Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants

Draft Report for Comment

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ABSTRACT

This document presents recommendations for electromagnetic operating envelopes to augment test criteria and test methods addressing electromagnetic interference (EMI), radio-frequency interference (RFI), and power surges that are applicable to safety-related instrumentation and control (I&C) systems in nuclear power plants. The Oak Ridge National Laboratory (ORNL) was engaged by the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research to assist in developing the technical basis for regulatory guidance on EMI/RFI immunity and power surge withstand capability (SWC). Previous research has provided recommendations on electromagnetic compatibility (EMC) design and installation practices, endorsement of EMI/RFI immunity and SWC test criteria and test methods, and determination of ambient electromagnetic conditions at nuclear power plants. The present research involves development of recommended electromagnetic envelopes that are applicable to nuclear power plant locations where safety-related I&C systems either are or may be installed. These recommended envelopes establish both emissions criteria and the levels of radiated and conducted interference that I&C systems should be able to withstand without upset or malfunction. The EMI/RFI operating envelopes are derived from conditions in comparable military environments and are confirmed by comparison with the nuclear power plant electromagnetic environment based on measured plant emissions profiles. Detailed information on specific power surge conditions in nuclear power plants is not available, so industrial guidance on representative surge characteristics for susceptibility testing is adopted. An engineering assessment of the power surge environment in nuclear power plants leads to the recommendation of operating envelopes based on location categories and exposure levels defined in IEEE Std C62.41-1991, *IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*.

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EXECUTIVE SUMMARY

Until recently, little was known about the prevailing ambient electromagnetic interference (EMI), radio-frequency interference (RFI), and power surge environment in nuclear power plants. This lack of information made it difficult to establish electromagnetic operating envelopes for safety-related instrumentation and control (I&C) systems—that is, the level of interference that systems should be able to withstand without upset or malfunction—with a high degree of confidence in their adequacy. Consequently, the Oak Ridge National Laboratory (ORNL) was engaged by the U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research to profile the electromagnetic emission levels in the nuclear power plant environment and provide recommended operating envelopes to augment the EMI/RFI and power surge test criteria and test methods discussed in NUREG/CR-5941, *Technical Basis for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related I&C Systems*.

The recommended EMI/RFI test criteria in NUREG/CR-5941 were extracted from Military Standard (MIL-STD) 461, *Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference*, and the associated test methods were extracted from MIL-STD 462, *Measurement of Electromagnetic Interference Characteristics*. These test criteria and methods were selected because they provide a well-established, systematic approach to ensuring electromagnetic compatibility for I&C equipment with the environment in which it operates. These recommended testing practices are based on the military services' considerable experience in evaluating EMI/RFI effects. The recommended surge withstand capability (SWC) test criteria and associated test methods are based on practices described in IEEE Std C62.41-1991, *IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*. They employ a manageable set of power surge waveforms selected to simulate realistic surge environments.

This report details the recommendations by ORNL for electromagnetic operating envelopes that contribute to ensuring that functional problems related to EMI/RFI and power surges are averted in safety-related I&C systems. Operating envelopes were first defined based on conditions in military environments comparable to the nuclear power plant environment. Electromagnetic measurement systems were then assembled by ORNL and used to monitor radiated electric field, radiated magnetic field, and conducted interference levels at eight nuclear units over a period of 14 months.

Measurement data and the resulting electromagnetic emission profiles for the selected plant sites are reported in NUREG/CR-6436, *Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants*. Those emission profiles were subsequently used to confirm that the recommended EMI/RFI operating envelopes were appropriately tailored to the nuclear power plant environment (i.e., they do bound with high confidence the projected electromagnetic conditions as determined from measured data). As an added measure, short-term emissions data collected during a 1994 study conducted by the Electric Power Research Institute were also used to confirm the recommended operating envelopes. Detailed information on specific power surge conditions in nuclear power plants is not available so industrial guidance on representative surge characteristics for susceptibility testing is adopted. An engineering assessment of the power surge environment in nuclear power plants leads to the recommendation of operating envelopes based on location categories and exposure levels defined in IEEE Std C62.41-1991.

The value added by developing the technical basis for EMI/RFI and SWC operating envelopes is that it (1) identifies acceptable operating envelopes which are based on similar military environments and confirmed with measurement data from nuclear power plants; (2) specifies complete suites of EMI/RFI

emissions and susceptibility operating envelopes (i.e., no mixing and matching of test methods and operating envelopes are promoted); (3) gives operating envelopes that are framed in the proper units and frequency ranges for each specific test method; and (4) applies to analog, digital, and hybrid safety-related I&C equipment.

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ACRONYMS

ABB	Asea Brown Boveri
ALWR	advanced light-water reactor
ANSI	American National Standards Institute
B&W	Babcock and Wilcox
BWR	boiling water reactor
CE	conducted emissions
COTS	commercial-off-the-shelf
CS	conducted susceptibility
EFT	electrically fast transients
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EPRI	Electric Power Research Institute
GE	General Electric
I&C	instrumentation and controls
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
MIL-STD	military standard
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PWR	pressurized water reactor
RE	radiated emissions
RES	Office of Nuclear Regulatory Research
RFI	radio-frequency interference
RPS	reactor protection system
RS	radiated susceptibility
SWC	surge withstand capability

GLOSSARY

ac	alternating current
dB	decibel—ten times the logarithm to base 10 of a ratio of two powers, or twenty times the logarithm to base 10 of a ratio of two voltages or currents
dB μ A	decibels referenced to one microampere, unit of conducted interference
dB μ V	decibels referenced to one microvolt, unit of conducted interference
dB μ V/m	decibels referenced to one microvolt per meter, unit of electric field strength
dBpT	decibels referenced to one picotesla, unit of magnetic field strength
dc	direct current
GHz	Gigahertz— 10^9 Hertz
Hz	Hertz—unit of frequency, one cycle per second
I(t)	instantaneous current at time t
I _p	peak current
kA	kiloamperes— 10^3 A, unit of current
kHz	kilohertz— 10^3 Hz
kV	kilovolt— 10^3 V, unit of voltage
MHz	Megahertz— 10^6 Hz
μ s	microsecond— 10^{-6} s
ns	nanosecond— 10^{-9} s
Ω	ohm, unit of resistance
rms	root mean square—square root of the average square of an instantaneous magnitude
V(t)	instantaneous voltage at time t
V/m	volts per meter, unit of electric field strength
V _p	peak voltage
W	watt, unit of power

1 INTRODUCTION

Instrumentation and control (I&C) systems for advanced light-water reactors (ALWRs) are expected to make use of both analog and digital equipment and will be significantly different from the predominantly analog-based I&C systems in use for safety-related functions at current nuclear power plants. Limited operational experience with digital technology and advanced analog electronics in the nuclear industry has caused concern about upsets and malfunctions in safety-related I&C systems due to electromagnetic interference (EMI), radio-frequency interference (RFI), and power surges. Hence, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research engaged the Oak Ridge National Laboratory (ORNL) to assist in developing the technical basis for regulatory guidance on EMI/RFI immunity and power surge withstand capability (SWC).

The NRC-sponsored confirmatory research project, *Regulatory Guide and Acceptance Criteria for EMI/RFI in I&C Systems*, addresses installation practices, test criteria, test methods, and methods for establishing operating envelopes for I&C equipment shielding, grounding, and noise rejection. The objectives of this project are to (1) develop the technical basis for regulatory guidance in the areas of EMI/RFI and SWC for safety-related I&C systems, (2) formulate testing criteria for evaluating both the susceptibilities and the emissions of such systems, and (3) conduct in-plant measurements to characterize the electromagnetic environment in nuclear power plants.

Previous findings and recommendations on EMI/RFI and SWC test criteria, test methods, and installation practices were reported in NUREG/CR-5941, *Technical Basis for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related I&C Systems*.¹ That document discusses the technical basis for recommended electromagnetic compatibility (EMC) design and installation practices to ensure operational safety in equipment and presents testing techniques to assure that the EMC practices do, indeed, achieve their intended purpose.

Until recently, little was known about the prevailing ambient electromagnetic environment in nuclear power plants. This lack of information made it difficult to recommend electromagnetic operating envelopes—that is, the level of interference that safety-related I&C systems should be able to withstand without upset or malfunction—with a high degree of confidence in their adequacy. Consequently, ORNL profiled the electromagnetic emission levels at selected plant sites. Those profiles were reported in NUREG/CR-6436, *Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants*,² and have been incorporated into the development of the technical basis for realistic operating envelopes. This report details the recommendations of ORNL for electromagnetic operating envelopes to augment the test criteria and test methods recommended in NUREG/CR-5941.

2 ELECTROMAGNETIC EFFECTS TEST CRITERIA

2.1 EMI/RFI Test Criteria

The EMI/RFI test criteria listed in Table 2.1 were extracted from Military Standard (MIL-STD) 461D, *Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference*,³ to evaluate the effects of EMI/RFI in safety-related I&C systems. Table 2.2 lists the corresponding counterparts to the recommended MIL-STD 461D test criteria found in the previous version of the standard, MIL-STD 461C.⁴ These two sets of criteria address many important EMI/RFI issues. It is intended that either set be applied in its entirety, without selective application of individual criteria (i.e., no mixing and matching of test criteria). The test criteria are specified by alphanumeric codes: the first designation declares the criterion to be either radiated (R) or conducted (C), and the

second designation specifies whether it covers emissions (E) or susceptibility (S). This alphabetic designation is followed by a numbering system that is specific to the particular test criterion.

Table 2.1 Recommended MIL-STD 461D test criteria

Criterion	Description
CE101	Conducted emissions, power leads, 30 Hz to 10 kHz
CE102	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
RE101	Radiated emissions, magnetic field, 30 Hz to 100 kHz
RE102	Radiated emissions, electric field, 10 kHz to 1 GHz
RS101	Radiated susceptibility, magnetic field, 30 Hz to 100 kHz
RS103	Radiated susceptibility, electric field, 10 kHz to 1 GHz

Table 2.2 MIL-STD 461C counterparts to applicable MIL-STD 461D test criteria

Criterion	Description
CE01	Conducted emissions, power leads, 30 Hz to 15 kHz
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, 50 kHz to 400 MHz
RE01	Radiated emissions, magnetic field, 30 Hz to 30 kHz
RE02	Radiated emissions, electric field, 14 kHz to 1 GHz
RS01	Radiated susceptibility, magnetic field, 30 Hz to 50 kHz
RS03	Radiated susceptibility, electric field, 14 kHz to 1 GHz

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

The purpose of the conducted emissions (CE) tests is to ensure that equipment connected to the power bus does not corrupt its power quality (introduce distortions in the voltage waveforms) or cause excess radiation from the power bus. The conducted susceptibility (CS) tests are intended to ensure that equipment performance will not be degraded in the event that distortions in the voltage waveforms and high frequency conducted EMI/RFI are somehow introduced on the power bus. The purpose of the radiated emissions (RE) tests is to control the magnetic field and electric field emissions from equipment

and its associated cables. The radiated susceptibility (RS) tests are intended to ensure that equipment will operate without degradation in the presence of significant electromagnetic field levels.

The EMI/RFI test criteria in Tables 2.1 and 2.2 are modified versions of the criteria originally recommended in NUREG/CR-5941. The MIL-STD 461D test criteria for radiated and conducted susceptibility to voltage spikes (CS115 and CS116), along with their corresponding MIL-STD 461C counterparts (CS06 and RS02), are no longer considered necessary. The reason for this recommendation is recognition that the results of applying the specified MIL-STD voltage spike waveforms will be duplicated by the application of the surge waveforms of the SWC test criteria discussed in Sect. 2.2. The MIL-STD voltage spike criteria are significantly less stringent, with the SWC test criteria exceeding them by greater than a factor of eight in frequency spectrum coverage and greater than a factor of seven in amplitude.

The rationale for the recommendation of the MIL-STD test criteria is that they provide a well-established, systematic approach to ensuring electromagnetic compatibility for I&C equipment with the environment in which it operates. These recommended testing practices are based on the military services' considerable experience (almost 30 years) in evaluating EMI/RFI effects. In particular, the MIL-STD test criteria in Tables 2.1 and 2.2 were selected because they are suitable for *military ground facilities*, the military environment that most closely resembles the nuclear power plant environment. The resemblance is thought to occur because *military ground facilities* are land-based structures employing earth grounding criteria and are typically used to facilitate industrial-type equipment in a *less-than-harsh* electromagnetic environment. It may be of interest to note that these test criteria are also considered suitable for the military's *aircraft*, *surface ship*, and *submarine* environments. In addition, close study of the test criteria indicates that a wide range of electromagnetic compatibility issues is thereby addressed, in that the criteria cover the gamut of associated problems—conducted and radiated interference, exposure to electric and magnetic fields, and noise coupling through equipment power and control leads.

As indicated by their descriptions, the MIL-STD 461D and corresponding 461C test criteria for conducted susceptibility in Tables 2.1 and 2.2 are not generally applicable for conducted EMI/RFI on signal lines. However, the MIL-STDs do leave open the possibility of specifying test criteria for signal leads when the sponsoring agency deems it necessary, but offer no guidance on acceptable test levels (these must be determined on a case by case basis). An earlier version of the standards, MIL-STD 461A, did address signal leads, but subsequent versions dropped that application based on the rationale that conducted EMI/RFI on signal leads would be addressed by system-level EMC requirements. The need to address equipment-level test criteria and operating envelopes for conducted EMI/RFI on signal leads in nuclear power plants is an open issue and is not covered by the present effort to develop the technical basis for regulatory guidance. However, a separate investigation has been initiated by U.S. NRC in an attempt to address the issue. The result is expected to be the development of a comprehensive approach to conducted EMI/RFI on signal lines.

Corresponding test methods in MIL-STD 462D, *Measurement of Electromagnetic Interference Characteristics*,⁵ are used to demonstrate compliance with the MIL-STD 461D test criteria. The previous version of the test methods can be found in MIL-STD 462⁶ and confirms compliance with the corresponding MIL-STD 461C test criteria. The MIL-STD test methods are well developed in that they have been reviewed and updated on a periodic basis since their inception in 1967.⁷ With the implementation of the test criteria in Tables 2.1 and 2.2 (and their associated test methods), it can be demonstrated through testing that equipment and subsystems can function properly in the presence of known EMI/RFI levels and that the emissions levels of that equipment will not appreciably increase the electromagnetic ambient conditions at the installation site.

2.2 SWC Test Criteria

The SWC practices described in IEEE Std C62.41-1991 (Reaff 1995), *IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*,⁸ are recommended in NUREG/CR-5941 to control the occurrence of upsets in safety-related I&C equipment caused by power surges originating from two major sources: lightning effects (direct or indirect) and switching transients. It is acknowledged that although the waveforms described in IEEE Std C62.41-1991 cannot completely include all possible surge environments, they nonetheless define a manageable and realistic set of surge waveforms selected to represent realistic conditions. Tests employing these waveforms should provide reproducible results that, in turn, can be expected to provide a reasonable degree of assurance that problems associated with power surges are averted.

Test procedures for the IEEE Std C62.41-1991 practices are described in IEEE Std C62.45-1992, *IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits*.⁹ Hence, IEEE Std C62.45-1992 should be used as a 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.

3 APPROACH TO RECOMMENDED OPERATING ENVELOPES

The EMI/RFI operating envelopes in MIL-STDs 461D and 461C are specified according to the particular application and the projected environments in which the equipment and subsystems must operate. Military EMI/RFI operating environments vary from low interference levels at ground-based locations to extremely high levels on the decks of aircraft carriers, and operating envelopes are selected accordingly. As an initial approach, EMI/RFI susceptibility and emissions operating envelopes were developed and recommended for the nuclear power plant environment based on those envelopes used to ensure the electromagnetic compatibility of military equipment designed for use in the *military ground facilities* described in the MIL-STDs. To confirm that the recommended operating envelopes were appropriately tailored to the nuclear power plant environment, ambient EMI/RFI conditions were then measured at eight nuclear units over a period of 14 months. Measurement data were collected, for up to 5 weeks (24 h/day) in each plant location, with electromagnetic spectral receivers assembled by ORNL to acquire and record peak radiated electric field, radiated magnetic field, and conducted interference levels. The measurement approach is described in detail in NUREG/CR-6436. As an added measure, short-term emissions data collected during a 1994 study conducted by the Electric Power Research Institute (EPRI) were also used to confirm the recommended EMI/RFI operating envelopes. Results of the EPRI study are reported in EPRI TR-102323, *Guidelines for Electromagnetic Interference Testing in Power Plants*.¹⁰

Since detailed information on specific power surge conditions in nuclear power plants is not available, the recommendation of SWC operating envelopes took a different approach. Given the dynamic nature of power systems, power surge measurements are very much site-dependent, and prediction of the future environment may require several years of monitoring. The surge environment is so complex that no set of test waveforms will ever completely simulate all possible surge conditions.¹¹ Hence, it is prudent to use the limited set of representative surge waveforms in IEEE Std C62.41-1991 as a baseline SWC environment. As discussed in NUREG/CR-5941, the typical environmental surge conditions in a nuclear power plant can be represented by the two standard waveforms—that is, the ring wave and the combination wave—plus the electrically fast transients (EFT) waveform. These waveforms were developed from data collected on power surges caused by lightning effects and system switching transients. Descriptions of the waveforms are given in Table 3.1.

Table 3.1 Representative power surge waveforms

Parameter	Ring Wave	Combination Wave		EFT
Waveform	Open-circuit voltage	Open-circuit voltage	Short-circuit current	Pulses in 15-ms bursts
Rise time	0.5 μ s	1.2 μ s	8 μ s	5 ns
Duration	100 kHz ringing	50 μ s	20 μ s	50 ns

Location categories and exposure levels are outlined in IEEE Std C62.41-1991 and define applicable amplitudes for the surge waveforms that should provide an appropriate degree of SWC. Location categories are defined as *Category A*, *B*, or *C*, depending on the proximity of equipment to the service entrance and the associated line impedance. *Category C* is exterior to an installation, *Category B* covers feeders and short branch circuits less than 10 m from the service entrance, and *Category A* covers long branch circuits greater than 10 m from the service entrance. Exposure levels are designated according to the rate of occurrence versus voltage level (e.g., surge crest) to which equipment is exposed and range from *Low* to *High*. A *Low Exposure* level describes systems in areas known for little load or capacitor switching and low power surge activity, while a *Medium Exposure* level describes systems in areas known for significant switching transients or medium to high power surge activity. A *High Exposure* level covers those rare installations that have greater surge exposures than those defined by *Low Exposure* and *Medium Exposure*. Consequently, based on these definitions, an engineering assessment of the power surge environment in nuclear power plants is that the location of safety-related I&C systems can likely be classified as *Category B*¹² and a *Low to Medium Exposure* level to induced surges can be assumed.¹³ This surge environment should be typical of the nominal nuclear power plant environment since it includes sites with moderate to slightly high surges (i.e., less than the 6 kV clearance sparkover limit for low-voltage, indoor environments). Although the guidance does take into account nominal lightning activity, the current technical basis is insufficient to confirm that it resolves all lightning-related issues.

4 RECOMMENDED EMI/RFI OPERATING ENVELOPES

The control of conducted EMI/RFI is essential to protect against poor power quality and excess radiation from the power bus. The phenomena of concern are distortions of the supplied voltage level caused by changing electrical loads and the introduction of high frequency conducted EMI/RFI that can radiate from the power bus. The CE operating envelopes limit the maximum voltage distortions and high frequency conducted EMI/RFI allowed on the power bus. The CS operating envelopes provide the conducted EMI/RFI levels to which equipment can be subjected and continue to operate without performance degradation.

The control of radiated EMI/RFI is essential to protect against equipment malfunctions caused by excess electromagnetic emissions. The RE operating envelopes limit the magnetic field and electric field emissions allowed from equipment. The RS operating envelopes provide the radiated EMI/RFI levels to which equipment can be subjected and continue to operate without performance degradation.

Recommended EMI/RFI operating envelopes are discussed herein for both the MIL-STD 461D and MIL-STD 461C test criteria based on envelopes specified for *military ground facilities*, with confirmation derived from the measurement profiles from the ORNL surveys and EPRI's short-term EMI/RFI test data.

Some EMI/RFI test laboratories are well versed in performing the MIL-STD 462D tests associated with the MIL-STD 461D test criteria, and several laboratories are equipped to perform the MIL-STD 462 tests associated with the MIL-STD 461C test criteria. With the recent downturn in military procurements due to the end of the Cold War, it is difficult to estimate how many test laboratories are actually implementing a MIL-STD 462D testing capability. Thus, EMI/RFI operating envelopes are recommended for both test criteria so that testing resources are not limited based on the number of available MIL-STD 462D test laboratories. Our study found these recommended EMI/RFI operating envelopes to be representative of the operating envelopes now accepted in a broad range of industries.¹⁴⁻¹⁶ For example, they are at least equal to (and in some instances slightly more stringent than) the proposed American National Standards Institute (ANSI) C63 immunity limits in the areas common to the ANSI standard and the MIL-STDs.

4.1 MIL-STD 461D Conducted EMI/RFI Operating Envelopes

4.1.1 CE101—Conducted emissions, low frequency

The CE101 test measures the low frequency conducted emissions on power leads of equipment and subsystems in the frequency 30 Hz to 10 kHz. Equipment tested under comparable power quality guidance should be exempt from this test. When the test is desired, it is applicable to ac and dc power leads, including grounds and neutrals, that obtain power from other sources not part of the equipment under test. Conducted emissions on power leads should not exceed the applicable root mean square (rms) values shown in Figure 4.1. The values are specified according to the type of power source feeding the equipment under test.

Figure 4.1 CE101 emissions envelopes

4.1.2 CE102—Conducted emissions, high frequency

The CE102 test measures the high frequency conducted emissions on power leads of equipment and subsystems in the frequency range 10 kHz to 10 MHz. The test is applicable to ac and dc power leads, including grounds and neutrals, that obtain power from other sources not part of the equipment under test. Conducted emissions on power leads should not exceed the applicable rms values shown in Figure 4.2. The values are specified according to the voltage of the power source feeding the equipment under test.

Figure 4.2 CE102 emissions envelope

4.1.3 CS101—Conducted susceptibility, low frequency

The CS101 test ensures that equipment and subsystems are not susceptible to EMI/RFI present on power leads in the frequency range 30 Hz to 50 kHz. The test is applicable to ac and dc input power leads, not including grounds and neutrals. If the equipment under test is dc operated, this test is applicable over the frequency range 30 Hz to 50 kHz. If the equipment under test is ac operated, this test is applicable starting from the second harmonic of the power frequency and extending to 50 kHz.

The equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to a test signal with the rms voltage levels specified in Figure 4.3. The test criterion is also met under the following condition: when the power source specified in MIL-STD 462D, adjusted to dissipate 80 W in a 0.5-Ω load, cannot develop the required voltage

(specified in Figure 4.3) at the power input terminals and the equipment under test is not adversely affected by the output of the signal. Acceptable performance should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

Figure 4.3 CS101 operating envelope

4.1.4 CS114—Conducted susceptibility, high frequency

The CS114 test simulates currents that will be developed on leads as a result of EMI/RFI generated by antenna transmissions. The test covers the frequency range 10 kHz to 400 MHz and is applicable to all interconnecting leads, including the power leads of the equipment under test. Although the CS114 test can be applied to assess signal line susceptibility, the test levels given apply only to power and control lines.

The equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to a test signal with the rms levels shown in Figure 4.4. Acceptable performance should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

Figure 4.4 CS114 operating envelope

4.2 MIL-STD 461D Radiated EMI/RFI Operating Envelopes

4.2.1 RE101—Radiated emissions, magnetic field

The RE101 test measures radiated magnetic field emissions in the frequency range 30 Hz to 100 kHz. Equipment not intended to be installed in areas where other equipment sensitive to magnetic fields is located should be exempt from this test. The test is applicable for emissions from equipment and subsystem enclosures, and all interconnecting leads. The test does not apply at transmitter fundamental frequencies or to radiation from antennas. Magnetic field emissions should not be radiated in excess of the levels shown in Figure 4.5 at the specified distances of 7 cm and 50 cm.

4.2.2 RE102—Radiated emissions, electric field

The RE102 test measures radiated electric field emissions in the frequency range 10 kHz to 1 GHz. It is applicable for emissions from equipment and subsystem enclosures, and all interconnecting leads. The test does not apply at transmitter fundamental frequencies or to radiation from antennas.

Electric field emissions should not be radiated in excess of the rms values shown in Figure 4.6. At frequencies above 30 MHz, the test criterion should be met for both horizontally and vertically polarized fields.

Figure 4.5 RE101 magnetic field emissions envelopes

Figure 4.6 RE102 emissions envelope

4.2.3 RS101—Radiated susceptibility, magnetic fields

The RS101 test ensures that equipment and subsystems are not susceptible to radiated magnetic fields in the frequency range 30 Hz to 100 kHz. The test is applicable to equipment and subsystem enclosures and all interconnecting leads. The test is not applicable for electromagnetic coupling via antennas.

The equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to the rms magnetic field levels shown in Figure 4.7. Acceptable performance should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

Figure 4.7 RS101 operating envelope

4.2.4 RS103—Radiated susceptibility, electric fields

The RS103 test ensures that equipment and subsystems are not susceptible to radiated electric fields in the frequency range 10 kHz to 1 GHz. The test is applicable to equipment and subsystem enclosures and all interconnecting leads. The test is not applicable at the tuned frequency of antenna-connected receivers, unless otherwise specified.

The equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to the radiated electric fields. The impressed electric field level should be 10 V/m (rms), measured at the surface of the equipment under test with a field strength meter. The test criterion should be met for both horizontally and vertically polarized fields. According to MIL-STD 462D, circularly polarized fields are not acceptable because radiated electric fields are typically linearly polarized. Acceptable performance should be defined in the test plan by the

end user or testing organization according to the applicable equipment, subsystem, or system specifications.

4.3 MIL-STD 461C Conducted EMI/RFI Operating Envelopes

4.3.1 CE01—Conducted emissions, low frequency

The CE01 test measures the low frequency conducted emissions on power leads of equipment and subsystems in the frequency range 30 Hz to 15 kHz. Equipment tested under comparable power quality guidance should be exempt from this test. When the test is desired, it 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.

The CE01 test is applicable for emissions on dc power leads from 30 Hz to 15 kHz. Conducted emissions on dc power leads in excess of the values shown in Figure 4.8 should not appear when measured with an effective bandwidth not exceeding 75 Hz. The CE01 test is applicable for emissions on ac power leads from the power line frequency to 15 kHz. Emissions on ac power leads in excess of the rms values shown in Figure 4.9 should not appear when measured with an effective bandwidth not exceeding the power line frequency plus 20% of the power line frequency (i.e., 72 Hz in the United States).

Figure 4.8 CE01 emissions envelope for dc power leads

Figure 4.9 CE01 emissions envelope for ac power leads

4.3.2 CE03—Conducted emissions, high frequency

The CE03 test measures the high frequency conducted emissions on 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 should not appear on the power leads in excess of the rms values shown in Figures 4.10 and 4.11 for narrowband and broadband emissions, respectively.

The terms *narrowband* and *broadband* refer to the values for the measurement receiver bandwidths to be employed during the emissions testing. A factor of 10 is typically specified as the separation between the narrowband and broadband bandwidths, and is used to differentiate between narrowband and broadband interference sources. If the interference is broadband (e.g., arc welders and motors), a reduction in the bandwidth by a factor of 10 on the measurement receiver should result in at least a 6 dB drop in the interference level. Otherwise, the interference is considered to be narrowband (e.g., two-way radios).

Figure 4.10 CE03 narrowband emissions envelope

Figure 4.11 CE03 broadband emissions envelope

4.3.3 CS01—Conducted susceptibility, low frequency

The CS01 test ensures that equipment and subsystems are not susceptible to voltage distortions 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 $\pm 5\%$ of the power line frequency (i.e., 57-63 Hz in the United States).

The equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to electromagnetic energy injected onto its power leads at the levels and frequencies given in Figure 4.12. The test criterion can also be met under the following condition: when the power source specified in MIL-STD 462, adjusted to dissipate 50 W into a 0.5- Ω load, cannot develop the required voltage (specified in Figure 4.12) at the power input terminals of the equipment under test and the equipment is not adversely affected by the output of the signal source. Acceptable performance should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

Figure 4.12 CS01 operating envelope

4.3.4 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 should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to 7 Vrms from a 50-Ω source across the frequency range cited above. The test signal should be applied directly to the equipment input terminals, not through its power line cord. The criterion can also be met under the following condition: when a 1-W source of 50-Ω impedance cannot develop 7 Vrms at the input terminals of the equipment under test and the equipment is not adversely affected by the output of the signal source. Acceptable performance should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

4.4 MIL-STD 461C Radiated EMI/RFI Operating Envelopes

4.4.1 RE01—Radiated emissions, magnetic field

The RE01 test measures the radiated magnetic field emissions from equipment and subsystems in the frequency range 30 Hz to 30 kHz. Equipment not intended to be installed in areas where other equipment sensitive to magnetic fields is located should be exempt from this test. Also, the test does not apply to radiation from antennas. When the test is desired, levels should be measured with a receiving antenna positioned 7 cm from the surface of the equipment under test. Radiated magnetic field emissions should not appear at the receiving antenna in excess of the rms values shown in Figure 4.13.

Figure 4.13 RE01 magnetic field emissions envelope

4.4.2 RE02—Radiated emissions, electric field

The RE02 test measures the radiated electric field emissions from equipment and subsystems in the frequency range 14 kHz to 1 GHz. The test does not apply to radiation from antennas. Levels should be measured with receiving antennas positioned 1 m from the surface of the equipment under test. Radiated electric field emissions should not appear at the receiving antennas in excess of the rms values shown in Figures 4.14 and 4.15.

Figure 4.14 RE02 narrowband emissions envelope

Figure 4.15 RE02 broadband emissions envelope

4.4.3 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 should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to the rms magnetic field levels and frequencies shown in Figure 4.16. The level of the imposed field is to be measured with a field strength meter positioned at the surface of the equipment under test. Acceptable performance should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

Figure 4.16 RS01 operating envelope

4.4.4 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 1 GHz. The fields are to be generated with high-impedance antennas selected so as to cover the specified frequency range.

The equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to radiated electric fields. The electric field level impressed should be 10 V/m (rms), measured at the surface of the equipment under test with a field

strength meter. Acceptable performance should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

5 RECOMMENDED SWC OPERATING ENVELOPES

Recommended SWC operating envelopes are discussed herein for the representative surge waveforms defined in IEEE Std C62.41-1991 (Reaff 1995). The withstand levels are based on a *Category B* location and a *Low to Medium Exposure* level. The selection of these specific criteria is discussed in Sect. 3.

The procedures to be employed in performing the surge testing are described in IEEE Std C62.45-1992. A surge generator capable of developing the representative surge waveforms is required and the surges are injected and monitored using coupling and decoupling circuits. Voltage probes and current transformers are used to monitor both the applied surges and the response of the equipment under test. The ac interface of the equipment under test is the point of application for the surge tests.

5.1 Ring Wave

The Ring Wave simulates oscillatory surges of relatively high frequency on the ac power leads of equipment and subsystems, and is represented by an open-circuit voltage waveform. The waveform is an 100 kHz sinusoid having an initial rise time of 0.5 μ s and continually decaying amplitude. A plot of the waveform is shown in Figure 5.1. The rise time is defined as the time difference between the 10% and 90% amplitude points on the leading edge of the waveform. The amplitude of the waveform decays with each peak being 60% of the amplitude of the preceding peak of the opposite polarity.

Figure 5.1 100-kHz Ring Wave

V_p , the peak voltage value of the Ring Wave, should be 3 kV. During the performance of the test, the equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to the Ring Wave. Acceptable performance of the equipment under test should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

5.2 Combination Wave

The Combination Wave involves two exponential waveforms, an open-circuit voltage and a short-circuit current. It is intended to represent direct lightning discharges, fuse operation, or capacitor switching on the ac power leads of equipment and subsystems. The open-circuit voltage waveform has a 1.2- μ s rise time and an exponential decay with a duration (to 50% of initial peak level) of 50 μ s. The short-circuit current waveform has an 8- μ s rise time and a duration of 20 μ s. Plots of the waveforms are shown in Figures 5.2 and 5.3.

The rise time is defined as the time difference between the 10% and 90% amplitude points on the leading edge of the waveform. The duration is defined as the time between virtual origin and the time at the 50% amplitude point on the tail of the waveform. Virtual origin is the point where a straight line between the 30% and 90% points on the leading edge intersects the 50% point on the tail of the waveform.

V_p , the peak value of the open-circuit voltage of the Combination Wave, should be 3 kV. I_p , the peak value of the short-circuit current, should be 1.5 kA. During the performance of the test, the equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to the Combination Wave. Acceptable performance of the equipment under test should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

Figure 5.2 Combination Wave, open-circuit voltage

Figure 5.3 Combination Wave, short-circuit current

5.3 Electrically Fast Transients

The EFT waveform consists of repetitive bursts, with each burst containing individual unidirectional pulses, and is intended to represent local load switching on the ac power leads of equipment and subsystems. The individual EFT pulses have a 5-ns rise time and a duration (width at half-maximum) of 50 ns. Plots of the EFT pulse waveform and the pattern of the EFT bursts are shown in Figures 5.4 and 5.5.

The rise time is defined as the time difference between the 10% and 90% amplitude points on the leading edge of the waveform. The duration is defined as the time between the 50% amplitude points on the leading and trailing edges of each individual pulse. Individual pulses occur in bursts of duration 15 ms.

The peak value of the individual EFT pulses should be 3 kV. During the performance of the test, the equipment under test should not exhibit any malfunction or degradation of performance beyond specified operational tolerances when subjected to the EFT pulses. Acceptable performance of the equipment under test should be defined in the test plan by the end user or testing organization according to the applicable equipment, subsystem, or system specifications.

Figure 5.4 Waveform of the EFT pulse

Figure 5.5 Pattern of EFT bursts

6 ASSESSMENT OF EMI/RFI OPERATING ENVELOPES

6.1 ORNL Electromagnetic Survey Findings

Ambient electromagnetic conditions were measured with electric and magnetic spectral receivers at eight nuclear units operated by four participating utilities. The units included one boiling water reactor (BWR) supplied by GE Nuclear Energy and seven pressurized water reactors (PWRs) supplied by Westinghouse Electric [3 units], Babcock and Wilcox (B&W) [3 units], and ABB Combustion Engineering [1 unit]. Measurements were taken over a 14-month period at a variety of operating conditions and observation locations within the plants. The operating conditions monitored included full-power operation, coastdown, low-power operation, shutdown, outage, startup, and plant trip. The locations for placement of the spectral receivers were determined in consultation with the responsible site engineer based on likely high field levels, proximity to safety-related I&C systems, and current or planned digital equipment installation sites. The EMI/RFI survey measurement locations are shown in Table 6.1. Some participating units provided measurement opportunities near reactor protection system (RPS) cabinets containing digital systems, as well as near conventional analog equipment. The measurement period at each location ranged from 1 to 5 weeks. Descriptions of the spectral receivers and the survey procedures are provided in NUREG/CR-6436.

Table 6.1 EMI/RFI survey measurement locations

Measurement Sites
Main Control Rooms
Control Area Equipment Rooms
Electrical Equipment Rooms
Auxiliary Instrument Rooms
Cable Spreading Rooms
Relay Rooms
Electrohydraulic Controller Room
Turbine Deck
Electrical Penetration Rooms

Comparison of the observations at the different plant sites demonstrated a remarkable similarity, based on monitoring locations and operating conditions, in the electromagnetic environment from site to site. For any given frequency band, the highest observed electric field strengths varied within ± 10 dB of the mean value for each frequency under the compared conditions. The comparison of the highest observed magnetic field strengths also showed a similar ± 10 dB variation about the mean for most frequencies. The exception to this comparison for the magnetic fields occurred in the 5-20 kHz frequency band where a ± 20 dB variation was observed.

The range of conditions and locations monitored, and the volume of data taken give a high level of confidence that the electromagnetic environment at nuclear power plants has been adequately determined. Hence, it is our opinion that operating envelopes that are characteristic of the electromagnetic conditions in nuclear power plants can be reasonably developed so that they bound the highest strength observations at each plant without setting unduly high expectations for specific plants. While there were differences detected in the highest strength observations at the various plants, these differences offer insufficient data to warrant plant-to-plant distinctions and do not justify the establishment of separate bounding envelopes. These observations are presented in more detail in NUREG/CR-6436.

The highest strength electromagnetic observations from the ORNL survey at the eight nuclear units are presented in Tables 6.2 through 6.4 and reported in rms units. Table 6.2 presents the highest strength radiated electric field observations, Table 6.3 presents the highest strength radiated magnetic field observations, and Table 6.4 presents the highest strength conducted EMI/RFI observations. The associated expanded observation uncertainty (i.e., the interval about the measurement results in which the values of the measurand or measured phenomenon can be expected to lie with a 95% confidence level) is also presented for each of the highest-strength observations. The confidence level does not provide any guarantee that there are no unmeasured events that may exceed the highest strength observations, only that there is reasonable assurance that plausible bounds on the characteristic electromagnetic environment have been confirmed.

Table 6.2 ORNL highest observations—radiated electric fields

Frequency (MHz)	Field Strength (dBμV/m)	Expanded Observation Uncertainty (dB)
5-100	130.7	± 7.8
100-200	132	± 3.5
200-300	109.9	± 3.5
300-400	110	± 3.5
400-500	127.3	± 3.5
500-600	106.2	± 3.5
600-700	108.8	± 3.5
700-800	115.5	± 3.5
800-900	107.6	± 3.5
900-1000	125.1	± 3.5

Table 6.3 ORNL highest observations—radiated magnetic fields

Frequency (kHz)	Field Strength (dBpT)	Expanded Observation Uncertainty (dB)
0.30-0.61	107	± 7.5
0.61-1.22	101	± 7.5
1.22-2.44	104	± 7.5
2.44-4.88	104	± 7.5
4.88-9.77	117	± 7.5
9.77-19.53	117	± 7.5
19.53-39.06	106	± 7.5
39.06-78.12	100	± 7.5
78.12-156.25	101	± 7.5
156.25-312.5	102	± 4.9
312.5-625	101	± 4.9
625-1250	101	± 4.9
1250-2500	51	± 4.9
2500-5000	51	± 4.9

Table 6.4 ORNL highest observations—conducted EMI/RFI, 300 Hz to 5 MHz

Frequency (kHz)	Strength (dBμA)	Expanded Observation Uncertainty (dB)
0.30-0.61	89.6	± 7.5
0.61-1.22	83.8	± 7.5
1.22-2.44	78	± 7.5
2.44-4.88	78	± 7.5
4.88-9.77	73.2	± 7
9.77-19.53	71.2	± 5.8
19.53-39.06	77.5	± 4.9
39.06-78.12	71.5	± 4.9
78.12-156.25	77.5	± 4.9
156.25-312.5	83.5	± 4.9
312.5-625	83.5	± 4.9
625-1250	77.5	± 4.9
1250-2500	53.4	± 4.9
2500-5000	53.4	± 4.9

6.2 Survey Data vs Recommended Operating Envelopes

A wealth of data was generated during the plant site surveys: ~650,000 electric field observations, ~35.7 million magnetic field observations, and ~6.4 million conducted EMI/RFI observations. This large volume of data was taken during extended observation periods under a wide variety of power plant conditions (reactor type, operating modes, site locations) and, in our opinion, enables the bounding electromagnetic conditions to be expected at nuclear power plants to be characterized with high confidence. The survey results show that the measured conditions do not exceed the recommended envelopes (the smallest difference between the data and the envelopes for any observed EMI/RFI event in any frequency band is 8 dB). In addition, when the expanded observation uncertainty is included with the bounding values from the survey, the results are still bounded by the envelopes with a high confidence level (the smallest difference between the expanded range and the envelopes for any observed EMI/RFI event in any frequency band is 1.5 dB). Therefore, the adequacy of the operating envelopes are confirmed by the survey results.

Figure 6.1 illustrates the comparison of the survey data and the recommended operating envelopes for radiated electric fields (RS03 and RS103). Figure 6.2 illustrates the comparison of the survey data and the recommended operating envelopes for radiated magnetic fields (RS01 and RS101). Likewise, Figure 6.3 illustrates the comparison of the survey data and the operating envelope recommendations for conducted interference for the frequency range 30 Hz to 50 kHz (CS01 and CS101), and Figure 6.4 illustrates the comparison of the survey data and the recommended operating envelopes for the frequency range 10 kHz to 400 MHz (CS02 and CS114). The bounded measurement data from EPRI TR-102323 for the three data types are also shown for comparison.

Figure 6.1 Data vs envelopes, radiated electric fields

Figure 6.2 Data vs operating envelopes, radiated magnetic fields

Figure 6.3 Data vs operating envelopes, conducted interference - 30 Hz to 50 kHz

Figure 6.4 Data vs operating envelopes, conducted interference - 10 kHz to 400 MHz

6.3 Discussion on the Need for Safety Margins

The determination of an "adequate" safety margin is a regulatory issue and falls outside of the ORNL research scope. However, ORNL can offer technical evidence to support a high confidence that the recommended envelopes are sufficient to bound the anticipated electromagnetic conditions. Application of these envelopes provides reasonable assurance that I&C systems successfully tested to those levels of interference will function properly in the nuclear power plant electromagnetic environment.

The nature of the ORNL survey of electromagnetic conditions and the expanded measurement uncertainty applied to the bounding EMI/RFI data implicitly account for many of the issues related to a margin. In the letter from J. Wermiel to B. Boger dated August 5, 1994, the justification for a safety margin was discussed. The NRC staff stated that the "selected safety margin should include (1) any instrumentation inaccuracy, (2) uncertainties in site survey, (3) variations between the measured sites (plants), (4) possible lack of sufficient data, and (5) variations in operating conditions." Instrumentation inaccuracy is explicitly included in the expanded observation uncertainty applied to the survey results. ORNL feels that issues #2, #3 and #5 are addressed by the survey approach taken. The survey measurements were taken at most locations within a nuclear power plant where safety-related I&C systems either are or are likely to be installed, were conducted at eight nuclear units representing each reactor manufacturer type, and included observations under a full range of operating conditions (including transients). In addition, coupling the ORNL results with the measurement results from the independent EPRI survey, measured electromagnetic conditions from 14 different nuclear units are available and have been shown to be bounded by the recommended operating envelopes.

Issue #4 addresses the concern about unmeasured events as well as statistical confidence in the data. As stated earlier, the ORNL survey generated ~650,000 electric field observations, ~35.7 million magnetic field observations, and ~6.4 million conducted EMI/RFI observations. Therefore, the survey results are based on a wealth of data. Regarding unmeasured events, ORNL believes that the survey results provide a realistic determination of the characteristic electromagnetic environment with a high confidence but do not absolutely guarantee that no higher interference levels are possible. In order to have high confidence in conditions determined by a site survey, IEEE 473-1985, *IEEE Recommended Practice for an Electromagnetic Site Survey (10 kHz to 10 GHz)*,¹⁷ recommends a two week observation period to characterize the electromagnetic conditions given man-made sources. These observations are to be made every hour for at least three minute periods. ORNL greatly exceeded these recommendations in its survey by taking continuous measurements for up to 5 week periods. Therefore, ORNL contends that the survey approach addresses many of the components expected of a safety margin and that the existing difference between the envelopes and the bounding observations with the expanded uncertainty applied provides additional assurance that nuclear power plant electromagnetic conditions are bounded.

7 IMPLEMENTATION OF THE OPERATING ENVELOPES

Many EMI/RFI issues can be resolved by applying the operating envelopes developed herein for the MIL-STD 461D and 461C test criteria. It is intended that either set of operating envelopes be applied in its entirety, without selective application of individual operating envelopes (i.e., no mixing and matching of operating envelopes).

The recommended operating envelopes are applicable for locations within a nuclear power plant where safety-related I&C systems either are or are likely to be installed. These locations include control rooms, cable spreading rooms, equipment rooms, relay rooms, auxiliary instrument rooms, and other areas (e.g., the turbine deck) where safety-related I&C system installations are planned. The recommended operating envelopes are also applicable for both analog and digital system installations.

It is recommended that an assessment of the electromagnetic conditions at the point of installation for safety-related I&C systems be performed to identify any unique EMI/RFI sources that may generate local interference. The EMI/RFI sources could possibly include both portable and fixed equipment (e.g., portable transceivers, arc welders, power supplies, and generators). Steps should be taken during installation to ensure that the systems are not exposed to EMI/RFI levels, from the identified sources, greater than 8 dB below the recommended operating envelopes.

The recommended EMI/RFI practices, SWC practices, and operating envelopes are only elements of the total package that is needed to ensure EMC within nuclear power plants. In addition to assessing the electromagnetic environment, the plants will still need to apply sound engineering practices for nonsafety-related upgrades and I&C maintenance as part of an overall EMC program. While nonsafety-related systems are not part of the regulatory guidance being developed, the control of EMI/RFI from these systems is essential to ensure that safety-related I&C systems can continue to perform properly in the nuclear power plant environment. It is suggested that, when feasible, the emissions from nonsafety-related systems be held to the same levels as safety-related systems.

To ensure that the recommended operating envelopes are being used properly, equipment should be tested in the same physical configuration as that specified for its actual installation in the plant. In addition, the physical configuration of the safety-related I&C system should be maintained and all changes in the configuration controlled. The design specifications that should be maintained and

controlled include wire and cable separations, shielding techniques, shielded enclosure integrity, apertures, gasketing, grounding techniques, EMI/RFI filters, and circuit board replacements.

It is suggested that any modifications to the presently recommended electromagnetic operating envelopes (e.g., lower site-specific envelopes) be based on comparable technical evidence to that presented herein. In effect, any relaxation in the recommended operating envelopes should be based on actual measurement data collected in accordance with IEEE Std 473-1985.

Exclusion zones should be established through administrative controls to prohibit the activation of portable transceivers in areas where safety-related I&C systems have been installed. The size of the exclusion zones is a regulatory issue, but should depend on the effective radiated power of the portable transceivers used within a particular nuclear power plant. Thus, the size of exclusion zones should be site-specific. For the recommended radiated electric field operating envelope of 10 V/m (140 dB μ V/m), a suggested rule of thumb could be that the size of exclusion zones be set such that the radiated electric fields emanating from the portable transceivers be at least 8 dB less (132 dB μ V/m) in the vicinity of safety-related I&C systems.

8 CONCLUSIONS

The recommended electromagnetic operating envelopes developed by ORNL and outlined in this report are consistent with envelopes currently used by both the military and a broad range of industries. Based on the ORNL electromagnetic survey results, the recommended envelopes also bound the characteristic electromagnetic operating environment at nuclear power plants with high confidence. When used in combination with the test criteria and test methods recommended in NUREG/CR-5941, these electromagnetic operating envelopes provide assurance that safety-related I&C systems will function according to specification within the projected electromagnetic environment. Proper testing and sound installation practices (as described in NUREG/CR-5941) will ensure with high confidence that EMI/RFI and power surge problems with safety-related I&C systems in nuclear power plants are averted for newly installed or upgraded systems.

The value added by developing the technical basis for regulatory guidance in both NUREG/CR-5941 and this report is that it (1) offers clear guidance on necessary practices that are a part of an overall EMC program; (2) endorses military and industry standards that have wide, long-standing application; (3) specifies complete suites of EMI/RFI emissions and susceptibility test criteria and methods from the two most prevalent military standards (i.e., no mixing and matching of test criteria and methods are promoted) and gives operating envelopes that are framed in the proper units and frequency ranges for each specific test method; (4) applies to analog, digital, and hybrid safety-related I&C equipment; and (5) identifies acceptable operating envelopes which are based on similar military environments and confirmed with measurement data from nuclear power plants.

In a cost-cutting initiative, the Department of Defense took a bold step in 1994 in deciding that it would move away from the MIL-STDs and began to purchase commercial-off-the-shelf (COTS) equipment. Thus, support for the MIL-STDs may diminish over the next decade and certified testing laboratories that can conduct these tests may decrease in availability. There are commercial standards under development by the International Electrotechnical Commission (IEC) and ANSI. Upon their completion, the military will likely specify these commercial standards in its acquisitions and continued reliance on the MIL-STDs by NRC, as consensus commercial standards supersede them, may become burdensome to the nuclear industry. Thus, it is recommended that NRC continue to follow the development of the commercial standards, and review them as they become available for their applicability to the nuclear power plant environment.

 

9 REFERENCES

1. P. D. Ewing and K. Korsah, *Technical Basis for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related I&C Systems*, NUREG/CR-5941, Oak Ridge National Laboratory, April 1994.
2. S. W. Kercel, M. R. Moore, and E. D. Blakeman, *Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants*, NUREG/CR-6436, Oak Ridge National Laboratory, November 1996.
3. MIL-STD 461D, *Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference*, U.S. Department of Defense, Jan. 11, 1993.
4. MIL-STD 461C, *Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference*, U.S. Department of Defense, Aug. 4, 1986.
5. MIL-STD 462D, *Measurement of Electromagnetic Interference Characteristics*, U.S. Department of Defense, January 11, 1993.
6. MIL-STD 462, *Measurement of Electromagnetic Interference Characteristics*, U.S. Department of Defense, July 31, 1967.
7. D. P. Rollinger, "The ABC's of MIL-STD 461: An Overview of Military EMC Standards and an Insight into Procurement Procedures," *EMC Test and Design*, pp. 19-25 (September/October 1991).
8. IEEE Std C62.41-1991 (Reaff 1995), *IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*, Institute of Electrical and Electronics Engineers.
9. IEEE Std C62.45-1992, *IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits*, Institute of Electrical and Electronics Engineers.
10. EPRI TR-102323, *Guidelines for Electromagnetic Interference Testing in Power Plants*, Electric Power Research Institute, September 1994.
11. F. D. Martzloff and T. S. Gruzs, "Power Quality Site Surveys: Facts, Fiction, and Fallacies," *IEEE Trans.*, IA-24 (6), pp. 100-118 (November/December 1988).
12. IEEE Std C62.41-1991, *IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*, p. 40.
13. IEEE Std C62.41-1991, *IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*, p. 31.
14. ANSI C63.12-1987, *American National Standard for Electromagnetic Compatibility Limits — Recommended Practice*, American National Standards Institute.

15. D. N. Heirman, "International Activity in Product Immunity Standards and Testing," *EMC Test and Design*, pp. 16-19 (May/June 1992).
16. W. Sperber, "SAE Automotive Electromagnetic Immunity Standards," *1992 Proceedings of EMC/ESD International*, Denver, Colorado, Apr. 22-24, 1992.
17. IEEE Std 473-1985, *IEEE Recommended Practice for an Electromagnetic Site Survey (10 kHz to 10 GHz)*, Institute of Electrical and Electronics Engineers.

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11. ABSTRACT <i>(200 words or less)</i> <p>This document presents recommendations for electromagnetic operating envelopes to augment test criteria and test methods addressing electromagnetic interference (EMI), radio-frequency (RFI), and power surges that are applicable to safety-related instrumentation and control (I&C) systems in nuclear power plants. The Oak Ridge National Laboratory (ORNL) was engaged by the U. S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research to assist in developing the technical basis for regulatory guidance on EMI/RFI immunity and power surge withstand capability (SWC). Previous research provided recommendations on electromagnetic compatibility (EMC) design and installation practices, endorsement of EMI/RFI immunity and SWC test criteria and test methods, and determination of ambient electromagnetic conditions at nuclear power plants. The present research involves development of recommended electromagnetic envelopes that are applicable to nuclear power locations where safety-related I&C systems either are or will be installed. These recommended envelopes establish both emissions criteria and the levels of radiated and conducted interference that I&C systems should be able to withstand without upset or malfunction. The EMI/RFI operating envelopes are derived from conditions in comparable military environments and are confirmed by comparison with the nuclear power plant electromagnetic environment based on measured plant emissions profiles. Such detailed information on specific power surge conditions in nuclear power plants is not available, so industrial guidance on representing surge characteristics for susceptibility testing is adopted. An engineering assessment of the power surge environment in nuclear power plants leads to the recommendation of operating envelopes based on location categories and exposure levels defined in IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits.</p>						
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