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EMI vs. EMC
What’s in an Acronym?

We have all seen advertising copy for test equipment manufacturers’ “EMC receivers,” and “EMC test services” provided by commercial EMI test facilities. While we know what the aforementioned receiver does, and what sort of services the test facility supplies, the nomenclature is wrong and is symptomatic of a deeper problem.

Ken Javor
In this 3-day intensive course we’ll cover practical aspects of noise and interference control in electronic systems and provide a working knowledge of EMC principles. Ideas are illustrated with examples of actual case histories and mathematical complexity is kept to a minimum. Participants will gain knowledge needed to design electronic equipment compatible with the electromagnetic environment and in compliance with national and international EMC regulations.

COURSE CONTENT

CABLING
Electric and magnetic field coupling, crosstalk. Cable types: coax, twisted pair and ribbon cables. Cable shielding and terminations.

GROUNDING PRINCIPLES

DIGITAL LAYOUT & GROUNDING
Noise sources, PCB layout, power distribution, ground grids, characteristics of ground planes. Decoupling capacitors: value, placement, resonance and limitations.

HIGH SPEED DIGITAL DECOUPLING
Alternative decoupling methods, use of distributed decoupling capacitance, power supply isolation, effect of paralleling capacitors. Embedded PCB capacitance.

DIFFERENTIAL-MODE EMISSION

COMMON-MODE FILTERING

TRANSMISSION LINES

MIXED SIGNAL PCBs
Defining the problem, A/D converter requirements, return current paths, split ground planes, PCB partitioning, bridges & moats, routing discipline.

RF & TRANSIENT IMMUNITY
RF immunity: circuits affected, PCB layout, audio rectification, RFI filters. Transient immunity: circuits affected, the three-prong approach, keeping transient energy out, protecting the sensitive devices, designing software/firmware for transient immunity.

CONDUCTED EMISSION
AC power line conducted emission models, switching power supplies, parasitic capacitance, layout. Common-mode and differential-mode conducted emission, common-mode chokes, saturation. Power line filters.

SHELDING
Absorption and reflection loss. Seams, joints, gaskets, slot antennas, and multiple apertures. Waveguides below cutoff, conductive coatings. Cabinet and enclosure design.
Who Should Attend

This course is directed toward electrical engineers. However, mechanical engineers, reliability and standards engineers, technical managers, systems engineers, regulatory compliance engineers, technicians and others who need a working knowledge of electromagnetic compatibility engineering principles will also benefit from the course.

EMC EXHIBITS AND EVENING RECEPTION: WEDNESDAY, APRIL 23, 2014

Exhibitors: for information contact Sharon Smith e-mail: sharon.smith@incompliancemag.com or call (978) 873-7722
FCC News

FCC Proposes $3.5 Million Fine for Slamming/Cramming

The U.S. Federal Communications Commission (FCC) has proposed a fine of more than a $3.5 million against a Nevada-based telecommunications firm that allegedly changed the preferred long-distance telecommunications service of a group of consumers without authorization (a practice known as “slamming”), and for placing unauthorized charges on consumers’ telephone bills (known as “cramming”).

In a recent Notice of Apparent Liability for Forfeiture, the Commission proposed a fine of $3,560,000 against Consumer Telecom Inc. of Henderson, NV for multiple instances of slamming or cramming. In this case, Consumer Telecom telemarketers allegedly represented themselves to consumers as employees of their incumbent long-distance carrier. According to the Commission, “CTI apparently took advantage of consumers by masking the true purpose of the call, and then profiting from their obvious confusion about the questions they were asked.”

The Federal Communications Act prohibits carriers from changing a subscriber’s selection of telephone service providers without their explicit permission, or for billing them without authorization.

The proposed forfeiture in this case is more than twice the amount proposed by the Commission in December 2012 against a California-based company.

In that instance, the Commission proposed a forfeiture of more than $1.4 million against Preferred Long Distance, Inc. of Encino, CA for allegedly switching long-distance telephone service for 14 consumers without authorization.

The complete text of the Commission’s Notice of Apparent Liability for Forfeiture against Consumer Telecom is available at incompliancemag.com/news/1402_01.

FCC Releases Consumer Complaints Report for Q2 2013

The U.S. Federal Communications Commission (FCC) has released its report on inquiries and complaints service of a group of consumers without authorization (a practice known as “slamming”), and for placing unauthorized charges on consumers’ telephone bills (known as “cramming”).

The Federal Communications Act prohibits carriers from changing a subscriber’s selection of telephone service providers without their explicit permission, or for billing them without authorization.

The proposed forfeiture in this case is more than twice the amount proposed by the Commission in December 2012 against a California-based company.

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FCC Proposes $44 Million in New Penalties for Lifeline Program Violations

The U.S. Federal Communications Commission (FCC) has proposed more than $44 million in new monetary forfeitures against three wireless Lifeline service providers who allegedly established multiple Lifeline wireless phone service subscriptions for individual consumers, in violation of the program’s rules.

The Commission issued Notices of Apparent Liability (NALs) in December 2013 against Cintex Wireless ($9.4 million), Telrite Corporation ($22.4 million) and Global Connection ($11.7 million). In each instance, the Commission says that the carriers knew or should have known that targeted consumers were already participants in the Lifeline program, and therefore ineligible for multiple subscriptions under Lifeline program rules.

The proposed monetary forfeitures were based on the number of unlawful payment requests made by each respective carrier, which was then adjusted upward by three times the total duplicate payments requested.

Established in 1985, the Lifeline program provides discounted wireless service subscriptions to low-income consumers. However, evidence of widespread abuse led the Commission to overhaul the program in 2012, and to aggressively pursue investigations of duplicate service and fraud. During the last three months of 2013 alone, FCC enforcement in connection with Lifeline program violations has resulted in proposed fines of $90 million.

FCC Releases Data on Internet Access

The U.S. Federal Communications Commission (FCC) has released its most recent report on access in the United States to fixed and mobile Internet connections, including information on the gap between current service levels and the benchmark Internet connection speeds recommended under the Commission’s National Broadband Plan.

According to the Commission’s report, entitled Internet Access Services: Status as of December 31, 2012, nearly 70% of fixed Internet connections to households meet or exceed the speed tier that most closely approximates the target set in the National Broadband Plan of 3 megabits per second (Mbps) downstream and 768 kilobits per second (kbps) upstream. This penetration rate for fixed high-speed service compares with just 49% in 2009.

At the same time, high-speed Internet access (defined at 3 Mbps downstream or greater) for subscribers of mobile wireless service continues to grow. As of December 2012, nearly 38% of mobile subscribers had access to high-speed service, compared with a 21% penetration rate as of December 2011.

Without accounting for speed, Internet connections overall are growing. By the end of December 2012, there were 262 million Internet connections offering access at speeds of at least 200 kbps, a 14% year-over-year increase. Overall growth continues to be driven by dramatic increases in mobile connections, which increased by 18% in just one year. With 169 million subscribers, the number of mobile Internet connections at the end of December 2012 was nearly 82% greater than the number of fixed Internet connections.

The complete text of the Commission’s latest report on Internet access is available at incompliancemag.com/news/1402_02.
**EU Commission Updates Standards List for PPE Directive**

The Commission of the European Union (EU) has an updated list of standards that can be used to demonstrate conformity with the essential requirements of its Directive 89/686/EEC concerning personal protective equipment.

For the purposes of the Directive, personal protective equipment (or PPE) is defined as “any device or appliance designed to be worn or held by an individual for protection against one or more health and safety hazards.” Specifically excluded from the scope of the Directive is equipment designed specifically for private use (such as seasonal outdoor clothing), equipment for use by armed forces or law enforcement personnel, and equipment intended for the protection or rescue of individuals on vessels or aircraft.

The extensive list of CEN and Cenelec standards was published in December 2013 in the *Official Journal of the European Union*, and replaces all previously published standards lists for the Directive.

The complete updated standards list for the EU’s PPE Directive is available at incompliancemag.com/news/1402_03.
Google and HP Recall Chromebook 11 Chargers

Google Inc. of Mountain View, CA and the Hewlett-Packard Company of Palo Alto, CA are voluntarily recalling about 145,000 power supplies/chargers manufactured in China and intended for use with HP’s Chromebook 11 tablet computer.

Google and HP report that the power supply/charger can overheat and melt, posing a fire and burn hazard to consumers. Google says that it has received nine reports of chargers overheating and melting during use, as well as one report of a minor consumer injury and a separate report of minor property damage.

The recalled power supplies/chargers were sold with HP’s Chromebook 11 between October and November 2013 for about $280 at Best Buy stores nationwide, as well as through ShoppingHP.com, Play.Google.com and Amazon.com.

Additional details regarding this recall are available at incompliancemag.com/news/1402_04.

Colby TVs Recalled Due to Fire Hazard

Eight U.S. retailers have announced a voluntary recall of Colby-brand 32-inch flat screen televisions manufactured in China.

According to a press release issued by the U.S. Consumer Product Safety Commission (CPSC), an electronic component in the recalled televisions can catch fire and ignite nearby items, posing a fire and burn hazard to consumers. The CPSC says that it

Bed Bug Heating Units Recalled

Nuvenco, Inc. of Fort Collins, CO. is recalling about 9000 of its Pack-Tite brand heating units for bed bug control.

Nuvenco reports that the bed bug heating units can overheat and/or melt, potentially causing a fire and posing a burn hazard to consumers.

The company has received three consumer complaints of heaters overheating, including one case in which treated items were singed. However, there have been no reports of injuries.

The recalled heating units were sold through pest control companies and pest control product distributors nationwide from October 2009 through January 2013 for between $300 and $330 for the heating system, and for $53 for the heating unit when sold separately.

More information about this recall is available at incompliancemag.com/news/1402_04.
has received six separate reports of televisions overheating, smoking or catching fire. However, there have been no reports of injuries.

The eight retailers that initiated this recall include ABC Warehouse, Best Buy, Fry’s Electronics, h.h. Gregg, Nebraska Furniture Mart, P.C. Richard & Son, Sears/Kmart and Toys R Us. The recall televisions were sold at these and other retailers nationwide from August 2011 through November 2013 for between $170 and $260.

Further details about this recall are available at incompliancemag.com/news/1402_06.

Pre-lit Christmas Trees Recalled Due to Fire Hazard

Seasonal Specialties LLC of Eden Prairie, MN is recalling about 1800 of its Enchanted Forest-brand pre-lit Christmas trees manufactured in China.

The company reports that electrical components in the trees’ light strings can overheat and melt, posing a fire, burn and shock hazards to consumers. There have been two separate reports of the trees’ light strings overheating, melting or smoking, but no reports of consumer injuries.

The recalled Christmas trees were sold exclusively through Menards retail stores nationwide, and through Menards.com, between September and November 2013 for about $300.

More information about this recall is available at incompliancemag.com/news/1402_07.

Company Recalls PERS Transmitters

Linear LLC of Carlsbad, CA has issued a voluntary recall for about 48,000 of the company’s personal emergency reporting system (PERS) transmitters manufactured in China.

According to the company, the battery clips in the transmitters can corrode, causing the transmitters to operate intermittently or not at all, thereby failing to generate a warning when appropriate. Linear says that it has received one report of a transmitter that failed to operate, but has not received any reports of injuries.

The recalled transmitters were sold through independent PERS distributors and dealers nationwide from June through August 2013 for about $45.

Additional details about this recall are available at incompliancemag.com/news/1402_08.
Frying the Flight Data Recorder
How Not to Impress

BY MIKE VIOLETTE

In this month’s In Compliance Magazine the focus is on military and aerospace topics. Along those lines, we worked on a project for an aviation company some years back. In mining the archives, so to speak, we head to the lower peninsula of Michigan, to the city of Grand Rapids.

Grand Rapids is the birthplace of Gerald Ford and the home of the Gerald Ford Presidential Library & Museum, where the late President was laid to rest. Ford served a partial term on the bully pulpit after a long run in Congress (1949-1973). He succeeded Spiro Agnew as Veep under Nixon after Agnew resigned, in disgrace, in December 1973.

Those were crazy days in politics and Nixon’s presidency crumbled nine months later under the weight of the Watergate scandal. It was a turbulent and challenging time, indeed, what with the imminent collapse of Saigon, the oil embargo, the threat of thermonuclear war, pastel leisure suit sightings and the woeful growth of disco music.

With all of that on his plate, I wonder if Mr. Ford, sometimes, wished he had stayed in Grand Rapids to practice something more peaceable than politics, like divorce law. Now, Michigan has a “no-fault divorce” provision on the books which, I suppose, makes it a bit easier to get un-hitched. One day, a few years back, I wished there was protection for “no-fault consulting.”

More on that later, but first a bit on Grand Rapids. Native Americans have inhabited the area around the Grand River for millennia. Westerners, first French fur trappers and later woodsmen, started arriving in the late 1700s. Foundations of the city’s industrial base were developed one hundred years later as craftsmen and
entrepreneurs built “The Furniture City.” To this day, she hosts several high-end furniture manufacturers. Grand Rapids is also home to a wide variety of technology industries, including machinery, automotive and aerospace.

Where once rapids roared and riffled on the Grand River, dams, power canals and tailraces have subdued her natural flow, now largely serene as it meanders through the town. In the spirit of post-environmental awareness, there are movements in the city to bring back the natural rapids to Grand Rapids.

Motu Viget means ‘strength in activity,’ which is her motto and is a paean that harks even back two thousand years to Native American Mound Builders, who stayed active constructing impressive edifices of dirt and clay to bury their dead.

As the town grew in the mid 1800s and accepted immigrants from Holland, Germany, Ireland, Sweden, Italians and Poland, the city’s location in the industrial heartland of America lends access to major markets and a diverse salt-of-the-Earth populace that boasts a strong work ethic, typical of the solid mid-western towns in the US. Later, refugees from war and foreign strife came to settle in the town. After the pogroms of the 1930s and World War II, European Jews found safety and peace in Grand Rapids. Hungarians settled after 1956 and Vietnamese after the fall of Saigon.

A place of activity—and strength—indeed.

The economy of Grand Rapids is diverse, too, with not as much vertical reliance on a single industry as, say, Motor City, a hundred and sixty miles to the East, with the avionics industry supplying sophisticated systems, to where this story arcs. One project that we were called to investigate was a Flight Data Recorder (FDR). These so-called “black boxes” (actually painted orange or yellow for better visibility at a crash site) have been standard in aircraft beginning in the 1950s. The earliest versions were analog and relied on a metal foil in a crash-survivable case.

The initial development of electronic FDRs for the Air Force (for the F-16)
began in 1982, starting a continuing evolution of solid-state based digital devices. With no moving parts, they were much better suited to survive the tremendous impact and related injuries associated with a high-speed nose into terra firma.

The designs of FDRs have tracked heavily integrated with flight systems; very rapid advances have been occurring since the 1980s. This is especially true as more aircraft are developed with fly-by-wire controls, which allow the monitoring and recordation of dozens of sensor signals. The FDR systems consist of not just a single box, but of multiple, linked modules including the Signal Acquisition Unit, Cockpit Control Unit, Data Acquisition and Recording Unit and the Voice and Data Recorder. By the late 1990s, these systems were growing in capacity and capability. Memory units with up to several hundred megabytes meant that more parameters could be stored, for longer periods of time, giving incident investigation loads of data for analysis after crashes. This means the integration and density of electronics has increased tremendously, along with rise of clock and data rates, and EMI.

Versions of these data recorders are now being deployed in railroad applications. Following a fatal crash in Chatsworth, CA in September 2008, the National Transportation Safety Board (NTSB) made the following recommendation to the Federal Railroad Administration to “Require the installation of crash- and fire-protected inward- and outward-facing audio and image recorders capable of providing recordings to verify that train crew actions are in accordance with rules and procedures that are essential to safety as well as train operating conditions.”

Passenger vehicle Event Data Recorders, monitoring speed, brake condition, seatbelt status and cruise control settings are now common in motor vehicles and have been used to prove assertions of reckless driving in court.

Our client in Grand Rapids was developing the Signal Acquisition Unit, a critical part of the FDR’s distributed component of the avionics system connected via a serial 1553 bus. The unit we worked on, a gray squat rugged aluminum box, had four connectors on its face. These were dense MIL-style circular multi-pin affairs that connected to harnesses made of dozens of individual wires. The device was failing RE102 emissions in the 30-60 MHz band. A quick look at the signals showed a mix of narrowband clock-like emissions and broadband data-generated noise: ugly stuff.

We were set up in a small shielded enclosure. A biconical antenna was set up and connected to a spectrum analyzer that was sitting on a cart next to the bench. The wiring connected to the EUT was splayed out on the bench. The analyzer display bloomed with green spikes, picking up energy radiating off the harness wiring.

Because of weight issues, shielding the wires was out of the question, not to mention the complexity of making a complete shield with routing for branches and to connect to various locations on the airframe.

So, what to do? Well, these kinds of situations are really the nasty ones: few options, a complex box, tons of wiring and any number of sources, any one of them could put the unit out of compliance.

We tried clip-on ferrites inside, squeezing them over the internal wiring. No luck. The thing about ferrites is: either they work, or they don’t. Besides, the mechanical guys weren’t too thrilled about installing an unsecured hunk of sintered iron inside the device that had to survive multiple-G environments.

After a morning of fiddling around, checking schematics and looking at pinouts, it was time to break for lunch. Reality engineering sometimes means...
knowing when to put down the scope probe, but I didn't. The question kept nagging at me: which of these pins had the most energy? Could we knock these signals down one-at-a-time? One of the tricks of the trade, so to speak, is to take a dental pick and carefully connect it to suspect pins, all the while looking at the spectrum display. If a particular node was “hot” the radiated energy off of the pick would peak frequencies on the analyzer.

One of the project technicians, a calm, older guy named Al who, as I recall, was a whiz at surface mount surgery, stood by as I poked the pinouts on C1, the largest of the four circulars.

“Be careful.” Al said.

The eye-hand coordination was better back then, but even so after a half-dozen pokes, my pick slipped and I crossed two pins. Something inside the unit popped and sizzled.

“Aw crap,” Al said and sighed. “There goes my afternoon.” I looked at him and he shrugged his shoulders. “Might as well go to lunch now.”

I put the dental pick down and followed him out of the room down the hall a few paces behind, head lowered and just a little shaken.

Al turned into the room where the engineers’ cubicles were arranged, tapped the lead engineer on the shoulder and told him, calmly. “The consultant fried the unit.”

A nanosecond later, I walked into the room to hear the lead, jumping up from his desk yelp: “What?! Kill Him!”

Lunch that day at the company cafeteria was quiet, I sat a few seats away from the project manager, trying to stay cool. He was picking at a plate of lukewarm lasagna, muttering something about the schedule getting ‘shot in the ass.’ Oops.

Back at the ‘shop’ I debriefed John, my supervisor, somewhat sheepishly. John was calm. “Those things happen. I blew out the front-end of a forty grand receiver when I was younger. It’s reality.”

They ultimately got the unit working again (it turns out that I blew out a simple line driver; thankfully back then DIP packages were pretty easy to de-solder and replace). Al did a fine job, but it did take the rest of the afternoon.

Ultimately, we found some filter-pins that were retrofitted to the circular connectors as a quick-fix and sold them an EMC design course. 

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<td>• FDR History: <a href="http://www.boeing.com/commercial/aeromagazine/aero_02/ntxonly/s01txt.html">http://www.boeing.com/commercial/aeromagazine/aero_02/ntxonly/s01txt.html</a></td>
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MIKE VIOLETTE is President of Washington Labs and Director of American Certification Body. For reasons that have nothing to do with frying that flight data recorder, he has not been back to Grand Rapids. He can be reached at mikey@wil.com.

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REALITY Engineering
**FAULTS**

The first question that must be addressed is: What fault protection is the fuse providing?

There are two kinds of faults: (1) phase-to-neutral (pole-to-pole) and (2) phase-to-ground.

(Note that a fuse cannot provide protection for a neutral-to-ground fault because, by definition, the neutral is grounded. In a neutral-to-ground fault, the neutral and ground conductors become parallel conductors. In accordance with Kirchoff’s Laws, the current in the neutral goes down, not up. Hence, the over-current does not occur, and a fuse cannot provide protection).

**SINGLE FUSING**

A single fuse in the phase conductor provides protection for both kinds of faults. This is one reason why a single fuse in the neutral is not permitted.

**DOUBLE FUSING**

The second question that must be addressed is: Under what conditions does double-fusing provide the same or better protection than a single fuse?

We have already determined that a single fuse in the phase conductor provides adequate protection against both kinds of faults, and that a fuse in the neutral conductor does not. If double fusing is employed, the equipment is protected against both faults, but the neutral fuse is redundant for phase-to-neutral faults, and inoperative for phase-to-ground faults.

The only condition where fusing both phase and neutral conductors yields non-redundant protection against both faults is where polarity reversal is possible. That is, where the phase and neutral conductors could be interchanged on the supply side of the fuse. If polarity reversal is possible, then double-fusing guarantees that the phase conductor will always be provided with a fuse.

With double fusing, protection against both faults is provided for both normal polarity and reverse polarity.

**POLARITY REVERSAL**

The third question that must be addressed is: Is polarity (phase-neutral) reversal possible in the circuit on the supply side of the fuse? That is, is the fuse location (ie: phase or neutral conductor) constant or variable?

**BUILDING WIRING AND PERMANENTLY-CONNECTED EQUIPMENT**

If we are dealing with building wiring or permanently-connected equipment, then fuse location is not variable, and polarity reversal is not possible. In this case, one fuse, in the phase conductor, provides protection for both phase-to-neutral and phase-to-ground faults.

The NEC, CEC, IEE Wiring Regulations and IEC 364 specifically prohibit fusing the neutral in building wiring and permanently-connected equipment.

**PLUG-AND-SOCKET-CONNECTED EQUIPMENT**

If we are dealing with plug-and-socket-connected equipment, then we must examine the supply configuration, socket configuration, plug configuration, and wiring codes to determine whether fuse location is variable or not.

**THREE-PHASE AND MULTI-VOLTAGE EQUIPMENT**

For three-phase (e.g. 208/120) and multi-voltage (e.g. 120-0-120) supplies, the plug and socket must maintain...
polarity in order to have functionality. In these cases, the fuse location is not variable because any polarity reversal (other than phase rotation) results in incorrect voltages applied to the equipment, usually with immediate catastrophic results, and opening of the building fuse or circuit breaker.

For these cases (plug-and-socket-connected three phase equipment and multi-voltage, e.g. 120-0-120 equipment), a fuse in each phase conductor provides protection for both phase-to-neutral and phase-to-ground faults. A fuse in the neutral conductor would be redundant and should it operate (open), the voltages applied to the various circuits will change and could cause overvoltage, overcurrent, and overheating conditions in at least one of the individual loads. For this reason, a fuse in the neutral must be prohibited, or it must be “ganged” with the phase conductor fuses such that if any one, including the neutral, operates, they all open.

**SINGLE PHASE EQUIPMENT**

For single-phase plug-and-socket-connected equipment, the plug and socket may or may not reliably maintain polarity, depending on the electrical code and the socket configuration.

Supposedly, the NEMA 5-15R socket maintains the polarity of the building wiring, with the wide blade being the neutral conductor. However, there are several versions of the NEMA 5-15P plug, some with wide blade and some without. Therefore, some plugs allow polarity reversal, while others do not.

In continental Europe, the socket wiring for the common 220 V, 16A plug is not polarized, and the equipment fuse location would be variable. In the UK and Australia, sockets and plugs are polarized, and the equipment fuse location would be constant.

The point is that each plug, socket, and building wiring is an independent situation which must be separately evaluated as to whether polarity reversal is possible. This in turn would make the equipment fuse location constant or variable.

**THE GENERAL CASE FOR SINGLE-PHASE PLUG-AND-SOCKET-CONNECTED EQUIPMENT**

For single-phase, single-voltage plug-and-socket-connected equipment, single fusing ONLY provides protection for both faults when polarity reversal is not possible. If polarity reversal is possible, then a single fuse can only provide protection against phase-to-ground faults 50% of the time.

For single-phase, single-voltage plug-and-socket-connected equipment, double fusing ALWAYS provides protection for both kinds of faults regardless whether polarity reversal is possible or not.

However, there are two hitches to double fusing.

First, when operating on a polarized system, some safety authorities insist that fusing be provided only in the phase conductor such that all of the equipment is de-energized for protection of the serviceman. This seems to require one fuse only.

However, this can be accommodated by using two, different value fuses. Select the fuse for the phase conductor (when connected to a polarized system) for proper overcurrent protection. Select the fuse for the neutral conductor to be one size larger than the phase conductor fuse. Thus, when connected to a polarized system, the smaller fuse properly opens for phase-to-neutral and for phase-to-ground faults. When connected to a non-polarized system and with reverse polarization, the smaller fuse provides protection for phase-to-neutral faults, and the larger fuse provides protection for phase-to-ground faults.

Second, some safety authorities insist that fusing be provided only in the phase conductor as required for building wiring. Any fuse in the neutral is cause for non-compliance of the equipment. The only solution here is to change our building codes and regulations to exempt single-phase plug-and-socket-connected equipment.

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**RICHARD NUTE**

is a product safety consultant engaged in safety design, safety manufacturing, safety certification, safety standards, and forensic investigations. Mr. Nute holds a B.S. in Physical Science from California State Polytechnic University in San Luis Obispo, California. He studied in the MBA curriculum at University of Oregon. He is a former Certified Fire and Explosions Investigator.

Mr. Nute is a Life Senior Member of the IEEE, a charter member of the Product Safety Engineering Society (PSES), and a Director of the IEEE PSES Board of Directors. He was technical program chairman of the first 5 PSES annual Symposia and has been a technical presenter at every Symposium. Mr. Nute’s goal as an IEEE PSES Director is to change the product safety environment from being standards-driven to being engineering-driven; to enable the engineering community to design and manufacture a safe product without having to use a product safety standard; to establish safety engineering as a required course within the electrical engineering curricula.

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(The author)
The word ion (in Greek, ἰόν) means wanderer. It denotes an entity, a particle, that will move under the action of an electric field. So, in principle, valence electrons in metals or holes in semiconductors could be considered ions. But in practice, the name ion is reserved for two species: electrolytic ions and gaseous ions.

**ELECTROLYTIC IONS**

If you have an aqueous solution of silver nitrate, the AgNO₃ is dissociated as:

\[
\text{AgNO}_3 \rightarrow \text{Ag}^+ + \text{NO}_3^-
\]

Ag⁺ is called a silver ion and NO₃⁻ a nitrate ion.

If an electric field is now applied to the liquid, the positive silver ions will move in the direction of the field toward the negative cathode, where they each will receive an electron, become neutralized, and plate out onto the electrode. This is the basis for electroplating.

A somewhat similar process takes place at the anode—but we are not going to discuss electrochemistry in detail. Rather, I will point out just a few facts about electrolytic ions. The silver and nitrate ions, as well as other electrolytic ions, have well-defined properties. All silver ions are identical, at least chemically speaking, and they never change their properties no matter what you do to them, as long as they remain ions.

If a given ion is exposed to an electric field with the strength E, it will move with a constant velocity v given by:

\[
v = kE
\]

where k is a constant representing the mobility of the ion. Again, a silver ion always has one positive charge and always the same mobility, at least when you consider a given isotope of silver. The same constancy is true for any other electrolytic ion.

**GASEOUS IONS**

Although ions may be formed in most gases, we will restrict ourselves here to discussion of those types of ions that may be formed and found in atmospheric air, the so-called air ions or atmospheric ions.

The formation of an air ion starts with an electron being knocked off a neutral air molecule, as shown in Figure 1. The now positive molecule (oxygen or nitrogen) will rapidly attract a number of polar molecules (10–15), mostly water, and this cluster is called a positive air ion. The electron will probably attach to an oxygen molecule (nitrogen has no affinity for electrons), and this negative molecule will attract a number of water molecules (maybe 8–10), forming a cluster called a negative air ion. It is important to note that ions are always formed in pairs, and always the same number of positive and negative ions.

It takes a certain energy, about 34 eV (~5.4 x 10⁻¹⁸ J) to knock off the initial electron. This energy may be delivered by shortwave electromagnetic radiation (x-rays or gamma rays), or more often from a colliding particle.
NATURAL IONIZATION

Most of the ionization in the lower atmosphere is caused by airborne radioactive substances, primarily radon and its short-lived daughters. In most places of the world, ions are formed at a rate of 5–10 pairs per cm$^3$ per second at sea level. With increasing altitude, cosmic radiation causes the ion production rate to increase. In areas with high radon exhalation from the soil (or building materials), the rate may be much higher.

It is primarily alpha-active materials that are responsible for the ionization. Each alpha particle (for instance, from a decaying radon atom) will, over its range of some centimeters, create approximately 150,000–200,000 ion pairs.

Figure 1: How air ions are formed

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FIELD IONIZATION

Although ionization from radioactive sources (often a polonium isotope) is used for technical purposes, and for certain applications it is to be preferred for any other method, the most common artificial method of producing ions is by field ionization.

It's somewhat ironic to realize that this method presupposes an ongoing, however weak, natural ionization. If a sufficiently strong electric field is established—for instance, between an electrode at a potential of some kilovolts and a ground—the electrons being freed by natural ionization may be accelerated to such velocities that they themselves can cause ionization, again creating pairs of (positive and negative) ions. It should be stressed that it does not take a high voltage, but high field strength, to cause ionization.

The breakdown field strength, as it is called, is somewhere around 3 MV/m between plane electrodes (in air at atmospheric pressure). If you have two metal plates at a distance of 1 cm, you need a voltage difference of about 30,000 V for ionization to take place in the space between the plates. If, however, one of the plates is replaced by a sharp metal point or a thin wire, the necessary voltage may be only a few kV. The explanation is that for a given voltage difference, the field strength in front of a point is much higher than between plane electrodes. Thus although the breakdown field strength is higher in front of a point, ionization is still established at lower voltages using sharp electrodes.

Now let's imagine an electrode, say a sharp metal point, kept at a positive potential of some kV with respect to ground, which may be represented by the walls of the room, as shown in Figure 2. In a small volume, perhaps a few cubic millimeters around the tip of the electrode, ion pairs are formed. The negative ions are attracted to the electrode, where they give off their charge and cease to exist as ions. The negative charge from the ions runs through the electrode to the voltage supply, making it look as though the electrode delivers a positive current to the air. The positive ions, formed in front of the electrode, are repelled by the electrode and move away. All in all, it appears that positive ions are emitted from the positive electrode.

But this conclusion is completely wrong. The positive ions have never been in contact with the electrode. The electrode, often called an emitter, doesn't emit anything. Rather, it collects things (specifically, negative ions). Sadly, it's probably too late to change this linguistic malpractice.

WHAT DO IONS DO?

Ions don't live forever. They may recombine with oppositely charged ions or, more likely, combine with aerosol particles in the air. The charged particles, sometimes called large ions, will also move in an electric field, although much more slowly than the air ions do.

This is the principle for the first technical electrostatic invention, the electro filter, without which we would have no means of effectively cleaning the smoke from coal- or oil-fired power plants and many other industrial installations.

Ions may also plate out onto surfaces, either by diffusion or aided by an electric field. And this is the basis for another important technical use of ionization.

Let's assume we have a charged insulator and we want to remove the charge.

Well, let's face it. It can't be done. There's no way by which a charge can be removed from an insulator. But don't panic. The charge in itself doesn't do...
any harm. It’s the field from the charge we have to worry about. And the field may be used to neutralize itself.

If the charged insulator is exposed to an atmosphere containing ions of polarity opposite that of the charge, the field will attract ions, which will move toward the body and neutralize the charge. At least that’s what appears to happen.

But a more strict formulation would be that the original (excess) charge is still there, and so is its field. The oppositely charged ions, attracted from the air, will deposit around the original charge, but not annihilate it. The resulting field, the sum of the fields from the opposite charges, will be zero, or at least very close to zero.

The use of air ionization for abating static electric effects is a slow method, compared to methods like the grounding of conductors or surface treatment with topical antistats. But it should be stressed that when we are talking about charged insulators, exposure to ionized air is the only method to remove the effects of the charge.

IONS AND PEOPLE

Soon after the discovery of atmospheric ions about a century ago, it was suggested that the ions might have an effect on people breathing the air containing the ions. Among the effects suggested was that air with an excess of negative ions would feel fresh, while an excess of positive ions would make the air stuffy.

This popular but still undemonstrated belief will be the subject of a subsequent column on static electricity and people.

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NIELS JONASSEN, MSC, DSC, worked for 40 years at the Technical University of Denmark, where he conducted classes in electromagnetism, static and atmospheric electricity, airborne radioactivity, and indoor climate. After retiring, he divided his time among the laboratory, his home, and Thailand, writing on static electricity topics and pursuing cooking classes. Mr. Jonassen passed away in 2006.
Regardless of the title, it turns out that the topic of EMC standards is not typically part of a university-based EMC curriculum. This is interesting, since EMC standards are important (and many times are a requirement) to demonstrate that a product not only has met its “functional” characteristics, but that the product complies to various types of EMC standards. These standards may range from those designed to ensure customer satisfaction to those that are legal requirements imposed by national governments. Unfortunately, many times the concept of requiring products to meet or comply with various engineering standards is seen as an unneeded and an undesired sequence of steps in “checking the box” in a product’s design, development, and production. Ironically, it’s actually the opposite situation.

Our modern society has developed many inventions and innovations to make our lives simpler and more efficient. A key to the success of these inventions and innovations is the ability to use standards to ensure the reliable and safe operation of these devices. It also turns out that the standards themselves can also spur innovation and development across a wide range of systems and ensure new technology meets user (or customer) requirements. Over the next several paragraphs I will highlight some of the resources that are available to help EMC educators become familiar with the concept of EMC standards, and I will provide information on where to go for additional resources to help include standards education in an EMC curriculum.

One of the best places to start is the IEEE Standards association website. This is the organization that has responsibility for all types of standards that the IEEE is concerned with. Much of the modern world of electrical and electronic systems is built upon IEEE standards, such as data bus definition (IEEE 488), and, of course, one of the most common “consumer” used...
standards, IEEE 802, standards for wireless communications.

Figure 1 shows a good starting point into EMC standards education. These standards cover a number of topics, from antennas to RF exposure, along with information about electromagnetic propagation which is important to know in order to understand and successfully apply the standards.

Realizing that education in standards development and their use is important, there is another IEEE resource called the “EAB/SA Standards Education Committee”. This website is shown in Figure 2.

As IEEE states:

“Recognizing the important role standards play within the engineering, technology and computing fields, IEEE is providing resources to help introduce and teach undergraduate and graduate students, as well as professors and educators, about technical standards by providing free online tutorials and case studies. Knowledge of standards can help facilitate the transition from classroom to professional practice by aligning educational concepts with real-world applications.

These resources will hopefully be of use in the classroom and help incorporate the teaching of standards into curricula to:

- benefit both students and their faculty mentors as they face challenging design processes;
- help electrical and computer engineering undergraduate programs incorporate standards into their learning processes;
- provide tools for use in learning about standards and their impact on design and development.”
Those important points (and additional details) can be seen on the website shown in Figure 3.

A good introduction and overview of EMC specific standards that can be referenced in EMC education is at the website shown in Figure 4.

So in closing, as you can see, this has been only an overview of EMC standards, and you are encouraged to dig deeper into this topic. I am sure once you do so you will see the benefits of incorporating this topic into your EMC educational curriculum!

Figure 3: Information about standards education

Figure 4: Introduction and overview of EMC standards
http://standards.ieee.org/findstds/standard/electromagnetic_compatibility.html

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

“A rose by any other name would stink.” – Kenneth Adamson

BY KEN JAVOR

We have all seen advertising copy for test equipment manufacturers’ “EMC receivers” and “EMC test services” provided by commercial EMI test facilities. While we know what the aforementioned receiver does, and what sort of services the test facility supplies, the nomenclature is wrong and is symptomatic of a deeper problem.

In this issue dedicated to defense and aerospace, we examine defense and aerospace EMC practices, and compare/contrast these processes with those of other market sectors. EMI vs. EMC nomenclature is a good introduction.

Per ANSI C63.14 we control electromagnetic interference in order to achieve the desired state of electromagnetic compatibility:

EMI: “Any electromagnetic disturbance … that … degrades … performance of electronic or electrical equipment.”

EMC: “The capability of electrical and electronic systems, equipments, and devices to operate in their intended electromagnetic environment … without … unacceptable degradation as a result of electromagnetic interference.”

Requirements controlling EMI characteristics such as CISPR 22, CISPR 25, RTCA/DO-160 and MIL-STD-461 are means to an end. That end is electromagnetic compatibility between devices qualified to these standards and between them and radios. Conjointly, EMI requirements are not an end in themselves. Any device with an FCC Part 15 sticker has a disclaimer to the effect that, “This device may not cause harmful interference…” This is the desired end result - EMC. If the device does cause interference (despite having met its EMI requirements), the user is advised to separate culprit and victim, and as a last resort, shut the culprit off: the licensed user of the spectrum has priority over the unlicensed polluter.

The bottom line is that standards controlling EMI are one of the tools by which we achieve EMC and EMC is demonstrated, if at all, on the integrated system, which is typically a vehicle that drives, sails (above or below the sea) or flies (within or above the atmosphere). Equipment designed for use in homes, offices, and factories don’t have a specific installation, and there is no EMC check for such equipment. EMI requirements to which they are subjected are the sole qualification relative to EMC. Hence, it is not surprising that this market segment most often fails to properly distinguish between EMI and EMC.
Integrated vehicles are functionally evaluated – EMC tested – ensuring that each subsystem operates properly as part of the greater whole, acting as neither a source of nor a victim to EMI within the vehicle. Separately, the entire vehicle is subjected to external stresses such as steady-state and transient electromagnetic fields, and the subsystems must operate properly. “Proper operation” might include graceful degradation, such as anti-lock brakes becoming purely hydraulic brakes with no electronic control.

Most importantly for this discussion, vehicle antennas will be interrogated by an EMI receiver looking for signals coupled to that antenna in-band to the receiver. On an automobile, that would mean 530 - 1710 kHz and 87.5 - 108 MHz at the point where the coaxial transmission line disconnects from the AM/FM receiver, and perhaps the “shark fin” antenna used for satellite reception. On a military aircraft, in contrast, there could be such measurements from 0.15-1.99 MHz (ADF), 2-30 MHz (hf), 30-88 MHz (vhf-FM), 108-152 MHz (vhf-AM, with both air navigation aids and communications residing in this band), 225-400 MHz (uhf-AM), 960-1215 MHz (TACAN), and perhaps others as well.

Such testing is the ultimate high fidelity EMC check, because the test set-up is the installation. All EMI standard test set-ups are approximations of expected installations, whether vehicle, home, office, or plant, and at best provide an upper bound of what would be expected to be measured in situ.

Along these lines, I like to quote a forerunner standard to MIL-STD-464, which is the present day military standard for electromagnetic effects that apply to a vehicle procurement. The 1967 vintage MIL-E-6051D, “EMC Requirements, Systems,” paragraph 3.2.4.1, “Subsystems and Equipment,” opens as follows: “Unless otherwise specified in the contract, subsystems/equipments shall be designed to meet the requirements of MIL-STD-461 and MIL-STD-462. Since some of the limits in these standards are very severe, the impact of these limits on system effectiveness, cost, and weight shall be considered…”

The importance of this paragraph cannot be overstated. The essence of system engineering – any engineering – is tradeoffs. In vehicle engineering, we can review EMI test data, and decide if out-of-tolerance signatures allow an acceptable level of EMC. Often we do that by test – for instance, by installing equipment with excessive radiated emissions (RE) in the vehicle and monitoring the antenna band wherein the offending signals reside to see if they do in fact couple into the receiver, or if the installation provides enough isolation via shielding, shading and distance between equipment and victim antenna to eliminate the potential for interference.

Vehicle EMC engineers can do all this because EMF qualification testing occurs after a contract has been signed between equipment vendor and integrator. Integrator and vendor can collaboratively find an optimal solution for “system effectiveness, cost, and weight” and schedule. The process can be bumpy, but it does work, especially within the military-industrial complex.

In the consumer marketplace, where FCC or European Norm or other national laws require passing EMI requirements before placing products on the market, there is no flexibility: the limit is the law. Therefore an extreme amount of attention is placed on measurement repeatability/uncertainty. A level playing field – irrespective of where a device is tested, or by whom – is an economic sine qua non.
It is commonplace to contrast military versus commercial EMI test practices, but that is not a fundamental distinction.

**non** (without which, nothing). Tight uncertainty requirements supporting repeatability requirements such as the +/- 4 dB normalized site attenuation for RE testing and the -0, +6 dB tolerance for the electric field immunity test uniform field area require more expensive test sites and more complex procedures than those required for equipments slated for vehicle usage. Two factors differentiating facility costs are the degree to which reflections are controlled, and separations between antenna and test sample, which drive chamber size.

It is commonplace to contrast military vs. commercial EMI test practices, but that is not a fundamental distinction. Commercial aerospace and automotive EMI test practices have much more in common with military practice than they do with qualification of consumer items on open area test sites (OATS) or in fully or semi-anechoic chambers (FAC/SAC). The fundamental difference is installation in a vehicle (usually metal) vs. equipment slated for use in homes, offices and industrial plants. EMI testing of equipment installed in vehicles requires acknowledgment of the immediate proximity of electrical ground (vehicle structure) and the possibility that vehicle antennas will be placed nearby culprit electrical noise generators. Neither of these are the case for non-vehicle equipment. Or more precisely, it is quite possible in the home, office or factory that someone may try to listen to or watch a broadcast program or receive a wireless phone call and find that some device in the receiver’s vicinity is causing interference. But it is under their control to increase culprit and victim separation, when the
Electric field structure is qualitatively, not just quantitatively different at one meter than at three and beyond. In close, we measure not only radiating signals, which are also picked up farther out, but in addition, inductive or quasi-static fields which do not propagate into the far field.

problem usually goes away. Separations up to three meters are deemed under the control of the Class B equipment end user, and separations up to ten meters are assumed under the control of the Class A end user.

Three or more meter separations coupled with RE control starting at 30 MHz and radiated immunity starting at 80 MHz happily allow for EMI measurements under far field, or nearly far field conditions.

Automobiles, aircraft and even large ships cannot guarantee such separations, and must impose one-meter RE measurements. Not all antenna-culprit separations will be precisely one meter, and while one-meter measurements are not scalable as are far field measurements, the vehicle EMC process does not stop at the one-meter measurement.

An example of the full vehicle EMC process offers insight into the fundamental differences between vehicle and non-vehicle EMI qualification. Medical devices designed for hospital use are needed in air ambulances. Part of ambulance qualification is EMI/EMC. The equipment in question already meets all medical device certifications, as it is commercially available and used in hospitals. But when re-qualified to aircraft EMI requirements, involving antenna-test sample separations of not three meters or more, but instead one meter, these devices often fail. Because the intent is to use existing off-the-shelf equipment, design modifications are undesirable and to be avoided, if at all possible.

When RE failures against the equipment limit are found, it is standard operating procedure to place the device in the aircraft and monitor aircraft antennas covering the failing frequencies with a spectrum analyzer, looking for evidence of excessive coupling. This is nothing new; the technique has been included in MIL-STD-464 since its inception in 1997. It is only the application to equipment neither designed for vehicle use, nor permanently installed in a fixed location within a vehicle that is different.

If the rfi signal measured at the aircraft antenna is deemed low enough to not be a problem, then the equipment-level EMI test failure does not force redesign. If the level measured at the vehicle antenna is too high, redesign is indicated despite the previous far field qualification for hospital use. One-meter re-qualification is necessary despite the previous qualification involving far field testing (three or ten meter), despite persistent voices calling for a single unified far-field test approach for EMI testing, which comes from the OATS/FAC/SAC faction.

Were we to accept the oft-repeated superiority of OATS/SAC/FAC measurements and replace vehicle type one-meter measurements we would at our peril violate basic physical laws. While far field measurements are attractive for deriving analytical relationships between various circuit parameters and the resultant electromagnetic field, these predictions are not useful to vehicle integrators working in the near field.

Electric field structure is qualitatively, not just quantitatively different at one meter than at three and beyond. In close, we measure not only radiating signals, which are also picked up farther out, but in addition, inductive or quasi-static fields which do not propagate into the far field. On vehicles where the separation between culprit emitter and victim antenna is much closer than three meters, three meter and farther out measurements do not protect against interference.

The traditional automotive whip antenna used in the AM & FM broadcast bands is a good example. In the far field of a wire radiator, the electric field will be parallel to the wire, assuming the wire is long enough to develop a potential drop across its length. For other than a large ship or very large aircraft, this can’t happen in the AM band, only at FM. But in close, whether AM or FM, there is a non-radiating electric field component that starts on the wire and ends on the ground plane beneath it, due to the potential on the wire relative to ground. It cannot propagate, because the magnetic field associated with that wire circulates around it, and is co-directional with it. Electromagnetic energy only propagates when electric and magnetic field vectors are at mutually non-zero angles (Poynting’s theorem).

If that whip antenna can be one meter from a noisy cable, then the EMI test has to also place the antenna at one-meter separation.

Then there is the issue of separation between test sample and ground plane. In the typical vehicle installation, equipment bonds directly or indirectly to vehicle structure. The EMI test simulates this with a tabletop ground plane mounted 80-90 cm above floor height. On an OATS or in a SAC/FAC, the test sample is 80 cm above the floor ground plane, with at most a green wire
connection to it. Including a tabletop ground plane on an OATS or in a SAC/FAC destroys the anechoic properties of the facility, and those who advocate for OATS/SAC/FAC use also advocate for removal of the tabletop ground plane.

But the tabletop ground plane five centimeters below test sample attached cabling is worth up to 20 dB in reduced cable radiation efficiency for emission work, and something similar in terms of the effective aperture of test sample-connected cables during immunity/susceptibility testing. Especially for automotive use, where unshielded cables are the norm, meeting very stringent radiated limits one meter away in the absence of that ground plane is at best impractical.

It is presuming to insist on OATS and SAC/FAC type measurements in lieu of one-meter measurements for vehicle equipments. The comparison is apples and oranges. Considering not only (vehicle) equipment EMI testing, but also on-vehicle EMC assessment, including the super-hi fidelity check of RE coupling to vehicle antennas, it is clear that the overall vehicle EMI/EMC program efficiently does exactly what is needed.

Finally, there is the issue of protection of off-vehicle receivers. Automobile-level RE limits are imposed at ten meters to protect radios operating near roadways. Army ground vehicle-level RE limits impose control at one meter, to protect radios in a tactical operations center adjacent to which the vehicle might be parked. Some military aircraft impose RE control at one nautical mile to protect against aircraft detection by hostiles.

The simple conclusion is we test things the way we use them. It is always better to separate noisemakers and sensitive receivers, and when we can separate them we do, but when we can’t, then we have to assess the potential for EMI at the separations we expect in actual use.

To demand that vehicle equipment-level EMI testing adopt SAC/FAC/OATS type methods is akin to the old joke about looking for lost car keys not where they were dropped in a dark alley, but a block away under a street lamp, because it is easier to see there.

The simple conclusion is we test things the way we use them. It is always better to separate noisemakers and sensitive receivers, and when we can separate them we do, but when we can’t, then we have to assess the potential for EMI at the separations we expect in actual use.

Hybrid & Microwave Polystyrene Absorbers

(ther author)

KEN JAVOR

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

BY MILITARY EMC STAFF, INTERTEK

The reliable operation of complex electronic communications, control and armament systems in extreme environments demands stringent design criteria and careful validation. Severe shock, vibration, heat, humidity and airborne contaminants are common in land, sea and air platforms.

Coupled with dense packaging, high-power radio and radar illumination, Hazards of Electromagnetic Radiation to Ordnance (HERO), and a possible electromagnetic pulse (EMP), the military equipment environmental requirements can be extreme indeed.

In order to expedite equipment availability and reduce cost, the acquisition of commercial-off-the-shelf (COTS) equipment for US military applications is an attractive consideration. But many types of commercial equipment are unlikely to meet all military environmental requirements as manufactured, so some modification or re-design is usually needed. Defining the gap between the commercial equipment’s environmental performance and its military expectations is a first step in determining its potential suitability.

The full cycle of US military product development from environmental assessment, to definition of requirements, to test reports, is carefully spelled out in the relevant military standards or ancillary documents for the applicable physical and electromagnetic environments. These provide the design guidance, along with competent engineering practices, for a cost-effective and robust military product design.

THE ELECTROMAGNETIC ENVIRONMENT

Electromagnetic compatibility (EMC) requires the component, equipment or system to perform its designed functions without causing or suffering unacceptable degradation due to electromagnetic interference to or from other equipment. The starting point for EMC is self-compatibility, where the final product or system does not interfere with its own operation. This is a basic requirement in military EMC standards; for example, in MIL-STD-461F clause 4.2.3:

The operational performance of an equipment or subsystem shall not be degraded, nor shall it malfunction, when all of the units or devices in the equipment or subsystem are operating together at their designed levels of efficiency or their design capability.

As we shall see, this is the modest starting point for military EMC, which extends to both lower and higher frequencies than most commercial EMC standards and to both lower emission limits and much higher susceptibility requirements. Test methods generally differ from their commercial counterparts in both setup and detail.

History of Military EMC

EMC problems in commercial applications were first noted worldwide in the 1930s, when early broadcast radios were being installed in automobiles. Reception was degraded by ignition noise and electrostatic buildup caused by non-conductive rubber tires.
The first US military specification on EMC also addressed this problem. It was published by the US Army Signal Corps in 1934 as SCL-49, “Electrical Shielding and Radio Power Supply in Vehicles”. It required shielding of the vehicle ignition system, regulator and generator. With the increased use of mobile military radio communications, SCL-49 became inadequate. In 1942 it was superseded by specification 71-1303, “Vehicular Radio Noise Suppression.”

In the period 1950 - 1965, each major military agency imposed its own EMC specifications. The Air Force used MIL-I-6181 and MIL-I-26600; the Navy used MIL-I-16910; the Army used MIL-I-11748 and MIL-E-55301(EL). These specifications limited the levels of conducted and radiated emissions, and they set susceptibility levels which systems and equipment must reject. These specifications also detailed the test configurations and methods for demonstrating compliance.

Unfortunately, over this period of time the various military EMC standards diverged from each other in test frequency ranges, limits and required test equipment. The differences made it quite expensive for a test lab or manufacturer to be fully equipped to test to all EMC specifications.

In 1960 the US Department of Defense enacted a comprehensive electromagnetic compatibility program that charged the military services to build EMC into all of their communications and electronics equipment. In 1966, EMC personnel of the three military departments jointly drafted standards addressing the overall EMC needs of the Department of Defense. That program resulted in 1967 in military standards 461 (requirements), 462 (methods) and 463 (definitions and acronyms). After revision, MIL-STD-461A was issued in August 1968. Subsequent revisions were designated B, C, and D. MIL-STD-463 was withdrawn after 1990.

In 1999 the 461D and 462D standards were merged into one document, MIL-STD-461E. The current version is MIL-STD-461F (2007), and updates to it are in the planning stage. Prior revision levels A-E may still be specified for testing.

**USA: Supporting Documentation**

The designer of military electronic equipment has an abundance of guidance available for successfully meeting the EMC demands of the intended operating environments.

**Standards**

Active military standards (Table 1) specify a variety of scopes, environmental sub-categories, limits and test methods clearly and in great detail.

The most commonly-used MIL standards are 461 (subsystems and equipment) and 464 (systems), and they apply to ground-based, shipboard and airborne applications. Other

<table>
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<td>MIL-STD-188-124</td>
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<tr>
<td>MIL-STD-1576</td>
<td>Electroexplosive Subsystem Safety Requirements and Test Methods for Space Systems</td>
</tr>
<tr>
<td>MIL-STD-1605A</td>
<td>Procedures for Conducting a Shipboard Electromagnetic Interference (EMI) Survey (Surface Ship)</td>
</tr>
</tbody>
</table>

**Table 1: Active US military EMC standards for equipment, systems and facilities**
government documents may apply to a specific platform or application, and some of these are listed in the standards such as MIL-STD-461 and -464.

**Handbooks**

In addition to the EMC standards listed in Table 1, there are a number of handbooks available that provide procedural, EMC assessment and design guidance for specific military applications. These provide guidance only, and are not to be construed as requirements. A list of relevant handbooks is given in Table 2.

Generally these handbooks are tutorial in nature, clearly written, and with explanations of the underlying physical principles. They provide invaluable assistance to the equipment or systems designer.

**Data Item Descriptions**

Finally, there are very detailed documentation specifications associated with military EMC standards. In some cases the required documentation is described in separate Data Item Descriptions (DIDs) or Test Operational Procedures (TOPs). These Data Item Descriptions cover EMC design procedures, test and verification procedures, and test reports. Table 3 contains a list of Data Item Descriptions and TOPs and the military standards with which they are associated.

For example, the Data Item Description DI-EMCS-80199C associated with standard MIL-STD-461F is very explicit in the level of detail to be provided regarding equipment design procedures:

3.2. **Design techniques and procedures.** The EMICP [Electromagnetic Interference Control Procedures] shall describe the specific design techniques and procedures used to meet each emission and susceptibility requirement, including the following:

a. Spectrum management techniques.

b. EMI mechanical design, including the following:

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
<th>Associated with</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIL-HDBK-235B</td>
<td>Electromagnetic (Radiated) Environment Considerations for Design and Procurement of Electrical and Electronic Equipment, Subsystems and systems</td>
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<tr>
<td>MIL-HDBK-237D</td>
<td>Electromagnetic Environmental Effects and Spectrum Supportability Guidance for the Acquisition Process</td>
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<tr>
<td>MIL-HDBK-240</td>
<td>Hazards of Electromagnetic Radiation to Ordnance (HERO) Test Guide</td>
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<tr>
<td>MIL-HDBK-274</td>
<td>Electrical Grounding for Aircraft safety</td>
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<tr>
<td>MIL-HDBK-419A</td>
<td>Grounding, Bonding and Shielding for Electronic Equipments and Facilities, Volume 1 of 2 Basic Theory</td>
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</tr>
<tr>
<td>MIL-HDBK-454B</td>
<td>General Guidelines for Electronic Equipment</td>
<td></td>
</tr>
<tr>
<td>MIL-HDBK-83578</td>
<td>Criteria for Explosive Systems and Devices used on Space Vehicles</td>
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</table>

Table 2: Active US military handbooks relating to EMC

<table>
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<tr>
<td>DI-EMCS-80199C</td>
<td>Electromagnetic Interference Control Procedures (EMICP)</td>
<td>MIL-STD-461F</td>
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<tr>
<td>DI-EMCS-80200C</td>
<td>Electromagnetic Interference Test Report (EMITR)</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
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<td>Electromagnetic Interference Test Procedures (EMITP)</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>DI-EMCS-81295A</td>
<td>Electromagnetic Effects Verification Procedures (EMEVP)</td>
<td>Engineering/manufacturing development phase - any</td>
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<tr>
<td>DI-EMCS-81528</td>
<td>Electromagnetic Compatibility Program Procedures</td>
<td>Demo of life cycle EMC compliance - any</td>
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<tr>
<td>DI-EMCS-81540A</td>
<td>Electromagnetic Environmental Effects (E3) Integration and Analysis Report (E31AR)</td>
<td>MIL-STD-464A</td>
</tr>
<tr>
<td>DI-EMCS-81541A</td>
<td>Electromagnetic Environmental Effects (E3) Verification Procedures (E3VP)</td>
<td>MIL-STD-464A</td>
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<tr>
<td>DI-EMCS-81542A</td>
<td>Electromagnetic Environmental Effects (E3) Verification Report (E3VR)</td>
<td>MIL-STD-464A</td>
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<tr>
<td>DI-EMCS-81777</td>
<td>Electromagnetic Interference Survey (EMIS) Test Report</td>
<td>MIL-STD-1605A</td>
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<td>DI-EMCS-81782</td>
<td>Electromagnetic Interference Survey (EMIS) Test Procedures</td>
<td>MIL-STD-1605A</td>
</tr>
<tr>
<td>TOP-1-2-511</td>
<td>Electromagnetic Environmental Effects System Testing</td>
<td>MIL-STD-464A</td>
</tr>
</tbody>
</table>

Table 3: EMC Data Item Descriptions and Test Operational Procedures
(1) Type of metals, casting, finishes, and hardware employed in the design.

(2) Construction techniques, such as isolated compartments; filter mounting, isolation of other parts; treatment of openings (ventilation ports, access hatches, windows, metal faces and control shafts), and attenuation characteristics of Radio Frequency (RF) gaskets used on mating surfaces.

(3) Shielding provisions and techniques used for determining shielding effectiveness.

(4) Corrosion control procedures.

(5) Methods of bonding mating surfaces, such as surface preparation and gaskets.

c. Electrical wiring design, including cable types or characteristics, cable routing, cable separation, grounding philosophy, and cable shielding types and termination methods.

d. Electrical and electronic circuit design, including the following:

(1) Filtering techniques, technical reasons for selecting types of filters, and associated filter characteristics, including attenuation and line-to-ground capacitance values of AC and DC power line filters.

(2) Part location and separation for reducing EMI.

(3) Location, shielding, and isolation of critical circuits.

<table>
<thead>
<tr>
<th>MIL-STD-461A</th>
<th>MIL-STD-461B/C</th>
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</thead>
<tbody>
<tr>
<td><strong>Test</strong></td>
<td><strong>Description</strong></td>
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<td>CE01</td>
<td>Power Leads</td>
</tr>
<tr>
<td>CE02</td>
<td>Control / Signal Leads</td>
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<tr>
<td>CE03</td>
<td>Power Leads</td>
</tr>
<tr>
<td>CE04</td>
<td>Control / Signal Leads</td>
</tr>
<tr>
<td>CE05</td>
<td>Inverse Filter Method</td>
</tr>
<tr>
<td>CE06</td>
<td>Antenna Terminal</td>
</tr>
<tr>
<td>CE07</td>
<td>N/A</td>
</tr>
<tr>
<td>CS01</td>
<td>Power Leads</td>
</tr>
<tr>
<td>CS02</td>
<td>Power Leads</td>
</tr>
<tr>
<td>CS03</td>
<td>Intermodulation</td>
</tr>
<tr>
<td>CS04</td>
<td>Undesired Signal Rejection</td>
</tr>
<tr>
<td>CS05</td>
<td>Cross Modulation</td>
</tr>
<tr>
<td>CS06</td>
<td>Spikes, Power Leads</td>
</tr>
<tr>
<td>CS07</td>
<td>Squelch Circuits</td>
</tr>
<tr>
<td>CS08</td>
<td>Undesired Sig. Rejection</td>
</tr>
<tr>
<td>CS09</td>
<td>N/A</td>
</tr>
<tr>
<td>CS10</td>
<td>N/A</td>
</tr>
<tr>
<td>RE01</td>
<td>Magnetic Field</td>
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<tr>
<td>RE02</td>
<td>Electric Field</td>
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<tr>
<td>RE03</td>
<td>Spurious &amp; Harmonic</td>
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<td>RE04</td>
<td>Magnetic Field</td>
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<td>Vehicle &amp; Eng. Equipment</td>
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<td>RE06</td>
<td>Overhead Powerlines</td>
</tr>
<tr>
<td>RS01</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>RS02</td>
<td>Magnetic Induction</td>
</tr>
<tr>
<td>RS03</td>
<td>Electric Field</td>
</tr>
<tr>
<td>RS04</td>
<td>Parallel Line Fields</td>
</tr>
<tr>
<td>RS05</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4: MIL-STD-461 requirement changes, versions A – E
This DID also requires, among other items, analysis (results demonstrating how each applicable requirement is going to be met) and developmental testing (testing to be performed during development such as evaluations of breadboards, prototypes, and engineering models). For the equipment designer, these points to be documented constitute a virtual punch list of EMC design attributes.

**MIL-STD-461F – EMC for Subsystems and Equipment**

This is no doubt the most widely-used standard for US military EMC assessment. Specific test requirements are grouped according to conducted (C) or radiated (R) coupling, and emissions (E) or susceptibility (S). Thus the tests are designated:

- Conducted emissions: **CE**---
- Radiated emissions: **RE**---
- Conducted susceptibility: **CS**---
- Radiated susceptibility: **RS**---

The dashes are replaced by the test reference number. Over time, the numerical test designations have transitioned from 01 to 101, 02 to 102, etc., but the prefixes have remained constant. Table 4 indicates the changes in MIL-STD-461 test requirements from versions A through E, and Table 5 (page 40) reflects the present version F requirements.

### Table 4: MIL-STD-461 requirement changes, versions A – E

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Frequency</th>
<th>Test</th>
<th>Description</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE01</td>
<td>Magnetic Field</td>
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<td>RE01</td>
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<td>30 Hz-100 kHz</td>
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<td>RE02</td>
<td>Electric Field</td>
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<td>RE02</td>
<td>Electric Field</td>
<td>10 kHz-18 GHz</td>
</tr>
<tr>
<td>RE03</td>
<td>Antenna Spurious &amp; Harmonics</td>
<td>10 kHz-40 GHz</td>
<td>RE03</td>
<td>Antenna Spurious &amp; Harmonics</td>
<td>10 kHz-40 GHz</td>
</tr>
<tr>
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<td>Magnetic Field, Equipment and Cables</td>
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<td>Magnetic Field, Equipment and Cables</td>
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</tr>
<tr>
<td>RS03</td>
<td>Electric Field, Equipment and Cables</td>
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<td>RS03</td>
<td>Electric Field, Equipment and Cables</td>
<td>2 MHz-40 GHz</td>
</tr>
<tr>
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<td>Bulk Cable Injection</td>
<td>10 kHz-200 MHz</td>
<td>RS15</td>
<td>Bulk Cable Injection</td>
<td>10 kHz-200 MHz</td>
</tr>
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<td>Power Leads</td>
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<td>CS03</td>
<td>Antenna Port-Intermod</td>
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<td>CS04</td>
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<td>Cross Modulation</td>
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</tr>
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<td></td>
<td>CS10</td>
<td>CS106</td>
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<td>Electric Field, Equipment and Cables</td>
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<td>CS105</td>
<td></td>
<td>CE10</td>
<td>CS105</td>
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</tr>
</tbody>
</table>

This table lists the test designations and associated frequencies for MIL-STD-461D and MIL-STD-461E.
ESD and lightning effects are not included in MIL-STD-461F, although they are being discussed for inclusion in the next (G) version which is currently in draft to be released in 2014. ESD and lightning protection are covered in MIL-STD-464A, and in the current US standard for commercial aircraft equipment DO-160G, “Environmental Conditions and Test Procedures for Airborne Equipment.” DO-160G contains a number of non-EMC environmental requirements, and equipment qualified to revisions C – F of RTCA DO-160 is often suitable for military aircraft applications. A summary of DO-160G test categories is given in Table 6.

The military electronic equipment designer needs to know the types of EMC tests that will be applied to the equipment, the magnitudes or limits of the tests, and the frequency ranges of the tests, in order to design for compliance. The designer also needs to know that, where the equipment will be used in more than one environment, the most stringent requirements apply. Generally of secondary importance to the designer are the test configuration details, which are amply documented in MIL-STD-461F. These test details are of course essential to the testing personnel.

What is important to the equipment designer, for the purpose of understanding the limits, are the radiated emissions test distances – which differ from the normal commercial separations of 3m or 10m. MIL-STD-461F is almost unique among EMC standards in requiring a 1m distance between the electric field antenna and the test setup boundary (RE102). Only DO-160G and CISPR 25 (Automotive) has a similar radiated

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Lowest Emission or Highest Susceptibility</th>
<th>Changes from 461E version</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE101</td>
<td>Conducted Emissions, Power Leads, 30 Hz to 10 kHz</td>
<td>76 dBµA</td>
<td></td>
</tr>
<tr>
<td>CE102</td>
<td>Conducted Emissions, Power Leads, 10 kHz to 10 MHz</td>
<td>60 dBµV</td>
<td></td>
</tr>
<tr>
<td>CE105</td>
<td>Conducted Emissions, Antenna Terminal, 10 kHz to 40 GHz</td>
<td>34 dBµV</td>
<td></td>
</tr>
<tr>
<td>CS101</td>
<td>Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz</td>
<td>136 dBµV</td>
<td>Applicability added for surface ships; setup modifications suggested.</td>
</tr>
<tr>
<td>CS103</td>
<td>Conducted Susceptibility, Antenna Port, Intermodulation, 15 kHz to 10 GHz</td>
<td>Per procurement specification</td>
<td></td>
</tr>
<tr>
<td>CS104</td>
<td>Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals, 30 Hz to 20 GHz</td>
<td>Per procurement specification</td>
<td></td>
</tr>
<tr>
<td>CS105</td>
<td>Conducted Susceptibility, Antenna Port, Cross-Modulation, 30 Hz to 20 GHz</td>
<td>Per procurement specification</td>
<td></td>
</tr>
<tr>
<td>CS106</td>
<td>Conducted Susceptibility, Transients, Power Leads</td>
<td>400 V peak</td>
<td>CS06 absent from E, added back.</td>
</tr>
<tr>
<td>CS109</td>
<td>Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz</td>
<td>120 dBµA</td>
<td></td>
</tr>
<tr>
<td>CS114</td>
<td>Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz</td>
<td>109 dBµA</td>
<td>Adds common mode test for some applications.</td>
</tr>
<tr>
<td>CS115</td>
<td>Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation</td>
<td>5A x 30 ns</td>
<td></td>
</tr>
<tr>
<td>CS116</td>
<td>Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz</td>
<td>10 A peak</td>
<td></td>
</tr>
<tr>
<td>RE101</td>
<td>Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz</td>
<td>76 dBpT @ 7 cm</td>
<td></td>
</tr>
<tr>
<td>RE102</td>
<td>Radiated Emissions, Electric Field, 10 kHz to 18 GHz</td>
<td>24 dBµV/m @ 1m</td>
<td>Applicability and frequency ranges modified. Rod antenna methods modified.</td>
</tr>
<tr>
<td>RE103</td>
<td>Radiated Emissions, Antenna Spurious and Harmonic Outputs, 10 kHz to 40 GHz</td>
<td>-80 dBc, far field</td>
<td>Minor test procedure changes.</td>
</tr>
<tr>
<td>RS101</td>
<td>Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz</td>
<td>180 dBpT</td>
<td>Scan rate is reduced.</td>
</tr>
<tr>
<td>RS103</td>
<td>Radiated Susceptibility, Electric Field, 2 MHz to 40 GHz</td>
<td>200 V/m</td>
<td>Sensor placement clarified; radiating antenna distance limited to ≥ 1m.</td>
</tr>
<tr>
<td>RS105</td>
<td>Radiated Susceptibility, Transient Electromagnetic Field</td>
<td>50 kV/m peak</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: MIL-STD-461F requirement changes from versions E to F (2007).
emissions test distance. The magnetic field measurement
distance in RE101 is 7 cm.

Radiated Susceptibility (RS 103) also has a 1 m separation
distance and typically requires a field strength of 200V/m in
contrast to the 3V/m and 10V/m commonly encountered
with commercial product standards such as EN61000-4-3.
This higher field strength requirement can often be a hurdle
for many designers involved with COTS or used to working
on products intended for the commercial market.

In addition to the changes noted in Table 5, MIL-STD-461F
addresses several topics of general applicability:

- The requirement to qualify “Line-Replaceable Modules
  (LRMs)” is added;
- Restricts the testing of shielded power cables;
- Includes software in the requirement
to verify test procedures;
- Frequency step size above 1 GHz
  has been increased for susceptibility
testing.

Simultaneously with the publication
of the F version of MIL-STD-461
(December 2007), the F version of
RTCA DO-160 was published. DO-
160F also included, for the first time,
the CS106 test that was originally in
MIL-STD-461 but later deleted only to
be restored in the latest version. Since
that time DO-160G has been released
(December 2010), bringing more
clarifications and updates.

RTCA DO-160F and G include the
ESD and lightning requirements
currently absent from MIL-STD-461F,
and it includes the environmental
requirements which are found in
separate MIL documents discussed
below. The European Union version of
DO-160G is EUROCAE/ED-14G, which
is identically worded.

**MIL-STD-464A – EMC
Requirements for Systems**

This standard establishes
electromagnetic environmental effects
(E3), interface requirements and
verification criteria for airborne, sea,
space, and ground systems, including
associated ordnance. MIL-STD-464A
contains two sections, the main body
and an appendix. The main body of the standard specifies a baseline set of requirements. The appendix portion provides a detailed rationale and guidance, so that the baseline requirements can be tailored for a particular application.

Verification is intended to cover all life cycle aspects of the system. This includes (as applicable) normal in-service operation, checkout, storage, transportation, handling, packaging, loading, unloading, launch, and the normal operating procedures associated with each aspect.

The scope of E3 as used in this standard is very broad: all electromagnetic disciplines, including electromagnetic compatibility; electromagnetic interference; electromagnetic vulnerability; electromagnetic pulse; hazards of electromagnetic radiation to personnel, ordnance, and volatile materials; and natural phenomena effects of lightning and static.

Margin requirements apply to all EMC related tests performed in a 464A verification exercise. The intent is to account for manufacturing variations, aging and maintenance to assure that all equipment, not just test samples, will be compliant in the field over the equipment lifetime. Additional compliance margins to the limits specified in the standard are required for safety-critical, mission-critical and electrically-initiated devices (EIDs) such as electroexplosive devices and fusible links. The additional margins are:

- \( \geq 6 \) dB for safety critical and mission critical system functions;
- \( \geq 16.5 \) dB of maximum no-fire stimulus for safety assurances;

<table>
<thead>
<tr>
<th>Clause</th>
<th>Parameter</th>
<th>Lowest Emission or Highest Susceptibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>Intra-system EMC (see also MIL-STD-461F clause 4.2.3)</td>
<td>Self-compatibility</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Hull-generated intermodulation interference (IMI)</td>
<td>Not detectable by onboard receivers</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Shipboard internal electromagnetic environment (EME).</td>
<td>50 V/m</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Multipaction, space applications, equipment and subsystems</td>
<td>No effect</td>
</tr>
</tbody>
</table>
| 5.3    | External RF electromagnetic environment (EME) | 2030 V/m peak, 200 V/m average  
Flight deck, ships  
Weather deck, ships  
Main beam of transmitter, ships  
Space and launch vehicle systems  
Ground systems  
Army rotary wing aircraft  
Fixed wing aircraft, excluding shipboard |
| 5.4    | Lightning | 200kA strike, 100 kA restrike  
Severe stroke  
Near strike |
| 5.5    | Electromagnetic pulse (EMP) per MIL-STD-2169B | classified |
| 5.6    | Subsystems and equipment EMI | Per MIL-STD-461F |
| 5.6.1  | Non-developmental items (NDI) and commercial items | System operational performance requirements shall be met. |
| 5.6.2  | Shipboard DC magnetic field environment. | See MIL-STD-1399, Section 070 |
| 5.7    | Electrostatic charge control. | 300 kV discharge  
Vertical lift and in-flight refueling.  
Precipitation static (p-static) control  
Ordinance subsystems. |
| 5.8    | Electromagnetic radiation hazards (EMRADHAZ) | See DoDI 6055.11  
Hazards of electromagnetic radiation to personnel (HERP).  
Hazards of electromagnetic radiation to fuel (HERF)  
Hazards of electromagnetic radiation to ordnance (HERO). |
| 5.10.3 | Mechanical interfaces – DC bonding levels | 2.5 – 15 mΩ |
| 5.11.1 | Aircraft grounding jacks – resistance between the mating plug and the system ground reference. | \( \leq 1 \) Ω |
| 5.13   | Emissions control (EMCON) | \( < 105 \) dB/m²/m @ 1 km, 500 kHz – 40 GHz |

Table 7: Summary of MIL-STD-464A requirements. The high field strength susceptibility values occur in radar bands.
• ≥ 6dB of maximum no-fire stimulus for other purposes.

The worst-case (lowest emission limit or highest susceptibility requirement) for the environments categorized in MIL-STD-464A are summarized in Table 7. In many cases the requirements are frequency-dependent, and are much lower than worst-case over much of the frequency range. The standard should be consulted for details and definitions.

**MIL-STD-1310H – Shipboard Bonding, Grounding and Other Techniques for EMC**

This document specifies standard practices in wiring, bonding, grounding and shielding to facilitate achievement of the intra-ship and inter-ship electromagnetic compatibility (EMC), electromagnetic pulse (EMP), bonding, and intermodulation interference (IMI) requirements of MIL-STD-464A. It applies to metal and nonmetallic hull ships and is applicable during ship construction, overhaul,alteration, and repair. MIL-STD-1310H is not a typical EMC standard, but it provides the methods guidance appropriate to obtaining EMC in the shipboard environment.

This revision of MIL-STD-1310 has been expanded to include procedures for Electromagnetic Pulse (EMP) hardening. It also provides procedures and guidance to more easily address MIL-STD-464A requirements in relationship to intra- and inter-ship EMC, hull-generated IMI, lifecycle electromagnetic environmental effects (E3) hardnness, EMP, and electrical bonding. A separate appendix is included, with procedures to identify whether commercial-off-the-shelf equipment (COTS) or non-developmental items (NDI) meets appropriate safety requirements before use, and to provide direction to bring them into conformance when necessary.

**MIL-STD-1541A – Space Systems**

The requirements covered by this standard apply to launch and space vehicles plus the associated grounds airborne, or spaceborne operational and support elements of the space system. It applies to new and modified or redesigned equipment or systems, and to existing equipment used in new applications.

MIL-STD-1541A establishes the electromagnetic compatibility requirements for space systems, including frequency management, and the related requirements for the electrical and electronic equipment used in space systems. It also includes requirements designed to establish an effective ground reference for the installed equipment and designed to inhibit adverse electrostatic effects. Bonding and prevention of electrostatic buildup are covered in detail.

As with MIL-STD-464A, this standard imposes additional compliance margin requirements in critical situations:

Category I: Serious injury or loss of life, damage to property, or major loss or delay of mission capability; 12 dB for qualification; 6 dB for acceptance

Category II: Degradation of mission capability, including any loss of autonomous operational capability; 6 dB

Category III: Loss of functions not essential to mission; 0 dB

Intersystem and intrasystem analysis is required by the standard, which also references all emission and susceptibility requirements in MIL-STD-461 (as modified by MIL-STD-1541A) for the relevant class of equipment. Some of the specific requirements of this standard not covered in MIL-STD-461 are summarized in Table 8. Thorough qualification testing is emphasized in the standard.

**MIL-STD-1542B – Space System Facilities**

This standard is intended for selected space system facilities. The requirements are applicable to all related facilities including, but not limited to, launch complexes, tracking stations, data processing rooms, satellite control centers, checkout stations, spacecraft or booster assembly buildings, and any associated stationary or mobile structures that house electrical and electronic equipment.

MIL-STD-1542B addresses in detail the appropriate bonding, shielding, electrical power and ground network for space system facilities. The facility ground network consists of the following electrically interconnected subsystems:
### Section 5.2.5
- **Lightning protection**
  - **Test:** 200 kA peak

### Section 5.2.6
- **Outer surface resistivity of ESD control**
  - Grounded semiconductive coating over insulating material
  - Painted surface over grounded semiconductive material-over dielectric
  - Volume resistivity of a coating\(t, \text{ cm}\) over a grounded metal conductor
  - Limit:
    - \(\leq 10^8 \Omega/\text{square}\)
    - \(\leq 4.6 \times 10^7 \Omega/\text{square}\)
    - \((2.5/t) \times 10^{10} \Omega-\text{cm}\)

### Section 5.2.10
- **Electrical power quality**
  - **Voltage ripple**
  - **Spikes**
  - **Surges**
  - **Load switching and load faults**
  - **Power subsystem faults – surge amplitude**
  - **Vehicle power output ground isolation**
  - Limit:
    - \(< 500 \text{ mV peak-to-peak}\)
    - \(< 3 \text{ times nominal load, } < 0.14 \times 10^{-3} \text{ V-s}\)
    - Return to steady-state in 5 ms (+) and 100 ms (-)
    - Remain within 65% to 130% of nominal
    - Remain within 0% to 175% of nominal
    - \(\geq 1 \text{ M\Omega}\)

### Table 5.3.3
- **Performance criteria – MIL-STD-461 applies as noted**
  - CE01 applies
  - CE06 and RE03 apply
  - CS01 limit applies
  - CS02 and RS03 apply
  - CS06 limits
  - Frequency extended to 30th harmonic or 100 GHz
  - Test under maximum and minimum supply
  - Susceptibility signals chosen for max. effect
  - 200 V \(\times 10\mu\text{s}\) pulse

### Table 8: Some requirements in MIL-STD-1541A

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
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</table>

### Table 9: UK Ministry of Defence EMC standards

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>STANAG 3516</td>
<td>Electromagnetic Interference and Test Methods for Aircraft</td>
</tr>
<tr>
<td>STANAG 3614</td>
<td>Electromagnetic Compatibility (EMC) of Aircraft Systems</td>
</tr>
<tr>
<td>STANAG 4234</td>
<td>Electromagnetic Radiation (Radio Frequency) - 200 kHz to 40 GHz Environment - Affecting the Design of Materiel for Use by NATO Forces</td>
</tr>
<tr>
<td>STANAG 4239</td>
<td>Electrostatic Discharge, Munitions Test Procedures</td>
</tr>
<tr>
<td>STANAG 4327</td>
<td>Lightning, Munition Assessment and Test Procedures</td>
</tr>
<tr>
<td>STANAG 4370</td>
<td>Environmental testing</td>
</tr>
<tr>
<td>STANAG 4416</td>
<td>Nuclear Electromagnetic Pulse Testing of Munitions Containing Electro-Explosive Devices</td>
</tr>
<tr>
<td>STANAG 4437</td>
<td>Electromagnetic Compatibility Testing Procedure and Requirements for Naval Electrical and Electronic Equipment (Submarines)</td>
</tr>
</tbody>
</table>

### Table 10: Some NATO STANAGs relating to EMC.
a. The earth electrode subsystem.
b. The lightning protection subsystem.
c. The equipment fault protection subsystem.
d. The signal reference (technical ground) subsystem.

EMC performance for equipment installed in space system facilities is referenced to MIL-STD-461. COTS (commercial-off-the-shelf) equipment installed in these facilities shall also meet the requirements of MIL-STD-461.

As with the other military EMC standards discussed here, MIL-STD-1542B requires electromagnetic self-compatibility of equipment and systems. Clause 4.2 stipulates:

Facility electrical and electronic subsystems and equipment shall be compatible with each other as well as with the technical equipment installed in the facility for support of space system operations.

UK: DefStan Documents

Equipment procured for military purposes by the UK’s Ministry of Defence must meet their defence standards (DefStan). Non-military equipment must meet the essential requirements of the EMC Directive 2004/108/EC. Ministry of Defence EMC standards are listed in Table 9.

Collectively the UK DefStan documents cover the same concerns as UK military standards. Specifically, DefStan 59-411-3 (Part 3) corresponds closely to MIL-STD-461F in methods, limits and frequency ranges. For example, Magnetic emissions are measured at 70 cm in both standards, and high-frequency radiated emissions are measured at 1m in both standards. However there are structural and content differences between the two standards:

- Individual EMC tests in 59-411-3 are denoted DCS---, DCE---, DRE---, DRS--- where the “D” denotes “Defence” and is absent from -461 test references.
- DefStan 59-411-3 uses susceptibility criteria A…D, which are familiar to users of commercial IEC and EU EMC standards. Default performance criteria are defined for each susceptibility test in terms of safety-critical or safety-related function, mission-critical function, or non-safety-critical or non-essential function.
- “Man worn” and “man portable” categories and test requirements are specified in detail in DefStan 59-411-3. Testing for man-worn applications requires the use of a non-conductive dummy approximating the shape

NATO: STANAG documents

The term “STANAG” stands for “Standardization Agreement” among the NATO member countries. There are literally hundreds of active agreements in place, usually drawing from one or more countries’ existing standards. Some of the STANAG agreements relating to EMC are summarized in Table 10.

Both environmental considerations and EMC are covered under STANAG 4370. It references several separate documents termed “Allied

Design for EMC Compliance

Military product development follows well-defined program steps. MIL-HDBK-237D defines these steps clearly – including tailoring of requirements - as well as providing useful information on potentially applicable commercial standards plus standards from all branches of the US military, and NATO. An extensive list of acronyms is also included.

Definition and refinement of the product EMC environment occurs during the course of program progress. Initial EMC testing in the laboratory is only the first step toward full qualification. MIL-235B provides information on the likely levels of RF field exposure in various stages of deployment to land-based and shipboard locations.

Generally, EMC test requirements will have been fully defined before the product reaches the test laboratory, although modules or subsystems may have been previously tested. The relevant parts of MIL-STD-461F (typically) will be stipulated, and it will be up to the manufacturer to have used prudent design techniques to meet the designated requirements.

As the EMC requirements in MIL-STD-461F are generally more stringent than commercial standards, designing for successful compliance involves careful review of each level of product integration. Can the designer support each of the design criteria in Data Item Description DI-EMCS-80199C, and summarized in this review? These criteria include PC layout, wiring, shielding, filtering and enclosure design. Designers familiar largely with commercial environments will need to review and enhance the use of EMC control techniques to meet military EMC requirements. Later qualification tests may require control enhancements.
Environmental Conditions and Test Publication” (AECPT). We will explore the environmental aspects later, but we will look at EMC first.

STANAG 4370 references AECPT-500 (Edition 3, 2009), “Electromagnetic Environmental Effects Test and Verification.” AECPT-500 draws for its tests and methods both from MIL-STD-461 and DefStan 59-411, as shown in Table 11. Individual EMC tests in AECPT-500 are denoted NCS---, NCE---, NRE---, NRS--- where the “N” denotes “NATO” and is absent from -461 test references.

AECPT-500 also contains a flow chart to guide the gap analysis between commercial and military EMC requirements, when COTS (commercial-off-the-shelf) or MOTS (military-off-the-shelf) acquisitions are being considered.

Look for Part 2 of this article in the April 2014 issue of In Compliance.

This paper was authored by Intertek. Currently Intertek sits on more than 70 SAE standards committees to help draft the test and certifications necessary to keep people safe. Find more articles on EMC issues at www.interk.com. For more information on this topic or to find an Intertek EMC testing lab near you contact icenter@interk.com or 1-800-WORLDLAB.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
<th>Test Derived from</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCE01</td>
<td>Conducted Emissions, Power Leads, 30 Hz to 10 kHz</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>NCE02</td>
<td>Conducted Emissions, Power Leads, 10 kHz to 10 MHz</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>NCE03</td>
<td>Conducted Emissions, Antenna Terminal, 10 kHz to 40 GHz</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>NCE04</td>
<td>Conducted Emissions, Exported Transients on Power Leads</td>
<td>Def Stan 59-411</td>
</tr>
<tr>
<td>NCE05</td>
<td>Conducted Emissions, Power, Control &amp; Signal Leads, 30 Hz to 150 MHz</td>
<td>Def Stan 59-411</td>
</tr>
<tr>
<td>NCS01</td>
<td>Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>NCS02</td>
<td>Conducted Susceptibility, Control &amp; Signal Leads, 20 Hz to 50 kHz</td>
<td>Def Stan 59-411</td>
</tr>
<tr>
<td>NCS03</td>
<td>Conducted Susceptibility, Antenna Port, Intermodulation, 15 kHz to 10 GHz</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>NCS04</td>
<td>Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals, 30 Hz to 20 GHz</td>
<td>MIL-STD-461F</td>
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<td>NCS05</td>
<td>Conducted Susceptibility, Antenna Port, Cross Modulation, 30 Hz to 20 GHz</td>
<td>MIL-STD-461F</td>
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<td>NCS06</td>
<td>Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz</td>
<td>MIL-STD-461F</td>
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<tr>
<td>NCS07</td>
<td>Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>NCS08</td>
<td>Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>NCS09</td>
<td>Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz</td>
<td>MIL-STD-461F</td>
</tr>
<tr>
<td>NCS10</td>
<td>Conducted Susceptibility, Imported Lightning Transient (Aircraft/Weapons)</td>
<td>Def Stan 59-411</td>
</tr>
<tr>
<td>NCS11</td>
<td>Conducted Susceptibility, Imported Low Frequency on Power Leads (Ships)</td>
<td>Def Stan 59-411</td>
</tr>
<tr>
<td>NCS12</td>
<td>Conducted Susceptibility, Electrostatic Discharge</td>
<td>Def Stan 59-411</td>
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<tr>
<td>NCS13</td>
<td>Conducted Susceptibility, Transient Power Leads</td>
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<td>NRE01</td>
<td>Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz</td>
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<td>Radiated Emissions, Electric Field, 10 kHz to 18 GHz</td>
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<td>Radiated Susceptibility, Electric Field, 50 kHz to 40 GHz</td>
<td>MIL-STD-461F / Def Stan 59-411</td>
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<td>Radiated Susceptibility, Transient Electromagnetic Field</td>
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<tr>
<td>NRS04</td>
<td>Radiated Susceptibility, Magnetic Field, (DC)</td>
<td>Def Stan 59-411</td>
</tr>
</tbody>
</table>

Table 11: Cross-reference between NATO EMC test references, MIL-STD-461 and DefStan 59-411
Join your Colleagues in Raleigh, North Carolina
where you can share your insight, ask questions, learn from the experts/innovators and see new products at the 2014 IEEE International Symposium on Electromagnetic Compatibility.

This keynote presentation traces the evolution of EMC engineering, starting with the EMC concerns of the military during WW II, progressing through present day commercial and military EMC issues, and then looking forward into the future.

The development of EMC standards, military and commercial, is traced along with the formation of the IEEE EMC Society and the emergence of various EMC educational options.

The presentation discusses the driving forces behind present day EMC technology and concludes with my gazing into a hazy crystal ball and speculating on the future trends in EMC.

This year’s symposium includes an embedded conference, 2014 IEEE International Conference on Signal and Power Integrity (SIPI 2014), featuring workshop, tutorials and technical sessions devoted to topics of interest to both EMC and Signal Integrity engineers.

For complete event details and information about paper submissions go to www.emc2014.org
Usability Engineering
Observe Users, Improve Product Safety

BY FRANK O’BRIEN

Up until now there’s been much emphasis on designing to make a product “idiot proof”. This has provided some benefit, but what Usability Engineering is reminding us is that it is the designers who are sometimes viewed as idiots by the users. It is the users who are the experts (in usability).

For those involved in product safety, we could perhaps congratulate ourselves. Based on my testing experience over the last three decades, it is my view that products have become safer. No longer is it common to see products cause electrical shocks, burns, fires, or crushing/cutting injuries. We continue to see where we need improvements, particularly when we see new technologies, such as recent events associated with rechargeable lithium batteries. Tragic events associated with energies and materials in electrical products occur, but they have become quite remote.

The focus of this article will be on Usability Engineering for medical devices. We will look at the present state of medical device safety. The data will show poor usability is to blame for more preventable deaths than traffic collisions and firearms combined. We’ll look at new Usability Engineering process requirements and provide an overview on how we can better control the risks associated with poor usability. Even though the focus of this article is on medical devices, the principals hold for all products. Poor usability represents the low lying fruit for safer products.

THE PRESENT STATE OF MEDICAL DEVICE SAFETY

As reported by the post-market surveillance group of the U.S. Food and Drug Administration (FDA), between 2005 and 2009, there were 56,000 adverse events (undesirable experience) involving infusion pumps, resulting in at least 700 deaths. There were 87 manufacturer initiated product recalls. In March 2010, the FDA ordered Baxter to recall 200,000 infusion pumps because of “numerous flaws”. Other pump manufacturers took note, and voluntarily instituted their own product design reviews and, where necessary, recalls.

Based on a new study, “A New, Evidence-based Estimate of Patient Harms Associated with Hospital Care” by John T. James, PhD, published in the Journal of Patient Safety in September 2013, it is estimated that between 210,000 and 440,000 patients die in US hospitals due to preventable medical errors; a four-fold increase over 1999 estimates. The study also estimates that medical errors cause serious harm (e.g. loss of limb, sight, hearing), ten-fold to twenty-fold more common than lethal harm. The study details how better analysis of four past studies justifies the new estimates. These medical errors include those caused by medical and in vitro devices (IVD), both active and non-active, and the administration of pharmaceutical drugs.
Prior to this recent study, the best estimate of preventable medical errors that cause death had been an Institute of Medicine article from 1999, “To Err Is Human”. This older study extrapolated data from hospitals in CO/UT, and NYC, and estimated at least 44,000 people, and perhaps as many as 98,000 people, die in hospitals each year as a result of preventable medical errors (adverse events).

Figure 1 shows the midpoint of the 210,000 to 440,000 estimated deaths due to medical error, alongside deaths due to traffic collisions and firearms.

The best source for aggregate medical device adverse incident/event data seems to be the UK based Medicines and Healthcare Products Regulatory Agency (MHRA). In Europe (including the UK), an adverse incident, causes, or has the potential to cause, unexpected or unwanted effects involving the safety of device users (including patients) or other persons.

The chart shown in Figure 2 shows adverse incidents by year, based on MHRA (UK) Annual Adverse Incident Reports from 2007 (which includes data back to 2001, and 2010 (which includes data back to 2008). We see the upward trend of adverse incidents. As this could be due to an increase in medical devices in use, I plotted as well UK population, based on World Bank data. From the population data, we begin to see some correlation between the two increases.

To better look at adverse incidents to population, I charted in Figure 3 adverse incidents per 1 million persons. I also broke out death and near death, from other adverse incidents having less severe outcomes.

Figure 4 shows adverse incidents by device type.

In Figure 4, the Other category includes (each with less than 5%) Surgical consumables, Aids for daily living, Syringes/needles, Disinfection/sterilization/disposal, Drainage/Suction, Beds/mattresses, Hoists, Artificial limbs, Walking aids, Physiotherapy equipment, and Orthoses.

Only some of reported adverse incidents are investigated by MHRA. Of those chosen for investigation, Figure 5 shows to whom responsibility for the incident was assigned. In assigning responsibility MRHA uses the following system:

- Healthcare facility, Use: After delivery; use errors, performance and/or maintenance failures and degradation
- Manufacturer: Before delivery; design, manufacture, quality control and packaging
- Unknown: intermittent faults (use error, software, EMC) or couldn’t investigate

In looking at the adverse incident data one needs to be wary of reaching any definitive conclusions. Problems with the data include:

- Increase real? Or due to better reporting?
- Need to know adverse incident per devices in use
  - Are high adverse incidents for a device type due to in use numbers, device complexity, or other?
- Cause investigations should target use error specifically
  - Don’t lump in with performance and/or maintenance failures and degradation by healthcare facility
  - Differentiate use error due to inadequate training by healthcare facility, etc; from insufficient usability by device manufacturer
Categorize by device failure mode (e.g. transformer, switch, software, EMC), or use error

- Increase in unknown causes results in less useful data (e.g. assigned causes)
- Pull out suspected use error, software, EMC causes

Hats off to MHRA for providing aggregate data, even if not perfect. It would be nice to see FDA publish aggregate data annually, and/or make their databases a bit more accessible (they’re searchable, but for aggregate data, not easy to download and reconstruct the relational tables).

Problems aside, one could reach the following qualified conclusions:

- 26% more adverse incidents per capita
- 29% more death or near death
- 82% involve more complicated equipment, such as implants, surgical, patient monitors, infusion pumps, IVDs, wheelchairs, imaging, and similar
- During 2005-06, majority of cause was health facility, use
- During 2007-10, cause was shared between healthcare facility, use; and manufacturer design, controls

**DO NO HARM**

The latin phrase, Primum non nocere, “first, do no harm”, is attributed to Thomas Sydenham (1624–1689) in a book by Thomas Inman (1860), Foundation for a New Theory and Practice of Medicine. Putting things in the terminology of modern risk management, (e.g. ISO 14971:2007), where a medical device has an unacceptable risk of harm, a designer needs to implement effective risk control measures.

With the above adverse incident/event data in mind, take a look at Figure 6. What’s the most likely hazard or failure mode that could result in harm? Hopefully everyone recognizes that it’s the User Interface. As designers we need to recognize that this is an important, and perhaps the most important, design responsibility.

**USABILITY ENGINEERING**

Usability Engineering, or as FDA refers to it, Human Factors Engineering, is the process to identify where user interactions with a medical device have the potential for harm, and to implement effective risk control measures. The Usability Engineering process touches all design aspects; the hardware interface, the software interface, product markings, and any user documentation. Considered is usability associated with the full product life cycle, from transport, normal use, maintenance, to decommissioning.

Key standards to guide a manufacturer’s Usability Engineering process:

• IEC 60601-1-6:2010, Medical electrical equipment -- Part 1-6: General requirements for basic safety & essential performance - Collateral standard: Usability
• ISO 14971:2007, Medical devices - Application of risk management
• Medical Device Use-Safety: Incorporating Human Factors Engineering into Risk Management, issued 2000
• Apply Human Factors and Usability Engineering to Optimize Medical Device Design, issued 2011 (draft)

The IEC and ISO standards have EN (CENELEC) versions for Europe, and are harmonized to the essential requirements of the Medical Device Directive related to ergonomics and information supplied by manufacturer. All are in the U.S. FDA recognized consensus standards database. They become the means to provide a presumption of compliance with essential requirements and a reasonable assurance of safety and effectiveness, with regards to acceptable usability.

All these standards are consistent with each other. The scope of IEC 62366 (which I consider the high level process standard) is all medical devices, including the more prevalent non-active devices like tubing sets, luer connectors, syringes, dental implants, sterile drapes; as well as electrical equipment like surgical equipment, patient monitors, in vitro diagnostic equipment, and non-implantable accessories to active implants. IEC 60601-1-6:2010, the medical electrical equipment collateral standard for usability, contains essentially only a normative reference to IEC 62366. The AAMI HE75 is useful as it has more specific guidance and examples. FDA guidance documents are also written to provide more specific examples, use FDA terminology, and provide references for further reading. Think of the AAMI HE75 and FDA guidance documents as informative annexes to IEC 62366.

In the remainder of this article we focus on IEC 62366.

IEC 62366 tells us that users want good usability:
• Effectiveness
• Efficiency
• Ease
• Satisfaction

With these user motivations and taking into account the use environment we can anticipate and investigate user actions (or interactions) such as pushing a button, toggling a switch, sliding a door, turning a screw, tapping a menu item, speaking into a microphone, filling a reservoir, or connecting a leadset.

Figure 8 provides terminology to refer to user actions (or interactions). Discussions are helped when we all use the same terminology. Note that ideally medical devices are desired to result in what we call, Correct Use; the designers intent; the device fulfilling its intended clinical purpose/use.

Figure 8: User action (interaction) categories (IEC 62366:2007, Figure B.1)
As designers we must also anticipate Use Error, (or reasonably foreseeable misuse), which can be Slips, Lapses, or Mistakes. Slips are due to buttons or menu items being too close together such as the maximize and close buttons in Windows. Lapses are due to too much complexity for the use environment. Slips and Lapses are unintentional. These should be fairly routine to anticipate and control.

Mistakes are more interesting. A designer needs to anticipate and investigate (assisted by user input and observation) where a user might default to behavior suggested by the user interface, or seek a shortcut. Mistakes are always intentional.

I like to think of mistakes as something Homer Simpson might do. Homer has good intentions, but nonetheless, somehow always seems to find himself in trouble.

Homer in the episode where he becomes "Max Power", says to Bart, "There's the right way, the wrong way, and the Max Power way.”

Bart asks, "Isn't that the wrong way?"

Homer explains, "Yeah, but faster." I think this sums up the new mentality that designers need to adopt.

Abnormal use is intentional and beyond any further reasonable means of risk control by the manufacturer. Think Pete Townshend from The Who and what he used to do to guitars after a concert (for young readers; he smashed them into bits and pieces). As reducing risk from abnormal use is beyond further reasonable means, a manufacturer has no further responsibility to reduce this risk.

For those versed in the terminology of the medical equipment safety standard series, IEC 60601, Table 1 provides a quick mapping.

We can see the intent of IEC 62366 is to remind us that reasonably foreseeable misuse or use error needs to be considered "normal". This is true of both IEC 60601 (clause 4.1) and IEC 62366, but IEC 62366 adds emphasis by using the term normal use for both correct and use error.

Consider as well that the term use error is NOT called user error. Use of the word use instead of user is intentional to emphasize that it is the designer’s responsibility to risk control use error where it could result in harm. Use error should not be considered the user's fault.

Figure 9 illustrates well that the Usability Engineering process has continuous improvement provided by its post-market surveillance feedback. This is much like a quality management system with its customer feedback, process metrics, and internal auditing, feeding into the management review and CAPA (corrective action, preventative action) process. A risk management process has post-market surveillance as feedback for risk control improvement.

Table 1

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<th>IEC 60601, Medical Equipment Term</th>
<th>Mapping to IEC 62366, Usability Term</th>
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<tr>
<td>Normal Use</td>
<td>Correct Use</td>
</tr>
<tr>
<td>Reasonably Foreseeable Misuse</td>
<td>Use Error (Slip, Lapse, Mistake)</td>
</tr>
<tr>
<td>Normal Use + Reasonably Foreseeable Misuse</td>
<td>Normal Use</td>
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Figure 9: Usability Engineering process (IEC 62366:2007, Figure D.1)
Key aspects of a Usability Engineering process during the design phase:

- Application specification
- Frequently used functions
- Usability hazards (user input & observation)
- Primary operating functions
- Usability specification
- Validation plan
- Design & implementation
- Verification
- Validation (user input & observation)

The Usability Engineering process starts with a documented list of what the device is intended to do -- the application specification. We analyze and investigate this list to determine frequently used and otherwise primary operations related to safety -- frequently used and primary operating functions.

Based on our analysis and investigations, where use error could result in unacceptable risk, we add risk controls. These risk controls are defined in the Usability Specification. These can be included with other design requirements related to customer, business, and device failure risk controls, but there needs to be a means (e.g. a flag), to identify those related to usability risk controls, as these are inputs for the usability validation plan. The usability risk analysis process is repeated as the design becomes more detailed.

A validation plan needs to be formulated to define the method(s), (e.g. test user population profile, interviews, simulated clinical use, actual clinical use, etc.), and criteria for usability validation. The testing method(s) and compliance criteria allow a validation of the effectiveness of the risk control measures.

Verification can be carried out by engineering, as usability risk control measures such as the color, or blink rate, volume, or spacing to adjacent buttons can be verified. Validation necessarily involves users, as detailed in validation plan.

USABILITY TRENDS IN OTHER PRODUCT SECTORS

Not only the medical device sector recognizes the importance of Usability Engineering. With the newest version of the safety standard for equipment for measurement, control, and laboratory use, IEC 61010-1:2010, 3rd ed, we have a new clause 16, which mandates that reasonably foreseeable misuse and ergonomic issues be addressed with risk assessment (analysis, evaluation, and where needed, effective risk control). Risk assessment is a new clause 17.

In the newest version of the safety standard for information technology equipment, IEC 60950-1:2005 + A1:2009 + A2:2013 (consolidated ed 2.2), in the principles for safety it mentions the need to consider foreseeable misuse. There is no separate clause for this hazard. But, as with all product safety standards, (i.e. the physical requirements for enclosures) foreseeable misuse is taken into account.

In the newly published, but as yet not widely used, safeguards based standard IEC 62368-1:2010, Audio/video, information and communication technology equipment - Part 1: Safety requirements, the term reasonably foreseeable misuse is defined. However its use is limited to the normative Annex on batteries and fuel cells. Nonetheless, having the term defined will facilitate useful safety discussions.

RISK MANAGEMENT AND USABILITY ENGINEERING

With both risk management and usability engineering, unacceptable risk is mitigated with risk control measures, defined by design requirements, in turn verified and validated. Post-market surveillance provides feedback.

With risk management, hazards are identified and risks defined by the design team including clinical application specialists.

With usability engineering, usability hazards are defined by user input and observation criteria user input and observation will be sought and evaluated. It is this emphasis on user input and observation that Usability Engineering brings to existing quality system design controls and risk management.

USABILITY ENGINEERING FOR LEGACY DEVICES

User interfaces and user manuals for legacy devices are already designed. We cannot very well go back and follow a Usability Engineering Process without having to go back and effectively undertake the whole design process again -- something that isn't going to make business sense for products that have good experience in the market. This is much like off-the-shelf software, or what IEC 62304, the software safety
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Manufacturers who adopt a Usability tool to help us design safer products. Usability Engineering represents a new contributor. The error would seem to be a significant device adverse incident/event data, use error.

• Users validate effectiveness of usability specification (risk control measures)

TAKE AWAYS

Designers need to anticipate and investigate use error (reasonably foreseeable misuse):

• Optimize Usability (effectiveness, efficiency, ease, satisfaction)

• Risk control behavior that could result in unacceptable risk of harm

Users are the experts:

• User input and observation needed by design team, including clinical application specialists

Based on a review of aggregate medical device adverse incident/event data, use error would seem to be a significant contributor.

Usability Engineering represents a new tool to help us design safer products. Manufacturers who adopt a Usability Engineering process will create safer products. Greater reliance on user input and observation makes intuitive sense if we are to reduce risk associated with use error.

Finally, with better adverse incident/event data collection, we will have the data to assist with root cause analysis, identify areas for improvement, and evaluate our performance.

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• Apply Human Factors and Usability Engineering to Optimize Medical Device Design, issued 2011 (draft)

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