NUREG/CR-6431
ORNL/TM-13158

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

Oak Ridge National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

AVAILABILITY NOTICE

Availability of Reference Materials Cited in NRC Publications

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy,* of the *Code of Federal Regulations,* may be purchased from one of the following sources:

1. The Superintendent of Documents
   U.S. Government Printing Office
   P.O. Box 37082
   Washington, DC 20402–9328
   <http://www.access.gpo.gov/su_docs>
   202–512–1800
2. The National Technical Information Service
   Springfield, VA 22161–0002
   <http://www.ntis.gov>
   1–800–553–6847 or locally 703–605–6000

The NUREG series comprises (1) brochures (NUREG/BR-XXXX), (2) proceedings of conferences (NUREG/CP-XXXX), (3) reports resulting from international agreements (NUREG/IA-XXXX), (4) technical and administrative reports and books [(NUREG-XXXX) or (NUREG/CR-XXXX)], and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Office Directors' decisions under Section 2.206 of NRC's regulations (NUREG-XXXX).

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: Office of the Chief Information Officer
Reproduction and Distribution
Services Section
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001
E–mail: <DISTRIBUTION@nrc.gov>
Facsimile: 301–415–2289

A portion of NRC regulatory and technical information is available at NRC's World Wide Web site:

<http://www.nrc.gov>

After January 1, 2000, the public may electronically access NUREG-series publications and other NRC records in NRC's Agencywide Document Access and Management System (ADAMS), through the Public Electronic Reading Room (PERR), link <http://www.nrc.gov/NRC/ADAMS/index.html>.

Publicly released documents include, to name a few, NUREG-series reports; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigation reports; licensee event reports; and Commission papers and their attachments.

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, Two White Flint North, 11545 Rockville Pike, Rockville, MD 20852–2738. These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
<http://www.ansi.org>
212–642–4900

NUREG/CR-6431
ORNL/TM-13158

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

Manuscript Completed: November 1999
Date Published: January 2000

Prepared by
P. D. Ewing, R. T. Wood

Oak Ridge National Laboratory
Managed by Lockheed Martin Energy Research Corporation
Oak Ridge, TN 37831-6050

C. E. Antonescu, NRC Project Manager

Prepared for
Division of Systems Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code L1951

For sale by the U.S. Government Printing Office
Superintendent of Documents, Mail Stop: SSOP, Washington, DC 20402-9328
ISBN 0-16-050333-7

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 and commercial emissions limits for typical industrial environments. 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.*

CONTENTS

FIGURES

TABLES

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 susceptibility 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 susceptibility operating envelopes. As a result, the susceptibility envelopes were adjusted in some cases to account for the plant emissions data. Adjustments to the equipment emissions envelopes considered margin with the susceptibility envelopes and the primary intent of the MIL-STD envelopes (e.g., whether the envelopes were based on protecting sensitive receivers on military platforms). 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.

Detailed information on specific power surge conditions in nuclear power plants was not available so industrial guidance on representative surge characteristics for susceptibility testing was adopted. An engineering assessment of the power surge environment in nuclear power plants led to the recommendation of basing the operating envelopes on location categories and exposure levels defined in IEEE Std C62.41-1991. The selected location category and exposure level define applicable amplitudes for the surge waveforms that should provide an appropriate degree of SWC.

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 electromagnetic compatibility (EMC) program; (2) endorses finalized 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 suitable measurement units and frequency ranges for each specific test method; (4) applies to analog, digital, and hybrid (i.e., combined analog and digital electronics) 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 and commercial emissions limits from typical industrial environments.

ACKNOWLEDGMENTS

The authors wish to thank Christina Antonescu, JCN L1951 Project Manager, of the U.S. NRC Office of Nuclear Regulatory Research (RES) for her help in initiating, planning, and implementing this research effort. The authors would also like to thank John Calvert, Steve Arndt,, Frank Coffman, and Jit Vora of RES for their review and comments on the project. Thanks are extended to Roger Kisner and Bob Kryter at ORNL for their management support and technical contributions to this long-term project. Thanks are also extended to Steve Kercel, Mike Moore, and Ed Blakeman at ORNL for their assistance in interpreting and analyzing the ORNL survey results.

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
CISPR	International Special Committee on Radio Interference
COTS	commercial-off-the-shelf
CS	conducted susceptibility
EFT	electrically fast transients
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EPRI	Electric Power Research Institute
FCC	Federal Communications Commission
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
dBμA	decibels referenced to one microampere, unit of conducted interference
dBμV	decibels referenced to one microvolt, unit of conducted interference
dBμV/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
μs	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. 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 MIL-STD 461C[4] version of the standard. These two sets of criteria address many important EMI/RFI issues. MIL-STD 461D provides the latest revision of the EMI/RFI test criteria (which includes improvements based on experience and the most recent technical information), 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 the MIL-STD 462D test capability. 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 50 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 purpo^ ^ ʿhe 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 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 test 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 EMC 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 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 interconnecting signal lines. However, the MIL-STDs do leave open the possibility of specifying test criteria for signal lines 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 lines, but subsequent versions dropped that application based on the rationale that conducted EMI/RFI on interconnecting signal lines 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 lines 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 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 interconnecting 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 462[6] 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] As a result, the susceptibility envelopes were adjusted in some cases to account for the plant emissions data. Adjustments to the equipment emissions envelopes considered margin with the susceptibility envelopes and the primary intent of the MIL-STD 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.

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 μs	1.2 μs	8 μs	5 ns
Duration	100 kHz ringing	50 μs	20 μs	50 ns

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. An engineering assessment of the power surge environment in nuclear power plants for safety-related I&C systems is that withstand levels can be based on *Category B* locations[12] and *Low to Medium Exposure* levels.[13] *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. The basis for the withstand levels provides reasonable assurance that the general power surge environment in nuclear power plants is adequately characterized. The withstand levels should be 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.

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. 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.

Development of the technical basis for the EMI/RFI operating envelopes began 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 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 data reported in NUREG/CR-6436 and EPRI TR-102323. Adjustments to the equipment emissions envelopes considered margin with the susceptibility envelopes and the primary intent of the MIL-STD envelopes (e.g., whether the envelopes were based on protecting sensitive receivers on military platforms). 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. As a result of these considerations, the operating envelopes presented herein are equivalent or less restrictive than the MIL-STD envelopes that served as their initial basis. A detailed technical basis for each operating envelope is given in the Appendix.

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 could be exempt from this test if the following two conditions exist. First, the power quality requirements of the equipment are consistent with the existing power supply; and second, the equipment will not impose additional harmonic distortions on the existing power distribution system that exceed 5% total harmonic distortion (THD) or other power quality criteria established with a valid technical basis. 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 for dc-operated equipment and Figure 4.2 for ac-operated equipment. Alternate envelopes are given for ac-operated equipment based on power consumption (less than or equal to 1 kVA and greater than 1 kVA). For ac-operated equipment with a fundamental current (i.e., load current at the power line frequency) greater than 1 ampere, the envelopes in Figure 4.2 may be relaxed as follows:

$$\text{dB relaxation} = 20 \log(\text{fundamental current}).$$

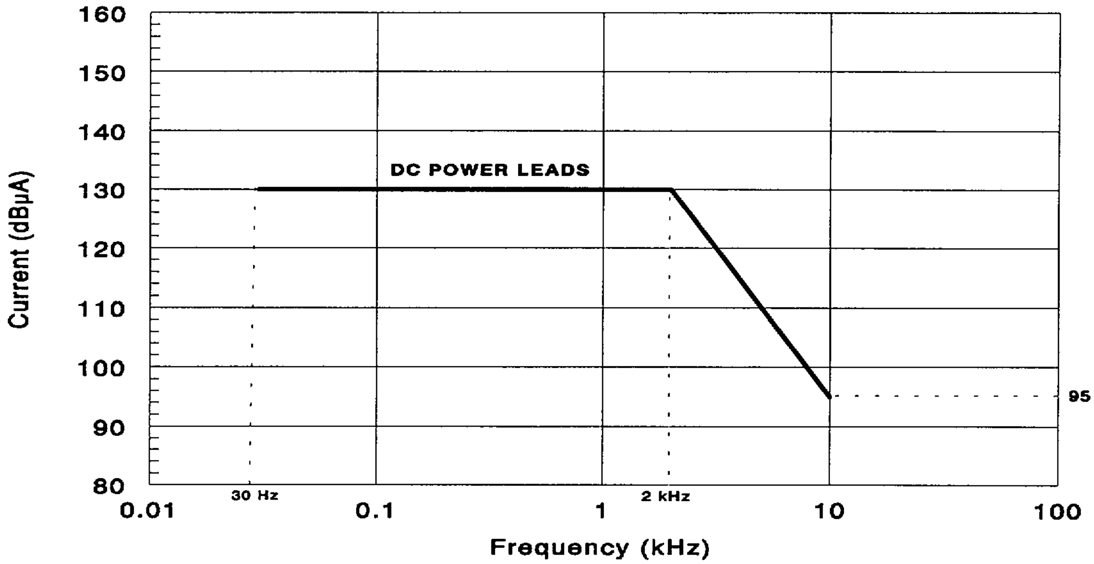

Figure 4.1 CE101 Emissions Envelopes for dc Power Leads

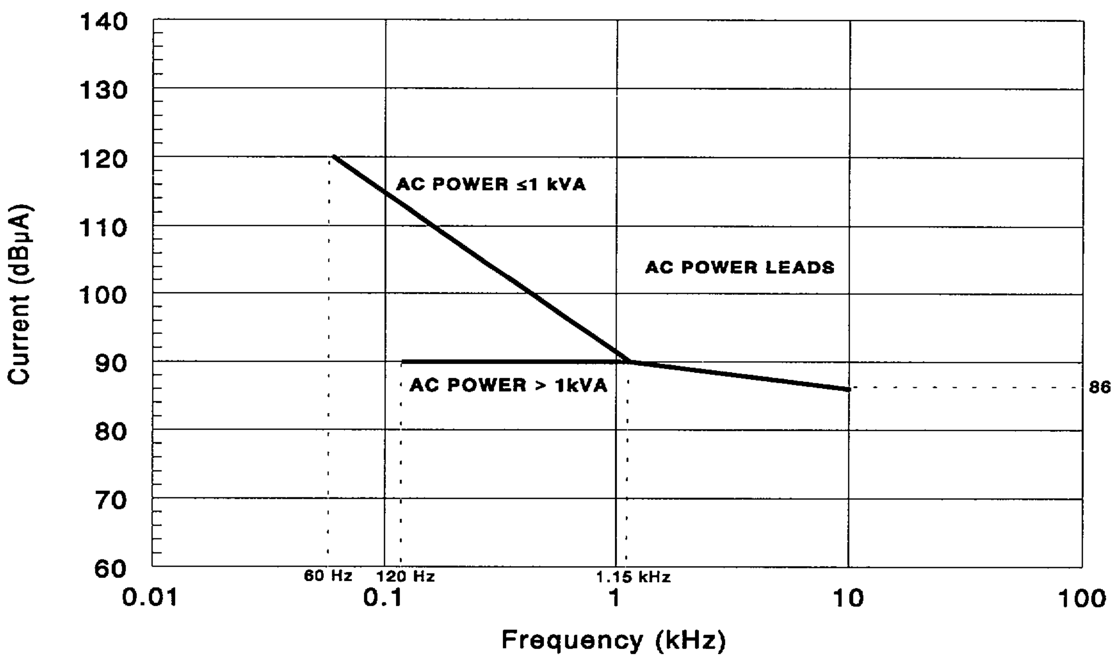

Figure 4.2 CE101 Emissions Envelopes for ac Power Leads

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 that are not part of the equipment under test. Conducted emissions on power leads should not exceed the applicable rms values shown in Figure 4.3. The values are specified according to the voltage of the power source feeding the equipment under test.

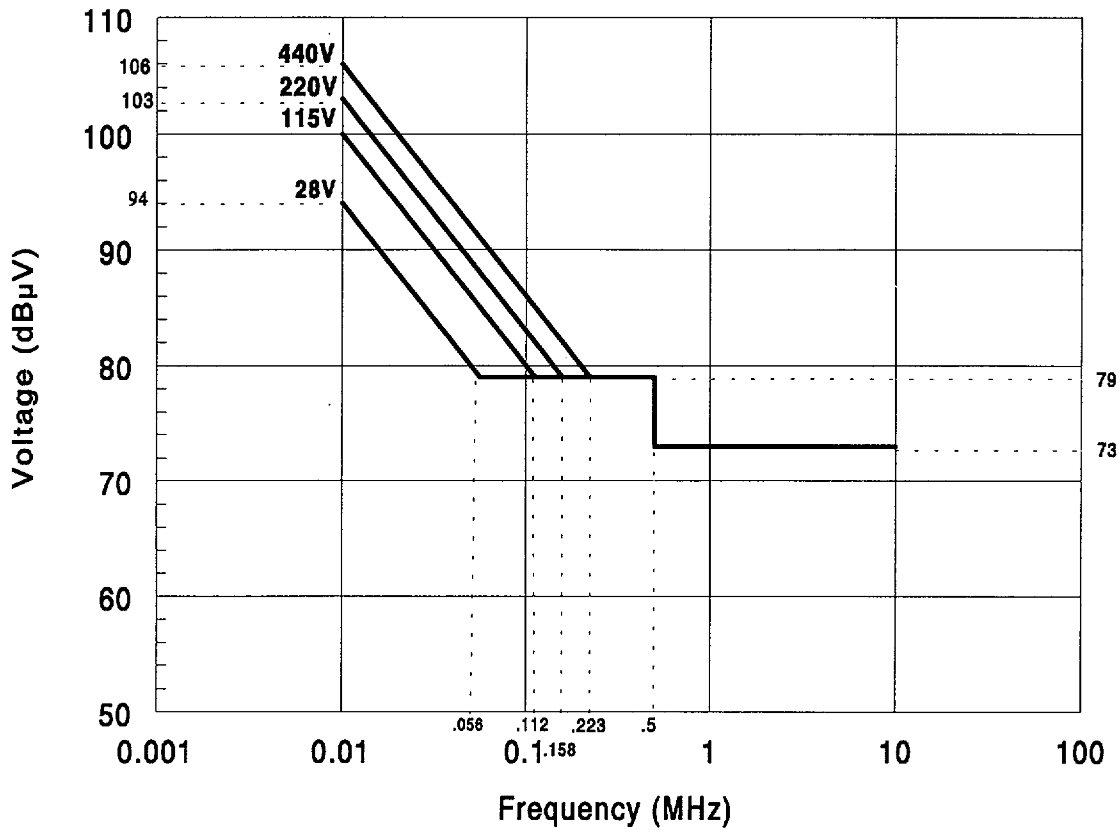

Figure 4.3 CE102 Emissions Envelopes

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 line 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 4.4. Alternative envelopes are given for equipment with nominal source voltages at or below 28 V and those operating above 28 V. The test criterion is also met 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 4.4) 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.

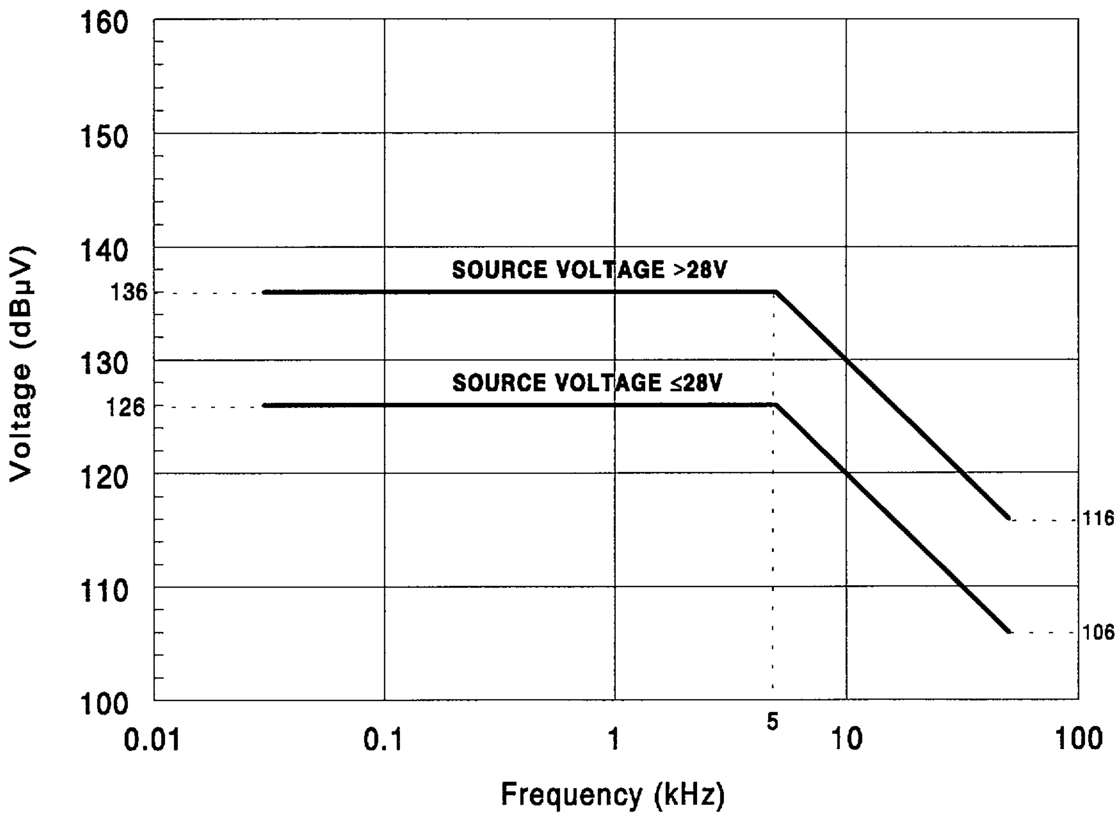

Figure 4.4 CS101 Operating Envelope

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. Equipment tested under the RS103 test may be exempted from application of this test in the frequency band from 30 MHz to 400 MHz. 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 4.5. 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.

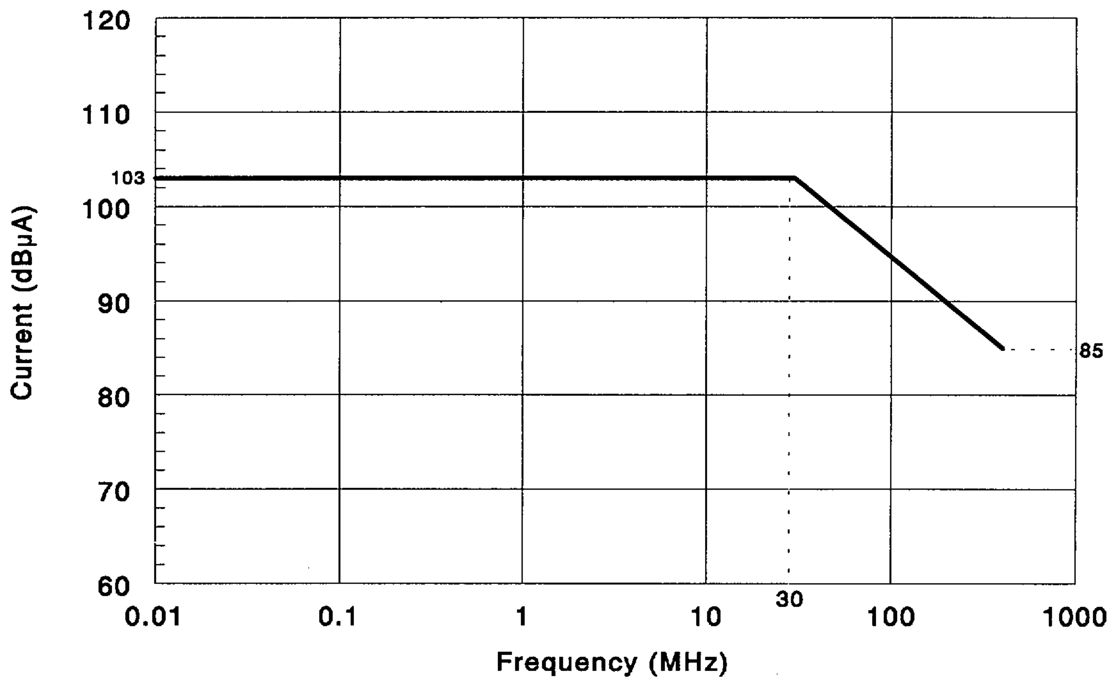

Figure 4.5 CS114 Operating Envelope

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 with other equipment sensitive to magnetic fields could be exempt from this test. The test is applicable for emissions from equipment and subsystem enclosures as well as 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 4.6. Magnetic field emissions may be measured at either one of the specified distances of 7 cm and 50 cm and compared against the corresponding envelope.

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, as well as 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 4.7. At frequencies above 30 MHz, the test criterion should be met for both horizontally and vertically polarized fields.

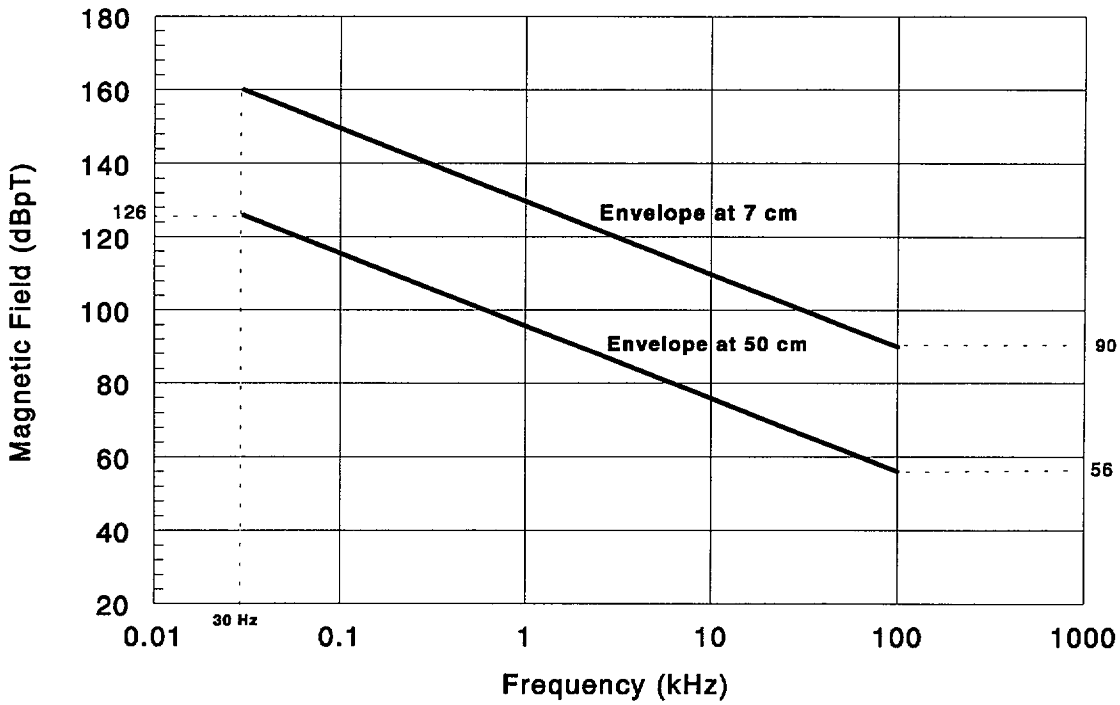

Figure 4.6 RE101 Magnetic Field Emissions Envelopes

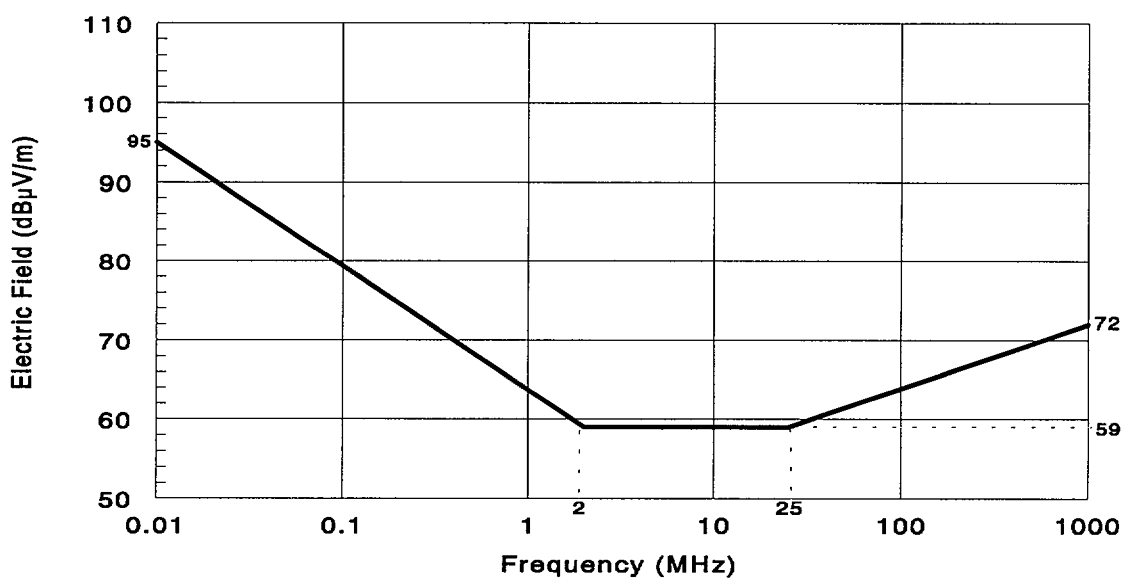

Figure 4.7 RE102 Emissions Envelope

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. Equipment that is not intended to be installed in areas with strong sources of magnetic fields (e.g., CRTs, motors, and cable bundles carrying high currents) and that follows the limiting practices endorsed in NUREG/CR-5941could be exempt from this test. 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 4.8. 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.

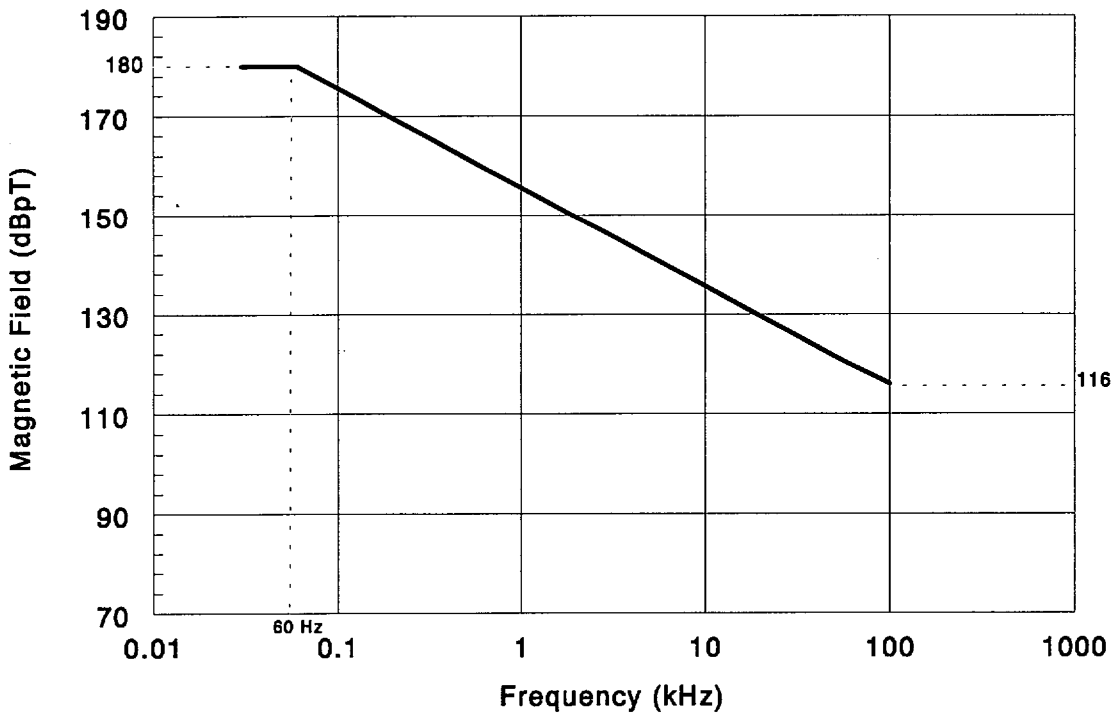

Figure 4.8 RS101 Operating Envelope

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. Equipment tested under the CS114 test may be exempted from application of this test in the frequency band from 10 kHz to 30 MHz. 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 in accordance with the techniques specified in the RS103 test method. 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 could be exempt from this test if first, the power quality requirements of the equipment are consistent with the existing power supply, and second, the equipment will not impose additional harmonic distortions on the existing power distribution system that exceed 5% total harmonic distortion (THD) or other power quality criteria established with a valid technical basis. 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 lines.

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 4.9 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 for low power consumption equipment (less than or equal to 1 kVA) and from the first harmonic of the power line frequency to 15 kHz for high power consumption equipment (greater than 1 kVA). Emissions on ac power leads in excess of the rms values shown in Figure 4.10 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). For ac-operated equipment with a fundamental current (i.e., load current at the power line frequency) greater than 1 ampere, the envelopes in Figure 4.10 may be relaxed as follows:

$$\text{dB relaxation} = 20 \log(\text{fundamental current}).$$

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 lines. Conducted emissions should not appear on the power leads in excess of the rms values shown in Figure 4.11 for narrowband emissions. Broadband emissions measurements are not necessary.

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 it 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).

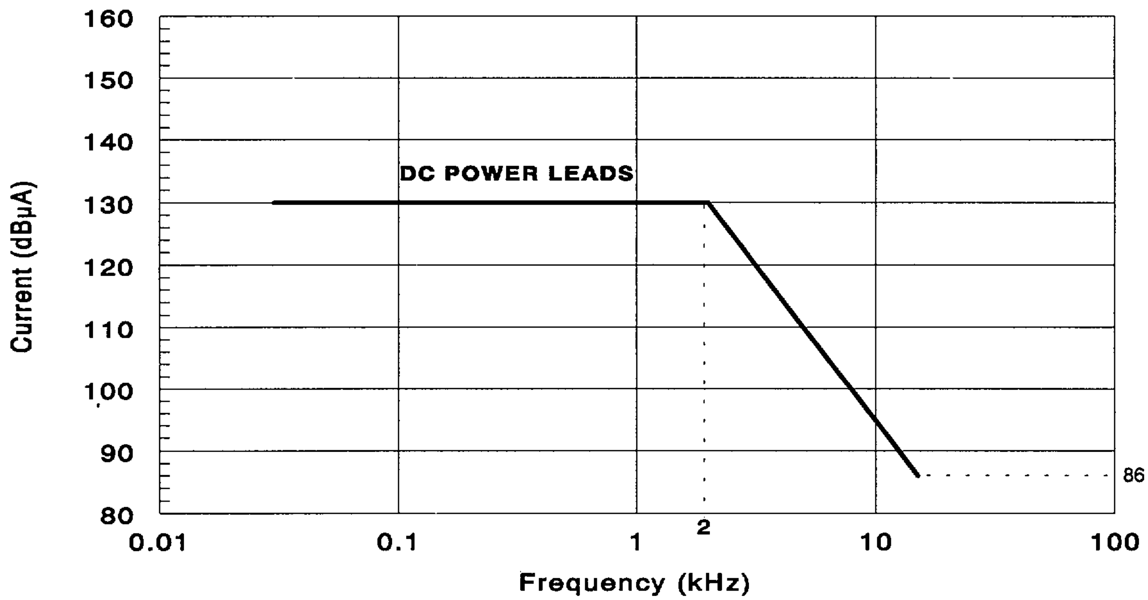

Figure 4.9 CE01 Emissions Envelope for dc Power Leads

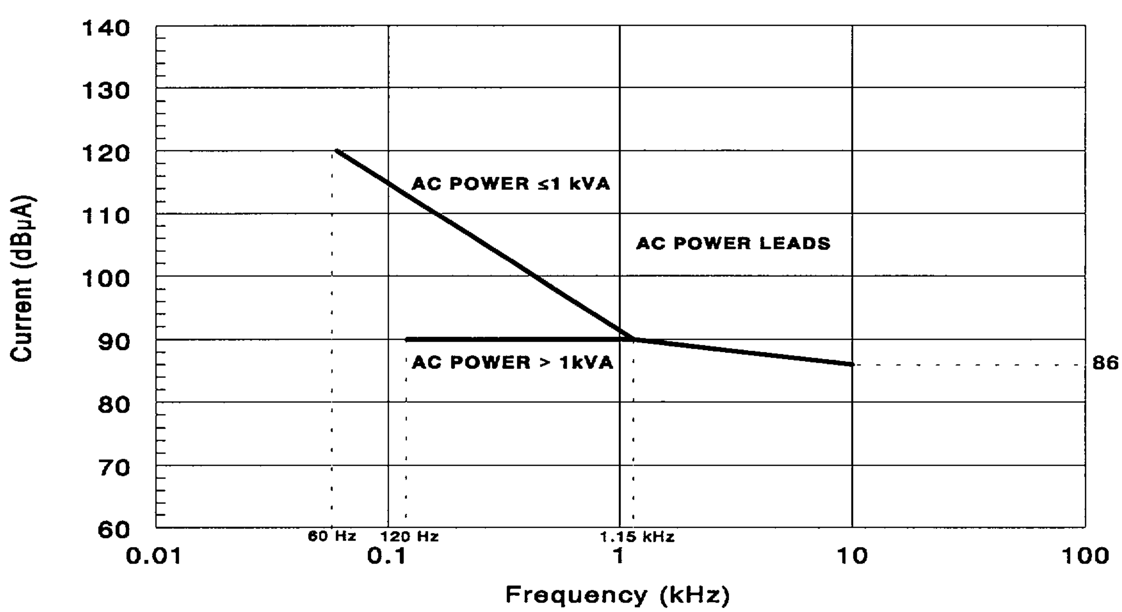

Figure 4.10 CE01 Emissions Envelope for ac Power Leads

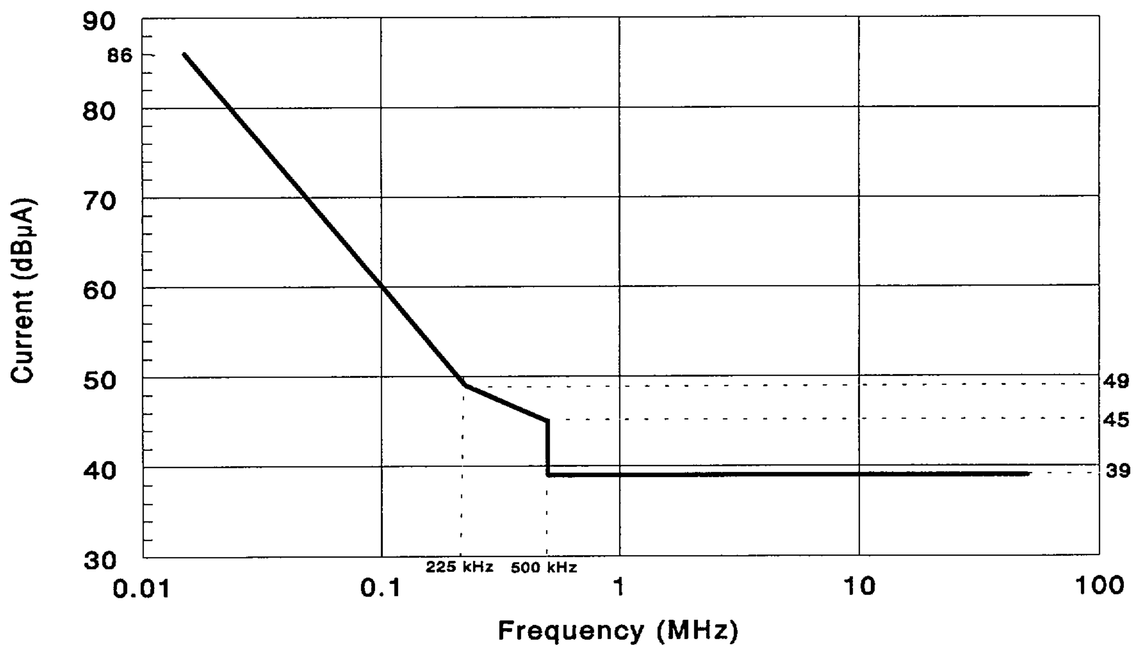

Figure 4.11 CE03 Narrowband Emissions Envelope

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 ±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 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.

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

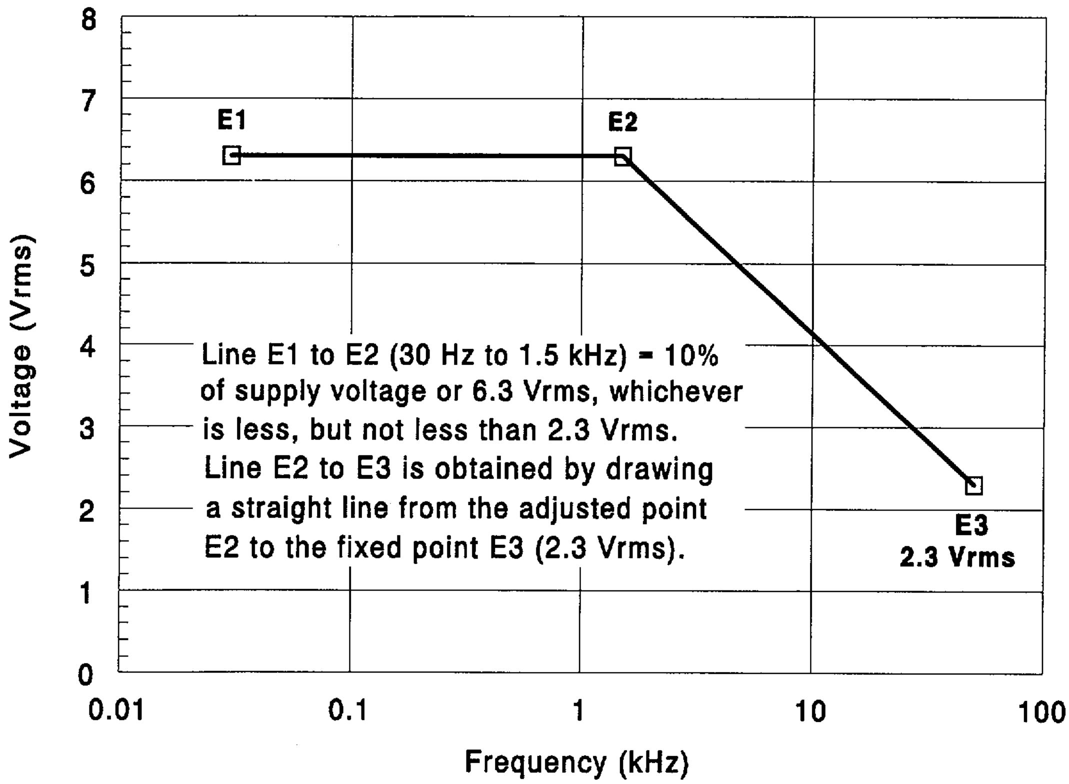

Figure 4.12 CS01 Operating Envelope

power line cord. The criterion can also be met 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 50 kHz. Equipment not intended to be installed in areas with other equipment sensitive to magnetic fields could 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.

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

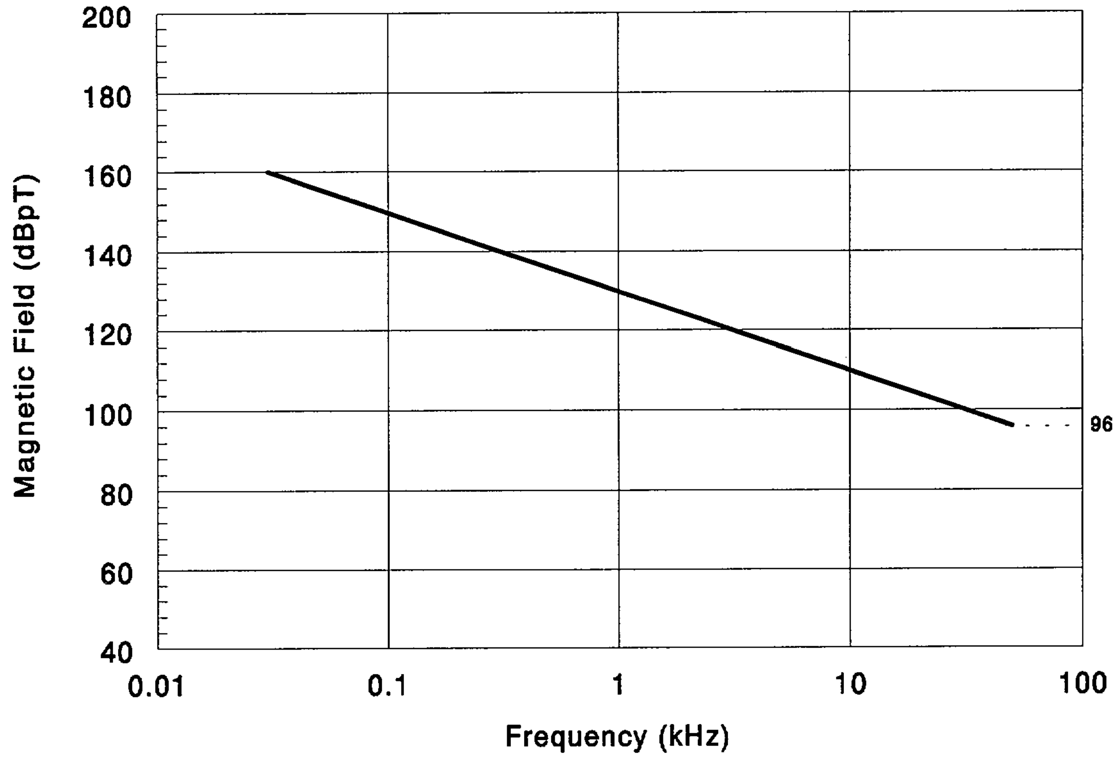

Figure 4.13 RE01 Magnetic Field Emissions Envelope

electric field emissions should not appear at the receiving antennas in excess of the rms values shown in Figure 4.14 for narrowband emissions. Broadband emissions measurements are not necessary.

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 it 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).

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. Equipment that is not intended to be installed in areas with strong sources of magnetic fields (e.g., CRTs, motors, and cable bundles carrying high currents) and that follows the limiting practices endorsed in NUREG/CR-5941could be exempt from this test. 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 4.15. 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.

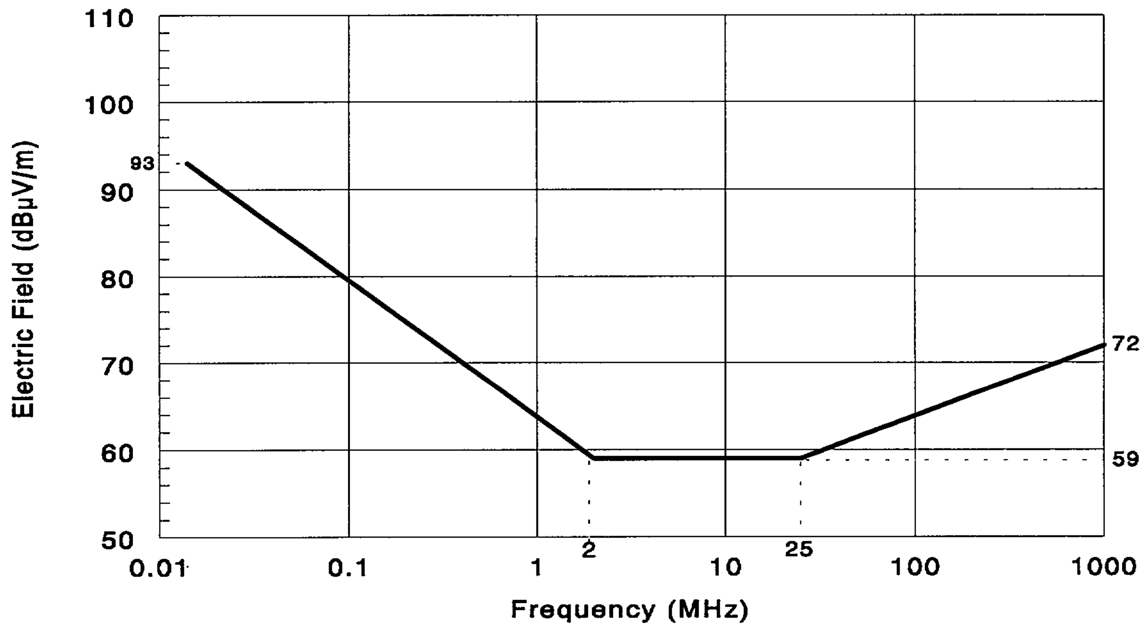

Figure 4.14 RE02 Narrowband Emissions Envelope

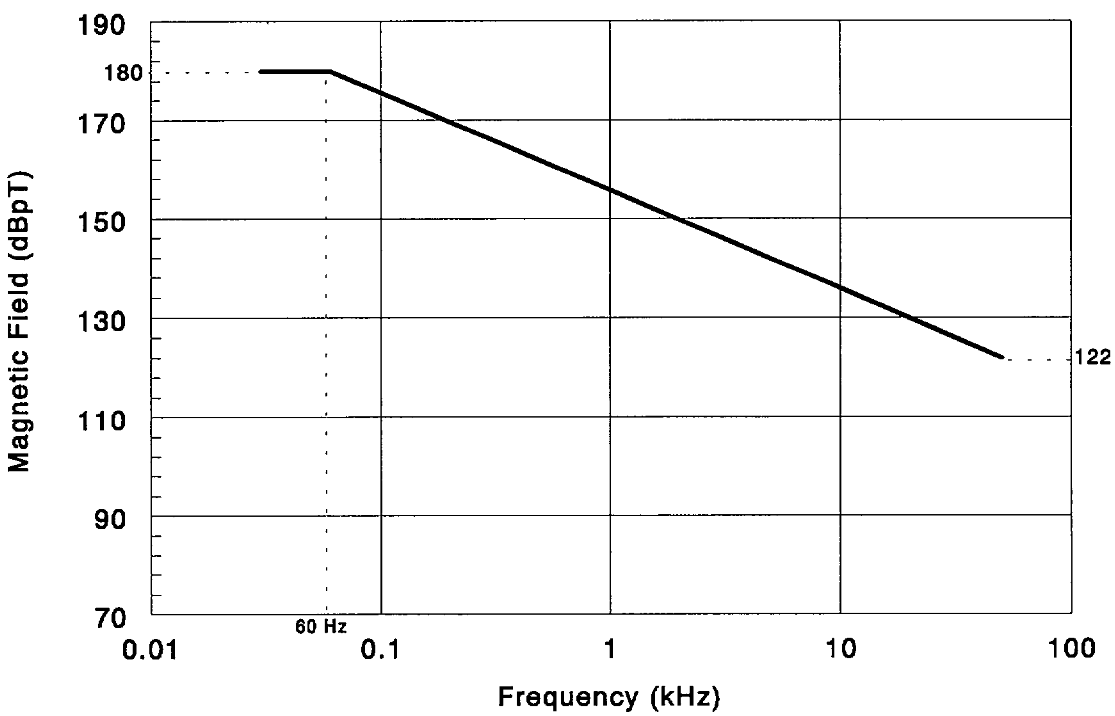

Figure 4.15 RS01 Operating Envelope

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 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 μs 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.

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-μs rise time and an exponential decay with a duration (to 50% of initial peak level) of 50 μs. The short-circuit current waveform has an 8-μs rise time and a duration of 20 μs. Plots of the waveforms are shown in Figures 5.2 and 5.3.

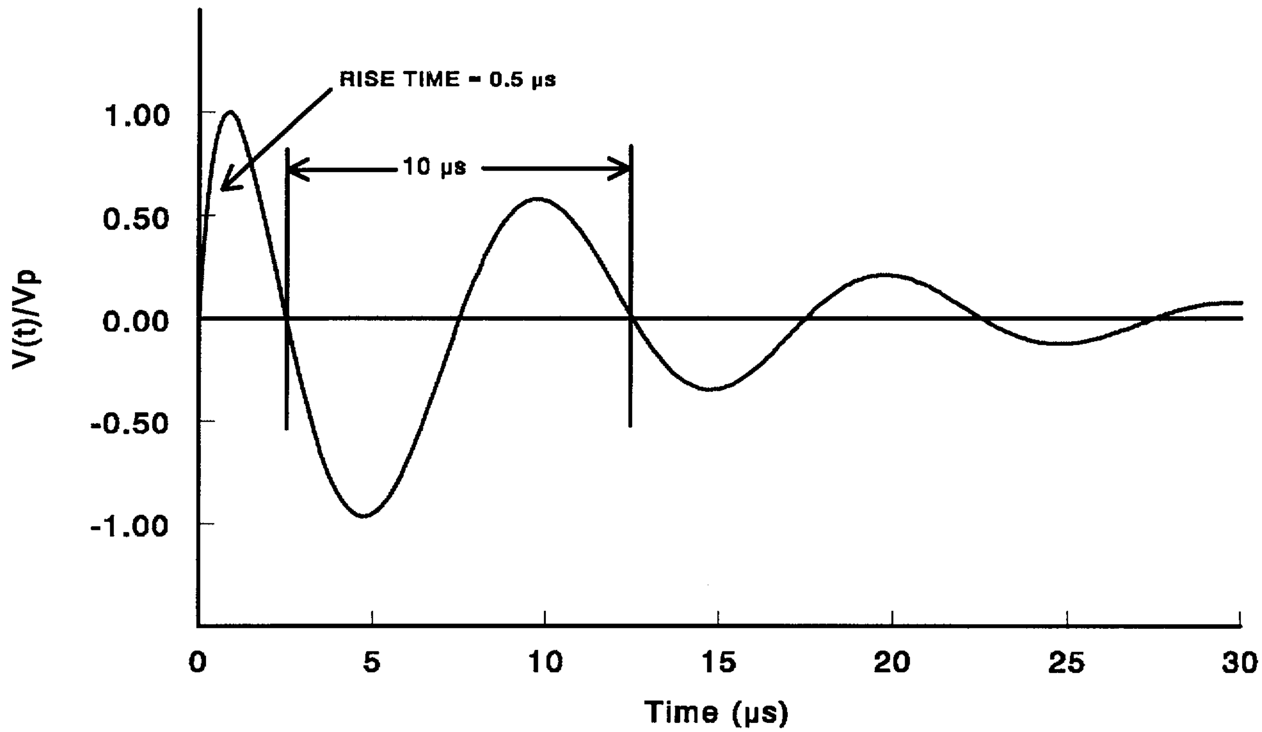

Figure 5.1 100-kHz Ring Wave

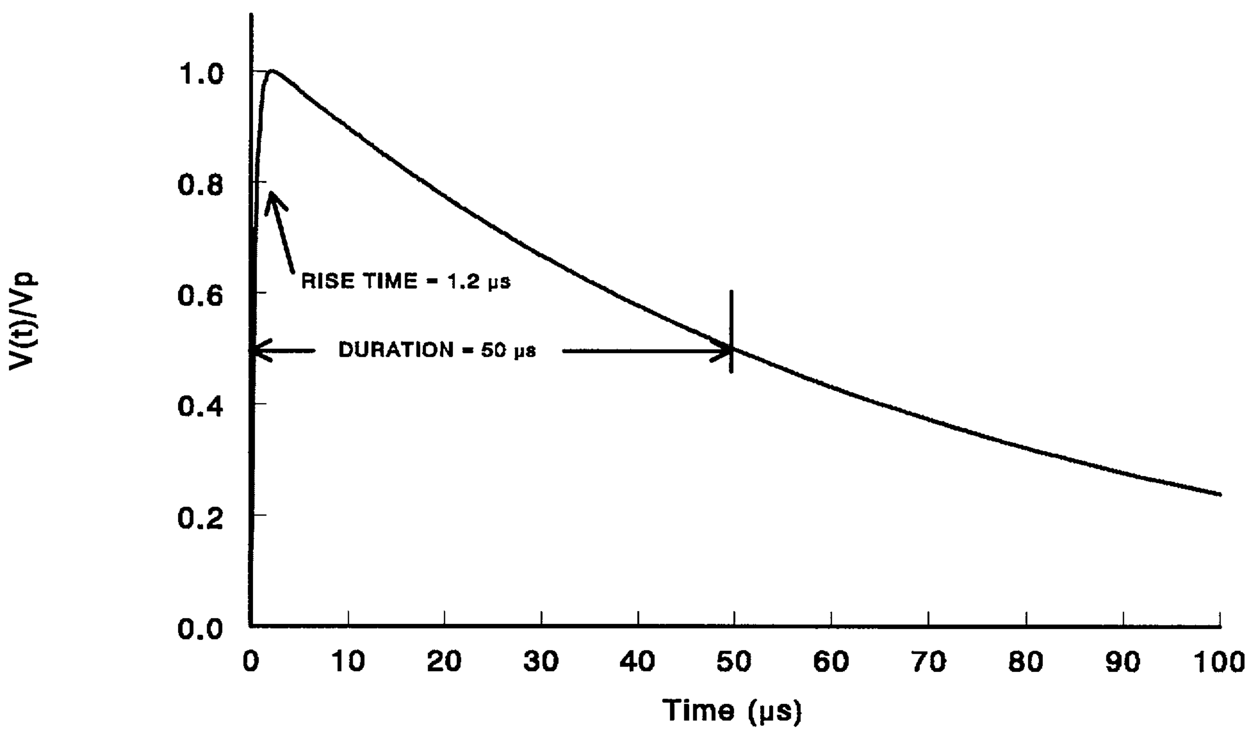

Figure 5.2 Combination Wave, Open-circuit Voltage

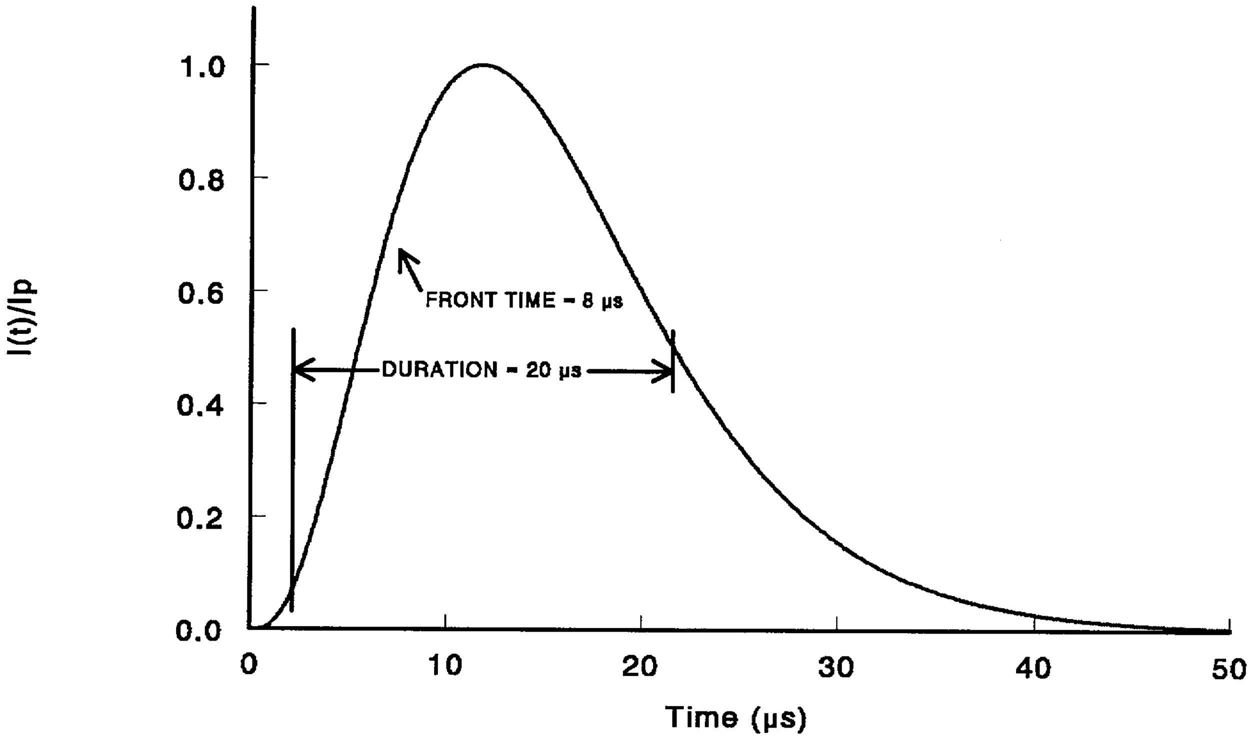

Figure 5.3 Combination Wave, Short-circuit Current

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 of the waveform intersects the V=0 line for the open-circuit voltage and the I=0 line for the short-circuit current.

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.

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 number of pulses in a burst is determined by the pulse frequency. For peaks less than or equal to 2 kV, the frequency shall be 5 kHz±1 kHz. For peaks greater than 2 kV, the frequency shall be 2.5 kHz±0.5 kHz. The differences in repetition rates are not intended to reflect characteristics of the power surge environment but to accommodate existing limitations in pulse generator performance.

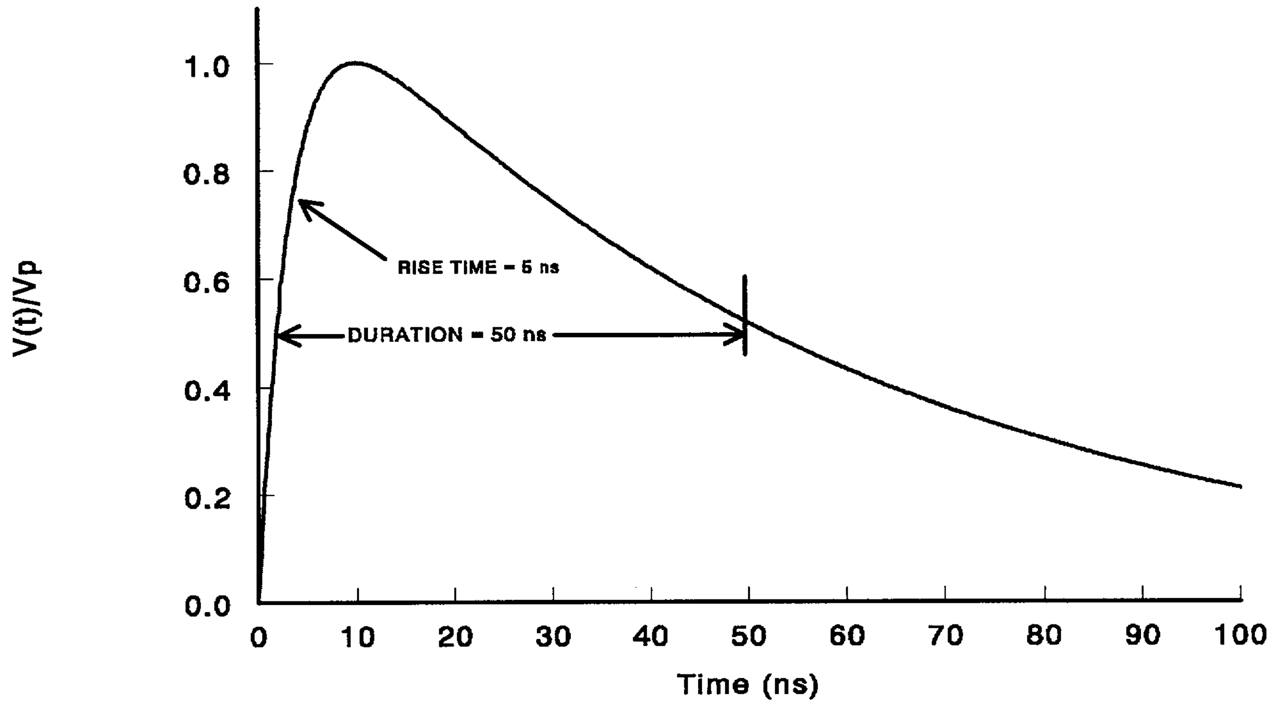

Figure 5.4 Waveform of the EFT Pulse

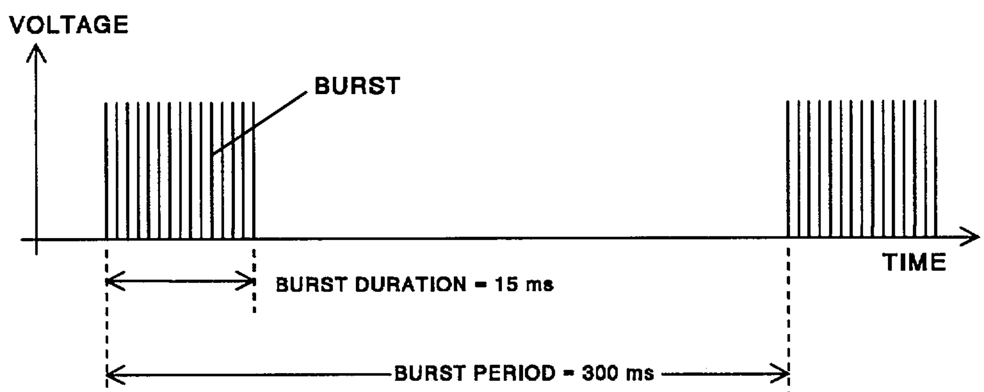

Figure 5.5 Pattern of EFT Bursts

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.

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.

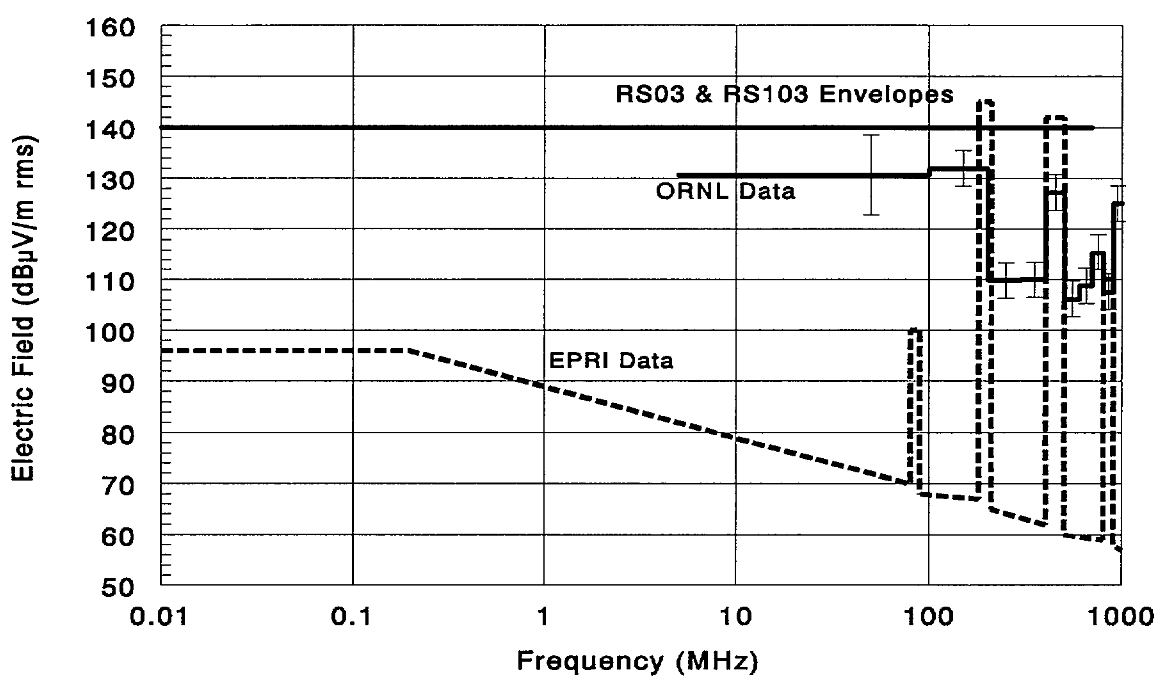

Figure 6.1 Data vs Envelopes, Radiated Electric Fields

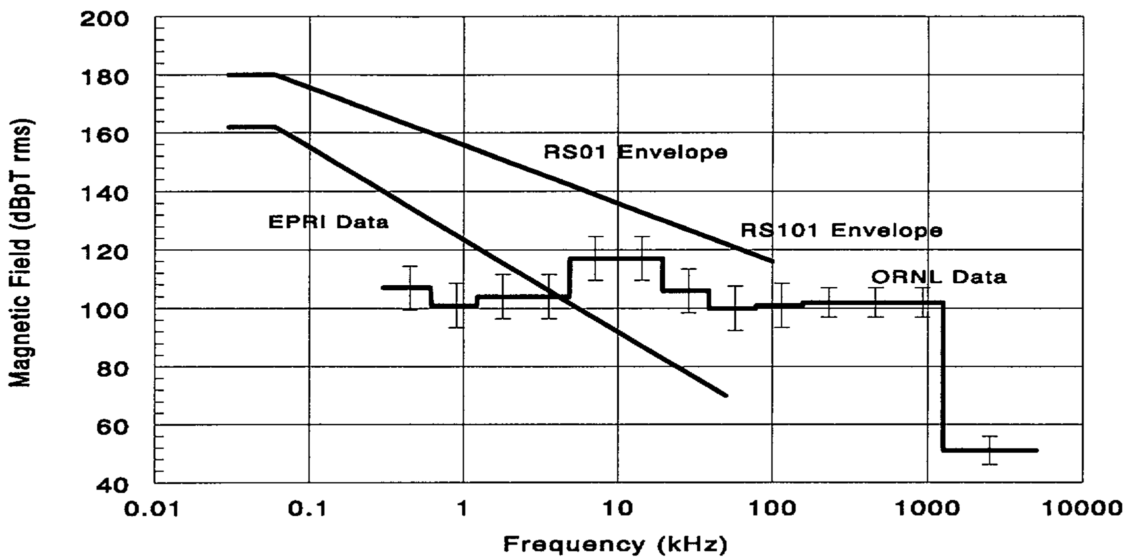

Figure 6.2 Data vs Operating Envelopes, Radiated Magnetic Fields

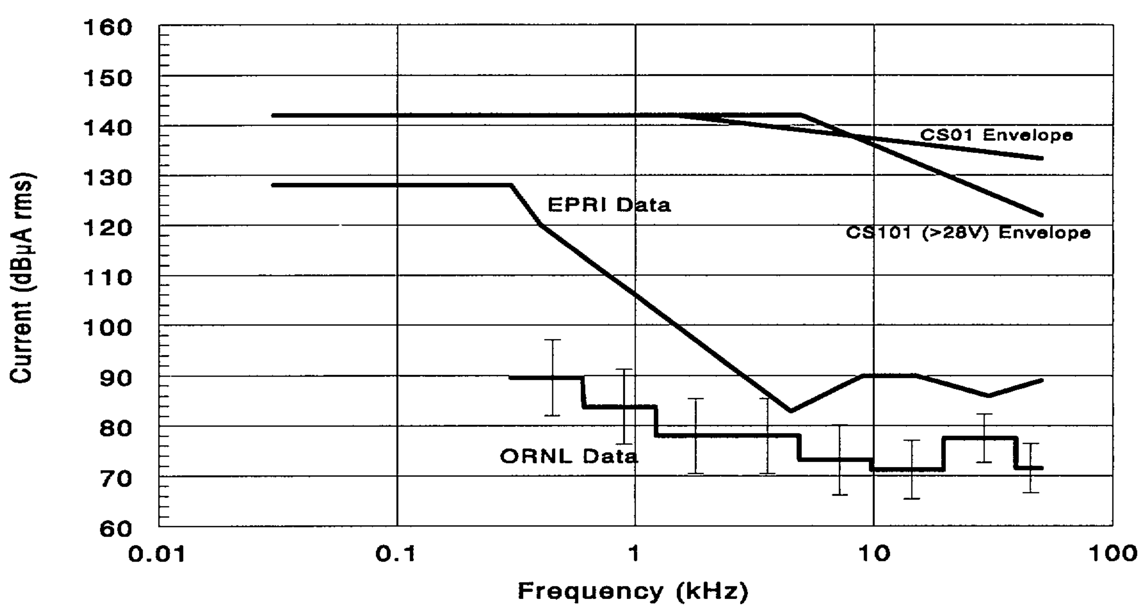

Figure 6.3 Data vs Operating Envelopes, Conducted Interference - 30 Hz to 50 kHz

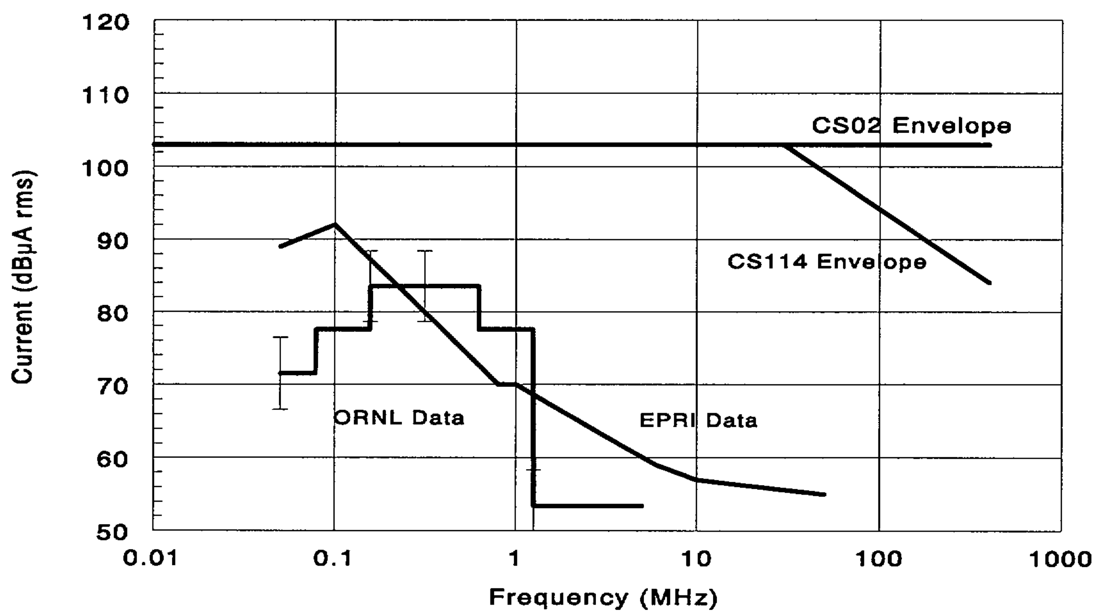

Figure 6.4 Data vs Operating Envelopes, Conducted Interference - 10 kHz to 400 MHz

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)*,[14] 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 general 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 electromagnetic operating envelopes are consistent with EMI/RFI envelopes currently used by both the military and a broad range of industries.[15-17]

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, remote shutdown panels, 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 compatibility of new or modified safety-related I&C systems with the local electromagnetic environment, nuclear power plants should still apply sound engineering practices for nonsafety-related modifications 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.

Any modifications to the presently recommended electromagnetic operating envelopes (e.g., lower site-specific envelopes) should be based on comparable technical evidence to that presented herein. 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 EMI/RFI emitters (e.g., welders, transceivers, cameras, flash attachments) 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 EMI/RFI emitters are allowed to be activated. The size of the exclusion zones is a regulatory issue. The size should be site-specific and depend on the effective radiated power and antenna gain of the portable EMI/RFI emitters used within a particular nuclear power plant. The size of exclusion zones should also depend on the allowable electric field emission levels designated for the area in the vicinity of the installed safety-related I&C system. To establish the size of an exclusion zone, a suggested rule of thumb could be that at least an 8 dB difference be maintained between the susceptibility operating envelope and the allowed emissions level. Hence, for the radiated electric field operating envelope of 10 V/m (140 dBμV/m), the size of the exclusion zones should be set such that the radiated electric fields emanating from the portable transceivers are limited to 4 V/m (132 dBμV/m) in the vicinity of safety-related I&C systems. The minimum distance of an exclusion zone (d) in meters should be calculated by:

$$d=(30PG)^{0.5}/E$$

where

P = the effective radiated power of the EMI/RFI emitter (in watts);
G = the gain of the EMI/RFI emitter antenna (assume G=1 is worst case); and,
E = the allowable radiated electric field strength of the EMI/RFI emitter (in V/m) at the point of installation.

8 CONCLUSIONS

The recommended envelopes 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 modified 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 finalized 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 suitable measurement units and frequency ranges for each specific test method; (4) applies to analog, digital, and hybrid (i.e., combined analog and digital electronics) 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 and commercial emissions limits from typical industrial environments.

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. IEEE Std 473-1985, *IEEE Recommended Practice for an Electromagnetic Site Survey (10 kHz to 10 GHz)*, Institute of Electrical and Electronics Engineers.

15. ANSI C63.12-1987, *American National Standard for Electromagnetic Compatibility Limits — Recommended Practice*, American National Standards Institute.

16. D. N. Heirman, "International Activity in Product Immunity Standards and Testing," *EMC Test and Design*, pp. 16-19 (May/June 1992).

17. W. Sperber, "SAE Automotive Electromagnetic Immunity Standards," *1992 Proceedings of EMC/ESD International*, Denver, Colorado, Apr. 22-24, 1992.

APPENDIX–Rationale for RG-1.180 Operating Envelopes

The technical basis for all of the EMI/RFI operating envelopes presented in this NUREG/CR and recommended for adoption as part of Regulatory Guide RG-1.180 begins with MIL-STD envelopes corresponding to the electromagnetic environment military ground facilities. The electromagnetic conditions in military ground facilities were judged to be comparable to that of nuclear power plants based on general layout and equipment type considerations. Plant emissions data were used to confirm the adequacy of the EMI/RFI operating envelopes. From the MIL-STD starting point, susceptibility envelopes were adjusted to account for the plant emissions data available from the site surveys reported in NUREG/CR-6436 and in EPRI TR-102323. Adjustments to the emissions envelopes were based on providing adequate margin with the susceptibility envelopes and on consideration of the primary intent of the MIL-STD limits (e.g., whether they were specified based on protecting sensitive receivers on military platforms). Finally, when changes to the operating envelopes were motivated by technical considerations, consistency among the envelopes for comparable test criteria from similar suites of test methods (e.g., between MIL-STD 461D and MIL-STD 461C or between the RG-1.180 and the SER on EPRI TR-102323) was promoted and commercial emissions limits for industrial environments were factored into the adjustments. These considerations contributed to meeting the goal of establishing comparable assurance that equipment will indeed be compatible with the projected electromagnetic environment.

It should be noted that in the discussion that follows, the designation RG will sometimes be used to identify the EMI/RFI operating envelopes presented in this NUREG/CR. This designation reflects the recommended usage of these envelopes in the Regulatory Guide RG-1.180.

Susceptibility Operating Envelopes

CS101/CS01—Conducted Susceptibility, Low Frequency

CS101 (conducted susceptibility, power leads, low frequency) in MIL-STD 461D provides two envelopes for military ground facilities. These envelopes correspond to equipment with source voltages at or below 28 V and equipment with source voltages above 28 V. The similarity in the military ground facility environment and the nuclear power plant environment supports the use of these envelopes. These envelopes are adopted without change in this NUREG/CR. In addition, notation is included specifying that the starting frequency for testing of ac powered equipment is the second harmonic (as is the case in the MIL-STD). An adjustment in envelope level from the MIL-STD basis is effected for the CS01 (conducted susceptibility, power leads, low frequency) envelope for use in this NUREG/CR. This adjustment enhances consistency between the envelopes for comparable test criteria from similar suites of test methods and meets the goal of establishing comparable levels of assurance among the test criteria.

Figure A.1 provides a comparative plot of the RG (i.e., NUREG/CR) envelopes for CS101 and CS01, the baseline MIL-STD envelopes, the corresponding envelope endorsed by the SER on EPRI TR-102323, and the plant emissions data presented in NUREG/CR-6436 and EPRI TR-102323. The RG and MIL-STD envelopes are converted from voltage to current for comparative purposes based on an assumption of 0.5 Ω impedance. It is seen that the RG and SER envelopes are similar in level. The most notable exception is the less restrictive RG envelope for equipment with source voltages at or below 28 V. As can be observed from the plot, this envelope only provides a 4 dBμA margin above the highest measured plant emissions data reported in EPRI TR-102323. However, in the frequency range below 120 Hz, the 4 dB margin is judged to be sufficient for two reasons. First, the starting frequency for testing of ac powered equipment is specified to be the second harmonic so the ac limit does not apply over the frequency range with the 4 dB margin. Second, although the envelope does apply over the frequency range with the 4 dB margin

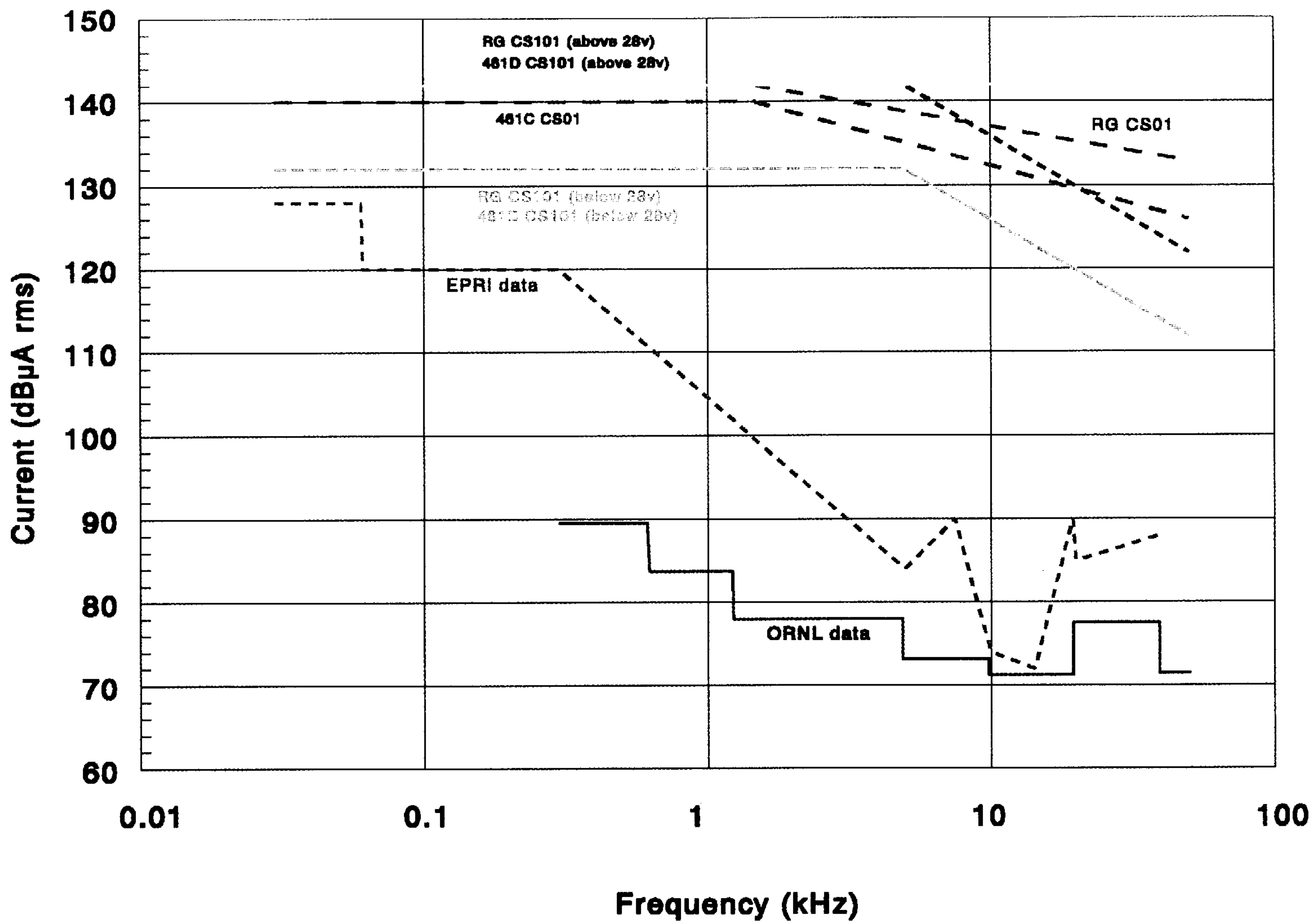

Figure A.1 Comparison of low-frequency conducted susceptibility envelopes for dc powered equipment, the bounding plant data resulted from ac powered equipment according to EPRI so adequate margin for dc powered equipment is probable.

CS114/CS02—Conducted Susceptibility, High Frequency

The operating envelope for military ground facilities (Army) from CS114 (conducted susceptibility, bulk cable injection, high frequency) in MIL-STD 461D are adjusted to account for conducted emissions levels measured in nuclear power plants. As a minimum, modifications of safety-related equipment must demonstrate that they can withstand the ambient conducted emissions in the plant. In the absence of other technical considerations, the level to which the operating envelope is raised is selected to be consistent with the operating envelope addressed in the SER on EPRI TR-102323. The break frequency at 30 MHz and the level at 400 MHz are maintained because of practical considerations regarding the ability of the test equipment specified in MIL-STD 462D to generate the desired test levels. The envelope from CS02 (conducted susceptibility, power and interconnecting control leads, high frequency) in MIL-STD 461C is also raised to account for conducted emissions levels measured in nuclear power plants. Again, the level to which the operating envelope is raised is selected to be consistent with the operating envelope addressed in the SER on EPRI TR-102323. These adjustments to the CS114 and CS02 operating envelopes are motivated by the need to provide adequate margin above plant emissions data and meet the goal of establishing comparable levels of assurance among the test criteria.

Figure A.2 provides a comparative plot of the RG (i.e., NUREG/CR) envelopes for CS114 and CS02, the baseline MIL-STD envelopes, the corresponding envelope endorsed by the SER on EPRI TR-102323, and the plant emissions data presented in NUREG/CR-6436 and EPRI TR-102323. The RG and MIL-STD envelopes for CS02 are converted from voltage to current for comparative purposes based on an assumption of 50 Ω impedance. The conflict between the MIL-STD emissions envelopes and the plant emissions data is clearly seen. For this reason, the RG envelopes are adjusted from their MIL-STD basis. It is also seen that the RG and SER envelopes are similar in level. The most notable exception is the less restrictive RG envelope CS114 above 30 MHz. This difference accounts for practical considerations regarding the ability of the test equipment specified in MIL-STD 462D to generate the desired test levels.

RS101/RS01—Radiated Susceptibility, Low Frequency

The operating envelope for military ground facilities (Army) with equipment sensitive to magnetic fields from RS101 (radiated susceptibility, magnetic field, low frequency) in MIL-STD 461D is adopted unchanged. The similarity in the military ground facility environment and the nuclear power plant environment supports the use of this envelope. The operating envelope for military ground facilities from RS01 (radiated susceptibility, magnetic field, low frequency) in MIL-STD 461C is adjusted to account for radiated emissions levels measured in nuclear power plants. In the absence of other technical considerations, the envelope is adjusted to match the corresponding RS101 operating envelope. The resulting RS101 and RS01 operating envelopes in this NUREG/CR are also consistent in level with the comparable envelope addressed in the SER on EPRI TR-102323. The adjustment to the RS01 operating envelope is motivated by the need to provide adequate margin above plant emissions data and meets the goal of establishing comparable levels of assurance among the test criteria.

Figure A.3 provides a comparative plot of the RG (i.e., NUREG/CR) envelopes for RS101 and RS01, the baseline MIL-STD envelopes, the corresponding envelope endorsed by the SER on EPRI TR-102323, and the plant emissions data presented in NUREG/CR-6436 and EPRI TR-102323. The conflict between the MIL-STD emissions envelopes for RS01 and the plant emissions data is clearly seen. For this reason, that RG envelope is adjusted from its MIL-STD basis. It is also seen that the RG and SER envelopes are identical.

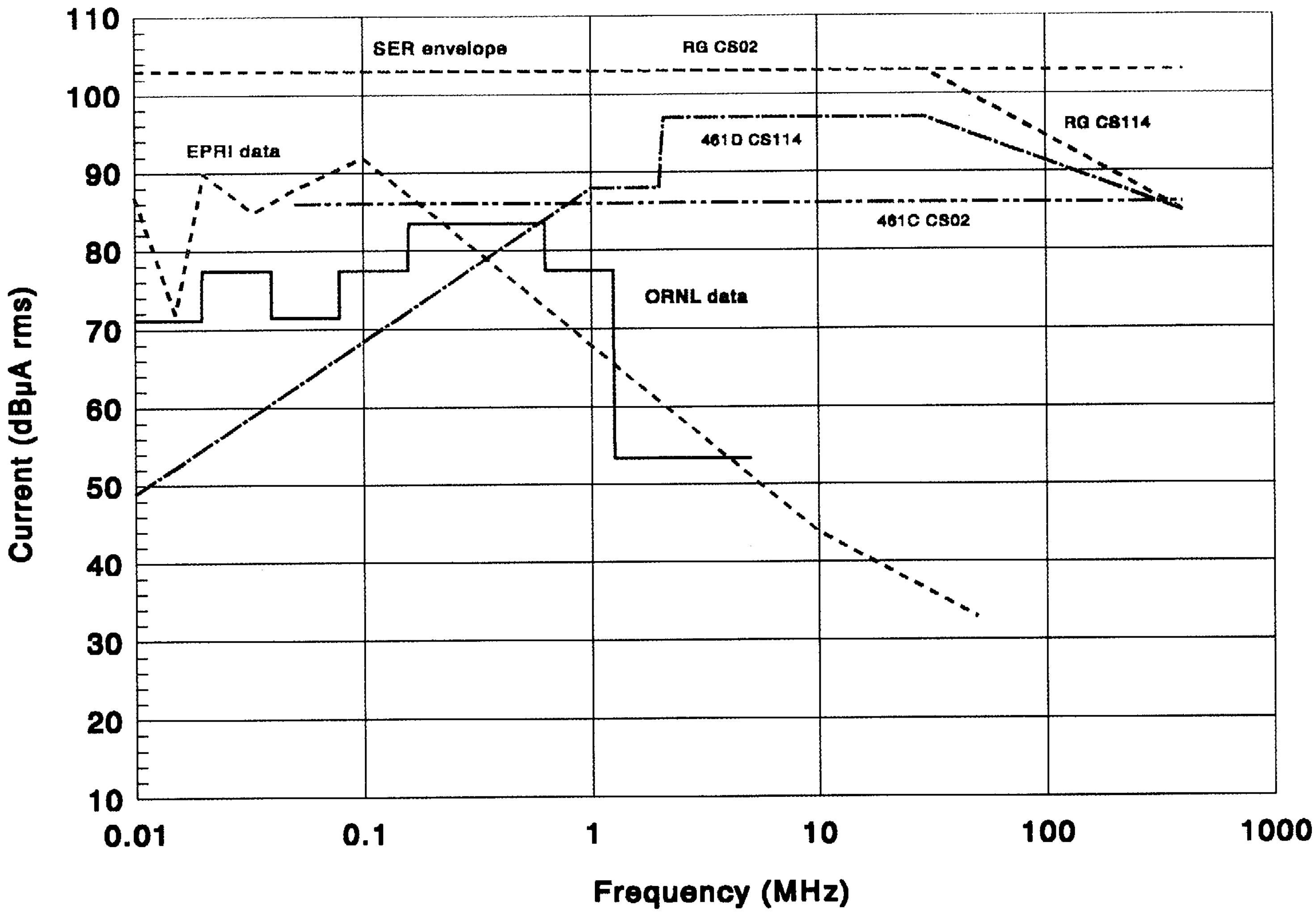

Figure A.2 Comparison of high-frequency conducted susceptibility envelopes

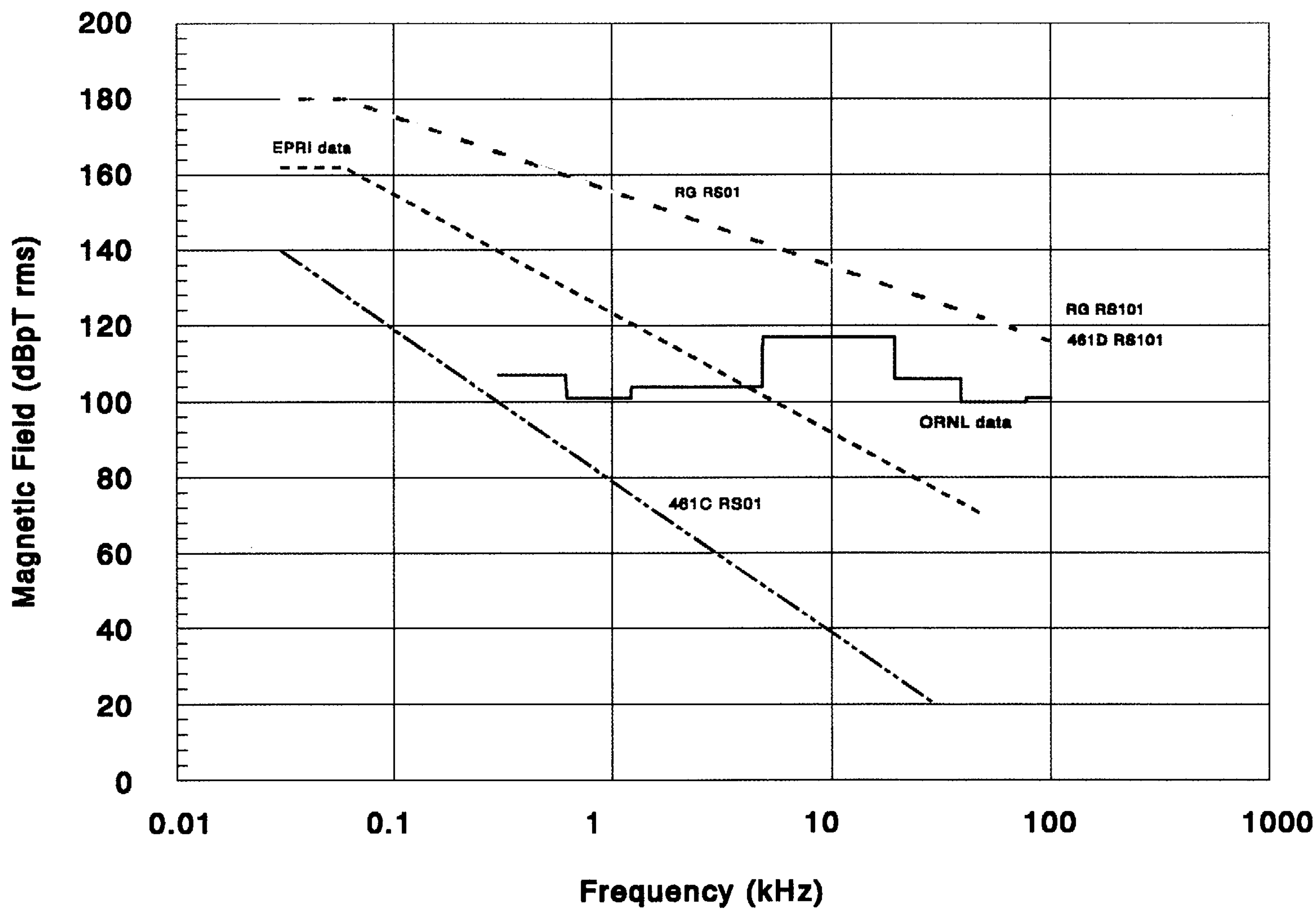

Figure A.3 Comparison of low-frequency radiated susceptibility envelopes

RS103/RS03—Radiated Susceptibility, High Frequency

The operating envelope for military ground facilities from RS103 (radiated susceptibility, electric field, high frequency) in MIL-STD 461D is based on envelopes for Navy and Air Force facilities. The Army ground facility envelope is higher across the frequency range, presumably to account for emissions from specialized transmitters and portable transceivers. Since administrative controls (exclusion zones) are specified in RG-1.180 to limit the contribution of such devices, it is considered appropriate to use the lower levels. In addition, the RS103 operating envelope in RG-1.180 is consistent with the comparable envelope addressed in the SER on EPRI TR-102323. The operating envelope for military ground facilities (Army) from RS03 (radiated susceptibility, electric field, high frequency) in MIL-STD 461C is adjusted to account for radiated emissions levels measured in nuclear power plants. In the absence of other technical considerations, the RS03 envelope is raised to be consistent with the RS103 operating envelope. These adjustments to the RS103 and RS03 operating envelopes are motivated by the need to provide adequate margin above plant emissions data without being unduly restrictive and meet the goal of establishing comparable levels of assurance among the test criteria.

Figure A.4 provides a comparative plot of the RG (i.e., NUREG/CR) envelopes for RS103 and RS03, the baseline MIL-STD envelopes, the corresponding envelope endorsed by the SER on EPRI TR-102323, and the plant emissions data presented in NUREG/CR-6436 and EPRI TR-102323. The MIL-STD 461D RS103 envelope for Army ground facilities is shown to illustrate differences that can result if administrative controls are not in place. The RG envelope is identical to the MIL-STD envelope for Navy and Air Force facilities. The conflict between the MIL-STD emissions envelopes for RS03 and the plant emissions data is clearly seen. For this reason, that RG envelope is adjusted from its MIL-STD basis. It is also seen that the RG and SER envelopes are identical.

Emissions Operating Envelopes

The equipment emissions operating envelopes described in this NUREG/CR and adopted for use in Regulatory Guide RG-1.180 have a clear technical basis. They are based on the equipment emissions operating envelopes for military ground facilities that are presented in MIL-STD 461D and MIL-STD 461C. The electromagnetic environment in military ground facilities is judged to be comparable to that for nuclear power plants based on general layout and equipment type considerations. A review of the rationale for the MIL-STD limits indicates that there are some instances where MIL-STD limits are primarily intended to protect sensitive receivers, which would not be common in nuclear power plants. In those cases, the Federal Communications Commission (FCC) Part 15 and International Special Committee on Radio Interference (CISPR) limits for industrial class equipment are factored into adjustments of the MIL-STD envelopes.

CE101/CE01—Conducted Emissions, Low Frequency

A review of the MIL-STD 461D specifications and rationale shows that the intent of the MIL-STD 461D CE101 (conducted emissions, power leads, low frequency) envelopes is to limit the "amplitude of harmonic currents conducted on the power distribution system." The envelopes are "based on maintaining the harmonic distortion of the (platform) power distribution system within 5% of the supply voltage with any single harmonic being less than 3%." The MIL-STD rationale also states that total harmonic distortion (THD) that is greater than "5% is above the tolerance of most electronic equipment, induction motors, magnetic devices, and measuring devices." Therefore, the MIL-STD envelopes provide a sound basis for the NUREG/CR envelopes.

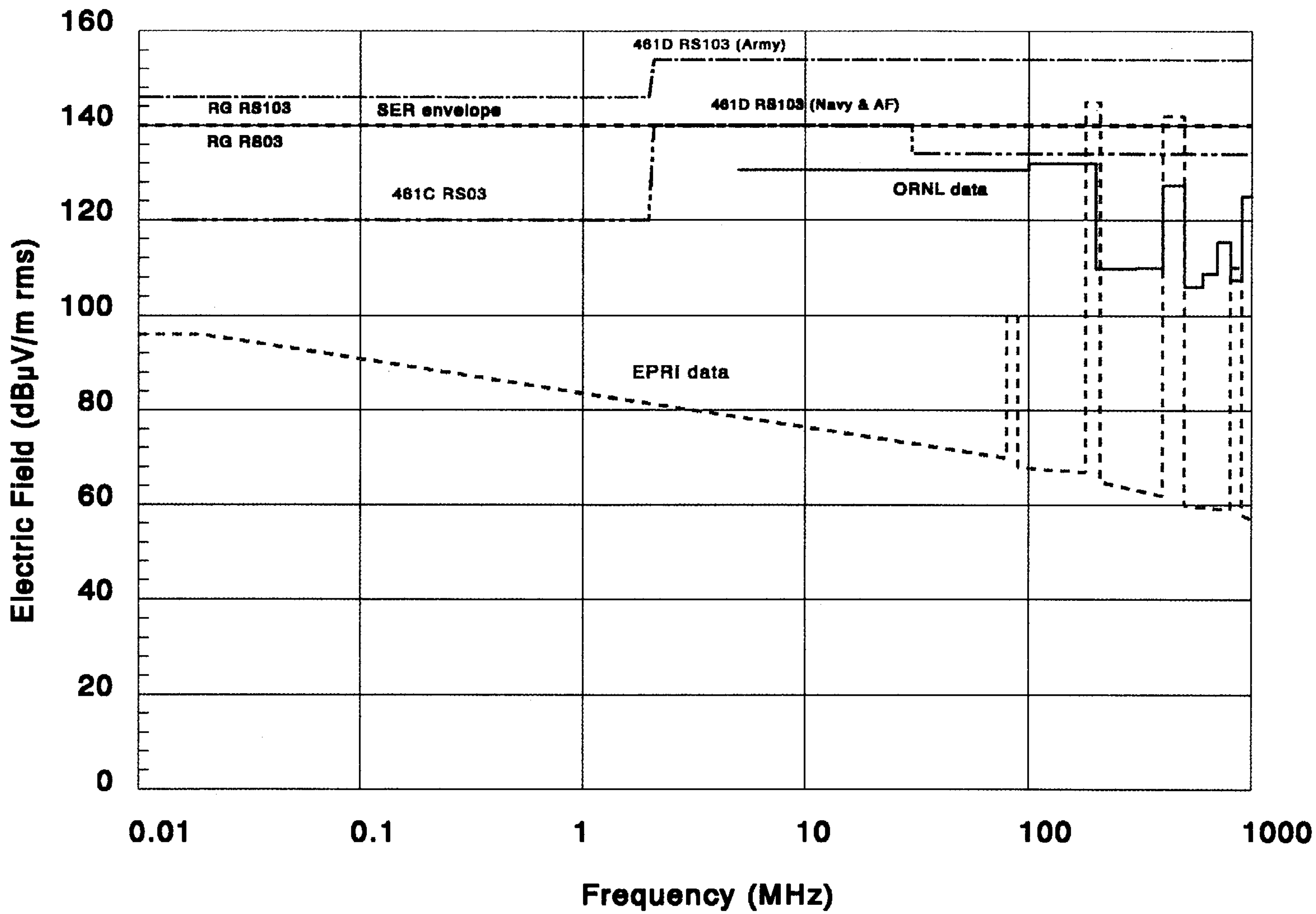

Figure A.4 Comparison of high-frequency radiated susceptibility envelopes

MIL-STD 461C CE01 (conducted emissions, power leads, low frequency) for military ground facility platforms and MIL-STD 461D CE101 for surface ship platforms each offer a single envelope for application to dc power leads and two separate envelopes for application to ac power leads for 60 Hz equipment. The operating envelopes for military ground facilities in MIL-STD 461C are adopted as the basis for the CE101 and CE01 emissions envelopes in this NUREG/CR. The two ac power lead envelopes correspond to equipment operating at input power ratings greater than 1 kVA and less than or equal to 1 kVA and these envelopes provide the guidance for variations in power consumption. The envelope for ac power leads on equipment operating at less than or equal to 1 kVA ranges from the power line frequency to 10 kHz for CE101 and to 15 kHz for CE01. The envelope for ac power leads on equipment operating at greater than 1 kVA ranges from the first power harmonic to 10 kHz for CE101 and to 15 kHz for CE01. The break frequency for the envelope for ac power leads on equipment operating at less than or equal to 1 kVA is 1.15 kHz. The high frequency range (> 1.15 kHz) of the CE101 and CE01 envelopes for ac power lead emissions are adjusted from their MIL-STD starting points for use in this NUREG/CR to promote consistency among the conducted emissions operating envelopes at 10 kHz for CE101 and CE102 (conducted emissions, power leads, high frequency) and at 15 kHz for CE01 and CE03 (conducted emissions, power leads, high frequency). The dc power lead emissions envelopes for CE101 and CE01 are adopted unchanged. Finally, notation is included in this NUREG/CR to identify an allowed relaxation of the emissions envelopes for ac-operated equipment and subsystems with a fundamental current (i.e., load current at the power frequency) that is greater than 1 ampere. The adjustments to the CE01 operating envelopes and the adoption of the CE01 envelope as the basis for CE101 are motivated by the need to adequately control harmonic distortion of the power distribution system and meet the goal of establishing comparable levels of assurance among the test criteria.

Since MIL-STD 461D CE101 provides no specific guidance on operating envelopes for military ground facilities, which have been identified as having electromagnetic conditions most comparable to nuclear power plants, it is appropriate to adopt the operating envelopes from MIL-STD 461C CE01. The technical basis for establishing immunity levels for a particular phenomenon (e.g., conducted EMI/RFI) over a selected frequency range (e.g., 30 Hz to 50 kHz) is not dependent on testing criteria or methods but rather on the environment in which the equipment will be installed. Therefore, the caution against mixing and matching test criteria and methods is not at issue.

Figure A.5 provides a comparative plot of the RG (i.e., NUREG/CR) envelopes for CE101 and CE01, the baseline MIL-STD envelopes, and the corresponding envelope endorsed by the SER on EPRI TR-102323. The envelopes for ac power leads are less restrictive than the MIL-STD envelopes in the higher frequency band (> 1.15 kHz) because of adjustments to promote consistency between the conducted emissions operating envelopes at 10 kHz for CE101 and CE102 and at 15 kHz for CE01 and CE03. The RG emissions envelope for dc power leads is less restrictive than the corresponding SER emissions envelope. The RG emissions envelopes for ac power leads are somewhat more restrictive than the corresponding SER emissions envelope. Nevertheless, the power quality basis for ac-power-lead emissions envelopes provides an appropriate foundation for the RG envelopes.

CE102/CE03—Conducted Emissions, High Frequency

The rationale in MIL-STD 461D Appendix states that the levels for the low frequency band for CE102 (conducted emissions, power lead, high frequency) are set to address power quality, which is a common issue with nuclear power plant applications. The levels for the higher frequency band are based on controlling potential radiated EMI that could affect sensitive receivers, which are not normally present in nuclear power plants. Therefore, the levels in the low frequency band of the MIL-STD emissions envelopes for CE102 and narrowband CE03 (conducted emissions, power lead, high frequency) are adopted unchanged while the levels

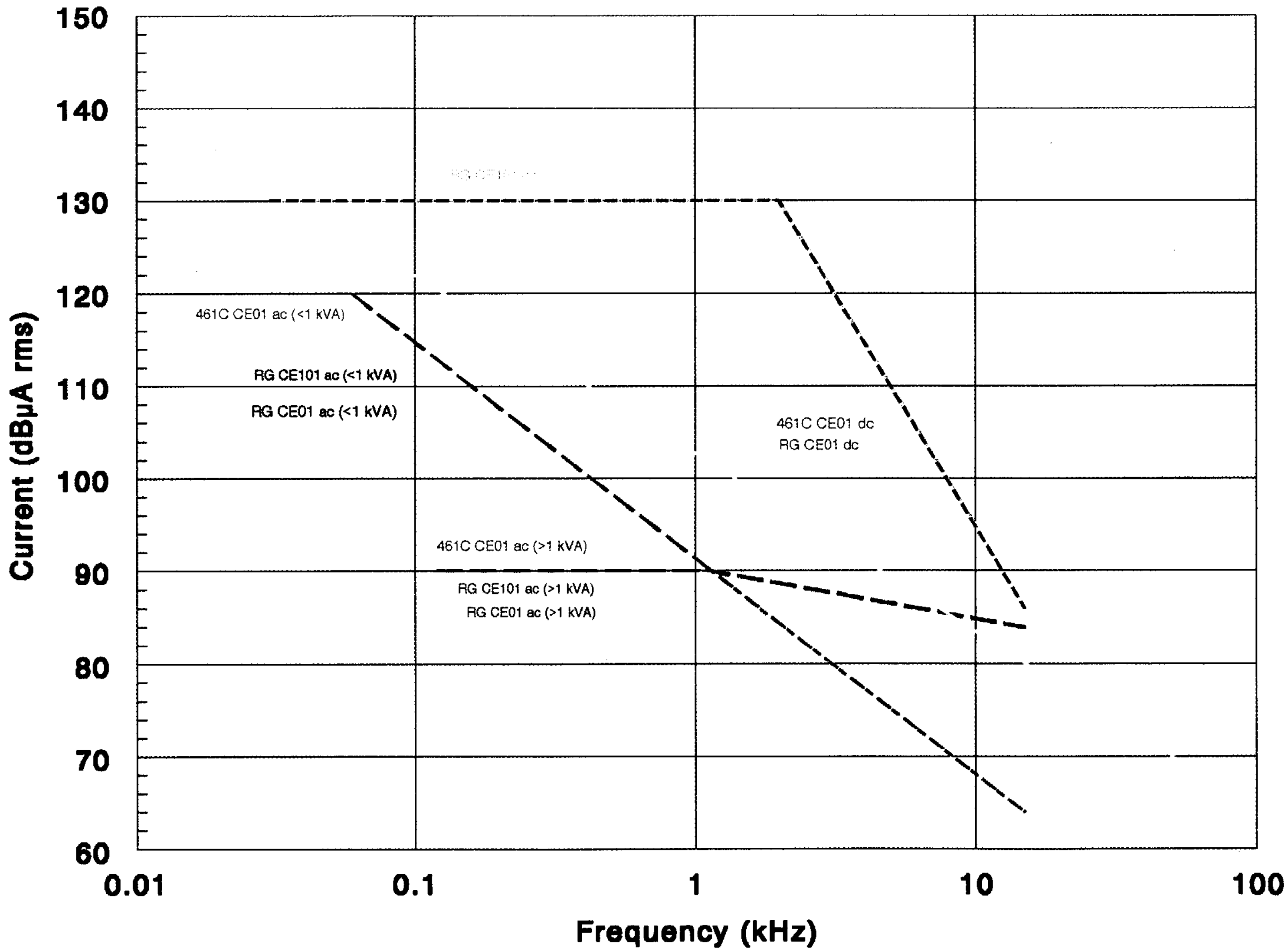

Figure A.5 Comparison of low-frequency conducted emissions envelopes in the higher frequency band are raised for application to nuclear power plants. The CISPR Class A and FCC Part 15 Class A conducted emissions levels are used as the basis for setting the envelope levels presented in this NUREG/CR. Thus, each envelope retains the low frequency slope and level of the corresponding MIL-STD envelope but the upper frequency levels are set to be equivalent to the CISPR limit, which encompasses the FCC limit. These adjustments to the CE102 and CE03 operating envelopes are motivated by consideration of the underlying MIL-STD rationale for the envelopes and incorporate equipment emissions limits for industrial environments. This approach supports the goal of establishing operating envelopes that are appropriately tailored for the nuclear power plant environment.

Figure A.6 provides a comparative plot of the RG (i.e., NUREG/CR) envelopes for CE102 and CE03, the baseline MIL-STD envelopes, the corresponding envelope endorsed by the SER on EPRI TR-102323, and the Class A equipment emissions limits for CISPR and FCC Part 15. The RG and MIL-STD envelopes for CE102 are converted from voltage to current for comparative purposes based on the test apparatus impedance established in MIL-STD 462D. The CISPR and FCC limits are converted from voltage to current for comparative purposes based on the test apparatus impedance defined for those test methods. The RG envelopes completely encompass the CISPR and FCC conducted emissions limits. The RG envelopes are slightly more restrictive than the corresponding SER envelope. Nevertheless, the power quality basis for the low frequency component of the emissions envelopes and the industrial emissions limit basis for the high frequency component of those envelopes provide an appropriate foundation for the RG envelopes for CE102 and CE03.

RE101/RE01—Radiated Emissions, Low Frequency

The RE101 (radiated emissions, magnetic field, low frequency) operating envelope is based on the Army ground facility envelope in MIL-STD 461D. The RE101 operating envelopes are adjusted because virtually no margin exists between the MIL-STD operating envelope for equipment emissions measured at 7 cm and the RS101 (radiated susceptibility, magnetic field, low frequency) operating envelope for radiated susceptibility over the same frequency range. Some margin is deemed necessary to control the potential future growth of radiated magnetic field levels within specific areas of nuclear power plants. In the absence of other technical considerations, the lowered level for the operating envelope for emissions measured 7 cm away from the equipment is selected to be consistent with the operating envelope addressed in the SER on EPRI TR-102323. A comparable shift in field strength is enacted for the operating envelope for emissions measured 50 cm away from the equipment. The operating envelopes for military ground facilities from RE01 (radiated emissions, magnetic field, low frequency) in MIL-STD 461C is adjusted to provide greater consistency between the RE101 envelope for emissions measured 7 cm from equipment and the RE01 envelope. The envelopes are similar in level with the comparable envelope endorsed in the SER on EPRI TR-102323. These adjustments to the RE101 and RE01 operating envelopes are motivated by the need to adequately control the growth of plant emissions and meet the goal of establishing comparable levels of assurance among the test criteria.

Figure A.7 provides a comparative plot of the RG (i.e., NUREG/CR) envelopes for RE101, RE01, and RS101, the baseline MIL-STD envelopes, and the corresponding envelope endorsed by the SER on EPRI TR-102323. It is seen that the RG envelope for emissions measured at a distance of 7 cm from the equipment and SER envelopes are similar in level. The RG envelope for emissions measured at a distance of 50 cm from the equipment provides an alternate envelope for area emissions control.

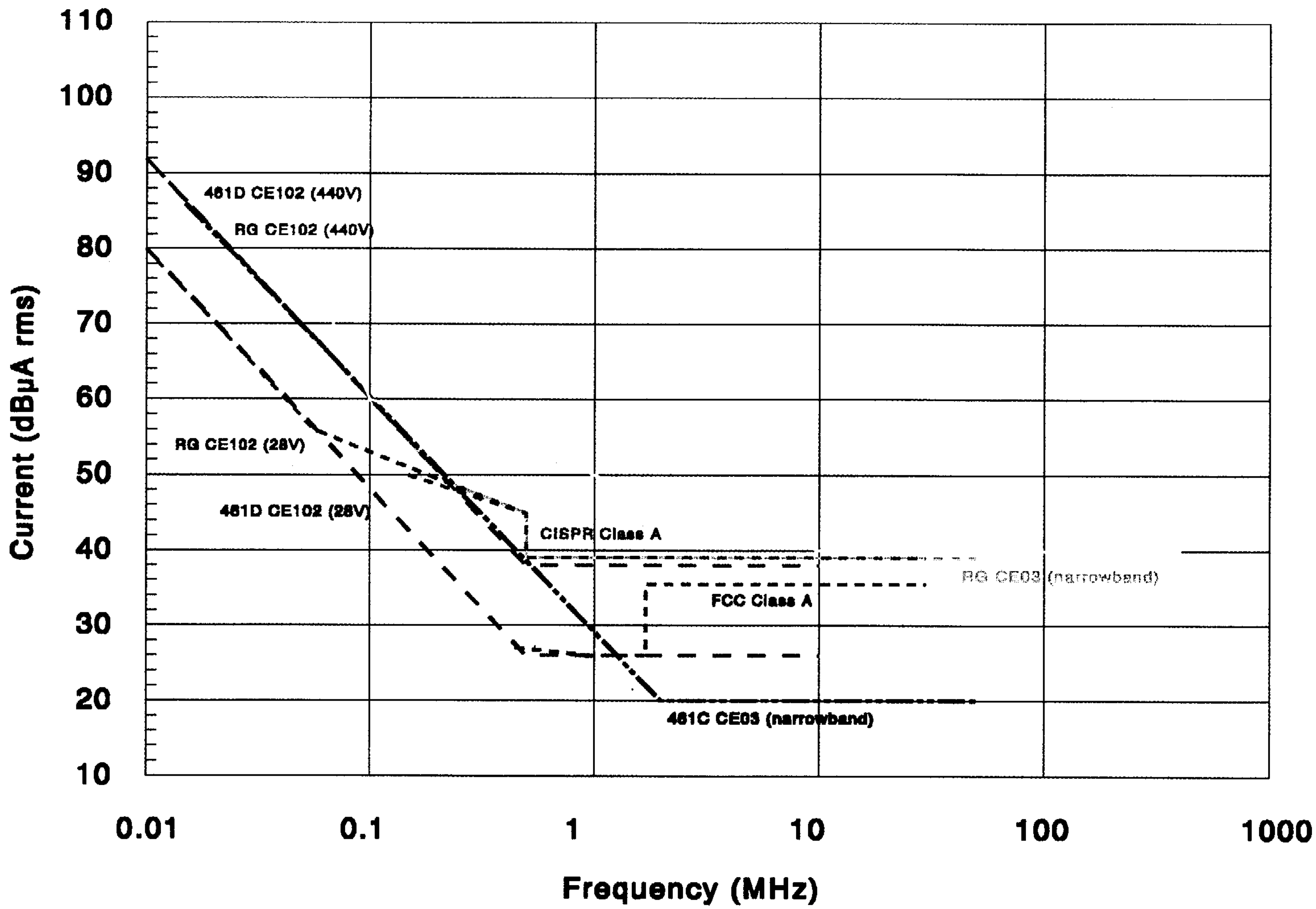

Figure A.6 Comparison of high-frequency conducted emissions envelopes

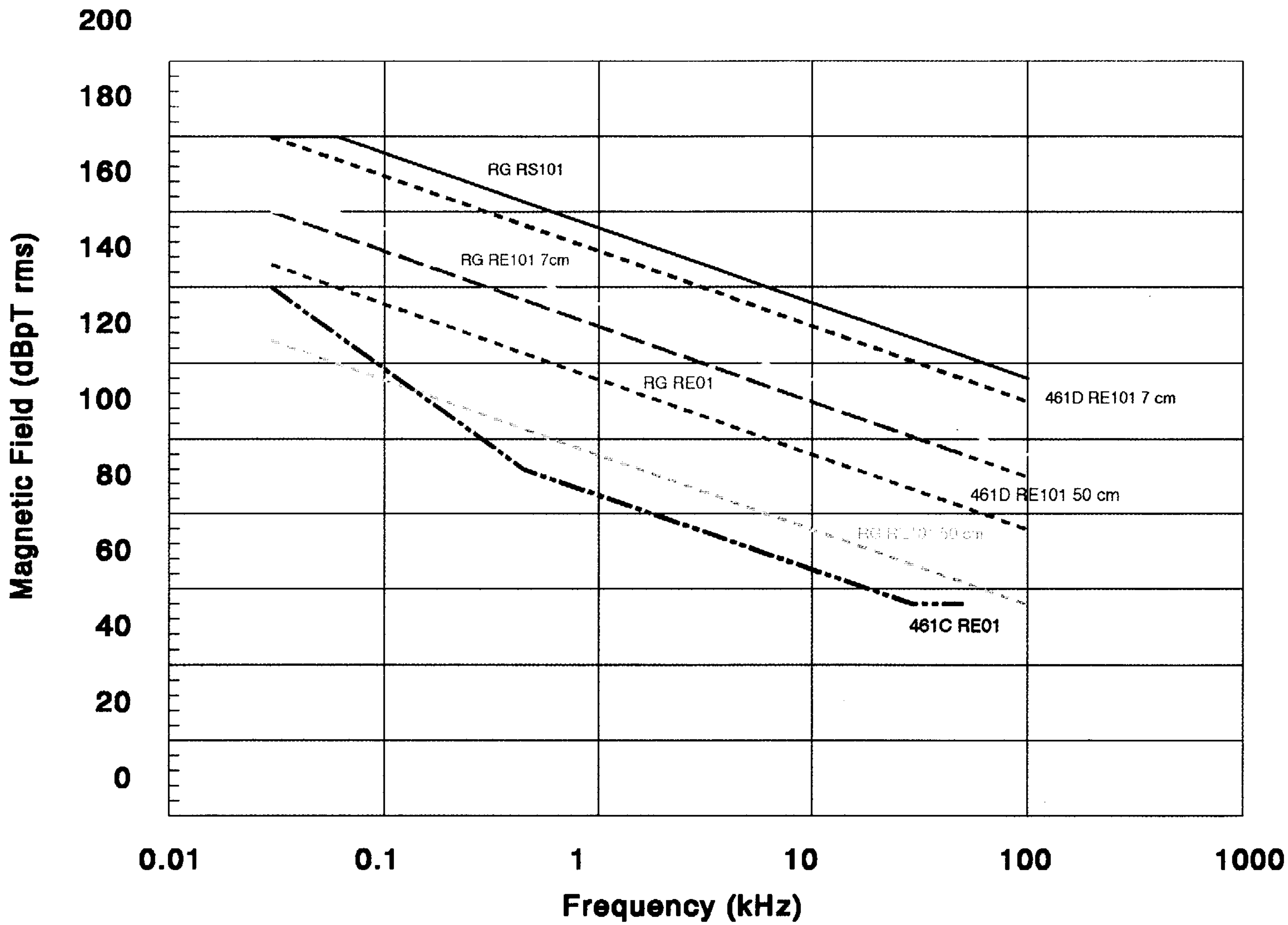

Figure A.7 Comparison of low-frequency radiated emissions envelopes

RE102/RE02—Radiated Emissions, High Frequency

The basis for the RE102 (radiated emissions, electric field, high frequency) operating envelope is the Army ground facility envelope in MIL-STD 461D. The basis for the MIL-STD envelope below 2 MHz is a relationship with CE102 (conducted emissions, power lead, high frequency), which addresses power quality issues that are common for nuclear power plants. The rationale for this envelope given in the MIL-STD 461D Appendix states that the primary intent of the RE102 test is to protect sensitive receivers. Therefore, the very restrictive levels for the envelopes are raised but the slope of the lowest frequency band (which is related to the CE102 envelope) is maintained. The highest frequency component is adjusted using the CISPR Class A and FCC Part 15 Class A radiated emissions levels as the basis for setting the slope and level for the envelopes above 25 MHz. The emissions envelope component over the remaining frequency band (below 25 MHz) is adjusted in level from its MIL-STD basis to correspond to the industrial emissions basis for the component of the envelope in the high frequency band. Thus, the RE102 emissions envelope presented in the NUREG/CR retains the low frequency slope of the MIL-STD envelope at levels comparable with those endorsed in the SER but the envelope levels in the upper frequency band are set to encompass the CISPR and FCC limits. Finally, the RE02 (radiated emissions, electric field, high frequency) narrowband envelope presented in this NUREG/CR adopts the RE102 envelope shape and level based on the same underlying rationale. The adjustments to the RE102 and RE02 operating envelopes are motivated by consideration of the underlying MIL-STD rationale for the envelopes and incorporate equipment emissions limits for industrial environments. This approach supports the goal of establishing operating envelopes that are appropriately tailored for the nuclear power plant environment.

Figure A.8 provides a comparative plot of the RG (i.e., NUREG/CR) envelopes for RE102 and RE02, the baseline MIL-STD envelopes, the corresponding envelope endorsed by the SER on EPRI TR-102323, and the Class A equipment emissions limits for CISPR and FCC Part 15. The RG envelopes completely encompass the CISPR and FCC radiated emissions limits. The RG envelopes are somewhat more restrictive than the corresponding SER envelope in the mid-frequency range and less restrictive in the lower and higher frequency ranges. Nevertheless, the relationship to the power quality criteria for the low frequency component of the emissions envelopes and the industrial emissions limit basis for the high frequency component of those envelopes provide an appropriate foundation for the RG envelopes for RE102 and RE02.

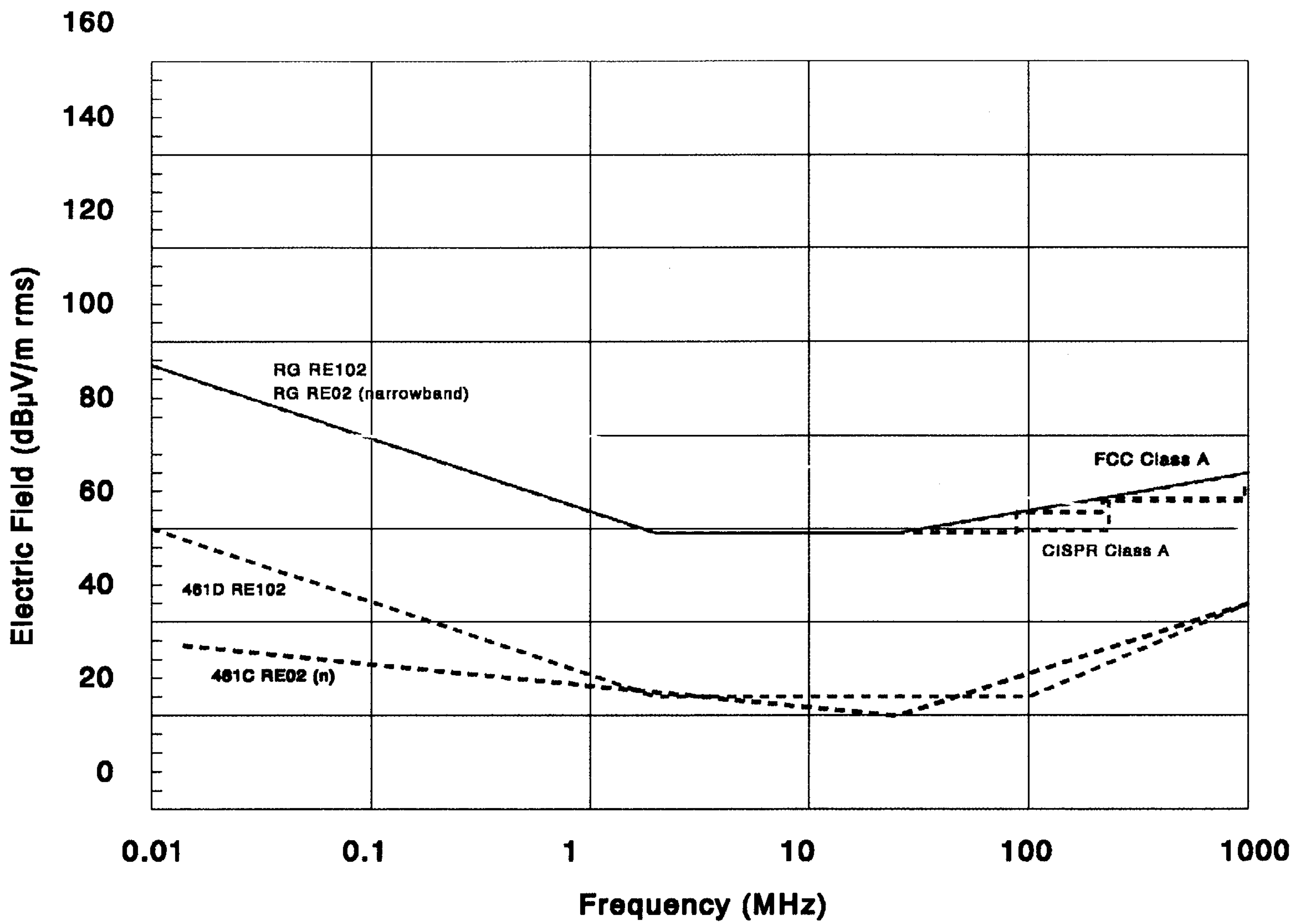

Figure A.8 Comparison of high-frequency radiated emissions envelopes

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)
NUREG/CR-6431
ORNL/TM-13158

2. TITLE AND SUBTITLE
Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants

3. DATE REPORT PUBLISHED
MONTH: January YEAR: 2000

4. FIN OR GRANT NUMBER
L1951

5. AUTHOR(S)
P. D. Ewing
R. T. Wood

6. TYPE OF REPORT
Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6010

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES
C. E. Antonescu, NRC Project Manager

11. ABSTRACT *(200 words or less)*
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 was 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.*

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*	
electromagnetic compatibility (EMC) electromagnetic interference (EMI) electromagnetic receivers instrumentation and control (I&C) nuclear power plant radio-frequency interference (RFI)	13. AVAILABILITY STATEMENT unlimited 14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified 15. NUMBER OF PAGES 16. PRICE

Printed on recycled paper

Federal Recycling Program

ISBN 0-16-050333-7

90000

9 780160 503337

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

1975 25 2000
years

FIRST CLASS MAIL
POSTAGE AND FEES PAID
USNRC
PERMIT NO. G-67