ORNL/SPR-2015/485

# Task 2—Limits for High-Frequency Conducted Susceptibility Testing—CS114 (NRC-HQ-60-14-D-0015)


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OAK RIDGE NATIONAL LABORATORY
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**ORNL/SPR-2015/485**

Reactor and Nuclear Systems Division
Electrical and Electronics Systems Research Division

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## ACRONYMS

| | |
|---|---|
| CFR | Code of Federal Regulations |
| CE | conducted emission |
| CS | conducted susceptibility |
| EMC | electromagnetic compatibility |
| EMI | electromagnetic interference |
| EPRI | Electric Power Research Institute |
| EDSC | experimental digital safety channel |
| EUT | equipment under test |
| I&C | instrumentation and control |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronics Engineers |
| MIL-STD | Military Standard |
| NPP | nuclear power plant |
| NRC | U.S. Nuclear Regulatory Commission |
| ORNL | Oak Ridge National Laboratory |
| RF | radio -frequency |
| RFI | radio-frequency interference |
| RG | Regulatory Guide |
| RS | radiated susceptibility |
| SER | Safety Evaluation Report |
| Std | standard |
| TR | Topical Report |

# 1. INTRODUCTION AND SCOPE

The U.S. Nuclear Regulatory Commission's (NRC's) regulations in Part 50, "Domestic Licensing of Production and Utilization Facilities," of Title 10 of the Code of Federal Regulations (10 CFR Part 50) state that structures, systems, and components important to safety in a nuclear power plant (NPP) are to be designed to accommodate the effects of environmental conditions (i.e., remain functional under all postulated service conditions) and that design control measures such as testing are to be used to check the adequacy of design. The electromagnetic environment of an NPP is an important element of the environmental conditions with which equipment must be compatible. Consequently, guidance on electromagnetic compatibility (EMC) has been provided by NRC and the nuclear power industry to provide acceptable methods for satisfying these regulatory requirements.

Three regulatory documents address acceptable methods to establish EMC for instrumentation and control systems in NPPs. These are the Electric Power Research Institute (EPRI) Safety Evaluation Report (SER) on TR-102323 [1], NRC Regulatory Guide (RG) 1.180 [2], and Revision 1 of RG 1.180 [3]. The SER establishes conditions under which a specific method defined in an industry guidance document is acceptable. In 1994, the EPRI Utility Working Group developed EMC guidance on testing and installation of equipment. This guidance addresses demonstration of immunity to electromagnetic and radio-frequency interference (EMI/RFI) and power surge (i.e., susceptibility testing), determination of the contribution of equipment to the electromagnetic environment of an NPP (i.e., emissions testing), and control of the impact of installed equipment on that environment (i.e., EMI eliminating practices such as grounding and shielding). The guidance was documented in EPRI Topical Report (TR) 102323, *Guidelines for Electromagnetic Interference Testing of Power Plant Equipment* [4]. EPRI TR-102323 was submitted to NRC for review and the SER was issued on April 17, 1996. Specifically, the SER finds that EPRI TR-102323 "contains an acceptable method of qualifying digital instrumentation and control (I&C) equipment when a suitable demonstration is provided that the electromagnetic environment at the plant is similar to that identified" in the report.

In parallel with the development of the EPRI guide, RG 1.180 was developed by NRC to provide guidance to licensees and applicants on methods acceptable to the NRC staff for complying with the NRC's regulations on design, installation, and testing practices for addressing the effects of EMI/RFI and power surges on safety-related I&C systems. The first version of RG 1.180 was issued in January 2000, and Revision 1 was issued in October 2003.

The revision of RG 1.180 differed from the initial version in endorsing U.S. Department of Defense Military Standard (MIL-STD)-461E [5] and the International Electrotechnical Commission (IEC) 61000 standard series of EMI/RFI test methods, extending the guidance to cover signal line testing, incorporating frequency ranges where portable communications devices are experiencing increasing use, and relaxing the operating envelopes (test levels) when experience and confirmatory research warranted. It also offered exemptions from specific test criteria based on technical considerations such as plant conditions and the intended location of the safety-related I&C equipment.

Since the last revision, new requirements have been identified, associated RGs have been created and updated, and additional industry guidance has been developed. Additionally, the operational environment has changed with the increase in wireless communication technology for both personal (smartphone) and industrial (remote I&C) purposes. Also, specific concerns and issues with test limits and methods have been identified that must be addressed. Further, most of the standards that serve as the basis for RG 1.180 have been revised.

Therefore, the NRC Office of Regulatory Research has contracted with Oak Ridge National Laboratory (ORNL) to provide technical input incorporating the latest information and resolving identified issues under NRC-HQ-60-14-D-0015, "Update to RG 1.180, Revision 2, *Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems*." The ultimate goal of this project is to provide NRC the technical basis for developing and publishing a new revision of the RG.

A principal focus of Task 2 under this project was for ORNL to evaluate the basis for susceptibility testing against high-frequency conducted interference and to establish recommendations to resolve concerns about the severity of test limits for the conducted susceptibility (CS) test, CS114, from MIL-STD-461. The primary concern about the test limit has been characterized by the EPRI EMI Working Group in the following terms: "Demonstrating compliance with the CS114 test limits recommended in TR-102323 has proven to be problematic, even for components that have been tested to commercial standards and demonstrated proper operation in industrial applications" [6]. Specifically, EPRI notes that the CS114 limits approved in regulatory documents "are significantly higher than those invoked by the US military and similar commercial standards" in the frequency range below 200 kHz. For this task, ORNL evaluated the original approach to establishing the test limit, EPRI technical findings from a review of the limit, and the regulatory basis through which the currently approved limits were accepted. Based on this analysis, strategies have been developed regarding changes to the CS114 limit that can resolve the technical concerns raised by the industry. Guided by the principles that reasonable assurance of safety must not be compromised but excessive conservatism should be reduced, recommendations on a suitable basis for a revised limit have been developed and can be incorporated into the planned Revision 2 of RG 1.180.

Chapter 2 of this report describes the various limits developed for the CS114 test by the U.S. Department of Defense, EPRI, and NRC. The rationale for the development of those limits is discussed and the evolution of the limits is presented. The findings of the EPRI review of the basis for the CS114 limit are covered in Chapter 3. Specifically, the chapter presents and analyzes EPRI arguments regarding why the limit is considered to be overly conservative and why the plant emissions data are not applicable to developing a basis for the CS114 limit. In addition, EPRI recommendations to resolve questions about what limit is appropriate are discussed. Chapter 4 provides an assessment of the compliance of EPRI guidance on CS114 with conditions of acceptance from the SER on EPRI TR-102323 and the consistency of the EPRI guidance with RG 1.180 guidance. The chapter concludes with a discussion of strategies that can resolve concerns about the CS114 limit and presents a recommended approach.

## 2. EVOLUTION OF TEST LIMITS FOR CS114

Guidance on test limits for CS114 is given in MIL-STD-461 versions D–F [7,5,8], EPRI TR-102323, Revisions 0–4 [4,9–12], and RG 1.180, Revisions 0 and 1 [2,3]. Each set of limits is discussed below according to the source organization.

### 2.1 U.S. DEPARTMENT OF DEFENSE

MIL-STD-461 specifies limits for CS114 based on predefined curves according to platform (e.g., ground, ship, aircraft), service (Army, Navy, Air Force), and frequency range. These limits apply to all interfacing cables for the equipment under test. The current baseline curves are shown in Fig. 1. Specifically, limits for Army ground facilities are identified as corresponding to curve 3 from 10 kHz to 2 MHz, curve 4 from 2 MHz to 30 MHz, and curve 4 from 30 MHz to 200 MHz. Limits for Navy and Air Force ground facilities are identified as corresponding to curve 2 for all frequencies. An additional special limit, set at 77 dBμA, is specified over the range of 4 kHz to 1 MHz for testing of equipment intended for use on surface ships and submarines. This special limit was devised to simulate common mode currents that had been found to be present on AC power cables. The military standard also states that the curves can be tailored in the procurement process to establish a suitable test limit "amplitude based on the expected field intensity for the installation."

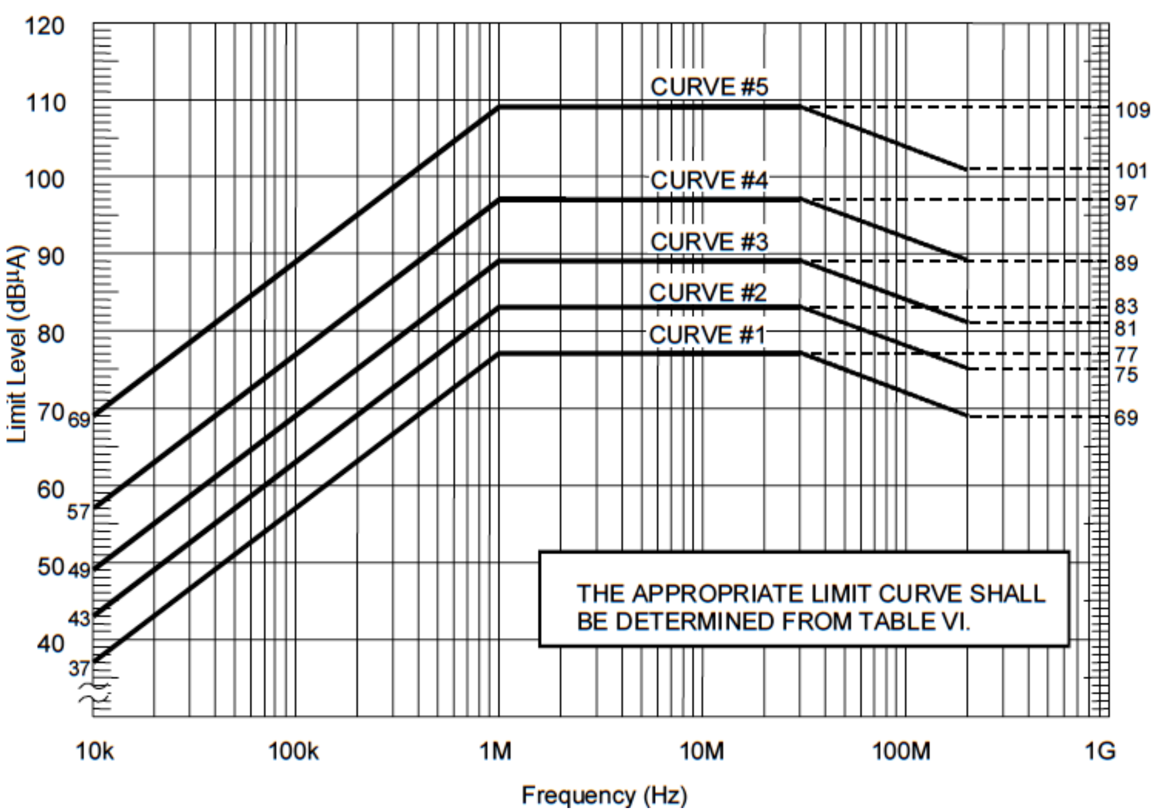


**Fig. 1. MIL-STD-461 limit curves for CS114 test [8].**

The curves that are shown in the figure represent those specified in the F version of the standard. These curves are identical to those in the E version. The limits in the D version differ in that the upper frequency range extended to 400 MHz rather than 200 MHz. In the D version of the standard, testing in this frequency range (200 MHz to 400 MHz) was identified as optional for all platforms but was included for specialized applications. Additionally, testing in the frequency range from 30 MHz to 200 MHz is identified in the standard as optional for all platforms but aircraft and spacecraft based on the condition that the high-frequency radiated susceptibility (RS) test, RS103, is applied. This exemption is based on the conclusion that the RS103 test adequately validates required performance for equipment subject to coupling with radiated interference above 30 MHz.

According to the standard [8], these curves were established primarily based on "testing on aircraft that were not designed to have intentionally shielded volumes" while the limit shape "reflects the physics of the coupling with regard to resonant conditions." This is consistent with a stated objective of the test, which is to "simulate currents that will be developed on platform cabling from electromagnetic fields generated by antenna transmissions both on and off the platform."

## 2.2 ELECTRIC POWER RESEARCH INSTITUTE

In establishing guidance on EMC testing, EPRI developed CS114 limits based on measurements taken at seven NPPs in 1993 and 1994, giving consideration to the corresponding limits in the military standard. The plant data reported in EPRI TR-102323 are shown in Fig. 2. The measurement approach is described in the EPRI report and was based on adapting the military standard emissions test methods for field measurements.

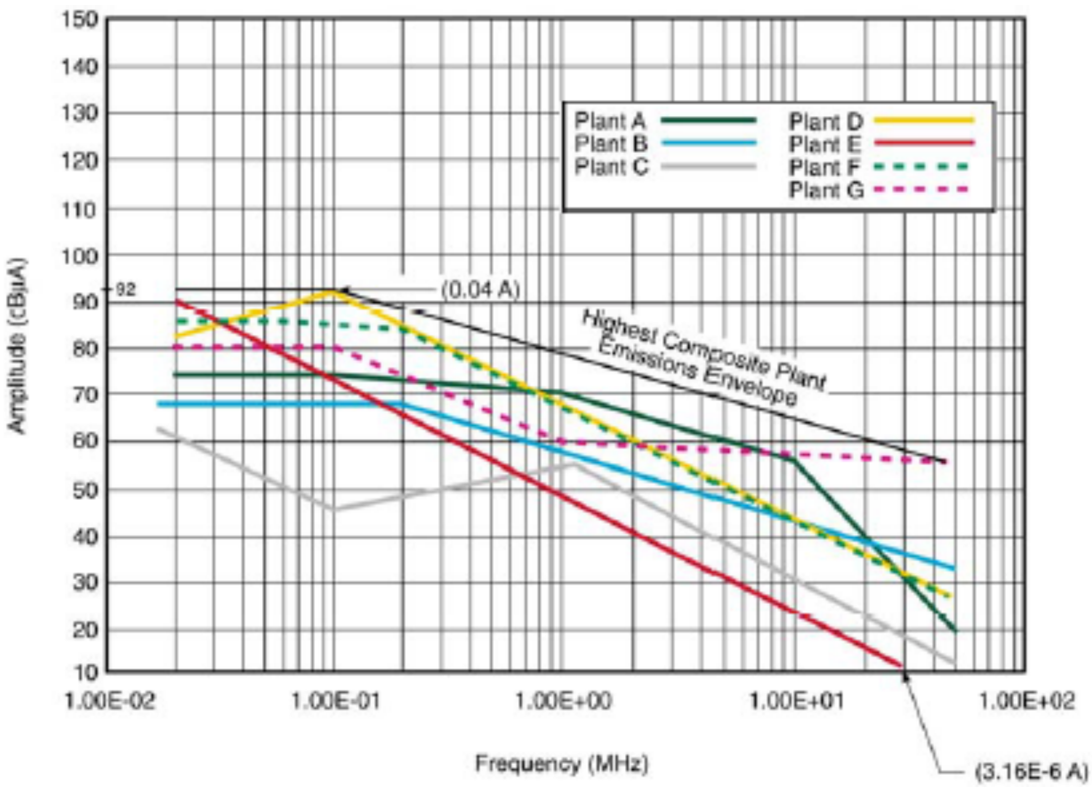


**Fig. 2. Highest observed high-frequency conducted emissions in EPRI plant data** (adapted from Ref. 10).

The initial high-frequency conducted limit developed by EPRI corresponded to the CS02 test defined in MIL-STD-462 [13]. This test specified the capacitive coupling of a voltage onto individual power leads. Its purpose was to evaluate the susceptibility of equipment to electromagnetic energy [e.g., radio-frequency (RF) signals] injected onto its power input terminals. The standard limit for this test, given in MIL-STD-461C [14], is specified as 1 V from a 50 Ω power source for all military platforms to which this test applies. This military standard limit corresponds roughly to an equivalent limit of

86 dBμA. In the process of accommodating the measured data, EPRI recommended a limit of 7 Vrms (i.e., equivalent to 103 dBμA across the frequency band from 50 kHz to 400 MHz). By doing so, EPRI was able to maintain a margin of no less than 10 dB between the measured data from NPPs and the specified susceptibility limit.

CS114 replaced CS02 in the D version of MIL-STD-461 and now serves as the high-frequency conducted susceptibility test. In TR-102323, Rev. 1, EPRI included CS114 as an equivalent alternate test method and adopted the 103 dBμA limit in its recommendations. Thus, the susceptibility limit for high-frequency conducted interference, specified in EPRI TR-102323, Rev. 1, bounded the plant measurements of conducted emissions (CEs) across the high-frequency band (see Fig. 3). These limits were reviewed by NRC staff and were accepted through issuance of the SER on EPRI TR-102323.

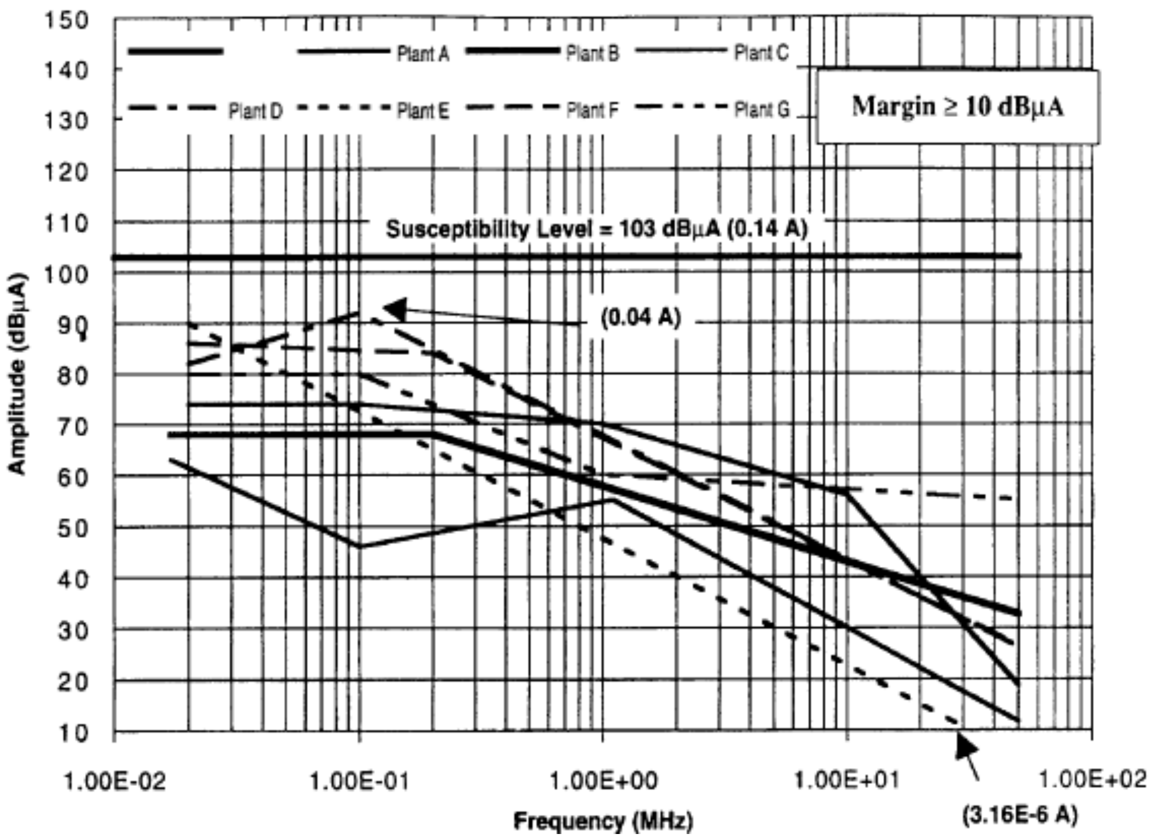


**Fig. 3. Initial EPRI limit for CS02/CS114 with margin above plant data** (adapted from Ref. 9).

ERPRI TR-102323, Rev. 2, dropped the option for the CS02 test [and other previously identified draft tests from IEC and the Institute of Electrical and Electronics Engineers (IEEE)], added an option for the IEC 61000-4-6 [15] test, modified the susceptibility limit for power lines, and added a relaxed susceptibility limit specifically for signal lines. The revised limits are shown in Fig. 4 and were applicable to military standard and IEC testing.

The power line susceptibility limit was reduced from 103 dBμA to 97 dBμA. Also, the upper frequency for testing was reduced from 400 MHz to 200 MHz. Finally, a roll off of the limit was incorporated from 30 MHz to 200 MHz, decreasing from 97 dBμA to 89 dBμA. The changes were incorporated to better align the EPRI limit with the MIL-STD-461E limit curve 4 (see Fig. 1) that is the basis for the Army ground facility limit from 2 MHz to 200 MHz. The roll off was also consistent with the limit specified in the initial version of RG 1.180 (i.e., Revision 0). With this change, the EPRI CS114 limit only provided a margin of 5 dB (i.e., 1.8 times greater) above the composite plant emissions envelope based on measured data in the frequency range below 100 kHz. However, EPRI gave the following argument as justification.

> "The elevated plant emissions levels were due to differential-mode signals measured on power cables. The differential-mode levels are generally higher than common-mode levels. The common-mode emissions data are more indicative of actual EMI levels capable of affecting digital system operation. The margin between the highest composite continuous-wave common-mode plant emissions and the equipment susceptibility level is expected to be much larger."

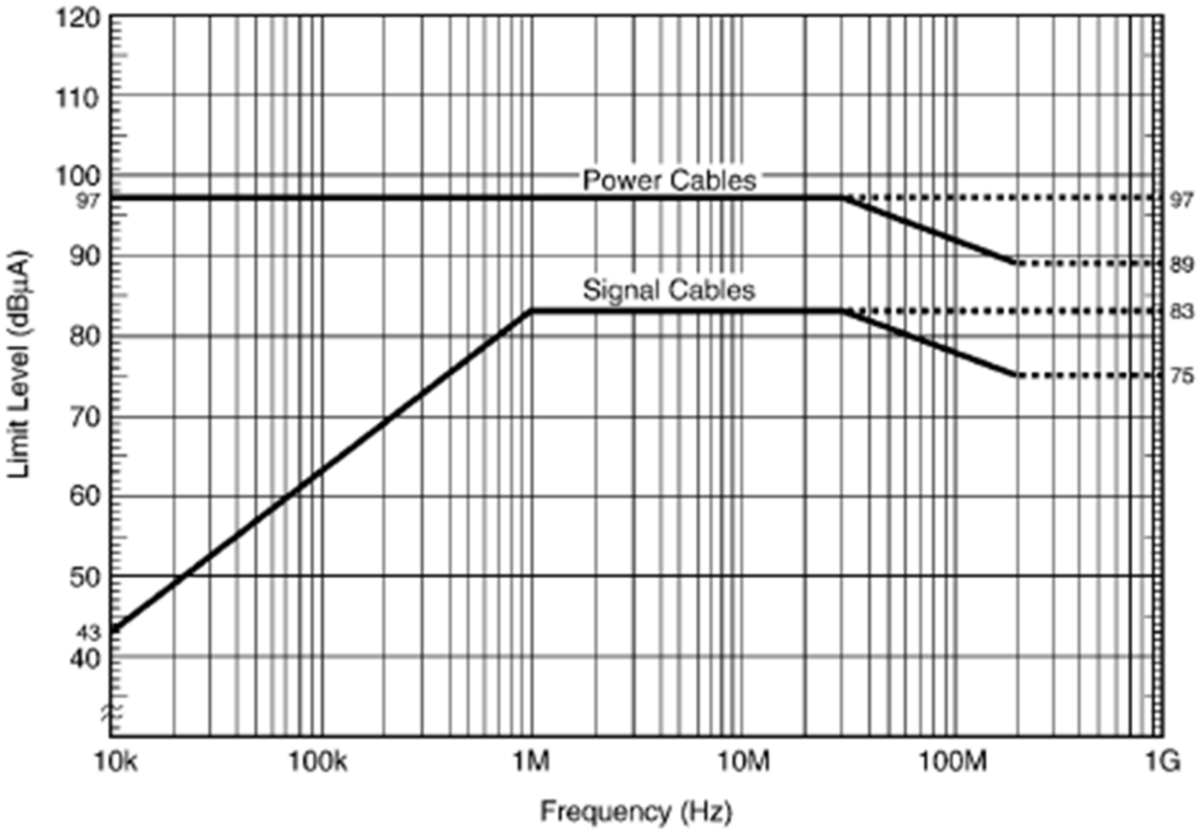


**Fig. 4. High-frequency conducted susceptibility limits from EPRI TR-102323, Rev. 2 [10].**

The basis for the signal line limit was identified as curve 2 from MIL-STD-461E. Curve 2 corresponds to the limit for Navy and Air Force ground facilities. EPRI stated that selection of this relaxed limit for signal lines was "supported by comparison with collected plant emissions data beyond 1 MHz."

EPRI TR-102323, Rev. 3, added a limit specific to IEC 61000-4-6, dropped the separate limit for signal lines (i.e., specified a single limit for both power and signal lines), and relaxed the combined limit for CS114 testing in comparison with the power line limit of Rev. 2. The limits are shown in Fig. 5.

The limit for IEC testing is based on Class 3 in the standard, which corresponds to an industrial environment. Testing based on the IEC method covers a frequency range from 150 kHz to 80 MHz. The limit is specified as 140 dBµV, which is equivalent to a limit of 96.5 dBµA based on the 150 Ω impedance specified for the test equipment. This limit compares favorably with the 97 dBµA limit for power line testing that was specified in revision 2 of the EPRI guide (see Fig. 4) and is consistent with amplitude in the mid-frequency range of the Army ground facility limit from MIL-STD-461 (see Fig. 1).

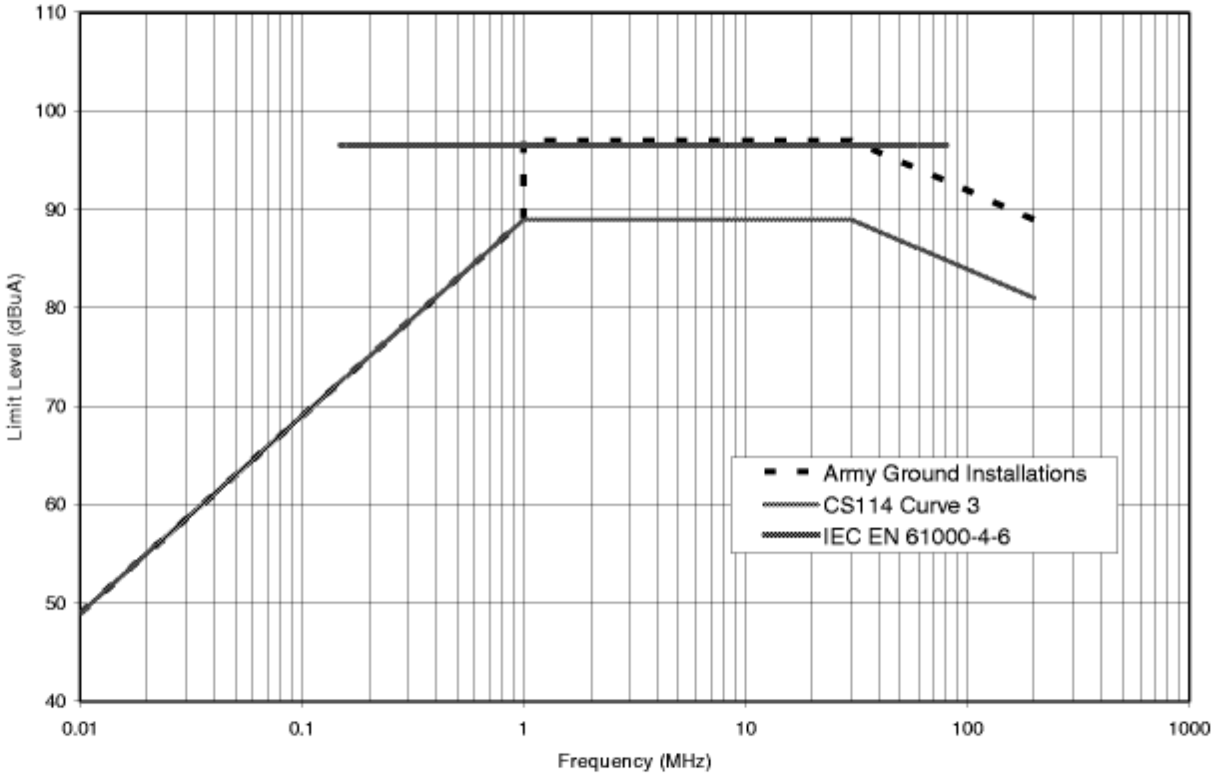


**Fig. 5. High-frequency conducted susceptibility limits from EPRI TR-102323, Rev. 3 [11].**

The deletion of a separate limit for signal lines corresponds to the guidance in both MIL-STD-461 (regarding CS114) and IEC 61000-4-6. Neither standard differentiates between power and signal lines in regard to limits or test methods. The rationale stated by EPRI is that, since each test is intended to evaluate "susceptibility to an RF energy-induced phenomenon, the test levels should be the same for both power and signal cables, as both are equally exposed to this source."

The CS114 limits in EPRI TR-102323, Rev. 3, do not attempt to bound the conducted emissions data measured from NPPs. Specifically, EPRI stated that it "abandoned use of conducted emissions data measured per conducted emissions test CE03 as a basis for CS114 test levels." Technical arguments regarding the validity of the data are articulated in EPRI TR-102323, Rev. 3, and supporting documents. The following chapter of this report will review these arguments in more detail. However, a key consideration that is directly relevant to development of the limits specified in this revision relates to the purpose of CS114. Essentially, the contention is that, because CS114 is intended to evaluate immunity to radiatively coupled interference, the conducted susceptibility limit is more appropriately based on an understanding of the radiated electromagnetic environment rather than measurements of conducted emissions from the field. As a result, new limits were developed in the form of two options.

First, the primary option for the CS114 limit was based on a direct adoption of curve 3 from MIL-STD-461 (see Fig. 1). The rationale behind selection of this curve is based on the expectation of worst-case exposure derived from the long-standing RS limit (i.e., 10 V/m for RS102). Following this logic, if the full energy from an electromagnetic environment characterized by a radiated interference level of 10 V/m (i.e., the limit against which high-frequency radiated susceptibility is established) were to be coupled to a cable bundle, then the resulting emissions level from the induced current would be 83.5 dBμA. EPRI observed that curve 3 of MIL-STD-461 has a plateau of 89 dBμA in the frequency range of 2 MHz to 30 MHz. Given that the postulated 10 V/m radiated electromagnetic environment contains margin, the 5.5 dBμA margin offered by curve 3 across the frequency range from 2 MHz to 30 MHz was "considered to be more than adequate to assure EMC with respect to high frequency conducted susceptibility." Thus, selecting this limit "conservatively bounds the conducted emissions current produced by a 10 V/m radiated electric field." Because the shape of the curve is based on laboratory measurements of induced current on a copper tube "supported 5 cm above a ground plane and terminated with 100 ohms" [11] and also because copper tubing provides the worst case for coupling given its very low inductance, it is considered that the curve provides a suitable representation for the frequency behavior of conducted interference induced by radiative coupling in NPPs.

In developing the second option for the CS114 limit, EPRI noted that the use of curve 3 alone is not specified for any of the military platforms, thus it would be a customized limit. To avoid any complications from customization, EPRI identified the test limit for Army ground facilities as being acceptable. It noted that that limit would conservatively bound a limit based solely on curve 3. Although EPRI TR-102323, Rev. 3, specifies the Army ground limit, the figure showing the limit does not correspond to the military standard limit (see Fig. 5). The limit that is depicted in the EPRI guide shows an amplitude step at 1 MHz while the Army ground limit has an amplitude step at 2 MHz. The Army ground limit is accurately portrayed in Fig. 6, which shows the limits for EPRI TR-102323, Rev. 4.

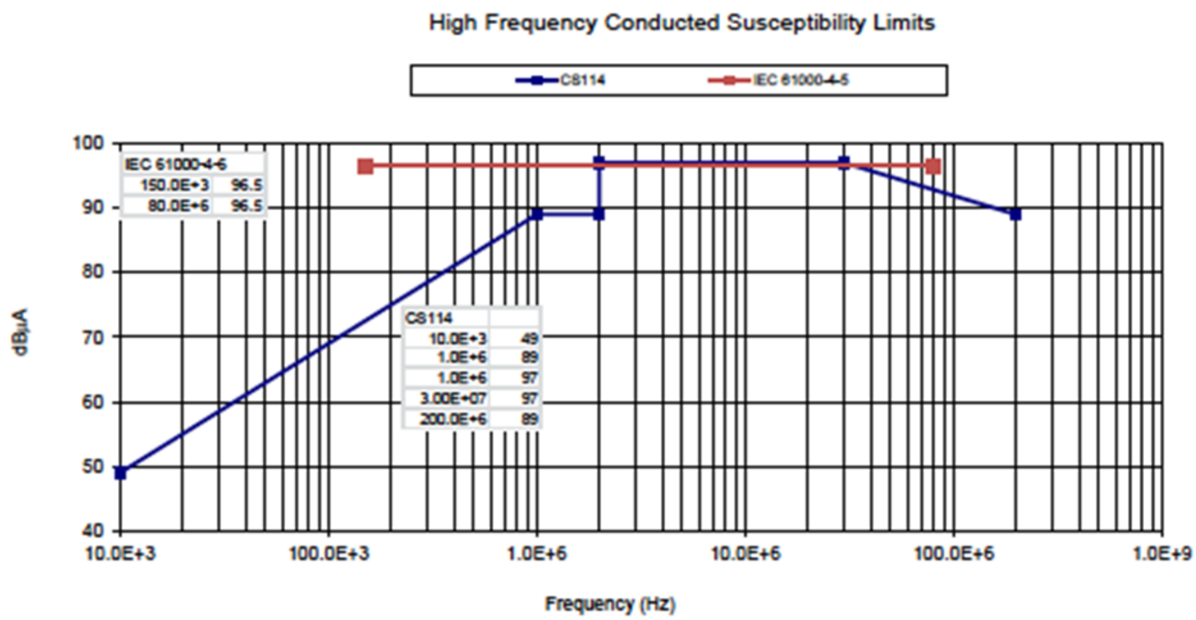


**Fig. 6. High-frequency conducted susceptibility limits from EPRI TR-102323, Rev 4 [12].**

EPRI TR-102323, Rev. 4, drops the customized limit (i.e., curve 3) for CS114 and offers only the Army ground facility limit. The IEC 61000-4-6 limit remains unchanged by continuing to specify the Class 3 limit. The limits are shown in Fig. 6. As with the limits in Rev. 3, the Rev. 4 limits for CS114 do not bound the measured conducted emissions data from NPPs below approximately 400 kHz. However, as with Rev. 3, the rationale for the high-frequency conducted susceptibility limits is not based on measured conducted emissions levels.

## 2.3 NUCLEAR REGULATORY COMMISSION

As documented in NUREG/CR-6431 [16], the technical basis for the limits incorporated into the first version of RG 1.180 begins with the military standard limits corresponding to the electromagnetic environment at military ground facilities. The electromagnetic conditions in military ground facilities were judged to be comparable to those of NPPs based on general layout and equipment type considerations. Plant emissions data then were used to confirm the adequacy of the EMC operating envelopes. From the military standard starting point, susceptibility limits were adjusted to account for the plant emissions data available from the site surveys reported in NUREG/CR-6436 [17] and in EPRI TR-102323. Adjustments to the military standard limits were based on providing an adequate margin between the susceptibility envelopes and available plant data and on consideration of the primary intent of the military standard limits (e.g., whether they were specified based on protecting sensitive receivers on military platforms). When changes to the limits were motivated by technical considerations, consistency among the limits for comparable test criteria from similar suites of test methods (e.g., between MIL-STD-461D and MIL-STD-461C or between RG 1.180 and the SER on EPRI TR-102323 [1]) was promoted.

The NRC data for high-frequency conducted emissions at NPPs, along with the comparable EPRI data, are shown in Fig. 7. The figure compares the data sets to the CS114 and CS02 limits specified in RG 1.180, Rev. 0. It should be noted that the limit for CS02 is specified in terms of voltage that is capacitively coupled onto individual power leads. What is shown in the figure is the equivalent level in terms of generated current. These limits provide a margin of at least 11 dB over the measured data.

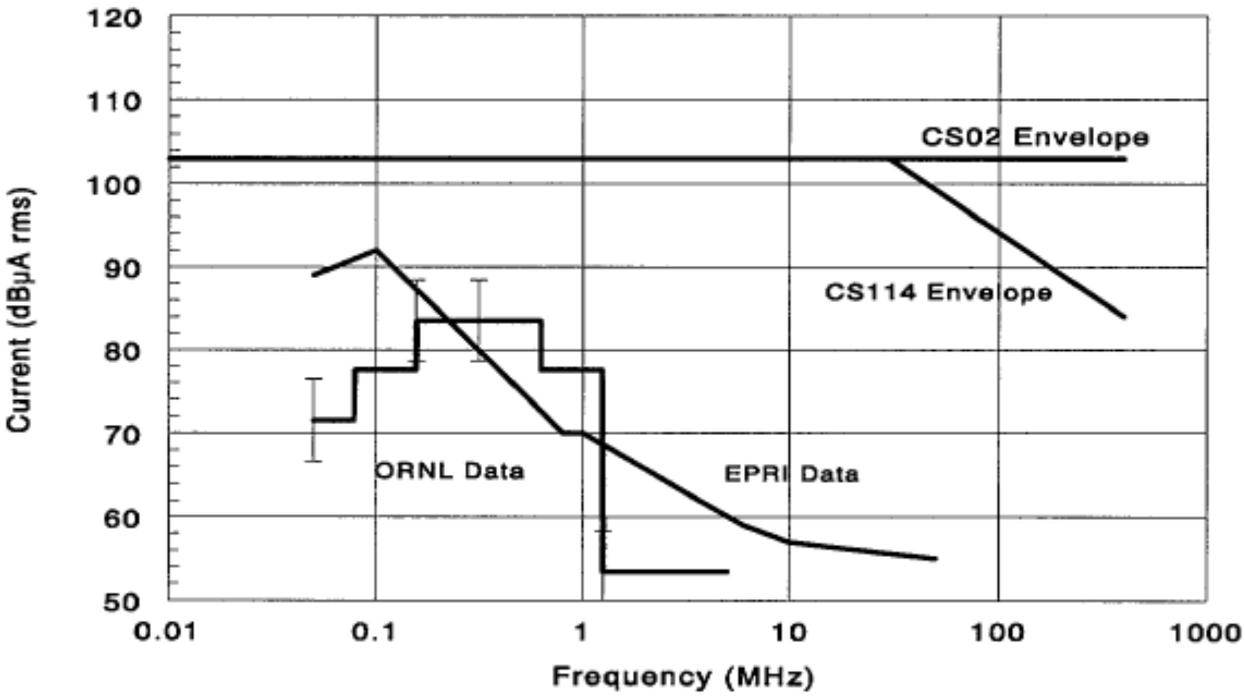


**Fig. 7. High-frequency conducted emissions data and RG 1.180, Rev. 0, susceptibility limits [16].**

The basis for the high-frequency conducted susceptibility limits for RG 1.180, Rev. 0, was described in NUREG/CR-6431. The CS114 limit for Army ground facilities was adopted as the starting point. This limit was adjusted to account for conducted emissions levels measured in NPPs. As a minimum, it was considered that the limit must bound the ambient conducted emissions in the plant. Comparison with the available emissions data showed that the Army ground facility limit did not bound the data in the lower frequency range (i.e., 10 kHz to ~400 kHz). In the absence of other technical considerations, the level to which the limit was raised was selected to be consistent with the limit accepted in the SER on EPRI TR-102323. As there was ample margin at higher frequencies, the break frequency at 30 MHz and the level at 400 MHz were maintained because of practical considerations regarding the ability of the test equipment to generate the desired test levels. The limit from CS02 was also raised to account for conducted emissions levels measured in NPPs. Again, the level to which the limit was raised was selected to be consistent with the limit accepted in the SER on EPRI TR-102323. The comparative analysis to form the basis for the CS114 and CS02 limits in RG 1.180, Rev. 0, is illustrated in Fig. 8. Basically, the adjustments to the CS114 and CS02 limits from the military standard were primarily motivated by the need to provide adequate margin above plant emissions data and to be consistent with the limits approved in the SER.

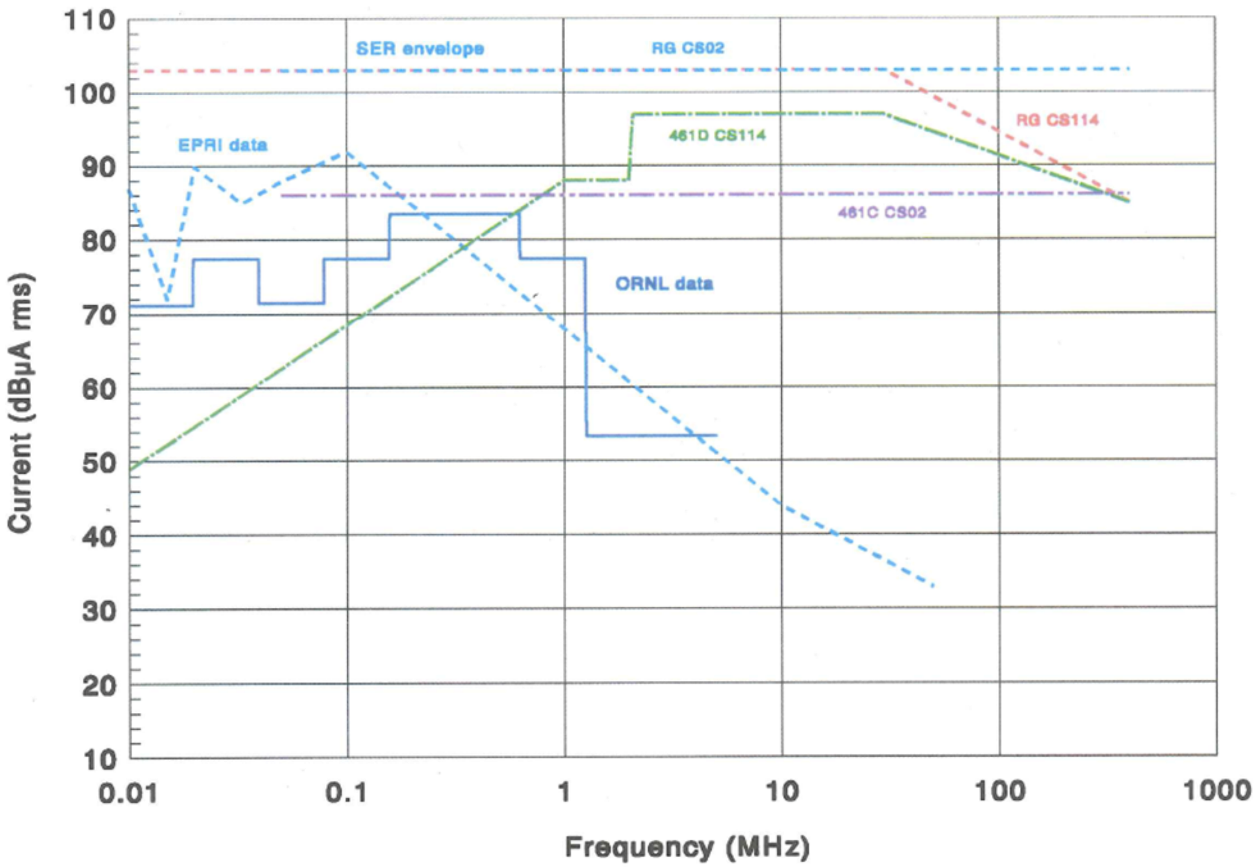


**Fig. 8. Comparison of high-frequency conducted emissions data with initial susceptibility limits [16].**

Regarding the available data, ORNL conducted the survey of EMC levels in NPPs for NRC. The site survey was conducted using specially designed electromagnetic spectral receivers used to acquire and record peak radiated electric field, radiated magnetic field, and conducted interference levels. The survey approach was based on the prevailing guidance for a site survey, IEEE Standard (Std) 473-1985 [18]. Ambient electromagnetic conditions were measured at eight nuclear reactor units over a period of 14 months. Measurement data were collected for up to 5 weeks (24 h/day) in each plant location. As part of this survey, ~6.4 million conducted emissions data points were taken in nine data sets. However, conducted emissions were only performed at three reactor units, with the measurements being conducted on three separate cable bundles at each site. The cable bundles contained both power lines and signal lines. Thus, it is not possible to separate the emissions arising from signal lines from those of power lines. However, the temporal behavior of the data was captured, so it is possible to parse the data in terms of transient and persistent (e.g., continuous-wave) noise.

Revision 1 of RG 1.180 was issued in 2003. This revision dropped the endorsement of test methods and criteria from MIL-STD-461C but added alternatives from the IEC 61000 standard series of tests. In addition, the revision included guidance on emissions and susceptibility testing above 1 GHz and on signal line susceptibility testing. Regarding CS114, the power line limit was relaxed based on an analysis of the available data (see Fig. 9), and a new limit was added to correspond to testing of signal lines.

The limit applicable to power lines was relaxed from 103 dBμA as specified in RG 1.180, Rev. 0, to 100 dBμA in RG 1.180, Rev. 1, over the frequency range from 10 kHz to 200 kHz. This level was selected to ensure a margin of at least 8 dB above the measured data. Specifically, the EPRI data showed data with amplitude up to 92 dBμA (i.e., at 100 kHz) in that frequency band. The power line limit was also relaxed to 97 dBμA in the frequency range from 200 kHz to 30 MHz. This adjustment maintained a margin of 10 dB or more (up to 50 dB in the higher frequencies) for this frequency band. No limit was specified above 30 MHz, and the applicable frequency range for the test was set from 10 kHz to 30 MHz. This adjustment to frequency band coverage was made to be consistent with an exception allowed by the military standard. Specifically, the military standard concludes that the RS103 test provides adequate demonstration of immunity to the interference phenomena above 30 MHz. Consequently, as the "no mixing or matching" provision of RG 1.180 requires both tests (RS101 and CS114) to be conducted, the application of CS114 above 30 MHz was not considered necessary to achieve the necessary reasonable assurance of safety.

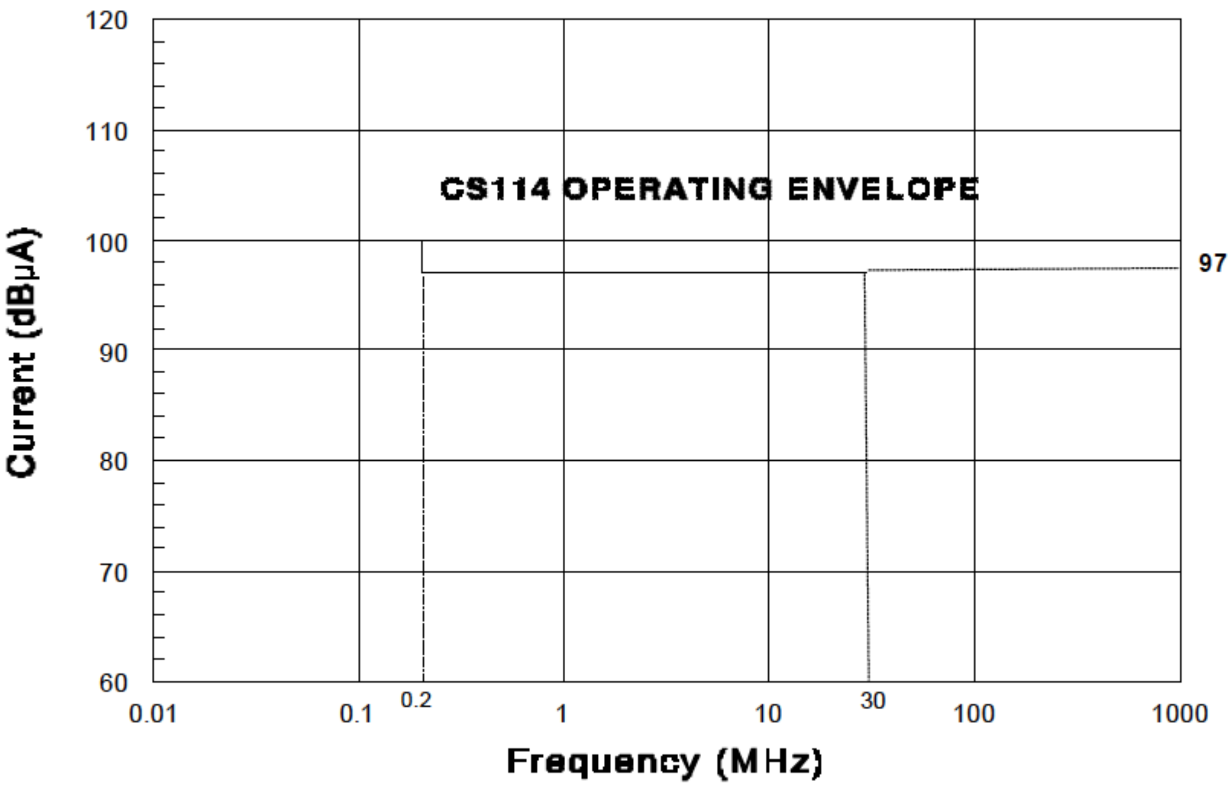


**Fig. 9. CS114 limit for power lines from RG 1.180 Rev. 1 [3].**

The limit applicable to signal lines was specified in RG 1.180, Rev. 1, at a constant amplitude of 91 dBμA from 10 kHz to 30 MHz. This limit constitutes a relaxation of 6 dB from the power line limit over most of the frequency band (i.e., greater than 200 kHz). The rationale for this limit was based on the expectation that the measured conducted emissions from NPPs were dominated by emissions arising from power lines and on observations of greater sensitivity by signal lines to injected conducted interference during EMC testing of an experimental digital safety channel (EDSC) as part of NRC-sponsored research [19]. The limit is essentially consistent with the approach taken in some IEC susceptibility tests in which the limits for testing signal lines are allowed to be half of the value specified for power lines [19].

## 2.4 ANALYSIS

Three limits for power line susceptibility and one limit for signal line susceptibility have been established in regulatory documents as acceptable for application to demonstrate immunity to high-frequency conducted interference through CS114 testing. These limits are contained in the two versions of RG 1.180 and in the initial version of EPRI TR-102323 as accepted through the associated SER. The CS114 limit for power lines in RG 1.180, Rev. 0, and the CS114 limits for power lines and signals lines in RG 1.180, Rev. 1, are described above, along with the bases for those limits, and shown in Fig. 10.

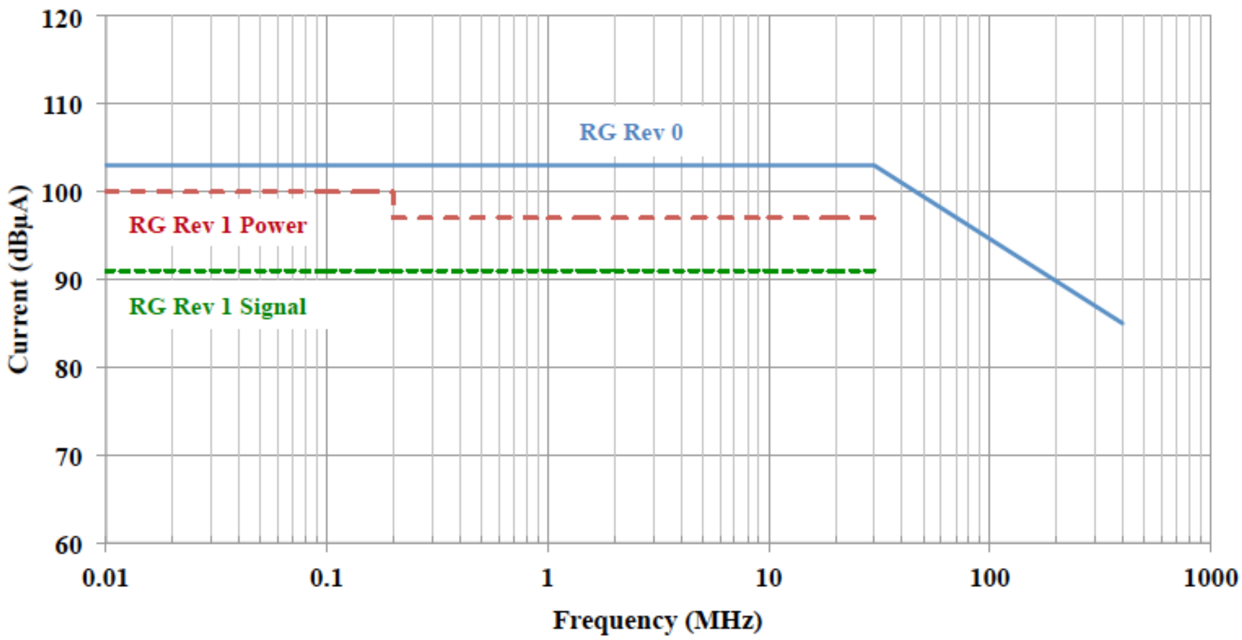


**Fig. 10. Limits for CS114 in both versions of RG 1.180.**

The CS114 limit presented in EPRI TR-102323, Revs. 0 and 1 (see Fig. 3), was approved through the SER on the EPRI report as part of the NRC staff determination that the EMC method described therein was acceptable for satisfying regulatory requirements, subject to certain specified conditions. A key condition of acceptance for the limits contained in EPRI TR-102323, Rev. 0/1, involved the applicability of the generic susceptibility limits in the guide to other NPPs in lieu of plant specific EMI surveys. Specifically, the NRC staff expressed concern about whether the plant emissions data used to establish the susceptibility limits were sufficient to adequately envelope other NPPs. This concern was resolved based on discussions of the impact of EMI-eliminating practices, statistical analysis of the data, and safety margin. First, the EPRI Working Group proposed that the eliminating practices in the guide would minimize the generation and coupling of EMI that "could otherwise potentially invalidate the susceptibility testing levels" [1]. The NRC staff agreed to the merit of this claim. However, additional conditions were specified regarding required testing methods and potential exceptions. Second, the EPRI Working Group performed a statistical analysis to establish confidence levels for the plant data. While the NRC staff did not fully agree with the EPRI conclusions, it was agreed that the "analysis provides some confidence in the collected data." Finally, the EPRI Working Group observed that there was a substantial margin between the susceptibility limits and the measured plant emissions data. Specifically, it was noted that the minimum margin between the high-frequency conducted susceptibility limit and the high-frequency conducted emissions data was 10 dB. Based on a separate analysis, the NRC staff concluded that there must be at least an 8 dB margin between susceptibility limits and measured interference levels to ensure that measurement errors and uncertainties in conditions are adequately bounded. Consequently, given the stated margins for all of the susceptibility limits, the NRC staff agreed that there is "adequate confidence that the recommended susceptibility levels envelope the EM emissions data and provide an appropriate bound for other nuclear plants with similar EMI environments." Essentially, NRC found the CS114 limit (and other susceptibility limits in the EPRI guide) to be acceptable based on the condition that these limits bound the measured emissions data with adequate margin. It should be noted that neither the SER nor the reviewed version of the EPRI guide addressed signal line susceptibility.

The CS114 limit in EPRI TR-102323 has undergone significant changes through the course of four revisions. The evolution of the limit is described above and shown in Fig. 11. The limit specified in Revisions 0 and 1 of the guide (103 dBμA from 50 kHz to 400 MHz) bound the measured conducted emissions data from the plant surveys conducted by EPRI. The limit for power lines specified in EPRI TR-102323, Rev. 2, also bounds the measured emissions data, but its margin around 100 kHz is only 5 dB. The limit for power lines specified in Revisions 3 and 4 of the guide do not bound the measured emissions data below about 400 kHz. Consequently, the CS114 limit for power lines specified in Revisions 2–4 of EPRI TR-102323 do not satisfy the conditions of acceptance established in the SER of EPRI TR-102323. Additionally, the limits in these documents are not consistent with the CS114 limit specified in the two versions of RG 1.180.

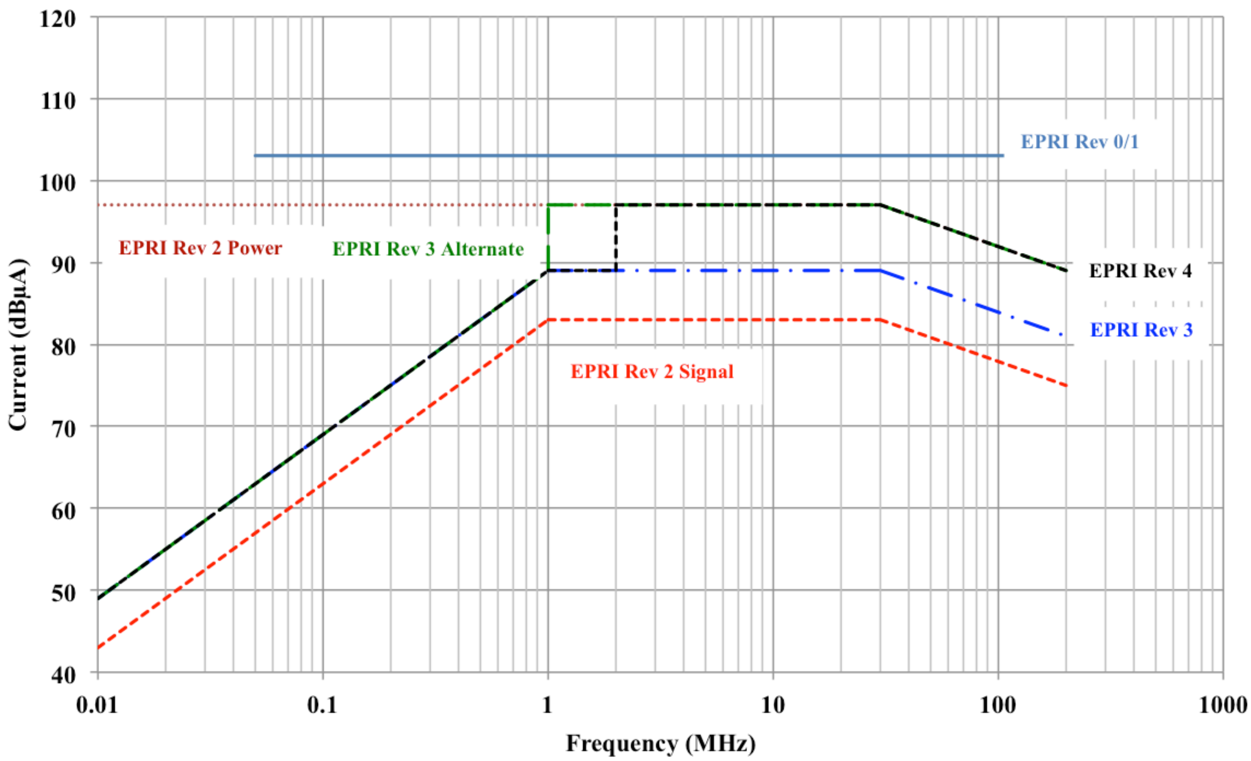


**Fig. 11. Evolution of CS114 limit in revisions of EPRI TR-102323.**

# 3. EPRI ASSESSMENT OF CS114 TEST LIMITS IN TR-102323

As described in the preceding chapter, the CS114 limits that have been accepted by NRC through regulatory documents bound with margin the reported plant emissions data for high-frequency conducted interference. This data came from two sources in the 1990s: an EPRI EMI Working Group plant emissions survey that is documented in EPRI TR-102323 and an NRC-sponsored plant emissions survey conducted by ORNL [17]. As noted, a key element to the basis for regulatory approval of the CS114 limit in EPRI TR-102323, Rev. 0/1, was that the recommended susceptibility limits bound the highest measured interference levels by significant margin (≥ 10 dB).

In the early 2000s, EPRI responded to concerns by some of its member utilities about difficulties in demonstrating immunity against the testing limit for CS114 by performing an investigation into the technical basis for the limit. This work was conducted by MPR Associates, Inc., under the guidance of the EPRI EMI Working Group. The approach for the investigation involved review of plant emissions data from the EPRI-sponsored survey, including the acquisition and analysis methods employed. As discussed in the previous chapter, this data contributed to the basis for establishing the limit in both the initial version of EPRI TR-102323 and its first revision. The findings of the investigation cite several technical factors that may have resulted in development of an overly conservative limit for the CS114 test. In addition to the analysis of the plant survey measurements and data, the investigation resulted in several suggested actions to develop additional bases for revising the limit to resolve the concerns. The findings of the EPRI investigation are summarized below.

## 3.1 FINDINGS OF EPRI REVIEW

The EPRI investigation into the basis for the CS114 limit is described in EPRI 1016158, *Review of High-Frequency Conducted Susceptibility Limits for Electromagnetic Compatibility Testing: Assessment of CS114 Test Limits in TR-102323* [6]. The main contention by EPRI is that the CS114 limit is overly conservative. The primary claim put forth in the EPRI document is that plant conducted emissions data are not appropriate to serve as the basis for the limit. A corollary to this claim is the conclusion that the CS114 limit no longer needs to bound the high-frequency conducted emissions data taken in the EPRI plant emissions survey.

To support its claim about the CS114 test limit, EPRI identifies several arguments about what should constitute an appropriate basis for the limit and why the original plant emissions measurements are inadequate and misleading for characterizing the conducted interference phenomenon that is the focus of CS114. These arguments are summarized below.

The first EPRI argument centers on the purpose of the CS114 test itself. The military standard rationale for the test states that it serves "to verify the ability of the EUT (equipment under test) to withstand RF (radio-frequency) signals coupled onto EUT associated cabling." Since the stated purpose of the test is to evaluate the susceptibility of equipment to conducted interference induced in interconnecting cables by RF radiated emissions, EPRI contends that the basis for the limit should only consider measurements that that solely capture that specific interference phenomenon. Specifically, EPRI notes that the test methods used to measure conducted emissions data in the participating NPPs do not discriminate among emissions from either radiated and conducted sources. Consequently, EPRI suggests that the measured levels are higher than would result from conducted emissions arising from radiated EMI sources only, especially at lower frequencies where radiated emissions with long wavelengths would couple little energy onto conductors of lengths found in power plants. Thus, the EPRI argument is that the plant conducted emissions data should not be used for establishing the CS114 limit for NPPs because of the capture of emissions originating from conducted sources.

To amplify its argument that the measured conducted emissions data are inconsistent with the nature of the phenomenon assessed under CS114 testing, EPRI states that the military standard limits for CS114 “were obtained by radiating a 2-meter long copper tube held above a ground plane and grounded to that plane at both ends with a radio-frequency (RF) electric field.” Consequently, the curves specifying the military standard limits for CS114 exhibit a plateau at the resonance band preceded by a ramp up in amplitude as frequency increases. This behavior in the lower frequency band is due to the poor coupling of RF energy onto cables at those frequencies. Implicit in EPRI’s argument is that the higher levels measured at the plants for conducted emissions in lower frequencies arise in large part due to the presence of noise imposed from conducted sources rather than from coupling due to exposure to radiated EMI emissions.

The second argument put forward by EPRI addresses the validity of the measurement procedures employed for the plant emissions survey that its EMI Working Group conducted in the early 1990s. The measurement procedures were based on emissions test methods from MIL-STD-462 [13] and 462D [20]. Most of the NPP measurements were based on procedures for the CE01 and CE03 tests while measurements at one plant were performed based on updated procedures specified in the CE101 and CE102 tests. The CE03 and CE102 tests address high-frequency conducted emissions. The military standard test methods are intended for laboratory application to measure emissions from specific equipment and, thus, the measurement procedures had to be adapted for field use. EPRI noted that these methods are not designed to distinguish between radiated and conducted sources of the emissions. Thus, one aspect of the EPRI argument is that the approach employed for the plant emissions survey was not suitable for measuring the phenomenon of interest. In this regard, this subargument is also supportive of the first EPRI argument related to the nature of the CS114 test, as described above. Additional concerns with the validity of the data measured using the military standard emissions test methods relate to the bandwidth of the measurement, detector voltage reading, and lack of corrections for the assumed current probe transfer impedance.

Regarding the bandwidth subargument, EPRI states that the difference in input bandwidth between CE03 and CE102 results in higher emissions being measured by CE03 than by CE102. In the review of test reports that remain available from the survey, EPRI found that a measurement bandwidth of 3 kHz was used for the CE03 test while a bandwidth of 1 kHz was used for the CE102 test, which was applied at only one plant. Before release of the D version of MIL-STD-461, no specific guidance on the selection of analyzer bandwidth or sweep times was given for narrowband emissions testing.* However, narrowband and broadband limits were specified by the standard and guidance was provided on how to manually determine the nature of the dominant emissions. Although the EPRI EMI Working Group used a different method for assessing whether significant broadband emissions were present, the EPRI review of the plant measurement reports determined that this difference would not affect the validity of the data. Nevertheless, EPRI concluded that larger analyzer bandwidths resulted in higher peak amplitudes being measured and stated that the impact of bandwidth differences is illustrated by comparison of emissions data measured according to CE03 with data measured according to CE01. The two tests overlap at 15 kHz. The data from the CE03 measurements showed a higher amplitude at 15 kHz than the data from the CE01 measurements, which used a 1.5 kHz bandwidth. The observed difference ranged from 10 to 20 dB higher. Additionally, EPRI observed that bandwidth changes, such as those specified in CE102 in transitioning between frequency ranges (e.g., at 250 kHz), can result in data artifacts in the form of spectral discontinuities at the point of transition. Effectively, the emissions spectra on the high side of a bandwidth transition show higher levels than on the low side of the transition point (up to 10 dB higher). EPRI suggested that a smaller bandwidth for the CE03 emissions measurement (or use of the CE102 method) would have resulted in detection of lower emissions levels and would have more accurately

* Beginning with MIL-STD 461D, analyzer bandwidths and sweep times are specified and the narrowband/broadband distinction is dropped.

captured the actual emissions environment. Thus, EPRI concluded that the CE03 emissions data captured by its survey do not accurately represent the continuous-wave conducted interference phenomenon present at NPPs.

Regarding the detector voltage reading subargument, the measurements were taken based on peak detector readings as specified in the test methods. EPRI contends that this is overly conservative for the purpose of establishing a basis for continuous-wave conducted interference because a peak detector will record the highest current measured during the time the analyzer is collecting data from a given bandwidth, regardless of the duration of that current level. Thus, if the peak value is assumed to represent the amplitude of a continuous waveform, it will overestimate the power imposed by the actual waveform (e.g., short transients or recurring pulses of differing periods). EPRI suggests that use of root-mean-square or average voltage detectors would have the effect of reducing (i.e., averaging out) the impact of transients and thereby give greater weight to the phenomenon of interest (i.e., continuous-wave conducted interference). The underlying assumption is that transient interference phenomena dominated the lower frequency range of the CE03 and CE102 measurements, so using those data as a basis for the CS114 limit results in equipment being subjected to unnecessarily harsh conditions during EMC testing.

Regarding the impedance subargument, because the assumed impedance for the measurement setup is based on laboratory configurations, EPRI contends that the actual impedance was probably significantly different and may have resulted in higher emissions values being indicated than were actually present. Specifically, the EMI analyzer used for the emissions measurement was programmed with the current probe transfer impedance based on probe calibration using cables of known characteristics. It is uncertain whether the impedance characteristics of the actual installation are comparable and it was not possible to determine an impedance correction factor. The consequence of this uncertainty is that the "power content of the emissions is not fully characterized," so the use of the measured currents to establish a basis for the CS114 limit may result in very high power being required to induce the specified currents. EPRI concludes that more accurate consideration of the power (actual energy) and nominal impedance of installed systems during plant measurements would have resulted in a more accurate analysis of the conducted interference emissions levels.

The third argument by EPRI suggests that the CS114 limit originally established in EPRI TR-102323 was erroneously influenced by an incomplete translation of the limit for the susceptibility test for high-frequency conducted interference from MIL-STD-461C (i.e., CS02) to define a comparable limit for the MIL-STD-461D test (i.e., CS114). The basis for the CS02 limit is described in the preceding chapter of this report. Basically, EPRI claims that the differences in testing method between the CS02 test and the CS114 test were not properly addressed, and the result was the invalid use of plant emissions data collected per CE03 and CE102 to recommend test levels applicable to CS114. EPRI states that the "primary difference between CS02 and CS114 is that the interference signal in CS02 was applied to the EUT through a capacitively-coupled voltage source rather than an inductively-injected current source as in CS114." As the CS114 test method involves inducing the current onto the cable inductively, EPRI identifies the error in the failure to consider the impact of the power level of the interference signal. Consequently, the CS114 limit results in high forward power being required to drive current at the level specified by the limit in the low-frequency band of the test. This argument is related to the fourth subargument described above for the second EPRI argument.

A fourth argument put forth by EPRI is related to the purpose of the CS114 test and the use of peak detectors coupled to spectrum analyzers. The contention is that the conducted emissions measurements captured transient phenomena as well as the continuous-wave interference phenomenon. The latter is the focus of the CS114 test while the former is the focus of surge tests such as IEEE Std C62.45 [21]. As noted above, peak detectors measure the highest amplitude at each frequency as it completes its sweep. Consistent with normal practice, the spectrum analyzer used for the EPRI plant emissions survey updated the maximum values at each sweep, discarding any previous lower maximums. Thus, there is no record of the temporal behavior of the plant emissions and it is not possible to determine the nature of the conducted emissions. Consequently, the EPRI measurements likely captured a combination of transient and continuous-wave emissions on the cables under test. This would result in a higher continuous-wave conducted emissions environment being inferred than is actually present.

A secondary claim from the EPRI investigation is that separate CS114 limits should be developed for power lines and signal lines. This claim is consistent with the approach taken in RG 1.180, Rev 1. The EPRI argument is that signal lines are subject to less conducted interference than power lines. An EPRI assessment of data reports from documented plant emissions measurements showed a limited set of conducted measurements where signal lines and power lines could be distinguished. In most of those instances, the emissions from the signal line bundles were considerably lower than for the power line bundles. However, the modest data set available is insufficient to generalize to a definitive basis for generic limits. Nevertheless, EPRI TR-102323, Rev. 2, provides a separate CS114 limit for signal lines. The rationale for the limit is described in the previous chapter of this report. As additional justification for separate limits, EPRI contends that power cable levels were excessive relative to commercial standards for signal cable conducted susceptibility test levels. In the course of developing EPRI TR-102323, Rev. 3, EPRI concluded that signal and power lines should be subject to the same limit. The rationale for this determination relies on the recognition that the military standard does not differentiate between power, control, or signal cables regarding application of the CS114 limit. Essentially, EPRI concluded that because the test is intended to evaluate "susceptibility to an RF energy-induced phenomenon, the test levels should be the same for both power and signal cables, as both are equally exposed to this source."

## 3.2 ELECTRIC POWER RESEARCH INSTITUTE RECOMMENDATIONS

The findings of the EPRI review of the limit for the high-frequency conducted susceptibility test (CS114) contain several recommendations for resolving questions about the basis for the limit. The recommended actions are as follows.

1. Develop more appropriate CS114 test levels based on MIL-STD-461E.

2. Develop new baseline for conducted emissions data using up-to-date test procedures.

3. Justify using average emissions rather than peak to determine CS114 test levels.

4. Develop separate CS114 test levels for signal and power cables.

5. Develop correction factor approach for loop impedance effects.

Recommended action 1 involves either "analytically adjusting" the baseline curves from MIL-STD-461E to "reflect cable lengths more characteristic of power plants" or collecting new emissions data from NPPs "using a test setup similar to the [one] used to establish" the limits in the military standard but with appropriate adaptation to reflect conditions that are representative of plant cable configurations. Recommended action 2 consists of additional plant measurements based on the procedures of the CE102 test rather than the CE03 test that was primarily used in the previous survey. It is also recommended that the revised measurement approach include reduced bandwidth and use average voltage detectors. Additionally, the data collection should be separated according to whether the measurements are taken on power or signal cables. In lieu of additional measurements, the action also identifies existing point of installation measurements taken by member utilities based on the CE102 method. Recommended action 3 begins with an investigation of whether average voltage detectors can be used to reject conducted interference emissions from transient events. If the investigation proves the hypothesis, then a recommended measurement procedure can be developed to ensure that only emissions from continuous-wave conducted interference are measured. Consequently, this action leads to additional plant measurements. Recommended action 4 supports an action that was taken in Revision 2 of EPRI TR-102323. Basically, that guide adopted a relaxed CS114 limit for application to signal lines based on the conclusion that conducted emissions from signal lines are lower than those for power lines. The recommended action also suggests the need for additional measurements or analysis of the "significant body of data" that exists in the industry from point of installation measurements. As discussed above, EPRI subsequently concluded that a single CS114 limit should apply to both power and signal lines because the primary concern is the coupling of radiated interference onto cables and the radiated environment is common to both types of cables. Recommended action 5 proposes research to investigate the "effects of the difference between the loop impedance of installed power and signal wiring and the loop impedance of the CS114 test configuration." The objective of this action would be to develop an approach to defining an impedance correction factor. However, even if such a factor cannot be developed, it is believed that the research would support the contention that the "power levels applied to equipment under test in the laboratory are more conservative than those the equipment will encounter" in the field.

## 3.3 ANALYSIS

EPRI presented several arguments to support its claim that the CS114 limits accepted in the SER on EPRI TR-102323 is overly conservative and the plant emissions data are not appropriate for use as a basis for the CS114 limit. An analysis of these arguments finds there is some merit to a subclaim that the plant emissions data shows higher levels of conducted interference than is likely attributable to continuous-wave conducted interference, which is the phenomenon of interest in susceptibility testing under CS114. However, there is insufficient data to determine what the actual high-frequency conducted interference levels may be at NPPs. Consequently, it is not possible to resolve how much the CS114 limit could be relaxed. At a minimum, it could be judged with high confidence that the conducted interference emissions data from the EPRI plant survey embeds additional, unquantified margin. Thus, some leeway could be considered in judging whether the 8 dB safety margin specified in the SER on EPRI TR-102323 must be rigorously applied in comparing the CS114 susceptibility limit to the plant emissions data. Basically, findings from the investigation performed by EPRI contain plausible arguments that lend support to the claim that the CS114 limit is conservative but are not sufficient given the available evidence to justify dismissing the plant conducted emissions data as a contributing factor in the basis for the CS114 limit. Conclusions from the technical analysis of the EPRI arguments are summarized below.

The first EPRI argument focuses on the purpose of the CS114 test and why measured conducted emissions data from NPPs are not suitable as a basis for the CS114 limit because they include interference from various sources. MIL-STD-461F describes the intent of the test in terms of simulating "currents that will be developed on platform cabling from electromagnetic fields generated by antenna transmissions both on and off the platform." Nevertheless, the application of the test effectively evaluates the susceptibility of equipment to conducted interference imposed on interconnecting leads regardless of the source. The argument put forth by EPRI speaks more to the appropriateness of applying the military standard curves as the basis for an NPP limit than to the suitability of the test method to determine immunity of equipment to conducted interference. Specifically, EPRI notes that the military standard limits are based on the physics for coupling radiated interference onto cables. However, the military standard guidance on CS114 limits includes an adjustment to the baseline curves in the form of a higher limit in the low frequency band for application specifically for surface ships and submarines. This element of the limit (i.e., 77 dBμA from 4 kHz to 1 MHz) accounts for measurements of much higher "common mode currents that have been found to be present on AC power cables" on those platforms. Conducted sources of these currents are cited in the rationale given by MIL-STD-461F. Additionally, the rationale for the CS114 limit described in MIL-STD-461F states that the limits are "primarily derived from testing on aircraft" and that the behavior of the upper band of the curves were developed based on "worst-case measurements for the various aircraft." Thus, the basis for the military standard curves does indeed rely on field measurement of conducted interference and the military standard guidance for the limit includes conditions to account for interference for conducted sources. The bottom line in assessing this argument is that the CS114 test is an appropriate means of evaluating immunity to high-frequency conducted interference regardless of the source. Therefore, the EPRI argument for dismissing the plant emissions data because it may contain noise imposed by conducted sources should be discounted.

The second EPRI argument contains several subarguments regarding the validity of the conducted emissions measurement methods. The first subargument deals with whether the CE03 and CE102 test methods are appropriate for adaptation to field measurements to form the basis for the CS114 limit. In principle, these are test methods intended for laboratory application to assess emissions from specific equipment. Therefore, it would have been more appropriate for the plant emissions measurements to be conducted in accordance with the site survey guidance that was in place at the time (i.e., IEEE Std 473-1985). Nevertheless, the approach used by EPRI was consistent with prior precedence in the nuclear power industry for point of installation measurements so the data cannot be discounted solely on the basis that these laboratory methods were adapted for field application. The primary point that EPRI puts forward regarding the validity of the survey is that these test methods do not readily support analysis to differentiate between radiated and conducted sources of interference. Consequently, the conducted emissions data do not correspond to the phenomenon of interest (i.e., interference induced on cables through coupling with radiated electromagnetic fields), which is identified by the military as the primary focus of the CS114 test. This subargument depends on the premise of the first EPRI argument, which is that CS114 is not appropriate for assessing immunity of equipment to currents arising from conducted sources of interference. As stated above, this argument should be discounted because CS114 is suitable to address immunity to conducted interference regardless of the source and the measurement approach was consistent with common practice.

The second subargument associated with the second EPRI argument relates to the supposition that measured conducted emissions levels overstate the signal power of the noise induced on cables because a wide measurement bandwidth was used. Because continuous-wave conducted interference is a narrowband phenomenon, the presumption is that the wide bandwidth for the CE03 measurements resulted in capture of the highest amplitude from among multiple noise sources in that frequency band, some of which may have corresponded to non-continuous-wave phenomena. Thus, the measured data may show higher levels than would have resulted if only continuous-wave conducted interference was measured. The primary evidence to support this assertion comes from the observed difference (up to ~20 dB) in the comparison of data that was measured at 15 kHz using the CE01 method with a 1.5 kHz bandwidth against data measured at the same frequency using the CE03 method with a 3 kHz bandwidth. EPRI suggests that measurements with a reduced bandwidth may result in data that are 10 to 15 dB lower than the original envelopes. However, comparison of data from different plants measured according to CE03 (3 kHz bandwidth) and CE102 (1 kHz bandwidth) did not show a consistent pattern of difference across the frequency range of the measurements. Consequently, while it seems plausible that bandwidth effects may have resulted in measured data that are higher than levels strictly associated with continuous-wave conducted interference, it is not possible to characterize the magnitude of the effect with the information currently available. The possibility that the high-frequency conducted interference levels demonstrated by the plant emissions data in the lower frequency range of the CS114 test may be elevated over actual plant conditions for the continuous-wave interference phenomenon suggests that more plant measurements are needed to properly characterize the correct emissions envelope. Indeed, performing additional measurements or reviewing other EMC data from industry are recommended by EPRI to resolve uncertainty. However, until the magnitude of the measurement bandwidth effect has been quantitatively characterized, it is not clear to what level the CS114 limit might be relaxed to account for this situation while still bounding the conducted emissions environment.

The third and fourth subarguments associated with the second EPRI argument involve issues associated with adapting the laboratory test methods for field measurements. First, EPRI suggests that using peak detectors, as specified in the test procedures, promotes capture of transient interference in addition to continuous-wave conducted interference. EPRI recommends that average voltage detectors should be used in future measurements to minimize the impact of short-duration transients. However, it should be noted that the standard that was in place in the 1990s for characterizing the electromagnetic environment at a site, IEEE Std 473-1985,[†] invokes the use of peak detectors. A change in test procedure would require careful consideration to adhere to the principles of consensus practice. Underlying this argument is the presumption that transients were captured in the measured emissions data. This point is the primary contention of the fourth EPRI argument and will be treated below. Second, EPRI suggests that uncertainties in the impedance of the measurement setup may have resulted in an overly conservative limit requiring substantial power to be delivered to induce the required currents. EPRI proposes that an investigation of impedance differences between laboratory test stands and cabling in field installations could improve translation of the emissions data into the basis for a limit. However, EPRI acknowledges that development of an impedance correction factor may not prove feasible. It is noted in this analysis that the guidance for CS114 allows provisions for circumstances where the test equipment cannot generate the "forward power" levels that correspond to the calibration setup. In these cases, the test procedure allows for the application of the test limit to be based on induced current with margin rather than driving power. Consequently, it seems that the impact of this uncertainty is overstated and no practical resolution is available. The main take-away from these two subarguments is that there are uncertainties in the data and its analysis that might be reduced through changes in the measurement approach. However, the uncertainties cannot be quantified and neither subargument provides compelling technical reasons as to why the plant emissions data should be discounted.

The third EPRI argument focuses on the impact of incomplete consideration of the differences between CS02 and CS114 in translating the former limit to the latter test method. In both cases, the limit established in EPRI TR-102323, Rev. 0/1 bounds the plant emissions data by at least 10 dB. The primary effect that EPRI cites as a challenge to its basis for establishing equivalent limits for the two test methods involves the resulting demand for high forward power in the CS114 test setup to induce current levels at the limit. This argument is similar to the fourth subargument for the second EPRI argument that is discussed above. Similarly, this argument suggest the possibility of uncertainty in the analysis for the CS114 limit but does not provide compelling technical reasons as to why that limit should not account for the plant emissions data.

The fourth EPRI argument involves the contention that the plant emissions data for high-frequency conducted interference includes measurement of transient events as well as continuous-wave conducted interference. As there are separate tests to address the capability to withstand transients (e.g., power surge), the CS114 limit should not be influenced by emissions levels associated with those transient effects. This argument is technically sound, and it seems likely that the highest levels for the conducted emissions data from the EPRI survey are attributable to transients. Indeed, the argument is supported by laboratory testing conducted by the Tennessee Valley Authority that showed that the imposition of surge waveforms on cables will result in detection of high interference levels for conducted emissions (see Appendix H of EPRI TR-102323, Rev. 4). However, the difficulty in crediting the EPRI argument lies in the uncertainty about where the actual levels for continuous-wave conducted interference lie. The EPRI data do not retain any information about the temporal behavior of the emissions (e.g., the amplitude and persistence of the various underlying interference phenomena), so it is not possible to differentiate between transient and continuous phenomena. As proposed by EPRI, additional measurements using different measurement procedures could confirm the presence of transient events and more properly

[†] IEEE Std 473-1985 was not maintained by IEEE and is currently withdrawn. However, it is understood that the IEEE Standards Association is currently developing a renewal of the standard for issuance in the near term.

characterize the continuous-wave conducted interference environment that is actually present in NPPs. It should be noted that the plant measurements conducted by ORNL for NRC followed the guidance of IEEE Std 473-1985 in terms of detection equipment and measurement duration. As noted, the purpose of this standard is to enable electromagnetic environment characterization at a site. The measurement approach used by ORNL allowed for retention of the temporal behavior of the measured emissions. Indeed, a review of the reported data in NUREG/CR-6436 finds that the highest levels measured correspond to transients. The amplitude difference between transient and persistent (e.g., continuous-wave) events is roughly on the order of 20 dB. Unfortunately, the ORNL survey only contains a limited amount of conducted emissions data from six cable bundles (measured at two units on the same plant site), so it is not suitable for generalized conclusions about the magnitude of the contribution from transients. Clearly, emissions data arising from transients should not be considered in establishing a bounding plant emissions envelope for continuous-wave conducted interference. However, without additional data, it is not possible to determine what level of relaxation in the limits would be warranted to address the impact of transient emissions data.

Regarding EPRI's initial contention, and subsequent rejection, of the need for a separate, less severe CS114 limit specific to signal lines, it is noted that RG 1.180 provides for a lower CS114 limit for signal lines. However, a review of the technical basis for signal line guidance documented in NUREG/CR-5609 [19] indicates that the rationale for a lower limit is flawed. Specifically, the NUREG/CR cites experience from the testing of the EDSC that showed a high sensitivity by signal lines to injected conducted interference during EMC testing. However, the EDSC was designed using readily available commercial off-the-shelf components that were representative, but not necessary comparable, to technologies being employed for safety-related digital I&C systems [22]. The purpose of testing for the EDSC was to identify the types of failures that environmental stress could cause. It was not intended to represent a qualified system. Therefore, EDSC test findings are appropriate to inform an understanding of potential vulnerabilities of digital technology to environmental stress but are not suitable to serve as a basis for establishing a qualification limit. A reassessment of the high-frequency conducted susceptibility guidance in more recent versions of the military standard (i.e., 461E and 461F) and IEC 61000-4-6 results in the determination that signal line susceptibility should be evaluated against the same limit as applied for power line susceptibility. Therefore, it is appropriate to drop the distinction between power and signal lines for the CS114 test and to specify only a single limit.

# 4. RECOMMENDATIONS FOR CS114 GUIDANCE

As noted, the nuclear power industry has experienced some difficulty in demonstrating compliance with CS114. EPRI contends that the limit accepted in regulatory guidance is overly conservative and should not be required to bound plant emissions data from conducted interference sources. In conducting this research activity, ORNL evaluated the evolution of the CS114 limit, analyzed the merit of EPRI arguments developed to support claims the accepted limit is too conservative, and assessed the compliance of the latest version of the EPRI guide to conditions of acceptance in the SER. Guided by the principles that reasonable assurance of safety must not be compromised but unnecessary conservatism should be reduced to the extent practical, recommendations on a suitable basis for a revised limit have been developed and can be incorporated into the planned Revision 2 of RG 1.180.

## 4.1 COMPLIANCE ASSESSMENT OF EPRI TR-102323 GUIDANCE ON CS114

As part of this research activity, the compliance of EPRI TR-102323, Rev. 4, was assessed against the commitments and conditions of acceptance established in the SER dated April 17, 1996. In this regard, the revised EPRI guide complies with all conditions of acceptance with one exception. The specific deviation from the commitments and conditions established in the SER involves the CS114 limit. As noted previously, EPRI TR-102323, Rev. 4, specifies the Army ground facility limit for the CS114 test. As shown in Fig. 12, this limit does not bound the plant emissions data documented in EPRI TR-102323 nor does it bound the conducted emissions data captured in the plant measurements conducted by ORNL under NRC sponsorship. Consequently, the limit does not satisfy the commitment that the recommended susceptibility levels would be sufficiently high to resolve the NRC staff's concern about whether the electromagnetic envelope at NPPs was adequately bounded. Additionally, the limit does not maintain the required 8 dB margin over plant emissions levels. Therefore, the guidance on CS114 in EPRI TR-102323, Rev. 4, does not comply with the commitments and conditions of acceptance from the SER.

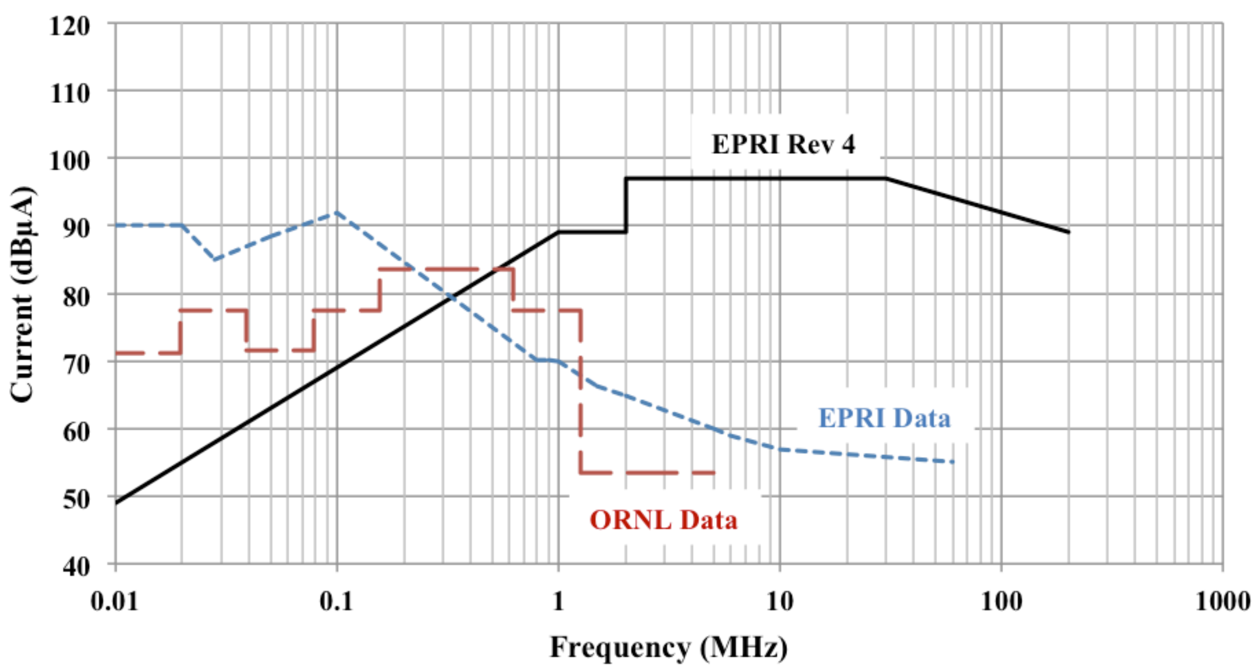


**Fig. 12. Comparison of EPRI TR-102323, Rev. 4, limit with plant emissions data.**

Another aspect of this research activity involves assessment of the consistency between EPRI TR-102323, Rev. 4, and RG 1.180, Rev. 1, regarding high-frequency conducted susceptibility testing. Both documents specify testing according to IEC 61000-4-6 or CS114. The EPRI guide specifies using the most current version of either standard, which are IEC 61000-4-6 (2013) [23] and MIL-STD-461F, respectively. RG 1.180, Rev. 1, specifies the CS114 method in MIL-STD-461E and IEC 61000-4-6 (1996). Based on a review of the guidance in the latest versions of the military and IEC standards, there is no significant difference between either set of revised test methods. Therefore, the guidance on test methods is equivalent between the guides with one exception. RG 1.180, Rev. 1, specifies that mixing and matching of test methods is not acceptable. Therefore, the user can choose to apply either the military standard or IEC methods for susceptibility testing, but the entire suite of tests must be applied in its entirety in either case. In effect, if CS114 is applied, then the military standard for other susceptibility tests must be used. In the EPRI guide, this condition is not specified for CS114. Thus, it is possible that EMC testing under the EPRI guide could consist of any combination of IEC and military standard susceptibility tests. Regarding the test limits for conducted susceptibility, the EPRI guide and RG 1.180, Rev. 1, are consistent for IEC 61000-4-6. However, the limits for the CS114 test are considerably different. The limit in RG 1.180, Rev. 1, continues to bound the plant emissions data while the limit in the EPRI guide does not. Additionally, RG 1.180, Rev. 1, contains a separate limit for application to signal line testing. As discussed in the previous chapter, the use of separate limits for signal and power lines is inconsistent with guidance in the military and IEC standards. Therefore, it will be recommended that only one limit be provided in the next revision of RG 1.180. In summary, the most significant differences between EPRI TR-102323, Rev. 4, and RG 1.180, Rev. 1, occur in the specification of test limits for CS114 and in the acceptance of mixing and matching among test methods from different standards.

Regarding the issue of whether the CS114 limit given by EPRI TR-102323, Rev. 4, fails to comply with commitments and conditions established in the SER, EPRI claims that plant conducted emissions data are not applicable as a basis for the CS114 limit. A related assertion by EPRI is that the CS114 limit no longer needs to bound the high-frequency conducted emissions data taken in the EPRI plant emissions survey. The previous chapter documents the analysis of the EPRI arguments to support these claims. The primary conclusion from this analysis finds that it is appropriate for plant emissions data to be used as part of the basis for the high-frequency conducted interference limit. Thus, the condition of acceptance that the recommended susceptibility limits must bound plant emissions data with margin is reasonable. However, EPRI does provide plausible arguments to justify an assertion that the plant emissions data contains uncertainties due to measurement techniques and contributions from other phenomena that are more appropriately addressed through other tests. These effects result in the likelihood that the conducted emissions data reported by EPRI are higher in amplitude than would strictly correspond to continuous-wave conducted interference, especially in the lower frequency range covered by the CS114 test. The difficulty in giving relief for this apparent conservatism is that there is insufficient evidence to determine what the actual bounding envelope would be for the high-frequency conducted interference phenomenon in NPPs. Thus, there is no basis to determine by how much the reported plant emissions levels could be reduced to filter out the influence of these uncertainties. Furthermore, the available knowledge of the plant electromagnetic environment would need to be supplemented by additional data and analysis to support the establishment of relaxed limits that would maintain reasonable assurance that susceptibility limits bound the prospective hazard. A reasonable conclusion to draw from this assessment is that the plant emissions data for the conducted interference phenomenon contains embedded margin that adds conservatism to the establishment of a bounding limit. However, without further technical information, the magnitude of that additional margin cannot be quantified.

## 4.2 RESOLUTION STRATEGIES

There are three strategies that can be devised to resolve the apparent conservatism in the CS114 limit. The first strategy is to adopt a limit from the military standard without regard for whether it bounds the reported plant emissions data for high-frequency conducted interference in NPPs. The second strategy is to develop a revised limit that continues to bound the measured NPP emissions data but gives some relaxation where justified. The third strategy is to collect and analyze additional plant emissions data to more accurately characterize the continuous-wave conducted interference environment at NPPs and thereby provide the basis for developing a new, less severe limit. In every strategy, the CS114 limit applies to both power and signal lines.

*Strategy 1: Adopt military standard limit*

This strategy was incorporated in Revision 3 of EPRI TR-102323 and updated in Revision 4 of that guide. The recommended limit in the current version of the EPRI guide (see Fig. 6) is a direct adoption of the Army ground facility limit from MIL-STD-461F. Basically, the limit established by the military, which is based on the physics for coupling specified levels of radiated interference onto interconnecting cables, is deemed adequate to demonstrate immunity to high-frequency conducted interference. As seen in Fig. 12, the limit for this strategy does not bound the high-frequency conducted emissions data collected by EPRI or ORNL across the full frequency range (i.e., below ~600 kHz). Consequently, implementation of this strategy requires acceptance of the EPRI claims that plant conducted emissions data are not applicable to serve as a basis for the CS114 limits and that the CS114 limit does not need to bound the high-frequency conducted interference data taken in plant surveys. As noted above, the lower frequency range of the plant emissions data for high-frequency conducted interference does appear to be influenced by noise arising from transient events. However, there is insufficient evidence to determine the underlying envelope for continuous-wave conducted interference at the plants or to confirm that these interference levels would be bounded by the proposed limit. Therefore, it is unclear to what degree the potential would remain for exposure to continuous-wave conducted interference at NPPs that exceeds the proposed CS114 susceptibility limit.

*Strategy 2: Develop a revised CS114 limit that still bounds the plant emissions data*

This strategy involves development of a revised CS114 limit that is relaxed over the currently accepted limits but still ensures that the reported plant emissions data is bounded. The rationale for the revised CS114 limit involves adjustment to the Army ground facility limit in MIL-STD-461F to maintain margin over the highest levels reported in the EPRI and ORNL plant emissions surveys but it also invokes the limits for the low-frequency conducted susceptibility test, CS101, to provide complementary coverage of the data. Basically, the CS101 limits are employed to bound the conducted emissions data from the plant surveys from the lowest measured frequencies through 150 kHz. This approach is feasible because MIL-STD-461E and its later versions extended the upper frequency range of the test from 50 to 150 kHz. Above 150 kHz, the CS114 limit is used to bound the data. To ensure that no less than 8 dB margin is maintained, the proposed CS114 limit differs from the Army ground facility limit from 150 kHz to 2 MHz. In this frequency band, the limit is raised to 97 dBμA, which corresponds to the limit in the resonance band for Army Ground facilities. Figure 13 shows the revised limit along with the comparable limit for IEC 61000-4-6, which is currently established in RG 1.180 and EPRI TR-102323, Rev. 4. The revised CS114 limit is specified at 97 dBμA from 150 kHz to 30 MHz. The comparable limit for IEC 61000-4-6 is equivalent to 96.5 dBμA from 150 kHz to 80 MHz. Because the revised CS114 limit is roughly equivalent to the IEC 61000-4-6 over the frequency range common to both tests and substantially lower below 150 kHz than the approved limits from the two versions of RG 1.180 or Revision 1 of EPRI TR-102323, the difficulties in conducting the CS114 test that are cited by EPRI should be resolved.

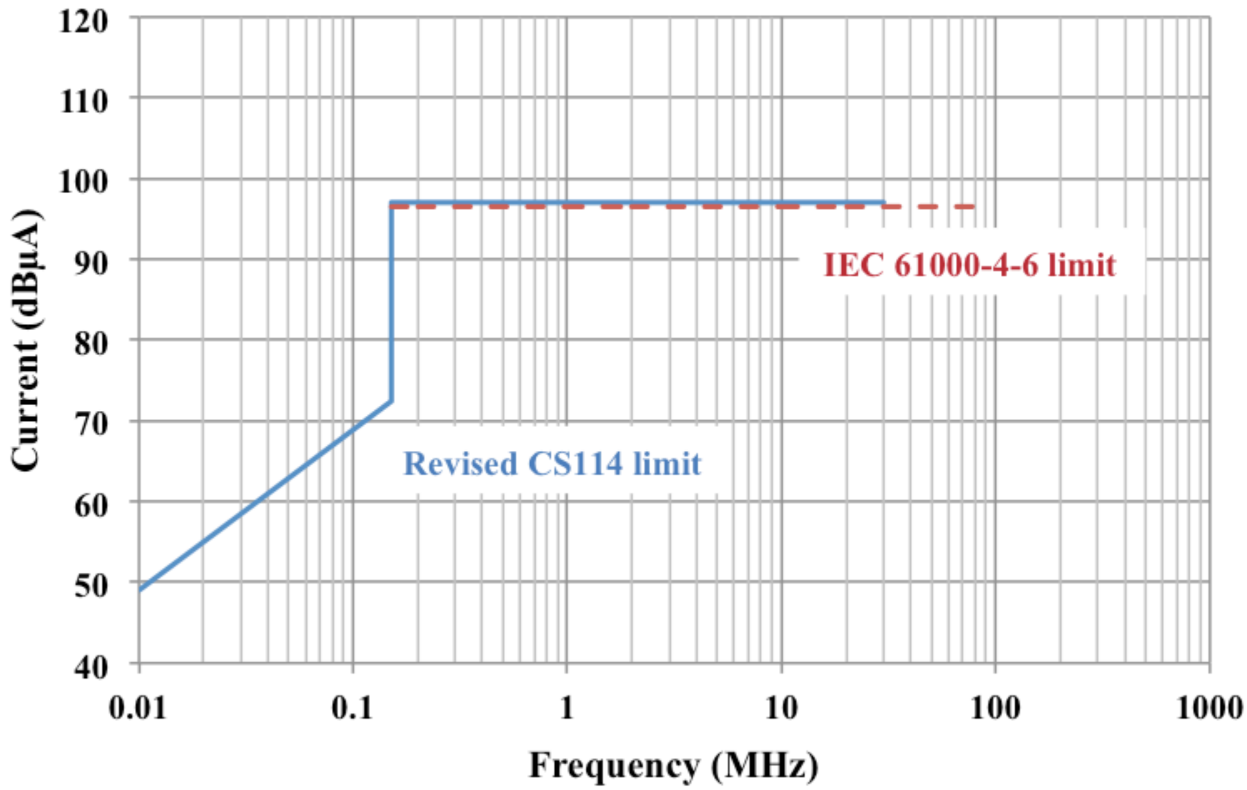


**Fig. 13. Comparison of revised CS114 limit and IEC 61000-4-6.**

To confirm that the revised CS114 satisfies the SER condition of approval related to maintaining adequate margin over plant emissions measurements, the coverage of the measured emissions data for conducted interference is shown in Fig. 14. In the guidance documents, the CS101 limits are specified in terms of decibels related to a microvolt for equipment whose source voltages are either greater than 28 V or less than or equal to 28 V. The equivalent limits are shown in terms of dBµA based on the 0.5 Ω impedance specified for calibration of the test equipment. It can be seen that the minimum margin for bounding the emissions data is maintained at 10 dB with these complementary limits. Thus, the revised CS114 limit can conform to the Army ground facility limit below 150 kHz as the data below that frequency are bounded by the CS101 limits.

*Strategy 3: Develop new CS114 limit based on additional plant emissions data*

This strategy is consistent with the recommended actions from EPRI 1016158 [6]. Based on the findings of its review of the CS114 limits, EPRI recommends that new emissions data be collected from NPPs or existing data be collected from recent point of installation measurements taken by member utilities. The purpose for analyzing additional conducted emissions data is to better characterize the actual plant environment for continuous-wave conducted interference. The most compelling of the EPRI arguments against continued reliance on the plant emissions data reported in EPRI TR-102323 involves the contention that transient events were measured in addition to continuous-wave interference and that those events were the source of the highest levels measured. As noted above, other tests address immunity to transients so the limit for the CS114 test should only consider continuous-wave conducted interference in establishing a bounding envelope for NPPs.

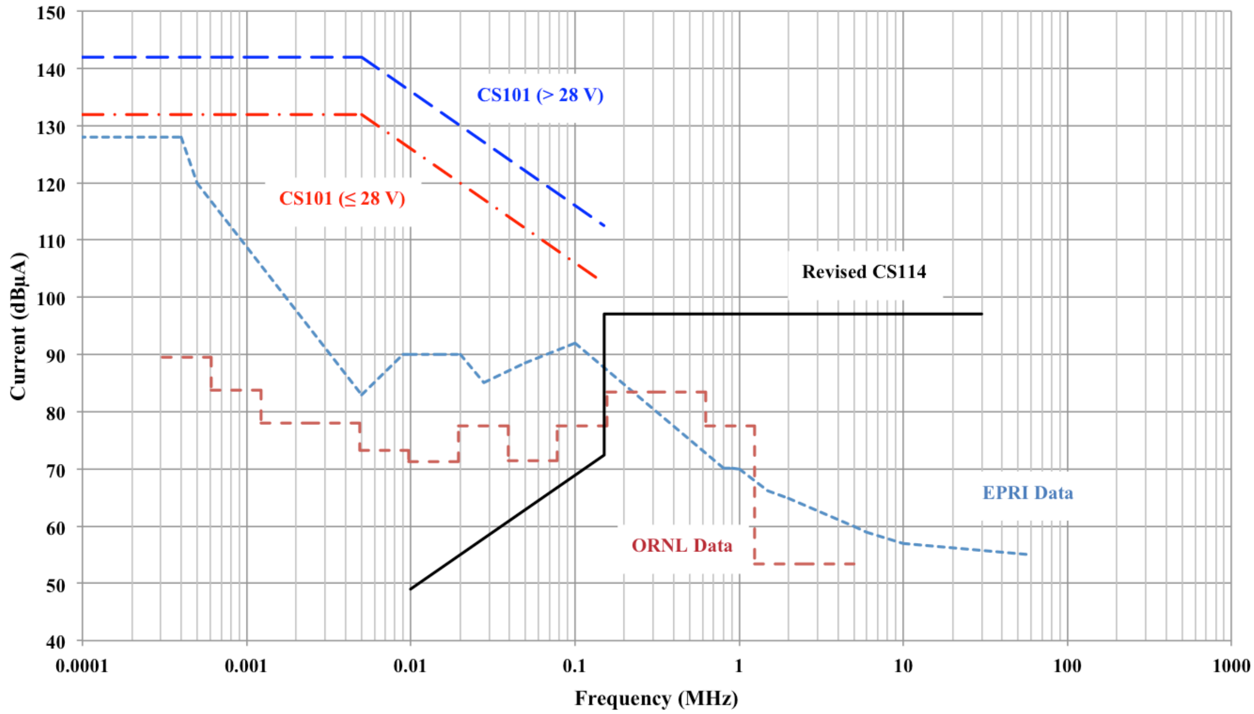


**Fig. 14. Plant emissions data coverage by CS101 and CS114 limits.**

The inherent supposition in the recommendation for more data by EPRI is that the influence of these events can be minimized through more appropriate measurement techniques. Indeed, the plant emissions survey performed by ORNL under NRC sponsorship [17] employed a measurement approach based on IEEE Std 473-1985 and was able to retain time-stamped data that captured the temporal behavior of the interference. An assessment of the data in NUREG/CR-6436 shows that the contribution of transient events can be discerned and lower emissions levels more likely to be the result of continuous-wave conducted interference can be identified. The weakness of the ORNL survey in supporting the development of a new CS114 limit is that it only captured a sparse set of measurements from a few cable bundles. Therefore, it does not provide sufficient data to generalize conclusions about representative plant envelopes for the conducted interference phenomenon. However, it does strongly support the expectation that a better characterization of the conducted interference conditions at NPPs can be determined through additional measurement and analysis.

## 4.3 RECOMMENDATIONS

The third strategy described above would enable uncertainty and potential unnecessary conservatism to be addressed in the basis for the CS114 limit. Specifically, additional measurements and analysis could definitively prove the EPRI contention that transient events unduly influenced the bounding plant emissions envelope for high-frequency conducted interference and serve to provide an appropriate basis for a new limit. This strategy is the preferred approach to resolving concerns about the CS114 limit. However, it is recognized that acquiring additional data could prove to be a costly and time-consuming effort. Therefore, it is recommend that, at least in the interim, the second strategy should be adopted. The revised CS114 limit under this strategy provides a relaxation in the severity of the test below 150 kHz. It is also roughly equivalent to the limit for IEC 61000-4-6 above 150 kHz so it is consistent with consensus industrial practice. Finally, the revised CS114 limit and the CS101 limits provide complementary frequency coverage to ensure that the conducted emissions data from NPPs, which were evaluated in the process of establishing current regulatory guidance, remain bounded by susceptibility testing.

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