

Introduction

1.1 FUNDAMENTAL DEFINITIONS

The following basic terms are used throughout this book.

Containment. A process whereby RF energy is prevented from exiting an enclosure, generally by shielding a product within a metal enclosure (Faraday cage or Gaussian structure) or by using a plastic housing with an RF conductive coating. Reciprocally, we can also speak of containment as preventing RF energy from entering the enclosure.

Electromagnetic compatibility (EMC). The capability of electrical and electronic systems, equipment, and devices to operate in their intended electromagnetic environment within a defined margin of safety, and at design levels or performance, without suffering or causing unacceptable degradation as a result of electromagnetic interference (ANSI C64.14-1992).

Electromagnetic interference (EMI). The lack of EMC, since the essence of interference is the lack of compatibility. EMI is the process by which disruptive electromagnetic energy is transmitted from one electronic device to another via radiated or conducted paths (or both). In common usage, the term refers particularly to RF signals. EMI can occur in the frequency range commonly identified as “anything greater than DC to daylight.”

Radio Frequency (RF). A frequency range containing coherent electromagnetic radiation of energy useful for communication purposes—roughly the range from 10 kHz to 100 GHz. This energy may be transmitted as a byproduct of an electronic device’s operation. RF is transmitted through two basic modes:

Radiated emissions. The component of RF energy that is transmitted through a medium as an electromagnetic field. RF energy is usually transmitted through free space; however, other modes of field transmission may occur.

Conducted emissions. The component of RF energy that is transmitted through a medium as a propagating wave, generally through a wire or interconnect cables.

Line Conducted Interference (LCI). Refers to RF energy in a power cord or AC mains input cable. Conducted signals do not propagate as fields but may propagate as conducted waves.

Immunity. A relative measure of a device or a system's ability to withstand EMI exposure while maintaining a predefined performance level.

Electrostatic discharge (ESD). A transfer of electric charge between bodies of different electrostatic potential in proximity to each other or through direct contact. This definition is observed as a high-voltage pulse that may cause damage or loss of functionality to susceptible devices. Although lightning differs in magnitude as a high-voltage pulse, the term *ESD* is generally applied to events of lesser amperage and more specifically to events triggered by human beings.

Radiated immunity. A product's relative ability to withstand electromagnetic energy that arrives via free-space propagation.

Conducted immunity. A product's relative ability to withstand electromagnetic energy that penetrates it through external cables, power cords, I/O interconnects, or chassis. EMI may also couple to a chassis, if interconnects are improperly implemented.

Susceptibility. A relative measure of a device, or a system's propensity to be disrupted or damaged by EMI exposure to an incident field or signal. It is the lack of immunity.

Suppression. The process of reducing or eliminating RF energy that exists without relying on a secondary method, such as a metal housing or chassis. Suppression may include shielding and filtering as well.

1.2 ELEMENTS OF THE ELECTROMAGNETIC ENVIRONMENT

When an EMI problem occurs, the engineer needs to approach the situation logically. A simple EMI model has three elements:

1. There must be a source of energy.
2. There must be a receptor that is upset by this energy when the intensity of the electromagnetic interference is above a tolerable limit.
3. There must be a coupling path between the source and receptor for the unwanted energy transfer.

For interference to exist, all three elements have to be present. If one of the three elements is removed, there can be no interference. It therefore becomes the engineer's task to determine which is the easiest element to remove. Generally, designing a PCB that eliminates most sources of RF interference is the most cost-effective approach (called *suppression*). The source of interference is the active element producing the original waveform. The PCB must be designed to keep the energy developed to only those sections of the assembly that require this energy. The second and third elements tend to be addressed with containment techniques. Figure 1.1 illustrates the relationship between these three elements and presents a list of items associated with each element.

With respect to PCBs, observe the following:

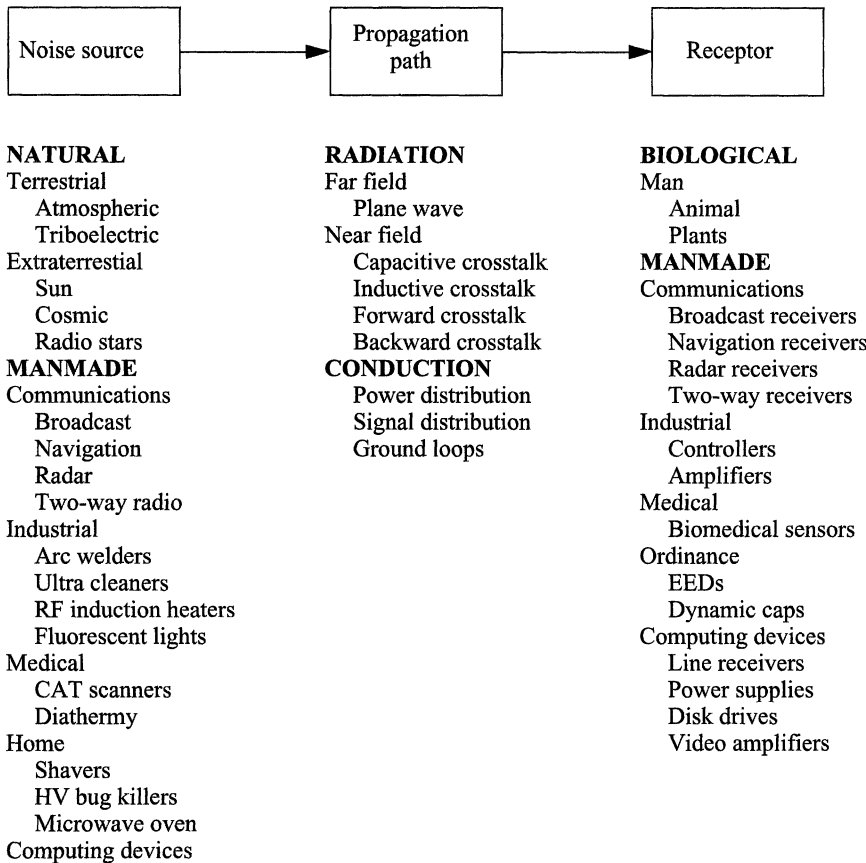


Figure 1.1 Items associated with the three elements of the EMI environment.

- Noise sources are frequency generation circuits, component radiation within a plastic package, incorrect trace routing, ground bounce from digital logic, and common-mode currents developed within an assembly.
- The propagation path is the medium that carries the RF energy, such as free space or interconnects (common impedance coupling).
- Receptors are devices that easily accept interference from I/O cables, or by radiated means, transferring this harmful energy to circuits and devices susceptible to disruption.

On the surface, a product must be designed for two levels of performance: one to minimize RF energy exiting an enclosure (emissions), and the other to minimize the amount of RF energy entering (susceptibility or immunity). Both emissions and immunity are transmitted by radiated or conductive means. This relationship is shown in Fig. 1.2. Also, it must be considered that a product must be compatible within itself, i.e., emitting levels must not compromise the performance of sensitive segments within the product.

When dealing with emissions, a general rule-of-thumb is

The higher the frequency, the greater the efficiency of a radiated coupling path; the lower the frequency, the greater the efficiency that a conducted coupling path will cause EMI. The extent of

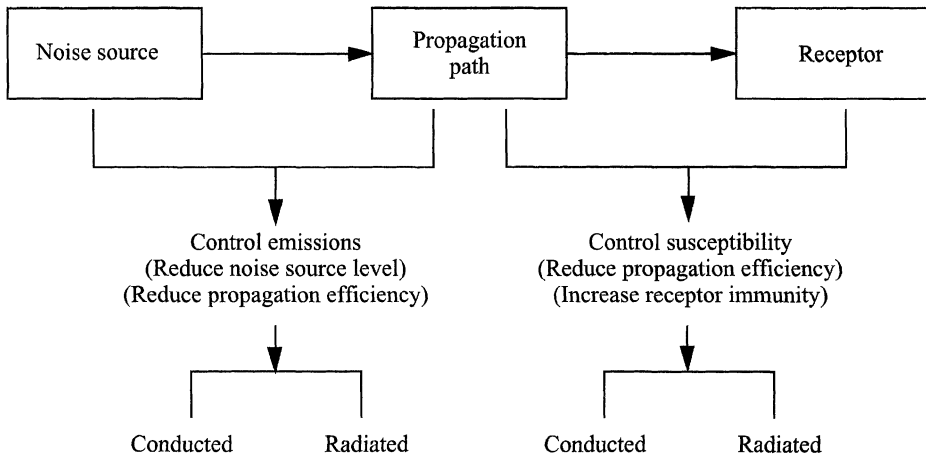


Figure 1.2 Variants of EMI coupling paths.

coupling depends on the frequency of the circuit and edge rate transition of digital components switching logic states and transfer mechanism.

1.3 NATURE OF INTERFERENCE

EMC is grouped into two categories: internal and external. The internal category is the result of signal degradation along a transmission path, including parasitic coupling between circuits in addition to field coupling between internal subassemblies, such as a power supply to a disk drive. Stated more specifically, the problems are signal losses and reflections along the path, along with crosstalk between adjacent signal traces.

External problems are divided into emissions and immunity. Emissions derive primarily from harmonics of clocks or other periodic signals. Remedies concentrate on containing the periodic signal to as small an area as possible, blocking parasitic coupling paths to the outside world.

Susceptibility to external influences, such as ESD or radio frequency interference, is related initially to propagated fields that couple into I/O lines, which then transfer to the inside of the unit, and secondarily to case shielding. The principal recipients are high-speed transmission lines and sensitive adjacent traces, particularly those terminated with edge-triggered components.

There are five major considerations when performing EMC analysis on a product or design [1].

1. *Frequency.* Where in the frequency spectrum is the problem observed?
2. *Amplitude.* How strong is the source energy level, and how great is its potential to cause harmful interference?
3. *Time.* Is the problem continuous (periodic signals), or does it exist only during certain cycles of operation (e.g., disk drive write operation or network burst transmission)?
4. *Impedance.* What is the impedance of both the source and receptor units, and the impedance of the transfer mechanism between the two?
5. *Dimensions.* What are the physical dimensions of the emitting device that cause emissions to occur? RF currents will produce electromagnetic fields that will exit

an enclosure through chassis leaks that equal significant fractions of a wavelength or significant fractions of a “rise-time distance.” Trace lengths on a PCB have a direct relationship as transmission paths for RF currents.

Whenever an EMI problem is approached, it is helpful to review this list based on product application. Understanding these five items will clear up much of the mystery of how EMI exists within a PCB. Applying these five considerations teaches us that design techniques make sense in certain contexts but not in others. For example, single-point grounding is excellent when applied to low-frequency applications, but it is completely inappropriate for radio frequency signals, which is where most of the EMI problems occur. Many engineers blindly apply single-point grounding for all product designs, without realizing that additional and more complex problems are created using this grounding methodology.

When designing a PCB, we are concerned with current flow within the assembly. Current is preferable to voltage for a simple reason: current always travels around a closed-loop circuit following one or more paths. It is to our advantage to direct or steer this current in the manner that is desired for proper system operation. To control the path that the current flows, we must provide a low-impedance, RF return path back to the source of the energy. We must also divert interference current away from the load or victim circuit. For those applications that require a high-impedance path from source to the load, consider all possible paths through which the return current may travel.

1.4 REGULATORY REQUIREMENTS—NORTH AMERICA

Electrical and electronic products generate RF energy. Electromagnetic emission levels are set by rules and regulations mandated by domestic and international governments or agencies. In the United States, the Federal Communications Commission (FCC) regulates the use of radio and wire communications. The FCC is an independent government agency, responsible for ensuring interstate and international communication by radio, television, satellite, and cable.

In Canada, Industry Canada (IC) is the agency responsible for regulating radio and wire communication. Industry Canada performs a function similar to that of the Federal Communications Commission. Harmonized test requirements and standards for North America exist between both the FCC and IC.

The FCC regulates electronic products by specifying technical standards and operational requirements through the Code of the Federal Register (CFR), Title 47. The sections within 47CFR that are most applicable to products discussed herein are Parts 2, 15, 18, and 68. These regulations, developed over many years, are based on complaints filed with the Commission. The most prominent FCC Parts are summarized in the following list. In Canada, the specification equivalent to 47CFR, Part 15, is SOR 88/475.

1. Part 2 is an administrative section that details aspects of how to comply with 47CFR. Included are allocated frequency bands, radio treaty matters, and general rules and regulations. The rules and regulations include registration requirements, authorization procedures, definitions, and various processes to ensure that the federal code is properly administered.
2. Part 15 regulates products that generate unlicensed radio frequency energy, both intentional and non-intentional. Information Technology Equipment (ITE) falls within Part 15.
3. Part 18 regulates Industrial, Scientific, and Medical (ISM) equipment. These devices use radio waves for proper operation.

4. Part 68 regulates electronic equipment connected to a telephone network. This part provides a uniform standard for protecting the telephone network from harm caused by connection of terminal equipment.

The FCC defines a digital device as

An unintentional radiator (device or system) that generates and uses timing signal or pulses at a rate in excess of 9,000 pulses (cycles) per second and uses digital techniques; inclusive of telephone equipment that uses digital techniques or any device or system that generates and uses radio frequency energy for the purpose of performing data processing functions, such as electronic computations, operations, transformation, recording, filing, sorting, storage, retrieval or transfer.

Digital computing products are classified into two categories: Class A and B. The FCC and IC use the same definitions.

Class A: A digital device that is marketed for use in a commercial, industrial, or business environment, exclusive of a device which is marketed for use by the general public or is intended to be used in the home.

Class B: A digital device that is marketed for use in a residential environment, notwithstanding its use in a commercial, industrial, or business environment. Examples of such devices include, but are not limited to, personal computers, calculators, and similar electronic devices that are marketed for use by the general public.

If a product contains digital circuitry and has a clock frequency greater than 9 kHz, it is defined as a digital device and is subject to the rules and regulations of the FCC and IC. Electromagnetic Interference (EMI) may occur as a result of both digital and analog circuits. These products are subject to domestic and international regulatory requirements.

1.5 REGULATORY REQUIREMENTS—WORLDWIDE

Test requirements, standards, and procedures have been harmonized on a worldwide basis. The principles discussed herein will allow regulatory compliance to be achieved with minimal development cost and shorter design cycles. The harmonization process is based on the work of expert technical committees reporting to the International Electrotechnical Commission (IEC).

The IEC works closely with the International Standards Organization (ISO), which is chartered by the United Nations. Many countries throughout the world are members. The IEC oversees the work of technical committees working on a particular product sector. The IEC's objectives are to "promote international co-operation on all questions of standardization . . . achieved by issuing publications including recommendations in the form of international standards."

Two IEC technical committees work on EMC standards. The first is TC77, *Electromagnetic compatibility between equipment including networks*. The second committee is *International Special Committee on Radio Interference* (Comité International Spécial des Perturbations Radioélectriques or CISPR). CISPR publications deal primarily with limits and measurements of the radio interference characteristics of potentially disturbing sources or emissions. CISPR and IEC standards coexist to define most technical aspects related to EMC compliance.

The IEC publications themselves have no legal requirements. National committees do not have to adopt them, although several countries outside of Europe have incorporated them

into their national laws. The important aspect of IEC standards is that they have been adopted and harmonized as a European standard for all members of the European Union. Once published as a harmonized document, a legal requirement now exists.

A separate organization, the Committee for European Electrotechnical Standardization (Comité Européen de Normalisation Electrotechnique, or CENELEC), is responsible for developing European standards for electrical equipment. CENELEC received its charter from the Parliamentary Commission of the European Union and produces EMC standards for use with the EMC Directive, usually based on IEC and CISPR publications.

For telecommunications equipment, the European Telecommunications Standards Institute, or ETSI, is the standards-making body. ETSI develops standards for telecommunications network equipment not supplied to the subscriber, in addition to radio communication equipment and broadcast transmitters.

CENELEC and ETSI adopt IEC and CISPR publications, whenever possible, as a basis for preparing a formal standard. The CENELEC committee responsible for preparing EMC standards is TC110. Technical Committee TC110 has several subcommittees, including SC110A, which is responsible for immunity requirements of Information Technology Equipment (ITE).

International EMC publications are commonly referred to as CISPR or IEC, when in fact the real standard, after adoption and publication by the European Commission, is prefixed with an EN (European Normalization) number. To summarize, the European Commission adopts into law requirements developed by CISPR and the IEC, as well as other European working groups and committees, under the auspices of CENELEC and ETSI.

Although this book focuses on products that fall within the category of ITE, many other product categories can use the information herein. For emission requirements, conducted limits exist from 150 kHz to 30 MHz. Radiated emissions are generally measured from 30 MHz to 1000 MHz, or up to 100 GHz for special products and applications. Immunity tests differ, based on product category, intended end-use environment, and constructional details.

The most commonly referenced CISPR and IEC test publications for products that incorporate printed circuit boards are listed in this section. Appendix B repeats this information with greater detail. Many other test publications and requirements also exist. This list is subject to periodic changes owing to continuing developments in standards writing, along with harmonization within the European Union (EU). The EU was formerly known as the European Community (EC) or the European Economic Community (EEC). This list is current at date of publication and is subject to change without notice. The reader is urged to verify the applicable and current requirements in force at the time of product design and release. For this reason, the year of publication in the *Official Journal of the European Union (OJ)*, the date of withdrawal, amendment updates, and other supporting information relating to date of publication or implementation are not provided in this book.

1.6 STANDARDS

Three tiers of standards have been generated: basic standards, generic standards, and product family standards.

1.6.1 Basic Standards

Basic standards are referenced within generic and product family standards as a basis for performing a particular test. The standards include most IEC and CISPR standards and are dedicated to aspects of EMC that are of general interest to what all committees are working on, creating, or developing other standards. This development work includes product

family standards. It is common for a product family standard to take the appearance of a generic standard. Specific operational modes and configurations are detailed in the standard, including performance criteria and test levels.

1.6.2 Generic Standards

Generic standards were developed for industry sectors for which no product family standard is available. Generic standards encompass all environments and applications, and are intended to represent the essential requirements of a directive. These standards are divided into two basic requirements: emissions and immunity. Environments are defined as residential, commercial, light industrial, or heavy industrial.

When a relevant product family standard is not available, generic standards take precedence. Regarding product categories, a particular device might have a product family emissions standard and yet be required to use a generic standard for immunity tests. The reason for this is that specific test requirements for immunity may be in the development stage or not yet published in the *OJ*.

Generic Standards (Sample List)

Part 1: Residential, Commercial, and Light Industry

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| EN 50081-1 | Electromagnetic compatibility—Generic emission standard. |
| EN 50082-1 | Electromagnetic compatibility—Generic immunity standard. |

Part 2: Industrial Environment

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| EN 50081-2 | Electromagnetic compatibility—Generic emission standard. |
| EN 50082-2 | Electromagnetic compatibility—Generic immunity standard. |

Part 3: Special Environment

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| EN 50081-3 | Electromagnetic compatibility—Generic emission standard. |
| EN 50082-3 | Electromagnetic compatibility—Generic immunity standard. |

1.6.3 Product Family Standards

Product family standards take precedence over generic and basic standards after they are published in the *Official Journal of the European Union*. These standards may be specifically designed to cover a particular aspect of EMC for a particular product, or product family, such as Information Technology Equipment (ITE) or Industrial, Scientific, and Medical Equipment (ISM). In addition, product family standards may be created as an addendum to existing product performance standards.

Product family standards refer to internationally adopted basic standards, such as the IEC 1000-4-X or EN 55024 series for immunity test requirements. These requirements define what tests are to be performed, test levels or limits, operational conditions, and performance criteria. Product family standards are generally based on input from professional engineers and companies who specialize within a particular industry. Companies generally have a more comprehensive concept of the EMC environment than does a technical committee. Working together, industrial and technical committees are best suited to developing realistic test procedures and methodologies to meet the essential requirements of the EMC directive.

The development of product family standards is a never-ending process. Frequent changes are made either with an addendum or with a new release. Whenever a standard is released for draft review, adopted, or published in the *Official Journal*, a date is provided next

to the standard number, such as EN 55022:1995. When use of standards is required for compliance purposes, one should refer to the latest edition or release date appropriate for the product using a reliable source, such as the European Union's web page. Amendments may or may not be applicable to a particular product being certified.

1.6.4 Classification of ITE Products

Products are classified into two categories for emissions: Class A and B. The definition provided by CISPR 22, which is identical to EN 55022 for ITE follows verbatim. Most products described within the present book fall within this definition [2].

Information Technology Equipment (ITE). Any equipment

- a) Which has a primary function of either (or a combination of) energy storage, display, retrieval, transmission, processing, switching, or control of data and of telecommunication messages and which may be equipped with one or more terminal ports typically operated for information transfer;
- b) With a rated supply voltage not exceeding 600 V.

ITE includes, for example, data processing equipment, office machines, electronic business equipment, and telecommunication equipment.

Class B ITE. Class B ITE is a category of apparatus, which satisfies the Class B ITE disturbance limits. Class B ITE is intended primarily for use in the domestic environment and may include

- equipment with no fixed place of use; for example, portable equipment powered by built-in batteries;
- telecommunication terminal equipment powered by a telecommunication network;
- personal computers; and auxiliary connected equipment.

Note: The domestic environment is an environment in which the use of broadcast radio and television receivers may be expected within a distance of 10 m of the apparatus concerned.

Class A ITE. Class A ITE is a category of all other ITE that satisfies the Class A ITE limits but not the Class B ITE limits. Such equipment should not be restricted in its sale, but the following warning shall be included in the instructions for use:

Warning: This is a Class A product. In a domestic environment, this product may cause radio interference in which case the user may be required to take adequate measures.

1.7 EMISSION REQUIREMENTS

The following list deals with emission requirements for the European Union. These standards are identified as product family standards.

Product Family Standards (sample list)

EN 55011	Limits and methods of measurements of radio disturbance characteristics of industrial, scientific, and medical (ISM) radio frequency equipment (CISPR 11).
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EN 55013	Limits and methods of measurements of radio disturbance characteristics of broadcast receivers and associated equipment (CISPR 13).
EN 55014	Limits and methods of measurements of radio disturbance characteristics of household electrical appliances, portable tools, and similar electrical apparatus (CISPR 14).
EN 55015	Limits and methods of measurements of radio disturbance characteristics of electrical lighting and similar equipment (CISPR 15).
EN 55022	Limits and methods of measurements of radio disturbance characteristics of Information Technology Equipment (CISPR 22).
EN 55024	Information Technology Equipment—Immunity characteristics—Limits and methods of measurement (CISPR 24).
EN61000-3-2	Harmonic Current Emissions.
EN61000-3-3	Voltage Fluctuations and Flicker in low-voltage supply systems.

1.8 IMMUNITY REQUIREMENTS

To be able to certify compliance to the EMC Directive, 89/336/EEC, manufacturers must construct products that meet not only emissions requirements, but also immunity levels, or protection against harmful disruption from other electronic equipment. Currently, only Europe requires immunity testing. Since the IEC and CISPR are international organizations, the scope of their work is used throughout the world. CENELEC adopts basic standards developed by both IEC and CISPR, and publishes them as harmonized standards to meet the EMC Directive. The European harmonized document and IEC publication numbers are similar. The IEC standard is prefixed with IEC 1000-4-X. When referenced as a European harmonized document, this number is changed to EN 61000-4-X.

International IEC standards for immunity are provided in the IEC 1000-4-X series. This series of standards describes the test and measurement methods detailed within the basic standards. Basic standards are specific to a particular type of EMI phenomenon, not a specific type of product. This series covers the following:

- Terminology
- Descriptions of the EMI phenomenon
- Instrumentation
- Measurement and test methods
- Ranges of severity levels with regard to the immunity of the equipment

The international IEC 1000-X series of standards, the most commonly used immunity standards adopted or recommended by CENELEC, were reissued using an EN 61000-X specification number. The EN 61000-4-X series of immunity specifications are as follows:

Comprehensive List of Immunity Standards

Standard	Description
EN 61000-4-2	Electrostatic discharge (ESD)
EN 61000-4-3	Radiated electromagnetic field
EN 61000-4-4	Electrical Fast Transient (EFT)/Burst

EN 61000-4-5	Surge
EN 61000-4-6	Conducted disturbance by RF fields
EN 61000-4-7	General guide on harmonics and interharmonics measurements and instrumentation (not a standard; procedure only)
EN 61000-4-8	50/60 Hz magnetic field
EN 61000-4-9	Pulsed magnetic field
EN 61000-4-10	Oscillatory magnetic field
EN 61000-4-11	Voltage dips and interruption
EN 61000-4-12	Oscillatory waves “ring wave”
EN 61000-4-13	Oscillatory waves 1 MHz
EN 61000-4-14	Harmonics, interharmonics, and main signaling
EN 61000-4-15	Voltage fluctuations
EN 61000-4-27	Unbalance in three-phase mains
EN 61000-4-28	Variation of power frequency

Note: Several EN 61000-4-x specifications have never been written or released. Titles have been issued and working groups assigned. When performing compliance testing, verify which standards are mandatory for your product along with required test levels and performance criteria.

1.9 ADDITIONAL REGULATORY REQUIREMENTS— NORTH AMERICA

Other agency requirements in North America include those listed in Table 1.1. These standards are very specific and beyond the scope of this design guideline. A sample list is presented, given that printed circuit boards are used in products covered by these standards.

1.10 SUPPLEMENTAL INFORMATION

In addition to EMC compliance, requirements exist for product safety. These requirements include energy hazards and flammability. All printed circuit boards are subject to high voltage and current levels that pose a possible shock hazard to the user. In addition, extensive current flow on traces generates heat, which can cause the fiberglass material used in the construction of the printed circuit board to burn or melt with an associated risk of fire. Components and interconnects placed on a printed circuit board also provide a source of fuel (combustionable material) that may contribute to a fire hazard under abnormal fault conditions.

The Appendixes of this book are an important part of this design guideline. Much technical information is contained in all chapters. To assist during the design and layout of a PCB, Appendix A, Summary of Design Techniques, provides a brief overview of items dis-

TABLE 1.1 Additional North American Standards

Standard	Subject Area
SAE Standard SAE J 551	Radiated EMI from vehicles and associated devices.
NACSIM 5100 (a.k.a. Tempest)	Classified standard. This requires emissions from certain products to be sufficiently low to prevent interception and deciphering data streams that contain intelligence.
MIL-STD-461/462	U.S. military standard and test procedure for both radiated and conducted emissions.

cussed, cross-referenced to their respective chapter. This summary may be used for quick review during the layout and design stage.

Appendix B is provided as a quick reference to international EMC specification limits for the United States and Canada (FCC/IC), Europe, and worldwide, in addition to the European immunity limits. Appendix C discusses the decibel as well as issues related to using this unit of measurement. Finally, Appendix D presents common conversion tables.

REFERENCES

- [1] Gerke, D., and W. Kimmel. 1994. "The Designer's Guide to Electromagnetic Compatibility." *EDN* (January 20).
- [2] EN 55022:1995 (CISPR 22:1993). *Limits and methods of measurement of radio disturbance characteristics of information technology equipment*.