Stability of Shielding Systems: Issues and Concerns

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INTRODUCTION

Recent articles in the technical literature, and personal experience involving electrical testing of EMI shielding materials strongly suggest that the shielding effectiveness of conductive materials (e.g., conductive organic coatings) and materials' couples (e.g., enclosure and EMI gasket mating surfaces) can decrease significantly with time depending on the environment. For example, the development of electroless coatings for plastic PC enclosures was prompted by the need for higher and more stable (vs time) shielding performance than that provided by conductive organic coatings (nickel- or copper-filled paints).[1] In another case, use of an EMI mesh gasket in the longeron area of the F-18[2,3] resulted in severe corrosion of the aluminum longeron in poorly sealed areas raising structural and shielding concerns. These two cases represent extremes in the level of environmental degradation of EMI shielding materials. With organic coatings and gasket flanges in commercial environments, large increases in electrical resistance can occur without visible signs of corrosion. Under salt spray or other highly corrosive conditions, both electrical and gross material degradation will occur.

Concerns about the changes in shielding effectiveness (SE) of electronic systems raise the question of their role in failures due to electromagnetic interference (EMI). System failures caused by EMI are inherently difficult to diagnose due to the intermittent nature of interference. Leakage of interference through EMI shields can occur for several reasons:

System failures caused by EMI are inherently difficult to diagnose due to the intermittent nature of interference.

- Fundamental design flaws,
- Poor quality control on materials and manufacturing operations, or
- Environmental degradation of the electrical properties of the shield.

In systems operating in high levels of ambient interference, one would expect failures due to design flaws to appear in large numbers and be corrected by engineering changes early in the product's life. Intermittent failures due to poor quality control and aging of the electrical properties of the shield would be more difficult to detect and diagnose.

The limited number of references to EMI failures in the open literature generally involve military systems and as a consequence, available information is not detailed. Examples of suspected EMI failures include crashes of Army Black Hawk helicopters, an F-111 during the Libya strike, and the downing of a Tornado by Radio Free Europe transmissions.[4] Existing shipboard electromagnetic compatibility problems were reportedly involved in the Stark and HMS Sheffield incidents.[4] Failures, if due to gradual loss of shielding effectiveness over time, are difficult to recognize due to their random nature. This author has seen only one reference, in *DEFENSE ELECTRONICS*, which mentioned the loss of shielding in TEMPEST systems due to aging.[5]

As digital devices continue to proliferate into all aspects of our daily lives, the question of the long-term performance of EMI shields and the impact on system reliability raises both application and maintenance issues. Three general application areas of potential concern are:

- Digital control of life critical functions, for example in transportation (fly-by-wire aircraft, automobiles), in medical (life support and monitoring), and industrial controls.
- Information transfer involving confidential, financial, and transaction data.
- Office environments where high densities of digital equipment increase the potential for interference.

Performance and system areas

of concern include the long-term reliability of shielding systems (SE vs time), and the maintainability of shielding systems (monitoring of SE versus time and repair).

This article will describe the principal mechanisms which degrade electrical properties, and review selected literature articles which discuss the aging of electrical properties of shielding materials and systems.

PROBLEM STATEMENT

The shielding effectiveness of electronic enclosures will degrade as the system ages due to corrosion and oxidation of metal surfaces and interfaces. Examples are increases in contact resistance between EMI gaskets and flanges, and increases in the surface resistivity of conductive coatings. The rate of change depends on several variables, some within the control of equipment manufacturers and others beyond their control. Choices of materials, mechanical design, and system design are defined by manufacturers. Environment, maintenance procedures, and patterns of usage are determined by the application, even though these should be anticipated in the design of the shielding system.

Shielding system, as used in this article, refers to the passive EMI shielding materials employed to form a "Faraday Cage" around the electronics of a device, including but not limited to: conductive enclosures, coatings, gaskets, surface treatments, vents, and windows. Examples of these materials include: conductive elastomers; mesh gaskets; silver, nickel, and copper paints; metal coatings on plastic enclosures; and conductive caulks. These materials form the components of the EMI shielding system. As such, they have discrete material (physical and electrical) properties and system properties when integrated within the overall design. The properties of the EMI shielding system can be characterized in terms of performance, reliability, and maintainability. Shielding performance is characterized in dBs of attenuation versus frequency for E and H fields and is typically measured by radiated methods, such as those in MIL-STD-461. Reproducibility, as manufactured, and stability of electrical properties as the system ages determine the reliability of the system design. Maintainability entails both being able to monitor changes in performance and being able to repair or restore performance to within recommended operating windows. Military systems are specified to have 10-to 15-year life spans. Improvements in technology tend to make commercial computing devices obsolete before their useable lives of 5 to 10 years.

An accurate assessment of the EMI shielding degradation of installed systems does not exist in the open literature at this time. Measurements of system components, e.g., gasketed joints (discussed in more detail later), suggest that significant changes in shielding effectiveness of these components can occur in relatively short time periods (1 to 2 years). Failure or degradation of shielding effectiveness is difficult to diagnose and measure in the field. Interference will generally occur on an intermittent basis depending on the location and usage patterns of the EMI source and receiver. Certification of military (e.g., MIL-STD-461 testing), commercial (e.g., FCC regulations) and TEMPEST systems and equipment only includes shielding effectiveness measurements on new systems. If environmental tests are performed, they are made after the shielding measurements and only include visual inspections for corrosion and operational tests of the electronics. As a consequence of these practices, a database is not maintained to track the stability of shielding systems. As a passive system, the EMI shield will age both sitting on the shelf and during use. Changes in shielding (electrical) performance of materials or mated materials will occur long before visual signs of corrosion become evident.

DEGRADATION OF ELECTRICAL PERFORMANCE

Electrical conductivity of materials and systems containing metal-to-metal interfaces are subject to increases in resistance due to the formation of insulating oxides in the contact interface. Examples of materials in which this would be of concern are conductive elastomers, coatings, caulks, adhesives, and plastics containing metallic particles. Initial conductivity and stability in various environments will depend on the choice of contacting metals. At the system level, flanges containing conductive gaskets which are placed against the enclosure surface have interfaces susceptible to oxidation. Oxidation of metal surfaces can occur via chemical (e.g., direct reaction with oxygen in air) or electrochemical reactions. Electrochemical oxidation or corrosion of metal surfaces is the principal mechanism for increasing the electrical impedance of shielding systems. (Figure 1 contains an overview of the degradation mechanisms.)

All metals, with the exception of gold, are subject to oxidation at ambient conditions. Exposure of fresh metallic surfaces to oxygen causes oxide layers of varying thicknesses to form immediately, the thickness depending on the metal. Contact resistance of this oxide covered surface depends on the thickness of the oxide, conductivity of the oxide, and physical properties (e.g., hardness and brittleness) of the metal and oxide. Tin has low contact resistance because it is a soft metal which forms a brittle oxide. In the process of contacting a tin surface, the oxide cracks and fresh metal is extruded to the surface forming an oxide- free contact. Contact resistance in this type of system will increase after repeated cycles due to the build-up of a thick oxide layer.

Corrosion of metals involves an electrochemical reaction, illus-

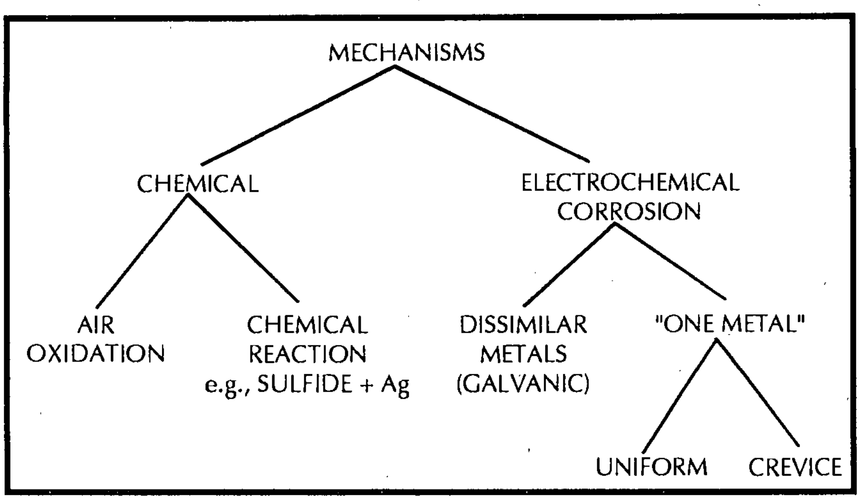

FIGURE 1. *Factors Influencing Aging of Electrical Contacts.*

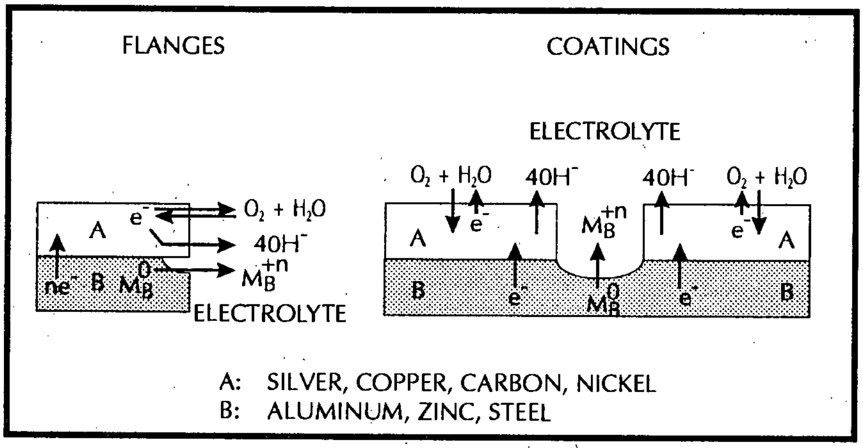

FIGURE 2. *Galvanic Corrosion (Dissimilar Metals).*

trated with two galvanic corrosion cells in Figure 2, comprised of three elements:

- Areas of different energy or "potential" where oxidation and reduction reactions can occur separately. Corrosion or oxidation of the metal (M^o ---> M^{+n} + ne^-) occurs at the anode. A reduction reaction (e.g., oxygen reduction - O_2 + H_2O + $4e^-$ ---> OH^-) takes place at the cathode and consumes the electrons generated at the anode.

- An ionically conductive solution bridging both the anode and cathode areas. Dissolution of common table salt, sodium chloride (NaCl), in water results in the formation of ions of sodium (Na^+) and chloride (Cl^-).

- An electronically conductive path between the anode and cathode.

If any of the above elements are absent, the reaction will not proceed. A battery stores energy in an electrochemical system and releases the energy in the form of electrons when an external electrical load is connected between the terminals. Corrosion cells can be viewed as short-circuited batteries which form naturally.

The corrosion form of principal interest in EMI shielding systems is galvanic corrosion, which results when dissimilar metals (e.g., copper and aluminum) are placed in contact in the presence of moisture. Galvanic series provide a measure of the difference in potential (electrochemical) between the metals. The more noble metal provides a surface where the cathodic reaction can occur. For the aluminum-copper couple, aluminum corrodes and oxygen reduction occurs on the copper surface. (The copper surface is actually protected in this situation.) Galvanic couples are present in most flanges sealed with conductive gaskets (e.g., mesh, elastomer) and where conductive coatings are applied onto a metallic substrate. Examples of the latter include: silver coatings on copper and aluminum particles; silver, nickel, and nickel paints on aluminum surfaces; and electroless nickel/copper multilayer deposits.

General or *uniform* corrosion occurs on a material as a result of variations in the metal surface and will increase contact resistance. Metallurgical differences (e.g., alloying additives such as copper in aluminum; grain boundaries) and variations in mechanical stress can generate potential differences in the presence of moisture films, which cause the metal to corrode. A piece of steel exposed to ambient air will form rust (iron oxide) by this mechanism. Other metal or alloys such as stainless steel and nickel form protective oxides which prevent further corrosion.

Many variables affect the rate of the corrosion reaction:

- Potential difference between dissimilar metals

- Relative surface areas of the dissimilar metals

- Characteristics of the moisture film on the metal surfaces

Higher conductivity (salt content), alkaline or acid pH's (presence of sulfur dioxide, SO_2, or hydrogen sulfide, H_2S), and aggressive ions (e.g., chloride from seawater) are electrolyte variables of the moisture film which accelerate corrosion. Other aggressive species include chlorine and sulfides.

MARKETS POTENTIALLY EFFECTED BY ENVIRONMENTAL DEGRADATION OF EMI SHIELDING

The aging of shielding systems can effect the performance and reliability of all digital electronic systems. Those of particular concern are discussed below. In many situations, malfunctions in digital systems due to EMI could lead to loss of life or personal injuries, particularly in the transportation sector. Issues of cost and product competitiveness must be balanced against the level and quality of the shielding system used. Designing to regulatory specifications (e.g., FCC) is often less demanding than internal design guidelines, where long-term performance is of concern.

AEROSPACE

With the advent of fly-by-wire aircraft, shielding of digital avionics and control systems has become a safety-of-flight issue in which interference with the computer systems could lead to loss of life. As an example, interference with hydraulic or flight controls in Black Hawk helicopters is alleged to have caused several crashes. In conversations with electronics and materials engineers in aerospace, one hears stories of losing cockpit displays during landing approaches (control not affected) and of high power (200-watt) radio transmissions from the tail antennas interfering with engine controls. In these situations, improvements in cable and airframe shielding resolved the problems.

The aerospace industry has long recognized the need for shielding in military aircraft, beginning with the shielding of digital avionics systems. In military fly-by-wire aircraft, (e.g., the F-18), the fuselage provides one layer of shielding to the internal electronics. All access panels and the longeron seal area contain EMI gaskets to electrically seal these areas. The Navy has gone to great lengths to maintain the performance of these seals.[2,3] In the case of the F-18 longeron gasket, the structural integrity of the aircraft was threatened by pitting induced by galvanic corrosion in early designs which did not seal out the environment from the gasket/longeron interface.

As a rule, the fuselage is expected to provide only low levels of shielding, on the order of 30 to 40 dB. Large numbers of riveted joints, large dimensional tolerances, and vibration and flexure of joints are factors inherent to aircraft design which limit the electrical shielding of a fuselage during flight. Aerospace applications also introduce vibration and wear factors into the aging of electrical contacts, particularly in mating surfaces on the fuselage. Increasing the use of composite skin panels to reduce weight or increase strength for the same weight further complicate the problem. Composites are nonconductive or of low conductivity and provide negligible to limited shielding. Composite panels are made conductive by inclusion of metal mesh layers or laminates, application of conductive organic coatings, or lamination of foils to the surface. (Retrofit of a digital backup control system (BUCS) on the Apache helicopter has necessitated upgrading the shielding of the fuselage, particularly with multi-service use placing the Apache in Naval EMI environments.) When choosing the shielding effectiveness of avionics systems housed inside the craft, if the shielding effectiveness of the fuselage is considered in the design of the shield, then the the electrical properties of the fuselage must be constant with time.

The aging aircraft issue has focused on the structural integrity of older aircraft (15 to 25 years). Electrical interfaces (e.g., contacts and joints in EMI enclosures) age in much shorter time periods, on the order of one to five years.

During the past year, fly-by-wire commercial aircraft have entered into scheduled service, (e.g., the new Airbus and the new Boeing 747). These aircraft must be able to land at any available airport, both commercial and military, if an emergency should arise. Field strengths on the order of 10 kV/meter are present.[6] The electronic systems of these craft must be able to function without interference during landing or take-off. The FAA asked the SAE AE-4 committee to develop test procedures for certifying the EMI shielding effectiveness of the systems and to develop recommended design procedures. The task has taken considerably longer than expected, partly due to the unexpectedly high field strengths reported, and work continues on this project.

The *aging aircraft* issue has focused on the structural integrity of older aircraft (15 to 25 years). Electrical interfaces (e.g., contacts and joints in EMI enclosures) age in much shorter time periods, on the order of one to fives years. Maintenance and inspection schedules for the electronics and shielding systems of aircraft should reflect these rates.

As the passenger cabin increasingly becomes an extension of the office, providing phone, computing, and fax capabilities, the potential for interference with aircraft systems increases. As with any electronics installed in aircraft, they must pass certification tests; however, these tests do not address the long-term performance of these systems.

AUTOMOTIVE

Microprocessors and digital

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electronics have played a pivotal role in the new generation of automobiles: for example, controlling engine function to minimize emissions while enhancing performance; anti-lock and skid brake systems; self-adjusting suspension systems; and dash board displays and monitoring systems. Many of these functions are critical to the function of the car and the safety of the occupants. (Traditionally, shielding of electronics in automobiles focused on maintaining the sound quality of the stereo system, since this would affect the consumer's perception of the vehicle in the showroom.)

The automobile inherently resides in a hostile environment with respect to corrosion and EMI. High voltage ignition systems (more so today with solid state distributors) can radiate high fields in close proximity to the microprocessors controlling engine and braking systems. High temperatures, condensing conditions, and salt spray make the engine compartment a highly corrosive environment. When parked under the midday sun, the car interior may experience large temperature extremes with the windows closed. Any open liquid container will maintain the relative humidity at saturation, creating ideal conditions for condensation when the temperature drops. Car interiors also contain plasticizers and the vapors of any materials that are brought into the car (e.g., bleach and ammonia cleaners, and solvents) which can accelerate corrosion at electrical contact surfaces. The reliability of the EMI shielding of automotive systems must be able to withstand these hostile environments.

MEDICAL APPLICATIONS

The use of sophisticated electronics has become pervasive in the hospital environment, including: patient monitoring; life support systems; surgical procedures; automated laboratory tests; and diagnostic instrumentation. High voltage emitters may be present in the hospital environment. For example some techniques, such as shockwave lithotrity used to breakup "stones," use spark gaps to generate energetic pulses.

COMMERCIAL/RESIDENTIAL COMPUTING ENVIRONMENT

The number of computing devices have increased in the commercial work environment (office and laboratory), with personal computers and workstations becoming essential tools of professional and support staff. A tour of most facilities will reveal the geneology of personal computer development, with early 8088 machines coexisting with the latest 486 microprocessors. As the price of microprocessors has decreased and the demand for *smart* electronics has increased, the use of digital devices have spread into appliances, industrial and home controllers, and other traditional analog devices. As the density of digital devices increases, the potential for interference increases, particularly with older machines remaining in use.

Secure communications are essential to the operations of the financial and banking sectors, where sensitive information is routinely exchanged between remote locations. Remote banking through card terminals and credit card confirmation at the point-of-sale are a routine part of life in the nineties. The stock exchanges and brokerages now use on-line computer systems for information and transactions. In the future, we will have the option of banking, shopping, and making reservations from our homes. In all of these situations, long-term shielding of devices and of cables must be maintained.

DISCUSSION OF SELECTED LITERATURE

Over the years, isolated articles have examined various aspects affecting the stability of EMI shielding systems. In an early article, Groshart[7] studied the contact resistance (DC values) between various metal couples as a function of environmental exposure. More recently, the National Association of Corrosion Engineers (NACE), held a one-day symposium on "Corrosion and EMI in Aerospace Equipment"[8] in which the speakers focused on aging EMI materials and enclosures, new materials and designs, and test methods. IEEE symposia also include periodic presentations on the aging of EMI shielding materials and the techniques used to characterize these effects (transfer impedance). Selected articles, specifications, and personal communications will be reviewed, which indicate that exposure to ambient environments will increase the impedance of electrical contact interfaces and consequently degrade the overall shielding effectiveness of the system. Integration of environmental and electrical measurements increases the complexity of an experimental plan and design, from technical and personnel perspectives. Different disciplines (electrical, materials, packaging) must be brought together and the question of overall project management arises.

R.B. Thibeau and co-authors[9,10] have characterized the impedance of different cabinet finishes and fingerstock mated together, and various cabinet finishes in simulated commercial environments. Impedance

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increases on the order of 10 to 100 were found. Several trends are clear from the data of the first study. The flanges with yellow chromate finish (zinc-plated steel and aluminum) had higher impedances after aging than did nickel or tin coated steel surfaces. For the chromated surfaces, tin/lead coated fingerstock had lower impedance before and after aging than did nickel and tin coated fingerstock. In the case of tin fingerstock against yellow chromated aluminum, the impedance increased from approximately 5 milliohms to greater than 160 milliohms, a factor of 30. The most stable cabinet finish was tin on steel, exhibiting no increase in impedance after aging for the tin/lead, nickel, and tin coated fingerstock. In the second study of cabinet finishes, results of accelerated laboratory tests and field exposures showed large increases in surface impedance after 24 months (6 days in accelerated tests). Again, chromated surfaces (conversion coatings) showed the largest increases. Impedance increases were on the order of 10 to 100 depending on the finish and the test condition. The reason for an induction period prior to resistance increases was not determined in this study. One would expect larger increases in impedance if galvanic couples were present, as in the fingerstock tests.

The above studies used a relatively new environmental test (mixed flowing gas test) to accelerate aging of the samples in the laboratory. Part per million (ppm) levels of chlorine (Cl_2), hydrogen sulfide (H_2S), and nitrous oxide (NO_2) are used to simulate various environments, from unreactive to highly corrosive industrial conditions. In contrast to other environmental tests (e.g., temperature/humidity cycling, salt spray), this technique has a quantitative acceleration factor (2 days approximates 1 year) for the specified class of exposure. Currently, ASTM is working to develop an accepted standard for this method.

One recent study[11] looked at the aging of chromate conversion coated flanges containing various EMI gaskets (spiral, mesh, oriented wire in elastomer, and elastomers) in outdoor, salt spray, and ambient conditions with transfer impedance. Table 1 shows the initial and aged dB Ω values reported in the paper converted to ohms and *normalized for gasket footprint.* (Comparison on equivalent contact areas is important at these frequencies, because the voltage drop depends on the cross-sectional area for conduction.) One immediately notices the large difference between the initial contact resistance of the elastomer and *metal* gaskets. The differing ability of the gaskets to penetrate the insulating conversion coating on the aluminum surface lead to the large differences in resistance. Conductive Class III conversion coatings, MIL-C-5541, are not conductive electrically, but rather, easier to break through than Class I coatings. From personal experience, the contact resistance of similar conductive elastomers will range from 0.1 to 10Ω/cm² which indicates that the conversion coating applied in this study was highly resistive.[12] Relative to clean bare aluminum, chromate conversion coatings will reduce the shielding effectiveness of otherwise identical elastomer flanged openings by approximately 20 to 30 dB in radiated measurements. In this study, the conversion coating increased the transfer impedance by 40 dB Ω.

The explanation of why the conductive elastomer shielding values differ significantly from MIL-G-83528 values of shielding effectiveness arises from the different flange surface finishes used in making the MIL-STD measurement. Bare aluminum flanges with low contact resistance are used for determining the radiated shielding values in the MIL-STD. The shielding effectiveness values are further biased by using 1-inch wide gaskets (atypical in practical applications) deflected at high flange closure forces.

Relative ranking of the different gaskets did not change after the environmental tests. On a ratio basis, the more conductive gaskets show greater resistance increases (10 - 40x) but still have lower absolute resistances than the elastomer flange. Salt spray exposures (2200 hours) resulted in 30 to

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MATERIAL	R_0 (Ω/cm²)	"FACTOR"	AFTER ENVIRONMENT* Ω/cm²
Spiral (Sn)	0.02	x 10-40	0.2 - 0.8
Monel Mesh	2	x 1-30	2 - 60
Oriented Monel Wire	4	x 2-25	8 - 100
Flat Elastomer	250**	x 1-3	250 - 750

* Approximately 14-week exposures (Ambient - Salt Spray)
** 0.1 - 10 Ω/cm² from other data [12]

***TABLE 1.** Effect of Environmental Exposures on Conversion Coated Flanges Containing Various EMI Gaskets.[11]*

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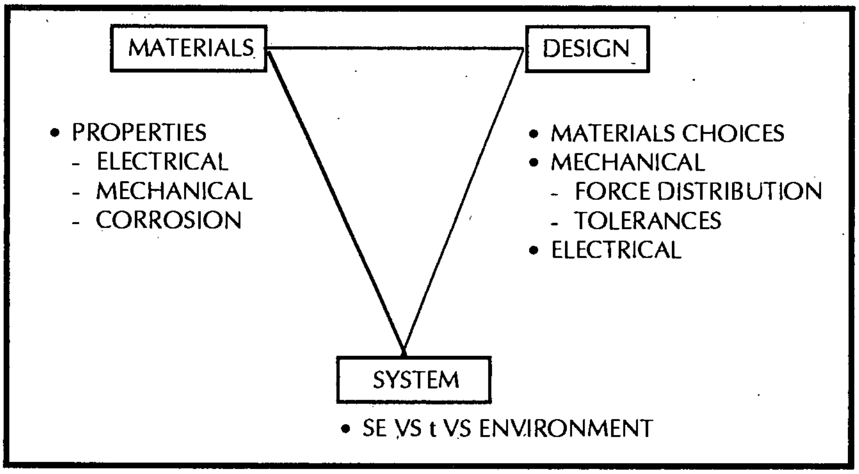

FIGURE 3. *Shielding Effectiveness of an Enclosure Depends on Materials Choices and Design.*

50 dB changes in the impedance. Rooftop exposures (Atlanta, GA) for similar times caused 10 to 30 dB increases in impedance. Addition of nonconductive environmental seals to the gasket designs showed no or marginal improvements relative to the gasket without nonconductive seals. This indicates that the aggressive elements of the environment were still able to penetrate to the critical electrical interfaces. As a result of these impedance increases, one would expect shielding to be lowered by at least 20 dB. (In reviewing this data, one should keep in mind that the military uses a resistance of 2.5 mΩ across an EMI joint as a minimum acceptance criteria.)

Both studies demonstrate several important design points:

- Chromate conversion coatings can significantly increase the initial impedance of EMI interfaces and the rate of change during use. The impedance of joints containing conductive elastomer gaskets are particularly sensitive to conversion coatings, because they do not easily penetrate the insulating film.

- Environmental exposure of EMI flanges will degrade the shielding effectiveness of enclosures by at least 20 dB. Exposure to severe environments will significantly accelerate and increase the amount of change.

Another area of potential concern is the shielding of enclosures (plastic or composite) with conductive coatings. Traditionally, metal-filled paints (nickel or copper in commercial devices and silver in military devices) have been used to create a conductive shield on plastic. The electrical properties of these coatings can change by oxidation of the metal fillers and/or relaxation of the polymeric binder. As previously cited, this was one reason for the use of electroless coatings (nickel phosphorus over copper) in personal computers.

Organic coatings will be subject to more variation than plated metallic coatings due to variations in raw materials; shelf-life of raw materials and formulated coatings; variation in application procedures, and the differences in vendor formulations. Stability of powder metal fillers depends on the powder production method, surface stabilization techniques, and stabilizers included in the coating formulation. Generic properties, for example, for a copper acrylic coating, do not exist because of the multitude of parameters which affect coating formulations and materials selection.

Cost factors enter into the selection of coatings for commercial computer equipment, with electroless metal coatings being the most expensive. Current FCC regulations specify only the shielding performance of a device as manufactured, not the performance after years of use. The design specifications of premium manufacturers tend to exceed those of the FCC, and consequently, use of electroless coatings on plastic enclosures is increasing. Where they use organic coatings, they have the quality control mechanisms and engineering organizations to ensure that the highest quality coatings are supplied. This is not the case for low cost manufacturers, where more emphasis may be placed on passing the minimum FCC requirements.

SPECIFICATIONS

In describing specifications concerning environmental aging, one must differentiate procedures which characterize the interactions of basic materials and those which look at the performance of materials in configurations simulating actual applications. The disparity arises from the effect of mechanical design on shielding performance and the use of additional environmental sealing techniques. Figure 3 highlights the interaction of materials and design in determining the long-term shielding effectiveness of systems. At the present time, government system specifications (e.g., MIL-STD-461 and FCC) do not require measurement of the shielding performance of systems after exposure to simulated use environments.[13]

Attempts have been made during the last ten years to develop methods and specifications for EMI shielding materials and for combinations of shielding materials mated together. Within the Society of Automotive Engineers (SAE), the AE-4 committee has written draft specifications (ARP-1705 and ARP-1481) for the characterization of the electrical properties of gasketed joints (transfer impedance) and for ranking the stability of various EMI material couples in different environments. At this time, neither of these procedures have been used widely. Further effort is needed to refine and implement these standards.

In its draft form, MIL-G-83528 contained specifications for the allowable change in dc resistance of aluminum test flanges (6061 with Class III chromate conversion coating) containing conductive elastomers and exposed to temperature/humidity and salt spray. This section was dropped, since the gasket manufacturers and the Air Force decided that all of the gaskets were corrosive and that the design of the flange and gasket (e.g., flange coatings, use of sealants, and environmental seals) had a large influence on performance and could not be covered in this materials specification. In fact, as the specification was written, none of the materials would have satisfied the requirements.

Within the military, both the Navy and Air Force have written design handbooks covering the use of EMI gaskets (Air Force - AFSC Design Handbook (DH) 1-4, Electromagnetic Compatibility; Navy - NAVMAT P 4855-2, Design Guidelines for Prevention and Control of Avionic Corrosion). These guidelines must satisfy the conflicting electrical (SE) and corrosion requirements of a system and in practice, do not give the designer a quantitative picture of the initial and long-term electrical tradeoffs between various designs and/or materials.

At this time, it is not clear how commercial specifications will deal with the question of environmental stability of EMI shielding systems. There are indications that the European community (ECC) may include environmental tests in new specifications.

CONCLUSIONS

Increased effort should be directed to determining the long-term shielding performance of digital systems by the military, aerospace, and commercial communities, particularly with the increasing use of digital electronics in critical control systems. The users of EMI shielding materials have to take a more active role in developing a technical database characterizing the stability of shielding "systems." This database would compare the performance of different conductive gasket materials, flange materials, and coatings in different environments. Until more data is available, designers should allow at least a 20 dB safety margin in their designs to account for aging of conductive coatings and EMI gasketed joints. Aggressive environments require still larger margins.

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