EMI/RFI and Power Surge Withstand Guidance for the U.S. Nuclear Regulatory Commission

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Summary

This paper discusses the regulatory guidance implemented by U.S. NRC for minimizing malfunctions and upsets in safety-related instrumentation and control (I&C) systems in nuclear power plants caused by electromagnetic interference (EMI), radio-frequency interference (RFI), and power surges. The engineering design, installation, and testing practices deemed acceptable to U.S. NRC are described in Regulatory Guide (RG) 1.180, "Guidelines for Evaluating Electromagnetic and Radio-Frequency in Safety-Related Instrumentation and Control Systems" (January 2000) and in a Safety Evaluation Report (SER) endorsing EPRI TR-102323, "Guidelines for Electromagnetic Interference Testing in Power Plants," (April 1996). These engineering practices provide a well-established, systematic approach for ensuring electromagnetic compatibility (EMC) and surge withstand capability (SWC).

Introduction

The typical environment in a nuclear power plant includes many sources of electromagnetic interference (EMI), radio-frequency interference (RFI), and power surges, e.g., hand-held two-way radios, arc welders, switching of large inductive loads, high fault currents, and high-energy fast transients associated with switching at the generator or transmission voltage levels. The increasing use of advanced analog- and microprocessor-based instrumentation and control (I&C) systems in reactor protection and other safety-related plant systems has introduced concerns with respect to the susceptibility of this equipment to EMI/RFI and power surges, as well as the creation of additional noise sources.

Digital technology is constantly evolving, and manufacturers of digital systems are incorporating increasingly higher clock frequencies and lower logic level voltages into their designs. However, these performance advancements may have an adverse impact on the operation of digital systems with respect to EMI/RFI and power surges because of the increased likelihood of extraneous noise being misinterpreted as legitimate logic signals and of surge potentials causing equipment/parts damage. With recent advances in analog electronics, many of the functions presently being performed by several analog circuit boards could be combined into a single analog circuit board operating at reduced voltage levels, thereby making analog circuitry more susceptible

to EMI/RFI and power surges, as well. Hence, operational and functional guidance related to safety in the nuclear power plant environment is necessary to address the possibility of upsets and malfunctions in I&C systems caused by EMI/RFI and power surges.

Regulatory Guide (RG) 1.180, *Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems*, was issued in January 2000 to address EMI/RFI and power surge issues for safety-related digital I&C systems in nuclear power plants. The technical basis behind the practices in RG-1.180 is given in NUREG/CR-5941, *Technical Basis for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related I&C Systems*, and NUREG/CR-6431, *Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants*. Prior to the issuance of RG-1.180, NRC staff had accepted the Electric Power Research Institute (EPRI) topical report TR-102323, *Guidelines for Electromagnetic Interference Testing in Power Plants*, in a Safety Evaluation Report (SER) by letter dated April 17, 1996 as one method for addressing electromagnetic compatibility (EMC) issues in safety-related digital I&C systems. RG-1.180 complements the position set forth in the SER by improving the technical basis for evaluating EMI/RFI immunity and power surge withstand capability (SWC).

RG-1.180 and the EPRI TR-102323 SER adhere to the same overall approach and are generally in agreement. Each recommends EMI/RFI-limiting practices based on IEEE Std 1050, endorses emissions and susceptibility test criteria and test methods to evaluate safety-related I&C systems, and identifies appropriate operating envelopes for equipment and systems intended for selected locations in nuclear power plants. Each document presents acceptable means for demonstrating EMC and they are consistent in their respective approaches. The licensee has the freedom to choose the method best suited to the situation.

Design and Installation Practices

RG-1.180 endorses the design and installation practices described in IEEE Std 1050-1996, *IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations*, as suitable for limiting the generation and effects of EMI/RFI and power surges. IEEE Std 1050-1996 was developed primarily to provide guidance on the design and installation of grounding systems for I&C equipment specific to power generating stations. Further purposes of the standard are to achieve both a suitable level of protection for personnel and equipment, and suitable electrical noise immunity for signal ground references in power generating stations. IEEE Std 1050-1996 addresses grounding and noise-minimization techniques for I&C systems and recommends practices for the treatment of both analog and digital systems. The standard specifically addresses the grounding and shielding of electronic circuits on the basis of minimizing emissions and their susceptibility to EMI/RFI and power surges. The SER accepts the 1989 version of IEEE Std 1050. There are minor differences between the 1989 and 1996 versions of IEEE Std 1050, with some technical ambiguities from the 1989 version being cleared up in the 1996 version.

One exception was taken in RG-1.180 to the design and installation practices in IEEE Std 1050-1996. Section 4.3.7.4, “Radiative Coupling,” of the standard maintains that the “field strength” of propagating electromagnetic waves is inversely proportional to the square of the distance from the source of radiation. This statement needs to be reevaluated because radiative coupling is a far-field effect. A distance, r, greater than the wavelength divided by 2π ($r > \lambda/2\pi$) from the source of radiation is considered to be far field, which is the region where the wave impedance is equal to the characteristic impedance of the medium. Both the electric and magnetic

"field strengths" fall off as 1/r in the far field, not as $1/r^2$. 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 (>377Ω), the electric and magnetic "field strengths" attenuate at rates of $1/r^3$ and $1/r^2$, respectively. If the source impedance is low (<377Ω), the rates of attenuation are reversed: the electric "field strength" will fall off at a rate of l/r^2 and the magnetic "field strength" at a rate of $1/r^3$. The significance of this exception lies in the appropriate application of the design and installation practices in IEEE Std 1050-1996. For example, the strength of magnetic fields from a low-impedance source is typically substantially much reduced within a short distance and simply moving equipment away from strong sources of magnetic fields can prevent interference problems.

IEEE Std 1050-1996 references other standards that contain complementary and supplementary information. In particular, IEEE Std 518-1982, *IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources*, and IEEE Std 665-1995, *IEEE Guide for Generating Station Grounding*, are referenced frequently. The portions of IEEE Std 518-1982 and IEEE Std 665-1995 referenced in IEEE Std 1050-1996 are endorsed by RG-1.180 and are to be used in a manner consistent with the practices in IEEE Std 1050-1996.

EMI/RFI Testing Practices

To verify the adequacy of safety-related I&C systems and equipment design, both RG-1.180 and the SER endorse applicable EMI/RFI test criteria in the U.S. Department of Defense's Military Standard (MIL-STD) 461, *Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference*. Also endorsed are the associated test methods in MIL-STD 462, *Measurement of Electromagnetic Interference Characteristics*. EMI/RFI test criteria from both MIL-STD 461C and 461D, as well as their respective MIL-STD 462 and 462D test methods, are cited in RG-1.180 and the SER. The bases behind the selections are detailed in NUREG/CR-5941 for RG-1.180 and in EPRI TR-102323 for the SER. MIL-STDs 461 and 462 were developed as measures to ensure EMC. Applications of the MIL-STD test criteria and test methods are tailored for the intended function of the equipment and the characteristic environment (i.e., which tests and what levels are applied depend on the function to be performed and the location of operation).

The MIL-STD 461D test criteria acceptable to the U.S. NRC in RG-1.180 and the SER for susceptibility and emissions testing on safety-related I&C systems intended for nuclear power plants are listed in Table 1. These criteria cover conducted and radiated interference (emissions and susceptibility), exposure to electric and magnetic fields, and noise coupling through power and control leads. The criteria do not cover conducted interference on interconnecting signal lines because the MIL-STD test methods do not explicitly address signal line conducted susceptibility. Research covering this area is presently ongoing. MIL-STD 461D provided the latest revision of the test criteria at the time that RG-1.180 and the SER were issued, thus it represents current practice. However, guidance on the MIL-STD 461C counterparts to the MIL-STD 461D test criteria is also given to avoid placing an undue burden on the nuclear power industry by limiting the available test resources to those test laboratories with just the MIL-STD 462D test capability.

Table 1 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

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

RG-1.180 provides two acceptable suites of EMI/RFI emissions and susceptibility criteria. It is intended that either set of test criteria be applied in its entirety, without selective application of individual criteria (i.e., no mixing and matching of test criteria). The reason for this is the avoidance of lapses in frequency coverage of the criteria, discontinuities in test phenomena coverage, miscalculations in test unit conversions, and unreasonable comparisons of operating envelope levels. The SER does allow mixing and matching, but exercising good engineering judgement in the performance of the EMI/RFI tests is recommended when doing so.

The MIL-STD 461 test criteria have associated operating envelopes that serve to establish test levels. The operating envelopes that are acceptable to the U.S. NRC are not given herein, but can be found in RG-1.180 and the SER. The operating envelopes in both documents are similar, with only minor differences. The detailed technical basis for the operating envelopes in RG-1.180 is presented in NUREG/CR-6431. The technical basis for the RG-1.180 operating envelopes begins with the MIL-STD envelopes corresponding to the electromagnetic environment for military ground facilities, which were judged to be comparable to that of nuclear power plants based on general layout and equipment type considerations. Plant emissions data measured at 14 nuclear units were used to confirm the adequacy of the operating envelopes. From the MIL-STD starting point, susceptibility envelopes were adjusted to account for the plant emissions measurement data collected at eight nuclear units in 1995 and reported in NUREG/CR-6436, *Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants*. In addition, emissions data collected at six nuclear units during a 1994 EPRI study were used as a basis for adjusting the susceptibility envelopes. Figure 1 illustrates the comparison of the power plant data and the operating envelope for radiated electric fields (RS103), while Figure 2 illustrates a similar comparison for radiated magnetic fields (RS101). The basis for adjustments to the equipment emissions envelopes included consideration of the primary intent of the MIL-STD envelopes and maintaining some margin with the susceptibility envelopes. Finally, when changes to the operating envelopes from the MIL-STD origin were motivated by technical considerations, consistency among the envelopes for comparable test criteria was promoted and commercial

emissions limits for industrial environments were factored into adjustments of the envelopes. The basis for the operating envelopes endorsed by the SER is detailed in EPRI TR-102323.

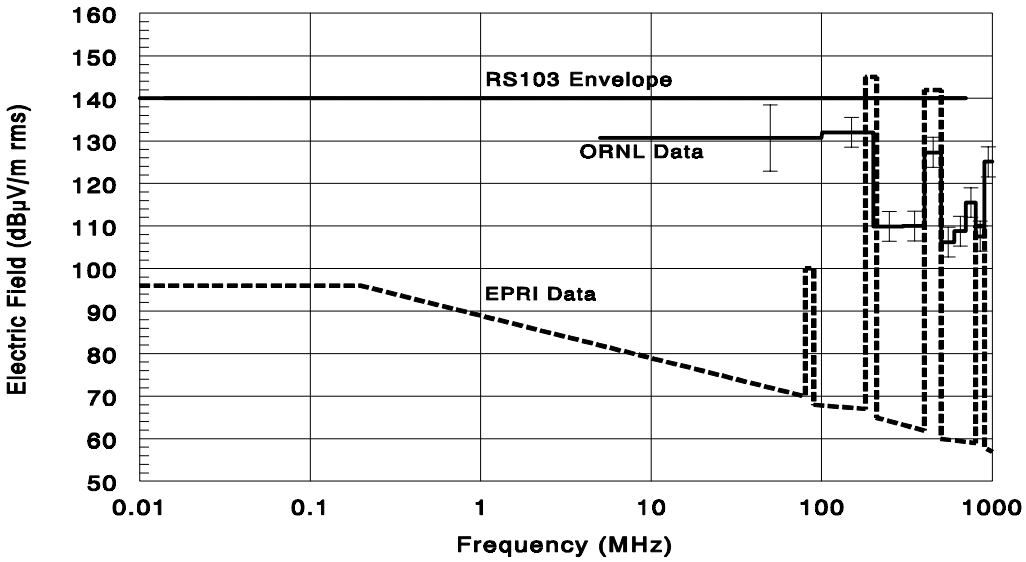

Figure 1 Plant Data vs Radiated Electric Fields Envelope.

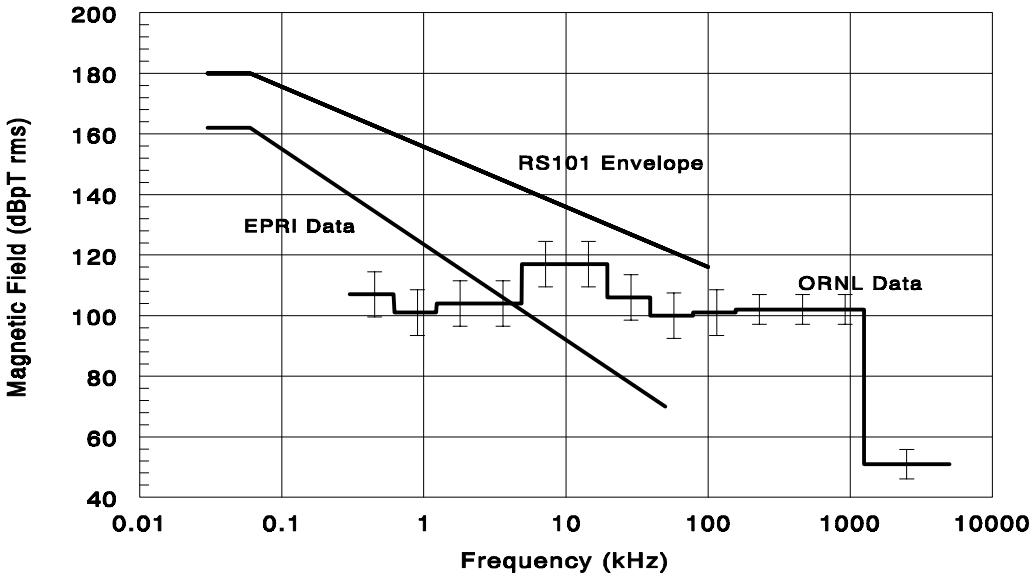

Figure 2 Plant Data vs Radiated Magnetic Fields Envelope.

The test methods that demonstrate compliance with the MIL-STD 461D EMI/RFI test criteria are specified in MIL-STD 462D. The test methods that demonstrate compliance with the MIL-STD 461C EMI/RFI test criteria are specified in MIL-STD 462. These methods are acceptable to the U.S. NRC staff for accomplishing EMI/RFI testing for safety-related I&C systems intended for installation in nuclear power plants.

Surge Withstand Capability (SWC) Testing Practices

RG-1.180 endorses the SWC test criteria recommended in IEEE Std C62.41-1991, *IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits*, and the associated test methods recommended in IEEE Std C62.45-1992, *IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits*. IEEE Std C62.41-1991 provides guidance for the selection of voltage and current surge test criteria for evaluating the SWC of equipment connected to low-voltage ac power circuits. The standard defines a set of surge test waveforms that includes lightning-induced transients, oscillatory ring waves, and electrically fast transients (EFT) caused by load switching. The recommended test waveforms have manageable dimensions and represent a baseline surge environment. IEEE Std C62.45-1992 provides guidance on the test methods and equipment to be employed when performing the surge tests. The SER endorses the comparable surge testing practices in Parts 4 and 5 of the International Electrotechnical Commission (IEC) Standard 801, *Electromagnetic Compatibility for Industrial Process Measurement and Control Equipment*. IEC 801 has been superseded by IEC 61000-4, *Electromagnetic Compatibility: Part 4, Testing and Measurement Techniques*. Typical environmental conditions for surges in a nuclear power plant can be represented by the waveforms given in Table 2.

Table 2 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 µs	1.2 µs	8 µs	5 ns
Duration	100 kHz ringing	50 µs	20 µs	50 ns
Peak value	3 kV	3 kV	1.5 kA	3 kV

Withstand levels that are acceptable to the U.S. NRC are given in RG-1.180 for each surge waveform. IEEE Std C62.41-1991 describes location categories and exposure levels that define applicable amplitudes for the surge waveforms that should provide an appropriate degree of SWC. Location categories depend on the proximity of equipment to the service entrance and the associated line impedance. Exposure levels relate to the rate of surge occurrence versus the voltage level (e.g., surge crest) to which equipment is exposed. Withstand levels are presented in NUREG/CR-6431 and based on *Category B* locations and *Low to Medium Exposure* levels. *Category B* covers feeders and short branch circuits less than 10 meters from the service entrance. *Low to Medium Exposure* levels encompass systems in areas known for little load or capacitor switching and low-power surge activity to areas known for significant switching transients or

medium- to high-power surge activity. Comparable IEC 801 SWC levels, also acceptable to the U.S. NRC, are given in the SER.

Regulatory Positions

Table 3 lists the specific regulatory positions in RG-1.180 that have been set forth by the U.S. NRC. This guidance complements the position set forth in the SER by improving the technical basis for evaluating EMI/RFI and power surges. The RG-1.180 guidance is applicable for all new safety-related systems or modifications to existing safety-related systems that include analog, digital, or hybrid (i.e., combined analog and digital electronics) equipment. While nonsafety-related systems are not part of the guidance, control of EMI/RFI from these systems is deemed necessary to ensure that safety-related I&C systems continue to perform properly.

The electromagnetic conditions at the point of installation for safety-related I&C systems should be assessed to identify EMI/RFI sources that may generate local interference. The EMI/RFI sources could include mobile, portable, and fixed equipment. Steps should be taken during installation to ensure that systems are not exposed to EMI/RFI levels from sources that are greater than 8 dB below the operating envelopes. When feasible, the emissions from nonsafety-related systems should be held to the same levels as safety-related systems.

The endorsed operating envelopes are acceptable for locations where safety-related I&C systems either are or are likely to be installed and include control rooms, remote shutdown panels, cable spreading rooms, equipment rooms, auxiliary instrument rooms, relay rooms, and other areas (e.g., the turbine deck) where safety-related I&C system installations are planned. To ensure that the 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 controlled include cable separations, shielding techniques, enclosure integrity, apertures, gasketing, grounding techniques, and EMI/RFI filters. Also, the endorsed test methods for evaluating electromagnetic emissions, EMI/RFI susceptibility, and power SWC are intended to be applied to the safety-related I&C equipment in test facilities or laboratories prior to installation.

Any modifications to the electromagnetic operating envelopes (e.g., lower site-specific envelopes) should be based on technical evidence comparable to that presented in NUREG/CR-6431. Relaxation in the operating envelopes should be based on actual measurement data collected in accordance with IEEE Std 473-1985, *IEEE Recommended Practice for an Electromagnetic Site Survey (10 kHz to 10 GHz).*

Exclusion zones should be established through administrative controls to prohibit the activation of mobile and portable emitters in areas where safety-related I&C systems have been installed. An exclusion zone is defined as the minimum distance permitted between the point of installation and where portable emitters are allowed to be activated. The size of the exclusion zones should be site-specific and depend on the effective radiated power and antenna gain of the portable emitters. The size of exclusion zones should also depend on the allowable emission levels designated for the installation area. Additional guidance on exclusion zones is provided in NUREG/CR-6431.

Table 3 Specific Regulatory Positions for EMC Guidance.

Regulatory Position	EMC Issue	Standards	Comments
2	EMI/RFI limiting practices	IEEE Std 1050-1996	Full standard endorsed with one exception taken.
		IEEE Std 518-1982 IEEE Std 665-1995	Endorsed as referenced by IEEE Std 1050-1996.
3, 4, 5	EMI/RFI emissions and immunity testing	MIL-STD 461D MIL-STD 462D	Selected MIL-STD 461 test criteria endorsed along with MIL-STD 462 test methods.
		MIL-STD 461C MIL-STD 462	Alternative test suites.
			Operating envelopes are included in Reg. Pos. 4 and 5.
6	Surge withstand capability testing	IEEE Std C62.41-1991 IEEE Std C62.45-1992	Selected IEEE Std C62.41 surge test waveforms endorsed with IEEE Std C62.45 test methods.
			Withstand levels for nuclear power plants are included in Reg. Pos. 6.

Conclusions

The issuance of RG-1.180 and the EPRI TR-102323 SER by U.S. NRC has resulted in clear guidance on the practices necessary for a comprehensive EMC program. Both documents represent guidance that is acceptable to U.S. NRC. These practices are presently being applied to analog, digital, and hybrid (i.e., combined analog and digital electronics) safety-related I&C equipment. The concurrence within the nuclear industry is that approval cycles have been significantly reduced, EMC awareness has been heightened, and the number of EMC-related occurrences has been reduced.

Adherence to the guidance in RG-1.180 and the SER for safety-related I&C systems has contributed to the assurance that structures, systems, and components important to safety are compatible with the environmental conditions associated with nuclear power plants. Consensus standards were endorsed that cover design, installation, EMI/RFI, and SWC practices. Test methods have been provided that contribute to a well established, systematic approach for ensuring EMC. Operating envelopes that have been confirmed with actual measurement data in nuclear power plants have been recommended.

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