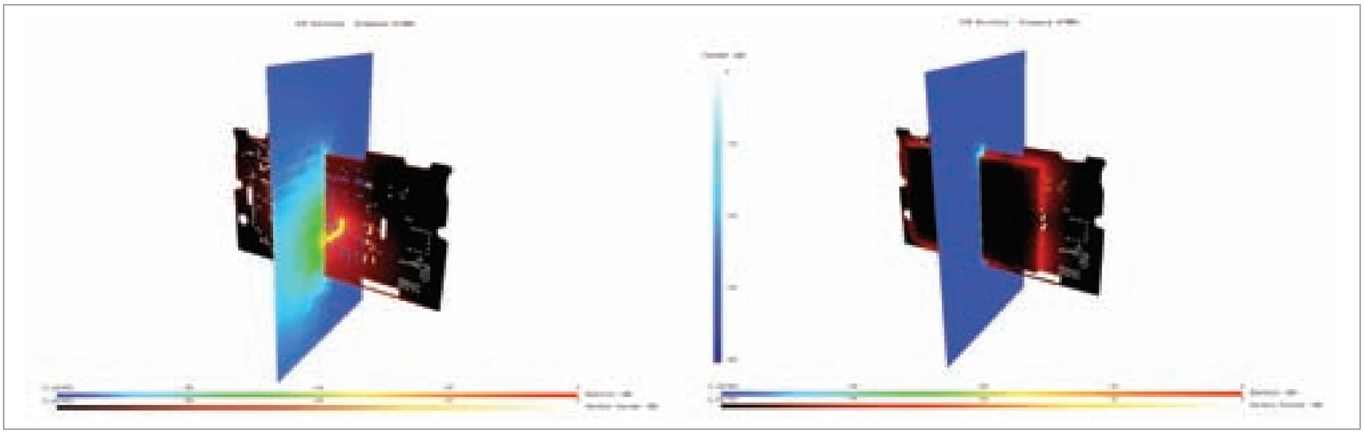


Figure 11: Surface Current and Electric field at 867 MHz: without Shield (left), with Shield (right)

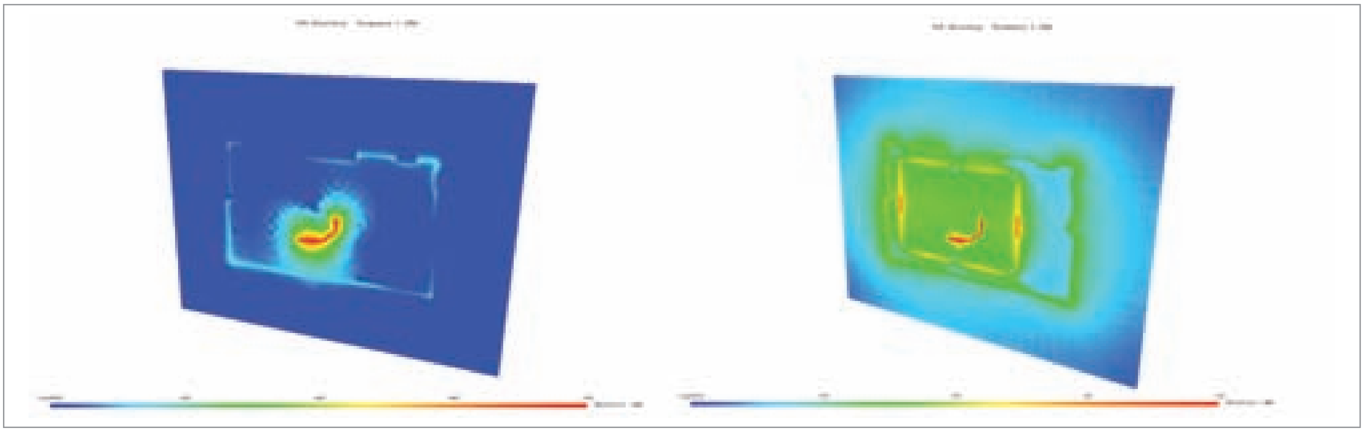


Figure 12: Electric field at 2.1 GHz: without Shield (left), with Shield (right)

Narrowband and Broadband Discrimination

with a Spectrum Analyzer or EMI Receiver

BY WERNER SCHAEFER

In the field of EMC, the two main categories of signals encountered are of particular importance: narrowband signals and broadband signals. The International Electrotechnical Vocabulary (IEV) defines a narrowband disturbance as "*an electromagnetic disturbance, or component thereof, which has a bandwidth less than or equal to that of a particular measuring apparatus, receiver or susceptible device.*" Consequently, a broadband disturbance is defined as "*an electromagnetic disturbance which has a bandwidth greater than that of a particular measuring apparatus, receiver or susceptible device.*" This means that the classification of a signal as narrowband or broadband is determined by the occupied frequency spectrum of the signal under investigation, relative to the resolution bandwidth (RBW) of the instrument used for measurement. If the signal spectrum is completely contained in the passband of the IF filter, it is defined as a narrowband signal. The general definition of a narrowband and broadband signal is depicted in Figure 1. It is important to note that continuous wave (CW) signals are a specific case of narrowband signals, since they consist of only one spectral line which is within the passband of the intermediate frequency (IF) filter. This case is depicted in Figure 2 (right). If the occupied signal spectrum exceeds the bandwidth of the filter, the signal is considered to be broadband. This is the case for the spectra of pulses (which are coherent signals) and noise (non-coherent signals). This scenario is shown in Figure 1 (left). This article presents various methods that are suggested for the determination of signal characteristics in EMC standards and literature. It also discusses their advantages and disadvantages. The presented material builds on previous papers that addressed the measurement of impulsive signals and discussed test equipment parameters such as the definition of impulse bandwidth and the purpose of preselection. Therefore, this article will defer to previous publications for details, as necessary.

Narrowband and broadband signals can be generated by a variety of sources and usually represent different interference potentials for radio services. Very often an interference spectrum from equipment under test (EUT) contains both signal types. Since both signal categories require a different interpretation of the result measured with a spectrum analyzer or EMI receiver, it is essential to know the characteristics of a signal in order to correctly determine its frequency and amplitude. In some cases, the characteristics must be known in order to select the correct limit for the determination of EUT compliance. The measurement results displayed on these instruments are also dependent on some control settings, such as the sweep time and resolution bandwidth. Their impact on the measurement of signal parameters, like frequency and pulse width, must be understood to avoid erroneous interpretations of measurement results.

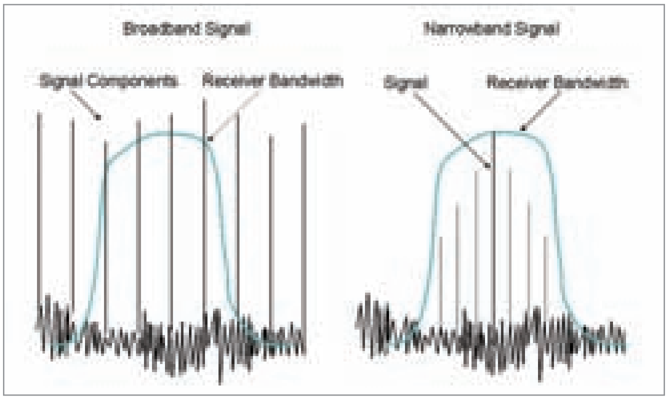


Figure 1: Generic definition of narrowband and broadband signals

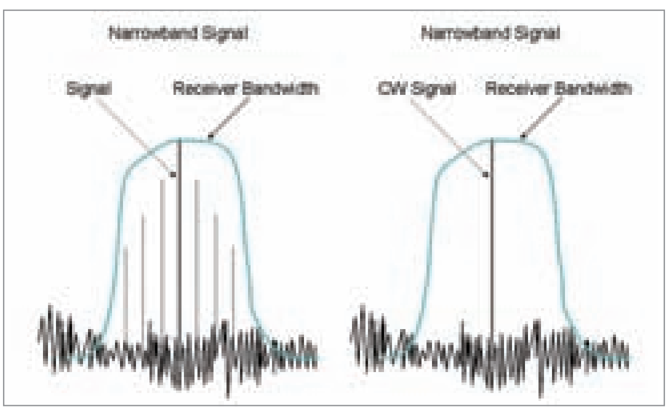


Figure 2: Two different types of narrowband signals

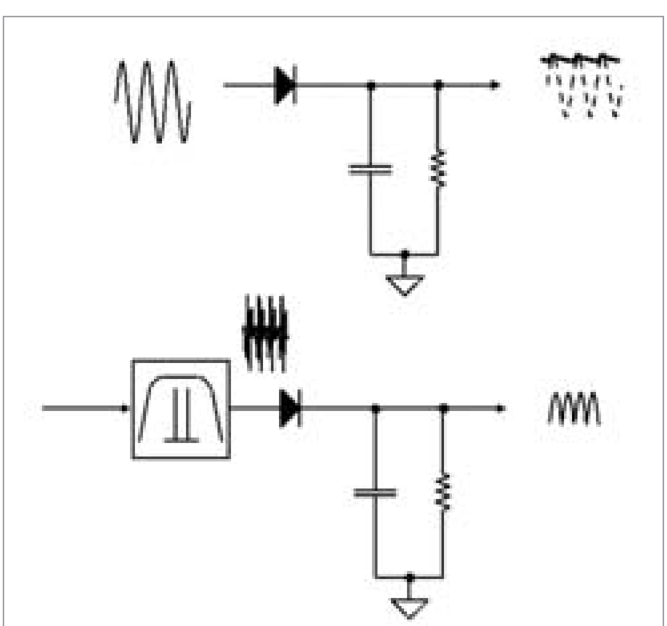


Figure 3: Envelope detector

THE ROLE OF INSTRUMENT IF

Most modern scanning receivers, spectrum analyzers and traditional EMI receivers are super-heterodyne receivers using one or multiple stages to convert the frequency of the RF input signal to a fixed IF. This is achieved by mixing the unknown signal with a local oscillator (LO) signal in a mixing stage. Since a mixer is a non-linear device, its output includes not only the two original signals at the input but also their harmonics and the sums and differences of the input signals and their harmonics. If any of the mixed signals falls within the passband of the IF filter, it is further processed at the IF and finally displayed. After the filtering, the signal is amplified by either a logarithmic or linear amplifier, rectified by the envelope detector, possibly filtered by a low-pass filter ("Video Filter") and finally graphically or numerically displayed.

EMI receivers as well as spectrum analyzers convert the IF signal to a video signal using an envelope detector. These signals have a frequency range from zero (dc) to some upper frequency which is determined by the detection circuit elements. In its simplest form an envelope detector consists of a diode followed by a parallel RC combination, as shown in Figure 3 (top). The output of the IF chain is applied to the detector. The time constants of the detector are chosen such that the voltage across the capacitor equals the peak value of the IF signal at all times which requires a fast charge and slow discharge time. In case the preceding resolution bandwidth of the receiver has only one spectral line in its passband (meaning, a CW signal is being measured), the IF signal is a steady sine wave with a constant peak amplitude. The output of the envelope detector will be a constant dc voltage without any variation for the detector to follow, as depicted in Figure 3 (top). However, often times there is more than one signal in the IF filter passband. For instance, in case of two sine waves, as shown in Figure 3 (bottom), these interact to create a beat note, and the envelope of the IF signal varies according to the phase change between the two sine waves. The maximum rate at which the envelope of the IF signals can change is determined by the resolution bandwidth. Since IF filters of receivers are not rectangular, the charge time of the detector needs to be a fraction of the reciprocal of the IF bandwidth (e.g. one-tenth) to obtain the envelope of the IF signal.

Specific instrument parameters like the selected detector, resolution bandwidth and sweep time do have an impact on the displayed measurement result, dependent on the characteristics of the signal to be measured. Therefore, they can be used to determine if a signal is broadband or narrowband.

When using spectrum analyzers or receivers for EMI troubleshooting measurements, no standard is to be applied that calls out a specific setting of the IF bandwidth.

Therefore, it is mandatory to know if a measured signal is displayed as a narrowband or broadband signal in order to correctly determine the frequency of signals. Furthermore, some EMI standards like the older MIL-STD 461B provide two different limits for narrowband and broadband signals, which require a determination of the signal characteristic as part of the compliance measurement process. In both cases, suitable discrimination methods are necessary to determine a signal to be narrowband or broadband.

RESOLUTION BANDWIDTH TEST

As mentioned before, the reference for a signal to be broadband or narrowband is the resolution bandwidth setting of the test instrument used for the measurement. Some standards suggest the variation of the resolution bandwidth of the test instrument and observation of the resultant amplitude change of the signal under investigation. It is stated that an amplitude change, introduced by the variation of the resolution bandwidth, indicates the presence of a broadband signal. Conversely, if no amplitude change is observed, the signal is considered to be narrowband. Figure 4 depicts the measurement of an impulsive signal with a pulse repetition

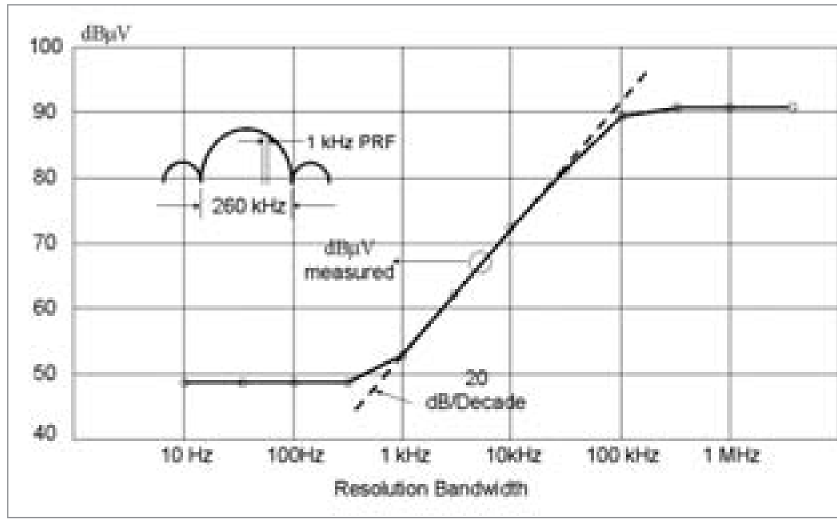


Figure 4: Impact of resolution bandwidth setting on measured amplitude of broadband signal

frequency (PRF) of 1 kHz and a pulse width of 7.7 µsec. If this signal is initially measured with a 100 Hz resolution bandwidth and the bandwidth is changed to 300 Hz, no change in amplitude is observed. Bandwidth settings that are lower than the PRF of the signal to be measured will result in the resolution of each individual spectral component. This will result in a narrowband measurement of the signal. A further increase in resolution bandwidth to 10 or 30 kHz will result in multiple spectral components located in the passband of the IF filter. A change in resolution bandwidth will result in an amplitude change of the measured signal, since wider IF bandwidths will encompass more spectral components and thus result in higher levels at the filter output. Using bandwidth settings that are wider than the PRF will indicate the presence of a broad band signal, since amplitude changes can be observed. Further increases of the resolution bandwidth to 1 MHz or greater will not yield changes in signal amplitude. This would indicate the presence of a narrowband signal, which is incorrect, in accordance with the definition. Large resolution bandwidths encompass the main spectral components of a signal (i.e., the main lobe and the first two side lobes of the spectrum), and do not lead to changes in the measured amplitude. Therefore, the variation of the resolution bandwidth as a means for determining the signal characteristic is of limited usefulness. Further information about the signal to be measured is required to avoid erroneous results. In addition, a change of bandwidth represents a change of the reference for the narrowband-broadband discrimination, which is very often neither permissible (by EMI standards) nor desirable for troubleshooting applications. It should be noted that this method provides conclusive results only when the signal under investigation is a CW signal.

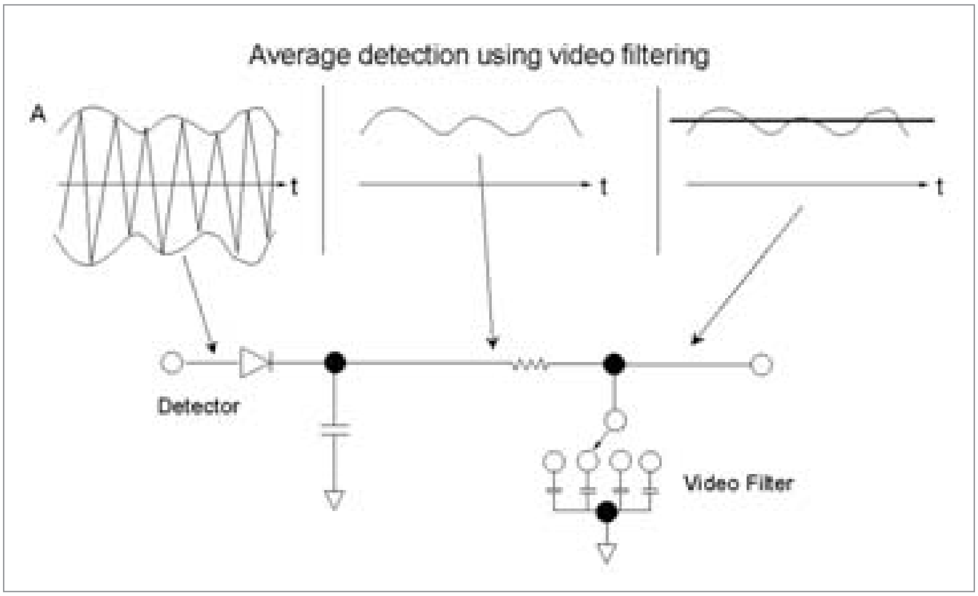


Figure 5: Peak versus average detection

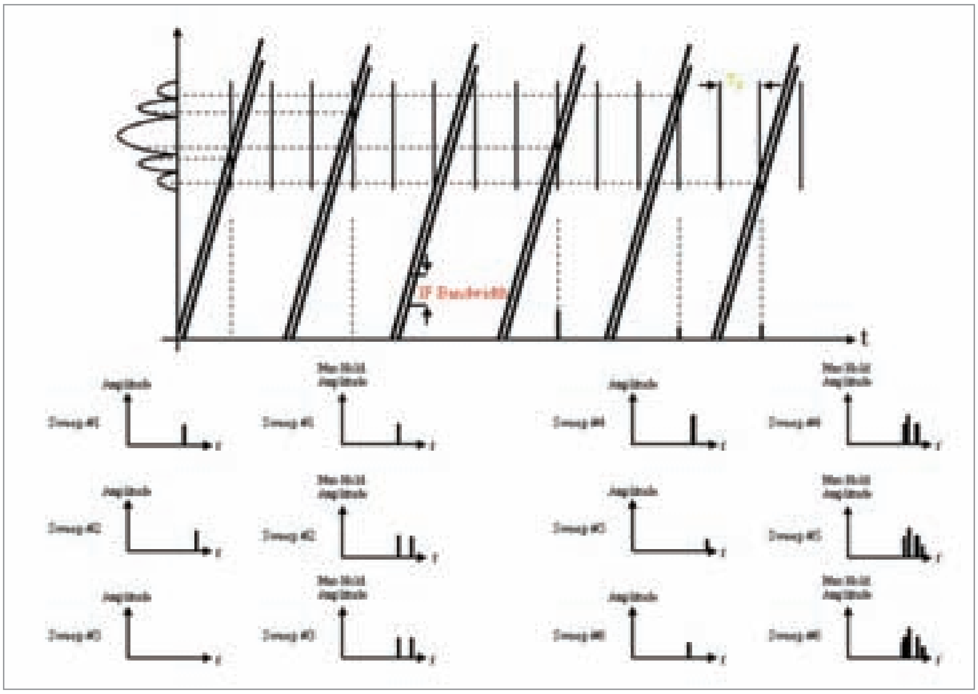


Figure 6: Broadband signal detection of a scanning receiver

PEAK VS. AVERAGE DETECTION TEST

A second discrimination for the determination of signal characteristics is the amplitude comparison between a peak and an average measurement. Both measurements are preferably made with the same instrument settings, especially with an identical resolution bandwidth setting. If no amplitude changes are observed between the two measurements, a signal is considered narrowband. A signal is considered broadband if an amplitude change between the two measurements is observed, with the average measurement yielding the lower amplitude. In practice, EMI standards that call out this discrimination method, like CISPR 25, specify an amplitude difference of, for example, 6 dB which is used as a decision criterion. Per CISPR 25, a signal is considered to be narrowband if the amplitude difference between the peak and average detected signal is less than 6 dB. If the amplitude difference is greater than 6 dB, the signal is determined to be broadband. This approach is meaningful since the relative amplitude accuracy of the instrument is to be considered as well as other uncertainty factors that are introduced by different instrument settings between the two measurements (e.g., change of reference level setting).

Figure 5 demonstrates the principle of this method by depicting the functionality of the peak and average detector. The peak detector will determine the envelope of the signal to be measured, which results in a low frequency signal at the detector output or a DC signal in case the signal to be measured is a CW signal. Since the peak detector determines the amplitude envelope, it will provide the maximum signal amplitudes. The average detector is often implemented as a low pass filter that is placed after the peak detector in the signal processing chain. This low pass filter, often referred to as video filter, will be used as an integrator by setting the bandwidth value to either a predefined value, called out in a standard (e.g., CISPR 16-1-1, which specifies an integration time) or to a value that is smaller than the lowest spectral component of the signal to be measured. For example, a video bandwidth setting of less than 100 Hz will result in the display of the average value of the signal depicted in Figure 4. It should be noted that the instrument is to be used in linear display mode in order to obtain the average value of the signal under investigation. The proper video bandwidth setting can be easily determined empirically by reducing the video bandwidth step-by-step and observing the resultant amplitude change. If further reductions in video bandwidth do not cause further reductions in measured amplitude, the proper video bandwidth for making an average measurement has been found.

The comparison of peak and average detected signal amplitudes allows the conclusive determination of signal characteristics without changing the resolution bandwidth. This method can also be automated easily and thus allow further automation of the overall compliance measurement process.

SWEEPTIME TEST

The presence of broadband signals is easily noticeable when a measurement is performed with a scanning receiver or spectrum analyzer. Moving responses can be observed on the instrument display; their actual location and number are dependent on the relationship of the pulse period and the sweeptime setting of the instrument. Figure 6 (top graph) shows how a scanning receiver or spectrum analyzer intercepts an impulsive signal when a slow, single sweep and peak detection is used. The impulse envelope is depicted on the vertical frequency axis, and the occurrences of the impulse are indicated by vertical frequency lines spaced along the time axis. The impulse of the period TP is detected only half way through the receiver sweep. The measured amplitude at the detection instant is determined by the envelope of the pulse spectrum, as traced out by

the IF bandwidth and represents the impulse response of the receiver to the input signal. The bottom graph of Figure 6 represents the scanning receiver's display, showing responses only at the detection instances. It is important to note that the pulse repetition frequency (PRF) **cannot** be determined directly from the display by measuring the frequency difference between two responses with marker functions, since a broadband signal is measured. The receiver's IF bandwidth is much wider than the PRF; thus the displayed responses are individual input pulses separated by the pulse period and the frequency and may be calculated from the sweep time of the receiver. The correct interpretation of the measurement result is difficult without prior knowledge of the presence of a broadband signal. After a single sweep, it is not obvious that the displayed responses are due to an impulse and not caused by individual sinusoidal signals or some type of modulation. However, a narrower measurement span and longer sweep time will lead to more intercepted pulses; hence the well-recognized sin(x)/x envelope shape will be traced out, and the impulsive signal will be easily identified. Broadband signals are displayed as time domain responses with amplitudes that are proportional to the envelope of the spectrum. With the instrument tuned to a particular frequency at a point in time, the spectral lines contained within the impulse bandwidth [1] around the tuning frequency, will add periodically at a rate corresponding to the signal PRF. As the analyzer is tuned to a different frequency, the maximum pulse amplitude will change in relation to the change in the envelope of the pulse spectrum. A scanning receiver or spectrum analyzer will therefore display a response every 1/PRF seconds with an amplitude proportional to the spectrum envelope at the tuning frequency of the instrument.

This phenomenon is used for the discrimination of narrowband and broadband signals. When changing the displayed frequency span on the instrument, the spacing of responses resulting from a broadband signal will not change, since they are a time phenomenon. In case of a narrowband signal, the responses are a frequency phenomenon and a change in span will cause a change in the spacing of the displayed responses. A change in sweeptime, however, will not affect the spacing of narrowband responses but have an impact on the spacing of the broadband responses. Slower sweeptimes will cause the display to show more responses, since more responses will be intercepted during a single sweep.

This discrimination method is useful to quickly determine the signal characteristic. However, if a complex spectrum is displayed, it may be difficult to observe the changes in spacing of responses.

TUNING TEST

Some older commercial and military EMC standards proposed a tuning test as a method for discrimination between narrowband and broadband signals. This test involves the de-tuning of a receiver by one or two impulse bandwidths to either side of the initial tuning frequency. The initial tuning frequency is to be identical with the frequency of the maximum signal response observed. The observed amplitude change on either side is then compared to a criterion (e.g., 3 dB or 6 dB) to determine if the signal is narrowband or broadband. If the de-tuning results in an amplitude change are greater than the criterion, the signal is considered narrowband. Conversely, if the amplitude change on either side of the initial tuning frequency is less than the criterion, the signal is determined to be broadband.

This method can provide inconclusive results when the de-tuning on one side of the maximum response is larger than the criterion, and on the other side a smaller amplitude variation is determined. This situation can occur if a signal spectrum is investigated that is rather complex, which may not allow the exact determination of the frequency at which the maximum response really occurs. Furthermore, this method requires the knowledge of the impulse bandwidth of the instrument, which is not identical to the 3 dB or 6 dB bandwidth of the measuring instrument. Furthermore, this method was initially based on the use of a fixed tuned receiver, as such, this approach is not suitable for automated testing.

Discrimination Method	Narrowband	Broadband
Bandwidth Test (par. 3)	No change in amplitude	Change in amplitude
Peak vs. Average Test (par. 4)	No change in amplitude	Change in amplitude
Sweeptime Test (par. 5)	No change in response spacing	Change in response spacing
Tuning Test (par.6)	Δ amplitude > 3dB (6 dB)	Δ amplitude < 3dB (6 dB)

Table 1

SUMMARY

In the literature and standards, four main methods for the determination of signal characteristics are described. Their main aspects are summarized in Table 1.

Their advantages and limitations have been described, and the peak versus average detector method has been identified as most suitable. This method is also called out by most EMC standards that currently require the determination of signal characteristics as part of the compliance measurement process.

ACKNOWLEDGMENT

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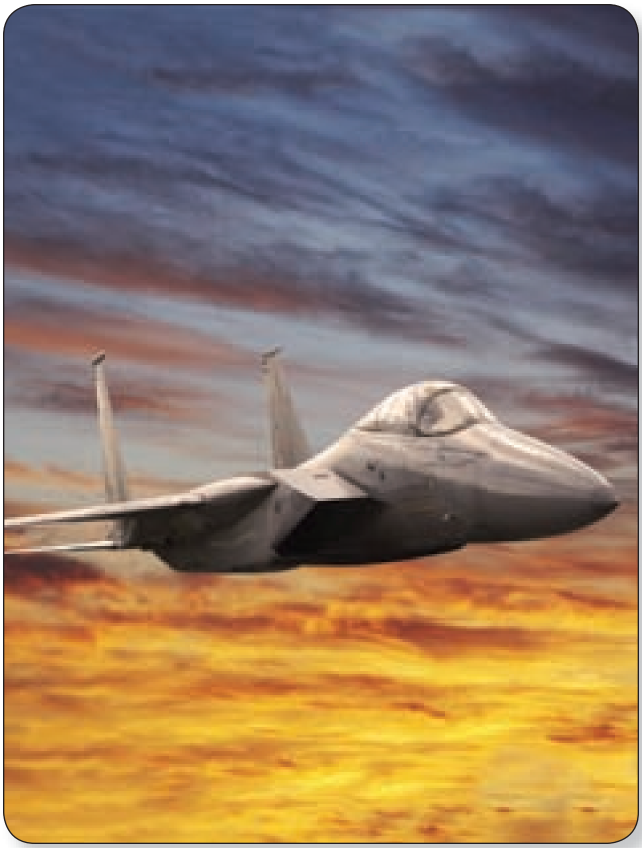
EMC in Military Equipment

BY DARYL GERKE, PE, AND BILL KIMMEL, PE



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

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

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

MULTIPLE ENVIRONMENTS WITH MULTIPLE THREATS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

MILITARY EMC REQUIREMENTS

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

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

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

These are further subdivided into specific tests, with a three number designator, such as RE101. As an aside, older versions of MIL-STD-461 (A,B, and C) used the same nomenclature but with two number designators, such as CS06. This distinction is important, as legacy systems may still be using the older versions of MIL-STD-461 for qualification purposes. For more details, see MIL-STD-461F, Table IV (page 70).

Note that not all tests are required for all equipment. Rather, different tests and different levels are recommended for various situations. These recommendations are based on anticipated environments and threats. For more details, see MIL-STD-461F, Table V (page 72).

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

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

There are two important philosophical differences between MIL-STD-461 and commercial requirements. First, MIL-STD-461 can be tailored as needed. Second, test failures can be waived. Of course, both require the customer to agree. We feel both of these options should be considered as needed, as they often yield good EMC systems engineering solutions.

One caveat on MIL-STD-461. It is not a guarantee of ultimate EMC, but rather it increases the overall probability of success. You still need to plug everything together and see if it works.

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

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

In spite of the system emphasis, we have seen increasing attempts by the platform designers to "flow down" their system requirements to the box designer. Since systems level

TABLE IV. Emission and susceptibility requirements.

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

Source: MIL-STD-461F

testing is not appropriate at the box level, the result is often a request for engineering analysis. This is certainly prudent early in the design, but should not be a substitute for testing later at the full system/platform level.

DESIGN SOLUTIONS – SYSTEMS ENGINEERING OVER CIRCUIT BOARDS

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

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

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

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

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

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

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

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

In addition to interfaces, risk management is an important aspect for EMC systems design. This is accomplished several ways:

Design reviews - Most military programs follow a detailed design procedure that includes formal design reviews at critical junctures. Additional design checkpoints may also be employed. We often recommend dedicated EMC reviews. These can be brief, yet can be helpful in uncovering potential EMC problems early in the design process.

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

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

MISSION SUCCESS TRUMPS COST

All this design effort, analysis, test, and documentation costs money, which can lead to complaints about $100 hammers or

TABLE V. Requirement matrix.

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

Legend:

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

Source: MIL-STD-461F

$400 toilet seats. In spite of carping by politicians, the extra costs are usually justified. Furthermore, since most military systems have relatively low volumes, there are fewer units over which to amortize the extra engineering and test costs.

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

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

CONCLUSIONS

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

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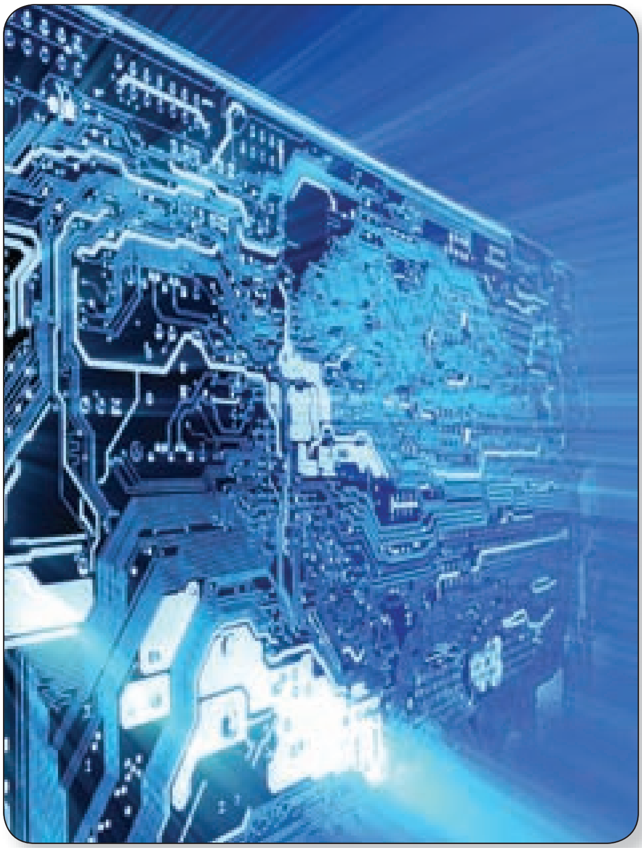
Daryl and Bill are both degreed Electrical Engineers, registered Professional Engineers, and NARTE Certified EMC Engineers. Between them, they share over 80 years of industry experience. For more information and resources, visit their web site at www.emiguru.com.



Testing for Immunity to EMP

BY JEFFREY VIEL

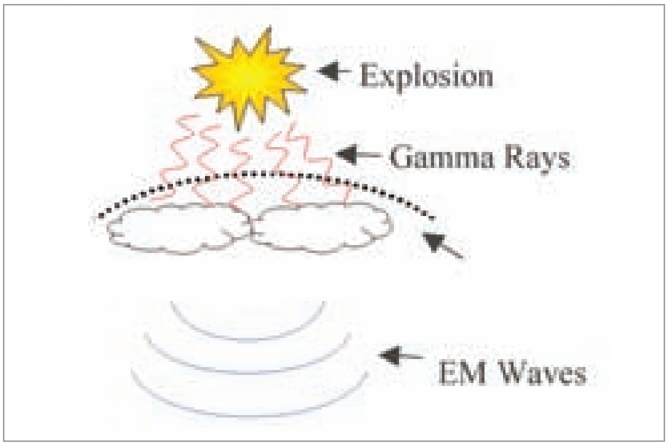
The 21st century as we know it, truly reflects the age of technology. Every aspect of life today is encompassed by the use of some sort of microprocessor based electronics intended to simplify tasks, to improve processes, and improve efficiency. Electronics are used to communicate with loved ones, manage finances, fly aircraft, even save lives. As greater advances in technology are achieved, electronics are found controlling more important safety critical functions at an exponential rate. Although electronics have provided us with obvious benefits, the increasing reliability on electronics has elevated our vulnerability to the effects electromagnetic pulses.

An electromagnetic pulse (EMP) is defined as a high amplitude, short duration, broadband pulse of electromagnetic energy which can have devastating effects on unprotected electronic equipment and systems.

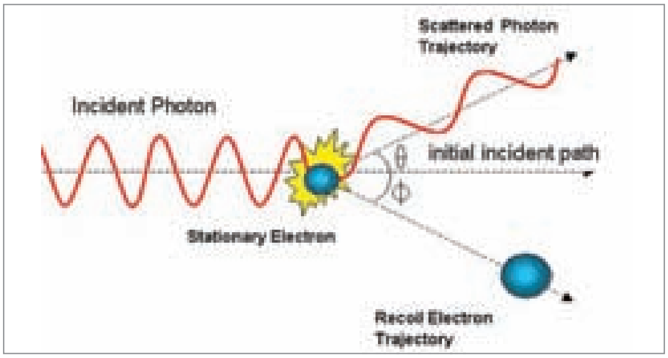
EMPs are historically known as the electromagnetic effects following a nuclear blast occurring at high altitudes (also known as HNEMP). The first discovery of the HNEMP incident was made by the U.S. in 1958 during a series of high-altitude atmospheric tests. The most noted was during the detonation of the nuclear payload named "Starfish Prime," over the Pacific Ocean over 800 miles away from Hawaii. Although the distance from the explosion was so great that physical detection was not possible, it caused a severe electromagnetic pulse which traveled distances much further than the shock wave and blast effects. The resulting electromagnetic pulse disrupted radio stations, damaged electrical equipment, and even blew out street lights throughout Hawaii.

To fully explain the physics behind how EMPs are created extends beyond the scope of this paper, but can be simplified to a short sequence of events:

- A nuclear payload is launched and detonated at an altitude within or above the earth's atmosphere.
- During the explosion, Gamma rays (*high energy photons)* are rapidly released in all directions from the blast.
- These gamma rays interact with air molecules in the earth's atmosphere which creates electromagnetic energy.
- This interaction process is called the "Compton's Effect."



When a gamma ray "incident photon" collides with an atom in the atmosphere, it knocks a stationary electron free on a trajectory away from the blast.

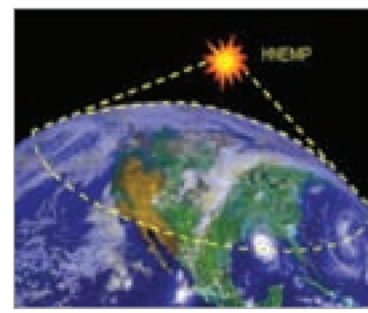


These electrons "*Compton's electrons*" being smaller than their corresponding positively charged atom travel at a higher rate of speed rapidly increasing the charge separation distance between them.

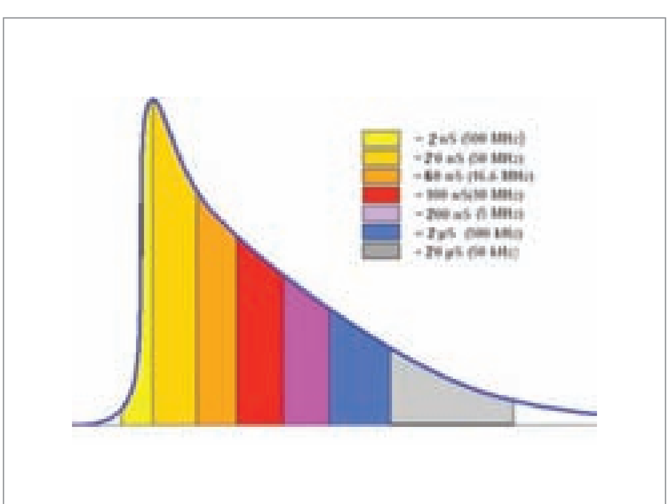
This separation time is expected to define the EMP rise time to peak voltage. The electrons quickly recoil back to their proton to conserve energy "*Compton's recoil electrons.*" This recoil time is expected to determe the EMP fall time from peak voltage much like that of charging and discharging a capacitor, and closely resemble the characteristics of an electrostatic discharge (ESD). Typical pulse rise times can range from 2 to 10 nanoseconds (2 – 10 billionths of a second) fall time duration's range from 100 ns to 20 microseconds (up to 20 millionths of a second). These pulse characteristics disperse energy across a broad spectrum ranging from 50 kHz to 500 MHz. However, the majority of the pulse energy resides in the frequency spectrum of 10MHz-100MHz which is considered the most predominant operating range for most microprocessor equipment and provides the greatest risk for vulnerability. Peak field strengths are estimated to reach into the 100s of thousands of volts.

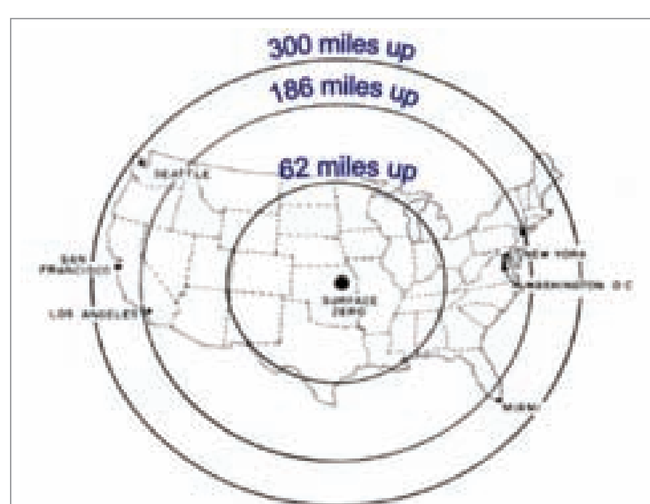
The exposure radius of a high altitude EMP commonly known as the "disposition region" is determined by three main elements, 1: Height of the blast, 2: size of the blast, and 3: type of explosive (kinetic energy). In general terms, the higher the explosion is, the greater the disposition region becomes. The size and type of the blast will determine the magnitude of the EMP. Theoretically, the size of the EMP disposition region is only limited by the curvature (horizon) of the planet.

To better understand the magnitude of this theory, it has been speculated that if a 100 Megaton nuclear payload was detonated at a height of approximately 300 miles over central United States, the EMP disposition region could effectively envelope the entire country. *A pulse from such a height would extend to the visual horizon of the planet as seen from the burst point perspective.*



What is the risk of a nuclear EMP attack? The Nuclear Non-Proliferation Treaty (NNPT) enforced since 1970 *intended to limit the spread of Nuclear weapons* currently includes 189 states, 5 of which are recognized as nuclear weapon states: U.S., Russia, the U.K., France and China. These states comprise the five permanent members of the UN Security Council). However, four non-parties of the treaty are known to or believed to possess nuclear weapons. India, Pakistan, Israel, and North Korea have openly tested and declared





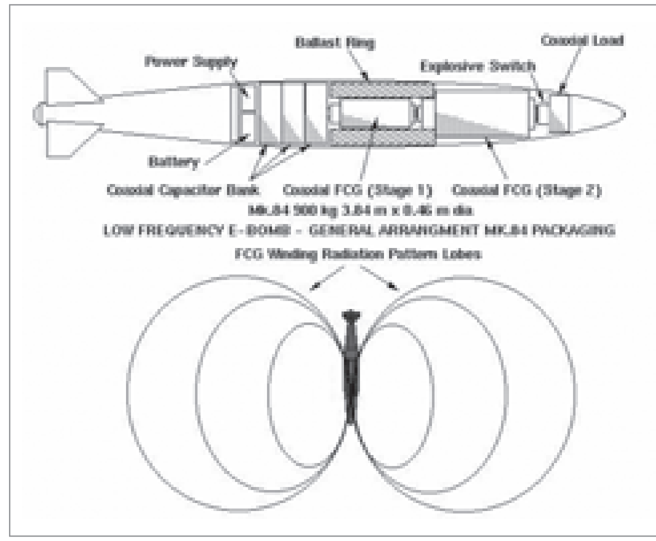
that they possess nuclear weapons. Israel claims ambiguity regarding its nuclear weapon program, while North Korea acceded to the treaty, violated it, and withdrew from it in 2003. The Comprehensive Nuclear-Test-Ban Treaty (CTBT) bans all nuclear explosions in all environments, for military or civilian purposes. It was adopted by the United Nations on 10 September 1996 but it has not yet entered into force. Advocates of nuclear disarmament say that it would lessen the probability of nuclear warfare from occurring, but critics say that it would undermine deterrence. Until CTBT is strictly enforced, and as creation nuclear weapons continue, the risk of a NEMP attack is expected to grow.

On a smaller scale, highly effective non-nuclear EMP technologies are progressively being developed worldwide. These technologies are classified as "Direct Energy Weapons" and are currently being used today by our U.S. armed forces, and state and local police departments. Direct energy weapons travel to the target at the speed of light much like that of a conventional EMP, and are capable of graduated effects on electronics ranging from disrupting operation, to permanent damage, and complete destruction.

A prime example of this technology is the arc discharge EMP generator. These devices use high voltage and massive energy storage of capacitors which is released across a thin under rated conductor to a low impedance load or short circuit. The wire acts like a fuse opening at the peak of the high current discharge of the capacitor resulting in a massive release of broadband electromagnetic pulse of energy similar to a conventional HNEMP. These generators typically integrate a small parabolic reflector to direct and focus the pulsed energy towards a target.

Another example of Non-nuclear EMP technology is the Flux Compression Generator (FCG). The FCG was first demonstrated by Clarence Fowler at Los Alamos National Laboratories (LANL) in the late fifties. This technology injects a high energy pulse into a large conductive coil. At the point of peak pulse current, a small explosive charge is deployed which quickly compresses the coil to one end of the generator creating massive amounts of electromagnetic energy. The first designs were several feet in length, but through technological advances, are now reported to be roughly the size of a beer can.

The US Navy reportedly used a FCG pulse weapon during the opening hours of the Persian Gulf War to effectively destroy vast amounts of Iraqi electronics, power and telecommunications systems quickly, efficiently. The deployment of EMP weaponry instantly caused what is known as the "Fog of War" (*complete loss of communications between troops and command posts*), which devastated the effectiveness of the opposing forces and essentially ended the war before it began.



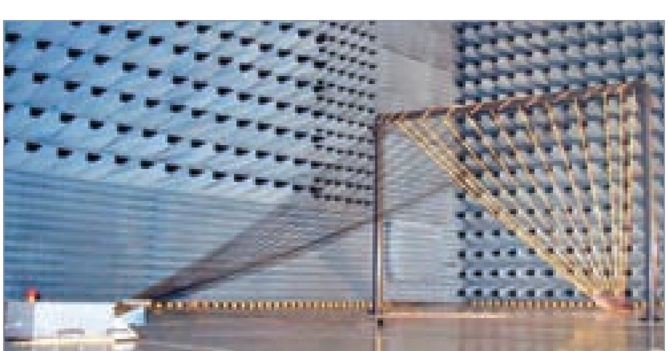
The effects of electromagnetic pulses on electronics can be severe, but poses an even more devastating threat to the processes and infrastructures that they support. Designing equipment and systems to withstand the effects of EMPs now will reduce the impacts of potential EMP attacks on our electronics in the future.

With the creation of non-nuclear direct energy weapons, and the existing use of the devices on the battle field, as well as civilian non-combat environments, the need to protect electronic equipment is at an all time high. The U.S. Military has been evaluating the effects of electromagnetic pulses on equipment for the past 50 years, and have developed protective design guidelines and hardening techniques currently used today.

MIL-STD-461F provides test methodology and screening levels for determining a device's immunity to EMP from a radiated and conducted standpoint. The coupling modes onto the equipment enclosure and its interconnecting cabling can be complex, therefore are evaluated separately.

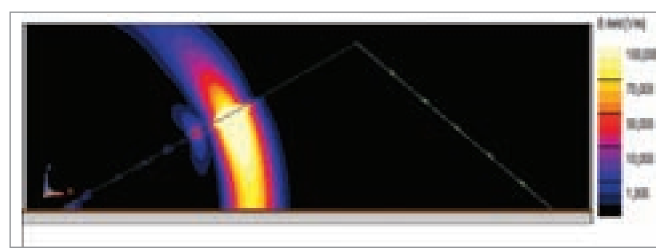
The RS105 test method specified in MIL-STD-461F addresses the risk of radiated exposure to an EMP event. RS105 testing is generally applicable for equipment installed in exposed and partially exposed environments. The U.S. Navy requires RS105 testing for nearly every installation platform, surface ships, submarines, and aircraft, to ground applications.

The RS105 pulse characteristics consist of a fast rise time, short pulse duration, and high amplitude which resemble those of an actual EMP. Peak field strengths of 50 kV/m are specified for exposed equipment. However, tailoring the peak field levels are often required for partially exposed installations due to the attenuated effects provided by enclosures such as the deckhouse structure, or hangar doors. For example, equipment installed near deckhouse apertures are required to meet the external stress reduced by the shielding effectiveness of that specific aperture or by the 40 dB of electromagnetic shielding provided by the deckhouse structure, whichever is less.



RS105 testing performed with a transmission line connected to a transient pulse generator. The generator and the far end of the transmission circuit are commonly bonded to reference ground. This connection provides a return path allowing current flow allowing for the generation of electromagnetic fields. The equipment under test is then installed underneath the transmission line within the predetermined uniform field area.

The field developed between the transmission line and the ground plane consists of large differential voltage and current fields. To ensure a proper uniform field distribution area, RS105 requires that transmission line length, and width are at least twice that of the equipment being tested and at least three times the height.



Prior to testing the uniform field is verified along a 5 point vertical grid. The results taken at each point are verified to be within 6dB (in terms of voltage) of each other, and greater than the specified test limit (no less than 50,000 v/m).

The purpose of RS105 testing is not to damage the equipment, but to determine its immunity threshold to the electromagnetic pulse. This is performed by starting at 10% of the peak field level and gradually increasing field until susceptibility is determined or the specified peak field level is reached. It is important to note that RS105 evaluates the equipment enclosure's ability to attenuate and withstand the effects of an EMP, not its cabling. The RS105 test setup requires that all metallic interconnecting cabling including power input lines are routed in shielded conduit and/or underneath the groundplane to minimize coupling.

The MIL-STD-461 CS116 test method evaluates the coupling effects of EMP on metallic interconnecting lines. The intent of this test is to ensure the equipment's ability to withstand conducted damped sinusoidal transients, excited by platform switching operations, indirect effects of lightning, and EMP. The minimum set of test frequencies includes 10 kHz, 100 kHz, 1 MHz, 10 MHz, 30 MHz, and 100 MHz. In accordance with MIL-STD-461F, CS116 testing is applicable for all installation platforms and procurement agencies with limited applicability for submarines. Similar to RS105, CS116 testing is not to damage the equipment, but to determine its immunity threshold to the electromagnetic pulse. This is performed by starting at 10% of the peak field level and gradually increasing field until susceptibility is determined or the specified peak field level is reached. One important aspect to note about the testing method is that the transient signals are inductively coupled to each line. The amount of voltage and current induced onto each line is dependent on its impedance. Higher impedance lines will allow for greater voltages to be achieved at lower currents, where low impedance lines such as shielded cabling, will achieve greater currents at lower voltages. To avoid excessive over testing, pre calibration of the injected currents into a 100 ohm loop impedance is performed, and the currents induced onto each line are monitored. As mentioned, test levels are gradually increased until equipment susceptibility is detected, the current limit is achieved, or the generator setting determined during the 100 ohm calibration are reached.

In summary, the effects of electromagnetic pulses on electronics can be severe, but poses an even more devastating threat to the processes and infrastructures that they support. Designing equipment and systems to withstand the effects of EMPs now will reduce the impacts of potential EMP attacks on our electronics in the future.

Jeffrey Viel *is a former U.S. Marine and a highly recognized electromagnetic interference and compatibility test engineer with over 18 years of experience. Jeffrey is currently employed as the EMI/EMC business development manager for National Technical Systems Mass Ops division, and has worked for NTS for approximately 10 years. Jeffrey also supports NTS engineering services as a senior technical consultant providing design for test, mitigation, and training services for the department of defense (DoD), aerospace, telecommunications, railway, nuclear power, and renewable energy industries. He is recognized by the Practicing Institute of Engineering, Inc (PIE) as a competent EMI/EMC course instructor for the New York City Transit.*

EMC Archaeology

Uncovering a Lost Audio Frequency Injection Technique

BY KEN JAVOR

Injection of audio frequency ripple on equipment input power conductors has a long history, going back to 1953 (MIL-I-6181B) in the United States military, and at least as far back as 1961 in commercial aviation (RTCA/DO-108). Audio frequency injection has been accomplished by inserting the secondary windings of a coupling (isolation) transformer in series with the power conductor to the test sample. While various transformers had been used prior to the 1960s, one has become standard since 1963. That Model is the Solar Electronics Model 6220, designed in 1962 and accepted by the United States Air Force in 1963 as being superior to previously used injection transformers. [1]

This device, which may be found in every EMI test facility that performs testing for automotive, aviation, or military applications, is admirably suited to the task, with perhaps one minor drawback. That being it inserts about one millihenry of inductance in series with the power line unless the primary side is properly loaded so as to shunt this leakage inductance. Such a large inductance in series with the power source can cause instability and even damage to a switched mode power supply lacking adequate decoupling from the power source.

Unlike the other markets mentioned previously, the space industry often conducts qualification testing on flight equipment, and is thus leery of anything that could have an even remote possibility of damaging flight hardware. The Jet Propulsion Laboratory EMI test facility has gone so far as to develop their own audio frequency injection technique which doesn't require the coupling transformer. [2]

However, such heroic measures are actually unnecessary for space equipment. An alternative injection technique similar to modern bulk current injection technology was developed for the Apollo program Lunar Excursion Module (LEM) in the mid-1960s. It is this forgotten technique that is exhumed and investigated herein.

BACKGROUND

The 1971 Solar Electronics catalog contains the following verbatim text on the reverse side of the ubiquitous Solar Model 6741-1 current probe data sheet:

> **Audio Frequency Induction Probes for LEM Testing**
>
> A clever new idea introduced by Grumman Specification LSP-530-001 for inducing up to one volt of audio on each wire inserted in the window of a split toroid for susceptibility testing. Includes monitoring winding to show how much audio is being induced on the wires being tested. Designed for 4 ohm audio amplifier output. 30 Hz to 15 KHz. Type 6541-1. 1 1/4 " I.D.

References to LSP-530-001 [3] appear in other NASA/Apollo publications as early as 1963. [4] The Solar Model 6541-1 means that the design was done in 1965; the first two digits of a Solar Model number being the last two digits of the year it was designed, in the last century.

The Solar Electronics data sheet for the 6541-1 lists the following pertinent information (verbatim):

"The Solar Electronics Type 6541-1 Induction Probe has been designed to provide induced signals from a 100 watt audio amplifier with a four ohm output impedance over the range of 20 Hz to 15 kHz. Such a test is required by paragraph 4.5.3 of LEM Specification LSP-530-001.

Using the Type 6541-1 Induction Probe, it is also possible to perform to the specification using the eight ohm output of a 60 watt audio amplifier, with some degradation of waveform at frequencies below 100 Hz. At low frequencies, the wave shape may be improved by lowering the output impedance to less than four ohms by connecting to the four ohm output tap and adding a fixed resistance load."

Other important information is that the Induction Probe saturation current is 35 Amps direct current, and most importantly for our investigation (verbatim), "the probe adds approximately 0.01 ohm in series with each wire passing through the probe." The probe, shown in Figure 1, is physically similar to the well-known Solar Model 6741-1 current probe, using the same enclosure with only a different multi-pin connector instead of a bnc.

It should be understood that the purpose of this new technique in LSP-530-001 was not to replace the coupling transformer injection technique that was included in it and was substantially the same as that used universally today.

Figure 1: Solar 6541-1 Audio frequency injection clamp

Figure 3: McIntosh MC60 amplifier specified for use with Solar 6541-1 in LSP-530-001

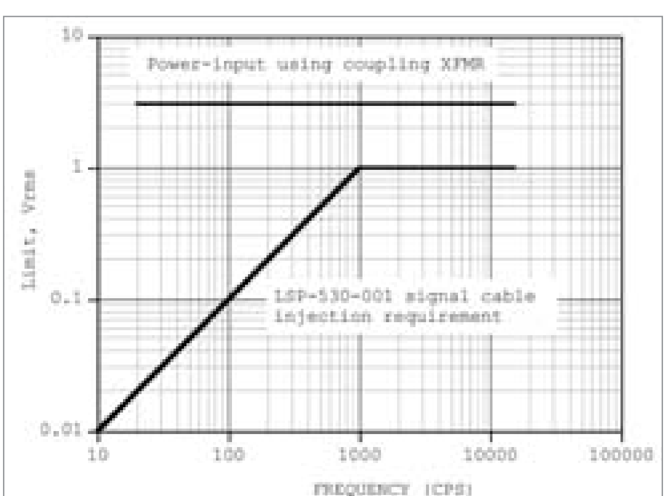


Figure 2: LSP-530-001 power input & signal bundle audio susceptibility limits

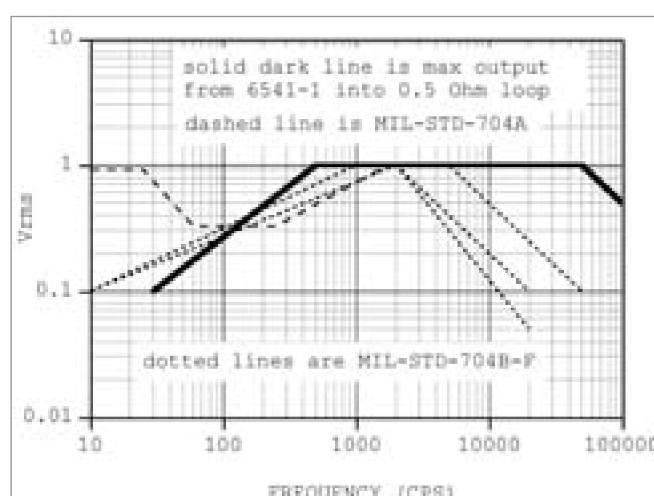


Figure 4: Maximum potential induced on 0.5 ohm load using Solar 6541-1 as intended. Compare to various MIL-STD-704 28 Vdc ripple limits.

Instead, injection using the Solar 6541-1 was aimed at common mode injection on signal cables, similar to how we perform MIL-STD-461D/E/F CS114 and RTCA/DO-160 section 20 rf conducted susceptibility testing today. The limit was much less stringent than the requirement for audio injection on equipment power input. The two LSP-530-001 limits are graphed together for comparison in Figure 2. The two curves are not completely an apples-to-apples comparison, because the "CS01-like" requirement is 3 Vrms open circuit, with no mention of the signal source impedance, whereas the bulk current injection-like limit is measured as induced on the cable-under-test (CUT).

However, a feel for the difference between the open-circuit and cable-induced limits can be obtained by noting that LSP-530-001 specifically references a McIntosh 60 audio power amplifier using the 8 ohm tap for the signal cable test. The McIntosh C60 amplifier shown in Figure 3 was specified to have a damping factor of 12 or better on the 4, 8, and 16 ohm taps so that the source impedance was well under one ohm. And audio frequency conducted susceptibility testing for power inputs was generally specified to have a 0.5 ohm or lower source impedance in the days running up to and including MIL-STD-462. [3] Which means that for most applications, the open-circuit and loaded potentials wouldn't have differed greatly.

RATIONALE FOR USE OF THE ALTERNATE INJECTION TECHNIQUE FOR SPACECRAFT EQUIPMENT

It will be noted that whereas the Model 6220 injection transformer is capable of injecting at least 6.3 Vrms using a 100 watt amplifier, the Model 6541-1 can only inject up to 1 Vrms (see graph, below). Clearly, the Model 6541-1 is not suitable for testing to MIL-STD-461 CS101, or RTCA/DO-160 section 18. However, the ripple levels in these standards derive from electro-mechanical power generation, where an engine of one sort or another turns a shaft that provides motive power to an electrical generator. Such power sources have inherent ripple, viz. MIL-STD-704, all revisions. MIL-STD-461 CS101 in particular is written to provide a margin with respect to MIL-STD-704. [5] RTCA/DO-160 section 18 also refers to harmonics of the power frequency as the source of ripple in all versions since and including RTCA/DO-160B in 1984. Boeing standard D6-16050-2, dated 1977, also refers to power generating equipment as the source of audio frequency ripple requirements.

Figure 5: The 6541-1, center, with ten turns through the window is driven from the 100 watt Solar 6550-1 power audio oscillator and induces the oscilloscope-measured potential across the two parallel 1 ohm resistors in the foreground.

But most spacecraft are different. Especially those operating in Earth orbit, or within Earth's orbit of the Sun, tend to use solar panel arrays that charge a battery. An electrical power subsystem based on solar charging has no inherent ripple, at least not at audio frequencies. The only source of audio frequency ripple is load-induced effects, and these are minor with a battery-dominated bus. The United States National Space Transportation System (Space Shuttle) quotes 0.8 Volts peak-to-peak in a dc to 50 MHz bandwidth, with no more than 0.4 Volts peak-to peak at any discrete frequency, with the bus resistively loaded (i.e., no load-induced effects). [6] The Space Shuttle uses fuel cells in lieu of batteries and solar arrays. Obsolete MIL-STD-1541A (dated 1987) required time domain ripple to be less than 0.5 Volts peak-peak. The International Space Station Power quality specification [7] required a maximum of 3 Volts peak-peak ripple in the time domain (20 MHz bandwidth), and no more than 0.3 Vrms ripple at any discrete frequency resistively loaded, even though this power was sent through a dc/dc switched mode converter between the solar arrays and the electrical bus. The orbiting x-ray observatory Chandra specified 1.5 Vpeak-peak time domain over a 1 Hz to 1 MHz bandwidth. At the current time, the orbiting infrared observatory James Webb Space Telescope is looking at under 1 Volt peak-peak ripple in the time domain and a 1 Vrms CS01 limit.

The graph in Figure 4 shows ripple limits for 28 Vdc power from MIL-STD-704, revisions A-F, vs. the maximum ripple the Solar 6541-1 injection clamp can induce in 0.5 ohms. It will be seen that except for the obsolete A revision, the Solar 6541-1 performance suffices except at the very low end below 100 Hz, and it is precisely that very low end that simply won't be there, meaning the ripple on a battery dominated spacecraft 28 Vdc bus.

MODERNIZING THE TECHNIQUE

While the Solar 6541-1 performs as needed for the LSP-530-001 requirement, it complains loudly (core vibration – "singing") when pushed to the maximum levels in the above graph. And while the author feels the Figure 4 levels available from the 6541-1 should suffice for spacecraft applications with a battery-dominated bus, it is possible to modify the clamp to get 1 Vrms across 0.5 ohms over a wider range. The clamp is a twenty-turn primary, single turn secondary transformer. As such, it is a step-down transformer with a 400:1 impedance transformation. Since the audio amplifier output is no more than 2.4 ohms (Solar audio Amps for conducted susceptibility testing) to well below an ohm (the McIntosh C60), this much step-down is not useful. Pulling ten turns through the clamp window converts the step-down ratio to the same as that for the 6220 coupling transformer, and allows the cited 1 Vrms to be induced across 0.5 ohms from 30 Hz to 80 kHz.

Ten turns, in addition to providing a 2:1 turns ratio, also provides about 100 uH secondary winding inductance, which is 10% that of the 6220. That 10% value was used as a benchmark. More turns give better performance, but at the cost of higher secondary inductance. The whole point of the modernization investigation was to finesse the minimum amount of secondary inductance that would result in the ability to inject the required potential into 0.5 ohm down to 30 Hz. It was felt that keeping that inductance to 100 uH should suffice to allay fears of damage to switching converters. Note that 100 uH is the power source impedance seen by any test sample undergoing MIL-STD-461D/E/F qualification. In other words, a robust power supply and filter design ought to be able to operate stably from a 100 uH power source impedance.

Figure 6a: 1 Vrms injected across 0.5 ohm at 30 Hz. Note considerable distortion, which can be ameliorated by more turns.

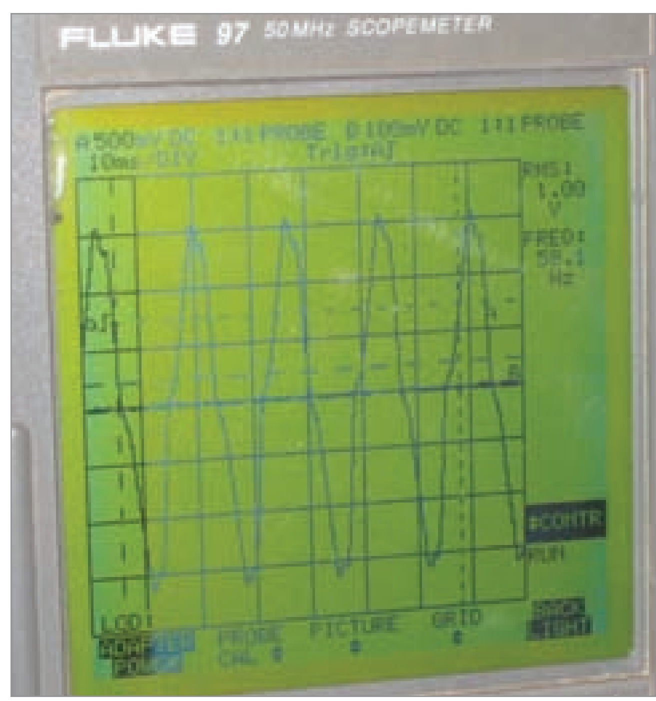


Figure 6b: 1 Vrms injected across 0.5 ohm at 60 Hz. Note distortion, which can be ameliorated by more turns.

CONCLUSION

A "space-race" era EMI test technique has been discovered and examined and modified to provide a safer technique to inject audio frequency ripple on dc power lines. The injection clamp is still available from Solar Electronics, and it is the author's hope that the technique described herein is adopted as an alternate audio frequency test technique in such standards as the Goddard Space Flight Center's General Environmental Verification Specification (GEVS), the American Institute of Aeronautics and Astronautics (AIAA) S-121-2009 Electromagnetic Compatibility Requirements for Space Equipment and Systems and other EMI control requirements with a spacecraft focus.

ACKNOWLEDGMENT

The author would like to thank EMC engineers at the Marshall Space Flight Center for sifting through old records and finding a copy of LSP-530-001.

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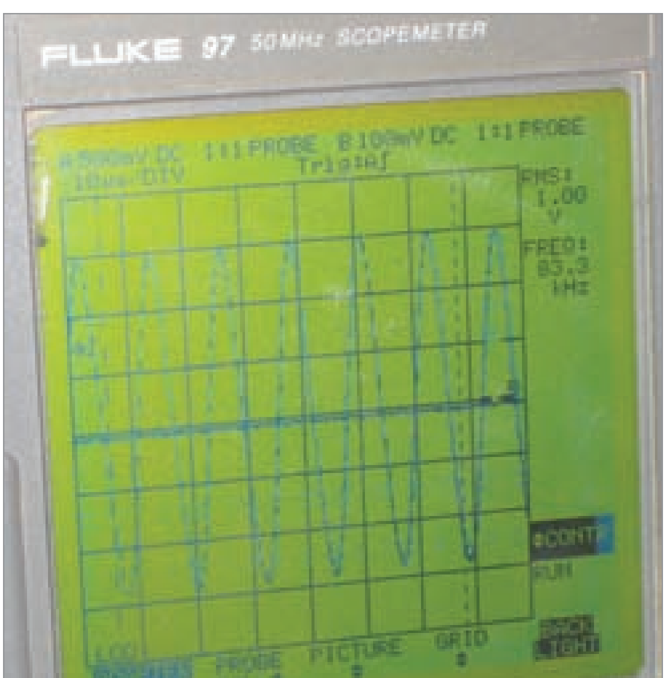
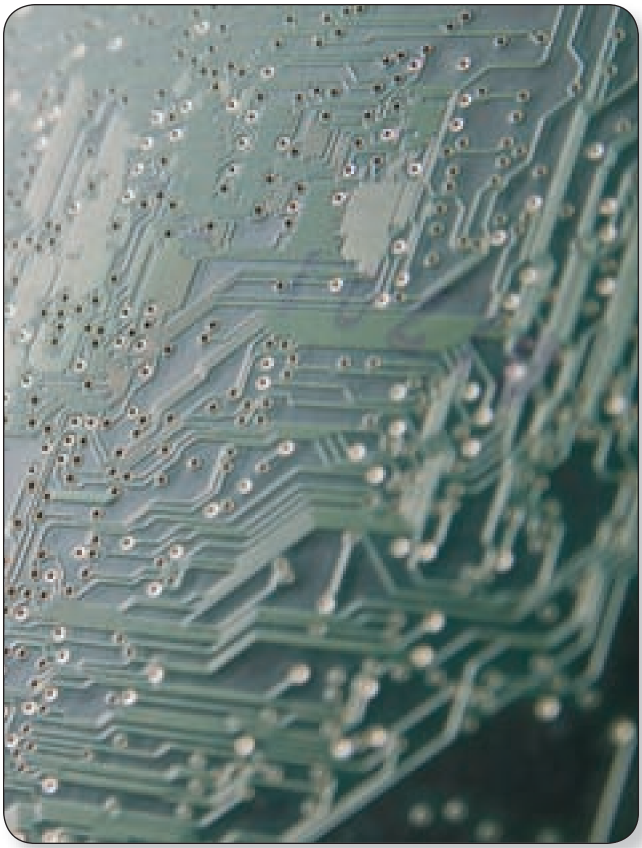


Figure 6c: 1 Vrms injected across 0.5 ohm at 80 kHz.

Ken Javor *has worked in the EMC industry for thirty years. He is a consultant to government and industry, runs a pre-compliance EMI test facility, and curates the Museum of EMC Antiquities, a collection of radios and instruments that were important in the development of the discipline, as well as a library of important documentation. Mr. Javor is an industry representative to the Tri-Service Working Groups that write MIL-STD-464 and MIL-STD-461. He has published numerous papers and is the author of a handbook on EMI requirements and test methods. Mr. Javor can be contacted at ken.javor@emccompliance.com.*



The Basic Principles of Shielding

BY GARY FENICAL

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

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

WHAT IS EMI?

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

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

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

THE PROBLEMS

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

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

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

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

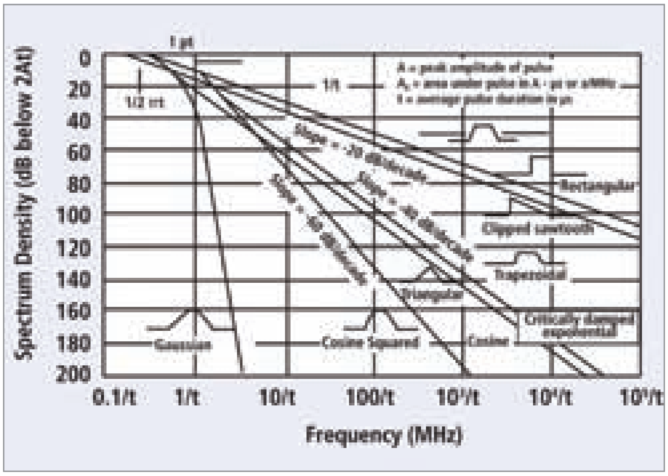


Figure 1: This chart compares the EMI characteristics of analog, low speed digital, and high speed digital logic.

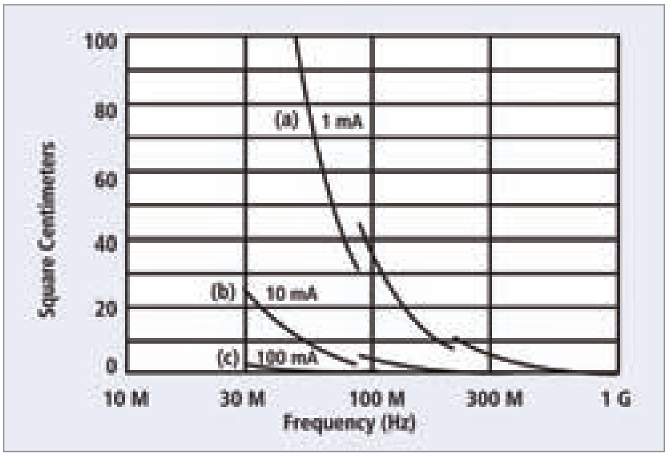


Figure 2: This chart correlates maximum loop area in square centimeters and the FCC Part 15B(B) limit for radiated RF at 1 mA (a), 10 mA (b), and 100 mA (c) of current. The measurement distance is 3 meters.

SOME SIMPLIFIED MATH

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

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

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

Where:

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

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

$$V_i = 2\pi\varepsilon AB_{pb}/\lambda S$$

Where:

V_i = volts induced into the loop

ε = field strength of incident wave in V/m

A = circuit capture area in square meters

B_{pb} = passband bandwidth response

λ = wavelength in meters of incident wave

S = shielding effectiveness ratio

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

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

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

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

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

SHIELDING

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

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

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

- Conductivity
- Permeability
- Thickness

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

- Conductivity
- Permeability

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

- "Apertures" - holes or slots in the enclosure.
- The mechanical characteristics and effectiveness of the gaskets used on the enclosure.

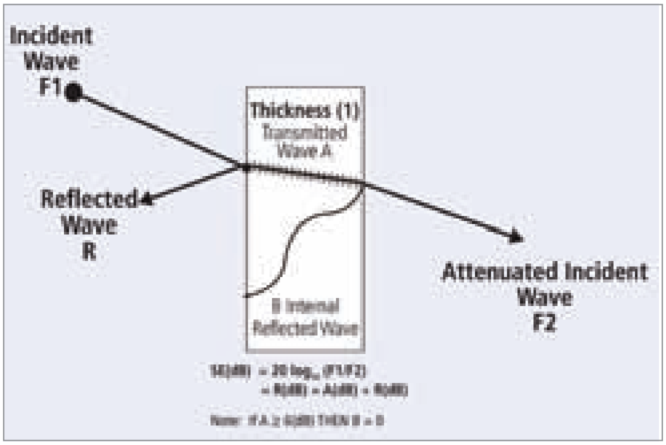


Figure 3: Graphical representation of shielding

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

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

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

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

APERTURES

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

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

Where:

λ = Wavelength

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

L = Longest dimension of the aperture

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

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

RF GASKETS

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

Below is a comprehensive list of selection factors.

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

Metal RF Gaskets (Fingerstock) and Spring Contacts

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

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

Wire Mesh and Knitted Gaskets

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

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

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

Oriented Wire

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

Fabric-over-Foam (FoF)

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

Electrically Conductive Elastomers

Conductive elastomers are ideal for applications requiring both environmental sealing and EMI shielding. They provide shielding effectiveness up to 120dB at 10GHz with a wide choice of profiles to fit a large range of applications.

EMC

Conductive fillers include, but are not limited to:

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

Form-in-Place (FiP)

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

Board-Level Shielding (BLS)

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

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

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

Combination Shielding Products

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

CONCLUSION

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

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

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

REFERENCES

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

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

Using Ferrites to Suppress EMI

BY CAROLE U. PARKER

In our ideal world, safety, quality and performance are paramount. However, the cost of the final component (which includes the ferrite) has in many cases, become the deciding factor. This article is written as an aide for the design engineer looking for alternative ferrite materials as a means to reduce cost.

FERRITE APPLICATIONS

The following are three major applications for soft ferrite:

1. Low Signal Level
2. Power
3. EMI

The required intrinsic material characteristics and core geometry are dictated by each specific application. The intrinsic characteristics controlling the performance of low signal level applications are permeability (particularly with temperature), low core loss, and good magnetic stability with time and temperature. Applications include high Q inductors, common mode inductors, wideband, matching and pulse transformers, antenna elements for radios and both active and passive transponders. For power applications the desirable characteristics are high flux density and low losses at the operating frequency and temperature. Applications include switchmode power supplies, magnetic amplifiers, dc-dc converters, power filters, ignition coils, and transformers for battery charging of electrical vehicles.

The intrinsic characteristic that most influences the performance of soft ferrite in suppression applications, is the complex permeability,[1] which is directly proportional to the core's impedance. There are three ways to use ferrites as suppressors of unwanted signals, conducted or radiated. The first, and least common, is as actual shields where ferrite is used to isolate a conductor, component or circuit, from an environment of radiated stray electromagnetic fields. In the second application, the ferrite is used with a capacitive element to create a low pass filter that is inductance - capacitance at low frequencies and dissipative at higher frequencies. The third, and most common use, is when the ferrite cores are used alone on component leads or in board level circuitry. In this application the ferrite core prevents any parasitic oscillations and/or attenuates unwanted signal pickup or transmission that might travel along component leads or interconnected wires, traces, or cables. In both the second and third application the ferrite core suppresses the conducted EMI by eliminating or greatly reducing the high frequency currents emanating from the EMI source. The introduction of the ferrite provides a sufficiently high frequency impedance that results in the suppression of the high frequency currents. Theoretically, the ideal ferrite would provide a high impedance at the EMI frequencies, and zero impedance at all other frequencies. In reality, ferrite suppresser cores provide a frequency dependent impedance. Low at frequencies below 1 MHz, and depending upon the ferrite material the maximum impedance can be obtained between 10 MHz to 500 MHz.

[1] See Glossary starting on page 99 for definition of other permeability terms

COMPLEX PERMEABILITY

As is consistent with electrical engineering principles in which alternating voltages and currents are denoted by complex parameters, so the permeability of a material can be represented as a complex parameter consisting of a real and an imaginary part. This is evidenced at high frequencies where the permeability separates into two components. The real component (μ') represents the reactive portion, and is in phase[2] with the alternating magnetic field, whereas the imaginary component (μ") represents the losses, and is out of phase with the alternating magnetic field. These may be expressed as series components (μ_s' μ_s") or parallel components (μ_p' μ_p"). The graphs in Figures 1, 2 and 3 show the series components of the complex initial permeability as a function of frequency for three ferrite materials. Material type 73 is a manganese zinc ferrite with an initial permeability of 2500. Material type 43 is a nickel zinc ferrite with an initial permeability of 850. Material type 61 is a nickel-zinc ferrite with an initial permeability of 125.

Concentrating on Figure 3, the series components of 61 type material, we see that the real part of the permeability, μ_s', remains constant with increasing frequency until a critical frequency is reached and then decreases rapidly. The losses, or μ_s", rise, then peak as, μ_s' falls. This decrease in μ_s' is due to the onset of ferrimagnetic resonance[3]. It should be noted that the higher the permeability, the lower the frequency at which this occurs. This inverse relationship was first observed by Snoek and given the following formula:

$$f_{res} = \frac{\gamma M_{sat}}{3\pi (\mu_i - 1)} \text{ Hz} \qquad \text{eq. (1)}$$

[2] In phase is when the maxima and minima of the magnetic field, H, and those of the introduction B, coincide. Out of phase is when the maima and minimum is displaced by 90°

[3] Ferromagnetic Resonance is also called spin precession resonance

where:

f_{res} = frequency at which μ_s" is maximum

γ = gyromagnetic ratio = 0.22 x 10^6 A^{-1} m

μ_i = initial permeability

M_{sat} = 250-350 Am^{-1}

This same equation can be approximated by:

$$f_{res} = B_{sat}/\mu_i \text{ MHz} \qquad \text{eq. (2)}$$

Since ferrite cores used in low signal level and power applications are concerned with magnetic parameters below this frequency, rarely does the ferrite manufacturer publish data for permeability and/or losses at higher frequencies. However, higher frequency data is essential when specifying ferrite cores used in the suppression of EMI.

RELATIONSHIP BETWEEN COMPLEX PERMEABILITY AND IMPEDANCE

The characteristic that is specified by most ferrite manufacturers for components used in EMI suppression is the impedance. The impedance is easily measured on readily available commercial analyzers with direct digital readouts. Unfortunately, the impedance is usually specified at particular frequencies and is the scalar quantity representing the magnitude of the complex impedance vector. Although this information is valuable, it is often not sufficient, especially when modeling the ferrite's circuit performance. In order to accomplish this, the impedance value and phase angle for the components, or the complex permeability for the specific material must be available.

But even before beginning to model the performance of a ferrite component in a circuit, the designer should know the following:

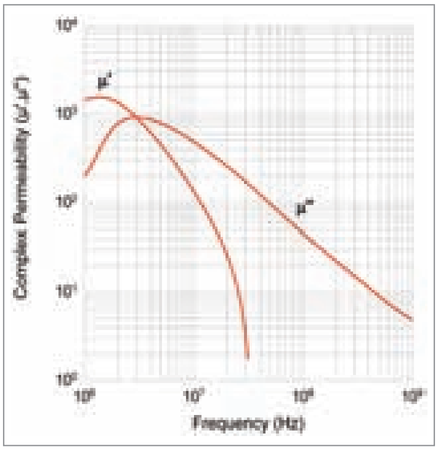


Figure 1

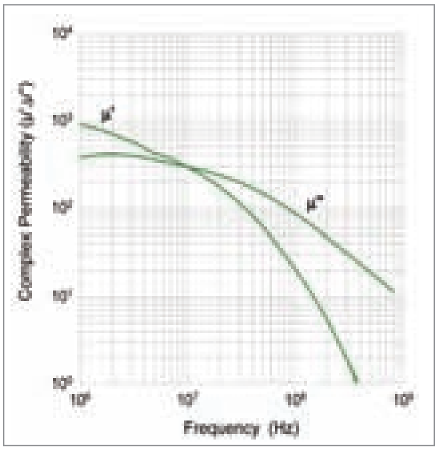


Figure 2

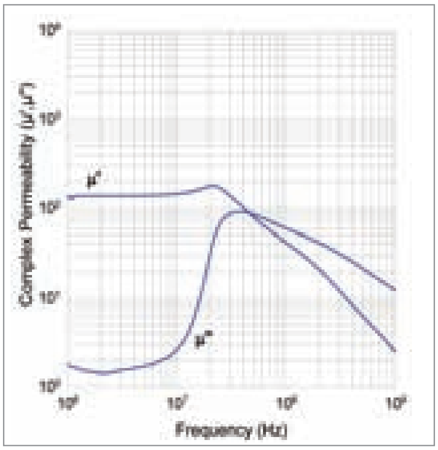


Figure 3

1. The frequency of unwanted signals.
2. The source of the EMI (radiated/conducted).
3. Operating conditions (environment).
4. If high resistivity is required because of multiple turns, conductor pins in a connector filter plate or position in the circuit.
5. The circuit impedance, source and load.
6. How much attenuation is required.
7. The allowable space on the board.

The design engineer can then compare materials at the relevant frequencies for the complex permeability, heeding effects of temperature and field strength. After this, core geometry can be selected, from which the inductive reactance and series resistance can be defined.

The Equations

The impedance of a ferrite core in terms of permeability is given by:

$Z = j\omega\mu L_o$ eq. (3)

and

$\mu = \mu' - j\mu'' = (\mu_s'^2 + (j\mu''_s)^2)^{1/2}$ eq. (4)

where

μ'= real part of the complex permeability

μ''= imaginary part of the complex permeability

j = unit imaginary vector

L_o= the air core inductance

therefore

$Z = j\omega L_o (\mu' - j\mu'')$ eq. (5)

The impedance of the core is also considered to be a series combination of inductive reactance (X_L) and the loss resistance (R_s), both of which are frequency dependent. A loss free core would have an impedance that would be given by the reactance:

$X = j\omega L_s$ eq. (6)

A core that has magnetic losses may be represented as having an impedance:

$Z = R_s + j\omega L_s$ eq.(7)

where:

R_s = total series resistance $= R_m + R_e$

R_m = Equivalent series resistance due to the magnetic losses

R_e = equivalent series resistance for copper losses

At low frequencies the impedance of the component is primarily the inductive reactance. As frequency increases, the inductance decreases at the same time the losses increase and the total impedance increases. Figure 4 is a typical curve of X_L, R_s and Z vs. frequency for our a medium permeability material.

Knowing that the magnetic quality factor

$Q = \mu'/\mu'' = \omega L_s/R_s$ eq. (8)

then the inductive reactance is made directly proportional to the real part of the complex permeability by L_o, the air core inductance:

$j\omega L_s = j\,\omega L_o \mu_s'$

The loss resistance is also made directly proportional to the imaginary part of the complex permeability by the same constant:

$R_s = \omega L_o \mu_s''$

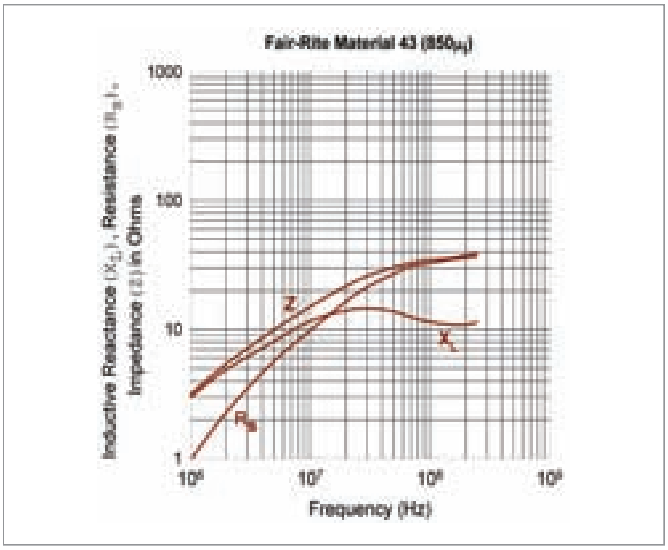


Figure 4

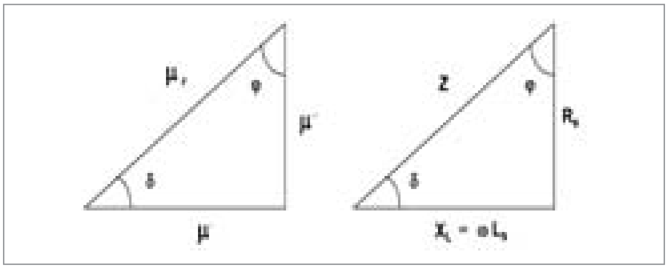


Figure 5

Substituting into equation (7) for impedance:

$$Z = \omega L_o \mu_s'' + j\omega L_o \mu_s'$$

and factoring:

$$Z = j\omega L_o (\mu_s' - j\mu_s'') \qquad \text{eq. (9)}$$

In equation 9, the core material is given by μ_s' and μ_s'', and the core geometry is given by L_o. Thus, knowing the complex permeability for different ferrites a comparison can be made to obtain the most suitable material at the desired frequency or frequency range. After the optimum material is chosen, the best size component can be selected. The vector representation for both the complex permeability and impedance is found in Figure 5.

If the manufacturer supplies graphs of complex permeability vs frequency for the ferrite materials recommended for suppression applications, then a comparison of core shapes and core materials for optimizing impedance is straight forward. Unfortunately this information is rarely made available. However, most manufacturers supply curves of initial permeability and losses vs. frequency. From this data a comparison of materials for optimizing core impedance can be obtained.

Material Selection

Example

Referring to Figure 6, Initial Permeability & Loss Factor[4] vs. Frequency for Fair-Rite 73 material, supposing a designer wants to guarantee maximum impedance between 100 and 900 kHz. 73 material is chosen. For purposes of modeling, the designer also needs to know the reactive and resistive portions of the impedance vector at 100 kHz (10^5 Hz) and 900 kHz. This information can be derived from the graphs as follows:

[4] The loss factor, which is the normalization of loss tangent per unit if permeability, is a material property describing the loss characteristics per unit of permeability.

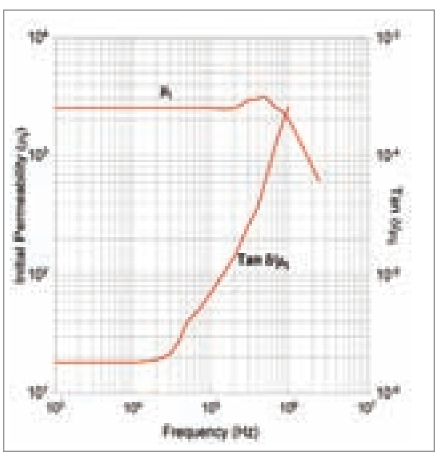


Figure 6

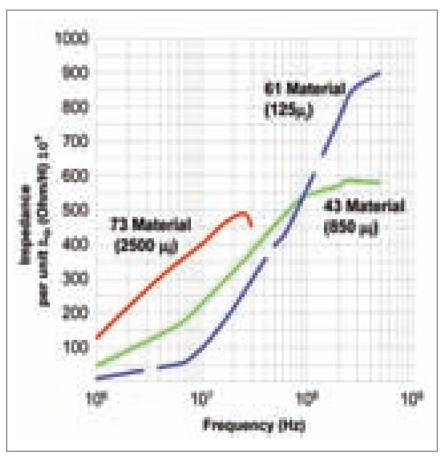


Figure 7

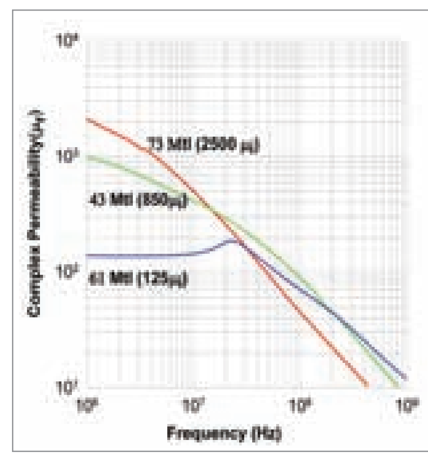


Figure 8

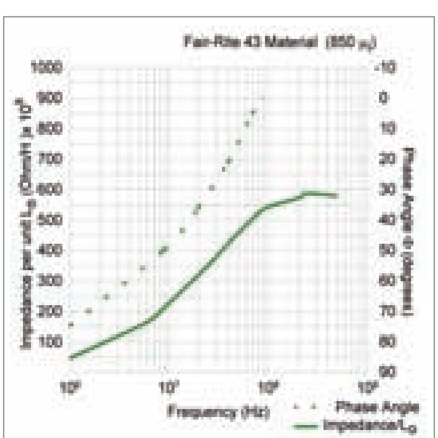


Figure 9

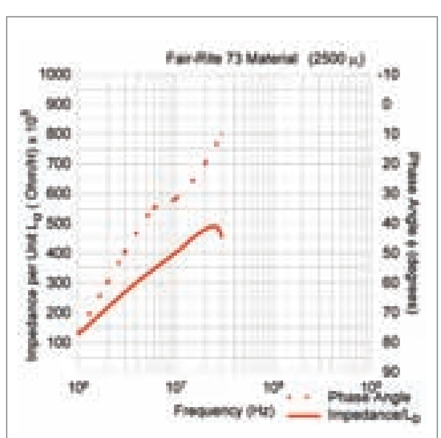


Figure 10

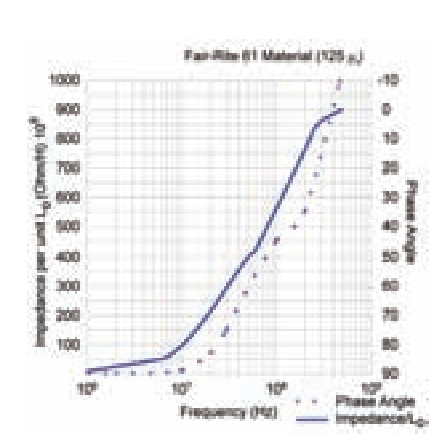


Figure 11

at 100kHz

$\mu_s' = \mu_i = 2500$ and

$(\tan \delta/\mu_i) = 7 \times 10^{-6}$ since

$\tan \delta = \mu_s''/\mu_s'$ then

$\mu_s'' = (\tan \delta/\mu_i) \times (\mu_i)^2 = 43.8$

Calculating for the complex permeability:

$\mu = \mu' - j\mu'' = (\mu_s'^2 + (j\mu_s'')^2)^{1/2} = 2500.38$

It should be noted that, as expected μ" adds very little to the total permeability vector at this low frequency. The impedance of the core is primarily inductive.

However at 900 kHz μ_s'' has become a significant contributor

$\mu_s' = 2100$, $\mu_s'' = 1014$ $\mu = 2332$

Core Selection

The designer knows that the core must accept a #22 wire, and fit into a space of 10 mm by 5 mm. The inside diameter will be specified as .8 mm. Solving for the estimated impedance and its components, first a bead with an outside diameter of 10 mm and a height of 5mm is chosen:

at 100 kHz

since $Z = \omega L_o \mu$ and Toroidal $L_o =$

$.0461 N^2 \log_{10} (OD/ID) Ht 10^{-8}$ (H)

then

$Z = \omega L_o (2500.38) = (6.28 \times 10^5) \times .0461 \times \log_{10} (10/.8) \times 5 \times (2500.38) \times 10^{-8} = 3.97$ ohms

where

$R_s = Lo\, \omega\, \mu_s'' = .069$ ohms

$X_L = Lo\, \omega \mu_s' = 3.97$ ohms

at 900 kHz

Z = 33.3 ohms, R_s =14.48 ohms,
X_L =30.0 ohms

Then a bead with an outside diameter of 5 mm and a length of 10 mm is selected:

at 100 kHz

$Z = \omega L_o (2500.38) = (6.28 \times 105) \times .0461 \times \log_{10} (5/.8) \times 10 \times (2500.38) \times 10^{-8} = 5.76$ ohms

where

$R_s = L_o\, \omega\, \mu_s'' = .100$ ohms

$X_L = L_o\, \omega\, \mu_s' = 5.76$ ohms

at 900 kHz

Z= 48.1 ohms, R_s = 20.9 ohms, X_L = 43.3 ohms

In this instance, as in most, maximum impedance is achieved by using a smaller OD with the longer length. If the ID were larger, for instance 4 mm, the reverse whould have been true.

This same approach can be used if graphs of Impedance per unit L_o and phase angle vs. frequency are supplied. Figures 9, 10 and 11 are representative of such curves for the same three materials used throughout this article.

Example

The designer wants to guarantee maximum impedance for the frequency range of 25 MHz to 100 MHz. The available board space is again 10mm by 5mm and the core must accept a #22 awg wire. Referring to Figure 7 Impedance per unit L_o for three ferrite materials, or Figure 8, complex permeability for the same three materials, an 850 μ_i material is chosen[5]. Using the graph of Figure 9, Z/L_o for the medium permeability material , at 25 MHz, is 350×10^8 ohm/H. Solving for the estimated impedance:

$Z = 350\ 10^8 \times .0461 \times \log_{10} (5/.8) \times 10 \times 10^{-8}$

Z=128.4 ohm Φ = 30 degrees
$X_L = Z \sin \Phi = 126.8$ ohms
$R_s = Z \cos \Phi = 19.81$ ohms

and at 100 MHz:
Z= 179.8 ohms Φ= 0
X_L= 0 ohms R_s= 179.8 ohms

The same approach may be used for different materials, dimensions, and frequencies.

The previous discussion assumed that the core of choice was cylindrical. If the ferrite core being used is for flat ribbon, or bundled cable, or a multi-hole plate, the calculation for the L_o becomes more difficult, and fairly accurate figures for the cores path length and effective area must be obtained in order to calculate the air core inductance. This can be done by mathematically sectioning the core and summing the calculated path length and magnetic area for each section. In all cases though, an increase, or decrease in impedance will be directly proportional to an increase or decrease in the height/length of the ferrite core.[6]

[5] It should be noted that the impedance for each ferrite material is optimum over a specific frequency range. As a rule of thumb, the higher the permeability, the lower the frequency range.

[6] This remains true so long as the increase in height/length does not cause the core to be in dimensional resonance.

RELATIONSHIP BETWEEN IMPEDANCE AND ATTENUATION

As stated most manufacturers are specifying cores for EMI applications in terms of impedance, but often the end user needs to know the attenuation. The relationship that exists between these two parameters is:

Attenuation = $20 \log_{10} ((Z_s + Z_{sc} + Z_L) / (Z_s + Z_L))$ dB

where

Z_s = Source impedance
Z_{sc} = Suppressor core impedance
Z_L = Load impedance

The relationship is dependent on the impedance of the source generating the noise and the impedance of the load receiving it. These values are usually complex numbers that can be infinite in scope and not easily obtained by the designer. Selecting a value of one ohm for both the load and the source impedance, as may be the case when the source is a switch mode power supply and the load many low impedance circuits, simplifies the equation and allows comparison of ferrite cores in terms of attenuation.

Under these conditions, the equation reduces to:

Attenuation = $20 \log_{10} (Z_{sc}/2)$ dB

The graph in Figure 12 is a family of curves that show the relationship between the shield bead impedance and the attenuation for a number of commonly used values of the load plus the generator impedance.

Figure 13 is the equivalent circuit of an interference source with an internal impedance of Z_s, generating an interference signal through the series impedance of the suppressor core Z_{sc} and the load impedance Z_L.

THE ENVIRONMENT

Temperature

As stated, ferrite's magnetic parameters can be effected by temperature and field strengths.

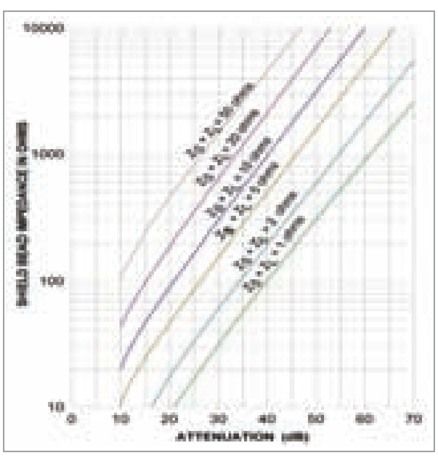


Figure 12

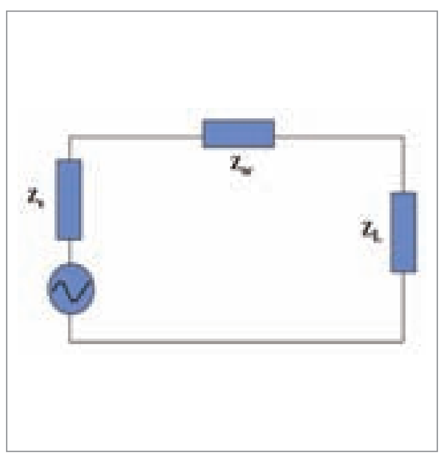


Figure 13

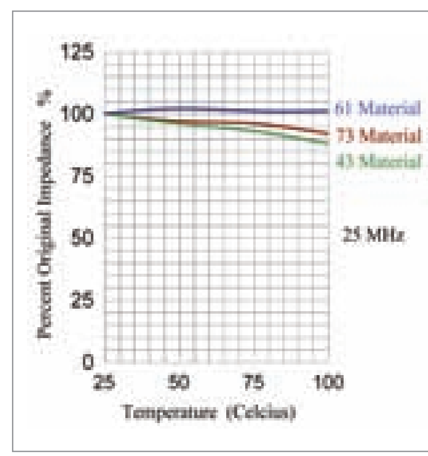


Figure 14

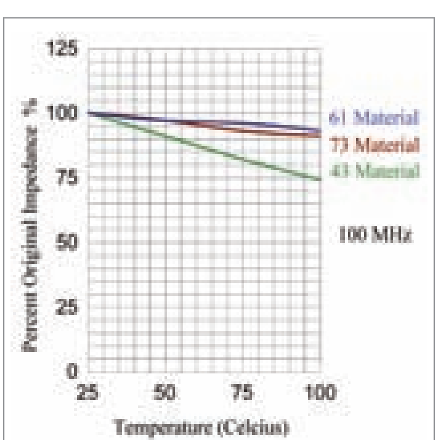


Figure 15

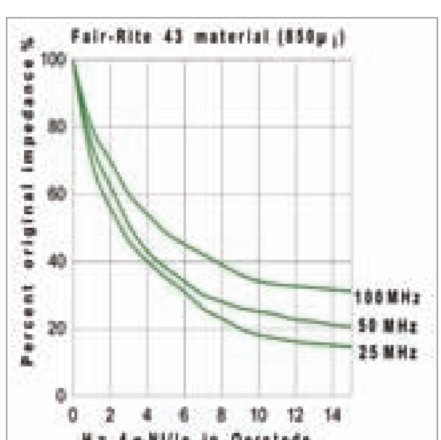


Figure 16

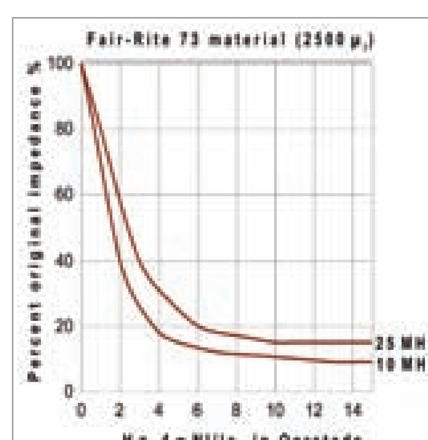


Figure 17

Figures 14 and 15 are graphs of impedance vs. temperature for the same three ferrite materials. The most stable of these materials is the 61 material, with a decrease in impedance of 8% at 100º C and 100 MHz. This is compared to a 25% drop in impedance for the 43 material at the same frequency and temperature. These curves, when supplied, may be used to adjust the specified room temperature impedance if desired attenuation is to be at elevated temperatures.

Field Strength

As in the case of temperature, dc and 50 or 60 Hz power current will also effect the same intrinsic ferrite characteristics which in turn with result in lowering of the impedance of the core. Figures 16, 17 and 18 are typical of curves that illustrate the effect of biases on impedance a ferrite material. The curve depicts the degradation of impedance as a function of field strength for a specific material as a function of frequency. It should be noted that as frequency increases the effect of biases diminishes.

NEW MATERIALS

Since the compilation of this data, Fair-Rite Products has introduced two new materials. Our 44 which is a nickel zinc, medium permeability material and our 31 which is a manganese zinc high permeability material.

Figure 19 is a plot of impedance vs. frequency for the same size bead in 31, 73, 44 and 43 materials. 44 material is an improved 43 material with higher dc resistivity, 109 ohm cm, better thermal shock characteristics, temperature stability and higher curie temperature (T_c). When compared to our 43 material, 44 material has slightly higher impedance vs. frequency characteristics. Still material 31 exhibits higher impedance than either 43 or 44 throughout the measured frequency range. Designed to alleviate the problem of dimensional resonance that effects low frequency suppression performance of the larger manganese-zinc cores, 31 has found successful applications as cable connector suppressor cores and large toroidal cores. Figures 20 is a curve of impedance vs frequency for 43, 31, and 73 material for a Fair-Rite core with an OD of .562", ID of .250 and a HT of 1.125. When comparing Figure 19 to Figure 20 it should be noted that for the smaller core in Figure 19, for frequencies up to 25 MHz, 73 material is the optimum suppression material. However as the core cross section increases, the maximum frequency decreases . As can be shown by the data in Figure 20 where the highest frequency where 73 is optimum is 8 MHz. Also noteworthy is that 31 material is superior from 8 MHz to 300 MHz. However, being a manganese zinc ferrite, 31 material has a much lower volume resisitivity of 102 ohm-cm and exhibits greater changes in impedance with extreme temperature variation.

GLOSSARY

Air Core Inductance - L_o (H)
The inductance that would be measured if the core had unity permeability and the flux distribution remained unaltered.
General formula $L_o = \frac{4\pi N^2 10^{-9}}{C^1}$ (H)

Toroidal $L_o = .0461 N^2 \log^{10} (OD/ID)\, Ht\, 10^{-8}$ (H)

Dimensions in mm's

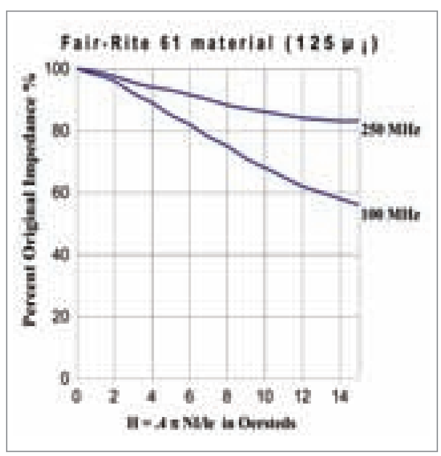


Figure 18

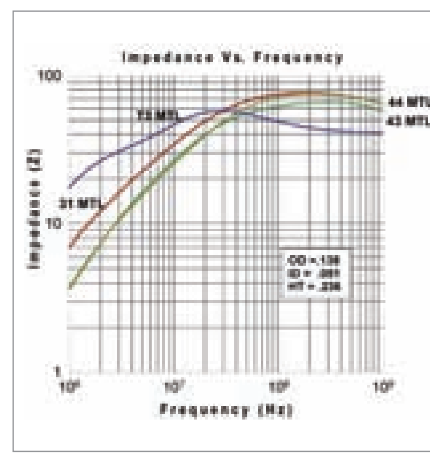


Figure 19

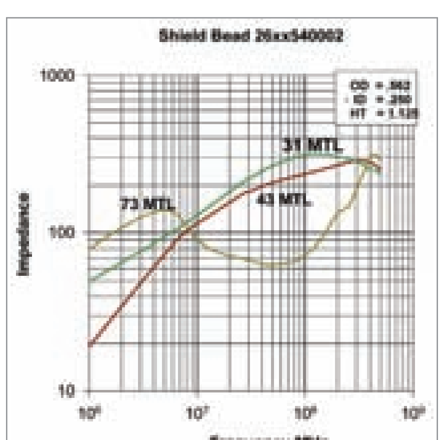


Figure 20

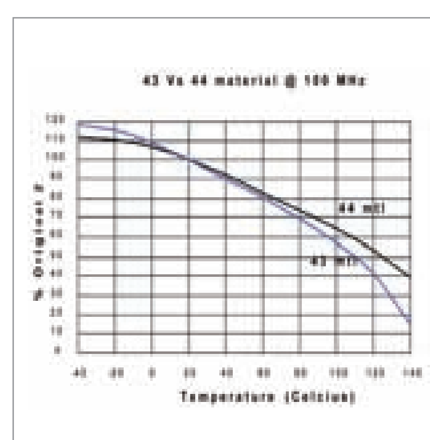


Figure 21

Attenuation - A (dB)
The decrease in signal magnitude in transmission from one point to another. It is a scalar ratio of the input magnitude to the output magnitude in decibels.

Core Constant - C^1 (cm^{-1})
The summation of the magnetic path lengths of each section of a magnetic circuit divided by the corresponding magnetic area of the same section.

Core Constant - C^2 (cm^{-3})
The summation of the magnetic path lengths of each section of a magnetic circuit divided by the square of the corresponding magnetic area of the same section.

Effective Dimensions of a Magnetic Circuit
Area Ae (cm^2), Path Length le (cm) and Volume Ve (cm^3)
For a magnetic core of given geometry, the magnetic path length, the cross-sectional area and the volume that a hypothetical toroidal core of the same material properties should possess to be the magnetic equivalent to the given core.

Field Strength - H (oersted)
The parameter characterizing the amplitude of the field strength.
$H = .4 \pi NI/le$ (oersted)

Flux Density - B (gauss)
The corresponding parameter for the induced magnetic field in a area perpendicular to the flux path.

Impedance - Z (ohm)
The impedance of a ferrite may be expressed in terms of its complex permeability.
$Z = j\omega L_s + R_s = j\omega L_o(\mu s' - j\mu_s'')$ (ohm)

Loss Tangent - tan δ
The loss tangent of the ferrite is equal to the reciprocal of the Q of the circuit.

Loss Factor - tan δ/μi
The phase displacement between the fundamental components of the flux density and the field strength divided by the initial permeability.

Phase Angle - Φ
The phase shift between the applied voltage and current in a inductive device.

Permeability - μ
The permeability obtained from the ratio of the flux density and the applied alternating field strength is.....

Amplitude Permeability, μa - when stated values of flux density, are greater than that used for initial permeability.

Effective Permeability, μe - when a magnetic circuit is constructed with an airgap or airgaps, and then the permeability is that of a hypothetical homogeneous material which would provide the same reluctance.

Incremental Permeability, μΔ - when a static field is superimposed.

Initial Permeability, μi - when the flux density is kept below10 gauss.

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EMI Shielding Thermoplastic Compounds

Dramatic Cost Reductions for Electronic Device Protection

BY NEIL HARDWICK

OVERVIEW OF EMI SHIELDING COMPOUNDS

Electromagnetic radiation that adversely affects device performance is generally termed EMI (**E**lectro**M**agnetic **I**nterference). Interference takes many forms such as distortion on a television, disrupted/lost data on a computer, or "crackling" on a radio broadcast. Many electronic devices not only emit electromagnetic fields which might cause interference in other systems, but they are also susceptible to stray external fields which could affect its performance. As a result, they must be shielded to ensure proper performance.

Currently, the FCC regulates EMI emission between 30 MHz and 2 GHz, but does not specify immunity to external interference. As device operating frequencies increase (applications over 10 GHz are becoming common), their wavelengths decrease proportionally, meaning that EMI can escape/enter very small openings (for example, at a frequency of 1 GHz, an opening must be less than 1/2").

The trend toward higher operating frequencies therefore is helping drive the need for more EMI shielding. As a reference point, computer processors operate in excess of 250 MHz and some newer portable phones operate at 900 MHz. Additional EMI background information is provided in an ***EMI Primer*** at the end of this article.

Shielding is the use of conductive materials to reduce EMI by reflection or absorption. Shielding electronic products successfully from EMI is a complex problem with three essential ingredients: a source of interference, a receptor of interference, and a path connecting the source to the receptor. If any of these three ingredients is missing, an interference problem cannot exist.

Traditional EMI Shielding

Metals (due to their inherent conductivity) traditionally have been the material of choice for EMI shielding. While effective in terms of shielding, metals can be heavy and bulky solutions to the design challenge of EMI. In recent years, there has been a tremendous surge in plastic resins (with conductive coatings or fibers) replacing metals due to the manufacturing flexibility, durability and weight reduction of plastic components. Even though plastics are inherently transparent to electromagnetic radiation, advances in conductive coatings, conductive fibers and compounding techniques have allowed design engineers to take advantage of the merits of plastics while enhancing EMI shielding effectiveness.

Advantages of Thermoplastics vs. Metals

In general, Thermoplastics deliver significant advantages over Metals. As related to EMI shielding, these include:

- Weight reduction – important in portable systems
- Design freedom – allows complex contours, part consolidation, and fastening options
- Cost effective – suitable for higher volumes (needed to offset tooling investment) and reduces assembly costs.

- Good physical properties – Inherently corrosion resistant and durability as well as high strength to weight ratio.

COMPETITIVE OPTIONS FOR EMI SHIELDING WITH THERMOPLASTICS

There are many alternative approaches for EMI shielding with thermoplastics. For purposes of this article, only the most popular approaches will be highlighted. A Business Communications Company industry report estimated that the plastics shielding sector will account for 37% ($156 million) of the total United States EMI shielding market ($422 million). The European market is substantially larger (due to more stringent agency standards) and the Asian market is even bigger due to the sheer volume of electronic systems assembled in that region.

EMI Shielding Compounds (Plastics filled with Conductive Fibers)

Over the past few years, EMI Shielding Compounds have arrived on the market by incorporating EMI shielding fiber technology (both Stainless Steel and Nickel Coated Graphite) into thermoplastic compounds. As the plastic resin is insulative, these conductive fibers (with a high aspect ratio) create a conductive network within the resin. Performance of conductive fiber filled compounds is maximized by utilizing special long fiber manufacturing techniques and cube (dry) blending metal fiber bundles in order to minimize conductive fiber damage.

Fiber properties are summarized in Table 1 for the most common fiber fillers for EMI shielding compounds:

Foils and Conductive Fabrics

A metal foil or conductive fabric applied to plastic is labor intensive and ideal only for low volume and simple geometry designs. Without higher volumes (justify tooling investment) or cost minimization objectives, these applications would not be appropriate for EMI Shielding Compounds.

On-Board Shielding

Using a *simple* metallic inner shield to isolate EMI at the most basic level (Printed Circuit Board, or "On-Board" Shielding) may reduce the requirements for shielding enclosures. EMI Shielding Compounds may be more appropriate than on-board shielding when weight savings, secondary operation reduction, and/or design complexity are desirable attributes.

Plastics with a Conductive Coating

Within Conductive Coatings, there are three significant coating technologies (vacuum metallization, electroless plating, and conductive paints). For the purposes of this article, these three coating technologies will not be compared versus each other. Rather, this article will help the reader become familiar with the competitive processes, advantages and disadvantages, and opportunities for EMI Shielding Compounds.

The three major coating processes are briefly discussed below. Conductive paints are the most common method of applying a conductive surface coating to plastics, but vacuum metallization is gaining ground due to its high quality control. An example of process costs is discussed in a section below.

Vacuum Metallization

- Multiple stage process that deposits a layer of aluminum on plastic in the absence of air.
- Size limitations due to vacuum chamber

Electroless Plating

- Multiple stage chemical process deposits a thin layer of copper (high conductivity and SE) and overplates it with nickel (corrosion inhibition and a good surface for painting).
- Not all plastics can be plated
- Offers best shielding of coatings

	Stainless Steel	Ni-Coated Graphite
Cost	Less than NCG	More than Stainless Steel
Fiber Loading	Typically 0.75% - 1.50% vol. Typically 6% - 12% wt.	Typically 6% - 15% wt.
Physical Properties	Minimal effect on compound. Reduced impact strength.	Improved over base resin. Reduced impact strength.
Dimensional Stability	Little effect	Some shrinkage due to reinforcement
Fiber	Ductile	Rigid

Table 1

Conductive Paints

- Contain particles of silver, copper, or nickel dispersed in an acrylic, vinyl, epoxy, or urethane binder. For general shielding, nickel/acrylic paints have captured major share of market.
- Automated spraying systems apply the coating with a high degree of consistency and repeatability
- Market for paints is highly competitive and two major suppliers of conductive paints offer good technical support services
- Most plastics can be painted (PPO and Nylon do not coat well)

Comparing the Plastic Shielding Alternatives

The advantages and disadvantages EMI Shielding Compounds and Conductive Coatings are summarized in Table 2.

While it is rather easy to compare the advantages and disadvantages, it is difficult to compare the shielding capabilities as EMI Shielding Compounds shield primarily by a different mechanism (absorption) than Conductive Coatings (reflection).

The coating industry (where electrical conductivity is a surface property) utilizes surface resistivity as a mechanism to denote shielding capability; however, for absorption shielding (where electrical conductivity is mostly within part walls), there is little correlation between surface resistivity and shielding capability. In EMI Shielding Compounds, there is good correlation between volume resistivity (10^0 – 10^{-3} ohm-cm thought to provide effective shielding) and shielding effectiveness.

Laboratory evaluation of shielding material samples (via ASTM D4935) can provide a measurement of shielding effectiveness, but determining the actual shielding effectiveness of a product requires testing of the finished assembly.

During production, coaters test the surface resistivity of parts. While this step eliminates non-conductive parts, it does not identify other quality problems (scratched surfaces or poor coating adhesion and coating thickness variations).

Actual Cost Example of Conductive Coatings

Much has been publicly stated about the “high” costs of EMI Shielding Compounds. This myth may be attributed to trying to compare $/pound compound costs with $/piece shielding

	EMI Shielding Compounds	Conductive Coatings
Durability	Integral property within protective plastic	• Can flake or scratch off during handling, shipping and assembly. • Scratching the coating may create slot antenna (shield failure and EMI leakage). • May delaminate during thermal cycling and other adhesion problems.
Consistency	Uniform EMI/RFI shielding throughout the part (even in sharp corners)	• Difficult to coat uniform thickness. • Difficult to measure conductive layer thickness without destructive test.
Part Design Compatibility	Easily accommodates complex designs	Simpler designs (due to line of sight process)
Lead times	Lower than Plastics with Conductive Coating	Higher than EMI Shielding Compounds.
Corrosion resistance	Integral property	Often requires protective topcoat.
Post-Mold Shielding Operations	Part shielded right out of the mold (Integral property).	• Additional shielding steps include masking and coating part with conductive • Usually requires additional supplier.
Special Handling during molding	None	Must be kept free of contaminants for coating to adhere properly.
Recyclability	Reusable and recyclable	Stripping process removes coating, but creates metallic “sludge” which must be disposed of.
Costs	See detailed example below	See detailed example below

Table 2

costs, and unsubstantiated claims made by the Conductive Coatings industry. When $/piece (not $/pound) costs are considered, EMI Shielding Compounds are less costly than Conductive Coatings.

An actual cost example is highlighted in Exhibit A.

Method of Gathering Information

1. Coaters were advised that an OEM was looking to convert a metal part to plastic. The "revised" plastic part would need to incorporate EMI shielding, which might require a conductive coating.
2. Drawing 981221-AA (see Exhibit A) was submitted to two painters, two electroless platers, and two vacuum metallizers.
3. Quotes were received from each coater. Typically, the coater included a unit cost to shield, a tooling/fixturing/masking cost, a scrap rate, and the shielding material. Some coaters quoted both part P1 and P2, while others
4. admitted that one or the other was not compatible with their process.

Assumptions

1. Does not include any molding costs
   - Molding time for EMI Shielding Compounds are the same or less than unfilled polymers due to better thermal conductivity
   - Does not include any injection molding tool or fixture costs. (Same for both.)
2. Typical 3% coating scrap rate not included (supply 103 parts to coater to make 100 "good" parts).
3. Coating costs based on "best" market price of $0.80/pound for ABS.
4. No shipping costs to/from coating supplier.
5. Quantity noted is a lifetime quantity. Not unusual, as part designs continually change when electronics are involved.

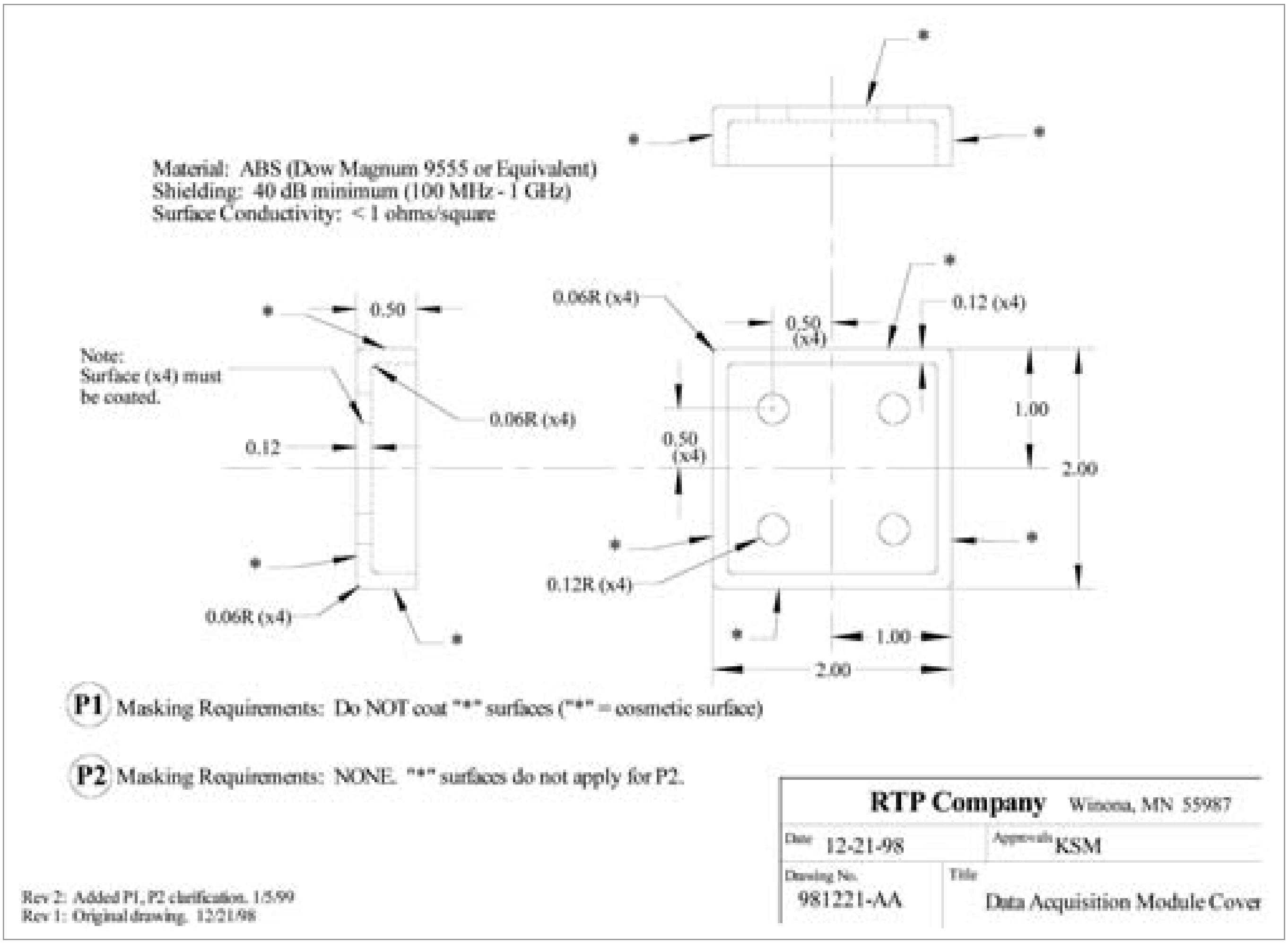

Exhibit A: Sample part drawing used to generate Conductive Coating costs.

6. Shielding effectiveness (and frequency range) is equivalent across all scenarios.

A few key insights related to the Conductive Coatings are:

- Coaters do not understand shielding. Rather, they just test ohms/square (surface resistivity) and declare the part good/bad.
- Part design and surface area to be coated are important, not plastic weight.
- Cost drivers include labor (cycle time), material usage, and batch quantity.
- No masking (coat entire part) appears cheaper for electroless plating and vacuum metallization (labor more costly than material). For painting, where material costs are significant, there is no clear cut "rule of thumb."
- EMI Shielding Compounds appear less costly than painting under both scenarios.

This example was designed to offer Conductive Coatings the most favorable conditions possible. The following items would increase Coating costs (but not affect EMI Shielding Compound costs):

- Small run quantities at coaters
- Shipping costs to/from coaters
- Special packaging requirements (avoid scratching surfaces)
- Including cost of scrap. Critical for expensive molded parts.
- Higher than $0.80/pound ABS cost
- Increasing part design complexity with deep recesses, more surface area, etc. (leading to higher coater cycle times, more conductive coating usage, and/or higher coater masking costs)
- Higher molding costs (than EMI Shielding Compounds) due to longer cycle times.

Exact cost comparisons are almost impossible to make as there are many variables and assumptions that apply. Yet, even under the most favorable conditions for Conductive Coatings, Figures 1 and 2 highlights that EMI Shielding Compounds are less costly than Coatings under both low and high volume applications.

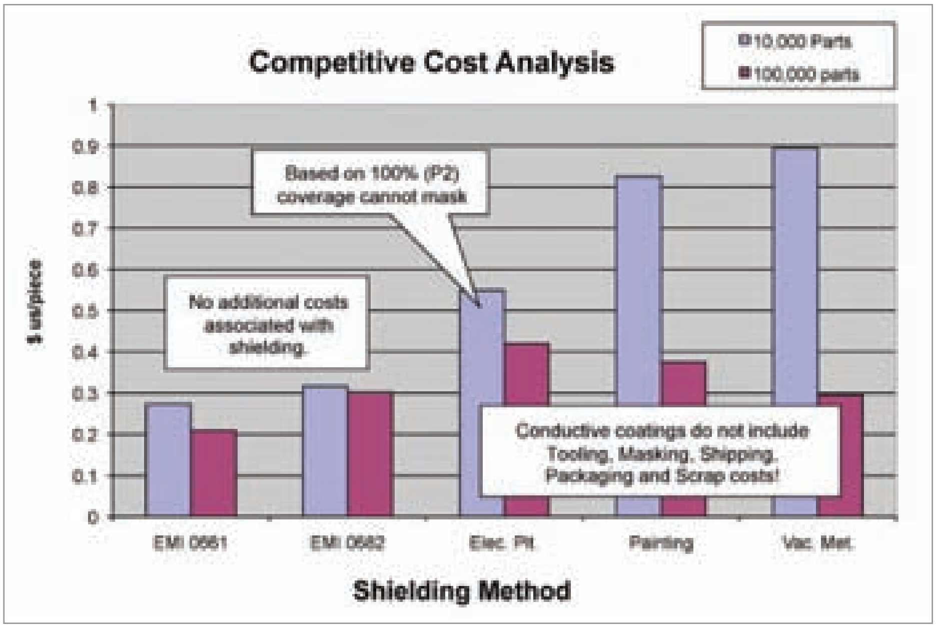

Figure 1

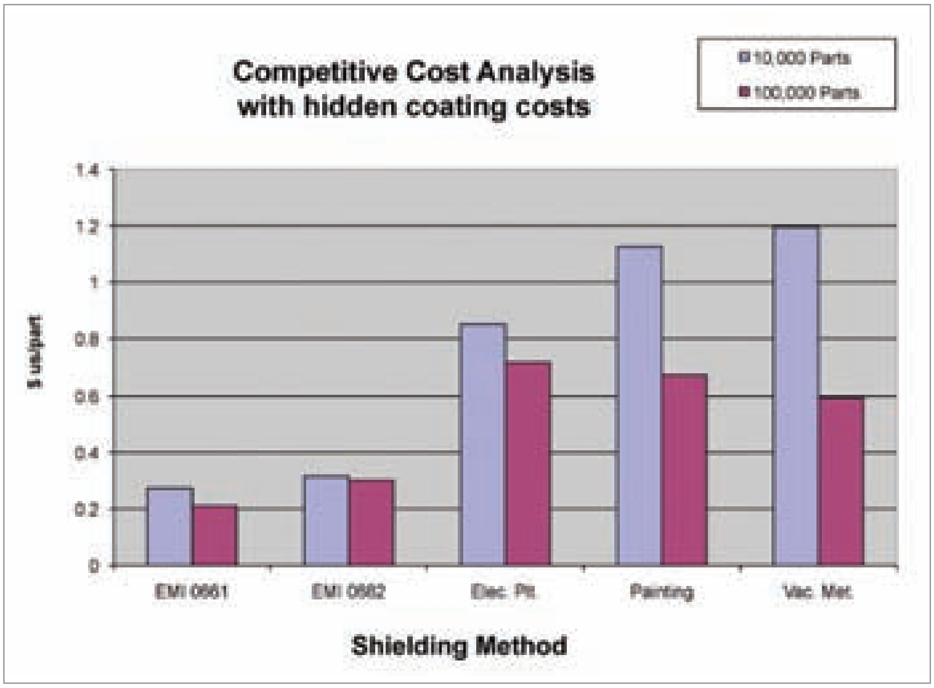

Figure 2

EMI PRIMER

What is EMI?

Electromagnetic radiation that adversely affects device performance is generally termed EMI (electromagnetic interference). Many electronic devices not only emit electromagnetic fields which might cause interference in other systems, but they are also susceptible to stray external fields which could affect its performance. As a result, they must be shielded to ensure proper performance.

An electronic device exhibits EMC (electromagnetic compatibility) if it operates effectively in its designated environment without unacceptable interference to other devices.

What does EMI consist of?

Electromagnetic waves consist of both an E (electric) field and an H (magnetic) field oscillating at right angles to each other. The ratio of E to H is called the wave impedance (measured in ohms). A device operating at high voltage, with only a small amount of current flow, generates waves with high impedance. These are considered E fields. Conversely, if a device contains a large current flow compared to its voltage, it generates a low impedance, H field.

The importance of wave impedance is shown by an EMI wave encountering an obstacle such as a metal shield. If the impedance of the wave differs greatly from the natural impedance of the shield, much of the energy is reflected and the rest is transmitted across the surface boundary where absorption in the shield further attenuates it.

EMI emissions from most electronic devices are typically high frequency, high impedance. The major wave component is the E field. Metals are intrinsically low impedance because of their high conductivity. Thus, the high impedance E wave energy is mostly reflected from metal shields. Low impedance waves (H field dominant) are mostly absorbed in a metal shield because they are more closely matched to the metal's inherent impedance. For maximum H-field absorption, shields need to have high magnetic permeability (ability of material to serve as path for magnetic energy).

In general, the intensity of the interference caused by the signal diminishes with increasing distance from its source.

What is EMI shielding?

Shielding is the use of conductive materials to reduce EMI by reflection and/or absorption. Shielding can be applied to different areas of the electronic system from equipment enclosures to individual devices (such as circuit boards).

Effective placement of shielding (barrier between a susceptible system and an external source of electromagnetic radiation) causes an abrupt discontinuity in the path of electromagnetic waves. At high frequencies, most of the wave energy is reflected from a shield's surface, while a smaller portion is absorbed. At lower frequencies, absorption generally predominates.

Shielding performance is a function of the properties and configuration of the shielding material (conductivity, permeability and thickness), the frequency, and distance from the source to the shield.

What does Grounding have to do with EMI shielding?

Conductive components are grounded to protect equipment users from electric shock. If a system is properly grounded, all conductive elements are theoretically at zero potential.

Shielding against EMI emissions is commonly provided by a conductive enclosure. The separate parts of the enclosure must be electrically bonded together and grounded for the shielding to work. Ineffective grounding may actually increase EMI emission levels, with the ground itself becoming a major radiating source.

What is Shielding Effectiveness?

How well a shield reduces (attenuates) the energy of a radiated electromagnetic field is referred to as its shielding effectiveness (SE). The overall expression is:

shielding effectiveness =
reflection loss + absorption loss + small correction factor for back surface reflections

The standard unit of SE measurement is the decibel (dB). The decibel value is the ratio of two measurements of electromagnetic field strength taken before and after shielding is in place. Every 20 dB increase in SE represents a tenfold reduction in EMI leakage through a shield. A 60 dB shield reduces (attenuates) field strength by a factor of 1,000 times (e.g., from 5 volts per meter to 5 millivolts/meter or a 99.9% attenuation level).

Shielding requirements for commercial electronics generally range from 40 to 60 dB. Establishing a system's shielding requirements involves determining the radiated frequencies and the government specifications the unit must meet.

Among the typical applications for EMI shielding are the following:

EMI should be considered at the design phase of any system so that potential interference problems can be minimized.

Since interference problems can occur anywhere within a system, shielding consideration needs to be given to the whole assembly:

- *Printed Circuit Boards (PCB)* – Noise originates and ultimately may affect the board level (most basic) components.
- *Cables* – Signal-carrying cables can act as antennas to radiate EMI. A number of shielding products (not related to EMI Shielding Compounds) can reduce EMI cable problems.
- *Apertures* – The amount of EMI leakage through an opening is a function of the maximum dimension of the opening. A long, narrow slot will leak much more radiation than a round hole of the same area. A slot can act as an antenna if the length exceeds one half of a wavelength (problem becomes greater at higher frequencies). Conductive EMI gaskets inserted between mating surfaces preserve current continuity of the enclosure, thereby minimizing leakage.
- *Enclosures* – Typically made from metal, Conductive Coatings, or EMI Shielding Compounds. Enclosures must be penetrated at various points to allow entry of cables, provide access for repair/assembly, provide ventilation, and create windows. Without attention to the design and shielding of these features, the assembly will behave like a leaky bucket.

Where is EMI shielding needed?

Uses for EMI shielding abound in computers, medical devices, telecommunications, and other types of electronic equipment. This type of equipment contains micro-circuitry that switches at high speed. Each switching event results in a short duration electrical pulse, which has a characteristic frequency inversely proportional to its time length.
The FCC regulations define specific field strength limits between 30 MHz and 2000 MHz (2 GHz).

A Word About EMI Regulations

FCC regulations classify devices by their intended market – Class A devices include products for industrial and business environments while Class B devices are primarily intended for use in homes. FCC emission standards are more stringent for the mass-market Class B equipment than the Class A equipment.

Manufacturers of electronic products contend with three EMI issues:

- **Suppression of internally generated EMI to prevent excessive levels of radiated and/or conducted emissions**. The FCC in the United States and European Community (EC) set standards for EMI emission levels that electronic devices must meet before being sold in those countries.
- **External ambient interference with equipment operation**. Many companies set their own specifications for immunity to EMI over a range of frequencies. This is not yet a FCC requirement, however EC regulations do include immunity requirements.
- **Internally generated emissions interfering with equipment operation.** EMI from one circuit can interfere with the function of another in the same system or subsystem (cross-talk). This problem frequently occurs in equipment with high-density packaging of PCBs and is the most common source of system EMI susceptibility.

How are devices tested for EMI Compliance?

Compliance testing requires sophisticated equipment and must be performed by accredited labs.
If emission problems are found, the device will require additional shielding or redesign.

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ABOUT RTP COMPANY

RTP Company is a global compounder of custom engineered thermoplastics. The company has 11 manufacturing plants on three continents, plus sales representatives throughout the Americas, Europe, and Asia. RTP Company's engineers develop customized thermoplastic compounds in over 60 different engineering resin systems for applications requiring color, conductive, elastomeric, flame retardant, high temperature, structural, and wear resistant properties.

Headquartered in Winona, Minnesota, RTP Company operates 10 additional full-service manufacturing facilities located throughout North America, Europe, and Asia. Each facility has complete make-to-order manufacturing, color lab, product development, and technical service on-site.

Additional information is available at http://www.rtpcompany.com .

Product Design:

How to Get the Design Right the First Time

BY CHERIE FORBES

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

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

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

DETERMINE THE MARKET WHERE THE PRODUCT WILL BE SOLD

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

Now that you know what countries you will be targeting, determine what safety related marks are required. The United States and Canada have a variety of options available; many certifiers (e.g. CSA, UL, TUV Rheinland, etc.) are accredited by both the Standards Council of Canada (SCC) and the Occupational Safety and Health Administration (OSHA) as a Nationally Recognized Test Lab (NRTL). Knowing that you can talk to a single certifier to gain simultaneous marks for both countries will make things much easier.
Europe uses a self-evaluation method called the CE Mark. The CE Mark declares compliance to all the directives applicable to the product (e.g. Low Voltage Directive, EMC Directive, and Machinery Directive). Because it is a self-evaluation mark, manufacturers can evaluate the product themselves (with a high level of risk to the manufacturer), or use an agency to evaluate the product on their behalf (low level of risk). Europe has some extra requirements to consider, namely the RoHS and WEEE directives, which have specific restrictions on toxins (mercury, lead commonly used in solder, etc.) and requirements for disposal methods. Many component manufacturers have lead-free alternates to be selected for European markets.

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

DETERMINE THE CORRECT SAFETY STANDARD FOR THE PRODUCT

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

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

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

SELECT COMPONENTS THAT ARE SUITABLE FOR THE STANDARD

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

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

OBTAIN COMPONENT LICENSES

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

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

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

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

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

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

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

DESIGN A SUITABLE ENCLOSURE

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

Material Selection

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

Material Thickness

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

Openings

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

Tests

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

DETERMINE THE REQUIRED SPACINGS

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

Identification of Circuits

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

Create a Block Diagram

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

Determine the Level of Insulation Required

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

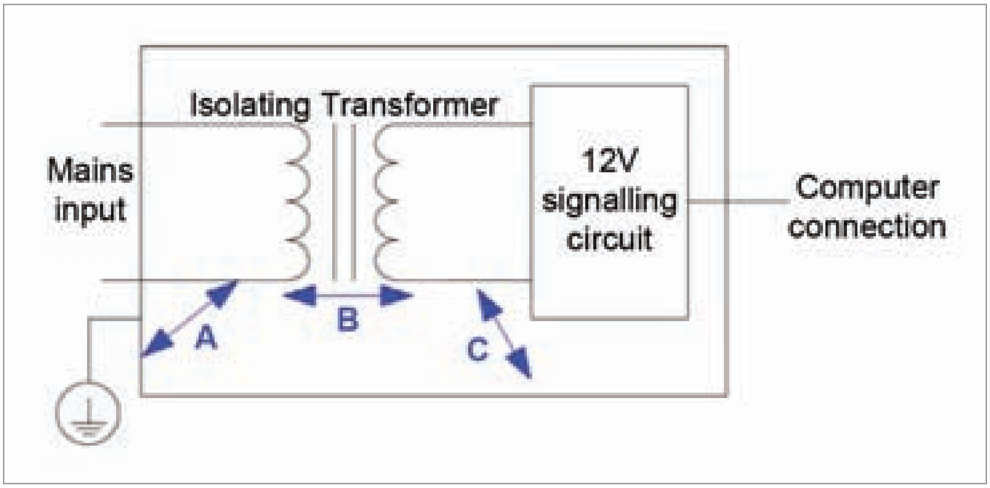


Figure 1: Sample block diagram

Using Tables in the Standard

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

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

SINGLE FAULT EXAMINATION

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

OTHER STANDARD REQUIREMENTS

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

USING CONSULTANTS WHO UNDERSTAND THE REQUIREMENTS OF YOUR SAFETY STANDARDS

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

SUMMARY

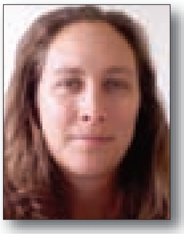
It's critical to know the market your product will be shipped to before the product design is started. Once you know this, you can use the appropriate safety standards when designing your product. Using consultants to assist with understanding the safety standard is another option to be considered.

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

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

REFERENCES

1. IEC 60950-1: 2005, *Information Technology Equipment – Safety – Part 1: General Requirements*.
2. UL 508, *Seventeenth Edition, UL Standard for Safety for Industrial Control Equipment*.
3. CAN/CSA-C22.2 No. 14-05, *Tenth Edition, Industrial Control Equipment*.
4. EN 61010-1: 2001, *Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use – Part 1: General Requirements.*



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Product Safety

How to Prepare for Possible Product Recalls

BY KENNETH ROSS

In 2011, Australia and Canada adopted new product safety laws that require manufacturers and others in the supply chain to monitor their products in use, and to report safety issues and take appropriate corrective actions in certain situations. In addition, the U.S. Consumer Product Safety Commission has become more aggressive in levying civil penalties on companies who do not report safety problems in a timely fashion.

Therefore, it is more important than ever that companies be prepared to meet these obligations as they design, manufacture and sell their products. Being proactive and prepared before sale can save all companies in the supply chain significant amounts of money and effort, and make any recall or corrective action implemented after sale much more effective.

PRE-SALE PREPARATION

One of the most difficult things I've ever done is try and convince a manufacturer to prepare for a recall when they are first designing a product. This is not something that most manufacturers want to do. They are focused on trying to get a product into production and sold. Unfortunately, after the product has been sold, it is too late to do many of the practices discussed below.

Various entities in the supply chain should try to establish procedures *before* the product is sold so that each entity can, after sale, easily and efficiently obtain information, analyze it, make decisions about appropriate post-sale remedial programs, and implement any necessary programs.

Some of the most significant elements to build into the product's design, manufacturing and distribution processes are traceability and marking procedures for use before and during manufacture and distribution.
To the extent possible, products and, especially, safety-critical components should be marked or coded so that anyone, including customers, can identify the product or component to be returned.

The Retail Industry Leaders Association and British Retail Consortium recently issued some safety guidelines for their suppliers. One of the requirements is that the supplier "shall have a system to identify and trace product lots including raw materials, components and packaging materials and follow this from the source of the incoming material through all stages of processing to supply of the product to the primary *customer* and vice versa in a timely manner."

This is not easy to do and many manufacturers, especially those who have never had to recall their products, will wonder if the effort is worth it. Of course, in the event of a recall, this tracing will allow the manufacturer of the finished product or component part to narrow the affected population and clearly identify the population to customers. In that case, everyone benefits, from the manufacturer to the retailer to the consumer.

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The IEEE Product Safety Engineering Society seeks original, unpublished papers and tutorials on all aspects of product safety and compliance engineering including, but not limited to:

Product Specific: Consumer, medical, computer (IT), test and measurement, power supplies, telecommunication, industrial control, electric tools, home appliances, cellular and wireless, etc.

Hazard Specific: Electrical, mechanical, fire, thermal, chemical, optical, software, functional, reliability, risk assessment, etc.

EMC/RF: Electromagnetic emissions, electromagnetic immunity, regulatory, Introduction to EMC/RF for the safety engineer and compliance engineer.

Components: Grounding, insulation, opto-couplers, cables, capacitors, connectors, current-limiters, transformers, current-limiters, fuses, lasers, ferrites, environmental, electromagnetic suppression & protection, surge protectors, printed wiring boards, etc.

Certification: Electromagnetic emissions & immunity, Environmental, Product safety, Processes, safety testing, regulatory, product liability etc.

Standards Activities: Development, status, interpretations, country specific requirements, Laboratory Accreditation, etc

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The next important consideration is for the manufacturer, in cooperation with all entities in the distribution chain, to design and maintain an effective database so that different types of entities, including product users if possible, can be identified. These databases must be updated periodically.

One of the most important and difficult tasks is for the manufacturer to set up a communications network before sale so that appropriate safety information is received. A manufacturer has a number of readily available sources of information anywhere their product is sold. Personnel should be trained to ensure that sufficient information is gathered concerning warranty claims, injury or damage claims, accidents, and near misses so that potential problems can be identified.

Personnel should also be trained to identify and clarify the information received so that it is accurate and substantiated. The manufacturer does not want to gather and maintain inaccurate and overstated complaints and claims that incorrectly make it appear that a problem exists.

Post-sale information, some of it unsubstantiated or even incorrect, can be posted by consumers on the Internet. This information needs to be monitored and followed up where necessary. Ignoring such information is risky, but following up on all alleged safety issues can be time-consuming and fruitless.

Manufacturers should think about what they will need to do to recall their product or withdraw it from the market. While the manufacturer will not know what the problem is before it occurs, it can at least think about the ways in which a recall or withdrawal would be communicated and be prepared to get the information out quickly.

For example, how will press releases, customer alerts, distributor bulletins, Web site postings, and questions and answers be used and how will the manufacturer be able to communicate this information quickly and efficiently to the appropriate people or entities. Another example of monitoring the communication stream is deciding whether the information in returned warranty cards is entered periodically or the company waits until a recall occurs.

As discussed below, the manufacturer must understand all legal reporting requirements for each country in which its product is being sold. The requirements have grown recently and are different from country to country. The result is that there may be a reporting responsibility in one country and not another. This may result in a recall in one country and not another.

Canada has a new reporting law that requires reports, in part, for an occurrence in Canada or anywhere in the world that resulted or may reasonably have been expected to result in an individual's death or serious injury. Australia's new reporting law is likewise based mostly on an occurrence anywhere in the world for a product that is sold in Australia. One difference though is that "near misses" can trigger a report in Canada but not in Australia. In both Australia and Canada, there is an interesting question as to when a foreign manufacturer has a duty to provide occurrence information to Canadian or Australian entities to trigger a report.

In December 2009, the EU issued a new post-sale risk assessment process (see http://ec.europa.eu/consumers/safety/rapex/guidelines_states_en.htm) that should be used to determine if a report to the EU is appropriate and whether any corrective action is necessary. This process could also be useful in analyzing post-sale risks elsewhere in the world.

There is a new draft ISO standard dealing with recalls that will be published in 2013. It is called ISO 10393 and is being developed by ISO/PC 240. It is a "guidance standard" that contains an "international model code of good practice for consumer product recalls and other corrective actions." This standard contains requirements for recall plans and policies that should be developed before sale.

Lastly, in 2004, the EU published a guide to corrective actions in Europe. This guide included suggestions for actions to take place before sale, many of them already discussed here. This guide is being updated and should be reissued in late 2011 or early 2012.

POST-SALE PREPARATION

As a manufacturer obtains and analyzes post-sale information, it must determine whether any post-sale action is necessary at any point in time. This includes reporting to the relevant governmental agency and possibly undertaking some form of recall.

Analyzing the information and deciding what it means is the most critical phase of this process. Many manufacturers use or should use risk assessment prior to selling their products. This process identifies the risk, probability of the risk occurring, consequences if it occurs, and methods to minimize the risk. Before sale, the manufacturer should make a best guess on the probability of the risk occurring. It is, of course, difficult to estimate the probability of an event occurring when it has never happened before.

After sale, the manufacturer is, in effect, considering new information from field experience. Post-sale incidents may indicate risks or consequences that were never imagined, or change the estimated probability calculated before sale. Redoing the pre-sale risk assessment is a good way to formally recalculate the numbers and assumptions. Unfortunately, doing so doesn't really answer the question of whether and what type of corrective action is necessary.

For products regulated by a government agency, the manufacturer needs to identify the threshold for taking action. For example, the CPSC provides criteria for determining the existence of a defect and substantial product hazard. The criteria to be considered are the pattern of defect, the number of defective products distributed in commerce, and the severity of risk to consumers. Using these criteria will provide guidance to the manufacturer about what information to gather and how to analyze it. However, the CPSC provides little further guidance on this basic question, and expects the manufacturer to report a substantial product hazard or any suspicion that the product contains such a hazard.

After the manufacturer reports to a government agency, the agency will most likely, if not always, strongly encourage some type of corrective action. So, the manufacturer must be prepared, if it can as part of its report, to describe the actions that it believes will minimize the risk. It is possible, however, to propose that no corrective action is necessary.

Every entity needs to have experienced technical and legal personnel who routinely evaluate post-sale data and information and decide whether to report to the government and whether to undertake a corrective action or to undertake a corrective action even if no government agency is involved. If adequate pre-sale planning has occurred, implementing the program will be less difficult and more organized than if no planning occurred. Everyone will know what to do and when to do it.

Again, there is guidance on how to undertake recalls. I mentioned the EU guide to corrective actions. ISO 10377 will also provide general suggestions on how to undertake a recall. The CPSC also has a recall handbook. All of these guidelines discuss "best practices" and it is up to the individual manufacturer or product seller to determine which of these practices to utilize in a particular situation. Therefore, there is no such thing as an "off the shelf" recall plan that would make sense for sales of any product around the world.

Recalls can be extremely difficult and very ineffective, despite the best of efforts. There are no clear guidelines in the common law or even with government agencies about how effective a recall has to be. Recalls or retrofit programs with an effective rate of less than 10 percent have been deemed acceptable by the CPSC; the CPSC has said that the average response rate from consumers for most recalls is between 4 and 18 percent.

Virtually no recalls have 100 percent compliance. As a result, the manufacturer will have many products in the field that it has admitted or intimated are defective or at least pose a risk of injury. After an injury occurs and a lawsuit is filed, how will the manufacturer defend its product?

As the program is implemented, the manufacturer must think about how it will prove that its actions were reasonable and appropriate under the circumstances. Again, experienced personnel in this area can help and should be utilized.

CONCLUSION

Preparing for a recall before it occurs can significantly increase its effectiveness and lessen the costs and disruption to the manufacturer, distributor and customer. The effort will be well worth it if something happens. These efforts will also generate post-sale information that can provide insights into how your products and maybe your competitor's products are being used. This will be helpful in making future product improvements. The end result will be safer products, less accidents, and more defensible products and actions if problems occur.

Kenneth Ross *is Of Counsel with Bowman and Brooke LLP in Minneapolis. Mr. Ross has provided legal advice and consulted with manufacturers on compliance with their post-sale duties, including recalls, for over 30 years. See his website, www.productliabilityprevention.com, for more of his articles on recalls. He can be reached at kenrossesq@comcast.net.*

Product Safety

Discovering EMC's Role in Functional Safety

BY DAVID SCHRAMM

Electromagnetic disturbances can greatly influence the performance of equipment and the functional safety of systems. Consider the current problems we hear in the news with unintended acceleration in some vehicles. While this complication's true cause may never be determined, analysts have theorized that electromagnetic disturbances could play a large role. Due to the amount of electronics and ever changing technologies found in today's automobiles, unintended acceleration is only one of many examples of unwanted anomalies that could occur due to an EMC issue. Automakers are faced everyday with the risk and associated liability that could come with a problem such as this once the vehicle is on the street with the consumer. That risk is why the automakers over time have had to develop specific test standards that relate to the EMC concerns of their vehicles and enforce their suppliers to meet them by way of specific test plans. The automotive industry is just one example of how EMC can relate to the functional safety of a product as guided by IEC TS 61000-1-2: 2008.

GENERAL CONSIDERATIONS

According to IEC TR 61508-0: 2005, Product Safety is the freedom from unacceptable risk of physical injury or of damage to the health of people, either directly or indirectly as a result of damage to property or to the environment. *Functional safety* is part of the overall safety that depends on a system or equipment operating correctly in response to its inputs.

Electromagnetic compatibility is the ability of an equipment or system to function satisfactorily in its electromagnetic environment, without introducing intolerable electromagnetic disturbances to anything in that environment.

Note that functional safety must be maintained over the anticipated lifetime of the product, which means taking into account all reasonably foreseeable faults, use/misuse, component tolerances and variations/errors in assembly, exposure to physical, climatic, biological, etc. conditions, and ageing. However, when we do EMC testing, we are usually only concerned with a new fault-free product passing its tests on one day, when operated correctly and in a benign environment. Doing EMC for functional safety reasons is therefore going to be a little different from what we are used to!

EMC testing traditionally involves identifying the test requirements, which varies in the different economies and sectors of industry. An automotive component designed for automakers, whose end product (the car) will be sold in the US market, has different EMC requirements than a notebook computer intended to be sold in the EU. For example automotive products could be subjected to much higher EM fields than the notebook

Functional safety as an aspect of EMC is based on assessment of the electromagnetic environment. However, it should also include consideration of the total environment that the product is expected to be exposed to in its lifetime

computer. As a result automotive radiated immunity testing is performed at a magnitude that is often 10 times or more than what is performed on a standard notebook PC. The basic EMC testing of the notebook computer would involve testing its immunity to EN 55024. If that same laptop were used in a situation where it controlled a safety function, the tests and test levels described in EN 55024 may not be adequate.

Functional safety as an aspect of EMC is based on assessment of the electromagnetic environment. However, it should also include consideration of the total environment that the product is expected to be exposed to in its lifetime such as physical (mechanical forces, shock, vibration, etc., exposure to liquids, gases, dusts, etc.) climatic (temperature extremes and cycling, humidity, condensation, rain, air pressure extremes and cycling, etc.) biological (mould growth, rodent gnawing, nesting bugs and animals, etc.)

It is also based on the product's intended function, acceptable level of safety risk, design (including the fact that some of its electronics might serve a safety function), and electromagnetic immunity verification/validation (i.e. immunity testing). For many of my friends in the world of EMC, we just crossed into uncharted territory. The relatively straight forward application of specific test standards to a product has given way to specifying the EMC tests based on automotive products could be subjected to much higher EM fields than the notebook computer. As a result automotive radiated immunity testing is performed at a magnitude that is often 10 times or more than what is performed on a standard notebook PC.

The basic EMC testing of the notebook computer would involve testing its immunity to EN 55024. If that same laptop were used in a situation where it controlled a safety function, the tests and test levels described in EN 55024 may not be adequate.

Functional safety as an aspect of EMC is based on assessment of the electromagnetic environment, the product design (the fact that some of its electronics serve a safety function), electromagnetic immunity verification/ validation, and immunity testing. For many of my friends in the world of EMC, we just crossed into uncharted territory. The relatively straight forward application of specific test standards to a product has given way to specifying the EMC tests based on hazard analysis and risk assessment.

EMC DESIGN CONSIDERATIONS

A risk assessment should be taken into consideration during the product's design and intended function into consideration, and acknowledge the electromagnetic environments in which the product will be used. EMC of the product should be considered and implemented in the design process. The product should be validated against immunity tests appropriate for its type, and the electromagnetic environment for its installation. Specific operation and maintenance instructions may be needed to ensure the desired functional safety.

It is important to recognize that waiting until the end of the design process to consider traditional EMC compliance, and especially EMC for functional safety, can be detrimental. In this process, procrastination can greatly increase the cost of compliance and decrease the time to market, should failures occur. The options available to fix compliance problems are sometimes limited without redesign of the product.

SOURCES OF ELECTROMAGNETIC DISTURBANCES

The electromagnetic environment consists of the total electromagnetic phenomena existing at a given location. There are three basic categories of phenomena: low-frequency (conducted and radiated from any source except ESD), high-frequency (conducted and radiated from any source except ESD), and electrostatic discharge (conducted and radiated). Table 1 shows an overview of types of electromagnetic phenomena.

SPECIFIC APPLICATIONS

Extensive work has been done by standards writing bodies to give general guidance to test levels for these different phenomena based on the location of intended use. A product intended to be used in a home will generally be exposed to lower levels of electromagnetic phenomena than one intended to be used in a heavy industrial environment. The electromagnetic environment in an automobile or the military defense facility may be even harsher than the heavy industrial environment.

Generic EMC standards, such as IEC 61000-6-1 and IEC 61000-6-2 are specifically targeted for the light industrial and heavy industrial environments, respectively.

Conducted low frequency phenomena	Harmonics, interharmonics Signalling voltages Voltage fluctuations Voltage dips and interruptions Voltage unbalance Power frequency variations Induced low frequency voltages d.c. in a.c. networks
Radiated low frequency field phenomena	Magnetic fields (continuous or transients) Electrical fields
Conducted high frequency phenomena	Directly coupled or induced continuous voltages or currents Unidirectional transients Oscillatory transients
Radiated high frequency field phenomena	Magnetic fields Electrical fields Electromagnetic fields – continuous waves – transients
Electrostatic discharge phenomena (ESD)	Human and machine
Phenomena of conducted and radiated HPEM Environment	
High altitude electromagnetic pulse (HEMP)	

Table 1: Overview of types of electromagnetic phenomena

Electromagnetic phenomena	IEC 61000-6-1 test level	IEC 61000-6-2 test level	EN 12016 test level All circuits	EN 12016 test level for safety circuits
Power frequency magnetic field (50/60 Hz)	3 A/m	30 A/m	N/A	N/A
Radio Frequency electromagnetic fields	80-1000 MHz: 3 V/m 1.4-2.0 MHz: 3 V/m 2.0-2.7 MHz: 1 V/m	80-1000 MHz: 10 V/m 1.4-2.0 MHz: 3 V/m 2.0-2.7 MHz: 1 V/m	80-1000 MHz: 10 V/m 1710-1784 MHz: 10 V/m 1880-1960 MHz: 3 V/m	80-166 MHz: 10 V/m 166-1000MHz: 30 V/m 1710-1784 MHz: 30 V/m 1880-1960 MHz: 10 V/m
Electrostatic Discharge	Contact: 4kV Air: 8kV	Contact: 4kV Air: 8kV	Contact: 4kV Air: 8kV	Contact: 6kV Air: 15kV
Radio Frequency common mode voltages	0.15-80 MHz: 3 Vrms	0.15-80 MHz: 10 Vrms	0.15-80 MHz: 3 Vrms	0.15-80 MHz: 10 Vrms
Fast transients	Signal: 0.5 kV DC power: 0.5 kV AC power: 1 kV	Signal: 1 kV DC power: 2 kV AC power: 2 kV	Signal: 0.5 kV DC power: 0.5 kV AC power: kV	Signal: 2 kV DC power: 4 kV AC power: 2 kV
Surge	Signal: N/A DC power: 0.5 kV AC power: 2 kV	Signal: 1 kV DC power: 0.5 kV AC power: 2 kV	Signal: N/A DC power: 0.5 kV AC power: 2 kV	Signal: 2 kV DC power: 0.5 kV AC power: 2 kV

Table 2: Comparison of test levels in IEC 61000-6-1 / IEC 61000-6-2 / EN 12016

Each of these standards contains the same basic tests with levels set appropriately for a specific type of environment. Other product-specific standards recognize that the product function is critical for safety and know when higher test levels are needed.

Each of these standards contains the same basic tests with levels set appropriately for a specific type of environment. Other product-specific standards recognize that the product function is critical for safety and know when higher test levels are needed. For example, the immunity standard for elevators and lifts, EN 12016, includes higher test levels for safety circuits.

Table 2 shows a non-exhaustive comparison of the test levels.

As expected, the test levels for the heavy industrial environment are generally higher than those specified for the light industrial environment. A notable exception is ESD, which is identical in both locations.

Note also that for the safety circuits of the lift standard, test levels are almost always higher than those for either the light or heavy industrial/elevator standard. Higher test levels were provided for radiated immunity due to the expectation that radio transmitters would be present. According to this document, radio transmitters are not commonly found below 166 MHz and mobile phones that operate in the 1710-1784 MHz and 1880-1960 MHz bands. In addition to higher test levels, the criteria for compliance have been modified specifically for safety circuits.

For each immunity test, criteria are specified so that compliance to the test may be assessed. The following are abbreviated descriptions of the different performance criteria.

Performance criterion A: Operation must continue as intended during and after the test. This criterion applies primarily to continuous phenomenon such as Radiated and Conducted RF Immunity.

Performance criterion B: Operation must continue as intended after the test. This criterion applies primarily to transient phenomenon such as fast transients and surge.

Performance criterion C: Temporary loss of function is allowed, provided the function is self-recoverable or can be restored by the operation of the controls. This criterion applies primarily to 5 second voltage interruption (not shown in table) where most products will shut down.

Performance criterion D (as defined in EN 12016): Operation must continue as intended during and after the test, including the associated safety components. No degradation of performance loss of function is allowed, other than a failure into a safe mode. This criterion applies to all safety circuits and is not dependent on the electromagnetic phenomenon. Not only are safety circuits tested to higher levels of electromagnetic phenomenon, they also have a stricter criterion for compliance.

Performance criterion FS: The performance criterion for functional safety is specified as FS and is only applicable for functions contributing to or intended for safety applications. As seen for the lift/elevator standard, the FS criterion shall be considered for all electromagnetic phenomena. There is no differentiation required between continuous and transient electromagnetic phenomena. Equipment performing safety functions must remain safe.

Performance criterion A is always acceptable for safety functions contributing to or intended for safety applications, whereas Performance criterion FS allows failure to a stable state that is defined by the manufacturer of a product intended for incorporation into a safety-related system, and in the case of a complete safety-related system means failure to a safe state.

EMC FOR MEDICAL EQUIPMENT

Functional safety is also a concern in IEC 60601-1-2, the collateral EMC standard for medical equipment. As detailed in Clause 6.2.1.10 of IEC 60601-1-2: 2007, the performance criteria is very specific, but could generally be considered to fall into criterion A, above. Degradation in performance, giving a condition of unacceptable risk is not allowed, even if accompanied by an alarm.

IEC 60601-1-2 also assigns higher immunity test levels to life-supporting medical equipment. Further specifications are made in compliance with the particular requirements of specific instruments. Table 3 shows a non-exhaustive comparison of the test levels for medical equipment.

From this information, we can conclude that the electromagnetic environment is expected to be similar for general medical equipment and for life supporting equipment. However, because of its potential to harm patients, life supporting medical equipment has higher test levels for Radio Frequency Electromagnetic fields, to correspond more closely with the maximum levels of an EM phenomenon that could occur in the environment over the lifetime.

The particular standard for infusion pumps classifies them as life-supporting equipment and generally uses the same test level. However, ESD and Magnetic Field immunity are exceptions. ESD levels were increased from 6 kV to 8 kV for contact discharge and from 8 kV to 15 kV for air discharge. The magnetic field immunity was increased from 3 A/m to 400 A/m. These higher test levels were used due to reports of interference from radio transmitters in ambulances and from electromagnetic fields, generated by diathermy equipment and mobile telephones. Examples of degradation included unpredictable cessation of infusion and a reversion to a purge mode of operation.

Note that IEC 60601-1-2 Ed3 states: "Subclause 6.2.1.1 – IMMUNITY TEST LEVELS The IMMUNITY TEST LEVELS in this collateral standard were selected to represent the normal use environment and therefore to be appropriate for an EMC IMMUNITY standard, rather than for a safety standard. Test levels for a safety standard would be significantly higher. (See IEC 61000-1-2 [4].)" In fact, IEC TS 61000-1-2 requires a great deal more than simply testing with higher levels!

FUNCTIONAL SAFETY CONSIDERATIONS

In most cases, there is no practical way to verify by testing alone that adequate immunity to functional safety risks has been achieved over the anticipated lifetime of the product. This is exactly the situation faced by the software industry in the 1990s, resulting in a great deal of international work on how to make software safe enough, out of which came IEC 61508-3:2000. What the software safety experts found was that to achieve the required levels of confidence in correct operation required the use of proven design methods and a variety or verification and validation methods (including, but not limited to, testing). This is exactly the approach that IEC TS 61000-1-2 applies to EMC - the only practical way to ensure that EMI does not cause unacceptable safety risks over the product's lifetime.

Let's say a product was expected to be installed in an environment where a particular electromagnetic phenomenon was present. Its prudent manufacturer would test for immunity against that phenomenon, even if said test was not specified in the generic or product specific EMC standards.

As observed in the specific EMC requirements for lift/elevator and medical equipment, the test levels may be higher than those specified in the normal test environments. In most cases, the adequacy of immunity can be assessed by evaluating to higher test levels. However, little safety benefit is achieved by testing at higher levels, other than achieving extra confidence that the immunity test applied the specified level or higher. Table 4 shows estimates of maximum electromagnetic disturbance levels.

Electromagnetic phenomena	General medical equipment	Life supporting medical equipment	Particular requirements for infusion pumps (IEC 60601-2-24)
Power frequency magnetic field (50/60 Hz)	3 A/m	3 A/m	400 A/m
Radio Frequency electromagnetic fields	80-2500 MHz: 3 V/m	80-2500 MHz: 10 V/m	26-1000 MHz: 10 V/m[i]
Electrostatic Discharge	Contact: 6kV Air: 8kV	Contact: 6kV Air: 8kV	Contact: 8kV Air: 15kV

[i] IEC 60601-2-24: 1998 references the 1993 version of IEC 60601-1-2, which specified a frequency range for radiated immunity of 26 MHz to 1000 MHz. In 2001, IEC 60601-1-2 was updated to specify a frequency range for radiated immunity of 80-2500 MHz and add a conducted immunity test for the frequency rage of 0.15-80 MHz. It is the author's recommendation that the guidance from Edition 2 and 3 of IEC 60601-1-2 be applied to the test levels.

Table 3: Comparison of immunity levels of medical equipment

<table>
<tr><td colspan="2"></td><td colspan="2">Maximum electromagnetic levels</td></tr>
<tr><td>Phenomena and ports</td><td>Units</td><td>Residential</td><td>Heavy Industrial</td></tr>
<tr><td>ESD air
contact</td><td>kV</td><td>15
8</td><td>15
8</td></tr>
<tr><td>RF fields [a]
≤80 MHz to 1000 MHz</td><td>V/m
modulated</td><td>50</td><td>50</td></tr>
<tr><td>RF fields digital phone
0.9 (1.8) GHz</td><td>V/m
Modulated</td><td>50</td><td>50</td></tr>
<tr><td>Fast transients
- AC power
- DC power
- control/signal
- functional earth</td><td>kV</td><td>
4
4
2
2</td><td>
8
8
4
2</td></tr>
<tr><td>Surges
- AC power L→G
- AC power L→L
- DC power L→G
- DC power L→L
- control/signal L→G
- control/signal L→L</td><td>kV</td><td>
4
2
2
2
2
1</td><td>
8
4
2
2
4
2</td></tr>
<tr><td>Conducted HF disturbances [a]
0.15 MHz to 80 MHz
- AC power Common Mode
- DC power Common Mode
- control/signal Common Mode
- functional earth</td><td>V
modulated</td><td>
vary
50
50
50
10</td><td>
vary
50
50
50
10</td></tr>
<tr><td>Power frequency magnetic fields</td><td>A/m</td><td>10</td><td>60</td></tr>
<tr><td>AC voltage dips</td><td>Δ % U_n
periods</td><td>10 to 95%
0.5 to 150</td><td>10 to 95%
0.5 to 300</td></tr>
<tr><td>AC voltage interruptions >95%</td><td>periods</td><td>2500</td><td>2500</td></tr>
<tr><td>Ring Wave
- 0.1 MHz (a.c. power)
- 0.1 MHz (control)</td><td>kV</td><td>
4
2</td><td>
4
2</td></tr>
<tr><td>Harmonics: THD
5^{th}</td><td>% U_n
% U_n</td><td>8
6</td><td>10
8</td></tr>
<tr><td>AC voltage fluctuations</td><td>Δ U_n%</td><td>+10, -10</td><td>+10, -15</td></tr>
<tr><td>Oscillatory Waves
- slow (0.1 and 1 MHz)
- fast (3, 10, and 30 MHz)</td><td>kV</td><td>
4
4</td><td>
4
4</td></tr>
<tr><td colspan="4">[a] Maximum levels are not necessarily observed in the entire frequency range</td></tr>
</table>

Table 4: estimates of maximum electromagnetic disturbance levels

Product Safety

Functional safety for EMC is about mitigating risk of electromagnetic phenomena by identifying the probability of occurrence of electromagnetic interference, and determining the severity of that interference. The product must then be designed and verified/validated accordingly.

Many of the phenomena found in Table 4 are associated with a basic EMC standard in the 61000-4 series. The test levels in Table 4 generally exceed the test levels given in the generic or product family standards. When designing an EMC test for functional safety, testing to these higher levels will give greater assurance or proper operation in the final installation. Testing to failure can give great insight as to what type of response might be observed when failures do occur.

In addition to elevated test levels, a product's immunity can be evaluated by using variants of these standard test methods. For example, extending the number of pulses or the duration of a particular test will increase the likelihood of exposing a particularly susceptible period in the operational cycle (might only last for a few nanoseconds!), and attempt different test setups of the product (i.e. testing a different combination of equipment, versions, and /or cabling).

Also, 1 kHz sinewave modulation might not represent the real-life worst-case "EM threat" to the product, and there may be significantly higher levels of carrier frequencies outside of the normally tested range. All products have specific frequencies to which they are particularly susceptible, and which they can be exposed to by direct interference (with the carrier wave), demodulation of the carrier's envelope, or intermodulation between two or more carrier frequencies. It is clearly impossible to test for all these possibilities, which is why it is necessary to adopt certain "good design practices" and a range of verification and validation techniques to prove them. However, test methods can be modified (e.g. by using different modulations) to more comprehensively test the product against its real-life EM environment.

Reverberation chamber testing may also be better at simulating the real-life environment, than anechoic chambers are, because in real-life EM waves can impinge from any angle and polarization, in fact with several angles and polarizations at once, and EM susceptibility can strongly depend upon both.

The impact of a particular environment on a product's immunity behavior should also be considered. Temperature and humidity may vary significantly depending on the location of final installation. For example, a product may be very susceptible to ESD when the relative humidity is 20%, and yet show no signs of degradation to ESD levels two to three times higher when the relative humidity is 60%. Surges may be withstood when dry, but not when there is condensation. Corrosion of earth/ground bonds, shielding joints/gaskets, etc., can have very great consequences for immunity, as can faults and misuse (e.g. leaving a shielding door open). And mains filter capacitors and surge protection devices can wear out and fail after just a few years if not suitably dimensioned for their real-life environment, which includes AC mains power surges reliably up to ±6kV (at least, in single-phase distribution systems, more in dedicated three-phase systems) – a lot more stress than the usual ±2kV!

The performance over the product's life should also be considered. After exposure to highly accelerated life testing (HALT) that simulates the maximum ("worst-case") environmental exposure over the anticipated lifetime of the product, EMC testing should be repeated to check that the product's immunity is still adequate for the safe operation of the product over its expected life.

Functional safety for EMC is about mitigating risk of electromagnetic phenomena by identifying the probability of occurrence of electromagnetic interference, and determining the severity of that interference. The product must then be designed and verified/validated accordingly.

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A special thanks to Keith Armstrong of Cherry Clough Consultants for his invaluable insight. Any error or omission found in this article is certainly mine, not his.

Safety Considerations

for Smart Grid Technology Equipment

BY DON GIES

Product Safety

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

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

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

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

WHAT IS A SMART GRID?

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

SMART GRID: WHAT TO EXPECT

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

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

ALEXANDER GRAHAM BELL VS. THOMAS EDISON

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

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

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

A MODULAR APPROACH TO SMART-GRID SAFETY

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

Hazard-Base Safety Engineering Standard IEC 62368-1

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

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

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

IEC 60950-1 Continued Use

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

IEC 60950-22 for Outdoor Information Technology and Communication Circuits

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

SAFETY OF UTILITY-OWNED SMART-GRID EQUIPMENT

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

EXAMPLES OF SMART-GRID TECHNOLOGY

Automatic Metering Infrastructure (AMI)

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

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

Safety Concerns of AMI-Enabled Equipment

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

EXAMPLE: ELECTRIC VEHICLE POWERING

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

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

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

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

B. Electric power metering to measure electricity use;

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

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

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

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

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

Higher Overvoltage Category for Information Technology in Charging Station

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

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

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

Protection of Communications Circuits

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

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

User Accessibility

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

ENERGY STORAGE SAFETY

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

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

Safety issues to be considered include:

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

OTHER SAFETY CONCERNS – LOCAL POWER GENERATION

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

Synchronization

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

Islanding

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

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

CONCLUSION

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

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

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Product Safety

Compliance with Product Safety Standards

as a Defense to Product Liability Litigation

BY KENNETH ROSS

Product liability has created problems for manufacturers and product sellers for many decades. These problems have been exacerbated by the expansion of product liability laws throughout the world. In addition, there has been a proliferation of safety regulatory requirements, starting in the United States and then moving to the European Union. In addition, countries such as Japan, China, Australia, Canada, Brazil and South Africa have all recently established or strengthened their product safety regulatory regimes and requirements.

This all creates additional challenges for companies who want to and must comply with all laws, regulations and standards in any country where they sell their products. Such companies may also need to consider safety requirements in countries where they do not sell products to the extent they believe that these requirements establish a "state of the art" that they want to meet.

This article will discuss the basic kinds of defects that can be alleged in any product liability case. Next, I will discuss the law as it pertains to compliance with standards. And finally, this article will discuss the EU directives applicable to electrical products and the effect of those directives on products sold in the EU and the United States.

U.S. THEORIES OF LIABILITY

Manufacturing Defects

A manufacturing defect exists if the product "departs from its intended design even though all possible care was exercised in the preparation and marketing of the product." In other words, even if the manufacturer's quality control was the best in the world, the fact that the product departed from its intended design meant that it had a manufacturing defect. The plaintiff need not prove that the manufacturer was negligent, just that the product was defective. The focus is on the product, not on the conduct of the manufacturer.

Common examples of manufacturing defects are products that are physically flawed, damaged, incorrectly assembled or do not comply with the manufacturer's design specifications. The product turned out differently from that intended by the manufacturer. If that difference caused injury, the manufacturer will be liable. There are very few defenses.

Design Defects

A product is defective in design if a foreseeable risk of harm posed by the product "could have been reduced or avoided by the adoption of a reasonable alternative design" and the failure to use this alternative design makes the product not reasonably safe.

An alternative definition used by some courts is that a product is defective in design if it is dangerous to an extent beyond that which would be contemplated by the ordinary consumer.

These tests are much more subjective than the test for manufacturing defects and this subjectivity is the cause of most of the problems in product liability today. Manufacturers cannot easily determine how safe is safe enough and cannot predict how a jury will judge their products based on these tests. It is up to the jury to decide whether the manufacturer was reasonable or should have made a safer product.

Warnings and Instructions

The third main kind of defect involves inadequacies in warnings and instructions. The definition is similar to that of design defects and says that there is a defect if foreseeable risks of harm posed by the product "could have been reduced or avoided by …reasonable instructions or warnings" and this omission makes the product not reasonably safe.

Again this is an extremely subjective test that uses negligence principles as a basis for the jury to decide. This makes it difficult for a manufacturer to know how far to go to warn and instruct about safety hazards that remain in the product.

Post-sale Duty to Warn

One other theory of liability that is very important in a product liability case is post-sale duty to warn. A manufacturer may have a duty, after sale, to warn customers about hazards the manufacturer learns about after sale. This duty can arise even if the product was not defective or hazardous when sold. This duty is clearly based on negligence and involves any of the three kinds of defects described above.

LAW OF DESIGN DEFECTS

There are two kinds of design defect cases: those involving "inadvertent design errors" and another involving "conscious design choices." Design errors are like manufacturing flaws and are treated easily by the courts. The design was wrong because someone made a mistake. The mistake created a hazard and someone was hurt. In that case, there is virtually no defense and the manufacturer would usually settle the case.

The more important type of design defect case involves conscious design choices. In these cases, the design turned out as intended by the designer and manufacturer. It had the level of safety expected by the designer for the intended use. However, the product still hurt someone who claims that the product should have been made safer. The plaintiff argues that an alternative safer design should have been used and the court must decide whether this alternative was preferable.

The development of the law in this area has caused confusion. There are several tests that have been developed for helping courts and juries decide whether there was a defective design.

Test for Design Defect

The predominant test in the United States for determining whether a product was "reasonably safe" involves, as mentioned above, whether there was a reasonable alternative design available. In many states, to answer this question, the jury is instructed to consider the following factors:

- Usefulness and desirability of the product.
- Safety of the product – the likelihood that it will cause injury and the probable seriousness of the injury.
- The availability of a substitute product that performed the same function and was safer.
- Ability of the manufacturer to eliminate the unsafe characteristic of the product without lessening its usefulness or making it too expensive.
- User's ability to avoid harm by being careful when using the product.
- User's awareness of the risk, either because it is obvious or because of suitable warnings and instructions.
- Feasibility by the manufacturer to spread the risk by way of price increases or purchasing insurance.

These factors provide a more comprehensive and understandable basis for a jury to make a decision. They also provide more guidance to the litigants to evaluate their case. Also, as importantly, they provide a basis by which a manufacturer could evaluate the safety of its product before sale and decide what is "reasonably safe."

COMPLIANCE WITH STANDARDS

Another complex area involves laws, standards and regulations. As part of the initial analysis, a manufacturer must identify those that apply to its product. Sometimes, that is not easy to determine or there are numerous and different ones that must be reconciled, especially if the product is sold internationally.

Official laws and regulations, such as those passed by a state or national legislature, that apply to the product's design must be complied with. If the product does not comply and this noncompliance caused the injury, then the manufacturer can be liable. Unfortunately, on the flip side, compliance with all applicable laws and regulations is not, for most products, an absolute defense in a product liability case. Therefore, a jury could come back and say a manufacturer should have exceeded laws and regulations pertaining to safety.

Similarly, industry standards and even certifications like UL are considered minimum. As a result, compliance with standards and certifications is not an absolute defense although it is pretty good evidence that the product was reasonably safe. Therefore, as with laws and regulations, the plaintiff can argue that you should have exceeded the standards. However, noncompliance is a problem if it caused or contributed to the injury. The reason is that the standard establishes a reasonable alternative design and the manufacturer has to justify why it didn't comply.

So where does this lead the manufacturer? You should meet or exceed all applicable laws, regulations and mandatory or voluntary consensus standards in the countries where you sell products. If you don't or can't, then document the reason and make a reasonable judgment as to why your product is still reasonably safe.

This is easier said than done. First, given the plethora of U.S. and international laws, regulations and standards, it is no easy task just to identify those that could apply to your product. Then, you need to Figure out which ones take precedence over others where there is overlap.

In the European Union, there are ISO standards, EN/ISO standards and then Directives. Directives are similar to laws and EN/ISO standards have more authority than ISO and ANSI standards. So some are more important to comply with. But the bigger problem is figuring out which ones apply as there can be substantial overlap. Some U.S. and EU laws, regulations and standards are general and apply to a wide range of products. Some are much narrower. Generally, you want to first look to the narrower product specific document and then look to the more general requirements. The problem is figuring out where the "gaps" are in the narrower document that are then filled by the more general document. This is difficult to do and manufacturers need to also consider interpretations and guidances concerning directives and standards that are sometimes issued by government agencies, the EU and industry groups.

EU DIRECTIVES

In the United States, there are various industry standards, some of which are voluntary and some of which are mandatory in that some federal, state or local agency adopted the standard and made it the law.

In the European Union, they developed a variety of directives that pertain to health and safety. A manufacturer must meet the requirements of applicable directives and obtain a CE mark to sell their products in Europe. These directives must be enacted by each member country of the EU during a given period of time. However, each country can try to modify the directive to meet their own needs and desires. Some directives allow such leeway, others don't.

One problem with these directives, some of which are described below, is that they may become worldwide safety requirements and raise the "state of the art" beyond what is required in the U.S. Therefore, if a manufacturer sells a "safer" product in Europe that complies with the EU Directives and a "less safe" product in the U.S. that complies with, let's say, ANSI standards, this could be a problem. Obviously, the safer product constitutes a "reasonable alternative design" and can be used by the plaintiffs to support a case of defective design.

So, you need to be especially careful when you have a safer product sold in Europe or elsewhere. While U.S. law allows different levels of safety in a product (i.e. automobiles), you may need to justify the reasonable safety of your less safe product to a government agency or jury sometime in the future.

I want to describe some of the Directives that generally apply to electrical products.

General Product Safety Directive ("GPSD")

GPSD, Directive 2001/95/EC, was adopted in December 2001 for implementation no later than January 15, 2004. This directive establishes general safety requirements of many products, even those that would not be considered consumer products. This directive provides that manufacturers must sell safe products, defined as follows:

> "safe product" shall mean any product which, under normal or reasonably foreseeable conditions of use including duration and, where applicable, putting into service, installation and maintenance requirements, does not present any risk or only the minimum risks compatible with the product's use, considered to be acceptable and consistent with a high level of protection for the safety and health of persons,

There is also a reporting requirement for products that do not meet the above safety requirement. It says:

> Where producers and distributors know or ought to know, on the basis of the information in their possession and as professionals, that a product that they have placed on the market poses risks to the consumer that are incompatible with the general safety requirement, they shall immediately inform the competent authorities of the Member States thereof…

There are also EU documents issued after 2004 which discuss the relationship of GPSD to products that fall under other directives, such as some of those discussed below.

The EU is undertaking further implementation and revisions to GPSD so that it conforms to their so-called "New Legislative Framework" which contains measures that have the objective of removing the remaining obstacles to free circulation of products between EU Member States.

Low Voltage Directive ("LVD")

The most recent edition of the EU's Low Voltage Directive is dated December 12, 2006. It is designated "Directive 2006/95/EC" and includes a conformity assessment procedure that is applied to equipment before placing it on the market. Compliance with this directive should confirm that the equipment meets the EU's Essential Health and Safety Requirements (EHSRs) which such equipment must meet. The intent is for this Directive to cover all health and safety risks, thus ensuring that the electrical equipment is safe for its intended use. The manufacturer, and not a third party, is allowed to perform the conformity assessment. This Directive will be modernized and is part of the so-called "New Legislative Framework" which will deal with market surveillance, conformity assessment and accreditation and the meaning of the CE mark.

Electromagnetic Compatibility (EMC)

This Directive was enacted in 2004 and designated Directive 2004/108/EC. The purpose of the directive is to keep the side effects of electromagnetic interference under reasonable control. There is a new guide to this Directive dated February 8, 2010

Machinery Directive

The original Machinery Directive was passed in 1998. It subsequently was replaced in 2006 by Directive 2006 42/EC. This new directive is also part of the "New Legal Framework" which promotes harmonization through a combination of mandatory requirements and voluntary harmonized standards. The EU just issued an extensive guide to the 2006 Directive, dated June 2010. There are significant electrical safety requirements in this directive. In addition, there may be portions of other directives that apply to machinery.

Medical Device Directives ("MDD")

EU Directives related to medical devices were harmonized in the 1990s. There are three directives that form the main legal framework for such products: active implantable medical devices (Directive 90/385/EEC), medical devices (Directive 93/42/EEC) and in vitro diagnostic medical devices (Directive 98/79/EC). These directives have been supplemented by additional directives, such as Directive 2007/47/EC, and the EU is considering revisions to this legal framework which will strengthen requirements for safety and surveillance.

The original Machinery Directive excluded medical devices. The current 2006 version does not exclude them and the EU issued an interpretation in August of 2009 on the relationship between the Machinery Directive and the active implantable portion of the MDD, Directive 93/42/EEC.

CE MARKING

The CE mark is supposed to indicate that the product to which this is attached conforms to all relevant safety, health, environmental and other requirements in harmonized EU legislation. And all products in certain categories where EU directives exist must have the CE label attached to be sold in the EU. This includes electrical products.

Depending on the applicable directive's requirements, conformity assessment can be performed by the manufacturer or by a "notified conformity assessment body." Improperly affixing the CE mark to a product has significant legal ramifications, including criminal sanctions.

As with U.S. standards, while meeting the EU's requirements in these directives allows the manufacturer to attach the CE mark, these requirements are a minimum and an individual member state can impose additional safety requirements for products sold in their country. Unfortunately, this diminishes the usefulness of harmonized standards based on directives.

Also, the CE mark has no legal significance in the U.S. Compliance with EU Directives can be helpful in proving that the product sold in the U.S. was reasonably safe in the U.S., but there is no extra weight given to the fact that a European legislative body enacted these requirements. This is no different than the weight that is given to U.S. enacted laws and regulations.

CONCLUSION

Product liability in the U.S. is based, in large part, on the plaintiff offering a safer design and arguing that the manufacturer should have sold this safer product. EU requirements are, in many respects, much more rigorous than U.S. requirements. They are more detailed and overlapping and difficult and costly to comply with. Manufacturers could decide to sell only the safest product in the U.S. and elsewhere, even if that safer product is not required by laws and standards.

The trouble is that competitors might sell products with different levels of safety that might put the manufacturer at a competitive disadvantage. This is a costly decision for any manufacturer. Selling a safer product in the EU than you sell in the U.S. can result in significant liability. Selling a safer product in the U.S. that is not required by laws or standards may reduce liability by being more defensible. Unfortunately, it could also result in reduced sales that exceed any savings in litigation.

This can be a tough choice for a manufacturer from a financial, commercial and ethical standpoint. But one that must be made. ■

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Product Safety

ESD Standards

An Annual Progress Report

BY THE ESD ASSOCIATION

ESD

Industry standards play a major role in providing meaningful metrics and common procedures that allow various manufacturers, customers and suppliers to communicate from facility to facility around the world. Standards are increasingly important in our global economy. In manufacturing, uniform quality requirements and testing procedures are necessary to make sure that all involved parties are speaking the same language.

In electrostatic discharge (ESD) device protection, standard methods have been developed for component ESD test models to measure a component's sensitivity to electrostatic discharge from various sources. In ESD control programs, standard test methods for product qualification and periodic evaluation of wrist straps, garments, ionizers, worksurfaces, grounding, flooring, shoes, static dissipative planar materials, shielding bags, packaging, electrical soldering/desoldering hand tools and flooring/footwear systems have been developed to ensure uniformity around the world.

The ESD Association (ESDA) is dedicated to advancing the theory and practice of electrostatic discharge protection and avoidance. The ESD Association is an American National Standards Institute (ANSI) accredited standards developer. The ESDA's consensus body, called the Standards Committee (STDCOM), has responsibility for the overall development of documents. Volunteers from the industry participate in working groups to develop new and to update current ESDA documents.

STDCOM is charged with keeping pace with the industry demands for increased performance. The existing Standards, Standard Test Methods, Standard Practices and Technical Reports assist in the design and monitoring of the Electrostatic Protected Area (EPA), and also assist in the testing of ESD sensitive electronic components. Many of the existing documents relate to controlling electrostatic charge on personnel and stationary work areas. However, with the ever increasing emphasis on automated handling, the need to evaluate and monitor what is occurring inside process equipment is growing daily. Since automation has become more dominant, the Charged Device Model (CDM) has become the primary cause of ESD failures and thus the more urgent concern. Together the Human Body Model (HBM) and CDM cover the vast majority of ESD events that might occur in a typical factory.

The ESD Association document categories are:

- **Standard (S):** A precise statement of a set of requirements to be satisfied by a material, product, system or process that also specifies the procedures for determining whether each of the requirements is satisfied.
- **Standard Test Method (STM):** A definitive procedure for the identification, measurement and evaluation of one or more qualities, characteristics or properties of a material, product, system or process that yield a reproducible test result.

- **Standard Practice (SP):** A procedure for performing one or more operations or functions that may or may not yield a test result. Note, if a test result is obtained it may not be reproducible.
- **Technical Report (TR):** A collection of technical data or test results published as an informational reference on a specific material, product, system or process.

The ESDA Technology Road Map is compiled by industry experts in IC protection design and testing to provide a look into future ESD design and manufacturing challenges. The roadmap previously pointed out that numerous mainstream electronic parts and components would reach assembly factories with a lower level of ESD protection than could have been expected just a few years earlier. This prediction has proven to be rather accurate. As with any roadmap, the view to the future is constantly changing and requires updating on the basis of technology trend updates, market forces, supply chain evolution and field return data. Work has commenced on the next version. Industry experts will be extending the horizon beyond 2013 predictions in the updated roadmap. The roadmap will also contain, for the first time, a roadmap for the evolution of ESD testing. This will include forward looking views of possible changes in the standard device level tests (HBM and CDM), as well as the expected progress in other important areas such as transmission line pulsing (TLP), transient latch-up (TLU), cable discharge events (CDE) and charged board events (CBE). A view of work on electrical overstress (EOS) will also be included. The revision is scheduled for publication in January 2012.

The ESD Association Standards Committee is continuing several joint document development activities with the JEDEC Solid State Technology Association. Under a Memorandum of Understanding agreement, the ESDA and JEDEC formed a Joint Task Force for standardization work in which volunteers from ESDA and JEDEC member companies can participate. This collaboration between the ESDA and JEDEC has paved the way for the development of harmonized test methods for ESD, which will ultimately reduce uncertainty about test standards among manufacturers and suppliers in the solid state industry. At the time of this publication, ANSI/ESDA/JEDEC JS-001-2011, a second revision of the joint HBM document, has been released for distribution. This document replaces ANSI/ESDA/JEDEC JS-001-2010, the current industry test methods and specifications for HBM device testing. A second joint committee is currently working on a joint CDM document with a goal of publishing in 2012. These efforts will assist manufacturers of devices by providing one test method and specification instead of multiple, almost (but not quite) identical versions of device testing methods.

The ESDA is also working on a process assessment document. The purpose of this document is to describe a set of methodologies, techniques and tools that can be used to characterize a process where ESD sensitive items are handled. The goal is to characterize the ability of a process to safely handle ESD sensitive devices that have been characterized by the relevant device testing models. The document will apply to activities that manufacture, process, assemble, install, package, label, service, test, inspect, transport or otherwise handle electrical or electronic parts, assemblies and equipment susceptible to damage by electrostatic discharges. At the present time, this document will not apply to electrically-initiated explosive devices nor flammable liquids or powders.

The standard covering the requirements for creating and managing an ESD control program is ANSI/ESD S20.20 "ESD Association Standard for the Development of an Electrostatic Discharge Control Program for – Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)". ANSI/ESD S20.20 is a commercial update of and replacement for MIL-STD-1686 and has been adopted by the United States Department of Defense. In addition, the 2007-2008 update of IEC 61340-5-1 Edition 1.0 "Electrostatics - Part 5-1: Protection of Electronic Devices from Electrostatic Phenomena General Requirements" is technically equivalent to ANSI/ESD S20.20. A five-year review of ANSI/ESD S20.20 began in February 2011 and technical changes are being made to the document based on industry changes and user requests. There are unique constraints with the revision that must be taken into account, including facility certification and continued harmonization with other standards (IEC 61340-5-1 and newly revised JEDEC 625B). A target date of February 2012 has been given for the release of a draft document.

In order to meet the global need in the electronics industry for technically sound ESD Control Programs, the ESD Association has established an independent third party certification program. The program is administered by the ESDA through country-accredited ISO9000 Certification Bodies that have met the requirements of this program. The Facility Certification Program evaluates a facility's ESD program to ensure that the basic requirements from industry standards ANSI/ESD S20.20 or IEC 61340-5-1 are being followed. More than 384 facilities have been certified worldwide since inception of the program. The Factory Certification bodies report strong interest in Certification to S20.20, and consultants in this area report that inquiries for assistance remain at a very high level. Individual education also seems of interest once again as 46 professionals have obtained Certified ESD Program Manager status and many more are attempting to qualify as Certified ESD Control Program Managers. A large percentage of the certification program requirements are based on the Standards and other related documents produced by the ESD Association Standards Committee.

CURRENT ESD ASSOCIATION STANDARDS COMMITTEE DOCUMENTS

Charged Device Model (CDM)

ANSI/ESD S5.3.1-2009 Electrostatic Discharge Sensitivity Testing - Charged Device Model (CDM) - Component Level
Establishes the procedure for testing, evaluating and classifying the ESD sensitivity of components to the defined CDM.

Cleanrooms

ESD TR55.0-01-04 Electrostatic Guidelines and Considerations for Cleanrooms and Clean Manufacturing
This document identifies considerations and provides guidelines for the selection and implementation of materials and processes for electrostatic control in cleanroom and clean manufacturing environments.

Compliance Verification

ESD TR53-01-06 Compliance Verification of ESD Protective Equipment and Materials
This technical report describes the test methods and instrumentation that can be used to periodically verify the performance of ESD protective equipment and materials.

ESD Control Program

ANSI/ESD S20.20-2007 Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)
This standard provides administrative and technical requirements for establishing, implementing and maintaining an ESD Control Program to protect electrical or electronic parts, assemblies and equipment susceptible to ESD damage from Human Body Model (HBM) discharges greater than or equal to 100 volts.

ESD TR 20.20-2008—ESD Handbook (Companion to ANSI/ESD S20.20)
Produced specifically to support the ANSI/ESD S20.20 ESD Control Program Standard, this 132-page document is a major rewrite of the previous handbook. It focuses on providing guidance that can be used for developing, implementing and monitoring an ESD control program in accordance with the S20.20 Standard.

Flooring

ANSI/ESD S7.1-2005 Resistive Characterization of Materials – Floor Materials
Covers measurement of the electrical resistance of various floor materials, such as floor coverings, mats and floor finishes. It provides test methods for qualifying floor materials before installation or application, and for evaluating and monitoring materials after installation or application.

Flooring and Footwear Systems

ANSI/ESD STM97.1-2006 Floor Materials and Footwear – Resistance Measurement in Combination with a Person
Provides test methods for measuring the electrical system resistance of floor materials in combination with a person wearing static control footwear.

ANSI/ESD STM97.2-2006 Floor Materials and Footwear – Voltage Measurement in Combination with a Person
This standard test method provides for measuring, as a system, the electrostatic voltage on a person in combination with floor materials and footwear.

Footwear

ANSI/ESD STM9.1-2006 Footwear – Resistive Characterization
This standard test method defines a way of measuring the electrical resistance of shoes used for ESD control in the electronics environment (not to include heel straps and toe grounders).

ESD SP9.2-2003 Footwear – Foot Grounders Resistive Characterization
This standard practice was developed to provide test methods for evaluating foot grounders and foot grounder systems used to electrically bond or ground personnel as part of an ESD Control Program. Static Control Shoes are tested using ANSI/ESD STM9.1.

Garments

ANSI/ESD STM2.1-1997 Garments - Resistive Characterization
Provides test methods for measuring the electrical resistance of garments. It covers procedures for measuring sleeve-to-sleeve resistance and point-to-point resistance.

ESD TR2.0-01-00 Consideration for Developing ESD Garment Specifications
This technical report addresses concerns about effective ESD garments by starting with an understanding of electrostatic measurements and how they relate to ESD protection.

ESD TR2.0-02-00 Static Electricity Hazards of Triboelectrically Charged Garments
This technical report is intended to provide some insight to the electrostatic hazards present when a garment is worn in a flammable or explosive environment.

Glossary

ESD ADV1.0-2009 Glossary of Terms
Definitions and explanations of various terms used in Association Standards and documents are covered in this advisory. It also includes other terms commonly used in the electronics industry.

Gloves and Finger Cots

ANSI/ESD SP15.1-2011 In-Use Resistance Testing of Gloves and Finger Cots
This standard practice provides test procedures for measuring the intrinsic electrical resistance of gloves and finger cots.

ESD TR15.0-01-99 ESD Glove and Finger Cots
This technical report reviews the existing known industry test methods for the qualification of ESD protective gloves and finger cots.

Grounding

ANSI/ESD S6.1-2009 Grounding
Specifies the parameters, materials, equipment and test procedures necessary to choose, establish, vary and maintain an electrostatic discharge control grounding system for use within an ESD Protected Area for protection of ESD susceptible items, and specifies the criteria for establishing ESD bonding.

Handlers

ANSI/ESD SP10.1-2007 Automated Handling Equipment (AHE)
This standard practice provides procedures for evaluating the electrostatic environment associated with automated handling equipment.

ESD TR10.0-01-02 Measurement and ESD Control Issues for Automated Equipment Handling of ESD Sensitive Devices below 100 Volts
This document provides guidance and considerations that an equipment manufacturer should use when designing automated handling equipment for these low voltage sensitive devices.

Hand Tools

ESD STM13.1-2000 Electrical Soldering/Desoldering Hand Tools
This standard test method provides electric soldering/desoldering hand tool test methods for measuring the electrical leakage and tip to ground reference point resistance, and provides parameters for EOS safe soldering operation.

ESD TR13.0-01-99 EOS Safe Soldering Iron Requirements
This technical report discusses soldering iron requirements that must be based on the sensitivity of the most susceptible devices that are to be soldered.

Human Body Model (HBM)

ESDA/JEDEC JDS-001-2011 ESDA/JEDEC Joint Draft Standard for Electrostatic Discharge Sensitivity Testing – Human Body Model (HBM) – Component Level
Establishes the procedure for testing, evaluating and classifying the electrostatic discharge sensitivity of components to the defined human body model (HBM).

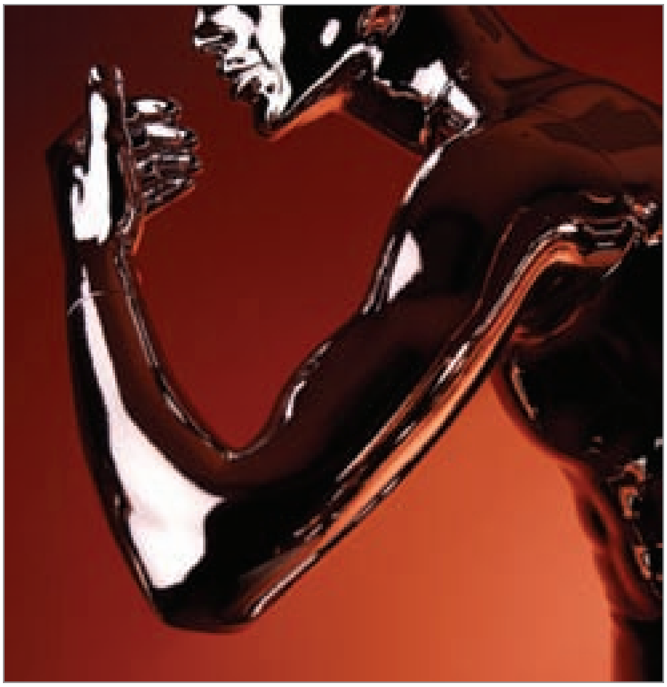
Human Body Model (HBM) and Machine Model (MM)

ANSI/ESD SP5.1.1-2006 Human Body Model (HBM) and Machine Model (MM) Alternative Test Method: Supply Pin Ganging – Component Level
This standard practice defines an alternative test method to perform Human Body Model or Machine Model component level ESD tests when the component or device pin count exceeds the number of ESD simulator tester channels.

ANSI/ESD SP5.1.2-2006 Human Body Model (HBM) and Machine Model (MM) Alternative Test Method: Split Signal Pin - Component Level
This standard practice defines another alternative test method to perform Human Body Model or Machine Model component level ESD tests when the component or device pin count exceeds the number of ESD simulator tester channels.

Human Metal Model (HMM)

ANSI/ESD SP5.6-2009 Electrostatic Discharge Sensitivity Testing - Human Metal Model (HMM) - Component Level
Establishes the procedure for testing, evaluating and classifying the ESD sensitivity of components to the defined HMM.



ESD TR5.6-01-09 Human Metal Model (HMM)
This technical report addresses the need for a standard method of applying the IEC contact discharge waveform to devices and components.

Ionization

ANSI/ESD STM3.1-2006 Ionization
Test methods and procedures for evaluating and selecting air ionization equipment and systems are covered in this standard test method. The document establishes measurement techniques to determine ion balance and charge neutralization time for ionizers.

ANSI/ESD SP3.3-2006 Periodic Verification of Air Ionizers
This standard practice provides test methods and procedures for periodic verification of the performance of air ionization equipment and systems (ionizers).

ESD TR3.0-01-02 Alternate Techniques for Measuring Ionizer Offset Voltage and Discharge Time
This technical report investigates measurement techniques to determine ion balance and charge neutralization time for ionizers.

ESD TR3.0-02-05 Selection and Acceptance of Air Ionizers
This document reviews and provides a guideline for creating a performance specification for the four ionizer types contained in ANSI/ESD STM3.1: room (systems), laminar flow hood, worksurface (e.g. blowers) and compressed gas (nozzles & guns).

Machine Model (MM)

ANSI/ESD S5.2-2009 Electrostatic Discharge Sensitivity Testing - Machine Model (MM) - Component Level
Establishes the procedure for testing, evaluating and classifying the ESD sensitivity of components to the defined MM.

ESD TR5.2-01-01 Machine Model (MM) Electrostatic Discharge (ESD) Investigation - Reduction in Pulse Number and Delay Time
This report provides the procedures, results and conclusions of evaluating a proposed change from 3 pulses (present requirement) to 1 pulse while using a delay time of both 1 second (present requirement) and 0.5 second.

Ohmmeters

ESD TR50.0-02-99 High Resistance Ohmmeters--Voltage Measurements
This technical report discusses a number of parameters that can cause different readings from high resistance meters when improper instrumentation and techniques are used, as well as the techniques and precautions to be used in order to ensure the measurement will be as accurate and repeatable as possible for high resistance measurement of materials.

Packaging

ANSI/ESD STM11.11-2006 Surface Resistance Measurement of Static Dissipative Planar Materials
This standard test method defines a direct current test method for measuring electrical resistance, replacing ASTM D257-78. This test method is designed specifically for static dissipative planar materials used in packaging of ESD sensitive devices and components.

ANSI/ESD STM11.12-2007 Volume Resistance Measurement of Static Dissipative Planar Materials
This standard test method provides test methods for measuring the volume resistance of static dissipative planar materials used in the packaging of ESD sensitive devices and components.

ANSI/ESD STM11.13-2004 Two-Point Resistance Measurement
This standard test method measures the resistance between two points on a material's surface without consideration of the material's means of achieving conductivity. This test method was established for measuring resistance where the concentric ring electrodes of ANSI/ESD STM11.11 cannot be used.

ANSI/ESD STM11.31-2006 Bags
This document provides a method for testing and determining the shielding capabilities of electrostatic shielding bags.

ANSI/ESD S541-2008 Packaging Materials for ESD Sensitive Items
This standard describes the packaging material properties needed to protect ESD sensitive electronic items, and references the testing methods for evaluating packaging and packaging materials for those properties. Where possible, performance limits are provided. Guidance for selecting the types of packaging with protective properties appropriate for specific applications is provided, as well as other considerations for protective packaging.

ESD ADV11.2-1995 Triboelectric Charge Accumulation Testing
Provides guidance in understanding the triboelectric phenomenon and relates current information and experience regarding tribocharge testing as used in static control for electronics.

Seating

ANSI/ESD STM12.1-2006 Seating – Resistive Measurement
This document provides test methods for measuring the electrical resistance of seating used for the control of electrostatic charge or discharge. It contains test methods for the qualification of seating prior to installation or application, as well as test methods for evaluating and monitoring seating after installation or application.

Socketed Device Model (SDM)

ANSI/ESD SP5.3.2-2008 Electrostatic Discharge Sensitivity Testing – Socketed Device (SDM) – Component Level
This standard practice provides a test method for generating a Socketed Device Model (SDM) test on a component integrated circuit (IC) device.

ESD TR5.3.2-01-00 Socket Device Model (SDM) Tester
This technical report helps the user understand how existing SDM testers function, offers help with the interpretation of ESD data generated by SDM test systems, and defines the important properties of an "ideal" socketed-CDM test system.

Static Electricity

ESD TR50.0-01-99 Can Static Electricity Be Measured?
This report gives an overview of fundamental electrostatic concepts, electrostatic effects and, most importantly, electrostatic metrology, with special attention to what can and what cannot be measured.

Susceptible Device Concepts

ESD TR50.0-03-03 Voltage and Energy Susceptible Device Concepts, Including Latency Considerations
This technical report contains information to promote an understanding of the differences between energy and voltage susceptible types of devices and their sensitivity levels.

Symbols

ANSI/ESD S8.1-2007 Symbols – ESD Awareness
Three types of ESD awareness symbols are established by this document. The first one is used on a device or assembly to indicate susceptible to electrostatic charge. The second is to be used on items and materials intended for electrostatic protection. The third symbol indicates the common point ground.

System Level ESD

ANSI/ESD SP14.1-2004 System Level Electrostatic Discharge (ESD) Simulator Verification
This standard practice was developed to provide guidance to designers, manufacturers and calibration facilities for verification and specification of the systems and fixtures used to measure simulator discharge currents.

ESD TR14.0-01-00 Calculation of Uncertainty Associated with Measurement of Electrostatic Discharge (ESD) Current
This technical report provides guidance on measuring uncertainty based on an uncertainty budget.

Transient Latch-up

ANSI/ESD SP5.4-2008 Latch-up Sensitivity Testing of CMOS/Bi CMOS Integrated Circuits – Transient Latch-up Testing – Component Level Supply Transient Stimulation
This standard practice was developed to instruct the reader on the methods and materials needed to perform Transient Latch-Up Testing.

ESD TR5.4-01-00 Transient Induced Latch-Up (TLU)
This report provides a brief background on early latch-up work, reviews the issues surrounding power supply response requirements, and discusses efforts in RLC TLU testing, transmission line pulse (TLP) stressing and the new bi-polar stress TLU methodology.

ESD TR5.4-02-08 Determination of CMOS Latch-up Susceptibility - Transient Latch-up - Technical Report No. 2
This technical report is intended to provide background information pertaining to the development of the transient latch-up standard practice originally published in 2004 and additional data presented to the group since publication.

Transmission Line Pulse

ANSI/ESD STM5.5.1-2008 Electrostatic Discharge Sensitivity Testing – Transmission Line Pulse (TLP) – Component Level
This document pertains to Transmission Line Pulse (TLP) testing techniques of semiconductor components. The purpose of this document is to establish a methodology for both testing and reporting information associated with TLP testing.

ANSI/ESD SP5.5.2-2007, Electrostatic Discharge Sensitivity Testing - Very Fast Transmission Line Pulse (VF-TLP) - Component Level
This document pertains to Very Fast Transmission Line Pulse (VF-TLP) testing techniques of semiconductor components. It establishes guidelines and standard practices presently used by development, research and reliability engineers in both universities and industry for VF-TLP testing. This document explains a methodology for both testing and reporting information associated with VF-TLP testing.

ESD TR5.5-01-08 Transmission Line Pulse (TLP)
This technical report is a compilation of the information gathered during the writing of ANSI/ESD SP5.5.1 and the information gathered in support of moving the standard practice toward re-designation as a standard test method.

ESD TR5.5-02-08 Transmission Line Pulse Round Robin
This report is intended to provide data on the repeatability and reproducibility limits of the methods of ANSI/ESD STM5.5.1.

Workstations

ESD ADV53.1-1995 ESD Protective Workstations
This Advisory document defines the minimum requirements for a basic ESD protective workstation used in ESD sensitive areas. A test method is provided for evaluating and monitoring workstations. It defines workstations as having the following components: support structure, static dissipative worksurface, any attached shelving or drawers, and means of grounding personnel.

Worksurfaces

ANSI/ESD S4.1-2006 Worksurface - Resistance Measurements
Provides test methods for evaluating and selecting worksurface materials, testing of new worksurface installations, and the testing of previously installed worksurfaces.

ANSI/ESD STM4.2-2006 ESD Protective Worksurfaces - Charge Dissipation Characteristics
Aids in determining the ability of ESD protective worksurfaces to dissipate charge from a conductive test object placed on them.

ESD TR4.0-01-02 Survey of Worksurfaces and Grounding Mechanisms
This document provides guidance for understanding the attributes of worksurface materials and their grounding mechanisms.

Wrist Straps

ANSI/ESD S1.1-2006 Wrist Straps
A successor to EOS/ESD S1.0, this document establishes test methods for evaluating the electrical and mechanical characteristics of wrist straps. It includes improved test methods and performance limits for evaluation, acceptance and functional testing of wrist straps.

ESD TR1.0-01-01 Survey of Constant (Continuous) Monitors for Wrist Straps
This technical report provides guidance to ensure that wrist straps are functional and are connected to people and ground.

*Founded in 1982, the **ESD Association** is a professional voluntary association dedicated to advancing the theory and practice of electrostatic discharge (ESD) avoidance. From fewer than 100 members, the Association has grown to more than 2,000 throughout the world. From an initial emphasis on the effects of ESD on electronic components, the Association has broadened its horizons to include areas such as textiles, plastics, web processing, cleanrooms and graphic arts. To meet the needs of a continually changing environment, the Association is chartered to expand ESD awareness through standards development, educational programs, local chapters, publications, tutorials, certification and symposia.*

Electrostatic Discharge Technology Roadmap

BY THE ESD ASSOCIATION

This article provides estimates of future ESD device thresholds and their potential impact on ESD control practices. The threshold estimates reflect the prevailing trends in semiconductor technology as viewed by selected industry leaders. These projections are intended to provide a view of future device protection limitations driven by performance requirements and technology scaling. It also provides a common view of expected performance for device suppliers and users. Finally, these trends point to the need for continued improvements in ESD control procedures and compliance.

In the late 1970s, electrostatic discharge, or ESD, became a problem in the electronics industry. Low level ESD events from people were causing device failures and yield losses. As the industry learned about this phenomenon, both device design improvements and process changes were made to make the devices more robust and processes more capable of handling these devices.

After going through a learning curve during the 1980s and early 1990s, device engineers were able to create protection structures that could withstand higher levels of ESD and thus made the devices less sensitive to ESD events. Both device engineers and circuit designers were able to identify key technology parameters that helped them develop more robust devices.

In the mid to late 1990s however, the requirements for increased performance (devices that operate at 1 GHz and higher) and the increase in the density of circuits on a device caused problems for traditional ESD protection circuits. This was exacerbated by the continued scaling of the technologies toward sub-100 nm feature sizes in order to achieve higher density and performance. The advent of IC chips with sub-50 nm technologies rapidly coming into production made the situation worse. Due to this trend, ICs became even more sensitive to ESD events in the years between 2005 and 2009. Therefore, the prevailing trend is circuit performance at the expense of ESD protection levels. This is now becoming critical for high speed serial link IOs (HSS), and even more so in the case of RF circuit applications.

DEVICE ESD THRESHOLD TRENDS

The following graphs show the device ESD design sensitivity trends based on the most relevant and important ESD models used by device manufacturers as part of the device qualification process: Human Body Model (HBM) and Charge Device Model (CDM). The sensitivity limits are a projection by engineers from leading semiconductor manufacturers. First, the projections for HBM design (min and max) are indicated in Figure 1. Also shown is the progression of ESD control capability for HBM during the same time period. Although design improvements were made from 1978 through 1993, advanced circuit performance effects started to take place around this time, eventually degrading the levels. The max levels represent what is generally possible with technology scaling and min levels represent the constriction coming from meeting circuit performance demands. It is interesting to observe that the gap between the ESD control and sensitive device HBM levels is closing in and that, at the beginning of this new decade, the control of ESD for HBM is just barely below the minimum expected high sensitivity HBM designs. Therefore, proactive implementation of advanced HBM controls using the limits and qualifications requirements in ANSI/ESD S2020 or IEC 61340-5-1 would become necessary within the next 5 years.

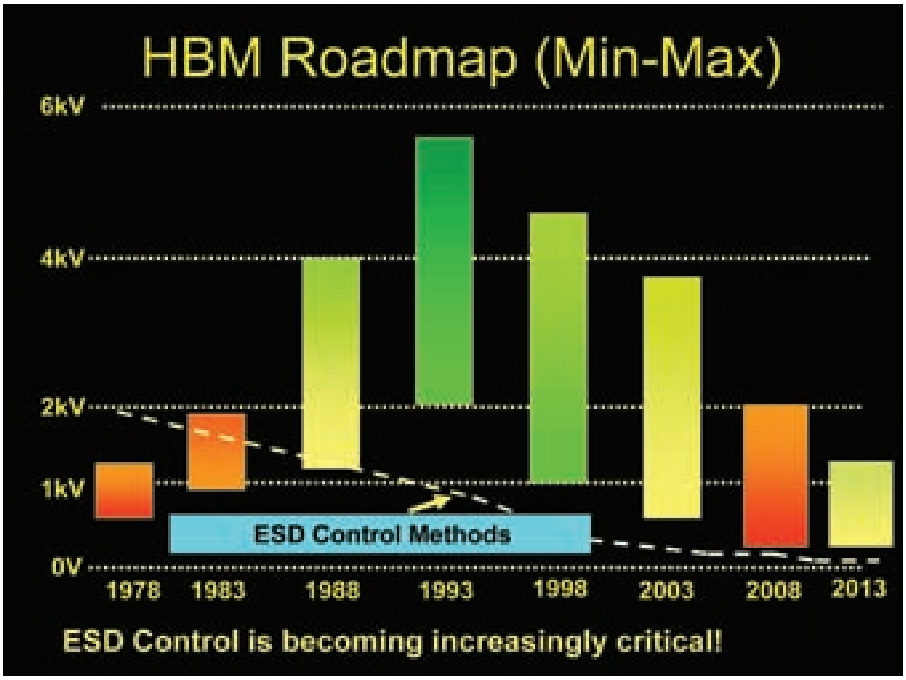


Figure 1: HBM sensitivity limits projections

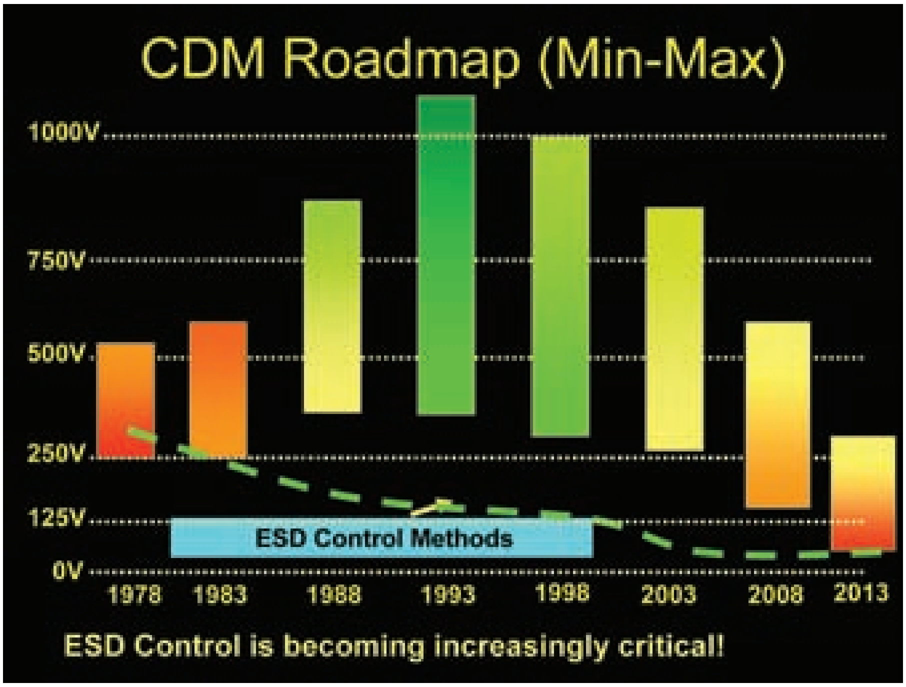


Figure 2: CDM sensitivity limit projections

The projections for CDM design (min and max) are indicated in Figure 2. Also shown is the progression of ESD control capability for CDM during the same time period. The same general arguments as given above for HBM also apply for CDM. However, the advanced designs will have a larger impact on CDM. This is because the HSS IOs are generally used in high pin-count, hence larger capacitance, IC packages. This higher capacitance leads to relatively higher magnitude discharge peak current levels, and thus greater challenges in CDM protection design. For CDM, a proactive implementation of advanced CDM controls would not only become necessary but would become mandatory within the next 5 years.

For future device qualification, HBM and CDM should fulfill the necessary requirements. Further, as documented in White Paper I from the Industry Council, Machine Model (MM) protection is intrinsic to HBM and does not need separate tracking for design purposes [1].

Thus, a separate technology roadmap for MM is not necessary. However, it can be assumed that the MM values are generally a factor of between 10 and 30 times lower than the published HBM qualification numbers for HBM >500V, and approximately 5 times lower for HBM <500V. It should also be pointed out that conductor-to-device discharges are not well represented by MM. The CDM method gives a better representation of these events. In summary, although machine discharge control is important for a factory environment, the MM device test method levels themselves, per-se, have no relevance. HBM and CDM levels are the important criteria for technology scaling.

Process Capability

These ESD sensitivity trends will have a major impact on manufacturing process yields over the next five years. Companies need to verify that the installed ESD processes are capable of handling these devices.

When designing ESD control processes they must be repeatable and consistent. In addition, there must be a way to evaluate how effective the ESD control items are, based on the sensitivities that are expected to be handled. The following notes provide guidelines on how to evaluate ESD control processes.

Human Body Model (HBM)

It has been shown that for a wrist strap system, the resistance of the person to ground has a direct correlation to the maximum voltage on a person. For wrist straps, Figure 3 may be used.

For an ESD control program that uses ESD footwear and flooring to ground personnel, the situation is more complex. As people walk across an ESD floor while wearing ESD footwear, it is difficult to predict the voltage on a persons' body due to the constantly changing body capacitance and the continuous charging and discharging of the person.

ANSI/ESD STM97.2 can be used to determine the process capability of the footwear flooring system. An example of the type of information provided can be seen in Figure 4.

Metal Discharge Events

Machine discharges occur when charged, conductive surfaces come into contact with ESD sensitive devices. To

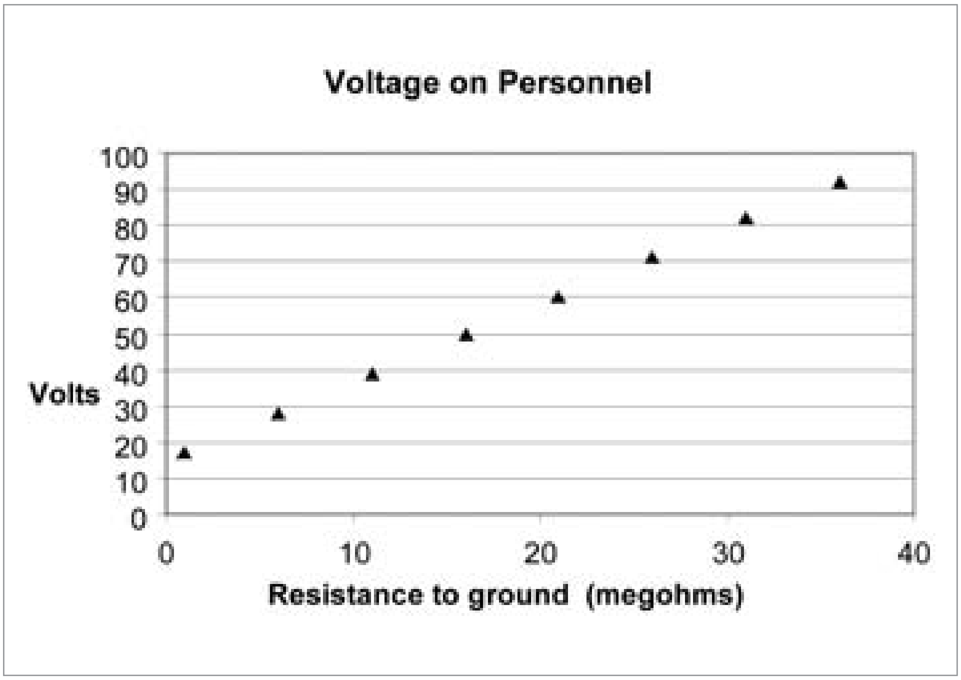


Figure 3: Resistance in a wrist strap system

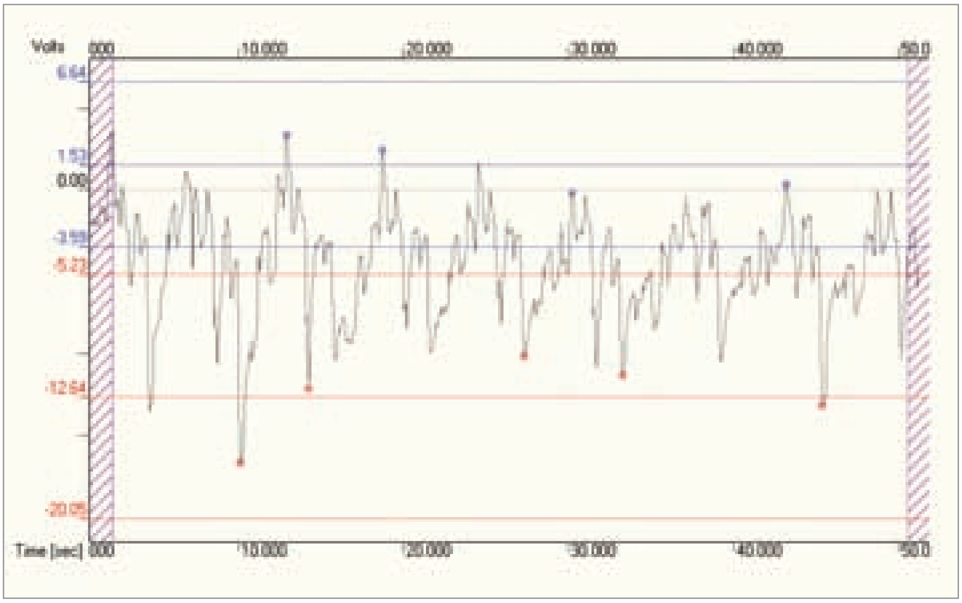


Figure 4: Determining process capability of a footwear/flooring system using ANSI/ESD STM 97.2

minimize machine discharges, ensure that all metal surfaces that come into contact with ESD sensitive devices are grounded. Measurements should be made to ensure that moving parts remain grounded throughout the process.

CDM Events (CDM)

CDM damage occurs when a charged ESD sensitive device is grounded or when a neutral device is grounded in the presence of an electrostatic field. Effective ESD control programs ensure that process required insulators will not induce damaging voltage levels onto the devices being handled, nor allow a device to acquire a charge by triboelectrification and then be subsequently grounded in an uncontrolled fashion.

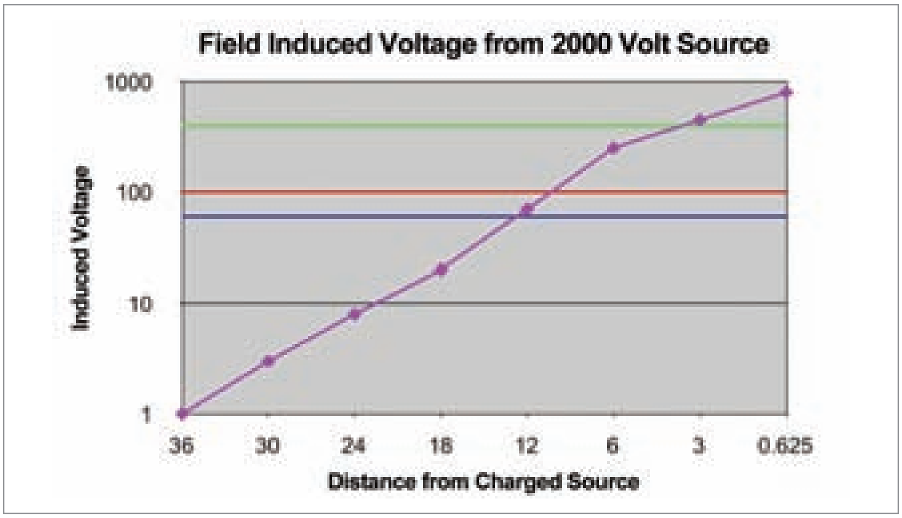


Figure 5: Voltage induced onto a 20 pF parallel plate capacitor from a 2000 volt uniform voltage source at varying distances

An example of the impact of decreasing CDM levels on factory practices is illustrated in Figure 5. This chart shows the voltage induced onto a 20 pF parallel plate capacitor from a 2000 volt uniform voltage source at varying distances. Overlaid onto the chart are the minimum CDM levels from the CDM roadmap for the years 2000, 2005, and 2010. Since devices become more sensitive over time, it will be necessary to either:

a. increase the distance between the ESD sensitive devices and the charged source or

b. reduce the charges on surfaces to limit the induced voltage to levels that will not damage ESD sensitive devices.

CONCLUSIONS

With devices becoming more sensitive through 2010-2015 and beyond, it is imperative that companies begin to scrutinize the ESD capabilities of their handling processes. Factory ESD control is expected to play an ever-increasingly critical role as the industry is flooded with even more HBM and CDM sensitive designs. For people handling ESD sensitive devices, personnel grounding systems must be designed to limit body voltages to less than 100 volts.

To protect against metal-to-device discharges, all conductive elements that contact ESD sensitive devices must be grounded.

To limit the possibilities of a field induced CDM ESD event, users of ESD sensitive devices should ensure that the maximum voltage induced on their devices is kept below 50 volts.

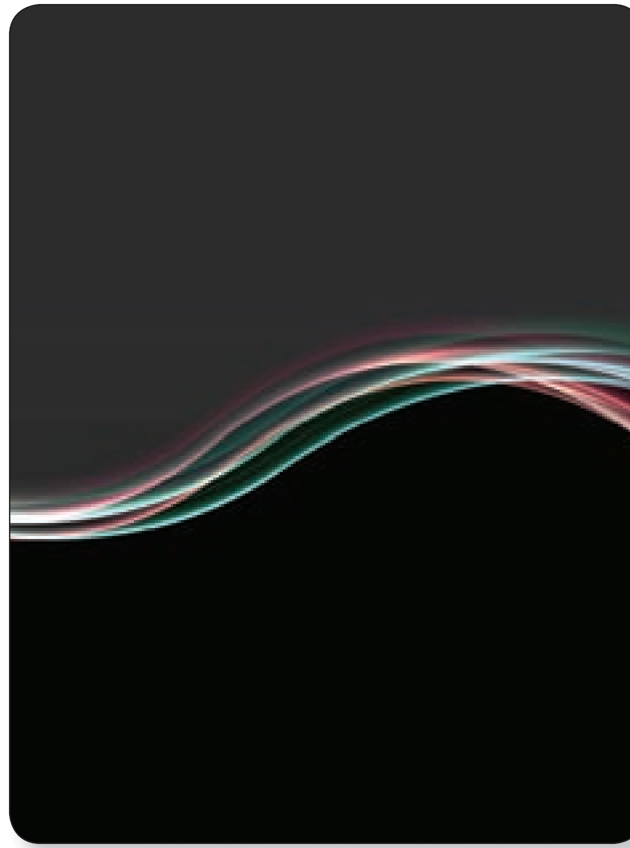
To limit CDM ESD events, device pins should be contacted with static-dissipative material instead of metal wherever possible.

REFERENCES

1. ESD Association, *White Paper 1: A Case for Lowering Component Level HBM/MM ESD Specifications and Requirements* (E 2008) http://www.esda.org/IndustryCouncil.html.

2. ESD Association, *White Paper 2: A Case for Lowering Component Level CDM ESD Specifications and Requirements* (March 2009) http://www.esda.org/IndustryCouncil.html.

The ESD Association
Founded in 1982, the ESDA is a professional voluntary association dedicated to advancing the theory and practice of electrostatic discharge (ESD) avoidance. From fewer than 100 members, the Association has grown to more than 2,000 throughout the world. From an initial emphasis on the effects of ESD on electronic components, the Association has broadened its horizons to include areas such as textiles, plastics, web processing, cleanrooms and graphic arts. To meet the needs of a continually changing environment, the Association is chartered to expand ESD awareness through standards development, educational programs, local chapters, publications, tutorials, certification and symposia.



Systems Response to Electrostatic Discharge

Applications of impulse waveform research toward evaluation of product performance

BY W. MICHAEL KING

A NOTE FROM THE AUTHOR

The research references provided in this article occurred between 1978 and 1987, and are as applicable today as they were then, when they advanced understanding of ESD phenomena and through that, the ESD state of the art of knowledge.

These were the first reports to display that: ESD currents to a system do not increase in direct proportion to the initial electrostatic charge amplitude produced before the ESD event (e.g. low ESD voltages produce higher current than higher voltages); ESD spectra is greater than 1GHz with rise-times much faster than 1.0 nanosecond (e.g. 50 pSec to 200 pSec); the ESD "equivalent network" is not a single R-C network as previously thought, but rather a complex cascade of several networks, each with a different time constant; a "single ESD event" may be comprised of many events, even showing the approximate periodicity between each sub-event; suggested the initial impact of ESD was from boundary charge displacements of electric fields; detailed the ESD impulse waveforms and currents related to many common conditions (finger-tip direct, humans discharging through metal objects, humans discharging through furnishings); described how systems produce ESD amplitude-response dependencies owing to the different spectra of ESD events at different amplitudes; and, that compliance with a higher amplitude of ESD (e.g. 15kV) does not assure that adequate immunity will be exhibited at lower (e.g. 2kV) levels. During these research efforts the "human body concept", the "human with metal object" concept; the "furnishings impact" equivalent values; the vertical and horizontal coupling planes for "radiated ESD equivalents" were all devised. The impact on the international community was sufficiently extensive starting circa 1979 that approximately five years of confirming work were required for the reports to achieve broad acceptance.

Since that time this work has been thoroughly disseminated and various standards and standard practices for ESD have been published, many (if not most) of which extend from these early research efforts. In the process of standardization some of the baseline foundational information delineating ESD mechanisms have been diffused. It didn't help that when the IEEE converted published symposia archives to microfiche some years ago, much of the original photographic data for ESD event waveforms was lost as the contrast of the original printed publications became often degraded to black rectangles. Thanks to the invitation of The Editor of this magazine, you have the opportunity to travel with me, back to history, and back to this future to gather a broad understanding of the underlying boundary charge displacements that establish ESD, catch a glimpse of the propagational spectral mechanisms that impact systems-product performance, and to review foundational information that extends to this day.

W. Michael King

(For further reading, I suggest the book "Electrostatic Discharge" Third Edition by Michel Mardiguian, Wiley/IEEE Press, ISBN: 978-0470-39704-6, and ANSI, C-63.16-1994 "Guide for Electrostatic Discharge Test Methodologies and Criteria for Electronic Equipment.")

In recent years, various research results have been published that define (for the first time) the true complexity of dynamic impulse waveforms developed through personnel electrostatic discharge (ESD) events (see reference list). These research studies have contributed significantly toward understanding the ESD susceptibility response mechanisms exhibited by systems products that previously were considered to be "mysterious".

Examples of such system responses are performance criteria failing at low ESD initialization levels (<2 kV) and complying at higher levels (>7 kV), or complying at low initialization levels failing at intermediate levels (5 to 7 kV) and complying at higher levels (>10 kV).

This paper discusses the application of ESP impulse waveform research results toward understanding the ESD amplitude-waveform dependency of susceptibility responses from systems products, and outlines the conceptual aspects of the test methodology required for thorough product evaluation.

BACKGROUND

During the time frame of 1978 through 1983, an experimental measurement series to determine the ESD waveform continuum was performed, with results published in various forums [1, 3 and 4]. Further work that tended to confirm the earlier results continued into 1986 [6]). The results of these experimental measurements indicated:

a. The dynamic waveform continuum of ESD events exhibited exceptionally high bandwidths of spectral level distribution at low ESD initialization levels [<5 kV] extending into the microwave domain, with risetimes measured and reported as fast as 200 picoseconds (See Figure 1);

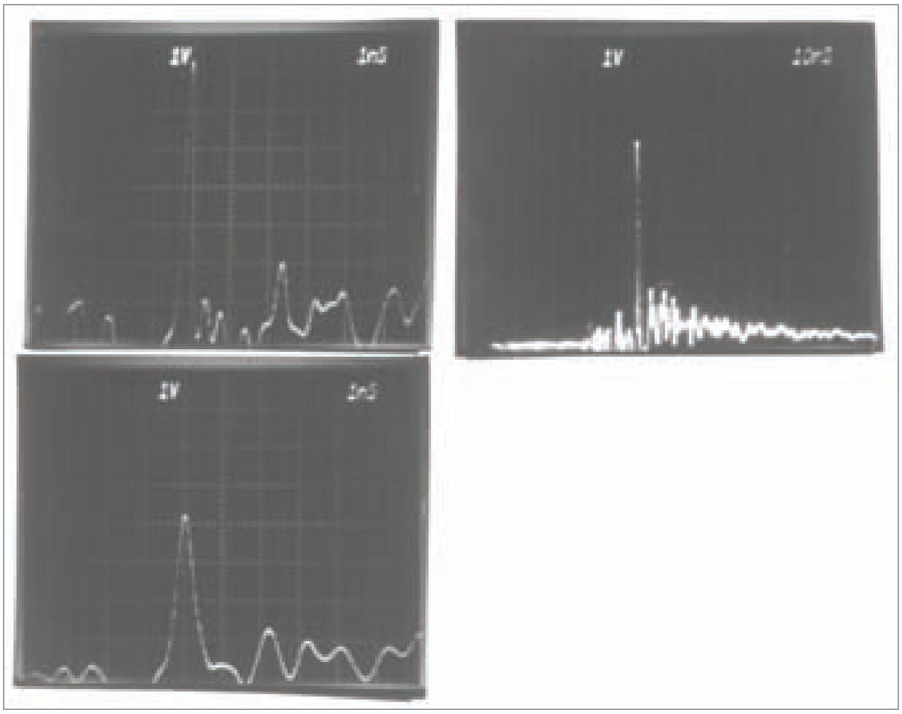


Figure 1a: ESD Impulse Waveform Distribution: Human with Metallic Object; 2,000 Volts Initialization.
Scale: 10 Amperes/Division. Displayed: 42 Amperes to 74 Amperes
(Tr = 200 pSec; Tf = 50 pSec)

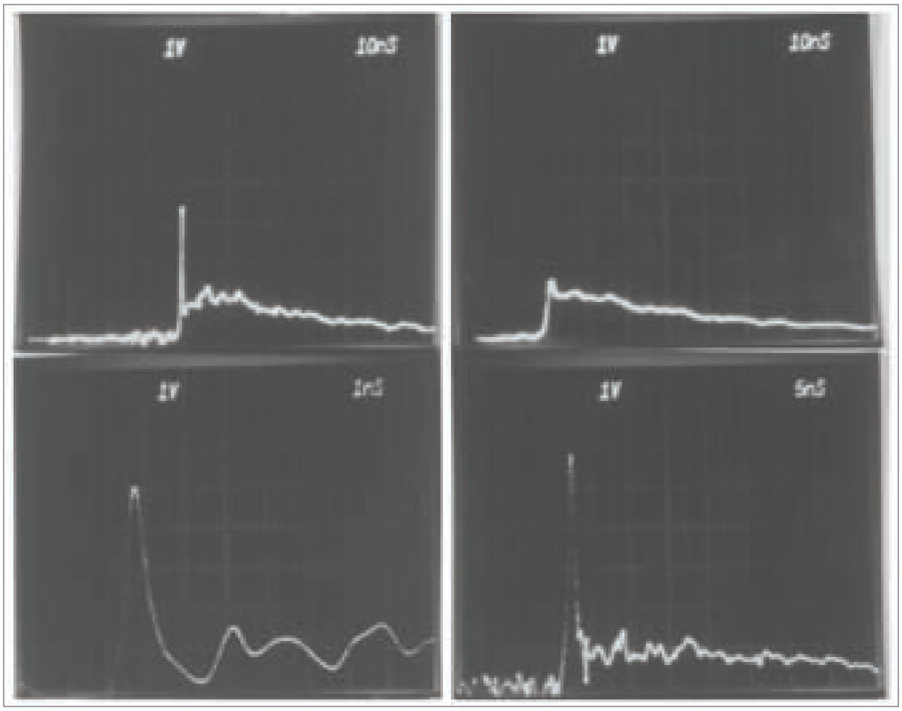


Figure 1b: ESD Impulse Waveform Distribution: Human with Metallic Object; 4,000 Volts Initialization. Examples of event-to-event distribution in nature
Scale: 10 Amperes/Division. Displayed: 15 Amperes to 58 Amperes

ESD

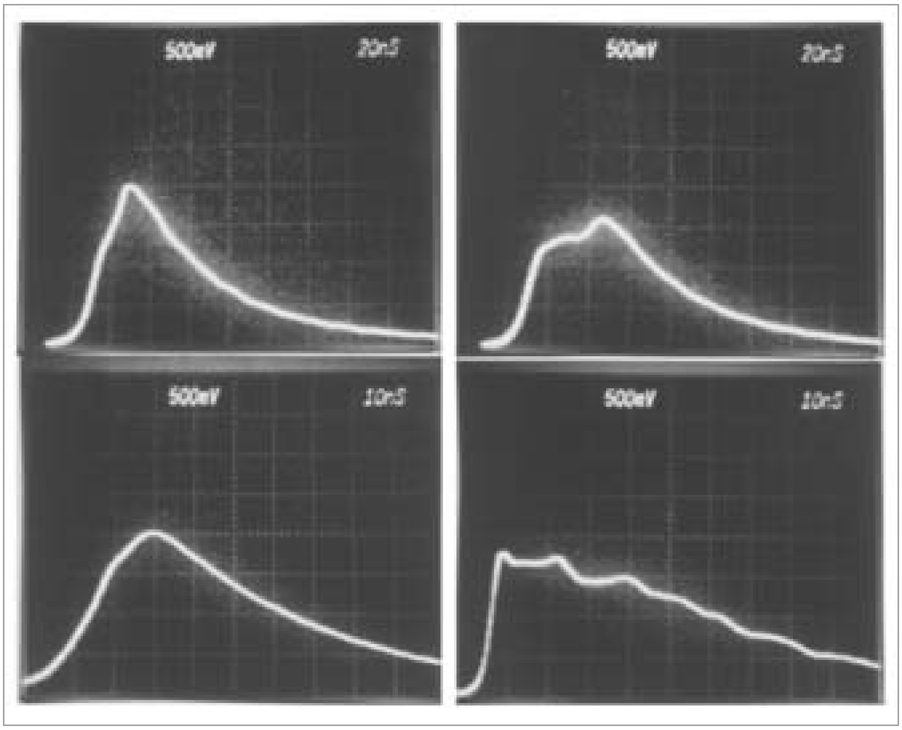


Figure 2a: ESD Impulse Waveform Distribution: Human with Metallic Object; 10,000 Volts Initialization.
Examples of event-to-event distribution in nature
Scale: 5 Amperes/Division. Displayed: 16 Amperes to 20 Amperes

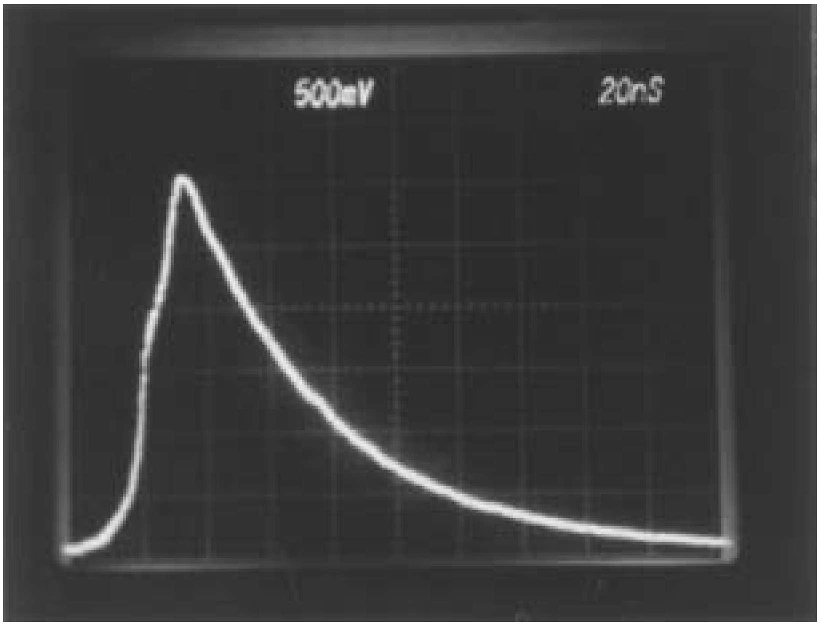


Figure 2b: ESD Impulse Waveform Example: Human with Metallic Object; 20,000 Volts Initialization
Scale: 5 Amperes/Division: Displayed: 31 Amperes

b. The spectral bandwidths of ESD resulting from higher initialization levels (>10 kV, <20 kV) ranged in the tens to hundreds of megahertz, with risetimes in the order of 4 nanoseconds to several tens of nanoseconds (See Figure 2). The spectral bandwidths of ESD initialization levels between these two extremes were found to range in between, with risetimes in the one to ten nanosecond range (See Figure 3);

c. There are vast differences in ESD peak current delivered (as impulse intensity) to a product when a human discharge occurs from a finger-tip as compared to a human holding a metallic object (key, coin, pen, tool). See Figure 4.

Independently worked from a theoretical approach, studies by William Byrne, then Senior Scientist at the Southwest Research Institute (in San Antonio, TX), generally provided theoretical confirmation of the previously described experimental results [2 and 5].

The experimental test methods developed to determine the ESD waveforms as described in the referenced research efforts have been utilized broadly in the international technical community, and form the basis of capital ESD publications of the International Electrotechnical Commission (IEC).

Based on the information provided through the research efforts noted above, a thorough understanding of systems response to ESD events becomes possible. When combined with these applications of impulse waveform research, an approach to comprehensive evaluation of product and systems performance during ESD event exposure is extrapolated.

ESD IMPULSE PROPAGATION

The propagation of ESD impulse current in a product or system is significantly influenced by the distributed common-mode impedance magnitude of the product/system's structure relative to external ground surfaces. Usually, these dynamic reference transfer impedances are simply referred to as being "coupled to ground", although spatially they may also couple/propagate to structures that are immediately adjacent to the product being subjected to the ESD event. (When the ESD is applied to a STRUCTURE that is immediately adjacent to the product under evaluation, a radiated field displacement occurs through these same distributed transfer impedances, causing (potentially) a form of radiated susceptibility.)

The distributed transfer impedance of a unit above the reference (ground) is paralleled by the ground wire connection in the primary AC power cable, as well as the power lines themselves. The combined product-level impedance that is ultimately transferred to "ground" as represented by these segments is, in turn, paralleled by the distributed and direct impedance of any interface cables that are connected to the product under evaluation. (This is because the interface cables, in themselves, are referenced [coupled] to "ground", and the interfaced product/system that is eventually connected to the opposite end of the interface cables are probably connected to "ground" through other primary AC power cables.) [7].

It may be recognized that the two axis of distributed transfer impedances (to ground and literally to adjacent structures) mutually share the ESD impulse currents within impedances that develop in the interface cables to ground and to other equipment. Further, these two axis provide current sharing interactions with the references yielded through the AC power cables.

Given the propagation of ESD energy via these multiple paths, it can be recognized that the magnitude of the ESD impulse current that circulates in the interface cables (entering or a exiting the product) must be influenced by the characteristics of the distributed transfer impedance of the product above ground. In other words, the lower the value of distributive transfer impedance formed between a product and ground, the higher value of impulse current will flow through the distributive vehicle, and lower will be the relative value of impulse ESD current that will propagate through the interface or power cables.

With these interactions of the ESD propagational "sharing" through impulse propagational references directed through the various paths noted above, substantial ESD performance (susceptibility) variances are encountered by altering the

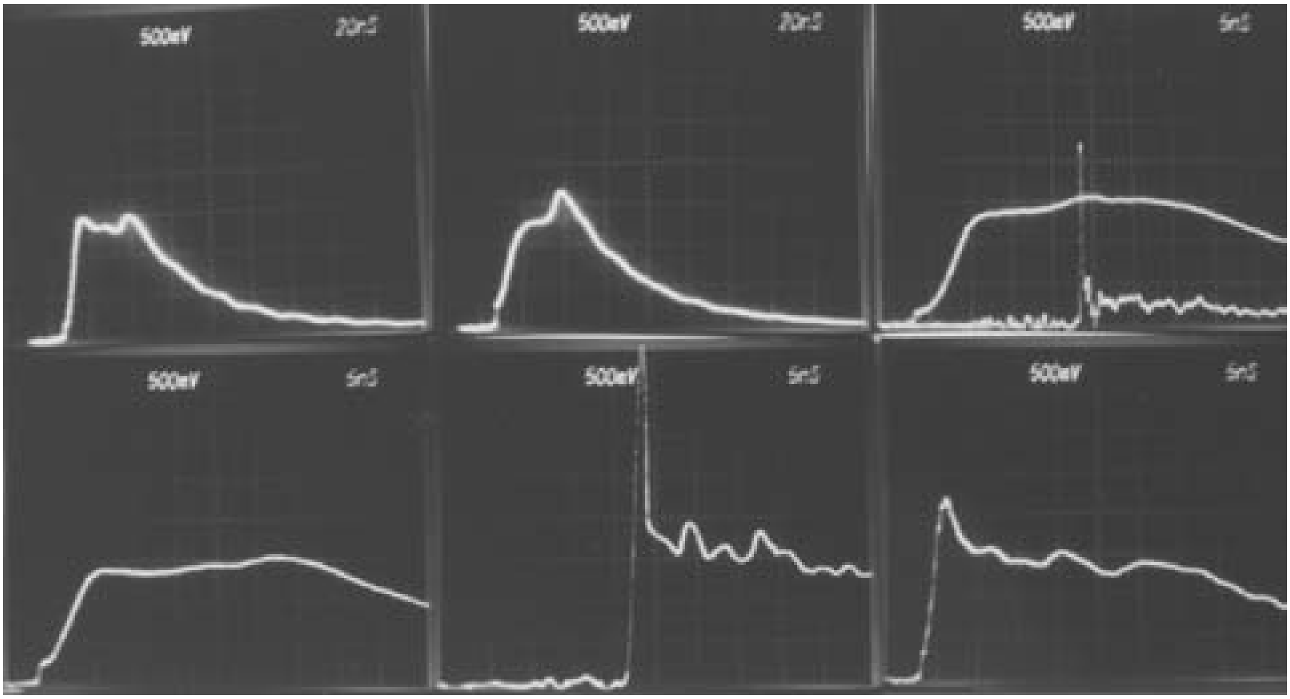


Figure 3: ESD Impulse Waveform Distribution: Human with Metallic Object; 8,000 Volts Initialization
Scale: 5 Amperes/Division: Displayed 15 Amperes to 40 Amperes.

distributed impedance parameters of products through conditional/installation means. Such would be the effect, for example, of encountering ESD susceptibility response variations from a desk-top unit by placing the unit on a metal desk versus placing the unit on a non-conductive wooden desk.

This variable-response effect is brought about because the lower distributive transfer impedance provided to the unit (to "ground") through the metal desk will, in execution:

a. Move ESD energy away from the interface and power cables, resulting in less potential interface susceptibility because there will be reduced ESD current/energy propagated in the interface (and power) cables.

b. Intensify the ESD current in the case and cabinet structures of the unit that are coupled to ground through distributive means, thereby increasing the potential for ESD susceptibility effects from case-derived (shielding or slot aperture) causes.

Accordingly, the potential of ESD performance variations available for smaller (desk-top or handheld) units may be far greater in terms of both ESD amplitude thresholds, and response characteristics, than those potential variations that may be exhibited for a larger system or floor-standing unit, in that the relative impedance ratios between the interface impedance paths and the distributive (structural) impedance is potentially more variable for the desk-top supported or hand-held unit.

On a unit level, these same interactions are responsible for variations in the ESD susceptibility performance of products with remote keyboards (or hand-held devices) if the ESD impulses are applied to the "remote" keyboard when it is supported above a non-conductive desk while the "host" product is above a common conductive (desk) support plane. The ESD impulse transfers in the keyboard cable will be significantly altered by execution of these relatively simple installation condition changes.

ESD AMPLITUDE DEPENDENCIES

Through the referenced research efforts, it has been recognized that the spectral bandwidth of the ESD event, considered as a continuum, is highly dependent on the electrostatic initialization amplitudes that are evident immediately prior to the displacement of the stored energy through the ESD event.

In general:

a. High ESD initialization amplitudes produce relatively lower frequency spectral bandwidth distributions.

b. Lower ESD initialization levels produce extremely high frequency (extending into microwave) spectral bandwidth distributions.

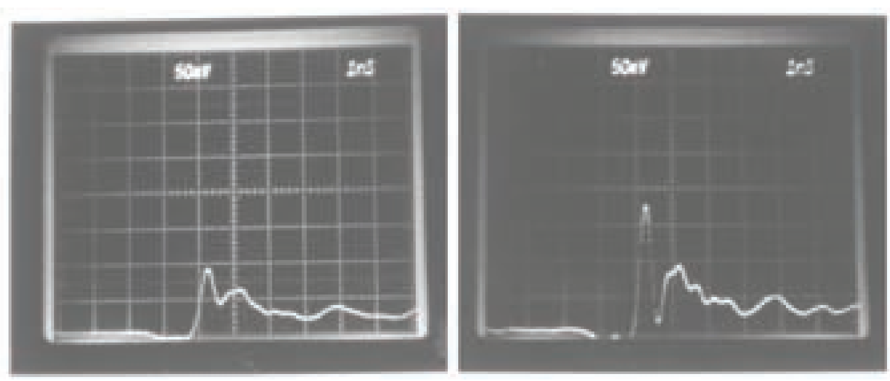


Figure 4a: ESD Impulse Waveform From Human Finger-tip: 500 Volts Initialization Scale: 0.5 Amperes/Division. Displayed: 0.9 Amperes to 1.8 Amperes; (Tr = 200 pSec)

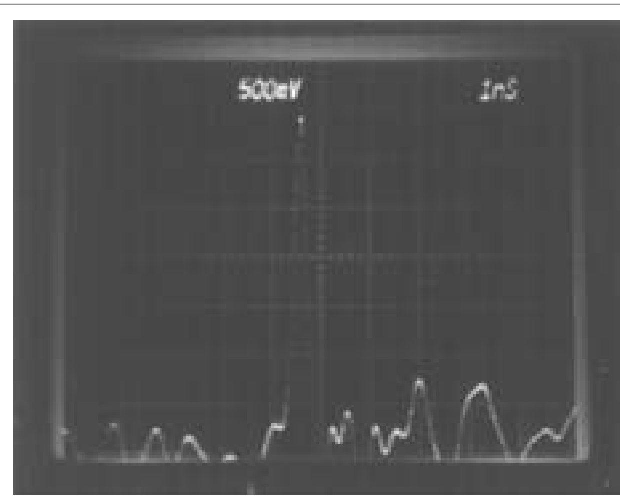


Figure 4b: ESD Impulse Waveform, Human with Metallic Object: 500 Volts Initialization
Scale: 5.0 Amperes/Division. Displayed: 34 Amperes

(COMMENT: The metal object condition yields 19:1 Greater Current than Finger-tip condition).

c. Mid-range ESD levels (5 to 10 kV) develop spectral bandwidth distributions that appear to center in the general area of 100 MHz (which is approximately midrange in the spectral bandwidth envelope of the available ESD spectral probabilities).

The ESD susceptibility dependencies intrinsic to system response are obviously influenced by the conditional mechanisms described above since these factors impact various ESD response excitations of related components of the product or system (e.g. cables or casework). In and of themselves, these conditional factors can alter the susceptibility performance of system products in terms of ESD response amplitude, response mechanism, and response characteristics with a causal relationship to the conditional basis.

Suppose, for example, that the interface circuit of a desktop product has a design weakness to common-mode currents with risetimes (spectra) in the area of approximately 5 nanoseconds, but not too common-mode current components with risetimes (spectra) at 1 nanosecond (or faster) or 20 nanoseconds (or slower). According to the referenced ESD research information, ESD impulse waveforms with risetimes in the 5 nanosecond range are exhibited in the area of approximately 7 to 10 kV of ESD initialization amplitudes. When the product is placed on a metal-top desk, a distributive transfer impedance is established that will effectively bypass a significant portion of the 5 nanosecond ESD component energy through the case or cabinet structure (through the desk-to-ground), circumventing significantly the excitation of the weakness of the common-mode design in the interface.

Should the same unit described above be placed on any non-conductive tabletop, however, a larger portion of the ESD levels with the 5 nanosecond component will be available to excite the weakness in the interface design. Assuming no other product susceptibility effects, the ESD responses exhibited will be a "window response" effect where the product responds in the area of 7 to 10 kV, but only when the product is positioned on a desk or table top that is non-conductive.

Due to these fundamental propagational responses in common-mode product/system design mechanisms, so-called "mystery" ESD responses that can be encountered in various products may be understood. These responses are identified in the paragraphs that follow.

OVERVIEW OF ESD PROPAGATIONAL PATHS

Consider the ESD propagational paths that are represented in Figure 5, where:

Z_s = source impedance of ESD event;

Z_t = distributed transfer impedance of product case-to-ground;

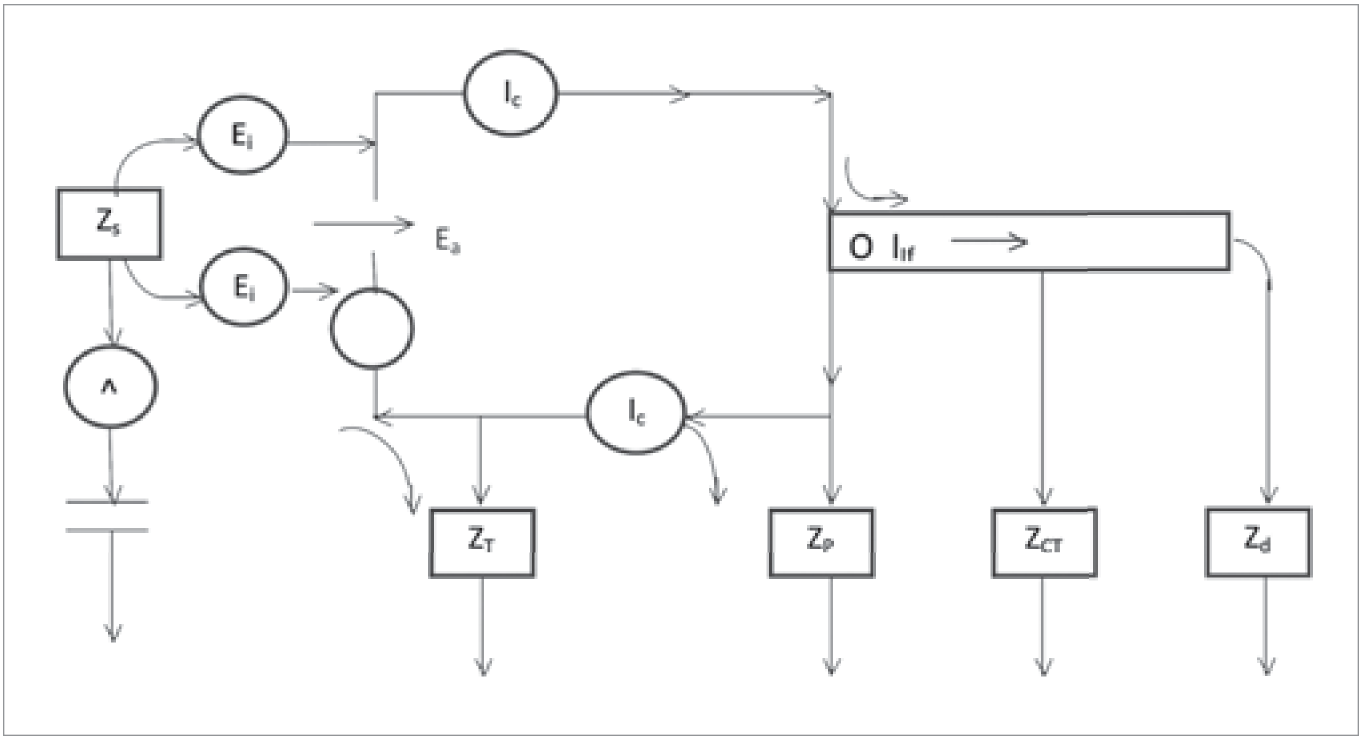


Figure 5: Propagational Overview

ESD

Z_p = impedance of external power to ground (including ground);

Z_{ct} = distributive transfer impedance of cables to ground;

Z_d = directly conducted connection impedance of interconnected product to ground;

I_c = case incident impulse current;

I_{if} = interface cable exit current;

E_a = aperture-produced fields;

E_i = impulsive field gradient.

ESD PROPAGATIONAL DESCRIPTION

The diagram in Figure 5 generally describes the fundamental propagational ESD paths (including interface) that have been described in overview in the preceding paragraphs. The description that follows delineates the interaction and significance of various spectral ESD components that are associated with these paths.

Initial Impulse Effect

On application of the initial excitation ESD impulse, through its intrinsic source impedance Z_s and an impulsive field displacement E_i, is instantaneously produced in the region of the charged structure that is causing the discharge. The specific size of this field displacement has a causal relationship to the size and shape of the structure causing the discharge, as well as the "load plane" (product surface) that is being subjected to the discharge as it opposes the structure being discharged.

The propagational activity of this initial impulse field displacement is very significant in the area of low ESD initialization levels, particularly below 5 kV. In that range, a surface-to-surface distribution of transfer impedance is established between the charged structure and the load plane, which results in intense impulse currents (which can range to approximately 100 amperes) and results from very severe field intensities (approximating 3 megavolts per meter). [2, 3 and 5] Further explanations are provided in Figure 6.

System Response Significance: Initial Field Spatial Displacement

The significance of the initial ESD impulse field displacement on a systems product is found in two immediate paths.

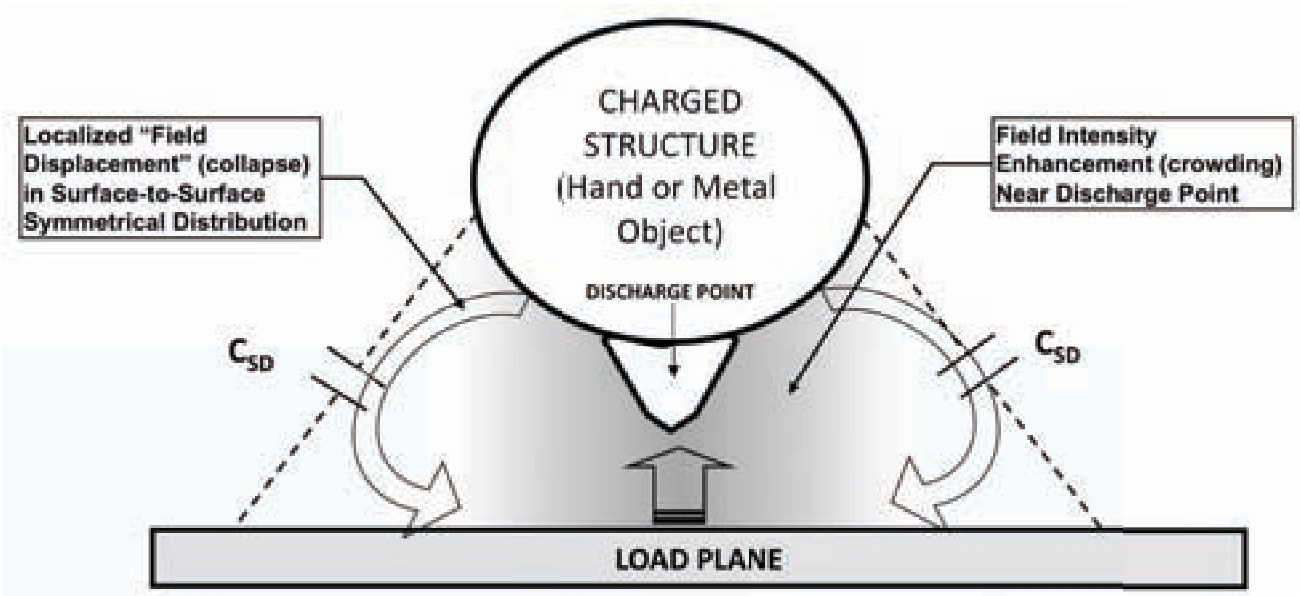
First, the displacement of the localized field can result in aperture currents that develop as a result of propagation of the field and incident currents across apertures (slots or holes) in the product's case structures. These apertures, given these excitations, function as slot antennas that produce field radials inside the product under evaluation. The effect on the product of these immediate fields, that are typically very intense in the close proximity of the slot-apertures, is dependent on the location of circuitry with respect to the slot-aperture, and the coincident match of the bandwidth of the circuitry with the effective propagational (transmitting) bandwidth of the slot-aperture incident field.

In the example above, the first interrelationship between ESD initialization amplitude and system-product response is encountered. Since it has been well established that ESD impulse bandwidths exhibit spectra well above 1 GHz at lower initialization amplitudes (in the references listed) it is to be anticipated that the size of many slots-apertures in typical products are efficient as antennas at lower initialization levels and much less efficient at higher levels due to the reduced spectral bandwidth of the higher level ESD impulse continuum. (Apart from slot apertures and owing to the limitations of various impedances in the casework at EHF, the same conclusion may be advanced when relating the general shielding effectiveness of case structures at these bandwidths.)

Assuming that in the immediate proximity of the excited aperture "antenna" there is an active circuit that has an intrinsic admittance (susceptibility-sensitivity) bandwidth complementing (coinciding with) the efficiency bandwidth produced by the ESD impulse propagating across the aperture, then a product susceptibility response is probable. In recent years, this response is typically *more probable* than in the past since many circuit and logic families are capable of exhibiting very high admittance bandwidths compared to older logic devices.

This affect is far less likely with the ESD initialization levels set at high levels. The simple basis for this statement is that the spectral bandwidth developed by the higher ESD initialization amplitudes are far less likely to produce efficient/coincident matches between the emission spectral capabilities of the product apertures and the spectral level distribution of the ESD impulse. Without such a match, aperture propagational efficiency is not developed, and consequently the probability of product susceptibility response becomes far less.

Second, the localized field displacement results in a case current that is propagated to ground (rather than surface-to-surface as in the previous example) through the distributive transfer impedance Z_t. Here, the second interrelationship between ESD initialization amplitude and system-product response is encountered. The Z_t case in impedance of the product will probably exhibit a broader bandwidth effect of response than the previously described localized service-to-surface distributions. This is because the Z_t case impedance operate throughout a (probably) larger structure: the case itself! The comparatively large surface area of the case is



The initial ESD "circuit equivalent" is a spatial electric field displacement (collapse) between the charged structure (e.g. a hand) and a load plane, with the field intensity collecting at the discharge point. This displacement is between two structures, and is not dependent upon earth ground. This can be represented by distributed capacitance as a "surface distribution" that exhibits a "very low" transfer impedance function.

Figure 6a: Approximation: Initial impact of spatial field distribution yielded by review of ESD waveform characteristics exhibited in nature

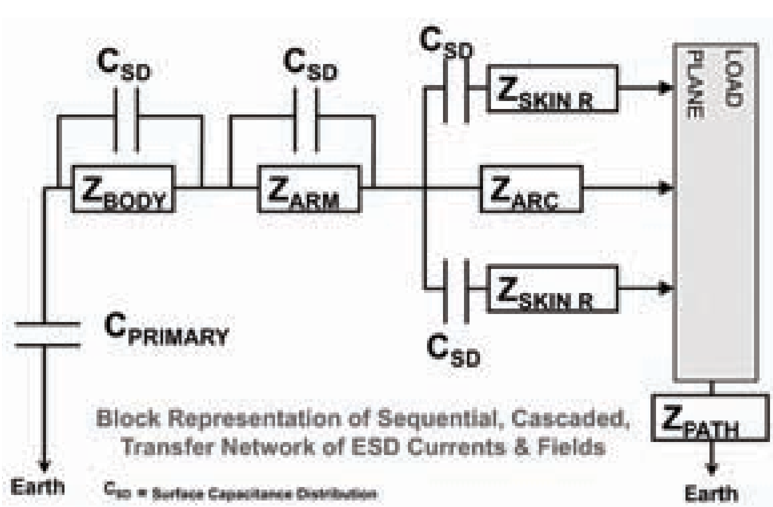


Figure 6b: Block diagram overview of ESD equivalent network

COMMENTS

Equivalent network implications for human finger-tip direct ESD and with small-metal objects intervening in the ESD path:

→ The Capacitance of "surface distribution" will, in probability, vary between equivalent values of approximately 1 pfd and 20 pfd for the "finger-tip" and "small metal object" conditions, depending on the angularity of the hand with respect to the load plane as a localized field displacement.

→ The "primary" Capacitance will, in probability, vary between equivalent values of approximately 100 pfd and 200 pfd for the "finger-tip" and "small metal object" conditions, since this value is presented to Earth (and space) from the human body.

→ For "finger-tip" conditions the "equivalent impedance" of "skin resistance" and "arc impedance" for the "first effect" of surface-field displacement, appears to approximate 200 Ohms. In this same "finger-tip" condition, the higher-voltage "second effect" impedance appears to approximate 1,000 Ohms.

→ For "small metal object" conditions, the "equivalent impedance" of "skin resistance" and "arc impedance" for the "first effect" of surface-field displacement, appears to approximate 20 Ohms. In "metal-object" conditions, the higher-voltage "second effect" impedance appears to approximate 150 to 200 Ohms.

excited not only by radiated field displacements, but by the direct conduction of current I_c. The transfer of energy across the distributive case impedance (Z_t) results in the enhancement of the case-to-ground field gradient (E_i) that is driven across the case as a result of the conducted current.

Case-conducted Current Effect

The next effect in the propagational path of ESD in a product is touched on in the above paragraph. This is the development of a case-conducted current (I_c) from the product surfaces to ground. The energy of this path flows through the distributive transfer impedance (Z_t) to ground, and additionally through the conduction impedances of the power lines (Z_p) and the interface cables (I_{if}).

System Response Significance: Distribution to Earth and Cables

The propagation of the impulse case current into the distributed transfer impedance of the case to ground is paralleled by the conductive path of the power cable and the signal/data interface cable(s). These cables will exhibit "antenna efficiency" that is a development of the common-mode impedances of the cables and their respective termination points. These cables (which typically exhibit far greater inductance than the casework) will interact with the distributive transfer impedance of the case (usually capacitance-based) to result in an L-C resonance.

The inductive and resonance effects noted above suggest that another value of spectral bandwidth dependency will be produced. It is entirely reasonable that these values will be encountered at ESD amplitudes that are much higher than the lower-initialization level effects first described above. This concept is advanced due to the fact that the inductive properties of cables typically limit the efficiency of energy transfer at very high frequency spectral distributions, which is the occupancy domain of lower-initialization levels of ESD.

The probability is that the interaction of the cases and cables, as they propagate the spectral components of the ESD continuum that is efficient for them, will be responsible for susceptibility effects with varying probability above 5 kV due solely to these factors of energy transfer efficiency.

Interface Impulse Effects

The final propagational effects of system-product ESD are found as conducted currents in interface cables, including power line cables. Generally, data and signal interface cables are capable of propagating faster risetime impulse currents than are power cables, since many interface cables are shielded (resulting in lower inductance) and consist of many parallel wires which mutually combine to reduce common-mode inductance and impedance. (This is an effect that functions in the same manner as litz wire.) Power cables frequently are not shielded and do not consist of many parallel separate conductors (unlike interface cables), and accordingly tend not to support the faster impulse risetimes of ESD due to their increased inductive properties.

System Response Significance: Interface Effects

Although exceptions may be found to any rule, the probability (considering cable-conducted ESD impulse currents) is that well-shielded interface cables (with well-terminated shields) will either not contribute to significant ESD product susceptibility or, if they do, it is more likely that susceptibility will be exhibited at higher ESD initialization amplitudes, where the risetimes produce lower frequency spectra and the conducted efficiency of the cables is greater. Unshielded (poorly shielded or well-shielded but poorly terminated) data and signal cables can result in higher-frequency (i.e., lower ESD amplitude) responses because localized fields around the cables or localized high frequency transfer impedances can effectively bypass the normally-anticipated conducted energy effects that are associated with the direct cable inductance. (However, it is possible to design a common-mode loop flow architecture in a product that is sufficiently inadequate for susceptibility considerations, to the point where it may become economically or technically difficult to provide enough cable shielding without resorting to additional means, such as the utilization of lumped common-mode inductance in the interface *ahead* of the interface cables shields.)

Under these conditions, the cables in effect become receiving (or localized loading) antennas with effective areas (efficiencies) that will *vary importantly with cable position* consequently resulting in instability of the ESD performance since antenna area and efficiency is related to the bandwidth of efficiency which, of course, is related to the ESD amplitude/waveform continuum.

ESD RESPONSE INSTABILITY IN NATURE MAY BE USEFUL TOWARD PRODUCTION COST EFFECTIVENESS

Descriptions of the dynamic interactions between the ESD impulse continuum (with its related initialization amplitude-dependent spectral energy shape migrations) and various systems/products response mechanisms (operating in conjunction with product/system physical arrangement conditions) all combine to develop significant variations in the observed ESD performance of the system. These variations may be encountered both in the measured ESD threshold-amplitude of response, as well as the exhibited operational response characteristics. These variations in response and performance may be recognized as anticipatable and "normal" to the nature of the spectra of the ESD continuum.

Although absolutely normal to the physics of ESD, these variations can result in confusion and consternation in personnel who may be attempting to evaluate the performance of a system or product during ESD impulse exposure. This is particularly true because the nature of ESD dynamic physics defies the common wisdom that views the ESD phenomenon simply as an effect that proportionally ascends in difficulty with ascending ESD amplitude. The problem with this approach is that it incorrectly assumes that the higher the ESD initialization amplitude, the worse the systems response will be. Since the inverse is frequently true based on understanding the spectral and propagational influences, it is of little wonder that confusion results.

The conclusions yielded and supported through research of ESD dynamics directly contradict the traditional viewpoint both theoretically and empirically that higher amplitudes will be the worst for product/systems performance. These relatively recent research efforts affirm that the study of ESD dynamics (and the related systems/product response) is actually a study of dynamic impulsive spectral distributions wherein the excitation amplitudes have significantly large field intensities that accompany the field displacements (megavolts per meter), large impulse currents (to over 100 amperes peak) and extraordinarily fast and variable risetimes (tens of picoseconds to tens of nanoseconds). All of these components propagationally interact in various ways with specific response mechanisms of a product/system design and the installation conditions of the product or system. Understanding of the systems and product responses, along with their associated variabilities, may be gained only through understanding the dynamic interactions between the ESD continuum and the system's spectral propagational mechanisms.

The variabilities that are natural to the physics of ESD and the propagational mechanisms of products may be viewed as instabilities by test personnel. The natural (human) reaction derived from the viewpoint of instability is to seek means of achieving stability, particularly during product validation tests. Toward this end, many attempts have been made at stabilizing the ESD test. Potentially, however, there are two major drawbacks to stabilizing the ESD test methodology (and consequently the ESD test results), especially if the means chosen to achieve the stabilization fixes the ESD pulse waveshape to the point that it cannot vary as it does in the "real world". Drawn from conclusions based on the research, these potential drawbacks are:

a. exaggerating the ESD susceptibility of the product under evaluation, resulting in exacerbated production costs to "fix" the overstated problem; and,
b. understating the ESD susceptibility of the product under evaluation, resulting in inadequate performance margins in the installed base.

Exaggerated ESD Responses

Having established the importance of the ESD amplitude-waveform dependencies toward system/product performance, it may be recognized (by studying the research noted in the reference list) that if a simulated test method were to produce ESD waveforms which happened to coincide with the worst-case spectral response windows from a product, the ESD responses from the product would be exaggerated in potentially two ways.

First, the constant (probably repetitive) simulated waveshape would over-emphasize the probabilities of the response since "natural" ESD impulse shapes are highly variable at any given initialization amplitude, as shown in the listed references. Second, the characteristic severity of the response may be magnified because more impulses of a possibly worst-case nature impact the probability timeframe of a systems logic sequence. Third, many standards dramatically over-test systems for the most probable ESD condition: humans direct through fingertips.

Understated ESD Responses

In the same manner that a stabilized ESD test approach might happen to unrealistically coincide with the worst-case response window of a system, it is also possible that the stabilized waveform might not match the susceptibility admittance characteristics of a product. This raises the possibility that the "stabilized" test would not produce the excitations that would be found in the natural environment and otherwise cause the system to be susceptible. Although the initial production costs might be lower for the product, the eventual costs could be unacceptably high in terms of both finance and customer goodwill due to the potential of product/system field performance problems and the attendant retrofit need.

CONCLUSION

Given the evidence based on accepted research results, it is reasonable to suggest that the historical concept of learning the characteristics of the ESD waveform continuum as it actually exists and replicating that continuum both in waveshape and waveshape-probability during simulation tests during product evaluation may actually be the best approach, both in terms of product costs and accuracy of the simulation performance result from products/systems.

This is despite the fact that it characteristically may cause a certain amount of test instability which in turn causes a certain amount of confusion and consternation among test personnel. It is possible that other simulation techniques that have been developed with a view toward simplifying and "stabilizing" the ESD test method may, in fact, be substituting test-lab efficiency for accurate and required ESD performance-measurement information that would serve as a vital predictor of product performance in the field. [8]. Further, it is possible that the current trend observed in efforts to "stabilize" (as opposed to "standardize") the ESD dynamic waveform continuum in the interest of product-evaluation test efficiencies will eventually become recognized as a misplaced, simplistic approach to a complicated and dynamic physics problem.

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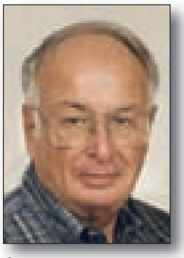
(*) The Vertical Coupling Plane (VCP), Horizontal Coupling Plane (HCP), Incremental Level Test Requirements and incremental probability criteria were first devised and presented in these (and similar) documents.

(**) Note: This article is based on, and is an expansion of, the above published paper.



W. Michael King *is a systems design advisor who has been active in the development of over 1,000 system-product designs in a 50 year career. He serves an international client base as an independent design advisor. Many terms used for PC Board Layout, such as the "3-W Rule", the "V-plane Undercut Rule", and "ground stitching nulls", were all originated by himself. His full biography may be seen through his web site: www.SystemsEMC.com. Significantly, he is the author of EMCT: High Speed Design Tutorial (ISBN 0-7381-3340-X) which is the source of some of the graphics used in this presentation. EMCT is available through Elliott Laboratories/NTS, co-branded with the IEEE Standards Information Network.*

Lightning Damage to Equipment

without a Metallic Connection to an External Communications Service

BY AL MARTIN

Lightning damage to equipment with a metallic (wired) connection to a communications service has been studied for many years, resulting in a series of Telcordia GR, ATIS and TIA standards in the United States, and ITU-T recommendations elsewhere.

With the development of systems that don't have a metallic connection to a communications service, e.g., fiber optic systems, the assumption has been that lightning damage won't occur. How could it? After all, there is no metallic path for the lightning to follow and thus impact the system. So imagine the surprise at some recent reports of customer premises fiber optic equipment that has suffered lightning damage. For example, this report:

I have fiber-optic connection to the phone network. My network consists of a router, 4 Desktops, a game console, and two 1gig switches. These devices are protected by UPS and surge protectors. Last night we had a near hit from lightning. No power disruption. However, my network and POTS phone (wired) went down hard. The router had a red light until I rebooted it. After a reboot it came up with no internet connection. None of my PCs could see each other on the network. The Optical Network Terminator (ONT) power supply and the Router were toast. I lost a host of NICs as well as several ports on the gig switches. The game console seems to be OK and the PC located in the room with the router is fine. My LAN printer's NIC is toast and will not print.

How could this have happened? There is an explanation, and it has to do with ground potential rise and systems with multiple grounds.

GROUND POTENTIAL RISE

Ground potential rise [GPR] is a result of lightning striking the ground. Current flows away from the point where the lightning hits, creating a series of equipotential surfaces. It's like throwing a pebble into a pond……

Think of the waves as equipotential surfaces. The voltage at each equipotential surface can be calculated, but in general the calculation is very complicated. In the simple case of a uniform earth surface, the ground potential GP of the earth at a distance r from the point where a lightning strike enters the ground is given by [1],

$$GP = \frac{\rho \cdot I}{2\pi \cdot r} \qquad (1)$$

where ρ is the resistivity of the earth (generally being a function of distance, angle, and depth), and I is the lightning current. The important feature of GP is that it falls off as 1/r. In the more general case, it falls off as a power series in $(1/r)^n$. For the simple case just discussed the equipotential surfaces look like those in Figure 1.

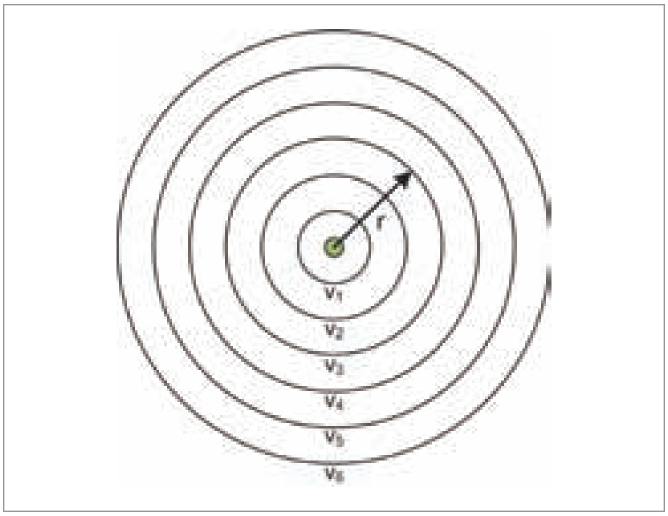


Figure 1: The fall-off of GPR with distance from the strike, where $V_1 > V_2 > V_3$ ... etc.

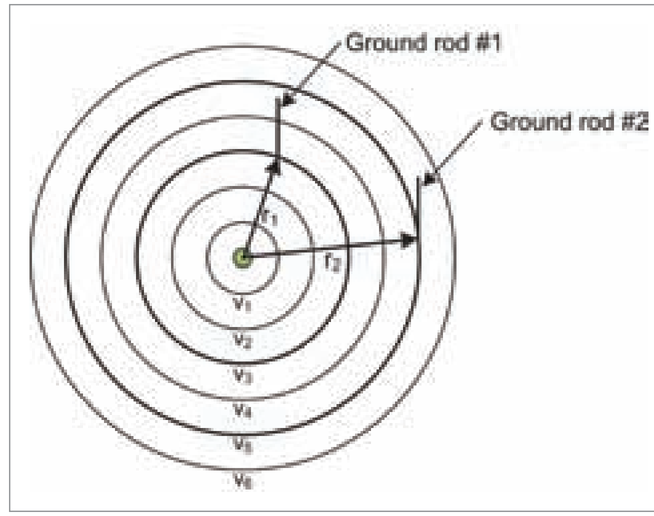


Figure 2: Ground rods located on different equipotential lines

There are two cases to consider:

- a strike to ground in the vicinity of the structure,
- a direct strike to either the AC power or the phone line (if it is a wired connection).

Case 1 – Lightning Strike to Ground

Suppose two ground rods are located at distances r_1 and r_2 from the lightning strike, as shown in Figure 2. The potential difference between a ground rod at r_1 and a ground rod at r_2 is $V_3 - V_5$. How big could this potential difference be?

The potential difference PD between the two ground rods is

$$PD = \frac{\rho \cdot I}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2}\right] \qquad (2)$$

Let $r_2 = r_1 + x$ (i.e. r_2 is farther from the lightning strike than r_1 by an amount x). Then

$$PD = \frac{\rho \cdot I}{2\pi}\left[\frac{x}{r_1 \cdot (r_1 + x)}\right] \qquad (3)$$

To see how big the potential difference could be, let's do an example calculation based on equation (3). To help visualize the situation, let r_1 and r_2 be in the same direction, as shown in Figure 3 (the angle of r_1 with respect to r_2 doesn't affect the calculation of PD – see Sidebar).

Assume a 30,000 A surge (a moderately strong lightning pulse 2), and that the lightning strike is 30 m (about 100 ft) from the first ground rod located at r_1. In the high lightning areas, the soil resistivity runs 100 – 1000 ohm-meters 3.

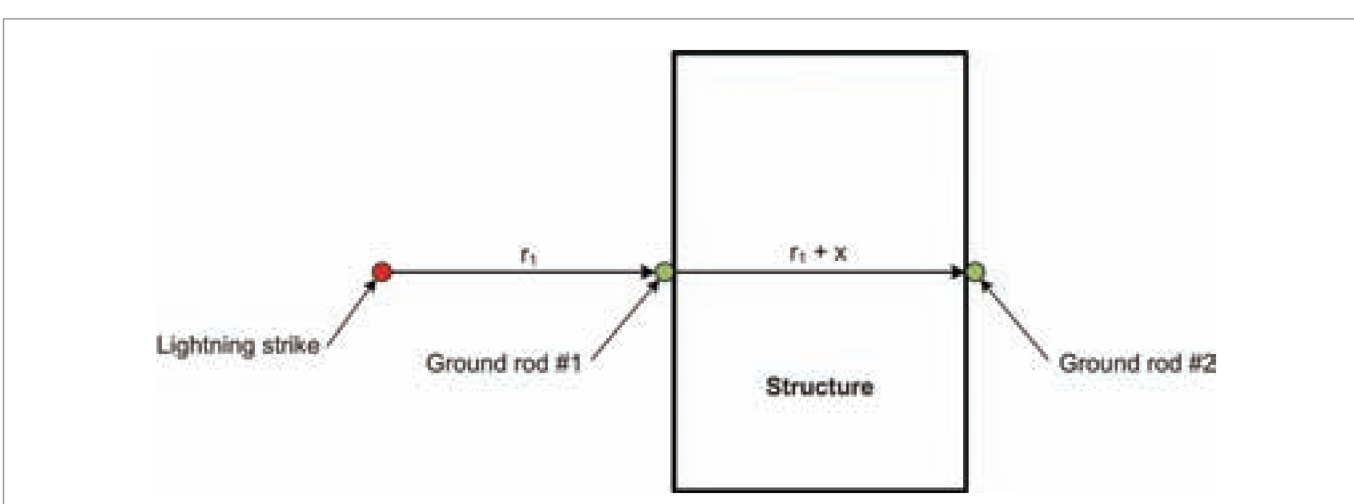
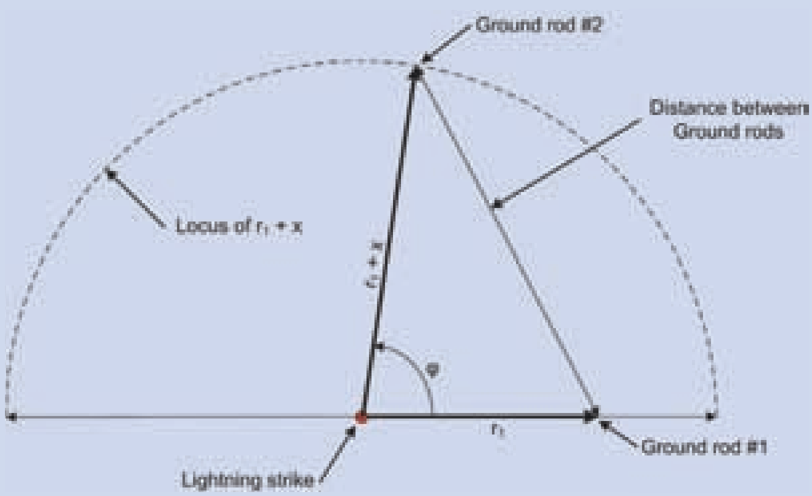


Figure 3: Geometry for the example calculation

Sidebar

Observe that ground rod #2 can be located anywhere on an equipotential circle of radius (r_1 + X) with respect to ground rod #1 without changing PD:



That being the case, the distance d between ground rods is given by:

$$d = \sqrt{r_1^2 + (r_1 + x)^2 - 2r_1(r_1 + x)\cos\varphi}$$

When φ = 0, d = X. When φ = 180, d = $2r_1$ + X. So the spacing between ground rods can range from a minimum of X to a maximum of ($2r_1$ + X) without changing PD. In the calculation of PD, note that since

$$X = d - r_1\sqrt{2(1 - \cos\varphi)},$$

knowing the distance d between ground rods is not sufficient to determine X and hence not sufficient to determine PD. For example, the PD between ground rods located 30 feet apart is not necessarily bigger than the PD between ground rods located 10 feet apart. What is needed to calculate PD is to know on which equipotentials the ground rods are located [in the present case, those at r_1 and r_2], because that determines the potential difference PD between the ground rods.

So for this example, assume 300 ohm-meters. For these assumptions, we can calculate the PD between ground rods as a function (X) of the difference in equipotentials at r_1 and (r_1 + X) (or as a function of the minimum spacing between ground rods). The result is shown in Figure 4. Alternatively, the distance X between r_1 and r_2 can be fixed at 10 m and the PD plotted as a function of how far away the lightning is from the structure, as shown in Figure 5.

Of course, altering the assumptions would result in different plots. The point is that a PD in the range of 5 - 10 kV is quite within reason. (Sanity check: ITU-T K.44 Table II.6-1 has 10/700 tests to 13 kV)

Case 2 – A Direct Strike to Power or Communications

Consider a home with a wired network connected to a communications service via a gateway (Figure 6). The NEC 4 requires both the gateway and the AC power neutral to be grounded, and also requires that there be a bond wire between the grounds. The bond wire may be long if the AC power and the communications are not co-located.

A direct or induced current due to a lightning strike to the AC power will seek a ground, either directly at A, via the bond wire to the ground at B, or a combination of these two. Current flowing into the ground at A will create a GPR with respect to B.

For this case, the lightning current flows in a circuit consisting of the parallel combination of the inductance L of the bond wire and the earth resistance between A and B. Assume the distance X between A and B is 10 m. The bond wire has an inductance of about 1 µhy/m, so L = 10 µhy. The resistance R of a ground rod of length L and diameter d can be calculated from 5,

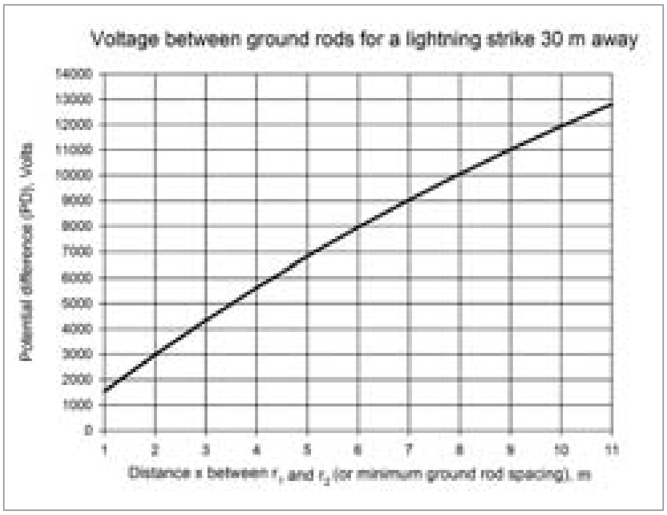


Figure 4: Fixed lightning strike distance

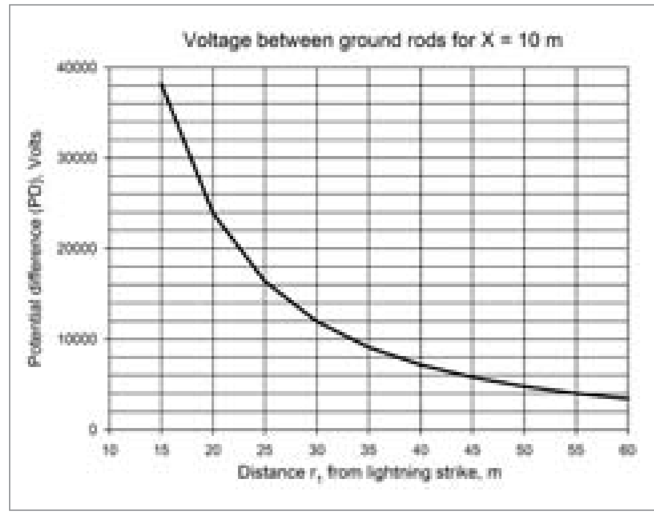


Figure 5: Fixed ground rod spacing

$$R = \frac{\rho}{2.73L}\log_{10}\frac{4L}{d} \qquad (4)$$

For a typical ground rod 1.5 m long and 0.014 m in diameter, R = 193 ohms.

Assume a moderately strong lightning surge of 3000 A on the AC power line 6. If, as assumed in 6, the surge is a linear ramp with a 3 µs rise time, then an L(di/dt) voltage of 3000 V would be generated. However, surges in the real world are not linear ramps – they are more like double exponentials.

So consider a double exponential with the same 3 µs (nominal) rise time – 3x1000 for this example. The result of applying this surge to the parallel combination of 10 µhy and 193 ohms is shown in Figure 7.

The reason the voltage is higher when the surge is a double-exponential is that the rise time of the double exponential is not constant but is relatively steep at the beginning. The actual PD calculated between grounds depends on the assumptions made and could be more or less that those of the examples. The point is that, as in Case 1, a 10 kV PD between grounds is within reason.

DAMAGE TO EQUIPMENT WITHOUT A WIRED CONNECTION TO A COMMUNICATIONS SERVICE

The damage case reported in the Introduction is a useful example for a discussion on how equipment without a wired

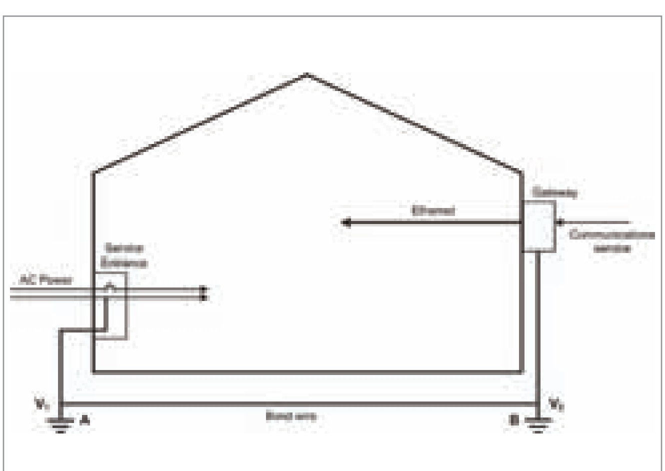


Figure 6: Fixed ground rod spacing

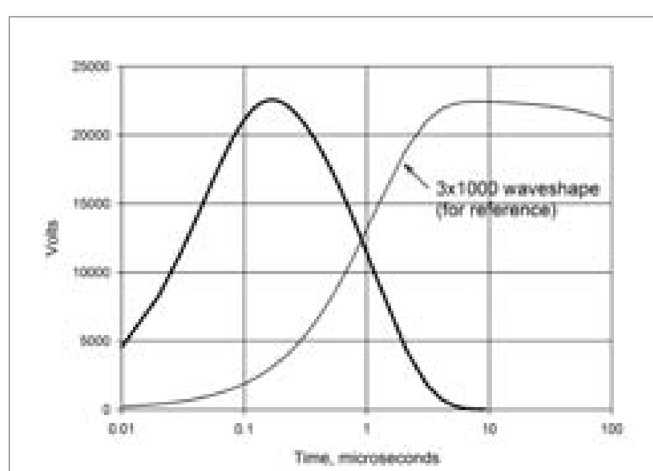


Figure 7: Potential across a parallel combination of 10 µhy and 193 ohms for a 3000 A peak 3x1000 surge

connection to an external communications service could be damaged by a lightning strike. Figure 8 is a simplified schematic of what the network and equipment layout might have been in the house. In Figure 8, V_1 and V_2 are the voltages created by the GPR due to the lightning strike. Remember that the lightning strike was a near hit, so from the example calculation, $V_1 – V_2$ could easily be in the 5 - 10 kV range.

Now consider the power supply PS that was reported damaged. It can be represented schematically, as shown in Figure 9. If the $(V_1 – V_2)$ resulting from the GPR exceeds the breakdown voltage of the transformer, flashover occurs, with likely power follow destroying the power supply.

Now consider the router failure. The router would likely have been connected to the ONT via an Ethernet connection as shown in Figure 10, where PHY represents the physical layer connections of the equipment to the Ethernet.

The two grounds have a potential difference between them of $(V_1 – V_2)$. Points A and B are essentially tied together, so the two equal impedances form a voltage divider, causing a voltage $(V_1 – V_2)/2$ to appear at A and B. If $(V_1 – V_2)/2$ is between 2400 V and 5000 V, the breakdown voltage of the router transformer will be generally be exceeded, flashover will occur, and the PHY circuit will be damaged. Again from the examples, 3 – 5 kV is a reasonable range for $(V_1 – V_2)/2$. If $(V_1 – V_2)/2$ did not exceed 5000 V, the ONT would have been OK if its transformer was designed for a 5000 V surge, which is often the case.

The example considered here is one of several similar reports posted on the web, so it isn't an isolated case. In fact, problems similar to those just discussed have been reported in a recent paper by Tokyo Electric Power 7.

CONCLUSIONS

The issue here is that the damaging surges are not coming from the outside world into the house or structure, as has always been assumed. Rather the existence of multiple grounds creates a path for the surge to come from inside the house toward the equipment. As equipment manufacturers

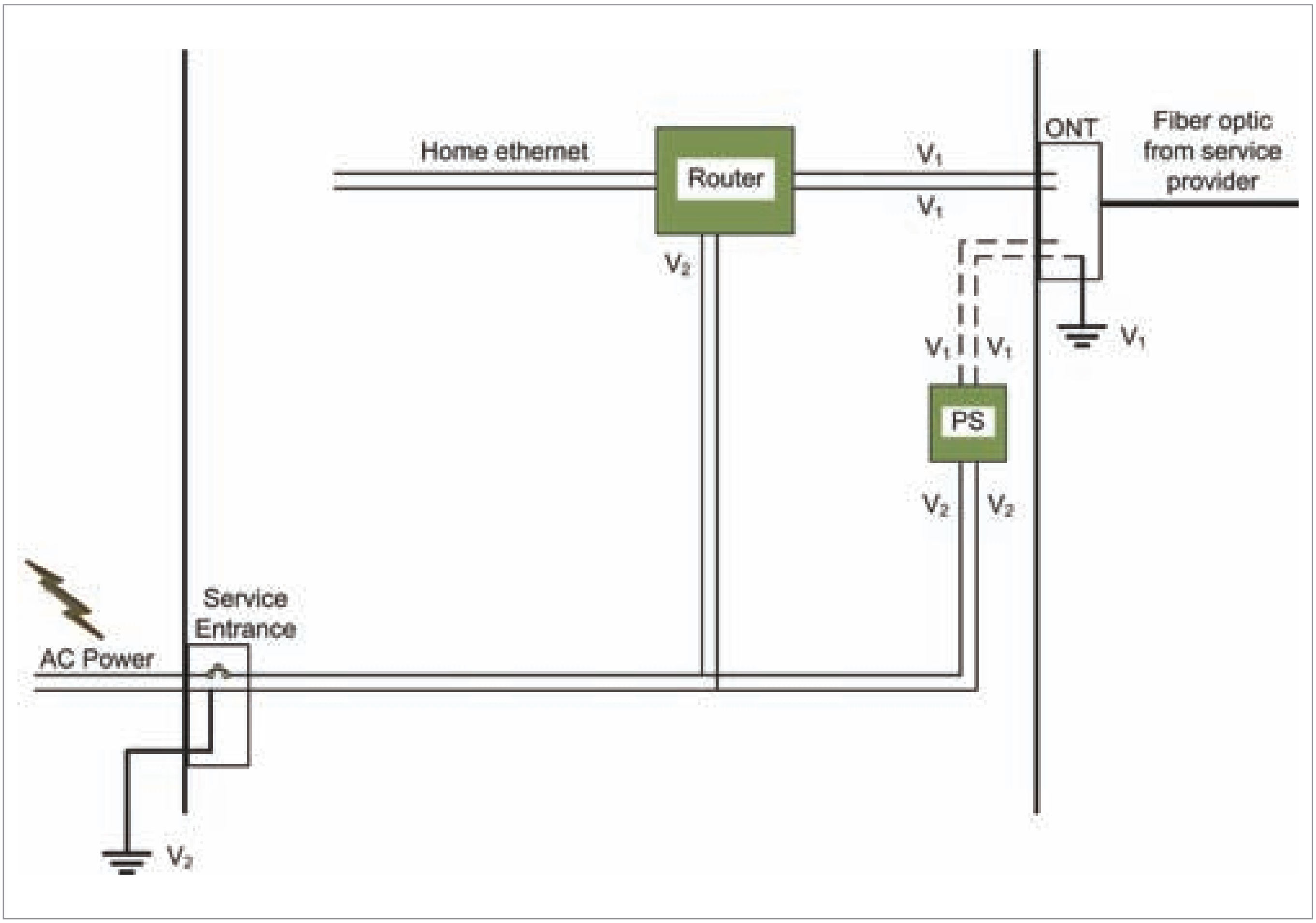


Figure 8: Possible layout of the equipment and connections in the use case

generally don't expect surges to come from this direction, surge protection is seldom provided on inside lines. As a result, equipment may be damaged by lightning surges even though it has passed all relevant standards, and has no metallic connection to the outside world.

It is worth pointing out that the problem exists if there is more than one ground at the house. If there is only one ground, the problem may go away. We say "may go away" because the power network in the house may have multiple grounds, particularly if there is a photovoltaic system on the roof, which could cause problems. But that is another story.

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Al is a contributing member of TIA TR41, ATIS NIPP-NEP, and IEEE. He has been an editor for TIA TR41, ATIS NIPP-NEP, and IEEE standards, and is presently chairman of IEEE WG3.6.7, and vice-chairman of WG3.6.2. He is the author or co-author of over 20 papers on EMC and telecommunications. Al is a Life Senior member of the IEEE.

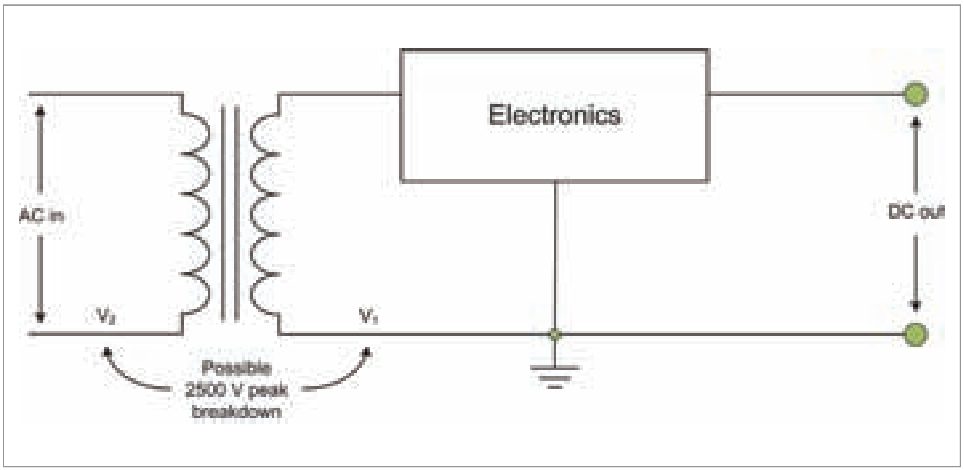


Figure 9: Schematic of the power supply for the ONT

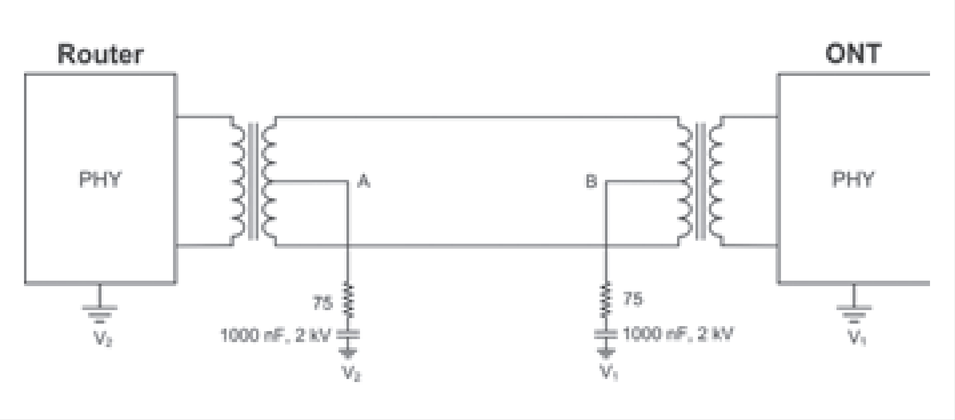
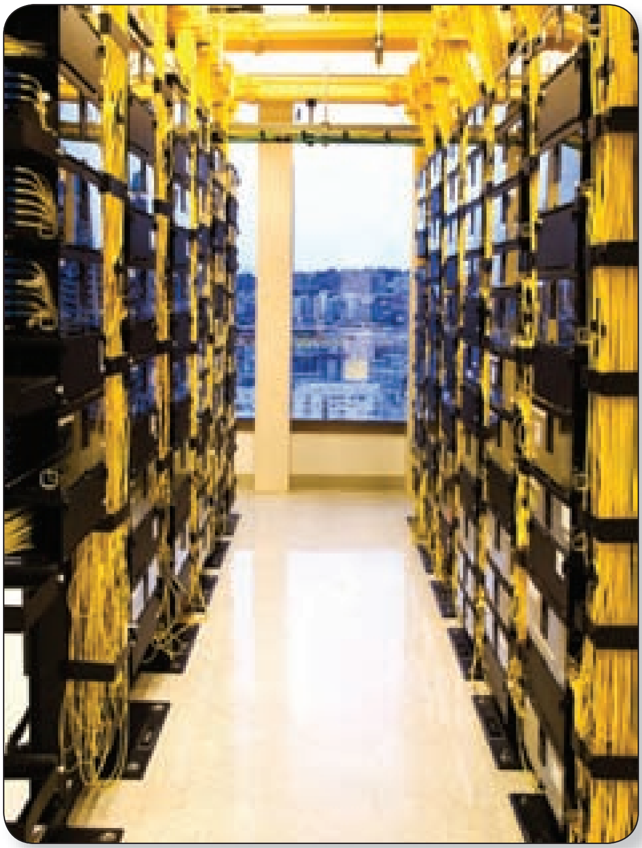


Figure 10: Schematic of an Ethernet connection between the router and the ONT



The "Core" of Designing for NEBS Compliance

BY DAVE LORUSSO

Telecom

Most of you know NEBS has something to do with telecommunications. It's true; NEBS has a lot to do with telecommunications. NEBS is the premiere set of documents used to ensure telecommunications equipment perform at their highest level possible.

NEBS stands for "Network Equipment – Building System". Breaking this down: "Network Equipment" is the hardware (and software?) that constitutes a telecommunications carrier's network. The network could be in a Central Office (CO) or part of an Outside Plant infrastructure. "Building System" emphasizes organization and structure, mainly around a Central Office. NEBS is primarily a series of tests meant to ensure that telecommunications equipment meets a vast array of safety, electromagnetic compatibility, and environmental requirements. NEBS indirectly describes the environment of a typical CO.

So, what is a Central Office environment like?

Typically, a CO is a large unobtrusive, windowless, secure building. There are approximately 35,000 COs in the United States. There might even be one in your neighborhood. Since the U.S. telecommunications system is more than 100 years old, COs often occupy prime real estate. There are many older COs throughout the country with harsh environments inside. This is why you'll see tough requirements around temperature, humidity, vibration, illumination, fire resistance, and contaminants. Your product must conform to this environment.

Copper pairs from your home or business eventually find their way to a local Central Office building. They enter the CO underground via a cable vault and terminate in a distribution frame. There is a demarcation between Outside Plant (OSP), where the wires come from, and the central office pairs. Since OSP is exposed to many transient events (both destructive and non-destructive), protection must be provided. Typically, this is in the form of a 5-pin Protector Module. This protection is taken into consideration when lightning and power cross criteria is presented to the copper pairs. Protected central office pairs then find their way to a CO switch that can switch calls locally or to long distance carrier phone offices.

For online virtual and pictorial tours of a CO, go to www.nebs-faq.com.

The core NEBS documents are available as a set from Telcordia: FD-NEBS-01, NEBS™ *Physical and Electrical Protection*, and include:

- GR-63-CORE, *NEBS™ Requirements: Physical Protection*
- GR-1089-CORE, *Electromagnetic Compatibility and Electrical Safety – Generic Criteria for Network Telecommunications Equipment*
- SR-3580, *NEBS Criteria Levels*

These documents will set you back about $2,500.00... expensive, but worth the investment. You need to understand what service providers require for their networks. But this is just the beginning. There are many more Telcordia documents you need to purchase to get a complete a understanding of NEBS.

GR-63-CORE

According to Telcordia's ROADMAP-TO-NEBS-1,Telcordia GR-63-CORE, *NEBS™ Requirements: Physical Protection, is considered the "backbone" of the NEBS program and identifies the minimum spatial and environmental criteria for all new telecommunications equipment systems used in a telecommunications network. Topics covered include temperature and humidity, fire resistance, spatial and vibration criteria, airborne contaminants, acoustic noise, and illumination.*

Let's look at the spatial criteria. Equipment and cabling must be compatible with the vertical and horizontal space allocations in a Central Office. Floor loading limits must also be taken into consideration since equipment can be mounted on a second floor or above. Section 2 "Spatial Requirements" provides a broad overview of criteria applicable to frames, distribution and interconnecting frames, dc power plant equipment, and cable distribution systems. Criteria is given right down to the hole pattern used to anchor a frame to the building floor (Figure 1).

An important area to understand is how frames are distributed in a typical Central Office (Figure 2). There is a Maintenance Aisle and a Wiring Aisle. This arrangement allows personnel to operate, maintain, and repair equipment from the front. Cables are in the back running upward to the overhead cable distribution tray. DC power is brought down to the equipment. Equipment is powered by -48 Vdc.

It's also important to understand how a typical central office is cooled. A typical cooling system is all-air usually using central fan rooms, overhead ducts, and diffusers to distribute air. The preferred cooling method for Network Equipment is for air to enter from the lower front and exit through the top rear (Figure 3). This results in a cold aisle (Maintenance) and a hot aisle (Wiring). The air supply to the cold aisle comes from ducting from top down. Hot air recovery from the hot aisle is generally done through ducting on top. GR-3028, "Thermal Management In Telecommunications Central Offices" is the guiding Telcordia document.

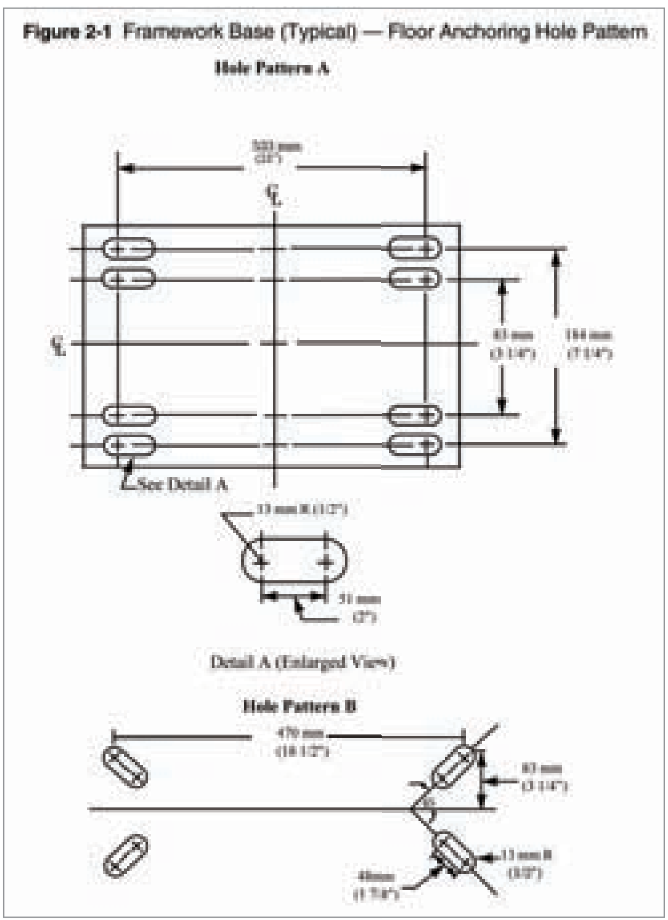


Figure 1: From Page 2-2 of GR-63-CORE, Issue 3, March 2006

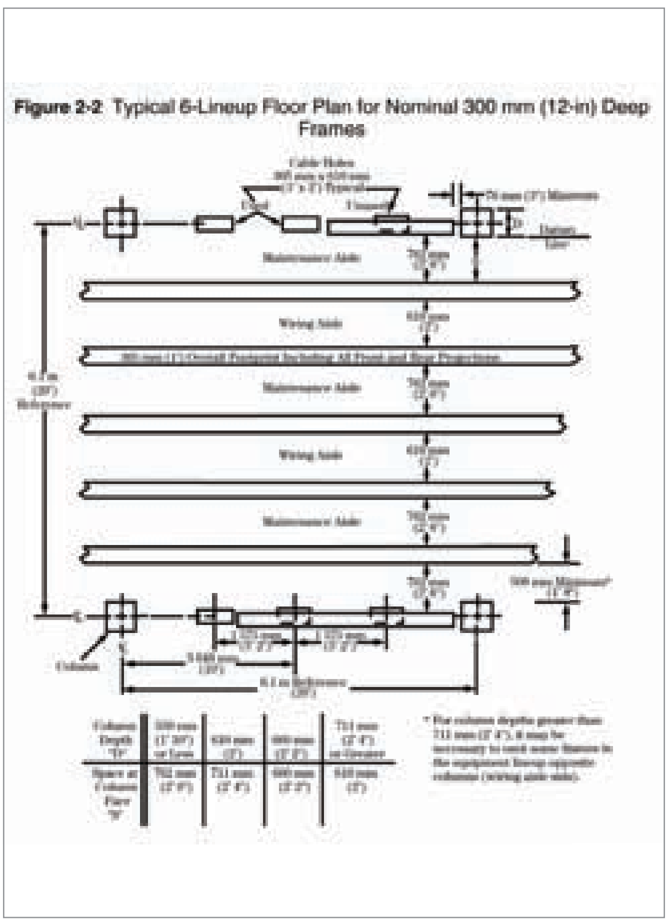


Figure 2: From Page 2-4 of GR-63-CORE, Issue 3, March 2006

Section 4 is the meat of the document. This section addresses environmental criteria in a CO:

- temperature, humidity, and altitude
- fire resistance
- equipment handling
- earthquake, office vibration, and transportation vibration
- airborne contaminants
- acoustic noise
- illumination

Section 5 describes the Environmental Test Methods used to prove that your equipment meets Section 4.
All of the environmental criteria above are important, however, there is not enough room in this article to go into detail. Let's look at some key areas.

Temperature, Humidity, and Altitude

Key to this area is the short-term limits, short-term being defined as "a period of not more than 96 consecutive hours and a total of not more than 15 days in 1 year. (This refers to a total of 360 hours in any given year, but no more than 15 occurrences during that 1-year period.)". That's four long days of wicked hot temperatures! Your equipment needs to stay operational from -5°C to 50°C (23°F to 122°F) if it's sold at the frame level or -5°C to 55°C (23°F to 131°F) if it's a shelf level product.

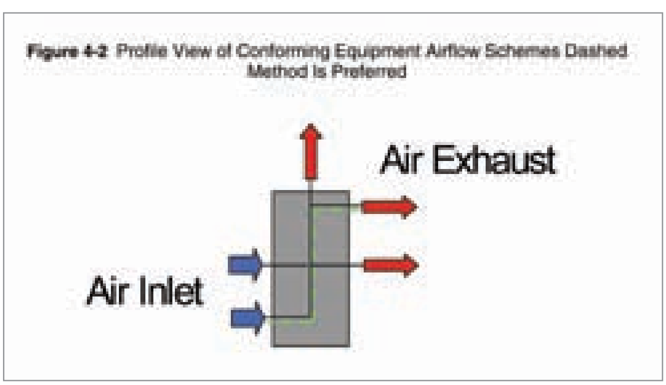


Figure 3: From Page 4-10 of GR-63-CORE, Issue 3, March 2006

Fire Resistance

Your product is going to get burned. Let me repeat that. YOUR PRODUCT IS GOING TO GET BURNED. You can't do a simulation – you have to burn it. This is not the same requirement you see in the 60950 safety standards. In 60950, there is a heavy reliance on the use of a Fire Enclosure to contain fire. You can have a compliant Fire Enclosure designed to 60950 and fail the NEBS Fire Resistance test. Material selection and construction techniques are emphasized in 60950. The risk of ignition is reduced by putting a limit on the maximum temperature of components under normal and single fault conditions; if there is ignition, the spread of flame is reduced by using flame retardant materials or by adequate separation. Using these proven practices will help, but not guarantee passing the NEBS Fire Resistance test. The best way to pass this test is to understand it.

In the early days of NEBS (circa 1985), a 5-3/4 inch diameter by 2-3/8 inch deep pan containing 200 ml of isopropyl alcohol was ignited 2 inches below the bottom of the lowest unit. Fire was not allowed to spread into adjacent equipment assemblies.

Furthermore, 15 minutes after flame outbreak, a Class 5 B:C portable fire extinguisher must put out the fire. If one fire extinguisher didn't do the job, the number required was recorded. If you used internal fans, you had to do the test twice.

Bellcore Technical Advisory, TA-NWT-000063, Issue 2, December 1992 introduced the currently used methane line burner. The original test was deemed to be severe. The line burner would be based on burning characteristics of typical printed circuit board. Calorimetric techniques would be used to determine the flame size and duration. As time went on, this method also was deemed too severe as it was tougher on smaller line cards and easier on larger ones.

The test now follows ANSI T1.319-2002 "Equipment Assemblies – Fire Propagation Risk Assessment Criteria". A methane line burner (Figure 4) is inserted into the product and allowed to burn for 5½ minutes following a pre-defined gas flow profile. All nearby flammable material is ignited.

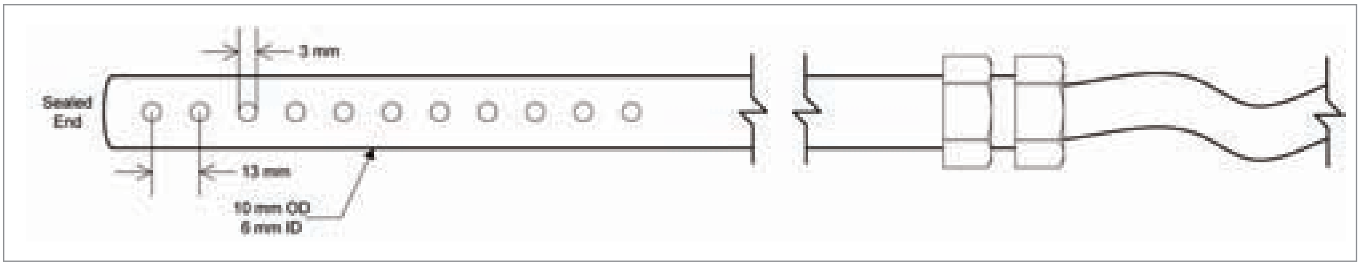


Figure 4

This is a simplification. There are many variables, including: fuel load, air flow, compartments, fan use, size and shape of printed circuit boards, and exemptions.

Some design guidelines:

- Understand where and what the flames touch.
- Use metal wherever possible.
- Use the least flammable parts throughout.
- Watch out for flame exposure to printed circuit board edges, including daughter and memory cards.
- Watch your airflow. Fan position is key. Keep fans away from sources that may ignite; recess your fans if possible as being too close to the outside edge could result in flaming material leaving the enclosure.

Earthquake

Will your equipment work after an 8.2 earthquake? Only a seismic test will prove if it does. GR-63-CORE lists five earthquake zones in the continental United States: Zone 0, no ground acceleration, through Zone 4, 0.40g of ground acceleration. California, Nevada, and the junction of Idaho, Montana and Wyoming have the distinction of being in Zone 4. Even though the great majority of products pass this test the first time, it’s best to do a thorough review of your mechanical design. Watch especially for cabling prior to the test due to the significant displacement the product will undergo.

Other NEBS related documents include:

- GR-78-CORE, *Generic Requirements for the Physical Design and Manufacture of Telecommunications Products and Equipment*
- GR-3160-CORE*, NEBS™ Requirements for Telecommunications Data Center Equipment and Spaces*
- GR-1217-CORE, *Generic Requirements for Separable Electrical Connectors Used in Telecommunications Hardware*
- GR-468-CORE*, Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications Equipment*
- GR-357-CORE, *Generic Requirements for Assuring the Reliability of Components Used in Telecommunications Equipment*
- GR-3028-CORE, *Thermal Management In Telecommunications Central Offices: Thermal GR-3028*
- GR-1221-CORE, *Generic Reliability Assurance Requirements for Passive Optical Components*
- GR-2930-CORE, *Network Equipment Building System NEBS(TM) Raised Floor Generic Requirements for Network and Data Centers*
- GR-2969-CORE*, Generic Requirements for the Design and Manufacture of Short-Life Information Handling Products and Equipment*

GR-1089-CORE

The title of this Telcordia document is “Electromagnetic Compatibility (EMC) and Electrical Safety”. As you can see from the list below, major areas of EMC are covered, as are some obvious and unique safety concerns:

- electrostatic discharge
- electromagnetic interference
- lightning and power fault
- steady-state power induction
- DC potential difference
- electrical and optical safety
- corrosion
- bonding and grounding
- DC power port of telecommunications load equipment

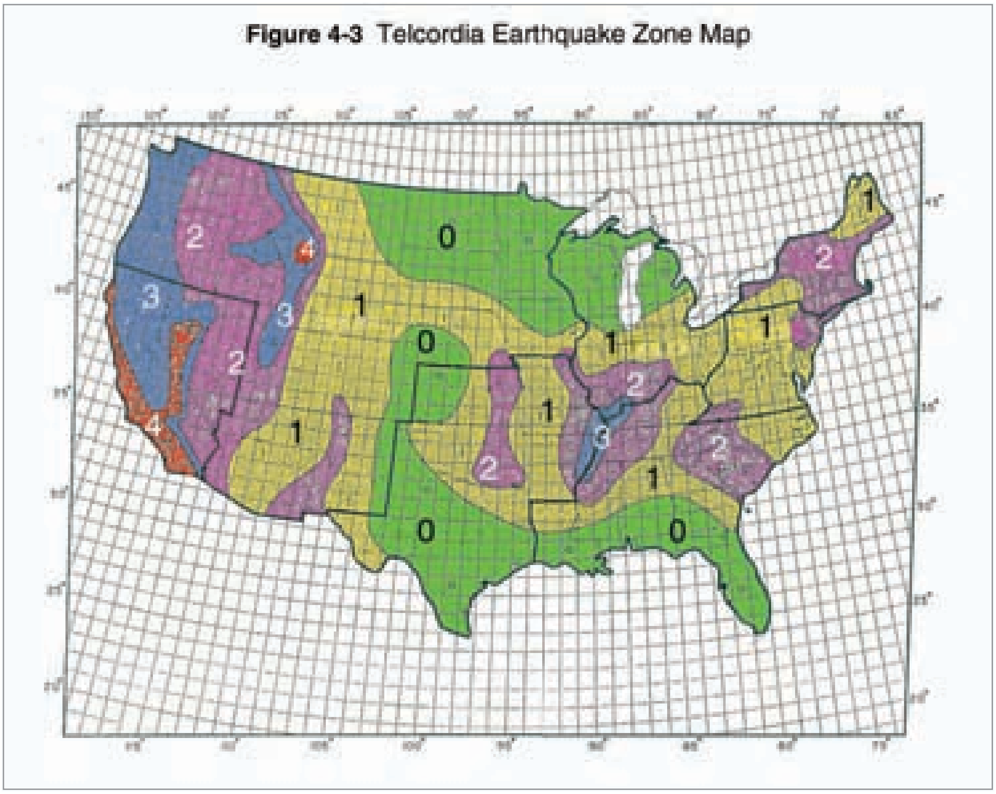


Figure 5: From Page 4-23 of GR-63-CORE, Issue 3, March 2006

There's more to NEBS than physical and electrical protection. Network reliability is key. Emergency phone service depends on it. GR-78-CORE provides guidance on how to design and build reliable products for telecom network use. It applies to design, engineering, manufacturing, and workmanship.

But wait, there's more...

With 35,000 COs scattered across the country and tons of equipment from multiple vendors, order must come from chaos. Yes, another document: GR-485-CORE "COMMON LANGUAGE® Equipment Codes (CLEI ™ Codes) – Generic Requirements for Processes Guidelines" (pronounced "klee-i"). CLEI Codes are 10-character, alpha-numeric codes having a one to one relationship with a product's part number. The codes are used to identify network equipment, including field replaceable units (FRUs). The largest carriers use CLEI Codes, and they have been adopted by other worldwide carriers. The use of these codes, in the form of a label on your product, help service providers manage their infrastructure and supply chain. There is a cost associated with each CLEI Code.

Even with high availability (99.999% or "5 nines"), something is going to break. COs tend to be lightly manned so there has to be a method to notify personnel that there's a problem. Enter alarms. Telcordia document GR-474-CORE "Alarm and Control for Network Elements" provides guidance on network equipment maintenance. Your equipment must have a means of tying into the CO's Operations Center when a failure or transient condition occurs. There must be an indication on your product that there's a problem (local indication), a means must be provided to tie into the audible and visual indications that are available at various locations in the CO, and ultimately, trouble indication must finds its way to the Operations Center. Contacts on the product are the typical method of notification.

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TEAMWORK

It is next to impossible for one person to grasp all of these requirements. Expertise is required in many engineering fields: electromagnetic compatibility, product safety, electrical, mechanical, chemical, and reliability.

It takes a team approach to design, test, and qualify a product to NEBS. A good approach is to appoint a NEBS technical lead who has an excellent grasp of the requirements and can manage the program, or hire a NEBS consultant.

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- SR-3580, *NEBS Criteria Levels.*
- GR-78-CORE, *Generic Requirements for the Physical Design and Manufacture of Telecommunications Products and Equipment.*
- GR-485-CORE, *COMMON LANGUAGE ® Equipment Codes (CLEI ™ Codes) – Generic Requirements for Processes Guidelines.*
- ANSI T1.319-2002, *Equipment Assemblies – Fire Propagation Risk Assessment Criteria.*
- IEC 60950, *Information Technology Equipment – Safety – Part 1: General Requirements.*

RESOURCES

- www.nebs-faq.com (Resource for NEBS Compliance information)
- www.telcordia.com (The creator and keeper of NEBS documents)
- www.verizonnebs.com (Verizon's NEBS Compliance Web Page)

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Managing the Use of Wireless Devices in Nuclear Power Plants

BY PHILIP KEEBLER AND STEPHEN BERGER

Telecom

Wireless technology is experiencing explosive growth. More than just devices of the same kind, there is a proliferation of applications that take advantage of wireless connectivity, using it in new and novel ways. Wireless technology itself is developing and radio access technologies are becoming increasingly complex and sophisticated. The result is that today's electromagnetic environment is changing. This means that old test methods and limits are no longer adequate to insure systems have adequate electromagnetic immunity.

Further, there is a movement to bring wireless into nuclear plants and make it part of plant design. Existing plants have examined the use of wireless, but formal integration is slow. Next generation, advanced plants, some plants presently under construct specify significant use of wireless technologies. There is a wide variety of beneficial applications, including mobile connectivity with personnel, sensing, and wireless data networks. Expanding applications make managing the use of wireless technology in nuclear power plants (NPPs) an emerging requirement.

This article discusses the need to go beyond traditional requirements for EMC interference protection to managing wireless and the use of spectrum so that interference is avoided and wireless services can coexist and operate at the high levels of reliability required by nuclear plants.

The first time a nuclear reactor generated electricity was on December 20, 1951, at the EBR-I experimental station near Arco, Idaho.[1] In 1956, when the first commercial nuclear power station was built, portable wireless devices were not in common use. Portable radio transceivers were first developed in 1940 by the Galvin Manufacturing Company (predecessor to Motorola) who coined the name "Walkie-Talkie". The first Walkie-Talkie was a backpacked unit. Motorola produced the first hand-held amplitude modulation (AM) radio during World War II for military use and called it the "Handie-Talkie". Both devices used vacuum tubes and high-voltage dry-cell batteries. The "Handie-Talkie" became a registered trademark of Motorola in 1951. After the war, Walkie-Talkies were adopted by public safety departments, followed by commercial entities and jobsites. Industrial plants and power plants also adopted them at this time.

The use of wireless devices that transmit and receive radio power in a nuclear power plant (NPP) has been a concern since the first wireless device (i.e., the simple hand-held portable radio transceiver, or Walkie-Talkie) was used in a power plant. Fossil and hydro power plants were the initial users of Walkie-Talkies. When the first NPP went on line in the late 1950s, instrumentation and control (I&C) engineers were surprised to find that Walkie-Talkies were able to cause malfunctions and upsets of analog I&C equipment. EMI problems with I&C equipment caused by portable radios were obviously among the first type of EMI-related I&C problems to be reported.

Similar to the historical path that Walkie-Talkies took, the concept of a radio telephone stemmed from the invention of the radiophone. This was followed by shore-to-ship demonstrations of radio telephony through World War II, when the US military used radio telephony links. Civil service personnel used radio telephony in the 1950s. In June 1946, the first mobile telephone call was made from St. Louis, Missouri using the Bell System's Mobile Telephone Service. The first automatic mobile phone system (Mobile System A), using vacuum tubes and relays designed for an automobile, was launched in Sweden in 1956. A more modern version (Mobile System B), which used transistors to reduce its weight and improve call capacity and operational reliability, was introduced in 1962. This was followed by the development of Mobile System D, which provided a pathway for different brands of equipment and stimulated the successful use of this technology in commercial markets. In a race against Bell Labs to develop the first practical mobile phone for non-vehicle use, Motorola was credited with its invention in 1973 (the same year that EPRI was founded). As the development of wireless technologies continued to expand, other wireless devices such as cellular telephones (cell phones) began to take shape.

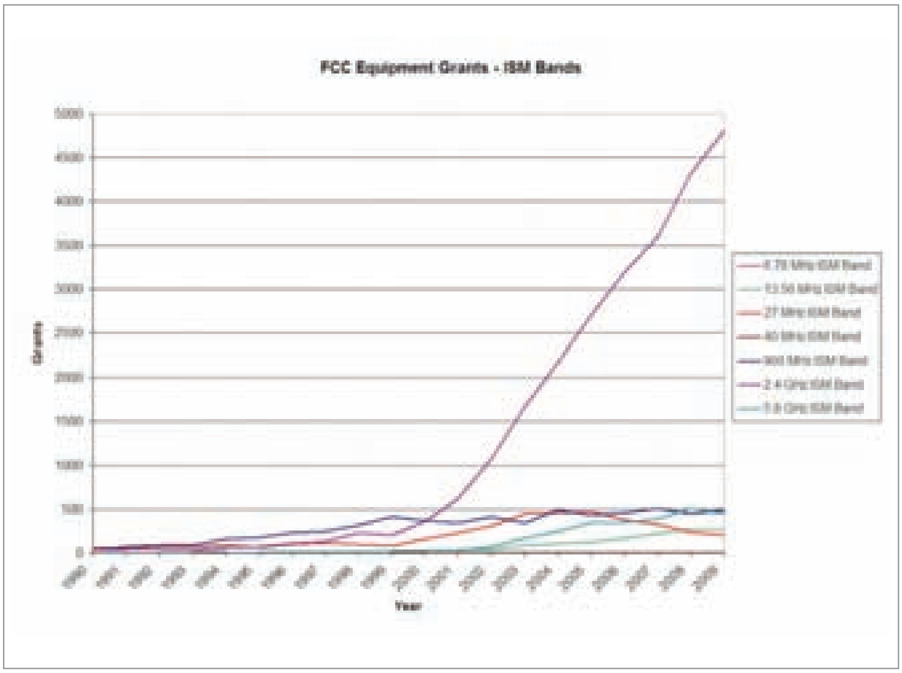

Figure 1: FCC equipment grants for the ISM bands, 1990-2010

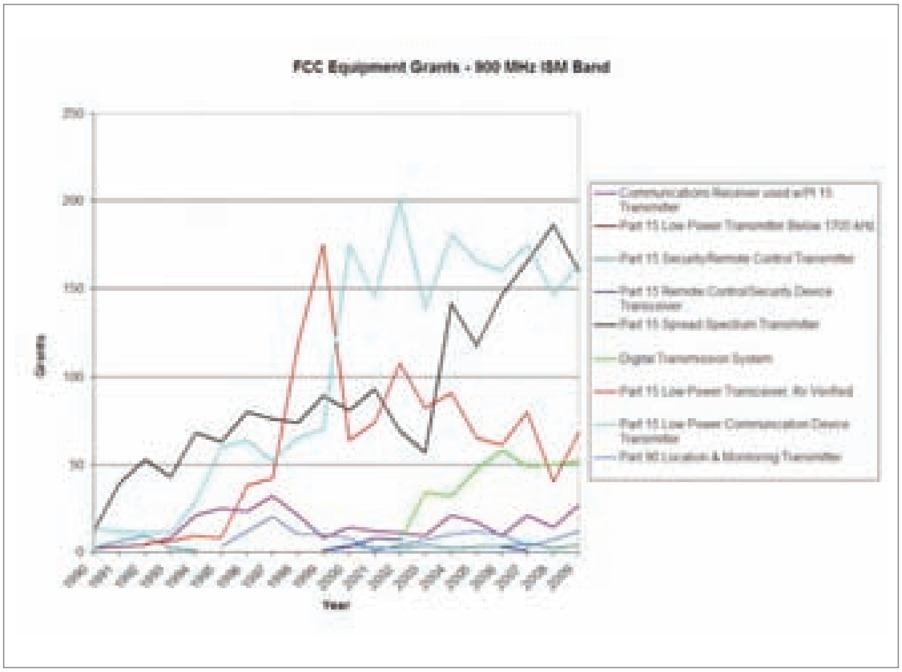

Figure 2: FCC equipment grants, by category, for the 900 MHz ISM band, 1990 to 2010

Since that time, efforts to protect against EMI-related events occurring in NPPs have been an ongoing part of risk mitigation. The potential for EMI events from natural and man-made sources has been known for many years. Over time, risk mitigation efforts have seen ongoing development as understanding of the physics of EMI events improves and as changing technology require continual development to keep protection appropriate to the current environment.

THE GROWTH OF WIRELESS TECHNOLOGIES

As the use of wireless technology grows dramatically, not only are the number of devices that use wireless transmission increasing, but the number of bands, modulations and protocols being used are also increasing. The rate of growth in number, as well as the increasing the variety of applications and diversity of potential interference sources, makes a complete listing almost impossible. Furthermore, the result would be of little use, being a

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long list of devices using virtually every available area of the spectrum for an ever increasing variety of applications. Such a list would provide little to help industries make decisions on how to deal with all the potential sources of interference. Even worse, the list would soon be out-of-date.

A prominent set of examples is the growth of the frequency bands used for industrial, scientific, and medical (ISM) equipment. The ISM bands were established by international agreement to be unlicensed bands, available for a wide range of uses. The ISM bands have been extremely popular, as demonstrated by the dramatic increase of US Federal Communications Commission (FCC) equipment grants for these bands. Figure 1 shows the continued heavy and increasing use of the ISM bands. The 900 MHz, 2.4 and 5.8 GHz bands support the most equipment by far, though recent growth of the 2.4 GHz band is extraordinary. The 900-MHz band seems to have stabilized at a level of approximately 500 new products introduced into it every year. While the 5.8-GHz band is experiencing heavy growth, is it not as notable as the 2.4 GHz band.

Figure 1 through Figure 4 report trends in equipment grants. Each unique model of wireless transmitter must have a FCC equipment grant to be legally marketed in the US. However, the existence of a grant does not indicate whether only a few devices or many millions of them are sold every year. The most popular, high volume product and the very specialized, custom product, each will have one equipment grant. To fully comprehend how widely a set of devices is used requires more information about sales volume, market trends, and whether old models are withdrawn as new ones are introduced. However, equipment grant data is easily quantified and provides an objective basis for demonstrating growth trends. It is important information, but does not provide all the information we want.

Figure 2 through Figure 4 show the most popular equipment categories in each band. As can be seen immediately, a variety of equipment types use each of the ISM bands. Under

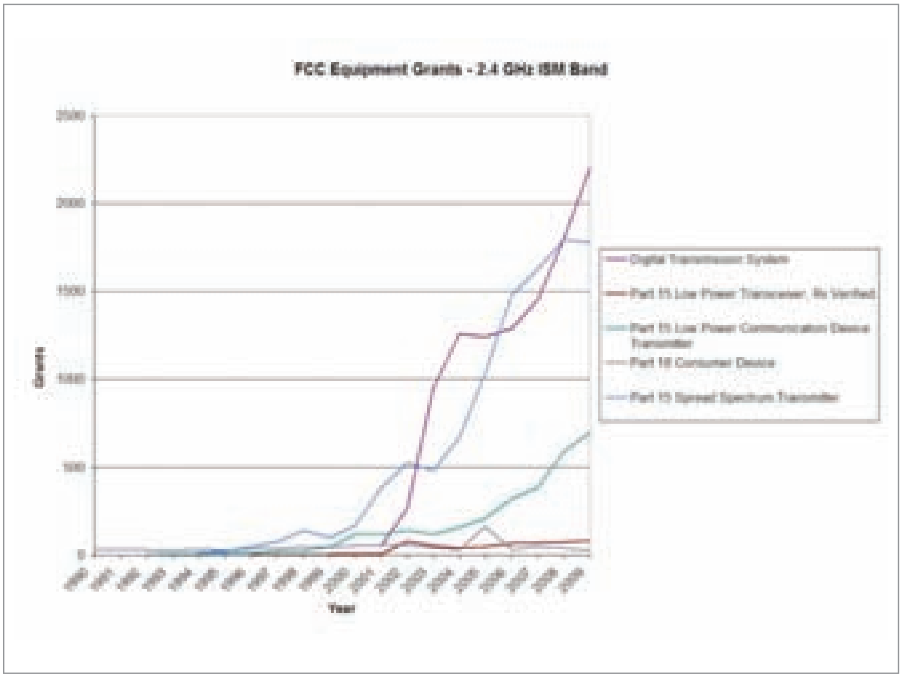

Figure 3: FCC equipment grants, by category, for the 2.4 GHz ISM band, 1990 to 2010

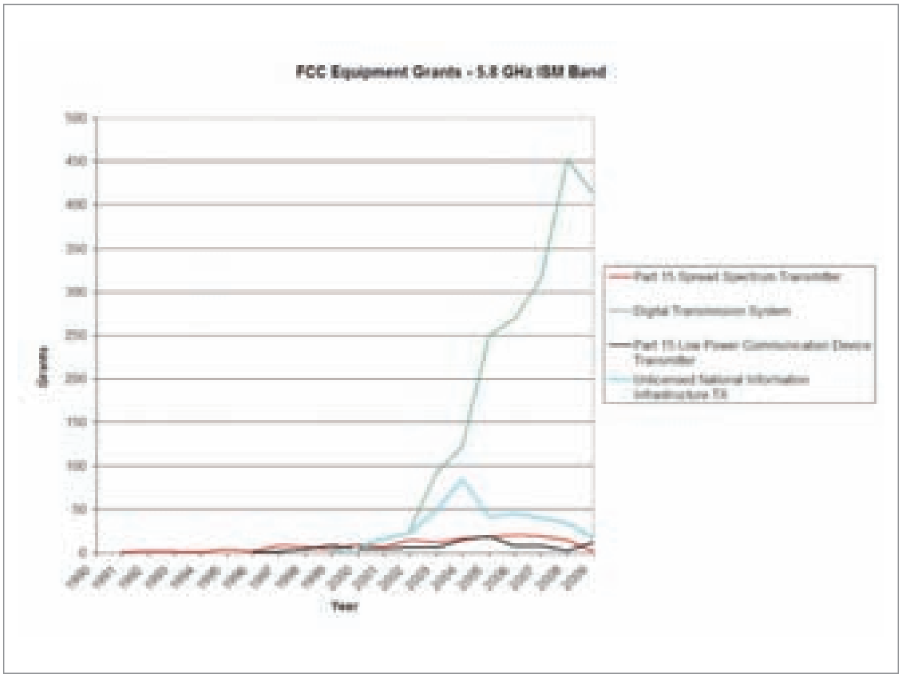

Figure 4: FCC equipment grants, by category, for the 5.8 GHz ISM band, 1990 to 2010

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FCC rules, any device may use the ISM bands so long as it complies with the service rules for that specific band. At one time the FCC tried to designate specific uses for each band, but generally has moved away from that practice for bands such as the ISM. These are now treated as general use bands, applying a minimum of restrictions and allowing a wide variety of equipment operating access to these spectrums.

Not only is the use of wireless growing dramatically, but the resulting spectrum crowding is requiring a bold, fresh look at how spectrum is regulated. There is an increasing trend toward more flexible spectrum regulations, allowing devices to dynamically share frequency bands. It is now common for devices to be capable of communicating on multiple frequency bands using multiple radio-frequency (RF) protocols. With software-defined radio, a device's capabilities may be changed by a remote software update. The result is that a single device may, from an RF interference viewpoint, be many devices, as it uses different frequency bands and protocols at different times. A single device may be capable of operating on the cellular networks using CDMA, GSM, UMTS or LTE protocols, on local area networks using any of several ISM frequency bands and 802.11 protocols, or by using Bluetooth, DECT, ANT or a number of other protocols and bands. Having access to multiple radio access technologies is a great benefit. However, this benefit presents a real challenge for EMC management.

What is needed for those with a role to play in managing spectrum or protecting against interference is a taxonomy that can bring order to the vast array of potential sources of interference, many of which are known to have caused interference in NPPs. A method is needed by which those with responsibility for interference avoidance or spectrum management can address classes of products that are of most concern, as well as monitor trends and market changes in many other classes of devices. Nuanced solutions are needed if overly conservative requirements, which are either wasteful of spectrum or unnecessarily burdensome on product designs, are to be avoided.

A taxonomy can be conceived that is designed to identify those types of device that have a significant potential for producing RF interference with I&C systems. To produce such a taxonomy, one must understand the characteristics that make a class of equipment sensitive to RF transmission. Using audio interference as an example, audio RF interference requires that the following two conditions exist:

1. The receptor device must be exposed to an RF field with sufficient intensity to overcome its RF immunity.
2. The modulation of the RF field must contain substantial baseband audio components.

Reduction of the RF power or the content of the audio band modulation will reduce the amount of interference created.

Further, for a particular source of audio RF interference to become common, the following two criteria must also be met:

3. The combination of RF field intensity and modulation must be common enough to have an unacceptable probability of causing an interference problem.
4. There must not be readily available and easily applied remedies available to the user. If interference is easily recognized as being caused by RF and its consequences are neither serious or to rapid for human action to adequately address, then it is entirely possible that some mitigation taken by the operator will be entirely acceptable. An example might be a noise coming from a speaker that is eliminated by moving a walkie-talkie off the console and further away from the speaker.

Relatively few RF devices have these four characteristics. So, serious concerns about RF interference can be focused on those wireless devices that, considered as a class, do have these characteristics and present a serious threat for producing EMI-related malfunctions and failures.
Similar analysis can be developed for I&C systems used in NPPs. The characteristics of a system's susceptibility must be understood in the context of the transmission parameters of potential interferes.

A well developed taxonomy extends from its focal point along multiple dimensions. It will seek to quantify modulation characteristics that impact interference. A constant wattage (CW) signal can introduce a direct current (DC) bias resulting in audio distortion or gain change, but generally these are not observed to be real field problems. At much lower power levels, modulated signals with strong content in the audio band result in disruptive audio interference in devices that produce sound, such as speakers or telephones. Similarly, pulsed modulations may interfere with digital circuits, like those used in digital I&C equipment, in a variety of ways.

Other dimensions may be explored. Some sources of severe interference are not widely distributed in the general population. However, NPPs may commonly find them introduced. Some kinds of transmitters are intended to be installed in fixed locations and remain stationary, while others are designed to be portable. The significance of these sources of interference must be evaluated based on their impact to NPPs.

An additional factor is that the methods used to provide RF immunity to the most common sources of RF interference tend to provide wideband immunity. The result is that I&C systems that are immune to mobile phones will also have good RF immunity to a number of other types of potential interference sources and electronic devices, even though they may operate in different frequency bands. This statement, like most generalities, will have exceptions and must be reexamined as new types of RF interferes are evaluated.

The purpose of this taxonomy is to assure that an adequate level of RF immunity is designed into I&C systems used in NPPs. To achieve this result, the taxonomy must identify the frequency range, power levels and modulation types that systems are likely to respond to. However, the taxonomy must equally identify the severity of the threat so that an inordinate level of RF immunity will not be required, with its attending cost and complexity resulting in overly burdensome specifications for I&C systems.

HUMAN BEHAVIOR

Can humans enable cell phone-related electromagnetic interference problems to occur in nuclear power plants? Perhaps the more significant question to consider is whether humans are in control of the wireless devices they carry. The answer increasingly is NO! Wireless devices are becoming progressively more sophisticated and consistently redesigned to provide new generations of services. At one time, a radio only operated when its user activated it. That is not true today. Many services now provided require that the device be continually in contact with the network and that the network sends information to the device as it becomes available. Consider the simple example of your text messages that appear on your device as soon as they are available. You don't call in to get your messages, they automatically come to you. That means that your device was in touch with the network, and conducted a communications session to receive the message without your ever being aware of it. If a sensitive piece of equipment like some part of an I&C system had been close at hand, an RF interference event could have occurred.

It is common for humans to assume their normal behavior cannot have negative consequences. Too many of us assume our normal eating and exercise habits do no harm, but our slowly increasing waistline foretells negative health issues in our future. Similarly, many people unconsciously assume their various wireless devices cannot cause problems because they haven't in the past. Perhaps more accurately, the devices caused problems that were easily solved. Most people have heard interference on their computer or

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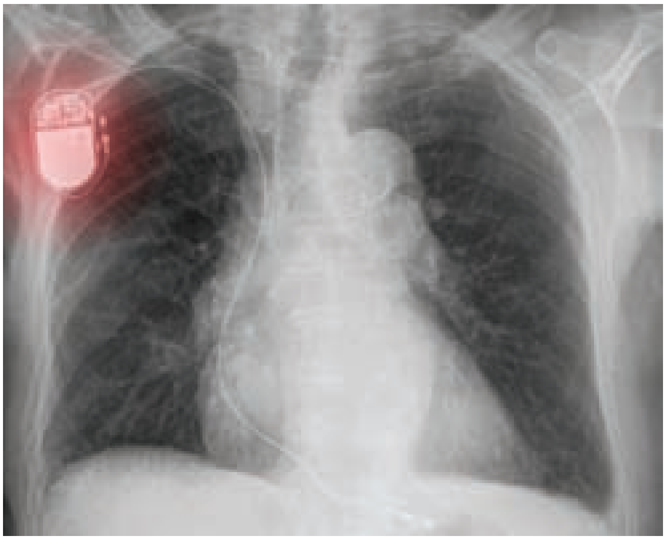
television speaker caused by their cell phones, but solved the problem by moving the cell phone or accepted the interference noise while they were on the phone. They experienced interference but its consequences were either easily dealt with or had little impact. However, in this case the past is not the future (is it ever?). Under the right set of circumstances, RF interference can lead to consequences which have much more impact and, once initiated, are much harder to mitigate or reverse, as in the case of interrupting the operation of a critical piece of I&C equipment in a NPP. Sometimes, once the damage is done, little can be put right and the damage is very bad indeed.

The challenge then is either to train people about the circumstances under which more care must be taken or, alternately, to manage the situation so that those circumstances cannot occur. Either approach works, but historically, if a lot of people (e.g., nuclear plant personnel and subcontractors) are involved, getting consistent, reliable behavior is the more difficult approach. It is often easier and more reliable to manage devices rather than people.

EMI PROBLEMS: CAN THEY REALLY STILL OCCUR?

The fact that wireless devices can cause interference is well documented and easily demonstrated in the laboratory. Even manufacturers of cell phones and other wireless devices know this. The fact that there are RF immunity standards, mandatory for CE Marking and many other requirements, and that many products initially fail these tests demonstrates that susceptibility to RF interference is a real issue. Few would argue that RF interference is impossible. However, it is more common to hear the defensive response, “My product passed the XYZ immunity standard. How can my product have a problem!!??”



What is not understood when such statements are made is that all RF immunity standards have a scope and are part of a two-part solution. RF immunity standards are meant to work with RF emission standards to provide a desired level of protection. Standards only work in the context they were written to address, and then only provide the degree of protection they were intended to provide. The commonly used IEC 61000 series of EMC immunity standards were written to provide a basic level of protection to commonly encountered RF environments. The writers of these standards well understand that there are more sever environments and that some kinds of products require a higher degree of protection. Their purpose was to provide general requirements that provide an acceptable level of protection for most equipment. However, as the following examples will make clear, this level of protection is not adequate for all situations or for more sensitive applications.

Medical Device Interference

Cell phone interference with pacemakers was raised as a problem in the 1990s and received considerable attention at the time. However, the issue of RF interference to medical devices is much broader. In a 1998 paper published by the IEEE Engineering in Medicine and Biology Magazine,[2] Howard Bassen of the FDA states:

> *Hundreds of incidents of RFI induced medical device failure have been reported, studied, and summarized. The most likely source of those failures has been RFI from mobile radio transmitters. The consequences have ranged from inconvenience to serious injuries and death. However, many more incidents may occur that are not reported because most users of medical devices are unaware that RF fields are present when problems are recognized and because of the intermittent nature of the failures that could cause them to be unobserved.*
>
> *In the mid-1980s, the US Food and Drug Administration (FDA) had become aware that approximately 60 infants died in the United States while being monitored for breathing cessation by one model of apnea monitor. Subsequent tests have shown that this particular monitor is extremely susceptible to low level RF fields, including those from mobile communication base stations several hundred meters away and FM radio broadcast stations more than one kilometer away. Other apnea monitors have been shown to be similarly susceptible to malfunction. This has resulted in voluntary recall of more than 16,000 apnea monitors.*
>
> *Another device that has demonstrated RFI susceptibility is the electrically powered wheelchair. Unintended motion has been initiated by RFI from transceivers in*

nearby emergency vehicles, causing persons to be ejected from their wheelchairs or propelled into traffic. New draft performance standards for wheelchairs are being developed by the Rehabilitation and Assistive Technology Society of North America (RESNA) to address these problems; many manufacturers are developing products that conform to these standards.

An additional problem area involves implanted cardiac pacemakers and defibrillators. Teams of engineers and cardiologists in several countries have independently studied these devices, either in patients or tissue simulating models, demonstrating that nearby digital cellular phones sometimes induce undesirable effects. The dominant effect observed has been loss of pacemaker adaptive control, causing the device to deliver stimuli either irregularly or at a preprogrammed fixed rate. This is not usually detected by the patient and, when the cellular phones are moved away, the pacemaker resumes its normal operation. Interference with pacemakers has not been observed when the phones are held at the ear. A panel of researchers has concluded that phone/pacemaker interference should not be considered a major public health concern and has offered specific recommendations for pacemaker wearers. Cellular phones have also been shown to cause unintended firings of implantable cardiac defibrillators.

Recently, handheld digital cellular telephones, that use pulse modulated time division multiple access (TDMA), have been found to disrupt the proper operation of in-the-ear hearing aids. TDMA phones include international Global System for Mobile (GSM) communications and North American Digital Cellular (NADC) pulse modulation formats, which utilize schemes that produce 100% amplitude modulated pulses of the RF carrier at frequencies within the audible hearing range. Subjective perception of interference varies from barely perceptible to annoying and loud, starting when the phones are within one meter of the hearing aids and becoming louder when the phones are several centimeters away. This type of interference also occurs in behind-the-ear hearing aids, making it impossible for wearers of this device to be able to use this type of phone.

Recently, warnings have been published concerning the use of wireless communications equipment in the clinical environment. Hospitals worldwide have recommended that cellular phones and two way radios not be used in intensive care units, operating theaters, and patient rooms, where critical care medical equipment is in use. Measurements that have been made inside an ambulance,

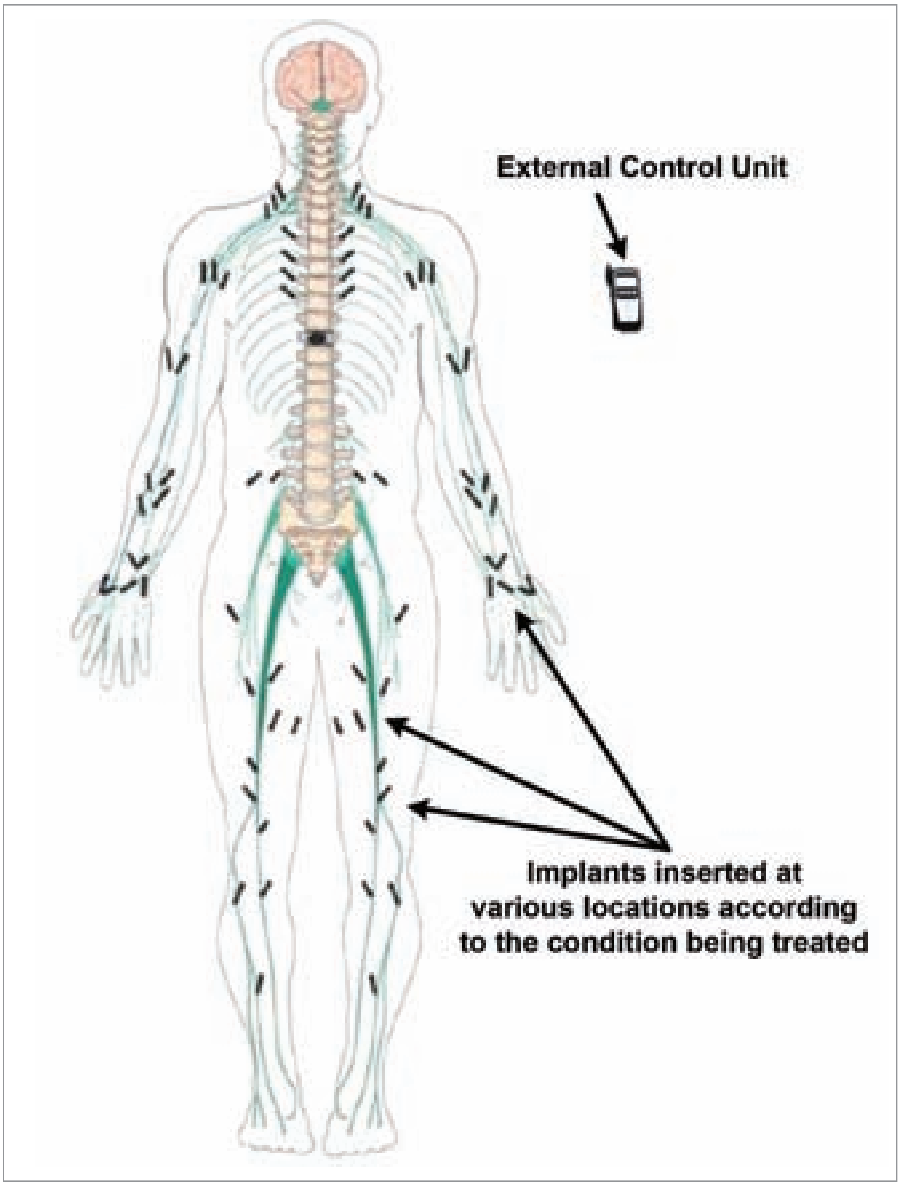


Figure 5: A Medical Micropower Network using RF communication with implants to treat a variety of medical conditions.

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where electronic patient monitoring equipment is used, have yielded field strengths of up to 22 V/m in the region of 800 MHz. Recommendations have also been made that patients using medical equipment at home be educated about possible hazards from the simultaneous use of portable telecommunication devices. Extensive measurements have been made to determine the field strengths produced by common RF sources in actual or simulated non-clinical environments, many that are greater than 3 V/m.

This history of medical device interference demonstrates a significant parallel to experiences in NPPs, where the need for constant vigilance of EMI-related interference is well justified. This vigilance is particularly justified by the increasing variety of devices that use wireless connectivity. Today, a powerful transmitter used to connect to the cellular network may not only be a cell phone, but also a laptop computer, electronic book reader, medical device, or even a light pole with a wireless emergency call box. A wireless transmitter may even be in a medical implant located inside an employee's body.

An example to consider is a Medical Micropower Network (MMN) system, which is an exciting new medical technology currently in clinical trials. In an MMN network, a control unit uses RF communications to receive or send data to implants in a person's body.[3] Improved treatment for a wide variety of conditions is potentially possible with such devices. As can quickly be seen, if an employee has an MMN network prescribed by his or her doctor, it will be extraordinarily hard to keep the MMN network away from the equipment that the employee works with. Reassigning the employee may be illegal, as the American's with Disabilities Act (ADA) requires that employers make reasonable accommodations for employees with disabilities.

Having digital I&C systems with adequate levels of RF immunity might be considered a reasonable accommodation.

The primary point to be made is that, in the future, wireless devices will be operating inside NPPs. Some even will be part of the I&C systems, such as wireless sensors used to report readings from locations where wired connectivity is not possible. As illustrated by MMNs, wireless transmitters may even be implanted in an employee's body to provide significant health benefits. Labeling wireless devices as "will not cause EMI" and further delaying the development of a wireless device use policy in NPPs is no longer an option. It must be managed intelligently.

Hearing Aid Interference

Early in 1996, the FCC called a Summit between the hearing industry, the wireless industry and consumers to resolve the compatibility issue between hearing aids and cellular phones. Cellular phones using digital technology were then just being introduced in the US. An interference problem with hearing aids had been discovered, and a group of concerned consumer groups petitioned the FCC. The new digital telephones caused many hearing aids to "buzz" due to their RF transmission. In their petition, the consumer groups asked the FCC to deal with the problem and assure that people with hearing aids would have the same ability to use these new technologies as everyone else.

As a result of the discussions held at the Hearing Aid Summit, it was decided that a technical standard was needed which would identify a solution to the EMI problem and develop tests to show that a hearing aid and cellular phone were compatible. In the spring of 1996, the American National Standards Institute (ANSI) Accredited Standards Committee (ASC) C63, which is focused on EMC, formed a task group to develop a measurement standard (C63.19) for hearing aid compatibility with wireless communications devices. The goal was to develop a set of parameters and tests that would evaluate and predict the compatibility of hearing aids with cellular phones. The committee recently released the fourth revision of its standard. Each revision has addressed the changing technologies in phones and hearing aids and improved the testing methodology needed to insure RF immunity.

The challenges presented to the task group were formidable. In order to accomplish this task, several significant technical issues had to be faced. The effort required to complete this project ultimately came to include five research projects and over 90 engineers from 50 different companies and organizations including, the FCC and the US Food and Drug Administration (FDA), working together.

The essence of the problem is that the RF energy transmitted by a cellular phone is received by the circuitry in hearing aids. Once the energy is in the hearing aid it may be audio rectified across some non-linear junction, resulting in a "buzz" of different audible noise levels depending on the modulation used by the cellular phone. Significant effort has been invested in understanding and addressing this issue. This mechanism of interference is well known. The challenge in this case is that hearing aid wearers want to be able to use cellular phones. This means that the hearing aid must be located well into the near-field region of the transmitting antenna. Accordingly, an evaluation of the immunity of the hearing aid must be for immunity in the near-field environment, not the usual far-field test used for immunity testing. These near fields can be an order of magnitude or larger than the "standard" immunity test field.

A second challenge is that, in the near-field, the fields from a wireless device are highly variable in intensity and field impedance. Quantification of the environment in which a hearing aid must operate presents a significant challenge. Movements of only a centimeter can produce significant changes in the field magnitude or impedance.

A third challenge is introduced by the hearing aid wearer. The human tissue in the head and hand has a very significant influence on the field generated by the cellular phone. The question of how to properly account for this field deformation when evaluating a hearing aid's immunity presents special challenges.

A fourth challenge is that many hearing aids are equipped with a magnetic coupling mode, called the TeleCoil (t-coil) mode, in addition to the primary audio coupling mode. Testing for compatibility in this mode has its own set of challenges. For example, there is the possibility of RF interference and electronic noise in the kHz region which adds a second, independent source of interference with the desired reception.

A fifth problem is that the actual annoying effect produced by the use of a cellular phone is highly dependent on the hearing impairment of the user regarding what is really "heard".

The measurement techniques developed for ANSI C63.19 allow the accurate evaluation of system performance for a hearing aid used with the new generation of cellular phones or other wireless communications devices. The resulting tests present new methodology for near-field evaluation of system immunity. This experience illustrates several important points. The first is that new RF immunity standards for specialized standards are necessary. The IEC 61000 series of standards on EMC existed when the ANSI C63.19 effort began, but were not adequate for this specialized issue. ANSI C63.19 also illustrates the need to simultaneously manage both emissions and immunity. In the case of ANSI C63.19, both are managed in the same standard. This is somewhat unusual. The more normal arrangement is that emissions are managed by one standard and often by one regulatory agency, while immunity is dealt with in a different standard and often enforced by a different regulator.

CURRENT PRACTICES IN MANAGING THE USE OF WIRELESS DEVICES IN NPPS

With the exploding development and use of wireless devices, utilities continue to receive requests for allowing wireless devices in areas of the plant where I&C equipment is installed. Most of these requests result from internal staff, subcontractors and utility personnel not part of the plant staff who must visit the plant as part of job responsibilities. Moreover, security personnel who move through all areas internal to the plant and areas external to the plant on the site must be free to use their wireless devices at any time and without limitations. With no formal industry-wide policy for controlling the approval or use of wireless devices in NPPs, utilities set out to develop their own internal policies or guidelines, realizing that they would continue to mature as more emphasis was placed on this problem. Some examples are listed below:

1. One NPP has restricted the use of cell phones inside their control room. This decision is based on concerns which stemmed from other plants that cell phones can indeed cause EMI problems with I&C equipment.
2. One utility that operates several plants uses a distributed antenna system in each plant for portable radios operating on the VHF band, cell phones from a specific cell phone manufacturer and approved cordless phones. This utility

restricts the use of any other cell phones to office and warehouse areas in NPPs. The utility tried to get another cell phone manufacturer to certify the manufacturer's cell phones to a manufacturing specification, but the manufacturer would not meet their request. As a result, the utility has to test each cell phone model from this manufacturer before allowing the use of that specific cell phone in the plant. Other cell phones have very limited coverage inside these plants.

3. Another utility who operates several NPPs allows intentional transmitters in various areas of the power-block portion of its plants. The utility has some restricted areas that contain sensitive electronic equipment, such as control rooms where only certain intentional transmitters of low power are allowed after they have been evaluated at the plant. The evaluation includes either testing or review of the test report from the FCC submittal of the wireless device, as well as in-situ testing with a setup of electronic equipment that has been shown to be sensitive to radiated emissions from the device. This utility installed a system of slotted coaxial cable in the general areas in most plants for use of portable radios. It also approved some wireless access points and phones to interface with these points. The cables are distributed in limited areas of the plants, including the control rooms. This utility evaluated these wireless systems as follows. It noticed that some modulation and other transmitting schemes had very high peaks of radiated power (many times the stated effective radiated power (ERP)) that do not show up on typical test reports. The peaks do show up on in-situ testing and other evaluations. The utility has requested other specific technical information from cell phone manufacturers, but responses to these requests have been limited. This utility also specifies an "exclusion distance" from electronic equipment that is potentially sensitive to EMI for various approved transmitting devices. The distance is generally three feet for most portable radios and other wireless devices over a few hundred milliwatts. For wireless devices with power levels below 100 milliwatts, this distance is generally one foot.

4. Another utility operating some NPPs states that their control rooms are located inside concrete buildings. The thickness of the concrete prevents wireless power needed to operate pagers and some cellular phones from entering the control rooms. Authorized wireless devices such as wireless telephones used by plant maintenance technicians are allowed to be used in controls rooms.

5. Another utility that owns and operates a number of NPPs does not allow personal cell phones inside its plants. The policy requires that cell phones must be turned off when using electronic dosimeters and at all times in the following areas: power blocks in all buildings, control rooms, cable spreading rooms and relay houses. This utility allows for the use of personal cell phones in the operations and maintenance buildings and in supporting buildings, as well as outdoor areas of the protected and owner-controlled areas. The policies listed above also apply to the line of intelligent interactive cell phones. The use of these policies for these phones stemmed from earlier model cell phones that caused more EMI-related problems in the NPP industry. This utility developed a more mature policy that restricted the use of all cell phones unless an evaluation of the cell phone is done. Usage of a cell phone was allowed because plant workers who came into the plant from the protected area came through the turbine building. This utility has no limitations on the use of older cell phone systems and voice-over-Internet protocol (VoIP) system phones. The utility is aiming to learn how to control wireless devices as they convert their wireless access points to handle data traffic. It also maintains a list of frequencies used by wireless devices inside the plant in an effort to minimize interference problems.

DEVELOPING A WIRELESS MANAGEMENT PLAN FOR NUCLEAR POWER PLANTS

A complete electromagnetic management plan for an NPP should address the following elements:

1. First, the tradition RF immunity requirements of I&C systems should be updated and kept current with changing technology and EM operating environments. As wireless devices are used inside NPPs, these systems must be tested for and immune to wireless transmitters that may operate in very close physical proximity to them. Having a transmitter operate close to a cable or equipment cabinet not only increases the field strength placed on the I&C system, but introduces near-field effects. The electric and magnetic fields will no longer have a fixed relationship, as they do in the far-field. These field components must be considered separately to adequately evaluate the RF immunity of a system.

2. The electromagnetic management plan assumes that wireless devices are part of plant operations, requires that they be tested for co-existence with other systems, and provides adequate levels of reliability even when the spectrum becomes crowded by the growing use of such devices.

3. The electromagnetic management plan should consider low-frequency, high-impact events. Examples are the terroristic and intentional use of electromagnetic interference, direct lightening strikes, and dramatic

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increases in the use of wireless brought about by the need for emergency personnel responding to a disaster.

4. Finally, the electromagnetic management plan should be alert to the potential for spectrum crowding, looking for bands that may be used by too many devices. Some systems may intentionally be designed to use difference frequency bands so as to separate them from other wireless transmitters. Alternately, RF power management (such as using femtocell base stations) may be part of the plan, allowing transmitters to operate but at much reduced RF power levels.

Together, these components of the electromagnetic management plan, implemented with insight and expertise, will insure that NPPs are prepared to function in their EM environment, benefit from the use of wireless connectivity, but have adequate protection against interference and band crowding issues that otherwise could prove problematic.

PRESENT EPRI GUIDANCE ON THE USE OF CELL PHONES IN NUCLEAR POWER PLANTS: WHAT'S WORKING AND WHAT'S NOT

As a result of EPRI's research on EMC and EMI/RFI issues, it published a first cut at developing guidance for the use of cellular phones in NPPs in 1994.

In January 1997, EPRI TR-102323-R1 Guidelines for Electromagnetic Interference Testing of Power Plant Equipment was published. In it, portable transceivers, commercial radios and cell phones were the wireless broadcast devices identified as a continuous, high-frequency radiated source of EMI [see Section 2.1.1 (Sources), Section 2.1.2 (Coupling Mechanisms), Table 4-1 and Table B-1 in TR-102323-R1]. Related susceptibility standards (and guides) MIL-STD-462C: Test RS03, MIL-STD-462D: Test RS-103, IEC 801-3 or IEEE ANSI C63.12 (guide) were also identified as tests that could be applied to I&C equipment to identify susceptibility issues and demonstrate that systems had adequate

RF immunity. No further guidance is included in TR-102323-R1 on how to manage the special challenges presented by portable wireless devices. At that time, cell phones were growing in popularity but most were still first generation devices using analog RF protocols. However, by the mid-1990s a second generation of cell phones was being introduced that used digital RF protocols. These devices further accelerated the growth of cell phone use and also introduced a much increased potential for interference. Although the RF power levels of cell phones were the same, the new digital modulation protocols brought a dramatic increase in the potential for EMI problems.

EPRI TR-102323-R2 published in November 2000 and EPRI TR-102323-R3 published in November 2004 provide no further guidance on the use of wireless devices, including cell phones. Further research to determine the propensity of these devices to cause EMI problems with I&C equipment used in NPPs was left for the future.

However, in another EPRI report (Product ID# 1011960, Requirements for the Application of Wireless Technology in the Power Industry published in 2005), one of the Equipment Attributes listed in Section 5.3 (Human Asset Requirements for Wireless Sensor Networks) in a table under Section 5.3.1 (Ability to determine what equipment needs to be, and can be, monitored), the following statement is made under 'Sensitivity to EMI/RFI' – "Some equipment itself may be sensitive to electro-magnetic or radio frequency interference. When selecting plant equipment to be monitored, take into account current practices regarding limitations on operation of radios near equipment or control panels." While it is vital to continue warning plant operators and plant I&C engineers on the propensity for wireless devices (in this case, radios) to cause potential EMI problems in power plants, no specific recommendations for determining which wireless devices (or radio) will likely cause EMI problems is made nor is guidance provided on how to mitigate that risk.

FUTURE RESEARCH

EPRI research focused on EMC for NPPs is planned into at least 2013. Through this focus, EPRI engineers are presently utilizing new approaches and methods developed in the EMC industry to solve today's complex EMI/RFI problems and apply them to solving similar problems in the NPP industry. This focused effort is addressing new test methods, developing new standards to integrate new EMI/RFI mitigation technologies into digital I&C equipment while reducing the schedules and costs of digital I&C upgrade projects, understanding what needs to be done to present and future I&C designs to avoid the use of exclusion zones, developing dynamic interactive training materials and modules, further developing electromagnetic management plans and frequency-spectral management plans, and supporting other activities aimed at reducing the risk of EMI/RFI events occurring in NPPs. In addition, EPRI has designed a programmable in-situ test system that can be used to determine if specific transmitting wireless devices will interfere with digital I&C equipment.

CONCLUSION

Wireless technology has developed and proliferated to the point where excluding it from NPPs and where utilizing a blanket-approval approach to allow the use of all wireless devices in NPPs are not practical solutions. Today, wireless connectivity is being planned into many I&C systems, such as reporting critical data from 1,000's of sensors in locations not accessible to plant personnel. What is needed is an RF protection plan complimented by a spectrum management plan which together insure that the risk of interference is adequately mitigated, but further, that the intentional use of wireless transmissions can co-exist and operate at very high levels of reliability.

Taken together, these risk mitigation measures will insure that I&C systems have adequate RF immunity to insure their protection from interference from wireless devices, even interference from low-frequency, high-impact electromagnetic events. Further, wireless connectivity intentionally used in NPPs should be tested for co-existence with other wireless transmission. The ultimate goal is that all systems used in NPPs, wired and wireless, are testing and designed to provide exceedingly high levels of reliability.

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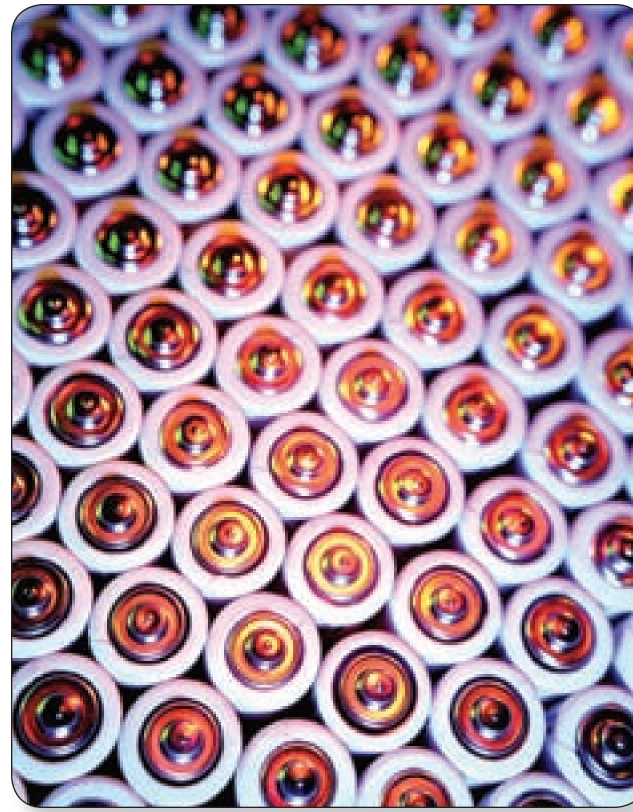

The Future of Battery Technologies

A General Overview & Focus on Lithium Ion

BY DR. MARIA WESSELMARK
AND TOM O'HARA

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A "battery" is the generic term for an electrochemical source of electricity, which stores energy in a chemically bound form, and which can convert this directly into electric power. A battery may be either a single cell or multiple cells connected in series/parallel configurations.

A battery cell consists of a container, electrodes (anode and cathode), separator material, electrolyte, and conductive current collectors. The container is the metal can, plastic case, or foil pouch housing of the cell. The anode (the negative electrode) is where the cell's oxidation reaction takes place, generating electrons to the external circuit. The cathode (the positive electrode) is where the cell's reduction reaction takes place, consuming electrons from the external circuit. The separator is a physical paper/non-woven film barrier which electrically insulates the anode from the cathode (preventing electrical internal short circuits but allowing anions/cations to freely pass. The electrolyte is the aqueous (non-aqueous for lithium batteries) medium providing the ionic conduction inside the battery. The conductive current collectors are typically the carrier metal substrates holding the anode/ cathode active ingredients. For Li-Ion, these are copper foil for the anode and aluminum foil for the cathode.

Batteries are categorized as being either primary or secondary systems. Primary batteries are disposable batteries, i.e. batteries that are used once then discarded. Primary batteries are not engineered for recharging and doing so may result in an explosion. Secondary batteries, whose anode and cathode discharge reactions are reversible, are engineered so they can be safely recharged. During recharge, the "discharged" anode and cathode are returned to their original "charged" state. Much of the engineering involved in the design of rechargeable batteries involves the management of gasses generated during cycling -- careful control of charge voltages and currents are critical in this management scheme, as is consideration of gas recombination mechanisms, where appropriate. Properly designed, a secondary battery can be recharged hundreds of times (with shallow cycling, many thousands of cycles can be achieved).

PRIMARY SYSTEMS

The most popular primary battery used in portable consumer products is the 1.5 Volt standard alkaline battery (Zn/ MnO_2). Well over one billion are manufactured and sold annually. One of the alkaline battery's many competitors are primary lithium metal batteries, but in replacing Zn/ MnO_2, system voltage and cost becomes a factor. Of the many different types of primary lithium battery chemistries in the marketplace, the most common is lithium/manganese dioxide (Li/MnO_2). These 3.0 Volt systems are primarily used for memory backup and in consumer products such as cameras and toys. Despite their better performance, Li/MnO_2 batteries have great difficulty in competing with alkaline batteries in many consumer products because of their price. Upcoming in popularity is the 1.5 Volt lithium/iron disulfide system (Li/FeS_2), which, because of its voltage, is a direct replacement for standard alkaline. On high rate applications, Li/FeS2 provides a 5X service life advantage over Zn/MnO2. On moderate to low rate applications, there is no service life advantage. Does the 5X high rate performance justify the 3X price increase? This simple example serves to highlight the performance/cost trade off offered across the board when considering various battery systems for specific applications.

Metal/air batteries are another category of primary batteries. These hold a huge volumetric energy density advantage over their competition because the active cathode is not contained within the cell -- the cathode is the O2 in the air, external to the cell. As a consequence, a much larger portion of the cell's internal volume can therefore be devoted to the anode. The metal anode occupies a far greater space than in a conventional primary battery, which results in a very high energy density. A number of different metal/air systems have been the subject of research (with Li/Air being the most coveted), but only the zinc/air battery has achieved extensive use. In the consumer market, Zn/air button cells are used almost exclusively for hearing aid applications.

BATTERY MARKET IN CHANGE

The use of lead-acid batteries (Pb/Ac) began in the nineteenth century. Because of low manufacturing costs, good performance and long life, the lead-acid battery is, in spite of its respectable age, still the most common battery in the entire world, with a market share of as much as 40 – 45 %. New manufacturing methods, cell designs and application areas are still introduced. The lead-acid battery has a wide field of applications. The most common use is as a starter battery in cars, with additional applications in industrial trucks and as reserve power. In the EV arena, Pb/Ac is well positioned to play a dominant role with micro-hybrids (start/stop hybrids)

NiCd batteries are a mature and thoroughly tested battery technology that was patented in 1899 by Waldemar Jungner. NiCd batteries are used in a huge variety of stationary, mobile and portable applications, ranging from large-scale backup power and start batteries for aircraft to handheld power tools and toys. Due to stricter EU environmental legislation, NiCd batteries are expected to gradually be phased out in Europe, at least in consumer electronics applications. However, NiCd batteries will still have a strong position on several niche markets, for many years ahead.

The NiMH battery exploits relatively new battery technology, which began to be used more at the beginning of the 1990s. NiMH batteries offer the same cell voltage as NiCd batteries, and can therefore replace them in many applications without special modifications being necessary. The cell voltage, combined with higher energy density and better environmental properties, are the driving forces that enabled NiMH batteries to win market share from NiCd during the 1990s in consumer electronic products, such as computers and mobile phones. Today, the significantly more energy-dense Li-ion batteries have completely taken over the computer and mobile phone battery markets. The portable NiMH batteries are, however, still expected to remain on the market in the near future as a low-cost alternative to lithium batteries. With their longer track record, relatively high energy density, and their good cyclic properties, NiMH batteries have also found applications in electric and hybrid vehicles.

ENERGY-DENSE LITHIUM-ION BATTERIES

Li-ion batteries were introduced onto the market in the mid 1990s and then began, as previously stated, to replace the NiMH batteries in mobile phones, notebook computers, and other portable electronic devices. At the present time, use of lithium batteries has been widely spread to other and cheaper consumer products. It is important to remember that Li-ion batteries are a generic name for a large number of different battery chemistries with varying properties and performance and therefore also suited for a wide range of products. At present, the development of lithium-ion batteries is mainly driven by the automotive industry and their need for an improved energy storage solution for their electric and hybrid vehicles.

Manufacture of lithium-ion batteries is primarily located in Japan, Korea, and China. Europe and North America are late to the game, but are coming on strong with significant investment. Li-ion batteries are still in a relatively early phase of development, seen in terms of the battery industry, and have only been readily available for 15 years in the commercial market. This means that there is a potential for both comprehensive technical development and price reductions.

SELECTING THE MOST SUITABLE BATTERY FOR YOUR APPLICATION

The choice of primary or secondary batteries depends on financial factors and the technical requirements imposed by its intended use. In general, primary batteries are principally used for applications with low energy consumption, in which there is a long storage time between use, or where it is difficult or inconvenient to charge the battery. Secondary batteries are primarily used when there is a need for high levels of energy or large load currents, and where it is convenient to charge the batteries. Although rechargeable batteries have a greater initial investment cost, they are cost effective in high energy applications where one rechargeable battery can be take the place of many primary battery replacements. It is interesting to note that on single use applications, primary batteries hold a 10% to 50% advantage in energy density. Design for rechargeability and long cycle life requires compromises in material use and construction. Cost is also a factor.

There is a wide range of primary and secondary batteries. The most common primary systems are alkaline, lithium metal and zinc/air batteries. Among secondary batteries, lead acid, nickel/cadmium (NiCd), nickel/metal hybrid (NiMH) and Lithium-ion (Li-ion)/Lithium-polymer (Li-polymer) batteries dominate. Ongoing battery research is constantly striving to develop new systems that can match or exceed the performance of existing systems, improve their safety, and reduce their cost.

YOUR LITHIUM BATTERY OPTIONS

The expression "lithium batteries" is a generic name for battery technologies in which lithium ions play a part in the primary electrochemical discharge and charge reactions. Lithium batteries are available both as primary batteries (disposable batteries) and secondary batteries (rechargeable batteries). The choice of the best battery for a specific purpose is determined by a number of parameters, such as the power and energy requirements of the application, the operating environment, the electrical preconditions and the cost aspects. The most important factors are:

1. The type of battery – disposable or rechargeable battery
2. Electrochemical system – matching the benefits and disadvantages of the battery type to the requirements of the application.
3. The voltage requirements – rated and operating voltage respectively, the minimum and maximum levels, voltage regulation, discharge profile, etc.
4. Load profile – type of load: resistive, current or power discharge, single vs. variable load, etc.
5. Work cycle – continual or intermittent
6. Temperature specifications
7. Lifetime
8. Physical requirements – size, shape, connections, etc.

9. Storage requirements – shelf life, charge state when stored, environment, etc.
10. Charge and discharge states (rechargeable batteries) – cycling batteries vs. energy storage batteries (flow charging), charge characteristics, efficiency and accessibility, discharge requirements
11. Environmental conditions – climate (temperature, humidity), pressure conditions, physical environment (impact, vibration, dust, acceleration, etc)
12. Safety and reliability – permitted variance, acceptable faults, sensitivity to gas leaks or leaks of electrolyte from the battery, etc.
13. Unusual or demanding operating conditions – e.g. extreme temperature conditions, standby times, high reliability and rapid activation, etc.
14. Maintenance and replacement of unserviceable batteries
15. Costs – initial, and lifetime operating costs

Note that although cost is at the bottom of this list, for many applications it is the number one consideration.

Lithium-based battery systems are characterised by high energy density levels, relatively high voltages, and low weight-to-volume ratio but, in general, tend to be more expensive than equivalent battery technologies with aqueous electrolytes, such as alkali disposable batteries and zinc/air batteries in the primary battery sector, and nickel metal hydride, nickel cadmium and lead batteries in the secondary battery sector. Because they are aqueous based, alkaline batteries are also viewed as being more safe than flammable organic electrolyte containing lithium batteries. This is NOT to say that lithium batteries are not safe..

PRIMARY LITHIUM BATTERIES

Primary lithium batteries have existed since the 1970s, are easy to use and provide convenient sources of energy for portable applications. The batteries usually require no or very little maintenance and they have a long shelf life; modern lithium batteries can usually be stored for up to 10 years, and there are special batteries with solid state electrolyte that can be stored for more than 20 years. The storage tolerance at elevated temperatures is generally good, in some cases up to 70°C.

There are 3 classes of primary lithium batteries:

1. **Solid state batteries –** Characterized by low power but superior shelf lives, and are used, for example, in pacemakers and computer memory backup. The expression 'solid state' is used because the electrolyte is solid and the ion transmission between the electrodes takes place in a solid, non-electrically conductive material, usually a polymer.

2. **Batteries with a solid cathode** – Usually found in coin cells or small cylindrical batteries and used in a huge numbers of applications, such as clocks, memory circuits, photo and communication equipment, toys, flashlights, etc.
3. **Batteries with soluble cathodes** – Industrial and military batteries that are manufactured in large cell sizes, up to 35-40 Ah, but are also available in smaller sizes, used, for example, in medical and civilian applications.

All of these batteries have lithium metal or lithium alloy anodes (the battery's negative terminal). The cathode material determines the battery system.

The two most common primary lithium batteries on the market are lithium disulphide ($LiFeS_2$) and lithium manganese dioxide (LiMnO2) batteries. Both of these are of the solid cathode type and are sold as consumer batteries from electrical goods stores and supermarkets. Other primary lithium batteries are mainly intended for the professional market. Table 1 lists the most common primary lithium battery chemistries and their properties.

Over the last few years the market has seen the introduction of battery types in which the cathode consists of a mixture of different electrode materials. The purpose of these batteries is to provide a system that can accommodate both high and low loads. One example is the battery that is used for implanted defibrillators that consist of silver-vanadium oxide (SVO) cathodes to absorbs the peak load of a defibrillation, and carbon monofluoride ((CF)x) for the baseline load between the defibrillation pulses.

SECONDARY LITHIUM BATTERIES

Today, nearly all rechargeable lithium batteries are of the lithium ion type, having a negative electrode that consists of a carbon-based material, usually graphite, or another type of alloy or material that permits intercalation, i.e. storage, of lithium in the structure. This category includes lithium polymer batteries, which differ from traditional lithium ion batteries in that they have an electrolyte that is bound within a non-conducting polymer matrix. Lithium ion batteries were introduced by SONY in 1991, and were first used in advanced consumer electronics products, mobile phones, digital still and video cameras, as well as laptop computers. This type of battery is constantly gaining new ground, and the areas of use are constantly expanding, and lithium ion batteries are currently used in all sorts of portable applications within consumer electronics, medical technology and military systems. The general properties that contribute to this are the high energy density of the lithium ion battery and its specific energy, i.e. a lot of energy from a small volume and weight, compared with other rechargeable types of battery. Its other properties include low self-discharge, relatively long recharge lifetimes (300-500 complete charges and even more if the battery is used within a more restricted charge state range). High costs and the safety aspects are the main barriers. Existing lithium ion batteries suffer from functional limitations at low temperatures and degrade rapidly at temperatures exceeding 55°C.

Carbon materials are used in lithium ion batteries because carbon has the ability to reversibly absorb and release large quantities of lithium (Li:C=1:6) without altering the mechanical and electrical properties of the material. Graphite and coke also have an electrode potential that is close to that of lithium, 0.0-0.1 for graphite, and 0.0-0.3 for coke. On the first charge of the battery (i.e. transport of lithium into the carbon), the a protecting outer layer is formed (Solid Electrolyte Interface, SEI). The SEI layer is important because it prevents the carbon anode from reacting with the electrolyte. Dissolution of the SEI layer at elevated temperature poses an important safety risk to lithium ion batteries.

There are a number of different chemistries within the lithium ion family that are based on the choice of chemistry

in the cathode material. Traditional lithium ion batteries use cathodes made from cobalt dioxide (LiCoO2). By adding nickel (LiNi1-xCoxO2), a layered material is obtained that is more stable and less expensive than pure CoO2. Manganese oxide spinel (LiMn2O4) is another common cathode material for lithium ion batteries. Compared to cobalt, manganese oxide is cheaper but has a lower energy density and is less stable than cobalt in terms of calendar and cycle life (note that from a thermal/safety perspective, cobalt is generally considered the least stable cathode chemistry -- but among the highest in terms of energy density). Extensive research is being carried out into new cathode materials, and in the last few years lithium ion batteries with cathodes made from lithium iron phosphate (LiFePO4) have been marketed on a large scale, based on their higher safety levels and low cost compared with conventional lithium ion systems. The benefits of LiFePO4 have been achieved at the expense of their energy density and voltage. New electrode materials are being developed and tested constantly in order to produce lithium ion batteries with properties that are suitable for different applications and areas of use. Table 2 shows a comparison of the main types of lithium ion batteries that are currently on the market. All of them have graphite as the most commonly occurring anode, but there are also high power batteries using hard carbon. At present, research into rechargeable lithium ion batteries is being driven mainly by the requirement in the automotive industry for long calendar and charge lifetimes, high discharge currents and the need for rapid charging, in addition to cost targets.

TRENDS IN LITHIUM ION BATTERIES

Trends that are noticeable within research & development of lithium ion batteries are:

1. A transition to cheaper and less toxic electrode materials (cathodes), e.g. phosphates and silicates.
2. The transition to materials that have higher reversible lithium reception. The more lithium atoms that the material can absorb in each unit cell, the higher will be the potential battery capacity.
3. Materials that can withstand rapid charges (from 0 to 90% SOC in ten minutes)
4. Power and energy batteries for the automotive industry and stationary installations.
5. Increased cell size in the form of stored energy capacity.

System	Construction	Cell voltage [V]		Specific energy [Wh/kg]
		Rated	Operating voltage (20 °C)	
Category 1 – Solid state system				
LiI_2		2.8	2.6-2.8	220-280
Category 2 – Batteries with solid cathodes				
$Li(CF)_n$	Coin cell Spiral ”jelly-roll” Rectangular plates	3.0	2.7-2.5	220-590
$LiFeS_2$	”Bobbin” and ”jelly-roll” cylindrical cells	1.5	1.5-1.4	260
$LiMnO_2$	Coin cell	3.0	3.0-2.7	230-270
$LiAgV_4O_{11}$	Prismatic	3.2	3.2-1.5	270
Category 3 – Batteries with soluble cathodes				
$LiSO_2$	Spiral ”jelly-roll”	3.0	2.9+-2.7	260
$LiSOCl_2$	Bobbin Spiral Prismatic cells with electrode plates	3.6	3.6-3.4	275-590
$LiSO_2Cl_2$	Spiral	3.95	3.5-3.1	450

Table 1: Primary lithium batteries

6. Battery systems with high voltage levels, including electrolytes that can withstand higher electrode potential without degrading or reacting with the environment.
7. Battery systems with enhanced safety compared to current battery types.

Titanate, silicon and silicides, as well as tin and tin alloys, are new anode materials that have been discussed in the context of research and development. All of these materials are regarded as offering improved safety as they do not form an SEI layer. Recently, titanate as well as mixed anodes of tin, carbon and silicon have started to enter the commercial

Energy density [Wh/l]	Power density	Discharge profile	Usages	Properties
Category 1 – Solid state system				
820-1030	Very low	Relatively flat	Coin cells and special batteries for e.g. pacemakers	• High energy density. • Withstands low current and power loads • High reliability • Cells constructed with cathode limitation • Long shelf life, 15-20 years under normal conditions, but can be stored for up to 1 year at 100 °C • Normally used in pacemakers and digital watches
Category 2 – Batteries with solid cathodes				
550-1050	Low-medium	Relatively flat	Coin cells Cylindrical batteries (commercial and military)	• Highest theoretical energy density • Withstands medium to low loads • Wide temperature range • -20-60 °C • Flat discharge curve
500	Medium-high	High initial drop in voltage, then flat		• Replacement batteries for type AA household batteries • Tolerates high power • Good temperature properties • Long charge retention
535-620	Low-high	Low-high	Cylindrical up to 22 Ah	• High specific energy and energy density • Wide temperature range • Withstands relatively high discharge currents • Relatively cheap
780	Low-medium	Rel. complex discharge curve	Special batteries for medical implants	• Used in implants and other medical applications • High energy density. • Multi-step discharge • Good load properties
Category 3 – Batteries with soluble cathodes				
415	High	Very flat	Cylindrical cells up to 35 Ah	• Manages high current and power loads • Excellent low temperature properties • Long shelf life
630-1100	Low-medium	Flat	Cylindrical cells 2-30 Ah	• One of the highest OCV voltages and energy densities of all of the commercial batteries • High specific energy • Withstands low discharge loads
900	Medium-high	Flat	Cylindrical cells 7-30 Ah	• High energy density. • Manages high discharge loads • Good high temperature properties • Excellent storage • Properties

battery market. The main advantage of titanate is that its structure is highly stable and there is no increase in volume during battery charging. Lithium's mobility within the material is very rapid, which permits the battery to be charged and discharged at high currents. The limitations include low cell voltage, due to the high electrode potential of titanate compared to that of lithium intercalation into carbon. In addition, the electrodes are also more expensive than carbon-based electrodes. Silicon and tin are limited both by very large electrode expansion during charging, around 300 and 250% respectively. However, both of these material groups are attractive because of their high energy density as well as relatively low electrode potential. Silicon is especially interesting as it permits storage of large quantities of lithium in the anode structure, e.g. the reversible Li ion insertion capacity is >1. Moreover, the material is neither expensive nor toxic.

Development on the cathode side is more multi-faceted. The list of substances and variants of substances that are being studied is extremely long, and many of them will never be marketed. Some of them will only be of interest for niche applications on cost grounds. Among the materials being discussed are metal phosphates (in particular vanadium, magnesium and manganese, as well as various compounds), layered metal oxides (often with manganese oxide bases) and silicates (e.g. iron silicate). The metal phosphates are being promoted thanks to their chemical stability, leading to increased safety compared to traditional cobalt-based cathode materials. Magnesium and manganese phosphates are also relatively cheap and non-toxic materials, which is also one of the strengths of iron silicate. The layered metal oxide structures are expected to offer rapid lithium mobility, thereby permitting high charge and discharge currents, but the material is still relatively expensive and associated with safety problems.

Cathode material	Rated voltage [V]	Charge limit [V]	Max charge and discharge currents	Energy density [Wh/kg]	Common applications	Comments
$LiCoO_2$	3.6	4.2	1C limit	110-190	• Mobile phones Cameras • Laptop PCs	• Highest energy density • The most common battery type in portable appliances since the 1990s.
$LiMn_2O_4$	3.7-3.8	4.2	10C continuous 40C pulse	110-120	• Hand tools • Medical equipment	• Low internal impedance • Withstands relatively rapid charging • Withstands relatively high discharge currents • Low energy density
NCM (compound oxide consisting of nickel, cobalt and manganese)	3.7	4.1-4.3[1]	5C continuous 30C pulse	95-130	• Hand tools • Medical equipment	• High energy density. • Withstands rapid charge • Withstands high discharge currents
NCA (compound oxide consisting of nickel, cobalt and aluminium)	3.7	4.3-4.5[1]			• Vehicles	• High energy density. • High cell voltage
$LiFePO_4$	3.2-3.3	3.6[1]	35C continuous	95-140	• Hand tools • Medical equipment	• Long charge lifetime • Withstands rapid charge • Withstands high discharge currents

Table 2: Rechargeable lithium ion batteries

[1] Charging at higher voltage leads to fewer charge cycles

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In summary, lithium batteries are expected, over the next 20 years, to dominate the market for rechargeable batteries, while NiCd and NiMH batteries will still be used in some niche applications.

RISKS/SAFETY FACTORS FOR LITHIUM BATTERIES

While one of the lithium battery's major strengths is its high energy density, high energy content is responsible for lithium-based chemistry's down side - safety risk, when compared to other battery systems. Although the risks are directly linked to the specific cell chemistry, cell size and the number of cells in the battery, there are certain common factors. Lithium batteries contain flammable material in the form of organic electrolytes that have a low flash point and polymers that can maintain a fire and increase the risk of spreading to surrounding areas. The anode in primary lithium batteries consists of metallic lithium that melts at 180°C (when molten, lithium metal is much more reactive and mobile, creating extensive internal short circuits across and around the separator system). Both lithium metal and charged Li-Ion anodes react violently with water, generating highly flammable (explosive) hydrogen gas. The cells also contain several compounds that are toxic themselves and which form harmful combustion products in the case of fire.

One should always try to avoid exposing batteries to heat. This is partly because the cell chemistry may become unstable if the temperature is too high, which can lead to venting, and in the worst case scenario, to explosion and fire. Elevated temperatures accelerate the normal chemical processes taking place in the battery cell, leading to cell aging and loss of capacity. Heat can either be generated by the cell itself (decomposition, internal short circuits and also during normal usage) or come from an external source. Uneven heat across the cells in a battery pack is an insidious problem in that the temperature differential will cause the cells to age at different rates. With time, this will lead to problems in cell balancing. Cell balancing relates to how cells perform together inside a battery pack. The greater the spread in max/min cell capacities, the quicker a battery pack will lose capacity and fail. This is why, during battery pack assembly, much care is taken to choose cells whose capacity and impedance are well matched. A battery stack is never stronger than the weakest cell.

Low temperatures can also pose a problem. Primary batteries generally only lose their function when it becomes too cold. Rechargeable batteries often have limited chargeability at low temperatures, and should not be charged if the ambient temperature is lower than the lowest recommended charge temperature, as it may lead to formation of metallic lithium (aka lithium plating). Lithium is well known to form dendrites when plated and these can result in internal cell short circuits if the dendrites pierce the separator barrier membrane.

COMMON EXTERNAL CAUSES OF BATTERY FAULTS

Some of the most common causes of battery faults originating from the user or application include:

1. External short circuit of the battery
2. Too high discharge or charge current
3. Pole reversal, i.e. discharge of a cell below 0V
4. Charging primary batteries
5. Incorrect or insufficient charge control (this is one key role of the BMS, the battery management system).

All five of these conditions generate heat to a varying extent in the battery cell, which leads to increased aging or breakdown of the cell. As these risks are caused by external factors, it is possible to prevent and avoid them.

External short circuit

When battery poles are short circuited, the high short circuit current leads to generation of a lot of heat in the cell. The most efficient way of preventing this from happening is to employ smart battery design that ensures that the + and - poles are physically isolated from each other, by countersinking them into the battery casing and designing them in such a way that it is not possible to connect the battery incorrectly. In certain cases, it may be necessary to integrate further forms of protection in the form of a fuse, or a PTC (Positive Temperature Coefficient) component, which breaks the electrical circuit if the current or the temperature begins to run away. Certain cell manufacturers integrate PTCs in their cells. PTCs are commonly found integrated into the caps of cylindrical sized cells, such as the 18650.

It is also important to be aware of the risk of a short circuit when transporting individual cells or batteries. The rules that exist for packaging lithium cells and batteries, with or without equipment, are intended to prevent accidents from accidental short circuits.

Too high discharge or charge current

If the current is too high, the mass transport of the reactants for the main reactions is limiting, and the energy supplied is partially consumed by side reactions in the cell, such as gassing and decomposition, which lead to increases in temperature. If the temperature increase is too high, it leads to further side reactions, which in turn generate even more heat. This increases the risk of venting and, in the worst-case scenario, uncontrolled cell reactions and thermal runaway.

When charging secondary cells, it is important not to exceed the recommended maximum charge current. If the charge current is too high, there is a risk of the lithium ions not managing to diffuse into the anode structure during charge, and instead being precipitated as lithium metal on the anode surface. This not only results in loss of cell capacity but also increases the risk of internal short circuits during subsequent use.

Apart from current limiters, it is important that there is a low voltage protection to prevent any cell discharging below the lowest recommended voltage limit of the cell. In rechargeable batteries, the low voltage protection prevents the anode's base metal, usually copper, from dissolving and contaminating the cell. Li-ion cells that are heavily discharged risk both irreversible loss of capacity and increased self-discharge in subsequent use. The dissolved copper may also serve as starting point for creating an internal short. Rechargeable batteries also need to be fitted with an over-voltage protection to prevent early aging. Depending on the application and the complexity of the battery, it is not always sufficient with over-voltage and low voltage protection at the stack level, and control may have to be implemented on an individual cell level within the battery stack.

Pole reversal

Pole reversal can take place in battery stacks that consist of multiple cells connected in series. It is important to make sure that the cells in a multi-cell battery stack are well matched to begin with, and they are exposed to mainly the same loads and other conditions, so that the capacity continues to be evenly distributed. Otherwise, in the worst case scenario, the weakest cell could risk being heavily discharged and forced to reverse its poles, which means that the cell would be charged by the other cells, which are still being discharged. Multi-cell battery stacks usually have a cell-balancing function that distributes the current between the cells in a suitable manner. If the battery stack is fitted with low voltage protection, this may help to prevent pole reversal. The pole reversal will lead to a number of unwanted reactions within the battery which leads to heat generation which has consequences both on aging and safety.

Charging primary batteries

Primary lithium batteries are not constructed to be charged. If this takes place, gas is formed within the cell, causing its internal pressure to rise. This may result in venting, or most seriously, in explosion. Primary lithium cells connected in parallel, and thereby exposed to a potential source of charging, should be protected by diodes.

Incorrect or insufficient charge control of rechargeable batteries

Charging is the single most risky element in the battery cycle, as energy is permitted to flow into the system from an external source. It is extremely important to comply with the charge recommendations of the cell and battery manufacturers, both with respect to current limitation, voltage limitation and temperature, in order to ensure a long and safe battery life. The risks involved in too high charge current, exceeding the voltage limits, and too high and low temperatures, have been discussed above.

INTERNAL CAUSES OF BATTERY FAILURE

In addition to external fault sources, there are risks that may be difficult to predict or prevent, and which are caused by unsuitable cell design, manufacturing faults or ageing mechanisms within the battery cell, such as:

1. Weak or faulty seals that can cause leakage or failure
2. Contaminants that can lead to gas-developing secondary reactions, resulting in aging or venting due to overpressure in the cell
3. Internal short circuits caused by formation of dendrites on the electrodes, metal particles or faulty insulation of conductors, etc.

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Primary lithium batteries

Primary lithium batteries have a higher energy density than the rechargeable Li-ion and Li-polymer cells. Small primary cells, e.g. coin cells, often lack the integrated safety components at cell level, but are considered safe simply because of their small energy content. Larger cylinder batteries and prismatic cells often have so-called safety valves, which is a form of a pressure vent, fuse, or PTC.

The greatest safety risks are involved when a battery consists of several cells. In such cases, the cells should be "permanently connected" together in a battery stack to lower the risk of the user mixing different types of cell, and cell chemistries when changing batteries. Even if the battery cells have integrated overheating protection, it is recommended that the battery is fitted with an external temperature limitation protector. The electrical protection must also include protection against charging, short circuit and a bypass connection protection that prevents pole reversal of an individual cell in a series, or a combination of serial and parallel connected cells.

Rechargeable lithium ion batteries

Most of us have seen images and videos of burning laptops on the Internet, TV and in newspapers. For those not deliberately induced by overcharging or heating, analysis of these "field failures" show that these were usually caused by an internal short circuit arising from debris during manufacture. The short circuit leads to the cell's energy being discharged through a very limited volume, which leads to a rapid local temperature increase, reaching up to > 200°C in seconds. The heat induces the electrodes and electrolyte to begin to decompose, and these reactions add further heat, tipping the cell into so-called thermal runaway in which the cell temperature and pressure increase exponentially. The overpressure leads to the cell venting, which liberates electrolyte aerosol in the surrounding area, and can easily ignite. In extreme cases, the cell splits or explodes unless the overpressure can be ventilated out sufficiently quickly. Depending on the construction of the cell and the internal positioning of the cells in a battery pack, the ignited electrolyte from one cell may heat up the adjacent cells and causes the cascade effect. This is particularly true for a series stack of cylindrical cells whose venting electrolyte ignites and behaves like a torch, with focus, directional burning of pressurized flammable organic electrolyte solvents.

Most Li-ion batteries on the market today indicate 60°C as their upper usage temperature. The majority of batteries currently on the market have graphite anodes. Graphite is not stable and can react chemically with the electrolyte in the cell. During manufacture and formation of the cell, a passive layer is formed on the anode surface, the SEI (Solid Electrolyte Interface) layer, which prevents continued reaction between the electrode and the electrolyte. Already at temperatures below 90°C, the layer can begin to break down, allowing exothermal gas evolving reactions to begin. If a sufficiently large area of the SEI layer breaks down, the cell may enter thermal runaway.

Not all cells that develop an internal short circuit suffer thermal runaway. Factors that influence this include:

- The size and location of the short circuit
- The size and design of the cell
- The active material in the cell; cobalt oxide is, e.g. more reactive than manganese dioxide and iron phosphate
- Thermal properties of the various materials in the cells and the cells' abilities to disseminate heat
- The cell's age and history and perhaps most importantly, the cell's state of charge.

Internal short circuits caused by production factors may occur in all types of Li-ion cells and it is unlikely that it will be possible to completely eliminate this type of fault. There are various types of integrated protection at cell level that attempt to prevent and counteract risks.

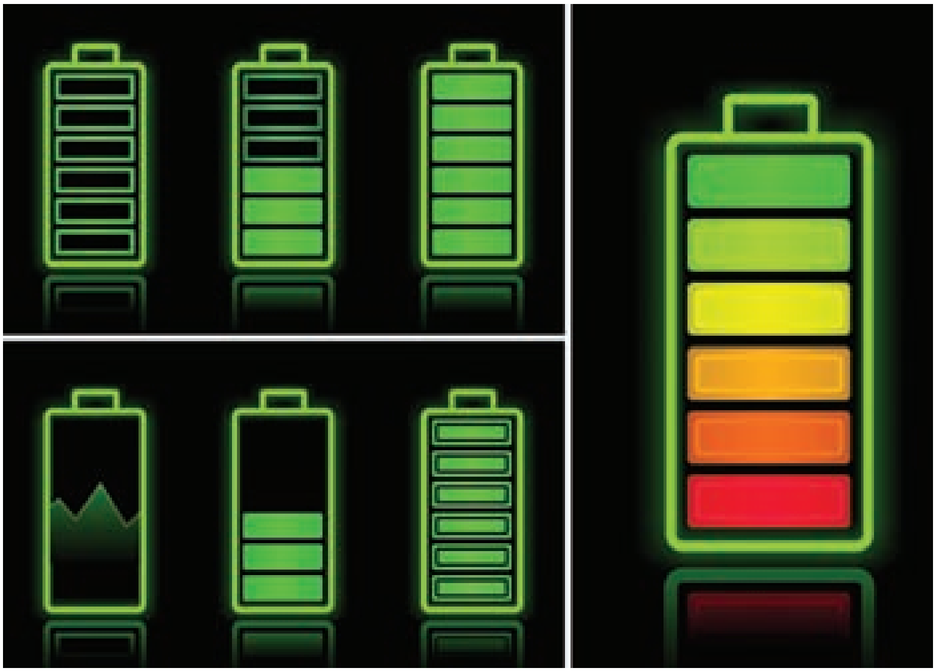

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Figure 1 shows a cut-through of a cylinder cell. At the top of the cell there are 2 mechanical protectors in the form of a CID (current interrupt device) that triggers at a pressure of around 10 bar, and a safety valve. Both of these are irreversible, and the cell no longer works if either of these protectors is triggered. In addition, there is usually a PTC that throttles the current at temperatures over 125°C.

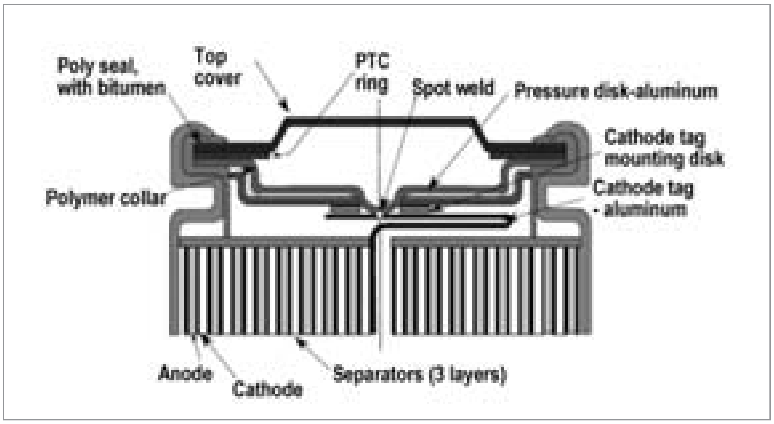

Figure 1: Cut-through of a Li-Ion cylinder cell

This PTC function is reversible and conduction restarts when the temperature falls. The separator between the anode and the cathode typically consists of 3 layers of polymer and is usually of the “shut-down” type, which means that when the cell temperature gets too high, around 165°C, the separator melts and the pores close. The consequence is that the electric circuit is broken as the ion conduction in the cell ceases to function. This effect is irreversible. A number of additives have also been added to the electrolyte in the form of flame retardants or inhibitors and redox shuttles. The role of the redox shuttle is to manage and consume any overcharge effect so that the cell voltage does not get too high. The cell container is also a part of the total protection which secures the cell’s integrity against its surroundings.

The increasingly more common “pouch” cells, i.e. cells with a soft coating that consists of a polymer-coasted metal foil, lack many of the mechanical protection components that are found in cylindrical and prismatic cells with steel or aluminum casing. Pouch cells have no integral CID, PTC or safety valve, but are completely dependent on external protection circuits. In the case of a strong overpressure, the cell’s welded seams split, generally in vicinity to the pole connectors where the weld is the weakest. Nor are pouch cells as resistant to impact or puncturing as cells with metal casing.

TESTING & EVALUATING LITHIUM BATTERIES

In order to ensure that a battery-driven product functions in a good way, there are different methods of testing and evaluating the battery’s functioning and safety. There are four different categories of tests that can be used in order to qualify a battery:

- Electrical performance testing – different types of test that investigate the battery’s electrical functioning, for example available capacity at different loads and surrounding temperatures, cycle lifetime, calendar lifetime in storage, charging receptivity, impedance as a function of charging state etc.
- Safety testing in relation to environmental effects – various tests that simulate different kinds of environmental conditions to which the battery could be exposed, for example, vibrations, falls, knocks and blows, damp, high temperatures or quick temperature changes.
- Safety testing in relation to faults or incorrect usage – various tests that evaluate the battery’s ability to deal with different types of stress that can arise intentionally or unintentionally when using the product, for example, overcharging, short circuiting, incorrect installation and similar situations.
- Effect on the environment – chemical analysis of heavy metal content.

Some of these tests have to be carried out because of rules and legal requirements. Amongst these is transport testing in accordance with the UN's transport rules for dangerous goods (UN Manual of Tests and Criteria section 38.3) which is required in order to transport lithium batteries and cells and products that contain lithium batteries, irrespective of the type of transport. Several countries apply limits for certain heavy metals in batteries. The chemical elements that are most commonly regulated are mercury, cadmium and lead. The EU Battery Directive regulates all three of these elements.

ELECTRICAL PERFORMANCE TESTING

A battery's technical specifications say a lot, but not everything, that an instrument manufacturer needs to know about the battery cell or battery pack that has been chosen to power a certain apparatus. Available battery capacity and the number of discharge cycles are two factors that are strongly affected by actual conditions of use. Similar battery cells from different manufacturers and even different models from the same manufacturer do not need to have the same properties, since the functioning of the battery is governed by those chemical reactions that are possible in each individual case. The balance between different components, additives, pollutant contents etc. are very important to cell chemistry. Cell design and the manufacturers' recipes for electrode and electrolyte composition are carefully guarded secrets and are important competitive tools among manufacturers. The extent of the testing which is carried out by cell and battery manufacturers can also vary from case to case. Testing represents a cost, and one can therefore assume that low-budget products in many cases have undergone less extensive testing than advanced products from more renowned and experienced manufacturers.

MINIMUM REQUIREMENTS IN STANDARDS

The type tests that are found in IEC standards are basic tools for evaluating lithium cells and batteries' electrical properties. IEC 60086-1 and IEC 60086-2 lay down dimensional requirements for different cell types and sizes of primary batteries. The corresponding standard for rechargeable cells and batteries is IEC 61960. It is generally the case that standard requirements are minimum requirements that all batteries must comply with. Most modern, battery-driven products available on the market impose higher or more extensive requirements on their batteries and so standard tests should be supplemented with application-specific discharge and lifetime tests.

When buying cells and batteries, one should demand that they fulfill the relevant standard requirements. Cell and battery suppliers should be able to provide reports from tests carried out and be able to account for the extent and frequency of tests, both as part of ongoing production checks and those that are carried out in final checks on the finished cells and batteries. It is not unusual for low-budget cell and battery specifications to state that the product is designed to conform to the requirements of IEC standards without any such testing having been carried out, or that limited testing is carried out covering only parts of the standards. In some cases testing has been performed in connection with the original product launch but is not updated in connection with product development or changes in components.

SAFETY TESTING FOR EXTERNAL INFLUENCES

The UN's transport testing is a typical example of safety testing designed to establish the battery's safety properties in the event of external influences. The test program includes a total of eight tests designed to simulate conditions that could occur in a transport situation.

- T1 Simulation of high height (test to recreate low pressure when flying)
- T2 Thermal shock (exposing the battery to alternating high and low temperatures)
- T3 Vibration test

- T4 Fall impact test
- T5 External short-circuiting
- T6 Blow test
- T7 Overcharging test
- T8 Forced discharging

It is important to note that it is not enough to test the individual cells that are included in a battery pack and that the whole battery pack must be tested if it consists of several cells. Re-testing is also required if the product is modified in a way that could affect the results of testing and if the product's weight (primary lithium batteries) or Wh-content or voltage (rechargeable lithium cells and batteries) are changed. As well as special testing, transport rules require that lithium batteries and products that contain lithium batteries are packed, marked and accompanied by safety documentation in accordance with given requirements. Some countries/ transport authorities set higher requirements than those that normally apply in UN 38.3. Today, transports in the USA are subject to more extensive requirements.

UL and IEC standards consist of a combination of environmental influence tests and tests that simulate predictable types of incorrect use. The tests focus on evaluating fire-safety and the requirement for approval is generally that the cell or battery does not explode or burn during the course of a test. The tests included in UL or IEC are similar, even though there can be differences in the degree of strictness between the different standards. UL holds a strong position in North America whilst IEC dominates in the rest of the world.

When buying cells or batteries, you should insist that the cell or battery supplier has carried out tests in accordance with the UN's transport requirements. If these have not been carried out, this can affect the timetable for the product launch and involve considerable costs for the equipment manufacturer, who must then take responsibility for carrying out the tests. Cell and battery suppliers should also be able to provide test reports from completed testing in accordance with UL 1642 (cells) and 2054 (battery packs) or IEC 60086-4 (primary lithium cells and batteries) or IEC 62133 (rechargeable cells and batteries) and to account for the extent and frequency of tests carried out, both as part of ongoing production checks and as final checks on the finished cells and batteries. If, as a buyer, you are unsure whether the battery has been tested or whether the testing has been carried out in the right way, then you should carry out your own verification in accordance with relevant standard methods.

REGULATED HEAVY METALS ARE UNCOMMON

There is no named method that has to be used for chemical analysis of batteries. None of the listed substances; mercury, cadmium or lead contributes to the electro-chemistry in lithium batteries. There is therefore no reason for manufacturers to add them intentionally. To the extent that they do occur, it's in the form of raw material contamination. It is extremely unusual for lithium-based cells and batteries to contain problematically high levels of these substances.

BATTERY TESTING STANDARDS

Below is a list of the testing standards mentioned earlier. Most national and regional standards, such as SS and EN, are based on the corresponding IEC standard and this is therefore referred to in the current version of IEC. In some cases, national standards are not updated at the same time as IEC and for that reason it is important to be certain that testing has been carried out in accordance with the current guidelines and, where necessary, supplement the tests carried out with further tests.

[Note: ANSI C18 series essentially contains the US equivalent of IEC battery standards]

For transport rules, the method of transport governs which guidelines that apply, i.e. ADR/RID for land transport, the IMDG-code for sea transport and the ICAO-TI and IATA-DGR for air transport. These are updated regularly, but there is sometimes a time delay which leads to transport law guidelines referring to an earlier edition of the UN Manual of Test and Criteria.

UN's transport testing for all batteries that contain lithium:
ST/SG/AC.10/11/Rev.5; UN
Manual of Tests and Criteria, Rev.5 (2009)

Primary batteries:

- IEC 60086-1: Primary batteries - Part 1: General, Ed 10.0 (2006)
- IEC 60086-2: Primary batteries - Part 2: Physical and electrical specifications, Ed. 11.0 (2006)
- IEC 60086-4: Primary batteries - Part 4: Safety of lithium batteries, Ed. 3.0 (2007)
- UL 1642: Lithium Batteries, Ed. 4, (2005, with revisions 11/2009)
- UL 2054: Household and Commercial batteries (2004, with revisions 11/2009)

Rechargeable batteries:

- IEC 62133: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications, Ed. 1.0 (2002)
- IEC 61960: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for portable applications, Ed.1.0, (2003)

- UL 1642: Lithium Batteries, Ed. 4, (2005, with revisions 11/2009)
- UL 2054: Household and Commercial batteries (2004, with revisions 11/2009)

Note that several of the listed standards are currently in revision.

CONSTRUCTION REQUIREMENTS FOR BATTERY POWERED EQUIPMENT

When applying for product certification for medical-technical equipment, an approved result of the safety test in accordance with IEC or UL standards constitutes a basis for being able to approve the battery as a safe component. This means that if there are several suppliers of cells and/or batteries for a specific item of equipment, then they must be approved individually in order to be used in the equipment.

CB-certification of products containing rechargeable Li-ion batteries requires testing according to IEC 62133 as of May 1, 2012, and that Li cells and batteries certified to UL 1642 and UL 2054, respectively, have to undergo and fulfill additional testing in order to conform to IEC 62133. Primary lithium batteries must be certified in accordance with IEC 60086-4. The corresponding timetable for products falling under IEC 60065 and IEC 60950-1 remains to be determined.

Product certification requires that the equipment must be safe if a component fails. Fire or dangerous explosions must not occur and a risk analysis is performed based on the test results of the device. For a primary battery or cell of the lithium type, protection is only required against reverse current. It may also be appropriate to specify regular checks on the protective components. For batteries or cells that are tested and certified as short-circuit-proof, no further protection is needed. For other batteries a current-limiting component is also required to limit the discharge current. The reverse and discharge currents that the battery is certified for must not be exceeded in the case of a fault.

For secondary lithium batteries, i.e. rechargeable batteries and cells, the charging battery protection circuits are investigated. The battery must be protected against excessive discharge current, charging current and charging voltage. Where appropriate, it may also be necessary to monitor the battery's temperature in order to shut down the device and mitigate the effects in case of over-temperature. If the battery protection is not certified, two independent protective measures are required for each of the three parameters, which is the most commonly occurring scenario.

In addition, a risk analysis based on testing should be carried out to show that it is improbable that faults should occur in both protective circuits simultaneously.

ENVIRONMENTAL CONSIDERATIONS FOR LITHIUM BATTERIES

There is a growing awareness of interest in environmental issues across all sectors of society in recent years. Many people argue that our long-term survival depends upon reducing our impact on nature and that we must stop releasing toxic materials into the environment. Batteries are not yet covered by legislation on chemicals, but the "Regulation on Batteries," which is based on the EU Battery Directive, governs the use of certain heavy metals in batteries. Unfortunately, this legislation has not kept pace with technological developments in the battery field. This is also the case when it comes to environmental labeling requirements on batteries, such as the Swan Label.

There are at least three key factors that can be used when determining how environment friendly a battery is:

- Battery lifespan and the number of cells required to achieve the desired battery function in the equipment or apparatus
- Recyclability
- Chemical content

UPPER LIMITS AND LABELING REQUIREMENTS

The EU Battery Directive is currently the most far-reaching Directive on the regulation of hazardous elements that are used in batteries. The Directive includes both fixed upper limits by weight for how much cadmium (20 ppm) and mercury (5 ppm) batteries can contain, with the exception of military and certain industrial batteries, plus batteries for emergency and alarm systems, cordless power tools and a number of medical equipment products. The Battery Directive and all related national legislation within the EU also covers labeling requirements for batteries with mercury (5 ppm), cadmium (20 ppm) and lead (40 ppm) content along with requirements on the collection and treatment of spent batteries, irrespective of the particular type of battery.

Several countries in Asia (e.g. China, Japan and Singapore) have introduced regulation on heavy metals and batteries. Parts of the USA and Canada have also come a long way on the collection and treatment of batteries.

NO MERCURY, CADMIUM OR LEAD

None of the listed elements (mercury, cadmium and lead) play a part in electrochemical cells in lithium batteries and therefore, there is no reason for manufacturers to deliberately include them. Where they are found, it is in the form of contamination of raw materials used. It is extremely unusual for lithium-based cells or batteries to contain problematically high levels of these elements. This has persuaded some manufacturers of these batteries to claim their products are "green" and environment friendly. The basis for such claims is debatable as lithium batteries, and rechargeable lithium-ion batteries in particular, are extremely complex and can contain a large number of different elements in varying degrees. This relationship is also reflected in the environment labeling requirements specified by Swan, which currently regulates these three heavy metals and, in the case of rechargeable batteries, arsenic.

RECHARGEABLE BATTERIES ARE PREFERABLE

Generally speaking, rechargeable batteries are more environment friendly than single-use batteries when used in the same application. This is because the total amount of battery waste will be lower as the same battery can be recharged numerous times, hundreds of times as a rule. Within the group of primary batteries (single use batteries), lithium cells offer an advantage in the form of higher energy density compared to alkaline batteries, which enable a longer operating time. Most primary lithium cells also have a higher cell voltage which also means they need fewer cells to achieve the desired operating voltage in the apparatus. Both these characteristics help make primary lithium cells appear more advantageous than other primary cells from an environment perspective, as fewer cells are required to achieve the same performance and lifespan. These same arguments can be used in favor of lithium-ion cells, as these have a higher cell voltage than other rechargeable cell types.

NICKEL FROM THE TOYOTA PRIUS CAN BE RECYCLED

Recyclability is totally dependent on the availability of efficient collection systems that ensure batteries do not end up in landfill sites and that there are financial incentives to recover the materials found in batteries. Here, traditional chemical batteries (e.g. lead, nickel cadmium and nickel metal hydride batteries) are actually an advantage compared to lithium-ion batteries, as traditional batteries have a high content of metals that have a second-hand value on the commodities markets. Exhausted lead batteries can be used directly in the manufacture of new lead batteries. Nickel from nickel cadmium and nickel metal hydride batteries is used by the steel industry in the manufacture of stainless steel. However, recycled nickel is not yet of sufficiently high quality to be used in new batteries.

Toyota has just announced that they have developed a method that enables them to recover nickel from old Prius batteries that can be used in new ones. It will be interesting to follow this development and whether this method can be used for nickel metal hydride batteries of the consumer type. Cadmium can also be recovered and recycled in the production of new nickel cadmium batteries.

SPENT CELL CONTENT USED IN CONSTRUCTION INDUSTRY

Lithium-ion batteries contain relatively small quantities of elements that are financially viable to recover. The large variety of cell chemistries available on the market also makes recycling more difficult. There are recycling processes currently available for lithium-ion batteries that recover cobalt, nickel and copper from battery waste. The residual cell content is combusted and the ash can be used in the construction industry. The trend within lithium-ion technology is moving towards a development characterized by an increased use of materials that are not of interest to recover, such as manganese dioxide, iron phosphate and mixed oxide materials with little or no cobalt in the mix. As a consequence, the cost of collection and recycling of lithium-ion batteries can largely fall on users when the manufacturers attempt to recoup their manufacturer product liabilities.

PRODUCT LIFE CYCLE MUST BE CONSIDERED

The environmental impact of batteries is a very complex issue. In order to be able to evaluate and compare different batteries against each other, it is desirable to take the entire life cycle of the product into account: the extraction and refining of the raw materials, cell and battery manufacturing, product lifespan in operation plus waste disposal and recycling processes. Both manufacturers and consumers of battery-powered products should do their utmost to minimize the total number of batteries required during the lifetime of the product in order to minimize its environmental impact. It is also important to persuade users to take batteries to recycling points and to continue work on developing technology that enables as much recycled material as possible to be used.

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Energy Storage Specialist
Dr Maria Wesselmark holds a PhD in Applied Electrochemistry from Royal Institute of Technology, Stockholm. She is working within Intertek's advisory group as Energy Storage specialist.

Tom O'Hara
Global Business Manager/Advisory Services, Intertek Semko, AB. Part of Intertek's Energy Storage Business Unit covering Batteries, Fuel Cells, and Super Capacitors. A consumer battery specialist with over twenty years R&D experience with Energizer Battery. Contributions touched nearly every product in Energizer's product portfolio. Ten years consulting with both established and start-up battery enterprises covering a wide variety of battery chemistries and applications.

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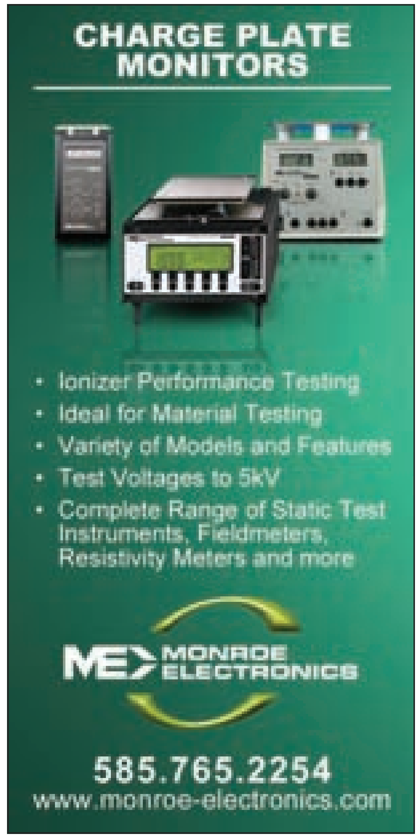

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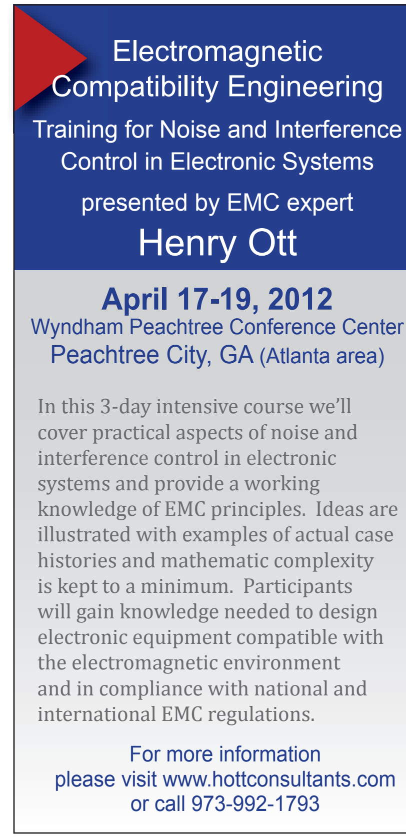

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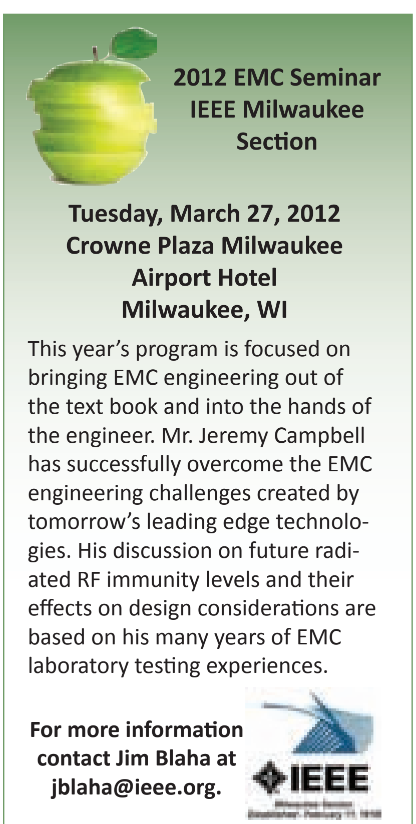

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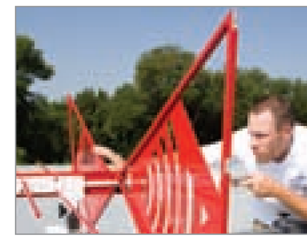

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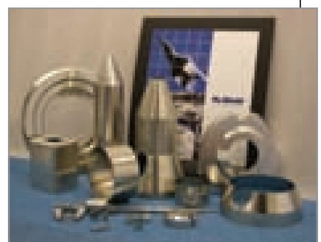

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Mag Daddy. 847-719-5600

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LCR Electronics. 610-278-0840
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DNB Engineering, Inc.. 714-870-7781
LCR Electronics. 610-278-0840
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Texas Spectrum Electronics. . 972-296-3699

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Oak-Mitsui Technologies . . . 518-686-4961

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Spira Manufacturing Corporation
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Filters, Shielded Room

Alco Technologies, Inc. 310-328-4770

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DJM Electronics 866-DJM-ELEC
Nextek, Inc. 978-486-0582

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Filters, Third-Party Approved, EU

LCR Electronics 610-278-0840

Filters, Third-Party Approved, US/Canada

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Ja-Bar Silicone Corp 973-786-5000
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Tech-Etch 508-747-0300
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Vanguard Products Corporation
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EMI - Spiral Wound Gaskets

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P&P Technology Ltd . . +44 (0)1376 550525
Schlegel Electronic Materials
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Formed-In-Place (FIP) Gaskets

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VTI Vacuum Technologies, Inc.
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P&P Technology Ltd . . +44 (0)1376 550525

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LCR Electronics 610-278-0840

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Ja-Bar Silicone Corp 973-786-5000
Schurter Inc. 800-848-2600
Zero Ground LLC 401-377-8389

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API Technologies Corp. 855-294-3800
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Fil-Coil 631-467-5328
Fotofab 773-463-6211
Leader Tech 866-TECH-EMI
Magnetic Shield Corporation
. . . . 888-766-7800
The MuShield Company, Inc.
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Select Fabricators, Inc. 888-599-6113
VTI Vacuum Technologies, Inc.
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The MuShield Company, Inc. 888-669-3539

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The MuShield Company, Inc. 888-669-3539

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EMC Technologists 732-919-1100
LCR Electronics 610-278-0840
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The MuShield Company, Inc. 888-669-3539
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VTI Vacuum Technologies, Inc. 800-482-1941

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3Gmetalworx Inc. 888-965-3634
Ad-Vance Magnetics 574-223-3158
Alco Technologies, Inc. 310-328-4770
Andre Consulting, Inc. 206-406-8371
East Coast Shielding 908-852-9160
FerriShield 866-TECH-EMI
Fotofab 773-463-6211
Intermark USA, Inc. 408-971-2055
Ja-Bar Silicone Corp 973-786-5000
Magnetic Shield Corporation 888-766-7800
MAJR Products, Inc. 877-625-7776
The MuShield Company, Inc. 888-669-3539
Omega Shielding Products, Inc. 800-828-5784
P&P Technology Ltd . . +44 (0)1376 550525
Panashield Inc. 203-866-5888
Pulver Laboratories Inc. 800-635-3050
SAS Industries, Inc. . . . 631-727-1441 x302
Schlegel Electronic Materials 800-204-0863
Spira Manufacturing Corporation 818-764-8222
Tech-Etch 508-747-0300
TechDream, Inc. 408-320-4021
VTI Vacuum Technologies, Inc. 800-482-1941
W. L. Gore & Associates, Inc.

Shielding Material, Magnetic Field

3Gmetalworx Inc. 888-965-3634
Ad-Vance Magnetics 574-223-3158
Andre Consulting, Inc. 206-406-8371
FerriShield 866-TECH-EMI
Fotofab 773-463-6211
Magnetic Shield Corporation 888-766-7800
MAJR Products, Inc. 877-625-7776
The MuShield Company, Inc. 888-669-3539
Panashield Inc. 203-866-5888
VTI Vacuum Technologies, Inc. 800-482-1941

Shielding, Board-Level

3Gmetalworx Inc. 888-965-3634

Suppressors

Suppressors, Transient

Captor Corporation 937-667-8484
Nextek, Inc. 978-486-0582
Okaya Electric America, Inc. . 800-852-0122
Texas Spectrum Electronics . . 972-296-3699

ESD Equipment & Products

Air Ionizers

3M Electronic Solutions 512-984-6747
MKS ION Systems 800-367-2452

ESD Tape

Mag Daddy 847-719-5600
Parker Hannifin, Chomerics Div 781-935-4850

Meters

Meters, Static Charge

Megalin Source International . . . . +886-2-8698-4181
MKS ION Systems 800-367-2452
Monroe Electronics, Inc. 585-765-2254
Prostat Corporation 630-238-8883
Staticworx Flooring 888-STATICWORX

Simulators

Simulators, EMP

EM Test USA 603-769-3477
Teseq Inc. 732-417-0501

Simulators, ESD

Advanced Test Equipment Rentals 888-554-ATEC
ARC Technical Resources, Inc. 408-263-6486
EM Test USA 603-769-3477
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . 703-365-2330
Teseq Inc. 732-417-0501
Thermo Fisher Scientific . . 678-546-8344

Simulators, Lightning

Advanced Test Equipment Rentals 888-554-ATEC
EM Test USA 603-769-3477
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . 703-365-2330
Mag Daddy 847-719-5600
NTS Pittsfield 800-270-2516
Teseq Inc. 732-417-0501
Thermo Fisher Scientific . . 678-546-8344

Static Control

Containers, Static Control

3M Electronic Solutions 512-984-6747

Flooring, Static Control

3M Electronic Solutions 512-984-6747
Protective Industrial Polymers 440-243-4560

Staticworx Flooring 888-STATICWORX

Footwear, Static Control

Staticworx Flooring 888-STATICWORX

Garments, Static Control

3M Electronic Solutions 512-984-6747

Mats, Static Control

3M Electronic Solutions 512-984-6747
Prostat Corporation. 630-238-8883

Monitoring Equipment, Static Control

3M Electronic Solutions 512-984-6747
MKS ION Systems 800-367-2452

Packaging, Static Control

3M Electronic Solutions 512-984-6747

Workstations, Static Control

3M Electronic Solutions 512-984-6747

Wrist Straps, Static Control

3M Electronic Solutions 512-984-6747
Prostat Corporation. 630-238-8883

Transient Detectors and Suppresors

MKS ION Systems 800-367-2452
Quell Corporation 505-243-1423
Texas Spectrum Electronics. . 972-296-3699

Materials, Adhesives & Coatings

Absorbing Materials

Intermark USA, Inc.. 408-971-2055
NTS Albuquerque 505-821-4740
Oak-Mitsui Technologies . . . 518-686-4961
Panashield Inc.. 203-866-5888
TechDream, Inc. 408-320-4021

Adhesives

Ja-Bar Silicone Corp 973-786-5000
Staticworx Flooring 888-STATICWORX

Alloys

Ad-Vance Magnetics. 574-223-3158
Lubrizol Conductive Polymers
. . . . 866-680-1555
Magnetic Shield Corporation
. . . . 888-766-7800
The MuShield Company, Inc.
. . . . 888-669-3539
NTS Albuquerque 505-821-4740

Coatings

Krefine Co.Ltd. 520-838-0548
Staticworx Flooring 888-STATICWORX

Conductive - Painting/Plating/ Transparent

Protective Industrial Polymers
. . . . 440-243-4560
VTI Vacuum Technologies, Inc.
. . . . 800-482-1941

Conductive Coatings

Protective Industrial Polymers
. . . . 440-243-4560
VTI Vacuum Technologies, Inc.
. . . . 800-482-1941

Electromagnetic Wave Absorbing Coatings

VTI Vacuum Technologies, Inc.
. . . . 800-482-1941

Foams and Foam Materials

Krefine Co.Ltd. 520-838-0548
TechDream, Inc. 408-320-4021
W. L. Gore & Associates, Inc.

Powders

Lubrizol Conductive Polymers
. . . . 866-680-1555

Resins and Compounds

Krefine Co.Ltd. 520-838-0548
Lubrizol Conductive Polymers
. . . . 866-680-1555
RTP Company. 800-433-4787

Sealants

W. L. Gore & Associates, Inc.

Silicone Conductive Sponge

Ja-Bar Silicone Corp 973-786-5000
P&P Technology Ltd . . +44 (0)1376 550525

Thermally Conductive Silicone Materials

Ja-Bar Silicone Corp 973-786-5000
TechDream, Inc. 408-320-4021

Thermoplastic Components

Lubrizol Conductive Polymers
. . . . 866-680-1555

Thermoplastics and Thermoplastic Materials

Krefine Co.Ltd. 520-838-0548
Lubrizol Conductive Polymers
. . . . 866-680-1555

Oak-Mitsui Technologies . . . 518-686-4961
RTP Company. 800-433-4787

Power & Power Management

Constant Voltage Regulators

OPHIR RF. 310-306-5556

Converters

Murata Electronics. 800-554-4070
OPHIR RF. 310-306-5556

Cord Sets

CSA Group 866-463-1785
HM Cragg 800-672-7244
Mag Daddy. 847-719-5600
Power Dynamics, Inc 973-560-0019
Schurter Inc. 800-848-2600

Interruptors, AC Power

OPHIR RF. 310-306-5556

Isolators, Power/Signal Line

OPHIR RF. 310-306-5556

Line Cords

Americor Electronics Ltd. . . . 800-830-5337
Mag Daddy. 847-719-5600
OPHIR RF. 310-306-5556
Power Dynamics, Inc. 973-560-0019

Motors

CSA Group 866-463-1785
The MuShield Company, Inc.
. . . . 888-669-3539

Multiple Outlet Strips

HM Cragg 800-672-7244
Mag Daddy. 847-719-5600

Overcurrent Protection

CITEL, Inc. 800-248-3548
Okaya Electric America, Inc. . 800-852-0122

Overvoltage Protection

CITEL, Inc. 800-248-3548
Nextek, Inc.. 978-486-0582
Okaya Electric America, Inc. . 800-852-0122

Power Amplifier

AE Techron, Inc.. 574-295-9495
Com-Power Corporation . . 714-528-8800
Mag Daddy. 847-719-5600
OPHIR RF. 310-306-5556

Power Cords

Americor Electronics Ltd. . . . 800-830-5337
CSA Group 866-463-1785
HM Cragg 800-672-7244
Schurter Inc.. 800-848-2600

Power Distribution Systems

API Technologies Corp. 855-294-3800
Captor Corporation. 937-667-8484
HM Cragg 800-672-7244
IQS, a Division of CMG 508-460-1400
Oak-Mitsui Technologies . . . 518-686-4961
Schurter Inc.. 800-848-2600

Power Entry Modules

Americor Electronics Ltd. . . . 800-830-5337
Corcom/Tyco Electronics . . . 847-573-6504
Oak-Mitsui Technologies . . . 518-686-4961
OPHIR RF. 310-306-5556
Power Dynamics, Inc. 973-560-0019
Schurter Inc.. 800-848-2600

Power Generators

Clarion Safety Systems 800-748-0241

Power Line Conditioning Equipment

Mag Daddy. 847-719-5600
Nextek, Inc.. 978-486-0582
Okaya Electric America, Inc. . 800-852-0122
WEMS Electronics 310-962-4410

Power Rectifier

HM Cragg 800-672-7244

Power Supplies

AE Techron, Inc.. 574-295-9495
Americor Electronics Ltd. . . . 800-830-5337
API Technologies Corp. 855-294-3800
Associated Power Technologies
. . . . 877-322-7693
CSA Group 866-463-1785
HM Cragg 800-672-7244
Murata Electronics. 800-554-4070
QuadTech 800-253-1230
Test Equipment Connection. .800-615-8378

Switch Mode Power Supply

AE Techron, Inc.. 574-295-9495
Associated Power Technologies
. . . . 877-322-7693

Switching Power Supplies

Americor Electronics Ltd. . . . 800-830-5337

Safety and Protective Equipment

Safety and Warning Labels

Clarion Safety Systems 800-748-0241
Lewis Bass International 408-942-8000
NTS Newark 510-378-3500

Software Suppliers

3D Simulation Software

Delcross Technologies, LLC. . 217-363-3396
EM Software & Systems - SA (Pty)
. . . . +27 21 8801880
EM Software & Systems (USA) Inc
. . . . .800-419-5566 (FEKO)

EMSS Consulting . . . . +27218801880
TechDream, Inc.. 408-320-4021

Anechoic Chamber Software

EM Software & Systems (USA) Inc
. . . . .800-419-5566 (FEKO)

EMC Simulation Software

ANDRO Computational Solutions
. . . . 315-334-1163
Delcross Technologies, LLC. . 217-363-3396
EM Software & Systems - SA (Pty)
. . . . +27 21 8801880
EM Software & Systems (USA) Inc
. . . . .800-419-5566 (FEKO)

EMC/EMI Software

AR RF/Microwave Instrumentation
. . . . 888-933-8181
ARC Technical Resources, Inc.
. . . . 408-263-6486
Delcross Technologies, LLC. . 217-363-3396
EM Software & Systems (USA) Inc
. . . . .800-419-5566 (FEKO)
NEC Corporation
TechDream, Inc.. 408-320-4021

ESD, Static Control Software

MKS ION Systems 800-367-2452

Product Safety Software

Aum Electro Technology Pvt Ltd
. . . . 00912512871365
EMSS Consulting . . . . +27218801880
Finero USA L.L.C. 239-898-8487

Signal Integrity and EMC Analysis Software

Aum Electro Technology Pvt Ltd 00912512871365
TechDream, Inc. 408-320-4021

Wireless Propagation Software

Aum Electro Technology Pvt Ltd 00912512871365
Delcross Technologies, LLC . . 217-363-3396
EM Software & Systems (USA) Inc . . . . . 800-419-5566 (FEKO)
EMSS Consulting . . . . . +27218801880
MetaGeek 208-639-3140

Standards Suppliers

Clarion Safety Systems 800-748-0241
EMC Compliance 256-650-5261
ESD Association 315-339-6937
Hoolihan EMC Consulting . 651-213-0966
Trace Laboratories, Inc.. 410-584-9099

Test & Measurement Equipment

Amplifiers

Amplifiers, Low Noise

A.H. Systems, Inc. 818-998-0223
Advanced Test Equipment Rentals 888-554-ATEC
API Technologies Corp. 855-294-3800
AR RF/Microwave Instrumentation 888-933-8181
Avalon Equipment Corporation 888-542-8256
Com-Power Corporation . . 714-528-8800
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
Giga-tronics Incorporated . . 800-277-9764
Instruments For Industry, Inc. 631-467-8400
OPHIR RF. 310-306-5556
Teseq Inc. 732-417-0501

Amplifiers, Power

Advanced Test Equipment Rentals 888-554-ATEC
AR RF/Microwave Instrumentation 888-933-8181
Avalon Equipment Corporation 888-542-8256
Com-Power Corporation . . 714-528-8800
CPI, Inc. 905-877-0161
Electro Rent Corporation . . . 800-688-1111
Giga-tronics Incorporated . . 800-277-9764
Instruments For Industry, Inc. 631-467-8400
MILMEGA Ltd . . . . . +44 (0) 1983-618004
OPHIR RF. 310-306-5556
Rohde & Schwarz, Inc. 888-TEST-RSA

Amplifiers, RF

Advanced Test Equipment Rentals 888-554-ATEC
API Technologies Corp. 855-294-3800
AR RF/Microwave Instrumentation 888-933-8181
ARC Technical Resources, Inc. 408-263-6486
Avalon Equipment Corporation 888-542-8256
Com-Power Corporation . . 714-528-8800
CPI, Inc. 905-877-0161
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
Instruments For Industry, Inc. 631-467-8400
MetaGeek 208-639-3140
MILMEGA Ltd . . . . . +44 (0) 1983-618004
OPHIR RF. 310-306-5556
Rohde & Schwarz, Inc. 888-TEST-RSA
Test Equipment Connection . . 800-615-8378

Analyzers

Analyzers, EMI/EMC Spectrum

Advanced Test Equipment Rentals 888-554-ATEC
Aeroflex 800-835-2352
Agilent Technologies 800-829-4444
ARC Technical Resources, Inc. 408-263-6486
Avalon Equipment Corporation 888-542-8256
Com-Power Corporation . . 714-528-8800
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
GAUSS INSTRUMENTS . . +49-89-99627826
MetaGeek 208-639-3140
Rohde & Schwarz, Inc. 888-TEST-RSA
Teseq Inc. 732-417-0501
Test Equipment Connection . . 800-615-8378

Analyzers, Flicker

Advanced Test Equipment Rentals 888-554-ATEC
ARC Technical Resources, Inc. 408-263-6486
Avalon Equipment Corporation 888-542-8256
EM Test USA 603-769-3477

Analyzers, Harmonics

ARC Technical Resources, Inc. 408-263-6486
Avalon Equipment Corporation 888-542-8256
Electro Rent Corporation . . . 800-688-1111
EM Test USA 603-769-3477

Analyzers, Network

Advanced Test Equipment Rentals 888-554-ATEC
Aeroflex 800-835-2352
Avalon Equipment Corporation 888-542-8256
Electro Rent Corporation . . . 800-688-1111
Giga-tronics Incorporated . . 800-277-9764
Rohde & Schwarz, Inc. 888-TEST-RSA
Test Equipment Connection . . 800-615-8378

Analyzers, Power Quality

Advanced Test Equipment Rentals 888-554-ATEC
Avalon Equipment Corporation 888-542-8256
Electro Rent Corporation . . . 800-688-1111
Test Equipment Connection . . 800-615-8378

Analyzers, Telecom

Advanced Test Equipment Rentals 888-554-ATEC
Aeroflex 800-835-2352
Avalon Equipment Corporation 888-542-8256
Hermon Laboratories TI . . +972-4-6268450
MetaGeek 208-639-3140

Analyzers, Tempest

Dynamic Sciences International 800-966-3713

Automatic Test Sets

Aeroflex 800-835-2352
Amber Precision Instruments, Inc. 408-752-0199 x102
ARC Technical Resources, Inc. 408-263-6486
Aum Electro Technology Pvt Ltd 00912512871365
Hermon Laboratories TI . . +972-4-6268450
Teseq Inc. 732-417-0501
Thermo Fisher Scientific . . 678-546-8344

Avionics Test Equipment

Aeroflex 800-835-2352
Avalon Equipment Corporation 888-542-8256
Dayton T. Brown, Inc. 800-TEST-456
EM Test USA 603-769-3477
HV TECHNOLOGIES, Inc. . . 703-365-2330
MI Technologies 678-475-8345
Narda Safety Test Solutions . . 631-231-1700
Thermo Fisher Scientific . . 678-546-8344

Buildings, EMC Testing

Cuming-Lehman Chambers, Inc. 717-263-4101
Narda Safety Test Solutions . .631-231-1700

Calibration & Repair Services

Aeroflex 800-835-2352
Avalon Equipment Corporation 888-542-8256
eti Conformity Services. 877-468-6384
Fischer Custom Communications 310-303-3300
GAUSS INSTRUMENTS . .+49-89-99627826
Liberty Labs, Inc. 712-773-2199
MI Technologies 678-475-8345
Prostat Corporation. 630-238-8883
Restor Metrology. 877-220-5554
World Cal, Inc. 712-764-2197

Current Leakage Testers

Advanced Test Equipment Rentals 888-554-ATEC
E. D. & D., Inc.. 800-806-6236
Ergonomics, Inc.. 800-862-0102
Finero USA L.L.C. 239-898-8487
NTS Santa Clarita. 800-270-2516
QuadTech 800-253-1230
Vitrek Corporation. 858-689-2755

Data Acquisition Monitoring Systems

Advanced Test Equipment Rentals 888-554-ATEC
Avalon Equipment Corporation 888-542-8256
Michigan Scientific Corp. 248-685-3939
MKS ION Systems 800-367-2452
NTS Albuquerque 505-821-4740

Dielectric Strength Testers

Advanced Test Equipment Rentals 888-554-ATEC
Associated Research, Inc . . . 800-858-8378
E. D. & D., Inc.. 800-806-6236
Ergonomics, Inc.. 800-862-0102
QuadTech 800-253-1230
Slaughter Company, Inc 800-504-0055
Vitrek Corporation. 858-689-2755

Electrical Safety Testers

Advanced Test Equipment Rentals 888-554-ATEC
Associated Research, Inc . . . 800-858-8378
Avalon Equipment Corporation 888-542-8256
E. D. & D., Inc.. 800-806-6236
Ergonomics, Inc.. 800-862-0102
Finero USA L.L.C. 239-898-8487
Prostat Corporation. 630-238-8883
QuadTech 800-253-1230
Slaughter Company, Inc 800-504-0055
Vitrek Corporation. 858-689-2755

EMC Testers

Advanced Test Equipment Rentals 888-554-ATEC
Aeroflex 800-835-2352
Amber Precision Instruments, Inc. 408-752-0199 x102

Avalon Equipment Corporation 888-542-8256

EM Test USA. 603-769-3477
EMC Test Design, LLC 508-292-1833
EMSCAN Corporation 877-367-2261
GAUSS INSTRUMENTS . .+49-89-99627826
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . 703-365-2330
Rohde & Schwarz, Inc. 888-TEST-RSA
Teseq Inc.. 732-417-0501
Test Equipment Connection. .800-615-8378
Thermo Fisher Scientific . . 678-546-8344
TÜV SÜD America Inc. 800-888-0123

EMP Simulators

EM Test USA. 603-769-3477
Fischer Custom Communications 310-303-3300
Teseq Inc.. 732-417-0501

Environmental Chambers

Advanced Test Equipment Rentals 888-554-ATEC
E. D. & D., Inc.. 800-806-6236
NTS Newark 510-378-3500
NTS Rockford 800-270-2516
TÜV SÜD America Inc. 800-888-0123

ESD Test Equipment

Amber Precision Instruments, Inc. 408-752-0199 x102
Avalon Equipment Corporation 888-542-8256
Barth Electronics, Inc. 702-293-1576
Electro Rent Corporation . . . 800-688-1111
Monroe Electronics, Inc.. 585-765-2254
NTS Newark 510-378-3500

Fiber-Optic Systems

Michigan Scientific Corp 248-685-3939 x111

Gaussmeters

Ergonomics, Inc.. 800-862-0102
Magnetic Shield Corporation 888-766-7800
Narda Safety Test Solutions . .631-231-1700

Generators

Generators, Arbitrary Wave Form

Aeroflex 800-835-2352
Electro Rent Corporation . . . 800-688-1111
Test Equipment Connection. .800-615-8378

Generators, ESD

EM Test USA. 603-769-3477
Haefely EMC Technology 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . 703-365-2330
Teseq Inc.. 732-417-0501
Thermo Fisher Scientific . . 678-546-8344

Generators, Fast/Transient Burst

Advanced Test Equipment Rentals . . . 888-554-ATEC
Electro Rent Corporation . . . 800-688-1111
EM Test USA . . . 603-769-3477
Fischer Custom Communications . . . 310-303-3300
Haefely EMC Technology . . . 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Thermo Fisher Scientific . . . 678-546-8344

Generators, Impulse

Applied EM Technology . . . 410-326-6728
Electro Rent Corporation . . . 800-688-1111
EM Test USA . . . 603-769-3477
Haefely EMC Technology . . . 845-279-3644 x240
Thermo Fisher Scientific . . . 678-546-8344

Generators, Interference

Electro Rent Corporation . . . 800-688-1111

Generators, Lightning

EM Test USA . . . 603-769-3477
Haefely EMC Technology . . . 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Thermo Fisher Scientific . . . 678-546-8344

Generators, Signal

Aeroflex . . . 800-835-2352
Agilent Technologies . . . 800-829-4444
AR RF/Microwave Instrumentation . . . 888-933-8181
Electro Rent Corporation . . . 800-688-1111
Giga-tronics Incorporated . . . 800-277-9764
Rohde & Schwarz, Inc. . . . 888-TEST-RSA
Test Equipment Connection . . . 800-615-8378

Generators, Surge Transient

Advanced Test Equipment Rentals . . . 888-554-ATEC
Electro Rent Corporation . . . 800-688-1111
EM Test USA . . . 603-769-3477
Haefely EMC Technology . . . 845-279-3644 x240
HV TECHNOLOGIES, Inc. . . . 703-365-2330
Thermo Fisher Scientific . . . 678-546-8344

Ground Bond Testers

Associated Research, Inc . . . 800-858-8378
E. D. & D., Inc. . . . 800-806-6236
Finero USA L.L.C. . . . 239-898-8487
QuadTech . . . 800-253-1230
Slaughter Company, Inc . . . 800-504-0055
Staticworx Flooring . . . 888-STATICWORX
Vitrek Corporation . . . 858-689-2755

Ground Resistance Testers

Associated Research, Inc . . . 800-858-8378
Ergonomics, Inc. . . . 800-862-0102
Finero USA L.L.C. . . . 239-898-8487
Prostat Corporation . . . 630-238-8883
QuadTech . . . 800-253-1230
Slaughter Company, Inc . . . 800-504-0055
Staticworx Flooring . . . 888-STATICWORX

Hipot Testers

Associated Research, Inc . . . 800-858-8378
Avalon Equipment Corporation . . . 888-542-8256
E. D. & D., Inc. . . . 800-806-6236
Electro Rent Corporation . . . 800-688-1111
Ergonomics, Inc. . . . 800-862-0102
Finero USA L.L.C. . . . 239-898-8487
QuadTech . . . 800-253-1230
Slaughter Company, Inc . . . 800-504-0055
Test Equipment Connection . . . 800-615-8378
Vitrek Corporation . . . 858-689-2755

Meters

Megohmmeters

Finero USA L.L.C. . . . 239-898-8487
Monroe Electronics, Inc. . . . 585-765-2254
QuadTech . . . 800-253-1230
Staticworx Flooring . . . 888-STATICWORX
Vitrek Corporation . . . 858-689-2755

Meters, Field Strength

AR RF/Microwave Instrumentation . . . 888-933-8181
EMC Test Design, LLC . . . 508-292-1833
Ergonomics, Inc. . . . 800-862-0102
Magnetic Shield Corporation . . . 888-766-7800
Narda Safety Test Solutions . . . 631-231-1700

Meters, Magnetic Field

EMC Test Design, LLC . . . 508-292-1833
Ergonomics, Inc. . . . 800-862-0102
Magnetic Shield Corporation . . . 888-766-7800
Narda Safety Test Solutions . . . 631-231-1700

Meters, Radiation Hazard

EMC Test Design, LLC . . . 508-292-1833
Narda Safety Test Solutions . . . 631-231-1700

Meters, RF Power

Aeroflex . . . 800-835-2352
Agilent Technologies . . . 800-829-4444
AR RF/Microwave Instrumentation . . . 888-933-8181
Electro Rent Corporation . . . 800-688-1111
EMC Test Design, LLC . . . 508-292-1833
Giga-tronics Incorporated . . . 800-277-9764
MetaGeek . . . 208-639-3140

Meters, Static Charge

Monroe Electronics, Inc. . . . 585-765-2254
Prostat Corporation . . . 630-238-8883
Staticworx Flooring . . . 888-STATICWORX

Meters, Static Decay

Monroe Electronics, Inc. . . . 585-765-2254
Prostat Corporation . . . 630-238-8883
Staticworx Flooring . . . 888-STATICWORX

Monitors

Monitors, Current

Pearson Electronics, Inc . . . 650-494-6444

Monitors, EMI Test

EMC Test Design, LLC . . . 508-292-1833
MKS ION Systems . . . 800-367-2452
Test Equipment Connection . . . 800-615-8378

Monitors, ESD

MKS ION Systems . . . 800-367-2452

Monitors, Ionizer Balance

MKS ION Systems . . . 800-367-2452

Monitors, Static Voltage

MKS ION Systems . . . 800-367-2452

Oscilloscopes and Transient Recorders

Aeroflex . . . 800-835-2352
Aum Electro Technology Pvt Ltd . . . 00912512871365
Avalon Equipment Corporation . . . 888-542-8256
Electro Rent Corporation . . . 800-688-1111
GAUSS INSTRUMENTS . . . +49-89-99627826
MetaGeek . . . 208-639-3140
Test Equipment Connection . . . 800-615-8378

Probes

Probes, Current/Magnetic Field

A.H. Systems, Inc. . . . 818-998-0223
Agilent Technologies . . . 800-829-4444
Amber Precision Instruments, Inc. . . . 408-752-0199 x102
AR RF/Microwave Instrumentation . . . 888-933-8181
Com-Power Corporation . . . 714-528-8800
EMC Test Design, LLC . . . 508-292-1833
Ergonomics, Inc. . . . 800-862-0102
ETS-Lindgren . . . 512-531-6400
Fischer Custom Communications . . . 310-303-3300
MI Technologies . . . 678-475-8345
Teseq Inc. . . . 732-417-0501
Test Equipment Connection . . . 800-615-8378
Van Doren Company . . . 573-341-4097

Probes, Electric Field

Agilent Technologies 800-829-4444
Amber Precision Instruments, Inc. 408-752-0199 x102
AR RF/Microwave Instrumentation 888-933-8181
Com-Power Corporation . . 714-528-8800
EMC Technologists 732-919-1100
EMC Test Design, LLC 508-292-1833
ETS-Lindgren 512-531-6400
Test Equipment Connection . . 800-615-8378
Van Doren Company. 573-341-4097

Probes, Voltage

ARC Technical Resources, Inc. 408-263-6486
Fischer Custom Communications 310-303-3300
Test Equipment Connection . . 800-615-8378

Receivers

Receivers, EMI/EMC

Advanced Test Equipment Rentals 888-554-ATEC
Agilent Technologies 800-829-4444
API Technologies Corp. 855-294-3800
AR RF/Microwave Instrumentation 888-933-8181
Com-Power Corporation . . 714-528-8800
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
GAUSS INSTRUMENTS . . +49-89-99627826
Rohde & Schwarz, Inc. 888-TEST-RSA

Receivers, RF

API Technologies Corp. 855-294-3800
Dynamic Sciences International 800-966-3713
Electro Rent Corporation . . . 800-688-1111
GAUSS INSTRUMENTS . . +49-89-99627826
MI Technologies 678-475-8345

Receivers, Tempest

API Technologies Corp. 855-294-3800
Dynamic Sciences International 800-966-3713
GAUSS INSTRUMENTS . . +49-89-99627826

RF Leak Detectors

AR RF/Microwave Instrumentation 888-933-8181
MetaGeek 208-639-3140
Narda Safety Test Solutions . . 631-231-1700
Test Equipment Connection . . 800-615-8378

Safety Test Equipment

Avalon Equipment Corporation 888-542-8256
Com-Power Corporation . . 714-528-8800
E. D. & D., Inc. 800-806-6236
EMC Technologists 732-919-1100
Ergonomics, Inc.. 800-862-0102
Finero USA L.L.C. 239-898-8487
Narda Safety Test Solutions . . 631-231-1700
QuadTech 800-253-1230

Shock & Vibration Testing Shakers

Aum Electro Technology Pvt Ltd 00912512871365
Dayton T. Brown, Inc. 800-TEST-456
NTS Newark 510-378-3500
NTS Santa Clarita. 800-270-2516
TÜV SÜD America Inc. 800-888-0123

Susceptiblity Test Instruments

Amber Precision Instruments, Inc. 408-752-0199 x102
AR RF/Microwave Instrumentation 888-933-8181
ARC Technical Resources, Inc. 408-263-6486
Com-Power Corporation . . 714-528-8800
EM Test USA. 603-769-3477
EMC Test Design, LLC 508-292-1833
Narda Safety Test Solutions . . 631-231-1700
Nextek, Inc.. 978-486-0582
Thermo Fisher Scientific . . 678-546-8344

Telecom Test Equipment

Aeroflex. 800-835-2352
E. D. & D., Inc. 800-806-6236
Electro Rent Corporation . . . 800-688-1111
EM Test USA. 603-769-3477
Haefely EMC Technology 845-279-3644 x240
Hermon Laboratories TI . . +972-4-6268450
HV TECHNOLOGIES, Inc. . . . 703-365-2330
MetaGeek 208-639-3140
NTS Newark 510-378-3500
NTS Tinton Falls. 732-936-0800
Test Equipment Connection . . 800-615-8378
Thermo Fisher Scientific . . 678-546-8344

Temperature Cycling Systems

E. D. & D., Inc. 800-806-6236

Used & Refurbished Test Equipment

A.H. Systems, Inc. 818-998-0223
AR RF/Microwave Instrumentation 888-933-8181
Avalon Equipment Corporation 888-542-8256
Giga-tronics Incorporated . . 800-277-9764
Test Equipment Connection . . 800-615-8378
TÜV SÜD America Inc. 800-888-0123

Testing Services

Accredited Registrar

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CKC Laboratories, Inc.. 800-500-4362
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Curtis-Straus (Bureau Veritas) 877-277-8880
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Nemko Canada. 613-737-9680
Nemko USA - SouthEast . . 813-662-4606
NQA Canada. 514-242-2655
NQA Indiana. 800-398-8282
NQA West Coast 888-734-4476
NQA, USA 800-649-5289
Parker Hannifin, Chomerics Div 781-935-4850
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CSA Group 866-463-1785
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Electro Magnetic Test, Inc. . . 650-965-4000
Elite Electronic Engineering . . 800-ELITE-11
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G&M Compliance, Inc. 714-628-1020
LS Research. 262-375-4400
Nemko Canada. 613-737-9680
Nemko USA - SouthEast . . 813-662-4606
Parker Hannifin, Chomerics Div 781-935-4850
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TÜV SÜD America Inc. 800-888-0123

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Test Site Services Inc. 508-962-1662
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Garwood Laboratories Inc. SC 888-427-4111
Green Mtn. Electromagnetics 802-388-3390
Keystone Compliance 724-657-9940
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Staticworx Flooring . . . 1-888-STATICWORX
Test Site Services Inc. 508-962-1662

Homologation Services

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Nemko Canada. 613-737-9680
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SGS Consumer Testing Services 800-777-TEST (8378)
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Pre-Assessments

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Curtis-Straus (Bureau Veritas) 877-277-8880
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O'Brien Compliance Management 978-970-0525
Product Safety Consulting . . 877-804-3066
Pulver Laboratories Inc. 800-635-3050
RF Exposure Lab. . . . . (760) 471-2100
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SIEMIC 408-526-1188
SILENT Solutions LLC. .603-578-1842 x203
Spectrum EMC Consulting, LLC 651-688-0634
Stephen Halperin & Associates 630-238-8883
Test Site Services Inc. 508-962-1662
TÜV Rheinland of North America 1-TUV-RHEINLAND

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Electronics Test Centre - Airdrie 403-912-0037
EMC Testing Laboratories, Inc. 770-475-8819
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Garwood Laboratories 888-427-4111
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Nexlogic Technologies, Inc. . 866-845-1197
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SGS Consumer Testing Services 800-777-TEST (8378)
SIEMIC 408-526-1188
Test Site Services Inc. 508-962-1662
UL Verification Services . . .86 20 28667188

Testing Laboratories

Accelerated Stress Testing

Cincinnati Sub-Zero 800-989-7373
Compliance Management Group 508-281-5985
Core Compliance Testing Srvs 603-889-5545
Dayton T. Brown, Inc. 800- TEST-456
DNB Engineering, Inc.. 714-870-7781
Elite Electronic Engineering . . 800-ELITE-11
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Flextronics. 613-895-2053
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Global EMC Inc. 866-996-8298
IQS, a Division of CMG 508-460-1400
Keystone Compliance 724-657-9940
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NTS Plano 877-717-2687
NTS Santa Clarita. 800-270-2516
NTS Tempe. 480-966-5517
NTS Tinton Falls. 732-936-0800
Retlif Testing Laboratories 631-737-1500 x111
Test Site Services Inc. 508-962-1662
Trace Laboratories, Inc.. 410-584-9099
TÜV SÜD America Inc. 800-888-0123

Acoustical Testing

Compliance Worldwide, Inc. 603-887-3903
Core Compliance Testing Srvs 603-889-5545
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DNB Engineering, Inc.. 714-870-7781
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NTS Northeast 800-723-2687
NTS Plano 877-717-2687
NTS Santa Clarita. 800-270-2516
NTS Tempe. 480-966-5517
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Pulver Laboratories Inc. 800-635-3050
Retlif Testing Laboratories 631-737-1500 x111

BSMI Compliant Certification Testing

Atlas Compliance & Engineering . . . 866-573-9742
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Compliance Management Group . . . 508-281-5985
Compliance Worldwide, Inc. . . . 603-887-3903
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NTS Fremont . . . 877-245-7800
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CB Test Report

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CE Marking

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G&M Compliance, Inc. . . . 714-628-1020

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Radiometrics Midwest Corp. . . . 815-293-0772
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China Compulsory Certification (CCC)

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Nemko USA - SouthEast . . . 813-662-4606
RTF Compliance . . . 949-813-6095
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American Certification Body, Inc. . . . 703-847-4700

CASE Forensics 877-736-1106
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CSA Group 866-463-1785
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EMC Testing

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Garwood Laboratories Inc. SC
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Nemko Canada 613-737-9680
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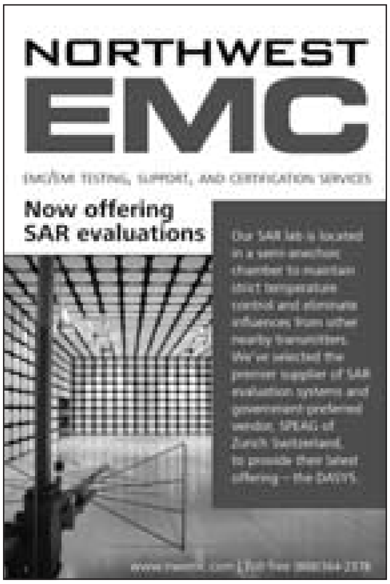
Nextek, Inc. 978-486-0582

EMC Testing *continued*

Northwest EMC, Inc. 888-364-2378



NTS - Corporate HQ 800-270-2516
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NTS Fremont 877-245-7800
NTS Fullerton 800-677-2687
NTS Newark 877-245-7800
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Qualtest Inc. 407-313-4230
Radiometrics Midwest Corp.
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RF Exposure Lab. . . . . (760) 471-2100
SGS Consumer Testing Services
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SIEMIC 408-526-1188
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Ultratech EMC Lab. 905-829-1570
Yazaki Testing Center 734-983-6012

Energy Efficiency Testing

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CSA Group 866-463-1785
G&M Compliance, Inc. 714-628-1020
Intertek 800-WORLDLAB
MET Laboratories. 800-638-6057
Nemko USA - SouthEast . . 813-662-4606
Pulver Laboratories Inc. 800-635-3050
SGS Consumer Testing Services
. . . . 800-777-TEST (8378)
SIEMIC 408-526-1188
TÜV Rheinland of North America
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UL Verification Services . . . 86 20 28667188

Environmental Simulation Testing

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Compliance Management Group
. . . . 508-281-5985
Core Compliance Testing Srvs
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Curtis-Straus (Bureau Veritas)
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Keystone Compliance 724-657-9940
L-3 Communications Cincinnati
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MET Laboratories. 800-638-6057
NCEE Labs 888-567-6860
Nemko USA - SouthEast . . 813-662-4606
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NTS Fullerton 800-677-2687
NTS LAX. 800-559-3202
NTS Northeast 800-723-2687
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Go Global Compliance Inc. . 408-416-3772
Keystone Compliance 724-657-9940
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GS Mark Certification

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RTF Compliance 949-813-6095
SGS Consumer Testing Services
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CASE Forensics 877-736-1106
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DNB Engineering, Inc.. 714-870-7781
Elite Electronic Engineering . . 800-ELITE-11
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Electro Magnetic Test, Inc. . . 650-965-4000
EMC Testing Laboratories, Inc. . . . 770-475-8819
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NTS Northeast . . . 800-723-2687
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NTS Tinton Falls . . . 732-936-0800
Product Safety Consulting . . 877-804-3066
Qualtest Inc. . . . 407-313-4230
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A2LA

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Advanced Compliance Solutions

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