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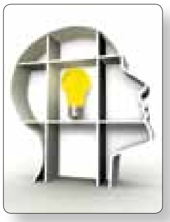

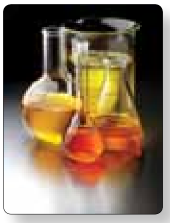

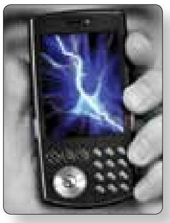

EMC (continued)

PRODUCT SAFETY

Contents continues on page 7

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Lorie Nichols
Publisher & Editor
lorie.nichols@incompliancemag.com

Erin C. Feeney
Director of Media Services
erin.feeney@incompliancemag.com

Sharon Smith
Director of Sales
sharon.smith@incompliancemag.com

Barbara Kovalchek
Media Consultant
barbara.kovalchek@incompliancemag.com

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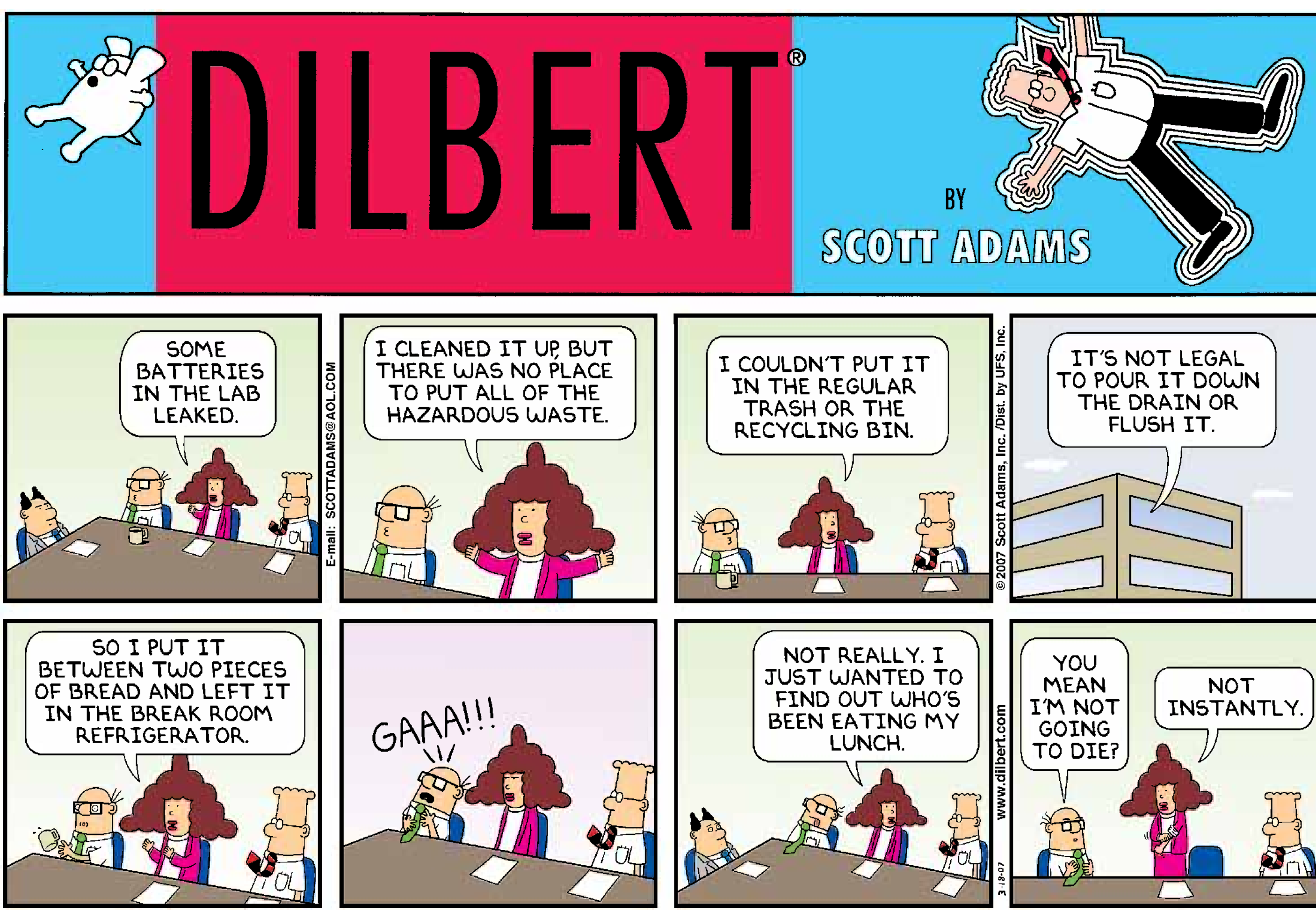

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PRODUCT SAFETY (continued)

ESD

ENVIRONMENTAL

ENVIRONMENTAL (continued)

ABOUT THE INSTRUCTOR

Henry W. Ott is President and Principal Consultant of Henry Ott Consultants (www.hottconsultants.com), an EMC training and consulting organization. He has literally "written the book" on the subject of EMC and is considered by many to be the nation's leading EMC educator. He is the author of the popular EMC book **Noise Reduction Techniques in Electronic Systems** (1976, 1988). The book has sold over 65,000 copies and has been translated into six other languages. In addition to knowing his subject, Mr. Ott has the rare ability to communicate that knowledge to others.

Mr. Ott's newly published (Aug. 2009) 872-page book, **Electromagnetic Compatibility Engineering**, is the most comprehensive book available on EMC. While still retaining the core information that made **Noise Reduction Techniques** an international success, this new book contains over 600 pages of new and revised material.

Prior to starting his own consulting company, Mr. Ott was with AT&T Bell Laboratories, Whippany, NJ for 30 years, where he was a Distinguished Member of the Technical Staff and a consultant on EMC.

Mr. Ott is a Life Fellow of the IEEE. For over 20 years, Mr. Ott has served the EMC Society in various capacities including: membership on the Board of Directors, Education Committee Chairman, Symposium Committee Chairman and Vice President of Conferences. He is also a member of the ESD Association and a NARTE certified ESD engineer. He is a past Distinguished Lecturer of the EMC Society, and lectures extensively on the subject of EMC.

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*Electromagnetic Compatibility Engineering, by Henry W. Ott

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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, 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.

Unique Solid State High Voltage Switching Technology Serves a Wide Range of Surge Testing Applications

EMC-PARTNER and HV TECHNOLOGIES provide a wide range of conducted transient immunity (susceptibility) test systems with impulse outputs up to 100kV / 100kA. These systems provide full compliance testing capability to a broad range of impulse test standards specified by CE Mark, Commercial, Industrial, Military, Avionics, Power Distribution, Surge Protection Device, Insulation, and Component regulatory environments.

Question: How does one manufacturer produce so many different products?

Answer: By using the same basic building blocks in different configurations.

6kV Solid State Building Block Circuit

The broad array of products offered by EMC-PARTNER are made possible through intelligent use of their patented and proprietary 6kV High Voltage Switching Modules. This technique and technology not only increases product range, they also eliminate problems traditionally associated with high voltage transient generators.

Wide Product Range

The various transient generators contain anywhere from 1 to 72 of these 6kV building block circuits. Each circuit contains an energy storage capacitor and a solid state high voltage switch. The circuits are arranged in appropriate series and parallel combinations to produce the desired open circuit voltage and short circuit current and wave shape in conjunction with a lumped R-L-C pulse shaping circuit.

Precision Wave Shape and Timing

A trigger signal is simultaneously sent via fiber optics to each switching circuit. This enables discrete switches to function as one. The final output pulse is crisp without any smearing caused by switch time variations and repeatable. An added benefit of this technique is unparalleled ability to synchronize pulses to AC power frequency or to create the complex multiple stroke and multiple burst patterns specified in Avionics standard like DO 160 section 22.

Troublesome Waveform Tamed – Damped Oscillatory Wave

The EMC-PARTNER solid state high voltage switching approach combined with elegant wave shaping circuit design solves several problems in generating a waveform which is becoming more prevalent; the Damped Oscillatory Wave (DOW). Variations of the DOW are called out by Military, Avionics, and Electric Power Apparatus test standards worldwide. The latter being driven new products for SMART GRID upgrades.

The DOWs are repetitive waveforms produced in "bursts". Individual pulses must meet very specific tolerances. The solid state switching handles the burst issue. Circuit design addresses the damping and symmetry problems of the DOW.

All DOW test standards specify a Damping Rate or Factor; sometimes called Q, which requires that subsequent peaks decrease in magnitude within certain tolerances. Many DOW generators produce pulses in which the first several peaks do not dampen at all. In some cases they even increase in magnitude! (See Figure 1)

EMC-PARTNER avoids this problem by employing unique circuitry to provide the necessary waveform symmetry (See Figure 2). This enables the true differential output specified in Section 5.3.4 "Test Mode Capability" of IEEE Std. C37.90.1-2002 specifies that the generator must have two floating independent outputs with balanced differential output. It also positions EMC-PARTNER as the only vendor able to provide the "fast" damped oscillatory waveforms of IEC 61000-4-18 at 3, 10, and 30MHz.

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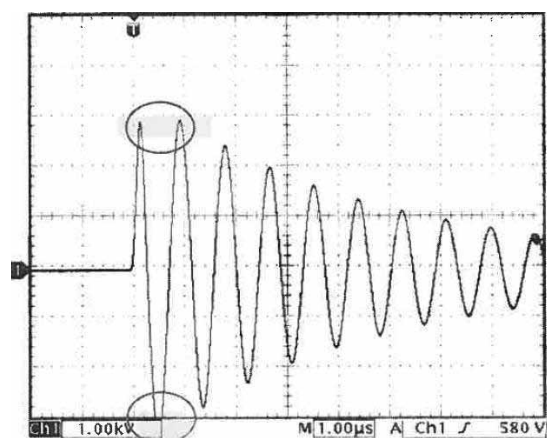

Figure 1: Problematic DOW

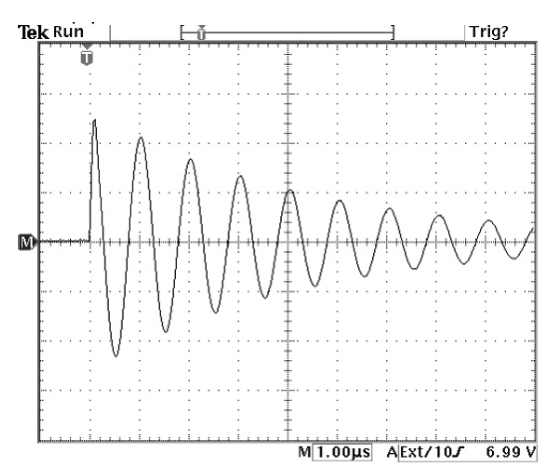

Figure 2: Typical EMC-PARTNER DOW (Symmetrical Circuit Design)

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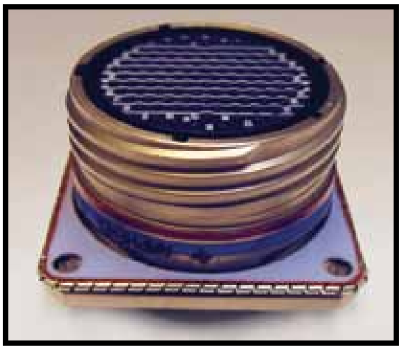

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Spira offers the finest and most reliable EMI/RFI shielding gaskets and honeycomb filters in the market, at very competitive prices. The company was founded by one of the leading EMI design engineers in the industry. Spira's commitment is to provide quality-engineered products, on-time delivery, superior customer service and technical support. Spira is **ISO-9001** and **AS9100** certified.

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Spira's NEW Connector-Seal gaskets now come in <u>front</u>-mount or standard configurations, providing excellent EMI and Environmental protection! Our unique design includes a rigid layer between either silicone or fluorosilicone elastomeric sealing, and includes our patented spiral gasket for excellent EMI shielding. This gasket is extremely durable and provides reliable one atmosphere environmental sealing for flange-mounted connectors.

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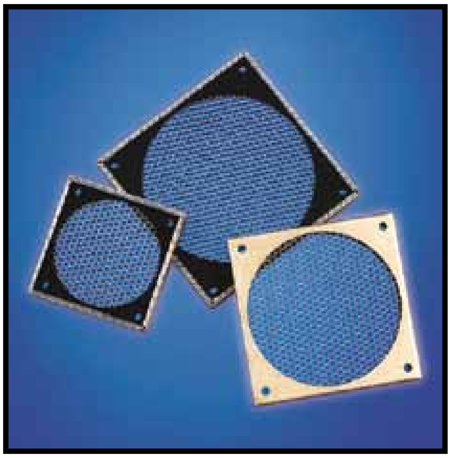

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TÜV SÜD America is a NRTL (Nationally Recognized Testing Laboratory) and SCC-certified, providing a full suite of services, including CE Marking assistance, electromagnetic compatibility (EMC), photovoltaic testing, electrical & mechanical testing, and many additional global conformity assessment services that help companies gain product compliance to enter individual country markets.

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Our EMC (Electromagnetic Compatibility) services unit is a leading provider of EMC testing solutions in the military and Aerospace/Defense fields. Services include Wireless testing, testing to MIL-STD-461E, RTCA/DO-160E, EUROCAE/ED-14E, Def-Stan 59-41, Multiple-Burst and Multiple-Stroke Lightning, and HIRF testing up to 9500 Volts/meter.

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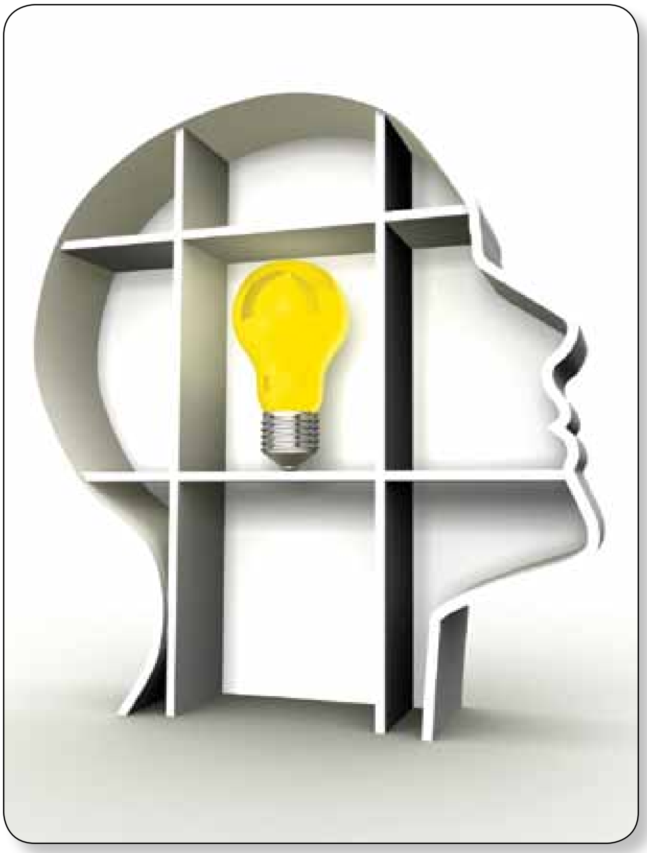
A Dash of Maxwell's

A Maxwell's Equations Primer

Part 1: An Introduction

BY GLEN DASH



And God said,
Let there be light:
and there was light.
--Genesis 1:3

And God said, Let:

$$\nabla \cdot D = \rho$$

$$\nabla \cdot B = 0$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

and there was light.
--Anonymous

Maxwell's Equations are eloquently simple yet excruciatingly complex. Their first statement by James Clerk Maxwell in 1864 heralded the beginning of the age of radio and, one could argue, the age of modern electronics as well. Maxwell pulled back the curtain on one of the fundamental secrets of the universe. These equations just don't give the scientist or engineer insight, they are literally the answer to everything RF.

The problem is that the equations can be baffling to work with. Solving Maxwell's Equations for even simple structures like dipole antennas is not a trivial task. In fact, it will take us several chapters to get there. Solving Maxwell's Equations for real life situations, like predicting the RF emissions from a cell tower, requires more mathematical horsepower than any individual mind can muster. For problems like that we turn to computers for solutions. Computational solutions to Maxwell's Equations is a field that offers great promise. Unfortunately, that does not necessarily mean great answers. Computational solutions to Maxwell's Equations need to be subjected to a reality check. That, in turn, usually requires a real live scientist or engineer who understands Maxwell's Equations.

So let's get started.

I will start by defining the terms *charge*, *force*, *field*, *voltage*, *capacitance*, *inductance*, and *flux*. That may sound like a bore, but the fact is that most of us take these terms for granted and sometimes use them improperly.

I'll start with charge. Each electron is assigned one negative elemental charge, each proton one elemental positive charge. We denote a single charge as q, and, by definition, call 6.24 x 10^{18} such charges a Coulomb (Q).

Take two positively charged objects, say metal spheres, and place them in proximity. There will be a repulsive force between them. We measure force in Newtons and in free space (a vacuum) it is equal to:

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 R^2}$$

Where, in MKS units:

Q_1 = Charge on sphere 1 in Coulombs

Q_2 = Charge on sphere 2 in Coulombs

F = Force in Newtons

R = Distance between the spheres in meters

ε_0 = Free space permittivity = 8.85 x 10^{-12}

An enigmatic force seems to radiate or flow outward from each charged sphere. In order to provide for a uniform measure of the magnitude of this force, we can design a probe as shown in Figure 2. It consists of a small metal sphere onto which we place one Coulomb of positive charge.

The amount of the force on our Test Probe will be:

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 R^2}$$

Where:

Q_1 = The charge on the large sphere of Figure 2 in Coulombs

Q_2 = The charge on our Test Probe in Coulombs, $Q_2 = 1$

The force on our one Coulomb Test Probe is equal to the *electric field* (E).

$$E = \frac{Q_1}{4\pi\varepsilon_0 R}$$

Since a repulsive force exists between like charges, bringing such charges together requires work (Force times Distance = Work). Figure 3 shows a large metallic sphere charged with one Coulomb and a much smaller charged sphere some distance away. As an experiment, we'll try transferring the charge on the small sphere to the large one by moving the smaller sphere from infinity into contact with the larger sphere. The closer the two are, the greater the repulsive force, and the greater the work required to move an additional, incremental amount. The calculation of the total work required to move the additional charge from infinity onto the surface of the large sphere requires integration. We'll be integrating the repulsive force over distance.

$$W = \Delta V = -\int_{-\infty}^{R} \frac{Q_1(\Delta Q)}{4\pi\varepsilon_0 R^2} \cdot dr = \frac{\Delta Q}{4\pi\varepsilon_0 R}$$

Where:

W = Work in Newton-meters

ΔV = Change in Voltage

ΔQ= Charge on the small sphere, $\Delta Q \ll 1$ Coulomb

Q1 = Charge on the larger sphere, $Q_1 = 1$ Coulomb

The work done becomes *potential energy* just as if we had compressed a spring. This can be referred to simply as a change in potential and is equal to the ΔV.

We can rearrange this equation like this:

$$\frac{\Delta V}{\Delta Q} = \frac{1}{4\pi\varepsilon_0 R} = \frac{1}{C}$$

Where:

ΔC = "Capacitance" of the sphere in Farads

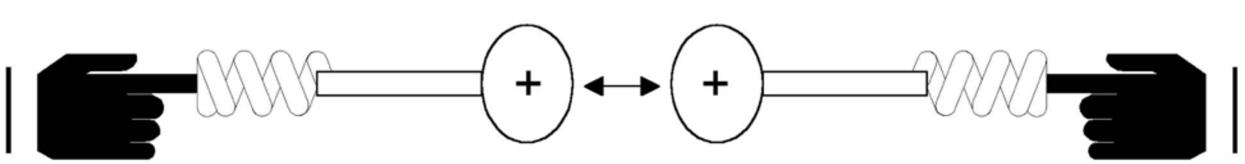


Figure 1: Two charged spheres are mounted on the ends of insulating rods loaded with springs. When forced together, a repulsive force pushes the charged spheres apart, compressing the springs.

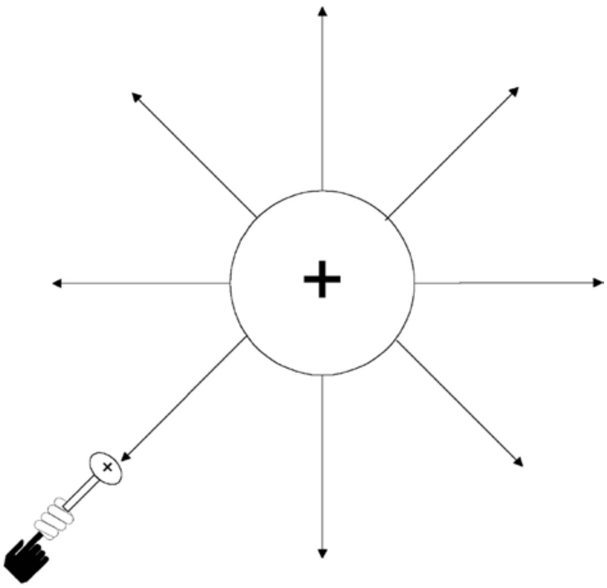


Figure 2: By mounting a small metal sphere on top of an insulated, spring loaded rod and charging the sphere with one Coulomb of charge, we can create a Test Probe which gives us a uniform way to measure the electric field. The electric field seems to "flow" outward from any charged object.

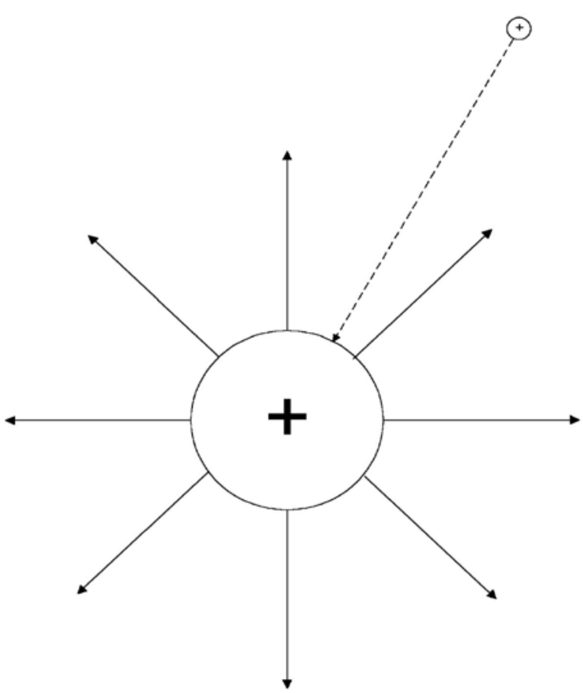


Figure 3: In this experiment, we take additional charge and move it from infinity onto the surface of a charged metallic sphere. Because the additional charge and the sphere have like signs, there's a repulsive force between them. Therefore, moving the charge onto the sphere requires work.

This equation states that the amount of work required to put an additional increment of charge on the sphere is a function of its size. The bigger the sphere, the easier it is to put on that extra increment of charge. The sphere's capacitance is equal to $4\pi\varepsilon_0 R$.

Capacitance is usually thought of in terms of opposing metal plates, but as our experiment shows that's not the only way to make a capacitor. Any conductive object will have an inherent capacitance. It's other "plate" is at infinity. Put two such objects in close proximity and the capacitance between them will be much greater than the capacitance between either of them and infinity, so the additional capacitance due to the "plate" at infinity is usually ignored.

Figure 4 suggests another experiment. We'll take our Test Probe with its one Coulomb of charge and move it, first forward, then back, and then in a circle. As we move it forward (toward the large sphere) work is required. Since they are of like charge, the Test Probe acts as if there's an invisible spring between it and the large charged sphere. The work we do in moving the Probe forward becomes additional stored potential energy of the system, raising the Voltage between the Probe and the sphere. As we move it back to our original position, the potential energy of the system drops, just as if we had let a compressed spring relax. The Voltage between the Test Probe and the sphere returns to the its initial value. That's true no matter what circuit we take to get back to our starting point, as shown.

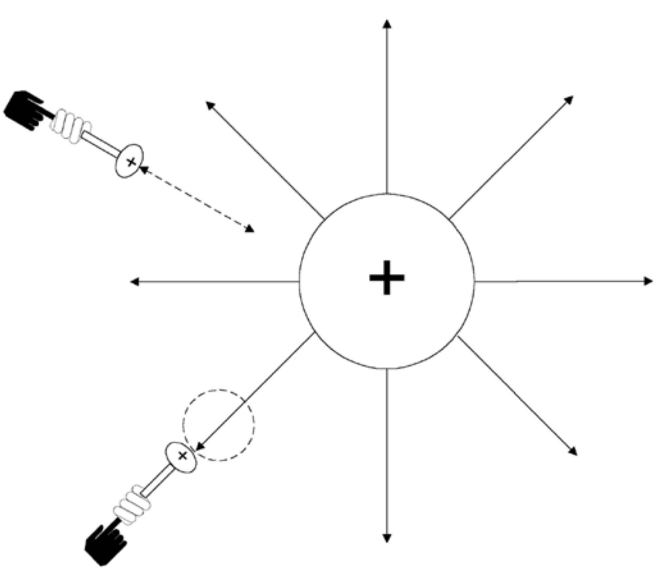


Figure 4: Moving our Test Probe towards the large sphere requires work. This work raises the potential energy of the system. The Probe feels a force pushing it away as if it was being pushed by an invisible spring between the Test Probe and the sphere. The net change in the system's potential energy required to get back to the starting point is zero whether we move forward and back or in a circle.

The fact that no change in potential energy results in returning to the starting point is the basis for one of Maxwell's Equations. Mathematically, the effect can be stated as follows:

$$\oint \varepsilon_0 E \cdot dl = 0$$

This states that the total change in potential energy which results from the movement of a charge in a closed circuit is zero. We could also state this in terms of the Voltage:

$$\sum_{Closed-Circuit} V = 0$$

This is a statement of Kirchhoff's Voltage law. Electrical engineers use Kirchhoff's Voltage law every day, but, as we will see, the validity of the law depends on certain assumptions, namely that the magnetic field through the closed circuit is unchanging. But that's a subject we'll return to in future chapters. For now we can accept the equations above to be true.

The term εE arises so often that it has its own abbreviation, D=εE. D is known as the electric flux density.

In order to proceed further, we'll need to introduce the concept of *flux*. The concept is illustrated in Figure 5. As we noted, two charged objects seem to have some invisible force between them. It's convenient to think of this force as flowing between the charged objects, and it's usually drawn that way. The electric field is drawn like water flowing from a sprinkler head.

Figure 5 shows a thin planar object placed within the field. The object, a plate, is shown edge on. Let's assume that the surface of the plate (the part we cannot see since it's "into" the page) has an area A, the plate is non-conductive and it has a dielectric constant of ε_0. Referring to the upper right hand portion of Figure 5, we calculate the total electric flux through the plate to be equal to the electric flux density, D, times the area. The electric flux density, by convention, is indicated by the density of the field lines. The closer the field lines are, the denser (stronger) the electric field is.

As the plate is tilted, fewer field lines pass through it until, finally at the bottom of Figure 5, virtually no field lines pass through the plate at all and the flux is near zero.

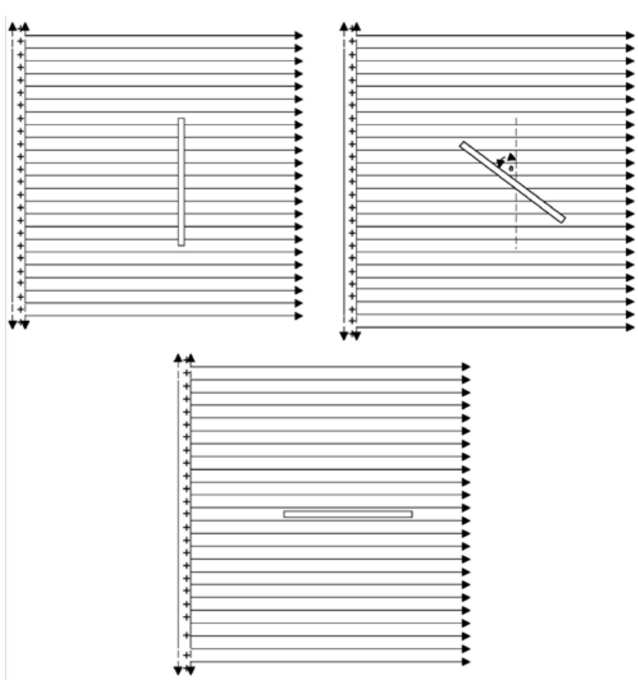


Figure 5: The concept of flux is illustrated. Flux is equal to the total field density (equal to the number of field lines per unit measure) passing through an object of interest, in this case, a thin non conductive plate (shown edge on). As the plate is tilted, fewer field lines pass through it until, at the bottom of the figure, the flux through the plate is near zero.

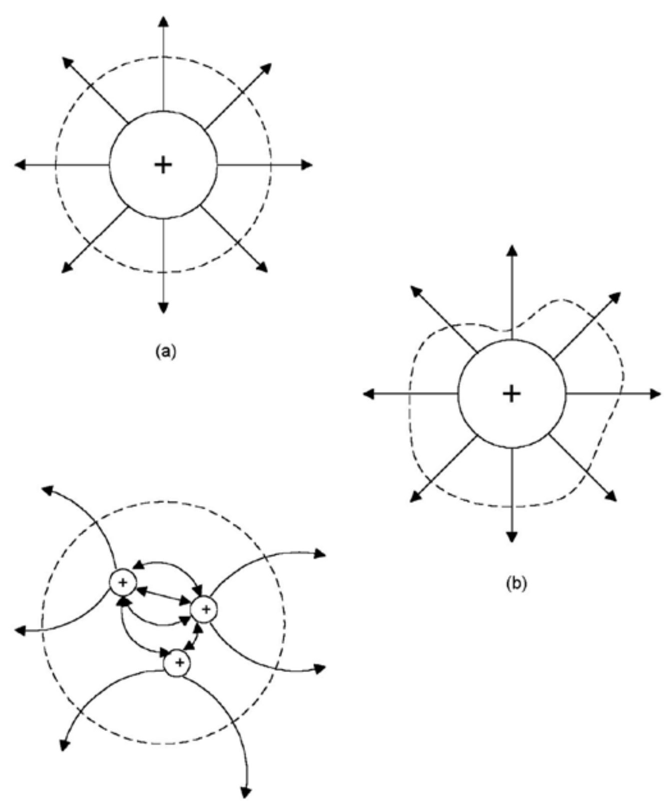


Figure 6: The total electric flux through an invisible envelope surrounding a charged object is equal to the charge contained. It does not matter if the envelope around the charged object is irregular, as in (b), or if the charges are separated, as in (c).

Mathematically, the flux through the plate in Figure 5 can be stated as:

$$\psi_E = |D||A|\cos\theta$$

Where:

ψ_E = Total electric flux through the plate

D = Electric flux density

A = Area of the plate

θ = Angle shown in Figure 5

We run into this form of equation so often that a special nomenclature been developed to express it, called the "dot product."

$$\psi_E = D \cdot A$$

Having described the concept of flux, we'll now return to our large, free floating charged sphere. We'll wrap an invisible, three dimensional envelope around the sphere as shown in cross section in Figure 6(a). The envelope is centered on the sphere. We can calculate the flux through this envelope simply by multiplying the field, which is uniform at a given distance from the sphere, by the area of the envelope. (I'll skip the mathematics and just give you the result.) The total flux through the envelope is equal to the charge on the sphere, Q. Though proving it requires a neat bit of mathematics, take it from me that the answer would be the same whether the envelope around the sphere is as shown in Figure 6(a), or irregularly shaped as in Figure 6(b). Further, the answer would still be the same if we were dealing with one charged object or many (Figure 6(c)). Expressed mathematically, we have Maxwell's first equation (also known as Gauss' first law):

$$\oiint D \cdot ds = Q$$

This equation states that total electric flux through an envelope equals the total charge contained within it. It's a remarkably simple result.

Many of the same experiments that we've done for electric fields we can now do for magnetic fields. We'll need some kind of test probe like we've used for measuring electric fields. To measure magnetic fields, we'll choose a small, one turn loop of wire carrying a static (dc) current of one Amp. Such a loop creates a magnetic field. See Figure 7.

Figure 8 shows what happens when we place our Test Loop in a uniform magnetic field. The loop feels a twisting influence known as a *torque*. Left to its own devices, the Test Loop will orient itself so that the plane of the loop is perpendicular to the magnetic field lines. The total torque is equal to the force on the loop in times its length.

We can use the maximum torque detected (which occurs when the plane of the Test Loop is aligned with the field) to measure the *magnetic field* H. It is:

$$H = \frac{T}{\mu_0 IA}$$

Where:

H = Magnetic field in Amps/meter

T = Torque in Newton-meters

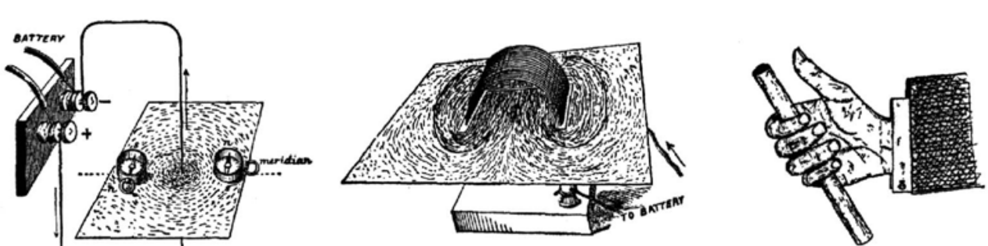
I = Current in the Test Loop in Amps

A = Area of the loop in m^2

μ_0 = Free space permeability = $4\pi \times 10^{-7}$

By convention, we usually move the constant μ_0 to the other side of the equation, expressing the result in terms of $B=\mu_0 H$. B is known as the *magnetic flux density* and is measured in Teslas.[1]

[1] Alternatively, the magnetic flux density can be expressed in CGS units as Gauss. There are 10,000 Gauss to one Tesla.



7(a) 7(b) 7(c)

Figure 7: The nature of magnetic fields has been observed for centuries. Magnetic fields around a current carrying wire form circles. Loops of wire create magnetic fields which in turn themselves form closed loops. The direction of the magnetic field can be determined using the right hand rule.

Having defined the "magnetic field" and the "magnetic flux density," and having devised a way to measure the field, we now can perform the same experiments for magnetic fields that we previously performed for electric fields. In Figure 9, we wrap an invisible envelope around a source of a magnetic field, in this case a loop of wire carrying a direct current. Note that all of the magnetic field line flowing outward from the loop end up returning to it. Magnetic fields always form closed circuits. Because of that, the total magnetic flux through our envelope is zero. Expressed mathematically, we have Maxwell's (and Gauss') second equation:

$$\oiint B \cdot ds = 0$$

Figure 10 illustrates another experiment. We can measure the magnetic field around a straight wire carrying direct current using our Test Loop. What we will find is that the magnetic field falls off linearly with the distance from the wire according to the formula:

$$H = \frac{I}{2\pi R}$$

Since 2πR is the circumference of a circle around the wire, we can restate this equation as follows:

$$H = \frac{I}{2\pi R}$$

$$2\pi R = \oint dl$$

$$H \cdot \oint dl = \oint H \cdot dl = I$$

This states is that the total magnetic field integrated around a closed loop is equal to the current passing through, and normal to, that loop.

We now have all that we need to state Maxwell's Equations for the case of direct currents and static fields.

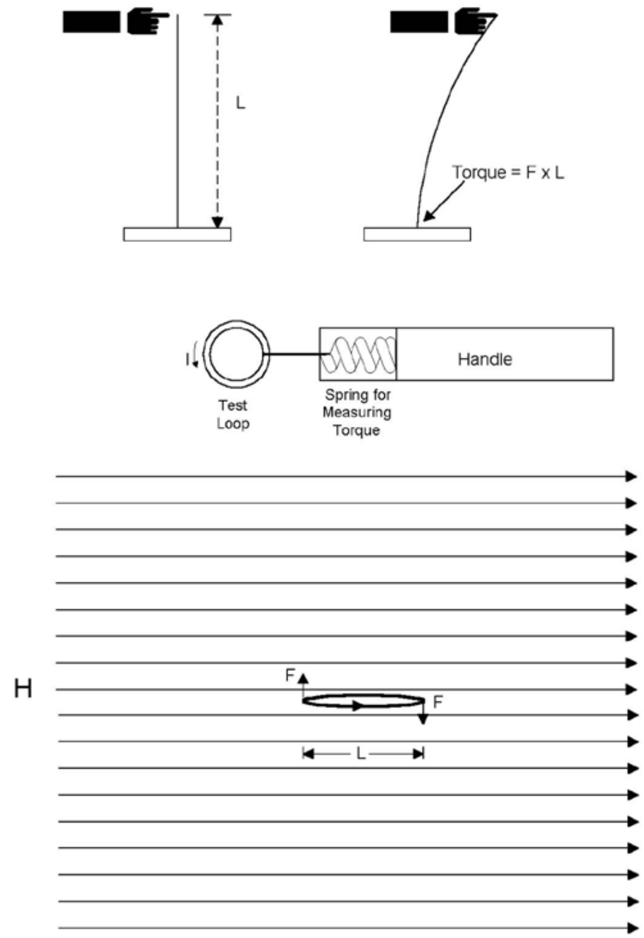


Figure 8: In order to measure magnetic fields, we can use a small loop of wire carrying direct current as a test probe. When immersed in a magnetic field, the loop will feel a torque which will tend to force it into an alignment perpendicular to the field lines shown. The torque is equal to the force times the length of the loop.

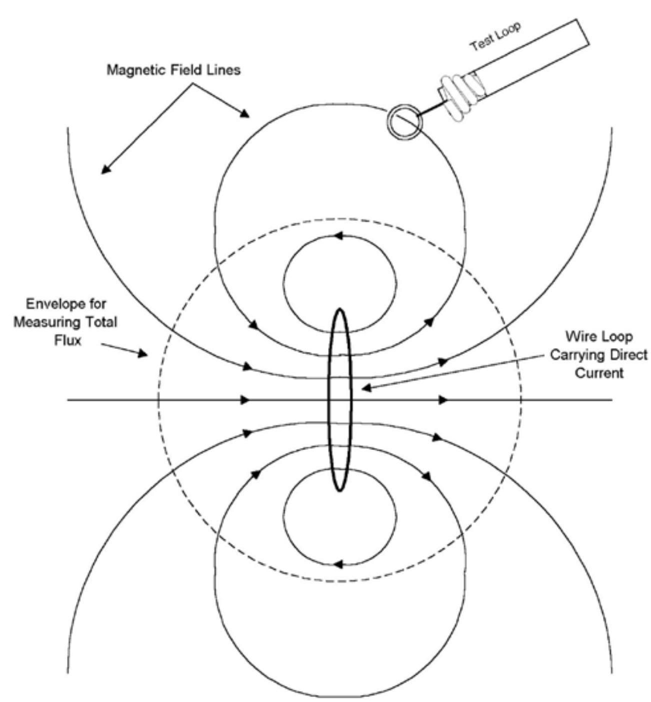


Figure 9: Magnetic fields formed by a loop of current are themselves closed loops. The net magnetic flux through an envelope surrounding such a loop is zero.

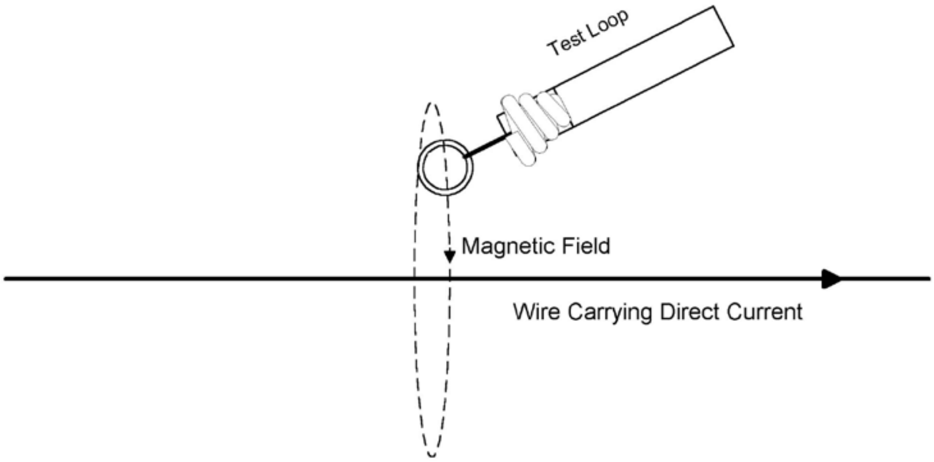


Figure 10: Our "Test Loop" can be used to measure the magnetic field produced by a wire carrying direct current. The field drops off linearly with the distance from the wire.

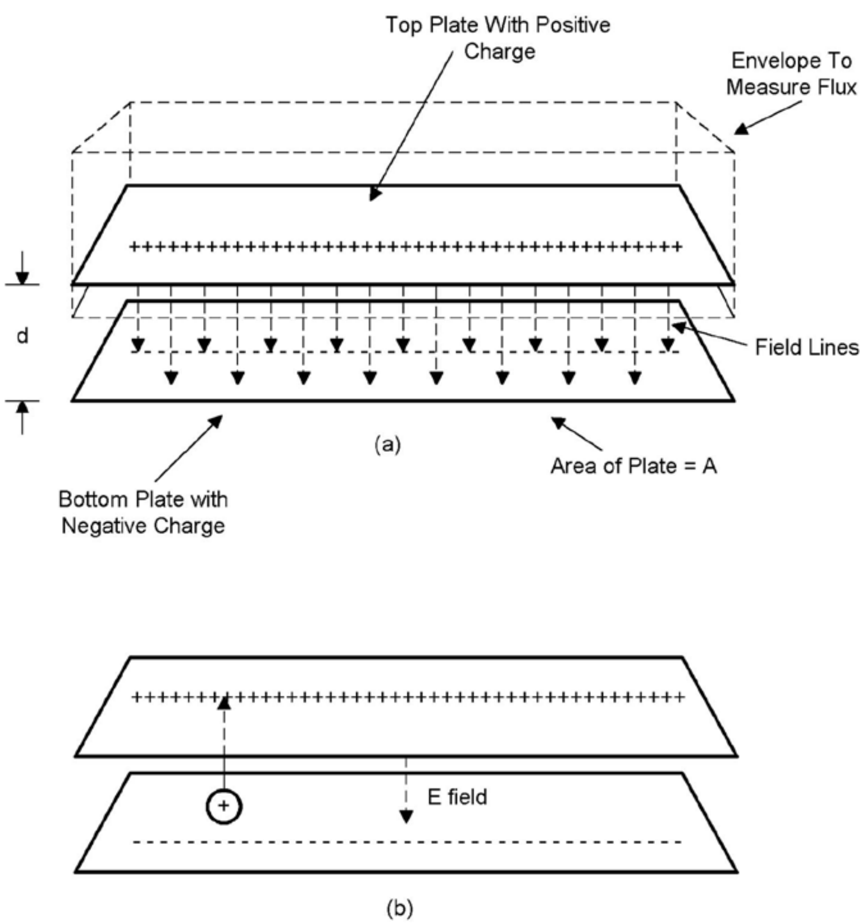


Figure 11: The capacitance of a parallel plate capacitor can be derived directly from Maxwell's Equations. In (a), the flux through the bottom of an imaginary box shaped envelope placed around the upper plate is calculated. This is used to derive the magnitude of the field. In (b) additional positive charge is moved from the lower plate to the upper plate. The calculation of the work needed to do that allows us to calculate the capacitance.

Here they are:

$$\oiint D \cdot ds = \oiint \varepsilon_0 E \cdot ds = Q$$

$$\oiint B \cdot ds = \oiint \mu_0 H \cdot ds = 0$$

$$\oint \frac{D}{\varepsilon_0} \cdot dl = \oint E \cdot dl = 0$$

$$\oint \frac{B}{\mu_0} \cdot dl = \oint H \cdot dl = I$$

Perhaps it's more intuitive to state these in terms of words rather than in terms of mathematics:

1. The electric flux through any envelope is equal to the charge contained.
2. The magnetic flux through any envelope is zero.
3. In a static field, the total change in a system's potential energy resulting from the movement of a charge in a closed loop is zero. (Or more simply, in a static field, the Voltage around a closed loop is zero.)
4. In a static field, the magnetic field integrated around a closed loop (the "line integral") is equal to the current flowing through, and normal to, the loop.

Before closing this chapter, let's do two final experiments. The first involves a typical parallel plate capacitor as shown in Figure 11. It has a positive charge on the top plate and a negative charge on the lower plate. We can use the first of Maxwell's Equations to compute the field between the plates. To do this, we have to define an envelope around one of the plates. The envelope can be any shape we want, and so we choose a box around the upper plate as shown in Figure 11(a). We know from experience that the electric field largely consists of parallel field lines between the two plates. All these field lines pass through the bottom of the box shaped envelope and are, for the most part, perpendicular to its surface. That will make it easy to work with the equations. Note that the flux through the bottom of the box is equal to the electric field density times the area of the bottom of the box, which in turn is equal to the area of the top plate. So:

$$\oiint \varepsilon_0 E \cdot ds = Q$$

$$E \cdot A = \frac{Q}{\varepsilon_0}$$

$$E = \frac{Q}{A\varepsilon_0}$$

Where:

Q = The charge on the upper plate in Coulombs

E = Electric field between the plates in Volts/meter

A = Area of the upper plate in meters^2

To find the capacitance, we first charge the plates with one Coulomb of charge. Then we calculate the work required to move a small amount of additional positive charge from the lower plate to the upper one:

$$W = \Delta V = F \cdot d = \frac{Q_1 \Delta Q}{\varepsilon_0 A} \cdot d$$

$$Q_1 = 1$$

$$\Delta V = F \cdot d = \frac{\Delta Q d}{\varepsilon_0 A}$$

$$C = \frac{\Delta Q}{\Delta V} = \frac{A\varepsilon_0}{d}$$

Our second experiment involves inductance. We'll start with its definition and then calculate the inductance of a loop of wire. Inductance is defined as the total magnetic flux through a loop divided by the current that gives rise to that flux:

$$L = \frac{\psi_M}{I}$$

Where:

ψ_M = Magnetic flux through the loop due to I

L = Inductance in Henries

I = Current in Amps

For our experiment, we'll use a single turn loop of wire carrying a direct current. We'll use our Test Loop to measure the magnetic field within the loop. We'll find that it's nearly uniform and equal to:

$$H = \frac{I}{d}$$

Where:

H = Magnetic field within the loop

I = Current in the loop in Amps

d = Diameter of the loop in meters

We then can derive its inductance as:

$$L = \frac{\psi_M}{I}$$

$$\psi_M = B \cdot A$$

$$B = \mu_0 H = \frac{\mu_0 I}{d}$$

$$\psi_M = \frac{\mu_0 I}{d} A$$

$$L = \frac{A\mu_0}{d}$$

The similarity of this equation to the one describing the capacitance of a parallel plate capacitor is no accident, as we'll see. ■

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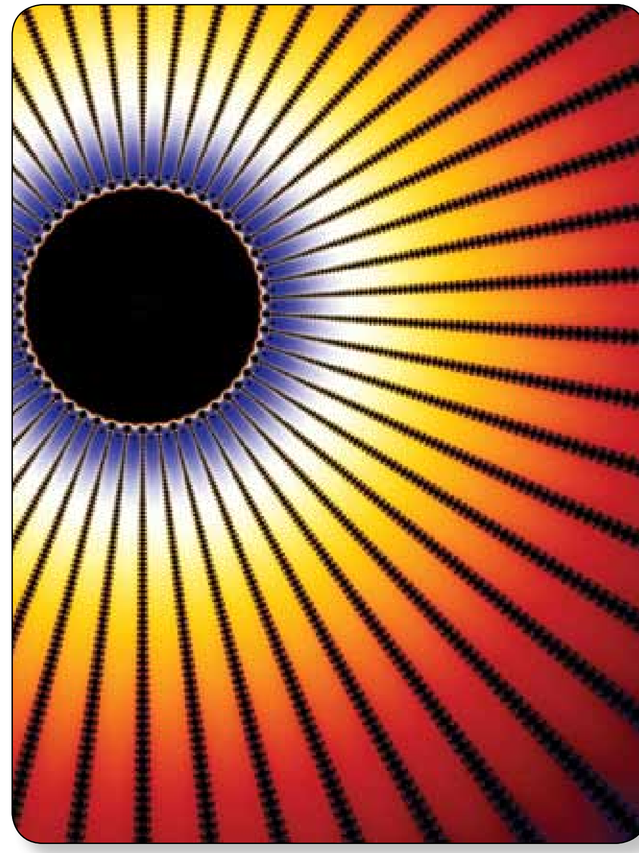
***Glen Dash** is the author of numerous papers on electromagnetics. He was educated at MIT and was the founder of several companies dedicated to helping companies achieve regulatory compliance. Currently he operates the Glen Dash Foundation which uses ground penetrating radar to map archaeological sites, principally in Egypt.*



A Dash of Maxwell's

A Maxwell's Equations Primer

Part 2: Why Things Radiate

BY GLEN DASH

In Chapter I, I introduced Maxwell's Equations for the static case, that is, where charges in free space are fixed, and only direct current flows in conductors. In this chapter, I'll make the modifications to Maxwell's Equations necessary to encompass the "dynamic" case, that is where magnetic and electric fields are changing. Then I will try to explain why things radiate.

Here are Maxwell's equations for the static case:

$$\oiint D \cdot ds = \oiint \varepsilon_0 E \cdot ds = Q$$

$$\oiint B \cdot ds = \oiint \mu_0 H \cdot ds = 0$$

$$\frac{1}{\varepsilon_0} \oint D \cdot dl = \oint E \cdot dl = 0$$

$$\frac{1}{\mu_0} \oint B \cdot dl = \oint H \cdot dl = I$$

Where:

D = Electric flux density = $\varepsilon_0 E$

E = Electric field in volts/meter

B = Magnetic flux density = $\mu_0 H$

H = Magnetic field in amps/meter

ε_0 = Free space permittivity = 8.85×10^{-12}

μ_0 = Free space permeability = $4\pi \times 10^{-7}$

The first of the modifications we need to explain the "dynamic" case we owe to the work of Michael Faraday. For the static case, the third equation states that the electric field integrated around a closed loop (the "line integral") is zero.

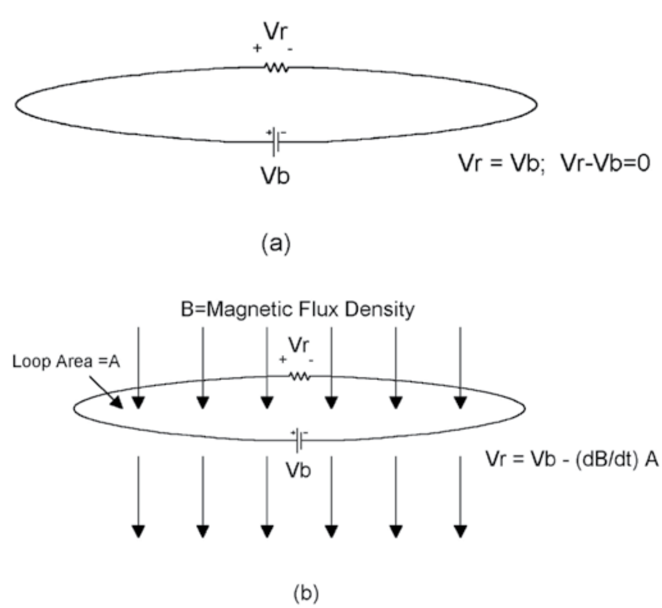


Figure 1: Kirchhoff's voltage law is illustrated in (a). The voltage around a closed loop is zero. In (b), a changing magnetic flux introduces an additional time varying voltage across the resistor.

$$\oint E \cdot dl = 0$$

Engineers more commonly deal with this in the form of Kirchhoff's voltage law:

$$\sum_{Closed-Circiut} V = 0$$

Faraday's contribution was to establish that Kirchhoff's voltage law is nearly always wrong. Where there is a changing magnetic flux through a loop, a voltage is created by that changing flux. That voltage is equal to:

$$\oint E \cdot dl = V = -\frac{\partial B}{\partial t} \cdot A$$

Where A equals the area of the loop.

The effect of this flux-induced voltage is illustrated in Figure 1(b). It shows up as an additional time varying voltage across the resistive load. So to account for changing magnetic fields through the loop, we must modify Maxwell's third equation as follows:

$$\oint E \cdot dl = -\frac{\partial B}{\partial t} \cdot A$$

This equation explains those ever-present and annoying "ground loops." They can be minimized by minimizing either the strength of the magnetic field ($B=\mu_0 H$), its rate of change ($\partial B/\partial t$) or the area of the loop (A). The equation assumes that the loop is two dimensional and the field uniform across the loop at any given instant. Where neither is so, we need a more generalized solution:

$$\oint E \cdot dl = -\oiint \frac{\partial B}{\partial t} \cdot ds$$

This equation is known as the "integral form" of Maxwell's third equation, but it's cumbersome to use, and, for the most part, we'll be dealing with two dimensional loops and fields that at any given instant are uniform over the loop area, so we can work with the simpler form.

It was Maxwell himself who completed what was to become the fourth of his equations for the dynamic case. The fourth equation for the static case states:

$$\frac{1}{\mu_0} \oint B \cdot dl = \oint H \cdot dl = I$$

The problem lay with the definition of current, I . Today, engineers are comfortable with thinking of current traveling through circuits either by way of conduction, by capacitive coupling or by induction. Faraday dealt with induction. Maxwell's contribution to was to separate "conduction" current from "capacitive" current, the latter which he called "displacement" current.

$$\oint H \cdot dl = I_{conduction} + I_{displacement}$$

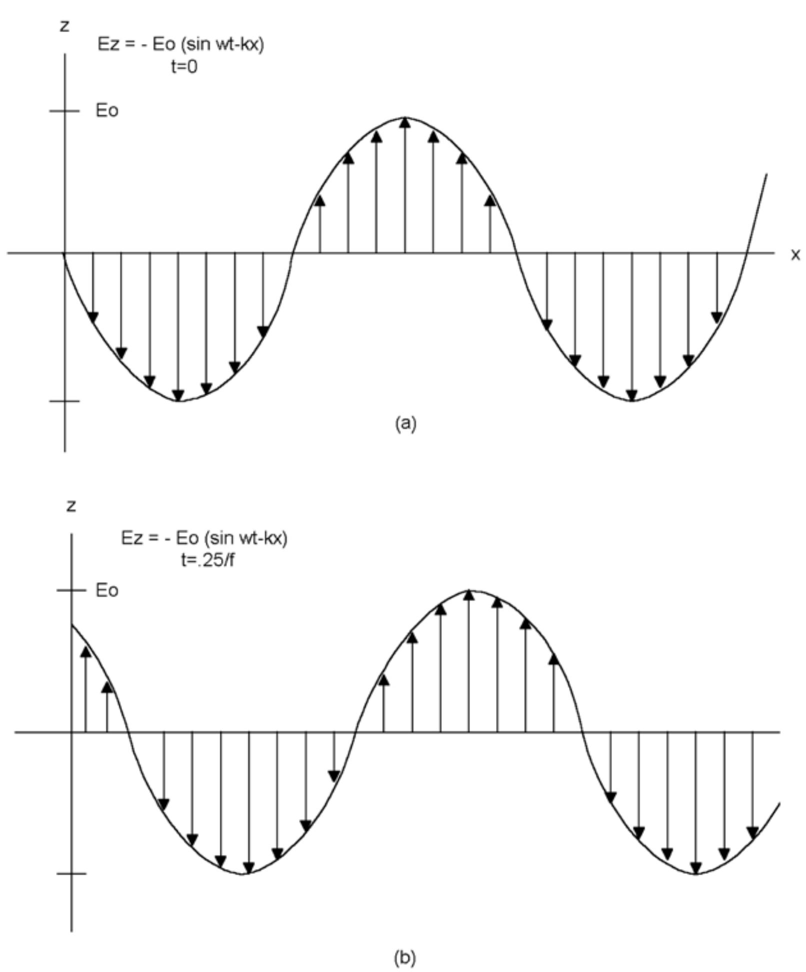


Figure 2: This proposed solution to Maxwell's Equations in free space uses, as one component, the electric field illustrated. It moves to the right with time.

Let's take the case of a parallel plate capacitor where $C=A\varepsilon_0/d$, $E=V/d$, and $Q = CV$. Noting that by definition, the time derivative of charge equals the current ($I=dQ/dt$) the displacement current passing through a parallel plate capacitor is equal to:

$$Q = CV$$
$$\frac{dQ}{dt} = C\frac{dV}{dt}$$
$$\frac{dQ}{dt} = I_{displacement}$$
$$I_{displacement} = C\frac{dV}{dt}$$
$$C = \frac{A\varepsilon_0}{d}$$
$$V = E \cdot d$$
$$I_{displacement} = A\varepsilon_0\frac{\partial E}{\partial t}$$

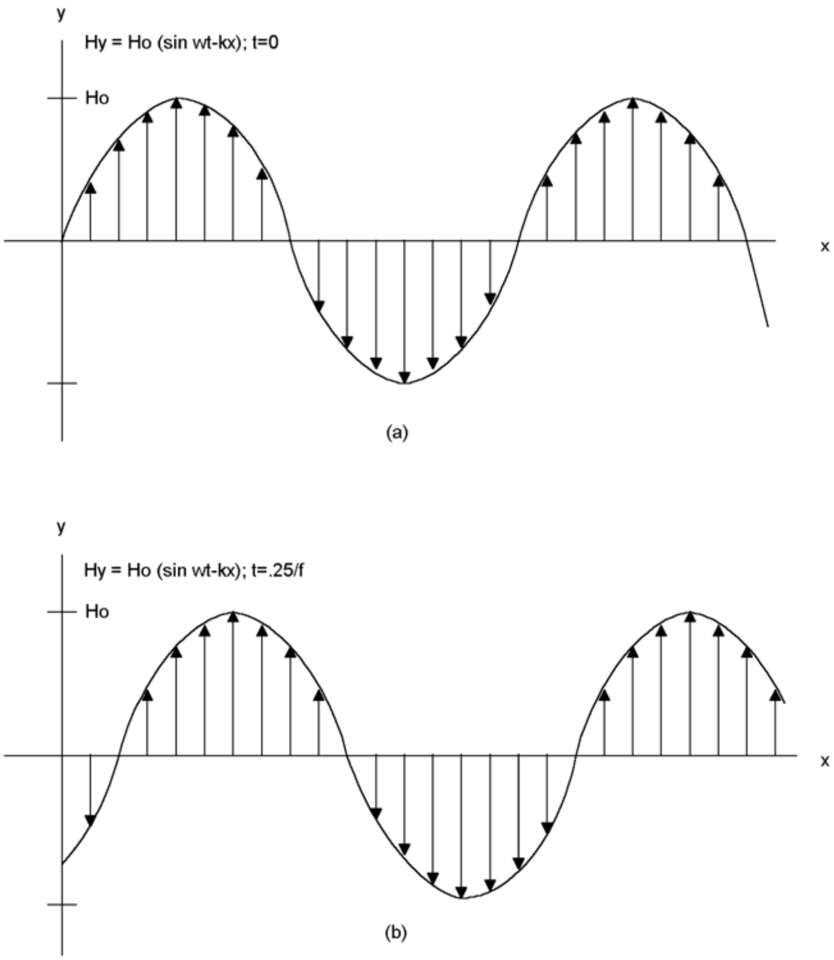


Figure 3: This proposed solution for Maxwell's Equations uses, as its other component, a magnetic field as shown. It is time correlated with the electric field of Figure 2, but is oriented 90 degrees from it in space.

Combing the above yields:

$$\frac{1}{\mu_0}\oint B \cdot dl = \oint H \cdot dl = I_{cond} + A \cdot \varepsilon_0 \frac{\partial E}{\partial t}$$

Variable A is, of course, the area of our capacitor's plates. As long as we're dealing with parallel plate capacitors, we can use the equation in the form above. More generally, however, area can be expressed as:

$$A = \oiint f(s) \cdot ds$$

Here, f(s) is a function that is integrated over a surface (or an envelope) to calculate the flux. In our case the function f(s) is the time derivative of the electric field density, D, $f(s)=\partial D/\partial t$, so:

$$\frac{1}{\mu_0}\oint B \cdot dl = I_{cond} + \oiint \frac{\partial D}{\partial t} \cdot ds$$

We can now state all four of Maxwell's equations in general form:

$$\oiint D \cdot ds = Q$$
$$\oiint B \cdot ds = 0$$
$$\frac{1}{\varepsilon_0}\oint D \cdot dl = -\oiint \frac{\partial B}{\partial t} \cdot ds$$
$$\frac{1}{\mu_0}\oint B \cdot dl = I_{cond} + \oiint \frac{\partial D}{\partial t} \cdot ds$$

Somewhat more intuitively, we can state Maxwell's Equations in words:

1. The electric flux through a closed envelope equals the charged contained.
2. The magnetic flux through a closed envelope is zero.
3. The electric field integrated around a closed loop (the "line integral") equals the negative of the rate of change of the magnetic flux through the loop.
4. The magnetic field integrated around a closed loop is equal to the total

current, both conductive and capacitive, that passes through it.

Next, I'll try to explain why radio waves radiate.

First, I'll have to take you to a place far, far away where there are no conduction currents and no free charges, a place we can truly call free space. There, Maxwell's Equations reduce to the following:

$$\oiint D \cdot ds = 0$$

$$\oiint B \cdot ds = 0$$

$$\oint E \cdot dl = -\mu_0 \oiint \frac{\partial H}{\partial t} \cdot ds$$

$$\oint H \cdot dl = \varepsilon_0 \oiint \frac{\partial E}{\partial t} \cdot ds$$

In free space, we need only to deal with the third and fourth of Maxwell's equations;

$$\oint E \cdot dl = -\mu_0 \oiint \frac{\partial H}{\partial t} \cdot ds$$

$$\oint H \cdot dl = \varepsilon_0 \oiint \frac{\partial E}{\partial t} \cdot ds$$

Our next task is to find expressions for the electric and magnetic fields that satisfy these two equations. I'll do this using a time honored tradition in calculus. I'll guess at the answer and then plug the answers into the equations to see if they work. Figures 2 and 3 show my guesses.

My proposed solution is a set of two fields, set perpendicular to each other as shown in Figure 4. Figure 2(a) shows the electric field at time equals zero. The electric field vector points in the z direction and it varies sinusoidally with time. As such, the entire waveform appears to move in the direction the x direction. Mathematically, it is expressed as:

$$E_z = -E_0 \sin(\omega t - kx)$$

Where:

ω = The frequency in radians per second = $2\pi f$

f = The frequency in Hertz

k = The "wavenumber" = $2\pi/\lambda$

λ = the wavelength in meters

Likewise, the magnetic field is oriented in the y direction and it also appears to move in the x direction. It is expressed as:

$$H_y = H_0 \sin(\omega t - kx)$$

Figure 4 shows this combination which is known as a "plane wave." The crests of the magnetic and electric fields seem to move through space in the positive x direction as if they were a wall, hence the term plane wave.

Next, we'll plug the proposed solution for the electric field into the third of Maxwell's Equations. To do this we'll have to calculate a line integral. The line integral is equal to the field times the distance around a closed loop.

Fortunately, there is an easy, graphical way to calculate the line integral. What we want to do is to find a convenient loop and multiply the field times the perimeter of the loop. The location that we pick for our convenient loop is shown in Figure 5(b). The loop aligns on the left with location x_0 and on the right with x_1.

At x_0, the electric field is at its maximum and is equal to $-E_0$. At a slight distance to the right, x_1, the electric field has lessened in magnitude slightly. At x_1 amplitude is:

$$E_{x1} = -(E_0 + (\frac{\partial E}{\partial x})(x_1 - x_0)) = -(E_0 + (\frac{\partial E}{\partial x})\Delta x)$$

In order to preserve the right hand rule, which requires us to move in a counter clockwise direction, we'll begin our line integral calculation by a move of a distance $-\Delta z$ as shown in Figure 5(b), creating the first component of our loop integral. This first component is equal to $(-E_0)(-\Delta z) = E_0 \Delta z$. There's no electric field in the x direction, so we don't have to consider the top and bottom sides of our rectangular loop. On the right side of our loop, we move a distance Δz times the field at that point. Adding the contributions of our loop movement together and noting that $\Delta x \, \Delta z$ equals the area of the loop (A), we get:

$$\oint E \cdot dl = \Sigma E \cdot dl = E_0 \Delta z + (-(E_0 + \frac{\partial E}{\partial x}\Delta x)(\Delta z)) = E_0 \Delta z - E_0 \Delta z - \frac{\partial E}{\partial x}\Delta x \Delta z = -\frac{\partial E}{\partial x} A$$

$$\oint E \cdot dl = -\frac{\partial E}{\partial x} A$$

Substituting this expression for the line integral of the electric field, and noting that:

$$\oiint ds = A$$

We find that:

$$\oint E \cdot dl = -\mu_0 \oiint \frac{dH}{dt} \cdot ds$$

$$-(\frac{\partial E}{\partial x})A = -\mu_0 \oiint (\frac{\partial H}{\partial t}) \cdot ds = -\mu_0 (\frac{\partial H}{\partial t})A$$

$$\frac{\partial E}{\partial x} = \mu_0 \frac{\partial H}{\partial t}$$

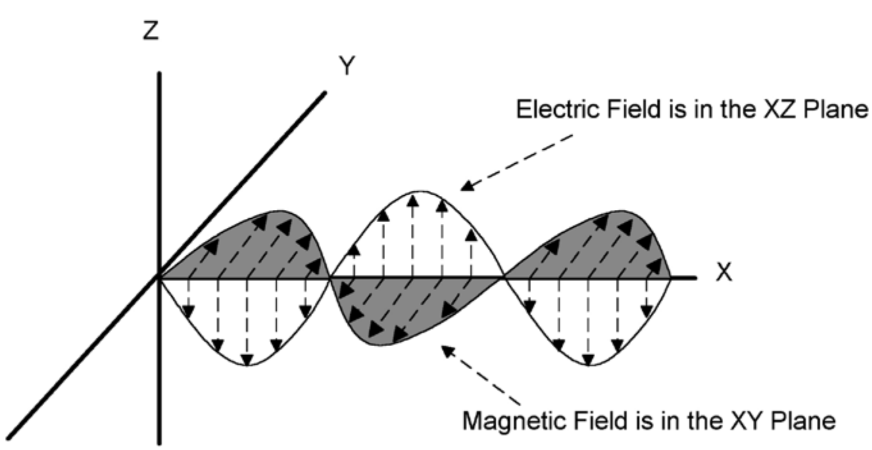


Figure 4 : The two fields of Figures 2 and 3 are combined on one graph. The electric field lies in the XZ plane and the magnetic field in the XY plane. Thus, their polarizations are 90 degrees apart. Together they form a "plane wave."

It's a remarkably simple solution. It states that the change in electric field with distance traveled is equal to the change in magnetic field with time, multiplied by a constant.

We can do the same for magnetic fields deriving a similar equation:

$$\frac{\partial H}{\partial x} = \varepsilon_0 \frac{\partial E}{\partial t}$$

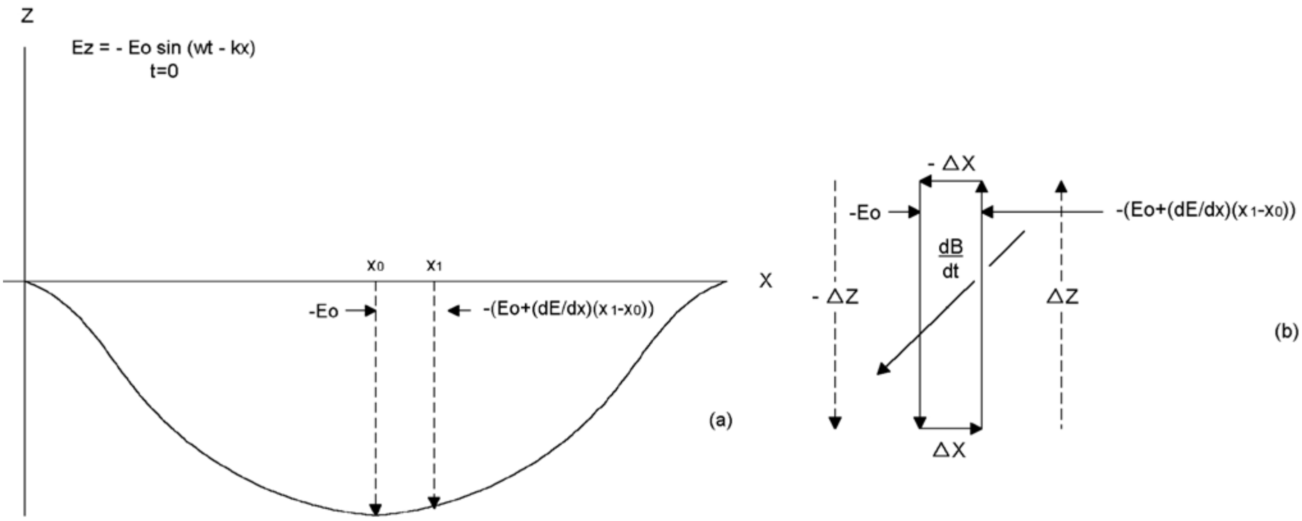


Figure 5: The line integral of the electric field can be computed as shown without using complex math. A portion of the electric field from Figure 2 is shown at the top. If we move in a loop as shown at the bottom of the figure, the product of the electric field times the distance moved is equal to the line integral. This, in turn, is equal to -(dB/dt)·A, where A is the area of the loop shown in (b). The term (dB/dt)·A is the rate of change of the magnetic flux through the loop.

It's now time to plug in the proposed solution -- the plane wave -- to see if it works. The proposed solutions was:

$$E_z = -E_0 \sin(\omega t - kx)$$

$$H_y = H_0 \sin(\omega t - kx)$$

Taking the derivative of E_z and H_y with respect to time and distance yields:

$$\frac{\partial H_y}{\partial x} = -k\, H_0 \cos(\omega t - kx)$$
$$\frac{\partial E_z}{\partial x} = -k\, E_0 \cos(\omega t - kx)$$
$$\frac{\partial H_y}{\partial t} = \omega\, H_0 \cos(\omega t - kx)$$
$$\frac{\partial E_z}{\partial t} = \omega\, E_0 \cos(\omega t - kx)$$

Therefore:

$$\frac{\partial H_y}{\partial x} = \varepsilon_0 \frac{dE_z}{dt}$$

$$\frac{\partial E_z}{\partial x} = \mu_0 \frac{dH_y}{dt}$$

$$-k\, H_0 \cos(\omega t - kx) = \varepsilon_0 \omega\, E_0 \cos(\omega t - kx)$$
$$-k\, E_0 \cos(\omega t - kx) = \mu_0 \omega\, H_0 \cos(\omega t - kx)$$
$$H_0 = -\frac{\varepsilon_0 \omega}{k} E_0$$
$$-kE_0 = \mu_0 \omega H_0 = -\mu_0 \omega \frac{\varepsilon_0 \omega}{k} E_0$$
$$\frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \frac{\omega}{k}$$

The proposed solution works if $1/\sqrt{(\mu_0\ \varepsilon_0)} = \omega/k$. Does it? Note that $\omega=2\pi f$, $k=2\pi/\lambda$ and therefore $\omega/k=f\lambda$. The units of $f\lambda$ are cycles/second times meters/cycle, or meters/second = velocity. The term ω/k must be the velocity of the wave as it moves in the x direction.

As for $1/\sqrt{(\mu_0\varepsilon_0)}$, it is equal to:

$$\frac{1}{\sqrt{(\mu_0 \varepsilon_0)}} = \frac{1}{\sqrt{(4\pi x\, 10^{-7})(8.85x\, 10^{-12})}} = 3x\, 10^8 \text{ meters/second}$$

This, of course, is the speed of light (c), which is exactly what we would expect.

Before closing this chapter, we'll use the equations above to derive two characteristics of plane waves. Since the electric field is expressed in terms of V/m and the magnetic field in A/m, dividing E by H at any given point in space produces a resultant is in units of V/A, or Ohms. In free space, this ratio is:

$$\left|\frac{E_z}{H_y}\right| = \frac{k}{\varepsilon_0 \omega} = \frac{1}{c\,\varepsilon_0} = \frac{\sqrt{\mu_0 \varepsilon_0}}{\varepsilon_0} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377 \text{ ohms}$$

The "impedance" of free space, we can conclude, is 377 ohms.

We can also multiply the magnitudes of the electric and magnetic fields at any point in space yielding a resultant that is in units of V/meter x A/meter or Watts/meter^2. From that we can conclude that a plane wave transmits power in the direction of its motion.

$$P_x = E_z \times H_y$$

P is known as the Poynting vector.

Why do things radiate? In short, electromagnetic fields radiate because a change in the electric field with time causes a change in the magnetic field around it. That, in turn, causes a change in the magnetic field with time which causes a change in the electric field around it. The two fields alter each other, causing a movement through space over time. ■

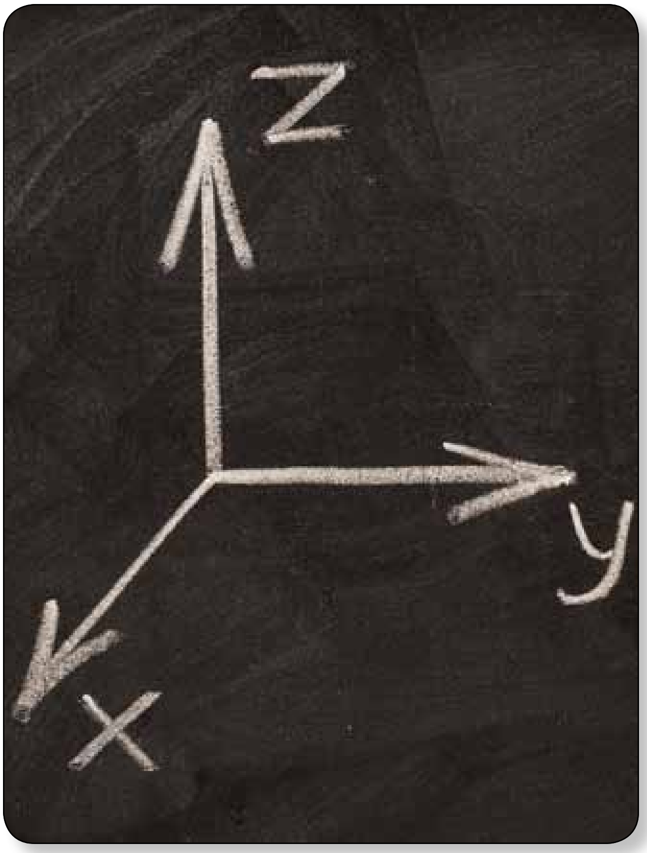
Glen Dash *is the author of numerous papers on electromagnetics. He was educated at MIT and was the founder of several companies dedicated to helping companies achieve regulatory compliance. Currently he operates the Glen Dash Foundation which uses ground penetrating radar to map archaeological sites, principally in Egypt.*

A Dash of Maxwell's

A Maxwell's Equations Primer

Part 3: The Difference a Del Makes

BY GLEN DASH



In Chapter 2, I introduced Maxwell's Equations in their "integral form." Simple in concept, the integral form can be devilishly difficult to work with. To overcome that, scientists and engineers have evolved a number of different ways to look at the problem, including this, the "differential form of the Equations." The differential form makes use of vector operations.

A physical phenomena that has the both the attributes of magnitude and direction may be described by a vector. Velocity can be drawn in vector form; it has the attributes of both direction and speed. Vectors can be illustrated graphically as shown in Figure 1(a) – the length of the vector represents its magnitude and its angle from the x axis defines its direction. However, we will be using Cartesian coordinates. In this system, vectors are described as a sum of "unit" denominated vectors. A unit vector along the x axis is simply a vector aligned with the x axis that is one unit long (one meter long in the MKS system). We'll denote a unit vector in the x direction as i. Similarly, unit vectors in the y and z directions will be denoted **j** and **k** respectively.

The vector shown in Figure 1 has a magnitude of 5 and is angled away from the x axis by 30 degrees. It can also be described as the sum of two unit denominated vectors one 3**j** units long and the other 4**i** units long.

Vectors are manipulated through the use of "vector operations." We have already seen one of these, the dot product which illustrated in Figure 2.

Use of the dot product allows computation of the component of Vector A which is aligned with Vector B. It is expressed as:

$$A \cdot B = |A||B|\cos\theta$$

However, the dot product can also be expressed in terms of unit vectors. I'll skip the proof and just give you the formula:

$$A \cdot B = |A||B|\cos\theta = A_x B_x + A_y B_y + A_z B_z$$

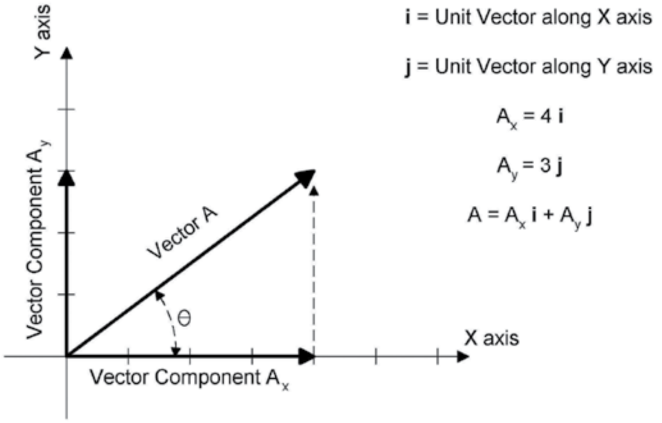


Figure 1: A vector can be described in terms of its length and angle, or it can be described in terms of unit vectors.

Where:

$A = A_x\,\mathbf{i} + A_y\,\mathbf{j} + A_z\,\mathbf{k}$

$B = B_x\,\mathbf{i} + B_y\,\mathbf{j} + B_z\,\mathbf{k}$

i, j, k = Unit vectors in the x, y and z directions respectively.

The dot product does not have any direction associated with it. It's a scalar, not a vector.

The second vector operation we'll need to use is known as the "cross product." The cross product is best illustrated by a real world example, the deflection of an electron beam within a Cathode Ray Tube.

Figure 3 shows a beam of electrons moving through a vacuum exposed to a magnetic field. The field here points out of the page. (By convention, a magnetic field that points out of the page is designated by a dot in a circle, and one that point into the page by an x within a circle.) As the charge moves through the field it is acted on by a force known as the Lorentz Force. The Lorentz Force operates through the "right hand rule," the charge "feels" a force perpendicular to the plane formed by the field and the direction of charge movement. The Lorentz Force is equal to:

$$F = e(v \times B)$$

Where:

F = Lorentz Force in Newtons. e = Positive electric charge in Coulombs.

v = Velocity of the charge in m/s.

B = Magnetic flux density in Teslas

The × in this equation is not simply a multiplier. Both v and B are vectors, and in this context × denotes a vector operation known as the cross product.

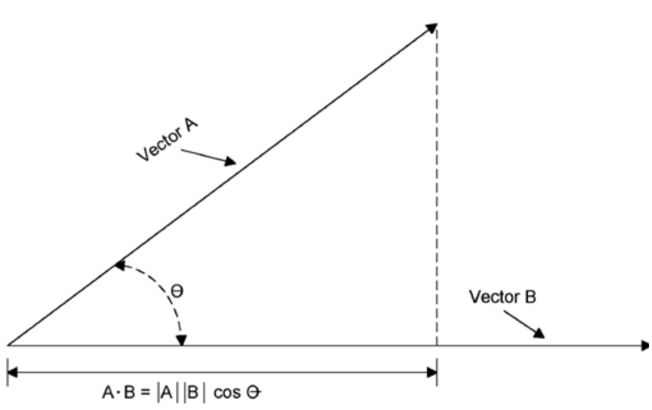


Figure 2: The dot product illustrated.

The cross product ($v \times B$) is equal to:

$$v \times B = |v||B|\sin\theta \perp$$

The symbol ⊥ denotes the direction of the force, perpendicular to the plane formed by the vectors *v* and B.

In Cartesian coordinates the cross product is equal to:

$$A \times B = |A||B|\sin\theta \perp = \mathrm{i}(A_y B_z - A_z B_y) + \mathrm{j}(A_z B_x - A_x B_z) + \mathrm{k}(A_x B_y - A_y B_x)$$

Unlike the dot product, the cross product is a vector itself.

Cross products can be solved for easily by using a "determinant." Take two vectors, A and B, and set them up in a matrix form as follows:

$$\begin{vmatrix} \mathrm{i} & \mathrm{j} & \mathrm{k} \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$$

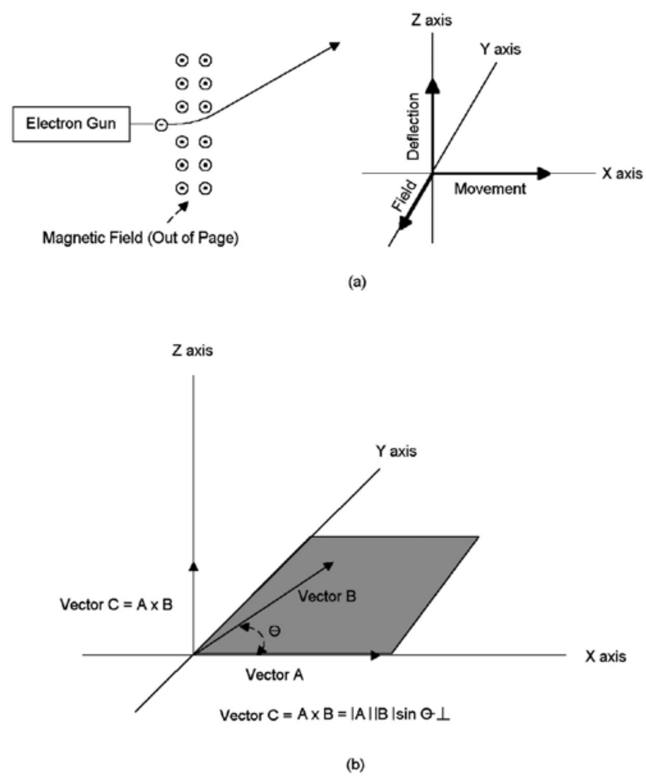


Figure 3: An electric charge moving through a magnetic field will "feel" a force perpendicular to the plane formed by the direction of the field and the direction of travel. This effect can be used to deflect an electron beam. (Note that the charge shown here is negative.) The force can be calculated using the cross product.

The determinant is used (expanded) as shown in Figure 4.

In what is known as "determinant form," the cross product of two vectors *A* and *B* can be expressed simply as:

$$A \times B = \begin{vmatrix} i & j & k \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$$

In our Chapter 2, we introduced Maxwell's Equations in their integral form:

$$\oiint D \cdot ds = Q$$

$$\oiint B \cdot ds = 0$$

$$\oint E \cdot dl = -\oiint \frac{\partial B}{\partial t} \cdot ds$$

$$\oint H \cdot dl = I_{cond} + \oiint \frac{\partial D}{\partial t} \cdot ds$$

Where:

D = Electric flux density = ε_0E

E = Electric field in Volts/meter

B = Magnetic flux density = μ_0H

H = Magnetic field in Amps/meter

ε_0 = Free space permittivity= 8.85 x 10^{-12}

μ_0 = Free space permeability= 4π x 10^{-7}

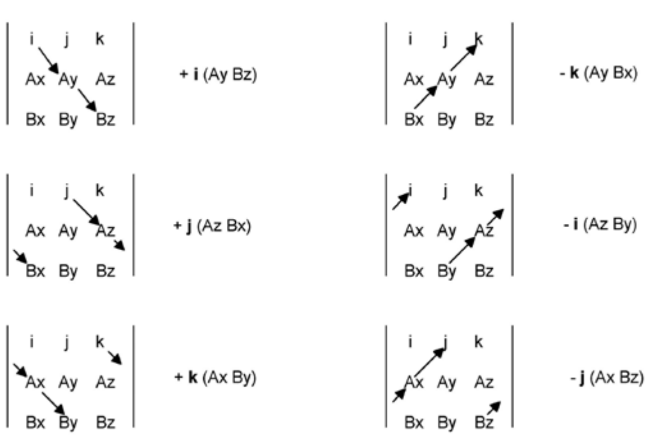


Figure 4: Calculation of a cross product is made easy through the use of a determinant. To "expand" the determinant, positive components are computed moving from the upper left to lower right. Then negative components are calculated by moving from the lower left to the upper right.

We also adapted Maxwell's Equations for the conditions of "free space." Operating in free space leaves us only with us only two equations to consider:

$$\oint E \cdot dl = -\mu_0 \oiint \frac{\partial H}{\partial t} \cdot ds$$

$$\oint H \cdot dl = \varepsilon_0 \oiint \frac{\partial E}{\partial t} \cdot ds$$

We did find one combination of electric and magnetic fields that satisfies these two equations. The combination consists of two sinusoidal fields set perpendicular to each other, forming what is known as a "plane wave." (Figure 5)

This plane wave consists of an electric field component in the form of:

$$E_z = -E_0 \sin(\omega t - kx)$$

and a magnetic field component in the form of:

$$H_y = H_0 \sin(\omega t - kx)$$

The plane wave is easy to visualize, but it is hardly a general solution for Maxwell's Equations. We'll make the solution more general by considering a composite magnetic field that itself is composed of two magnetic field components. These components are:

$$H_y = H_0 \cos(\omega t - kz)$$

$$H_z = H_0 \cos(\omega t - ky)$$

The first component, $H_y = H_0\cos(\omega t\text{-}kz)$ is a wave traveling in the z direction consisting of magnetic field vectors oriented in the y direction. The second component, $H_z = H_0\cos(\omega t\text{-}ky)$ is a wave consisting of field vectors oriented in the z direction and traveling in the y direction.

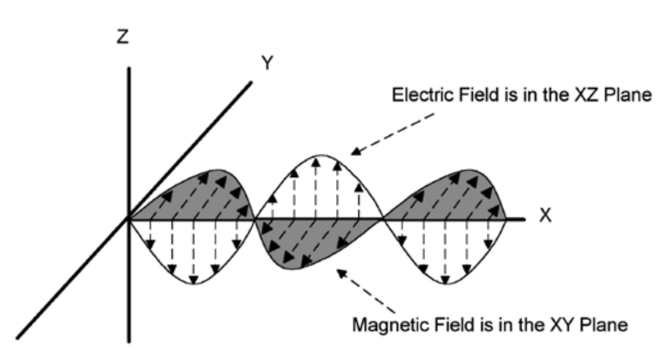


Figure 5: The plane wave

The equation we'll need to satisfy is:

$$\oint H \cdot dl = I_{cond} + \oiint \varepsilon_0 \frac{\partial E_x}{\partial t} \cdot ds$$

We'll assume that the derivative of the electric field with respect to time is uniform over the small rectangular surface shown in Figure 6. In that case, the right side of this equation can be simplified as follows:

$$I_{cond} + \oiint \varepsilon_0 \frac{\partial E_x}{\partial t} \cdot ds = I_{cond} + \varepsilon_0 \frac{\partial E_x}{\partial t} \Delta z \Delta y$$

We'll use the same technique we used before to solve for the line integral of the magnetic field. We'll solve for it pictorially by multiplying the length traveled around the perimeter of the small rectangle in Figure 6 by the field in the direction of travel.

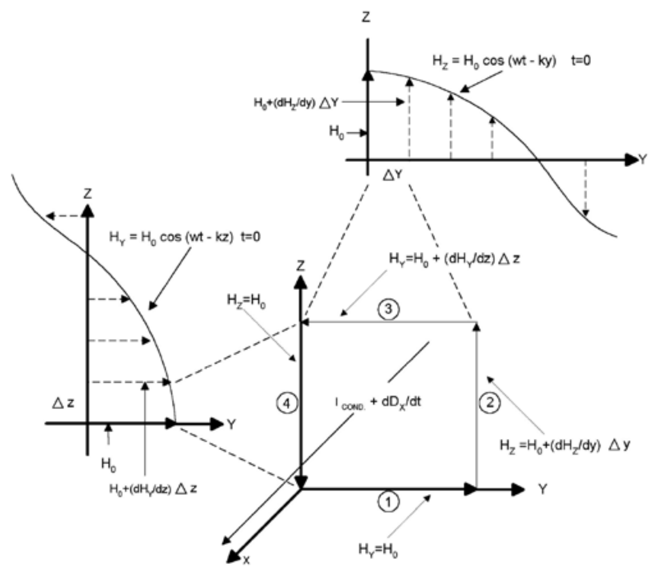


Figure 6: Two magnetic field waves are shown, one consisting of magnetic field vectors oriented in the z direction and traveling in the y direction, and the other consisting of vectors oriented in the y direction and traveling in the z direction. A small rectangular movement in the y-z plane can be used to compute a loop integral of the magnetic field. This must be equal to the current, plus the change in the electric flux density, passing through and normal to the loop.

H_0 is the magnetic field along Segments 1 and 4 of our perimeter. As for the magnetic fields along the other two segments, they are:

$$H_{Segment\ 2} = H_0 + \frac{\partial H_z}{\partial y}\Delta y$$

$$H_{Segment\ 3} = H_0 + \frac{\partial H_y}{\partial z}\Delta z$$

Remembering that we have to move counter clockwise to preserve the right hand rule, the line integral is:

$$\oint H \cdot dl = H_0 \ \Delta y + (H_0 + \frac{\partial H_z}{\partial y}\Delta y)\Delta z - (H_0 + \frac{\partial H_y}{\partial z}\Delta z)\Delta y - H_0 \ \Delta z$$
$$= (\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z})\Delta y \Delta z$$

Therefore the fourth of Maxwell's Equations for the fields illustrated in Figure 6 can be expressed as:

$$(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z})\Delta y \Delta z = I_{cond} + \varepsilon_0 \frac{\partial E_x}{\partial t}\Delta y \Delta z$$

$$(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}) = \frac{I_{cond}}{\Delta y \Delta z} + \varepsilon_0 \frac{\partial E_x}{\partial t}$$

We can also define the "current density" J as being equal to I/ΔyΔz, so:

$$(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}) = J_{cond} + \varepsilon_0 \frac{\partial E_x}{\partial t}$$

We could extend this analysis to situations involving magnetic fields, electric fields and currents in three dimensions, but the analysis will become ever more complex. Fortunately, there is a short cut. Things are made vastly easier because the line integral is, in fact, a cross product.

To see that, we'll start where we left off with vectors, with the determinant form of the cross product of two vectors *A* and *B*.

$$A \times B = \begin{vmatrix} i & j & k \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$$

Now for a bit of a trick. We substitute for Vector A in the determinant:

$$\frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k$$

and for Vector B:

$$H_x i + H_y j + H_z k$$

Our determinant becomes:

$$\begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{vmatrix}$$

Then we note that there is no current and no change in the electric field in the y or z directions. We also note that there is no magnetic field component in the x direction. Replacing these elements in our determinant with zeros yields the following:

$$\begin{vmatrix} i & 0 & 0 \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ 0 & H_y & H_z \end{vmatrix}$$

Expanding the determinant, we find:

$$\begin{vmatrix} i & 0 & 0 \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ 0 & H_y & H_z \end{vmatrix} = i\frac{\partial H_z}{\partial y} - i\frac{\partial H_y}{\partial z} = i(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z})$$

More generally, if we have components of magnetic fields, electric fields and currents in the three dimensions, Maxwell's fourth equation becomes:

$$\begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{vmatrix} =$$

$$i\frac{\partial H_z}{\partial y} + j\frac{\partial H_x}{\partial z} + k\frac{\partial H_y}{\partial x} - i\frac{\partial H_y}{\partial z} - j\frac{\partial H_z}{\partial x} - k\frac{\partial H_x}{\partial y} =$$

$$i\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}\right) + j\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\right) + k\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right)$$

So Therefore :

$$i\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}\right) + j\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\right) + k\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) = J_x + \frac{\partial D_x}{\partial t} + J_y + \frac{\partial D_y}{\partial t} + J_z\frac{\partial D_z}{\partial t}$$

Determinants may make a solution easier to obtain, but the solution obtained is still unwieldy. Here, mathematicians have come to the rescue. The have defined a vector operator known as the "del" which is equal to (∂/∂x)**i** + (∂/∂y)**j** + (∂/∂z)**k** and is drawn as an upside down triangle ∇. Using it, we can state an equivalent to the fourth of Maxwell's Equations by writing simply:

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

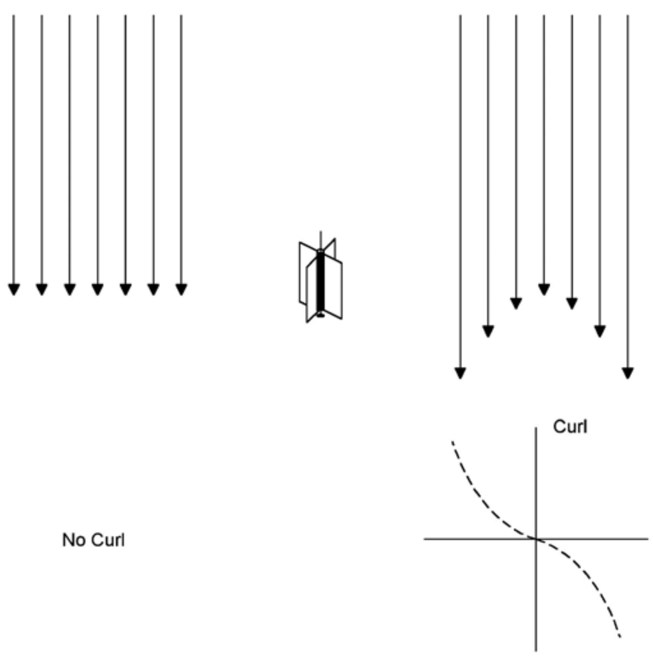


Figure 7: Curl is illustrated. A paddlewheel can be used to measure the curl of an air stream. The air stream at the left exhibits no curl, the paddlewheel will not turn when inserted into the stream. The stream at the right will cause the paddlewheel to turn, except when it is place in the dead center of the stream. (After Ref. 1.)

Similarly, it can be shown that:

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

The technical name for ∇ × E is the "curl" of the electric field. It has very real physical properties. An electric field circulating in a loop is linked to the changing magnetic flux through it. A gyroscope serves as a useful mechanical analog. The spinning ring of the gyroscope creates an angular momentum, which, through the conservation of angular momentum, keeps the ring spinning in the same plane. Angular momentum is describe by a vector perpendicular to the plane of the spinning ring. The two are linked, the spinning ring creates an angular momentum which, in turn, keeps the ring spinning in the same plane. Similarly, a circulating electric field creates a vector perpendicular to the plane of circulation equal to the change in electric flux through and normal to it. The two are inexorably linked. The same is true of the circulating magnetic field and its normal vector, the conduction and displacement currents.

Another mechanical analog is also useful. Figure 7 shows two air streams. The air stream at the left has a velocity uniform across its breadth. The one at the right has a velocity which peaks at the sides of the stream. We can use a paddlewheel as a tool to measure the curl. The air stream at the left exhibits no curl. Insert the paddlewheel into that air stream and it doesn't turn. Insert the paddlewheel into the air stream at the right and it will turn, except in the dead center. To either the left or right of dead center, the stream exhibits curl which causes a change in the angular momentum of the paddlewheel.

The first two of Maxwell's equations can also be expressed in their "differential" form. Again, we'll describe what is meant by these equations pictorially in order to then derive their differential expression. We'll begin with the first of Maxwell's equations:

$$\oiint D \cdot ds = Q$$

In Figure 8, we calculate the net flux into a small cube. We'll adapt the convention that flux into the cube is negative and out of it, positive. The flux into the cube from the left (positive x direction) is:

$$D_x \Delta y \Delta z$$

Likewise, the flux out of the cube in the x direction is:

$$\left(D_x + \frac{\partial D_x}{\partial x}\Delta x\right)\Delta y \Delta z$$

That makes the net flux in the x direction equal to:

$$(-D_x + D_x + \frac{\partial D_x}{\partial x}\Delta x)\Delta y \Delta z$$

Likewise, the flux contributions from the electric flux density in the y and z directions are:

$$(-D_y + D_y + \frac{\partial D_y}{\partial y}\Delta y)\Delta x \Delta z$$

$$(-D_z + D_z + \frac{\partial D_z}{\partial z}\Delta z)\Delta x \Delta y$$

That makes the total flux, the sum of the net flux along all three axes, equal to:

$$(\frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z})\Delta x \Delta y \Delta z = \oint\!\!\oint D \cdot ds = Q$$

Since ΔxΔyΔz = Δvolume, we can define charge per unit volume as the charge density, ρ. So,

$$(\frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z}) = \rho$$

Once again, we can use the del operator to convert the left side of this equation into a vector expression, in this case one utilizing the dot product:

$$(\frac{\partial}{\partial x}\mathrm{i} + \frac{\partial}{\partial y}\mathrm{j} + \frac{\partial}{\partial z}\mathrm{k}) \cdot (D_x\mathrm{i} + D_y\mathrm{j} + D_z\mathrm{k}) = (\frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z}) = \rho$$

or more simply:

$$\nabla \cdot D = \rho$$

Similarly, it can be shown that:

$$\nabla \cdot B = 0$$

The latter equation is known as the "divergence" of the magnetic flux density (B). It is the measure of the flux out of a small volume of space. In the case of electric fields, the divergence of the electric flux density is equal to the charge density at a given point in space. Divergence is a scalar value, not a vector. In the case of magnetic fields, the divergence of B is always zero.

We're now in a position to state Maxwell's equations in their differential form. Here they are:

$$\nabla \cdot D = \rho$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\frac{\partial B}{\partial t}$$
$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

■

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Glen Dash *is the author of numerous papers on electromagnetics. He was educated at MIT and was the founder of several companies dedicated to helping companies achieve regulatory compliance. Currently he operates the Glen Dash Foundation which uses ground penetrating radar to map archaeological sites, principally in Egypt.*

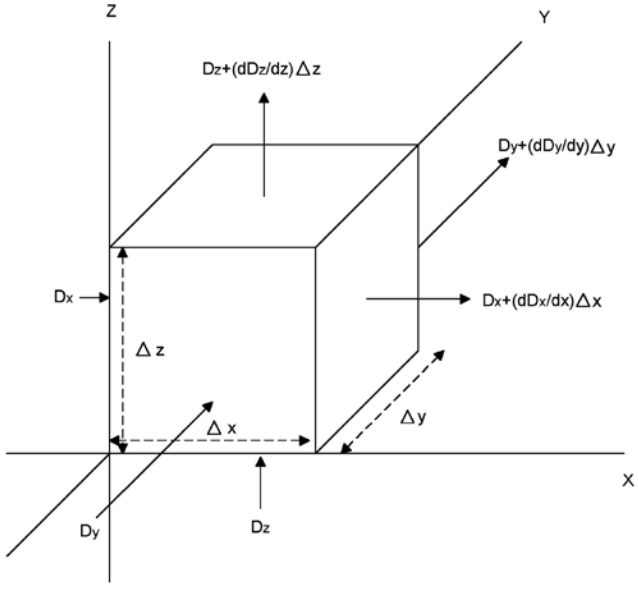

Figure 8: By measuring the net flux out of a small cube, "divergence" can be calculated.

A Dash of Maxwell's

A Maxwell's Equations Primer

Part 4: Equations Even a Computer Can Love

BY GLEN DASH

In the preceding chapters we have derived Maxwell's Equations and expressed them in their "integral" and "differential" form. In different ways, both forms lend themselves to a certain intuitive understanding of the nature of electromagnetic fields and waves. In this installment, we will express Maxwell's Equations in their "computational form," a form that allows our computers to do the work. To give you an idea where we are going, here are those equations:

$$E = -(\nabla V + \frac{\partial A}{\partial t}) \qquad (a)$$

$$B = \nabla \times A \qquad (b)$$

$$V = \frac{1}{4\pi\varepsilon} \sum_{n=0}^{n=N} \frac{\rho_n}{r_n} v_n \qquad (c)$$

$$A = \frac{\mu}{4\pi} \sum_{n=0}^{n=N} \frac{J_n}{r_n} l_n a_n \qquad (d)$$

Equation 1

E = Electric field in V/m

B = Magnetic flux density, B=μH

H = Magnetic field in Amps/m

V = Voltage

A = The "vector potential" (which we will explain shortly)

ρ_n = Charge density in Coulombs/m^3 of a particular charge element, n

r_n = Distance from a given charge or current element, n, to the location of interest

v_n = Volume of a particular charge element, n

l_n = Length of a particular current element, n

a_n = Area of a particular current element, n

J_n = Total current density (both conductive and displacement) in amps/m^2 of a particular current element, n

ε, μ = Permittivity and permeability respectively

We have added two elements we have not seen before: the *gradient of the voltage* (∇V)and the "*vector potential*" (A). We will explain these terms in a moment, but for now note the following:

1. If we know the current density (J) at every point within a volume of interest, we can calculate the "vector potential" (A) by simple summation (Equation 1(d)). By taking the curl of the vector potential (A), we can derive the magnetic flux density (B), and hence the magnetic field (H) (Equation 1 (b)).
2. If we know the charge density (ρ) at every point within a volume of interest, we can calculate the voltage at every point (Equation 1(c)). We can calculate the electric field (E) by taking the gradient of the voltage and adding the time derivative of the vector potential (Equation 1(a)).

Obviously, to use these equations we will need to understand what we mean by the "gradient of the voltage" and the "vector potential" (A). To do that, there is a bit of additional math to master.

In Part 3, we introduced two vector operations, the dot and cross product. The dot product of two vectors, R and S, computes the component of Vector R which is aligned with Vector S. The resultant is a scalar, not a vector. It is equal to:

$$R \cdot S = |R||S|\cos\theta$$

By contrast, the cross product of two vectors is a vector itself. The cross product is equal to:

$$T = R \times S = |R||S|\sin\theta \perp$$

As indicated by the symbol ⊥, the direction of the cross product Vector T is determined by the right hand rule. The fingers of the right hand point from Vector R to Vector S, and the direction of the cross product T is indicated by the thumb of the right hand.

To these two operations, we now add a third, the gradient. As with the common usage of the term, the gradient is a slope. A steep hill has a large gradient, a small one a lesser gradient. The gradient of a function is itself a vector, that is at any point within an area of interest it has both magnitude and direction. Mathematically, the gradient is equal to:

$$Gradient\ \phi = \frac{\partial\phi}{\partial x}\mathrm{i} + \frac{\partial\phi}{\partial y}\mathrm{j} + \frac{\partial\phi}{\partial z}\mathrm{k}$$

Where:

φ = A scalar function of x, y and z

i, j, k = Unit vectors in the x, y and z directions respectively

Gradients are only applicable to *scalar* functions. These are functions which have a magnitude at every point within an area of interest, but no direction. A mountain can be described as a scalar function with the height at any point in within an area of interest being expressed as:

$$H_t = f(x, y)$$

Where H_t equals the height of mountain in meters

If we want to know the slope of the mountain, we can mathematically compute it by taking the gradient.

$$Slope\ H_t = \frac{\partial Ht}{\partial x}\mathrm{i} + \frac{\partial Ht}{\partial y}\mathrm{j}$$

It is conventional to write the gradient operation using the "del" operator. We introduced the del operator in Part 3. It is equal to:

$$\nabla = \frac{\partial}{\partial x}\mathrm{i} + \frac{\partial}{\partial y}\mathrm{j} + \frac{\partial}{\partial z}\mathrm{k}$$

We can multiply the del operator by our scalar height function to derive its gradient:

$$Slope\ H_t = \nabla H_t = (\frac{\partial}{\partial x}\mathrm{i} + \frac{\partial}{\partial y}\mathrm{j} + \frac{\partial}{\partial z}\mathrm{k})(H_t) = \frac{\partial H_t}{\partial x}\mathrm{i} + \frac{\partial H_t}{\partial y}\mathrm{j} + \frac{\partial H_t}{\partial z}\mathrm{k}$$

$$and\ since\ \frac{\partial H_t}{\partial z} = 0$$

$$Slope\ H_t = \nabla H_t = (\frac{\partial}{\partial x}\mathrm{i} + \frac{\partial}{\partial y}\mathrm{j})(H_t) = \frac{\partial H_t}{\partial x}\mathrm{i} + \frac{\partial H_t}{\partial y}\mathrm{j}$$

Known what is meant by the dot product, cross product, and gradient, we are now in a position to introduce "vector identities." Vector identities are manipulations of the dot product, cross product, and gradient which can greatly speed up our mathematical analysis. For example, suppose we first take the cross product of two vectors R and S and then take the dot product of the resultant and Vector R. Mathematically, this would be expressed as:

$$T = R \cdot (R \times S)$$

A moment's reflection, however, will reveal that the result of this operation is always equal to zero. The cross product of vectors R and S is a vector, T, whose direction is in a plane perpendicular to both R and S. Therefore, the dot product of R with T must equal zero. So we have the first of our vector identities shown in Table 1. For any two vectors R and S:

$$R \cdot (R \times S) = 0$$

There are many more such vector identities that we could derive and which we will find useful. For example, both the dot product and the cross product are distributive. That is:

$$R \cdot (S + T) = (R \cdot S) + (R \cdot T)$$

$$R \times (S + T) = (R \times S) + (R \times T)$$

Further, multiplying a cross product of two vectors, R and S by -1 produces the same result as taking the cross product of R and -S:

$$-(R\times S)=(R\times(-S))$$

Table 1 lists more vector identities. For the proofs of these, see Reference 1.

Vector Identity	Vector Identity Number
$R\cdot(R\times S)=0$	1(a)
$R\cdot(S+T)=(R\cdot S)+(R\cdot T)$	1(b)
$R\times(S+T)=(R\times S)+(R\times T)$	1(c)
$-(R\times S)=(R\times -S)$	1(d)
$-(R\cdot S)=(R\cdot -S)$	1(e)

Table 1: Some Vector Identities

Vector Identity	Vector Identity Number
$\nabla\cdot(\nabla\times S)=0$	2(a)
$\nabla\cdot(S+T)=(\nabla\cdot S)+(\nabla\cdot T)$	2(b)
$\nabla\times(S+T)=(\nabla\times S)+(\nabla\times T)$	2(c)
$-(\nabla\times S)=(\nabla\times -S)$	2(d)
$-(\nabla\cdot S)=(\nabla\cdot -S)$	2(e)
$\nabla\times\nabla\phi=0$	2(f)
$\nabla\times(\nabla\times S)=\nabla(\nabla\cdot S)-\nabla^2 S$	2(g)
$\frac{\partial}{\partial t}(\nabla\times S)=\nabla\times\frac{\partial S}{\partial t}$	2(h)

Table 2: Some vector identities using the "del" operator (∇) are shown. S and T are vector functions or fields, while ϕ is a scalar function. Note that the gradient of a scalar is itself a vector function or field, so ∇ϕ can be substituted for S or T in any of the above.

As we described in Part 3, we can always substitute the del operator for one of the vectors in our identities. We will substitute the del operator for Vector R in Table 1 to produce Table 2, to which we will add a few more useful identities. Once again, for derivations of see Reference 1.

The first of the expressions making up the "computational" form of Maxwell's Equations, Equation 1(a), is used to derive the electric field at any point within a volume of interest. The electric field is a function of voltage. Voltage is a scalar function, like the height of a mountain. At any point within a volume of interest it has magnitude, but no direction. We can take its gradient to produce vectors which give us the "slope" of the voltage. If the vector potential A in Equation 1(a) is unchanging, then:

$$E=-\nabla V$$

This simply means that the electric field is equal to the gradient of the voltage when $\partial A/\partial t=0$. In one dimension:

$$E=-\frac{\Delta V}{\Delta x}$$

Where:

ΔV = Voltage between two points, V_1 and V_2

Δx = Distance in meters between points 1 and 2

Or, equivalently for small Δx:

$$E=-\frac{\partial V}{\partial x}$$

More generally in three dimensions:

$$E=-(\frac{\partial V}{\partial x}\mathrm{i}+\frac{\partial V}{\partial y}\mathrm{j}+\frac{\partial V}{\partial z}\mathrm{k})$$

What this says is that if we know the voltage at every point within a volume of interest and if A is unchanging, then we can derive the electric field.

To derive the voltage at any point within a volume of interest, it turns out that we only need to know where the electric charges are. This is illustrated in Figure 1. A number of charged spheres are shown suspended in space. Other than for these charged spheres, the space is empty. We will calculate the voltage at point P due to these charged spheres.

In the first part in this series, we calculated the work required to move a charge q from infinity to some point, such as point P in Figure 1. The work required is:

$$W = \sum_{n=0}^{n=n} \frac{q Q_n}{4\pi\varepsilon r_n}$$

Where:

W= Work in joules

q = The charge being moved in Coulombs

Q_n = Charge on sphere n in Coulombs

r_n = Distance in meters from sphere n to point P in Figure 1

The work per unit charge moved (W/q) is equal to the voltage V, and is in units of Joules per Coulomb. The voltage at P is therefore:

$$V = \frac{1}{4\pi\varepsilon} \sum_{n=0}^{n=N} \frac{Q_n}{r_n}$$

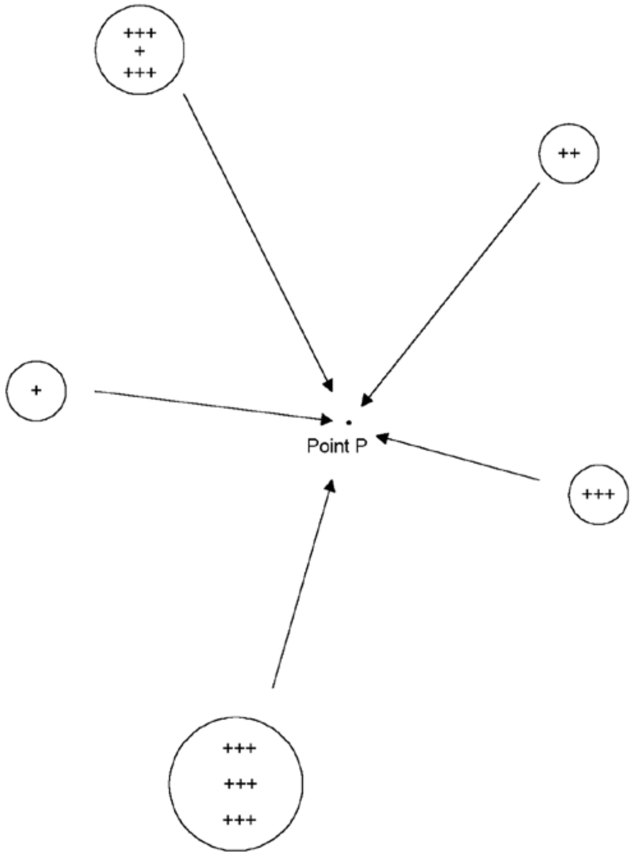

Figure 1: Where charges are static, the voltage at point P can be computed by summing the contributions of surrounding charges.

We will find it convenient to re-express this equation in terms of charge density ρ rather than the total charge on a given sphere, Q_n. Charge density is simply the total charge on each sphere divided by its volume, v. So:

$$\rho_n = \frac{Q_n}{v_n}$$

$$V = \frac{1}{4\pi\varepsilon} \sum_{n=0}^{n=N} \frac{\rho_n}{r_n} v_n$$

The vector potential A does not have the kind of readily measurable substance that an electric or magnetic field has. It is mostly just a mathematical tool. Mathematicians have *defined* the vector potential A as being a hypothetical field with the following characteristics:

$$\nabla \times A = B$$
$$\nabla \cdot A = 0$$

In words rather than symbols, the curl of the vector potential is, by definition, equal to the magnetic flux density, and the divergence of A is everywhere equal to zero.

Before we move on to explore the usage of the vector potential, A, we will need to take yet another math detour. We will use some of our vector identities to manipulate Maxwell's Equations.

We know that the differential form of the first of Maxwell's equations is:

$$\nabla \cdot D = \rho$$

Since D=εE and, from Equation 1(a) E = -∇V-∂A/∂t:

$$\nabla \cdot (-\nabla V - \frac{\partial A}{\partial t}) = \frac{\rho}{\varepsilon} \qquad \textit{(By Substitution and Multiplication)}$$

$$-\nabla \cdot (\nabla V + \frac{\partial A}{\partial t}) = \frac{\rho}{\varepsilon} \qquad \textit{(By Identity 2(e))}$$

$$\nabla \cdot (\nabla V + \frac{\partial A}{\partial t}) = -\frac{\rho}{\varepsilon} \qquad \textit{(By Multiplication)}$$

$$\nabla \cdot \nabla V + \frac{\partial}{\partial t}(\nabla \cdot A) = -\frac{\rho}{\varepsilon} \qquad \textit{(By Idenities 2b and 2h)}$$

$$\nabla \cdot A = 0 \qquad \textit{(By Definition)}$$

$$\nabla \cdot \nabla V = -\frac{\rho}{\varepsilon} \qquad \textit{(By Substitution)}$$

The last line is known as "Poisson's Equation" and is usually written as:

$$\nabla^2 V = -\frac{\rho}{\varepsilon}$$

Where:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

$$\nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}$$

In a region where there is no charge, ρ=0, so:

$$\nabla^2 V = 0$$

which is known as "Laplace's Equation." The operator ∇^2 is known as the "Laplacian."

From Maxwell's fourth equation expressed in differential form, we can, with some difficulty, state the vector potential in terms of currents using our vector identities.

$$\nabla \times H = J_{cond} + \frac{\partial D}{\partial t} \qquad \textit{(Maxwell's 4}^{th}\textit{ Equation in Diff. Form)}$$

$$J = J_{cond} + J_{displacement} \qquad \textit{(By Definition)}$$

$$J_{displacement} = \frac{\partial D}{\partial t} \qquad \textit{(By Definition)}$$

$$\nabla \times H = J \qquad \textit{(By Substitution)}$$

$$\nabla \times \mu H = \nabla \times B = \mu J \qquad \textit{(By Multiplication)}$$

$$\nabla \times (\nabla \times A) = \mu J \qquad \textit{(By Definition and Substitution)}$$

$$\nabla \times (\nabla \times A) = \nabla(\nabla \cdot A) - \nabla^2 A \qquad \textit{(From Vector Identity 2g)}$$

$$\nabla \cdot A = 0 \qquad \textit{(By Definition)}$$

$$\nabla \times (\nabla \times A) = -\nabla^2 A = \mu J \qquad \textit{(By Definition)}$$

$$\nabla^2 A = -\mu J$$

This derivation may seem daunting, but we have seen the form of the last line before. It is in the form of Poisson's Equation. Therefore, we know that the solution is going to be – it is in the form of the solution to Poisson's Equation. Poisson's Equation states:

$$\nabla^2 V = -\frac{\rho}{\varepsilon}$$

And we have already derived this expression for V.

$$V = \frac{1}{4\pi\varepsilon} \sum_{n=0}^{n=N} \frac{\rho_n}{r_n} v_n$$

So we can simply substitute the A for V and μJ for ρ/ε and we have the solution for the vector potential, A, in terms of the total current density, J:

$$A = \frac{\mu}{4\pi} \sum_{n=0}^{n=N} \frac{J_n}{r_n} v_n = \frac{\mu}{4\pi} \sum_{n=0}^{n=N} \frac{J_n}{r_n} l_n a_n$$

Where $v_n = l_n$ an (volume equals length times area).

We can also break both the vector potential A and the current density J into their Cartesian components:

$$Since\ J = J_x \mathrm{i} + J_y \mathrm{j} + J_z \mathrm{k}\ \ and\ \ A = A_x \mathrm{i} + A_y \mathrm{j} + A_z \mathrm{k}:$$

$$A_x = \frac{\mu}{4\pi}\sum_{n=0}^{n=N}\frac{(J_x)_n}{r_n}(l_x)_n(a_x)_n$$

$$A_y = \frac{\mu}{4\pi}\sum_{n=0}^{n=N}\frac{(J_y)_n}{r_n}(l_y)_n(a_y)_n$$

$$A_z = \frac{\mu}{4\pi}\sum_{n=0}^{n=N}\frac{(J_z)_n}{r_n}(l_z)_n(a_z)_n$$

This equation tells us that the vector potential is aligned with the currents that produce it. If we sum the currents flowing in the x direction as shown in the equation, we will be able to calculate the vector potential in the x direction at any particular point of interest. The same is true for the vector potential in the y and z directions. That means that the vector potential A, like the scalar potential V, can be derived by mere addition, multiplication and division, things a computer does handily.

The last piece of the puzzle requires relating the vector potential A to the electric field E. To do this we will use that time-honored tradition in mathematics, propose a solution and plug it into our equations to see if it works. The solution that we will propose which relates A to E is:

$$\frac{dA}{dt} = -(E + \Delta V)$$

We will test this solution by plugging it into the third of Maxwell's Equations:

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad \text{(By Maxwell's Third Equation)}$$

$$\nabla \times A = B \qquad \text{(By Definition)}$$

$$\nabla \times E = -\frac{\partial}{\partial t}(\nabla \times A) \qquad \text{(By Substitution)}$$

$$\nabla \times E = \nabla \times (-\frac{\partial A}{\partial t}) \qquad \text{(By Identity 2h)}$$

$$\nabla \times E - \nabla \times (-\frac{\partial A}{\partial t}) = 0 \qquad \text{(By Subtraction)}$$

$$(\nabla \times E) + (\nabla \times \frac{\partial A}{\partial t}) = 0 \qquad \text{(By Identity 2d)}$$

$$\nabla \times (E + \frac{\partial A}{\partial t}) = 0 \qquad \text{(By Identity 2c)}$$

$$\frac{\partial A}{\partial t} = -E - \nabla V \qquad \text{(Our Guessed - At Solution)}$$

$$\nabla \times (E - E - \nabla V) = 0 \qquad \text{(By Substitution)}$$

$$\nabla \times (-\nabla V) = 0 \qquad \text{(By Subtraction)}$$

$$-\nabla \times (\nabla V) = 0 \qquad \text{(By Identity 2d)}$$

$$\nabla \times (\nabla V) = 0 \qquad \text{(Which, by Identity 2f must be true, since V is a scalar function)}$$

Having verified the relationship between the vector potential A and the electric field E, we can now state Maxwell's Equations in their computational form, which, of course is where we started:

$$E = -\nabla V - \frac{\partial A}{\partial t} \qquad (a)$$

$$B = \nabla \times A \qquad (b)$$

$$V = \frac{1}{4\pi\varepsilon}\sum_{n=0}^{n=N}\frac{\rho_n}{r_n}v_n \qquad (c)$$

$$A = \frac{\mu}{4\pi}\sum_{n=0}^{n=N}\frac{J_n}{r_n}l_n a_n \qquad (d)$$

Before moving on, we should note one caveat. These equations assume that the effects of changing charges and currents are felt throughout the volume of interest instantaneously. That is, of course, not true, the effects propagate outward at a finite speed. In the next part of the series we will adapt these equations to deal with finite propagation speeds using the theory of "retarded currents." Then we will act as the computer and calculate by hand the near and far field radiation from a short length of wire. That short length of wire will, in turn, become our building block for the powerful Method of Moments which we will introduce in the chapters to come. ■

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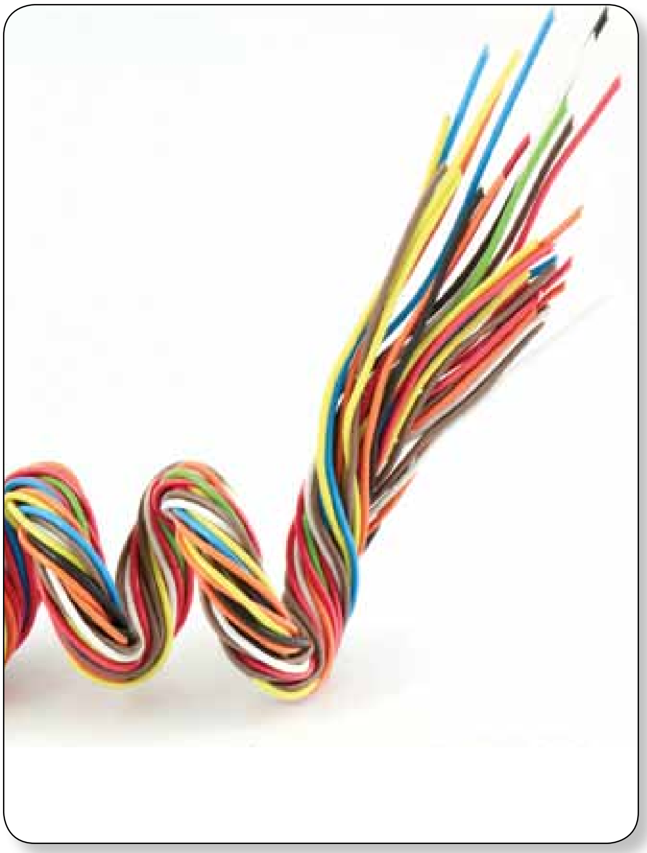
__Glen Dash__ is the author of numerous papers on electromagnetics. He was educated at MIT and was the founder of several companies dedicated to helping companies achieve regulatory compliance. Currently he operates the Glen Dash Foundation which uses ground penetrating radar to map archaeological sites, principally in Egypt.

A Dash of Maxwell's

A Maxwell's Equations Primer

Part 5: Radiation from a Small Wire Element

BY GLEN DASH



In Part 4, we derived our third form of Maxwell's Equations, which we called the computational form:

$$E = -(\nabla V + \frac{dA}{dt}) \qquad (a)$$

$$B = \nabla \times A \qquad (b)$$

$$V = \frac{1}{4\pi\varepsilon} \sum_{n=0}^{n=N} \frac{\rho_n}{r_n} v_n \qquad (c)$$

$$A = \frac{\mu}{4\pi} \sum_{n=0}^{n=N} \frac{J_n}{r_n} \ell_n a_n \qquad (d)$$

Where:

E = Electric field in V/m

B = Magnetic flux density, B=μH

H = Magnetic field in Amps/m

V = Voltage

A = Vector potential

ρ_n = Charge density in Coulombs/m^3 of a particular charge element, n

r_n = Distance from a given charge or current element, n, to the location of interest

v_n = Volume of a particular charge element, n

l_n = Length of a particular current element, n

a_n = Area of a particular current element, n

J_n = Total current density (both conductive and displacement) in amps/m^2 of a particular current element, n

ε, μ = Permittivity and permeability respectively

The magic of these equations lies in their suitability for computational use. To solve Maxwell's Equations for a given assemblage of wires and sources, all we need to know is the distribution of current and charge. Equations 1(c) and 1(d) allow us to compute the voltages and vector potential over a volume of interest. Equations 1(a) and 1(b) then allow us to compute the free space electric and magnetic fields at any point in that volume by simple summation.

It is time to put these equations to work by computing the radiation from a simple structure, a short wire element. We choose for our element the one shown in Figure 1. It is a short piece of wire with the following properties:

$$\ell << \lambda$$

$$d << \ell$$

$$I = I_0 \cos(\omega t) = \mathrm{Re}[I_0 e^{j\omega t}]$$

$$I,\ \textit{at any given instant, is constant along the length of the element}$$

Where:

l = length of wire in meters

ω = frequency in radians = 2πf

λ = wavelength in meters

d = diameter of wire in meters

I = current on the wire in amps

Note that this wire element has constant current along its entire finite length. Since the current has to go somewhere, two plates are provided, one at each end. They form a capacitor and serve as reservoirs of charge.

We will start our analysis by computing the vector potential A. A is always aligned with the currents that produce it. Since we only have currents in the z direction, A will only point in the z direction. A is simply:

$$A_z = \frac{\mu_0}{4\pi}\sum_{n=1}^{N}\frac{J_n}{r_n}a_n\ell$$

$$J_n a_n = I_n$$

$$n = N = 1$$

$$A_z = \frac{\mu_0 (I)(\ell)}{4\pi r}$$

Where:

J_n = current density on a wire element in amps/meter^2

a_n = area of wire element n in meter^2

I_n = current on a wire element in amps

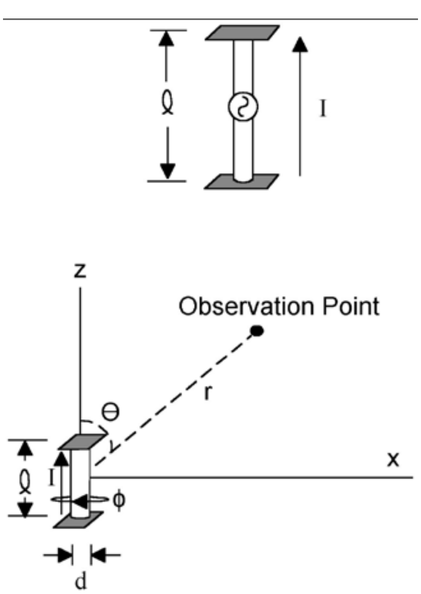


Figure 1: A small wire element carries a current I. Our task is to derive the magnetic and electric fields at any given observation point. The length of the wire element is l. We will be using two coordinate systems, Cartesian (x, y, z) and spherical (r, θ, ϕ).

However, these results are not complete. We have to account for the fact that the vector potential propagates as a wave through space. Since our hypothetical wire element is suspended in free space, this wave propagates away from the wire element with the speed of light, c. To account for this propagation, we adjust the solution in by adding a phase term:

$$I = I_0 \cos(\omega t - \omega\tau)$$

Where:

τ = Time to the observation point in seconds

ω = Frequency in radians per second

ωτ = Total phase change in radians

The term ωτ accounts for the fact that the vector potential at the observation point is a function of something that happened earlier, namely the current at the source at time t-τ . The time it takes for the field to propagate to the observation point is equal to the distance r divided by the speed of light: τ = r/c. Therefore:

$$I = \mathrm{Re}\left(I_0 e^{j(\omega t - \omega\tau)}\right)$$

$$\text{Noting that: } \tau = \frac{r}{c} \text{ and } \omega = 2\pi f, \quad \omega\tau = \frac{2\pi f r}{c}$$

$$\text{And since: } f\lambda = c \text{ and } \beta = \frac{2\pi}{\lambda}, \quad \omega\tau = \beta r$$

$$I = I^* = \mathrm{Re}[I_0 e^{j\omega t - \beta r}] = \mathrm{Re}[I_0 e^{j\omega t} e^{-j\beta r}]$$

$$A_z = \frac{\mu_0 I^* \ell}{4\pi r}$$

I* is known as the "retarded current." The use of retarded currents and retarded potentials are common in electromagnetics. As above, their purpose is to account for the finite propagation speed of electromagnetic waves as they move through space.

In the case of our wire element, the vector potential A is plotted in Figure 2.

From our solution for the vector potential A we can compute the magnetic flux density B using Equation 1(b). Note that the magnetic flux density, and hence the magnetic field, is a function only of A, and therefore only a function of the currents. Computing the curl is somewhat complex mathematically, but we can get an intuitive feel from Figure 3. As described in previous parts, we can use an imaginary paddlewheel-type device to test for the existence of curl in a field. At Point 1 in Figure 3, the vector potential to the right of the axis of the paddlewheel is greater than that to the left and in an opposing direction. This causes the paddlewheel to turn, demonstrating that there is curl at that point. The curl of a vector field is a vector in itself whose direction is determined by the right hand rule. The fingers of the right hand point in the direction of the paddlewheel spin and the thumb gives us the direction of the curl. The curl of the vector potential at Point 1, which is equal to the magnetic flux density, points toward the reader (outward from the page). At Point 2, the opposite is true. At Point 3, the paddlewheel does not spin. There is no curl at all.

With a little bit of imagination we can discern that:

1. There is no curl in the z direction.
2. The curl of the vector potential points only in the ϕ direction.
3. Even in the ϕ direction, there is no curl along the z axis.

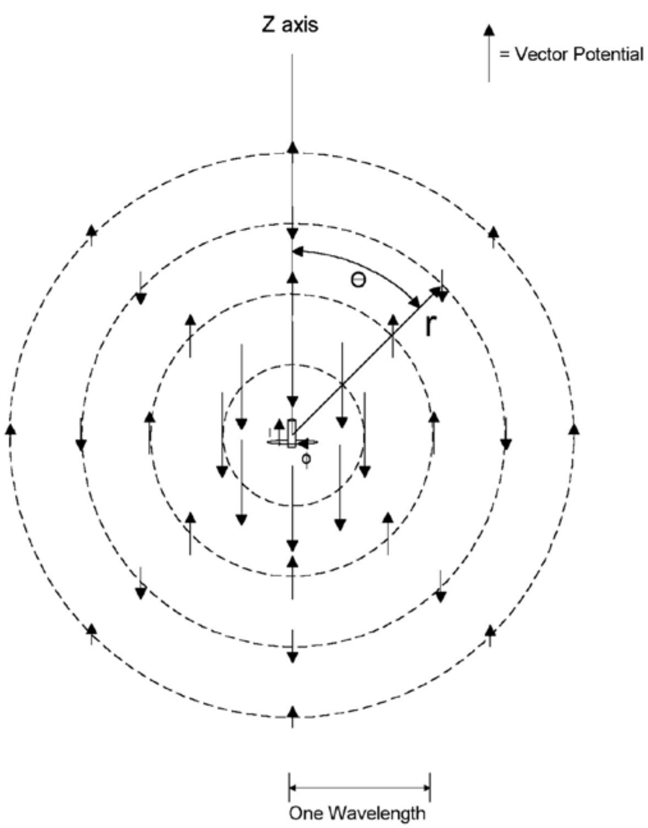


Figure 2: The vector potential A is plotted. The small current element creates a vector potential which falls off linearly with distance. It reverses in phase every half wavelength as it propagates outward.

Having calculated the vector potential and studied in at least an intuitive way the form of the magnetic field, our next step is to compute the scalar potential V. To do this, we need to know the distribution of the charge at any given point in time. The charge is related to the current on the wire by:

$$I = \frac{dq}{dt}$$

$$q = \int I dt + C$$

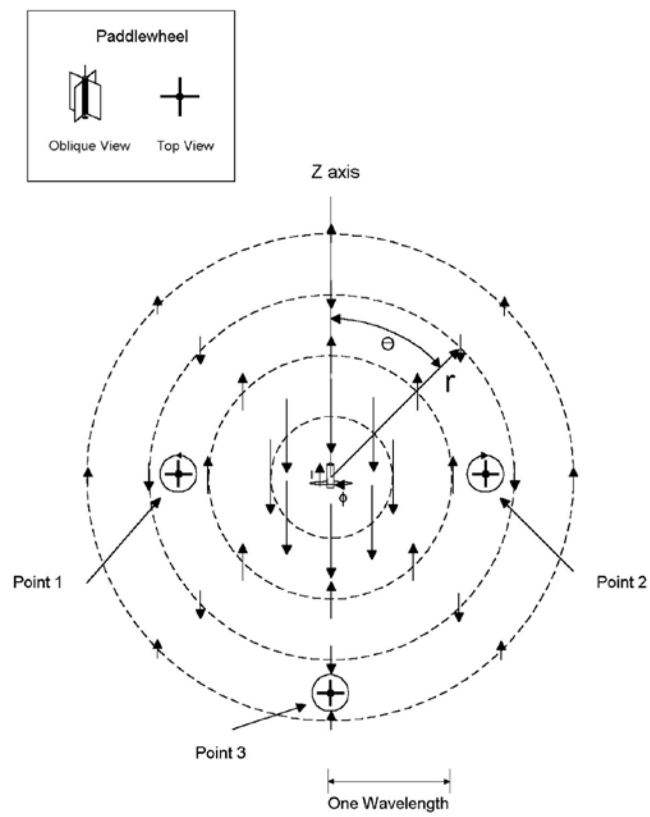


Figure 3: The vector potential A is used to calculate the magnetic flux density, B, and the magnetic field, H. The magnetic flux density is equal to the curl of the vector potential. We can get an intuitive feel for the magnitude and direction of the curl by using an imaginary paddlewheel, shown in the upper left hand corner. Inserted into the field, it will spin if the vectors on one side of the paddlewheel are different than on the other. At Point 1, there is curl in the counterclockwise direction and at Point 2, the clockwise direction. There is no curl at Point 3. The direction of the magnetic field is determined by the right hand rule. The fingers of the right hand point in the direction of the curl. Therefore, the magnetic field at Point 1 points outward and at Point 2, inward.

We can ignore the constant C (static charge) and compute q as follows:

$$I = \mathrm{Re}[I_0 e^{j\omega t}]$$

$$q = \int I dt = \mathrm{Re}[\frac{I_0}{j\omega} e^{j\omega t}]$$

$$q = \frac{I_0}{\omega} \sin(\omega t)$$

For brevity, in the analysis that follows we will assume that the last mathematical step is always to take the real part of the solution, and simply state that:

$$q = \frac{I_0}{j\omega} e^{j\omega t}$$

We assumed above that the current I was constant over the length of the wire, but we do not make the same assumption for the charge q. Rather, we assume just the opposite; that the charge q tends to be concentrated on the plates at the ends of the wire.

The voltage at an observation point can be computed knowing the distribution of charge (Equation 1(c). (Figure 4)

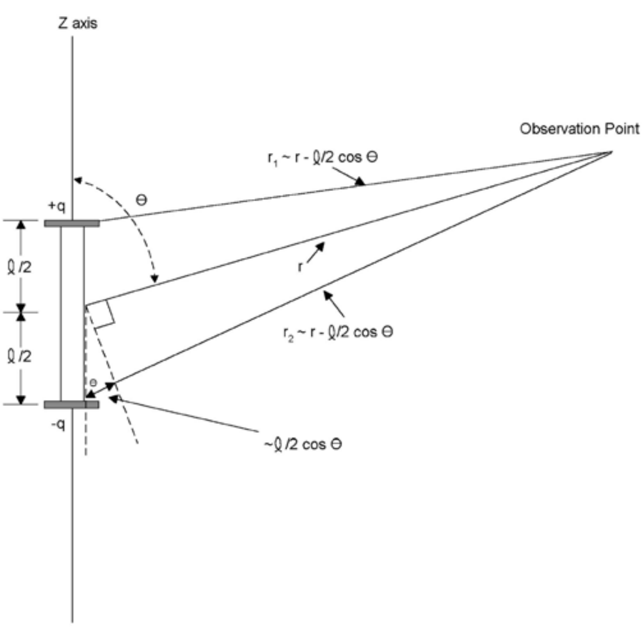


Figure 4: The small wire element is assumed to have its charge concentrated on the plates at its ends. The voltage at an observation point is calculated from the electric field. Some simplifying geometric assumptions are used.

$$V = \frac{1}{4\pi\varepsilon_0} \sum_{n=1}^{N} \frac{\rho_n}{r_n} v_n$$

$$\rho_n v_n = q_n$$

$$V = \frac{1}{4\pi\varepsilon_0} \left(\frac{q}{r_1} - \frac{q}{r_2} \right)$$

$$q = \frac{I_0}{jw} e^{j\omega t}$$

$$V = \frac{I_0 e^{j\omega t}}{j\omega 4\pi\varepsilon_0} \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

Once again, we will account for propagation time by using retarded currents.

$$V = \frac{I^*}{j\omega 4\pi\varepsilon_0} \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

By assuming that r >> l, l >>d, $r_1 = r - (l/2) \cos \theta$, $r_2 = r + (l/2) \cos \theta$ and $\lambda >> l$, we can show that this equation is equal to the following (see Appendix A for derivation):

$$V = \frac{I_0 \ell}{4\pi\varepsilon_0 c} e^{j(\omega t - \beta r)} \cos\theta \left(\frac{1}{r} + \frac{c}{j\omega r^2} \right)$$

We are almost ready to compute the magnetic and electric fields. However, we will find it convenient to use spherical coordinates instead of Cartesian coordinates. The transformation between coordinate systems is illustrated in Figure 5.

Expressing the vector potential in spherical coordinates we have:

$$A_z = \frac{\mu_0 I^* \ell}{4\pi r}$$

$$A_r = A_z \cos\theta$$

$$A_\theta = -A_z \sin\theta$$

$$A_\phi = 0$$

To find B, and hence the magnetic field $H = B/\mu_0$, we take the curl of A. In a previous part, we derived the curl operation in Cartesian coordinates. We will dispense with a similar derivation in spherical coordinates and just state the formula for curl in spherical coordinates here. Where, as in this case, $A_\phi = 0$, $\partial A_\theta/\partial_\phi = 0$ and $\partial A_r/\partial_\phi = 0$:

$$Curl\ of\ A\ in\ Spherical\ Coordinates = \nabla \times A = B_\phi = \frac{1}{r}\left(\frac{\partial(r A_\theta)}{\partial r} - \frac{\partial A_r}{\partial \theta}\right)$$

Solving for the term $\partial(rA_\theta)/\partial r$:

$$rA_\theta = -\frac{\mu_0 \ell}{4\pi} I_0\, e^{j\omega t} e^{-j\beta r} \sin\theta$$

$$\frac{\partial(r A_\theta)}{\partial r} = -\frac{\mu_0 \ell}{4\pi} I_0\, e^{j\omega t} \sin\theta \frac{\partial(e^{-j\beta r})}{\partial r} = j\beta \frac{\mu_0 \ell}{4\pi} I^* \sin\theta$$

Solving for the term $\partial A_r/\partial\theta$:

$$\frac{\partial A_r}{\partial \theta} = -\frac{\mu_0 \ell}{4\pi r} I^* \sin\theta$$

The curl of A is therefore:

$$\nabla \times A = B_\phi = \frac{1}{r}\left(j\beta \frac{\mu_0 \ell}{4\pi} I^* \sin\theta + \frac{\mu_0 \ell}{4\pi r} I^* \sin\theta \right)$$

$$B_\phi = \frac{\mu_0 \ell}{4\pi} I^* \sin\theta \left(\frac{j\beta}{r} + \frac{1}{r^2}\right)$$

$$H_\phi = \frac{\ell}{4\pi} I^* \sin\theta \left(\frac{j\beta}{r} + \frac{1}{r^2}\right)$$

That solves for the magnetic field. To find the electric field, we use Equation 1(a).

$$E = -\Delta V - \frac{dA}{dt}$$

As with the curl operation, we introduced the gradient operation in an earlier part and derived it in Cartesian coordinates. As above, we will dispense with the derivation here and just state the formula for the gradient in spherical coordinates. Where, as here, $\partial V/\partial\phi = 0$, the gradient of the voltage expressed in spherical coordinates is:

$$\Delta V = \Delta V_r + \Delta V_\theta$$

$$\Delta V_r = \frac{\partial V}{\partial r}$$

$$\Delta V_\theta = \frac{1}{r}\frac{\partial V}{\partial \theta}$$

Solving for the electric field in the r direction:

$$E_r = -\Delta V_r - \frac{dA_r}{dt}$$

$$\Delta V_r = \frac{\partial V}{\partial r}$$

$$\frac{\partial V}{\partial r} = \frac{\partial}{\partial r}\left(\frac{\ell}{4\pi\varepsilon_0 c} I_0 e^{j(\omega t - \beta r)} \cos\theta \left(\frac{1}{r} + \frac{c}{j\omega r^2}\right)\right)$$

In Appendix B we show that this is equal to:

$$\frac{\partial V}{\partial r} = -\frac{\ell}{4\pi\varepsilon_0 c} I^* \cos\theta \left(\frac{j\beta}{r} + \frac{2}{r^2} + \frac{2c}{j\omega r^3}\right)$$

Likewise:

$$\frac{dA_r}{dt} = \frac{d}{dt}\left(\frac{\mu_0 \ell}{4\pi r} I_0 e^{j(\omega t - \beta r)} \cos\theta\right) = \frac{j\omega\mu_0 \ell}{4\pi r} I^* \cos\theta = \frac{\mu_0 \ell}{4\pi}\frac{j\omega}{r} I^* \cos\theta$$

But we know that since $1/c^2 = \mu_0\varepsilon_0$:

$$\frac{\mu_0 \ell}{4\pi} = \frac{\mu_0 \ell \varepsilon_0}{4\pi\varepsilon_0} = \frac{\ell}{4\pi\varepsilon_0 c^2}$$

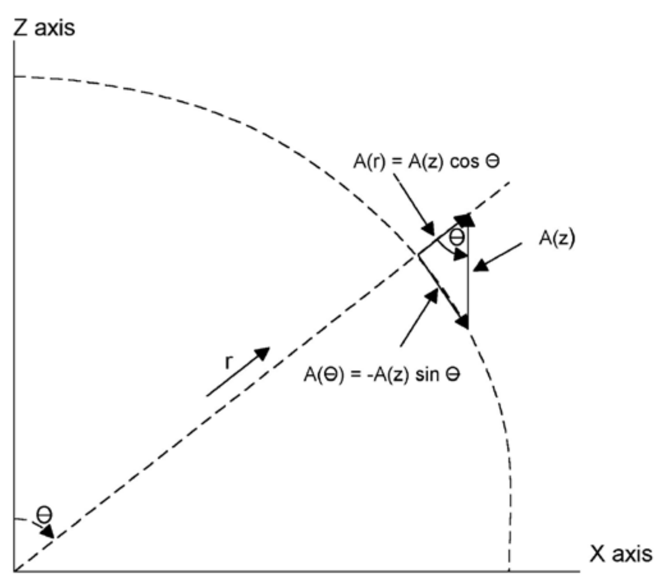


Figure 5: Conversion from Cartesian to spherical coordinates in the x, z plane is illustrated.

So:

$$\frac{d\,A_r}{dt} = \frac{\ell}{4\pi\varepsilon_0 c}\left(\frac{j\omega}{cr}\right) I^* \cos\theta = \frac{\ell}{4\pi\varepsilon_0 c}\left(\frac{j\beta}{r}\right) I^* \cos\theta$$

$$Since\ \frac{\omega}{c} = \frac{2\pi f}{f\lambda} = \frac{2\pi}{\lambda} = \beta$$

Therefore:

$$E_r = \frac{\ell}{4\pi\varepsilon_0 c} I^* \cos\theta\left(\frac{j\beta}{r} + \frac{2}{r^2} + \frac{2c}{j\omega r^3}\right) - \frac{\ell}{4\pi\varepsilon_0 c} I^* \cos\theta\left(\frac{j\beta}{r}\right)$$

$$= \frac{\ell}{2\pi\varepsilon_0} I^* \cos\theta\left(\frac{1}{cr^2} + \frac{1}{j\omega r^3}\right)$$

For E_θ:

$$E_\theta = -\Delta V_\theta - \frac{d\,A_\theta}{dt}$$

$$\Delta V_\theta = \frac{1}{r}\left(\frac{dV}{d\theta}\right)$$

$$\frac{dV}{d\theta} = \frac{d}{d\theta}\left(\frac{\ell}{4\pi\varepsilon_0 c} I^* \cos\theta\left(\frac{1}{r} + \frac{c}{j\omega r^2}\right)\right) = -\frac{\ell}{4\pi\varepsilon_0 c} I^* \sin\theta\left(\frac{1}{r} + \frac{c}{j\omega r^2}\right)$$

$$\frac{d\,A_\theta}{dt} = \frac{d}{dt}\left(-\frac{\mu_0 \ell}{4\pi r} I_0 e^{j\omega t} e^{-\beta r} \sin\theta\right) = -\frac{j\omega\mu_0 \ell}{4\pi r} I_0 e^{j\omega t} e^{-\beta r} \sin\theta = -\frac{j\omega \ell \mu_0 \varepsilon_0}{4\pi r\,\varepsilon_0} I^* \sin\theta$$

$$= -\frac{\ell}{4\pi\varepsilon_0} I^* \sin\theta\left(\frac{j\omega}{c^2 r}\right)$$

Therefore:

$$E_\theta = \frac{1}{r}\left[\frac{\ell}{4\pi\varepsilon_0 c} I^* \sin\theta\left(\frac{1}{r} + \frac{c}{j\omega r^2}\right)\right] + \frac{\ell}{4\pi\varepsilon_0} I^* \sin\theta\left(\frac{j\omega}{c^2 r}\right)$$

$$E_\theta = \frac{\ell}{4\pi\varepsilon_0} I^* \sin\theta\left(\frac{j\omega}{c^2 r} + \frac{1}{cr^2} + \frac{1}{j\omega r^3}\right)$$

We now can definitively state the solution to Maxwell's Equations for the short current element in Figure 1:

$$H_\phi = \frac{1}{4\pi} I^* \ell \sin\theta\left(\frac{j\omega}{cr} + \frac{1}{r^2}\right)$$

$$E_r = \frac{1}{2\pi\varepsilon_0} I^* \ell \cos\theta\left(\frac{1}{cr^2} + \frac{1}{j\omega r^3}\right)$$

$$E_\theta = \frac{1}{4\pi\varepsilon_0} I^* \ell \sin\theta\left(\frac{j\omega}{c^2 r} + \frac{1}{cr^2} + \frac{1}{j\omega r^3}\right)$$

These three equations may seem a jumble, but they can be dissected readily to reveal the underlying physics of radiation from a wire element. Take the expression for the magnetic field:

$H_\phi =$	$\left(\frac{1}{4\pi}\right)$	$(I^* \ell)$	$\sin\theta$	$\left(\frac{j\omega}{cr} +\right.$	$\left.\frac{1}{r^2}\right)$
	↑	↑	↑	↑	↑
	constant	*current moment (retarded)*	*radiation pattern*	*Far Field component*	*Near Field component*

Four fundamental elements make up the expression: a constant, a current element adjusted for propagation (that is, retarded), a pattern term, and two terms which denote the fall off of the field with distance. One of these terms is proportional to 1/r, the other to $1/r^2$. The first denotes the "far field" component of the magnetic field, and the latter the "near field" component. We define the far field as follows:

$$\frac{j\omega}{cr} >> \frac{1}{r^2}$$

$$r >> \frac{c}{\omega}$$

$$c = f\lambda \quad \omega = 2\pi f$$

$$r >> \frac{\lambda}{2\pi}$$

At a distance much greater than $\lambda/2\pi$ (far field), the magnetic field can be expressed as:

$$H_\phi = \frac{1}{4\pi}\left(I^* \ell\right)\sin\theta\left(\frac{j\omega}{cr}\right)$$

In the near field, where $r << \lambda/2\pi$:

$$H_\phi = \frac{1}{4\pi}\left(I^* \ell\right)\sin\theta\left(\frac{1}{r^2}\right)$$

The electric far field is defined using the same criteria as the magnetic far field, that is the far field is defined as existing where $r >> \lambda/2\pi$. Indeed, in the far field the radial electric field, E_r, can be ignored and the electric field considered equal to:

$$E_\theta = \frac{1}{4\pi\varepsilon_0} I^* \ell \sin\theta\left(\frac{j\omega}{c^2 r}\right)$$

In the near electric field:

$$E_r = \frac{1}{2\pi\varepsilon_0} I^* \ell \cos\theta \left(\frac{1}{j\omega r^3} \right)$$

$$E_\theta = \frac{1}{4\pi\varepsilon_0} I^* \ell \sin\theta \left(\frac{1}{j\omega r^3} \right)$$

Much of our interest will focus on the far fields. Once again, these are:

$$H_\phi = \frac{1}{4\pi} I^* \ell \sin\theta \left(\frac{j\omega}{cr} \right)$$

$$E_\theta = \frac{1}{4\pi\varepsilon_0} I^* \ell \sin\theta \left(\frac{j\omega}{c^2 r} \right)$$

Note the following:

1. The magnetic and electric fields are oriented 90 degrees from each other in space, and
2. The fields are in time phase.

We have seen this combination of magnetic and electric fields before. These equations describe a plane wave. The direction of movement is determined by the cross-product of the two fields:

$$P = E \times H$$

The vector P is known as the Poynting vector. The electric field E is in units of V/m, and the magnetic field H in A/m. Their product is in units of W/m^2, representing the energy per unit area being carried outward by the wave.

The ratio of two fields is in units of ohms and is equal to:

$$\frac{E}{H} = \frac{1}{\varepsilon_0 c} = \frac{\sqrt{\mu_0 \varepsilon_0}}{\varepsilon_0} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\ \Omega$$

The value 377 ohms is known as the free space impedance.

In the near field:

$$H_\phi = \frac{1}{4\pi} I^* \ell \sin\theta \left(\frac{1}{r^2}\right)$$

$$E_r = \frac{1}{2\pi\varepsilon_0} I^* \ell \cos\theta \left(\frac{1}{j\omega r^3}\right)$$

$$E_\theta = \frac{1}{4\pi\varepsilon_0} I^* \ell \sin\theta \left(\frac{1}{j\omega r^3}\right)$$

The near electric and magnetic fields are not in time phase. For example, at θ = 90 degrees,

$$H_\phi = \frac{1}{4\pi} I^* \ell \left(\frac{1}{r^2}\right)$$

$$E_\theta = \frac{1}{4\pi\varepsilon_0} I^* \ell \left(\frac{1}{j\omega r^3}\right)$$

$$Where \;\; I^* = I_0 e^{j\omega t} e^{-\beta r} \;\; and \;\; \beta = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$

First, we note that the propagation term $e^{-\beta r}$ can be ignored in the near field. Then, expanding $e^{j\omega t}$:

$$H_\phi = \frac{1}{4\pi} I^* \ell \left(\frac{1}{r^2}\right) = \frac{1}{4\pi} I_0 \ell e^{j\omega t}\left(\frac{1}{r^2}\right) = \frac{1}{4\pi} I_0 \ell (\cos\omega t + j\sin\omega t)\left(\frac{1}{r^2}\right)$$

$$E_\theta = \frac{1}{4\pi\varepsilon_0} I^* \ell \left(\frac{1}{j\omega r^3}\right) = \frac{1}{4\pi\varepsilon_0} I_0 \ell e^{j\omega t}\left(\frac{1}{j\omega r^3}\right) = \frac{1}{4\pi\varepsilon_0} I_0 \ell (\cos\omega t + j\sin\omega t)\left(\frac{1}{j\omega r^3}\right)$$

$$Re[H_\phi] = \frac{1}{4\pi} I_0 \ell \cos(\omega t)\left(\frac{1}{r^2}\right)$$

$$Re[E_\theta] = \frac{1}{4\pi\varepsilon_0} I_0 \ell \sin(\omega t)\left(\frac{1}{\omega r^3}\right)$$

The two fields are out of phase in time, just as V and I are out of phase in a reactive circuit. No power is dissipated into space through the action of the near fields. Energy is just temporarily stored in the magnetic and electric near fields just as energy is temporarily stored in the capacitors and inductors of a reactive circuit.

In our next part, we will apply our solutions for the short wire element to real world antennas such as half wave dipoles. From then on, things will get easier as we let our computers do most of the work. ■

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***Glen Dash** is the author of numerous papers on electromagnetics. He was educated at MIT and was the founder of several companies dedicated to helping companies achieve regulatory compliance. Currently he operates the Glen Dash Foundation which uses ground penetrating radar to map archaeological sites, principally in Egypt.*

APPENDIX A

We start with these formulas:

$$V = \frac{I^*}{4\pi\varepsilon_0}\left(\frac{q}{r_1} - \frac{q}{r_2}\right)$$

$$I^* = I_0 e^{j(\omega t - \beta r)}$$

We note that:

$$q = \frac{I_0 e^{j(\omega t - \beta r)}}{j\omega} = \frac{I^*}{j\omega}$$

By substitution:

$$V = \frac{1}{4\pi\varepsilon_0}\left(\frac{I_0 e^{j(\omega t - \beta r_1)}}{j\omega r_1} - \frac{I_0 e^{j(\omega t - \beta r_2)}}{j\omega r_2}\right)$$

From Figure 4 we note that where r >> l and λ >> r :

$$r_1 = r - \frac{\ell}{2}\cos\theta \;\; and \;\; r_2 = r + \frac{\ell}{2}\cos\theta$$

So the voltage is equal to:

$$V = \frac{1}{j4\pi\omega\varepsilon_0} I_0 e^{j(\omega t - \beta r)}\left(\frac{e^{j(\frac{\ell\beta}{2}\cos\theta)}}{r - \frac{\ell}{2}\cos\theta} - \frac{e^{-j(\frac{\ell\beta}{2}\cos\theta)}}{r + \frac{\ell}{2}\cos\theta}\right)$$

Let:

$$\frac{\ell\beta}{2}\cos\theta = \gamma$$

By substitution, and noting that r >> l, the last term is equal to:

$$\left(\frac{e^{j(\frac{\ell\beta}{2}\cos\theta)}}{(r-\frac{\ell}{2}\cos\theta)}-\frac{e^{-j(\frac{\ell\beta}{2}\cos\theta)}}{(r+\frac{\ell}{2}\cos\theta)}\right)=\left(\frac{e^{j\gamma}}{(r-\frac{\gamma}{\beta})}-\frac{e^{-j\gamma}}{(r+\frac{\gamma}{\beta})}\right)=\frac{re^{j\gamma}+\frac{\gamma}{\beta}e^{j\gamma}-re^{-j\gamma}+\frac{\gamma}{\beta}e^{-j\gamma}}{r^2-(\frac{\gamma}{\beta})^2}$$

$$=\frac{r(e^{j\gamma}-e^{-j\gamma})+\frac{\gamma}{\beta}(e^{j\gamma}+e^{-j\gamma})}{r^2-(\frac{\gamma}{\beta})^2}$$

We can further simplify this expression by noting that:

$$\frac{\gamma}{\beta}=\frac{\frac{\ell\beta}{2}\cos\theta}{\beta}=\frac{\ell}{2}\cos\theta$$

and since r >> l:

$$\frac{r(e^{j\gamma}-e^{-j\gamma})+\frac{\gamma}{\beta}(e^{j\gamma}+e^{-j\gamma})}{r^2-(\frac{\gamma}{\beta})^2}=\frac{2jr\sin\gamma+2\frac{\gamma}{\beta}\cos\gamma}{r^2}$$

However, since β = 2π/λ:

$$\gamma=\frac{\ell\beta}{2}\cos\theta=\frac{\ell\pi}{\lambda}\cos\theta$$

$$\textit{and since } \lambda>>\ell,\ \gamma<<1,\ \textit{so}:$$

$$\sin\gamma\approx\gamma$$

$$\cos\gamma\approx1$$

We can state that the voltage is approximately equal to:

$$V=\frac{1}{j4\pi\omega\varepsilon_0}I_0e^{j(\omega t-\beta r)}\left(\frac{2jr\gamma+2\frac{\gamma}{\beta}}{r^2}\right)=\frac{1}{j4\pi\omega\varepsilon_0}I_0e^{j(\omega t-\beta r)}\left(\frac{2jr(\frac{\ell\beta}{2}\cos\theta)+2(\frac{\ell}{2}\cos\theta)}{r^2}\right)$$

$$=\frac{1}{j4\pi\omega\varepsilon_0}I_0e^{j(\omega t-\beta r)}\left(\frac{jr\ell\beta\cos\theta+\ell\cos\theta}{r^2}\right)$$

$$=\frac{\beta}{4\pi\omega\varepsilon_0}I_0\ell e^{j(\omega t-\beta r)}\cos\theta\left(\frac{1}{r}+\frac{1}{j\beta r^2}\right)$$

$$\frac{\omega}{\beta}=c,\ so:$$

$$V=\frac{I_0\ell}{4\pi\varepsilon_0 c}e^{j(\omega t-\beta r)}\cos\theta\left(\frac{1}{r}+\frac{c}{j\omega r^2}\right)$$

APPENDIX B

We start with the expression for the radial electric field, E_r :

$$E_r=-\Delta V_r-\frac{\partial A_r}{\partial t}$$

$$\Delta V_r=\frac{\partial V}{\partial r}$$

$$\frac{\partial V}{\partial r}=\frac{\partial}{\partial r}\left(\frac{\ell}{4\pi\varepsilon_0 c}I_0e^{j(\omega t-\beta r)}\cos\theta\left(\frac{1}{r}+\frac{c}{j\omega r^2}\right)\right)$$

This partial derivative is equal to:

$$\frac{\partial V}{\partial r}=\frac{\ell}{4\pi\varepsilon_0 c}I_0e^{j\omega t}\cos\theta\frac{\partial}{\partial r}\left(\frac{e^{-j\beta r}}{r}+\frac{e^{-j\beta r}c}{j\omega r^2}\right)$$

We note that:

$$\frac{\partial}{\partial r}\left(\frac{e^{-j\beta r}}{r}\right)=-\frac{e^{-j\beta r}}{r^2}-\frac{j\beta e^{-j\beta r}}{r}$$

$$\frac{\partial}{\partial r}\left(\frac{e^{-j\beta r}c}{j\omega r^2}\right)=-\frac{2e^{-j\beta r}c}{j\omega r^3}-\frac{j\beta e^{-j\beta r}c}{j\omega r^2}=-\frac{2e^{-j\beta r}c}{j\omega r^3}-\frac{e^{-j\beta r}}{r^2}$$

$$\frac{\partial}{\partial r}\left(\frac{e^{-j\beta r}}{r}+\frac{e^{-j\beta r}c}{j\omega r^2}\right)=-\frac{e^{-j\beta r}}{r^2}-\frac{j\beta e^{-j\beta r}}{r}-\frac{2e^{-j\beta r}c}{j\omega r^3}-\frac{e^{-j\beta r}}{r^2}$$

$$=-e^{-j\beta r}\left(\frac{j\beta}{r}+\frac{2}{r^2}+\frac{2c}{j\omega r^3}\right)$$

Plugging this result in yields:

$$\frac{\partial V}{\partial r}=-\frac{\ell}{4\pi\varepsilon_0 c}I_0e^{j(\omega t-\beta r)}\cos\theta\left(\frac{j\beta}{r}+\frac{2}{r^2}+\frac{2c}{j\omega r^3}\right)$$

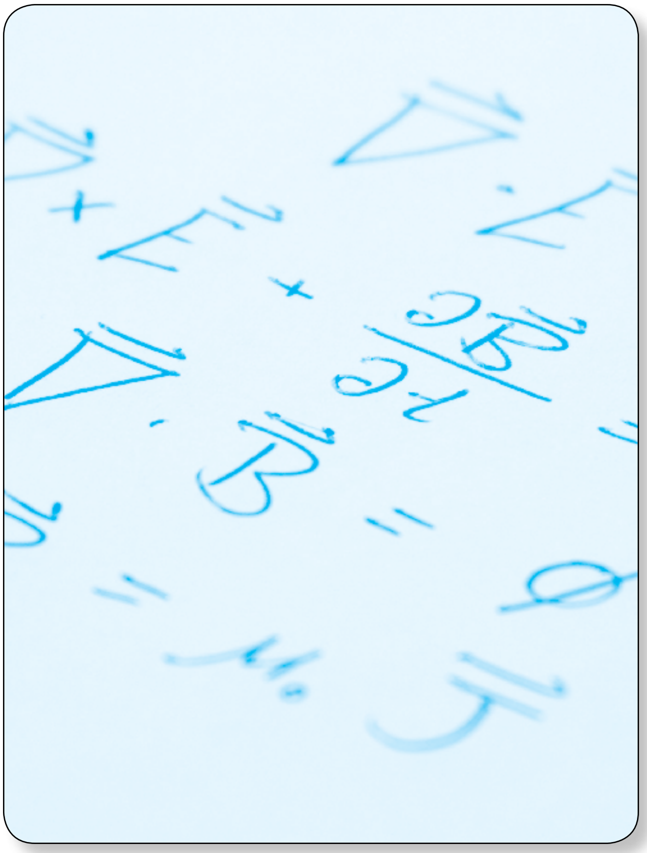
$$=-\frac{\ell}{4\pi\varepsilon_0 c}I^*\cos\theta\left(\frac{j\beta}{r}+\frac{2}{r^2}+\frac{2c}{j\omega r^3}\right)$$

A Dash of Maxwell's

A Maxwell's Equations Primer

Part 6: The Method of Moments

BY GLEN DASH



The Method of Moments has become one of the most powerful tools in the RF engineer's arsenal. In this chapter, we make the transition from theory to practice, first by attempting to compute the characteristics of a "short dipole" by hand, and then by demonstrating that a computer can do that in just a few seconds.

In our last article, we calculated the emissions from a "short current element" (Figure 1). The far field emissions were:

$$H_\phi = \frac{1}{4\pi} I^* \ell \sin\theta \left(\frac{j\omega}{cr}\right)$$

$$E_\theta = \frac{1}{4\pi\varepsilon_0} I^* \ell \sin\theta \left(\frac{j\omega}{c^2 r}\right)$$

Where:

H_φ = Magnetic field in the φ direction (A/m)

E_θ = Electric field in the θ direction (V/m)

I* = The "retarded current," $I^* = I_0\, e^{j(\omega t - \beta r)}$

r = Distance from the current element to our observation point in meters

l = Length of current element in meters

ω = Frequency in radians per second = $2\pi f$

c = Speed of light (m/s)

ε_0 = Permittivity of free space

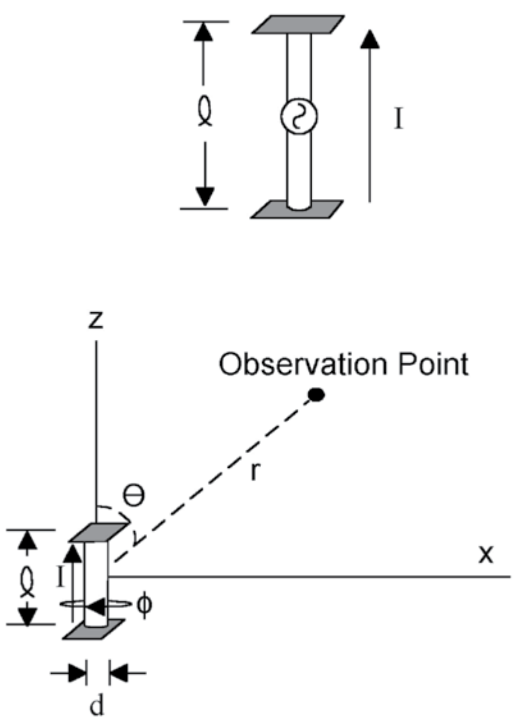


Figure 1: The starting point for our analysis is the short current element shown. It is a small, center driven antenna (small, that is, compared with the wavelength) loaded with plates at its ends. This produces a radiating element whose current distribution is relatively constant over its length.

The "short current element" differs from the "short dipole" in that the current element has constant current along its length. In contrast, the short dipole has no plates and consequently its current varies from a maximum at the center (where the drive is) to a minimum at its ends.

We will use the current element, however, to calculate the characteristics of the short dipole. To this end, we divide the short dipole into segments, each with constant current. By knowing the characteristics of the short current element we should be able to calculate the characteristics of the short dipole, or any antenna for that matter, from superposition.

To use the Method of Moments, we start with this now familiar equation:

$$E = -\Delta V - \frac{dA}{dt}$$

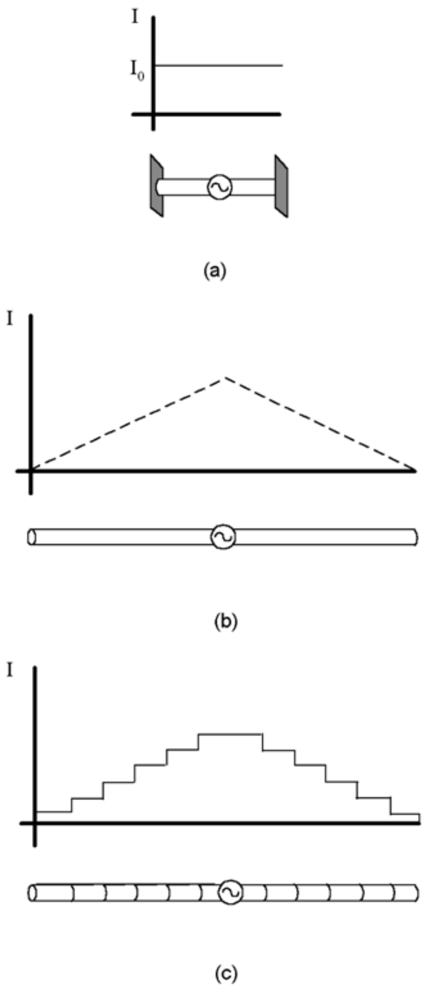


Figure 2: Our current element (a) has constant current along its length. For most antennas the current varies along the length (b). Nonetheless, almost any antenna can be approximated by one made up of constant current elements in a piece-wise linear fashion as shown in (c).

Where:

E = Electric field in V/m

V = Voltage

A = The vector potential

In our last chapter we calculated the vector potential produced by a short current element aligned with the z axis. It was:

$$A_z = \frac{\mu_0 I^* \ell}{4\pi r}$$

The vector potential is aligned with the currents that produce it, Since our current element only has currents flowing in the z direction, the vector potential is also aligned in the z direction.

Our first task is to calculate the electric field produced at a given point along the z axis, say observation point *m* in Figure 3. Due to the "skin effect," the current in the current element flows only in its outer skin. We will make the assumption that all the current in our current element is flowing in a filament placed a distance *a* from the z axis, *a* being the diameter of the current element (Figure 3).

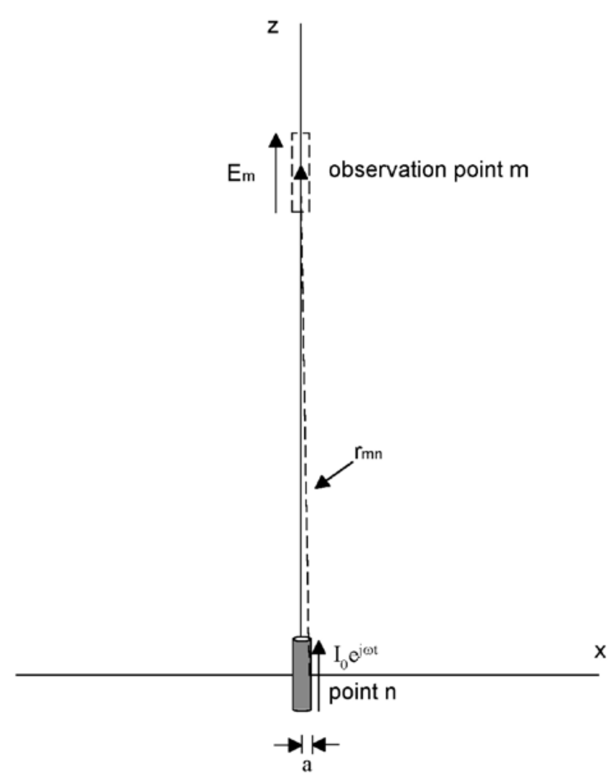


Figure 3: A current element at point n produces an electric field at observation point *m*. This field can be calculated using the vector potential.

At observation point *m*, the vector potential is:

$$A = \frac{\mu_0 I^* \ell}{4\pi\sqrt{\left((z_m - z_n)^2 + a^2\right)}}$$

Our next step is to relate the vector potential at observation point m to the electric field there. To do that, we need to explore once again what is meant by the vector potential.

The vector potential is a hypothetical construct, a mathematical tool. Because it is just a mental construct, we can define it any way we want. Fields can be defined by specifying their curl and their divergence. For the vector potential these are:

$$\nabla \times A = B$$
$$\nabla \cdot A = -j\omega\mu_0\varepsilon_0 V$$

Having defined the vector potential,[1] we can derive the electric field at observation point *m* as follows:

$$E_m = -\Delta V - \frac{dA}{dt}$$
$$\frac{dA}{dt} = j\omega A$$
$$\Delta V = \frac{\partial V}{\partial z}$$
$$\nabla \cdot A = \frac{\partial A}{\partial z} = -j\omega\mu_0\varepsilon_0 V$$
$$\frac{\partial^2 A}{\partial z^2} = -j\omega\mu_0\varepsilon_0\left(\frac{\partial V}{\partial z}\right)$$
$$\frac{\partial V}{\partial z} = -\frac{1}{j\omega\varepsilon_0\mu_0}\left(\frac{\partial^2 A}{\partial z^2}\right)$$
$$E_m = \frac{1}{j\omega\mu_0\varepsilon_0}\left(\frac{\partial^2 A}{\partial z^2}\right) - j\omega A$$
$$E_m = \frac{1}{j\omega\mu_0\varepsilon_0}\left(\frac{\partial^2 A}{\partial z^2} + \beta^2 A\right)$$

The vector potential *A* is, in turn, a function of the current *I*. Therefore it should be possible to state the electric field at observation point *m* in terms of the current at point *n*.[2] J. H. Richmond [4] has done that, calculating that it is equal to:

$$E_m = j\frac{377\lambda\left(\frac{\Delta z}{\lambda}\right)}{8\pi^2}\left(\frac{e^{-j2\pi\left(\frac{r}{\lambda}\right)}}{\left(\frac{r}{\lambda}\right)^3\lambda^3}\right)\left(\left(1 + j2\pi\left(\frac{r}{\lambda}\right)\right)\left(2 - 3\left(\frac{a}{r}\right)^2\right) + 4\pi^2\left(\frac{a}{\lambda}\right)^2\right)I(z_n)$$
$$E_m = X_{mn} I(z_n)$$
$$\text{Where: } X_{mn} = j\frac{377\left(\frac{\Delta z}{\lambda}\right)}{8\pi^2\lambda^2}\left(\frac{e^{-j2\pi\left(\frac{r}{\lambda}\right)}}{\left(\frac{r}{\lambda}\right)^3}\right)\left(\left(1 + j2\pi\left(\frac{r}{\lambda}\right)\right)\left(2 - 3\left(\frac{a}{r}\right)^2\right) + 4\pi^2\left(\frac{a}{\lambda}\right)^2\right)$$

This field develops a voltage at observation point m equal to:

$$V_m = E_m \Delta z$$

Since V_m is a function of $I(z_n)$, we can restate the voltage in terms of a "mutual impedance" Z_{mn}:

$$V_m = Z_{mn} I(z_n)$$
$$\text{Where: } Z_{mn} = j\frac{377\left(\frac{\Delta z}{\lambda}\right)^2}{8\pi^2\lambda}\left(\frac{e^{-j2\pi\left(\frac{r}{\lambda}\right)}}{\left(\frac{r}{\lambda}\right)^3}\right)\left(\left(1 + j2\pi\left(\frac{r}{\lambda}\right)\right)\left(2 - 3\left(\frac{a}{r}\right)^2\right) + 4\pi^2\left(\frac{a}{\lambda}\right)^2\right)$$

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[1] In a previous chapter we defined the divergence of the vector potential as being equal to zero. In that case, we were dealing with static fields, therefore ω=0.

[2] In a milestone in the study of electromagnetic theory, H. C. Pocklington [3] published in 1897 what became known as *Pocklington's Equation.* Each segment *n* along a wire aligned with the z axis contributes a vector potential element ∂ Az :

$$\partial A_z = \frac{\mu_0 I(z_n) e^{-j\beta r} dz}{4\pi r}$$

Each differential element ∂A_z creates a differential element ∂E_z at an observation point *m*:

$$\partial E_z = \frac{I(z_n)}{j4\pi\omega\varepsilon_0}\left(\frac{\partial^2}{\partial z^2}G_{mn} + \beta^2 G_{mn}\right)dz$$
$$\text{Where: } G_{mn} = \frac{e^{-j\beta r}}{r_{mn}} \text{ and } r_{mn} = \sqrt{\left((z_m - z_n)^2 + a^2\right)}$$
$$m = \text{observation point}$$
$$n = \text{source point}$$

G is known as *Green's function*.

To find the total electric field at an observation point *m*, ∂Ez is integrated:

$$E_z = \frac{1}{4\pi j\omega\varepsilon_0}\int_{-L/2}^{L/2}\left(\frac{\partial^2}{\partial z}G_{mn} + \beta^2 G_{mn}\right)I(z)dz$$

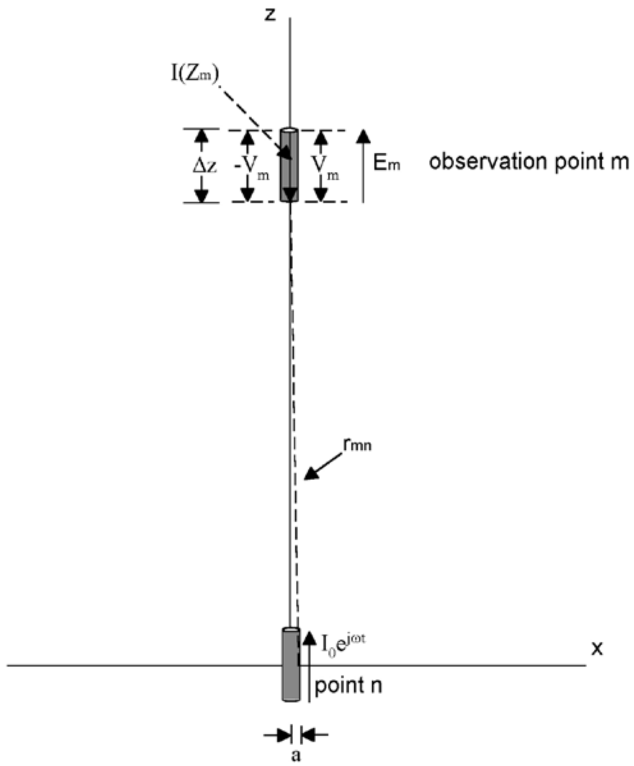

Figure 4: If we place a perfectly conductive wire at observation point m, it serves to "short out" the electric field produced by the current element at point n. This happens because the conductive wire produces its own field internally which offsets the electric field produced by the current element.

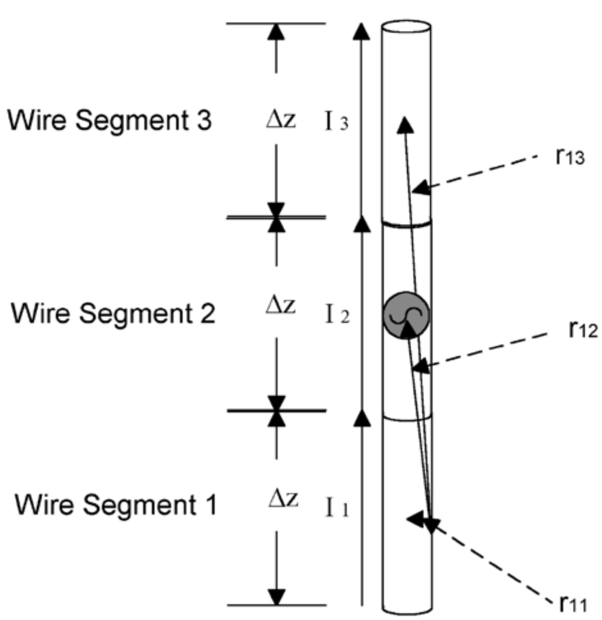

Figure 5: A small dipole is shown divided into three segments. Our first task in applying the Method of Moments is to calculate the self and mutual impedances of the segments.

Or alternatively,

$$Z_{mn} = j\frac{377(\Delta z_\lambda)^2}{8\pi^2\lambda}\left(\frac{e^{-j2\pi r_\lambda}}{r_\lambda{}^3}\right)\left[\left(1 + j2\pi(r_\lambda)\right)\left(2-3\left(\frac{a}{r}\right)^2\right)+4\pi^2(a_\lambda)^2\right]$$

$$\text{Where}: r_\lambda = \frac{r}{\lambda},\ \Delta z_\lambda = \frac{\Delta z}{\lambda} \text{ and } a_\lambda = \frac{a}{\lambda}$$

We now place a perfectly conducting metal wire of length Δz at observation point *m*. Being perfectly conducting, no voltage develops across it. This happens because the impressed field Em causes current to flow in the conductor. This in turn causes a voltage drop across the segment's self impedance, Z_{mm}. This voltage drop is just equal and opposite to the voltage caused by the impressed field E_m. Said another way:

$$V_{m(internal)} + V_{m(external)} = 0$$
$$V_{m(internal)} = I(z_m)Z_{mm}$$
$$V_{m(external)} = I(z_n)Z_{mn}$$
$$I(z_m)Z_{mm} + I(z_n)Z_{mn} = 0$$

Where:

$I(z_m)$ = The current in the wire segment at point *m*

$I(z_n)$ = The current in the segment at point *n*

Z_{mm} = The "self impedance" of the segment at point *m*

Z_{mn} = The mutual impedance between the segments at points *m* and *n*

Extending the analysis to an antenna with N segments, each contributing to the field at observation point *m*, we have:

$$I(z_1)Z_{m1} + I(z_2)Z_{m2} + I(z_3)Z_{m3} \cdots + I(z_N)Z_{mN} = \sum_{n=1}^{n=N} I(z_n)Z_{mn} = 0$$

We now consider the voltages on each one of the segments. Given N such segments, self and mutual impedances relate the current on each segment to the voltages on all others, forming a matrix:

$$I(z_1)Z_{11}+I(z_2)Z_{12}+I(z_3)Z_{13}+\cdots I(z_{1N})Z_{1N}=V_1$$
$$I(z_1)Z_{21}+I(z_2)Z_{22}+I(z_3)Z_{23}+\cdots I(z_{2N})Z_{2N}=V_2$$
$$I(z_1)Z_{31}+I(z_2)Z_{32}+I(z_3)Z_{33}+\cdots I(z_{3N})Z_{3N}=V_3$$
$$\vdots$$
$$I(z_1)Z_{N1}+I(z_2)Z_{N2}+I(z_3)Z_{N3}+\cdots I(z_{NN})Z_{NN}=V_N$$

This matrix makes the Method of Moments possible. Once the mutual impedances are calculated the matrix can be solved and the currents on each of the segments determined. Once the currents on each segment are known, the total fields, both electric and magnetic, can be calculated by superposition.

We will use the Method of Moments to analyze a short dipole modeled (somewhat crudely) as consisting of three co-linear wire segments (Figure 5). Each segment is .033λ. All 3 together are .1λ. The diameter *a* equals .001λ. A voltage source equal to 1 volt is set in the center of Segment 2. Using the above analysis, we can state:

$$I_1Z_{11}+I_2Z_{12}+I_3Z_{13}=0$$
$$I_1Z_{21}+I_2Z_{22}+I_3Z_{23}=V_0=1$$
$$I_1Z_{31}+I_2Z_{32}+I_3Z_{33}=0$$

Only segment 2 has a voltage associated with it. All the other segments, being perfectly conducting and without sources, have no voltage associated with them.

Noting that Z_{13} equals Z_{31}, we can calculate Z_{13} by plugging in these numbers: r~.066λ, a=.001λ, λ=1, and Δz = .033λ. The result is:

$$Z_{13}=j\frac{377(\Delta z_\lambda)^2}{8\pi^2\lambda}\left(\frac{e^{-j2\pi r_\lambda}}{r_\lambda{}^3}\right)\left((1+j2\pi(r_\lambda))\left(2-3\left(\frac{a_\lambda}{r_\lambda}\right)^2\right)+4\pi^2(a_\lambda)^2\right)$$

$$Z_{13}=j\frac{377\lambda^2(\Delta z_\lambda)^2}{8\pi^2\lambda}\left(\frac{\cos(2\pi r_\lambda)-j\sin(2\pi r_\lambda)}{r_\lambda{}^3}\right)\left((1+j2\pi(r_\lambda))\left(2-3\left(\frac{a_\lambda}{r_\lambda}\right)^2\right)+4\pi^2(a_\lambda)^2\right)$$

$$\Delta z_\lambda=.033 \quad r_\lambda=.066 \quad a_\lambda=.001 \quad \lambda=1$$

$$Z_{13}=j\frac{377(.033)^2}{8\pi^2}\left(\frac{\cos(2\pi(.066))-j\sin(2\pi(.066))}{(.066)^3}\right)\left((1+j2\pi(.066))\left(2-3\left(\frac{.001}{.066}\right)^2\right)+4\pi^2(.001)^2\right)$$

$$Z_{13}\approx .83+j39$$

Similarly, $Z_{12}=Z_{21}=Z_{23}=Z_{32}$ and, according to this formula, is equal to:

$$Z_{12}\approx 1.02+j296$$

For the "self impedances" $Z_{11}=Z_{22}=Z_33$ however, we run into a problem. The term r^3 combined with the relatively long segment length makes the solution unstable.

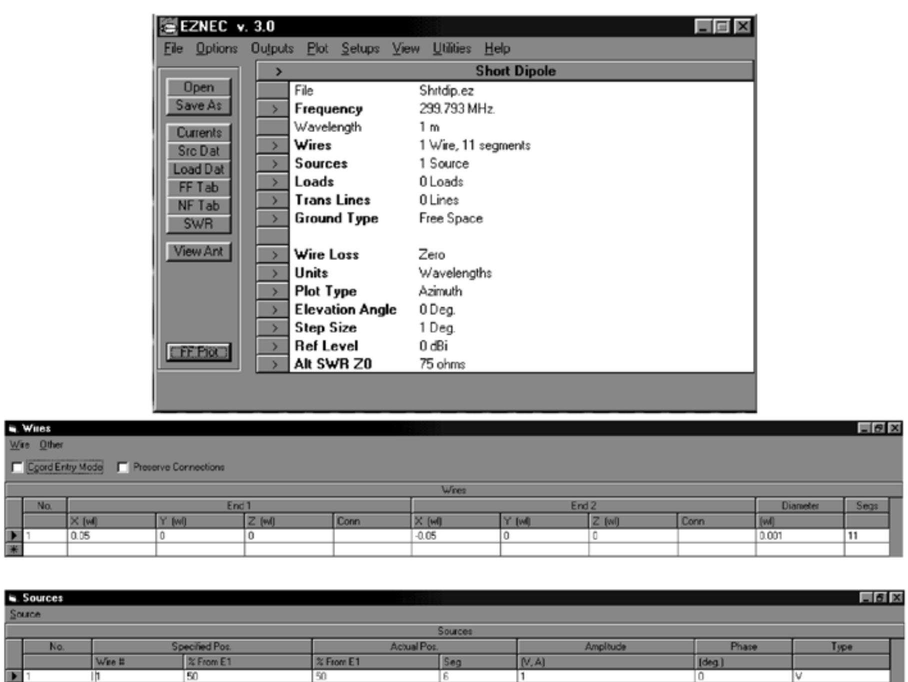

Figure 6: EZNEC opens with a screen that allows parameters such as the driving frequency, wire loss and type of ground to be entered. Separate dialogue boxes allow the antenna to be defined.

To deal with this, we could divide our short dipole into smaller segments. Choosing 11 segments for example, our matrix becomes:

$$I(z_1)Z_{11} + I(z_2)Z_{12} + I(z_3)Z_{13} + \cdots I(z_{1-11})Z_{1-11} = 0$$
$$I(z_1)Z_{21} + I(z_2)Z_{22} + I(z_3)Z_{23} + \cdots I(z_{2-11})Z_{2-11} = 0$$
$$I(z_1)Z_{31} + I(z_2)Z_{32} + I(z_3)Z_{33} + \cdots I(z_{3-11})Z_{3-11} = 0$$
$$\vdots$$
$$I(z_1)Z_{61} + I(z_2)Z_{62} + I(z_3)Z_{63} + \cdots I(z_{6-11})Z_{6-11} = 1$$
$$\vdots$$
$$I(z_1)Z_{11-1} + I(z_2)Z_{11-2} + I(z_3)Z_{11-3} + \cdots I(z_{11-11})Z_{11-11} = 0$$

But solving for all those variables will require a lot of computation, so it may be a good time to turn to our computers.

There are a number of very good computer programs that employ the Method of Moments.[3] We will use a program called EZNEC [2]. We input the same parameters as above, dividing our short dipole into 11 segments and setting λ equal to one meter. That is done by entering the data into the start screen (Figure 6). The frequency of 299.793 MHz is the equivalent of a one meter wavelength. We have chosen to place the wire in free space (the program has the option of simulating an antenna over earth). In the "Wires" dialogue box we enter the position of the one wire that makes up our short dipole, it starts at X=.05 meter, ends at X=-.05 meter and is .001 meter in diameter. Using the "Source" dialogue box, we place our 1 volt source in the middle of the wire.

A press of a button produces the results. The computer first computes the self and mutual impedances, then uses those impedances to solve for the currents on each of the segments. The magnitude and phase of these currents is tabulated in Figure 7. Once these are known, the fields can be computed by superposition.

The field pattern is plotted in Figure 7. Here, the "azimuth" field is displayed, which is the field in the X-Y plane. The pattern resembles a broad Figure eight, typical of a dipole, even a short one. A host of other parameters are calculated including the impedance seen by the one volt source (2.081 –j1397 ohms). The antenna has a very low radiation resistance (2.081 ohms) and "looks" capacitive to the source (-j1397 ohms).

[3] In the last two decades the Method has been refined repeatedly and algorithms have become increasingly complex. Among other things, the programs no longer make the simple assumption that the current along each segment is constant. The Numerical Electromagnetics Code (NEC) developed by Lawrence Livermore National Laboratory for example uses a combination of sinewaves and cosines on each segment. Nonetheless, reduced to their basics, the programs all do what we have attempted to do here: calculate mutual impedances, use matrix calculations to solve for the currents on each segment and calculate fields by superposition.

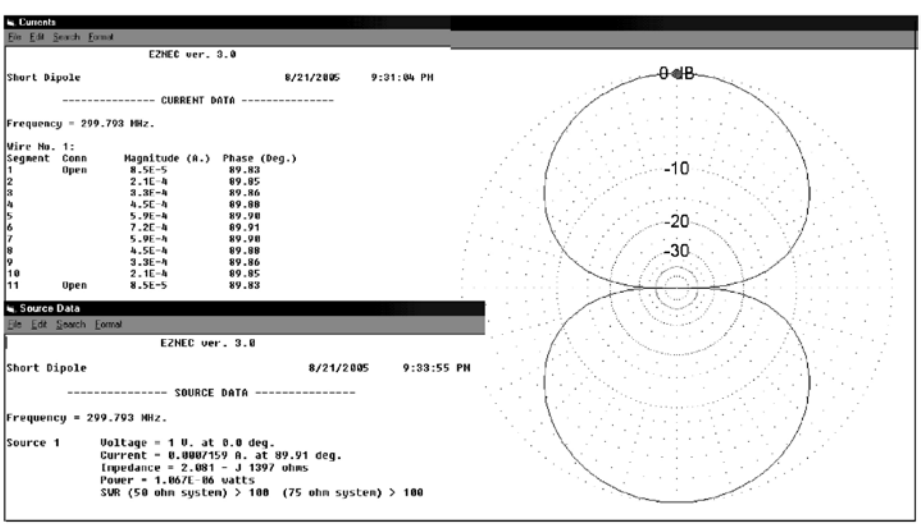

Figure 7: The output of EZNEC can provide the current on each segment, the fields generated, the pattern of the fields and such other parameters as the antenna's impedance as seen from the source.

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Glen Dash *is the author of numerous papers on electromagnetics. He was educated at MIT and was the founder of several companies dedicated to helping companies achieve regulatory compliance. Currently he operates the Glen Dash Foundation which uses ground penetrating radar to map archaeological sites, principally in Egypt.*

EPILOGUE

Morphing Maxwell's

In this series we hoped to provide the reader with a roadmap to get from the place where an engineer typically starts – with a knowledge of circuits and math -- to the Method of

Moments. A second aim was to help the engineer understand the technical papers written in the field. Such papers often start with some statement of Maxwell's Equations in one of its various forms -- integral, differential, etc. -- without much introduction. We hope that that missing introduction can now be found here.

But there are some forms of Maxwell's Equations that we did not touch on. So here, for good measure, are a few more:

We derived Maxwell's Equations in what we called their "computational" form:

$$E = -(\nabla V + \frac{\partial A}{\partial t})$$
$$B = \nabla \times A$$
$$V = \frac{1}{4\pi\varepsilon_0} \sum_{n=0}^{n=N} \frac{\rho_n}{r_n} v_n$$
$$A = \frac{\mu_0}{4\pi} \sum_{n=0}^{n=N} \frac{J_n}{r_n} l_n a_n$$

But the equations can also be stated in this form, which relates the electric and magnetic fields to the scalar potential (voltage) and vector potential (A):

$$E = -(\nabla V + \frac{\partial A}{\partial t})$$
$$B = \nabla \times A$$
$$V = \frac{1}{4\pi\varepsilon_0} \int_v \frac{\rho e^{-j\beta r}}{r} \partial v$$
$$A = \frac{\mu_0}{4\pi} \int_v \frac{J e^{-j\beta r}}{r} \partial v$$

We also discussed the definition of the vector potential, something that is made up and which we could have defined any way we wished. We chose to define it as:

$$\nabla \times A = B$$
$$\nabla \cdot A = -j\omega\mu_0\varepsilon_0 V$$

For the "static" case, ω=0, so;

$$\nabla \times A = B$$
$$\nabla \cdot A = 0$$

To derive an expression for the vector potential in term of currents, we used these equations:

$$\nabla^2 V = -\frac{\rho}{\varepsilon_0}$$
$$\nabla^2 A = -\mu_0 J$$

But these equations were for the static case. Where ω is not zero, these equations become:

$$\nabla^2 V + \mu_0\varepsilon_0\omega^2 V = -\frac{\rho}{\varepsilon_0}$$
$$\nabla^2 A + \mu_0\varepsilon_0\omega^2 A = -\mu_0 J$$

Finally, some technical papers will analyze phenomenon using what are known as Hertz vectors. The Hertz vector (Π) is defined as:

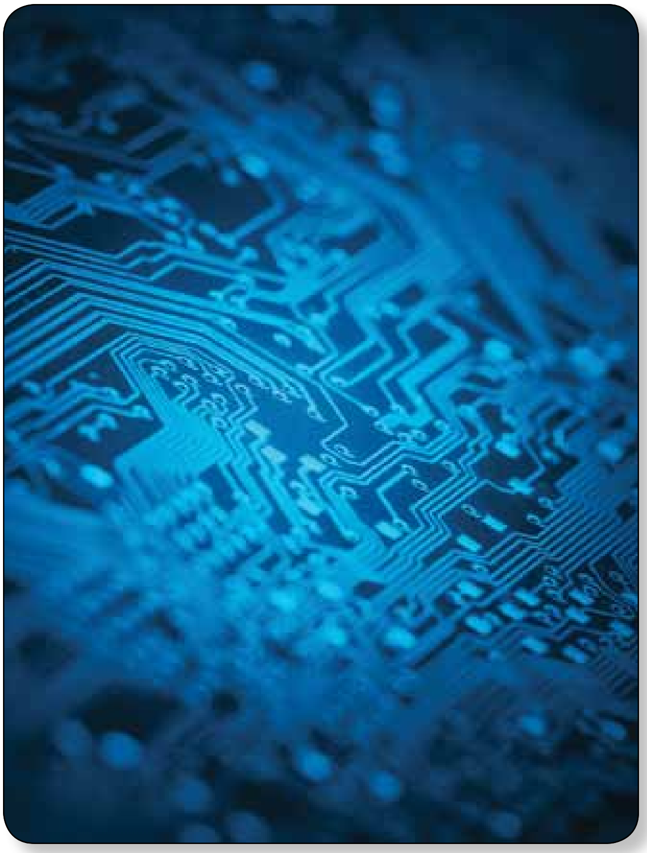
$$A = \mu_0\varepsilon_0 \frac{d\Pi}{dt}$$
$$\Pi = \Pi_0 e^{j\omega t}$$
$$A = j\omega\mu_0\varepsilon_0\Pi$$

Therefore any expression in terms of *A* can also be expressed in terms of the Hertz vector Π.

EMC

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.

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:

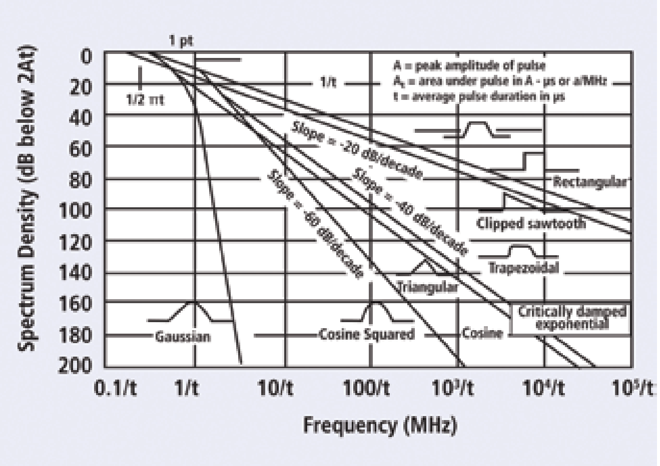


Figure 1: This chart compares the EMI characteristics of analog, low speed digital, and high speed digital logic.

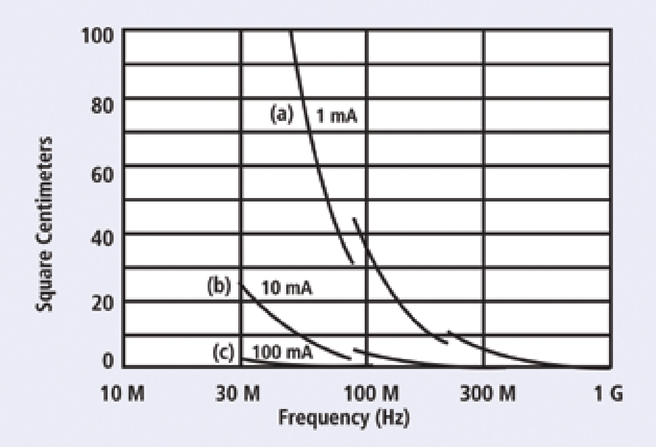


Figure 2: This chart correlates maximum loop area in square centimeters and the FCC Part 15B(B) limit for radiated RF at 1 mA (a), 10 mA (b), and 100 mA (c) of current. The measurement distance is 3 meters.

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

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.

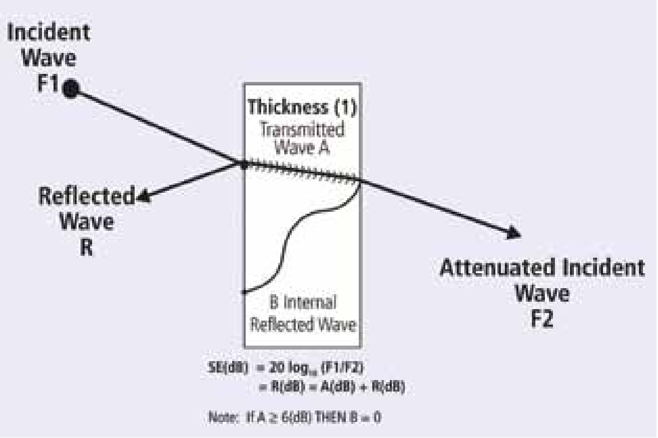


Figure 3: Graphical representation of shielding

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.

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

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

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

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

APERTURES

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

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

Where:

λ = Wavelength

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

L = Longest dimension of the aperture

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

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

RF GASKETS

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

Below is a comprehensive list of selection factors.

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

Metal RF Gaskets (Fingerstock) and Spring Contacts

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

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

Wire Mesh and Knitted Gaskets

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

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

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

Oriented Wire

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

Fabric-over-Foam (FoF)

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

Electrically Conductive Elastomers

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

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

Form-in-Place (FiP)

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

Board-Level Shielding (BLS)

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

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

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

Combination Shielding Products

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

CONCLUSION

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

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

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

REFERENCES

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

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

All Ferrite Beads

Are Not Created Equal

BY CHRIS BURKET

A common scenario: A design engineer inserts a ferrite bead into a circuit experiencing EMC problems, only to find that the bead has actually caused the unwanted to noise to be WORSE. How can this be? Aren't ferrite beads supposed to remove noise energy and not make the problem worse?

The answer to this question is fairly simple, but may not be widely understood outside of those who work a majority of their time solving EMI issues. Simply put, a ferrite bead is not a ferrite bead is not a ferrite bead, etc. Most ferrite bead manufacturers provide a table which lists their part number, the impedance at some given frequency (usually 100 MHz), the DC resistance (DCR), a maximum current rating and some dimensional information (see Table 1). All pretty much standard stuff. What is not shown in the data table is material information and the respective performance characteristics over frequency.

WHAT IS A FERRITE BEAD?

A ferrite bead is a passive device that removes noise energy from a circuit in the form of heat. The bead creates impedance over a broad frequency range that eliminates all or part of the undesired noise energy over that frequency range. For DC voltage applications (such as Vcc lines for ICs), it is desirable to have a low DC resistance value as to not have large power losses within the desired signal and/or voltage or current source (I^2 x DCR losses). However, it is desirable to have high impedance over some defined frequency range. Therefore, the impedance is related to the material used (permeability), the size of the ferrite bead, the number of windings and the winding construction. Obviously, the more windings within a given case size and for a specific material used, the higher the impedance, but this will also yield higher DC resistance as the physical length of the inner coil is longer. The part's rated current is inversely proportional to its DC resistance.

One of the fundamental aspects of using ferrite beads for EMI applications is that the component must be in its resistive stage. What does this mean? Simply, it means that "R" (AC resistance) must be greater than "X_L" (inductive reactance). At frequencies where $X_L > R$ (lower frequencies), the part behaves more as an inductor than a resistor. At frequencies where $R > X_L$, the part behaves as a resistor

Electrical Characteristics

Part No.	Impedance (Ω)[100MHz][*1]	DC resistance (Ω)max.	Rated current[*2] (A)max.	Thickness T(mm)
MPZ1608S300A	30±10Ω	0.01	5	0.6
MPZ1608S600A	60±25%	0.02	3.5	0.6
MPZ1608S101A	100±25%	0.03	3	0.6
MPZ1608S221A	220±25%	0.05	2.2	0.8
MPZ1608R391A	390±25%	0.12	1.2	0.8
MPZ1608S471A	470±25%	0.15	1	0.8
MPZ1608S601A	600±25%	0.15	1	0.8
MPZ1608Y600B	60±25%	0.03	2.3	0.8
MPZ1608Y101B	100±25%	0.04	2	0.8
MPZ1608Y151B	150±25%	0.05	1.8	0.8
MPZ1608D300B	30±10Ω	0.06	1.8	0.8
MPZ1608D600B	60±25%	0.1	1.2	0.8
MPZ1608D101B	100±25%	0.15	1	0.8

Table 1: Typical Ferrite Bead Data Table

which is the desired property of the ferrite bead. The frequency, at which "R" becomes greater than "X_L," is called the "cross-over" frequency. This is shown in Figure 1 with the cross-over frequency marked, 30 MHz in this example, by the red arrow.

Another way to look at this is in terms of what the part is actually doing while in its inductive and resistive stages. Like other applications where there is an impedance mismatch with inductors, part of the introduced signal is reflected back to the source. This can provide some protection for sensitive devices on the other side of the ferrite bead, but also introduces an "L" into the circuitry and this can cause resonances and oscillations (ringing). So when the bead is still inductive in nature, part of the noise energy will be reflected and some percentage will pass through, depending on the inductance and impedance values.

When the ferrite bead is in its resistive stage, the component behaves, as stated, like a resistor and therefore impedes the noise energy and absorbs this energy from the circuit and does so in the form of heat. Though constructed in an identical manner as some inductors, using the same processes, manufacturing lines and techniques, machinery and some of the same component materials, the ferrite bead uses a lossy ferrite material while an inductor utilizes a lower loss ferrite material. This is shown in curves of Figure 2. This Figure shows [μ''] which is used to reflect the behavior of the lossy ferrite bead material.

DIFFERENCES IN FERRITE MATERIALS

The fact that impedances are given at 100 MHz is also part of the selection problem. In many EMI cases, the impedance at this frequency is irrelevant and misleading. This "spot" value does not state if the impedance is increasing at this frequency, decreasing, flat, peaked in impedance, whether the material is still in its inductive stage or has transformed into its resistive stage. In fact, many ferrite bead suppliers use multiple materials for the same perceived ferrite beads, or at least as shown in the data table. See Figure 3. All five curves in this Figure are for different 120 Ohm ferrite beads.

What the user must obtain, then, is the impedance curve that shows the frequency characteristics of the ferrite bead. An example of a typical impedance curve is shown in Figure 4.

Figure 4 shows a very important fact. The part is specified as a 50 Ohm ferrite bead, at 100 MHz, but its cross-over frequency is roughly 500 MHz, and it achieves over 300 Ohms between 1 and 2.5 GHz. Again, by simply looking at the data table would not allow the user to know this and can be very misleading.

EMC

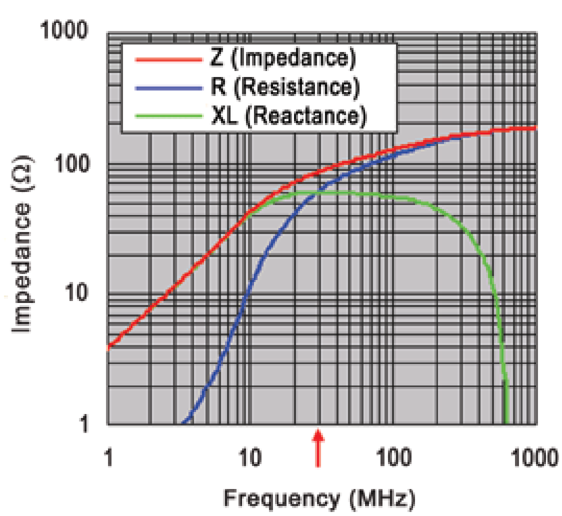


Figure 1: Cross Over Frequency

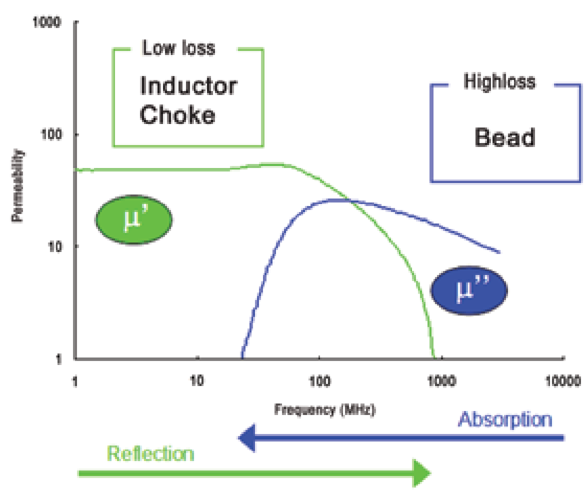


Figure 2: Reflection vs. Absorption

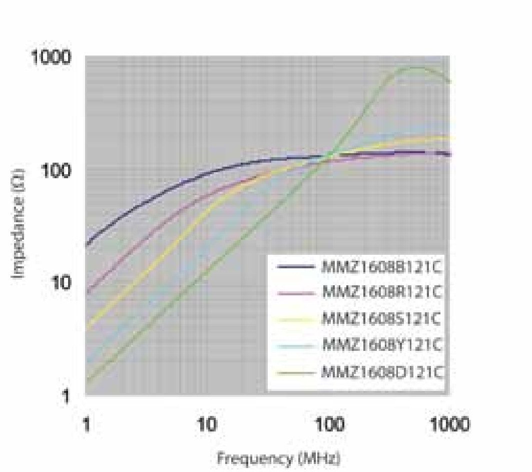


Figure 3: 120 Ohm (at 100 MHz) Ferrite Beads

As shown, materials vary in their performance. There are numerous variations of ferrite used in the construction of ferrite beads. Some materials are high loss, wide frequency, high frequency, low insertion loss and others. A general grouping by application frequency and impedance is shown in Figure 5.

Another common problem is that the board designer is sometimes limited in ferrite bead choices by what is in their approved component database. If the company has only a few approved ferrite beads which have been used on other products and were deemed satisfactory, in many cases there is no perceived need to evaluate and approve other materials and part numbers. This has many times, in the recent past, led to some of the worsening effects of the original EMI noise problem mentioned above. What worked before may or may not work on the next project. One can't simply carry over the last project's EMI solution, especially if the frequency has changed for the desired signal or there are frequency changes in potentially radiating components such as clock devices.

COMPARING CROSS-OVER FREQUENCIES

If one takes a look at the two impedance curves in Figure 6, a comparison can be made of the material effects of two similar specified parts.

For both parts, the impedance at 100 MHz is 120 Ohms. For the part on the left, using the "B" material, the

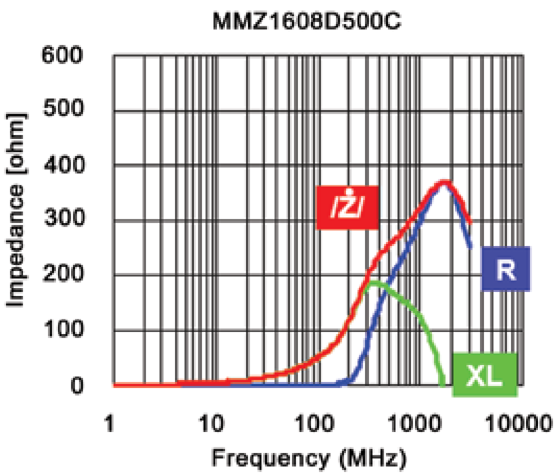


Figure 4: Typical Impedance Curve with /Z/, R, XL

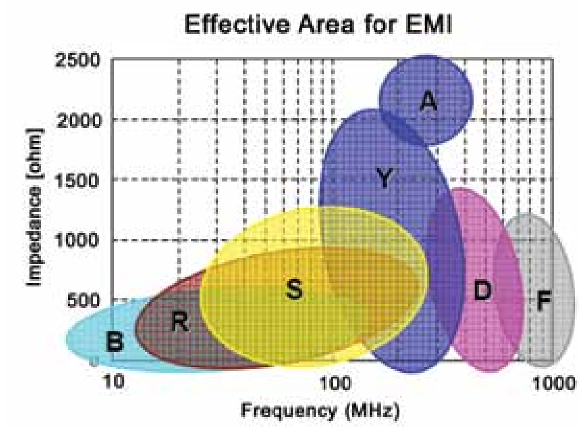


Figure 5: Material Characteristics Based Upon Frequency[1]

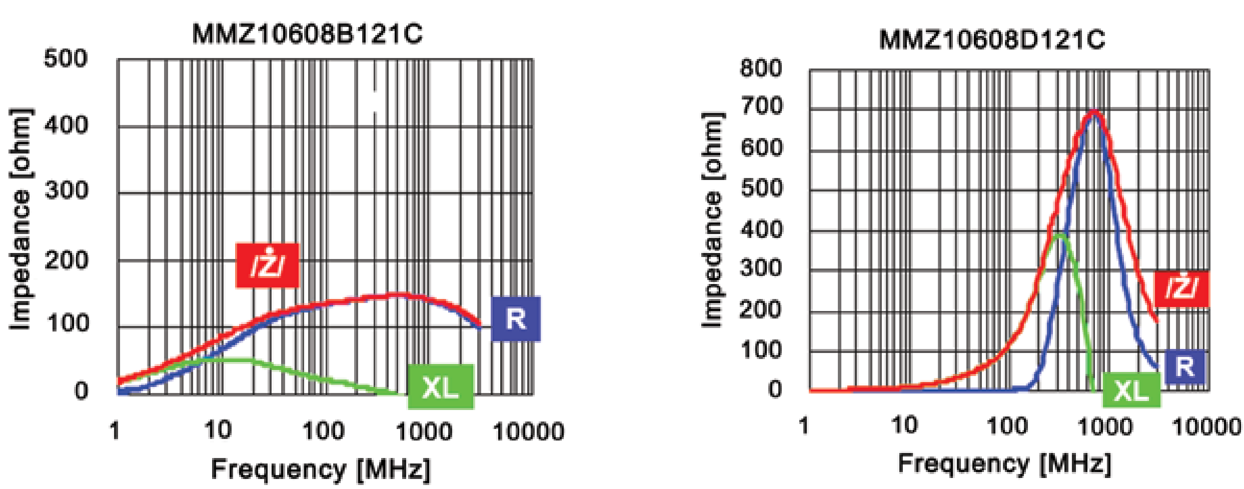


Figure 6: Impedance Curves for B Material (left) and D Material (right)

Resolve EMI Performance Issues Early to Avoid Costly Rework

Make Radiated and Conducted Emissions Measurements

If you are developing prototype electrical devices and need to evaluate the EMI performance of your new designs and devices, Agilent's N6141A/W6141A EMC measurement application for its X-Series signal analyzers can help complete your compliance testing successfully. It is the only pre-compliance test solution that enables you to reduce test margins while ensuring your device meets all regulatory limits.

The concept of getting a new product to market on time and within budget is nothing new. Recently, manufacturers have realized that electromagnetic interference (EMI) compliance testing can be a costly bottle neck in the product development process. To help ensure successful EMI compliance testing, pre-compliance testing has become an important addition to the development cycle. The basic premise is to measure the conducted and radiated emissions performance of a product during the development phase to identify problems early and thereby solving them before moving on to the next phase of development.

Conducted and radiated EMI emissions

Many manufacturers use EMI measurement systems to perform conducted and radiated EMI emissions evaluation prior to sending their product to a test facility for full compliance testing. Conducted and radiated emissions testing focuses on unwanted signals that are on the AC mains generated by the equipment under test (EUT).

Pre-compliance testing

The frequency range for conducted commercial measurements is from 9 kHz to 30 MHz, depending upon the regulation. Radiated emissions testing looks for signals broadcast for the EUT through space. The frequency range for these measurements is between 30 MHz and 1 GHz and based upon the regulation, can go up to 6 GHz and higher. These higher test frequencies are based on the highest internal clock frequency of the EUT. This preliminary testing is called pre-compliance testing.

Reduce test margins with superior measurement accuracy

- Identify low-level signals with excellent sensitivity from X-Series signal analyzers
- Ensure more precise signal measurements

Easily identify out-of-limit device emissions

- See device emissions typically hidden in the noise floor
- Differentiate between ambient and DUT signals using signal list features
- Identify intermittent signals using Strip Chart features

Maximize signals and compare against commercial and MIL-STD limits

- Meet test requirements with built-in commercial and MIL-STD compliant bandwidths, detectors and presets
- Compare measured emissions with pass/fail and delta indicators
- Use frequency scan to identify, measure and store results

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maximum impedance is around 150 ohms and is achieved at 400 MHz. For the part on the right, using the "D" material, the maximum impedance is 700 Ohms as is achieved at approximately 700 MHz. But the biggest difference is in the cross-over frequencies. The super high loss "B" material transitions (R > XL) at 6 MHz while the very high frequency "D" material remains inductive until around 400 MHz. Which is the right part to use? It depends on each individual application.

ACTUAL EXAMPLE

Figure 7 demonstrates an all too common problem that arises when the wrong ferrite bead is chosen to suppress EMI. The unfiltered signal demonstrates a 474.5 mV undershoot on a 3.5V, 1 uS pulse.

In the result using the High Loss type material (center plot), the measured undershoot is increased due to the part's higher cross-over frequency. The signal undershoot is increased from 474.5 mV up to 749.8 mV. The Super High Loss material, with its lower cross-over frequency, performs adequately and would be the right material to use in this application (plot on right). The undershoot using this part is reduced to 156.3 mV.

DC BIAS PHENOMENON

As the DC current through the bead increases, the core material begins to saturate. For inductors, this is called the saturation current and is specified as some percentage decrease in the inductance value. With ferrite beads, while the part is in its resistive stage, the effect of saturation is reflected in the reduction of impedance values over frequency. This drop of the impedance reduces the effectiveness of the ferrite bead and its ability to remove EMI (AC) noise. Figure 8 shows a set of typical DC bias curves for a ferrite bead.

In this figure, the ferrite bead is rated at 100 Ohms at 100 MHz. This is the typical measured impedance when there is no DC current through the part. But as can be seen, once a DC current is applied (such as for IC VCC inputs), there is a sharp drop-off of effective impedance, going from 100 Ohms to 20 Ohms in the above curves for just a 1.0 A current at 100 MHz. Maybe not too critical, but something the design engineer must be aware of. Again, by using only the parts' electrical characteristic data from the supplier's datasheet, the user would have no knowledge of this DC bias phenomenon.

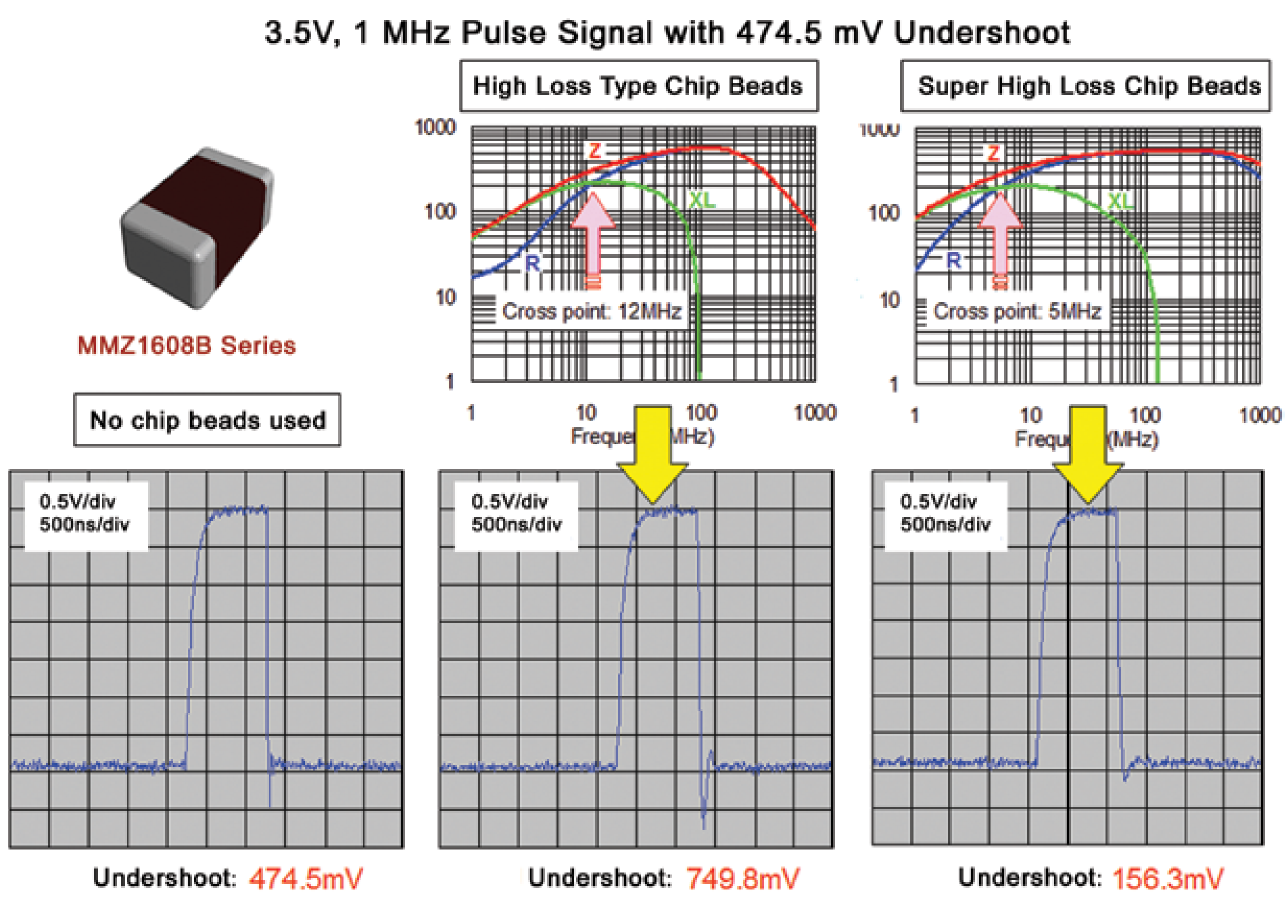


Figure 7: Measured Performance of High Loss and Super High Loss Materials

FREQUENCY RESPONSE VS. WINDING CONSTRUCTION

As with high frequency RF inductors, the winding direction of the inner coils within the ferrite bead has a large impact on the frequency behavior of the bead. The winding direction influences not only the impedance versus frequency levels, but also shifts the frequency response. In Figure 9, two 1000 Ohm ferrite beads, in the same case size and made of the same material but with two different winding configurations, are shown.

The part on the left, with coils wound in the vertical plane and stacked in the horizontal direction, yields higher impedance and a higher frequency response than the part on the right which is wound in the horizontal plane and stacked in the vertical direction. This is, in part, due to the lower capacitive reactance (X_C) associated with the reduced parasitic capacitance between the end terminations and the inner coils. The lower X_C creates a higher self resonance frequency which then allows the ferrite bead to continue to increase in impedance up to the higher self resonance frequency, resulting also in a higher obtainable impedance value than possible with a standard constructed ferrite bead. The curves for the above two 1000 Ohm ferrite beads are shown in Figure 10.

ACTUAL TEST RESULTS

To further show the impact of correct and incorrect ferrite bead selection, a simple test circuit and test board were used to demonstrate much of what has been discussed above. In Figure 11, a test board is shown with three ferrite bead locations and test points labeled as "A", "B", and "C" at 0 mm, 50 mm, and 100 mm distance from the output of the transmitting (T_X) device, respectively.

Signal conditions for this test were the following:

Frequency:	8 MHz
Duty Cycle:	50%
High voltage:	5V
Low voltage:	0V
Rise time:	1.6 nS
Fall time:	1.8 nS

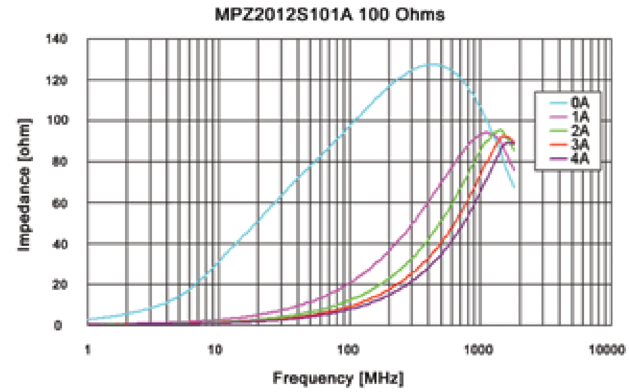


Figure 8: Effects on Impedance by DC Current

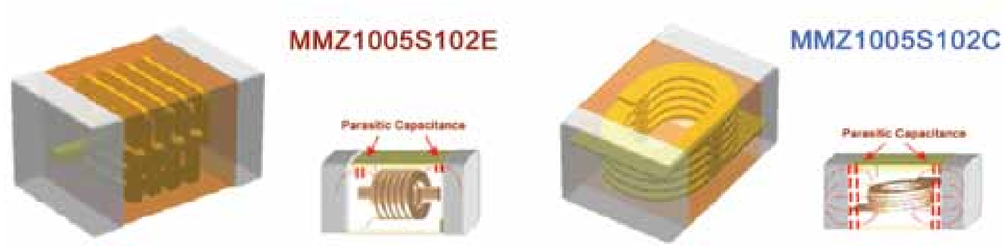


Figure 9: "Giga" Bead on Left, Standard Bead on Right[2]

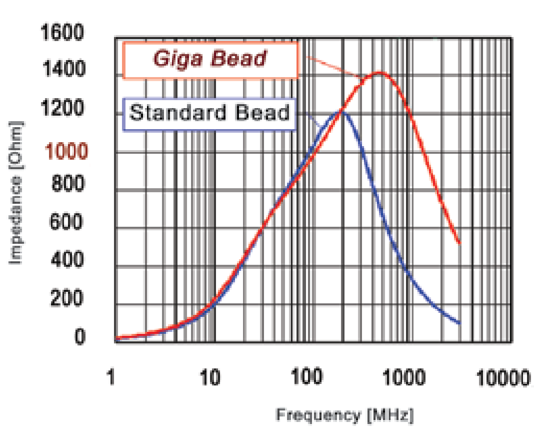


Figure 10: Comparison of Frequency Response Due to Winding Configuration

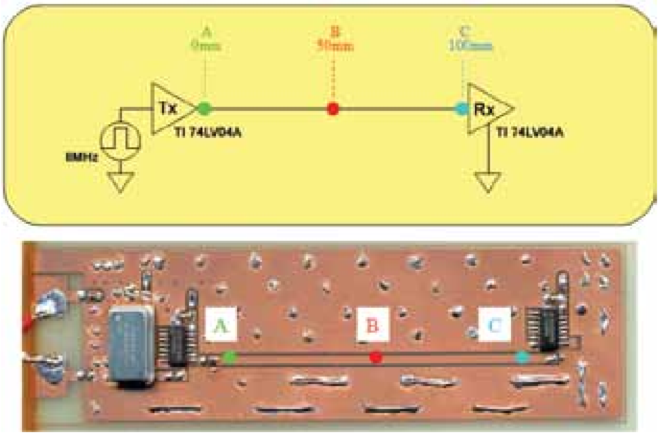


Figure 11: Test Setup and Test Board

The signal integrity was measured on the output side of the ferrite bead at each of the three locations and duplicated with two ferrite beads made of different materials. The first material, a low frequency, lossy "S" material was tested at points "A," "B" and "C". Next, a higher frequency "D" material was used. The point to point results using these two ferrite beads are shown in Figure 12.

The "through" unfiltered signal is shown in the center row and exhibits some overshoot and undershoot on the rising and falling edges respectively. As can be seen, with the use of the correct material for the above test conditions, the lower frequency, lossy material exhibited good overshoot and undershoot signal improvement on the rising and falling edges. These results are shown in Figure 12 in the upper row. The results using the high frequency material caused ringing that magnified the levels of each and increased the period of instability. These test results are shown in the bottom row.

When looking at the improvement on EMI over frequency for the recommended upper part (in Figure 12) in the horizontal scan shown in Figure 13, it can be seen that this part substantially reduces the EMI spikes and reduces the overall noise levels, for all frequencies in the 30 to approximately 350 MHz range, to an acceptable level well below the EMI limit highlighted by the red line, which is the general regulatory standard for Class B devices (FCC part 15 in the US). The "S" material used in the ferrite bead is specifically for these lower frequencies. And as can be seen, the "S" material has limited impact on the original, unfiltered EMI noise levels once the frequency gets above 350 MHz, but does reduce the one major spike at 750 MHz around 6 dB. If the major portion of the EMI noise problem was above 350 MHz, one would need to look at using a higher frequency ferrite material that has its impedance maximum higher in the frequency spectrum.

Of course all of the ringing, shown in the bottom curves in Figure 12, is typically avoided by actual performance testing and/or simulation software, but it is hoped that this article will allow the reader to bypass a lot of the common errors, decrease the amount of time needed to select the correct ferrite bead and allow for a more "educated" starting point when a ferrite bead is needed to help solve an EMI issue.

CONCLUSION

To avoid misuse in your future ferrite bead needs, it is recommended that you always:

1. Understand the noise problem within your circuit, including noise sources
2. Choose the correct material behavior needed, e.g., high loss at low frequencies
3. Determine the allowable trade-off for DC resistance and needed AC impedance
4. Get the impedance curve and other data for the part to be used
5. Don't automatically use what has worked before
6. Don't assume that a ferrite bead will be the best EMI component to use
7. If in doubt, contact your ferrite bead supplier as they will have EMI experts

In closing, it is desirable to approve families or series of ferrite beads, not just individual part numbers, to have

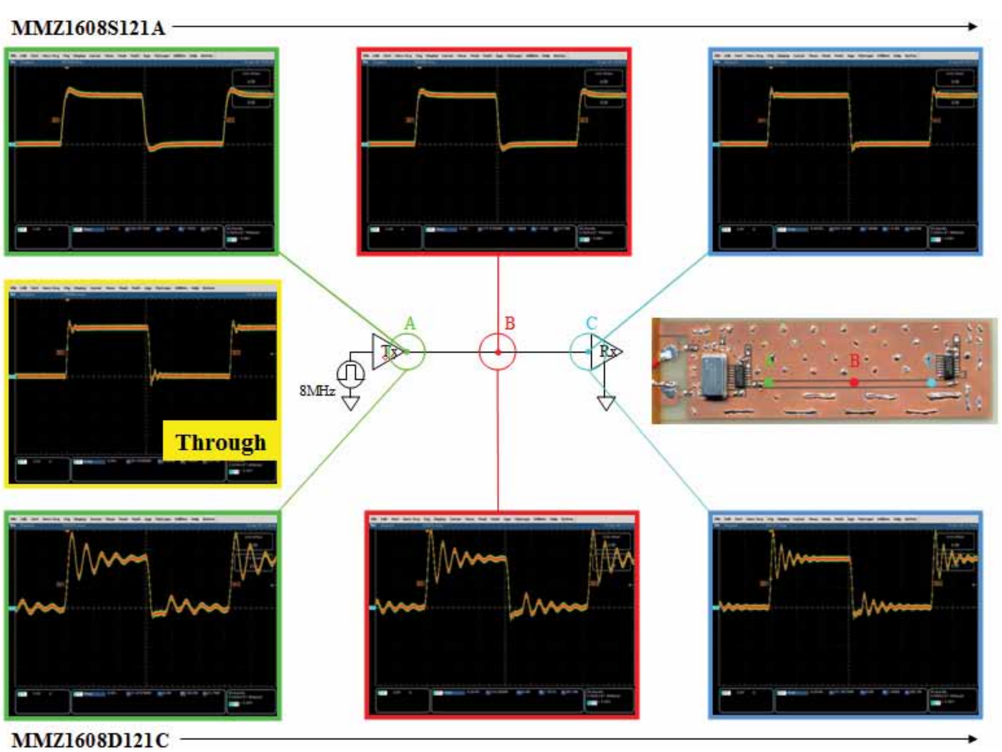


Figure 12: In-Circuit Performance Testing Results

more options and design flexibility. It needs to be noted that different suppliers use different materials, and it is a must that the frequency performance of each be reviewed, especially when doing multiple sourcing for the same project. This is somewhat easy to do on a first time basis, but once parts are entered into a component database under one control number, and they can be used anywhere thereafter, it is important that the frequency performance of the different suppliers' parts closely resemble each other in order to eliminate potential future problems for other applications. The best way to do this is to have similar data from the various suppliers and, as a minimum, have the impedance curve. This will also ensure the right ferrite bead is being used to solve your EMI problem.

And remember, not all ferrite beads are created equal. ■

NOTES

1. Material designations "B," "R," "S," "Y," "A," "D" and "F" are those of the author's company only and reflect different frequency behavior. Other ferrite bead suppliers have their own material designations.
2. "Giga" is a product name of the author's company only.

Chris Burket *joined TDK in 1995 and has held several sales related positions. He has been involved in product design, technical sales and marketing and currently is employed as a Senior Applications Engineer supporting a vast array of passive components. For more information visit www.tdk.com or email chris.burket@us.tdk.com.*

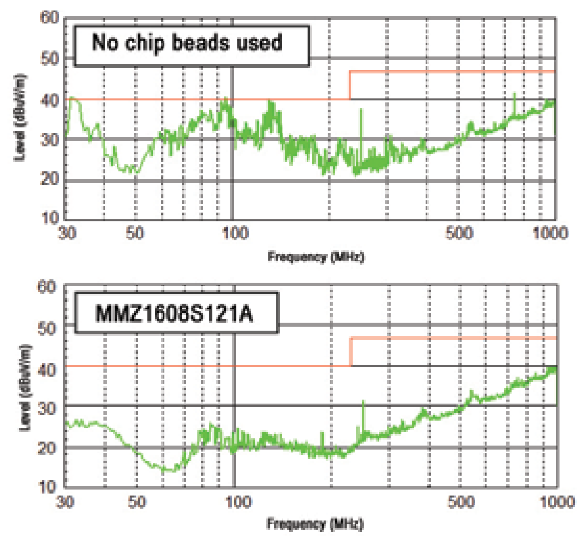
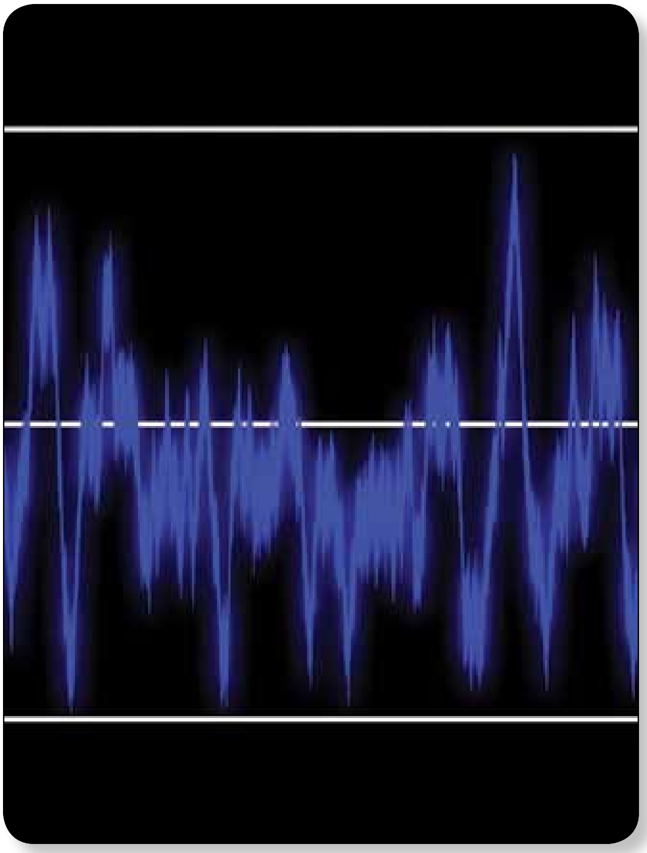


Figure 13: Radiated EMI Noise (Horizontal) Suppression

EMC



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.

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,

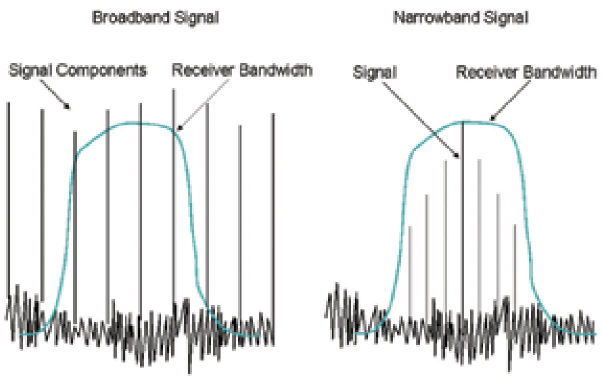


Figure 1: Generic definition of narrowband and broadband signals

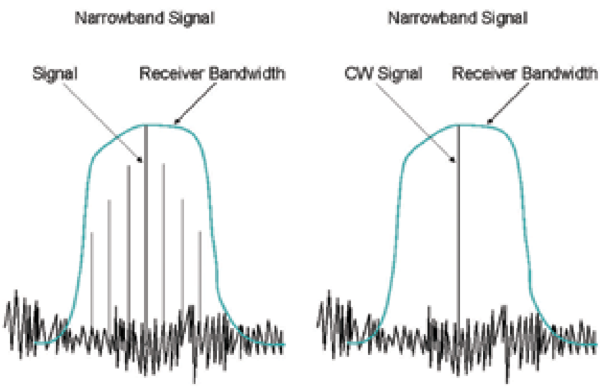


Figure 2: Two different types of narrowband signals

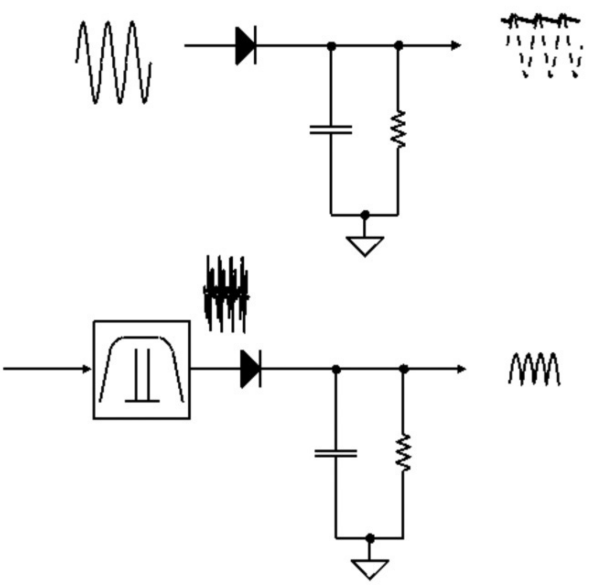


Figure 3: Envelope detector

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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 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.

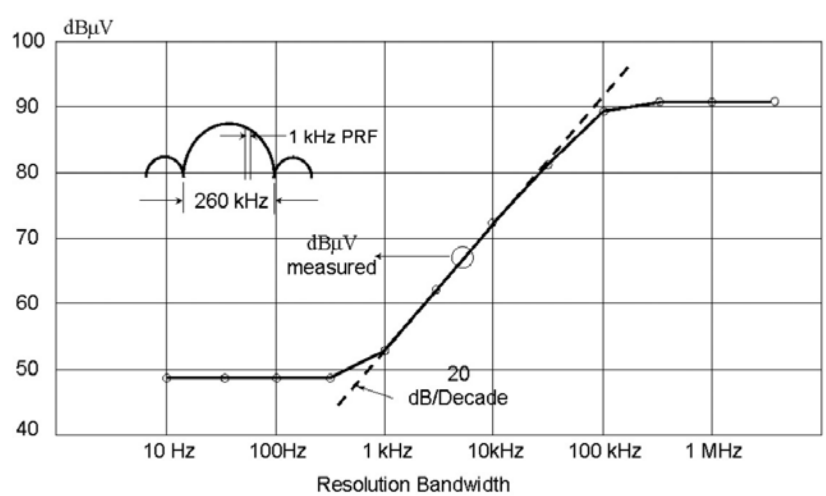

Figure 4: Impact of resolution bandwidth setting on measured amplitude of broadband signal

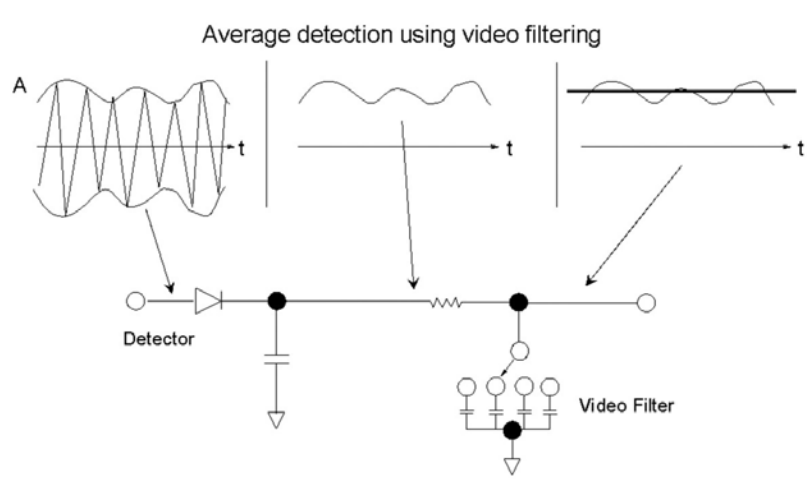

Figure 5: Peak versus average detection

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.

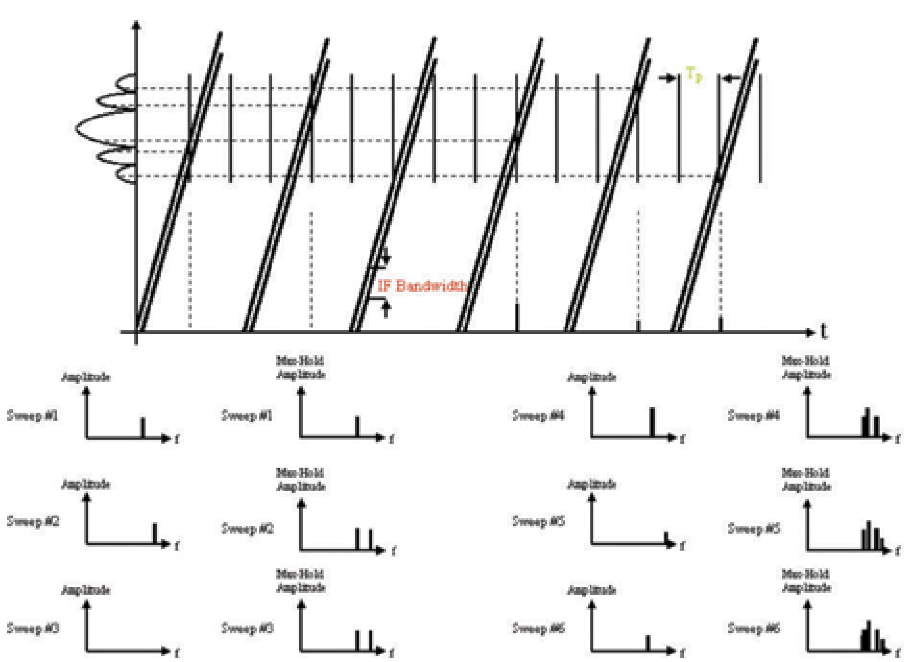

Figure 6: Broadband signal detection of a scanning receiver

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.

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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Werner Schaefer *is a compliance quality manager and technical leader for EMC and RF/uwave calibrations at Corporate Compliance Center of Cisco Systems in San Jose, CA. He has 25 years of EMC experience, including EMI test system and software design, EMI test method development and EMI standards development. He is the chairman of CISPR/A/WG1 and a member of CISPR/A/WG2 and CISPR/B/WG1. He also is the US Technical Advisor to CISPR/A and a member of ANSI C63, SC1/3/5/6/8, and serves as an A2LA and NVLAP lead assessor for EMI and wireless testing, software and protocol testing and RF/microwave calibration laboratories. He also serves as an ANSI representative to ISO CASCO, responsible for quality standards like ISO 17025 and ISO 17043. He is a member of the Board of Directors of the IEEE EMC Society.*

He was actively involved in the development of the new standard ANSI C63.10 and the latest revision of ANSI C63.4, mainly focusing on test equipment specifications, use of spectrum analyzers and site validation procedures.

Werner Schaefer is also a RAB certified quality systems lead auditor, and a NARTE certified EMC engineer.

He published over 50 papers on EMC, RF/uwave and quality assurance topics, conducted numerous trainings and workshops on these topics and co-authored a book on RF/uwave measurements in Germany.

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

EMC

EMC

Design and Selection of Shielding Gaskets

for Medical Devices and the Effect of Cleaning Solutions on Material Performance

BY ANJALI KHOSLA, JIM KLINE,
CLAUDINE LUMIBAO-ARM
AND DOUGLAS S. MCBAIN

EMI shielding is a critical component of many electronics-based medical devices, which are in turn integral for life-saving procedures and ongoing patient health care. Medical devices are frequently used in the vicinity of other electronic instruments, resulting in an increased risk of electromagnetic interference (EMI). This risk can be mitigated through the use and care of EMI shielding gaskets. For more than a decade the FDA has also expressed concerns for public health and safety in regards to device EMI and the solutions for these concerns.

Understanding the environment in which these devices are used is important in preventing and addressing EMI issues. Also, many medical devices are not only around each other, but are subjected to frequent and aggressive cleaning and sterilization regimens. The design of the device needs to be one which maintains EMI shielding of the electronic components over time in the expected conditions of use.

Electrically conductive elastomers (EcE) are based on dispersed particles in an elastomer matrix. EcE are used to create highly electrically conductive, yet resilient gasketing materials for electromagnetic interference shielding as well as pressure and environmental sealing. Conductive elastomers used for shielding electronic enclosures against EMI usually consist of a conductive gasket placed between a metal housing and cover. The primary function of these gaskets is to provide sufficient electrical conductivity across the enclosure, gasket, and lid junction to meet grounding and EMI shielding requirements, as well as a secondary role to prevent intrusion of fluids into the electrical compartment.

Some fundamental factors are involved when considering the service life of an EMI gasket. The first of these is the number of times the joint will be opened and closed during the projected operating life of the equipment. Second, gasket life is affected by the severity of gasket deformation when the joint is closed. Yet another factor is the presence of chemicals and fluids, ozone aging and temperature extremes. Finally, inadvertent damage to an EMI gasket during the initial installation and future maintenance must also be considered.

Basic cleaning and sterilization procedures can expose an EMI gasket to chemicals which can negatively affect material performance. Therefore, the choice of environmental sealing and shielding materials, the design of the device, and field conditions of use are all critical for on-going device function and reliability. In this article, we reviewed the results of a study of typical shielding gaskets when exposed to typical medical cleaning solutions, and we also cover design guidelines for effective environmental and EMI shielding.

MATERIALS COMPATIBILITY STUDY

Sample Description

The materials evaluated were three sets of electrically conductive elastomers, identified as EcE A (silver/glass-filled silicone), EcE B (silver/aluminum-filled fluorosilicone), EcE C (silver/aluminum-filled EPDM), as well as a non-conductive silicone elastomer commonly used for co-extrusion (see below). The filler particles possess a silver coating on a base particle, namely aluminum or glass. For testing the samples were soaked in test solutions falling under three categories:

1. Strongly oxidizing agents such as Clorox® Bleach diluted with deionized water (1:9 bleach:water), Oxivir TB®, and Aseptrol® S10-TAB;
2. Alcohol-based solutions with ionic and non-ionic surfactants, namely Cavicide® and Virex TB®,(respectively); and
3. A soap solution, Acquet® detergent.

In addition, the samples were also evaluated with Sani-Cloth® germicidal wipes for surface cleaning.

All of the materials were used as supplied or in dilution with water, following the manufacturer's recommendations.

Test Methods

The mechanical and physical properties of the elastomers such as hardness (ASTM D2240), tensile strength and elongation (ASTMD-412), were evaluated before and after fluid immersion, and under compressed or uncompressed conditions. The fluid immersion method was performed in accordance to ASTM D471-06e1.

In the uncompressed method, three test specimens of each elastomer were soaked in each of the test solutions for five days at room temperature. After immersion, the samples were wiped dry, rinsed with deionized water and air-dried for 24 hours. The mechanical properties of the materials were then tested.

In the compressed method, three specimens of each sample were compressed (15%) using polyethylene fixtures, as shown in Figure 1. The elastomers, together with the fixtures, were soaked in the test solutions for 5 days at room temperature. After soaking, the text fixture was unclamped, and the materials were wiped dry, rinsed with DI water and air-dried for 24 hours. Again, the mechanical properties were evaluated.

The elastomers were also subjected to 1,000 repetitive surface wipes (500 cycles) using a mechanized Crockmeter, with a two inch stroke and a 9N force. The surface was wiped with cotton gauze soaked in one of the test solutions, or with the Sani-Cloth® wiper. The scrub-pad was remoistened whenever necessary during the test. The samples were then wiped dry and their visual properties and surface electrical properties evaluated.

Test Material Properties

Table 1 shows the physical and mechanical properties of the different elastomers before immersion to the test solutions. EcE B, the silver/aluminum-filled fluorosilicone elastomer exhibits the lowest hardness among the conductive gaskets while EcE C, the silver/aluminum-filled EPDM rubber shows the smallest elongation. EcE A, which is a silver/glass-filled silicone elastomer, exhibits a very good tensile strength.

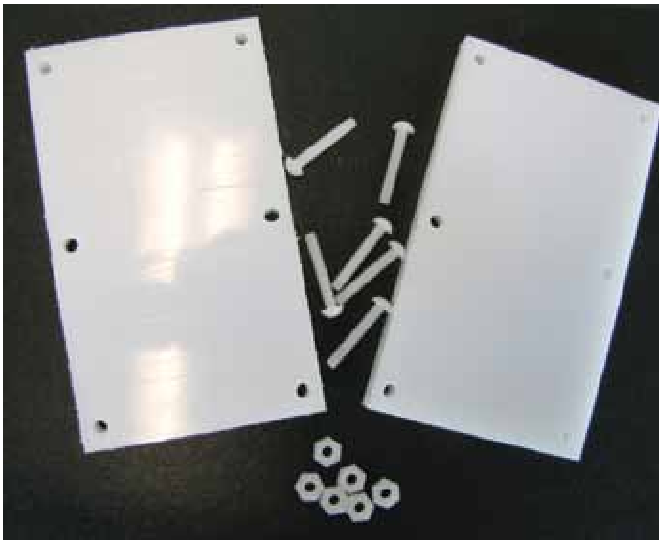

Figure 1: Un-assembled Polyethylene Compression Fixture

	Units	EcE A	EcE B	EcE C	Non-conductive
Hardness	Shore A	83	73	82	59
Tensile Strength	psi	384	237	242	723
Ultimate elongation	%	113	77.2	32.2	347
50% modulus	psi	255	202	-	176
100% modulus	psi	368	-	-	288
200% modulus	psi	-	-	-	487

Table 1: Physical and Mechanical Properties

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Physical and Mechanical Properties Changes with Chemical Exposure

Hardness

Figure 2 shows the effect of the different cleaning solutions on the hardness of the elastomer gaskets under uncompressed state. As shown in Figure 2, hardness of the material is either minimally or not significantly affected by immersion in the disinfectant solutions.

Tensile Strength

Figures 3 to 5 show the effect of various types of cleaning solutions on the tensile strength of the different elastomers, under compressed and uncompressed immersion. Strongly oxidizing agents such as Clorox® bleach, Oxivir® TB (shown in Figure 3) and Aseptrol® significantly affect the tensile strength of metal-filled silicone and fluorosilicone compounds, resulting in a loss of greater than 20% of strength. The EPDM-based elastomer, as well as non-conductive silicone showed a smaller percentage loss of about 10%.

The results were more pronounced when the materials were in the uncompressed state than when the gaskets were under compressed conditions. This is because in the uncompressed state the elastomers have a much greater exposure of surface area to the cleaning solution. In the compression fixture, only the edges of the test specimen are exposed, similar to a compressed gasket application.

Disinfectant solutions containing alcohol and non-ionic surfactants, such as Cavicide® and Virex® TB, also affect the tensile strength significantly. All four elastomers suffered a loss of tensile strength greater than 15%.

Soap and detergent solutions, such as 1% Acquet® soap solution, exhibit none to minimal loss of tensile strength.

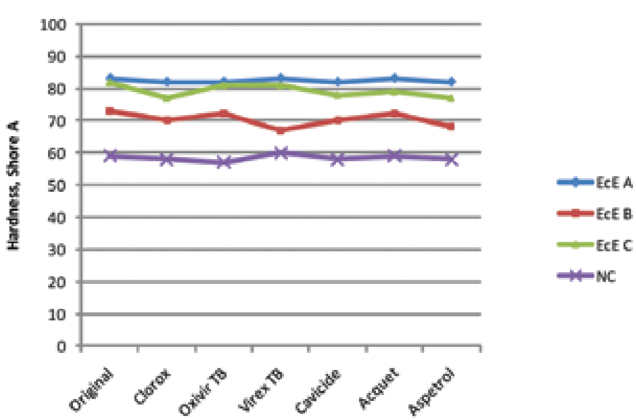


Figure 2: Effect of Cleaning Solutions on the Hardness of the Elastomers

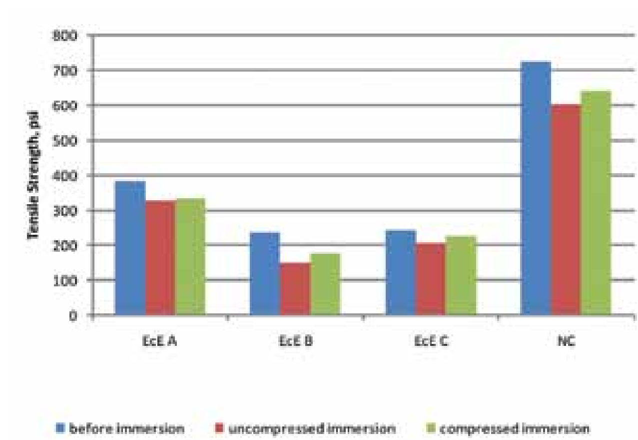


Figure 4: Effect of Alcohol-based disinfectants (Virex® TB) on Tensile Strength

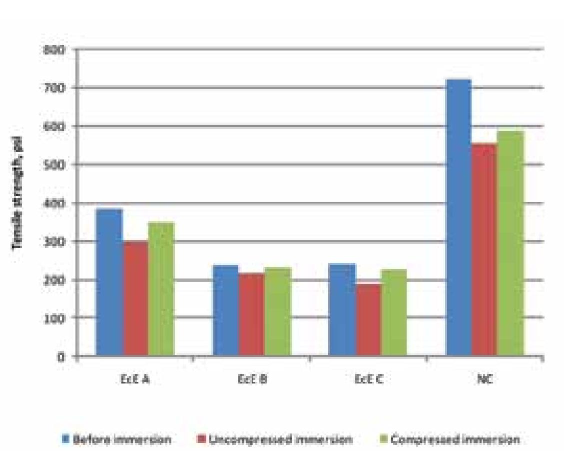


Figure 3: Effect of Oxidizing agents (Oxivir® TB) on Tensile Strength

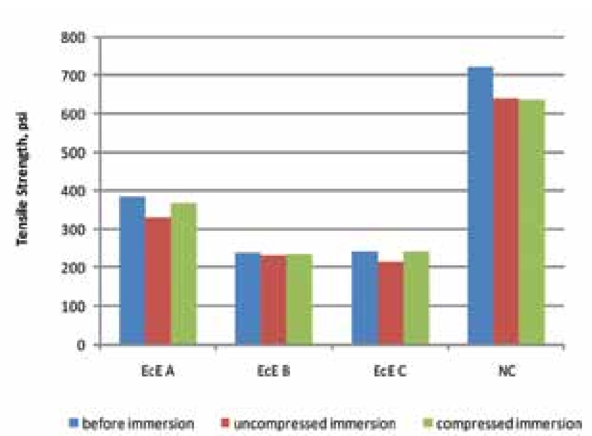


Figure 5: Effect of Soaps (Acquet) on Tensile Strength

Surface Wipe

Table 2 shows the summarized result of wiping the elastomer gaskets 1000 times with cotton gauze dipped in disinfectant solutions, as well as with Sani-Cloth ®wipes. Application of bleaches and oxidizing agents resulted in moderate to severe discoloration of the elastomer gaskets. This is specifically true for electrically conductive gaskets with metal fillers. Soap and detergent solutions, as well as alcohol-based disinfectants with ionic and non-ionic surfactants, exhibited discoloration ranging from very slight to moderate. Sani-cloth wiper yielded results similar to those of soaps and alcohol-based surfactants.

Change in Electrical Properties with Chemical Exposure

The effect of the disinfectant solutions on the electrical properties of the three electrically conductive elastomers is shown in Table 3. As expected, immersion of the elastomers in strongly oxidizing agents resulted in a major to total loss of electrical surface conductivity. Virex® TB, an alcohol-based cleaning solution with ionic surfactants resulted in some loss in conductivity for EcE A and B and a total loss for C. Elastomers immersed in Cavicide®, an alcohol-based solution with non-ionic surfactants, as well as in a soap solution exhibited no change in electrical properties.

Material Compatibility Conclusions

Strongly oxidizing agents such as hypochlorite bleach and hydogen peroxide can affect the mechanical and physical properties of conductive elastomer gaskets, and a total loss of electrical conductivity, as well as moderate to severe discoloration, were also observed. It is therefore recommended that these types of disinfectant solutions, which corrode the conductive filler, be widely avoided.

Alcohol-based cleaning agents with ionic and non-ionic surfactants, although less severe in their tendency to affect the mechanical and electrical properties of the elastomers, exhibited "wicking" and are therefore also not recommended.

Soap and detergent solutions show minimal to no siginificant effect on the properties of the electically conductive gaskets and can be safely used.

Finally, surface wiping of the conductive elastomer with strongly corrosive materials, although of perhaps minimal impact on physical properties, can still produce a total loss of surface conductivity, potentially compromising the essential EMI function of the gasket.

EMC

DESIGN CONSIDERATIONS FOR COST-EFFECTIVE SEALING

Medical devices in hospitals must routinely be washed down to prevent transmission of disease. It is rarely practical to print a list of allowed cleaning materials directly on a device and expect hospital personnel completely comply. As has been seen, a single exposure of EcE to any of several common hospital disinfectants can cause severe loss of electrical conductivity, which can cause malfunction of the device and/or other nearby devices through RF emission and susceptibility. Such malfunctions can be costly in terms of both equipment and patient health and safety. It is therefore critical to seal medical devices in a way that EMI gaskets are protected from exposure to cleaning solutions.

There are two ways to protect the EMI gasket from cleaning solution exposure, and for consistency, shown in Figure 6, electrically-conductive material is shown as gray, while non-conductive material is shown in blue.

1. Use an environmental gasket to the exterior of an EMI gasket, as shown in Figure 6.

   The two gaskets may be separate, or bonded together to save space and assembly effort. The interior EMI gasket may be:

   a. EcE or Form-In-Place (FIP) technology,

   b. wire mesh,

   c. metal fingerstock,

   d. Conductive Fabric Over Foam (FOF) technology

2. Use a single EcE gasket, as in Figure 7, having multiple contact lines, with the outermost contact line being electrically redundant, and incorporating intermediate gap(s) that are large enough to prevent capillary flow of cleaning solution to the innermost contact line.

   A single EcE gasket having a single broad area of contact may retain conductivity toward the inside of the enclosure for a time, but the probability of solution wicking across the contact area and causing eventual loss of conductivity does bring risk.

EcE materials can be expensive, and the second option (above) does not minimize EcE material use. However, the dual gasket options in 1 can also be more expensive to implement, because they require the enclosure to have enough space and stiffness to handle two gaskets. Also, two gaskets are often more expensive than one. The most cost effective option is often a hybrid of options 1 and 2, or more specifically a coextrusion of electrically-conductive and non-conductive elastomer.

The goal for any gasket is to meet or exceed sealing requirements at minimum cost. The cost of the gasket itself is only a part of the total cost of sealing an enclosure. The enclosure must be made large enough to provide space and retention for the gasket, and it must be rigid enough to adequately compress the gasket along its length. Closely spaced fasteners are often needed to compensate for relatively low enclosure stiffness and for manufacturing dimensional variation. The enclosure manufacturing process must be precise enough for the compression response of the gasket. The costs of added enclosure mass, complexity, and dimensional control, plus fasteners and assembly labor should be considered part of the total cost of sealing an enclosure.

Since much of the cost of a typical EcE gasket is in the cost of the electrically conductive particle filler material, minimizing

Test Fluid	EcE A	EcE B	EcE C	Non-conductive
Clorox Bleach	severe	severe	severe	moderate
Oxivir, TB	moderate	moderate	slight	very slight
Virex TB	very slight	moderate	severe	very slight
Cavicide	very slight	moderate	very slight	very slight
1% Acquet	very slight	moderate	very slight	very slight
Aspetrol	severe	severe	severe	moderate
Sani-cloth wiper	slight	moderate	slight	slight

Table 2: Effect of Surface Wipes on Material Appearance (Discoloration)

Test Fluid	EcE A	EcE B	EcE C
Bleach	Total Loss	Ten-Fold Loss	Total Loss
Oxivir TB	Total Loss	Ten-Fold Loss	Total Loss
Virex TB	Two-Fold Loss	Two-Fold Loss	Total Loss
Cavicide	No Change	No Change	No Change
Acquet	No Change	No Change	No Change
Aseptrol	Total Loss	Ten-Fold Loss	Total Loss

Table 3: Effect of Cleaning Solutions on EcE Electrical Properties (Surface Conductivity)

this component minimizes gasket cost. A smaller gasket also takes up less space on the enclosure. It would seem that the smallest possible gasket is the best option because it minimizes cost. However, the total cost of sealing an enclosure is rarely minimized this way. For a reliable seal to be created, small gaskets require stiff enclosures and very precise dimensional control of both the gasket and the enclosure. Such dimensional control is usually either unavailable or cost prohibitive.

One could also avoid expensive filler materials by choosing from gasket options 1.b., c., or d. These options generally require a relatively large area on the enclosure, and most must be mitered and bonded to traverse around corners. Joints like this add cost and can be a weak point for both handling and sealing. (Two rows of FIP are an exception, and can be a very efficient solution when the enclosure has sufficient dimensional precision and stiffness.)

The Case for Coextrusion

By using a coextruded gasket, made with non-conductive and conductive elastomer portions, the volume of filler material may be kept low, while using a gasket size that tolerates typical manufacturing and assembly variation. Another advantage of coextrusion is that the nonconductive portion reduces the overall gasket stiffness, making it more conformable for better environmental sealing, and allowing for a less rigid enclosure. Coextruded gaskets may be designed and analyzed using the same techniques as for EcE gaskets, with the following additional considerations:

1. A coextruded gasket must be oriented properly. It would not make sense to coextrude a round cross section, because it would be impossible to ensure that the non-conductive portion remains on the outside and EcE on the inside. Proper orientation not only protects the EcE from the effects of cleaning solutions, but maintains the conductive path that provides EMI shielding effectiveness. ‘D’ shapes and others that are easy to restrain in proper orientation are simple solutions.

2. For a conductive path to exist, the EcE material must be in compression in the path direction. Most typical gasket shapes are in tension on portions of their outer surface between the two compressing/sealing surfaces. This is why simply putting an electrically conductive coating on the exterior of a nonconductive gasket does not create an effective EMI shield; when the gasket is compressed, the coating is in tension, conductive particles separate, and conductivity is lost in the desired direction. Finite element analysis (FEA) can be used to determine areas of tension/compression, so that nonconductive/conductive regions may be well

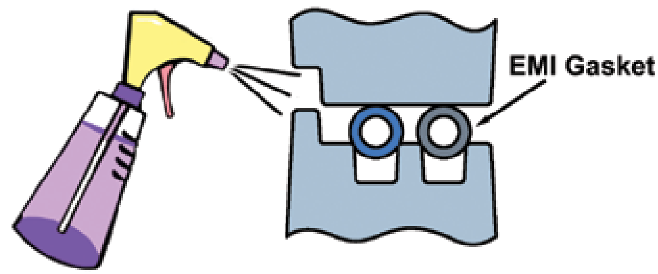


Figure 6

Figure 7: Single Gasket with Multiple Contact Points

EMC

chosen. For example, a co-extrusion of the shape shown above, but with non-conductive and conductive portions, is shown in Figure 8. The FEA output, shown in Figure 8, shows areas in tension (red) and compression (blue) during compression of an EcE gasket, but is not meant to depict a co-extrusion.

General Design Considerations for Elastomeric Gaskets

1. Solid elastomers (including EcE) are volumetrically incompressible for all practical purposes. Gaskets made from solid (non-foam) elastomer compress by changing shape. When sizing the space for such gaskets, verify that the maximum gasket cross sectional area will be less than the minimum cross sectional area of the allowed compressed space.

2. Larger and hollow-section gaskets are more conformable than smaller and solid-section gaskets, and create an environmental seal with much lower compression force, as shown in Figures 9 and 10.

3. Perform tolerance stack analysis on the gasket fit and compression, and verify sealing performance predictors at the extremes of tolerance. Many extruded hollow-section solid elastomeric environmental seals make very effective environmental seals at compression forces less than 6 lbs/in (1 N/mm.) How much gasket force is needed depends on sealing requirements, gasket size, and gasket shape. Gasket force can vary dramatically with gasket stiffness and level of compression.

For example, compression force of the solid section gaskets shown in the chart above (0.136” and 0.217” diameter) will vary by about ± 8 lbs/in with ± 0.010” deflection. The pressure sealed chart indicates that these gaskets must be compressed with at least 12 lbs/in for a minimal environmental seal. If tolerance stack analysis yields a potential compression variation of ±0.020”, then minimum, nominal, and maximum forces will respectively be 12, 28, and 44 lbs/inch, or a substantially large force. Such a high force would require a very stiff and strong enclosure.

Since larger and hollow section gaskets are less stiff than smaller and solid section gaskets, they will have lesser compression force variation. A special patented[1] gasket shape shown in Figure 11, produces nearly constant force

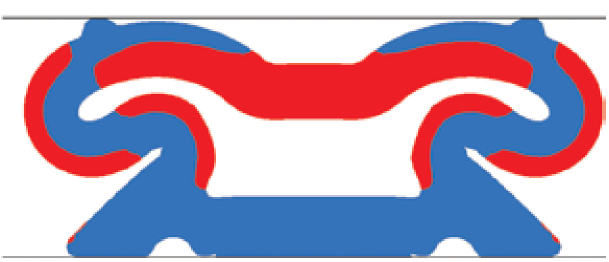


Figure 8: Gasket analysis showing areas in tension (red) and compression (blue)

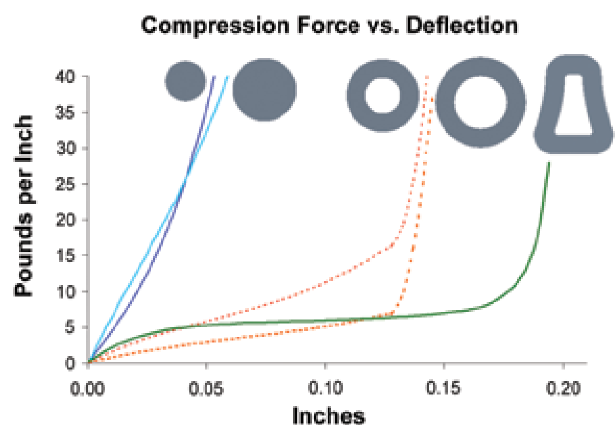


Figure 10: Hollow and Solid Gasket Comparison

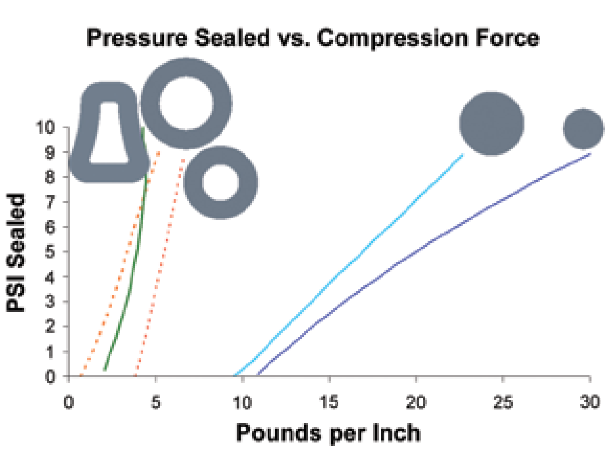


Figure 9: Hollow and Solid Gasket Comparison

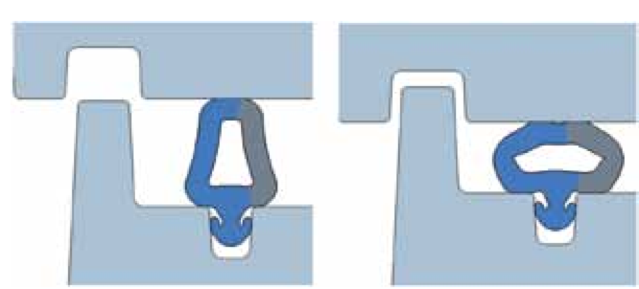


Figure 11: Constant Force Gasket Design with Non-Conductive and Conductive Portions and a Hard Stop for Added Protection

over a relatively very wide compression range (±1 lb/in with ±0.055” compression.) This ‘Constant Force Gasket’ shape is very effective at neutralizing compression variation to provide a reliable environmental seal.

4. Analyze the enclosure for deflection and stress. Enclosure deflection takes away from gasket compression, and potentially degrades sealing performance.

5. Protect the gasket from high velocity flow (sprays, jets, etc.) by adding barriers on the enclosure.

6. Surfaces mating with EMI gaskets should be electrically-conductive and galvanically compatible with the EMI gasket material to inhibit corrosion and loss of conductivity. For environmental seals, surface roughness should be in the neighborhood of 32 to 63 µin RMS, which is typically achieved by most casting and machining methods.

7. Prevent gasket over-compression with hard stops. This may be accomplished many ways, including groove and ledge mounting.

8. Elastomeric materials, particularly those filled with conductive particles, soften and take on permanent set over the first few compressions. Softening (Mullins Effect) often results in a roughly 50% reduction in EcE gasket stress and force, and is separate from permanent set. Permanent set in typical extruded EcE gasket shapes is between 5 and 20% of maximum compression, depending on material type, gasket shape, and % compression. This is significantly lower than compression set percentages published along with bulk material properties.

Figure 11 shows the uncompressed and nominal compressed state of a coextruded nonconductive/conductive elastomer Constant Force Gasket. The fluid spray barrier shown also acts as a hard stop against over-compression. This gasket provides environmental and EMI sealing in a minimal space and at minimal cost.

OVERALL CONCLUSIONS

The purpose of this paper is to inform and remind the community of individuals who design and specify materials for this market that the interplay of their design, their materials choice, and also the conditions of use must all be considered. The consequences of choice, while obvious to someone skilled in one discipline, may be less obvious to someone skilled in a different discipline but yet responsible for the entire device. Good design, good materials, and an understanding of use can lead to high reliability, and in the field of health care, no one would have it any other way. ■

__Ms. Anjali Khosla__ is a Product Manager with Laird Technologies, located at their St. Louis, Missouri, headquarters. Ms. Khosla has worked with management and marketing of EMI products, and has a Bachelors degree in Marketing and International Business.

__Mr. Jim Kline__ is has worked for Laird Technologies for over 10 years, specializing in product mechanical design and non-linear finite element analysis. Mr. Kline holds MS and BS degrees in Mechanical and Structural Engineering, and has been awarded several patents for commercial shielding and gasket designs.

__Ms. Claudine Lumibao-Arm__ is a Research Chemist with Laird Technologies, located in the Cleveland, Ohio, materials laboratory. Ms. Lumibao-Arm holds MS and BS degrees in Chemistry, and has been involved in the development of new material products and processes.

__Dr. Douglas McBain__ is the Global Technology Director for EMI Elastomer products of Laird Technologies, and is also located in Cleveland, Ohio. Dr. McBain has in his career been widely involved in the formulation of elastomers, coatings, and thermoset resins. Dr. McBain has a Ph.D. in Organic Chemistry.

EMC

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

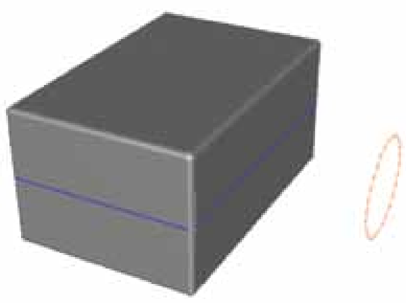


Figure 1: 3D TLM model of Conductive Coated Enclosure with Transmit Loop

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.

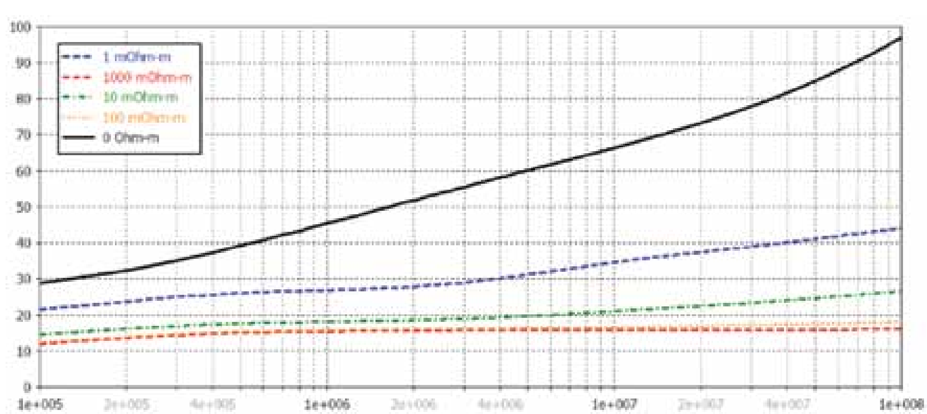


Figure 2: Magnetic Shielding Effectiveness Plotted Against Frequency

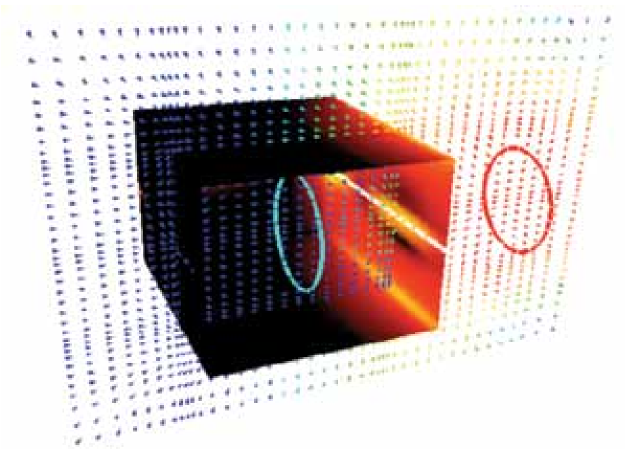


Figure 3: Magnetic Field at 1 MHz with 10 milli Ohm-m Seam Transfer Impedance

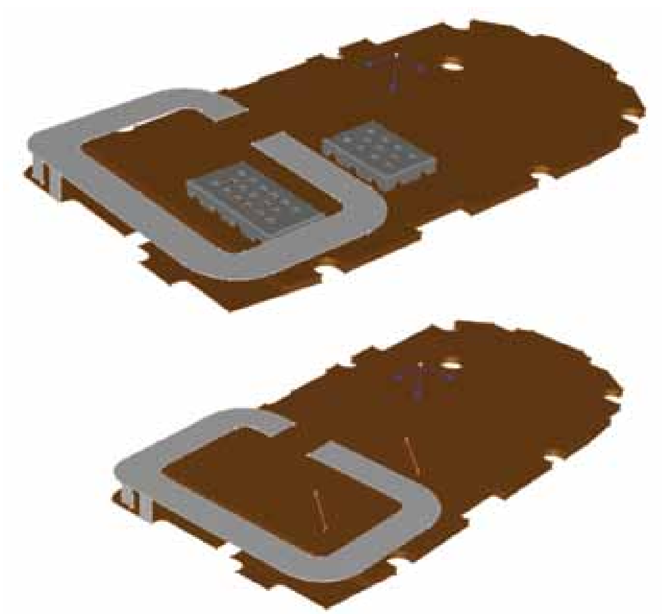


Figure 4: Cell Phone Model with Component Shields Present and Removed

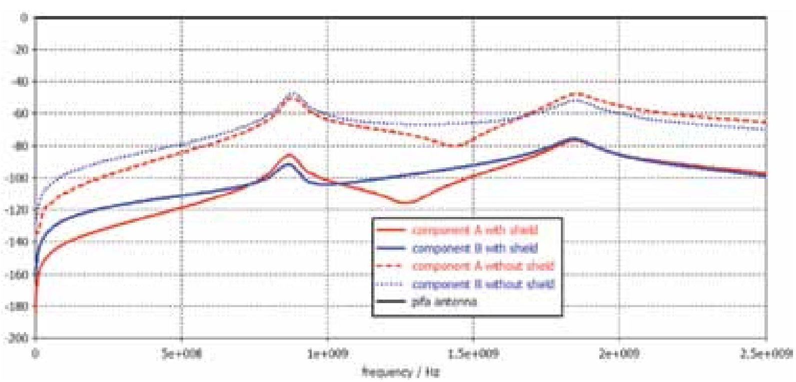


Figure 5: Coupling Between PIFA and Components With and Without Shields

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.

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.

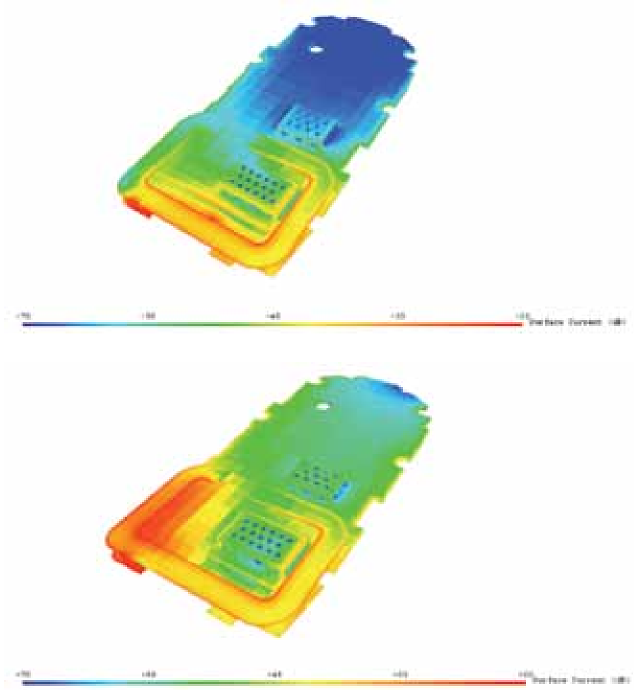


Figure 6: Surface Current and Field Distribution at 850 MHz (top), Surface Current and Field Distribution at 1900 MHz (bottom)

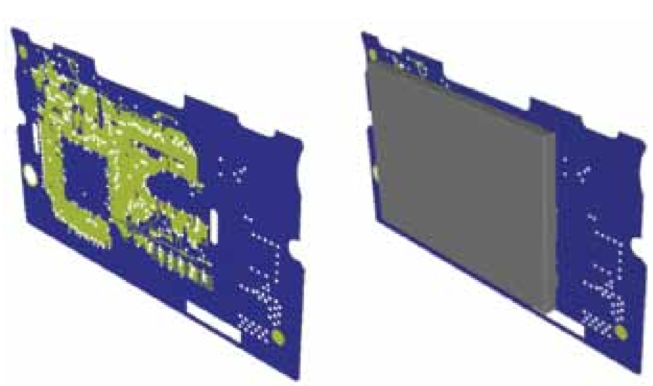


Figure 7: Automotive Display System Graphics PCB Model With and Without Shield

The 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.

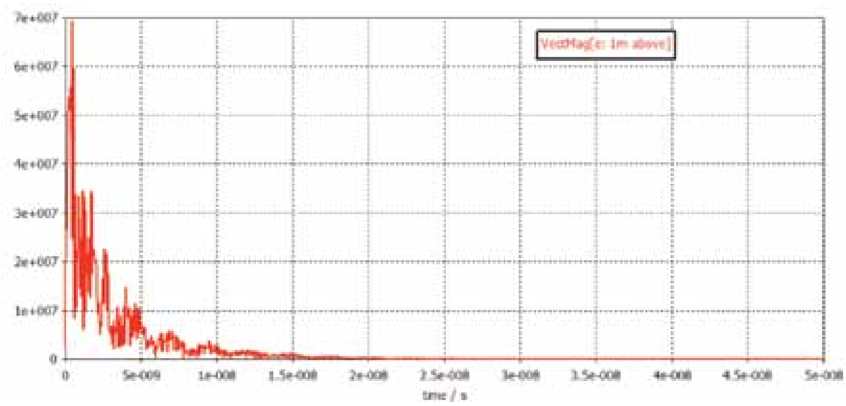


Figure 8: Typical Impulse Response from the Time-Domain TLM Analysis

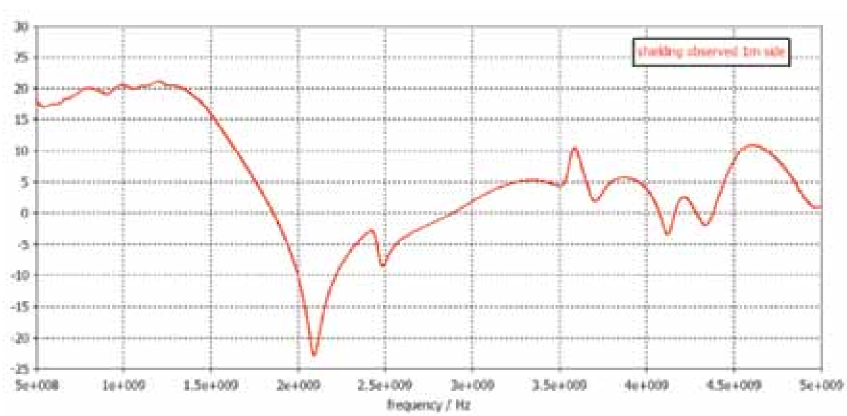


Figure 9: Shielding Effectiveness Observed 2cm above the PCB/Shield

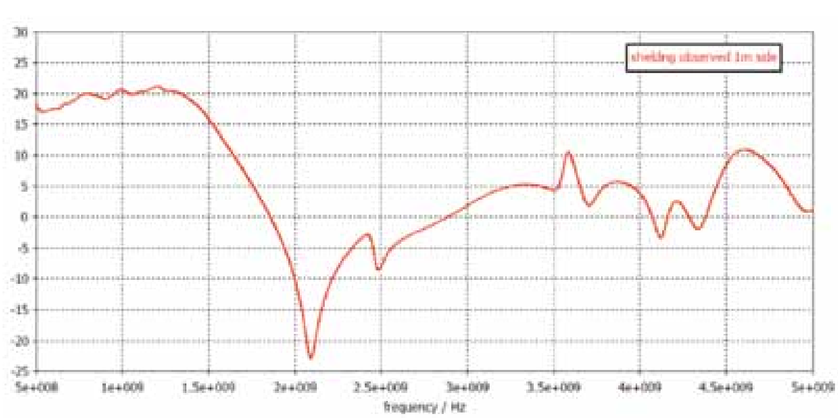


Figure 10: Shielding Effectiveness Observed 1m Away from the PCB/Shield

The 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.

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.

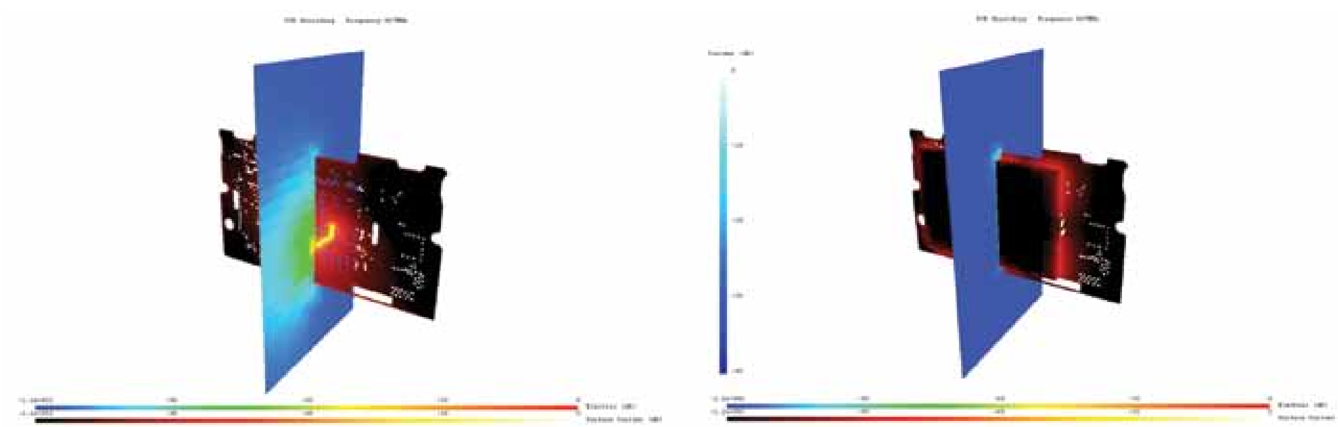


Figure 11: Surface Current and Electric field at 867 MHz: without Shield (left), with Shield (right)

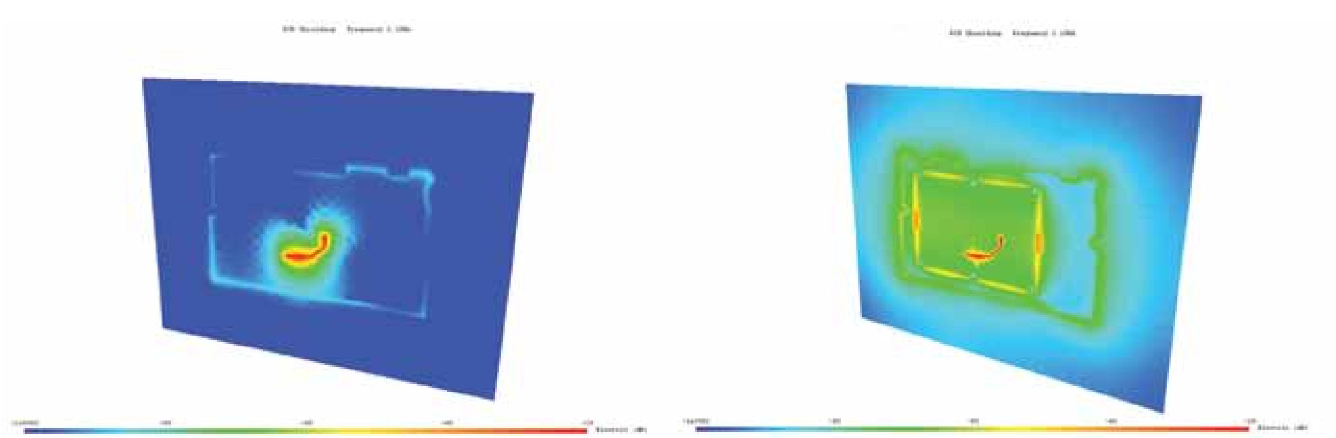


Figure 12: Electric field at 2.1 GHz: without Shield (left), with Shield (right)

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.*

Testing for Immunity to EMP

BY JEFFREY VIEL

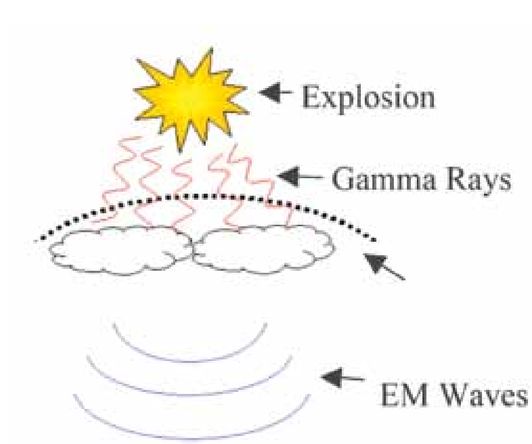
The 21st century as we know it, truly reflects the age of technology. Every aspect of life today is encompassed by the use of some sort of microprocessor based electronics intended to simplify tasks, to improve processes, and improve efficiency. Electronics are used to communicate with loved ones, manage 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.

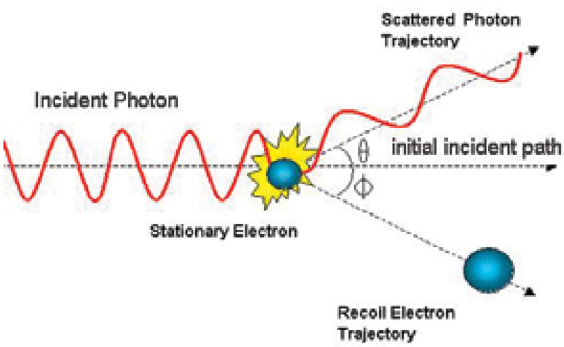
EMPs are historically known as the electromagnetic effects following a nuclear blast occurring at high altitudes (also known as HNEMP). The first discovery of the HNEMP incident was made by the U.S. in 1958 during a series of high-altitude atmospheric tests. The most noted was during the detonation of 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."

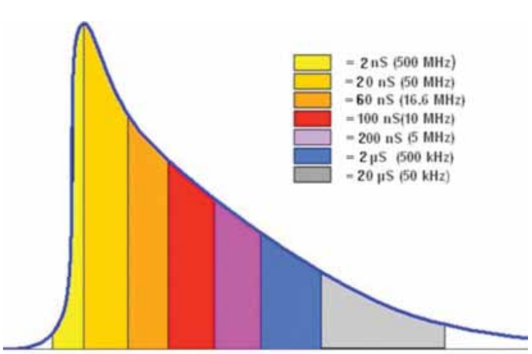


When a gamma ray "incident photon" collides with an atom in the atmosphere, it knocks a stationary electron free on a trajectory away from the blast.



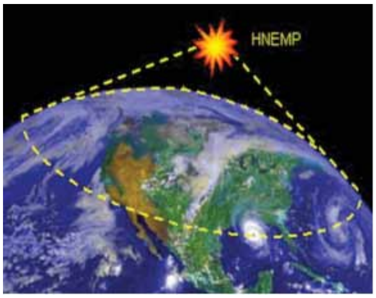
These electrons "*Compton's electrons*" being smaller than their corresponding positively charged atom travel at a higher rate of speed rapidly increasing the charge separation distance between them.

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.



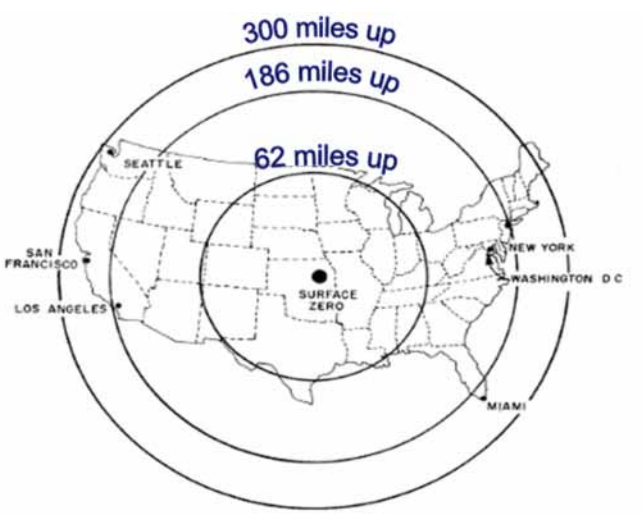
The exposure radius of a high altitude EMP commonly known as the "disposition region" is determined by three main elements, 1: Height of the blast, 2: size of the blast, and 3: type of explosive (kinetic energy). In general terms, the higher the explosion is, the greater the disposition region becomes.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



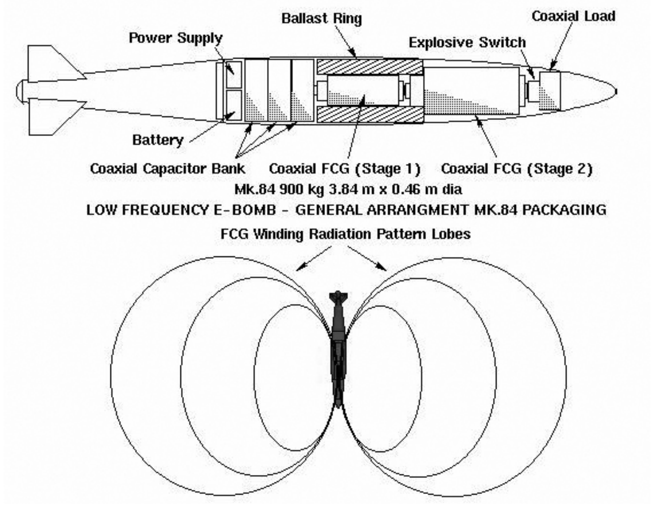
EMC

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.



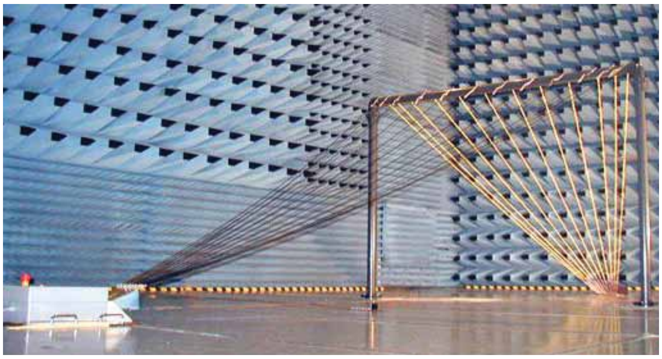
The US Navy reportedly used a FCG pulse weapon during the opening hours of the Persian Gulf War to effectively destroy vast amounts of Iraqi electronics, power and telecommunications systems quickly, efficiently. The deployment of EMP weaponry instantly caused what is known as the “Fog of War” (*complete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

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.

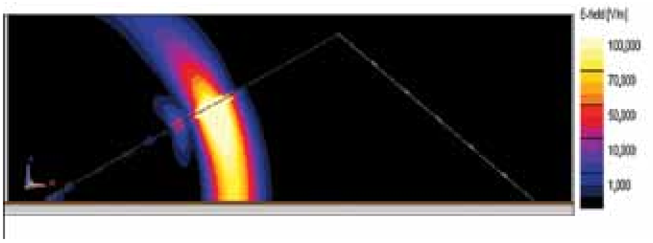
The RS105 pulse characteristics consist of a fast rise time, short pulse duration, and high amplitude which resemble those of an actual EMP. Peak field strengths of 50 kV/m are specified for exposed equipment. However, tailoring the peak field levels are often required for partially exposed installations 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

History of CISPR

BY DON HEIRMAN
AND MANFRED STECHER

The history of the International Special Committee on Radio Interference (CISPR) is one that extends over 75 years. There have been papers written over the years on its history. The one that is used as the basis for this article was presented at the 2005 Zurich EMC Symposium. The title was "A History of the Evolution of EMC Regulatory Bodies and Standards", written by the authors of this article [1]. Manfred provided the majority of the research on CISPR up to the time of the Zurich symposium and Don continued the history up to the present time. This article will then present a brief history of CISPR from its inception to the present time.

HISTORY OF THE CISPR

There was general agreement that the most important international problem was to secure uniformity in the methods of measurement and in the specification of limits to avoid difficulties for the exchange of goods and services [2]. In 1933 an ad-hoc conference of interested international organizations was held in Paris to decide how the subject of radio interference should be dealt with internationally. It was agreed to form a Joint Committee of the International Electrotechnical Committee (IEC) and the Union Internationale de Radiotéléphonie (UIR, International Sound Broadcasting Union). The first meeting of the CISPR (then called "Comité International Spécial des Perturbations Radiophoniques" (only in 1953 in view of the importance of television, the last word was replaced by "Radioélectriques") was in June 1934 in Paris, with representatives of six national committees of the IEC (Belgium, The Netherlands, Luxembourg, France, Germany and UK), the UIR and of other international organizations such as the International Union of Producers and Distributors of Electrical Energy (UNIPEDE), the International Conference on Large High Tension Electric Systems (CIGRE), the International Union of Railways (IUR) and of the World Power Conference. The Comité Consultatif International de Radio (CCIR) did not wish to become a full member. During the first meeting, two Subcommittees (SCs) (A on limits and B on measuring methods) were founded [3]. The proposal to "measure the high-frequency interference voltage at the terminals of the interfering electrical appliance" and to "evaluate the attenuation of the interference between the source and the input terminals of a receiver on the basis of statistical experimental data" was proposed by Germany and The Netherlands. International work continued until 1939 (with meetings held in Berlin, December 1934 and April 1935; in London November 1935 and May 1936; Brussels in March and December 1937; and in Paris in July 1939). The recommendations of CISPR were contained in the proceedings of the meetings and Reports RI Numbers 1 to 8 cover the period up to 1939.

The CCIR did not become a CISPR member, but later (in 1966) they adopted a recommendation (433), that as far as possible, administrations should take into account the recommendations, reports and publications of the CISPR and that national regulation concerning interference suppression should be based on the measuring methods and apparatus described by the CISPR. There was and is a clear division of work: interference between radio services or between transmitters of the same service is in the province of the CCIR (now ITU-R) and not the CISPR. The member nations of the ITU have signed the International Telecommunications Convention, urging the national administrations to keep radio interference levels as low as possible and which is a basis for national laws on interference suppression.

Agreement was reached on the CISPR delta network that makes it possible to measure the symmetrical (differential mode) and asymmetrical (common mode) component of the disturbance voltage [2]. In 1937, provisional limits were proposed for the symmetrical voltage of 3 mV from 160 to 240 kHz and of 1 mV from 550 to 1400 kHz and for the asymmetrical voltage of 1,5 mV both from 160 to 240 kHz and from 550 to 1400 kHz. In 1939, twelve copies of the first CISPR measuring receiver (designed in Belgium) were ready. Its frequency range included the long wave and medium wave bands (150 to 1500 kHz) and it had essentially the characteristics of today's CISPR quasi-peak measuring receiver for Band B (0,15 to 30 MHz) with 9 kHz bandwidth and 1 ms charge time and 160 ms discharge time constant of the detector. However, the spread of results of measurement on a standard commutator motor in different countries was disappointing.

International CISPR work restarted in 1946 – now including a strong delegation from the USA. Canada, Japan and, since 1956, the USSR also took part in the meetings. In 1956, delegates from 17 countries took part in the meeting. In the meeting of 1946, it was recognized that measurements would be required for frequencies greater than 1.6 MHz and that major receiver design would be required for frequencies greater than 20 to 30 MHz. At this meeting the measurement of the RF voltage at the mains terminals of an appliance using the 150 Ω V-network was proposed [4]. In 1950, it was decided CISPR should be formally constituted as a special committee of the IEC [5]. The recommendations and reports continued to appear in the proceedings of the plenary meetings and the numbers RI 11 to 14 covered sessions in Paris 1950, London 1953, The Hague 1958 and Brussels 1959. Considerable progress was made on the specifications for measuring receivers and techniques for the frequency ranges 0,15 to 30 MHz and 30 to 300 MHz and both CISPR publications 1 and 2 appeared in 1961. In 1953, a steering committee was formed to aid the chairman and SC C on Safety Aspects of Interference Suppression was added. In 1958 eight working groups were established. Reference [2] gives the status of work up to 1970 as follows:

- WG 1 on Radio Interference Measuring Equipment which until 1967 defined all measuring receivers from 10 kHz to 1000 MHz including publications 1 through 4.
- WG 2 on Interference from ISM Equipment. Radiated emission limits were published as recommendations in the frequency range 0,15 to 1000 MHz.
- WG 3 on Interference from Overhead Power Lines and High Voltage Equipment.
- WG 4 on Interference from Ignition Systems and Internal Combustion Engines. Until 1970, limits were given for 30 to 300 MHz. At this time, limits were also considered up to 1000 MHz. Limits for interference to radio reception on the vehicle itself were under discussion, but it wasn't until 1995 when CISPR 25 appeared.
- WG 5 on Interference and Immunity Characteristics of Audio and TV Receivers.
- WG 6 on Interference from Motors, Domestic Appliances, Lighting Apparatus and the like. Interference in the frequency range up to 300 MHz was a difficult item because different countries used different measurement methods, ranging from open site field-strength measurements, stop filter tuned supply cord substitution measurements, as well as earth current measurements to terminal voltage measurements. Finally, agreement was reached on a method proposed by Meyer de Stadelhofen of Switzerland, Chairman of the WG [6]. Limits were also approved for thermostatically controlled apparatus

(From left) Ray Garret, a member of the Australian organizing committee of the CISPR meetings held in Sydney in 2007, as well as a member of the Australian CISPR delegation, is shown with Don Heirman, newly elected CISPR Chairman; Dr. Ralph Showers, head of the US delegation to the CISPR plenary meeting in Australia and past CISPR Chairman; and Peter Kerry, outgoing CISPR Chairman from the United Kingdom.

emitting discontinuous disturbance, e.g. irons and refrigerators using the counting of clicks and applying click weighting.

- WG 7 on the Impact of Safety Regulations on Interference Suppression. The chairman of this WG was a member of the IEC Committee on Safety (A.C.O.S.).
- WG 8 on Statistical Methods and Correlation between Measured Value and Disturbing Effect. A recommendation on the Significance of a CISPR limit was approved in Leningrad (1970) which implied that type approval may be made on the basis of measurements of a single sample whereas conformity of production should be ensured on a statistical basis.
- WG 9 on Terminology which contributed a chapter to the International Electrotechnical Vocabulary (IEV).
- WG 10 on Lists of Complaints. This was necessary in order to harmonize the national lists of complaints for better comparability.

In the period of 1961 – 1973 CISPR saw the appearance of Recommendations in Pub. 7 (1966), Reports and Study Questions in Pub. 8 (1966) and National Specified Requirements and Legal Regulations in Pub. 9 (1966). In addition to the Pubs. 3 and 4, Pub. 5 specifying the peak, average and RMS detectors appeared in 1968. In 1973, CISPR was reorganized by reconstituting the WGs as Technical SCs, each with its own national secretariat, thus sharing the administrative burden which hitherto had fallen on the CISPR secretariat.

Don Heirman receives the prestigious Lord Kelvin award at the 2008 IEC General meeting in Sao Paulo, Brazil. The then president of the IEC, Jacques Régis (left) of Canada, presented the certificate and medal to Mr. Heirman. Don follows in the footsteps of another well regarded CISPR Chairman, Dr. Ralph Showers, who received the Lord Kelvin award in 1998. The award was first presented in 1995.

Period 1973 to 1986. In 1973, the decision was made to incorporate all measuring receiver details and the common measurement techniques into one publication (No. 16) covering the work of SC A and to create self-contained publications including reports, recommendations and limits and specialised measurement methods. Thus, Pubs. 11 to 15 came into existence on the subjects of ISM, motor vehicles, radio and TV receivers, household appliances and fluorescent lighting and covering the work of SCs B, D, E and F. The work of SC C on high voltage lines appeared at a later stage in Pub. 18. It had also become evident that digital electronic equipment, microprocessors etc. could be a serious source of interference to radio reception and this was recognised in 1975 by creating a working group reporting first to the steering committee and later to SC B. This working group was reconstituted in 1985 as SC G with the terms of reference to include Information Technology Equipment. SC G was responsible for Pub. 22, the first edition of which appeared in the same year, doing away with the problem of NB/BB discrimination and establishing for the first time limits for QuasiPeak and Average detections in conducted emission measurements. The first international commercial immunity product standard was published in 1985 - Pub. 20 for the immunity of sound and TV broadcast receivers - to which the Italian NC provided many contributions [7].

Period 1987 to 2004. In these years, much effort was expended in the development of CISPR Pub. 16 to become "The CISPR Handbook". Measurements in the field of EMC for a long time were known as an "estimation with expensive test equipment". Therefore, the work concentrated on improving the reproducibility of measurements by adding requirements for test site validations, requirements for measurement uncertainty and by improving the definitions of the test methods and setups. Major steps forward were the publications of CISPR 16-4:2002 on measurement uncertainty and of reports on compliance uncertainty in CISPR 16-4-1:2004. SC G developed the CISPR 24:1997 "Immunity of ITE", using the test methods in IEC 61000-4-x as basic standards. Also, SC F published CISPR 14-2:1997 "Immunity of Household Equipment, etc." In 1999, CISPR created a new SC H on the development of limits. In 2000, SC C was dissolved and the merging of SCs E and G was decided to form a combined SC I taking into consideration that multi-media equipment was in the scope of E and G. Most of the CISPR work is well described by the publications developed from the early 1990s until the present day:

10:2001-08	Rules and Procedures of CISPR (withdrawn with most of the material placed in Annex K of the Supplement to the ISO/IEC Directives)
11	Limits and measurement methods: ISM
12	Automobiles and ignition system emissions
13	Emission of sound and TV receivers
14-1	Emission of household appliances etc.
14-2	Immunity of household appliances etc.
15	Emission of fluorescent and lighting eq.
16	Equipment, methods and reports of EMC testing (16 parts)
17	Test methods of EMI filters
18	Overhead power lines, phenomena, limits, test methods, suppression (3 parts)
19	Microwave oven substitution measurement
20	Immunity of sound and TV broadcast receivers
21	Mobile radio reception in presence of impulsive noise
22	Emission of IT equipment
23	Determination of limits for ISM equipment
24	Immunity of IT equipment
25	Emission limits for radio reception in cars
28	ISM equipment – guidelines for emission
29	TR: Immunity of TV receivers – methods of objective picture assessment
30	TR: Test method on EM emissions from fluorescent lamps
31	Database on the characteristics of radio services

Generic emission standards:

CISPR 61000-6-3 Emission for residential, commercial and light-industrial environments

CISPR 61000-6-4 Emission for industrial environments

PERIOD 2004-PRESENT

CISPR continues to evolve with a focus on controlling the emissions from a wide variety of products as can be seen by the short descriptive titles of its publications noted above. A particular burst of activity has come from the need to expand the application to products that have multiple ways in which RF energy can be emitted. In addition, functions that heretofore were found in specific products have now been incorporated into modern consumer products. This has led to naming the merging of receivers and information technology into what is now termed "multimedia". At the same time, there are many ways in which communication can now be sent, such as by incidental emissions from a microprocessor, to intentional emissions for radio services, to conveying information over a telecommunication port, to signal and control over the mains network.

The major activity in the past six years has been in the following areas (this list is not meant to be exhaustive but to give a broad perspective of the types of ongoing activities):

1. Specifying new test facilities (and appropriate emission limits) including fully absorber lined rooms (FARs), reverberating chambers, absorber lined (over the conducting ground plane) open area test sites (called the free-space open area test site or FSOATS), TEM waveguides, and those that are to be used for antenna calibration.
2. Expanding measurement instrumentation uncertainty into compliance uncertainty in applying test standards.
3. Defining better test instrumentation calibration, especially the calibration of antennas used to measure radiated emissions from products being tested.
4. Specific measurement techniques for complex products that define those with multimedia application (generally comprised of ITE and receivers).
5. Determining the interference potential and ways to control it when signals are placed on telecommunications cables and the mains (this is referred to as powerline telecommunications or powerline communications - PLT or PLC).
6. Addressing the emissions from automobiles and the concern for handling the electric vehicle charging system to ensure acceptable disturbance levels to radio services.
7. Incorporating EMC into such mega projects as SMART GRID to ensure the interoperability of this system in controlling the use of power.
8. Continuing the application of product immunity appropriately based on basic standards published by the IEC Technical Committee 77 (EMC).

The list goes on including maintaining test methods and limits for ITE, appliances, RF lighting, and industrial/scientific and/medical equipment. For further information on CISPR, visit: http://www.iec.ch/dyn/www/f?p=102:17:0::::FSP_SEARCH_TC:cispr. This web site has several links under "CISPR Dashboard" to contact the chairman and subcommittee chairs to see publications issued, and so forth. A link is also provided that identifies the national committees which are members of CISPR. The site http://www.iec.ch/zone/emc/cispr_guide_09_2008.pdf provides guidance on the use of CISPR standards.

NEXT CISPR MEETING

To continue with all of its activity, CISPR works throughout the year mostly by electronic means and a smattering of face to face meetings. However, for conducting a full range of business, resolving major actions and reporting progress, an annual face to face meeting is held. At these meetings, over 200 technical experts and national committee representatives typically attend.

This year's CISPR meeting will be in the United States in Seattle, Washington during October 6-15, 2010. Over 20 countries will be sending delegates including, of course, the US. This meeting will be held in conjunction with the annual IEC General Meeting where the business of the IEC is conducted along with that of up to 100 technical committees. The host is the US National Committee of the IEC. They have graciously accommodated CISPR's request for meeting space and support to increase the success of the CISPR meetings. Attendees are assigned by their national committee as there is a need to clearly identify experts that are named by their national committee to participate.

SUMMARY

This article has brought up to date the history of CISPR and how its standards were developed with an indication when key events occurred along the way. Its history is rich in accomplishments and service to the international EMC standards community. Challenges still remain. But the authors believe that when the CISPR history is updated in the future, clear progress in its EMC standardization work will be evident by the wide spread use of its standards. ■

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Donald Heirman *is president of Don HEIRMAN Consultants – a training, standards, and educational electromagnetic compatibility (EMC) consultation corporation. He chairs, or is a principal contributor to, US and international EMC standards organizations including ANSI ASC C63® (chairman) and the International Electrotechnical Commission's (IEC) Special International Committee on Radio Interference (CISPR) where in October 2007 he was named the chairman of CISPR moving from his previous role as its Subcommittee A chairman responsible for CISPR Publication 16. He is a member of the IEC's Advisory Committee on EMC (ACEC) and the Technical Management Committee of the US National Committee of the IEC. In November 2008, he was presented with the prestigious IEC Lord Kelvin award at the IEC General Meeting in Sao Paulo, Brazil. This is the highest award in the IEC and recognizes Don's many contributions to global electrotechnical standardization in the field of EMC. He is a past president of the IEEE Standards Association (SA), past member of the SA Board of Governors and past member of the IEEE's Board of Directors and Executive Committee.*
Mr. Heirman may be reached at phone +1 732-741-7723 or by e-mail at d.heirman@ieee.org. For more information, visit www.DonHeirman.com.

Manfred Stecher *was born in Munich, Germany in 1942. He received the Dipl.-Ing. Degree in electrical engineering in 1967 from the Technical University of Munich. In 1967 he joined Rohde & Schwarz, Munich. He was engaged in the development of EMI and signal monitoring test receivers and field strength meters, became group leader in 1980, and was responsible for the development of test receivers and accessories - hard and software. Since 1985, he has been a member of various German national standardizing committees on EMI instrumentation and measurement methods and since 1990 he has been an active member of various CISPR Subcommittees (mainly CISPR/A on measurement equipment and methods, but also CISPR/D and /I) and has contributed to ITU-R Study Groups on radio monitoring (mainly Study Group 1). He retired from Rohde & Schwarz in 2007. Presently he is Chairman of CISPR/A, the CISPR Subcommittee on EMI measurement instrumentation and methods. He has published approximately 150 papers in the field of EMI and signal monitoring. He holds several patents and has been awarded the DKE needle and the IEC 1906 award for his standardization activities. He is a senior member of the IEEE EMC Society and has been awarded a Certificate of Acknowledgement for contributions to the development and standardization of EMC measurement techniques.*
He may be reached by phone at + 49-8177-8632 or by e-mail at Manfred.Stecher@rohde-schwarz.com.

Requirements of the
Automotive EMC Laboratory Recognition Program

BY WERNER SCHAEFER

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The Automotive EMC Laboratory Recognition Program (AEMCLRP) was established in 1998 by the three major automobile manufacturers in the United States, Chrysler LLC (Chrysler), Ford Motor Company (Ford) and General Motors (GM). These companies formed a committee responsible for the definition, documentation and maintenance of a set of EMC tests that an accredited and recognized test laboratory may perform in order to determine the EMC characteristics of automotive components that are integrated in vehicles by the three manufacturers. Since 1998, the AEMCLRP requirements document has been reviewed several times, and revision 4 (with an addendum issued in May 2007), the most current revision, has been used for the past four years. Future revisions are to be expected, due to improvements identified during the assessment process, feedback of laboratories or changes in underlying EMC specifications.

In order for a test laboratory to be recognized by the three manufacturers, a process has to be completed that consists of two major steps. In the first step, the applicant laboratory has to seek accreditation from a recognized accreditation body (e.g., A2LA in the US or JAB in Japan). In order to be accredited, the laboratory must implement and operate a quality system that meets the requirements of ISO 17025-2005. In the technical area, the laboratory will have to identify the specific AEMCLRP tests for which it seeks accreditation. For all the tests, performance history data will have to be submitted prior to the actual on-site assessment for review by the assessor and the AEMCLRP committee. During the on-site assessment, all test methods the laboratory seeks accreditation for are reviewed. This includes an inspection of the actual test setup, verification of suitability of test equipment and the test environment, as well as technical interviews of staff members identified as being competent to perform specific tests. Upon resolution of any deficiencies identified during the on-site assessment, accreditation is granted by the accreditation body. The second step the laboratory has to complete is the performance of proficiency tests for some of the AEMCLRP tests. This involves the testing of an artifact the laboratory is provided with by the committee. This artifact has to be tested in accordance with the related test method, (e.g., Bulk Current Injection – BCI) and the test data has to be submitted to the accreditation body within 1 month after receiving the artifact. The accreditation body will forward the test data to the AEMCLRP committee for a technical review. Based on the review results, the applicant laboratory will be recognized by the individual members of the AEMCLRP committee. It should be noted that the different companies may require the submission of additional documentation before the actual recognition is granted. The representatives of Chrysler, Ford and GM are to be contacted to determine these details.

The AEMCLRP requirements document serves as the basis for both the accreditation and recognition phases. It includes an appendix that defines general requirements a test laboratory has to meet (i.e., Appendix C) as well as separate appendices (i.e., Appendix D though M) for each of the test methods that are part of the AEMCLRP program. The various representatives of Chrysler, Ford and GM on the AEMCLRP committee are responsible for different test methods. The responsible manufacturer is identified as the "Appendix Owner" in each test method appendix. If questions arise about stated requirements, the appendix owner is to be contacted for clarification or guidance. The relevant contact information of each representative is listed on the cover page of the AEMCLRP program document.

This article will discuss the general requirements called out in Appendix C of the AEMCLRP document, as well as the most important details of technical requirements related to the test methods that are most often requested by laboratories for accreditation. An evaluation of these requirements, from an assessment point of view, will also be included to indicate possible areas of the technical review during the on-site assessment. The important requirements related to the quality system that a laboratory has to implement in order to obtain accreditation will not be discussed in this paper.

GENERIC REQUIREMENTS (APPENDIX C)

Appendix C of the AEMCLRP document states generic requirements that do apply to all test methods a laboratory seeks accreditation for. In general, there are three categories of requirements: Clause C.1 summarizes the prerequisites that have to be met before an on-site assessment can be considered. One requirement that is sometimes misunderstood is the necessity to submit written test procedures, per clause C.1.b. In accordance with this requirement, the laboratory has to prepare specific test procedures for each test method. The use of the underlying standard itself is not permissible since standards are often ambiguous, and therefore, require interpretation of details. The purpose of these written test procedures is to ensure the consistent interpretation of these requirements within the laboratory. Furthermore, performance history for each test method, in accordance with section 2.E of each test method annex, is to be submitted to the accreditation body for review. The purpose of this review is the determination of any unusual variances in test results or problems with the test system before the on-site assessment. Confidence has to be established that the test system and procedure that is in place is suitable to demonstrate the proficiency of the laboratory to perform specific tests. This requirement is called out in clause C.1.d. In addition, three different sample test reports of previously completed projects (for each test method) as well as completed test plans will have to be submitted to the accreditation body and to each AEMCLRP committee member company for review prior to the on-site assessment.

Appendix C, clause C.2 defines the method for the determination of the interference threshold. This principle is to be applied to all immunity measurements (e.g., Bulk Current Injection, radiated immunity measurements). It is therefore mandatory for each qualified test engineer to understand and correctly apply this method. A practical demonstration of the application, involving test control software, is usually required to ensure the proper understanding of this principle.

Clause C.3 of Appendix C defines further important requirements for test equipment and the technical management of the applicant laboratory. All test equipment that has an impact on the test result requires calibration. Calibration can be performed by a qualified external calibration laboratory (ideally one that is accredited for the work required to calibrate equipment) or internally. If calibrations are performed internally by the test laboratory itself, it should be noted that this internal calibration group must assume all responsibilities of an external calibration laboratory. There responsibilities include: evidence of traceability to national standards, provision of documented calibration procedures, determination of measurement uncertainty estimates for all parameters calibrated, provision of an adequate calibration environment (e.g., temperature and humidity controlled facility) and evidence of proper training of internal calibration personnel. Evidence of equipment calibration is to be provided in form of equipment records, specifically calibration certificates.

Other parts of a test system that do not require calibration (e.g., cable insertion loss) need to be verified over a predefined period. This means that the test laboratory must determine an adequate verification period and provide evidence of verification. Furthermore, each piece of equipment must be uniquely identified, per clause C.3.3, to simplify the identification of components if a repetition of tests is required or troubleshooting of the test system is required.

Any testing of devices under the AEMCLRP program requires an approved test plan. The main purpose of such a test plan is to document the testing parameters for the evaluation of an EUT in detail: for example, the acceptance criteria for immunity tests are specified, the exposure levels for immunity tests, the discharge points for ESD testing, the EUT test setup and the description of auxiliary equipment or simulators necessary to put the EUT in an operational state. These test plans have to be approved by a responsible representative of the three manufacturers (i.e., Chrysler, Ford and/or GM) before testing commences. The test laboratory must follow the documented details in the test plan and include relevant details in the final test report.

Clause C.3.6 calls out a requirement for a documented process that is to be followed by the laboratory to determine if auxiliary equipment or simulators are suitable for use in the test setups. This is of particular importance for immunity tests, since the laboratory must ensure that the auxiliary equipment used is working properly when the specified field strength is applied or an interference current is coupled into the test setup. It must be ensured that this auxiliary or monitoring equipment is not affecting the test results in an adverse manner. Similar considerations are to be applied for emissions testing. The emissions emanating from auxiliary or monitoring equipment, if required to be used inside the test environment, must be known and properly identified as such.

Clause C.3 also provides a very important table with applicable tolerances for all quantities, like length, time, voltage, current values and test parameters. These tolerances are applicable unless the test methods call out specific tolerances for a parameter, like for example, the supply voltage tolerance in clause 1.A.7 of Appendix D. The laboratory needs to pay close attention to these tolerances since they will be used during the assessment to determine both the proper test setup and correct performance of the test itself.

SPECIFIC TECHNICAL REQUIREMENTS (APPENDIX D - M)

General Remarks

In this part, requirements are summarized that are common to all test methods in Appendix D through M. For each test method, the laboratory must have the stated reference materials available. These consist of the generic standard(s) listed (e.g., ISO 10605 in Appendix D) as well as the specific manufacturer specifications, which are the internal standards of Chrysler, Ford and GM. If a laboratory seeks accreditation for ESD for example, but only for one or two of the three manufacturers, then only those specifications have to be available that will be accredited. The specific manufacturers are listed on the scope of accreditation of the laboratory that documents the accredited testing capability of the laboratory. It is important for a laboratory to demonstrate how the standards are kept current and how the laboratory keeps current with the developments in the responsible standardization organizations (i.e., ISO, IEC and the three manufacturers).

It is to be noted that the AEMCLRP document may make reference to the manufacturer's standards that have already been superseded. For example, the current AEMCLRP document Edition 4 (January 26, 2006) references Chrysler document DC-10614 and Ford document ES-XW7T-1A278-AC. These documents have been superseded by Chrysler document CS 11809 (issued on June 4, 2009) and Ford document EMC-CS-2009 (issued on September 30, 2009). All assessments under the AEMCLRP program, however, will be performed against the manufacturer's specifications that are cited in the AEMCLRP document, until further notice from the manufacturers. Chrysler specifically agreed to have the document DC-11224 (issued in June 2007) to be part of the AEMCLRP document, replacing DC-10614. If a test laboratory seeks accreditation to the manufacturers specifications other than those currently listed in the AEMCLRP document, then the assessment will have to be performed outside the AEMCLRP program, and the listing of these automotive EMC methods on the scope of accreditation will not be under the AEMCLRP program.

For each test method a "Configuration Control List" is to be prepared that itemizes each of the major elements of a test system. This list is used during the assessment to verify the validity of the previously submitted performance history data and to evaluate the capability of performing the actual test method. It is to be noted that if one test method is to be performed in two or more locations (e.g., ESD testing is performed in three different shielded rooms in a laboratory), each test setup requires the preparation of a configuration control list as well as a review during the on-site assessment. The test location in the laboratory will be stated on the scope of accreditation.

The supply voltage for the EUT is to be verified by the laboratory to meet certain values (e.g., 13 V ± 1 V). This verification is to be performed under load conditions, meaning, with the EUT connected and operating as intended. This monitoring is to be performed on an on-going basis while the test is being performed.

Environmental parameters for temperature and humidity have to be determined before testing commences. The laboratory must ensure that the stated ranges for these parameters are met while testing is performed.

ESD Test Procedure – Appendix D

The ESD test procedure is divided into a general part and parts specifically related to the individual manufacturer's requirements. All manufacturers require that the ESD generator be verified by the laboratory in accordance with ISO 10605 (2001). Close attention is to be paid to the verification of the RC time constant. This determination is to be made differently for the Ford requirements. Here, the RC time constant is to be determined on the part of the waveform that is exponentially decaying and exposes minimum amount of ringing. The RC time constant requirement, per ISO 10605 clause A.2.3, is to be determined with reference to the second maximum I_{p2}.

Grounding in general often presents a problem in the laboratory. This applies to the bonding of horizontal coupling planes in case they consist of multiple metal sheets or grounding of horizontal coupling planes (HCP) to a ground plane. In order to ensure repeatable results, adequate grounding is required. One Figure of merit is a DC resistance of 2.5 mΩ that can be used to determine the suitability of

EMC

a bond. Furthermore, an adequate length to width ratio of grounding straps on less than 7:1 (per errata sheet to the AEMCLRP document revision 3) can be selected, with a ratio as low as possible.

The ESD test procedure in accordance with Chrysler specifications is deviating very significantly from the procedure called out in ISO 10605 (2001). For this reason the laboratory must carefully study all details in the Chrysler document to ensure the proper test setup and repeatable performance of the test. For **handling tests** (un-powered EUT) in accordance with Chrysler specifications, the position of the ESD generator power supply must be more than 50 cm away from the EUT, and the ground reference of the generator must be connected to the HCP at a point 50 cm from the EUT. Furthermore, evidence is to be provided by the laboratory that the ESD generator voltage is verified each time a test series commences. This verification is to be done with an electrometer with an input impedance of greater 1 GΩ. The removal of the charge between two individual discharges is specified in detail and varies somewhat from the approach outlined in ISO 10605 (2001). The charge has to be removed by contacting the bleed-off resistor to the discharge point **and** the housing of the EUT. Alternatively, a 5 s waiting period between individual discharges has to be implemented in order to sufficiently remove the charges from the EUT.

There are two ESD operating tests described in the Chrysler specifications: the direct coupled and field coupled tests. For the direct coupled test, an ESD simulator, in accordance with IEC 61000-4-2, is to be used (although the latest Chrysler document CS-11809 now references ISO 10605). A specific test fixture is to be provided by the laboratory that meets the requirements called out in clause 10.2.2, Figure 32. Attention is to be paid to the proper grounding of the ESD generator to the defined point at the ESD coupling plane. Furthermore, the EUT grounding and battery grounding points are defined in Figure 32 and grounding is to be implemented accordingly. Finally, the ground plane is required to have a 0.5 m separation from any wall or conductive surface of the test chamber.

The field coupled test requires a discharge network of 330 pF and 330 Ω for testing. It is to be noted further that no discharge is to be applied directly to the harness; discharges have to be applied to the discharge islands of the fixture and only to the parts that are not occupied by the harness. If the test harness is made up of more than 40 lines, the harness bundle shall be flipped over (180 degrees), and the field coupled test is to be repeated.

Conducted Emissions Test Procedure (CISPR 25) – Appendix F

The conducted emissions test procedure, per CISPR 25 (2002), consists of two parts: a voltage measurement using Artificial Networks (ANs) and a current measurement using a current probe. Under the AEMCLRP program only Chrysler requires a current measurement. In general, these measurements have to be made with an EMI receiver that conforms to the specifications in CISPR 16-1-1 (a spectrum analyzer cannot be used for this test). The impedance characteristics of the ANs used have to be verified by providing calibration certificates. Furthermore, the ANs have to be properly bonded to the ground plane by bonding them to the ground plane or providing a very low impedance bond in the form of a strap or even copper tape. The ground plane that is placed on top of a table is to be bonded to the shielded enclosure itself with straps that are no further apart than 30 cm. A sufficient length to width ratio is to be considered for these straps as well (see above).

Clause 1.A.9 of Appendix F states that the measuring cable is to be fed through a bulkhead connector in the shielded room. This clearly indicates that all measuring equipment is to be placed outside the shielded room – not within the measurement environment itself. Furthermore, measurements of the ambient levels have to be made. A test system is deemed suitable for this measurement if the ambient levels are 6 dB or less below the applicable limit (narrowband and broadband). It should be noted that the ambient measurements are to be performed with the same IF bandwidth setting as the actual measurement of the EUT. Only in this case can a proper comparison of the ambient signal levels to the emission limits be made.

The test setup for a specific EUT may involve a second AN, depending on the grounding of the EUT. If the EUT is remotely grounded, (i.e., the ground lead length exceeds 20 cm) then a second AN is to be used, per CISPR 25. The second AN is not necessary if the EUT is locally grounded.

For the current measurement, the current probe has to be positioned at defined locations (50 cm and 100 cm from the EUT connector). It should be noted though that the reference for this distance on the current probe side is not defined. This may cause repeatability issues, especially in the higher frequency range. For that reason, the laboratory should define the reference at the current probe and consistently perform the measurements that way.

Radiated Emissions Test Procedure (CISPR 25) – Appendix G

Radiated emissions measurements have to be performed inside semi-anechoic chambers. The suitability of these chambers is stated as a requirement of reflectivity in the test area (i.e., the area the EUT is set up in). However, there is no clear guidance as far as the measurement of the reflectivity parameter is concerned. For that reason, the AEMCRP committee decided to accept a chamber if the 3 m NSA data meets the requirements of the theoretical NSA. As an alternative, the chamber manufacturer's reflectivity specifications for the absorbing material used can be provided as evidence of the suitability of the test chamber. Both alternatives are somewhat questionable from a technical standpoint, since the test distance for radiated emissions measurements is not 3 m but 1 m, and the NSA requirement only covers the frequency range up to 1 GHz. The manufacturer's reflectivity specifications are usually determined using the assumption of a straight incident wave that travels through the complete depth of the absorbing material. This is obviously the best case scenario and the reflectivity of the absorbing material will assume the lowest numbers. However, at present, the suitability of the semi-anechoic chamber can be validated by the laboratory using these two approaches.

The calibration of antennas is a crucial point that directly affects the measurement results and the repeatability of the measurements. The laboratory must ensure that broadband antennas like biconical, logarithmic-periodic or horn antennas are calibrated in accordance with SAE ARP 958. Any other antenna calibration method will result in different antenna factors that will yield different test results. Evidence of the correctly applied method can be found in antenna calibration certificates that need to clearly state the standard used for the calibration of the antennas. For horn antennas, the reference point for the calibration is to be in the plane of the aperture of the antenna, not the feed point. Rod antennas are to be calibrated using the Equivalent Capacitance Substitution Method (ECSM), per CISPR 25 (2002), Appendix E.

The determination of the antenna height is relative to the height of the setup table – not relative to the floor of the chamber. This specification often leads to deficiencies. For example if the table height is 94 cm (which is within the specified tolerance), then the permissible antenna height range is from 103 to 105 cm. In addition, it is to be ensured that no radiating element of the antenna (in both horizontal and vertical polarization) is closer than 25 cm to the floor and 2 m to the ceiling or the wall of the chamber. Furthermore, the radiating elements must be no closer than 1 m from the absorbing material in the chamber.

Clause 1.A.24 in Appendix G states that the measuring cable is to be fed through a bulkhead connector, meaning that all test equipment is to be placed outside the semi-anechoic chamber. This requirement may lead to the use of preamplifiers, especially for the frequency range above 1 GHz, because of limitations introduced by cable losses and relatively high antenna factors. The laboratory must show that the test system provides enough sensitivity for the measurement by providing noise floor measurements that indicate the noise floor to be at least 6 dB below the applicable limit.

A Ford specific requirement states in clause C.2 that a process for the determination of overload conditions of the test receiver is to be implemented and applied during the test. Despite the fact that the requirement is only applicable when amplifiers are used with a gain of larger than 30 dB, it is good measurement practice to ensure linearity of the receiver **and** the preamplifier during each measurement. The application of this process is essential in order to avoid erroneous test results.

For measurements according to GM specification GMW 3097, EUTs are to be measured in three orthogonal orientations. The orientations of the EUT for these measurements are to be defined in the approved test plan.

Bulk Current Injection Test Procedure – Appendix I

The setup for BCI test procedure requires insulation of the current probe from the ground plane and positioning of the probe in two or three predetermined locations along the harness. Usually, a fixture is provided by the laboratory, made out of Styrofoam, that allows meeting both the insulation and positioning requirement. The positioning of the probe is referenced to the outermost edge of the EUT connector and not the casing of the EUT. On the current probe side, the distance is to be referenced to the center of the current probe, not the edge closest to the EUT. Furthermore, it is to be observed that the test harness is centered in the current probe itself, which can be achieved by providing slotted Styrofoam pieces that keep the harness centered during the measurements.

The injection current used to perform the test is to be established during a calibration process, involving a test fixture. The control parameter for the actual measurement of the EUT is to be the forward power. This means that the forward power is to be used to adjust the current level for the EUT measurement, such that the predetermined levels of the calibration process can be re-created. The forward power levels have to be established and will be reviewed during the on-site assessment.

In clause 1.D.7, it is stated that measures have to be taken to avoid the coupling of RF energy into the test area. This means that the test equipment is to be placed outside of the testing area.

For measurements in accordance with the GM standard GMW 3097, all simulator equipment is to be placed inside the shielded room along with the EUT. In addition, monitoring equipment must be connected with high impedance connections to avoid an adverse impact on the test results. This is a rather important point to be observed since many proficiency test results are negatively impacted by the use of improper connections of the monitoring equipment. In accordance with GM, Ford and the latest Chrysler specifications, two different types of measurements are to be performed: in the frequency range below 30 MHz, differential mode testing is required. This means that the ground (return) lines are routed outside the current probe. In the frequency range above 30 MHz, these return lines are to be routed through the current probes, along with all other lines of the harness.

Absorber-lined Shielded Enclosure Test Procedure – Appendix K

The laboratory must define which type of test accreditation is sought. The main difference is the use of metallic versus non-metallic bench. The use of the non-metallic bench is only permissible for tests in accordance with Chrysler specifications. Furthermore, the laboratory must state which type of modulations can be applied during the test (i.e., CW, AM and pulse) and which frequency range and field strength levels are available based on the test equipment. These parameters will be stated on the scope of accreditation to correctly reflect the capability of the laboratory.

Radiated immunity tests have to be performed inside semi-anechoic chambers. The suitability of these chambers is stated as a requirement of reflectivity in the test area (i.e., the area the EUT is set up in). However, there is no clear guidance as far as the measurement of the reflectivity parameter is concerned, similar to the situation discussed for radiate emissions measurements in *Radiated Emissions Test Procedure (CISPR 25) – Appendix G*. For that reason, the AEMCRP committee decided to accept a chamber if the 3 m NSA data meets the requirements of the theoretical NSA. As an alternative the chamber manufacturer's reflectivity specifications for the absorbing material used, can be provided as evidence of the suitability of the test chamber. The same concerns that were outlined in *Radiated Emissions Test Procedure (CISPR 25) – Appendix G* apply to this approach.

The E-field probes used to establish the test field strengths during a calibration process must meet a stated isotropicity specification. Evidence can be provided through manufacturer's specifications and subsequently by providing calibration certificates that include a calibration of the probe for isotropicity. It should be observed that the manufacturer's approach for the calibration of the isotropicity is to be used during subsequent calibrations. This includes the knowledge of the frequency and orientation of the probe for this part of the probe calibration.

In clause 1.A.14, it is stated that the cable that connects the signal generation system to the antenna is to be fed through a bulkhead connector. This again requires that the test equipment is to be placed outside the test area. Any deviation the laboratory tries to implement (for example, placing amplifiers close to the antenna inside the chamber) is to be approved by the AEMCLRP committee. The assessor will have to cite a deficiency if equipment is placed inside the chamber, but upon approval of the AEMCLRP, this deficiency will be considered addressed.

For testing with a **metallic bench,** it is to be ensured that the closest antenna element is located more than 25 cm from the floor for both polarizations and more than 150 cm from the walls and ceiling of the shielded room. Based on the antenna type used, this will require a certain minimum size for the shielded room. A calibration process using calibrated E-field probes is to be performed to establish the power levels necessary in order to achieve the stated E-fields for EUT testing. The control parameter to be used for adjustment of the levels during the EUT test is the forward power.

For testing with a **non-metallic bench** in accordance with Chrysler specifications, the calibration process is similar to the one defined in IEC 61000-4-3. A uniform E-field plane is to be established, and this is positioned in the location the harness is to be placed. For this type of test, the EUT is to be placed on a bench made from Styrofoam (or another material with a low permittivity). In addition, the EUT is to be tested in three orthogonal planes that are to be defined in the approved test plan. Lastly, the laboratory must provide a fixture so that the E-field probes can be positioned in a repeatable manner during the calibration process. This is also a requirement for metallic bench testing in accordance with clause 1.C.7 (testing in accordance with Ford standard ES-XW7T-1A278-AC). This will greatly enhance the repeatability between calibration processes.

In addition, for Ford specific tests, the laboratory must determine the harmonic content of the test signal at the output of the power amplifier. This test is to be performed at the frequency which requires the highest input level to the power amplifier. The calibration files have to be evaluated in order to determine this frequency, and the input power level to the amplifier has to be selected when performing this measurement. The stated requirement of 20 dBc for the harmonics has to be met at this frequency.

An additional requirement based on the antenna aperture is documented in clause 1.D.11 for GM specific tests in accordance with GMW 3097. The antenna used for testing has to be selected such that the aperture of a horn antenna, or in an approximation, the length of the largest radiating elements of a logarithmic-periodic antenna, will meet the stated far field condition of (2*d2)/λ. The laboratory must investigate if the antenna used for radiated immunity testing meets this requirement. If deviations are considered, the AEMCLRP committee will have to specifically approve the use of antennas that do not meet this requirement.

Absorber-lined Shielded Enclosure Radar Test Procedure – Appendix M

An addition to the radiated immunity procedure described in Appendix K is the procedure for radiated immunity testing where radar pulses are simulated. These tests are only applicable to Ford and GM specific tests (although Chrysler also utilizes radar pulse modulation in their specifications). The laboratory must perform a field characterization, per clause 1.C.5, utilizing a horn antenna pulsed amplifier. This verification method requires use of one of a predefined group of receiving antennas. If another antenna is to be used, specific approval of the AEMCLRP committee is to be obtained. The following additional requirements will have to be met during testing for the verification of the pulsed E-field:

a) The phase center of the antenna is positioned 125 mm above the surface of the dielectric support used during actual testing

b) Forward Power shall be the reference parameter for characterization of the field

c) Calibration at lower field strengths with subsequent power scaling for higher field strengths is not permitted

d) Pulse modulation characteristics shall conform to that illustrated in Figure 4. The maximum RMS forward power (Ppulse) used for pulsed modulation testing, shall be the same as the CW calibration power (P_{CW_CAL}) (i.e. $P_{PULSE} = P_{CW\_CAL}$).

SUMMARY

The AEMCLRP program provides a comprehensive set of quality-related and technical requirements for the accreditation and recognition of EMC test laboratories. For a test laboratory to successfully complete the accreditation and recognition steps of the overall process, the applicable manufacturer's specifications and underlying automotive ISO standards are to be studied in detail, and the implementation of these requirements are to be checked. Hands-on testing experience is necessary in order to successfully demonstrate proficiency of performing the tests the laboratory seeks accreditation for. In addition, the preparation of performance history for tests will help demonstrate the repeatability of the test equipment and parts of the test setup and test environment. All these elements will be evaluated by the assessor during the on-site assessment. If the laboratory has reasons for deviating from stated requirements, the assessor will have to cite a deficiency if no written approval from the AEMCLRP committee is available. This approach ensures that deviations are directly approved by the AEMCLRP committee and are therefore consistent and not dependent on the assessor. This type of approval by the AEMCLRP committee can be sought by the laboratory before the on-site assessment to avoid cited deficiencies or after the on-site assessment as a response to documented deficiencies. ■

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Werner Schaefer *is a compliance quality manager and technical leader for EMC and RF/uwave calibrations at Corporate Compliance Center of Cisco Systems in San Jose, CA. He has 25 years of EMC experience, including EMI test system and software design, EMI test method development and EMI standards development. He is the chairman of CISPR/A/WG1 and a member of CISPR/A/WG2 and CISPR/B/WG1. He also is the US Technical Advisor to CISPR/A and a member of ANSI C63, SC1/3/5/6/8, and serves as an A2LA and NVLAP lead assessor for EMI and wireless testing, software and protocol testing and RF/microwave calibration laboratories. He also serves as an ANSI representative to ISO CASCO, responsible for quality standards like ISO 17025 and ISO 17043. He is a member of the Board of Directors of the IEEE EMC Society.*

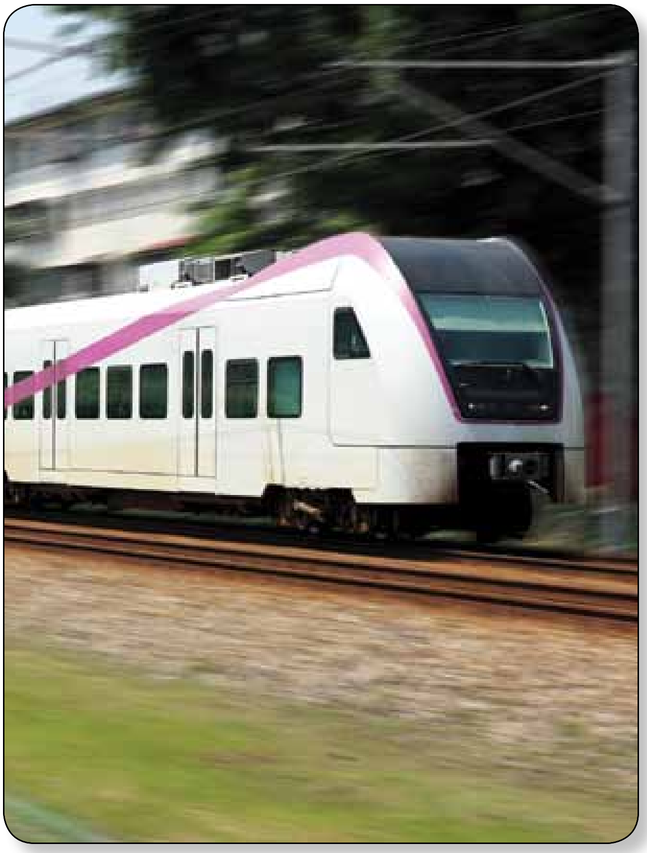
He was actively involved in the development of the new standard ANSI C63.10 and the latest revision of ANSI C63.4, mainly focusing on test equipment specifications, use of spectrum analyzers and site validation procedures.

Werner Schaefer is also a RAB certified quality systems lead auditor, and a NARTE certified EMC engineer.

He published over 50 papers on EMC, RF/uwave and quality assurance topics, conducted numerous trainings and workshops on these topics and co-authored a book on RF/uwave measurements in Germany.

EMC and Railway Safety

BY CHRIS MARSHMAN
AND NICK WAINWRIGHT



The railway environment is generally regarded as a "severe" electromagnetic environment. For an electrified railway, Megawatts of power are required to be converted into the propulsion of trains in order to transport passengers or freight from one destination to another. The railway presents a complex electromagnetic environment made up of many systems including signalling, traction, telecommunications and radiocommunications.

Electromagnetic Compatibility (EMC) between electrical and electronic systems is an essential requirement for the reliable and safe operation of the railway. It is all too apparent that interference from traction power equipment may affect the signalling system with potentially dire consequences. The railway industry strives to reduce the risk of such incidents occurring through processes of hazard identification and risk mitigation. Electromagnetic compatibility forms an essential part of these processes. So in the UK, EMC is one of the requirements included in the Safety Case for the introduction of new rolling stock, locomotives or track maintenance vehicles onto the rail network.

The key EMC problem for the railway industry is the multi-use of the rail itself. In the 1840s the rails were simply a mechanical guidance system. The advent of electricity prompted the signalling engineer to invent train detection systems within track sections, involving using the rail as an electrical conductor. Today we have the situation where the rail is the guidance system, the return power conductor in ac or dc railway electrification schemes and is also being used as a conductor of low power level coded signals for the signalling system (track circuits). The interference problem is compounded by the introduction in recent years of inverter driven ac traction motor drives that have to be compatible with "legacy" equipment, for example in the UK, the type "R" reed signalling circuits introduced in the 1950s operating at 300-400Hz.

THE EUROPEAN EMC DIRECTIVE

The EMC Directive (2004/108/EC) [1] and, for example, the implementing UK regulations (SI 2006 no. 3418) [2], have an impact on the whole Railway. The railway is defined as a "fixed installation" under these regulations and the "good [EMC] engineering practices" used for the installation of equipment must be documented and held by a "responsible person" and be available to the enforcement authorities whilst the fixed installation remains in operation. The definition of "responsible person" will affect contractors and infrastructure controllers; it will require clarification in contracts for the hand-over of responsibility and of documentation.

Whilst the EMC Directive itself is not a "safety" directive, the management of the EMC documentation provides for a record to be maintained of the EMC of the railway and as such provides a model that can be adopted outside of Europe.

The Directive also affects equipment manufacturers. All equipment carrying the CE marking requires "technical documentation" to be prepared, equivalent to the Technical

Construction File under the previous EMC Directive 89/336/EEC. The manufacturer, at his option, can choose for this to be assessed by a third party Notified Body.

It is therefore essential to manage EMC to meet the technical, safety and legal requirements from project concept by implementing an EMC Management Plan. Subsequently EMC testing must be carried out to verify that EMC has been achieved.

EMC RAILWAY STANDARDS

The legally binding EMC Directive has forced many sectors of the electrical/electronics industry to consider EMC and to review the procedures taken to ensure EMC between electrical/electronic systems and the correct operation of external radiocommunications and broadcast services; the railway industry is no exception. Building on the Railway Industry Association EMC standards RIA 12 and 18, CENELEC has produced a whole raft of EMC standards for Railways.

The European EN 50121 parts 1-5 [4] were introduced in 1995 as pre-standards, were adopted in 2000 and the 2006 version became fully effective from July 2009. Manufacturers may assess their products against the EN 50121 series of standards as a means of demonstrating compliance with the Directive. These standards have also found international acceptance resulting in their implementation in equipment specifications from Hong Kong and Singapore for example.

The key concept of the EN 50121 standards is that they attempt to achieve EMC within the railway environment and also confer EMC between the railway and the "outside world." The disclaimer is included within this series of standards that EMC is likely to be achieved if the standards are met, but that, because of the complexity of the environment, EMC cannot be guaranteed.

The 50121 series of standards is subdivided into 6 parts, covering different aspects of the railway environment. The structure of the standards and the way in which they are subdivided has not changed since the original publication.

EN50121 comprises the following parts:

- EN50121-1 General
- EN50121-2 Emission of the whole railway system to the outside world
- EN50121-3-1 Rolling stock – Train and complete vehicle
- EN50121-3-2 Rolling stock – Apparatus
- EN50121-4 Emission and immunity of signalling and telecommunications apparatus
- EN50121-5 Emission and immunity of fixed power supply installations and apparatus

Each standard calls up "basic" EMC standards for the measurement methods.

It should be noted that EN 50121 parts 2, part-3-1 and part 5 require "on-site" testing where the measurement environment does not have the same degree of control as for laboratory testing.

The EN 50121-X series of standards represents what can be agreed in relation to EMC in railways by CENELEC. Similarly the IEC 62236-x series of standards represents what can be agreed at an international level. However, because of the adoption of a wide range of technologies and the retention of "legacy" equipment within railways around the world, it is apparent that these international standards represent the minimum requirement to achieve EMC and that other "local" measures will be required. In many cases, these national standards build on the requirements of EN 50121 such that the resulting standard more adequately reflects the requirements of a particular part of the railway.

In 2002, Network Rail and the Railway Standards and Safety Board (RSSB) published a new group standard; GE/RT 8015 – **Electromagnetic Compatibility between railway infrastructure and trains.** This standard mandates the requirements for the management of EMC between the railway infrastructure and trains to enable safe operation to be assured.

Similarly, in 2000 London Underground Limited (LUL) published its own EMC standard and in particular document M1027 A2, a manual of EMC best practice, which defines and clarifies the key EMC requirements for all types of new, modified and "off the shelf" systems. It also defines the requirements for the EMC Control Plan, Test Plan and Test Reports. The latest versions of these LUL documents are respectively: standard 2-01018-001/1-222 A1 and manual of best practice 5-01018-001/G-222 A1

EN 50155 - Railway applications: Electronic equipment used on rolling stock is a standard which has caused much confusion over the years with manufacturers, primarily because this standard too contains EMC requirements.

The intention of EN 50155 was that it would be a product performance standard rather than a standard used for CE marking purposes; that was the remit of EN 50121. EN 50155 was, however, a contractual requirement for some manufacturers and therefore had to meet the EMC requirements of both EN 50155 and (usually) EN 50121-3-2.

THE RAILWAY AS A FIXED INSTALLATION

Fixed installations (FIs) are assemblies of various apparatus and other devices, carrying the CE Marking, installed and/or constructed "applying good engineering practices" and intended to be used permanently at a pre-defined location within the EU (e.g. electricity distribution networks, telecoms networks, large machinery and assemblies of machinery on manufacturing sites). An FI is not subject to conformity assessment, but it must, however, meet the protection requirements. The "good engineering practices" shall be documented and the documentation held by "person(s) responsible" for inspection by the national authorities for as long as the FI is in operation.

The railway clearly meets the definition of a fixed installation.

The Competent Authority may request evidence of compliance of the FI with the protection requirements and, when appropriate, initiate an assessment. Member States are required to set out the provisions for the identification of the person(s) responsible for the compliance of a FI; this is simply reinforced by the Commission's guide to the directive [3]. Under the UK regulations a "responsible person" means "…in relation to a fixed installation, the person who, by virtue of their control of the fixed installation is able to determine that the configuration of the installation is such that when used it complies with the essential requirements" [2]. If a FI is identified as an unacceptable source of emissions, a Competent Authority can request that the responsible person bring it into compliance with the protection requirements.

Since the constituent apparatus of the fixed installation will conform to the EMC Directive and this conformance is likely to have been demonstrated by compliance with harmonized standards, then, the Commission argues, the EM environment of the fixed installation is defined, allowing for addition of apparatus employing "rapidly changing technologies" itself conforming to harmonized standards. This is consistent with the EN 50121 standards [4], which cover all the constituent parts of the railway.

Where apparatus is designed and built for incorporation into a specific FI and is not otherwise commercially available, it is not required to undergo formal conformity assessment procedures. The manufacturer may choose to either follow conformity assessment procedures or to provide accompanying documentation detailing the name and site of the FI and the EMC precautions to be taken for the incorporation of the apparatus in order to maintain the conformity of the installation. The manufacturer must also provide identification of the apparatus and his name and address, or the name and address of his authorized representative (if the manufacturer is outside the EEA) or the person within the Community responsible for placing the equipment on the market.

THE IMPACT OF THE FI REQUIREMENTS ON THE RAILWAY

Railway infrastructure controllers will need to appreciate the implications and implement policy.

In the case of new build the "responsible person" will be the Prime Contractor who will oversee and coordinate all collaborators/suppliers, EMC installation and approvals documentation. After commissioning and hand-over, the infrastructure controller will become the responsible person e.g. Chief Engineer/Technical Director, who will arrange to hold all the EMC documentation. This documentation will be "living" documentation; as upgrades occur, information will be added.

For existing build, the new EMC Directive is not retrospective. Therefore the EMC documentation will be built up over time by upgrading project documentation, plus any existing data/documentation.

So the questions remaining are:

- How will it be put into practice?
- Will there be enforcement?
- Are there benefits?

Suggested scenarios for possible implementations have been outlined in the article.

Enforcement action seems unlikely, since Competent Authorities have shown little appetite to enforce the EMC requirements for products. The latter should actually be easier under 2004/108/EC with the new requirement for Technical Documentation (TD) retention, as authorities can demand to see the TD, not just a Declaration of Conformity (DoC). We shall wait with interest!

There are benefits. The FI requirements lend weight to the need for a structured approach to EMC encompassing safety aspects, interoperability and EMC Directive conformance. This model can clearly be used in non-EU countries as a means of demonstrating EMC assurance for railways.

It should be noted that the FI regulatory regime came into effect in July 2007. The FI documentation, based on recording "good engineering practices," includes initial EM site surveys to benchmark the environment, EMC Management Plans, hazard identification, the use of compliance matrices and in many instances on-site testing to verify that the measures undertaken ensure that EMC has been achieved.

EMC MANAGEMENT

In order to achieve EMC for railway equipment it is necessary to include EMC as a design parameter from the concept stage of a project. It is also necessary to control the design process to ensure that the documentation is produced which will support and be included within the Safety Case to cover the EMC aspects of safety and which will enable the manufacturer to declare conformance with appropriate EMC regulations.

The first stage of this process is to include EMC as a requirement within the Invitation to Tender (ITT) and to include an EMC specification. At this stage it may simply define the EN 50121-x:2006 series of standards plus the appropriate infrastructure standards eg RSSB Group standards such as GM/RC 1500, GM/RT8015 or the London Underground standard 2-01018-001/1-222 A1 and manual of best practice 5-01018-001/
G-222 A1.

The main contractor will then produce an EMC Management Plan (also known as an EMC Control Plan or EMC Strategy Document) which should be drawn up at the commencement of the project and typically will include:

- A hazard identification (HAZID): an identification of the likely sources of interference from the equipment that will affect other equipment in the operating environment; an identification of the sources of interference in the environment affecting or likely to affect the system;
- A listing of references: for example, the appropriate EMC regulations, customer specifications, standards, or in-house specifications;
- The EMC management rationale;
- Definition of responsibilities of the prime contractor and his suppliers;
- Control of suppliers: this may include the requirement for each supplier to produce an EMC plan and to demonstrate compliance;
- "Whole system EMC management," declaring the overall intention of managing EMC by design, identifying particular areas of concern;
- Deliverable documentation;
- EMC time management: identification of milestones e.g. on-site whole system EMC emission tests, for incorporation into whole project plan.
- Appended to the EMC Management Plan will be the EMC design guidelines and practices used by the prime contractor.

For a large system, whilst it will be necessary to perform some EMC measurements on the whole system, initially it is necessary to identify the various electrical sub-systems and determine the procurement policy from suppliers. In this instance a reasonable approach is to task each sub-contractor with providing documentary evidence that his product is compliant with appropriate standards.

As indicated by the management plan, each supplier will be responsible for demonstrating that his equipment meets the EMC requirements specified and will submit his EMC Control Plan, Test Plans and Test Reports to the system contractor who will include these within the system EMC Technical Documentation. It is then necessary for the system manufacturer to validate, from an EMC viewpoint, the installation and wiring techniques he has used. This will be partly by reference to the management plan, which lays down the essential EMC working practices, by reference to the Quality Assurance procedures for the contractor's organization, but also verification, by whole-system EMC emission tests.

Immunity testing may be largely impractical on-site for large systems and reliance must be placed on the integrity of the immunity testing performed on the individual items of apparatus or systems and

EMC

the installation practices used. It is vital that the installation practices must ensure that the integrity of the sub-system immunity is maintained, whether by using for example, screened cables, cable separation, or grounding and bonding techniques. Hence good communication is required between supplier and main contractor to ensure the flow of information. It should be noted that for European apparatus carrying the CE Marking it is a legal requirement to provide the user with "user information," covering installation and operation of equipment.

A NOVEL TECHNIQUE FOR MEASURING EMISSIONS FROM HIGH SPEED TRAINS

The EN 50121-2 and EN 50121-3-1 require emissions to be measured from moving trains from a single observation point at the side of the railway. The measurements need to be made using a peak detector since the "window of opportunity" to make the measurement is very small and is derived from the beam width of the antenna, the scan rate of the measuring instrument and the speed of the train. This means that transient emissions, such as those due to pantograph bounce or shoegear gapping are included in the actual measurement.

The standard limits are derived from such measurements which mean that potentially a manufacturer of rolling stock can produce continuous emissions up to these limits and so we may have "noisier" trains than in the past! Also the standards require individual train passes for different frequency ranges, a time consuming and expensive operation, usually requiring the measurements to be made on a test track or on the network during a possession.

CONCLUSIONS

For EMC assurance for equipment or large installed systems, within the railway environment, a practical approach has been described which relies on rigorous testing of sub-systems and the verification of installation and design practices by a combination of managing EMC from the outset, QA procedures and whole system emission testing accepting practical limitations.

This approach can be seen to fulfill demonstration of the essential protection requirements of the EMC Directive, in Europe, in relation to effect of the system on the external environment, the need to control the internal EMC within the system and the manufacturer's need to satisfy a court that he has used all due diligence to avoid committing an offence.

Further the EMC Technical Documentation and the incorporated test data can be used to support the EMC aspects of the equipment/system Safety Case and in the case of signalling projects, for example, the documentation can be added to the EMC "Fixed Installation" documentation for the railway. It must be stressed that the railway EMC standards represent the minimum technical requirement and that additional measures may need to be taken on the basis of the hazard identification and risk closure.

The technical difficulties of making EMC measurements on moving trains have been addressed and a cost effective solution referred to.

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Chris Marshman *is the Managing Director and* ***Nick Wainwright*** *the Operations Director of York EMC Services Ltd, operating three UKAS accredited EMC testing laboratories and BIS appointed Notified Body. YES Ltd provides EMC consultancy, testing and training services to the railway industry. They can be reached by phone at +44(0)1904 434440 or at enquiry@yorkemc.co.uk.*

ITE Requirements Around the Globe

BY JOHN MAAS

EMC

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 cases, 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 (DOC verification, certification)
- Product 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, 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. Classification of the product with respect to the regulation (for example, Class A or Class B for EMC emissions test results)
3. Description of the device being tested for approval, including marketing designation or model number
4. Product specification sheet describing its functions and capabilities
5. Functional block diagram
6. Specific identification of the device that was tested, including serial number and detailed list of all hardware content
7. Description of software used to exercise the unit being tested
8. Measuring equipment, including bandwidth and calibration details
9. Test results
10. Description of any changes required during testing to meet the test limits
11. Photographs of the test setup
12. Photographs of the device being tested
13. Diagram of the physical arrangement and configuration of the unit tested
14. Drawing or photograph of the product label showing required marking(s) and location of label on the device

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

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

- Certification
- Suppliers Declaration of Conformity
- Verification

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

In a Suppliers Declaration of Conformity procedure, the supplier (typically the product's manufacturer) completes a form attesting, or declaring, that the device complies with the required regulation. The method used for demonstrating compliance is often listed on the declaration. In some 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 activities undertaken by the authorities to verify that the 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.

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. These newer limits will need to be met for the Republic of China (Taiwan) starting in October 2010, in March 2011 for the Peoples Republic of China, and October 2011 in Australia, the European Union and Japan.

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. ■

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

EMC

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

Discovering EMC's Role in Functional Safety

BY DAVID SCHRAMM

Product Safety

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 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. 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.

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

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

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

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.

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

Table 4: estimates of maximum electromagnetic disturbance levels

Product Safety

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!

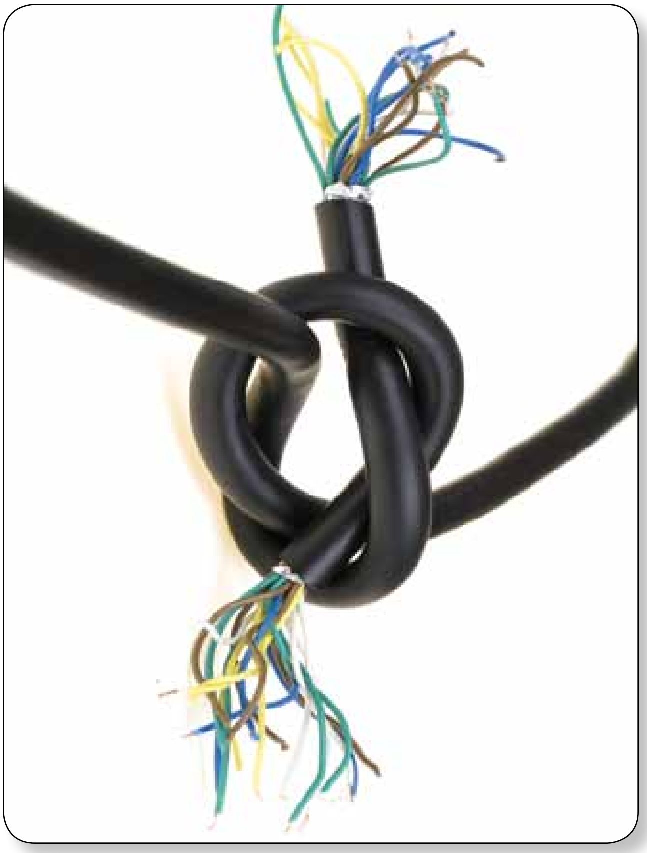
The performance over the product's life should also be considered. After exposure to highly accelerated life testing (HALT) that simulates the maximum ("worst-case") environmental exposure over the anticipated lifetime of the product, EMC testing should be repeated to check that the product's immunity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

David Schramm *is the Assistant Chief Engineer, EMC, for Intertek C&E. In this capacity he is responsible for the technical activities in EMC testing of Intertek's laboratories in the US; he coordinates these activities with the Intertek Notified Bodies in the European Union, and with other Intertek laboratories worldwide. He is also the Telecommunication Certification Body (TCB) Manager for Intertek. His responsibilities within industry trade groups have included: Member, ANSI C63.10 Working Group, which is establishing a set of unified test methods for wireless test procedures for FCC Certification testing and is a iNARTE Certified EMC Engineer (EMC-002792-NE).*

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.

Product Safety



Ensuring Connectivity

During Product Safety Testing

BY SHARI RICHARDSON

There is nothing worse than believing the correct voltage is being applied to a Device Under Test (DUT), only to find out a cable is broken and the only thing that has been tested is the hipot tester itself and part of the cable. This is especially true if this fault was not caught in time and product has already been shipped to the customer. While a skilled operator may notice a difference in leakage, collecting data and evaluating the data on a regular basis may also reduce such an error. However, there are other precautions that may be put in place to ensure the safety test is performed correctly. Two common product safety tests seen in production are the dielectric strength test (commonly referred to as hipot) and a ground test. The hipot test stresses the insulation of a product, while the ground test ensures proper ground connections within the product. The two most common ground tests are ground bond and ground continuity. This article will discuss these two common tests, as well as safeguards to ensure proper testing.

DIELECTRIC WITHSTAND TEST

A dielectric strength test, commonly called a “dielectric withstand”, “high potential”, or “hipot” test, is a stress test of the insulation barrier of a device under test. The dielectric barrier protects the user from exposure to dangerous electrical potentials. The most common points of application for a dielectric withstand test are between AC primary circuits and low voltage secondary circuits, as well as between AC primary circuits and user-accessible conductive parts/ground.

Such a test applies a voltage to the DUT that is much higher than normal operating voltage, typically 1000V AC plus twice the normal operating voltage. Therefore, for a household appliance designed to operate at 120V AC or 240V AC, the test voltage is usually about 1250 to 1500V AC. Voltage is applied to the DUT and any current leaking through the insulation is measured.

When performing this test, it is important to ensure the connection between the hipot tester and the DUT. A hipot test can produce a false pass if the high voltage cable between the DUT and tester is broken or unconnected. The test is designed to stress the insulation of the DUT. If the output test lead is broken the DUT will not be exposed to the high voltage, thus the insulation will not be stressed and the test will pass.

Programming Limits

During an AC hipot test there is typically some leakage current due to the capacitive characteristics of the DUT. Hipot on a three pronged device is performed with voltage applied to line and neutral tied together, measuring the leakage to ground. If the device under test has a capacitance of 100pF between these connections, there will naturally be 47uA of leakage for a 1250V hipot test.

This can easily be calculated using ohms law.

$$Z = \frac{1}{2*(pi)*f*C} \qquad Z = \frac{1}{2*(3.14)*60*100e\text{-}12} \qquad Z = 26.5M\Omega$$

$$I = \frac{V}{Z} \qquad I = \frac{1250}{26.5e6} \qquad I = 47.1E\text{-}6$$

Knowing that the leakage of the DUT must be at least 47uA based on the design of the product, a low limit can be used to ensure the leakage at a minimum reaches a specific level. Most digital hipot testers include programmable high and low limits. The high limit being the maximum amount of leakage current allowed and the low limit the minimum amount of current. If the test lead is broken the minimum amount of leakage current will not be present, resulting in a Fail Low. Figure 1 shows Pass Fail ranges.

Setting a low limit to ensure connection is a valid option for AC hipot testing. However, determining whether a product is attached during a DC hipot test is more challenging. Often the leakage from a DC hipot is zero or in the low microAmps. Setting a low limit is not feasible.

One solution is to first perform a low voltage AC hipot test, with a low limit programmed to ensure the connection, to measure the leakage current, and then to perform the DC hipot. By performing the test at a low AC hipot voltage, the DUT is not being stressed twice with high voltage, the result of which could produce unpredictable results. It also allows for an AC test to actually run. Typically DC hipot is performed because the leakage from capacitors within the DUT exceeds the AC specifications of the tester. By lowering the voltage the leakage is reduced to a manageable current within the tester's limit.

Charge Current

Setting low limits is not the only solution to ensure connections. Some testers on the market contain a function to measure the charge current during a DC hipot test. A limit can be set around the charge current to ensure there is an in-rush of current at the beginning of the test. This acts the same as setting a low limit. If no charge current is present the test fails.

Measuring Capacitance

Other testers measure the capacitance of the device under test and compare the measurement with a known value. The device under test contains some capacitance (C_x) as shown in Figure 2. The tester measures the capacitive load of the DUT to determine whether the connection is good.

If the connection is open, additional capacitance (C_c) will be measured (C_m) and the total capacitive load will be less the capacitance of the product under test, resulting in an open circuit Failure. Figure 3 shows C_c added in series with C_x.

$$C_m = C_c*C_x/(C_c+C_x)<<C_x$$

A hipot test will pass if not connected to the DUT, if preventions such as low limits, measuring charge current or capacitance have not been put in place. The ground test however, will fail if no connection is in place.

Figure 1: Pass Fail ranges for a hipot test

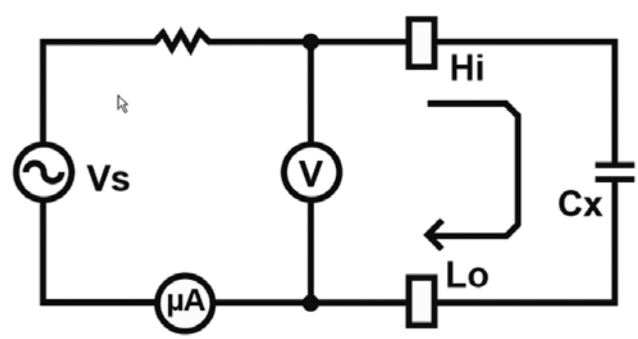


Figure 2: Voltage applied to a DUT with capacitance C_x

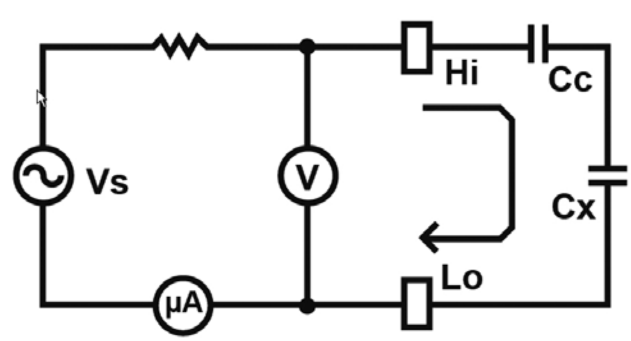


Figure 3: Voltage applied to DUT with capacitance C_x and additional open circuit capacitance C_c

GROUND TEST

Ground continuity is performed using a low DC current source, typically less than 1 Amp, between the ground blade on the power cord and any exposed metal on the product. Ground bond is not always required for production testing but some manufacturers choose this test over ground continuity because it may detect a problem in the ground circuit that the continuity test may pass. The ground bond test applies high current, usually 25 – 40 Amps, to the same ground path as the continuity test. The resistance of the ground path, normally less than 100 mΩ is measured using a Kelvin connection. Not only does ground bond verify the continuity but it verifies the integrity of the circuit and its capability to carry high current.

Since current must have a path to travel, if connection is not made during the ground bond or ground continuity test the test will fail. The test result on most digital testers today would be a high failure or current overload. Broken leads are not usually an issue when it comes to the ground test. If the lead is broken, the test will fail. If there is an internal short within the tester, the test will pass. Knowing the typical resistance of the device under test can help raise flags if the expected resistance drops. The use of a load box will ensure the tester is measuring properly and no internal faults have occurred. This holds true for both hipot and ground bond.

LOAD BOX

A load box is a simple box which consists of high voltage resistors with values based upon the test specification in which the hipot tester is being used. The resistors in the load box do not have to be precision resistors or have an accurate calibration. They are only intended to check the tester, not verify or calibrate it. The box typically contains two connections, a Pass and a Fail. When attached to Pass the intent is for the hipot to Pass. Conversely, when connected to Fail, the hipot shall fail. Recently the demand for load boxes has increased as Nationally Recognized Test Laboratories (NRTLs) such as Underwriters Laboratories are requiring a daily load box check.

Load Box Example

An appliance manufacturer has the hipot tester configured for a 1200V hipot test. The high limit is programmed for 10mA. The resistor from ground to Pass would need to be greater than 120kΩ. Let's say, the manufacturer chooses to use a 140kΩ resistor. The user would expect to have his hipot tester measure 8.5mA, which would be considered a PASS given the set 10mA high limit. The Fail resistor would need to be less than 120kΩ. The manufacturer chooses a 100kΩ resistor. The 100kΩ load with 1200V produces 12mA of current, resulting in a FAIL.

Figure 5 illustrates how to calculate the PASS and FAIL current values based on the manufacturer's specifications of a 1200V hipot test with a 10mA high limit.

A load box can also be used to verify the ground bond function of the tester. For a ground bond test high current resistor values of 50mΩ and 150mΩ are used. The most common ground bond test is performed at 25A, the resistance shall not exceed 100mΩ. Ground Bond (GB) verification is performed from the ground blade of the power entry adapter to the binding post. Connecting to the red binding post and to the FAIL power entry module will result in a failure in the GB test because the actual value of resistance (150mΩ) is greater than the set limit of 100mΩ. The pass circuit has the 50mΩ resistor, so in connecting between the green binding post and the PASS power entry module, the GB test will pass.

One load box can be used for both hipot and ground bond. Figure 6 shows a load box configured for hipot and ground bond. Performing the load box test to Pass will ensure the tester is capable of measuring a good product. Attaching to the Fail will ensure the tester will produce a failure if the current exceeds the programmed limit for hipot or the resistance exceeds the limit for ground bond.

Choosing the correct resistor for a high voltage application requires some thought. It is necessary to take the maximum voltage rating, voltage coefficient and power rating into consideration when specifying resistors for a load box.

The voltage rating is the maximum voltage that can be applied to the resistor without causing damage to the resistor due to arcing or breakdown.

The voltage coefficient expresses the change in resistance value due to a change in the amount of applied voltage. The voltage coefficient for a resistor is normally expressed in ppm/Volt and is always negative. This means the higher the applied voltage, the lower the resistance value.

The power rating defines how much power the resistor can dissipate without damaging the resistor. Calculate the power being dissipated at the intended operating voltage. Do not assume that just because the resistor is being used under the maximum voltage rating that there will not be an issue. It is always advisable to calculate the power using $P=V^2/R$, where V is the test voltage and R is value of the resistor, $P = I^2*R$ can also be used where I is the current through the resistor.

The required power dissipation for the load box example above would be $P = (1200V)^2/ 100e^3 = 14.4W$ for the fail condition and $P = (1200)^2/140e^3 = 10.28W$ for the pass condition. Finding a 15 or 20 Watt resistor may be difficult. Vishay RS10 resistors are readily available in a variety of values; this series by Vishay is rated for 10W. Using multiple resistors in series will help reduce the power and voltage requirements, as only half the voltage would be applied to each resistor.

Performing a daily load box check will verify the tester is operating properly at the time the test is performed. However, it will not ensure the cables won't break at some point during the day. It may not be until the next morning when the load box check is performed until a fault in cabling is recognized.

DATA COLLECTION

Collecting data while testing will provide history if an issue occurs. For years, hipot and ground bond or continuity were simple pass/fail tests. Today, more and more manufacturers have strayed away from the traditional pass fail result and are recording actual measurement values. Hand recording the values on a product traveler will provide operator awareness as to the leakage current, for hipot, or resistance for the ground measurement. If the values were to differ significantly as in the case of a broken wire, a good operator will identify there is an issue. Hand recording data has its downfalls as human error increases the likelihood of an error. Further, manually digging through the travelers to identify if and when an issue occurred is time-consuming and tedious.

Hipot testers now provide flexibility with data collection by connecting to a PC so that data does not need to be manually recorded. Testers have command protocols to be used in custom program which allow full control over the tester and its results. Software or sample programs, as well as Labview Drivers, are generally available for most testers on the market today. Recording data electronically provides the benefit of easily retrieving test results and viewing test history. Imagine if a broken cable goes undetected and product ships. Having data to track when the problem occurred is extremely helpful to any manufacturer.

Data collection likely will not prevent a hipot test from passing if the high voltage cable breaks, however it will help assist with the aftermath of the issue at hand. It will also provide trending so safeguards such as setting a low limit can be put in place easily. There are options to ensure the test is being performed correctly. Unfortunately, many companies wait for a breakdown before they implement safeguards. ■

***Shari Richardson** is a Manufacturing Engineer at a major medical device manufacturer. She has written many articles for publications as well as been a guest speaker and presenter at the Product Safety Engineering Symposium. Shari earned a BSEE from University of Massachusetts – Lowell. Shari can be reached at shari.richardson@incompliancemag.com.*

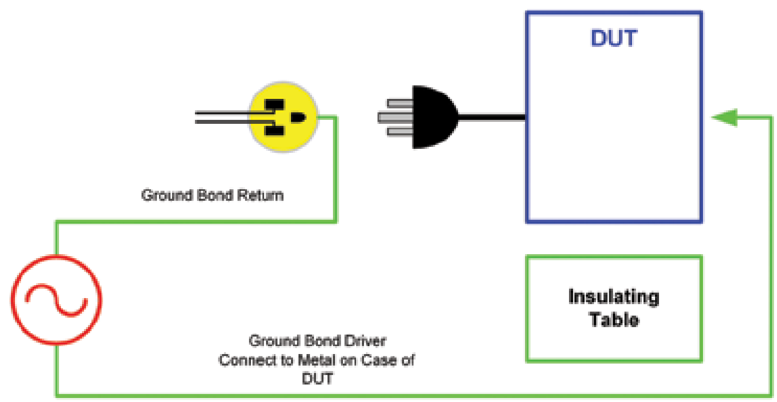


Figure 4: Typical ground bond test

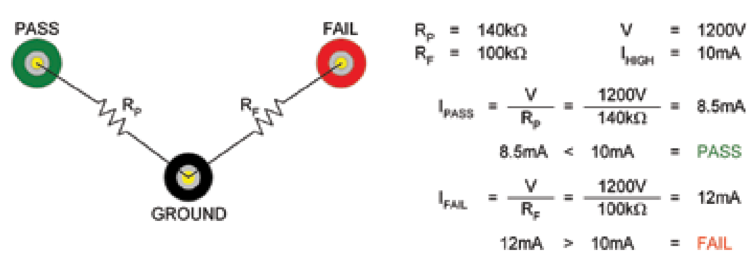


Figure 5: Resistor configuration for a hipot load box

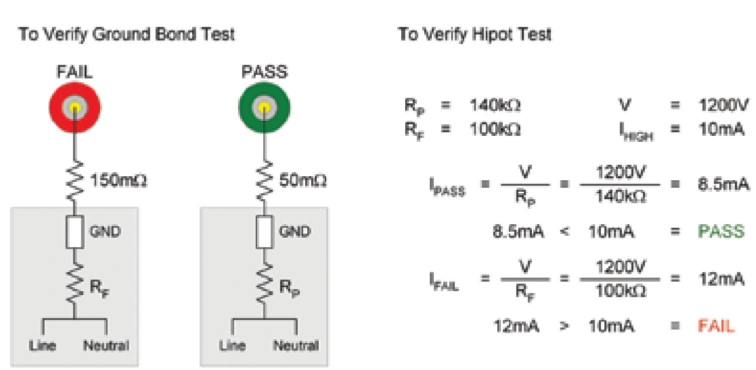
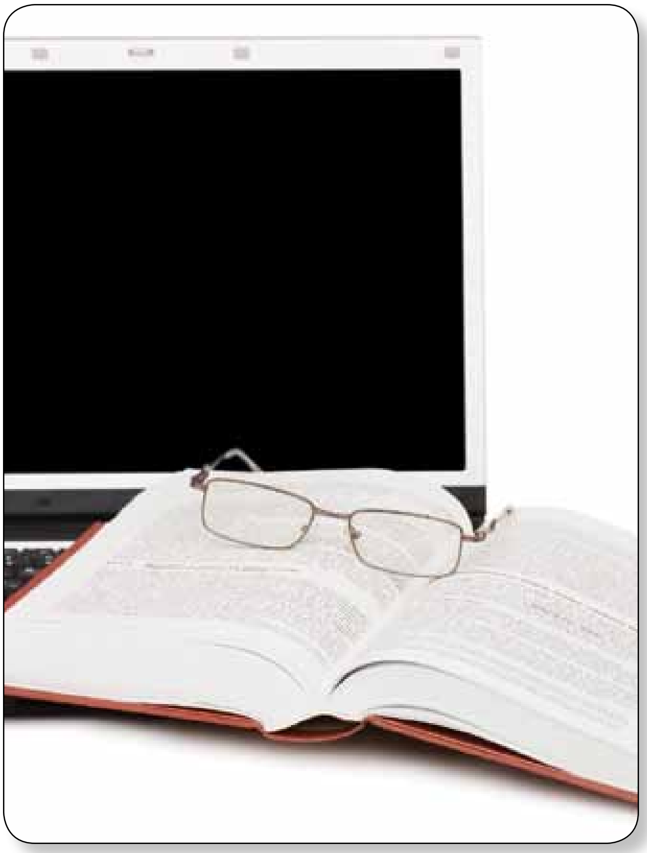


Figure 6: Resistor configuration for hipot and ground bond load box

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.

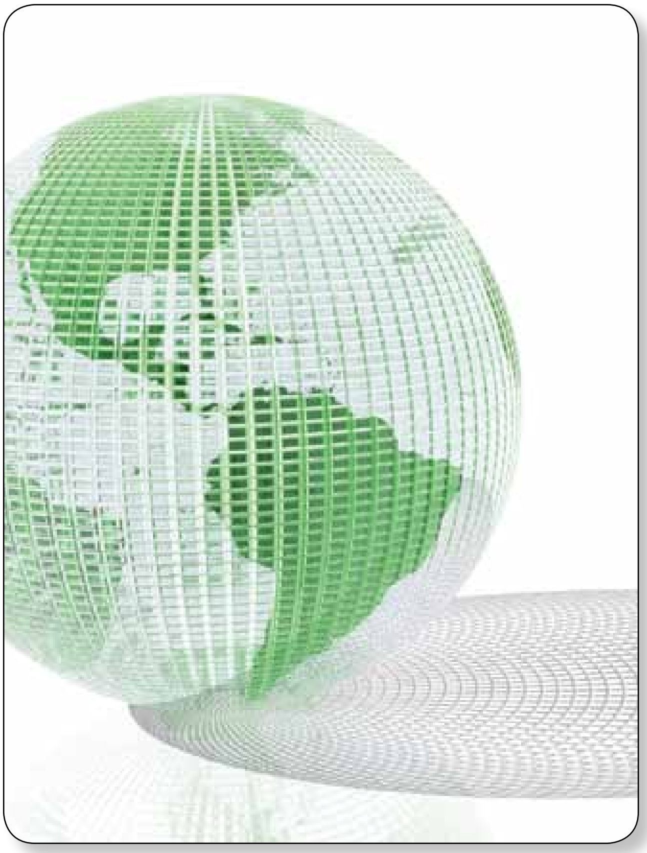
CONCLUSION

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. ■

Kenneth Ross *is a very experienced lawyer and consultant who advises U.S. and foreign manufacturers and product sellers on product safety, product liability prevention and legal and regulatory compliance. This includes advice on how to identify, evaluate and minimize the risk of liability, especially product and contractual liability. Prior to entering private practice, Ken was an in-house lawyer at Westinghouse Electric and Emerson Electric where he counseled on safety and prevention issues and managed litigation. Ken can be reached at kenrossesq@comcast.net. More of Ken's articles can be accessed at www.productliabilityprevention.com.*



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

Product Safety

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 shut-down 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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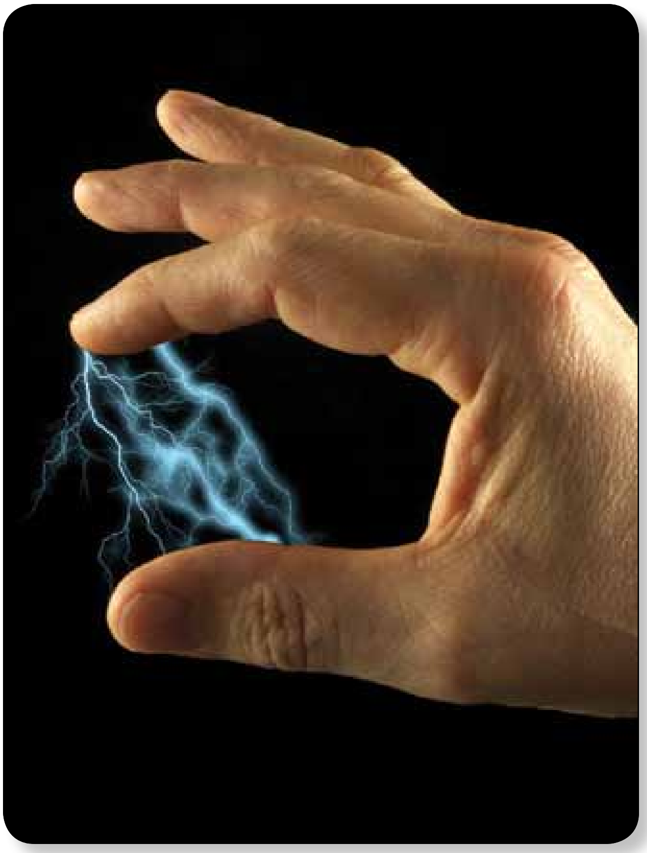
Fundamentals of Electrostatic Discharge

Part 1: An Introduction to ESD

BY THE ESD ASSOCIATION



ESD

Protecting your products from the effects of static damage begins by understanding the key concepts involved in electrostatics and Electrostatic Discharge. This is Part 1 of a six-part series on The Fundamentals of Electrostatic Discharge (ESD), 2010. It addresses the impact of ESD productivity and product reliability. The ESD fundamentals were first developed in 2001 by the ESD Association. In Part 1: An Introduction to ESD; the basics of electrostatic charge, discharge, types of failures, ESD events, and device sensitivity are discussed.

HISTORY & BACKGROUND

To many people, static electricity is little more than the shock experienced when touching a metal doorknob after walking across a carpeted room or sliding across a car seat. However, static electricity has been a serious industrial problem for centuries. As early as the 1400's, European and Caribbean forts were using static control procedures and devices to prevent electrostatic discharge ignition of black powder stores. By the 1860's, paper mills throughout the U.S. employed basic grounding, flame ionization techniques, and steam drums to dissipate static electricity from the paper web as it traveled through the drying process. Every imaginable business and industrial process has issues with electrostatic charge and discharge at one time or another. Munitions and explosives, petrochemical, pharmaceutical, agriculture, printing and graphic arts, textiles, painting, and plastics are just some of the industries where control of static electricity has significant importance.

The age of electronics brought with it new problems associated with static electricity and electrostatic discharge. And, as electronic devices become faster and smaller, their sensitivity to ESD increases. Today, ESD impacts productivity and product reliability in virtually every aspect of the global electronics environment.

Despite a great deal of effort during the past twenty-five years, ESD still affects production yields, manufacturing costs, product quality, product reliability, and profitability. The cost of damaged devices themselves ranges from only a few cents for a simple diode to thousands of dollars for complex integrated circuits. When associated costs of repair and rework, shipping, labor, and overhead are included, clearly the opportunities exist for significant improvements. Nearly all of the thousands of companies involved in electronics manufacturing today pay attention to the basic, industry accepted elements of static control. Industry standards are available today to guide manufacturers in establishing the fundamental static mitigation and control techniques (see Part 6: ESD Standards). It is unlikely that any company which ignores static control will be able to successfully manufacture and deliver undamaged electronic parts.

STATIC ELECTRICITY: CREATING CHARGE

Static electricity is defined as an electrical charge caused by an imbalance of electrons on the surface of a material. This imbalance of electrons produces an electric field that can be measured and that can influence other objects at a distance. Electrostatic discharge is defined as the transfer of charge between bodies at different electrical potentials.

Electrostatic discharge can change the electrical characteristics of a semiconductor device, degrading or destroying it. Electrostatic discharge also may upset the normal operation of an electronic system, causing equipment malfunction or failure. Charged surfaces can attract and hold contaminants, making removal of the material difficult. When attracted to the surface of a silicon wafer or a device's electrical circuitry, air-borne particulates can cause random wafer defects and reduce product yields.

Controlling electrostatic discharge begins with understanding how electrostatic charge occurs in the first place. Electrostatic charge is most commonly created by the contact and separation of two materials. For example, a person walking across the floor generates static electricity as shoe soles contact and then separate from the floor surface. An electronic device sliding into or out of a bag, magazine or tube generates an electrostatic charge as the device's housing and metal leads make multiple contacts and separations with the surface of the container. While the magnitude of electrostatic charge may be different in these examples, static electricity is indeed generated.

Creating electrostatic charge by contact and separation of materials is known as "triboelectric charging." The word "triboelectric" comes from the Greek words, *tribo* – meaning "to rub" and *elektros* – meaning "amber" (fossilized resin from prehistoric trees). It involves the transfer of electrons between materials. The atoms of a material with no static charge have an equal number of positive (+) protons in their nucleus and negative (-) electrons orbiting the nucleus. In Figure 1, Material "A" consists of atoms with equal numbers of protons and electrons. Material B also consists of atoms with equal (though perhaps different) numbers of protons and electrons. Both materials are electrically neutral.

When the two materials are placed in contact and then separated, negatively charged electrons are transferred from the surface of one material to the surface of the other material. Which material loses electrons and which gains electrons will depend on the nature of the two materials. The material that loses electrons becomes positively charged, while the material that gains electrons is negatively charged. This is shown in Figure 2.

Static electricity is measured in coulombs. The charge "q" on an object is determined by the product of the capacitance of the object "C" and the voltage potential on the object (V):

$$q=CV$$

Commonly, however, we speak of the electrostatic potential on an object, which is expressed as voltage.

This process of material contact, electron transfer and separation is a much more complex mechanism than described here. The amount of charge created by triboelectric generation is affected by the area of contact, the speed of separation, relative humidity, and chemistry of the materials,

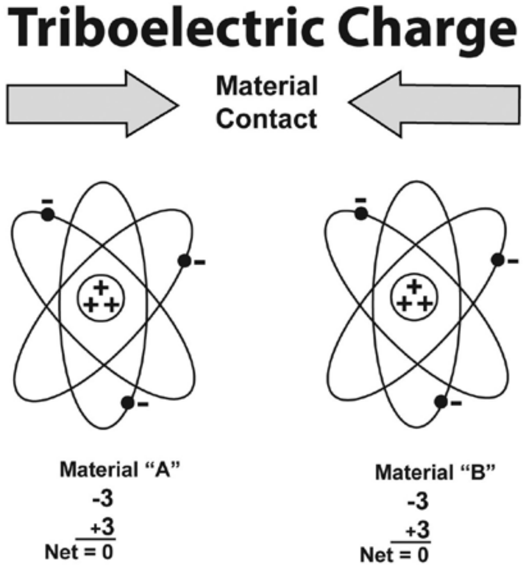


Figure 1: The Triboelectric Charge - Materials Make Intimate Contact

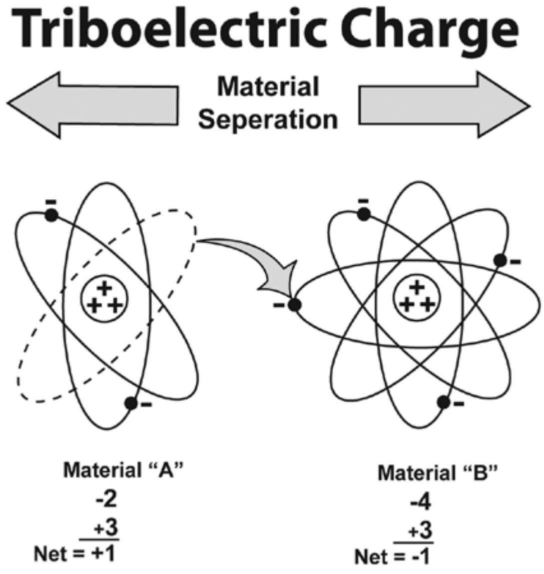


Figure 2: The Triboelectric Charge - Separation

surface work function and other factors. Once the charge is created on a material, it becomes an "electrostatic" charge (if it remains on the material). This charge may be transferred from the material, creating an electrostatic discharge, or ESD, event. Additional factors, such as the resistance of the actual discharge circuit and the contact resistance at the interface between contacting surfaces also affect the actual charge that is released. Typical charge generation scenarios and the resulting voltage levels are shown in Table 1.

Means of Generation	10-25% RH	65-90% RH
Walking across carpet	35,000V	1,500V
Walking across vinyl tile	12,000V	250V
Worker at bench	6,000V	100V
Poly bag picked up from bench	20,000V	1,200V
Chair with urethane foam	18,000V	1,500V

Table 1: Examples of Static Generation Typical Voltage Levels

+ Positive	Rabbit fur
	Glass
	Mica
	Human Hair
	Nylon
	Wool
	Fur
	Lead
	Silk
	Aluminum
	Paper
	COTTON
	Steel
	Wood
	Amber
	Sealing Wax
	Nickel, copper Brass, silver
	Gold, platinum
	Sulfur
	Acetate rayon
	Polyester
Negative	Celluloid
	Silicon
-	Teflon

Table 2: Typical Triboelectric Series

ESD

In addition, the contribution of humidity to reducing charge accumulation is also shown. It should be noted however that static generation still occurs even at high relative humidity.

An electrostatic charge also may be created on a material in other ways such as by induction, ion bombardment, or contact with another charged object. However, triboelectric charging is the most common.

HOW MATERIAL CHARACTERISTICS AFFECT STATIC CHARGE

Triboelectric Series

When two materials contact and separate, the polarity and magnitude of the charge are indicated by the materials' positions in a triboelectric series. The triboelectric series Tables show how charges are generated on various materials. When two materials contact and separate, the one nearer the top of the series takes on a positive charge, the other a negative charge. Materials further apart on the table typically generate a higher charge than ones closer together. These tables, however, should only be used as a general guide because there are many variables involved that cannot be controlled well enough to ensure repeatability. A typical triboelectric series is shown in Table 2.

Virtually all materials, including water and dirt particles in the air, can be triboelectrically charged. How much charge is generated, where that charge goes, and how quickly, are functions of the materials' physical, chemical and electrical characteristics.

Insulative Materials

A material that prevents or limits the flow of electrons across its surface or through its volume is called an insulator. Insulators have an extremely high electrical resistance, generally greater than 1×10^{11} ohms (surface resistance) and 1×10^{11} ohm-cm (volume resistivity). A considerable amount of charge can be generated on the surface of an insulator. Because an insulative material does not readily allow the flow of electrons, both positive and negative charges can reside on insulative surface at the same time, although at different locations. The excess electrons at the negatively charged spot might be sufficient to satisfy the absence of electrons at the positively charged spot. However, electrons cannot easily flow across the insulative material's surface, and both charges may remain in place for a very long time.

Conductive Materials

A conductive material, because it has low electrical resistance, allows electrons to flow easily across its surface or through its volume. Conductive materials have low electrical resistance, less than 1×10^4 ohms (surface resistance) and 1×10^4 ohm (volume resistance) for electrostatic discussions. When a conductive material becomes charged, the charge (i.e., the deficiency or excess of electrons) will be uniformly distributed across the surface of the material. If the charged conductive material makes contact with another conductive material, the electrons will be shared between the materials quite easily. If the second conductor is attached to an earth grounding point, the electrons will flow to ground and the excess charge on the conductor will be "neutralized."

Electrostatic charge can be created triboelectrically on conductors the same way it is created on insulators. As long as the conductor is isolated from other conductors or ground, the static charge will remain on the conductor. If the conductor is grounded, the charge will easily go to ground. Or, if the charged conductor contacts another conductor, the charge will flow between the two conductors.

Static Dissipative Materials

Static dissipative materials have an electrical resistance between insulative and conductive materials (1×10^4 - 1×10^{11} ohms surface or volume resistance). There can be electron flow across or through the dissipative material, but it is controlled by the surface resistance or volume resistance of the material.

As with the other two types of materials, charge can be generated triboelectrically on a static dissipative material. However, like the conductive material, the static dissipative material will allow the transfer of charge to ground or other conductive objects. The transfer of charge from a static dissipative material will generally take longer than from a conductive material of equivalent size. Charge transfers from static dissipative materials are significantly faster than from insulators, and slower than from conductors.

Electrostatic Fields

Charged materials also have an electrostatic field and lines of force associated with them. Conductive objects brought into the vicinity of this electric field will be polarized by a process known as induction. A negative electric field will repel electrons on the surface of the conducting item that is exposed to the field. A positive electric field will attract electrons to near the surface thus leaving other areas positively charged. No change in the actual charge on the item will occur in polarization. If, however, the item is conductive or dissipative and is touched to ground while polarized, charge will flow from or to ground to compensate for the charge imbalance. If the electrostatic field is removed and the ground contact disconnected, the charge will be trapped on the item. If a nonconductive object is brought into the electric field, the electrical dipoles will tend to align with the field creating apparent surface charges. A nonconductor cannot be charged by induction.

ESD DAMAGE—HOW DEVICES FAIL

Electrostatic damage to electronic devices can occur at any point from manufacture to field service. Damage results from handling the devices in uncontrolled surroundings or when poor ESD control practices are used. Generally damage is classified as either a catastrophic failure or a latent defect.

Catastrophic Failure

When an electronic device is exposed to an ESD event, it may no longer function. The ESD event may have caused a metal melt, junction breakdown, or oxide failure. The device's circuitry is permanently damaged causing the device to stop functioning. Such failures usually can be detected when the device is tested before shipment. If a damaging level ESD event occurs after test, the part may go into production and the damage will go undetected until the device fails in final test.

Latent Defect

A latent defect, on the other hand, is more difficult to identify. A device that is exposed to an ESD event may be partially degraded, yet continue to perform its intended function. However, the operating life of the device may be reduced dramatically. A product or system incorporating devices with latent defects may experience premature failure after the user places them in service. Such failures are usually costly to repair and in some applications may create personnel hazards.

It is relatively easy with the proper equipment to confirm that a device has experienced catastrophic failure. Basic performance tests will substantiate device damage. However, latent defects are extremely difficult to prove or detect using current technology, especially after the device is assembled

ESD

into a finished product. Great strides have been made in recent years to understand latency and improve factory control levels so that the risks are lower.

BASIC ESD EVENTS—WHAT CAUSES ELECTRONIC DEVICES TO FAIL?

ESD damage is usually caused by one of three events: direct electrostatic discharge to the device, electrostatic discharge from the device or field-induced discharges. Whether or not damage occurs to an ESDS device by an ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the voltage levels involved. The level at which a device fails is known as the device's "ESD sensitivity."

Discharge to the Device

An ESD event can occur when any charged conductor (including the human body) discharges to an ESDS (electrostatic discharge sensitive) device. The most common cause of electrostatic damage is the direct transfer of electrostatic charge from the human body or a charged material to the electrostatic discharge sensitive (ESDS) device. When one walks across a floor, an electrostatic charge accumulates on the body. Simple contact of a finger to the leads of an ESDS device or assembly allows the body to discharge, possibly causing device damage. The model used to simulate this event is the Human Body Model (HBM). A similar discharge can occur from a charged conductive object, such as a metallic tool or fixture. The model used to characterize this event is known as the Machine Model.

Discharge from the Device

The transfer of charge from an ESDS device is also an ESD event. Static charge may accumulate on the ESDS device itself through handling or contact with packaging materials, worksurfaces, or machine surfaces. This frequently occurs when a device moves across a surface or vibrates in a package. The model used to simulate the transfer of charge from an ESDS device is referred to as the Charged Device Model (CDM). The capacitance and energies involved are different from those of a discharge to the ESDS device. In some cases, a CDM event can be more destructive than the HBM for some devices.

The trend towards automated assembly would seem to solve the problems of HBM ESD events. However, it has been shown that components may be more sensitive to damage when assembled by automated equipment. A device may become charged, for example, from sliding down the feeder. If it then contacts the insertion head or another conductive surface, a rapid discharge occurs from the device to the metal object.

Device or Part Type
Microwave devices (Schottky barrier diodes, point contact diodes and other detector diodes >1 GHz)
Discrete MOSFET devices
Surface acoustic wave (SAW) devices
Junction field effect transistors (JFETs)
Charged coupled devices (CCDs)
Precision voltage regulator diodes (line of load voltage regulation, <0.5%)
Operational amplifiers (OP AMPs)
Thin film resistors
Integrated circuits
GMR and new technology Disk Drive Recording Heads
Laser Diodes
Hybrids
Very high speed integrated circuits (VHSIC)
Silicon controlled rectifiers (SCRs) with Io <0.175 amp at 100°C ambient
*Specific Sensitivity Levels are available from supplier data sheets

Table 3: ESD Sensitivity of Representative Electronic Devices
Devices or Parts with Sensitivity Associated with HBM and CDM*

Field Induced Discharges

Another electrostatic charging process that can directly or indirectly damage devices is termed Field Induction. As noted earlier, whenever any object becomes electrostatically charged, there is an electrostatic field associated with that charge. If an ESDS device is placed in that electrostatic field, a charge may be induced on the device. If the device is then momentarily grounded while within the electrostatic field, a transfer of charge from the device occurs as a CDM event. If the device is removed from the region of the electrostatic field and grounded again, a second CDM event will occur as charge (of opposite polarity from the first event) is transferred from the device.

HOW MUCH STATIC PROTECTION IS NEEDED?

Damage to an ESDS device by the ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the voltage levels involved—as explained previously these factors determine the parts ESD sensitivity. Defining the ESD sensitivity of electronic components is the first step in determining the degree of ESD protection required. Test procedures based on the models of ESD events help define the sensitivity of components to ESD. These procedures and more are covered in Part 5 of this series.

Many electronic components are susceptible to ESD damage at relatively low voltage levels. Many are susceptible at less than 100 volts, and many disk drive components have sensitivities below 10 volts. Current trends in product design and development pack more circuitry onto these miniature devices, further increasing their sensitivity to ESD and making the potential problem even more acute. Table 3 indicates the ESD sensitivity of various types of components.

SUMMARY

In this introductory article on electrostatic discharge, we have discussed the basics of electrostatic charge and discharge, types of failures, ESD events, and device sensitivity. We can summarize this discussion as follows:

1. Virtually all materials, even conductors, can be triboelectrically charged.
2. The level of charge is affected by material type, speed of contact and separation, humidity, and several other factors.
3. Electrostatic fields are associated with charged objects.
4. Electrostatic discharge can damage devices so they fail immediately, or ESD may result in latent damage that may escape immediate detection, but cause the device to fail prematurely once in service.
5. Electrostatic discharge can occur throughout the manufacturing, test, shipping, handling, or operational processes.
6. Component damage can occur as the result of a discharge to the device, from the device, or from charge transfers resulting from electrostatic fields. Devices vary significantly in their sensitivity to ESD.

Protecting your products from the effects of static damage begins by understanding these key concepts of ESD. Armed with this information, you can then begin to develop an effective ESD control program. In Part 2 we will focus on some basic concepts of ESD control. ■

REFERENCES

1. *ESD-ADV 1*.0, Glossary, ESD Association, Rome NY.
2. *ESD TR20.20, Handbook*, ESD Association, Rome, NY.
3. *ESD ADV 11.2, Triboelectric Charge Accumulation Testing*, ESD Association, Rome, NY.
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ESD

Fundamentals of Electrostatic Discharge

Part 2: Principles of ESD Control

BY THE ESD ASSOCIATION

In Part 1 of this series, *An Introduction to ESD*, we discussed the basics of electrostatic charge, discharge, types of failures, ESD events, and device sensitivity. We concluded our discussion with the following summary:

1. Virtually all materials, even conductors, can be triboelectrically charged.
2. The level of charge is affected by material type, speed of contact and separation, humidity, and several other factors.
3. Electrostatic fields are associated with charged objects.
4. Electrostatic discharge can damage devices so they fail immediately, or ESD may result in latent damage that may escape immediate attention, but cause the device to fail prematurely once in service.
5. Electrostatic discharge can occur throughout the manufacturing, test, shipping, handling, or operational processes.
6. Component damage can occur as the result of a discharge **to** the device, **from** the device, or from charge transfers resulting from electrostatic fields. Devices vary significantly in their sensitivity to ESD.

Understanding these key concepts is crucial to protecting your products from the effects of static damage. Armed with this information, you can then begin to develop an effective ESD control program. In Part 2 we will focus on some basic concepts of ESD control.

BASIC PRINCIPLES OF STATIC CONTROL

Sometimes, controlling electrostatic discharge (ESD) in the electronics environment seems to be a formidable challenge. However, the task of designing and implementing ESD control programs becomes less complex if we focus on just six basic principles of control. In doing so, we also need to keep in mind the ESD corollary to Murphy's law, "no matter what we do, static charge will try to find a way to discharge."

1. Design In Protection

The first principle is to *design products and assemblies to be as resistant as reasonable* from the effects of ESD. This involves such steps as using less static sensitive devices or providing appropriate input protection on devices, boards, assemblies, and equipment. For engineers and designers, the paradox is that advancing product technology requires smaller and more complex geometries that often are more susceptible to ESD. Recent (2009) published work by the Industry Council on ESD Targets and the ESDA Technology Roadmap suggests that designers will have less ability to provide the protection levels that were available in the past. When very sensitive devices must be used and handled, application-specific controls beyond the principles described here may be required.

2. Define the Level of Control Needed in Your Environment

What is the sensitivity level of the parts you are using and the products that you are manufacturing and shipping? In order to have a complete picture of what is required, it is best to know the Human-Body Model (HBM) and Charged-Device Model (CDM) sensitivity levels for all devices that will be handled in the environment. ANSI/ESD S20.20 defines a control program for items that are sensitive to 100 volts HBM. The procedures in ANSI/ESD S20.20 may need to be tailored or expanded in specific situations.

3. Identify and Define the Electrostatic Protected Areas (EPA)

These are the areas in which you will be handling sensitive parts and the areas in which you will need to implement the basic ESD control procedures including bonding or electrically connecting all conductive and dissipative materials, including personnel, to a known ground.

4. Eliminate and Reduce Generation

Obviously, product design will be increasingly less effective in minimizing ESD losses. The fourth Principle of control is to *eliminate or reduce the generation and accumulation of electrostatic charge* in the first place. It's fairly basic: no charge–no discharge. We begin by reducing as many static generating processes or materials, such as the contact and separation of dissimilar materials and common plastics, as possible from the work environment. We keep other processes and materials at the same electrostatic potential. Electrostatic discharge does not occur between materials kept at the same potential or at zero potential. We provide ground paths, such as wrist straps, flooring and work surfaces, to reduce charge generation and accumulation. While the basic principle of reasonable minimization of charging should be followed, complete removal of charge generation is not achievable.

5. Dissipate and Neutralize

Because we simply can't eliminate all generation of static in the environment, our fifth Principle is to *safely dissipate or neutralize those electrostatic charges* that do occur. Proper grounding and the use of conductive or dissipative materials play major roles. For example, workers who "carry" a charge into the work environment can rid themselves of that charge when they attach a wrist strap or when they step on an ESD floor mat while wearing ESD control footwear. The charge goes to ground rather than being discharged into a sensitive part. To prevent damaging a charged device, the rate of discharge can be controlled with static dissipative materials. For some objects, such as common plastics and other insulators, grounding does not remove an electrostatic charge because there is no conductive pathway. Typically, ionization is used to neutralize charges on these insulating materials. The ionization process generates negative and positive ions that are attracted to the surface of a charged object, thereby effectively neutralizing the charge.

6. Protect Products

Our final ESD control Principle is to *prevent discharges that do occur from reaching susceptible parts and assemblies*. One way is to provide our parts and assemblies with proper grounding or shunting that will "dissipate" any discharge away from the product. A second method is to package and transport susceptible devices in proper packaging and materials handling products. These materials may effectively shield the product from charge, as well as reduce the generation of charge caused by any movement of product within the container.

ELEMENTS OF AN EFFECTIVE ESD CONTROL PROGRAM

While these six principles may seem rather basic, they can guide us in the selection of appropriate materials and procedures to use in effectively controlling ESD. In most circumstances, effective programs will involve all of these principles. No single procedure or product will do the whole job; rather effective static control requires a full ESD control program.

How do we develop and maintain a program that puts these basic principles into practice? How do we start? What is the process? What do we do first? Ask a dozen experts and you may get a dozen different answers. But, if you dig a little deeper, you will find that most of the answers center on similar key elements. You will also find that starting and maintaining an ESD control program is similar to many other business activities and projects. Although each company is unique in terms of its ESD control needs, there are at least six critical elements to successfully developing and implementing an effective ESD control program.

1. Establish an ESD Coordinator and ESD Teams

A team approach particularly applies to ESD because the problems and the solutions cross various functions, departments, divisions and even suppliers in most companies. Team composition includes line employees as well as department heads or other management personnel. The team may also cut across functions such as incoming inspection, quality, training, automation, packaging, and test. ESD teams or committees help assure a variety of viewpoints, the availability of the needed expertise, and commitment to success. An active ESD committee helps unify the effort and brings additional expertise to the project.

Heading this team effort is an ESD Program Coordinator. Ideally this responsibility should be a full-time job. However, we seldom operate in an ideal environment and you may have to settle for the function to be a major responsibility of an individual. The ESD coordinator is responsible for developing, budgeting, and administering the program. The coordinator also serves as the company's internal ESD consultant to all areas.

2. Assess Your Organization, Facility, Processes and Losses

Your next step is to gain a thorough understanding of your environment and its impact on ESD. Armed with your loss and sensitivity data, you can evaluate your facility, looking for areas and procedures that may be contributing to your defined ESD problems. Be on the lookout for things such as static generating materials and personnel handling procedures for ESD-sensitive items.

Document your processes. Observe the movement of people and materials through the areas. Note those areas that would appear to have the greatest potential for ESD problems. Remember that ESD can occur in the warehouse just as it can in the assembly areas. Then conduct a thorough facility survey or audit. Measure personnel, equipment, and materials to identify the presence of electrostatic fields in your environment.

Before seeking solutions to your problems, you will need to determine the extent of your losses to ESD. These losses may be reflected in receiving reports, QA and QC records, customer returns, in-plant yields, failure analysis reports, and other data that you may already have or that you need to gather. This information not only identifies the magnitude of the problem, but also helps to pinpoint and prioritize areas that need attention. Where available, the potential for future problems as a result of technology roadmaps and internal product evolution should be considered.

Document your actual and potential ESD losses in terms of DOA components, rework, customer returns, and failures during final test and inspection. Use data from outside sources or the results of your pilot program for additional support. Develop estimates of the savings to be realized from implementing an ESD control program.

You will also want to identify those items (components, assemblies, and finished products) that are sensitive to ESD and the level of their sensitivity. You can test these items yourself, use data from suppliers, or rely on published data for similar items. However, estimates can be wrong when the person making the estimate doesn't have enough information. In general, two functionally identical items from two different suppliers may *not* have similar ESD ratings.

3. Establish and Document Your ESD Control Program Plan

After completing your assessment, you can begin to develop and document your ESD control program plan. The plan should cover the scope of the program and include the tasks, activities, and procedures necessary to protect the ESD sensitive items at or above the ESD sensitivity level chosen for the plan. Prepare and distribute written procedures and specifications so that everyone has a clear understanding of what is to be done. Fully documented procedures will help you meet the administrative and technical elements of ANSI/ESD S20.20 and help you with ISO 9000 certification as well.

4. Build Justification to Get the Management Support Top Management

To be successful, an ESD program requires the support of your top management, at the highest level possible. What level of commitment is required? To obtain commitment, you will need to build justification for the plan. You will need to emphasize quality and reliability, the costs of ESD damage, the impact of ESD on customer service, and product performance. It may be useful to conduct a pilot program if the experience of other companies is not sufficient and you have an expectation that you can show meaningful results in the pilot.

Prepare a short corporate policy statement on ESD control. Have top management co-sign it with the ESD coordinator. Periodically, reaffirm the policy statement and management's commitment to it.

5. Define A Training Plan

Train and retrain your personnel in ESD and your company's ESD control program and procedures. Training should include testing to verify comprehension. Proper training for line personnel is especially important. They are often the ones who have to live with the procedures on a day-to-day basis. A sustained commitment and mindset among all employees that ESD prevention is a valuable, on-going effort by everyone is one of the primary goals of training.

6. Develop and Implement a Compliance Verification Plan

Developing and implementing the program itself is obvious. What might not be so obvious is the need to continually review, audit, analyze, feedback, and improve. Auditing is essential to ensure that the ESD control program is successful. You will be asked to continually identify the return on investment of the program and to justify the savings realized. Technological changes will dictate improvements and modifications. Feedback to employees and top management is essential. Management commitment will need reinforcement.

Include both reporting and feedback to management, the ESD team, and other employees as part of your plan. Management will want to know that their investment in time and money is yielding a return in terms of quality, reliability, and profits. Team members need a pat on the back for a job well done.

Other employees will want to know that the procedures you have asked them to follow are indeed worthwhile. It is helpful to integrate the improvement process into the overall quality system and use the existing root cause analysis and corrective action infrastructure.

Conduct periodic evaluations of your program and audits of your facility. You will find out if your program is successful and is giving you the expected return. You will spot weaknesses in the program and shore them up. You will discover whether the procedures are being followed.

As you find areas that need work, be sure to make the necessary adjustments to keep the program on track.

CONCLUSION

Six principles of static control and six key elements to program development and implementation are your guideposts for effective ESD control programs. In Part 3, we'll take a close look at specific procedures and materials that become part of your program. ■

FOR ADDITIONAL INFORMATION

- *ANSI/ESD S20.20—Standard for the Development of Electrostatic Discharge Control Program*, ESD Association, Rome, NY
- Dangelmayer, Theodore, *ESD Program Management: A Realistic Approach to Continuous, Measurable Improvement in Static Control*, 1999, Kluwer Academic Publishers, Boston, MA
- *ESD TR20.20, ESD Control Handbook*, ESD Association, Rome, NY
- *ESD TR53, Compliance Verification of ESD Protective Equipment and Materials*
- Industry Council White Papers I & II
- ESDA Technology Roadmap

Fundamentals of Electrostatic Discharge

Part 3: Basic ESD Control Procedures and Materials

BY THE ESD ASSOCIATION

In Part 2, *Principles of ESD Control,* we introduced six principles of static control and six key elements of ESD program development and implementation. In Part 3, we will cover some of the primary specific static control procedures and materials that will become part of your program. First, we review the principles.

BASIC PRINCIPLES OF STATIC CONTROL

We suggested focusing on just six basic principles in the development and implementation of effective ESD control programs:

- **Design in protection** by designing products and assemblies to be as robust as reasonable from the effects of ESD.
- **Define the level of control** needed in your environment.
- **Identify and define** the electrostatic protected areas (EPA), the areas in which you will be handling sensitive parts.
- **Eliminate and reduce generation** by reducing and eliminating static generating processes, keeping processes and materials at the same electrostatic potential and by providing appropriate ground paths to reduce charge generation and accumulation.
- **Dissipate and neutralize** by grounding, ionization and the use of conductive and dissipative static control materials.
- **Protect products from ESD** with proper grounding or shunting and the use of static control packaging and materials handling products.

At the facility level, our static control efforts concentrate on the last five principles. In this column we will concentrate on the primary materials and procedures that eliminate and reduce generation, dissipate and neutralize charges or protect sensitive products from ESD.

IDENTIFYING THE PROBLEM AREAS AND THE LEVEL OF CONTROL

One of the first questions we need to answer is "How sensitive are the parts and assemblies we are manufacturing or handling?" This information will guide you in determining the various procedures and materials required to control ESD in your environment.

How do you determine the sensitivity of your parts and assemblies or where can you get information about their ESD sensitivity? A first source would be the manufacturer or supplier of the component itself or the part data sheet. An additional source is System Reliability Center in Rome, NY, which publishes ESD susceptibility data for 22,000 devices, including microcircuits although this data is very generic and may not specifically cover the part you are actually using. It is also critical that you obtain both human-body model (HBM) and charge-device model (CDM) ratings. You may find that you need to have your specific parts tested for ESD sensitivity especially if the parts are known to operate at high speed or if the device performs a particularly critical function. We will discuss device sensitivity testing in Part 5 of this series.

The second question you need to answer is "Which areas of our facility need ESD protection?" This will allow you to define your specific electrostatic protected areas (EPAs), the areas in which you will be handling sensitive parts and the areas in which you will need to implement the control principles. Often you will find that there are more areas that require protection than you originally thought, usually wherever ESDS devices are handled. Typical areas requiring ESD protection are shown in Table 1.

GROUNDING

Grounding is especially important to effective ESD control and ESD grounding should be clearly defined and regularly evaluated.

The ESD ground provides a path to bring ESD protective materials and personnel to the same electrical potential. All conductors and dissipative materials in the environment, including personnel, must be bonded or electrically connected and attached to a known ground to create an equipotential balance between all items and personnel. Electrostatic protection can be maintained at a potential above a "zero" voltage ground reference as long as all items in the system are at the same potential. It is important to note that, by definition, insulators cannot lose their electrostatic charge by attachment to ground.

ESD Association Standard *ANSI/ESD S6.1 – Grounding* recommends a two-step procedure for grounding ESD protective equipment.

The first step is to ground all components of the work area (worksurfaces, people, equipment, etc.) to the same electrical ground point called the "common point ground." This common point ground is defined as a "system or method for connecting two or more grounding conductors to the same electrical potential."

This ESD common point ground should be properly identified. ESD Association Standard *ANSI/ESD S8.1 – Symbols*, recommends the use of the symbol in Figure 1 to identify the common point ground.

The second step is to connect the common point ground to the equipment ground or the third wire (green) electrical ground connection. This is the preferred ground connection because all electrical equipment at the workstation is already connected to this ground. Connecting the ESD control materials or equipment to the equipment ground brings all components of the workstation to the same electrical potential. If a soldering iron used to repair an ESDS item was connected to the electrical ground and the surface containing the ESDS item was connected to an auxiliary ground, a difference in electrical potential could exist between the iron and the ESDS item. This difference in potential could cause damage to the item.

Any auxiliary grounds (water pipe, building frame, ground stake) present and used at the workstation must be bonded to the equipment ground to minimize differences in potential between the two grounds. Detailed information on ESD grounding can be found in ESD Association Standard *ANSI/ESD S6.1 – Grounding*.

CONTROLLING STATIC ON PERSONNEL AND MOVING EQUIPMENT

People can be one of the prime generators of static electricity. The simple act of walking around or the motions required in repairing a board can generate several thousand volts on the human body. If not properly controlled, this static charge can easily discharge into a static sensitive device—a human body model (HBM) discharge. Also, a

Receiving
Inspection
Stores and warehouses
Assembly
Test and inspection
Research and development
Packaging
Field service repair
Offices and laboratories
Clean rooms

Table 1: Typical Facility Areas Requiring ESD Protection

Figure 1: Common Point Ground Symbol

person can transfer charge to a board or other item making it vulnerable to charged-device model (CDM) events in a subsequent process.

Even in highly automated assembly and test processes, people still handle static sensitive devices…in the warehouse, in repair, in the lab, in transport. For this reason, static control programs place considerable emphasis on controlling personnel generated electrostatic discharge. Similarly, the movement of carts and other wheeled equipment through the facility also can generate static charges that can transfer to the products being transported on this equipment.

WRIST STRAPS

Typically, wrist straps are the primary means of controlling static charge on personnel. When properly worn and connected to ground, a wrist strap keeps the person wearing it near ground potential. Because the person and other grounded objects in the work area are at or near the same potential, there can be no hazardous discharge between them. In addition, static charges are safely dissipated from the person to ground and do not accumulate.

Wrist straps have two major components, the cuff that goes around the person's wrist and the ground cord that connects the cuff to the common point ground. Most wrist straps have a current limiting resistor molded into the ground cord head on the end that connects to the cuff. This resistor is most commonly one megohm, rated at least 1/4 watt with a working voltage rating of 250 volts.

Wrist straps have several failure mechanisms and therefore should be tested on a regular basis. Either daily testing at specific test stations or continuous monitoring at the workbench is recommended.

FLOORS, FLOOR MATS, FLOOR FINISHES

A second method of controlling electrostatic charge on personnel is with the use of ESD protective floors in conjunction with ESD control footwear or foot straps. This combination of floor materials and footwear provides a ground path for the dissipation of electrostatic charge, thus reducing the charge accumulation on personnel and other objects to safe levels. In addition to dissipating charge, some floor materials (and floor finishes) also reduce triboelectric charging. The use of floor materials is especially appropriate in those areas where increased personnel mobility is necessary. In addition, floor materials can minimize charge accumulation on chairs, carts, lift trucks and other objects that move across the floor. However, those items require dissipative or conductive casters or wheels to make electrical contact with the floor. When used as the primary personnel grounding system, the resistance to ground including the person, footwear and floor must be the same as specified for wrist straps (< 35 x 10E6 ohms) or the accumulation in a standard walking voltage test (ANSI/ESD STM97.2) must be less than 100 volts.

SHOES, GROUNDERS, CASTERS

Used in combination with ESD protective floor materials, static control shoes, grounders, casters and wheels provide the necessary electrical contact between the person or object and the floor material. Insulative footwear, casters or wheels prevent static charges from flowing from the body to the floor to ground.

CLOTHING

Clothing is a consideration in some ESD protective areas, especially in clean rooms and very dry environments. Clothing materials can generate electrostatic charges that may discharge into sensitive components or they may create electrostatic fields that may induce charges on the human body. Because clothing usually is electrically insulated or isolated from the body, charges on clothing fabrics are not necessarily dissipated to the skin and then to ground. Grounded static control garments are intended to minimize the effects of electrostatic fields or charges that may be present on a person's clothing.

WORKSTATIONS AND WORKSURFACES

An ESD protective workstation refers to the work area of a single individual that is constructed and equipped with materials and equipment to limit damage to ESD sensitive items. It may be a stand-alone station in a stockroom, warehouse or assembly area or in a field location such as a computer bay in commercial aircraft. A workstation also may be located in a controlled area such as a clean room. The key ESD control elements comprising most workstations are a static dissipative worksurface, a means of grounding personnel (usually a wrist strap), a common grounding connection and appropriate signage and labeling. A typical workstation is shown in Figure 2.

The workstation provides a means for connecting all worksurfaces, fixtures, handling equipment and grounding devices to a common point ground. In addition, there may be provision for connecting additional personal grounding devices, equipment and accessories such as constant ground monitors and ionizers.

Static protective worksurfaces with a resistance to ground of 10^6 to 10^9 provide a surface that is at the same electrical potential as other ESD protective items in the workstation. They also provide an electrical path to ground for the controlled dissipation of any static potentials on materials that contact the surface. The worksurface also helps define a specific work area in which ESD sensitive devices may be

ESD

safely handled. The worksurface is connected to the common point ground.

PRODUCTION EQUIPMENT AND PRODUCTION AIDS

Although personnel generated static is usually the primary ESD culprit in many environments, automated manufacturing and test equipment also can pose an ESD problem. For example, a device may become charged from sliding down a feeder. If the device then contacts the insertion head or another conductive surface, a rapid discharge occurs from the device to the metal object—a Charged Device Model (CDM) event. In addition, various production aids such as hand tools, tapes or solvents can also be ESD concerns.

Grounding is the primary means of controlling static charge on equipment and many production aids. Much electrical equipment is required by the National Electrical Code to be connected to the equipment ground (the green wire) in order to carry fault currents. This ground connection also will function for ESD purposes. All electrical tools and equipment used to process ESD sensitive hardware require the 3 prong grounded type AC plug. Hand tools that are not electrically powered, i.e., pliers, wire cutters and tweezers, are usually grounded through the ESD worksurface and the (grounded) person using the conductive tools. Holding fixtures should be made of conductive or static dissipative materials when possible. Static dissipative materials are often suggested when very sensitive devices are being handled. A separate ground wire may be required for conductive or dissipative fixtures not sitting on an ESD worksurface or handled by a grounded person. For those items that are composed of insulative materials, the use of ionization or application of topical antistats may be required to control generation and accumulation of static charges.

PACKAGING AND HANDLING

Direct protection of ESDS devices from electrostatic discharge is provided by packaging materials such as bags, corrugated boxes and rigid or semi-rigid plastic packages. The primary use of these items is to protect the product when it leaves the facility, usually when shipped to a customer. In addition, materials handling products such as tote boxes and other containers primarily provide protection during inter- or intra-facility transport.

The main ESD function of these packaging and materials handling products is to limit the possible impact of ESD from triboelectric charge generation, direct discharge and in some cases electrostatic fields. The initial consideration is to have low charging materials in contact with ESD sensitive items. For example, the low charging property would control triboelectric charge resulting from sliding a board or component into the package or container. A second requirement is that the material provides protection from direct electrostatic discharge. A third property that is sometimes specified is shielding from electrostatic fields. The selection of a suitable packaging material should consider all of these properties but in many cases not all are needed.

Many materials are available that provide all three properties: low charging, discharge protection and electric field suppression. The inside of these packaging materials have a low charging layer, but also have an outer layer with a surface resistance generally in the dissipative range. In many cases a low-charging, static dissipative package is adequate for handling within an EPA. Effectiveness, cost and device vulnerability to the various mechanisms need to be balanced in making packaging decisions (see *ANSI/ESD S541* for more detailed information).

Resistance or resistivity measurements help define the material's ability to provide electrostatic shielding or charge dissipation. Electrostatic shielding attenuates electrostatic fields on the surface of a package in order to prevent a difference in electrical potential from existing inside the package. Electrostatic shielding is provided by materials that have a surface resistance equal to or less than 1.0×10^3 when tested according to *ANSI/ESD STM11.11* or a volume resistivity of equal to or less than 1.0×10^3 ohm-cm when tested according to the methods of *ANSI/ESD STM 11.12*. In addition, effective shielding may be provided by packaging materials that provide an air gap between the package and the product. Dissipative materials provide charge dissipation characteristics. These materials have a surface resistance greater than 1.0×10^4 but less than or equal to 1.0×10^{11} when tested according to *ANSI/ESD STM11.11* or a volume resistivity greater than 1.0×10^5 ohm-cm but less than

ESD

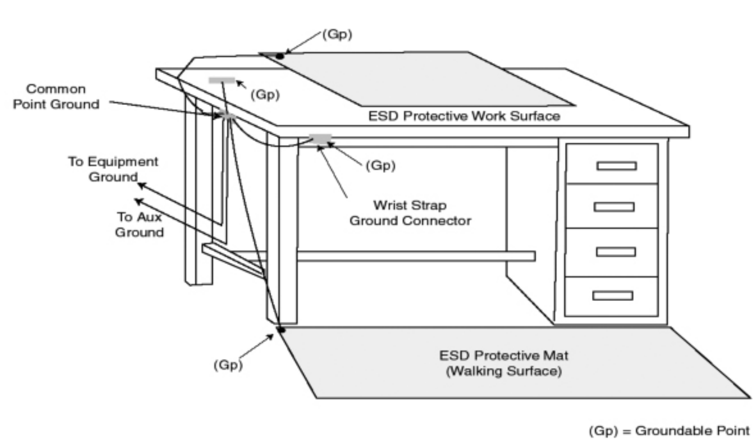

Figure 2: Typical ESD Workstation

or equal to 1.0 x 10^{12} ohm-cm when tested according to the methods of *ANSI/ESD STM11.12*. The ability of some packages to provide discharge shielding may be evaluated using *ANSI/ESD STM11.31* which measures the energy transferred to the package using an HBM discharge. A material's low charging properties are not necessarily predicted by its resistance or resistivity.

IONIZATION

Most static control programs also deal with isolated conductors that cannot be grounded or insulating materials (e.g., most common plastics). Topical antistats may provide temporary ability to dissipate static charges under some circumstances.

More frequently, however, air ionization is used to neutralize the static charge on insulated and isolated objects by providing a balanced source of positive and negative ionized molecules of the gases of the surrounding air. Whatever static charge is present on objects in the work environment will be neutralized by attracting opposite polarity charges from the air. Because it uses only the air that is already present in the work environment, air ionization may be employed even in clean rooms where chemical sprays and some static dissipative materials are not usable.

Air ionization is one component of a complete static control program, not necessarily a substitute for grounding or other methods. Ionizers are used when it is not possible to properly ground everything and as backup to other static control methods. In clean rooms, air ionization may be one of the few methods of static control available.

CLEANROOMS

While the basic methods of static control discussed here are applicable in most environments, cleanroom manufacturing processes require special considerations.

Many objects integral to the semiconductor manufacturing process (quartz, glass, plastic and ceramic) are inherently charge generating. Because these materials are insulators, this charge cannot be removed easily by grounding. Many static control materials contain carbon particles or surfactant additives that sometimes restrict their use in clean rooms. The need for personnel mobility and the use of clean room garments often make the use of wrist straps difficult. In these circumstances, ionization and flooring/footwear systems become key weapons against static charge.

IDENTIFICATION

A final element in our static control program is the use of appropriate symbols to identify static sensitive devices and assemblies, as well as products intended to control ESD. The two most widely accepted symbols for identifying ESDS parts or ESD control materials are defined in ESD Association Standard *ANSI/ESD S8.1 — ESD Awareness Symbols*.

The ESD Susceptibility Symbol (Figure 3) consists of a triangle, a reaching hand and a slash through the reaching hand. The triangle means "caution" and the slash through the reaching hand means "Don't touch." Because of its broad usage, the hand in the triangle has become associated with ESD and the symbol literally translates to "ESD sensitive stuff, don't touch."

The ESD Susceptibility Symbol is applied directly to integrated circuits, boards and assemblies that are static sensitive. It indicates that handling or use of this item may result in damage from ESD if proper precautions are not taken. If desired, the sensitivity level of the item may be added to the label.

The ESD Protective Symbol (Figure 4) consists of the reaching hand in the triangle. An arc around the triangle replaces the slash. This "umbrella" means protection. The symbol indicates ESD protective material. It is applied to mats, chairs, wrist straps, garments, packaging and other items that provide ESD protection. It also may be used on equipment such as hand tools, conveyor belts or automated handlers that is especially designed or modified to provide ESD control.

Figure 3: ESD Susceptibility

Figure 4: ESD Protective Symbol

ESD

Neither symbol is applied on ESD test equipment, footwear checkers, wrist strap testers, resistance or resistivity meters or similar items that are used for ESD purposes, but which do not provide actual protection.

SUMMARY

Effective static control programs require a variety of procedures and materials. We have provided a brief overview of the most commonly used elements of a program. Additional in-depth discussion of individual materials and procedures can be found in publications such as the ESD Handbook
(ESD TR20.20) published by the ESD Association.

Your program is up and running. How do you determine whether it is effective? How do you make sure your employees follow it? In Part 4, we will cover the topics of Auditing and Training. ■

FOR ADDITIONAL INFORMATION

ESD Association Standards

- *ANSI/ESD S1.1: Wrist Straps*, ESD Association, Rome, NY
- *ANSI/ESD STM2.1: Garments – Characterization*, ESD Association, Rome, NY
- *ANSI/ESD STM3.1: Ionization*, ESD Association, Rome, NY
- *ANSI/ESD SP3.3: Periodic Verification of Air Ionizers*, ESD Association, Rome, NY
- *ANSI/ESD S4.1: Worksurfaces – Resistance Measurements*, ESD Association, Rome, NY
- *ANSI/ESD STM4.2: ESD Protective Worksurfaces – Charge Dissipation Characteristics*, ESD Association, Rome, NY
- *ANSI/ESD S6.1: Grounding,* ESD Association, Rome, NY
- *ANSI/ESD S7.1: Resistive Characterization of Materials – Floor Materials*, ESD Association, Rome, NY
- *ANSI/ESD S8.1: Symbols – ESD Awareness*, ESD Association, Rome, NY
- *ANSI/ESD STM9.1: Footwear – Resistive Characterization*, ESD Association, Rome, NY
- *ESD SP9.2: Footwear – Foot Grounders Resistive Characterization*, ESD Association, Rome, NY
- *ANSI/ESD SP10.1: Automated Handling Equipment*, ESD Association, Rome, NY
- *ANSI/ESD STM11.11: Surface Resistance Measurement of Static Dissipative Planar Materials*, ESD Association, Rome, NY
- *ANSI/ESD STM11.12: Volume Resistance Measurement of Static Dissipative Planar Materials*, ESD Association, Rome, NY
- *ANSI/ESD STM11.13: Two – Point Resistance Measurement*, ESD Association, Rome, NY
- *ANSI/ESD STM11.31: Evaluating the Performance of Electrostatic Discharge Shielding Bags*, ESD Association, Rome, NY
- *ANSI/ESD STM12.1: Seating – Resistive Measurement*, ESD Association, Rome, NY
- *ESD STM13.1: Electrical Soldering/Desoldering Hand Tools*, ESD Association, Rome, NY
- *ANSI/ESD SP15.1: In-Use Resistance Testing of Gloves and Finger Cots, ESD Association,* Rome, NY
- *ANSI/ESD S20.20: Standard for the Development of an ESD Control Program*, ESD Association, Rome, NY
- *ANSI/ESD STM97.1: Floor Materials and Footwear – Resistance in Combination with a Person*, ESD Association, Rome, NY
- *ANSI/ESD STM97.2: Floor Materials and Footwear – Voltage Measurement in Combination with a Person*, ESD Association, Rome, NY
- *ANSI/ESD S541: Packaging Materials for ESD Sensitive Devices, ESD Association,* Rome, NY
- *ESD ADV1.0: Glossary of Terms, ESD Association,* Rome, NY
- *ESD ADV11.2: Triboelectric Charge Accumulation Testing*, ESD Association, Rome, NY
- *ESD ADV53.1: ESD Protective Workstations*, ESD Association, Rome, NY
- *ESD TR20.20: ESD Handbook*, ESD Association, Rome, NY
- *ESD TR53: Compliance Verification of ESD Protective Equipment and Materials*, ESD Association, Rome, NY

OTHER RESOURCES

- System Reliability Center, 201 Mill Street, Rome, NY
- *ANSI/IEEE STD142, IEEE Green Book*, Institute of Electrical and Electronics Engineers
- *ANSI/NFPA 70, National Electrical Code*, National Fire Protection Association, Quincy, MA

ESD

Fundamentals of Electrostatic Discharge

Part 4: Training and Auditing

BY THE ESD ASSOCIATION

ESD

Your static control program is up and running. How do you determine whether it is effective? How do you make sure your employees follow it? In Part 3, we suggested that there were at least nine critical elements to successfully developing and implementing an effective ESD control program. In Part 4, we will focus on two more of these elements: training and auditing.

PERSONNEL TRAINING

The procedures are in place. The materials are in use. But your ESD control program just does not seem to yield the expected results. Failures declined initially, but they have begun reversing direction. Or perhaps there was little improvement at all. The solutions might not be apparent in inspection reports of incoming ESD materials, nor in the wrist strap log-in sheets. In large companies or small, it is hard to underestimate the role of training in an ESD control program. ANSI/ESD S20.20 ESD Control Program development standard cites training as a basic administrative requirement within an ESD control program. There is significant evidence to support the contribution of training to the success of the program. [2, 11, 18, 19, 23, 24] We would not send employees to the factory floor without the proper soldering skills or the knowledge to operate the automated insertion equipment. We should provide them with the same skill level regarding ESD control procedures.

ELEMENTS OF EFFECTIVE TRAINING PROGRAMS

Although individual requirements cause training programs to vary from company to company, there are several common threads that run through the successful programs.

1. Successful training programs cover all affected employees.

Obviously we train the line employees who test their wrist straps or place finished products in static protective packaging. But we also include department heads, upper management and executive personnel in the process. Typically, they are responsible for the day-to-day supervision and administration of the program, or they provide leadership and support. Even subcontractors and suppliers should be considered for inclusion in the training program if they are directly involved in handling your products.

Because ESD control programs cover such a variety of job disciplines and educational levels, it may be necessary to develop special training modules for each organizational entity. For example, the modules developed for management, engineering, assembly technicians and field service could differ significantly from one another because their day-to-day concerns and responsibilities are much different.

2. Effective training is comprehensive and consistent.

Training not only covers specific procedures, but also the physics of the problem and the benefits of the program as well. Consistent content across various groups, plants and even countries (adjusted for cultural differences, of course) reduces confusion and helps assure conformance. The training content should include topics such as the fundamentals of static electricity and ESD, the details of the organization's ESD Control Program plan and each person's role in the plan.

3. Use a variety of training tools and techniques.

Choose the methods that will work best for your organization. Combine live instruction with training videos or interactive computer-based programs. You may have in-house instructors available, or you may need to go outside the company to find instructors or training materials. You can also integrate industry symposia, tutorials and workshops into your program.

Effective training involves employees in the process. Reinforce the message with demonstrations of ESD events and their impact. Bulletin boards, newsletters and posters provide additional reminders and reinforcement.

Maintaining a central repository for educational ESD control materials will help your employees keep current or answer questions that may occur outside the formal training sessions. Materials in such a repository might include:

- Material from initial and recurring training sessions
- ESD Association or internal bulletins or newsletters
- Videos or CDs
- Computer based training materials
- Technical papers, studies, ESD Association standards, test methods and specifications
- ESD Control material and equipment product sheets

In addition, a knowledgeable person in the organization should be available to answer trainee questions once they have begun working.

4. Test, certify and retrain

Your training should assure material retention and emphasize the importance of the effort. If properly implemented, testing and certification motivates and builds employee pride. Retraining or refresher training is an ongoing process that reinforces, reminds and provides opportunities for implementing new or improved procedures. Establish a system to highlight when employees are due for retraining, retesting or recertification.

5. Feedback, auditing and measurement

Motivate and provide the mechanism for program improvement. Sharing yield or productivity data with employees demonstrates the effectiveness of the program and of their efforts. Tracking these same numbers can indicate that it's time for retraining or whether modifications are required in the training program.

Design and delivery of an effective ESD training program can be just as important as the procedures and materials used in your ESD control program. A training program that is built on identifiable and measurable performance goals helps assure employee understanding, implementation and success.

AUDITING

Developing and implementing an ESD control program itself is obvious. What might not be so obvious is the need to continually review, verify, analyze, feedback and improve. You will be asked to continually identify the program's return on investment and to justify the savings realized. Technological changes will dictate improvements and modifications. Feedback to employees and top management is essential. Management commitment will need continuous reinforcement.

Like training, regular program verification and auditing becomes a key factor in the successful management of ESD control programs. The mere presence of the auditing process spurs compliance with program procedures. It helps strengthen management's commitment. Program verification and audit reports trigger corrective action and help foster continuous improvement.

The benefits to be gained from regular verification of ESD control procedures are numerous.

- They allow us to prevent problems before they occur rather than always fighting fires.
- They allow us to readily identify problems and take corrective action.
- They identify areas in which our programs may be weak and provide us with information required for continuous improvement.
- They allow us to leverage limited resources effectively.
- They help us determine when our employees need to be retrained.
- They help us improve yields, productivity and capacity.
- They help us bind our ESD program together into a successful effort.

An ESD program verification audit measures performance to the defined ESD Control Program Plan. Typically, we think of the ESD program verification audit as a periodic review and inspection of the ESD work area covering use of the correct packaging materials, wearing of wrist straps, following defined procedures and similar items. Auditing can range from informal surveys of the processes and facilities to the more formal third-party audits for ISO 9000 or ANSI/ESD S20.20 certification.

REQUIREMENTS FOR EFFECTIVE AUDITING

Regardless of the structure, effective ESD auditing revolves around several factors. First, auditing implies the existence of a written and well-defined ESD Control Program Plan. It is difficult to measure performance if you do not have anything to measure against. Yet, you quite frequently hear an auditor ask, “Some people say you should measure less than 500 volts in an ESD protected area, but others say you should measure less than 100 volts. What’s acceptable when I audit the factory floor?” Obviously, this question indicates a lack of a formal ESD Control Program Plan and the audit will be relatively ineffective.

Second, most audits require the taking of some measurements – typically measuring resistance and detecting the presence of charge or fields. Therefore, you will need specific instrumentation to conduct work area verification audits. As a minimum, you will need an electrostatic field meter, a wide range resistance meter, a ground/circuit tester and appropriate electrodes and accessories. Although this equipment must be accurate, it need not be as sophisticated as laboratory instruments. The audit is intended to verify basic functions and not as a full qualification of ESD control equipment or materials. You want the right tool for the job. Remember, many of the instruments you might choose for auditing are good indicators, but not suitable for precise evaluation of materials. However, be sure that you can correlate the values obtained on the factory floor with those obtained in the laboratory.

Third, our verification audits need to include all areas in which ESD control is required to protect electrostatic discharge sensitive (ESDS) devices. Typically these areas would include receiving, inspection, stores and warehouses, assembly, test and inspection, research and development, packaging, field service repair, offices and laboratories and cleanrooms. All of the areas listed in the ESD Control Program Plan are subject to verification. Even the areas that are excluded from the Plan need to be reviewed to ensure that unprotected ESDS devices are not handled in those areas. In the event that devices do enter those areas (e.g. Engineering and Design), mechanisms must be put in place to ensure that the devices are handled as non-conforming product. Similarly, we need to audit all of the various processes, materials and procedures that are used in our ESD control programs – personnel, equipment, wrist straps, floors, clothing, worksurfaces, training and grounding.

Fourth, we need to conduct verification audits frequently and regularly. The actual frequency of these audits depends upon your facility and the ESD problems that you have. Following an ESD Control Program initial audit, some experts recommend auditing each department once a month if possible and probably a minimum of six times per year. If this seems like a high frequency level, remember that these regular verification audits are based upon a sampling of work areas in each department, not necessarily every workstation. Once you have gotten your program underway, your frequency of audit will be based on your experience. If your audits regularly show acceptable levels of conformance and performance, you can reduce the frequency of auditing. If, on the other hand, your audits regularly uncover continuing problems, you may need to increase the frequency.

Fifth, we need to maintain trend charts and detailed records and prepare reports. They help assure that specified procedures are followed on a regular basis. The records are essential for quality control purposes, corrective action and compliance with ISO-9000.

Finally, upon completion of the verification audit, it is essential to implement corrective action if deficiencies are discovered. Trends need to be tracked and analyzed to help establish corrective action, which may include retraining of personnel, revision of requirement documents or processes or modification of the existing facility.

TYPES OF AUDITS

There are three types of ESD audits: program management audits, quality process checking and work place audits. Each type is distinctively different and each is vitally important to the success of the ESD program

Program management audits measure how well a program is managed and the strength of the management commitment. The program management audit emphasizes factors such as the existence of an effective implementation plan, realistic program requirements, ESD training programs, regular verification audits and other critical factors of program management. The program management audit typically is conducted by a survey specifically tailored to the factors being reviewed. Because it’s a survey, the audit could be conducted without actually visiting the site. The results of this audit indirectly measure work place compliance and are particularly effective as a means of self-assessment for small companies as well as large global corporations.

Quality process checking applies classical statistical quality control procedures to the ESD process and is performed by operations personnel. This is not a periodic verification audit, but rather daily maintenance of the program. Visual and electrical checks of the procedures and materials, wrist strap testing for example, are used to monitor the quality of the ESD control process. Checking is done on a daily, weekly or monthly basis.

Trend charts and detailed records trigger process adjustments and corrective action. They help assure that specified procedures are followed on a regular basis. The records are essential for quality control purposes, corrective action and compliance with ISO-9000.

ESD Control Program Verification audits verify that program procedures are followed and that ESD control materials and equipment are within specification or are functioning properly. Compliance Verification audits are performed on a regular basis, often monthly and utilize sampling techniques and statistical analysis of the results. The use of detailed checklists and a single auditor assures that all items are covered and that the audits are performed consistently over time.

BASIC AUDITING INSTRUMENTATION

Special instrumentation will be required to conduct work area audits. The specific instrumentation will depend on what you are trying to measure, the precision you require and the sophistication of your static control and material evaluation program. However, as a minimum, you will need an electrostatic field meter, a wide range resistance meter, a ground/circuit tester and appropriate electrodes and accessories. Additional instrumentation might include a charged plate monitor, footwear and wrist strap testers, chart recorders/data acquisition systems and timing devices, discharge simulators and ESD event detectors.

Although this equipment must be accurate, it needs not be as sophisticated as laboratory instruments. The audit is intended to verify basic functions and not as a full qualification of ESD control equipment or materials. Remember, you want the right tool for the job. Just as you would not buy a hammer if you are were planning to saw wood, you would not purchase an electrometer to measure static voltages on a production line. If you are making measurements according to specific standards or test methods, be sure the instrumentation meets the requirements of those documents.

With a hand-held electrostatic field meter, you can measure the presence of electrostatic fields in your environment allowing you to identify problem areas and monitor your ESD control program. These instruments measure the electrostatic field associated with a charged object. Many field meters simply measure the gross level of the electrostatic field and should be used as general indicators of the presence of a charge and the approximate level of electrical potential of the charge. Others will provide more precise measurement for material evaluation and comparison.

For greater precision in facility measurements or for laboratory evaluation, a charged plate monitor is a useful instrument that can be used in many different ways; for example to evaluate the performance of flooring materials or balance ionizing equipment.

Because resistance is one of the key factors in evaluating ESD control materials, a wide range resistance meter becomes a crucial instrument. Most resistance measurements are made at 100 volts and some at 10 volts. The equipment you choose should be capable of applying these voltages to the materials being tested. In addition, the meter should be capable of measuring resistance ranges of 103 to 1012 ohms. With the proper electrodes and cables, you will be able to measure the resistance of flooring materials, worksurfaces, equipment, furniture, garments and some packaging materials.

The final instrument is a ground/circuit tester. With this device you can measure the continuity of your ESD grounds, check the impedance of the equipment grounding conductor (3rd wire AC ground) as well as verify that the wiring of power outlets in the work area is correct.

AREAS, PROCESSES AND MATERIALS TO BE AUDITED

Previously we stated that ESD protection was required "wherever unprotected ESDS devices are handled." Obviously, our audits need to include these same areas. Table 1 indicates some of the physical areas that may be part of the ESD Control Program Plan and therefore will be involved in Compliance Verification Audits. Remember, some areas may be excluded from the Plan depending on the Scope of the Plan.

Similarly, we need to conduct Compliance Verification audits for all of the various processes, materials and procedures that are used in our ESD Control Program Plan. Some of these are shown in Table 2.

Receiving
Inspection
Stores and Warehouses
Assembly
Test and Inspection
Research and Development
Packaging
Field Service Repair
Offices and Laboratories
Clean Rooms

Table 1: Typical Facility Areas

CHECK LISTS

Check lists can be helpful tools for conducting Compliance Verification audits. However, it is important that ESD control program requirements are well documented and accessible to avoid a tendency for checklists becoming de facto lists of requirements. Table 3 indicates the type of questions and information that might be included in an auditing check list. Your own check lists, of course, will be based on your specific needs and program requirements. They should conform to your actual ESD control procedures and specifications, and they should be consistent with any ISO 9000 requirements you may have. For ANSI/ESD S20.20 based ESD Control Programs, the recognized Certification Bodies (Registrars) use a formal checklist supplied by the ESD Association to aid in conducting the Certification Audit.

In addition to check lists, you will use various forms for recording the measurements you make: resistance, voltage generation, etc. Part of your audit will also include the daily logs used on the factory floor such as those used for wrist strap checking.

REPORTING AND CORRECTIVE ACTION

Upon completion of the auditing process, Reports should be prepared and distributed in a timely manner. Details of the audits need to be fully documented for ISO 9000 or ANSI/ESD S20.20 certification. As with all audits, it is essential to implement corrective action if deficiencies are discovered. Trends need to be tracked and analyzed to help establish corrective action, which may include retraining of personnel, revision of requirement documents or processes or modification of the existing facility.

Personnel
Moving Equipment (Carts, lift trucks)
Wrist Straps
Floors, Floor Mats, Floor Finishes
Shoes, Grounders, Casters
Clothing
Workstations
Worksurfaces
Packaging and Materials Handling
Ionization
Grounding
Production Equipment
Tools and Equipment (Soldering irons, fixtures, etc.)
Labeling and Identification
Purchasing Specifications and Requisitions
ESD Control Program Procedures and Specifications
ESD Measurement and Test Equipment
Personnel Training
Engineering Specifications and Drawings

Table 2: Typical Processes, Materials and Procedures

CONCLUSION

Auditing and training are key elements in maintaining an effective ESD control program. They help assure that procedures are properly implemented and can provide a management tool to gauge program effectiveness and make continuous improvement. ■

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21. "ESD Demonstrations to Increase Engineering and Manufacturing Awareness," G. Baumgartner, *EOS/ESD Symposium Proceedings, 1996,* ESD Association, Rome, NY.

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23. "Procedures For The Design, Analysis and Auditing of Static Control Flooring/Footwear Systems," L. Fromm, et al, *EOS/ESD Symposium Proceedings*, 1997, ESD Association, Rome, NY.

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25. "A Comparison of High-Frequency Voltage, Current and Field Probes and Implications for ESD/EOS/EMI Auditing," A. Wallash, V. Kraz, *EOS/ESD Symposium Proceedings*, 2007, ESD Association, Rome, NY.

Function/Area Audited: Facilities

Date:

Auditor:

Audit Questions	Y	N	Comments
Where ESD protective flooring is used for personnel grounding, are foot grounding devices or conductive footwear worn?			
Where conductive floors and footwear are used for personnel grounding, do personnel check continuity to ground upon entering the area?			
Are personnel wearing grounded wrist straps at the ESD protective workstations?			
Are personnel checking wrist straps for continuity or using a continuous ground monitor?			
Where continuous ground monitors are not used, are wrist straps checked and logged routinely and at frequent intervals?			
Are wrist strap checkers and continuous ground monitors checked and maintained periodically?			
Do wrist straps and foot grounders fit correctly?			
Are wrist straps and foot grounders working correctly?			
Are wrist strap cords checked, on the person, at the workstation?			
Are disposable foot grounders limited to one time use?			
Are test records for wrist straps and foot grounders kept and maintained?			
When required, are ESD protective garments correctly worn?			
Are nonessential personal items kept out of ESD controlled areas?			
Are personnel working in the ESD controlled area currently certified or escorted?			
Are all personnel with access to the ESD controlled area trained?			
Are ESD Control requirements imposed on visitors?			

Table 3: Partial Audit Check List for ESD Control Program

Fundamentals of Electrostatic Discharge

Part 5: Device Sensitivity and Testing

BY THE ESD ASSOCIATION

In Part 2 of this series we indicated that a key element in a successful static control program was the identification of those items (components, assemblies and finished products) that are sensitive to ESD and the level of their sensitivity. Damage to an ESDS device by the ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the current levels involved. This is known as device "ESD sensitivity" or "ESD susceptibility."

Some devices may be more readily damaged by discharges occurring within automated equipment, while others may be more prone to damage from handling by personnel. In this article we will cover the models and test procedures used to characterize, determine and classify the sensitivity of components to ESD. These test procedures are based on the two primary models of ESD events: Human Body Model (HBM) and Charged Device Model (CDM). The models used to perform component testing cannot replicate the full spectrum of all possible ESD events. Nevertheless, these models have been proven to be successful in reproducing over 99% of all ESD field failure signatures. With the use of standardized test procedures, the industry can:

- Develop and measure suitable on-chip protection.
- Enable comparisons to be made between devices.
- Provide a system of ESD sensitivity classification to assist in the ESD design and monitoring requirements of the manufacturing and assembly environments.
- Have documented test procedures to ensure reliable and repeatable results.

HUMAN BODY MODEL (HBM) TESTING

One of the most common causes of electrostatic damage is the direct transfer of electrostatic charge through a significant series resistor from the human body or from a charged material to the electrostatic discharge sensitive (ESDS) device. When one walks across a floor, an electrostatic charge accumulates on the body. Simple contact of a finger to the leads of an ESDS device or assembly allows the body to discharge, possibly causing device damage. The model used to simulate this event is the Human Body Model (HBM).

The Human Body Model is the oldest and most commonly used model for classifying device sensitivity to ESD. The HBM testing model represents the discharge from the fingertip of a standing individual delivered to the device. It is modeled by a 100 pF capacitor discharged through a switching component and a 1.5kΩ series resistor into the component. This model, which dates from the nineteenth century, was developed for investigating explosions of gas mixtures in mines. It was adopted by the military in MIL-STD-883 Method 3015 and is referenced in *ANSI/ESDA-JEDEC JS-001-2010: Electrostatic Discharge Sensitivity Testing - Human Body Model*. This document replaces the previous ESDA and JEDEC methods, STM5.1-2007 and JESD22-A114F respectively. A typical Human Body Model circuit is presented in Figure 1.

Testing for HBM sensitivity is typically performed using automated test systems. The device is placed in the test system and contacted through a relay matrix. ESD zaps are applied. A part is determined to have failed if it does not meet the datasheet parameters using parametric and functional testing.

CHARGED DEVICE MODEL (CDM) TESTING

The transfer of charge *from* an ESDS device is also an ESD event. A device may become charged, for example, from sliding down the feeder in an automated assembler. If it then contacts the insertion head or another conductive surface, which is at a lower potential, a rapid discharge may occur from the device to the metal object. This event is known as the Charged Device Model (CDM) event and can be more destructive than the HBM for some devices. Although the duration of the discharge is very short - often less than one nanosecond - the peak current can reach several tens of amperes.

The device testing standard for CDM *(ESD STM5.3.1: Electrostatic Discharge Sensitivity Testing - Charged Device Model)* was originally published in 1999. The test procedure involves placing the device on a field plate with its leads pointing up, then charging it and discharging the device. Figure 2 illustrates a typical CDM test circuit. The CDM 5.3.1 ESDA document was last published in 2009.

OTHER TEST METHODS

Machine Model (MM) Testing

A discharge which is different in shape and size to the HBM event also can occur from a charged conductive object, such as a metallic tool or an automatic equipment or fixture. Originating in Japan as the result of trying to create a worst-case HBM event, the model is known as the Machine Model. This ESD model consists of a 200 pF capacitor discharged directly into a component with no series DC resistor in the output circuitry. The industry is in the process of removing this model from qualification requirements. The technical background on this change is described in Industry Council White Paper 1, “A Case for Lowering Component Level HBM/MM ESD Specifications and Requirements.”

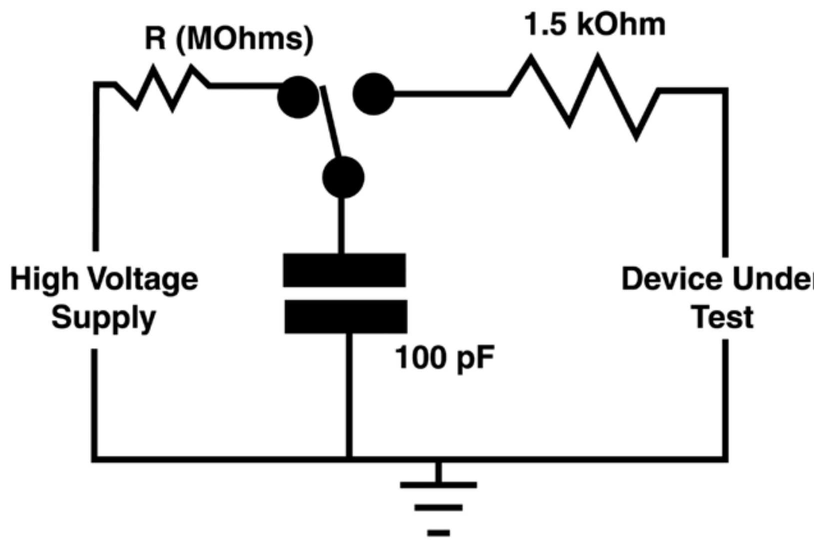

Figure 1: Typical Human Body Model Circuit

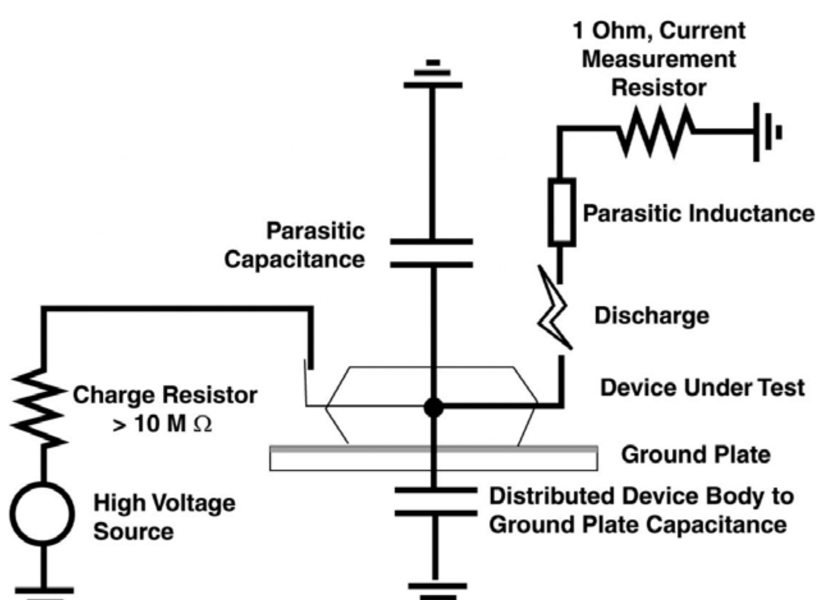

Figure 2: Typical Charged Device Model Test

As a worst-case human body model, the Machine Model may be over severe. However, there are real-world situations that this model may simulate, for example the rapid discharge from the metallic contacts on a charged board assembly or from the charged cables or handles/arms of an automatic tester.

Testing of devices for MM sensitivity using ESD Association standard *ESD STM5.2: Electrostatic Discharge Sensitivity Testing - Machine Model* is similar in procedure to HBM testing. The test equipment is the same, but the test head is slightly different. The MM version does not have a 1,500 ohm resistor, but otherwise the test board and the socket are the same as for HBM testing. The series inductance, as shown in Figure 3, is the dominating parasitic element that shapes the oscillating machine model wave form. The series inductance is indirectly defined through the specification of various waveform parameters like peak currents, rise times and the period of the waveform. The MM 5.2 document was last published in 2009.

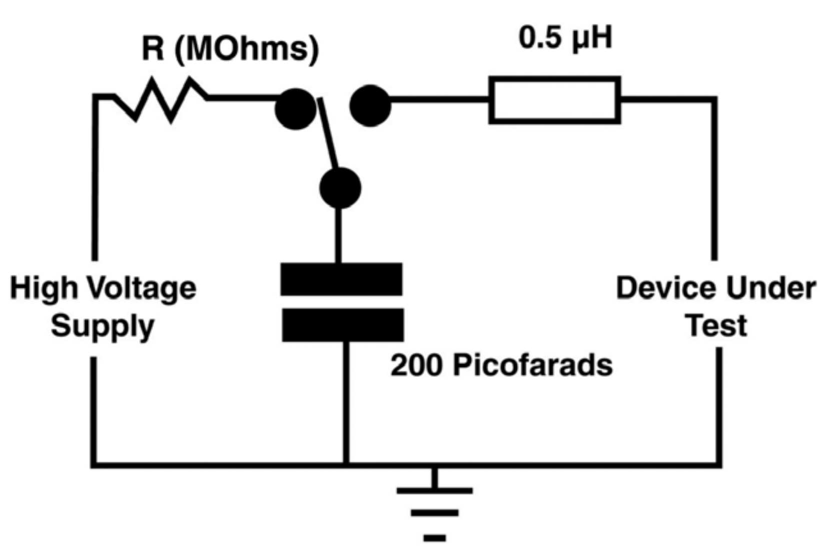

Figure 3: Typical Machine Model Circuit

Socketed Device Model (SDM) Testing

SDM testing is similar to testing for HBM and MM sensitivity. The device is placed in a socket, charged from a high-voltage source and then discharged. This model was originally intended to provide an efficient way to do CDM testing. However, the model did not have sufficient correlation with the CDM standard and there was too great a dependency on the specific design of the SDM tester. A Standard Practice (SP) document, SDM-5.3.2, was first published in 2002 and re-published in 2008. A technical report, *ESD TR5.3.2 (formerly TR08-00): Socket Device Model (SDM) Tester* is also available from the ESD Association.

DEVICE SENSITIVITY CLASSIFICATION

The HBM and CDM methods include a classification system for defining the component sensitivity to the specified model (See Tables 1 and 2). These classification systems have a number of advantages. They allow easy grouping and comparing of components according to their ESD sensitivity and the classification gives you an indication of the level of ESD protection that is required for the component.

A fully characterized component should be classified using Human Body Model and Charged Device Model. For example, a fully characterized component may have 2 of the following: Class 1B (500 volts

Class	Voltage Range
Class 0	<250 volts
Class 1A	250 volts to <500 volts
Class 1B	500 volts to < 1,000 volts
Class 1C	1000 volts to < 2,000 volts
Class 2	2000 volts to < 4,000 volts
Class 3A	4000 volts to < 8000 volts
Class 3B	≥ 8000 volts

Table 1: ESDS Component Sensitivity Classification - Human Body Model (Per ESD STM5.1-2007)

Class	Voltage Range
Class C1	<125 volts
Class C2	125 volts to <250 volts
Class C3	250 volts to <500 volts
Class C4	500 volts to <1,000 volts
Class C5	1,000 volts to <1,500 volts
Class C6	1,500 volts to <2,000 volts
Class C7	≥ 2,000 volts

Table 2: ESDS Component Sensitivity Classification - Charged Device Model (Per ESD STM5.3.1-2009)

to <1000 volts HBM) and Class C3 (500 volts to <1000 volts CDM). This would alert a potential user of the component to the need for a controlled environment, whether assembly and manufacturing operations are performed by human beings or machines.

A word of caution; however, these classification systems and component sensitivity test results function as guides, not necessarily as absolutes. The events defined by the test data produce narrowly restrictive data that must be carefully considered and judiciously used. The two ESD models represent discrete points used in an attempt to characterize ESD vulnerability. The data points are informative and useful, but to arbitrarily extrapolate the data into a real world scenario can be misleading. The true utility of the data is in comparing one device with another and to provide a starting point for developing your ESD control programs.

SUMMARY

Device failure models and device test methods define the sensitivity of the electronic devices and assemblies to be protected from the effects of ESD. With this key information, you can design more effective ESD control programs.

FOR FURTHER REFERENCE

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- *ESD STM5.2-2009: Electrostatic Discharge Sensitivity Testing - Machine Model,* ESD Association, Rome, NY.
- *ESD STM5.3.1-2009: Electrostatic Discharge Sensitivity Testing - Charged Device Model,* ESD Association, Rome, NY.
- *ESD TR 5.3.2- (formerly TR08-00): Socket Device Model (SDM) Tester,* ESD Association, Rome, NY.
- ESD Industry Council White Paper 1: "A Case for Lowering Component Level HBM/MM ESD Specifications and Requirements," August 2008, http://www.esda.org/IndustryCouncil.html.
- ESD Industry Council White Paper 2: "A Case for Lowering Component Level CDM ESD Specifications and Requirements," March 2009, http://www.esda.org/IndustryCouncil.html.
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- "Mechanisms of Charged-Device Electrostatic Discharges," Renninger, Robert G., *EOS/ESD Symposium Proceedings,* 1991, ESD Association, Rome, NY.
- "Analysis of HBM ESD Testers and Specifications Using a 4th Order Lumped Element Model," Verhaege, Koen, et al, *EOS/ESD Symposium Proceedings,* 1993, ESD Association, Rome, NY.
- "A Comparison of Electrostatic Discharge Models and Failure Signatures for CMOS Integrated Circuit Devices," Kelly, M., et al, *EOS/ESD Symposium Proceedings,* 1995, ESD Association, Rome, NY.
- "Study of ESD Evaluation Methods for Charged Device Model," Wada, Tetsuaki, *EOS/ESD Symposium Proceedings,* 1995, ESD Association, Rome, NY.
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- "Issues Concerning CDM ESD Verification Modules - The Need to Move to Alumina," Henry, L.G., et al, *EOS/ESD Symposium Proceedings,* 1999, ESD Association, Rome, NY.
- "The Importance of Standardizing CDM ESD Test Head Parameters to Obtain Data Correlation," Henry, L.G., et al, *EOS/ESD Symposium Proceedings,* 2000, ESD Association, Rome, NY.
- "Component Level ESD Testing," Review Paper, Verhaege, Koen, *Microelectronics Reliability Journal*, 1998.

Fundamentals of Electrostatic Discharge

Part 6: ESD Standards

BY THE ESD ASSOCIATION

ESD

The electronics industry is continually shifting. Device density and technology is more complex. Electronics manufacturing is more heavily reliant on out-sourcing. The ESD industry seems to have jumped into this swirling eddy headfirst. ESD control programs have mushroomed. Black has been replaced by green, blue and gold. Shielding bags dominate the warehouse. Ionizers exist along side wrist straps and ground cords. An early history of "smoke and mirrors," magic and lofty claims of performance is rapidly and safely being relegated to the past.

Today, more than ever, meeting the complex challenge of reducing ESD losses requires more than reliance on faith alone. Users require a way to legitimately evaluate and compare competing brands and types of products. They need objective confirmation that their ESD control program provides effective solutions to their unique ESD problems. Contract manufacturers and OEMs require mutually agreed-upon ESD control programs that reduce duplication of process controls.

That's where standards come into play. They provide guidance in developing programs that effectively address ESD process control. They help define the sensitivity of the products manufactured and used. They help define the performance requirements for various ESD control materials, instruments and tools. Standards are playing an ever-increasing role in reducing marketplace confusion in the manufacture, evaluation and selection of ESD control products and programs.

THE WHO AND WHY OF STANDARDS

Who uses ESD standards? Manufacturers and users of ESD sensitive devices and products, manufacturers and distributors of ESD control products, certification registrars and third party testers of ESD control products.

Why use ESD standards? They help assure consistency of ESD sensitive products and consistency of ESD control products and services. They provide a means of objective evaluation and comparison among competitive ESD control products. They help reduce conflicts between users and suppliers of ESD control products. They help in developing, implementing, auditing and certifying ESD control programs. And, they help reduce confusion in the marketplace.

In the United States, the use of standards is voluntary, although their use can be written into contracts or purchasing agreements between buyer and seller. In most of the rest of the world, the use of standards, where they exist, is compulsory.

KEY STANDARDS AND ORGANIZATIONS

Just 20 years ago, there were relatively few reliable ESD standards and few ESD standards development organizations. Today's ESD standards landscape is not only witnessing an increase in the number of standards, but also increasing cooperation among the organizations that develop them.

Today's standards fall into three main groups. First, there are those that provide ESD program guidance or requirements.

These include documents such as *ANSI ESD S20.20-2007 – Standard for the Development of an ESD Control Program*, *ANSI/ESD S8.1 – Symbols-ESD Awareness* or *ESD TR20.20 – ESD Handbook*.

A second group covers requirements for specific products or procedures such as packaging requirements and grounding. Typical standards in this group are *ANSI/ESD S6.1 – Grounding* and *ANSI/ESD S541 – Packaging Materials for ESD Sensitive Items*.

A third group of documents covers the standardized test methods used to evaluate products and materials. Historically, the electronics industry relied heavily on test methods established for other industries or even for other materials (e.g., *ASTM-257 – DC Resistance or Conductance of Insulating Materials*). Today, however, specific test method standards focus on ESD in the electronics environment, largely as a result of the ESD Association's activity. These include standards such as *ANSI/ESDA-JEDEC JS-001-2010 – Device Testing, Human Body Model* and *ANSI/ESD STM7.1: Floor Materials – Resistive Characterization of Materials* to cite just a few.

WHO DEVELOPS STANDARDS?

Standards development and usage is a cooperative effort among all organizations and individuals affected by standards. There are several key ESD standards development organizations.

MILITARY STANDARDS

Traditionally, the U.S. military spearheaded the development of specific standards and specifications with regard to ESD control in the U.S. Today, however, U.S. military agencies are taking a less proactive approach, relying on commercially developed standards rather than developing standards themselves. For example, the ESD Association completed the assignment from the Department of Defense to convert MIL-STD-1686 into a commercial standard called ANSI/ESD S20.20.

ESD ASSOCIATION

The ESD Association has been a focal point for the development of ESD standards in recent years. An ANSI-accredited standards development organization, the Association is charged with the development of ESD standards and test methods. The Association also represents the US on the International Electrotechnical Commission (IEC) Technical Committee 101-Electrostatics.

The ESD Association has published 36 standards documents and 23 Technical Reports. These voluntary standards cover the areas of material requirements, electrostatic sensitivity and test methodology for evaluating ESD control materials and products. In addition to standards documents, the Association also has published a number of informational advisories. Advisory documents may be changed to other document types in the future.

ESD ASSOCIATION STANDARDS CLASSIFICATIONS AND DEFINITIONS

There are four types of ESD Association standards documents with specific clarity of definition. The four document categories are consistent with other standards development organizations. These four categories are defined below.

Standard: 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: 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 yields a reproducible test result.

Standard Practice: 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 between labs.

Technical Report: A collection of technical data or test results published as an informational reference on a specific material, product, system, or process.

As new documents are approved and issued, they will be designated into one of these four new categories. Existing documents have been reviewed and have been reclassified as appropriate. Several Advisory Documents still exist and may be migrated to either Technical Reports or Standard Practices in the future.

INTERNATIONAL STANDARDS

The international community, led by the European-based International Electrotechnical Commission (IEC), has also climbed on board the standards express. IEC Technical Committee 101 has released a series of documents under the heading IEC 61340. The documents contain general information regarding electrostatics, standard test methods, general practices and an ESD Control Program Development Standard that is technically equivalent to ANSI/ESD S20.20. A Facility Certification Program is also available. Global companies can seek to become certified to both ANSI/ESD S20.20 and to IEC61340-5-1 if they so choose. Japan also has released its proposed version of a national electrostatic Standard, which also shares many aspects of the European and U.S. documents.

ORGANIZATIONAL COOPERATION

Perhaps one of the more intriguing changes in ESD standards has been the organizational cooperation developing between various groups. One cooperative effort was between the ESD Association and the U.S. Department of Defense, which resulted in the Association preparing ANSI/ESD S20.20 as a successor to MIL-STD-1686. A second cooperative effort occurred between the ESD Association and JEDEC, which started with an MOU and resulted in the development of 2 documents: a joint HBM document was published in 2010; a joint CDM document will be published in 2011.

Internationally, European standards development organizations and the ESD Association have developed working relationships that result in an expanded review of proposed documents, greater input and closer harmonization of standards that impact the international electronics community.

For users of ESD standards, this increased cooperation will have a significant impact. First, we should see standards that are technically improved due to broader input. Second, we should see fewer conflicts between different standards. Finally, we should see less duplication of effort.

SUMMARY

For the electronics community, the rapid propagation of ESD standards and continuing change in the standards environment mean greater availability of the technical references that will help improve ESD control programs. There will be recommendations to help set up effective programs. There will be test methods and specifications to help users of ESD control materials evaluate and select products that are applicable to their specific needs. And there will be guidelines for vendors of ESD products and materials to help them develop products that meet the real needs of their customers.

Standards will continue to fuel change in the international ESD community. ■

SOURCES OF STANDARDS

- ESD Association, 7900 Turin Road, Building 3, Rome, NY 13440. Phone: 315-339-6937. Fax: 315-339-6793. http://www.esda.org
- IHS Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112. Phone: 800-854-7179. Fax: 303-397-2740. http://global.ihs.com
- International Electrotechnical Commission, 3, rue de Varembe, Case postale 131, 1211 Geneva 20, Switzerland. Fax: 41-22-919-0300. http://www.iec.ch
- Military Standards, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120
- JEDEC Solid State Technology Association, 3103 North 10th Street, Suite 240-S, Arlington, VA 22201-2107, http://www.jedec.org

PRINCIPLE ESD STANDARDS

U.S. Military/Department of Defense

MIL-STD-1686C: Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)
This military standard establishes requirements for ESD Control Programs. It applies to U.S. military agencies, contractors, subcontractors, suppliers and vendors. It requires the establishment, implementation and documentation of ESD control programs for static sensitive devices, but does NOT mandate or preclude the use of any specific ESD control materials, products, or procedures. It is being updated and converted to a commercial standard by the ESD Association. Although DOD has accepted the new ANSI/ESD S20.20 document as a successor, it has not yet taken action to cancel STD-1686

MIL-HBDK-263B: Electrostatic Discharge Control Handbook for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)
This document provides guidance, but NOT mandatory requirements, for the establishment and implementation of an electrostatic discharge control program in accordance with the requirements of MIL-STD-1686.

MIL-PRF 87893 – Workstation, Electrostatic Discharge (ESD) Control
This document defines the requirements for ESD protective workstations.

MIL-PRF-81705 –Barrier Materials, Flexible, Electrostatic Protective, Heat Sealable
This documents defines requirements for ESD protective flexible packaging materials.

MIL-STD-129 –Marking for Shipment and Storage
Covers procedures for marketing and labeling ESD sensitive items.

ESD Association

Standards Documents

ANSI/ESD S1.1: Evaluation, Acceptance and Functional Testing of 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.

ANSI/ESD STM2.1: Resistance Test Method for Electrostatic Discharge Protective Garments
This Standard Test Method provides test methods for measuring the electrical resistance of garments used to

control electrostatic discharge. It covers procedures for measuring sleeve-to-sleeve and point-to-point resistance.

ANSI/ESD STM3.1: Ionization
Test methods and procedures for evaluating and selecting air ionization equipment and systems are covered in this standard. The document establishes measurement techniques to determine ion balance and charge neutralization time for ionizers.

ANSI/ESD SP3.3: 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).

ANSI/ESD S4.1: Worksurfaces – Resistance Measurements
This Standard establishes test methods for measuring the electrical resistance of worksurface materials used at workstations for protection of ESD susceptible items. It includes methods for evaluating and selecting materials and testing new worksurface installations and previously installed worksurfaces.

ANSI/ESD STM4.2: Worksurfaces – Charge Dissipation Characteristics
This Standard Test Method provides a test method to measure the electrostatic charge dissipation characteristics of worksurfaces used for ESD control. The procedure is designed for use in a laboratory environment for qualification, evaluation or acceptance of worksurfaces.

ESDA-JEDEC JS-001: Electrostatic Discharge Sensitivity Testing – Human Body Model
This Standard Test Method updates and revises an existing Standard. It establishes a procedure for testing, evaluating and classifying the ESD sensitivity of components to the defined Human Body Model (HBM).

ANSI/ESD STM5.2): Electrostatic Discharge Sensitivity Testing – Machine Model
This Standard establishes a test procedure for evaluating the ESD sensitivity of components to a defined Machine Model (MM). The component damage caused by the Machine Model is often similar to that caused by the Human Body Model, but it occurs at a significantly lower voltage.

ANSI/ESD STM5.3.1: Electrostatic Discharge Sensitivity Testing – Charged Device Model – Non-Socketed Mode
This Standard Test Method establishes a test method for evaluating the ESD sensitivity of active and passive components to a defined Charged Device Model (CDM).

ANSI/ESD SP5.3.2: Electrostatic Discharge Sensitivity Testing – Socketed Device Method (SDM) – Component Level
This standard practice provides a test method generating a Socketed Device Model (SDM) test on a component integrated circuit (IC) device.

ANSI/ESD SP5.4: Latchup Sensitivity Testing of CMOS/BiCMOS Integrated Circuits – Transient Latchup Testing – Component Level Suppl Transient Simulation
This standard practice method was developed to instruct the reader on the methods and materials needed to perform Transient latchup testing.

ANSI/ESD STM5.5.1: 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: 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.

ANSI/ESD SP5.6: 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.

ANSI/ESD S6.1: Grounding
This Standard recommends the parameters, procedures and types of materials needed to establish an ESD grounding system for the protection of electronic hardware from ESD damage. This system is used for personnel grounding devices, worksurfaces, chairs, carts, floors and other related equipment.

ANSI ESD S7.1: Floor Materials – Resistive Characterization of Materials
Measurement of the electrical resistance of various floor materials such as floor coverings, mats and floor finishes is covered in this document. It provides test methods for qualifying floor materials before installation or application and for evaluating and monitoring materials after installation or application.

ANSI ESD S8.1: ESD Awareness Symbols
Three types of ESD awareness symbols are established by this document. The first one is to be used on a device or assembly to indicate that it is susceptible to electrostatic charge. The second is to be used on items and materials intended to provide electrostatic protection. The third symbol indicates the common point ground

ANSI/ESD S9.1: Resistive Characterization of Footwear
This Standard defines a test method for measuring the electrical resistance of shoes used for ESD control in the electronics environment.

ANSI/ESD SP10.1: Automated Handling Equipment
This Standard Practice provides procedures for evaluating the electrostatic environment associated with automated handling equipment.

ANSI ESD STM11.11: Surface Resistance Measurement of Static Dissipative Planar Materials
This Standard Test Method defines a direct current test method for measuring electrical resistance. The Standard is designed specifically for static dissipative planar materials used in packaging of ESD sensitive devices and components.

ANSI/ESD STM11.12: 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: Two-Point Resistance Measurement
This Standard Test Method provides a test method to measure the resistance between two points on an items surface.

ANSI ESD STM11.31: Evaluating the Performance of Electrostatic Discharge Shielding Bags
This Standard provides a method for testing and determining the shielding capabilities of electrostatic shielding bags.

ANSI/ESD STM12.1: Seating-Resistive Characterization
This Standard provides test methods for measuring the electrical resistance of seating used to control ESD. The test methods can be used for qualification testing as well as for evaluating and monitoring seating after installation. It covers all types of seating, including chairs and stools.

ANSI/ESD STM13.1: 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.

ANSI/ESD SP15.1: Standard Practice for In-Use Testing of Gloves and Finger Cots
This document provides test procedures for measuring the intrinsic electrical resistance of gloves and finger cots as well as their electrical resistance together with personnel as a system.

ANSI ESD S20.20: Standard for the Development of an ESD Control Program
This Standard provides administrative, technical requirements and guidance for establishing, implementing and maintaining an ESD Control Program.

ANSI/ESD STM97.1: Floor Materials and Footwear – Resistance in Combination with a Person
This Standard Test Method provides for measuring the electrical resistance of floor materials, footwear and personnel together, as a system.

ANSI/ESD STM97.2 – Floor Materials and Footwear Voltage Measurement in Combination with a Person
This Standard Test Method provides for measuring the electrostatic voltage on a person in combination with floor materials and footwear, as a system.

Advisory Documents

Advisory Documents and Technical Reports are not Standards, but provide general information for the industry or additional information to aid in better understanding of Association Standards.

ESD ADV1.0: 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 ESD industry.

ESD ADV3.2: Selection and Acceptance of Air Ionizers
This Advisory document provides end users with guidelines for creating a performance specification for selecting air ionization systems. It reviews four types of air ionizers and discusses applications, test method references and general design, performance and safety requirements.

ESD ADV11.2: Triboelectric Charge Accumulation Testing
The complex phenomenon of triboelectric charging is discussed in this Advisory. It covers the theory and effects of tribocharging. It reviews procedures and problems associated with various test methods that are often used to evaluate triboelectrification characteristics. The test methods reviewed indicate gross levels of charge and polarity, but are not necessarily repeatable in real world situations.

ESD TR53.1: ESD Protective Workstations
This Advisory document defines the minimum requirements for a basic ESD protective workstation used in ESD sensitive areas. It provides a test method for evaluating and monitoring workstations. It defines workstations as having the following components: support structure, static dissipative worksurface, a means of grounding personnel and any attached shelving or drawers.

ESD TR 20.20: ESD Handbook
New handbook provides detailed guidance for implementing an ESD control program in accordance with ANSI/ESD S20.20.

Basic Understanding of

IEC Standard Testing for Photovoltaic Panels

BY REGAN ARNDT
AND DR. ING. ROBERT PUTO

The photovoltaic (PV) industry has experienced incredibly fast transformation after year 2000 as a result of extraordinary technology breakthroughs, from the material level up to large-scale module manufacturing.

With the PV industry expected to grow consistently in the coming years, two main questions are capturing the attention among market operators:

1. What constitutes a "good quality" module?
2. How "reliable" will it be in the field?

Both, for now, remain unanswered in a comprehensive way.

The performance PV standards described in this article, namely IEC 61215 (Ed. 2 – 2005) and IEC 61646 (Ed.2 – 2008), set specific test sequences, conditions and requirements for the design qualification of a PV module.

The design qualification is deemed to represent the PV module's performance capability under prolonged exposure to standard climates (defined in IEC 60721-2-1). In addition, there are several other standards (IEC 61730-1, IEC 61730-2 and UL1703) that address the safety qualifications for a module, but this area will be addressed in a future article.

In the certification field, design qualification is based on type testing according to IEC, EN or other national standards.

It is worth pointing out the inappropriateness of terms such as "IEC certification," or "IEC certificate," as well as the advertising using the IEC logo instead of the logo of the certification body that released the certification. IEC is not a certification body; it is the acronym for International Electrotechnical Committee, an international standardization organization.

When type testing is combined with periodic factory inspections by a certification body, this constitutes the basis for the certificates issued by that certification body (thus bearing their particular mark/logo).

This may constitute, to some extent, a standard criterion for "basic quality." However, the term "quality" is too generic and often misused if only based on IEC conformance.

Another sensitive facet of "quality" is the module's "reliability" - a major concern for PV contractors/investors.

Reliability is neither defined nor covered by the existing IEC standards. The lack of reliability standards is partially due to the fact that, to date, there is not enough statistical data collected from the PV fields (even the "oldest" PV installations still have to reach their 20/25-year lifetime as per warranty).

But both IEC 61215 and IEC 61646 clearly state that reliability is not addressed therein, thus the design qualification to those standards does not imply the PV module's reliability. Therefore, experts from manufacturers, testing houses and standardization bodies are coming together in an effort to elaborate the basis for a PV reliability standard. A first draft is to be expected, hopefully sometime in the near future.

Warranty is also an issue worthy of mention. It is common practice in the market to sell/buy PV modules covered by a 20+ year warranty. The warranty is supposed to cover safe operation (no electrical, thermal, mechanical and fire hazards) and acceptable level of performance, i.e. limited power output degradation (most declare 1% Pmax loss per year).

Having clarified the general scope of application and limitations with regard to quality of IEC 61215/61646, the following provides a general description of the tests, highlighting those of major importance for crystalline silicon (c-Si) and thin film photovoltaic modules. While IEC 61215 has been designed based on solid knowledge of the main existing crystalline silicon technologies, IEC 61646 was mainly based on amorphous silicon (a-Si) technology. Therefore, relatively new technologies such as CIGS, CdTe, etc. presenting particular behavior and sensitivity to light exposure and thermal effects require particular care and considerations during the testing.

Differences in the two standards will be pointed out in italicized text.

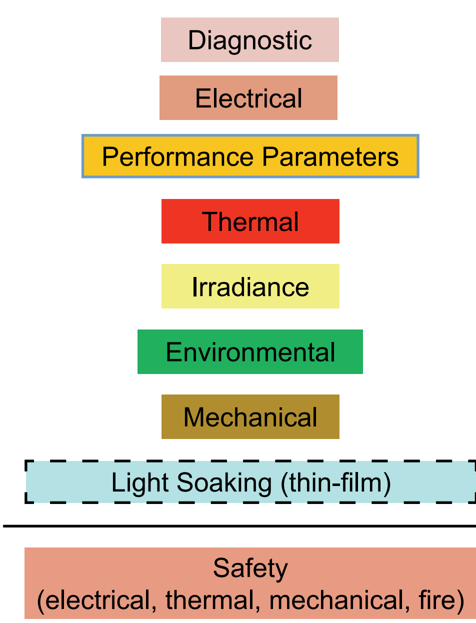
Both standards require that samples for testing be taken at random from a production batch in accordance with IEC 60410.

Modules must be manufactured from specified materials and components and subjected to manufacturer's quality assurance processes. All samples must be complete in every detail and supplied with the manufacturer's mounting/installation instructions.

Figure 1 describes the nature of the tests.

The general approach of both standards can be summarized in:

- Define "major visual defects."
- Define "pass/fail" criteria.
- Do initial tests on all samples.
- Group samples to undergo test sequences.



Performance standards IEC 61215/61646

Diagnostic: Visual inspection, Hot spot.

Electrical: Insulation resistance, Wet leakage current

Performance: Pmax at STC, Temperature coefficients, NOCT, Pmax at low irradiance.

Thermal: Bypass diode test, Hot spot.

Irradiance: Outdoor exposure, UV exposure, Light soaking.

Environmental: Temperature cycles, Humidity freeze, Damp heat.

Mechanical: Mechanical load, Robustness of terminations, Hail impact.

Safety standards IEC 61730-1, 2

Electrical hazards: Dielectric withstand, Ground continuity, Accessibility, Cut susceptibility, Impulse voltage, Reverse current, Partial discharge.

Mechanical hazards: Module breakage.

Thermal hazards: Temperature test

Fire hazard: Fire resistance

Figure 1

- Do <u>post tests after single tests</u>, and <u>test sequences</u> (IEC 61215).
- *Do <u>post tests after single tests</u>, and <u>final light soaking after test sequences</u> (IEC 61646).*
- <u>Look for "major visual defects</u>" and <u>check "pass/fail"</u> criteria.

Different samples go through different test sequences in parallel, as indicated in Figures 2 and 3.

Five "major visual defects" are defined in IEC 61215, while there are six in IEC 61646 *(italicized are the differences in IEC 61646)*:

a) broken, cracked, or torn external surfaces, including superstrates, substrates, frames and junction boxes;

b) bent or misaligned external surfaces, including superstrates, substrates, frames and junction boxes to the extent that the installation and/or operation of the module would be impaired;

c) a crack in a cell the propagation of which could remove more than 10% of that cell's area from the electrical circuit of the module;

c) voids in, or visible corrosion of any of the thin film layers of the active circuitry of the module, extending over more than 10% of any cell; (IEC 61646)

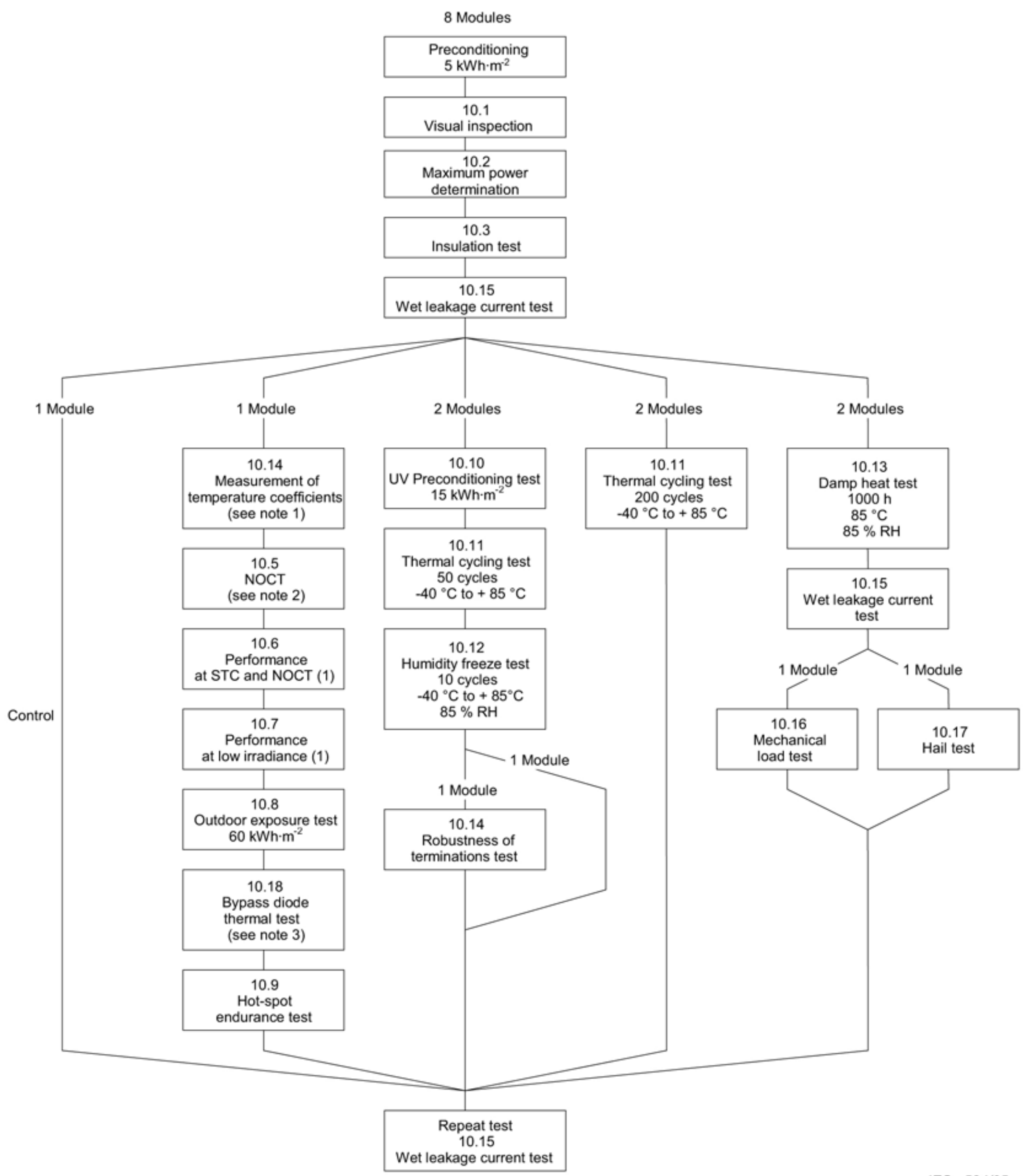


Figure 2: Qualification Test Sequence (IEC 61215)


Can you tell the difference?

d) bubbles or delaminations forming a continuous path between any part of the electrical circuit and the edge of the module;
e) loss of mechanical integrity, to the extent that the installation and/or operation of the module would be impaired;

f) Module markings (label) are no longer attached, or the information is unreadable. (IEC 61646)

Along with 6 operational "pass/fail" criteria:

a) the degradation of maximum output power does not exceed the prescribed limit after each test nor 8% after each test sequence;

a) after the final light soaking, the maximum output power at STC is not less than 90% of the minimum value specified by the manufacturer. (IEC 61646)

b) no sample has exhibited any open circuit during the tests;

c) there is no visual evidence of major defects;

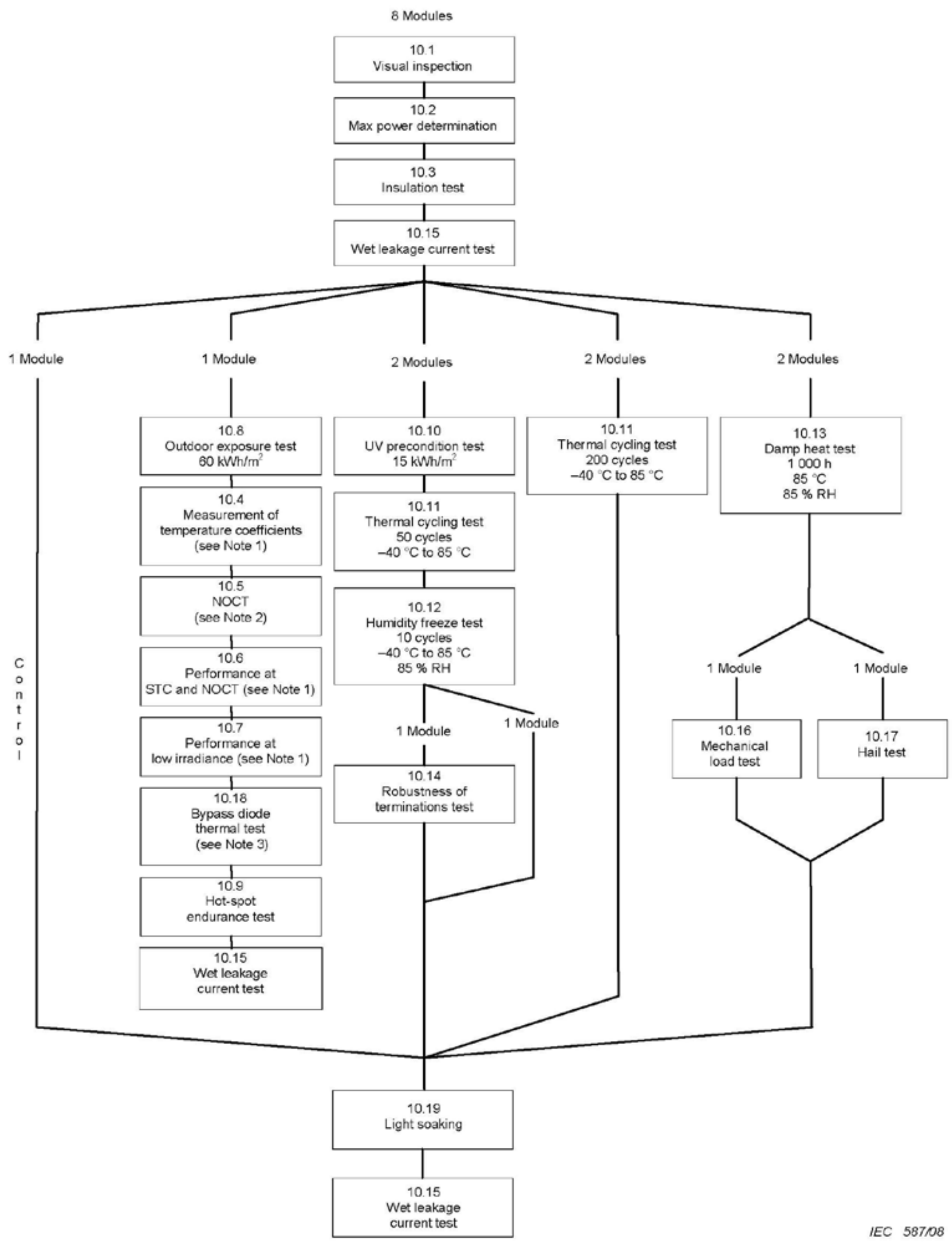


Figure 3: Test Sequence (IEC 61646)

d) the insulation test requirements are met after the tests;

e) the wet leakage current test requirements are met at the beginning and the end of each sequence and after the damp heat test;

f) specific requirements of the individual tests are met.
If two or more samples fail any of these test criteria, the design is deemed to fail qualification. Should one sample fail any test, another two samples shall undergo the whole of the relevant test sequence from the beginning. If one or both of these new samples also fail, the design is deemed to fail qualification requirements. If both samples pass the test sequence, the design is deemed to meet qualification requirements.

Note: Certain failures, even though on a single sample, can be an indicator of serious design problems requiring failure analysis and a design review to avoid returns from the field (reliability problem). In such cases, the laboratory should stop the test sequence and invite the manufacturer to perform a detailed failure analysis, identify the root cause and put in place the necessary corrective actions before submitting the modified samples for retesting.

The difference in item a) between IEC 61215 and IEC 61646 concerning Pmax degradation is worth commenting on.

In IEC 61215, Pmax degradation shall not be more than 5% of the initial Pmax measured at the beginning of each single test, and not more than 8% after each test sequence.

In IEC 61646 there are two crucial elements:

1. Definition of Minimum Pmax (derived from the marked Pmax ± t(%) on the rating label, where t(%) indicates the production tolerance).
2. All samples shall undergo light soaking and must show a final Pmax ≥ 0.9 x (Pmax – t(%)).

In other words, IEC 61646 abandons the criterion of degradation of Pmax after the single tests (-5%) and the test sequences (-8%) used in IEC 61215, and instead relies on checking Pmax degradation with reference to the power rating after all tests have been completed and the samples light-soaked.

Another difference is that IEC 61215 requires all samples to be "pre-conditioned" by exposing them (open-circuited) to a total of 5.5 kWh/m^2.

There is no requirement in IEC 61646 with the purpose of avoiding the specific effects that preconditioning can have on different thin-film technologies. Some thin-film technologies are more sensitive to light induced degradation, while others are more sensitive to dark heat effects. Therefore, the initial-post tests would be an inhomogeneous approach to evaluate the changes through the test sequences. Instead, IEC 61646 calls for final light soaking on all samples after the environmental sequences and for the control sample, and measuring the final Pmax to judge whether degradation is acceptable with reference to the rated minimum value of Pmax.

Here follows a brief description of the tests. *(Differences in IEC 61646 will be pointed out italicized.)*

Visual inspection: is typically a diagnostic check.
The purpose is to detect any of the "major visual defects" defined above by checking the module in a well illuminated area (1000 lux).

It is repeated multiple of times throughout all the test sequences and is conducted more than any other test.

Maximum power (Pmax): is typically a performance parameter.
It is also performed several times before and after the various environmental tests. It can be performed either with a sun simulator or outdoors.

Although the standard gives the possibility to perform the test for a range of cell temperatures (25°C to 50°C) and irradiance levels (700 W/m^2 to 1,100 W/m^2), it is common practice among PV laboratories to perform it at the so-called Standard Test Conditions (STC). By definition, STC corresponds to: 1000 W/m^2, 25°C cell temperature, with a reference solar spectral irradiance called Air Mass 1.5 (AM1.5), as defined in IEC 60904-3.

Most laboratories use indoor testing with solar simulators having a spectrum as close as possible to the AM1.5. Solar simulator's characteristics and deviations from the standard AM1.5 can be classified according to IEC 60904-9. Many solar simulator suppliers offer systems classified at the highest rating possible: AAA, where the first letter indicates spectrum quality, the second letter; the uniformity of irradiance on the test area and the third letter; the temporal stability of irradiance. The classification of solar simulators can be found in IEC 60904-9:2007.

Note: Self-declarations by suppliers do not necessarily constitute evidence of measurement traceability to the World PV Scale.

A correct and traceable Pmax measurement to the World PV Scale is of critical importance. Not only is it one of the pass/fail criteria, but the measured values can also be used by the end users as a performance indicator for power yield evaluations.

Both standards set several accuracy requirements for the measurement of temperature, voltage, current and irradiance.

It is important to note the required repeatability for the power measurement in IEC 61215 is a mere ±1%.

There is no mention of such requirement in IEC 61646, probably due to the well-known "instability" and "repeatability" issues of the different thin-film technologies. Instead, IEC 61646 has a general recommendation:

"Every effort should be made to assure that peak power measurements are made under similar operating conditions, that is, minimize the magnitude of the correction by making all peak power measurements on a particular module at approximately the same temperature and irradiance."

Another important factor contributing to the accuracy of Pmax measurement, especially for thin-film, is the spectral mismatch between the reference cells used by the laboratory and the specific technology under test.

Insulation resistance: is an electrical safety test. The purpose is to determine whether a module has a sufficient electrical insulation between its current-carrying parts and the frame (or the outside world). A dielectric strength tester is used to apply a DC voltage source of up to 1000 V plus twice the maximum system voltage. After the test, there shall be no breakdown, nor any surface tracking. For modules with an area larger than 0.1 m^2, the resistance shall not be less than
40 MΩ for every square meter.

Wet leakage current test: is an electrical safety test, too. The purpose is to evaluate the insulation of the module against moisture penetration under wet operating conditions (rain, fog, dew, melted snow), to avoid corrosion, ground fault and thus electric shock hazard.

The module is submersed in a shallow tank to a depth covering all surfaces except cable entries of junction boxes not designed for immersion (lower than IPX7). A test voltage is applied between the shorted output connectors and the water bath solution up to the maximum system voltage of the module for 2 minutes.

The insulation resistance shall be not less than 40 MΩ for every square meter for modules with an area larger than 0.1 m^2.

It is critical to know that the mating connectors should be immersed in the solution during the test and this where a faulty connector design can be the cause of an important FAIL result.

Note: Failure of wet leakage current test due to faulty connectors is not a rare event, and as such, it definitely represents a real hazard for operators in the field. There is no IEC standard addressing PV connectors, but there is a harmonized European standard (EN 50521). Certified connectors to EN 50521 have undergone severe tests, including Thermal Cycles (200) and Damp Heat (1000 hrs), and it can be used as a criterion for selecting suppliers. However, the test with the module will have the final say. Keeping a close eye on connectors supplied with the junction boxes is a delicate task for PV module manufacturers. "Easy" change of connector suppliers with different design can represent a major risk for wet leakage current test.

The wet leakage current test is ranked as one of the most reoccurring failures during PV qualification at the testing laboratories. When the failure is not due to a connector issue (as mentioned above), the failure will most likely happen after the Damp Heat test and/or Humidity Freeze test for modules that have problems with lamination and edge sealing processes during production.

Temperature coefficients: is a performance parameter. The purpose is to determine the temperature coefficients of short-circuit current Isc (α), open-circuit voltage Voc (β) and maximum power (Pmax) (δ) from module measurements. The coefficients so determined are only valid at the irradiance at which the measurements were made (i.e. at 1000 W/m^2 for most laboratories using the solar simulator).

For modules with known linearity over a certain irradiance range according to IEC 60891, the calculated coefficients can be considered valid over that irradiance range.

IEC 61646 is more "cautious" and makes an additional note regarding thin-film modules, whose temperature coefficients may depend on the irradiation and the thermal history of the module… But from a testing viewpoint, the temperature coefficient test box is simply put under the first left-hand test sequence (fig. 3). The "irradiation and thermal history" of that sample consists simply of the "journey" it took to get to the laboratory, of the environment conditions under which it was stored, of the initial tests, and finally of the outdoor exposure test (60 kWh/m^2).

Two methods are used for the measurement with solar simulators:

1. during heating up of the module or
2. cooling down of the module;

over an interval of 30°C (for instance, 25°C - 55°C), and at every 5°C intervals, the sun simulator takes an I-V measurement (Isc, Voc, Pmax are not reflected, but measured during the I-V sweep) including Isc, Voc and Pmax.

The values of Isc, Voc and Pmax are plotted as functions of temperature for each set of data. The coefficients α, β and δ are calculated from the slopes of the least-squares-fit straight lines for the three plotted function

Given a certain irradiance level, it is to be noted that β (for Voc) and δ (for Pmax) are the two most sensitive to temperature changes. They both have the "-" sign, denoting that Voc and Pmax decrease with increasing temperature, whereas α (for Isc) has the "+" sign, though much a smaller value than β and δ. All three coefficients can be expressed as relative percentages by dividing the calculated α, β, and δ by the values of Isc, Voc and Pmax at 25°C (1000 W/m^2).

Temperature coefficients are performance parameters often used by end users to simulate energy yields of the modules in hot climates. One must remember that they are valid at 1000 W/m^2 irradiance level used in the lab unless the linearity of the module at different irradiance levels has been proven.

Nominal Operating Cell Temperature (NOCT): is a performance parameter.
NOCT is defined for an open-rack mounted module in the following standard reference environment:

- tilt angle: 45° from the horizontal
- total irradiance: 800 W/m^2
- ambient temperature: 20°C
- wind speed: 1 m/s
- no electrical load: open circuit

NOCT can be used by the system designer as a guide to the temperature at which a module will operate in the field and it is therefore a useful parameter when comparing the performance of different module designs. However, the actual operating temperature is directly dependent on the mounting structure, irradiance, wind speed, ambient temperature, reflections and emissions from the ground and nearby objects, etc.

The so-called "primary method" to determine NOCT is an outdoor measurement method used by both IEC 61215 and IEC 61646, and is universally applicable to all PV modules. In the case of modules not designed for open-rack mounting, the primary method may be used to determine the equilibrium mean solar cell junction temperature, with the module mounted as recommended by the manufacturer.

The test setup requires data logging and selection for irradiance (pyronameter), ambient temperature (temperature sensors), cell temperature (thermocouples attached on the back side of the module corresponding to the two central cells), wind speed (speed sensor) and wind direction (direction sensor). All these quantities shall be within certain intervals in order to be acceptable for the calculation of NOCT.

A minimum set of 10 acceptable data points taken both before and after 'solar noon' are used for the calculation of the final NOCT.

Outdoor exposure: is an irradiance test.
The purpose is a preliminary assessment of the module's ability to withstand exposure to outdoor conditions. However, it only involves exposure for a total of 60 kWh/m^2 which is a rather short period of time to make any judgments about the module's lifetime.

On the other hand, this test can be a useful indicator of possible problems which might not be detected by the other laboratory tests.

IEC 61215 requires degradation of maximum power (Pmax) not to exceed 5% of the initial value.
IEC 61646 requires maximum power (Pmax) not to be lower than the marked "Pmax – t%."

While pre-conditioned c-Si modules according to IEC 61215 (5.5 kWh/m^2) do not show a criticality with this test, certain thin-film technologies might experience more problems. The reason can be explained with the fact that in IEC 61646, the measured Pmax after 60 kWh/m^2 exposure must be higher than the marked "Pmax – t% by the manufacturer. This one sample is under the first test sequence, where the only "history" are the initial tests and the outdoor exposure for total 60 kWh/m^2 under various climatic conditions over 24 hrs depending on the laboratory's location. A solid knowledge of the technology under test by the manufacturer in terms of light induced degradation, sensitivity to heat, moisture etc. is essential to correctly determine the rated Pmax and pass the test.

Hot-spot endurance: is a thermal/diagnostic test.
The purpose is to determine the module's ability to withstand localized heating caused by cracked, mismatched cells, interconnection failures, partial shadowing or soiling.

Hot-spot heating occurs when the operating current of the module exceeds the reduced short-circuit current of a faulty (or shadowed) cell(s). This will force the cell(s) into a reverse bias condition when it becomes a load that dissipates heat. Serious hot spot phenomena can be as dramatic as outright burns of all the layers, cracking or even breakage of the glass. It is important to note that even under less severe hot spot conditions, with the intervention of the bypass diode, a part (also known as a string) of the module is excluded thus causing a sensible drop in power output of the module.

The approach to simulate realistic hot-spot conditions of the relevant clause 10.9 in IEC 61215 is constantly being debated.

It is well accepted by the main test laboratories that the current version of the hot-spot method does not represent, nor is it able to represent a real hot-spot situation. An improved hot-spot method has been drafted within TC82 of the IEC and is expected to become normative with the 3rd edition of IEC 61215 in 2010. Some test laboratories have decided to already use the improved method.

Further insight and details will be provided in a future article.

Although failure rate statistics in different laboratories may differ, hot-spot still appears to be among the 5 most frequent failures for both c-Si and thin-film modules.

Bypass diode: is a thermal test.
Bypass diode is a very important aspect of module design. It is a critical component determining the thermal behavior of the module under hot-spot conditions and therefore also directly affecting reliability in the field.

The test method requires attaching a thermocouple to the diode(s) body, heating the module up to 75°C ± 5°C and applying a current equal to the short circuit current Isc measured at STC for 1hr.

The temperature of each bypass diode body is measured (Tcase) and the junction temperature (Tj) is calculated using a formula using the specs provided by the diode's manufacturer (RTHjc = constant provided by diode manufacturer relating Tj to Tcase, typically a design parameter, and UD = diode voltage, ID = diode current).

Then the current is increased to 1.25 times the short-circuit current of the module Isc as measured at STC for another hour while maintaining the module temperature at the same temperature.

The diode shall still be operational.

Failures of bypass diode tests still occur with a certain frequency caused by either overrating by the diode manufacturer or incorrect electrical configuration with respect to the module's Isc by the module manufacturer.

In most cases, the bypass diodes are supplied as incorporated components in the junction box of the whole sub-assembly (junction box + cable + connector). Therefore, it is of critical importance to make sure that this small component is closely checked during the incoming goods controls by the module manufacturer.

UV preconditioning: is an irradiance test.
The purpose is to identify materials that are susceptible to ultra-violet (UV) degradation before the thermal cycle and humidity freeze tests are performed.

IEC 61215 requires to subject the module to a total UV irradiation of 15 kWh/m² in the (UVA + UVB) regions (280 nm – 400 nm), with at least 5 kWh/m², i.e. 33% in the UVB region (280 nm – 320 nm), while maintaining the module at 60 °C ± 5 °C.

(IEC 61646 requires a UVB portion of 3% to 10% of the total UV irradiation). This requirement has now been harmonized also for IEC 61215 by a CTL Decision Sheet n. 733 within IECEE CB Scheme.

One critical aspect of the setup of the UV chambers is having calibrated UVA and UVB sensors ensuring traceability also at operating temperatures of 60°C ± 5°C while still operating correctly during the long exposure times in the hot UV chambers.

The very low failure rate of UV exposure test in PV laboratories can be explained with the relatively low amount of UV irradiation as compared to real exposures during the lifetime of the module.

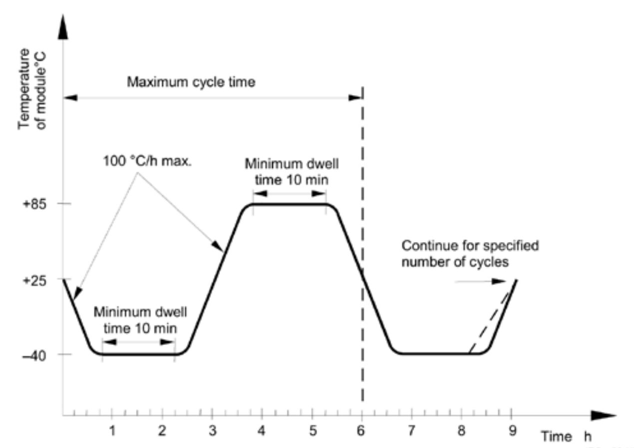


Figure 4: Thermal cycling test (IEC 61215)

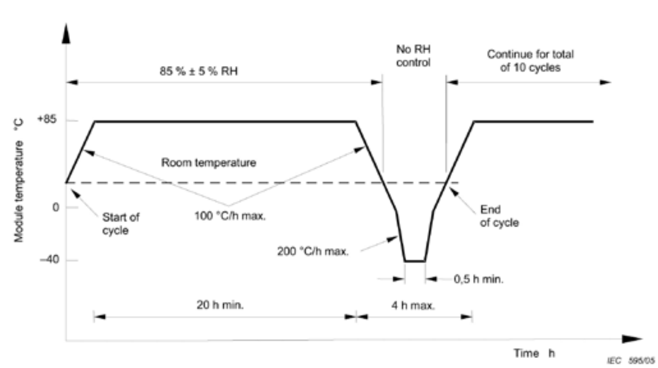


Figure 5: Humidity-freeze cycle (IEC 61646)

Thermal cycling TC200 (200 cycles): is an environmental test.
This test has the purpose of simulating thermal stresses on materials as a result of changes of extreme temperatures. Most frequently, soldered connections are challenged inside the laminate due to the different thermal expansion coefficients of the various encapsulated materials. This may result in failure for major defects, for Pmax degradation, interruption of the electric circuitry, or insulation test.

IEC 61215 requires the injection of a current within ±2% of the current measured at peak power (Imp) when the module temperature is above 25°C.
There is no current injection for IEC 61646, however the continuity of the electric circuit has to be monitored (a small resistive load would suffice).

The module is subjected to the cycling temperature limits of –40°C ± 2°C and +85°C ± 2°C with the profile in Figure 4.

Failure rates for TC200 can be as high as 30-40%. If in combination with Damp Heat, in some laboratories, both can account for more than 70% of the total failures for c-Si modules.

TC200 failure rate is lower for thin-film, but still worth the attention of the manufacturers.

Humidity-freeze: is an environmental test.
The purpose is to determine the module's ability to withstand the effects of high temperatures combined with humidity followed by extremely low temperatures.
The module is subjected to 10 complete cycles as per the harmonized profile in Figure 5 (IEC 61646).

Relative humidity requirement
RH = 85% ± 5% applies only at 85°C.

After this test, the module is allowed to rest between 2 and 4 hours before the visual inspection, maximum output power and insulation resistance are measured.

Failure rates of this test remain in the range 10-20%.

Diameter mm	Mass g	Test velocity $m \cdot s^{-1}$	Diameter mm	Mass g	Test velocity $m \cdot s^{-1}$
12.5	0.94	16.0	45	43.9	30.7
15	1.63	17.8	55	80.2	33.9
25	7.53	23.0	65	132.0	36.7
35	20.7	27.2	75	203.0	39.5

Table 1

Robustness of terminations: is a mechanical test.
To determine the robustness of the module's terminations, which can be wires, flying leads, screws, or as for the majority of the cases, PV connectors (Type C). The terminations undergo a stress test that simulates normal assembly and handling through various cycles and levels of tensile strength and bending and torque tests as referenced in another standard, IEC 60068-2-21.

Damp-heat DH1000 (1000 hours): is an environmental test.
The purpose is to determine the ability
of the module to withstand long-term exposure to penetration of humidity by applying 85°C ± 2°C with a relative humidity of 85% ± 5% for 1000 hours.

DH1000 is the most "malign" and on the top-list of failure rates in some laboratories accounting for up to 40-50% of total failures for c-Si modules. Similar failures rates can be observed for DH1000 also with thin-film.

The severity of this test particularly challenges the lamination process and the edge sealing from humidity. Important delaminations and corrosion of cell parts can be observed as a result of humidity penetration. Even in case of no major defects detected after DH1000, the module has been stressed to the point that it becomes "fragile" for the subsequent mechanical load test.

Mechanical load test
This loading test is to investigate the ability of the module to withstand wind, snow, static or ice loads.

Mechanical load comes after Damp Heat and is therefore done on a sample that has undergone a severe environmental stress.

The most critical aspect of this test is related to the mounting of the module as per manufacturer's mounting instructions, i.e. using the intended fixing points of the module on the mounting structure with the intended inter-distance between these points, and using the appropriate mounting accessories, if any (nut, bolts, clamps, etc).

Certain cases of large-area and frameless thin-film modules are of critical concern with respect to the above conditions.

If care is not taken regarding proper mounting, one remains with the question whether the failure was caused because of structural problems or because of an inappropriate mounting technique.

Another aspect to be considered is the uniformity of the applied load over the surface of the module. The standards require the load to be applied "in a

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gradual, uniform manner" without specifying how to check uniformity.

2,400 Pa is applied (which equates to a wind pressure of 130 km/hour) for 1 hour on each face of the module.

If the module is to be qualified to withstand heavy accumulations of snow and ice, the load applied to the front of the module during the last cycle of this test is increased from 2,400 Pa to 5,400 Pa.

At the end there shall be no major visual defects, no intermittent open-circuit detected during the test. Also Pmax (for IEC 61215 only) and insulation resistance are checked after this test.

Hail impact: is a mechanical test.
To verify that the module is capable of withstanding the impact of hailstones which are at a temperature of ~ –4°C. The test equipment is a unique launcher capable of propelling various weights of ice balls at the specified velocities so as to hit the module at 11 specified impact locations +/- 10 mm distance variation. (Table 1)

The time between the removal of the ice ball from the cold storage container and impact on the module shall not exceed 60 s.

It is quite common practice to use 25 mm/7.53 g ice balls.

Again, after the test one should check if there are any major defects caused by the hailstones and also Pmax (for IEC 61215 only) and insulation resistance are checked.

Laboratory statistics show very low failure rates for this test.

Light-soaking: irradiance *(only applicable to thin-film IEC 61646)*
This is a critical passage for the final pass/fail verdict of thin-film modules. The purpose is to stabilize the electrical characteristics of thin film modules by means of prolonged exposure to irradiance after all the tests have been completed before checking Pmax against the minimum value as marked by the manufacturer.

The test can be performed under natural sunlight or under steady-state solar simulator.

The modules, under a resistive load condition, are placed under an irradiance between 600 – 1000 W/m^2 within a temperature range of 50°C ± 10°C until stabilization occurs which is when the measurements of Pmax from two consecutive periods of exposure of at least 43 kWh/ m^2 each satisfied the condition (Pmax – Pmin)/P(average) <2%.

Finally, a note regarding the IECEE Retest Guideline. Interestingly, it is not well defined what can be considered as "change in cell technology" for thin-film, thus leaving a big grey area of different interpretations and approaches in cases where one could state a "technology and efficiency improvement," "stabilization improvement," or "power output increase." Are these cases of "change in cell technology" and if yes, to what extent and what tests have to be repeated? As it is read today, the Retest Guideline leaves a path to extending previous certifications going up in power (>10%) by simply repeating the hot-spot test.

Note 2 of the Retest Guideline quotes "…Final light soaking 10.19 test is compulsory for all test samples," but in practice it is often ignored by the test labs with the result of extending sensibly increased power without putting under test the main aspect of thin-film technology: power stabilization.

In summary, the testing described in this article was determined by the IEC as the minimal requirements for performance testing but as stated in the beginning, one must also adhere to the safety design and test requirements in IEC 61730-1 and IEC 61730-2. As manufacturers strive to be more competitive in the marketplace, most are working with a certification body to prove that their module has undergone an impartial, unbiased test program. If any changes occur during re-design or their production processes, certification bodies use the 'harmonized' IECEE CB Scheme retesting guideline to determine what tests to repeat prior to extending previous certifications. With regards to reliability, some are going so far as to conduct an extension of combined indoor and outdoor reliability testing programs greater than one year. ■

Mr. Regan Arndt *is the North American manager and technical certifier for TÜV SÜDs Photovoltaic Team located in Fremont, CA. He graduated from Electronics Engineering at the Southern Alberta Institute of Technology (SAIT) in Calgary, Alberta, Canada and has over 15 years of experience in testing and certification in the areas of Photovoltaics, Information Technology Equipment, Telecommunications and Electrical Equipment for Measurement, Control, and Laboratory Use. Regan obtained formal training for Photovoltaic Design and testing at the Beijing Chinese Academy of Sciences Renewable Energy Department. He can be reached at rarndt@tuvam.com.*

Dr. Ing. Robert *Puto is the Global director of Photovoltacs at TUV SUD. He holds a doctor's degree in Electronic Engineering from Politecnico di Torino (Polytechnic University of Turin), Italy and a master diploma in International Business Management from CEIBS - Shanghai, China. He has 15 years experience in testing and certification of a variety of electrical products including photovoltaics. He also acts as the PV Senior Product Specialist within TÜV SÜD group, has Technical Certifier status for PV, and is authorized auditor for ISO IEC 17025 laboratory assessments. He can be reached at robert.puto@tuv-sud.cn.*

Electronic Waste

How Waste Leads to Design Challenges

BY JAMES CALDER

HISTORY OF GLOBAL E-WASTE ISSUES

Since the onset of the 21st Century, the electronic sector has experienced a significant increase of environmental regulations. Historically, the majority of regulations affecting this product group has focused on safety and quality requirements. It was not until October 2001, following a large enforcement action taken against Sony for cadmium, that the electronics industry first sensed a looming mandate to restrict substances in electronics. However, calls for waste limitations were made even earlier.

On July 30, 1996, the European Commission began stressing the importance of reducing hazardous substances in electronic waste as a way to enhance the economic profitability of recycling electronic waste and decrease the negative health impacts on workers in recycling plants.

At that time, electronic waste was shipped to third world and developing countries where people and the environment were exposed to toxins as a result of improper treatment and resource reclamation techniques.

Instances of the illegal shipment of waste have been detected by a number of non-profit organizations, including the environmental group, Basel Action Network (BAN). BAN has identified from Hong Kong authorities that an estimated 50-100 containers of electronic waste enters its port each day. As recent as March 2010, Indonesian authorities turned away nine containers of old CRT monitors from a recycling company based in Massachusetts. In addition, the UK Environment Agency has conducted large-scale raids on sites suspected of shipping electronic waste to Africa. Arrests were made.

Proper treatment of electronic waste is one of the most assured methods of protecting humans and the environment. However, others argue that eliminating the hazardous substances used in electronics altogether would prove just as effective. It is hard to argue against both of these methods, but the latter requires a sufficient social-economic

Figure 1: Informal e-waste recycling
photo courtesy of StEP-EMPA, © UNEP

impact assessment to properly quantify impacts caused by substitution of such harmful substances.

RESTRICTION OF HAZARDOUS SUBSTANCES (ROHS) DIRECTIVE (2002/95/EC)

This reasoning led to the promulgation of the European Union's Restriction of Hazardous Substances (RoHS) Directive (2002/95/EC). This law restricts the use of lead, cadmium, hexavalent chromium, mercury and two brominated flame retardants in electrical and electronic equipment captured within its scope. The majority of its impact has been felt by the manufacturers and distributors due to redesign efforts requiring significant resource allocation in new technology, supplier/customer management, and education. This impact can divert the understanding of where the origin of the RoHS Directive stems.

The reasoning behind restricting these six substances is not solely the human health and environmental concerns during the typical use of the electronics during their functional life, but the exposure created during end of life (waste) treatment. This reasoning should allow the industry to project future restrictions on electronics.

ROHS AND WEEE DIRECTIVES ARE UNDER REVISION

The RoHS Directive is currently undergoing revision with a number of requested changes stemming from the effects of electronic waste and its treatment.

Jill Evans, Committee on the Environment, Public Health and Food Safety has stated the following as part of the European Commission's Codecision procedures:

The RoHS recast needs to be put into the context of the EU's international obligations to reduce total releases of dioxins and furans, with the goal of their continuing minimization and, where feasible, ultimate elimination. The final destiny of large quantities of WEEE remains unclear. High-temperature incineration remains the exception. Sub-standard treatment of WEEE – in the EU or in third countries - risks remaining a reality for significant amounts. Emissions of dioxins and furans can only be addressed via material choices at design stage.

In addition, the Commission has used information provided by its contracted body, the Öko-Institut, to assess recommendations on other substances to be restricted under the RoHS Directive. The following excerpt is provided based on that contracted findings:

The study commissioned by the Commission on hazardous substances in electrical and electronic equipment highly recommended a phase-out of organobromines and organochlorines due to their potential to form polybrominated and polychlorinated dioxins and furans in waste treatment operations, and gave priority to the phase-out of PVC over selective risk management options to guarantee a reduced release of PVC, of its additives and of hazardous combustion products.

This shows the strength of the waste treatment argument on restricting substances in electronics.

NGOS STRONGLY VOICE THEIR OPINIONS ON E-WASTE

The majority of this reasoning comes from recycling associations, workers unions, and Non-Government Organizations (NGOs) promoting safer substances. One example is the recent joint statement issued in February 2010 by three NGOs: European Environment Bureau (EEB), the Health and Environment Alliance (HEAL), and Women in Europe for a Common Future (WECF).

The main points are as follows:

- *Provide a coherent framework to include all EEE;*
- *Restrict by 2014 hazardous substances and materials in EEE that cause serious concern throughout their lifecycle (production, use, disposal) and hamper recyclability, such as halogenated organic substances, to a maximum of 0,1% (weight by weight);*
- *Restrict by 2014 the use of nano silver to the detection limit in homogenous EEE parts;*
- *Ensure a specific methodology for future substance restrictions focusing on waste considerations which are in line with the specific aims of the RoHS Directive.*

The above statement is not a law and none of these three NGOs are part of the government of the European Union, but they have a significant voice and are very dedicated to having their considerations addressed in the coming recast of the RoHS Directive. In retrospect, trade associations and government authorities also have a similar standing when it comes to being heard and provide the other ends of the argument.

If any of the substances described in this article, that are not already covered by the existing RoHS Directive, would cause significant impact to the quality or continued function of electronic equipment, then now is the time for manufacturers to voice their reasoning. In a sobering reflection, it may be too late to submit information to support the continued use of these substances if it has not already been done since the timeline for the recast of the RoHS Directive is as follows:

- **9 March:** Deadline for amendments
- **4 May:** Vote in the ENVI committee
- **15-16 June:** Vote in plenary

THE ROHS DIRECTIVE'S FUTURE IMPACT ON THE MEDICAL PRODUCT INDUSTRY

The current RoHS Directive does not include medical equipment or monitor and control equipment within its scope. This will soon change. These categories of electronics will need to adhere to the RoHS Directive's substance restrictions by as early as 2014. The recast of the RoHS Directive does provide an additional annex for application exemptions related to these two product categories, but studies on the availability of substitutes for new substances being recommended for restriction are quite limited.

Medical Device manufacturers have been significantly alarmed about the restriction of PVC. This material is used significantly within this industry due to its flexibility and endurance. It would be expected that significant studies and research would need to be conducted before restricting such a material in medical devices. This thought can be strengthened by the following statement in the Commission's suggestion regarding the recast of the RoHS Directive:

The placing on the market of medical devices requires a conformity assessment procedure, according to Directives 93/42/EC and 98/79/EC, which could require the involvement of a notified body designated by Competent

Indicator	Environmental benefit	Number*	Unit
2005 WEEE: Arising: 8.3 Mt Collected: 2.2 Mt		**2011 WEEE: Arising: 9.7 Mt Collected: 5.3 Mt**	
Weight	Growth in WEEE arising	1,359	kt WEEE Arising
Eco-indicator 99 H/A v203**	Total environmental load per year of	643,591	Europeans
Idem, Human Health**	Total environmental load per year of	423,125	Europeans
Idem, Ecosystem Quality**	Total environmental load per year of	46,038	Europeans
Idem, Resource Depletion**	Total environmental load per year of	174,589	Europeans
Cumulative Energy Demand	Equivalent with:	-75	million GJ
Abiotic depletion	Equivalent with:	-40	kt Sb
Global warming (GWP100)****	Equivalent with:	-36****	Mt CO_2
Ozone layer depletion (ODP)	Equivalent with:	-4.8	kt CFC11
Human toxicity	Equivalent with:	-4,047	kt 1,4-DB***
Fresh water aquatic ecotox.	Equivalent with:	-404	kt 1,4-DB***
Marine aquatic ecotoxicity	Equivalent with:	-3,551	Mt 1,4-DB***
Terrestrial ecotoxicity	Equivalent with:	-74	kt 1,4-DB***
Photochemical oxidation	Equivalent with:	-3.0	kt 1,4-DB***
Acidification	Equivalent with:	-50	kt SO_2
Eutrophication	Equivalent with:	-1,493	t PO_4---

Table ii: Estimated Environmental improvement due to the WEEE Directive 2011 versus 2005

Negative means avoided environmental impact, ** Meant as a rough illustration only: 1 Pt roughly equals 1/1000 of the environmental load of one European p.year (Goedkoop 1999) ***kg 1,4-dichlorobenzene ** Under the assumption of an unchanged 80% presence of CFC fridges in the WEEE stream over time*

Figure 2: Estimated Environmental improvement due to the WEEE Directive 2011 versus 2005

Table ii from the 2008 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment, United Nations University

Authorities of Member States. If such a notified body certifies that the safety of the potential substitute for the intended use in medical devices or in vitro medical devices is not demonstrated, this will be viewed as a clear negative socio-economic, health and consumer safety impact. It should be possible to apply for exemptions of equipment coming under the scope of this Directive from the date of its entry into force, even when that is before the actual inclusion in the scope of that equipment.

INITIAL ELECTRONIC PRODUCT RE-DESIGN CHALLENGES

The conversion to safer alternatives may require a significant initial investment. Once alternatives are established and their production scaled up, costs will be reduced quickly and the benefits will prevail. Socioeconomic considerations should therefore only be used when making a decision on the duration of an exemption. Insufficient availability of substitutes should not be a yes/no criterion for an exemption, but should have an effect on the time until a prohibition is fully enacted. There is no need to introduce “reliability” as a separate criterion, as it is already covered by the safety consideration.

This statement shows that restrictions will be applied to all electronics under the scope of the new RoHS Directive and applied exemptions are clearly noted to be held within a determinate timeline, not an exclusion from scope of the law.

REACH REGULATION (EC1907/2006) VS ROHS DIRECTIVE (2002/95/EC)

Another hot topic surrounding substance restrictions and electronics is the European Union’s REACH (Registration, Evaluation and Authorization of Chemical Substances) Regulation. This chemical safety law enacts an incredible amount of information disclosure on the identity and safe use of chemicals. When it comes to the scope of electronics, this disclosure requirement narrows to identifying Substances of Very High Concern (SVHC) if found in concentrations of 0.1% (w/w). Since having this requirement applied to all Articles (includes electronics), it has been argued that the RoHS Directive should no longer be necessary since the REACH Regulation mandates substance control in its own manner.

This argument has been quashed because of the waste treatment aspect surrounding electronics. The REACH Regulation does not address the safety issues regarding products when they become waste and some substances are not properly taken into account (i.e. polymers). The European Commission’s justification below is clear:

It should be stated specifically that RoHS supplements REACH. RoHS and REACH have different objectives, scope, timelines, and outreach. RoHS was created to address the specific problems of a fast-growing waste stream, REACH addresses chemical substances at a general level, with no special focus on waste.

REACH is a regional law still in its infancy, RoHS is already setting a global standard. Key problems with WEEE are due to polymers, which are exempted from REACH. RoHS should be further developed to address the specific problems of the recovery and disposal of WEEE at the origin.

EU ROHS - A PIONEERING "GLOBAL STANDARD"

The interesting portion of this statement is defining the RoHS Directive as a "global standard." This is quite true, as we have now seen the implementation of laws placing the same restrictions on electronics in California, South Korea, China, Japan, and Turkey. Plus many other jurisdictions are investigating the application of an RoHS law or standard. The justification for the majority of these movements outside the European Union is the need to reduce toxic substances entering the waste stream. These substances not only have the potential to cause adverse effects to humans and the environment, they also reduce the feasibility of resource reclamation in the form of recovery processes in lieu of a landfill.

To this date, over two thirds of the world have enacted electronic waste laws or are in the process of enacting such laws requiring diversion to environmentally sound management and disposal. This will lead to a significant increase in studies and visibility as to what effects this new recycling stream will pose to human health and environment. Older studies lead to the creation of the RoHS Directive, but with a new focus on identifying toxicity of substances (REACH, TSCA, CEPA 1999, etc.) there will be many available references in justifying further restrictions to electronics (and many other products).

THE COSTS OF E-WASTE REGULATIONS

The electronics industry needs to be aware of developments stemming from the waste laws to avoid costly redesign efforts and negative customer satisfaction responding to the unavailability of compliant products.

This is punctuated by a Consumer Electronics Association (CEA) survey that stated the following:

About 29% of companies surveyed reported lost sales due to RoHS with the average loss being $1.84 million. Sales losses were due to delay in new product sales and discontinued business in the EU.

Another example of costs arising from electronic waste laws is the approach some systems are taking in France. The implementation of France's Waste Electrical Electronic Equipment (WEEE) Directive mandates that "producers" finance the collection and treatment of their market share's worth of electronic waste. To fulfill this requirement, producers are offloading this responsibility to producer compliance organizations that will fulfill the collection and treatment on their behalf. These compliance organizations will be introducing a two tiered cost model (July 2010) for their members. Costs for collection and treatment will be more expensive for products that do not have a good lifespan, are not recyclable and/or contain hazardous substances.

To avoid this type of monetary loss, environmentally conscious design aspects must be initiated at the outset of product introduction or concept. This should include programs for substance management, recyclability, energy efficiency, and reusability. Not only will this avoid loss of sales due to product availability, but will strengthen internal system efficiencies and reduce excess waste in processes.

POTENTIAL SOLUTIONS FOR COST-EFFECTIVE E-WASTE COMPLIANCE

Businesses have options when they address compliance. The process they follow can include:

- Identification of applicable requirements
- Compliance Assurance Process implementation and certification
- Employee and vendor communication and training
- Supplier data collection
- GAP Analysis and Risk Assessment
- Product re-engineering (if required)
- Product screening and testing based upon GAP/Risk Assessment
- Green claims verification/certification, product labeling, and marketing launch

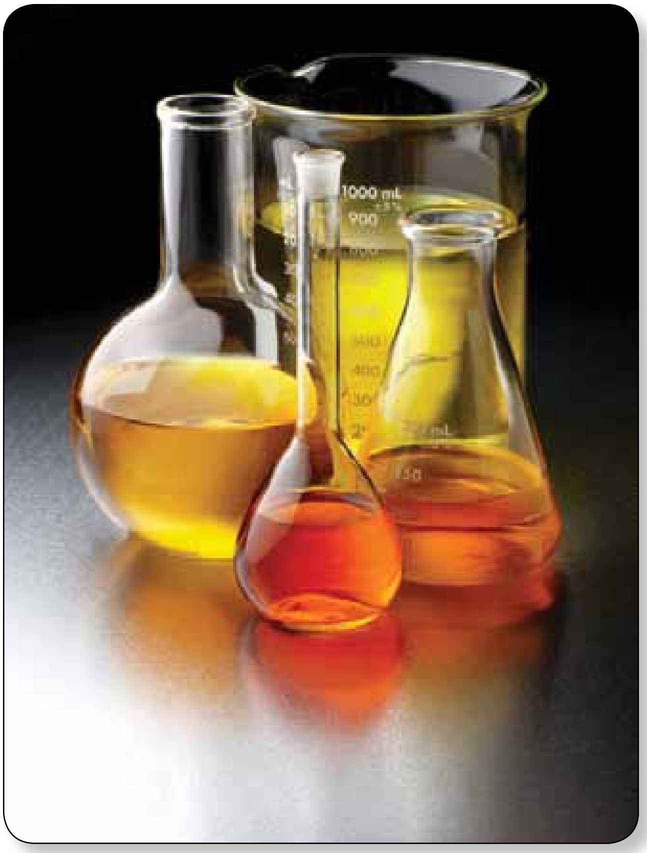
The decision depends upon a business, the target market, legislative requirements, and customer requirements. Further, which of the process steps can be completed using internal resources or is there a need to fill the gaps by partnering with a third party? Third parties can assist in understanding the requirements, developing corporate or product strategy, providing education and training to employees and suppliers, conducting inventory assessments, testing, verifying, auditing, and ensuring ongoing compliance. ■

James Calder *is Intertek's Manager – Global Services for Health and Environmental Services, and can be reached at james.calder@intertek.com.*

Best Practices for

REACH Compliance Management for Electronics OEMs

BY LARRY YEN



THE REACH ERA

The regulation referred to as REACH (Registration, Evaluation and Authorization of Chemicals), came into effect in European Union Member States in June of 2007. The intent of REACH is to regulate chemicals that can cause cancer and other diseases.

REACH applies to thousands of chemicals (substances) that are used or present in electrical equipment. REACH also applies to mixtures or solutions of substances (preparations), and end products (articles). Substances of Very High Concern (SVHCs), are the most hazardous and harmful substances and are highly regulated. Products containing SVHCs may not receive authorization if a safer alternative exists.

REACH affects all organizations that export, manufacture, or use chemicals. Early planning and good communications are urgently needed to avoid disruptions in the supply chain. Parts and equipment manufacturers will be affected by unexpected withdrawal of substances from their suppliers due to REACH.

Compliance with REACH will require manufacturers to have more detailed knowledge of the substances they use or are present in their products. The burden of compliance falls not just on large OEMs that export to the EU. Small and medium enterprises (SMEs) also share the burden of compliance, even if they do not directly export to the EU. Large OEMs are responding to REACH by developing compliance standards of their own and asking their suppliers for chemical composition data on products.

Complying with RoHS, which regulated just 6 substances and related compounds, was a difficult enough task. REACH regulates more than 30,000 substances. Making the task even more difficult are changes to the SVHC list. On January 13, 2010, the European Chemicals Agency added 14 chemical substances to the Candidate List of SVHC for authorization, bringing the total to 29 substances. The ECA promises to revise the SVHC list twice a year. The task of collecting detailed information about which substances are contained in products will be extensive and ongoing.

THE CHALLENGES OF REACH COMPLIANCE FOR ELECTRONICS OEMS

Data Collection

The biggest challenge for electronics OEMs in managing REACH compliance is to discover the chemical composition of all components and materials used in their products. With full knowledge of the chemicals used, OEMs can create a compliance plan that will work short and long-term. However, collecting chemical substance information from suppliers is a tedious and resource-intensive job. It takes numerous phone calls or e-mails; suppliers often do not understand aspects of regulations such as SVHCs; and suppliers sometimes demand a rationale for sharing information.

Ask for full-disclosure substance data whenever possible. When the SVHC list changes, for example, you don't have to ask for more data in the future if you have full disclosure data already. If full-disclosure data is not available from a supplier, at the very least, try to obtain a non-use SVHC statement or certificate. Ideally, suppliers should inform you about their use of SVHC when it exceeds 0.1% in concentration. In reality, it is risky not to pursue this data and to rely only on suppliers to provide notification.

Data Validation and Consolidation

The second challenge begins after chemical substance data starts to arrive from suppliers. The data may not be clean and it needs to be validated. Here are some common problems: (1) the chemical substance name does not match the CAS number; (2) the CAS number is incomplete or missing; (3) two different substances use the same CAS number; (4) different suppliers refer to identical substances with different names and different CAS numbers. In Figure 1, SIO2 is correlated to two different CAS numbers. In this case, and in all others where data cleansing and consolidation has not taken place, it is not possible generate an accurate rollup of the total weight of chemicals used in the product. Resolving these issues is necessary before conducting substance analysis for REACH compliance.

Establishment of Chemical Substance Database

The third challenge is to establish an enterprise-level chemical substance database covering all components used to build the products. A software system is necessary to manage the enterprise-level chemical substance database. The system needs to be able to roll up substance data from homogeneous materials. In order to help identify problem areas, the software system should be able to calculate substance data at the component, assembly, and product level. The system will also enable proper reporting on particular substances (such as SVHC or CMR substances) at the product level or even across different products.

Breakdown of all Materials	(All materials in the part)			
Materials	***% Weight***	***PPM***	***Where Used***	***CAS #***
Al203	68.97	689700	substrate	12036-10-1
Si02	2.155	21550	substrate	7440-21-3
Mg0	.0575	5750	substrate	1313-13-9
Ag	3.638	36380	inner electrode top	7440-22-4
Pd	0.099	990	inner electrode top	7440-05-3
Pbo	0.08	800	inner electrode top	1309-60-0
B203	0.04	400	inner electrode top	1303-86-2
Si02	0.08	800	inner electrode top	7631-86-9
Ni	0.338	3380	inner electrode side	7440-02-0
Cr	0.338	3380	inner electrode side	7440-47-3
Ru02	0.992	9920	Resistive Film	12036-10-1
Pbo	1.006	10060	Resistive Film	1309-60-0
B203	0.292	2920	Resistive Film	1303-86-2
Si02	0.569	5690	Resistive Film	7631-86-9
Pbo	0.696	6960	inner protective coat	1309-60-0
B203	0.277	2770	inner protective coat	1303-86-2
Si02	0.419	4190	inner protective coat	7631-86-9
Epoxy Resin	1.547	15470	outer protective coat	129915-35-1
Si02	0.184	1840	outer protective coat	7631-86-9
Cu0	0.231	2310	outer protective coat	1317-38-0
Cr2303	0.472	4720	outer protective coat	1308-38-9
Mn02	0.079	790	outer protective coat	1313-13-9
Ni	8.85	88500	middle termination	7440-02-0
Sn	6.929	69260	outer termination	7440-31-5
Others	1.147	11470	others (all locations)	---

Figure 1: Correction of CAS number for SiO2 is necessary

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A chemical substance database covering potentially thousands of components is complex and far beyond the limits of a spreadsheet application like Excel. Moreover, entering the data by hand is impractical and will introduce errors. Requesting that suppliers send chemical substance data in a common format that your software is able to import directly is also not feasible in reality. Finding a proper way of entering the chemical substance data to the software system is a challenge.

Limited Resources

Most electronics OEMs have no one devoted to or specializing in chemical management. Most likely, the task of REACH compliance will go either to component engineering or the quality group. Designers of products have little need to know the chemical substances used in the components, though they do need to know whether the components they select are REACH-compliant. With limited resources and budget, most companies can only afford to have a few people be responsible for this task and cannot afford to spend several hundreds of thousands of dollars on REACH compliance modules available with ERP or PLM upgrades. Finding a way of implementing REACH compliance management in a limited budget with limited resources is another challenge that most companies have to face.

BEST PRACTICES OF COMPLIANCE MANAGEMENT IN REACH

Scrub your BOMs

Most BOMs are dirty. Dirty BOMs contain inaccurate manufacturer names and part numbers. Before calling suppliers for chemical substance data, it's best to start by cleaning up the dirty BOMs stored in the ERP or PLM. You may have done this several years ago while requesting RoHS data from suppliers. If not, now is the time to scrub your BOMs by validating the manufacturer names, manufacturer part numbers and part description on all components in the BOMs. It will save a tremendous amount of time in getting data from your suppliers.

Collect full-disclosure chemical substance info from suppliers whenever possible

In order to be REACH-compliant, you need to know the chemical substance composition of the components in your products. This means collecting full-disclosure chemical substance data from your suppliers. If you are an "Article Producer" and only care about REACH SVHC compliance, you should still collect full-disclosure chemical substance data on all parts from suppliers whenever possible. Collecting REACH SVHC certificates from suppliers can only get you through compliance for 6 months to a year. New substances will be added to the SVHC Candidate list regularly. Collect full-disclosure chemical substance information from suppliers whenever possible so you don't need to recollect the certificates from the same suppliers when the SVHC Candidate list changes. *This is the most critical step in compliance management.*

It is highly recommended, if financially viable, to outsource the data collection to a 3rd-party solution provider. By tapping into the component chemical substance database established by a 3rd-party solution provider, you may find that data collection is actually cheaper, faster, and more accurate than doing it in-house. In our experience with electronics manufacturers, a typical BOM of 1000 parts will have more than 60% coverage in full-disclosure chemical substance data in our component database. This means the effort of data collection has been reduced to 40%. The challenge of recollecting data from the same suppliers when regulations change has also been reduced. Outsourcing data collection enables your component or quality engineers to focus on their core competencies of completing the product with quality, instead of dealing with mismatched or incorrect part numbers, CAS numbers, substance names, etc.

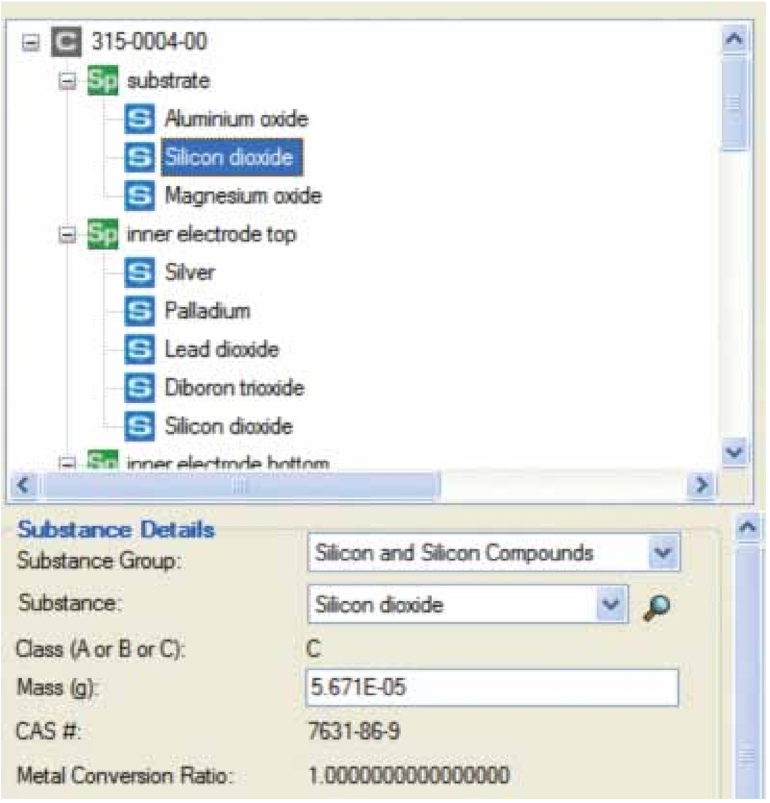

Figure 2: Import of full-disclosure substance data of a component after data validation

Select the proper software tool to help manage REACH compliance

Once you start collecting chemical substance data from suppliers, a software tool is necessary to help manage collection activities, establish the internal chemical substance database, and analyze the substances used in your products. The tool needs to tell you what has been collected and what has not, and should be able to report the aggregated weight of a substance in a product based on the projected annual shipment to the EU or customers in another region. The tool should also report on any SVHC substance contained in components used in your product in order to communicate with your suppliers for replacements and to alert your customers to proper usage scenarios. You may need to notify the ECHA on the use of SVHC substances in your products if they account for more than 0.1% of the product weight when more than 1 tonne is shipped to the EU per year. The tool should also be capable of scanning all components for substances in the categories of CMR (Carcinogenic, Mutagenic or Reprotoxic), PBT (Persistent, Bioaccumulative and Toxic) or vPvB (very persistent, very bioaccumulative) for possible violation of SVHCs in the future.

Enter chemical substance data in the software tool to establish an internal chemical substance database

In the process of collecting and validating chemical substance data from the components used in your products, you need to establish an internal chemical substance database by entering the substance data to the software tool. Be aware of these issues:

Data Format: Suppliers can provide chemical substance data in various formats, including pdf, Excel, html, XML and IPC-1752 forms. These formats need to be consolidated into one standard format in order to import them to the software tool. If you have outsourced the data collection job to a 3rd-party data provider, ask them to provide a common format that can be imported to the software tool.

Consolidated Substance Master: Entering substance data into the software tool can reveal several potentially difficult issues:

1. Some substances have a different CAS number but have the same substance name because they actually are the same substance. See Figure 3, an illustration from the SVHC Candidate List. CAS number 7789-12-0 and CAS number 10588-01-9 are both Sodium Dichromate. When a part contains substance 7789-12-0 and substance 10588-01-9, the software tool will need to be able to recognize that these two are actually the same and aggregate them properly.

2. Some substances have different CAS numbers and different substance names, but are in the same group of restricted substances. See Figure 4, again from the SVHC Candidate List. Note that HBCDD could have 2 different CAS numbers: 25637-99-4 or 3194-55-6, an alias CAS number. HBCDD could also have 3 isomeric series: alpha-HBCDD (134237-51-7), beta-HBCDD (134237-50-6), and gamma-HBCDD (134237-52-8). When parts contain any of these substances, the software tool will need to be able to recognize that these actually belong to the same group and aggregate them properly.

3. The software tool should maintain a consolidated substance master that covers all alias substances provided by suppliers and all isomeric series of substances. In

Substance name	CAS number	EC number	Basis for Identification as SVHC
Diarsenic pentaoxide	1303-28-2	215-116-9	Carcinogen, cat. 1
Diarsenic trioxide	1327-53-3	215-481-4	Carcinogen, cat. 1
Sodium dichromate	7789-12-0 10588-01-9	234-190-3	Carcinogen, cat. 2 Mutagen, cat. 2 Toxic for reproduction, cat. 2

Figure 3: Substance aliasing between 7789-12-0 and 10588-01-9

Hexabromocyclododecane (HBCDD) and all major diastereoisomers identified (α – HBCDD, β – HBCDD, γ – HBCDD	25637-99-4 and 3194-55-6 (134237-51-7, 134237-50-6, 134237-52-8)	247-148-4 and 221-695-9	Persistent, bioaccumulative and toxic

Figure 4: Substance grouping of 5 CAS numbers

reality, it is almost impossible for any software tool to cover all possible substances with their aliases and isomeric relatives. A good way to solve this issue is to make sure the software tool has a substance master that covers almost all substances provided by suppliers and can handle substance aliases and isomeric series. Most important, the tool should receive updates whenever a new substance provided by the supplier is not covered in the substance master. If you have outsourced the data to a 3rd-party data solution provider, make sure they will work with the software vendor so that both will maintain the same substance master and both will update their substance master whenever a new substance is identified.

4. Almost all software vendors claim to be able to import substance data in IPC-1752 format, but this format has limitations. IPC-1752's substance master is based on JIG specifications, so only about 300 substances are covered. Substances beyond JIG will be tagged as either Supplier Specific or Requester Specific. You will almost certainly see suppliers submit substance data and tag it Supplier Specific. If you are working with a data vendor to perform data collection, make sure to ask that they consolidate the substances so that all Supplier Specific substances or Requester Specific substances be grouped so that they can be aggregated in the software.

5. One recommendation is to find a 3rd-party solution provider that both collects data and provides the software tool. This is the preferred solution because the substance master for both the data service and the software tool are the same and synched for updates and aliases. This eliminates the issue of consolidated substances and substance maintenance, and reduces management of two vendors (or more) to one.

Make sound decision on change of parts or change of suppliers based on REACH compliance performance

Should you discover that components used in your BOMs contain certain regulated substances (from SVHC, CMR, PBT or vPvB), communicate with your suppliers for replacements. If the supplier fails to provide a plan for replacement, you may need to consider changing the suppliers. Based on the analysis from the tool, you should be able to make such decision quickly in order to avoid any disruption in businesses.

CONCLUSION

Compliance with REACH demands thorough and accurate data and an efficient way to analyze and manage the data. Companies throughout the supply chain will be feeling the impact of REACH and need to develop strategies to ensure that disruptions are minimized. These strategies include:

1. Clean the data you already have by scrubbing your BOMs.
2. Collect full-disclosure chemical data for all your components if it is available. A third-party solution provider may save you time and money.
3. Find a software tool to manage REACH compliance, including reporting on data collection, and chemical analysis at the component, subassembly, and product level.
4. Be rigorous in finding replacements for problem components.

Applying these strategies will help prevent product delays, redesigns, and supply chain disruptions. ■

__Larry Yen__ is President and CEO of GreenSoft Technology, Inc., a data services provider and developer of software solutions for environmental compliance regulations such as RoHS and REACH.

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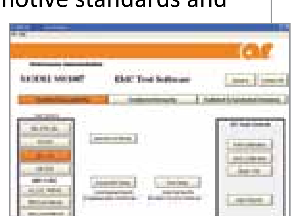

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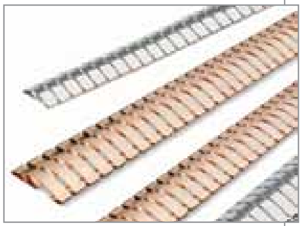

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Elite Electronic Engineering. . 800-ELITE-11
F-Squared Laboratories. 877-405-1580
Go Global Compliance Inc.. . .408-416-3772
Intl Cert Svcs, Inc. 888-286-6888
Kimmel Gerke Associates, Ltd.
. . . . 888-EMI-GURU
The MuShield Company Inc.
. . . . 888-669-3539
NCEE Labs 888-567-6860
Nemko Canada. 613-737-9680
NTS Northeast. 800-723-2687
O'Brien Compliance Management
. . . . 978-970-0525
Pulver Laboratories Inc.. 800-635-3050
Trace Laboratories, Inc.. 410-584-9099
Versus Global Certifications Pty Ltd.
. . . . +27 83 5140709

Consultants, Product Safety

Advanced Compliance Solutions
. . . . 321-223-2528
Alberi EcoTech. 702-677-6923
American Certification Body, Inc.
. . . . 703-847-4700
CASE Forensics 877-736-1106
Compliance & More, Inc. 303-663-3396
Compliance Management Group
. . . . 508-281-5985
D.L.S. Electronic Systems, Inc.
. . . . 847-537-6400
DNB Engineering, Inc.. 714-870-7781
EMCplus LLC 303-663-3396
F-Squared Laboratories. 877-405-1580
Go Global Compliance Inc.. . .408-416-3772
IQS, a Division of CMG 508-460-1400
Montrose Compliance Services
. . . . 408-247-5715
NCEE Labs 888-567-6860
Nemko Canada. 613-737-9680
NTS Northeast. 800-723-2687
O'Brien Compliance Management
. . . . 978-970-0525
Pulver Laboratories Inc.. 800-635-3050
RTF Compliance 949-813-6095
Trace Laboratories, Inc.. 410-584-9099
Versus Global Certifications Pty Ltd.
. . . . +27 83 5140709

Consultants, Quality

Alberi EcoTech. 702-677-6923
American Certification Body, Inc.
. . . . 703-847-4700
CASE Forensics 877-736-1106
O'Brien Compliance Management
. . . . 978-970-0525
Pulver Laboratories Inc.. 800-635-3050
Trace Laboratories, Inc.. 410-584-9099
Unitek, A Division of NQA . . . 800-998-9395

Consultants, Telecom

D.L.S. Electronic Systems, Inc.
. . . . 847-537-6400
Elite Electronic Engineering. . 800-ELITE-11
Go Global Compliance Inc.. . .408-416-3772
Hermon Labs TI. . . . . +972-4-6268450
Nemko Canada. 613-737-9680

NTS - Corporate HQ 800-270-2516
Versus Global Certifications Pty Ltd. . . . . +27 83 5140709

Consultants, Tempest

American Certification Body, Inc. 703-847-4700
Braden Shielding Systems . . . 918-624-2888
General Dynamics C4 Systems 480-441-5321

Consultants, Transients

American Certification Body, Inc. 703-847-4700
BestESD Technical Services . . . 831-824-4052
D.L.S. Electronic Systems, Inc. 847-537-6400
DNB Engineering, Inc. 714-870-7781
Kimmel Gerke Associates, Ltd. 888-EMI-GURU
Pulver Laboratories Inc.. 800-635-3050

Consultants, VCCI

American Certification Body, Inc. 703-847-4700
Atlas Compliance & Engineering 866-573-9742
Compliance & More, Inc. 303-663-3396
Compliance Management Group 508-281-5985
D.L.S. Electronic Systems, Inc. 847-537-6400
EMCplus LLC 303-663-3396
Go Global Compliance Inc. . . . 408-416-3772
H.B. Compliance Solutions . . 480-684-2969
Nemko Canada 613-737-9680

Design Services

American Certification Body, Inc. 703-847-4700
BestESD Technical Services . . . 831-824-4052
D.L.S. Electronic Systems, Inc. 847-537-6400
DNB Engineering, Inc. 714-870-7781
EMC Compliance. 256-650-5261
F-Squared Laboratories. 877-405-1580
High Voltage Maintenance. . . 937-278-0811
IQS, a Division of CMG 508-460-1400
MAJR Products, Inc. 877-625-7776
Montrose Compliance Services 408-247-5715
NCEE Labs 888-567-6860
NTS Northeast. 800-723-2687
NTS Test Systems Engineering 505-345-9499
Pulver Laboratories Inc.. 800-635-3050

Equipment Rental & Leasing

Dynamic Sciences International 800-966-3713
EMCC DR. RASEK . . . . +49-9194-9016

Shielded Enclosure Design, Relocation Services

ARC Technical Resources, Inc. 408-263-6486
Magnetic Shield Corporation 888-766-7800
MAJR Products, Inc. 877-625-7776
The MuShield Company Inc. 888-669-3539

Site Attenuation Testing Services

Alion Science and Technology 610-825-1960
ETS-Lindgren 512-531-6400
Retlif Testing Laboratories . . . 631-737-1500

Site Survey Services

Alion Science and Technology 610-825-1960
ARC Technical Resources, Inc. 408-263-6486
DNB Engineering, Inc. 714-870-7781
eti Conformity Services 877-468-6384
F-Squared Laboratories. 877-405-1580
High Voltage Maintenance. . . 937-278-0811
Magnetic Shield Corporation 888-766-7800
Retlif Testing Laboratories . . . 631-737-1500
RMV Technology Group, LLC 650-964-4792
Stephen Halperin & Associates 630-238-8883

Electrical & Electronic Components

Adapters

Conec Corporation 919-460-8800
Instruments For Industry, Inc. . . .631-467-8400
Murata Electronics. 800-554-4070
Power Dynamics, Inc. 973-560-0019
Sabritec 949-250-1244

Air Filters

MAJR Products, Inc. 877-625-7776

Arrestors

CITEL, Inc. 800-248-3548
Okaya Electric America, Inc. . 800-852-0122

Attenuators

Instruments For Industry, Inc. . . .631-467-8400

Backshells

Conec Corporation 919-460-8800
Power Dynamics, Inc. 973-560-0019
Sabritec 949-250-1244

Bluetooth Modules

Murata Electronics. 800-554-4070

Breakers

eti Conformity Services 877-468-6384

Circuit Breakers

eti Conformity Services 877-468-6384

Connectors

ARC Technologies, Inc. 978-388-2993
Conec Corporation 919-460-8800
eti Conformity Services 877-468-6384
Power Dynamics, Inc. 973-560-0019
Sabritec 949-250-1244

Couplers

AR 888-933-8181
Conec Corporation 919-460-8800
Instruments For Industry, Inc. . . .631-467-8400
Murata Electronics. 800-554-4070
TDK Corporation 972-409-4519
Teseq Inc. 978-764-7358

Diodes
Sabritec 949-250-1244

Fuses
eti Conformity Services 877-468-6384

Impedance Matching Networks
AR 888-933-8181

LEDs and Displays
Okaya Electric America, Inc. . 800-852-0122

Potentiometers
Murata Electronics. 800-554-4070

RF Frequency Converters
Test Equipment Connection. . 800-615-8378

Surge Suppressors
CITEL, Inc. 800-248-3548
Fil-Coil 631-467-5328
Murata Electronics. 800-554-4070
Okaya Electric America, Inc. . 800-852-0122
WEMS Electronics. 310-962-4410

Switches
eti Conformity Services 877-468-6384
The MuShield Company Inc.
. . . . 888-669-3539

Terminal Blocks
eti Conformity Services 877-468-6384

Transformers
Transformers, Power Line Isolation
Elna Magnetics 800-553-2870

Transformers, Signal Line Isolation
Elna Magnetics 800-553-2870

Transformers, Third-Party Approved, US/Canada
eti Conformity Services 877-468-6384

Transformers, Toroidal
The MuShield Company Inc.
. . . . 888-669-3539
Pearson Electronics, Inc. . . 650-494-6444

EMC Control
Air Cooling Systems
HM Cragg 800-672-7244

Architectural Shielding Products
Fil-Coil 631-467-5328

Arrestors, Lightning and Surge
Okaya Electric America, Inc. . 800-852-0122

Capacitors
Capacitors, Decoupling
Captor Corporation 937-667-8484
Oak-Mitsui Technologies . . 518-686-4961

Quell Corporation 505-243-1423
TDK Corporation 972-409-4519
TechDream, Inc. 408-320-4021

Capacitors, Mains (X and Y)
Captor Corporation 937-667-8484
LCR Electronics. 610-278-0840
Okaya Electric America, Inc. . 800-852-0122

Chokes
Captor Corporation 937-667-8484
Corcom/Tyco Electronics. . . . 847-573-6504
Elna Magnetics 800-553-2870
LCR Electronics. 610-278-0840
Murata Electronics. 800-554-4070
TechDream, Inc. 408-320-4021

Conductive Materials
Conductive Additives
Parker Hannifin, Chomerics Div
. . . . 781-935-4850

Conductive Adhesive
Ja-Bar Silicone Corp 973-786-5000

Conductive Epoxy
Parker Hannifin, Chomerics Div
. . . . 781-935-4850

Conductive Foam
Parker Hannifin, Chomerics Div
. . . . 781-935-4850
Tech-Etch 508-747-0300

Conductive Lubricants
Parker Hannifin, Chomerics Div
. . . . 781-935-4850

Connector Fingers
Alco Technologies, Inc.. . . . 310-328-4770
East Coast Shielding 908-852-9160
Fotofab 773-463-6211
Ja-Bar Silicone Corp 973-786-5000
Leader Tech 866-TECH-EMI
Tech-Etch 508-747-0300

Cord Sets, EMI
Captor Corporation 937-667-8484
Power Dynamics, Inc. 973-560-0019
Schurter Inc. 800-848-2600

Ferrite Beads, Rods and Forms

Elna Magnetics 800-553-2870
Fair-Rite Products Corp. . . . 888-324-7748

FerriShield 866-TECH-EMI
Leader Tech 866-TECH-EMI
MAJR Products, Inc. 877-625-7776
Murata Electronics. 800-554-4070
TechDream, Inc. 408-320-4021

Filter Coils

Captor Corporation 937-667-8484
Fil-Coil 631-467-5328
LCR Electronics. 610-278-0840

Filter Pins

Quell Corporation 505-243-1423

Filtered Connectors

Captor Corporation 937-667-8484
Corcom/Tyco Electronics. . . . 847-573-6504
Curtis Industries 800-657-0853
Quell Corporation 505-243-1423
Schurter Inc. 800-848-2600

Filters

Filters, Absorptive

Captor Corporation 937-667-8484

Filters, Antenna

Captor Corporation 937-667-8484
Murata Electronics. 800-554-4070
Oak-Mitsui Technologies . . 518-686-4961

Filters, EMC Test Chamber

Captor Corporation 937-667-8484
Corcom/Tyco Electronics. . . . 847-573-6504
LCR Electronics. 610-278-0840
Panashield, Inc. 203-866-5888
Spira Manufacturing Corporation
. . . . 818-764-8222
TDK Corporation 972-409-4519

Filters, Power Line

Captor Corporation 937-667-8484
Corcom/Tyco Electronics. . . . 847-573-6504
Curtis Industries 800-657-0853
DNB Engineering, Inc.. 714-870-7781
LCR Electronics. 610-278-0840
Murata Electronics. 800-554-4070
Okaya Electric America, Inc. . 800-852-0122
OnFILTER, Inc. 831-824-4052
Panashield, Inc. 203-866-5888

Filters, Shielded Air

Alco Technologies, Inc. 310-328-4770
Spira Manufacturing Corporation
. . . . 818-764-8222
Tech-Etch 508-747-0300

Filters, Shielded Room

Alco Technologies, Inc. 310-328-4770
Captor Corporation 937-667-8484

Filters, Signal Line

Captor Corporation 937-667-8484
Corcom/Tyco Electronics. . . . 847-573-6504
DNB Engineering, Inc.. 714-870-7781
Oak-Mitsui Technologies . . 518-686-4961
Quell Corporation 505-243-1423
TDK Corporation 972-409-4519

Filters, Third-Party Approved, EU

LCR Electronics. 610-278-0840

Filters, Third-Party Approved, US/Canada

LCR Electronics. 610-278-0840

Foils, Shield Tape

Ad-Vance Magnetics 574-223-3158
East Coast Shielding 908-852-9160
Parker Hannifin, Chomerics Div
. . . . 781-935-4850
TechDream, Inc. 408-320-4021

Gaskets

Alco Technologies, Inc. 310-328-4770
East Coast Shielding 908-852-9160
Fotofab 773-463-6211
Ja-Bar Silicone Corp 973-786-5000
MAJR Products, Inc. 877-625-7776
Omega Shielding Products, Inc.
. . . . 800-828-5784
Parker Hannifin, Chomerics Div
. . . . 781-935-4850
Spira Manufacturing Corporation
. . . . 818-764-8222
Tech-Etch 508-747-0300
TechDream, Inc. 408-320-4021
Vanguard Products Corporation
. . . . 203-744-7265
W. L. Gore & Associates, Inc.

Shielded Cable Assemblies and Harnesses

Alco Technologies, Inc. 310-328-4770
LCR Electronics. 610-278-0840

Shielded Conduit

Magnetic Shield Corporation
. . . . 888-766-7800

Shielded Connectors

Ad-Vance Magnetics 574-223-3158
Alco Technologies, Inc. 310-328-4770
East Coast Shielding 908-852-9160
Ja-Bar Silicone Corp 973-786-5000

Buyer's Guide

Shielded Enclosures

Ad-Vance Magnetics 574-223-3158
Cuming-Lehman Chambers, Inc. 717-263-4101
Fil-Coil 631-467-5328
Fotofab 773-463-6211
Leader Tech 866-TECH-EMI
Magnetic Shield Corporation 888-766-7800
Panashield, Inc. 203-866-5888
VTI Vacuum Technologies, Inc. 800-613-7296

Shielded Modules

Ad-Vance Magnetics 574-223-3158

Shielded Tubing

Ad-Vance Magnetics 574-223-3158

Shielded Wire and Cable

Alco Technologies, Inc. 310-328-4770
LCR Electronics. 610-278-0840
Magnetic Shield Corporation 888-766-7800
W. L. Gore & Associates, Inc.

Shielding Coatings

Magnetic Shield Corporation 888-766-7800
VTI Vacuum Technologies, Inc. 800-613-7296

Shielding Material

Shielding Material, EMI/RFI

Ad-Vance Magnetics 574-223-3158
Alco Technologies, Inc. 310-328-4770
East Coast Shielding 908-852-9160
FerriShield 866-TECH-EMI
Fotofab 773-463-6211
Ja-Bar Silicone Corp 973-786-5000
Magnetic Shield Corporation 888-766-7800
MAJR Products, Inc. 877-625-7776
Omega Shielding Products, Inc. 800-828-5784
Panashield, Inc. 203-866-5888
Pulver Laboratories Inc.. 800-635-3050
Spira Manufacturing Corporation 818-764-8222
Tech-Etch 508-747-0300
TechDream, Inc. 408-320-4021
VTI Vacuum Technologies, Inc. 800-613-7296
W. L. Gore & Associates, Inc.

Shielding Material, Magnetic Field

Ad-Vance Magnetics 574-223-3158
FerriShield 866-TECH-EMI
Fotofab 773-463-6211
Magnetic Shield Corporation 888-766-7800
MAJR Products, Inc. 877-625-7776
Panashield, Inc. 203-866-5888

Suppressors

Suppressors, Transient

Captor Corporation 937-667-8484
Okaya Electric America, Inc. . 800-852-0122

ESD Equipment & Products

Air Ionizers

3M Electronic Solutions. 512-984-6747
MKS ION Systems. 800-367-2452

ESD Tape

Parker Hannifin, Chomerics Div 781-935-4850

Meters

Meters, Static Charge

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. 978-764-7358

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
HV TECHNOLOGIES, Inc. . . 703-365-2330
Teseq Inc. 978-764-7358
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
HV TECHNOLOGIES, Inc. . . 703-365-2330
Teseq Inc. 978-764-7358
Thermo Fisher Scientific 678-546-8344

Static Control

Static Control, Containers

3M Electronic Solutions. 512-984-6747

Static Control, Flooring

3M Electronic Solutions. 512-984-6747
Protective Industrial Polymers . . 440-243-4560
Staticworx Flooring 888-STATICWORX

Static Control, Footwear

Staticworx Flooring 888-STATICWORX

Static Control, Garments

3M Electronic Solutions. 512-984-6747

Static Control, Mats

3M Electronic Solutions. 512-984-6747
Prostat Corporation 630-238-8883

Static Control, Monitoring Equipment

3M Electronic Solutions. 512-984-6747
MKS ION Systems. 800-367-2452

Static Control, Packaging

3M Electronic Solutions. 512-984-6747

Static Control, Workstations
3M Electronic Solutions 512-984-6747

Static Control, Wrist Straps
3M Electronic Solutions 512-984-6747
Prostat Corporation 630-238-8883

Transient Detectors and Suppresors
MKS ION Systems. 800-367-2452
Quell Corporation 505-243-1423

Materials, Adhesives & Coatings

Absorbing Materials
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

Coatings
Krefine Co.Ltd.. 520-838-0548
Staticworx Flooring 888-STATICWORX

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

Sealants
W. L. Gore & Associates, Inc.

Silicone Conductive Sponge
Ja-Bar Silicone Corp 973-786-5000

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

Power & Power Management

Constant Voltage Regulators
OPHIR RF 310-306-5556

Converters
Murata Electronics. 800-554-4070
OPHIR RF 310-306-5556

Cord Sets
HM Cragg 800-672-7244
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
OPHIR RF 310-306-5556
Power Dynamics, Inc. 973-560-0019

Motors
The MuShield Company Inc. 888-669-3539

Multiple Outlet Strips
HM Cragg 800-672-7244

Overcurrent Protection
CITEL, Inc. 800-248-3548
Okaya Electric America, Inc. . 800-852-0122

Overvoltage Protection
CITEL, Inc. 800-248-3548
Okaya Electric America, Inc. . 800-852-0122

Power Amplifier
AE Techron, Inc. 574-295-9495
Com-Power Corporation . . . 714-528-8800
The MuShield Company Inc. 888-669-3539
OPHIR RF 310-306-5556

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HM Cragg 800-672-7244
Schurter Inc. 800-848-2600

Power Distribution Systems
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
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
The MuShield Company Inc. 888-669-3539

Power Line Conditioning Equipment
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
Associated Power Technologies
. . . . 877-322-7693
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

Software Suppliers

3D Simulation Software

EM Software & Systems (USA) Inc.
. . . . 800-419-5566 (FEKO)

TechDream, Inc. 408-320-4021

Anechoic Chamber Software

EM Software & Systems (USA) Inc.
. . . . 800-419-5566 (FEKO)

EMC Simulation Software

EM Software & Systems (USA) Inc.
. . . . 800-419-5566 (FEKO)

EMC/EMI Software

AR 888-933-8181
ARC Technical Resources, Inc.
. . . . 408-263-6486
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

Finero USA L.L.C. 239-898-8487

Signal Integrity and EMC Analysis Software

TechDream, Inc. 408-320-4021

Wireless Propagation Software

EM Software & Systems (USA) Inc.
. . . . 800-419-5566 (FEKO)
MetaGeek 208-639-3140

Standards Suppliers

EMC Compliance. 256-650-5261
ESD Association 315-339-6937
Hermon Labs TI. . . . . +972-4-6268450
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
AR 888-933-8181
Com-Power Corporation . . . 714-528-8800
Dynamic Sciences International
. . . . 800-966-3713
Giga-tronics Incorporated . . . 800-277-9764
Instruments For Industry, Inc. . . .631-467-8400
OPHIR RF 310-306-5556
Teseq Inc. 978-764-7358

Amplifiers, Power

Advanced Test Equipment Rentals
. . . . 888-554-ATEC
AR 888-933-8181
Com-Power Corporation . . . 714-528-8800
CPI, Inc.. 905-877-0161
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
AR 888-933-8181
ARC Technical Resources, Inc.
. . . . 408-263-6486
Com-Power Corporation . . . 714-528-8800
CPI, Inc.. 905-877-0161
Dynamic Sciences International
. . . . 800-966-3713
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
AR 888-933-8181
ARC Technical Resources, Inc.
. . . . 408-263-6486
Com-Power Corporation . . . 714-528-8800
CPI, Inc.. 905-877-0161
Dynamic Sciences International
. . . . 800-966-3713
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, Flicker

Advanced Test Equipment Rentals 888-554-ATEC
ARC Technical Resources, Inc. 408-263-6486
EM Test USA 603-769-3477

Analyzers, Harmonics

ARC Technical Resources, Inc. 408-263-6486
EM Test USA 603-769-3477

Analyzers, Network

Advanced Test Equipment Rentals 888-554-ATEC
Aeroflex 800-835-2352
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
Test Equipment Connection. . 800-615-8378

Analyzers, Telecom

Advanced Test Equipment Rentals 888-554-ATEC
Aeroflex 800-835-2352
Hermon Labs TI. . . . +972-4-6268450
MetaGeek 208-639-3140

Analyzers, Tempest

Dynamic Sciences International 800-966-3713

Automatic Test Sets

Aeroflex 800-835-2352
ARC Technical Resources, Inc. 408-263-6486
Teseq Inc. 978-764-7358
Thermo Fisher Scientific 678-546-8344

Avionics Test Equipment

Aeroflex 800-835-2352
Dayton T. Brown, Inc. 800-TEST-456
EM Test USA 603-769-3477
HV TECHNOLOGIES, Inc. . . 703-365-2330
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 and Repair Services

Aeroflex 800-835-2352
eti Conformity Services 877-468-6384
Liberty Labs, Inc. 712-773-2199
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
Finero USA L.L.C. 239-898-8487
QuadTech 978-461-2100
Vitrek Corporation 858-689-2755

Data Acquisition Monitoring Systems

Advanced Test Equipment Rentals 888-554-ATEC
Michigan Scientific Corp. . . . 248-685-3939
MKS ION Systems. . . . 800-367-2452
NTS Test Systems Engineering 505-345-9499

Dielectric Strength Testers

Advanced Test Equipment Rentals 888-554-ATEC
Associated Research, Inc. . . . 800-858-8378
E. D. & D., Inc. 800-806-6236
QuadTech 978-461-2100
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
E. D. & D., Inc. 800-806-6236
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
Agilent Technologies 800-829-4444
EM Test USA 603-769-3477
EMSCAN Corporation 877-367-2261
Haefely EMC Technology . . 845-279-3644
HV TECHNOLOGIES, Inc. . . 703-365-2330
Rohde & Schwarz, Inc. . . . 888-TEST-RSA
Teseq Inc. 978-764-7358
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
Teseq Inc. 978-764-7358

Environmental Chambers

Advanced Test Equipment Rentals 888-554-ATEC
E. D. & D., Inc. 800-806-6236
TÜV SÜD America Inc. 800-888-0123

Gaussmeters

Magnetic Shield Corporation 888-766-7800
Narda Safety Test Solutions . . 631-231-1700

Generators

Generators, Arbitrary Wave Form

Aeroflex 800-835-2352
Test Equipment Connection. . 800-615-8378

Generators, ESD

EM Test USA 603-769-3477
Haefely EMC Technology . . 845-279-3644
HV TECHNOLOGIES, Inc. . . 703-365-2330
Teseq Inc. 978-764-7358
Thermo Fisher Scientific 678-546-8344

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Generators, Fast/Transient Burst

Advanced Test Equipment Rentals 888-554-ATEC
EM Test USA 603-769-3477
Haefely EMC Technology . . . 845-279-3644
HV TECHNOLOGIES, Inc. . . 703-365-2330
Thermo Fisher Scientific 678-546-8344

Generators, Impulse

Applied EM Technology 410-326-6728
EM Test USA 603-769-3477
Haefely EMC Technology . . . 845-279-3644
Thermo Fisher Scientific 678-546-8344

Generators, Lightning

EM Test USA 603-769-3477
Haefely EMC Technology . . . 845-279-3644
HV TECHNOLOGIES, Inc. . . 703-365-2330
Thermo Fisher Scientific 678-546-8344

Generators, Signal

Aeroflex 800-835-2352
AR 888-933-8181
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
EM Test USA 603-769-3477
Haefely EMC Technology . . . 845-279-3644
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
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
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
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 888-933-8181
Magnetic Shield Corporation 888-766-7800
Narda Safety Test Solutions . . 631-231-1700

Meters, Magnetic Field

Magnetic Shield Corporation 888-766-7800
Narda Safety Test Solutions . . 631-231-1700

Meters, Radiation Hazard

Narda Safety Test Solutions . . 631-231-1700

Meters, RF Power

Aeroflex 800-835-2352
AR 888-933-8181
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

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

Oscillators

Applied EM Technology 410-326-6728
Giga-tronics Incorporated . . . 800-277-9764

Oscilloscopes and Transient Recorders

Aeroflex 800-835-2352
MetaGeek 208-639-3140
Test Equipment Connection. . 800-615-8378

Probes

Probes, Current/Magnetic Field

Aeroflex 800-835-2352
MetaGeek 208-639-3140
Test Equipment Connection. . 800-615-8378

Probes, Electric Field

AR 888-933-8181
Com-Power Corporation . . . 714-528-8800
ETS-Lindgren 512-531-6400
Test Equipment Connection. . 800-615-8378

Probes, Voltage

ARC Technical Resources, Inc. 408-263-6486
Test Equipment Connection. . 800-615-8378

Receivers

Receivers, EMI/EMC

Advanced Test Equipment Rentals 888-554-ATEC
AR 888-933-8181
Com-Power Corporation . . . 714-528-8800
Rohde & Schwarz, Inc. . . . 888-TEST-RSA

Receivers, RF

Agilent Technologies 800-829-4444
Dynamic Sciences International 800-966-3713

Receivers, Tempest

Dynamic Sciences International 800-966-3713

RF Leak Detectors

AR 888-933-8181
MetaGeek 208-639-3140
Narda Safety Test Solutions . . 631-231-1700
Test Equipment Connection. . 800-615-8378

Safety Test Equipment

Com-Power Corporation . . . 714-528-8800
E. D. & D., Inc. 800-806-6236
Finero USA L.L.C. 239-898-8487
Narda Safety Test Solutions . . 631-231-1700
QuadTech 800-253-1230

Shock & Vibration Testing Shakers

Dayton T. Brown, Inc. 800-TEST-456
TÜV SÜD America Inc. 800-888-0123

Susceptiblity Test Instruments

AR 888-933-8181
ARC Technical Resources, Inc. 408-263-6486
Com-Power Corporation . . . 714-528-8800
EM Test USA 603-769-3477
Narda Safety Test Solutions . . 631-231-1700
Thermo Fisher Scientific 678-546-8344

Telecom Test Equipment

Aeroflex 800-835-2352
E. D. & D., Inc. 800-806-6236
EM Test USA 603-769-3477
Haefely EMC Technology . . . 845-279-3644
Hermon Labs TI. . . . . +972-4-6268450
HV TECHNOLOGIES, Inc. . . 703-365-2330
MetaGeek 208-639-3140
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 888-933-8181
Giga-tronics Incorporated . . . 800-277-9764
Test Equipment Connection. . 800-615-8378
TÜV SÜD America Inc. 800-888-0123

Testing Services

Accredited Registrar

Advanced Compliance Solutions 321-223-2528
Curtis-Straus (Bureau Veritas) 877-277-8880
Electro Magnetic Test, Inc. . . 650-965-4000
Nemko Canada 613-737-9680
Nemko USA – SouthEast . . 813-662-4606
NQA Canada 514-242-2655
NQA Indiana 800-398-8282
NQA West Coast 888-734-4476
NQA, USA 800-649-5289
Parker Hannifin, Chomerics Div 781-935-4850
TUV Rheinland of North America 1-TUV-RHEINLAND
TÜV SÜD America Inc. 800-888-0123

CE Competent Body

American Certification Body, Inc. 703-847-4700
Compliance Management Group 508-281-5985
Curtis-Straus (Bureau Veritas) 877-277-8880
D.L.S. Electronic Systems, Inc. 847-537-6400
Electro Magnetic Test, Inc. . . 650-965-4000
Elite Electronic Engineering. . 800-ELITE-11
EMCC DR. RASEK . . . . . . +49-9194-9016
Nemko Canada 613-737-9680
Nemko USA – SouthEast . . 813-662-4606
Parker Hannifin, Chomerics Div 781-935-4850
TÜV SÜD America Inc. 800-888-0123

CE Notified Body

American Certification Body, Inc. 703-847-4700
Curtis-Straus (Bureau Veritas) 877-277-8880
D.L.S. Electronic Systems, Inc. 847-537-6400
Electro Magnetic Test, Inc. . . 650-965-4000
EMCC DR. RASEK . . . . . . +49-9194-9016
Intertek 800-WORLDLAB
Nemko Canada 613-737-9680
Northwest EMC, Inc. 888-364-2378
TUV Rheinland of North America 1-TUV-RHEINLAND
TÜV SÜD America Inc. 800-888-0123

Environmental Testing and Analysis Services

Alberi EcoTech 702-677-6923
Staticworx Flooring 888-STATICWORX

Homologation Services

American Certification Body, Inc. 703-847-4700
Curtis-Straus (Bureau Veritas) 877-277-8880
Electro Magnetic Test, Inc. . . 650-965-4000
H.B. Compliance Solutions . . 480-684-2969
IQS, a Division of CMG 508-460-1400
Jacobs Technology 248-676-1101
Nemko Canada 613-737-9680
Nemko USA – SouthEast . . 813-662-4606
O'Brien Compliance Management 978-970-0525
Versus Global Certifications Pty Ltd. . . . . +27 83 5140709

Pre-Assessments

Advanced Compliance Solutions
. 321-223-2528
Alberi EcoTech. 702-677-6923
American Certification Body, Inc.
. 703-847-4700
CASE Forensics 877-736-1106
Corcom/Tyco Electronics. . . . 847-573-6504
Curtis-Straus (Bureau Veritas)
. 877-277-8880
Electro Magnetic Test, Inc. . . 650-965-4000
H.B. Compliance Solutions . . 480-684-2969
IQS, a Division of CMG 508-460-1400
Jastech EMC Consulting, LLC . .248-876-4810
NCEE Labs 888-567-6860
O'Brien Compliance Management
. 978-970-0525
Pulver Laboratories Inc.. 800-635-3050
RMV Technology Group, LLC
. 650-964-4792
Stephen Halperin & Associates
. 630-238-8883
TUV Rheinland of North America
. . . . 1-TUV-RHEINLAND

Product and Component Testing Services

Jastech EMC Consulting, LLC . .248-876-4810

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
IQS, a Division of CMG 508-460-1400
MET Laboratories 800-638-6057
NTS - Corporate HQ 800-270-2516
NTS Canada 403-568-6605
NTS Fullerton, CA 800-677-2687
NTS LAX 800-559-3202
NTS Northeast. 800-723-2687
NTS Plano, TX. 877-717-2687
NTS Tempe, AZ 480-966-5517
NTS Tinton Falls, NJ 732-936-0800
Retlif Testing Laboratories . . . 631-737-1500
SGS Consumer Testing Services
. . . . .800-777-TEST (8378)
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
Dayton T. Brown, Inc. 800-TEST-456
DNB Engineering, Inc.. 714-870-7781
ETS-Lindgren. 512-531-6400
Hermon Labs TI. . . . . +972-4-6268450
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MET Laboratories 800-638-6057
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NTS Northeast. 800-723-2687
NTS Plano, TX. 877-717-2687
NTS Tempe, AZ 480-966-5517
NTS Tinton Falls, NJ 732-936-0800
Pulver Laboratories Inc.. 800-635-3050
Retlif Testing Laboratories . . . 631-737-1500

BSMI Compliant Certification Testing

Atlas Compliance & Engineering
. 866-573-9742
Compliance & More, Inc.. . . . 303-663-3396
Compliance Management Group
. 508-281-5985
Compliance Worldwide, Inc.. .603-887-3903
D.L.S. Electronic Systems, Inc.
. 847-537-6400
DNB Engineering, Inc.. 714-870-7781
Electro Magnetic Test, Inc. . . 650-965-4000
Elliott Laboratories. 877-245-7800
EMCplus LLC 303-663-3396
Nemko USA – SouthEast . . 813-662-4606
Northwest EMC, Inc. 888-364-2378
TUV Rheinland of North America
. . . . 1-TUV-RHEINLAND

CB Test Report

Advanced Compliance Solutions
. 321-223-2528
Compliance & More, Inc.. . . . 303-663-3396
Curtis-Straus (Bureau Veritas)
. 877-277-8880
DNB Engineering, Inc.. 714-870-7781
Electro Magnetic Test, Inc. . . 650-965-4000
Elliott Laboratories. 877-245-7800
EMCplus LLC 303-663-3396
MET Laboratories 800-638-6057
Nemko USA – SouthEast . . 813-662-4606
O'Brien Compliance Management
. 978-970-0525
SGS Consumer Testing Services
. . . . .800-777-TEST (8378)
TUV Rheinland of North America
. . . . 1-TUV-RHEINLAND

CE Marking

Advanced Compliance Solutions
. 321-223-2528
American Certification Body, Inc.
. 703-847-4700
Atlas Compliance & Engineering
. 866-573-9742
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Compliance Management Group
. 508-281-5985
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Curtis-Straus (Bureau Veritas)
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D.L.S. Electronic Systems, Inc.
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DNB Engineering, Inc.. 714-870-7781
Electro Magnetic Test, Inc. . . 650-965-4000
Electronics Test Centre. . . . 613-599-6800
Elite Electronic Engineering. . 800-ELITE-11
Elliott Laboratories. 877-245-7800
EMCC DR. RASEK. . . . . . . +49-9194-9016
EMCplus LLC 303-663-3396
F-Squared Laboratories. 877-405-1580
H.B. Compliance Solutions . . 480-684-2969
Ingenium Testing, LLC. 815-315-9250

Intertek . . . 800-WORLDLAB
Intl Cert Svcs, Inc. . . . 888-286-6888
MET Laboratories . . . 800-638-6057
Montrose Compliance Services . . . 408-247-5715
NCEE Labs . . . 888-567-6860
Nemko Canada . . . 613-737-9680
Nemko USA – SouthEast . . . 813-662-4606
Northwest EMC, Inc. . . . 888-364-2378
NTS Canada . . . 403-568-6605
NTS Fullerton, CA . . . 800-677-2687
NTS Northeast . . . 800-723-2687
O'Brien Compliance Management . . . 978-970-0525
Pulver Laboratories Inc. . . . 800-635-3050
Radiometrics Midwest Corp. . . . 815-293-0772
Retlif Testing Laboratories . . . 631-737-1500
SGS Consumer Testing Services . . . 800-777-TEST (8378)
TUV Rheinland of North America . . . 1-TUV-RHEINLAND
TÜV SÜD America Inc. . . . 800-888-0123

China Compulsory Certification (CCC)

American Certification Body, Inc. . . . 703-847-4700
Compliance & More, Inc. . . . 303-663-3396
D.L.S. Electronic Systems, Inc. . . . 847-537-6400
Electro Magnetic Test, Inc. . . . 650-965-4000
EMCplus LLC . . . 303-663-3396
Go Global Compliance Inc. . . . 408-416-3772
Nemko Canada . . . 613-737-9680
Nemko USA – SouthEast . . . 813-662-4606
RTF Compliance . . . 949-813-6095
SGS Consumer Testing Services . . . 800-777-TEST (8378)
TUV Rheinland of North America . . . 1-TUV-RHEINLAND
TÜV SÜD America Inc. . . . 800-888-0123

Electrical Safety Testing

Advanced Compliance Solutions . . . 321-223-2528
American Certification Body, Inc. . . . 703-847-4700
CASE Forensics . . . 877-736-1106
Compliance Management Group . . . 508-281-5985
Curtis-Straus (Bureau Veritas) . . . 877-277-8880
D.L.S. Electronic Systems, Inc. . . . 847-537-6400
DNB Engineering, Inc. . . . 714-870-7781
Electro Magnetic Test, Inc. . . . 650-965-4000
Elite Electronic Engineering . . . 800-ELITE-11
Elliott Laboratories . . . 877-245-7800
EMCC DR. RASEK . . . +49-9194-9016
eti Conformity Services . . . 877-468-6384
F-Squared Laboratories . . . 877-405-1580
High Voltage Maintenance . . . 937-278-0811
Intertek . . . 800-WORLDLAB
MET Laboratories . . . 800-638-6057
NCEE Labs . . . 888-567-6860
Nemko Canada . . . 613-737-9680
Nemko USA – SouthEast . . . 813-662-4606
NTS Fullerton, CA . . . 800-677-2687
NTS Tinton Falls, NJ . . . 732-936-0800
Pulver Laboratories Inc. . . . 800-635-3050
Retlif Testing Laboratories . . . 631-737-1500
SGS Consumer Testing Services . . . 800-777-TEST (8378)
Trace Laboratories, Inc. . . . 410-584-9099
TUV Rheinland of North America . . . 1-TUV-RHEINLAND
TÜV SÜD America Inc. . . . 800-888-0123

EMC Testing

Advanced Compliance Solutions . . . 321-223-2528
Alion Science and Technology . . . 610-825-1960
American Certification Body, Inc. . . . 703-847-4700
Atlas Compliance & Engineering . . . 866-573-9742
Compliance & More, Inc. . . . 303-663-3396
Compliance Management Group . . . 508-281-5985
Compliance Worldwide, Inc. . . . 603-887-3903
Core Compliance Testing Srvs . . . 603-889-5545
Curtis-Straus (Bureau Veritas) . . . 877-277-8880
D.L.S. Electronic Systems, Inc. . . . 847-537-6400

Dayton T. Brown, Inc. . . . 800-TEST-456
Electro Magnetic Test, Inc. . . . 650-965-4000
Electronics Test Centre . . . 613-599-6800
Elite Electronic Engineering . . . 800-ELITE-11
Elliott Laboratories . . . 877-245-7800
EMC Compliance . . . 256-650-5261
EMCC DR. RASEK . . . +49-9194-9016
EMCplus LLC . . . 303-663-3396
eti Conformity Services . . . 877-468-6384
F-Squared Laboratories . . . 877-405-1580
General Dynamics C4 Systems . . . 480-441-5321
H.B. Compliance Solutions . . . 480-684-2969
Ingenium Testing, LLC . . . 815-315-9250
Intertek . . . 800-WORLDLAB
Intl Cert Svcs, Inc. . . . 888-286-6888
Jacobs Technology . . . 248-676-1101
MET Laboratories . . . 800-638-6057
Montrose Compliance Services . . . 408-247-5715
NCEE Labs . . . 888-567-6860
Nemko Canada . . . 613-737-9680
Nemko USA – SouthEast . . . 813-662-4606

Buyer's Guide

Testing Laboratories

EMC Testing continued

Northwest EMC, Inc. ... 888-364-2378

NTS - Corporate HQ ... 800-270-2516

NTS Canada ... 403-568-6605

NTS Europe GmbH ... +49 89 722 29448

NTS Fullerton, CA ... 800-677-2687

NTS Northeast ... 800-723-2687

NTS Plano, TX ... 877-717-2687

NTS Tempe, AZ ... 480-966-5517

NTS Tinton Falls, NJ ... 732-936-0800

Pulver Laboratories Inc. ... 800-635-3050

Qualtest Inc. ... 407-313-4230

Radiometrics Midwest Corp. ... 815-293-0772

Retlif Testing Laboratories ... 631-737-1500

SGS Consumer Testing Services ... 800-777-TEST (8378)

Southwest Research Institute ... 210-522-2122

Trace Laboratories, Inc. ... 410-584-9099

TUV Rheinland of North America ... 1-TUV-RHEINLAND

TÜV SÜD America Inc. ... 800-888-0123

Energy Efficiency Testing

Advanced Compliance Solutions ... 321-223-2528

Intertek ... 800-WORLDLAB

MET Laboratories ... 800-638-6057

Nemko USA – SouthEast ... 813-662-4606

Pulver Laboratories Inc. ... 800-635-3050

TUV Rheinland of North America ... 1-TUV-RHEINLAND

Environmental Simulation Testing

Advanced Compliance Solutions ... 321-223-2528

Cincinnati Sub-Zero ... 800-989-7373

Compliance Management Group ... 508-281-5985

Core Compliance Testing Srvs ... 603-889-5545

Curtis-Straus (Bureau Veritas) ... 877-277-8880

Dayton T. Brown, Inc. ... 800-TEST-456

DNB Engineering, Inc. ... 714-870-7781

Elite Electronic Engineering ... 800-ELITE-11

EMCC DR. RASEK ... +49-9194-9016

Intertek ... 800-WORLDLAB

MET Laboratories ... 800-638-6057

NCEE Labs ... 888-567-6860

Nemko USA – SouthEast ... 813-662-4606

NTS Canada ... 403-568-6605

NTS Europe GmbH ... +49 89 722 29448

NTS Fullerton, CA ... 800-677-2687

NTS LAX ... 800-559-3202

NTS Northeast ... 800-723-2687

NTS Plano, TX ... 877-717-2687

NTS Santa Clarita, CA ... 661-259-8184

NTS Tempe, AZ ... 480-966-5517

NTS Tinton Falls, NJ ... 732-936-0800

Qualtest Inc. ... 407-313-4230

Retlif Testing Laboratories ... 631-737-1500

SGS Consumer Testing Services ... 800-777-TEST (8378)

Trace Laboratories, Inc. ... 410-584-9099

TÜV SÜD America Inc. ... 800-888-0123

EuP Directive Compliance

Advanced Compliance Solutions ... 321-223-2528

Curtis-Straus (Bureau Veritas) ... 877-277-8880

Intertek ... 800-WORLDLAB

Nemko USA – SouthEast ... 813-662-4606

SGS Consumer Testing Services ... 800-777-TEST (8378)

TUV Rheinland of North America ... 1-TUV-RHEINLAND

GOST R certification

Advanced Compliance Solutions ... 321-223-2528

DNB Engineering, Inc. ... 714-870-7781

Electro Magnetic Test, Inc. ... 650-965-4000

Go Global Compliance Inc. ... 408-416-3772

Nemko Canada ... 613-737-9680

Nemko USA – SouthEast ... 813-662-4606

Green Energy Compliance

Intertek ... 800-WORLDLAB

TUV Rheinland of North America ... 1-TUV-RHEINLAND

GS Mark Certification

Compliance & More, Inc. ... 303-663-3396

Curtis-Straus (Bureau Veritas) ... 877-277-8880

Electro Magnetic Test, Inc. ... 650-965-4000

EMCplus LLC ... 303-663-3396

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MC-483-340-145
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Cedar Park, TX 78613 USA
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tel: 978-764-7358
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