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Technical Basis for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related I&C Systems

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Prepared for
U.S. Nuclear Regulatory Commission

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Abstract

This report discusses the development of the technical basis for the control of upsets and malfunctions in safety-related instrumentation and control (I&C) systems caused by electromagnetic and radio-frequency interference (EMI/RFI) and power surges. The research was performed at the Oak Ridge National Laboratory (ORNL) and was sponsored by the U.S. NRC Office of Nuclear Regulatory Research (RES). The motivation for research stems from the safety-related issues that need to be addressed with the application of advanced I&C systems to nuclear power plants. Development of the technical basis centered around establishing good engineering practices to ensure that sufficient levels of electromagnetic compatibility (EMC) are maintained between the nuclear power plant's electronic and electromechanical systems known to be the source(s) of EMI/RFI and power surges. First, good EMC design and installation practices need to be established to control the impact of interference sources on nearby circuits and systems. These EMC good practices include circuit layouts, terminations, filtering, grounding, bonding, shielding, and adequate physical separation. Second, an EMI/RFI test and evaluation program needs to be established to outline the tests to be performed, the associated test methods to be followed, and carefully formulated acceptance criteria based on the intended environment to ensure that the circuit or system under test meets the recommended guidelines. Third, a program needs to be developed to perform confirmatory tests and evaluate the surge withstand capability (SWC) and of I&C equipment connected to or installed in the vicinity of power circuits within the nuclear power plant. By following these three steps, the design and operability of safety-related I&C systems against EMI/RFI and power surges can be evaluated, acceptance criteria can be developed, and appropriate regulatory guidance can be provided.

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Executive Summary

This report discusses the development of the technical basis aimed at controlling upsets and malfunctions in safety-related instrumentation and control (I&C) systems caused by electromagnetic and radio-frequency interference (EMI/RFI) and power surges. The research was performed at the Oak Ridge National Laboratory (ORNL) and was sponsored by the U.S. NRC Office of Nuclear Regulatory Research (RES). The motivation for research stems from the safety-related issues that need to be addressed with the application of advanced I&C systems, both analog- and digital-based, in nuclear power plants. Manufacturers of digital circuits are incorporating increasingly higher clock frequencies, faster operating speeds, and lower logic voltage levels into their designs. In turn, recent experiences have shown that industrial equipment using the faster digital logic families often have a greater susceptibility for upsets and malfunctions due to the effects of EMI/RFI and power surges, and accordingly must be protected so that extraneous noise is not misinterpreted as legitimate logic. Also, sensors and some of the electronic circuitry in advanced I&C systems, particularly at the front end interface, are still based on analog technology. Guidelines are needed to ensure that EMI/RFI and power surge issues are properly addressed in the designs and applications of I&C systems in nuclear power plants.

Development of the technical basis for regulatory guidance centered around establishing good engineering practices to ensure that sufficient levels of electromagnetic compatibility (EMC) are maintained between the nuclear power plant's electronic and electromechanical systems throughout their life cycles. First, good EMC design and installation practices need to be established to control the impact of interference sources on nearby circuits and systems. These EMC good practices include circuit layouts, terminations, filtering, grounding, bonding, shielding, and adequate physical separation. Second, an EMI/RFI test and evaluation program needs to be established to outline the tests to be performed, the associated test methods to be followed, and carefully formulated acceptance criteria based on the intended environment to ensure that the circuit or system under test meets the recommended guidelines. Third, a program needs to be developed to perform confirmatory tests and evaluate the surge withstand capability (SWC) of I&C equipment connected to or installed in the vicinity of equipment connected to power circuits within the nuclear power plant. By following these three steps, the design and operability of safety-related I&C systems against EMI/RFI and power surges can be evaluated, acceptance criteria can be developed, and appropriate regulatory guidance can be provided.

It became apparent during the course of the research that acceptance criteria and regulatory guidance could be based on the EMC engineering practices that are routinely applied throughout the nuclear industry and that have been shown to yield good results. Accordingly, the grounding and noise minimization techniques outlined in IEEE Std 1050-1989, *Guide for Instrumentation and Control Equipment Grounding in Generating Stations*, were found–for the most part–to be acceptable EMC design and installation practices for the nuclear power plant environment. Exceptions to IEEE Std. 1050-1989 were also identified and clarifications from related documents were found to enhance the use of the standard. Because the military services regularly incorporate advanced I&C systems into their hardware, it seemed reasonable to assume that an EMI/RFI test and evaluation program could be developed around the digital equipment test requirements from Military Standard (MIL-STD) -461, *Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility* and the associated test methods extracted from MIL-STD-462, *Measurement of Electromagnetic Interference Characteristics*. Also, the SWC guidelines in IEEE Std C62.41-1991, *Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*, were found to be acceptable to ensure adequate surge protection for safety-related I&C systems in nuclear power plants.

The industrial electromagnetic environment–including that in a commercial nuclear power plant–differs drastically from that on the deck of a ship or inside an armored personnel carrier. Hence, the EMI/RFI acceptance criteria specified in the MIL-STD-461 test requirements are not necessarily applicable to the nuclear power plant environment. Furthermore, it is suspected that the electromagnetic environment differs among nuclear power plants and the establishment of a single set of acceptance criteria for the nuclear industry will prove to be a difficult task.

The electromagnetic environment in nuclear power plants is relatively unknown because existing emissions measurement data are rather limited. Thus, in nuclear power plant areas where safety-related I&C systems are destined to be installed, EMI/RFI emissions measurement data need to be collected and emission profiles established. Such profiles would provide a realistic assessment of the probable ambient electromagnetic environment so that acceptance criteria can be established accordingly. Future efforts by the ORNL investigators include the collection of emissions measurement data at various nuclear power plants and subsequently the establishment of *representative* emission profiles.

Acknowledgements

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1 Introduction

This report describes the technical basis for in addressing the control of upsets and malfunctions in safety-related instrumentation and control (I&C) systems caused by electromagnetic and radio-frequency interference (EMI/RFI) and power surges. I&C systems in advanced nuclear reactors are expected to make use of both analog and digital equipment and will be significantly different from the totally analog-based designs currently in use. Since the U.S. nuclear industry has limited operational experience with digital technology and advanced analog electronics, the full extent of upsets and malfunctions in I&C systems due to EMI/RFI and power surges is unknown. Acceptance criteria need to be developed for the use of advanced technologies in safety-related I&C systems that are consistent with the safety issues cited in Subpart B, Part 52, of Title 10 of the Code of Federal Regulations (10 CFR Part 52).

Although several U.S. nuclear power plants have replaced selected totally analog-based systems with primarily digital-based systems, complete replacement of all analog systems in a plant has not been performed to date. Digital signals can carry an increased amount of information as compared to analog signals, and digital equipment has a much faster information processing capability than that of analog counterparts. Thus, the widespread use of digital-based I&C systems in the design of monitoring, control, and protection systems is almost inevitable and can be expected to improve both safety and performance in nuclear power plants. This trend away from totally analog-based systems has led the U.S. NRC Office of Nuclear Regulatory Research to sponsor this research for establishing the technical basis for regulatory guidance aimed at controlling upsets and malfunctions in safety-related I&C systems caused by EMI/RFI and power surges.

2 Statement of Need

The need for research was cited in Section 9.d of Enclosure 1 (*List of Research Needs that Require Early Attention*) to NRC Policy Issue SECY-91-273, "Review of Vendors' Test Programs to Support the Design Certification of Passive Light Water Reactors." Digital technology is constantly evolving; and manufacturers of digital systems are incorporating increasingly higher clock frequencies, faster operating speeds, and lower logic-level voltages into their designs. Industrial experiences[1-3] have shown that I&C systems using the faster digital logic families generally have an increased susceptibility to the effects of EMI/RFI and power surges, and therefore must be protected so that extraneous noise is not misinterpreted as legitimate logic signals. With recent advancements in analog electronics, many of the functions presently being performed by several analog circuits could be combined into a single miniaturized analog circuit operating at reduced voltage levels; thereby making analog circuitry more susceptible to EMI/RFI and power surges as well. Guidelines are needed to ensure that problems in safety-related I&C systems caused by EMI/RFI and power surges are minimized in nuclear power plants.

I&C systems in nuclear power plants have experienced a number of EMI/RFI and power surge problems in recent years, as cited in the Licensee Event Report (LER) database available through the Nuclear Safety Information Center at ORNL. The LER database was examined by ORNL investigators to assess the nature of reactor trips and engineered safety feature (ESF) actuations linked to EMI/RFI and power surges in existing light-water reactors. The search covered a ten year-period (1982-1991) and yielded a total of 74 reportable events. The criterion used for selection was that a safety-related fault subsequently resulted in a channel trip, a full reactor trip, or an ESF actuation. The LER events were selected without regard to operating power. That is, the reactor might have already been in cold shutdown when the trip or ESF actuation occurred. The assumption was made that whether or not the reactor was actually operating when the problem occurred, there is no reason to believe that the results would have been different.

The LER events attributed to EMI/RFI and power surges constituted approximately 15% of the total number of events linked to environmentally-related faults in I&C systems. Of the 74 reportable events, 80% were EMI/RFI-related and the other 20% were power-surge-related. A graphical representation of the distribution is shown in Fig. 1. The trips and ESF actuations were caused by transient noise spikes (the source of which could not be ascertained from the LERs), the use of portable two-way radios resulting in false readings on transmitters, EMI/RFI-induced noise spikes, electrostatic discharges, and lightning-induced spikes. Additional information about the search can be found in NUREG/CR-5904,[4] *Functional Issues and Environmental Qualification of Digital Protection Systems of Advanced Light-Water Nuclear Reactors*.

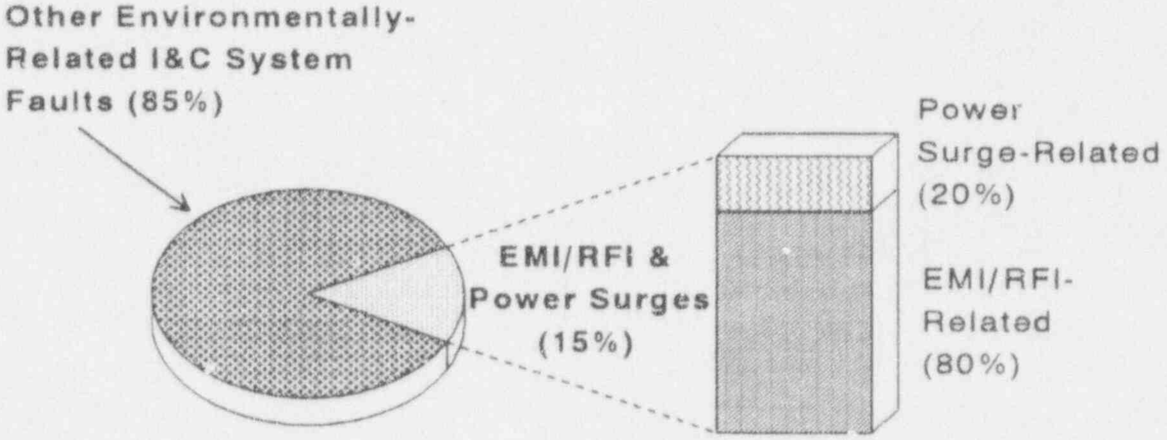

Figure 1 Distribution of safety-related system faults

3 Review of Applicable Standards

In establishing the technical basis for regulatory guidance on controlling upsets and malfunctions in safety-related I&C systems caused by EMI/RFI and power surges, ORNL investigators concentrated on three areas: 1) electromagnetic compatibility (EMC) design and installation practices, 2) EMI/RFI testing and verification techniques, and 3) surge withstand capability (SWC). The effort has resulted in recommendations for design and installation practices for I&C systems that will help ensure operational safety in equipment and testing techniques for verifying that the EMC practices do indeed achieve their intended purposes. The recommendations are designed to help the NRC staff establish the practices and techniques acceptable for complying with NRC regulations.

First, for maximum benefit, regulatory guidance should concentrate on the establishment of good engineering practices that will ensure that EMC is maintained between the nuclear power plant's electronic and electromechanical systems. The goal here is to control the emissions from interference sources and minimize their impact on nearby I&C systems. *Second*, the level of EMI/RFI that safety-related I&C systems should be able to withstand without upset and malfunction needs to be established. Information for determining this level should be derived from electromagnetic emission profiles measured at specific plant sites and used to establish acceptance criteria. Well-founded test and verification techniques could then be implemented to demonstrate that the EMC engineering practices used provide suitable EMI/RFI immunity, i.e., that the safety-related I&C system will operate in its intended environment. These techniques should center around an EMI/RFI test and evaluation program consisting of test criteria, the associated testing methods, and acceptance criteria based on carefully formulated safety margins. *Third*, regulatory guidance should emphasize the importance of ensuring the surge withstand capability of digital I&C equipment to power transients encountered in the nuclear power plant environment. SWC specification and test guidelines should be implemented to achieve this goal. With nuclear power plants' incorporation of good EMC design and installation practices, followed by EMI/RFI and SWC testing/verification, the probability of encountering problems with safety-related I&C equipment will be greatly reduced.

ORNL's work began with reviewing the EMI/RFI- and power surge-related guides and standards in widespread use today for their applicability to I&C systems. Also, a literature search was conducted to ensure that all relevant information was included in the process. The ORNL investigators found that the Institute of Electrical and Electronics Engineers, Inc. (IEEE) Standard 1050-1989, *Guide for Instrumentation and Control Equipment*

Grounding in Generating Stations does—for the most part—an adequate job of specifying EMC design and installation practices that are applicable to the nuclear power plant environment. However, exceptions are taken to certain portions of IEEE Std 1050-1989, and enhancements and clarifications are recommended to improve its applicability. The military services regularly incorporate advanced I&C systems into their hardware, and so Military Standard (MIL-STD)-461C, *Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility* and MIL-STD-462, *Measurement of Electromagnetic Interference Characteristics*, were found to be reasonable points from which to begin an evaluation of relevant EMI/RFI test criteria and methods. Since the research began, MIL-STD-461C and MIL-STD-462 have been superseded by MIL-STD-461D and MIL-STD-462D, and this update is discussed in detail in Section 4.2.4. Also, IEEE Std C62.41-1991, *Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*, was found to provide a practical basis for the selection of voltage and current tests to be applied in evaluating the SWC characteristics of digital I&C equipment connected to ac power circuits.

3.1 EMC Practices (IEEE Std 1050-1989)

IEEE Std 1050-1989 was developed to provide guidance specific to a power generating station for the design of grounding systems for I&C equipment. Creation of this document was sponsored by the Energy Development and Power Generation Committee of the IEEE Power Engineering Society and was approved by the IEEE Standards Board on February 2, 1989.

3.1.1 Organization of IEEE Std 1050-1989

IEEE Std 1050-1989 comprises 8 sections, and the applicable technical content is contained primarily in Sections 4, 5, and 6. It should be noted that the terms *standard* and *guide* are used interchangeably in IEEE Std 1050-1989. Sections 1 and 2 (**Scope and Introduction**) provide background information about the power generating station environment and outline the technical direction taken by the guide. Section 3 (**Definitions**) reviews the definitions and acronyms helpful in understanding the terminology used throughout the guide. Section 4 (**Design Considerations for Electrical Noise Minimization**) provides an in-depth overview of typical noise sources, noise-coupling methods, and techniques useful for minimizing electrical noise.

Section 5 (**Grounding**) outlines the philosophy underlying grounding systems and provides general guidance for grounding I&C systems in a power generating station environment. Section 6 (**Typical Grounding Requirements for Generating Station Applications**) covers the accepted practices for grounding I&C equipment in specific situations. Section 7 (**Testing**) addresses detection and avoidance of ground loops on I&C single-point ground systems; and Section 8 (**Bibliography**) contains an extensive listing of commercial guides, books, and papers relevant to grounding and noise minimization techniques.

3.1.2 Applicability of IEEE Std 1050-1989

IEEE Std 1050-1989 is directed specifically toward grounding and noise-minimization techniques for I&C systems in a power generating station environment. The guide is comprehensive in that it covers both the theoretical and practical aspects of grounding and EMC. Consequently, it provides extremely useful guidance to design engineers who lack an extensive background in grounding and noise-minimization techniques. The authors of the guide thoroughly describe EMI/RFI in the power generating station environment. Section 4 of IEEE Std 1050-1989 covers the gamut of possible interference sources and the mechanisms by which noise can couple into equipment and systems. Section 5 gives background information on the fundamentals of a grounding system, and Section 6 outlines the problems associated with designing a centralized grounding system for a distribution system environment.

3.1.3 Complementary Documents

IEEE Std 1050-1989 is intended to be complementary to and complemented by IEEE Std 518-1982, *IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources;* and by

IEEE Std 665-1987, *IEEE Guide for Generating Station Grounding*. These guides are referenced throughout IEEE Std 1050-1989.

Like IEEE Std 1050-1989, IEEE Std 665-1987 was sponsored by the Power Generation Committee of the IEEE Power Engineering Society. IEEE Std 665-1987 identifies the grounding practices that have been generally accepted by the electric utility industry and provides guidance in designing a safe and effective grounding system. It is particularly thorough in its treatment of electrical bonding. Sponsored by the Industrial Control Committee of the IEEE Industrial Applications Society, IEEE Std 518-1982 provides guidance for the installation of controllers and control systems to ensure proper operation in their intended environment. In addition, the guide thoroughly covers shielding, grounding, and bonding techniques used to minimize noise on signal cables.

IEEE Stds 518-1982 and 665-1987 offer greater detail and more effective explanations than does IEEE Std 1050-1989 on some topics. For example, Sections 4.3.3 and 5.4 of IEEE Std 1050-1989 describe the grounding guidelines for signal cable shields in a style that lacks effectiveness, whereas Section 4.4 (pg. 64) of IEEE Std 518-1982 explains this subject matter much more effectively. Also, the treatment of bonding (i.e., the interconnection of conductive parts in such a manner as to maintain a common electrical potential) is not concise in IEEE Std 1050-1989; references to bonding in the discussions on grounding systems are vague and lack sufficient detail. Section 5.2 of IEEE Std 665-1987 covers this subject in considerably greater detail.

3.2 Testing/Verification (MIL-STD-461 and MIL-STD-462)

A different pair of guidance documents, MIL-STD-461 and MIL-STD-462, were developed for use by Department of Defense agencies to evaluate electromagnetic compliance. Applying to both equipment designs and procurement specifications, these standards are intended to ensure that equipment and subsystems are compatible with their electromagnetic environment and that EMI/RFI effects are considered early in the design process. Note that the term *requirements* is used throughout the MIL-STDs; it is relevant to applications where a specific performance is demanded.

3.2.1 Background of MIL-STD-461 and MIL-STD-462

MIL-STD-461 and MIL-STD-462, first issued in 1967, were intended to consolidate the requirements and test methods of the Army, the Navy, and the Air Force. The tri-services have since revised MIL-STD-461 such that it became three separate documents under a single cover until recently when it reverted back to a single document. The first two revisions, MIL-STD-461A and MIL-STD-461B, were issued on August 1, 1968, and April 1, 1980, respectively. They focused on establishing separate test requirements for each military service branch. A third revision, released on August 4, 1986 as MIL-STD-461C, updated the standard to include electromagnetic pulse (EMP) requirements and changed the acceptance criteria for some existing requirements. The fourth and most recent revision was released on January 11, 1993 as MIL-STD-461D. Rather than making evolutionary changes like the past revisions, the MIL-STD-461D revision was *revolutionary* in nature. Very little went unchanged and many of the existing test requirements from MIL-STD-461C were either modified, dropped entirely, or replaced with new requirements.

MIL-STD-462 has also been updated through the years. The most recent update, MIL-STD-462D was also released on January 11, 1993 and incorporates drastic modifications to the EMI/RFI test methods to reflect the test requirements called out in MIL-STD-461D. It may be of interest to note that there never was an *A*, *B*, or *C* version of MIL-STD-462 and the *D* designation only references its MIL-STD-461D counterpart. Before the last update, the original version had been superseded by six "Notices" designed to adapt MIL-STD-462 to the unique requirements of the Army, the Navy, and the Air Force. Notices 1 and 2 were released by the Air Force on August 1, 1968, and May 1, 1970, respectively. Notice 1 corrected grammatical errors and modified the structure of the document. Notice 2 made changes to some of the test procedures and redefined the applicability of others. Notice 3 was released on February 9, 1971, by the Army as a complete stand-alone document to meet their requirements. Notice 4 was released by the Navy on April 1, 1980, to add a test method for evaluating the susceptibility of equipment to common-mode currents. Notice 5 was issued on August 4, 1986 by the Navy and

Notice 6 was issued on October 15, 1987 by the Air Force to include the new EMP test methods and changes to existing test methods.

3.2.2 Applicability of MIL-STD-461 and MIL-STD-462

MIL-STD-461 establishes the military's emission and susceptibility requirements for electronic, electrical, and electromechanical equipment and subsystems. The standard ensures that control of both conducted and radiated interference is addressed over the frequency range 30 Hz to 10 GHz. (The frequency range can extend to as high as 40 GHz for specific types of equipment and subsystems.) MIL-STD-461 also provides a basis for evaluating the electromagnetic characteristics of equipment and subsystems by setting operational acceptance criteria. The requirements of MIL-STD-461 are typically applicable only as specified in the contracting agreement between a private enterprise and the federal government. Since the ORNL research began before the issuance of MIL-STD-461D and MIL-STD-462D, our evaluation was conducted primarily on the MIL-STD-461C test requirements and associated MIL-STD-462 test methods.

The applicability of the MIL-STD-461C test requirements depends on the class designation assigned to the equipment or subsystem under review. MIL-STD-461C consists of 10 parts that describe the requirements for different classes of equipment and subsystems according to their mission, platform, and intended environment. Part 1 establishes the general documentation and design requirements, while Parts 2 through 6 cover the requirements for equipment and subsystems installed in critical areas. Parts 7 through 10 cover support and miscellaneous general-purpose equipment. The equipment and subsystem class designations and their applicable parts in MIL-STD-461C are shown in Table 1.

Table 1 MIL-STD-461C equipment and subsystem classes vs applicable parts

Class	Description	Applicable part
A	Equipment and subsystems that must operate compatibly when installed in critical areas, such as the following platforms and installations:	
	A1 Aircraft (including associated ground support equipment)	2
	A2 Spacecraft and launch vehicles (including associated ground equipment)	3
	A3 Ground facilities (fixed and mobile including tracked and wheeled vehicles)	4
	A4 Surface ships	5
	A5 Submarines	6
B	Equipment and subsystems that support the Class A equipment and subsystems but will not be physically located in critical ground areas. Examples are electronic shop maintenance and test equipment used in noncritical areas, theodolites, navaids, and similar equipment used in isolated areas	7
C	Miscellaneous general-purpose equipment and subsystems not usually associated with a specific platform or installation, such as the following specific items:	
	C1 Tactical and special-purpose vehicles and engine-driven equipment	8
	C2 Engine generators and associated components, uninterruptible power supplies and mobile electric power equipment supplying power to or used in critical areas	9
	C3 Commercial electrical and electromechanical equipment	10

The MIL-STD-461C requirements are specified by alphanumeric codes and are shown in Table 2. The first designation declares the requirement to be either radiated (R) or conducted (C), and the second designation specifies whether it covers emissions (E) or susceptibility (S). A unique method (UM) assignment is given to requirements that do not fall into any of these predefined categories. The alphabetic notation is followed by a numbering system that is specific to the particular test requirement.

Table 2 MIL-STD-461C emission and susceptibility requirements

Requirement*	Description
CE01	Conducted emissions, power and interconnecting leads, low frequency (up to 15 kHz)
CE03	Conducted emissions, power leads, 15 kHz to 50 MHz
CE06	Conducted emissions, antenna terminals, 10 kHz to 26 GHz
CE07	Conducted emissions, power leads, spikes, time domain
CS01	Conducted susceptibility, power leads, 30 Hz to 50 kHz
CS02	Conducted susceptibility, power and control leads, 0.05 to 400 MHz
CS03	Intermodulation, 15 kHz to 10 GHz
CS04	Rejection of undesired signals, 30 Hz to 20 GHz
CS05	Cross-modulation, 30 Hz to 20 GHz
CS06	Conducted susceptibility, spikes, power leads
CS07	Conducted susceptibility, squelch circuits
CS09	Conducted susceptibility, structure (common-mode) current, 60 Hz to 100 kHz
CS10	Conducted susceptibility, damped sinusoidal transients, pins and terminals, 10 kHz to 100 MHz
CS11	Conducted susceptibility, damped sinusoidal transients, cables, 10 kHz to 100 MHz
RE01	Radiated emissions, magnetic field, 0.03 to 50 kHz
RE02	Radiated emissions, electric field, 14 kHz to 10 GHz
RE03	Radiated emissions, spurious and harmonics, radiated technique
RS01	Radiated susceptibility, magnetic field, 0.03 to 50 kHz
RS02	Radiated susceptibility, magnetic and electric fields, spikes and power frequencies
RS03	Radiated susceptibility, electric field, 14 kHz to 10 GHz
RS05	Radiated susceptibility, electromagnetic pulse field transient
UM03	Radiated emissions and susceptibility, tactical and special-purpose vehicles and engine-driven equipment
UM04	Conducted emissions and radiated emissions and susceptibility, engine generators and associated components, uninterruptible power supplies and mobile electric power equipment
UM05	Conducted and radiated emissions, commercial electrical and electromechanical equipment

*C = conducted, E = emissions, R = radiated, S = susceptibility, and UM = unique method.

The test methods corresponding to the MIL-STD-461C requirements are described in MIL-STD-462 and are designated by the same alphanumeric codes. MIL-STD-462 establishes the procedures to be followed in making the test measurements and in determining the electromagnetic characteristics of the equipment or subsystem under test. Although some of the tests must be made in a shielded room or anechoic chamber, others do not require a special low-ambient electromagnetic environment. MIL-STD-462 also specifies the test equipment, setup, and grounding configuration necessary to ensure meaningful and repeatable test data.

As related to the establishment of test criteria that meet the needs of the NRC, certain specific MIL-STD-461C test requirements were found to be directly applicable to safety-related I&C equipment. These applicable test requirements and their associated MIL-STD-462 test methods are discussed in Section 4.2. As well, a summary of the most recent revisions, MIL-STD-461D and MIL-STD-462D, and how they compare to MIL-STD-461C and MIL-STD-462 is given.

3.3 Surge Withstand Capability (IEEE Std C62.41-1991)

IEEE Std C62.41-1991 provides guidance for the selection of voltage and current surge tests to be applied in evaluating the surge withstand capability of equipment connected to low-voltage ac power circuits. The document was sponsored by the Surge Protective Devices Committee of the IEEE Power Engineering Society and approved by the IEEE Standards Board on February 25, 1991. IEEE Std C62.41-1991 was later approved by the American National Standards Institute (ANSI) on September 6, 1991, thereby gaining additional credibility by its recognition as an ANSI standard.

3.3.1 Organization of IEEE C62.41-1991

IEEE Std C62.41-1991 comprises 10 sections and 3 appendices, with Sections 7, 9, and 10 providing most of the quantifying technical data for a manageable set of waveforms representative of complex surge environments. Recommendations on surge waveforms are presented as guidelines and should not be misinterpreted as performance standards. Section 1 (**Scope**) describes the purpose and technical direction of the document. Section 2 (**How to Use This Document**) presents a brief outline of the document, guidance on its application, and actions to be taken by the user in achieving practical immunity to surges. Sections 3 and 4 (**Definitions** and **References**) define terms not provided in IEEE Std 100-1988[5] and also give a list of key documents supporting the basic concepts of IEEE Std C62.41-1991. Section 5 (**Origin of Surge Voltages**) provides an overview of the circumstances and mechanisms leading to the occurrence of surge voltages and currents.

Section 6 (**Summary of Database**) discusses the available database on power surge occurrences, its limitations, and the assumptions made to develop the definition of a simplified generic surge environment. Section 7 (**Recommended Selection of Representative Environments**) presents the rationale for going from the limited database on the complex surge environment to a manageable set of representative surge waveforms. Section 8 (**Recommended Planning for Surge Immunity**) explains the tradeoffs which must be made to realistically match the surge withstand capability of equipment with its intended operational environment. Section 9 (**Definition of Standard Surge Testing Waveforms**) and Section 10 (**Definition of Additional Surge Testing Waveforms**) provide detailed information on the two standard surge waveforms and the three additional (optional) waveforms recommended in IEEE Std C62.41-1991. This information includes waveshapes, amplitudes, energy contents, tolerances, and applications. Appendix A (**Detailed Database**), Appendix B (**Additional Information**), and Appendix C (**Annotated Bibliography**) provide information that enhances the credibility of the guide, but would burden the reader if included in the main body.

3.3.2 Applicability of IEEE Std C62.41-1991

Protection from voltage and current surges in ac power circuits is best achieved through the application of surge withstand devices matched to both the equipment being protected and its operational environment. IEEE Std C62.41-1991 recognizes that there are no specific models representative of all surge environments, but tries to simplify the complexities of the real world so as to define a set of representative surge test waveforms having ıanageable dimensions. This set of waveforms then serves as a baseline surge environment to make SWC testing uniform, meaningful, and reproducible. The representative waveforms are described on page 32 of the guide as follows:

(1) Oscillatory surges of relatively high frequency, generally labeled "Ring Wave." Those at the higher end of the frequency range have limited energy deposition capability, but may have high peak voltages. Those at the lower end of the frequency range generally have higher energy deposition capability but lower peak voltages.

(2) High-energy surges of various waveforms that are generally accepted as appropriate representations of stresses associated with nearby direct lightning discharges, fuse operation, and capacitor switching.

(3) Bursts of very fast surges (such as produced by local load switching) having little energy but capable of producing serious interference or upset.

It is our opinion that IEEE Std C62.41-1991 can be adapted for regulatory guidance. The guide is well documented in that it provides precise definitions and mathematical equations for the surge waveforms to be applied. Tolerances on the performance of test equipment are also provided to help assure standardized waveforms among test laboratories. Also, information is presented relevant to the intended surge environment based upon location within the facility, power line impedance to the surge, and available energy content. Location categories and exposure levels are outlined in the guide that, if properly selected, lead to recommendations on applicable surge waveforms that will provide an appropriate degree of surge withstand capability.

Typical environmental conditions in a nuclear power plant can be represented by the two standard surge waveforms, and special situations may also be identified for which the additional waveforms may be appropriate. Situations classified as "special" include load switching, the presence of capacitor banks, or the operation of fuses. One situation that has been recognized to impact digital logic circuits is the burst of fast transients which sometimes accompanies load switching in nearby equipment. These bursts have the potential for interfering with the logic states of digital systems and thereby causing upsets.

4 Discussion of Technical Basis

4.1 IEEE Std 1050-1989

In the opinion of the ORNL investigators, the design and installation practices described in IEEE Std 1050-1989 provide useful to guidelines for controlling upsets and malfunctions in safety-related I&C systems caused by EMI/RFI. However, some exceptions need to be made, and enhancements are also suggested to increase the comprehensibility and usefulness of IEEE Std 1050-1989. The associated IEEE guides that complement the design and installation practices in IEEE Std 1050-1989 were discussed briefly in Section 3.1.3.

ORNL recommends the endorsement of IEEE Std 1050-1989, *Guide for Instrumentation and Control Equipment Grounding in Generating Stations*, with the exceptions listed in Section 4.1.1. The suggested enhancements listed in Section 4.1.2, although meant to be helpful, are by no means necessary. It is also suggested that associated guides (like IEEE Std 518-1982 and IEEE Std 665-1987) that are not intended to be endorsed as regulatory guidance be used in a manner consistent with current NRC practices. That is, endorsement of IEEE Std 1050-1989 should not automatically imply the endorsement of any other guide. A look-up listing, illustrating how the guides complement one another, is given in Table 3, which is organized by topics and locations of pertinent information.

4.1.1 Exceptions to the Practices of IEEE Std 1050-1989

The authors take the following significant exceptions to the design and installation practices promoted by IEEE Std 1050-1989. The boldfaced, numbered reference at the beginning of each exception indicates the section in IEEE Std 1050-1989 to which our recommended exception is directed.

Table 3 Look-up listing on EMI/RFI guidelines

Topic	Reference
Electromagnetic Interference Sources	IEEE Std 1050-1989, Section 4.1 IEEE Std 518-1982, Section 3.3
Noise Coupling Mechanisms	IEEE Std 1050-1989, Section 4.2 IEEE Std 518-1982, Section 3.4
Susceptibility of Digital Systems	IEEE Std 1050-1989, Section 6.6 IEEE Std 518-1982, Section 3.5
Grounding: Philosophy	IEEE Std 1050-1989, Section 5 IEEE Std 518-1982, Section 6.2
Power Ground System	IEEE Std 1050-1989, Sections 5 & 6 IEEE Std 665- 1987, Section 5.2
Signal Ground System	IEEE Std 1050-1989, Sections 5 & 6 IEEE Std 665- 1987, Section 5.2
Lightning and Transients	IEEE Std 665-1987, Section 5.3
Electrical Noise Minimization Techniques	IEEE Std 1050-1989, Section 4.3 IEEE Std 518-1982, Sections 4 & 5
Installation Practices: Shielding	IEEE Std 518-1982, Sections 6.3 & 6.4
Filtering and Buffering	IEEE Std 518-1982, Section 4.5
Grounding and Bonding	IEEE Std 1050-1989, Sections 5.4 & 6 IEEE Std 518-1982, Section 6.2 IEEE Std 665-1987, Section 5.2

4.3.7.1 Common Impedance Coupling

".... 2. Optimize circuit impedances for minimum coupling. Maximum power will be coupled between circuits when the load and source impedances are equal."

The statement made about the coupling of maximum power needs to be revisited. In accordance with the Maximum Power Transfer Theorem in electric circuit theory, a load impedance connected to a circuit will absorb maximum power when the load impedance is equal to the *conjugate* of the source impedance.[6-8] A given impedance and its conjugate are defined as $Z = R + jX$ and $Z = R - jX$, respectively, where Z is impedance, R is the resistive component of Z, and X is its reactive component.

As shown in Fig. 2, the source voltage $\mathbf{V}_S$ and source impedance Z_S are the Thévenin equivalents of the voltage and impedance observed looking back into the circuit. These values are fixed and so the load impedance Z_L has to be selected to match Z_S for maximum power transfer; that is,

$$Z_L = Z_S^*. \tag{1}$$

To derive how maximum power is transferred, we begin by expressing Z_S and Z_L in rectangular form; thus

$$Z_S = R_S + jX_S \tag{2}$$

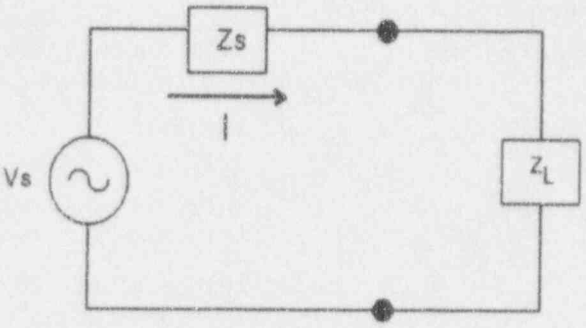

Figure 2 Thévenin equivalent circuit

and

$$Z_L = R_L + jX_L. \tag{3}$$

Because it is assumed that we are calculating average power, voltage and current can be expressed in terms of their root mean square (rms) values. Also, the source voltage can be taken as the reference phasor. With this in mind, it follows from Fig. 2 that the rms value of the load current I is

$$I = \frac{V_S \angle 0^\circ}{(R_S + R_L) + j(X_S + X_L)}. \tag{4}$$

The average power delivered to the load is

$$P = |I|^2 R_L. \tag{5}$$

By substituting Eq. (4) into Eq. (5), the average power can be expressed as

$$P = \frac{|V_S|^2 R_L}{(R_S + R_L)^2 + (X_S + X_L)^2}. \tag{6}$$

The goal is to maximize the average power. Since the source voltage and source impedance are fixed, the average power can only be maximized by finding values for the load impedance components (R_L and X_L) such that $\partial P/\partial R_L$ and $\partial P/\partial X_L$ are both zero. Expressing the partial derivatives of Eq. (6) in terms of R_L and X_L yields

$$\frac{\partial P}{\partial R_L} = \frac{|V_S|^2[(R_S + R_L)^2 + (X_S + X_L)^2 - 2R_L(R_S + R_L)]}{[(R_S + R_L)^2 + (X_S + X_L)^2]^2} \tag{7}$$

and

$$\frac{\partial P}{\partial X_L} = \frac{-|V_S|^2 2R_L(X_S+X_L)}{[(R_S+R_L)^2+(X_S+X_L)^2]^2}. \tag{8}$$

From Eq. (7), $\partial P/\partial R_L$ will be zero when

$$R_L = \sqrt{R_S^2+(X_S+X_L)^2}. \tag{9}$$

From Eq. (8), $\partial P/\partial X_L$ will be zero when

$$X_L = -X_S. \tag{10}$$

By combining the results expressed in Eq. (9) and Eq. (10), we see that both partial derivatives are equal to zero when $R_L=R_S$ and $X_L=-X_S$. Thus, maximum power is transferred when

$$Z_L = Z_S^*.$$

In the context of common impedance coupling, maximum power will **not** be coupled when the circuit impedances are equal. Nonetheless, a considerable amount of power can be coupled, depending on which impedance component is dominant. Circuit impedances should be made as **unequal** as practical in order to ensure minimum coupling.

4.3.7.4. Radiative Coupling

"…. field strength is inversely proportional to the square of the distance."

This statement needs to be reevaluated because radiative coupling is a **far-field** effect. The distribution of *field strength* about a radiating source is dependent on the source characteristics, the medium through which the field is propagating, and the distance of the observation point from the source.[9-11] The region close to the source is known as the near, or induction, field and the electromagnetic field properties in this region are determined primarily by the characteristics of the source. At an observation point far from the source, the field properties depend on the propagation medium and this region is known as the far, or radiation, field. The transition region between the near and far fields is where the observation point is around a distance r equal to the wavelength λ divided by 2π ($\lambda/2\pi$).

The wave impedance of a field varies with distance and is dependent on whether the field is electric or magnetic. In the *far field* ($r > \lambda/2\pi$) the wave impedance is equal to the characteristic impedance of the medium through which the field is propagating (e.g., 377 Ω in air and free space). Both the electric and magnetic *field strengths* fall off as 1/r in the far field, i.e., in inverse proportion to distance (not as its square). This concept is not to be confused with the propagation of electromagnetic waves in the *near field* ($r < \lambda/2\pi$) where the wave impedance is determined by the characteristics of the source and the distance from the source. In the near field, if the source impedance is *high* compared to 377 Ω, the electric and magnetic *field strengths* attenuate at rates of $1/r^3$ and $1/r^2$, respectively. If the source impedance is *low* compared to 377 Ω, the rates of attenuation are reversed: the electric *field strength* will fall off at a rate of $1/r^2$ and the magnetic *field strength* at a rate of $1/r^3$.

As stated earlier, the role of the source characteristics becomes less significant in determining the electromagnetic field's wave impedance in the far field, i.e., the source has little impact on the rate at which the *field strength* attenuates or the field pattern observed. A theoretical isotropic point source radiates a spherical wave in both the near and far fields. Conversely, a line source or antenna has a very distinctive near-field radiation pattern that depends primarily on its construction techniques (dipole, conical, etc.). However, when viewed from a great distance, the dimensions of the line source or antenna seem small and their radiation appears to take the form of a spherical wave. Thus, most sources can be considered as point sources when describing their far-field effects. It is therefore recommended that a rate of 1/r always be used to estimate the attenuation of field strength with distance in the far field.

5.2.1 AC and Signal Ground Buses

".... Under normal operating conditions the ac ground (safety ground) wire should not carry any current. Safety grounds should be differentiated from signal grounds, which do carry current under normal conditions."

This statement can lead to the use of **improper** grounding practices. In this context, the term *signal ground* is referring to the signal return, a current-carrying conductor that returns the signal back to its source. The *signal ground* is actually a reference plane for a circuit which is as close to an equipotential plane as possible.[12] Depending on the configuration of the grounding system, the *signal ground* and signal return are very often the same. However, the signal return does **not** have to be a *signal ground* and the two terms should not be used synonymously.

The *safety ground* is a low-resistance connection to earth capable of conducting fault current and limiting the voltage with respect to ground during a fault. Typically identified as the "green wire," the safety ground's primary function is to protect personnel against injury and its secondary function is to protect equipment. Under normal operating conditions, the *safety ground* does not carry current.[13] The real functional difference between *safety ground* and *signal ground* is that **safety grounds are always at earth potential** whereas *signal grounds* are usually–but not necessarily–at earth potential.

In a cabinet housing electronic equipment, a clear distinction has to be drawn between the *safety ground* and *signal ground*. The cabinet chassis is bonded to the *safety ground* which is at earth potential. In turn, the *signal ground* may or may not be bonded to the *safety ground*. In the multipoint grounding system, an equipotential ground is maintained between the various circuits of the system. The cabinet chassis is connected to *safety ground* and the *signal grounds* of the various circuits are connected to the chassis. In the single-point grounding system, a single point within the cabinet is designated as the reference ground and is connected to the *safety ground*. All *signal grounds* are then tied to the one reference point. This isolates the circuits in the cabinet and prevents any circulating currents in the *safety ground* from producing potential drops within the cabinet. Conversely, in the floating ground system, the *signal grounds* of the circuits in the cabinet are completely insulated from *safety ground*.[14] Thus, it is concluded that **not** all signal grounds carry current, whereas signal returns carry current (however small) under normal conditions.

6.7 Grounding for High-Frequency Signals

".... If the signal is at ground potential on either end of the cable, the shield is grounded at that end. Any additional grounding point will allow shield current to flow, which adds noise to the RF signal."

This statement on grounding for high-frequency signals requires further evaluation. While it is true that at *low frequencies* a shield should be grounded at a single point to eliminate the shield ground loop, at *high frequencies* stray capacitive coupling completes the ground loop and it is often necessary to ground the shield at both ends (and, in fact, at multiple points in between) to guarantee that the shield remains at ground potential over its entire length.[15-16]

If the shield is not grounded on both ends and at multiple points in between, a noise voltage can be picked up that is proportional to the frequency of the noise source, the resistance of the affected circuit to ground, the capacitance between the interference source and affected circuit, and the magnitude of the noise source voltage.

Two rules of thumb are cited by Ott[17] to help decide when a shield should be grounded at one end only or at both ends and points in between. These rules require some knowledge of the frequencies of potential interference sources present in a particular electromagnetic environment. The two rules of thumb are as follows:

(1) At frequencies less than 1 MHz, shields should normally be grounded at one end only. Otherwise, large power-frequency currents can flow in the shield and introduce noise into the signal circuit. The single-point ground also eliminates the shield ground loop and its associated magnetic pickup.

(2) At frequencies above 1 MHz or where cable length exceeds one-twentieth of a wavelength, it is often necessary to ground a shield at more than one point to guarantee that it remains at ground potential. It is common practice at *high frequencies* to ground cable shields at both ends. For long cables, grounding may be required every one-tenth wavelength.

It is therefore recommended that high-frequency signal shields be grounded at both ends and at points every one-tenth wavelength along long cable lengths.

4.1.2 Enhancements to the Practices of IEEE Std 1050-1989

The following commentary and additional background information is intended to enhance the comprehensibility and usefulness of IEEE Std 1050-1989. The boldfaced, numbered reference at the beginning of each enhancement concept indicates the section in IEEE Std 1050-1989 to which the enhancement is directed.

4.1.2 Incidental Sources

".... some of the incidental sources mentioned in this section originate predominately in the substation environment."

Switching transients occur frequently in the substation environment and are the result of redistribution of the total (source and stored) electrical energy. Transients are described in terms of the frequency spectrum of the source and the natural frequencies of the system. For example, the natural frequencies of a cable of length ℓ are

$$S_n = -\frac{1}{2}\left(\frac{R}{L} + \frac{G}{C}\right) \pm j\frac{1}{2}\sqrt{\frac{4\pi^2 n^2}{\ell^2 LC} - \left(\frac{R}{L} - \frac{G}{C}\right)^2}\ , \quad n = 1, 2, \ldots\ , \tag{11}$$

where R, L, G, and C are the resistance, inductance, conductance, and capacitance of a unit length.[18]

4.1.2.10 Computer Systems

".... The highest noise frequency, however, will be a function of the rise and fall times of the clock pulse."

Knowing the quantitative relationship between the rise time t_r and the frequency bandwidth f_c of the clock pulse also provides a useful tool for evaluating the noise spectrum of computers. These parameters are related by[19]

$$f_c \approx (\pi t_r)^{-1}\ . \tag{12}$$

4.1.2.12 Mechanical Vibrations

".... they also can produce an arc discharge and introduce noise into the ground system."

Mechanical vibrations and shock may also give rise to two additional noise sources: (1) induction signals produced by the motion of cables in electromagnetic fields, i.e., flux cutting, and (2) triboelectric cable noise produced by cable flexure or deformation. This second source of noise is due to the disruption of charges built up on the cable's dielectric surfaces and can result in noise levels as large as a few volts. It can be quite troublesome in sensing circuitry operating at low signal levels, e.g., ionization chambers and thermocouple signal leads.[20]

4.1.2.13 Chemical Contamination

".... Most plant atmospheres contain suspended chemicals; i.e., oil, coolants, degreasing solutions...."

For an electrical connection to survive and remain trouble-free for years, it is necessary to clean all contamination from it before mechanically bonding and sealing it.[21]

4.1.2.15. Cable Resonance

".... Electrical disturbances travel at 186,000 miles/s in a vacuum, slightly slower in conductors."

Strictly speaking, waves **cannot** travel **in** a conductor. Rather, electromagnetic waves are guided by the surface of a conductor.[22]

4.3.2.1 Cabling Routing

".... 4. AC power, which enters control cabinets, should be routed as close as possible to the conductive cabinet, while the control cabling should be routed within the interior of the cabinet...."

Certainly, care should be taken to avoid poor wire routing that could result in undesired coupling. Like the ac power, the **control cabling** should also be routed close to the conductive cabinet or reference ground plane, while maintaining an adequate physical separation from the ac power cabling.[23]

4.3.2.2 Physical Separation

".... Refer to 4.3.3, Fig. 8 ...."

The relationship between the capacitance C in Fig. 8 and inductance L is given by $LC = 1/v_p^2$, where v_p is the phase velocity of the wave in the medium. Knowledge of this relationship makes Fig. 8 equally useful for the evaluation of the inductance L.[24]

4.3.3.1 Electronic Equipment Shielding

".... shielding can be accomplished by using waveguides operating beyond cutoff frequency."

For a circular waveguide, the attenuation S (in decibels) for frequencies below cutoff ($f < f_c$) is given by $S(\text{dB}) \approx 32\ T/W$, where $f_c(\text{Hz}) \approx 1.76 \times 10^8/W$. Here, W is the radius and T is the length (in meters) of the circular waveguide. For rectangular apertures (slots), $S(\text{dB}) \approx 27.3\ T/W$, where $f_c(\text{Hz}) \approx 1.5 \times 10^8/W$. Here, W is the larger internal dimension of the cross section of the slot and T is the smaller dimension (both in meters).[25]

4.3.3.2 Cable Shielding

".... In general, the individually shielded conductors or conductor pairs should have their shields connected to ground at the signal source."

This general admonition to ground the shield at the signal source is unnecessarily vague. More specifically, the shield should be grounded at the point where the signal is grounded or at the source common.[26]

4.3.6.1 Isolation Transformers

"....When both ends of a wire pair are fed by isolation transformers, the wires become isolated from ground potential differences in the terminal equipment. The use of isolation transformers is only possible for ac signals."

The reader should be reminded that isolation transformers are useful only to reduce the low-frequency noise caused by ground potential differences.[27]

4.3.6.5 Fiber Optic Cables

".... Use fiber optic cables since they are immune to the interference sources which plague standard current-carrying control cables."

This is good advice, but it needs to be kept in mind that the use of fiber optics is not a cure-all. The input and output circuits of the fiber-optic link are likely to be sensitive to electromagnetic interference.[28]

4.3.7.1 Common Impedance Coupling

".... 3. Make ground connections as short as possible."

The definition of **short** will differ for high- and low-frequency applications. For high frequencies, **short** may be on the order of a few inches; and for low frequencies, **short** may be on the order of tens of feet.[29]

".... 4. Reduce the resistance and impedance of ground conductors."

However low in value, the inductance of a ground conductor at higher frequencies will increase the ground's impedance. It is also possible for a ground conductor to act as an antenna and thereby radiate noise, so the ground conductor cannot be viewed as a sink into which limitless quantities of noise can be dumped harmlessly.[29]

5.1.2 Generating Station Grounding System

".... The instrumentation and control grounding system, while also providing personnel protection from electrical shock, is primarily designed to minimize the generation and transfer of noise voltages."

This statement needs to be revisited. Authorities are in general agreement that the primary requirement of a grounding system is *personnel safety*; the minimization of electrical noise through the grounding system is of secondary importance.[30]

5.2.2 Ground Conductor Lengths

".... The total inductance of a typical ground path is usually less than 750 μH, which at 60 Hz represents an impedance of less than 0.3 Ω. At 10 MHz, however, the impedance can be greater than 40,000 Ω."

The text implies that a ground conductor can be treated approximately like a linear inductor; thus, its impedance at 10 MHz would be $(10 \times 10^6/60)$ times its impedance at 60 Hz. Generally, such an assumption is **not** correct. Deviations from linearity are caused by distributed capacitance and skin-effect losses. The calculations should take these high-frequency effects into consideration.[31]

".... At MHz frequencies, the impedance of a long ground cable can become high enough that the conductor no longer provides an effective low-impedance current path to ground."

This statement is **true** but makes implications that are somewhat ambiguous. The conductor of a safety ground was never intended to carry high-frequency currents to ground (earth). Rather, its purpose is to provide an effective low-impedance current path to ground *at the power line frequency* (i.e., 50-60 Hz).[32]

5.3.1 Single-Point Ground System

".... When the shield is connected to ground at both ends and these two points are widely separated, there is a risk that large shield currents may be induced by system transients. Since cable shields are not very robust conductors, grounding at intervals of 0.15 wavelength is recommended."

The statements presented in this discussion are **not** universally correct. The practice of providing multiple grounding points is nonetheless generally followed because it is often necessary to ground a shield at multiple points in order to guarantee that the shield remains at ground potential.[33] Hence, the standard provides a good recommendation but for incorrect reasons.

".... This grounding system is very effective and adequate when dealing with equipment operating at frequencies below 300 kHz."

Normally, at frequencies below 1 MHz, a single-point ground system is preferable; above 10 MHz, a multipoint ground system is best. Between 1 and 10 MHz, a single-point ground can usually be used, provided the length of the longest ground conductor is less than one-twentieth of a wavelength. Otherwise, a multipoint ground system should be used.[34]

5.4.6 Balanced Circuits

".... There is little benefit from using a twisted pair if the circuit is unbalanced by connecting one side to ground."

It is true that an unbalanced twisted pair will be more susceptible to capacitive coupling and thus offer less protection against electric fields. However, since the unbalanced twisted pair will still offer protection against magnetic fields, its use continues to be beneficial.[35]

6.2.3 Floating Ground

".... For example, if a piece of equipment was to be integrated into a single- or multiple-point grounded system and its components could not withstand the common mode voltages which would be present, its signal ground should be floated with respect to its local ac ground."

To be effective, floating ground systems must really float. It is difficult to insulate large systems well enough to maintain a true floating ground. Also, floating systems present considerable personnel hazard because large potentials can easily accumulate between the floating ground and other accessible grounds.[36]

4.2 MIL-STD-461 and MIL-STD-462

MIL-STD-461 and MIL-STD-462 were developed as measures against which to rate the required electromagnetic compatibility of equipment and subsystems according to their intended electromagnetic environments. The standards have been used successfully by the military services for many years and are commonly referenced in commercial applications as well. Since the ORNL research began well before the issuance of MIL-STD-461D and MIL-STD-462D, the MIL-STD-461C test requirements and associated MIL-STD-462 test methods were assessed for their applicability to an environment typical of nuclear power plants.

4.2.1 Test Criteria

Tabular information characterizing the applicability of the MIL-STD-461C test requirements vs equipment and subsystems is available in two formats, depending on the different classes of equipment and subsystems. Data entries are sometimes presented in tables that compare the applicability of the test requirements to an entire class of equipment or subsystems. Conversely, the data are sometimes tabulated in a manner that compares the applicability of the test requirements to specific types of equipment within a class. In terms of this research, the second format proves to be the more useful because different types of equipment are compared to the requirements. *Digital equipment*, *test equipment*, *commercial equipment*, and *electrical equipment with solid state* were the types of equipment selected for comparison to the test requirements because they most closely resemble the descriptions of industrial equipment found in nuclear power plants.

The information in MIL-STD-461C specifically pertinent to the test requirements for the four selected equipment types can be extracted and compiled for four classes of equipment and subsystems: platforms for aircraft (A1), ground facilities (A3), surface ships (A4), and submarines (A5). Although these platforms would not at first appear to resemble a nuclear power plant environment, a comparison of their test requirements gives some insight into the commonality of specific test criteria for industrial-type equipment.

Table 4 summarizes the emission and susceptibility test requirements in MIL-STD-461C that apply to industrial-type equipment and subsystems. The entries in the table denote the relationship between the requirements and the equipment class. Depending on the type of entry, the extent to which the requirement is applicable and the level to which the acceptance criteria will be imposed can vary. Note that a Y entry denotes that the requirement is applicable and that the acceptance criteria shall be met by employing the test method described in MIL-STD-462. A Y_L entry denotes that there are limitations to the applicability of the test requirement, and a T entry denotes that the applicability of the requirement will be determined on a case-by-case basis. Absence of an entry means that the test requirement is *not* applicable.

Using the evaluation criterion that a requirement must be applicable to multiple classes of equipment before it can be termed *generally applicable*, we narrowed the test requirements in Table 4. The military test requirements listed in Table 5 meet this evaluation criterion, and we suggest that they be considered as test criteria to evaluate safety-related I&C equipment in nuclear power plants.

Our rationale for the selection of the test criteria in Table 5 is that the NRC can thus take advantage of the tri-services' experience in evaluating upsets and malfunctions caused by EMI/RFI. A critique of the test criteria indicates that they are applicable to a nuclear power plant environment and address the concerns of the NRC. The test criteria listed in Table 5 cover conducted and radiated interference (emissions and susceptibility), transients, exposure to electric and magnetic fields, and noise coupling through equipment power and control leads. By specifying these test criteria and their associated test methods, a conclusion can be reached on whether equipment and subsystems can be expected to function properly in their intended electromagnetic environments.

4.2.2 Test Methods

The test methods specified in MIL-STD-462 are applicable to evaluating the susceptibility of safety-related I&C systems only to the extent that they follow the MIL-STD-461C test requirements (i.e., they are just the means by which compliance can be demonstrated). The MIL-STD-462 test methods have become well developed through the years and are generally accepted by the industry. Therefore, their adaptation to a test and evaluation program would be relatively straightforward and inexpensive since many laboratories have already invested in the necessary test equipment. A brief description of the test methods and their applicability are discussed in the pages that follow.

CE03 - Conducted Emissions

The CE03 test measures the conducted emissions on the power leads of equipment and subsystems in the frequency range 15 kHz to 50 MHZ. The test is applicable to ac and dc power leads, including grounds and neutrals, that are not grounded internally to the equipment or subsystem. The test is not applicable to interconnecting signal leads. Conducted emissions shall not appear on the power leads in excess of prespecified values.

Table 4 MIL-STD-461C requirements vs industrial-type equipment classification*

Susceptibility requirement**	Aircraft	Ground facilities	Surface ships	Submarines
CE01	T	Y_L	Y	Y
CE03	Y	Y	Y	Y
CE06	Y	Y_L		
CE07	T	T		
CS01	Y_L	Y_L	Y	Y
CS02	Y	Y	Y	T
CS03				
CS04				
CS05				
CS06	Y	Y	Y	Y
CS07				
CS09		Y_L	Y_L	Y_L
CS10		T	T	T
CS11		Y_L	Y_L	Y_L
RE01		Y_L	Y	Y
RE02	Y	Y	Y	Y
RE03		Y_L	Y_L	
RS01		Y_L	Y	Y
RS02	T	Y_L	Y	Y
RS03	Y	Y	Y	Y
RS05		Y_L	Y_L	

*Y = applicable, Y_L = applicable with limitations, and T = tailored on a case-by-case basis.
**C = conducted, E = emissions, R = radiated, and S = susceptibility.

Table 5 Recommended test criteria for industrial-type equipment

Criterion*	Description
CE03	Conducted emissions, power leads, 15 kHz to 50 MHz
CS01	Conducted susceptibility, power leads, 30 Hz to 50 kHz
CS02	Conducted susceptibility, power and interconnecting control leads, 0.05 to 400 MHz
CS06	Conducted susceptibility, spikes, power leads
RE02	Radiated emissions, electric field, 14 kHz to 10 GHz
RS01	Radiated susceptibility, magnetic field, 0.03 to 50 kHz
RS02	Radiated susceptibility, magnetic and electric fields, spikes and power frequencies
RS03	Radiated susceptibility, electric field, 14 kHz to 10 GHz

*C = conducted, E = emissions, R = radiated, and S = susceptibility.

CS01 - Conducted Susceptibility, Low frequency

The CS01 test ensures that equipment and subsystems are not susceptible to EMI/RFI present on the power leads in the frequency range 30 Hz to 50 kHz. The test is applicable to ac and dc power leads, including grounds and neutrals, that are not grounded internally to the equipment or subsystem. The test is not applicable at frequencies within ±5 percent of the power line frequency (i.e., is not applicable in the range 57 - 63 Hz in the U.S.).

The equipment under test shall not exhibit any malfunction, degradation of performance, or deviation from specified performance indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when subjected to electromagnetic energy injected onto its power leads. The test criterion can also be met under the following condition: when the power source specified in MIL-STD-462, adjusted to dissipate a prespecified power level into a 0.5-ohm load, cannot develop the required voltage at the power input terminals of the equipment under test, and the equipment is not adversely affected by the output of the signal source.

CS02 - Conducted Susceptibility, High frequency

The CS02 test is similar to the CS01 test, except that it covers the higher frequency range 50 kHz to 400 MHz. The CS02 test is applicable to equipment and subsystem ac and dc power leads, including grounds and neutrals, that are not grounded internally to the equipment or subsystem.

The equipment under test shall not exhibit any malfunction, degradation of performance, or deviation from specified performance indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when subjected to a prespecified voltage level from a 50-ohm source. The test signal shall be applied directly to the equipment input terminals, not through its power line cord. The test criterion can also be met under the following condition: when a prespecified power source of 50 ohms impedance cannot develop the required voltage at the input terminals of the equipment under test, and the equipment is not adversely affected by the output of the signal source.

CS06 - Conducted Susceptibility, Spikes

The CS06 test evaluates the response of the equipment under test to spikes on the power leads. It is applicable to equipment and subsystem ac and dc power leads, including grounds and neutrals, that are not grounded internally to the equipment or subsystem.

The equipment under test shall not exhibit any malfunction, degradation of performance, or deviation from specified performance indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when a test spike having the waveform shown in Fig. 3 is sequentially applied to the ac or dc power input leads, whichever is applicable, for a period of not less than 1 minute on each lead. The total test period need not exceed 15 minutes in duration. The values of E and t in Fig. 3 shall be specified for the area where the equipment under test will be installed. The spike shall be superimposed on the power line voltage waveform.

RE02 - Radiated Emissions

The RE02 test measures the radiated emissions from equipment and subsystems in the frequency range 14 kHz to 10 GHz. The test does not apply to radiation from antennas. Levels are to be measured with receiving antennas 1 meter from the surface of the equipment under test.

RS01 - Radiated Susceptibility, Magnetic fields

The RS01 test ensures that equipment and subsystems are not susceptible to radiated magnetic fields in the frequency range 30 Hz to 50 kHz. A radiating loop antenna, positioned 5 cm from the equipment under test, is used to generate the magnetic fields.

The equipment under test shall not exhibit any permanent malfunction, degradation of performance, or deviation from specified performance indications, beyond the tolerances indicated in the individual equipment or subsystem

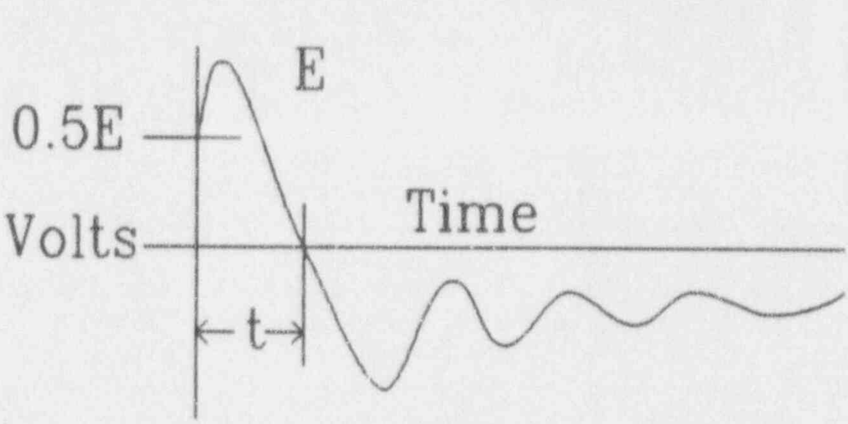

Figure 3 Acceptable waveshape for CS06 and RS02

specification, when subjected to prespecified magnetic field levels and frequencies. Levels are to be measured with a field strength meter at the surface of the equipment under test.

RS02 - Radiated Susceptibility, Spikes

The RS02 test evaluates the response of the equipment under test to radiated magnetic and electric fields generated by spikes and power line frequency current. The RS02 test is applicable to equipment and subsystem enclosures, as well as to signal cables, but power input and output leads are exempt. For the enclosure test, fields are generated by wrapping insulated test wire around the entire enclosure and sequentially applying spikes and power line frequency current to the test wire. This procedure is repeated for the cable test, with the insulated wire now being wrapped around the signal wire bundles instead of the equipment enclosure.

The equipment under test shall not exhibit any malfunction, degradation of performance, or deviation from specified performance indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when subjected to spikes and power line frequency current. The test spikes shall have the waveform shown in Fig. 3 and the values of E and t in the figure shall be specified for the area where the equipment under test will be placed. A current of prespecified value at the power line frequency shall also be applied to the test wire surrounding the equipment under test.

RS03 - Radiated Susceptibility, Electric fields

The RS03 test ensures that equipment and subsystems are not susceptible to radiated electric fields in the frequency range 14 kHz to 10 GHz. The fields are to be generated with high-impedance antennas selected to cover the specified frequency range.

The equipment under test shall not exhibit any malfunction, degradation of performance, or deviation from specified performance indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when subjected to radiated electric fields. The electric field level shall be specified according to the location where the equipment under test will be installed and measured at the surface of the equipment under test with field strength meters.

4.2.3 Evaluation of Acceptance Criteria in MIL-STD-461C

The acceptance criteria in MIL-STD-461C are specified according to the particular application and the expected environment in which the equipment and subsystems must operate. The electromagnetic operating environment may vary from low interference levels at ground-based locations to extremely high levels on the decks of aircraft carriers. In past surveys of nuclear power plant environments, the radiated emissions from most equipment were found to be *moderate or less*. Nevertheless, equipment was identified that could not be expected to operate reliably in its intended environment.[37] From the results of these surveys, it might be reasonable to assume that a nuclear power plant can be categorized as an industrial environment, with its electromagnetic ambient being typically less harsh than the military environment.

The electromagnetic environment will most likely differ for each nuclear power plant, indicating that the acceptance criteria should be specific to a particular site. In nuclear power plant areas where safety-related I&C systems are to be installed, the radiated and conducted emission levels should be measured and acceptance criteria with adequate safety margins established accordingly. Steps should also be taken to ensure that the new I&C systems do not significantly impact the electromagnetic environment. A choice of criteria less stringent than those specified in MIL-STD-461C will avoid unnecessary testing and thereby realize substantial savings. The acceptance criteria for a particular nuclear power plant environment should be based on radiated and conducted emission profiles anticipated at that site. Such profiles will provide a realistic assessment of the probable ambient electromagnetic environment; a safety margin can then be added to ensure the operability of the equipment and subsystems under conditions more adverse than ambient. This type of approach will help to establish acceptance criteria that are realistic and appropriate.

4.2.4 Update to MIL-STDs

The susceptibility test criteria recommended by the ORNL investigators are listed in Table 5. Since the inception of our research, the latest revisions of the MIL-STDs, MIL-STD-461D and MIL-STD-462D, have been issued and there are some changes that impact the test criteria recommended previously. Some of the MIL-STD-461C test requirements have been modified slightly and others have been deleted or replaced. A listing and description of the new MIL-STD-461D test requirements that supersede the existing MIL-STD-461C test requirements related to industrial-type equipment are shown in Table 6. The old and new test requirements are directly compared in Table 7. Note that the new requirements are designated by the 100 series numerical nomenclature.

Table 6 MIL-STD-461D counterparts to applicable requirements

Requirement*	Description
CE103	Conducted emissions, power leads, 10 kHz to 10 MHz
CS101	Conducted susceptibility, power leads, 30 Hz to 50 kHz
CS114	Conducted susceptibility, bulk cable injection, 10 kHz to 400 MHz
CS115	Conducted susceptibility, bulk cable injection, impulse excitation
CS116	Conducted susceptibility, damped sinusoidal transients, cables and power leads, 10 kHz to 100 MHz
RE102	Radiated emissions, electric field, 10 kHz to 18 GHz
RS101	Radiated susceptibility, magnetic field, 30 Hz to 50 kHz
RS103	Radiated susceptibility, electric field, 10 kHz to 10 GHz

*C = conducted, E = emissions, R = radiated, and S = susceptibility.

The new CE103 and RE102 test requirements are similar to the old MIL-STD-461C CE03 and RE02 test requirements, with some modifications. The most significant of these is that the performance of both broadband and narrowband measurements has been eliminated and a single bandwidth is used in making the new measurements. The new CS101 and RS101 test requirements are very similar to the old MIL-STD-461C CS01 and RS01 test requirements. The CS02, CS06, and RS02 test requirements have been replaced with the bulk cable

Table 7 Old vs new MIL-STD-461 test requirements

Old*	New*	Comparison
CE03	CE103	Modifications. Low end of frequency range is lowered to 10 kHz and high end is lowered to 10 MHz. Single bandwidth measurements are specified rather than broadband and narrowband measurements.
CS01	CS101	Slight modification. Test setup is improved to avoid the distortion of ripple voltages coupled on power leads.
CS02	CS114	Replacement. CS02 test (capacitive coupling) has been replaced with the continuous wave bulk cable test of CS114 (inductive coupling).
CS06	CS115 CS116	Replacement. CS06 test spike requirements have been replaced with the impulse excitation test of CS115 and damped sine wave test of CS116.
RE02	RE102	Modifications. Low end of frequency range is lowered to 10 kHz and high end extended to 18 GHz. Changes have been made in the antenna types specified in the test setup and single bandwidth measurements are specified rather than broadband and narrowband measurements.
RS01	RS101	Slight modification. Minor changes have been made in the antenna types specified in the test setup.
RS02	CS115 CS116	Replacement. RS02 test spike requirements have been replaced with the impulse excitation test of CS115 and damped sine wave test of CS116.
RS03	RS103 CS114	Modifications. Lower frequency range is decreased to 10 kHz and RS103 test procedures require real time monitoring and field intensity leveling. Low frequency portion of RS103 can be replaced with bulk cable injection test of CS114.

*C = conducted, E = emissions, R = radiated, and S = susceptibility.

injection test requirements specified in CS114 (continuous wave), CS115 (impulse excitation) and CS116 (damped sine wave). The major difference between the old and new test requirements is that the CS02, CS06, and RS02 tests called for capacitive coupling of test signals onto single power or control lines, while the new test requirements specify the inductive coupling of current waveforms simultaneously into all the lines within a cable assembly. The CS114, CS115, and CS116 bulk cable injection tests are considered to be more representative of the potential threat from radiated fields and transients than the threat simulated by CS02, CS06, and RS02. This is because most coupled signals and transients appearing on power and control lines have been found to be sinusoidal in nature. Thus, the new bulk cable injection requirements offer a closer simulation of real-world conditions. The RS103 test requirement is similar to the old RS03 test requirement, but with some changes. The lower frequency limit is decreased to 10 kHz, and real time monitoring and field intensity leveling are required. Also, the low frequency portion of the RS103 test requirement can be replaced with the continuous wave bulk cable injection test of CS114.

Revisions in the MIL-STD-462D test methods and detailed procedures account for the incorporation of the newest technologies in measurement and control instrumentation. Also, susceptibility testing is now required to be performed in partially anechoic chambers to minimize test signal reflections. These changes should assist in establishing increased uniformity in the results obtained from susceptibility testing performed at various test laboratories.

Some test laboratories are already gearing up to perform the MIL-STD-462D test methods called out in the MIL-STD-461D test requirements. However, it's hard to estimate how long it will take for the majority of test laboratories performing MIL-STD testing to switch over and work out all of the *bugs*. With the recent downturn in military procurements due to the end of the Cold War, there is even discussion in the military community about specifying commercial standards rather than military standards for their procurements. This type of action could jeopardize whether the MIL-STD-462D testing will ever be fully implemented.

4.3 IEEE Std C62.41-1991

In the opinion of the ORNL staff, the surge withstand capability practices described in IEEE Std C62.41-1991, *Recommended Practice on Surge Voltages in Low Voltage AC Power Circuits*, are applicable to the establishment of NRC guidelines for controlling upsets in safety-related I&C equipment caused by ac power surges. It is acknowledged that although the waveforms described in IEEE Std C62.41-1991 cannot possibly represent the complex real-world surge environments, they nonetheless define a manageable set of surge waveforms that have been selected to simulate the real world. It is our opinion that tests employing these waveforms will provide meaningful and reproducible results that will provide a reasonable degree of assurance that problems associated with power surges are minimized.

Test procedures for the IEEE C62.41-1991 practices are described in IEEE C62.45-1987, *Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits*. Hence, IEEE Std C62.45-1987 should always be used as the companion document to IEEE Std C62.41-1991. The test procedures are recognized throughout the power industry and have been endorsed by a number of equipment manufacturers and utilities.

5 Assessment of Commercial Programs

The ORNL investigators reviewed the EMI/RFI programs and associated standards of a number of domestic and international industrial organizations. These programs were assessed on how well they relate to testing and evaluating upsets and malfunctions in safety-related I&C systems caused by EMI/RFI and power surges. The organizations reviewed, shown below, varied from nuclear equipment manufacturers, design and construction contractors, a power utility, to volunteer standards-developing associations:

Domestic Programs

- ABB Combustion Engineering
- The Foxboro Company
- Westinghouse Electric Corporation
- Tennessee Valley Authority (TVA)
- Federal Communications Commission (FCC)
- American National Standards Institute (ANSI)
- Scientific Apparatus Makers Association (SAMA)
- Society of Automotive Engineers (SAE)

International Programs

- International Electrotechnical Commission (IEC)
- Comite Europeen de Normilisation Electrotechnique (CENELEC)
- International Special Committee on Radio Interference (CISPR)

5.1 Domestic Programs

Domestic EMI/RFI emissions test programs were assessed and found to primarily center around the test methods in ANSI C63.4-1991, *Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic*

Equipment in the Range of 9 kHz to 40 GHz. ANSI C63.4-1991 sets forth uniform methods for the measurement of both radiated and power line conducted emissions. The procedures in ANSI C63.4-1991 have been adopted by the FCC and used to verify that emissions from information technology equipment do not exceed the limits spelled out in the FCC Rules and Regulations, Part 15. Some domestic test programs also reference the emissions test methods called out in the Department of Defense (DoD) MIL-STDs.

An evaluation of domestic EMI/RFI susceptibility test programs and associated EMI/RFI standards revealed that most find their origin in the DoD MIL-STDs. The military services have been concerned about the impact of EMI/RFI on electronic equipment for the past 40 years, i.e., since the introduction of solid-state devices. DoD's expertise and experience has since led many industrial organizations to fashion their standards after the MIL-STDs, with customized test methods and acceptance criteria to match the intended electromagnetic environments. The standards place heavy emphasis on protecting equipment against being susceptible to radiated electric fields. This is primarily due to the fact that two-way radios are known to cause EMI/RFI-related upsets. Of the domestic industrial standard developers, the SAE has the most stringent acceptance criteria–based on the close proximity of equipment within a vehicle and its somewhat unpredictable electromagnetic environment. The domestic EMI/RFI susceptibility standards reviewed are as follows:

- TVA SS-E18.14.01, *Electromagnetic Interference Testing Requirements for Electronic Devices*;
- ANSI C63.12-1987, *American National Standard for Electromagnetic Compatibility Limits - Recommended Practice*;
- SAMA PMC 33.1-1978, *Electromagnetic Susceptibility of Process Control Instrumentation*;
- SAE J1113, *Automotive Component Electromagnetic Compatibility Standard*; and
- SAE J551, *Automotive Vehicle Electromagnetic Compatibility Standard*.

Domestic manufacturers and contractors typically perform EMI/RFI susceptibility tests called out in the ANSI, DoD, SAMA, and SAE standards, as well as the IEC 801 standard and some developed internally within their organizations. ABB Combustion Engineering performs its EMI/RFI testing according to the test methods specified in MIL-STD-462.[38] The test results are then evaluated against customized acceptance criteria based on the expected electromagnetic environment. Foxboro uses the IEC 801, SAMA PMC 33.1, and MIL-STD-462 standards, along with internally developed test methods, to evaluate its I&C systems.[39] Westinghouse follows test methods and acceptance criteria that appear to be derivations of the SAMA and DoD standards.[40] TVA has developed its own standard, SS-E18.14.01, that frequently references the DoD and SAMA standards.[41] SS-E18.14.01 specifies the EMI/RFI test requirements (both emissions and susceptibility) for electronic devices used on all TVA projects.

Domestic test programs to evaluate the impact of upsets caused by power surges center around the test methods in IEEE Std C62.41-1991. This standard has been discussed previously in Sections 3.3 and 4.3.

5.2 International Programs

An assessment of international EMI/RFI emissions test programs revealed that most are centered around the test methods in CISPR Publication 22, *Limits and Methods of Measurements: Information Technology Equipment*. CISPR is a committee organized under the auspices of the IEC to work on interference problems associated with information technology equipment. CISPR Pub. 22 is very similar to ANSI C63.4-1991 and has been adopted by CENELEC as a harmonized standard under European Norm EN 55022.[42,43] CENELEC is an expert technical committee commissioned to recommend EMI/RFI standards for adoption by the European Community (EC) under its EMC Directive, 89/336/EEC.

Inquiries were made into the EMI/RFI susceptibility standards used by the nuclear community in Europe during a recent foreign trip by an ORNL investigator and the NRC Project Manager.[44] It was discovered that the nuclear facilities visited either used IEC 801, *Electromagnetic Compatibility for Industrial-Process Measurement and Control Equipment*, or some variation of the standard. The French Atomic Energy Commission (CEA) uses IEC 801 and IEC 1000-4, a generic EMC standard developed to detail testing and measurement techniques for all products, as opposed to IEC 801, which was developed for industrial process control equipment. IEC 1000-4 is very similar to IEC 801. AEA Technology, the trading name of the United Kingdom Atomic Energy Authority, uses an internal standard AEEW R-919, *Interference Immunity Tests for Nucleonic Instrumentation*, that was understood by the visitors to be similar to IEC 801. Siemens in Germany uses IEC 801, as well as internal standards, to qualify safety-related I&C systems in German plants.

The IEC 801 standard, first published in 1984, consists of a series of tests developed to address upsets and malfunctions that may disrupt electronic devices in industrial process control equipment. The six parts of IEC 801 are listed in Table 8. IEC 801-1 (1990) gives a general introduction to EMI/RFI and power surge immunity (typically referred to as susceptibility in the U.S.). It is intended to make the reader aware of the problems involved in achieving and maintaining EMC and to provide the background information necessary to understand the development of the different parts of the standard. IEC 801-2 (1991) defines test methods to evaluate whether equipment can withstand electrostatic discharges from operators directly or from operators to objects adjacent to the equipment. In addition, severity levels are defined which relate to different environmental conditions.

Table 8 IEC 801 immunity test methods

Designation	Description
IEC 801-1	Part 1: General Requirements
IEC 801-2	Part 2: Electrostatic Discharge Requirements
IEC 801-3	Part 3: Radiated Electromagnetic Field Requirements
IEC 801-4	Part 4: Electrical Fast Transients/Burst Requirements
IEC 801-5	Part 5: Surge Immunity Requirements
IEC 801-6	Part 6: Immunity to Conducted Disturbances, Induced by Radio Frequency Fields Above 9 kHz

IEC 801-3 (1992) establishes the test methods and severity levels to evaluate equipment exposure to EMI/RFI generated by portable radio transceivers (walkie-talkies) or any other device that will generate continuous-wave electromagnetic energy. IEC 801-4 (1988) establishes a common and reproducible basis for evaluating the performance of equipment subjected to repetitive fast transients (bursts) on power, signal, or control lines. IEC 801-5 (draft-1990) establishes a common reference for evaluating the performance of equipment subjected to power surges caused by overvoltages/currents from switching and lightning transients. IEC 801-6 (draft-1990) defines the test method and severity levels to evaluate the performance of equipment subjected to EMI/RFI coupled into the equipment via power cables, signal lines, and ground connections.

The IEC 801 series of tests have been performed extensively throughout Europe and are well accepted. So much so, that CENELEC is presently developing a harmonized immunity standard, EN 50082-2, for the EC based on the IEC 801 test methods. The IEC 801 standard is also finding some use in the U.S., as well.

5.3 Comparison of EMI/RFI and Power Surge Standards

The domestic ANSI C63.4-1991, the international CISPR Pub. 22, and the CENELEC EN 55022 standards are very similar in their methodologies for measuring radiated and power line conducted emissions. However, they do differ significantly from the MIL-STD 462 RE02 and CE03 test methods. The commercial test methods are conducted at open-field sites, whereas the MIL-STD tests are conducted in shielded enclosures. The MIL-STD emissions testing is performed with the measurement antenna 1 meter from the equipment under test, while commercial radiated emissions testing is performed with the antenna 3 or 10 meters distant.[45] Also, the commercial standards use quasi-peak or average detectors whereas the MIL-STDs use peak detectors to measure the signal from the measurement antenna. The quasi-peak detector is a weighted averaging filter with a fast rise time and a slow fall time that takes into account the "human factor" associated with a person's reaction to the effects of EMI/RFI, namely, the degree of annoyance is related to the persistence of the EMI/RFI. Thus, continuous EMI/RFI will charge the quasi-peak detector fully, whereas intermittent EMI/RFI will be reported at a level significantly lower than the peak level. EMI/RFI that is continuous in nature will have identical quasi-peak and peak signal readings.[46]

IEC 801-2 deals with electrostatic discharge and does not have a MIL-STD-462 counterpart. The test methods in IEC 801-4 and 801-5 are very similar to the methods described in IEEE Std C62.41-1991 to evaluate the surge withstand capability of I&C equipment. Table 9 compares the MIL-STDs and commercial susceptibility test methods. The comparisons are based on the *disruption* that the tests are intended to simulate. It is difficult to compare the methods head-to-head because of the differences in the test equipment requirements and the fact that the test electrical parameters (frequency, amplitude, duration, etc.) are not always the same.

Table 9 Comparison of susceptibility test methods

Disruption	MIL-STD-462	MIL-STD-462D	IEC 801
Low frequency, conducted	CS01	CS101	801-6
High frequency, conducted	CS02	CS114	801-6
Impulses/surges, conducted	CS06	CS115 CS116	801-4 801-5
Magnetic fields, radiated	RS01	RS101	None
Impulses/surges, radiated	RS02	CS115 CS116	801-4 801-5
High frequency, radiated	RS03	RS103 CS114	801-3 801-6

Thus, although commonality was found among the various commercial EMI/RFI susceptibility standards, a feeling of consensus was missing. Most of the standards had the radiated susceptibility test in common and then diverged quickly into differing approaches to the same end, namely, electromagnetic compatibility. Most of the test methods are appropriate to demonstrate the compatibility of equipment with its electromagnetic environment but a few seemed lacking. Also, trying to compare test results obtained with the different test methods and test setups is, at best, a frustrating and subjective process. The MIL-STDs and IEC 801 are the most comprehensive of the susceptibility standards reviewed. However, the MIL-STDs seem to offer a better common ground, since they are the original source from which most of the other standards were derived.

6 Implementation

6.1 Recommendations

Use of the engineering practices, test criteria, test methods, and acceptance criteria discussed in this report is strongly recommended to ensure that EMI/RFI- and power-surge-associated problems in a nuclear power plant environment will be minimal. To avoid poor design and installation practices, particular attention should be given not only to IEEE Std 1050-1989 but also to the suggested exceptions. Also, any deviations in the levels and frequencies from the specified test criteria, test methods, and acceptance criteria should be reviewed prior to their implementation.

6.2 Benefits

So far as the authors are aware, no NRC document presently exists that describes the design and installation practices, test criteria, test methods, and acceptance criteria necessary to ensure that EMI/RFI and power surge problems with safety-related I&C systems are avoided in a nuclear power plant. As a consequence, the NRC performs regulatory review of the impact of EMI/RFI and power surges on a case-by-case basis, which is clearly inefficient.

Engineering practices and verification techniques similar to those outlined in this report are currently being employed informally by the nuclear industry. Through compliance with the suggested practices of IEEE Std 1050-1989, the prescribed verification techniques from MIL-STD-461 and MIL-STD-462, and the suggested practices of IEEE Std C62.41-1991, a consistent and broadly applicable methodology can be established for ensuring that safety-related I&C systems are minimally susceptible to EMI/RFI and power surges. This methodology should improve both the evaluation methods used and the application of I&C equipment to nuclear power plant environments.

6.3 Effects

The ORNL recommendations for electromagnetic compliance, as outlined in this report, are consistent with current practices throughout a broad spectrum of industries (including nuclear). Furthermore, the engineering practices and verification techniques suggested to alleviate problems associated with EMI/RFI and power surges are familiar to practicing professionals in the EMC field. These facts make adoption of the recommendations by the utilities and reactor vendors relatively straightforward and economical.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report discusses the development of the technical basis for the control of upsets and malfunctions in safety-related instrumentation and control (I&C) systems caused by electromagnetic and radio-frequency interference (EMI/RFI) and power surges. The research was performed at the Oak Ridge National Laboratory (ORNL) and was sponsored by the U.S. NRC Office of Nuclear Regulatory Research (RES). The motivation for research stems from the safety-related issues that need to be addressed with the application of advanced I&C systems to nuclear power plants. Development of the technical basis centered around establishing good engineering practices to ensure that sufficient levels of electromagnetic compatibility (EMC) are maintained between the nuclear power plant's electronic and electromechanical systems known to be the source(s) of EMI/RFI and power surges. First, good EMC design and installation practices need to be established to control the impact of interference sources on nearby circuits and systems. These EMC good practices include circuit layouts, terminations, filtering, grounding, bonding, shielding, and adequate physical separation. Second, an EMI/RFI test and evaluation program needs to be established to outline the tests to be performed, the associated test methods to be followed, and carefully formulated acceptance criteria based on the intended environment to ensure that the circuit or system under test meets the recommended guidelines. Third, a program needs to be developed to perform confirmatory tests and evaluate the surge withstand capability (SWC) and of I&C equipment connected to or installed in the vicinity of power circuits within the nuclear power plant. By following these three steps, the design and operability of safety-related I&C systems against EMI/RFI and power surges can be evaluated, acceptance criteria can be developed, and appropriate regulatory guidance can be provided.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

electromagnetic interference (EMI)
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surge withstand capability (SWC)
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